Section II: Workshop Presentations

Presentation Themes

The workshop was organized around three primary themes. The themes represent the multidisciplinary nature of the workshop and include physical/biological, technical, and management considerations. The implications and importance of these interacting components are integral in developing remote sensing products that are both informed by sound science and provide information to managers that assists them in making credible management decisions. This portion of this document will provide an overview of these themes through synopses of workshop presentations. An asterisk (*) indicates a workshop presenter.

Physical and Biological Considerations

Presentations on physical oceanography and coral reef biology contributed to the workshop by providing participants with an understanding of the extent of our knowledge in regard to the environmental factors that influence coral reefs and our knowledge of how coral reefs are affected by these factors. Topics included the role of waves and mechanical damage to coral reefs, monitoring systems available for monitoring physical parameters, factors that influence coral resilience to climate change, variables that influence coral vulnerability, coral reef monitoring methods, and the symbiotic relationship between coral and zooxanthellae. The following is a synopsis of each presentation in this section of the workshop.

Oceanography, waves, and mechanical damage

Scott F. Heron[1] and Craig R. Steinberg[2]*

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Coral reefs are affected by a number of oceanographic and atmospheric physical phenomena Factors such as thermocline tipping as a result of the acceleration of major currents, connectivity between reefs, eddies and recirculation, upwelling and downwelling, and gradients in salinity as a result of freshwater inputs or evaporative effects from isolated water bodies all play a role in the health of coral. Most of these components can be measured by remote sensing devices, such as the monitoring of waves and salinity with satellites. Other sources of obtaining useful wave information include the use of ground-based radar and hydrodynamic wave modeling. Through the use of these tools it is possible to analyze the physical forces that influence the health of coral reefs. If these data were to be combined with additional ecosystem impacts, as Heron pointed out, a composite index of reef longevity may be of use in management planning decisions.

Abstract
The interactions of the physical ocean with coral reef ecosystems cause a multitude of effects. These include thermocline tipping related to the acceleration of major currents; physical connectivity between reefs; mesoscale eddies and recirculations, and resultant upwelling or downwelling; and salinity effects, such as freshwater inputs from river plumes and evaporative hypersalinity in enclosed water bodies (atolls, lagoons). Mixing of the vertical water column can be due to current shear (bottom friction) and/or wave energy, particularly at the reef front. Waves can be monitored using satellite and ground-based radar systems and by hydrodynamic-wave modeling. Mechanical damage to coral reefs is an extreme of wave impacts that may result from tropical storm and tsunami events. The combination physical oceanography with other ecosystem impacts and responses can define the longevity of reef ecosystems.

Vulnerability of coral reefs in a changing climate

Ove Hoegh-Guldberg

University of Queensland

This presentation describes, the complexities of understanding how corals react to climate change. While coral bleaching has utility in indicating the sensitivity of coral to thermal stress, more research is needed to ascertain the role of other factors in the bleaching process. For instance, there is some evidence that seasonality, coral and/or *Symbiodinium* species, sedimentation, and nutrient concentrations can influence coral sensitivity to sea temperature. In addition to stressors of coral, there is a need to include other organisms and ecologically important processes to fully understand coral reef sensitivity to climate change, such as coral reproduction and inhabitation of impacted coral areas by fish. This is necessary because bleaching does not tell researchers how the ecosystem is responding to increased sea temperatures and other disturbance factors at the ecosystem level. A number of considerations for ways coral may be able to cope with these external stressors were also mentioned, but it was emphasized that these considerations were not likely due to temporal constraints and evolutional incompatibility. Two of the prevailing considerations included (i) whether or not corals can change their sensitivity over time and (ii) whether or not it is possible for corals to exchange less thermally tolerant *Symbiodinium* for more thermally tolerant *Symbiodinium*. In the first consideration there are a number of ways that corals can alter their sensitivity through adaptive processes such as mutation, genetic drift, social recombination and gene flow; however, it is largely thought that the temporal pace of climate change will exceed that of the aforementioned evolutionary processes. In the second consideration Hoegh-Guldberg explained the idea of exchanging the *Symbiodinium* of the coral to increase its thermal tolerance. While some coral may manipulate the mix of two or more genetic strains of *Symbiodinium,* the relationship between coral colonies and their *Symbiodinium* are tightly linked and much of the evidence indicates that the ability to exchange thermally tolerant *Symbiodinium* amongst different coral types is an unlikely prospect. In summation, Hoegh-Guldberg recommends that local factors on coral sensitivity be explored in conjunction with the expansion of current measures to include reef processes and other reef organisms. In addition, seasonal variability, ocean acidification, and the notion that corals from highly variable environments have greater tolerance to climate change need to be explored.

Abstract

Understanding the vulnerability of coral reefs to climate change is central to our ability to develop effective strategies for managing these important environmental assets sustainably. In this talk, the component parts of vulnerability are presented and related to the three distinct expert communities that are concerned with the sustainable management of coral reefs into the future. Figure 1, adapted from (Schröter and ATEAM, 2004) illustrates the relationship between exposure (measured by remote sensing) and sensitivity (measured by biologists) in determining the potential impact on a reef attribute of value. Reef managers are principally tasked with the role of modifying the exposure and/or sensitivity through an influence on the adaptive capacity of the system being managed. How much they are able to do that influences the overall vulnerability of, in this case, the coral reef ecosystem. In this talk, I am going to focus on several issues that arise when measuring the sensitivity given that other more appropriate experts will discuss the exposure and adaptive capacity elements of vulnerability in depth.

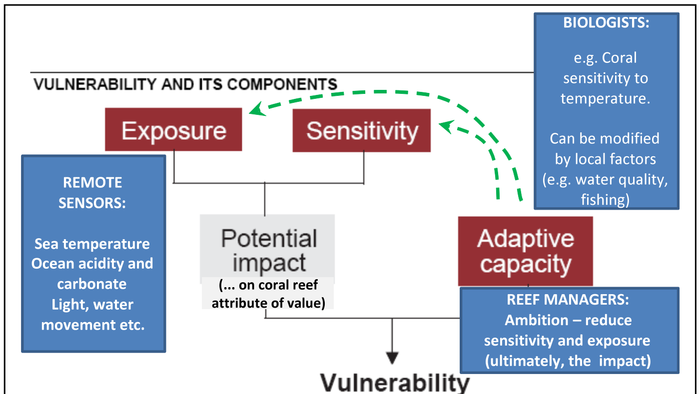

Fig 1. Adapted from D. Schroter and the ATEAM consortium 2004, *Global change vulnerability — assessing the European human–environment system*, Potsdam Institute for Climate Impact Research.

Bleaching as a proxy for the overall sensitivity of coral reefs to climate change

The tendency for corals to undergo bleaching (breakdown of their symbiosis with *Symbiodinium*) has been used as a proxy for the sensitivity of coral reefs to changes such as rising water temperature. In many ways, this has been highly successful and has led to accurate predictions of underlying retail. As Associate Professor Sophie Dove outlined in her presentation, there are some problems with using bleaching as the sole indicator of whether or not coral reefs are in a good condition or not. Corals that regain their color after a bleaching event, for example, have often been used as evidence that the reef has 'recovered' from the impacts of bleaching. Given that physiological processes such as coral reproduction may take several years to recover, using coral bleaching as an indicator would miss these sub-chronic impacts on health. As well, a study which we undertook as part of the ARC Linkage NOAA project (Diaz-Pulido et al., 2009) indicates that coral reefs that would have been written off had remarkable if not stunning rates of recovery (indicating that bleaching and mortality was not a good indicator of overall reef sensitivity to climate driven changes in water temperature). Similarly, as Associate Professor Dove indicated, many fish species remain absent from coral communities that would otherwise appear to have recovered or be in a high state of health. For this reason, it is very important that we consider adding other organisms and potentially ecologically important processes to the set of proxies, which we might use to determine how sensitive coral reefs are to climate change.

Factors affecting the sensitivity of corals to climate change.
Understanding how the sensitivity of corals can be affected by other factors, both local and global, is very important to the development of tools, which aim to track the vulnerability of corals over time. For example, it is important in terms of predicting the vulnerability of corals to a factor like sea temperature depends on how local factors such as water quality influences the overall sensitivity of corals to elevated sea temperatures. The influence of other factors on the sensitivity of corals will also be important within strategies aiming to reduce the influence of climate change on coral reefs. In this respect, there is evidence (albeit, in need of further exploration) that the sensitivity of reef-building corals to sea temperature is influenced by:

a. Seasonality
b. Coral and/or Symbiodinium species
c. Sedimentation
d. Nutrient concentrations

Can sensitivity change over time?
One of the most debated issues of recent times has been whether or not corals can change their sensitivity to climate change through genetic adaptation (evolution) quickly enough to keep pace with climate change. In this respect, sources of genetic variability are required in a population if natural selection is to produce individuals that have new traits with respect to new environments created by climate change. In this respect, new genetic variability can arise from mutation, genetic drift, social recombination, and gene flow. If one looks at the overall probability of new variation arising for a complex trait like thermal tolerance (which invariably involves multiple genes), the chance that these processes will provide enough variability to fuel the production of new individuals appears to be too short. The basis of this conclusion is the subject of a review of I am currently writing, and which will be in press later this year.

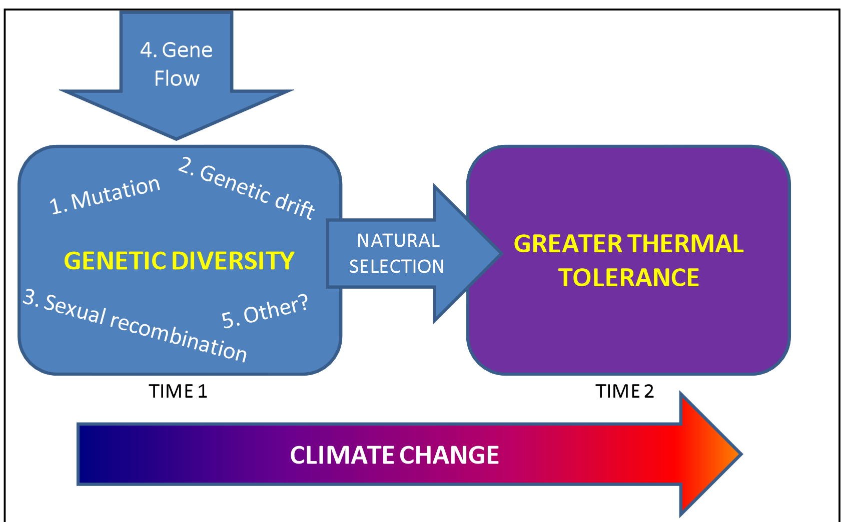

Fig 2. Key components of the variability that is needed to underpin the adaptation of corals through natural selection.

Changing the holobiont

The last source of potential variability for corals dealing with rapid changes to the environment around them comes from the idea proposed over 15 years ago (Buddemeier and Fautin, 1993). Inherent within this proposal is the assumption that the genetic strain of *Symbiodinium* ultimately determines the thermal tolerance of the coral-*Symbiodinium* holobiont. Despite the obvious problems with assigning thermal tolerance to solely to a partner (which only represents less than 10% of the biomass of the holobiont), the evidence for corals being able to form completely novel symbioses with new varieties of *Symbiodinium* in ecological time frames is completely absent from the scientific literature. On the other hand, there is some evidence that a small number of corals may manipulate the relative mix of two or more genetic strains of *Symbiodinium*, and that some of these symbionts are associated with hosts that have higher thermal tolerances. Our laboratory has accumulated substantial evidence that the variability in the genotype of *Symbiodinium* is directly correlated with genetic variations in the host species.

In a series of transplant experiments, (Sampayo et al., 2007) were able to show that deep water members of some species of corals had different symbionts to the same species found in the shallows. The critical piece of information comes when deep-water corals are transferred to the shallows and shallow-water corals are transferred to the deep. If corals transferred to deep-water switch to deep-water symbionts, then co-evolution is minimal and switching represents a possible way to vary sensitivity. If, on the other hand, corals transferred to deep water retain shallow water symbionts, then co-evolution of host and symbiont would be suspected – and the sensitivity of corals relatively inflexible in ecological time frames. Sampayo *et al.* (2007)'s observation that transplantation did not lead to a change in the host-symbiont combinations confirms that host and symbiont are involved in a closely coevolved relationship which does not allow the flexibility in ecological time frames for changing the type of symbionts that inhabit host coral tissues. This work backs up similar observations by (Iglesias-Prieto et al., 2004) and others (Bongaerts et al., 2010), and suggests that the ability for the sensitivity of corals to change as a result of this mechanism is more or less non-existent.

Conclusion and recommendations:

Understanding the sensitivity of reef-building corals factors such as temperature and acidity is critical to the development of effective and accurate satellite tools for tracking their overall vulnerability to climate change. In exploring the sensitivity of coral reefs to climate change, it is important that we begin to consider other types of organisms and ecological processes which will give us a more complete picture of their vulnerability to climate change. There is strong evidence, as well, that the sensitivity of corals to factors such as elevated sea temperature may be seasonal, influenced by local factors such as water quality, and may vary significantly geographically and among species and communities. Evidence that corals and their symbionts can undergo rapid evolutionary change is missing at this point, and even the most optimistic assumptions about sources of variability lead to the conclusion that the evolution of the sensitivity of corals is far too slow to keep pace with our rapidly changing global climate.

Given this and other issues outlined in this talk, it is recommended that:

1. Current measures of sensitivity are expanded beyond coral bleaching and mortality (*e.g.,* to include other organisms, reef processes, *etc.*). Caution must also be applied in

terms of how we interpret changes in the frequency of bleaching given that communities structure may be changing towards more thermally tolerant yet more vulnerable (to other factors such as disease) communities and coral reef ecosystems.

2. Seasonal variability in sensitivity needs to be explored and, if it exists, incorporated into how seasonality is used to inform predictive models (*e.g.,* seasonally shifting thresholds) – as well used to recognize how communities might change as conditions change.
3. The impact of local factors on sensitivity must be explored. If this is significant, the influence of local factors needs to be incorporated into measurement systems and remote sensing strategies.
4. Exploring how ocean acidification is likely to vary the sensitivity of coral reefs to other climate change related stresses such as sea temperature must be a priority of future studies.
5. Understanding how sensitivity varies according to environmental variability in stresses will be important if we are to understand coral reef vulnerability to climate change. In this regard, the suspicion that corals from highly variable environments have greater tolerance to climate change needs to be explored.

<u>The zooxanthellae story: Does it matter for management? How can satellites help?</u>

Ray Berkelmans and Madeleine van Oppen

Australian Institute of Marine Science

In this presentation Ray Berkelmans expands on the question of whether or not zooxanthellae have the potential to withstand the changes brought about by climate change, how this links to management, and the use of remote sensing tools. Beginning with an overview of the corals in Australia's Great Barrier Reef (GBR) that have the ability to host a mixture of zooxanthellae genotypes (70% of GBR species are capable of this) Berkelmans discussed the concept of 'shuffling' wherein individual corals change the dominant symbiont types after a period of thermal stress. *Acropora millepora* is one species of coral with this ability. This is interesting because experimental evidence suggests that shuffling from sensitive clades of zooxanthellae, such as C2, to tolerant clades of zooxanthellae, such as D, can increase thermal tolerance in *Acropora millepora* by 1- 1.5^{o} C. While Berkelmans noted this as an interesting prospect, he also explained that there are caveats. The research is still in its early stages and it is not possible to extrapolate, from one coral species to all coral, the ability to acclimate to climate change. Furthermore, in some of the studies where coral have shifted their symbionts, the corals shift back to the original zooxanthellae after a few months. Lastly, Berkelmans pointed out that even if the shift to more tolerant zooxanthellae was possible, there could be physiological costs to the coral as a result. Despite these caveats, there are insightful uses to the knowledge gained in these preliminary findings. Managers may be able to use this information in efforts to map resilience. For example, coral communities with diverse symbiont types may be able to cope with thermal stress more adeptly and serve as a resilience indicator for managers. High fluorescent proteins in coral have the ability to modulate light stress in corals and may be yet another useful resilience indicator. Pigment is another characteristic that would be useful when mapping resilience. Corals with dark pigment are more sensitive to bleaching than corals with a lighter pigment. Therefore, if remote sensing could be used to identify locations of darkly pigmented corals, it would contribute to the mapping of resilience. While the science of investigating thermally tolerant symbionts is still in its preliminary stages, there is a great deal of contemporary information that would allow scientists and managers to move forward with conservation efforts.

Abstract
The biology of corals can have a substantial effect on their bleaching susceptibility. Symbiont (zooxanthellae) make-up and pigment state of corals are two important characteristics, which can modulate its bleaching response. Approximately 70% of corals on the GBR contain a mixture of zooxanthellae genotypes. It has also been established that individual corals have the potential to change dominant symbiont types following thermal stress by a process known as 'shuffling'. Symbiont shuffling in *Acropora millepora* on the southern Great Barrier Reef has been shown to occur after an intense but relatively small-scale bleaching event in 2006. Experimental evidence suggest that shuffling from sensitive C2-type zooxanthellae to tolerant D-type zooxanthellae can increase thermal tolerance in this species by 1 – 1.5 deg C. These are tantalizing snippets of science that suggest a capacity of reefs to acclimatize to warming waters. However the science is in its early stages and it would be dangerous to extrapolate beyond a small number of studies where symbiont shuffling has been shown to occur, or the single coral species in which increased thermal tolerance was demonstrated. In addition, where symbiont shuffling has occurred, a gradual drifting back to pre-stress symbiont communities has occurred over a period of months. We also do not know what the necessary pre-conditions are for corals to shuffle symbiont types. Even if coral communities could acclimatize permanently to a more thermally tolerant type, there are physiological costs, in particular in decreased growth and reduced fecundity.

Notwithstanding the above caveats, there may be value to managers in mapping the natural occurrence of symbiont types on coral reefs. Communities with diverse symbionts types may have a greater capacity to withstand acute thermal stress events and as such may be an important resilience indicator. High levels of fluorescent proteins in corals may be another resilience indicator as these provide an additional mechanism to modulate light stress in corals. High zooxanthellae pigment density on the other hand is likely to make them more vulnerable to bleaching. Tissue temperatures of dark corals have been shown to be 1.5 – 2.0 deg C warmer than the surrounding water in calm, high irradiance conditions. These are the exact conditions we usually experience during "doldrum" periods, which are frequently associated with coral bleaching episodes. Inshore turbid reefs generally have darkly pigmented corals and are hence likely to be more bleaching sensitive. Satellites may be able to help predict where areas of high symbionts diversity and/or fluorescent corals are, or conversely, areas of darkly pigmented corals.

Monitoring the biological state of coral reefs: Current technology

Hugh Sweatman

Australian Institute of Marine Science

This presentation emphasized how monitoring serves two primary functions. The first of these is providing "situational awareness" to provide observations on stressors to coral reefs, which can in turn be used to inform managers so that they may use this information to inform stakeholders and policy. The second is determining whether or not management policies are effective. Information gathered through this process is helpful but there are different categories of useful monitoring information. The best variables or indicators are derived from ecosystem functional processes. However, these are complex to measure. The more tangible means of monitoring include identifying stressed ecosystems as opposed to healthy ecosystems. By examining the abundance of sensitive organisms it is possible to determine the extent to which external factors are impacting the location. According to Sweatman, an ideal suite of indicators would include sub-lethal stress variables. Numerous advancements have been made in order to enhance the monitoring process, such as using autonomous vehicles and *in situ* instrumentation, but more work needs to be done to automate this process. This is largely because the extensive amount of data that is gathered through these mechanisms requires an individual to analyze the data, which can be time consuming.

Abstract
Monitoring the biological state of coral reefs serves two primary functions.

(1) Monitoring can give managers "Situational awareness" – information on occurrences that may need management intervention such as damage from flooding or bleaching as well as the appearance of new threats such as diseases or introduced pests. Sharing such knowledge with stakeholders (and with political masters) builds credibility.
(2) Monitoring can show whether or not management is effective. This can range from general information such as whether various indices of condition are increasing or decreasing across a reserve network to whether specific management interventions as no-take areas are achieving their goals.

This often touches on the complex subject of ecosystem health, which in turn comprises both "status" and the more conjectural "resilience," which can only really be assessed in retrospect. The best variables (indicators) to monitor are related to the maintenance of ecosystem functions, though these are often more complex to measure. Thus the extra effort involved in assessing the size structure of the coral colonies and fishes in a location can give information about population dynamics and allow distinction between relic assemblages of old individuals and assemblages with sustaining rates of recruitment that are likely to persist.

It is easier to identify attributes of stressed ecosystems than healthy ones. As a generalization, stress reduces the abundance of sensitive organisms resulting in drops in diversity and different frequencies of disturbance favor organisms with different life-history strategies, with frequent disturbances favoring "weeds" and long intervals between disturbances favoring species that occupy and hold on to space.

The ideal suite of indicators would include some that indicate sub-lethal stress.

There are moves to make more use of autonomous vehicles and *in situ* instrumentation. The former needs to be linked with major advances in automated processing, primarily of image data; it is currently relatively easy to gather enormous numbers of images, but the task of analyzing them for useful biological content involves many laborious man-hours.

What are the key environmental variables that contribute to coral vulnerability and resilience?

Roberto Prieto-Iglesias

Universidad Nacional Autónoma de México

In a presentation about the role of multiple stressors on coral reefs, Roberto Prieto-Iglesias explained the fundamental biological and societal roles of coral reef health and contribution, such as net increase in calcification of the reefs and environmental services (biodiversity, tourism, fishing, coastal zone protection) provided by the reef. Iglesias also discussed the multiple roles of light in the life of corals. With the advent of climate change many of these fundamental biological processes and ecosystem services are threatened by increasing sea temperatures (bleaching) and ocean acidification (erosion). Therefore, it is important to analyze the multiple stressors of coral to provide a realistic and holistic explanation of how combined factors affect coral. Prieto-Iglesias began with the processes of photosynthesis and respiration of coral reefs, which are essential for coral growth via calcification. Insolation used for photosynthesis is not constant, however, and coral have developed mechanisms (photoacclimation) to regulate light by interchanging intensity of the light field and/or photosynthetic sinks. Coral symbionts can sense the changes in light conditions, in addition to other sinks, such as carbon, nitrogen, oxygen, and sulfur, which can modulate the flow of electrons to the host and sense excessive light. Because of the symbiotic relationship coral have with zooxanthellae, the effects of light and other factors like temperature, water motion, and nutrients in a particular location can have varied influences on coral. For instance, the same coral species in one area may look very different in color and shape depending on light, nutrients and other conditions in another habitat. This prospect is very exciting for scientists using remote sensing to asses coral health because if there is a potential for incorporating all of the varied factors that influence coral growth, it is possible to derive coral products from remote sensing data and models that indicate coral growth and calcification. In order to obtain light information from coral it is necessary to measure the incoming light and reflected light through direct *in situ* remote sensing of the coral and to take core samples of coral for laboratory tests. Several studies were discussed to illustrate multiple conditions wherein light either damages corals enough so that they will not fully recover or conditions where light inputs are adequate for recovery. Another important example was the role of seawater flow and mixing over corals. In a study by (Mass et al., 2010), which was discussed in the presentation, there is evidence that water flow over corals enhances the photosynthetic rate of corals by increasing the release of oxygen from the organism into the water. Light stress is a result of whether the coral can deal with the incoming light (temperature) and if the coral has enough sinks to buffer itself from excess excitation energy. After a certain degree of increased temperature, most corals will reach a point where they are incapable of repairing themselves. However, some coral species have zooxanthellae that are more capable of repairing themselves. Prieto-Iglesias provided an example where *Porites cylindrica* was capable of experiencing thermal stress and repairing itself to previous conditions whereas *Stylophora pistillata* was not. Another notable distinction was that the pigment or color of the zooxanthellae was not important to bleaching, but the quantity of symbionts in the coral was. This is an important biological component to consider when determining bleaching criteria for remote sensing products. Ocean acidification was discussed next. Because ocean acidification is linked to photosynthesis it is important to consider how these interact. In numerous examples a consistent trend emerged; where water temperatures increased, coral calcification decreased. Another example highlighted how ocean acidification model predictions are in agreement with current observations and in some cases worse. In summation, biological information exists that allow us to take into consideration multiple coral stressors, specifically light, temperature, nutrients and acidification and model these to see how corals will react to changing conditions. Current outlooks, however, are not good and even in the best modeling circumstances where "super corals" would somehow have the ability to acclimate to increasing temperatures, a characteristic many biologists agree is improbable at best, calcification rates would still decrease due to suboptimal temperature conditions.

Is coral bleaching a reliable indicator of coral reef vulnerability to climate change?

Sophie Dove

University of Queensland

A central argument of Dove's presentation was that "corals don't make reefs, other things have to be incorporated in it." In line with this logic is the assumption of recognizing that different attributes are appropriate at different scales. For instance, at the reef scale, net positive carbon balance is important. At the coral and Symbiont scale, genet or highest proportion of gene set survival into the future is important. Given these preconceptions, Dove asked the question "Is coral bleaching a reliable indicator of the reefs vulnerability to climate change"? Dove pointed out that from the point of view of managers and scientists, the predictability of mass bleaching has increased their credibility amongst policy makers and the general public. However, Dove's concern is if reefs were to stop bleaching, what symptom or indicator could scientists use to illustrate how environmental stressors adversely affect the health of coral reefs (*i.e.,* climate change, ocean acidification, land-based pollution, *etc.*). What additional indicators could be used to show that coral reefs are vulnerable to external stressors? An example of this used by Dove is one in which coral were subjected to highly acidic water where the coral polyps proved to be resilient, but the skeletons of the coral were affected, thereby diminishing the net reef building capacity of the coral. The corals in the study started out as hard corals with a skeleton. When the corals were subjected to highly acidic water, the coral polyps were resilient and able to exist biologically, but their reef building functionality was diminished or eliminated. There were corals but no reef. In other words, corals are a "necessary" contributor to reef building, but there are instances in which they are not "sufficient" reef builders. These characteristics of being "necessary" but not "sufficient," Dove argues, hold true for other organisms in coral reefs. For instance, presence of a symbiont is a necessary condition for coral autotrophy but not a sufficient condition, meaning that there may be a symbiont in the coral but the energy exchange between it and the coral may not be sufficient enough to say that the symbiotic relationship is "healthy." Finally, corals aren't a necessary condition for reef survival as Rudist Reefs (bivalve created reefs) were once prevalent.

Given these observations, Dove argues that looks can be deceiving and that new, alternative ways of gauging coral reef health and vulnerability should be considered. For instance, Dove argues that the statement "Shifting to new algal symbionts may safeguard devastated reefs from extinction" (Baker et al., 2004) is inherently flawed because of the previously mentioned argument. Just because a symbiont is in the coral does not mean that this relationship is sufficient. And just because coral is on the reef it does not mean that the contributions of the coral to the reef, in terms of calcification rates, is sufficient for net reef growth. Therefore, Dove suggests that Baker's logic is flawed and that coral reef scientists need to develop alternative means of assessing coral reef health. Despite this contradiction Dove mentions there are widespread uses of this line of logic from introductions of peer reviewed papers to reef health identification cards used for monitoring in which pigments are associated with coral health. The difficulty with developing alternatives to these widely used methods largely centers on developing individualized species thresholds for determining when a coral is healthy or unhealthy. This is no easy feat given the dynamics of coral reefs. Investigating this concept further Dove asks the question "Does bleaching necessarily lower net photosynthesis in *Acropora millepora?"* She found no one to one relationship between the photosynthetic production and pigment densities of symbionts. If the pigmentation densities are reduced, the symbionts work harder. If the pigmentation levels are higher, they work less. Another question posed was "Does bleaching necessarily increase propensity for polyp mortality"? Ray Berkelmans noted that he had data to suggest that bleaching does increase the propensity for polyp mortality, but Dove argued that it does not make a difference and that in previous studies bleaching resistant clade D coral had the same mortality as bleaching prone clade C coral. Another common assumption is that coral mortality is more important than coral growth. Dove argues that as long as the coral keep producing asexually in excess of their mortality then it really does not matter what their mortality rate is, considering they are largely from similar genets, and that it may be more beneficial to measure coral health by their growth. In summation, Dove argued that the reasons for reduced growth / death of coral, despite the abundant presence of the symbiont, is a result of a reduction in energy translocation from the symbiont to the host. This energy not only contributes to coral growth but also calcification. This is important because it suggests that bleaching tolerant corals are unlikely to contribute to the carbonate balance of reefs and further challenges the argument of Baker if we are to consider ocean acidification within the ambit of climate change. In the end, the challenge Dove emphasized is how do scientists convey the importance of reef growth in relation to reef health and how can we monitor the carbonate balance remotely?

Abstract
The ability of derived algorithms to predict mass bleaching events from remotely collected data has been highly successful from a management point of view, principally because it has increased the credibility of scientists, and thereby facilitated the uptake of "no-take" zones and other management strategies. Given that thermally driven mass bleaching events first appeared 30 years ago, most analyses point irrevocably to the conclusion that our reefs are changing negatively, especially given the high rates of mortality that follow many mass bleaching events. There has, however, been a tendency to identify "bleaching" as the problem, rather than as a symptom or a manifestation of a more insidious underlying threat to reefs. The later being a reef syndrome that is not necessarily accompanied by a beacon as obvious as a bleaching event. This syndrome is the decline in the ability of hermatypic corals to sustain net reef calcification and hence provide valuable ecosystem services such as coastal barriers and fisheries habitat. Coral bleaching is also frequently presented as the breakdown in the symbiosis between corals and their endosymbiotic algal partners. Frequently forgotten from this statement, however, is the notion that symbiosis covers a continuum from

mutualism, to commensalism, and ultimately to parasitism. Coral growth and calcification are sustained because the relationship is mutualistic and that the coral derives sufficient supplementary energy from their symbionts for these processes in addition to that which it can acquire through heterotrophy. The key observation is that symbionts can persist within corals, but that the relationship can, through environmental change, be driven towards a commensalism that does not effectively support long-term positive net coral growth or the required rates of calcification that are necessary for reefs to stay ahead of the natural forces of physic and biological erosion. Some have postulated that the advent of non-bleaching corals may save coral reefs. To maintain our credibility as scientists, however, we should be asking: Will coral reefs be safe from global warming if reefs were to stop bleaching? If 'bleaching' is identified as the problem *per se* (as it is in all those scientific articles where dark corals are explicitly labeled healthy, and pale corals implicitly assumed unhealthy), then the answer to this question would be 'yes'. However, to conclude this would be to ignore periods as long as several million years in the history of our planet where corals have existed yet coral reefs have been absent. This issue is discussed in terms of understanding and solving potential shortcomings of satellite-based products for the detection of coral reef health.

Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia

Scott A. Wooldridge

Australian Institute of Marine Science

In this presentation Wooldridge argues Dissolved Inorganic Nitrogen (DIN) contributes to temperature stress by reducing the bleaching resistance of symbiotic reef corals. In the first section of the talk Wooldridge explains the direct linkages between DIN and bleaching that have been found in other studies, which suggest that exposure to DIN with concentrations of $< 1 - 10$ μM have a detectable impact on temperature-dependent bleaching sensitivity. Wooldridge provided additional studies that have indirectly suggested that DIN works in conjunction with water temperature to reduce the bleaching resistance of coral reefs. In Wooldridge's studies, near shore and off shore sites were used in comparison to determine whether or not increased nutrients supplied by river plumes near land influence the bleaching tolerance of coral reefs. Using methods such as geographically weighted regression and Bayesian network-modeling, Wooldridge was able to spatially discriminate amongst areas that had more or less of a propensity to bleach. An additional consideration mentioned the role of currents in the process of bleaching and exposure to DIN via mixing and upwelling. To investigate this, the influence of riverine and upwelling impacts were merged into a singular DIN product. The relevance of this product is that DIN exposed corals have enlarged (fast growing) zooxanthellae populations and that bleaching sensitive corals are characterized by the same type of (large) zooxanthellae population. Therefore, if we have a metric for identifying areas of high DIN, it is possible to locate bleaching sensitive corals. It was also pointed out that these same large zooxanthellae populations may be an asset during the colder winter months and that high nutrient levels and temperatures may not need to co-occur for the impacts of nutrients to be important. The significance of these findings can inform management efforts, such as designating protected areas, and serve as preliminary studies to more fully understand the concept of a DIN / bleaching biophysical linkage. This is especially the case when Wooldridge estimates that within a disturbed inshore area, the reduction of terrestrial DIN has the potential to reduce the upper thermal threshold of bleaching by roughly 2 °C.

Abstract
The threats of wide-scale coral bleaching and reef demise associated with anthropogenic climate change are widely known. In this presentation, I consider the additional role of poor water quality in lowering the bleaching 'resistance' of symbiotic reef corals. In particular, I outline a quantitative linkage between terrestrially-sourced dissolved inorganic nitrogen (DIN) loading and the upper thermal bleaching thresholds of inshore reefs on the Great Barrier Reef, Australia. Significantly, this biophysical linkage provides concrete evidence for the oft-expressed belief that improved coral reef management will increase regional scale resilience of corals reefs to global climate change. Indeed, for the most disturbed inshore areas I demonstrate that the potential benefit of this 'local' management imperative is equivalent to ~2.0° C in relation to the upper thermal bleaching limit.

***In situ* monitoring of environmental coral stress**

Al Strong[1], Jim Hendee[2], Craig Steinberg[3] and Rusty Brainard[4]*

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A number of observing systems are placed adjacent to coral reefs throughout the world. Many of these are collectively situated within the network of NOAA's Coral Reef Ecosystem Integrated Observing System (CREIOS). Platforms such as the Coral Reef Early Warning System (CREWS) stations, which are part of NOAA's Integrated Coral Observing Network (ICON), and Virtual Stations, operated by Coral Reef Watch, provide data to researchers and managers for a variety of purposes. These observation stations provide high-quality meteorological and oceanographic *in situ* data in real-time. The equipment used to gather this data include satellites and multiple generations of remote access data loggers attached to buoys and pylons. With the use of these systems researchers have been able to compare disparate ecosystems with one another on a variety of ecological impacts such as nutrient loading, sedimentation, ocean warming and ocean acidification. Furthermore, if these stations acquire reliable data they can be used for remote sensing calibration and validation.

Abstract
To provide integrated *in situ* interdisciplinary ecosystem observations, a network of Coral Reef Ecosystem Integrated Observing Systems (CREIOS) is evolving within NOAA's Coral Reef Conservation Program to better organize and build upon some of the existing coral reef observation systems being developed domestically. These *in situ* programs throughout the Pacific and Caribbean are outlined in this paper to demonstrate some of the approaches and technologies available for acquiring biological, physical, and geochemical observations

using combinations of visual surveys, moored instrument arrays, spatial hydrographic and water-quality surveys including satellite remote sensing (Virtual Stations – NOAA's Coral Reef Watch). Efforts to integrate across scientific disciplines and observational approaches including observations and monitoring will become more efficiently facilitated under CREIOS.

It is envisaged that CREIOS will ultimately sit at the pinnacle of a larger international coral reef monitoring and assessment network, providing the scientific validation and explanation for data obtained through basic, government-level monitoring, as encouraged by the GCRMN, and community and volunteer monitoring, as encouraged by Reef Check and other volunteer networks. Such a nested network would permit greater coverage of the world's coral reef areas, and increase awareness of reef status and problems. Though beyond the scope of this presentation, all monitoring activities should be complemented by socioeconomic assessments to ensure that the explanations are complete and conveyed to affected communities.

With a common goal that versatile, accessible, and robust observations will be enhanced, the existing infrastructure and capacity provides a foundation by which increased global cooperation and coordination to develop common protocols and standards could naturally lead to a broader, more globally comprehensive CREIOS. This fledgling network represents the early stages of an integrated observing system for coral reef ecosystems capable of providing policymakers, resource managers, researchers, and other stakeholders with essential information products needed to assess various responses of coral reef ecosystems to natural variability and anthropogenic perturbations. The network's continued support and further development will ensure the increasing value of its data holdings and the network's observational and predictive capacity.

The CREIOS-Pacific *in situ* network, directed by Dr. Rusty Brainard out of NOAA's Coral Reef Ecosystem Division in Honolulu, combines an array of instrumented platforms with regular ecological field observations that are capable of providing resource managers, researchers, and other stakeholders with the ability to discern and assess responses of coral reef ecosystems to oceanographic processes. The network has enabled comparisons of heavily impacted and degraded reef systems with remote, relatively pristine reef systems on multiple spatial scales through comprehensive standardized data sets. Through these direct comparisons, researchers are rapidly improving their ability to assess both local ecological impacts, such as nutrient loading and sedimentation, extractive activities such as fishing, and predicted global effects such as ocean warming and ocean acidification.

The Integrated Coral Observing Network (ICON) program, under the leadership of Dr. Jim Hendee of NOAA's Atmospheric & Oceanographic Marine Laboratory in Miami, has constructed and installed a series of Coral Reef Early Warning System (CREWS) stations which provide a wealth of high-quality meteorological and oceanographic *in situ* data in near-real-time. CREWS stations date back to 2001 with the deployment of an early buoy-type design in the Bahamas. Beginning in 2002, the program shifted to a pylon-type design, which was reengineered in 2005, resulting in the modern CREWS stations found in the Bahamas, Puerto Rico, the US Virgin Islands, Little Cayman and Jamaica. The ICON/CREWS instrumentation architecture described has evolved over time into a robust package that, combined with a regimen of regular instrument cleaning and recalibration, has yielded a continuous, long-term, high-quality dataset from these harsh marine environments.

Technical Considerations

Technical considerations constituted a large portion of the presentations and discussions mentioned in the workshop. These included remote sensing, modeling, and information technologies that applied, or could apply, to coral reef biology, monitoring and databases. This segment of the paper will sequentially discuss the technical aspects of remote sensing, modeling and information technologies mentioned during the workshop.

Satellites and remote sensing: An introduction to environmental remote sensing of the marine environment

William Skirving[1] *and Kelvin Michael*[2]

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This presentation discussed the fundamental components of remote sensing, which included the definition of remote sensing, the use of the electro-magnetic spectrum and ways in which algorithms can be constructed from a combination of brightness (radiometric analyses), color (spectral analyses), and texture (spatial analyses). The presentation provided a simple and effective way of understanding how remotely sensed products are developed. In addition to the way data are analyzed, Skirving pointed out some of the common platforms that are used to obtain remotely sensed data of the marine environment, such as satellites, aircraft, near surface, and sub-surface instruments. Additional topics included the types of indices we can obtain through remote sensing and the algorithms that we can employ to derive additional data from raw, remotely sensed, images.

Abstract
This talk covers the basics of Remote Sensing methodologies and algorithms. It describes the various platforms in use and how they are used to derive the amazing array of marine products.

Remote sensing coral reef environmental stress: Where we are now

C Mark Eakin[1], *Dwight K. Gledhill*[2] *and Gang Liu*[1]

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This presentation focused on two of the most prominent stressors to coral reefs, increased sea surface temperatures and ocean acidification, both of which are the result of climate change. Remote sensing is a useful tool for monitoring these indices because it provides multiple types of information gathered from a global scale, a scale that *in situ* measurements are simply not capable of monitoring. By providing data at these scales, coral reef managers are able to identify, prioritize, and mobilize management efforts in specific locations. Furthermore, through the archiving of this data it is possible to analyze change over time and track disturbances. Remote sensing data is not without errors, however. Cloud cover and coastal areas with turbulent waters (a.k.a. case 2 waters) can result in images that are incapable of being analyzed or difficult to analyze, respectively. Imagery correction, acquisition of some types of remotely sensed data, and calibration and validation with *in situ* instruments can also be expensive. Despite the technical complications inherent with remotely sensed data, the benefits often outweigh the disadvantages. Currently several coral reef watch products are operational and there are more experimental products in development that Mark Eakin discussed. The operational products Coral Reef Watch provide include near global coverage of 50-kilometer pixel sea surface temperature (SST), SST Anomaly, Coral Bleaching HotSpots, Degree Heating Weeks, "Virtual Stations" and Coral Bleaching Alert Areas. Experimental products currently under development include a finer resolution land mask to make more of the coastline available for analysis, an enhanced spatial resolution for both remote sensing data and climatology, transitioning from a 50 km to 4km pixel resolution, and the repair of inaccuracies in the climatology. Additional new products include an ocean acidification product, a disease outbreak product, a winds product, and an ocean color product for detecting stressors like sediment and chlorophyll *a*. Future products in consideration include a light proximity index that provides a proxy for development in coastal areas and the mapping of coral reefs at high spatial resolutions to map community changes over time and bleaching incidents. Currently high spatial resolution data are not feasible for use at a regional or global scale due to prohibitive costs and time investments.

Abstract

As carbon dioxide rises in the atmosphere, climate change and ocean acidification are impacting physical and chemical parameters in the oceans causing important changes to coral reef ecosystems. At the same time local perturbations continue to have significant impacts on reef systems. As we look to manage coral reefs, especially in light of climate change, there are key environmental parameters that we need to monitor. Because satellites can usually provide products at a wide geographic coverage at no cost to local managers, they can provide monitoring at sites and spatial scales that are not possible through *in situ* monitoring alone. We can combine satellite remote sensing with other monitoring to enhance capabilities, can track disturbances and environmental changes, and provide moderately-long, continuous time series for hindcasting and research. Satellite data are not without their weaknesses. Calibration and validation of new algorithms and data streams can be an expensive process and relies on *in situ* data that may not exist. Most satellites detect light for parameters like temperature and color and are blocked by clouds. Some parameters require data from commercial satellites and may be too expensive for monitoring.

Monitoring for the Stress that Causes Coral Bleaching

The Coral Reef Watch (CRW) program at the US National Oceanic and Atmospheric Administration (NOAA) uses near-real-time satellite measurements of sea surface temperature to monitor for thermal stress. These operational data provide up-to-date measurements to pinpoint areas that are currently at risk for coral bleaching using 50 km (0.5°x0.5°) nighttime SST data. The most important index that CRW produces is the Degree

Heating Week (DHW) that provides the accumulation of thermal stress over time that can cause coral bleaching. When SST rises above a bleaching threshold temperature, 1°C above the mean temperature for the warmest month, DHWs begin to accumulate. Thermal stress builds up over a 12-week window, providing a reliable indicator for coral bleaching and mortality. While these products are made available through broad-scale data fields, NOAA's "virtual stations" provide information on thermal stress at over 190 coral reef sites around the world. Like the broad-scale products, these can be accessed through the Internet. An important tool for local managers is the automated bleaching e-mail alert system for the virtual stations. These are sent out to subscribers around the world, providing information on threats at the local level at times when corals are threatened with bleaching.

Recent improvements have addressed three limitations in NOAA's current operational global data:

1) Inaccuracies in the climatology
2) Land mask
3) Data/product resolution

NOAA has developed a new experimental product that addresses the first two of these issues globally. Using a new climatology built from the 4km Pathfinder dataset, CRW has produced a new climatology that corrects the climatology in certain areas of the world where there were known errors in the old climatology. More importantly, the 4km data allowed CRW to develop a climatology that encompasses near shore areas. This has been used with near-real-time satellite data within pixels previously masked out to extend the existing product site right up to the coastline. Where the old land mask prevented direct observations on 60% of the world's reefs. The new Enhanced 50km products directly observe SST and thermal stress on over 99% of reefs. Local efforts have developed higher resolution products such as the operational ReefTemp product from the Great Barrier Reef Marine Park Authority and developmental efforts at the Australian Institute for Marine Science and the University of South Florida are providing high resolution (1-3 km) SST data and thermal stress products for the Great Barrier Reef (GBR) and Caribbean. Combining temperature and light is providing new possibilities of improving our monitoring of bleaching. As bleaching occurs as a result of the thermal stress to the photosystem of zooxanthellae, a new physiology-based algorithm using these two parameters especially promises a potential for better estimates of coral mortality and rates of recovery from bleaching.

New Observations and Improved Applications

Other new developments are bringing new data into our observations of coral reef stress and existing data are being used in new ways. One new project uses SST to predict the potential for infectious disease outbreaks in corals, currently for the GBR and the Hawaiian archipelago. Another new parameter used for coral reefs is satellite-based winds. By looking at low wind conditions, it is possible to detect the doldrum-like conditions that can set off coral bleaching.

In a completely different area, recent work by NOAA has developed a system for monthly monitoring of ocean carbon chemistry. The model uses SST, salinity, and atmospheric CO2 levels to estimate changes in surface water chemistry. Currently limited to the Caribbean, these data provide information on changes in carbonate saturation state and other parameters relevant to ocean acidification and its impacts.

Optical remote sensing is another field of remote sensing that has been very helpful in oceanic waters and potential for coral reefs. While there are challenges in developing algorithms and quantitative ocean color products for coastal waters, new developments suggest that we may soon be able to develop products with application in coral reef management. Satellite observations of surface lights can provide new information on human development. The Light Proximity Index provides information on the development and human stress to reefs. This is important in remote areas with poor census and land use data. Finally, optical remote sensing can be used to map coral reefs, detect community changes, and directly observe coral bleaching. Some of these use publicly available data, but many of these efforts require high resolution (meters) data sensed from commercial satellites. In these cases, cost is currently a limiting factor in the widespread application of these techniques.

The important questions for coral reef managers are:
1) What are the new observations required from satellites?
2) What enhancements are needed for existing products?

Thermal stress links with coral bleaching and infectious diseases

Scott F. Heron and Alan E. Strong*

NOAA Coral Reef Watch

In this presentation two key satellite-SST monitoring efforts were mentioned, namely Coral Reef Watch's (CRW) Satellite Monitoring Product Suite and the ReefTemp project, a collaboration between Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), Great Barrier Reef Marine Park Authority (GBRMPA) and Bureau of Meteorology (BoM). In the coral bleaching segment of the talk, the methodology of how these products determine key SST indicators, such as CRW's HotSpots, Degree Heating Weeks (DHW) and ReefTemp's Degree Heating Days (DHD) and Heating Rate, were discussed in the context of how their respective climatologies are calculated. The presentation discussed the relevance of the fixed +1^{o}C threshold above the maximum monthly mean, currently employed by the CRW product suite, as an indicator of bleaching and whether or not we should be using additional components, such as local temperature variability, extreme lower temperatures, and current coral health status to assess bleaching. An additional thermal metric by CRW, the Short-Term SST Trend, was also presented. The short-term SST trend uses a shorter temporal span (21 days) to calculate the recent change in SST at a given location to provide managers with a rate of temperature change. SST data are currently being combined with other variables to experimentally predict coral disease. (Bruno et al., 2007) used weekly SST anomaly data with coral cover to illustrate how coral diseases have the tendency to occur in thermally stressed waters with high percentages of coral cover. Subsequent research efforts have led to the experimental coral disease outbreak product by CRW (Heron et al., 2010) as well as a ReefTemp coral disease outbreak predictor (Maynard et al., In Preparation). These efforts defined temperature metrics based on thresholds that include climatological averages and their standard deviations and then combined these with observations of *Acropora* spp. cover to predict outbreaks of white syndrome disease. By using SST metrics in conjunction with other variables, like coral cover, it is possible to predict coral disease events. A thorough understanding of the climatologies used in the bleaching and disease products, as well as the experimental nature of several of these, is essential for end users.

Abstract
Preceded by early findings of bleaching-inducing thermal thresholds during summer periods, several satellite-monitoring efforts are now operational, globally and regionally, to monitor thermal stress. These efforts utilize varying parameterizations for long-term means (climatologies) and thresholds to produce metrics that associate coral bleaching and disease outbreak events. Here we discuss the metrics and their differences with a view to applying similar methods in other applications.

Combining heat stress and light to produce a new bleaching product

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The experimental light stress damage (LSD) product uses remotely sensed SST and light data to monitor and predict coral stress that leads to bleaching. Developed from coral photobiology studies conducted in a series of studies from the Universidad Nacional Autónoma de México in the Mexican Caribbean, Skirving explained how the relationship between light and temperature results in the LSD product. Based on a function of SST and Photosynthetically Active Radiation (PAR), the LSD product is expressed as an index that mimics the reef-scale relative potential quantum yield (F_v/F_m). The index ranges from 0 – 1 where corals are expected to cope with light / temperature conditions in the 0.4 – 1 range and where corals experience light / temperature stress in the 0 – 0.4 range, which will result in bleaching and may result in coral death. Recovery is expected once values return above 0.4 on the index. The LSD product is another experimental product designed by CRW to predict various aspects of coral bleaching.

Abstract
NOAA Coral Reef Watch's (CRW) global near-real-time coral bleaching operational monitoring product suite is extensively used by US and international resource managers, reef scientists, and the general public to monitor thermal stress and predict the onset, development, and severity of mass coral bleaching. However, its algorithms are based solely on satellite sea surface temperature (SST) observations. The new experimental Light Stress Damage (LSD) introduced here is the first product to combine satellite-derived light and SST data to monitor/predict coral stress that can lead to bleaching.

The LSD product provides a relative measure of the effect of the combined light and thermal stress on the coral photo-system with values ranging between 0 and 1. Corals are expected to efficiently cope with light/temperature conditions when LSD value is close to 1,

but are expected to bleach when LSD value falls below 0.4. Recovery is expected once the value moves back above 0.4.

The LSD product is underpinned by a series of experiments done on corals at the Universidad Nacional Autónoma de México, Cancun, Mexico. These experiments allowed the determination of relationships between the excessive excitation energy (EEE), relative potential quantum yield (F_v/F_m), change in SST and differences in total daily photosynthetically active radiation (PAR), such that:

$$\left.\begin{array}{ll}\textbf{Temp:} & \dfrac{F_v}{F_m} = f(SST) \Rightarrow EEE_T = f\left(\dfrac{F_v}{F_m}\right) \\ \textbf{Light:} & EEE_L = f(PAR)\end{array}\right\} EEE = EEE_T + EEE_L \Rightarrow \dfrac{F_v}{F_m} = f(EEE)$$

Hence, in simple terms LSD is based on a function of SST and PAR and is expressed as an index that mimics the reef-scale relative F_v/F_m.

Monitoring coral surface UV & visible solar radiation from space

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This presentation described how light interaction affects coral and discussed the historical role of remote sensing in estimating surface radiation fluxes over land and the ocean. Characteristics that remote sensing satellites have been able to detect, such as cloud coverage, cloud fraction, and cloud thickness at various levels in the lower atmosphere were also discussed. Additional topics included surface reflectivity and atmospheric aerosol characteristics. These characteristics are important measurements for surface radiation characteristics but they may be unavailable for measurement by remote sensing satellites due to cloud cover or surface albedo. Applying simple statistical models to determine surface radiation flux can circumvent this issue. Radiative transfer models (RTM) have been used to develop comparatively accurate estimates of surface radiation flux under specific conditions. A complication with radiative transfer models is that they are computationally expensive, but as Michael pointed out, there are accepted hybrid approaches available that populate a multidimensional matrix (lookup table) through a more limited set of RTM calculations. This lookup table is then used in conjunction with satellite images to produce surface radiation fluxes. A drawback to the use of these models is that it is reliant on *in situ* measurements of light and water conditions for calibration and validation. Currently these *in situ* measurements are lacking in a variety of locations, especially in coral reef locations. Moreover, the spatio-temporal variability and optical properties of these measurements are not well understood. Nonetheless, research in this area is making strides. Michael presented animations from a three-dimensional radiative transfer model that depicted the way light flux interacts with coral and a map of global solar radiation over the Great Barrier Reef and its agreement with an independent assessment of coral bleaching during the 2001-2002 summer (Masiri et al., 2008).

Abstract
There is a rich history of satellite data being used to assist in the estimation of surface radiation fluxes over land or ocean regions. At a basic level, satellite data can map the coverage of cloud, but at a more sophisticated level can provide information on cloud fraction and cloud thickness at various levels in the lower atmosphere. Satellite data can also provide information on surface reflectivity, and more recently on atmospheric aerosol characteristics.

A surface radiation flux estimate can be derived with a simple statistical model, where the role of satellite data may be restricted to cloud information and surface albedo. More commonly over the last decade, radiative transfer models are employed to produce more accurate estimates of surface radiation flux under specified conditions – however these RTMs are computationally expensive. An accepted hybrid approach is to populate a multi-dimensional matrix (look-up table) via a more limited set of RTM calculations. Then the look-up table is employed to produce surface radiation fluxes corresponding to a given satellite image.

Model development requires *in situ* measurements – for calibration and validation in the case of statistical models, and usually for validation only in the case of physically-based models. The *in situ* data need to be collected with an appropriate radiometer, working in the relevant region of the spectrum (*e.g.*, global solar radiation, PAR, UV, UV-A, UV-B, *etc.*). Reliable *in situ* data is not widely available in space and time, and its availability in coral reef regions is particularly limited. The accuracy of surface radiation fluxes is typically 5-20% for instantaneous / daily values. These errors can be greatly reduced via temporal averaging.

To estimate light delivered to the *coral surface*, it is necessary to have knowledge of the water conditions, in particular its optical properties in the relevant part of the spectrum. Again, there is little data on these optical properties, and even less is understood about its spatio-temporal variability.

Finally, some example animations from a three-dimensional radiative transfer model for shallow water environments are shown, as well as some discussion of the results of a large-scale mapping of global solar radiation over the Great Barrier Reef and the level of agreement with an independent assessment of coral bleaching over the 2001-2002 summer (Masiri et al., 2008).

Water quality: What is the current capability of ocean color products in shallow coastal waters?

Arnold Dekker

The Commonwealth Scientific and Industrial Research Organization

Water quality stressors such as sediment and nutrients adversely affect coral reefs. In this presentation Dekker explained the biological and remote sensing complexity of analyzing water quality in coastal areas. In a singular remote sensing scene Dekker illustrated how it is possible to discern sediment deposited by river plumes, tidal resuspension of sediment near reefs, and algal blooms caused by nutrients. Due to natural variation in particulate matter and seasons, coastal (case 2) waters are difficult to analyze using remote sensing platforms. Many remote sensing platforms are specifically designed to analyze open (Case 1) waters and therefore require intensive *in situ* calibration and validation data, in addition to place specific algorithms for analyzing Case 2 waters. In examples of Australian rivers, such as the Burdekin and the Fitzroy River, varied water quality conditions were portrayed along with their respective spectral histograms. Each of these cases requires a unique algorithm for analyzing a specific type of water quality criteria. The primary types of water quality that are capable of being distinguished consist of chlorophyll, colored dissolved organic matter (CDOM), non-algal particulate matter and the vertical attenuation of light in the water column. In addition, when remote sensing conditions are not optimal, such as during times of cloud cover, it is possible to incorporate models to estimate where plumes are going until they can be verified again with satellite data. Products Dekker thought would be useful included threshold maps that are able to distinguish CDOM from river sources and coral reef primary productivity and a compliance mapping tool that uses chlorophyll as an indicator. When measured over time, these maps can be used to analyze which areas are noncompliant with regional regulations. The need for developing products that incorporate compliance measures, primary productivity, flood plumes, algal blooms and coral bleaching were emphasized; however, it was also noted that these required more work in reference to the calibration and validation of remotely sensed data. Additional products of interest included plume monitoring using Multifunctional Transport Satellite (MTSAT) geostationary satellites for their high temporal revisit time, which would allow researchers to analyze fluvial dynamics associated with flood plumes. Another application dealt with determining the bathymetry of lagoon areas using Medium Spectral Resolution Imaging Spectrometer - Full Resolution (MERIS-FR) data. Detection of coral bleaching was also mentioned as a possibility, but this needs to be validated by bleaching events, which can be difficult to obtain temporally speaking. Finally, while incorporating remotely sensed data into sophisticated (or simplified) products is useful for making products accessible, this is difficult and much work needs to be done to accomplish this.

Abstract

The Great Barrier Reef lagoon coastal marine environment, along with the reef itself, is an important and integral part of Australian environmental heritage and culture. However, recent degradation in water quality in some of the source catchments, flowing into the GBR lagoon receiving waters threatens the system such that now a challenge exists to assess and discriminate the effects of anthropogenic land-use change (increased run off with sediment, organic matter, pesticides and nutrients) from anthropogenic-induced climate change and shorter natural shorter term weather variability effects due to La Niña-El Niño cycles.

Overall aims

Reliable Earth Observation data from coastal-marine sensors has existed from 1997 onwards. Over the last 13 years for the GBR lagoon CSIRO has collated a sophisticated time series of satellite data from ocean and coastal water color/quality sensors, and has spent considerable effort in developing physics-based inversion methods to quantitatively assess optical water quality variables. To determine with a sufficient reliability what changes in the GBR lagoonal waters are taking place it is essential to validate the remote sensing data at the raw, pre-processed and processed processing stages such that we have reliable quantitative (temporal and spatial) measures of: phytoplankton contents (and blooms) and composition; suspended sediments composition and concentration; dissolved organic matter concentrations and source material identification and; light availability assessments for photosynthesis.

Although a satellite time series from 1997 onwards is relatively short, it is also the sole spatially and temporally comprehensive data set available for this large coastal water body (2500 km long by 300 km wide). As more sophisticated satellite-based measurements will continue into the future, an accurate and reliable baseline over the past 13 years will create a reliable point of reference (over 1997- 2009, with 2010+ added during this project). *In situ* data are unable to adequately assess spatial and temporal variability effects, and thus are limited in detecting trends in water quality. This research intends to address shortfalls in knowledge of water quality trends in GBR waters by developing methods for extracting relevant water quality information for the GBR lagoon from 13 years of satellite data (amounting to several Terabytes of data) covering a La Niña-El Niño-La Niña cycle.

Remote sensing global algorithms versus regional specific algorithms

Global algorithms for Moderate Resolution Imaging Spectroradiometer (MODIS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS), based on research in the 1980's-1990's, were designed for ocean type waters and based on the assumption that phytoplankton and their breakdown products determine all variable optical properties. More recent global algorithms are improving but commonly applied algorithms (*e.g.,* NASA) still cannot cope with high optical variability such as occurs in GBR World Heritage Area waters and can produce errors of 600 % or more (Qin et al., 2007). As the presence of clear blue water is commonly assumed in atmospheric correction routines, frequent failure in turbid waters results and the water quality algorithms (that translate water color to quantitative water quality variables) are unsuited for discriminating chlorophyll from suspended matter from colored dissolved organic matter. Thus, NASA global algorithms are less suitable for these optically complex waters.

By significantly improved atmospheric correction and water quality algorithms the CSIRO has developed methods for remote sensing of inland-estuarine, coastal and marine water quality, which are applicable to any satellite system available, thereby avoiding total dependency on single satellite sensors. CSIRO also accesses all MERIS (European Coastal Water Sensor) data and could easily switch to any other coastal or ocean color sensor (*e.g.,* Indian, Chinese, Korean, Japanese, *etc.*). Furthermore, the CSIRO method can be applied to much higher spatial resolution data if required, such as WorldView-2, QuickBird, IKONOS, SPOT, Landsat, Advanced Land Observing Satellite (ALOS), *etc.* The CSIRO method therefore provides independence from any one sensor system and any one space agency, thereby ensuring longer-term provision of data (the current MODIS and MERIS sensors are beyond their planned lifetimes).

Through collaborative research CSIRO has invested significantly in developing a regionally-specific approach to remote sensing algorithms that provides reliable, quantifiable information, even in the most complex water such as river flood plumes on:

- Chlorophyll (CHL) and related pigments: primary productivity and eutrophication, light availability factor)
- Colored Dissolved Organic Matter (CDOM): carbon land-ocean, freshwater plume tracer, light availability factor)
- Suspended Matter (TSS): erosion, smothering, light availability factor)
- Light interaction properties such as: vertical attenuation of downwelling irradiance (Kd); Secchi Disk Transparency and Turbidity

The simultaneous estimation of concentrations of CHL, TSS and CDOM via inverting the full visible and near-infrared spectrum using the Specific Inherent Optical Property sets (and the resultant Kd assessment) makes this method significantly more reliable than global algorithm approaches as the resultant concentrations *always create a spectrum close to the input thus ensuring a physics based internal consistency in the solution*. This reliability is expressed as error maps that are also provided with our products (note that NASA does not provide error maps although they do provide an overall global estimate of error). Once water quality variable maps and associated error maps are available per pixel, per image, *etc*., it is possible to assimilate this remotely sensed data into biogeochemical and hydrodynamic models, a feature unique to the CSIRO approach. Analysis of such error maps also allows systematic assessment of where "increased predictability" gains are most likely, and hence provides a means to help direct future strategic research, and more importantly provides a mechanism to discuss continued improvement with management agencies.

The quantitative water quality variable maps produced, are validated with the Australian Institute of Marine Sciences (AIMS long term *in situ* data as well as with dedicated fieldwork *in situ* data and with the newly installed Integrated Marine Observing System (IMOS) funded Lucinda Jetty Coastal Observatory data (see the Water Quality and Ecosystem Monitoring Program Reef Water Quality Protection Plan; Final Report, Volume 1, August 2006 (Revised November 2006)). These water quality maps are suitable for:

Water quality maps

- Analysis of the distribution and temporal changes in Chlorophyll, TSM, CDOM and Kd maps:
    - Min, Max, Median, Mean, Standard Deviation of Chlorophyll, TSM, CDOM and Kd for the GBRWHA
    - Weekly and monthly (seasonal See Figure 1) and yearly and whole of life means
    - Trend analysis Chlorophyll, TSM, CDOM and Kd over satellite sensor system life period
    - Spatial and temporal autocorrelation analysis of Chlorophyll, TSM, CDOM and Kd
- Trichodesmium and other algal bloom detection (incl. early warning) and monitoring

Process analysis of river discharges

- Determining maximum direct influence of river-estuarine waters by tracing CDOM (also suitable as an inverse salinity tracer)

- River plume extent of a flood events and analysis of transformation processes in river plumes as they progress further away from the estuary (see Fig 2.).
- Average distribution of river material in plumes into GBR lagoon for all events

Adaptive management related:

- Light availability maps of GBRWHA to be superimposed on bathymetry maps for calculation of light availability in the water column and at the bottom for primary productivity assessment.
- Data set to put into a spatio-temporal perspective for relation to *in situ* data sets collected by others: *e.g.,* seeming anomalous TSM or turbidity measurements or the relevance/representativity of current AIMS long term monitoring plans.
- Relevance of current water compliance guidelines and creation of improved water quality compliance guidelines based on the actual behavior of the coastal waters
- Analysis of the correctness of hydrodynamic and biogeochemical models and subsequent improvement by data assimilation techniques.

Further strategic considerations include:

Integration of measurement systems, where, through data –assimilation, best returns on investment are obtained:

- Optical, sea surface temperature and radar remote sensing data integration
- Integration with *in situ* measurement systems
- Assimilation into biogeochemical and hydrodynamic models

Development of remote sensing products that caters to

- Near-real-time needs
- Project needs
- Long-term trend monitoring needs

Information from remote sensing must:

- Show processes
- Be quantitative and fit-for-purpose
- Be presented in a manner that can be interpreted and used by managers (training and education loop between providers and users, allowing providers to better understand end-users decision making processes which impacts assessment of accuracy, timeliness and refresh rates when designing operational systems)
- Be media, web and water quality report card suitable

Some relevant publications of the CSIRO team

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Dekker, A.G., Brodie, J. and Steven, A (2006) Cattle, crops and coral: Flood plumes and the Great Barrier Reef (ed: Stephanie Renfrow), NASA Distributed Archive Center Annual Report 2006, NASA National Snow and Ice Data Center DAAC; Boulder , Co, USA.

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Dekker, A. G. , Jordan, A. and Mount, R. (2008). Satellite and airborne imagery including aerial photography. Chapter in "Marine benthic habitat mapping special publication" : p 11-28. Geological Association of Canada: 327 p. ISBN-13: 978-1-897095-33-1; ISSN: 0072-1042.

Kutser, T., Metsaama, L, Dekker, A.G. (2008) Influence of the vertical distribution of cyanobacteria in the water column on the remote sensing signal, Estuarine, Coastal and Shelf Science 78: pp 649-654.

Phinn, S.R., Roelfsema, C.M., Brando, V.E., Dekker, A.G. and Anstee, J. (2008) Mapping Seagrass Species, Cover and Biomass in Shallow Waters: An Assessment of Satellite Multi-spectral and Airborne Hyper-spectral Imaging Systems in Moreton Bay (Australia). Remote Sensing of Environment. 112(8):3413-3425.

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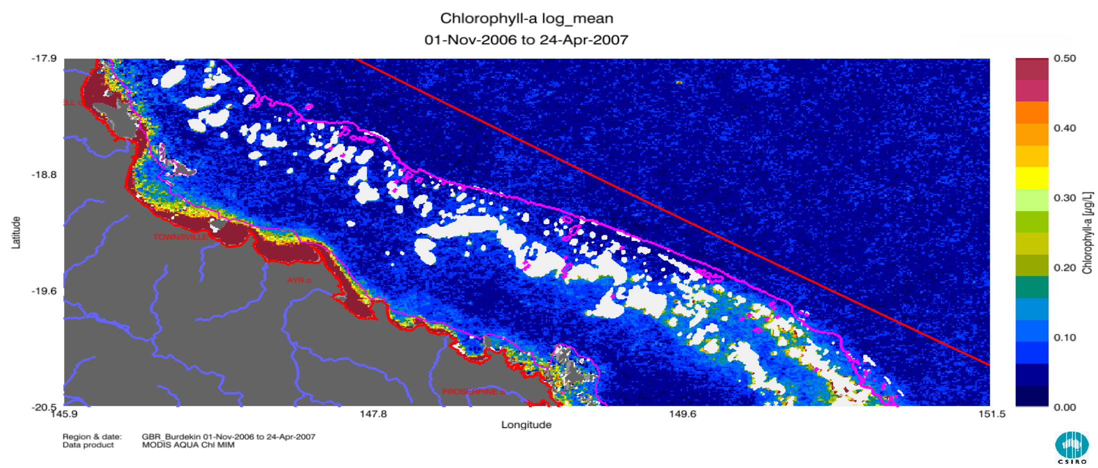


Figure 1: Log Mean values for Chlorophyll a for the Burdekin Region for the wet season from 1 November 2006 – 24th April 2007 (based on averaging +/- 180 daily images)

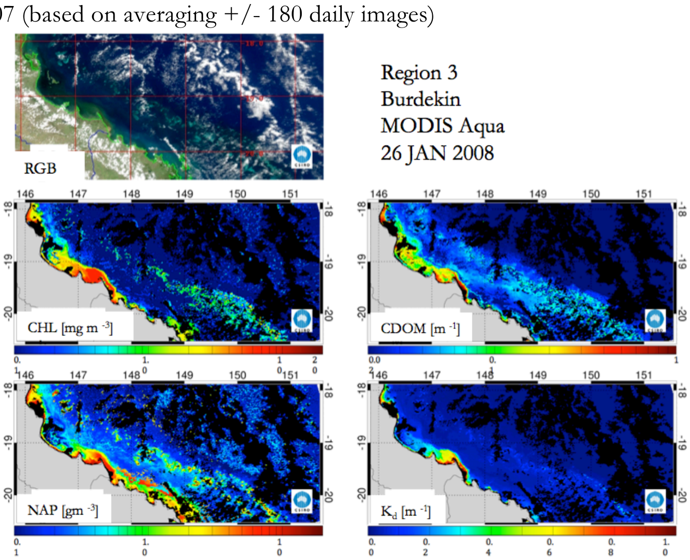


Figure 2: CSIRO algorithms applied to river flood plume of the Burdekin River on 26th January 2008. RGB = (Pseudo) true color image; CHL = chlorophyll; NAP= total suspended matter; CDOM = colored dissolved organic matter; K_d = vertical attenuation of light coefficients.

<u>What is being done to make ocean color products work over coral reefs?</u>

Scarla J. Weeks

University of Queensland

This presentation revisited some of the difficulties of utilizing remote sensing data to extract information from coastal areas, or Case 2 waters, and explained how remote sensing scientists are working to overcome them. The difficulties of extracting useful data on water quality and light availability in these areas include bottom reflectance, which results in the need for masking areas in the image or significantly inaccurate calculations. Currently, standard operational algorithms do not correct for bottom reflectance. This is of particular concern for the Great Barrier Reef where the bathymetry is complex. The primary objective of Week's work is to collaborate with NASA scientists to develop an operational remote-sensing algorithm that can efficiently and reliably correct for backscattering effects in optically shallow waters where the effects of bottom reflectance are evident and significant.

The euphotic zone depth, the depth where photosynthetic available radiation reaches 1% of its surface value, provides a measure of water clarity. This is based on the principle that the Inherent Optical Properties (IOP) of the water column determines the vertical variation of the subsurface light field. NASA recently implemented a Quasi-Analytical Algorithm (Lee et al., 2007) describing the vertical attenuation of the subsurface light field. This algorithm has now been validated in a number of locations globally, including the Arabian Sea, Monterey Bay, Gulf of Mexico, and the Yellow Sea, but not in the Great Barrier Reef since the IOPs are not available. However, collaborative work is in progress to develop an operational remote-sensing algorithm that can efficiently and reliably derive the key IOPs to determine the transparency or turbidity of Great Barrier Reef waters. Once completed, the water-clarity algorithm will be integrated into NASA's freely available SeaDAS software so as to be able to provide maps of water clarity for coral reef and coastal waters from multiple platforms, such as SeaWiFS, MODIS, MERIS.

Abstract
Monitoring and management of coral reefs has a high demand for efficient ocean color algorithms that can produce accurate synoptic imagery and estimates of water-column optical properties. These products are essential for understanding the links between oceanographic processes, climate change, water quality and the biological response in optically shallow habitats such as the Great Barrier Reef (GBR). The current state of operational satellite remote sensing is that algorithms for measuring geophysical parameters, such as chlorophyll concentration or water turbidity, are reasonably reliable over deep water. However, these algorithms are currently unable to correct for bottom reflectance in optically shallow regions so their products are either significantly inaccurate or masked out. This limits the ability to use satellite data in coastal areas.

Considerable progress is being made in the applications of polar-orbiting satellite data in mapping parameters such as phytoplankton concentration, turbid river outflows, and near shore optical properties where there are no bottom reflectance effects. Aircraft sensors are proving effective in mapping shallow water habitats and bathymetry in focused, high spatial resolution campaigns. Validation and comparison workshops in coastal waters globally have demonstrated the maturity of the shallow water remote sensing science.

Over the next three years, a collaborative project between Australian and NASA scientists will combine quasi-analytical deep water algorithms with shallow water mapping optimization schemes to develop an operational remote-sensing algorithm that can efficiently and reliably derive water clarity information in shallow waters of the GBR. This capability is especially important for studies of coral reef ecosystems where water clarity is one of the key factors influencing reef growth and health. Once validated, the algorithm will be integrated into a widely-used NASA satellite image processing package (Sea Data Analysis

System -SeaDAS) so that, in combination with existing algorithms for optically-deep waters, the algorithm suite will be able to provide measurements of water properties for all natural waters of the GBR and coral reefs globally from current and near-future ocean-color sensors. This will have significant benefits for scientists and coastal managers who will be able to use these products to understand and monitor these important parameters in coastal waters of coral reef ecosystems.

Can we develop other useful satellite-based management tools?: A seagrass algorithm. Utility of seagrasses for satellite monitoring of coral reef condition

Susana Enríquez

Universidad Nacional Autónoma de México

This presentation advocates advancements in ocean color remote sensing observations of ecosystems associated with coral reef ecosystems, specifically seagrass habitats. Monitoring seagrass beds is important due to their interconnected relationship with coral reefs, for example acting as juvenile reef fish habitats. Enríquez pointed out how seagrasses can be used as powerful early bioindicators of coral reef deterioration before those changes can impact water quality on the coral reef community. Seagrasses and their associated macroalgae display large changes in abundance and diversity of species, but also in the morphology of the main builder/s of seagrass canopies. The productivity of seagrass is so substantial that they are second in productivity only to swamps, marshes and tropical and temperate forests in terms of dry weight production per day (Duarte and Chiscano, 1999). They also provide an important contribution to carbon uptake. While seagrasses only cover 0.15% of the ocean floor, they take up 15% of the total CO_2 processed by oceanic biota. The interconnected processes between seagrass and coral reefs are not fully understood, and neither are seagrass responses to the same global and local threats currently affecting coral reefs. (Waycott et al., 2009) reported an alarming reduction in seagrass area since 1980 for the temperate meadows. However, less information is available on the actual situation of tropical seagrass beds. The large morphological plasticity shown by seagrass beds is indicated by adjustments in leaf self-shading, which is a response to the light levels of the water column (Enríquez and Pantoja-Reyes, 2005). This response is also dependent on the magnitude and frequency of coastal perturbations, hydrodynamics and, especially important in the tropics, the trophic condition of the ecosystem. Given these important ecological functions and needs, and the large morphological plasticity and fast response shown by seagrasses to environmental changes, Enríquez discussed the utility of monitoring these ecosystems with remote sensing techniques. By using remote sensing platforms it would be possible to monitor spatial and temporal changes in canopy biomass and light utilization at scales beyond manual surveys and without geographic restrictions (Green et al., 2000). Research using remote sensing in conjunction with *in situ* determinations of the physiological condition of seagrass leaves and the information "registered" in the pattern of growth of the underground biomass, can provide strong tools for monitoring seagrass bed condition and productivity but also coastal dynamics of erosion and sedimentation and abnormal changes in the coral reef system. Specifically, Enríquez proposed that the pattern of variation associated with the vertical growth of *Thalassia testudinum* shoots provides useful information on the magnitude and time of occurrence of different coastal events such as storms, hurricanes, and even coastal management projects related to beach restoration. She also showed that the pattern of variation in Fv/Fm along seagrass leaves may allow an understanding of the spatial and temporal changes in leaf growth and seagrass productivity if it is combined with (1) a seagrass algorithm based on the estimation of the excessive excitation energy (EEE); and (2) the description of the canopy light fields. To develop this seagrass algorithm it requires similar information already being used in the LSD product, and radiative transfer descriptions of light propagation within the seagrass canopy that have been recently published (Hedley and Enriquez, 2010) as an application of a 3D global illumination method for aquatic environments developed earlier (Hedley, 2008). With these new tools, effective monitoring of the expansion and reduction of seagrass biomass will allow managers to use seagrass beds as early bioindicators of coral reef changes and environmental deterioration before poor water quality can produce serious and irreversible effects on the coral community.

Abstract
Seagrass beds rank among the most productive autotrophic ecosystems, second only to swamps, marshes, and tropical and temperate forests in terms of dry weight production per day (Duarte & Chiscano 1999). They are responsible for 15% of the total net CO2 uptake by oceanic biota, despite only covering around 0.15% of the ocean surface. Seagrass beds are also important associated ecosystems of coral reefs where they display large morphological variation related to the complexity of the macrophyte community (abundance and diversity) but also to the changes experienced by the main builder/s of the seagrass canopy (Enríquez & Pantoja-Reyes 2005). This variation is strongly regulated by light to adjust leaf self-shading to the light levels of the water column, and is also dependent on the magnitude and frequency of coastal perturbations. Optical remote sensing by airborne sensors or satellites offers the possibility for monitoring spatial and temporal changes in both canopy biomass and canopy light utilization at scales greater than can be achieved by manual surveys alone and with less geographical restrictions (Green *et al.* 2000). These tools can be reinforced adding "*in situ*" information contained in the underground seagrass biomass and in the physiological condition of seagrass leaves. Specifically, the pattern of variation of Fv/Fm along the leaf may allow understanding changes in leaf growth and seagrass productivity that can be predicted by means of a seagrass algorithm that requires for its development similar information already being used in the LSD product, based on the estimation of the excessive excitation energy (EEE). A recent quantitative global assessment of seagrass loss (Waycott *et al.* 2009) has reported an alarming reduction in seagrass aerial extent since 1980 for the temperate meadows. Less information is available about the actual situation of tropical seagrass beds and their responses to local and global impacts. Effective monitoring of the expansion and reduction of canopy biomass should be a key objective for management of seagrass beds and associated marine environments. Seagrasses can provide very useful information to understand many processes in coastal areas but they also can be used as powerful early bioindicators of coral reef deterioration before those changes can impact water quality or the coral reef community. A recent application of a 3D global illumination method for aquatic environments (Hedley 2008) that allows describing radiative transfer of light propagation within the seagrass canopy (Hedley & Enríquez 2010) has clear applications to improve understanding of seagrass canopy light harvesting and photosynthetic carbon fixation, and to aid the development of quantitative bio-optical remote sensing methods for seagrass beds.

The future of ocean colour products on coral reefs: What can we expect in the near future?

Peter Fearns[1] *and Arnold Dekker*[2]

[1]*Curtin University of Technology*
[2]*The Commonwealth Scientific and Industrial Research Organisation*

In the presentation by Peter Fearns remote sensing advancements, such as future technologies, remote sensing products, coordination and management of research efforts, integration of data, and uptake and applications of data, were discussed. Enhanced technologies mentioned included constellations of mini, micro, and nano-satellites with enhanced spatial and spectral resolution to provide more detailed images of surface features and better signal to noise characteristics, all of which are important components in coastal remote sensing. Another desirable characteristic of future satellite platforms include multi-sensor platforms that span the electro-magnetic spectrum and would include visible, near infrared (NIR), thermal, and radar capabilities. Off-nadir capability is also a desirable characteristic of future satellites so that temporal constraints as a result of infrequent revisit time are reduced and areas of interest can be readily acquired. With the improvement of sensor technical accuracy and the increased understanding of *in situ* optical properties of various water and substrate types, it is possible to derive improved water column products, such as chlorophyll concentration, dissolved substance concentrations, water temperature, and water quality, and more detailed habitat maps. Improved, derived (separate remote sensing products that are combined), and hybrid (remote sensing data combined with models or *in situ* data) products will also become more sophisticated resulting in the ability to take into consideration multiple factors to create an index of coral reef sensitivity or to track and predict the course of algal blooms, for example. While these improvements will likely enhance management decisions, Fearns noted that there is a need to enhance the communication channels between remote sensing scientists and end users. Through the development of networked, online data-stores that are abundant with remote sensing and coastal biology data that is easily searchable and accessible to authorized users, the possibility for collaboration amongst interested parties could be facilitated. These centers of information would provide a storehouse of information that would serve to establish baseline data to inform long term monitoring, provide data for multi-scale views of environmental problems and historical data for environmental assessment amongst other applications. Through increased use and application, standardization of the processes used in the analysis of remote sensing products will become routine and the information derived will become more accessible through software and applications like Google Earth.

Abstract
We present reflections on the future of coral reef remote sensing under the topics:

1. Future technologies - implications
2. Products
3. Coordination/management
4. Integration
5. Uptake & Applications

Current airborne remote sensing systems can demonstrate the technologies that will one day be space-borne. Technological developments in satellite vehicles, with coordinated constellations of mini-, micro- and nano-satellites, increased spatial resolution, as well as increased temporal coverage will be available from space. Advanced sensor technologies will lead to better signal-to-noise characteristics, an important aspect of marine and coastal remote sensing.

Multi sensor approaches to environmental observation will provide information from across the electromagnetic spectrum, encompassing visible, near-IR, thermal sensing, as well as radar. Add to these improvements in technology the capability to steer the view direction of a sensor, these space-borne sensors will be able to provide rapid response capabilities to the routine monitoring and management of reefs and other shallow water coastal environments.

New remotely sensed products will come about due partly to the improved accuracy of sensors, but also as we gather more information on *in situ* optical properties of different water types, and different substrate classes such as algal species or coral species. The outcome of better sensors, more spectral knowledge and improved in-water optical models will lead to improved and new water column products (*e.g.,* chlorophyll concentration, dissolved substance concentrations, water temperature, water clarity) and more detailed habitat maps.

An interesting development based partly on remote sensing data will be higher level derived and hybrid products. We make the distinction here between derived and hybrid products as, derived are based essentially on remotely sensed products, combined to generate a new products. An example is primary productivity, which can be derived from remotely sensed temperature and chlorophyll concentration. Hybrid products are those that combine remotely sensed data with information from non-remote sensing systems, such as circulation or ecosystem models, or with *in situ* instrument data, to derive a new product. A circulation model might be used to propagate a remotely sensed algal bloom through time to track the likely path and impact of the bloom.

Better technologies, with improved products will lead to potentially better management. However, the timely access to and dissemination of data is often a key to the efficient management and monitoring of a coral reef. To this end we suggest the communication channel between remote sensing scientist and end users needs to be improved such that information can spread rapidly and efficiently to the end users, and at the same time feedback to the remote sensing scientists can help guide the development and validation of new products. More efficient and easy-to-use data search tools, with free and open access to on-line data stores, with the potential for the date store to be updated by remote sensors as well as end-users will foster the development, via feedback, of more useful and applicable remote sensing products.

On their own, remote sensing data can provide an invaluable large-scale view of coral reefs and other coastal environments, but the value of such data can be multiplied by integration with other advanced application systems such as ecosystem models, or simply delivered within universal "standard" data display systems such as Google Earth. In our experience, remotely sensed products are often utilised in one-off novel applications, in support of a larger mutli-disciplinary project, or might be included to provide a snapshot of spatial relationships in an environmental impact assessment for example. The potential of long term monitoring with space based sensors, the value of large scale views and baseline information contained in long term data bases is often overlooked. As databases grow through time, and extreme events, as well as base line conditions, are observed over longer periods of time, remote sensing data will be the only source of historical data for many environmental assessment projects. There are currently "standards" for the processing, analysis, application and display of many environmental measurements (water quality measurement methods, data analysis and reporting protocols, observations required for environmental impact assessments), but applications of remote sensing data to environmental assessment tasks have not yet been standardised. As remotely sensed products develop and improve, as the use of remote sensing data increases and more end users realise the potential and value of remotely sensed data, these products will be adopted as required routine and added as regular additions to coral reef management and monitoring.

Use of climate models to predict coral reef vulnerability

Claire Spillman[1], Mark Eakin[2] and Simon Donner[3]*

[1]*Australian Bureau of Meteorology*
[2]*NOAA Coral Reef Watch*
[3]*University of British Columbia*

Predictive models provide the ability to forecast environmental conditions and their potential impacts on coral reefs. To understand and compare the various types of models used in forecasting stresses on coral reefs, Claire Spillman explained the various characteristics of forecast models such as model type, resolution, timescales, forecasts, products, downscaling, skill and applications.

Common models can generally be classified as either statistical or dynamical systems, with different characteristics and distinctions particular to each. A primary distinction between these two types of models is the way in which statistical models use historical data and stochastic relationships to predict future events, while dynamical models use recent observations and the principles of physics to provide predictions. Examples of the Bureau of Meteorology's statistical and dynamical models provided included Australia's current statistically based seasonal rainfall forecasts and dynamical oceanic predictions from the Predictive Ocean Atmosphere Model for Australia (POAMA). Hybrid models combine characteristics and techniques of both statistical and dynamical models and can lead to more accurate predictions than either approach alone.

Much like remote sensing products, forecast models differ in both temporal and spatial resolution, so it is important to choose scales that are appropriate to the study. Computing power is often a limiting factor when developing models of increasing resolution. Timescales are also an important consideration for studies and, depending on the topic of interest, very different timescales may be used. For instance, when predicting coral bleaching, seasonal or intra-seasonal timescales may be used whereas long-term climate predictions require centennial timescales. One technique used for obtaining higher resolution information from a model forecast is "downscaling". This is the process whereby high-resolution climate information is derived from output of coarse resolution General Circulation Models (GCMs). Both temporal and spatial downscaling is possible. Statistical downscaling uses statistical relationships between historically observed small-scale and large-scale variables to transform predictions. Dynamical downscaling is an additional process that uses a regional climate model driven by boundary conditions from a GCM. Downscaling using these processes does, however, have caveats; the primary one being that, even though downscaling is in some cases possible, the uncertainty in predictions at coarse scales may translate into meaningless predictions at fine scales.

Model forecasts are either deterministic or probabilistic, and may be accompanied by uncertainty estimates or tolerances. Deterministic forecasts generally predict a single outcome and uncertainty is not measurable. Probabilistic forecasts are derived from ensemble prediction systems and provide the user with the likelihood of occurrence; these forecasts provide added benefits, such as the ability to be used for cost/benefit analyses. Methods of assessing forecast skill, or performance, were also discussed. Some techniques include comparing predictions with observed events, finding correlations in time/space with observed events, using skill metrics (*e.g.* hit rates), comparing forecasts with other models, and how the predictions capture trends and characteristic features. The desired level of forecast skill is dependent on the application and there is often lower accuracy in predicting local scale events compared to large climate processes.

Forecast products of interest to the coral reef remote sensing community include sea surface temperature (SST) anomalies, tropical cyclone frequency, Madden-Julian Oscillation, thermal stress duration, bleaching risk and climate change indices. A consideration for forecast users is the distinction between operational and research model products. Most models used for research products are experimental, and are in the process of being designed and evaluated for efficacy. Operational products are well maintained and supported to reliably provide regular information to end-users. It is important that managers and policy makers are aware of both the type of forecasts product they are utilizing, and the assumptions and limitations of the models that are used to develop the product.

The applications of models are numerous and include advance warning of bleaching risk, allowing coral reef managers to implement mitigating strategies, cost/benefit analyses, identification of future threats for policy development and long term planning, in addition to an improved understanding of physical processes and large-scale climate drivers. In order to develop the best possible models and products, Spillman re-emphasized the need for communication between reef managers and modelers. Finally, examples of Coral Reef Watch and POAMA predictions for bleaching were presented (Goreau and Hayes, 2005; Strong *et al.*, 2004; McClanahan *et al.*, 2007; Spillman and Alves, 2009), along with how these forecasts have the potential to be invaluable tools in reef management.

Abstract
Climate models can be used in a variety of ways to predict reef vulnerability, from seasonal bleaching risk to long-term impacts under climate change. Forecast models vary greatly in their composition, resolution, timescales, type of forecasts produced, performance, and applications. This talk serves as a brief introduction to both statistical and dynamical forecast models and their use in coral reef management and research.

Statistical models are built on empirical relationships derived from historical data and can often be quite skilful, though assume stationarity and thus may not capture future climate changes. Statistically based forecast products such as the NOAA Coral Reef Watch Seasonal Coral Bleaching Thermal Stress Outlook have been quite successful in forecasting upcoming summer conditions and potential bleaching risk (http://coralreefwatch.noaa.gov). The current seasonal rainfall and temperature outlooks for Australia are also based on a statistical forecast system run by the National Climate Centre.

In contrast, Global Circulation Models (GCMs) are dynamical multivariate models, comprised of differential equations based on the basic laws of physics and fluid motion. GCMs can simulate system responses to a changing climate though require a detailed understanding of the processes involved. The global ocean-atmosphere forecast system POAMA is currently run by the Bureau of Meteorology to produce seasonal SST forecasts for determining bleaching risk as well seasonal ENSO outlooks (http://poama.bom.gov.au). GCMs can also be used for decadal and centennial predictions, including system response under climate change scenarios.

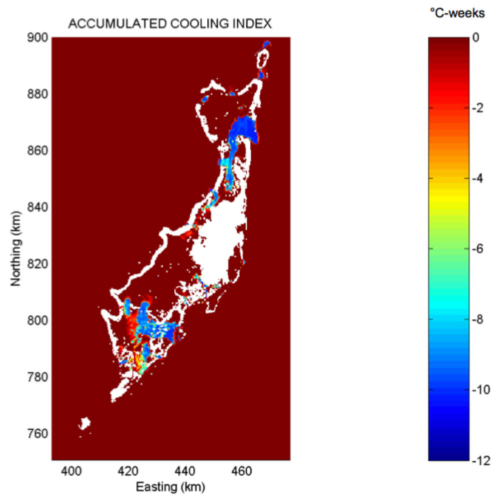
Both statistical and dynamical models have limitations, depending on the application and the design of the forecast system, and can include poor model resolution, limited data availability and an inability to capture future conditions under global warming. However, these models can provide invaluable insight into future conditions as well as the processes occurring over reef regions, leading to improved management of coral reef systems.

Integrating remote sensing data into ecosystem models to predict vulnerability

C. Mark Eakin[1], Peter J. Mumby[2], Ian A. Elliott[2], William Skirving[1] and Scott F. Heron[1]*

[1]*NOAA Coral Reef Watch*
[2]*University of Exeter*

Mark Eakin's presentation focused on combining models and remote sensing to aid in planning protected areas that have the potential to reduce coral vulnerability to thermal stress. Models can be powerful and effective tools for understanding how physical phenomena are likely to occur, and when they are coupled with additional data they can apply to broader applications. The first example of the presentation focused on a joint project between Coral Reef Watch and AIMS to examine small-scale hydrodynamic modeling in Palau (Skirving et al., 2010). Through the use of intensive instrumentation that collected *in situ* measurements and the application of a model with a 250-meter resolution, researchers developed a local scale hydrodynamic model that revealed the thermal capacitance of waters in coral reef areas of Palau, which could then be used for fine-scale reserve planning. Palau is heavily influenced by tides and this has an influence on coral conditions. The parameters measured in this study included tidal flow, currents, tides, temperatures, connectivity and salinity. The objective of the study was to spatially measure the thermal capacitance of Palau's reefs and to identify areas that are characterized as having a high thermal variability with a low thermal capacitance (reef areas that are capable of withstanding bleaching events) and areas that are characterized as having a low thermal variability with a high thermal capacitance (reefs areas that are less capable of withstanding bleaching events). Findings suggested that there are few areas where there are natural mechanisms for facilitating thermal capacitance in Palau and that when bleaching events occurred, areas that had a high thermal capacitance and low temperature variability recovered faster than those in low thermal capacitance and high temperature variability areas. This information provides managers with another data set that allows marine park planners to maintain diversity and protect organisms. In short, it allows managers to look at stressors in addition to the overall ecosystem when designing MPAs.



Final output from the Palau model of thermal capacitance, expressed as surface cooling degree-weeks (*i.e.,* how much the mixing cooled the surface temperature during the one-month period) (from Heron and Skirving 2004).

Another question in reference to long-term trends and climate change was "how can thermal stress and current circulation aid management"? This is the research question of the second study recently published by (Mumby et al., 2010). This project utilized thermal regimes and larval connectivity to prioritize reserve areas. Over a 20-year data set this study examined which areas were getting warm the fastest rather than areas that were the warmest. Given this analytical foundation, a distinction was made in reference to the type of thermal exposure corals are subjected to, which consists of chronic and acute exposure to thermal stress. When plotted on an X-Y graph, a quadrant of thermal regimes was developed and used to classify corals that were accustomed to thermal stress that varied across the following spectrum: High Chronic and Low Acute, Low Chronic and Low Acute, High Chronic and High Acute, and Low Chronic and High Acute. A variety of reefs (*Montastrea* and gorgonian) were identified from the national habitat map and mapped using polygons. A total of 286 polygons were created that contained these coral sites. The thermal history was then determined for each site. The utility of this data lies in being able to consider the reserve design and classifying areas as high, medium and low priority for inclusion in reserves based on their climate history and predicted climate change. Then an additional component, larval connectivity, is included in the analysis. In this portion of the study, areas adversely impacted by climate change (locations with low chronic and low acute thermal exposure) are identified and prioritized in the design of the reserve so they are located within proximity to areas that will be minimally affected by climate change, locations with high chronic and low acute thermal exposure, for example.

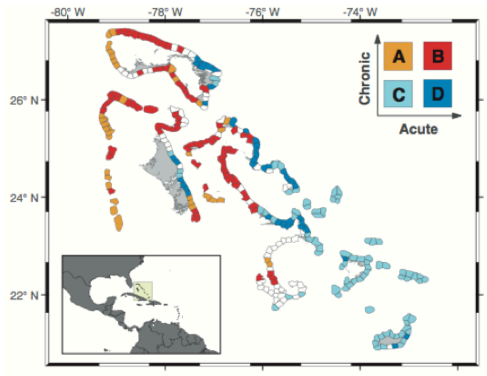


Figure 1 Categorization of coral reefs in the Bahamas by thermal stress regime. Empty (white) polygons are unclassified, falling between thermal regimes.

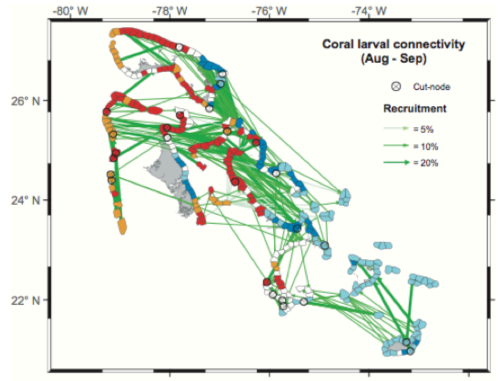


Figure 3 Graph-theoretical representation of coral larval connectivity among reefs in the Bahamas. Polygons represent reefs of habitats *Montastraea* and hardbottom and lines denote predicted flux of *Montastraea* larvae during a single spawning and recruitment event. Graph cut-nodes (crossed circles) are important locations for maintaining network cohesion and cause network fragmentation if such reefs are lost.

This configuration allows less impacted coral reefs to disperse their larvae to areas that are more impacted by climate change, thereby potentially rejuvenating the areas impacted by climate change. To model these scenarios researchers used the high-resolution biophysical computer model (HYCOM-based), which simulates the release of larval particles into the 3-D model and predicts where the larvae will settle. Researchers can then select options for preferential larvae settlement sites, which results in the selection of the most viable reefs for withstanding climate change impacts. Another valuable component to this research is that these models are to be added as an extension tool to MARXAN, the marine reserve-planning tool. The benefit of combining climate change stress potential and larval connectivity in these models is a doubling of larval connections when compared with conventional reserve planning methods, which has the potential to improve the resilience of reefs within reserves.

Abstract
Recent efforts have begun to incorporate remote sensing with modeling to improve the data needed for planning and managing marine protected areas. This work is introduced on two scales: modeling of hydrodynamics

Determining Thermal Capacitance for Protected Area Network Design in Palau
During the latter half of 1998, Palau experienced unprecedented bleaching that resulted in significant mortality and the loss of significant proportions of one of the few remaining pristine coral reefs in the world. The Nature Conservancy and the Palau Government joined forces to design and implement a protected areas network (PAN) for Palau's coral reef ecosystem. At the same time, NOAA and the Australian Institute of Marine Science (AIMS) were collaborating on the use of hydrodynamic models to predict heat stress during a bleaching event. In 2003, it was decided to combine these efforts and for NOAA and AIMS to produce a heat stress model for Palau for use in the PAN planning as an attempt to identify factors that might confer resilience to climate change. NOAA and AIMS

implemented a data collection effort to develop bathymetry, measure high-frequency currents, temperatures, tides, and other parameters needed to develop a high-resolution (250 m) two-dimensional hydrodynamic model for the largely tidally driven circulation within Palau.

Currents and mixing were used in conjunction with the vertical temperature profile to determine cooling of surface water due to mixing and thus the likely spatial distribution of sea surface temperature during a bleaching event. In fact, this model is best interpreted as a measure of thermal capacitance. The warmer regions in the model represent areas with a low thermal capacitance meaning that a given amount of solar energy heats these regions faster than the cooler regions in the model, which have a high thermal capacitance and resist temperature change. The warm regions portray those locations that likely experience little to no mixing and hence represent low thermal capacitance. The organisms that live in these regions experience an extreme climate, characterized by relatively large temperature ranges. In contrast, those regions shown as cool were most likely to experience greatest cooling at the surface due to mixing and hence represent the regions with high thermal capacitance. This provides the organisms that live there with a very mild climate, characterized by relatively small temperature ranges.

In general, most protected area networks (PANs) are currently designed so as to provide protection to "representative bioregions." However, it is important to recognize that an ecosystem is not only made up of different species but also of organisms within each species that can have unique physiological characteristics. With respect to a changing climate, the phenotypes that result in varied physiological characteristics are likely to correspond to different thermal capacitances throughout the region. While we may not know what these characteristics are, the relevant characteristics for resilience against climate change are more likely to be better protected if representative samples of each thermal region within the thermal capacitance map are protected. The innovative techniques and methodologies presented in this report represent a new approach for MPA/PAN design.

Incorporating Thermal Stress and Connectivity in MPA Design

Rising sea temperatures cause mass coral bleaching and threaten reefs worldwide. While reef managers are unable to avert warming, maps of variations in thermal stress across the seascape can be used to help manage reefs for climate change. In particular, a model that incorporates both thermal stress and connectivity has been tested to provide information to inform protected area network planning. The first step involves mapping chronic and acute thermal stress to develop evidence-based hypotheses for the future response of corals to each stress regime. Then the model incorporates spatially-realistic patterns of larval connectivity among reefs and applies novel reserve design algorithms to create reserve networks for a changing climate. By selecting preferred source and recipient populations based on potential connectivity and the relative amount of chronic and acute stress, the model can be used to optimize the potential survival of coral recruits under an expected climate change regime.

Using remotely-sensed thermal stress data for the largest Atlantic reef system in the Bahamian archipelago, we show that reefs predicted to experience the most benign future conditions should have sufficient larval connectivity to be networked into a reserve system. Optimal reserve designs differ according to the anticipated scope for phenotypic and genetic adaptation in corals. Unfortunately, both the rate and possible extent of adaptation in corals remains uncertain. While this effort provided reserve design criteria that hedge against present uncertainty, the approach is flexible and new discoveries such as coral and algal adaptation can be integrated to update the reserve design algorithms. This information can be incorporated into planning tools such as MARXAN and can play an important role in adaptive management.

Machine learning and data mining

Vic Ciesielski

Royal Melbourne Institute of Technology

This presentation focused on how to develop remote sensing products from a multitude of data in a way that is efficient both temporally and economically. New advancements in computer science have developed methodologies for accomplishing these objectives through the process of machine learning. Vic Ciesielski described the capabilities of this concept and how this could be used to develop new and improved satellite products. The presentation began by drawing parallels with remote sensing and machine learning in the areas of data analysis and vocabulary similarities. This was followed with an organizational depiction of the subfields within machine learning, which highlighted the breadth of the field and the abundance of applications the field can contribute to. Numerous areas such as data mining, evolutionary computing, classification, clustering, association finding, feature selection, outlier detection, anomaly, multi-dimensional visualization, and genetic programming were just some of the more prevalent machine learning subfields. The first subfields mentioned consisted of classification and discrimination. The primary foci areas for developing algorithms in this subfield consist of distinguishing items that are disparate or have varying degrees of differences. In order to accomplish this it is imperative to have abundant, known, and labeled examples of each class. Numeric prediction is one type of classification noted as an example. Algorithms are different in this case from class predictions when viewed from a machine learning perspective. Regression is one method of doing numeric prediction, which has focused on linear regression classically, but is moving to include nonlinear numeric prediction. A major area of data mining and machine learning is in time series analysis and prediction. Ciesielski provided an example of how machine-learning methodologies would tell the difference between land and water in an image. This process, he pointed out, is not exclusive to imagery and is applicable to any type of data. The first step involves taking samples of the items we want to differentiate between. From this point image features to be used are determined, training data is constructed, test data is constructed, then an algorithm is run from numerous choices (*e.g.,* decision tree, neural network, nearest neighbor, support vector machine) to develop a classifier. Known test data is then passed through the classifier created from the algorithm and the error rate is determined. Once an acceptable error rate is achieved, the classifier is applied to unseen examples. Another method in development is using texture for segmentation. While it is incredibly easy for the human eye to distinguish between different textures, getting a computer to discern these differences is another matter. The goals of classification are to be as accurate as possible and to explain and understand the data.

The second major area is clustering and in this methodology there are no labels. The primary question is "how do separate clusters of groups interact"? Some examples of this were middle-aged people who bought vitamins, and consumers who bought both beer and diapers at convenience stores. The obvious benefits of using this methodology are that this information can be used for identifying target markets. With clustering there are fewer algorithm choices (roughly 5) and it can be used in anomaly detection and change detection but the researcher generally does not want to know about any change unless the change is significant. Association finding is another task in machine learning and is used often in market basket analysis, which is the analysis of what items people buy with other items. Feature selection is another machine learning technique that is used for finding the important variables from numerous possibilities. Data visualization is another technique that has been successful at certain levels, specifically 2 and 3 dimensions, but unsuccessful at higher dimensions (*e.g.,* 25-100 dimensions). The last example of machine learning mentioned is symbolic regression using genetic programming. The programs are made up at random and make it perform in a task where it is evaluated on how well it performs that task. Working along an evolutional philosophy, the fitter programs are selected and combined with other, fitter programs. Over time these programs become better and better at performing the tasks and are utilized in various capacities, such as time series modeling and relationships between variables. In conclusion, there are many robust techniques, some good software, and many successful applications but data preparation and cleaning can be time consuming, some techniques are computing intensive, and in some cases nothing interesting is found.

Abstract

Machine learning is a large field that is concerned with the development of algorithms that make it possible for computers to exhibit various kinds of intelligent behavior by learning from examples rather than by direct programming. Data mining is a major subfield, which is primarily concerned with learning from data. Most data mining algorithms expect the data to be available in the following form.

No	Attribute1	Attribute2	Attribute3	Attribute5
1	1.5	2.3	5.4	GOOD
2	3.7	2.1	1.5	BAD
.	.	.	.	.

There are number of data mining techniques that can be used on data of this form.

Classification: This is basically the task of learning to tell the difference. If the above data were to be given to a classification algorithm the output would be a classifier, that is, a program that can take an unseen example and predict whether it is good or bad, that is, its class. There are several hundred different classification algorithms. These include decision trees, rules, neural networks, support vector machines and nearest neighbor classifiers. Some classification algorithms can accept a numeric attribute as the class. Some classification algorithms focus on high accuracy and the classifier is a black box, other classification algorithms focus on understanding and the classifier is a rule or decision tree that could reveal relationships in the data. Assuming that suitable data were available, it would be possible to have the class attribute as BLEACHED or NOT-BLEACHED and to learn and analyze a classifier.

Of course the classifier needs to be tested on data not used in its construction to determine its error rate.

Clustering: In contrast to classification where one of the attributes must be designated as the class, clustering algorithms on operate on data in which no one attribute is designated as special. The task is to divide the examples into groupings, or clusters. The members of a cluster should be similar to each other in some identifiable way, and each cluster should be different to the others. In analyzing shopping transactions, for example, one might identify a cluster of old people buying vitamins and another cluster of young people buying CDs. Using clustering techniques on coral reef data might identify unanticipated groupings.

There is only a small number of clustering algorithms. Clustering generally requires a lot of search and the algorithms are practical only on relatively small data sets.

Association Finding: This is the task of directly looking for relationships between the attributes and is primarily used in market basket or transaction processing analysis. In analyzing supermarket transactions one might find, for example, that buying bread is frequently associated with buying milk. There are a small number of algorithms, which are computationally expensive. A disadvantage of the approach is that trivial associations, such as not buying bananas are associated with not buying fly spray, which need to be filtered out.

Attribute Selection: In some situations there can be very many attributes, perhaps hundreds. Attribute selection is the task of determining which of these attributes are the most relevant/significant to a classification task. Only these attributes will subsequently used in building a classifier. There are around a dozen algorithms for attribute selection, some of which are computationally expensive.

Symbolic Regression: This is the task of finding a formula to relate the attributes. For example, one could find that attribute3 = (2*attribute2-attribute1) / log (attribute1). These algorithms tend to be computationally expensive, but there have been a number of successes for a small number of attributes.

Other Tasks: There is a small number of algorithms for tasks such as outlier detection, anomaly detection and change detection.

Experience in the practical use of data mining techniques is mixed, but promising. There are many robust techniques, some good software and there have been many successful applications. However, preparing and cleaning the data can be costly, some of the algorithms are computationally very expensive, and sometimes nothing of real interest is discovered.

An excellent, public domain system for machine learning is Weka: http://www.cs.waikato.ac.nz/ml/weka/

Web-based delivery of NOAA Coral Reef Watch products

Gang Liu and Tyler R. L. Christensen*

NOAA Coral Reef Watch

CRW works to meet the various needs of its growing user community by utilizing both existing and emerging new technologies, by collaborating with partners to prepare data in various formats, and to deliver products through various mechanisms. Coral Reef Watch's (CRW) user community comprises coral reef managers, scientists, and stakeholders from broad and versatile backgrounds who have significantly different information and data requirements and handling capacities. The locus for all CRW products and data is the CRW website http://coralreefwatch.noaa.gov. Liu's presentation emphasized CRW's goal to make its online products easy to access and its web site easy to navigate. By working with users directly and collecting user comments and feedback, CRW has been working to understand how its users access and use the data. A simple product overview webpage introduces all of the CRW products and describes all the data formats and product delivery mechanisms provided. Users have the convenience of choosing the best options of data format and mechanism suitable for them.

CRW's data formats and delivery mechanisms include:

- Suites of images, graphs, charts, and animation products
- Image product suites in the Google Earth format
- Numerical data
    - global and regional data in Hierarchical Data Format (HDF)
    - time series data in text (ASCII) format for Virtual Stations
- Automated bleaching e-mail alerts
- Interactive data query and delivery via ReefBase's online GIS
- Online message board
- Data analysis tool software package for CRW's HDF data
- Online product tutorials and methodologies

Image format, as the simplest and most straightforward format for viewing data, is provided for all of the CRW products with continuous spatial coverage. Both global and regional images are provided for showing the global scale of the targeted environmental conditions and for close examinations of the condition in the regions of interest, respectively. Animations of these products are also available for easy viewing of the change in the coral reef environmental conditions. CRW also takes advantage of existing software packages that are free and widely used. For instance, CRW produces most of its products in the Google Earth format. Numerous useful built-in functionalities and data layers of Google Earth allow users to enhance CRW's products and to combine them with products from other sources. Interested users can download the numerical data of CRW's products, currently in HDF format, for further analysis and application. Although HDF data are especially useful for users who handle the data using computer programming languages, many free software packages are available for viewing HDF data and performing certain analyses. CRW provides free, customized HDF data viewing and analysis software package, CoastWatch Data Analysis Tool (CDAT), to its users. For easy and quick access to the current environmental conditions at some major coral reef locations, CRW developed more than 190 Virtual Stations globally. Users can visit CRW's Virtual Stations webpage to see the current condition at the reefs of their interest or simply subscribe to CRW's automated Satellite Bleaching Alert e-mail system, which sends the update of the status of environmental conditions to subscribers' e-mail addresses as soon as the update becomes available. Time series data of these stations are provided in ASCII text format on CRW's website. These text data are desired by many users because this type of data is ready to be read on any computer and can be analyzed easily in a spreadsheet. CRW also summarizes its near-real-time monitoring products into composite products to show monthly and annual mean and extreme conditions. CRW also works with many collaborators to deliver CRW products through as many useful and unique mechanisms as possible. For instance, monthly and annual composites, along with the Virtual Station data, are sent routinely to ReefBase (http://www.reefbase.org) for users to obtain the data via the ReefBase online GIS system, a system that CRW has not yet developed. CRW's online tutorial and product methodology, along with basic introductions on coral bleaching, the coral reef environment, satellite remote sensing, and links to related educational resources, can be found on the CRW website. This provides a means for users to learn and understand how CRW's products are produced and how the products can be used on their own before personal assistance is needed from CRW. Users can also send CRW (coralreefwatch@noaa.gov) their special requirements for data and information and CRW will make the best effort to meet their needs. The presentation indicated that user feedback and suggestions have been critical for determining and developing data formats and delivery mechanisms that work best for CRW's broad range of users. Comments and suggestions are welcome and can be sent to coralreefwatch@noaa.gov.

Abstract
Since the first Coral Reef Watch (CRW) satellite monitoring product for coral bleaching thermal stress, Bleaching HotSpots, was launched on the internet in 1997, CRW has developed and implemented a suite of web-based products and tools to monitor and predict thermal stress conducive to mass coral bleaching and to monitor and estimate the change of sea surface carbonate chemistry related to ocean acidification. In the core of this product suite are near-real-time satellite bleaching thermal stress monitoring products, model-based seasonal bleaching outlook product, and ocean acidification products based on satellite and *in situ* measurements and model estimates. Satellite-based Doldrums wind product and sea surface insolation products have been developed to enhance the sea surface temperature-based satellite bleaching thermal stress monitoring products. CRW products can be accessed at http://coralreefwatch.noaa.gov. The list of CRW products will continue to grow and improve. To meet the various needs of our growing user community and to take advantage of emerging new web technologies, the data format and delivery mechanism of CRW web-based products have become increasingly versatile and will even be more so. Different users have different Internet accessibilities, requirements for data format, and geographic coverage of interest. As a result, we have been providing our products in both images and numerical data formats, in both global data sets and individual data packages for selected reef sites, and in both passive web postings and active e-mail alerts, among others.

A product overview web page is set up to guide our users through the maze of CRW products and their forms. All the available data formats and delivery mechanisms for each of

our web-based products are described there. Users have the convenience of choosing the best data format and mechanism suitable for them.

The most basic format of CRW products is images that CRW has been serving since the very beginning of the service. For global products, images for different geographic coverages are provided: global scale, basin scale, and regional scales. Large scale features can be identified easily in the global or basin scale images, while local scale details can be observed directly and easily in the regional scale images. Animations are provided for most of the CRW image products in various formats. Animation players are convenient for users to customize their own animation settings, and animated image formats can be easily downloaded to users' computers for offline use and presentation purposes.

Numerical data are available in both HDF (Hierarchical Data Format) for full global coverage and ASCII (text) data format for Virtual Stations at selected individual data grids. HDF data format is a common data format containing both data and metadata and readily accessible by many computer programming languages. There are also many free HDF data viewers available for data display and certain data analysis. Along with HDF data, CRW provides a free software package called Coast Watch Data Analysis Tool, that is customized for CRW data, for graphic display, data viewing, basic data survey and image output.

At present, CRW has satellite Virtual Stations at or near 191 selected coral reef sites around the world. All the data provided for the Virtual Stations are extracted from CRW satellite measurements and their derived monitoring products at the corresponding data grids, without any instrument in the water. Each station is color-coded with its current thermal stress status. A data package containing both graphs and ASCII text data files of time series of coral bleaching thermal stress data and other relevant information is provided for each station. Users often ask for ASCII time series data files for specified data grids so that they can easily import and process the data in their spreadsheets or other software packages. Automated e-mail alerts for these stations issued from the CRW Satellite Bleaching Alert system are available for free subscription. At each monitoring update, thermal stress level at each station is examined. E-mail alerts are sent to the subscribers for the stations where thermal stress levels change from their previous levels. This significantly reduces the need for users to constantly visit CRW web site looking for any updates, and subscribers get new information as soon as it becomes available.

Most CRW image-based products and Virtual Stations are available in the Google Earth format. A free version of the Google Earth software needs to be installed before CRW Google Earth product can be used. Once it is installed, a click on a Google Earth product link on the CRW web site automatically launches the product on user's computer. Many comprehensive and powerful features of Google Earth can be applied on CRW's products. Different layers of the CRW products can be overlaid and many useful built-in layers of the Google Earth software can be utilized. Furthermore, users can overlay other relevant products or data layers from other sources for examining and evaluating coral the reef environment and potential impacts from atmosphere and land, among others.

All of our near-real-time products are archived and available on our website. Monthly, annual and current year composites of most of CRW near-real-time products are also produced, for instance, the maximum level of coral bleaching thermal stress observed during a particular month or year.

Through collaboration with ReefBase, a global information system for coral reefs developed by The World Fish Center, CRW's monthly and annual composite data are available in an online GIS system (http://www.reefbase.org). The CRW bleaching thermal stress data can be overlaid with bleaching observations and other useful data layers provided by ReefBase. Data can be extracted and downloaded. The metadata of the core CRW products and publications are also stored in the NOAA Coral Reef Information System (CoRIS, http://coris.noaa.gov), a one-stop data shopping portal for NOAA coral reef data. These core products are searchable by users through the CoRIS online data and information search engine.

To inform CRW's users up-to-date information on coral reef environmental conditions and availability of any new and/or improved CRW products, CRW has been utilizing the Coral-List, an e-mail list group, to reach out to its more than 6,000 (as of May 2010) subscribers worldwide. The Coral-List is not only a fast message delivery channel but also an efficient mechanism for collecting information and feedback.

To provide background information about CRW products and how these products are used for monitoring and predicting coral bleaching and other stresses and changes in the coral reef environments, an online tutorial and product methodologies are provided at CRW's website. Some hands-on exercises and activities are also provided for educating our users. These educational materials are provided not only for coral reef managers and scientists but also for the general public and school students.

New data formats and delivery mechanisms are constantly under evaluation and development for potential incorporation to improve the services that CRW has been providing to users for over a decade. We are planning to make our products available in many new formats, such as Google Maps, online GIS, and GeoTIFF, to name a few. User feedback and suggestions have been critical for us to determine and develop data formats and delivery mechanisms that work best for our broad range of users. Comments and suggestions are cordially welcome and can be sent to coralreefwatch@noaa.gov.

Delivering tools and products to managers through trainings and workshops: Taking the next steps

Britt-Anne A. Parker[1], Tyler R.L. Christensen[2] and Paul Marshall[3]*

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Outreach efforts and workshops for CRW products are central forums for informing coral reef managers of useful tools for coral reef conservation. Formal and informal outreach events and workshops increases the number of people using the product, creates a dialog between users and producers that facilitates product improvement, clarifies the intent and limitations of the product and spurs innovation through exchanges with users and managers. To highlight the advantages of outreach and workshops, Parker used three different case studies. The first case study focused on the Satellite Tools Training workshops, which were funded by the World Bank Coral Reef Targeted Research & Capacity Building for Management (CRTR) Remote Sensing Working Group. Participants were from a broad, but targeted, community including scientists, students, researchers and managers. The overall goal of the workshops were to enhance capacity for monitoring coral reefs by providing the coral reef communities in developing countries with a technical background of the CRW satellite tools. Most of these workshops were located near Centers of Excellence.

The second case study highlighted the Reef Resilience and Climate Change (RRCC) workshops that were an outcome of the Turtle Bay, Hawaii workshop. At the time "A Reef Manager's Guide to Coral Bleaching" had just been published and workshop attendees thought that in order to bring the concepts captured in the text into practice, it would be necessary for workshops to take place in order to get the information out to managers. The goal of this workshop was "To build a global network of reef managers who are taking action to test and refine strategies to effectively manage coral reefs in the face of climate change to build a resilient management community." While the concepts covered in the workshop were broad, encompassing climate change basics, coral reef resilience and incorporation of resilience into MPA design and management, just to name a few of the topics, the component of identifying tools for managers and bleaching early warning systems was a central piece of the workshop series.

The third case study was the Socioeconomic-Monitoring (SocMon) training workshops led by the NOAA CRCP, which are more involved in capacity building efforts than the RRCC workshops and include follow-up visits and seed funding. The trainings are held in numerous sites in six regions globally, with tailored methodologies for each region. The presenter focused on the Pacific Region and SEM-Pasifika as an example. The workshop goal is to deliver a set of socioeconomic monitoring methodologies that included participatory, community-based assessments, such as household surveys for participants from areas that have management plans in place. In this way communities benefit through increased stakeholder participation and by building capacity themselves. Since 2003, over 60 assessments have been completed in 30 countries. The SocMon Initiative funds participation for accepted delegates and additional funding is provided to the attendees to implement their monitoring protocols once implementation strategies have been developed. Indicators suggest that this method has been very successful. Additional outreach tools include informational online tutorials for remote sensing and ocean acidification. Educational remote sensing and coral reef curriculum and remote sensing lessons, in addition to an oceanography activity and a data activity that use data from the 2005 bleaching event, are also available on the CRW website. These have been presented and discussed at National Science Teachers Association (NSTA) meetings and webinars and have been well received. Lessons learned from these training and outreach activities are that training ought to meet the needs of the Managers, be flexible and identify what Managers want, and address the technological challenges of respective locations. Future improvements considered developing focused user dialogues with key institutions and users, providing online courses for training, and enhanced training of RR and CC workshop trainers.

Abstract
It is important that any discussion of new and improved remote sensing based products designed to assist coral reef managers should include not only product development but also dissemination and delivery. Product outreach plays many important roles that include building a community of users who can provide feedback to improve products and seed discussions on new product and an opportunity to communicate clearly the intents and limitations of a product. This outreach can occur as both informal one on one conversation with users or formal training environments such as workshops. Three examples of formal training models that each approach outreach differently at the World Bank funded Satellite Tools Trainings, the Responding to Climate Change: A Workshop for Coral Reef Mangers based on The Reef Manager's Guide to Coral Bleaching, and the SEM:Pasifika Training as part of the Global Social Economic Monitoring Initiative. These workshops all have different approaches in their focus, participants, and model for follow up but all work to get tools into the hands of those who use them. It is also important to consider other audiences with whom you might communicate as well as other methods of communication. NOAA Coral Reef Watch has used online tutorials to reach managers who have not been involved in trainings or to provide review for those that have. These tutorials have been written at a level that is also appropriate for high school students who have an interest in remote sensing. There is also the recognition that coral reefs, remote sensing, and climate change are provocative subject matter for the classroom. Lesson plans, curriculum and data activities have been made available through the Coral Reef Watch website and through presentation to teachers at venues such as the National Science Teachers Association. This has been a very successful and rewarding interaction that goes beyond disseminating products to a primary audience and a great way to communicate the issues of climate change and coral reefs to the public and the next generation. Through these training and outreach activities we have learned many lessons. Just as it is important to match product resolution with the resolution of management response, it is also important to present the products at the level necessary to understand and use the products. Communicating the intent and limitations of the products is absolutely necessary. Technological considerations are also important as not all users will have the connectivity to deal with visualization tools such as the world-wide web, Google Earth, *etc*. Next steps that Coral Reef Watch will be involved in include Focused User Dialogues with key users, Online Courses with partners like The Nature Conservancy and Training of Trainers for the Reef Resilience and Climate Change Workshops. For more information on the Coral Reef Watch Education and Outreach efforts see www.coralreefwatch.noaa.gov/satellite/education. For more information on the Global Social Economic Monitoring Initiative Trainings see www.reefbase.org/socmon.

Information sharing, integration and quality control for coral reef-related datasets

Jane Hunter

University of Queensland

This presentation focused on efforts to broaden the deliverability and access of coral reef information. Jane Hunter discussed three projects that have enhanced this possibility. All three projects were done by University of Queensland students and included the design of a Coral REef Semantic Informatics System (CRESIS), A Data Registry for Coral Reef Data, and a project that focused on improving the quality of citizen science data. The goals of the CRESIS project included integrating existing research data sets into one unified data store, provide a common search platform across disparate datasets, provide a visualization of search results using a GIS system, provide statistical analysis facilities and provide the ability to export data and analysis results. Numerous challenges, such as different temporal and spatial scales of data, different measurement units, and the cross-disciplinary nature of the data sets had to be overcome. By creating a model using information science ontologies (formal representation of a particular domain of knowledge and the relationships between these concepts), the project was able to map existing data sets into these ontologies (*e.g.,* Excel, Access, MySQL, HDF), create a storage system, and develop an automated query system. The detail-oriented process of modeling the relationships amongst data types required a substantial amount of organization and modification in order to effectively store and query related information using complex search criteria. A user query and display interface was designed and then once the databases or data stores were designed they were evaluated using a range of assessment criteria and queries. Conclusions of the project were that RDF triple stores were good for simple queries and small data sets, PostgreSQL RDBMS performed well for all queries and all data volumes, PostGIS extensions enabled spatial indexing and querying and the Google Web Toolkit provided ideal results visualization.

The second project Hunter described is an Australian Research Data Commons. Currently, the coral reef semantic informatics system provides coral researchers with a central store, but the objective of this project is to integrate this data center with a University dataset registry in the University of Queensland that would begin integrating information from coral reef research and then expand it to other disciplines. Once the data is collected in the University of Queensland dataset registry it is sent to ANDS (Australian National Data Service), which makes the information available to other researchers. Currently IT product developers are designing a web portal for registering, searching, and browsing research data collections. This browser will provide researchers with metadata, and eventually data, on the temporal, spatial and source location for this information. The last example Hunter explained was a method of improving the quality of citizen science data. The emphasis is to exploit web browser and social networking capabilities to produce a credible citizen science program. The aims are to develop IT tools and services, authenticate users, validate and verify data and metadata input, rank users by reliability and trust, rank reliability of datasets, and filter searches based on data reliability. Various software tools have been developed that allow users to login, search and upload data in established formats (*e.g.,* Reef Watch), in addition to user and administrator tools that rank users and their data based on trust values. These are based on a 1-5 star trust ranking from other users, social network analysis, expertise of the member, and the member's frequency of participation. Accumulative trust value is base don ratings from other members and consistency with related data, such as Reef Check and Satellite Data. Members can then access a user page that allows them to see how they are ranked amongst other users. Questions from workshop participants about the use of the word "trust" and the ranking of individuals by other users were raised but it was pointed out that administrators could regulate many of these issues.

Abstract
This presentation provides an overview of three research projects being undertaken within the eResearch group at the School of Information Technology & Electrical Engineering

(ITEE) at the University of Queensland - through collaborations with the Centre for Marine Studies (CMS).

The three projects are:

1. The CRESIS project (Coral REer Semantic Informatics System), a Masters project undertaken by Cam Allen, that compares and evaluates alternative RDF triple store architectures with traditional relational database management systems (PostgreSQL).

2. The e-Reef project (Bevan Koopman) that is developing search, browse and registry services enabling the establishment of a registry of coral-reef related datasets to facilitate discovery, sharing and re-use.

3. The "REPUTE" project (being undertaken by Abdul Alabri)- that is developing mechanisms for measuring the reliability of citizen science data and improving the quality of it. Unreliable data will be filtered out or weighted lower than reliable data during subsequent scientific analyses and re-use. These tools are being developed and evaluated in the context of the Coral Watch project.

Management Considerations

The physical/biological and technical presentations of the workshop were helpful in understanding current scientific issues and remote sensing technical capacities associated with monitoring coral reefs. However, without considering the broader political and economic forces that shape environmental stressors and policies alike, which in turn affect coral reefs, conservation of these resources is unlikely to be effective. The management portion of the workshop brought all of these components together and provided a robust view of the myriad issues faced by, and the needs of, coral reef managers in locations throughout the world.

Managing Coral Reefs 101

Randy Kosaki

NOAA Papahānaumokuākea Marine National Monument

This presentation emphasized questions for the audience rather than explaining specific ways coral reefs can be managed. Kosaki explained how managers, projects, issues, goals and objectives require site-specific management methods. Using the Papahānaumokuākea Marine National Monument (PMNM) as a case study, Kosaki raised the first question managers should ask themselves. What are you managing for? The primary way to identify and ensure management is effective is to outline relevant goals and objectives. Management strategies include sustainable fisheries, food security, restoration/remediation, conservation of biodiversity, ecosystem integrity, indigenous use, and mixed uses. Each one of these can be managed in a different way depending on the strategies of the manager. An additional question managers need to ask is, who are your constituents? Because areas are managed for the general public, and this differs from location to location, it is important to consider who will use these resources. In smaller areas, the local community could be the population of interest. In larger areas, national or international communities may be the key stakeholders. At the federal level, future generations, international cooperation or trans-boundary MPA agreements may be the emphasis. Another question was what resources does the manager have authority to manage? Depending on the classification of the managed area only specific organisms may be protected or they may be protected to varying degrees. This begs the question, how is management defined? Marine spatial planning and zoning boundaries, promulgation of regulations, education, monitoring, research, and acquisition of knowledge all may define management in particular areas. To explain how these questions were addressed, Kosaki provided a case study of the NWHI and how it developed into the Papahānaumokuākea Marine National Monument.

The U.S. Coral Reef Task Force (USCRTF) visited Hawaii in 1998 looking for large coral reef resources in U.S. waters. After realizing the importance of the NWHI, the USCRTF designated it as a US coral reef ecosystem reserve with orders to become a national NOAA marine sanctuary. Goals and objectives of the designation process included prioritizing public input on what the NWHI sanctuary should look like and to research biogeographic, biologic, scientific (spp. richness, abundance of apex and endangered species) information, in addition to fishing catch data. This extensive amount of data was then used to inform decisions made on the locations of protected areas, which were identified by their biological and fishing importance. However, all of the sanctuary designation research came to a standstill with the executive order to make NWHI a Marine Protected Area (MPA) on June 15, 2006. In an unforeseen turn of events, the endemism and charismatic mega fauna that was being identified by researchers in the NWHI piqued the interest of Jean-Michel Cousteau and resulted in the production of the documentary "Voyage to Kure." This documentary was viewed by then President George W. Bush and it influenced him to establish the NWHI MPA. While the policy rationale for this decision may not have originated directly from the science generated by the studies conducted by NOAA researchers, the ecological significance of the area seems to have influenced an alternative way of obtaining legislative attention to serve a common good, which resulted in the designation of the world's largest MPA at the time. The moral of Kosaki's story is that science is still very important and that researchers need to find ways to present scientific data in a palatable format to the general public and policy makers in order to motivate change. The NWHI is now a strongly protected marine monument but more work is necessary. While many of the local anthropogenic threats are accounted for, many problems still exist in the NWHI that originate from distant locations, specifically marine debris, alien species, sea level rise, and climate change. A key sector of involvement that Kosaki mentioned is collaboration with international entities to address the issue of climate change. Kosaki plotted the historical trends of MPAs in the Pacific by noting how the Great Barrier Reef was the first to pioneer the idea of large scale MPAs with the U.S. following suit. Currently, agreements have been made with the French to conduct joint research in French territories in the Pacific to eventually develop MPAs in the region and proposed MPAs have been discussed in the coral triangle. The benefits of these collective, and in some cases, networked MPAs lies in their ability to provide some type of refugia, whether that is for coral reef resilience to climate change or to reduce fishing pressure. Another role for MPAs lies in their ability to change societal values by acting as centers of education and outreach efforts to illustrate how anthropogenic forces are affecting oceanic ecosystems.

Managing coral reefs in a changing climate

Billy D. Causey

NOAA Office of National Marine Sanctuaries

This presentation by Billy Causey juxtaposed the management requirements of the NWHI with those of the southeast U.S. One common thread found in both presentations was the idea that coral reef managers are not managing natural resources, but the people who interact with those resources. In the southeast U.S., Causey pointed out that the management mandate is much broader than that of the NWHI and there are many management strategies in place that include assessing and restoring sanctuary resource damage, responding to emergency incidents and contingency planning, permitting and regulating multi-use areas, conducting research, monitoring, education, outreach, enforcement, and marine spatial planning. The Florida Keys had the first comprehensive marine zoning plan in the U.S., although the concept had been derived from the management efforts initiated for the Great Barrier Reef. Five zones were established in the early 1990's and three were established as no-take zones. The Florida Keys are surrounded by an area to be avoided (ATBA), which requires sea-going ships to be more than 50 meters from the coral reefs. Since the ATBA has been established no shipwrecks have occurred since 1997. In a high use management area like the Florida Keys, managers have the ability to temporarily close certain areas if they are under stress from bleaching or diseases. The ability of being able to use Coral Reef Watch tools to predict bleaching events has made the public more receptive to the idea of closing areas in order to protect them and has eased some tensions between managers and the populace. The Florida Keys have dealt with climate change and the implications of this (*i.e.,* coral bleaching) since 1983. Because of the contrasts between coral cover in the Florida Keys and Flower Garden Banks in the Gulf of Mexico, these areas serve as sentinel sites to identify coral stressors under varied environmental conditions and baselines and serve as optimal long-term monitoring sites. While the increased frequency in bleaching of coral reefs was detrimental to coral reefs, this opportunity provided a chance for managers to engage MPA stakeholders, gain credibility and trust due to the manager's ability to predict bleaching events and build a constituency as well as social resilience.

As a result of increased stakeholder support, the Florida Keys National Marine Sanctuary (FKNMS) was able to team up with the Mote Marine Laboratory (MML) to develop a community-based reporting and response project called Marine Ecosystem Event Response and Assessment (MEERA). Under this program anyone can submit a MEERA report, which is evaluated and forwarded on to an appropriate agency. Another community monitoring program is the Keys Association of Dive Operators (KADO) who are often dive boat captains trained in taking water samples and measuring other parameters. Unusual biological activity on the water is noted, which helps to ensure events are recorded, and then the samples are sent to the state of Florida for lab analysis. Bleach Watch is another volunteer based monitoring program that acts as a coral bleaching early warning network in the Florida Keys. This project was informally started in Florida and then developed into a formal project in Australia by Dr. Paul Marshall. In Florida, MML and NOAA monitor climate and sea temperatures from a variety of sources, such as CRW products and monitoring buoys that are part of the Coral Reef Ecosystem Integrated Observing System (CREIOS), to provide "Early Warning Alerts" and "Current Conditions Reports" for coral bleaching in the FKNMS and surrounding waters. The program involves the community in monitoring coral reef health, which provides FKNMS with the reefs current conditions in the form of summaries, community feedback and environmental conditions. Training and coordination of volunteer observers is conducted by Mote Marine Laboratory and involves training them to identify the severity of bleaching, the types of corals bleached and the percentage of bleaching apparent on the coral. The objective of this is to support the research and management of resilient coral reefs. The program has been effective in this endeavor with 289 bleaching reports, over 100 volunteers trained, 50 volunteers reporting in 2009, 25 volunteers reporting every two weeks, 10 "Current Conditions Reports" distributed, and great relationships with several organizations as indicators of efficacy. Ways in which Causey thought the program could be improved included measuring real-time bottom temperatures at select reef locations and selecting volunteers for ground-truthing ICON and CRW stations. Another program Causey mentioned was the Florida Reef Resilience Program (FRRP). This program is managed by The Nature Conservancy (TNC) and builds on the MEERA and Bleach Watch programs to find reefs that are likely to resist or recover from bleaching in order to guide protection and management of those areas. Guidance is provided by a steering committee and it is a partnership of numerous institutions. One of the primary tasks of the FRRP is the disturbance response-monitoring program. As the name implies, this effort monitors coral reef health after disturbances, such as coral bleaching and hurricanes. From 2005-2009 the FRRP focused on climate change and trained experts from 12 agencies to survey corals and bleaching on Florida reef tracts during peak annual temperatures. Follow-up surveys were conducted after moderate or severe bleaching years, such as 2005. The impacts of bleaching, *e.g.* disease is also monitored in the rapid response and survey sites are randomly generated. Data generated from these projects can be incorporated into maps to illustrate bleaching extents by zones to allow for comparison and contrasting with other zones. Although cold water bleaching is less common than warm weather bleaching, in January of 2010 the MEERA project documented widespread bleaching of coral throughout the Florida Keys. In many of these locations, the reefs were considered as some of the most resilient reef segments. Therefore, Causey recommended that the notion of resiliency be reexamined.

Abstract

Threats to the coral reefs of the world are predominantly: climate change; land-based sources of pollution; habitat loss and degradation; and overfishing. These are occurring at global, regional and local scales. While we are developing strategies to work on the global impacts of climate change, it becomes even more important to address the impacts to coral reefs at the regional and local scales. In National Marine Sanctuaries we have developed and implemented an array of management tools to achieve our mandate of resource protection in our multiple-use areas. These are in the form of management strategies, including: education and outreach; regulatory, including issuance of permits; enforcement; research and monitoring; marine spatial planning (marine zoning); maritime heritage programs; and direct resource protection measures such as installing mooring buoys, channel marking, restoration, water quality protection programs and a variety of other directed management actions. While at the same time of implementing regional and local management strategies in the Florida Keys National Marine Sanctuary (FKNMS), we have had to take a global perspective in our protection and conservation of our coral reef ecosystem. Some of the earliest effects of climate change were witnessed and reported in the late 1970's and early 1980's in the Florida Keys. The combination of *in situ* observations, later coupled with hydrographic parameters measured and recorded by an array of C-MAN stations supported our local interpretation of the potentially severe impacts of global climate change on our local coral reefs. These observations were later incorporated into more remote monitoring programs as the advances in satellite technology moved us toward a global response to climate change and the various secondary impacts to coral reefs, such as coral bleaching, coral diseases and the impacts of ocean acidification. At the local level, our response has been to work with local partners such as Mote Marine Laboratory, The Nature Conservancy and other partners to implement local management strategies to raise the awareness. Along with Mote Marine Laboratory, the FKNMS implemented a program called Marine Ecosystem Event Response and Assessment (MEERA), which is a community-based reporting and response management program to environmental perturbations in the FKNMS. MEERA involves people who may or may not work on the water, but have observations to report of some kind of marine related problem. Another program initiated by the FKNMS and Mote Marine Laboratory is BleachWatch, which is a more formally trained network of observers who monitor the conditions leading up to and during coral bleaching events. BleachWatch makes it possible for a rapid response to coral bleaching by combining remote sensing with *in situ* observations. This allows time

for managers to mobilize a coordinated scientific and public response to coral bleaching. The reliability and accuracy of predictions and these early warnings have increased the credibility of the scientists and managers in the eyes of the public and has served to elevate the impacts of climate change to the broader public who visit the Florida Keys during such events. The Nature Conservancy has implemented the Florida Reef Resilience Program (FRRP), which includes a number of public and private partners. There are several components to the FRRP with disturbance monitoring and a rapid response to environmental perturbations such as coral bleaching, coral diseases and severe weather events such as the cold-water impacts to corals in the Florida Keys in January 2010.

U.S. coral reef managers' requests for remote sensing products

Jessica A. Morgan

NOAA Coral Reef Conservation Program

In this presentation Jessica Morgan highlighted technical mapping needs that managers have. The decision to identify the needs of coral reef managers was undertaken by NOAA's Coral Reef Conservation Program (CRCP) and the Coral Reef Ecosystem Integrated Observing System (CREIOS) as part of a strategic planning process that identified the goals and the objectives of the CRCP. One concern that was addressed in the process was identifying managers' needs for technical mapping and monitoring products in U.S. jurisdictions.

In order to address this, investigatory workshops were conducted by CREIOS and took place in Hawai'i and Puerto Rico to discuss CREIOS mapping and monitoring activities in 2008 and 2009 respectively. Representatives from numerous U.S. coral reef jurisdictions attended, including American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), Florida, Guam, Hawai'i, Puerto Rico, and the U.S. Virgin Islands (USVI). Attendees had mixed affiliations and included NOAA scientists, federal, state and territory resource managers, and local university scientists.

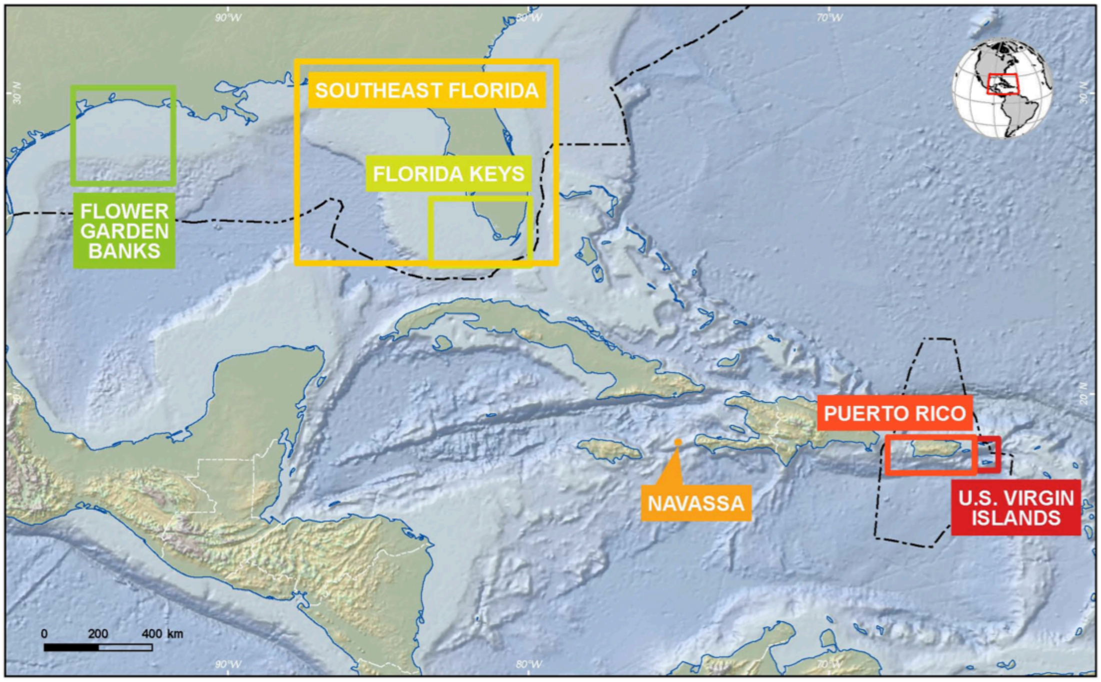
The objectives of the workshop were to:

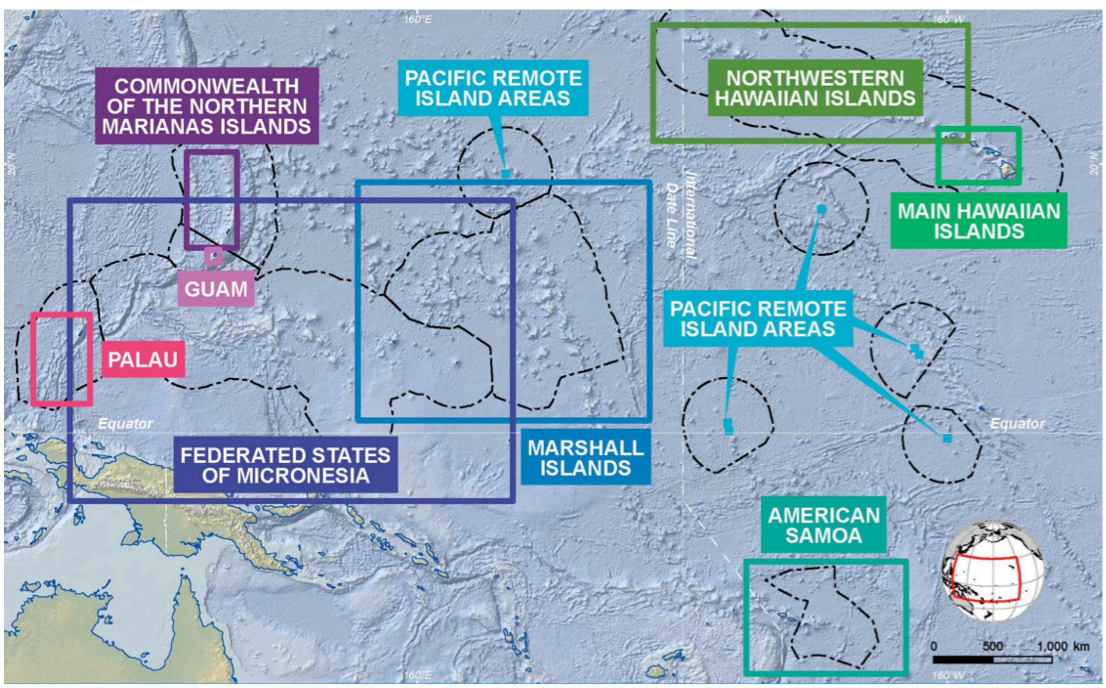
- Identify mapping and monitoring needs to address management for coral reef conservation
- Identify possible products and solutions to meet management needs

The outcomes of these workshops are used to inform strategic long-term funding decisions, and included:

- Increased technical capacity within jurisdictions (*i.e.,* technical experts)
- Improved communication of scientific information to general audiences
- Improved and targeted dissemination of NOAA data and information products
- Increased emphasis on mapping and monitoring at finer scales in specific areas of importance to managers

The CREIOS workshop report can be downloaded under the "Strategic Planning for Coral Ecosystems" heading at the website below:
http://coralreef.noaa.gov/resources/publicationsdata/.





Morgan provided several examples of the similar needs expressed across jurisdictions. In American Samoa, there is a need for the mapping of marine resource distributions to support Marine Protected Area (MPA) design and the "Two Samoas" initiative, gathering information on near-shore oceanic currents for connectivity studies, and information on nutrient and sediment loading in near-shore waters. In CNMI and Guam, there is a need for bathymetric data of shallow water areas and maps of Apra Harbor to assist with the planning assessment and mitigation efforts of military expansion, and hydrographic data and models to investigate coral phenomena such as larval dispersal, which is important for planning and management efforts. Hawai'i needs maps of improved satellite imagery for critical areas in the NWHI, bathymetric gap filling in the main Hawai'ian islands, acoustic surveys for understanding the magnitude of legal fishing pressure and as a tool for enforcement in MPAs, and integration of watershed information. In Florida, there is a need for consistent bathymetric and benthic habitat maps of unsurveyed areas, *Acropora* monitoring and mapping, increased physical, chemical, and water quality properties monitoring, increased coverage for fishery dependent and fishery independent monitoring, and hydrodynamic models for scenario testing and hindcasting. In USVI and Puerto Rico, there is interest in hydrodynamic models and water quality monitoring to understand land based sources of pollution issues, in addition to bathymetric and benthic habitat maps of near-shore and shallow bay marine environments near priority watersheds. The Atlantic and Caribbean region (including the Flower Garden Banks and Navassa Island) needs the same products as USVI and Puerto Rico, in addition to fish tracking and water quality monitoring in all jurisdictions, monitoring of reference sites with relatively low human impacts, and centralized access to datasets from multiple sources.

The primary remote sensing data requested included high spatial and spectral resolution LIDAR, IKONOS, and Landsat imagery for large-scale observational data that could support local monitoring and management in addition to calibration and validation data for *in situ* measurements and models. Mapping products included bathymetry and change analysis products. Physical monitoring products included near-real-time oceanographic data, such as high-resolution sea surface temperature, sea surface currents, and benthic water temperature. Chemical and biological products include ocean chemistry, chlorophyll *a,* and change analysis products of these parameters (*e.g.,* turbidity/chlorophyll *a* anomalies). Another suite of parameters consisted of water quality indicators that could be accessed in near-real-time. Parameters of interest included clarity, turbidity, chlorophyll *a,* light attenuation, and photosynthetically active radiation (PAR) for detecting events like sediment plumes and harmful algal blooms. Ancillary data requested to support these parameters in more applied applications are topography, digital elevation models and land use land cover data. In closing, the priority needs that Morgan identified consisted of bathymetry, surface circulation, water quality parameters, land-use parameters and technical assistance to build capacity to use remote sensing in U.S. jurisdictions.

Morgan, J.A. and J.E. Waddell [Eds.] (2009). NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) Workshops Report. NOAA Technical Memorandum CRCP 9, NOAA Coral Reef Conservation Program, Silver Spring, MD, 68 pp.

Abstract

The NOAA Coral Reef Conservation Program (CRCP) conducted two regional workshops in Hawaii (2008) and Puerto Rico (2009) to address its Coral Reef Ecosystem Integrated Observing System (CREIOS). NOAA scientists with technical expertise in mapping and monitoring coral reef ecosystems met with resource managers and local scientists from all U.S. coral reef jurisdictions. In general, managers requested increased technical capacity within jurisdictions, improved communication of scientific information to general audiences, improved dissemination of NOAA data and information products, and increased emphasis

on mapping and monitoring at finer scales in specific areas of importance to managers. Many jurisdictions requested better maps, hydrographic models, water quality monitoring, and fish tracking. Specifically related to remote sensing, data managers requested large-scale observational data to support local monitoring and management, and calibration and/or validation data for models and *in situ* instrumentation. Priority requests for remote sensing products included bathymetry, surface circulation, water quality, and land use analyses. Finally, managers stressed the need for technical assistance to build capacity to use remote sensing data in the local jurisdictions.

Use of coral stress monitoring for management

Billy D. Causey

NOAA Office of National Marine Sanctuaries

The monitoring of coral stress is a preliminary step in the management process and was the subject of Billy Causey's talk. Using the Florida Keys as a case study, Causey provided a historical outline of the various stressors to coral reefs in the Florida Keys and the scales in which they function. Beginning as a manager in the Looe Key National Marine Sanctuary (NMS) in 1983, Causey was responsible for managing 5.5 square nautical miles. Soon after, Causey learned that *Diadema* were dying off in the Caribbean near Panama. During this same year, there was the first bleaching event in the lower Florida Keys. Harilaos Lessios investigated the *Diadema* die off throughout the Caribbean, which destroyed 95% of the population within a year, and he developed a diagram that portrayed its progression. Lessios found that it followed the oceanic circulation patterns in the Caribbean region. With the events of the *Diadema* die off, and later evidence of connectivity within the Caribbean region from current drifters equipped with satellite global positioning systems (GPS), Causey called into question the role of broader forces that were affecting Looe Key NMS. In 1986, after the bleaching event of 1983, Causey found that black band disease was present in Looe Key reefs. In 1987 another bleaching event occurred. Causey pointed out how at the time scientists knew that multiple stressors were affecting coral reefs and that water quality was a chief suspect in the decline of coral reefs, but the emphasis was on stressors at a local scale. Causey then noted how he went to St. Vincent and the Grenadines in 1989 for a workshop and had expected clear waters and healthy coral reefs. When he arrived he found that there were more coral diseases than in Looe Key and the water visibility was worse. When he asked the captain of the live aboard why the water quality was so poor, the captain explained that it was the sediment plume from the Orinoco River. Faced with the broad scale of these stressors, Causey realized the value of remote sensing to understand the broader forces that affected the health of the reefs under his management. Causey then pointed out the primary oceanographic connectivity patterns, obtained from ocean current satellite trackers, in the Caribbean and the Gulf of Mexico that influence coral reefs in the Florida Keys. These forces operate at a variety of scales. At a regional Caribbean scale, the Loop Current circulates water from Caribbean waters near the Mesoamerican Barrier Reef, or the coast of Central America, and connect to the Gulf of Mexico and later the Atlantic. At a regional Gulf of Mexico scale, the Mississippi river basin drains 40% of the water in the U.S. into the Gulf of Mexico, which then bypasses the Florida Keys, occasionally promoting harmful algal blooms in the south of Florida. And at a local scale, the modification of freshwater drainage

in the Everglades of Florida has impacted coral reef ecosystems and their associated ecosystems, for example the collapse of sea grass beds from 1990 - 1992. Changes in tropical marine ecosystem were partly the result of the drainage engineering efforts on the part of numerous state and federal entities, such as the U.S. Army Corps of Engineers. Currently these projects drain roughly 80% of the freshwater that falls in south Florida. Recently the ecological importance of the Everglades was recognized and Congress has asked the U.S. Army Corps of Engineers to drain much of the water that was diverted through canals and rivers like the Caloosahatchee and Saint Lucie, back into the Everglades. Ecosystem disturbance as a result of human development and engineering modifications have provoked broad water quality monitoring programs in the Florida Bay and the Florida Keys by the Florida Keys National Marine Sanctuary (FKNMS) Water Quality Protection Program.
http://ocean.floridamarine.org/fknms_wqpp/index.html

Causey pointed out how data collected in this program not only identify trends in the water quality near coral reefs and seagrass beds, such as the mass bleaching of 1997-1998, but they can also provide engineers with data that will help them design projects that are less damaging to these ecosystems by regulating the flow of water to these areas as needed. These data have also allowed managers in the area to identify resilient reef habitats, which have been inshore patch reefs and mid-channel reefs. With the cold water bleaching event of January, 2010 these areas were amongst the hardest hit, which has made many coral reef managers question their criteria for resiliency. Just a few of the remote sensing products currently utilized by FKNMS include sea surface temperature and harmful algal blooms, the web sites of which are below, respectively.
http://coralreefwatch.noaa.gov/satellite/current/products_sst.html
http://tidesandcurrents.noaa.gov/hab/

These technologies are very useful for understanding the oceanographic physical characteristics of the region, the connectivity of stressors to tropical marine ecosystems in southern Florida, and the dispersal of larvae from spiny lobsters, conch, and coral species. In addition, understanding how the region is interconnected aids in making more informed management decisions based on proximity to ecosystem stressors and important ecosystem services, such as fish spawning and feeding locations.

Abstract
In order to under the sources of stress on coral reefs it is imperative that managers and scientists alike understand some of the fundamental characteristics that exist among and between coral reef ecosystems of the world. The coral reefs of the Wider Caribbean are far less biologically diverse than those of the Indo-west Pacific region and geographically exist in a far-more enclosed system than those of the Pacific. The Wider Caribbean is considerably smaller geographically speaking and essentially comprised of two semi-enclosed basins, influenced by watersheds from South America, Central America and North America. The tendency has been for mangers to look solely at the local stressors on the coral reefs of the Wider Caribbean, while ignoring the greater influences of the regional and global stressors. While searching for the "silver bullet" causing coral reef decline, some environmental groups and a select few scientists choose to ignore the complexities in the search for sources of coral reef decline. Now, through advanced and continually improved remote sensing capabilities, we (coral reef managers and scientists) can comprehend the vast connectivity that exists within the Wider Caribbean, and the far-reaching influences of stressors to our

coral reef ecosystems. No longer can managers and scientists rely on protecting their areas with artificial boundaries out in the ocean. We have to apply an ecosystem-based approach to management, working across domestic and international boundaries. The more we can export our remote technologies and our ability to assess marine environments on large spatial scales, the sooner we can comprehensively join ranks to address the remote influences on our coral reefs and the sooner we can turn the public's attention toward global solutions, coupled with regional and local management actions. The Florida Keys National Marine Sanctuary (FKNMS) relies on the available satellite and remote sensing capabilities of NOAA's Coral Reef Watch Program and those of NOAA's Atlantic Oceanographic and Meteorological Laboratory to integrate our *in situ* observations with real-time, remotely sensed observations. This is essential in order to mobilize and implement several management programs directed at monitoring and assessing the health of our coral reefs during severe environmental perturbations, such as: elevated sea surface temperatures; harmful algal blooms; influence from distant watersheds; or other the impact of extreme weather events. The reliability of NOAA's remote sensing capabilities and their spatial and temporal coverage has made it possible for mangers to incorporate these capabilities into every day management actions. Whether the remote sensing technology is used to track water circulation, calculate sea surface temperatures, the level of chlorophyll in the water, or track fish and lobster movements, the use of satellite data is essential for management applications. This reliance will be even greater as new remote sensing tools are developed, such as the ability to assess and monitor ocean acidification, dissolved oxygen content, and other parameters.

Key environmental variables for management

Randy Kosaki

NOAA Papahānaumokuākea Marine National Monument

From a basic information need standpoint, there are two primary needs for coral reef managers, characterization and monitoring of the coral reefs. Kosaki pointed out how these two information needs varied with characterization requiring a singular description of the habitat types, spatial extent, distribution and abundance of biological resources, and physical parameters of the abiotic environment. Monitoring requires numerous descriptions of these characteristics to evaluate the temporal and spatial status and trends of biological resources as well as changes over time and space in the abiotic environment. Kosaki pointed out that both characterization and monitoring are important for different reasons. Characterization is important for establishing which resources are present and in need of management, while monitoring allows for the changes and shifts of these resources to be identified so the patterns and processes that are taking place in these management areas are understood. Kosaki then described the environmental variables that affect the distribution and health of coral reefs, which included temperature, nutrient levels, water quality and clarity, wave energy and terrestrial inputs to coastal systems. Sea surface temperature is an important variable due to the relatively narrow range of temperatures that are necessary for coral and their associated fauna to be healthy. Nutrient levels are important because coral reefs are generally found in oligotrophic (low nutrient) waters and if high nutrients are present other organisms (*e.g.,* algae) can outcompete coral. Water quality and clarity is also important because coral reefs require photosynthetically active radiation (PAR) to grow. This limits coral growth to certain depth and areal extents as light penetration decreases with depth and highly turbid waters can restrict sunlight availability for coral reefs. Wave energy is an important parameter for a couple of reasons. When wave energy is low, it is beneficial to coral reefs because it promotes mixing, which provides the water with oxygen and promotes evaporation and cooling of the water. However, during episodic and intense wave energy periods, coral reefs can break, altering the coral reef's geomorphology. Terrestrial inputs of sediment and nutrients to coastal systems are important to monitor because they can bury coral reefs with silt or alter their environments by contributing to increased algal growth. This information can be provided to local land use managers to inform and modify watershed management practices, which have the potential to improve the health of coral reefs in coastal areas. Of the variables mentioned above, we can measure sea surface temperature, both by satellite and *in situ*. Light can be measured in various forms (*e.g.,* PAR and UV) at various remote sensing scales (*i.e.,* satellite and *in situ*). Water quality and ocean chemistry have the potential to be monitored by remote sensing satellites but more work needs to be done. Waves and sea surface conditions can be determined by satellite, and geomorphology accretion is another area of research interest, but technical hurdles must be overcome first to see how this parameter is potentially affected by climate change.

The kinds of change coral reef managers want to monitor include natural variability, episodic events and long-term change. Examples of natural variability include daily, lunar, annual, and decadal events. Episodic events include bleaching, disease, storms and upwelling situations and long-term change examples include climate warming or cooling, sea level rise, ocean acidification and topography and bathymetry variations. While most coral reef managers do not use remote sensing analysis in their work, they do utilize a number of monitoring methods that can benefit from remote sensing information. Because coral reef managers often study small areal extents to gather data of a high taxonomic and spatial resolution, there tend to be large data gaps when analyzing large areas. Kosaki mentioned how there has been a shift in the NWHI from fixed sampling sites to a stratified random sampling design to sample areas in a way that preserves statistical assumptions. Remote sensing maps can aid in this effort by providing sampling locations that are randomly chosen. Throughout the workshop spatial and temporal scale have been prominent themes in the discussion about what type of data would be the best to have. As Kosaki pointed out, these vary depending on the individual using the data. In an example, Kosaki mentioned that it would be great to have the revisit time (1 day) of a POES satellite of the reefs in the NWHI because current *in situ* monitoring trips only occur once a year and any improvement in filling in data gaps, even if the spatial resolution was not as good as with divers in the water, would be an improvement. Considerations of scale are important and powerful because at the global scale it is possible to utilize multiple local events around the world to exemplify global trends. At the regional scale it is possible to monitor remote areas and link neighboring events to local communities. At the local scale, it is possible to highlight socioeconomic impacts that capture people's attention and engage local communities in monitoring, ground truthing and response efforts. While gathering the data is an important step, managers are most often concerned with how they can use this data in a way that conserves resources for the people in their area. Examples Kosaki used included predicting climate change impacts pertaining to biological and socioeconomic impacts. Billy Causey in the FKNMS echoed this point whereby credibility with local stakeholders was gained through being able to accurately predict bleaching events. From a monitoring perspective, data can be used to develop preimpact baselines, identify post-impact recovery and long-term trends. Other beneficial ways in which the data can be used is through mitigation, education and outreach efforts. To exemplify this, Kosaki mentioned the August 2002 thermal anomaly over the NWHI that was predicted by CRW products 2-3 weeks ahead of a research cruise. In the short-term, CRW data allowed Kosaki to bring specialists in the areas of coral bleaching and coral diseases on the cruise, an effort that without the CRW data may be subject to skepticism. It also allowed Kosaki to ensure that the cruise plan visited affected atolls and conducted transects in all habitat types. Lastly, it gave Kosaki time to prepare media materials, press releases and other outreach materials. In the long term, the monitoring conducted allowed for studies of coral recovery, mortality, and disease among bleached corals, legitimated the planning of a return survey trip three months later, and provided an opportunity to examine the recolonization and succession of coral and fish communities in the NWHI.

Managing coral reefs: Aspects other than those directly related to corals

Billy D. Causey

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A prevailing theme throughout many of the management presentations centered on the concept that managers are not managing coral reefs, they are managing for the actions of the people who interact with these areas. Billy Causey began the presentation by explaining a few of the characteristic distinctions between the coral reefs of the Caribbean and those of the Pacific and Indian Ocean. The first impressive distinction pointed out was the vast difference in the biodiversity of coral between the two regions. The Pacific and Indian Ocean contain the majority of coral species found in the world, whereas the Caribbean is relatively low in coral reef biodiversity. Another distinction between these regions is the lag time associated with coral reef stressors, such as bleaching and disease. Coral stressors, such as bleaching and disease, were documented in the Caribbean 10-12 years earlier than similar events in the Pacific and Indian Oceans. Causey then explained how changes have been taking place with organisms other than coral at the ecosystem, community and species levels. The first example Causey provided of this was with the sponge (*Xestospongia muta*) die-off of 1979 that occurred during higher than average water temperatures. The next year, in 1980, there was a massive fish die-off as a result of *Brooklynella hostilis*, a parasite often triggered by warmer waters, which was recurrent in 1997, 1998 and 2002 (Landsberg, 1995). In 1983 there was the *Diadema* die-off of Long Spine Sea Urchin near Panama as a result of a microbe disease, which also occurred with higher than average sea temperatures. Once abundant in the 1970's, crinoids and brittle stars are now difficult to find. During a six-hour survey by Causey in 2001 Causey found none. Causey noted how echinoderms are often the first things to die if the chemistry is wrong in marine aquariums. Corallimorphs, such as *Ricordea florida,* are now only found in some mid channel areas but they used to be found along the tops of many coral reef structures. Another disastrous event was the seagrass die-off of 1987 in the Florida Bay documented by (Robblee et al., 1991). Without seagrass to take up the nutrients flowing into the Florida Bay, a series of harmful algal blooms occurred from 1987-1994. A huge rainstorm eventually stopped the pattern by flushing the area with fresh water. In an effort to determine whether *Diadema antillarum* have made a comeback in the Florida Keys, a survey was conducted near NOAA's Aquarius Habitat. In 1998 there were three *Diadema antillarum* and in 2007 there was only one. This finding contrasts with other locations in the Caribbean, for example Jamaica, that have noted that there has been a comeback. The limiting factor appears to be fish abundance. In Jamaica fish populations are low and the lack of predation is speculated as the reason for the comeback of *Diadema antillarum*. However, in the Florida Keys, where fish populations are high, predation appears to be limiting *Diadema antillarum* populations in some locations. Brittle stars are also disappearing. In a study Causey mentioned that investigated the abundances of Brittle stars, the populations of these echinoderms have decreased from 1977 to present. Encrusting sponges in shallow reef areas are also in decline. Encrusting sponges are important food sources for many coral reef fish species, including Angelfish, which are important to managers because they often indicate shifts in coral reefs. Many of the aforementioned declines are the result of increased sea surface temperatures, according to Causey, and there has been so much of a coral-centric emphasis that we have failed to notice a decline in the biodiversity of the coral reefs. In some of the worst cases we may not even know what we have lost after it is gone. While some locations in the Florida Keys have decreased in their coral cover and species and keystone species abundance as a result of increased sea surface temperatures and overfishing, there are still areas of beauty and ecological health. The Flower Garden Banks are one of these areas and are known as a sentinel site that has not experienced significant change, largely due to its remote location. Vast protected areas and distance from development are two of the key variables in preserving sentinel sites, which are incredibly important if we are to conserve coral reef habitats that can tell us more about how these ecosystems function and the ecosystem services they can provide in an area that is undisturbed by human interactions.

Abstract
As we look beyond corals and coral reefs at other aspects in the coral reef community that demonstrate change or decline as a result of climate change, we have to weigh such regional or global characteristics as biodiversity, spatial and temporal distribution, as compared to regional or local influences. The Wider Caribbean began showing signs of environmental degradation in coral reef communities approximately 10-12 years ahead of the Pacific. These changes have occurred at the ecosystem, community and species scales, with all having a common adverse environmental parameter – elevated sea surface temperatures. Ironically, some of the first signs of coral reef community stress in the Florida Keys did not begin with the corals themselves, but with other members of the coral reef community. In the Florida Keys, we first began to observe and record decline with a massive die-off of the large barrel sponge *Xestospongia muta* in June of 1979. Areas along the reef track that were exposed (by way of large tidal passes) to the extremely elevated sea surface temperatures of Florida Bay and the Gulf of Mexico, resulted in hundreds this species dying in a matter of weeks in a narrow geographic range. In 1980, similar doldrums and excessively warm waters returned to the Florida Keys, which resulted in a massive fish die-off caused by *Brooklynella*, a ciliated protozoan called *Brooklynella hostilis*. Such an outbreak of fish disease was reported in other parts of the Caribbean in the late 1980's, but it wasn't until the 1997-98 timeframe when the fish disease occurred again in the Keys (coinciding with coral bleaching events) and elsewhere in the Caribbean that we were able to identify the infectious organism. In January 1983 the die-off of the long-spine sea urchin began in the Panama Canal area during unseasonably warm conditions and swept through the wider Caribbean in a one-year timeframe. The die-off reached the Florida Keys in July of 1983, and while a water-born pathogen was never identified, it was clearly the stress of the elevated sea surface

temperatures that promoted the reproduction of a microorganism that was spread by way of the current highways around the Caribbean. In the 1983-87 timeframe, other reef dwellers such as crinoids, brittle stars and corallimorphs began to decline in numbers and mass on the coral reefs of the Florida Keys and have not recovered to date. What else has been disappearing before our eyes, while our attention has been too "coral centric?" At the same time a massive coral bleaching event was occurring on all of the outer reefs of the Florida Keys and we were receiving reports of massive bleaching from around the Caribbean, the seagrass community of Florida Bay began to collapse. A combination of elevated sea surface temperatures, combined with elevated salinities and low dissolved oxygen resulted in a massive die-off of turtle grass (*Thalassia testudinum*). Even mangroves succumbed to the elevated salinities in Florida Bay. It wasn't until later that we could connect the dots of all of the causative environmental conditions, created in part locally by the way waters had been diverted away from Florida Bay and globally by climate change impacts that some still debate today. It's not just the corals that have been affected by climate change; it's the entire coral reef community and its inhabitants that gave us the earliest warning signs. Everything in the coral reef community has been affected and we are only now able to assess the extent of this environmental degradation, including the yet to be discovered disruption of entire food webs and trophic structures.