Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012
16B Coral-microbe interactions and disease

Developments in understanding relationships between environmental conditions and coral disease

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Abstract. Coral disease events are emerging as a significant threat to coral reefs in a changing climate. Over the past few years, several modelling studies have derived empirical relationships linking white syndrome (WS) disease outbreaks on Pacific coral reefs with unusual temperatures in summer and winter, and host density. These relationships have informed development of a series of predictive tools – maps of outbreak likelihood for Australia's Great Barrier Reef and the Hawaiian archipelago. These tools are key to strategic regional frameworks to respond to coral disease outbreaks. They inform both the targeted monitoring that can improve our understanding of coral disease dynamics and trials of experimental management actions that may mitigate disease impacts. Early research suggests that water quality could be another key driver of coral disease prevalence on reefs, as poor water quality has been correlated with increased susceptibility of corals to diseases and bleaching. Therefore we plan to test the inclusion of water quality measurements as a means of increasing the predictive capacity of these management-directed tools. By reducing the number of false positives and negatives, we aim to refine and improve the accuracy of tools developed to assess disease outbreak likelihood. Ongoing and future work also includes testing for links between environmental parameters and other coral diseases; expanding this work spatially, including a specific focus on coral disease dynamics in the Caribbean; and combining the learned relationships with climate predictions to examine potential future disease scenarios.

Key words: Coral Disease, Satellite Temperature, Predictive Tools, Water Quality, Climate Change.

Introduction

Infectious coral disease outbreaks have received increasing attention in recent years. Beyond the direct effects that diseases have on the health of corals, the combination of disease events with other disturbances (e.g., bleaching, cyclones, overfishing) leads to declines in the condition of coral reefs, potentially resulting in phase shifts from coral- to algal-dominated benthic communities.

A relationship between disease and anomalously warm temperature has been established for a variety of terrestrial and marine organisms. As temperatures increase during an era of climate change, increased disease susceptibility is predicted to lead to reductions in the fitness of organisms and potentially to the loss of susceptible species. A seminal review of disease risks in a warming climate by Harvell et al. (2002) highlighted links between increasing coral pathogen virulence, decreasing host resistance and increased temperatures in the marine environment. They also suggested that at least some mortality in the 1998 global bleaching event was accelerated by coral diseases triggered by thermal stress and called for the development of predictive tools for coral diseases based on satellite data, similar to those used in coral bleaching monitoring. Observations that disease outbreaks often follow bleaching events in various ocean basins (e.g., 2005 in the Caribbean, see Eakin et al. 2010 and references therein) provide further evidence for either direct or indirect links (e.g., host susceptibility, pathogen abundance and/or virulence) between disease and thermal stress.

Collaboration between the Coral Disease and Remote Sensing Working Groups of the Coral Reef Targeted Research (CRTR) Program, funded through the Global Environment Facility of the World Bank, was established to increase our understanding of conditions under which coral disease outbreaks occur and to develop predictive tools. In that collaboration, our group focused on investigating links between coral disease events and environmental parameters, leading to a series of advances in our understanding of the influence of temperature on outbreaks of specific coral diseases.

Here we review the historical development of a series of regional tools produced from these collaborative studies. These tools enable reef managers and stakeholders to focus monitoring efforts and research programs in locations that are most likely to be affected by coral disease, thereby targeting management responses to mitigate outbreaks and/or enhance the likelihood of ecosystem recovery. We also highlight areas requiring further development, particularly the need to: modify predictive tools for applications in other reef regions, identify temperature-disease relationships for other disease types, determine the impact of other environmental parameters on the likelihood of disease outbreaks, and predict impacts of coral disease events on coral assemblages under climate change scenarios.

Modeling Temperature-Disease Relationships

Three modeling studies have helped explain spatial and temporal variation in the abundance of white syndromes (WS) on the Great Barrier Reef (GBR) using satellite-derived sea surface temperatures (SSTs). These studies have successively refined the predictive capacity of modeling tools. Importantly, algorithms can be further developed as technologies improve and as our understanding of coral disease outbreak causation increases.

Bruno et al. (2007)

The first study to compare satellite temperature data with coral disease observations revealed a highly significant relationship between the frequency of thermal stress and abundance of WS diseases on the GBR, Australia (Bruno et al. 2007). This study developed the *Weekly Sea Surface Temperature Anomaly* (WSSTA) metric, which counted the number of weeks of the year preceding a disease observation for which the temperature anomaly exceeded 1 °C. The SST data were of ~4km resolution. Analysis also incorporated the total coral cover as an indicator of host abundance, determining this to be a critical factor in the occurrence of disease. Thermal stress was suggested to be necessary but not sufficient for disease outbreaks to occur. The study demonstrated that the highest abundance of WS diseases at the study sites occurred when coral cover was 50% or greater and when thermal stress was measured at 5 WSSTAs or greater.

Heron et al. (2010)

Seasonal observations of coral disease events (e.g., Willis et al. 2004; Harvell et al. 2009; Sato et al. 2009), some with in situ records of temperature, have indicated that the abundance of many coral diseases is greater during summer months. Heron et al. (2010) built upon the work described above by separating the influence of seasons, including the magnitude of anomalies (rather than only the occurrence), and incorporating the impact of negative (cold) anomalies as well as warm anomalies.

Using the same WS dataset used in Bruno et al. (2007), three metrics were developed that, in combination, improved the modeling capacity by correctly predicting 9 (vs 6, WSSTA ≥ 5) of 13 outbreak events and by reducing false predictions. Combining the magnitude and duration of warm events, the metric *Summer Hot Snap* accumulates thermal stress through summer months for temperature anomalies that exceed the long-term summer mean plus one standard deviation. This metric describes the level of thermal stress and showed a strong correlation with WS abundance during outbreak events, likely related to host vulnerability and pathogen virulence. Two winter metrics were drawn from temperature records preceding the summer metric to examine the hypothesis that cold winters cause a reduction in pathogen loading and to consider the level of vulnerability of the host leading into summer stress. *Winter Cold Snap* is the corollary to Summer Hot Snap and summed (negative) temperature anomalies below the long-term winter mean less one standard deviation. The third metric accumulated anomalies above and below the winter mean throughout winter months to give a measure of the overall *Winter Conditions*. Though restricted by the small number of outbreak events, the analysis of these metrics suggested a significant reduction in outbreaks following especially cold winter periods, while outbreaks typically occurred after mild winters.

In conjunction with a threshold for coral cover (≥ 30%) of the genus most susceptible to WS (*Acropora* spp.), a decision tree system was developed from the three metrics to increase the effectiveness of predicting outbreak risk. It is of note that the temperature metrics were produced and tested at two spatial resolutions: the resolution of the SST dataset (~4km) and the ~50km resolution of the global coral bleaching monitoring SST dataset currently provided by NOAA's Coral Reef Watch (CRW).

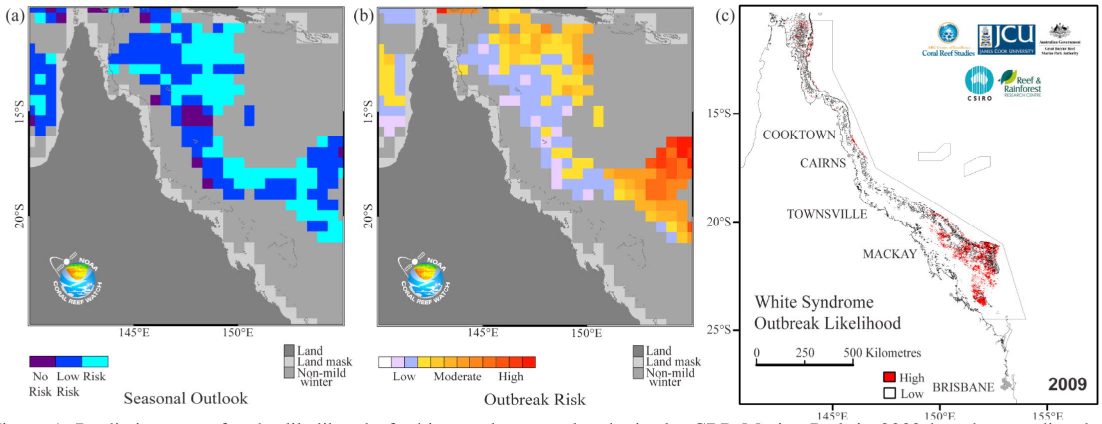

Figure 1: Predictive maps for the likelihood of white syndrome outbreaks in the GBR Marine Park in 2009 based on studies described herein. (a) Seasonal Disease Outlook after Heron et al. (2010): risk occurs when cold snaps do not occur and winters are mild; (b) Disease Outbreak Risk after Heron et al. (2010): levels of summer stress at locations deemed at-risk in the Seasonal Disease Outlook; (c) *ReefTemp Disease* Outbreak Likelihood after Maynard et al. (2011): incorporates a measure of host density and predicts the likelihood of outbreaks at the scale of individual reefs.

Analysis revealed a consistent relationship between temperature and disease abundance at both SST resolutions. Based on this, CRW implemented an experimental product in parallel with its coral bleaching monitoring to provide a satellite-based risk assessment to guide reef management on the GBR. Predictions from this model require using existing knowledge of coral cover. Two phases of risk assessment are provided: 1) a Seasonal Disease Outlook (Fig. 1a) at the conclusion of winter, summarising how winter conditions are likely to have affected pathogen development and coral host condition (i.e., cold stress), providing information to managers and researchers on the likely status of the pathogen-host system prior to summer; and 2) a near real-time Outbreak Risk (Fig. 1b) during summer to focus monitoring efforts if conditions are conducive to an outbreak.

Maynard et al. (2011)

Further advances in predictive modeling by Maynard et al. (2011) led to the development of a high-resolution satellite tool that incorporates a host abundance threshold to simplify interpretation for reef managers and stakeholders. A regression model that incorporates both summer thermal stress (*Mean Positive Summer Anomaly,* MPSA) and host density (*Acropora* spp. cover) was developed and calibrated using disease observations from the year in which outbreaks were most severe and widespread on the GBR. Thresholds for thermal stress (MPSA $\geq$ 0.35 °C) and host density (cover $\geq$ 26%) were conservatively determined from the available observations; these values can be refined as more information is obtained. The nature of the model suggests that as thermal stress increases, the threshold of host density for disease outbreaks to occur decreases, which suggests that the host density threshold for an outbreak - previously identified by Bruno et al. (2007) as being 50% - may decrease as the climate changes.

Based on these findings, annual predictions of disease risk are published for the GBR at ~1.5 km resolution as part of the *ReefTemp* suite (Maynard et al. 2008). These maps (Fig. 1c) indicate where recent temperature has exceeded the defined MPSA threshold, filtered by locations whose long-term coral cover exceeds the host density threshold. While no severe outbreaks of disease have occurred on the GBR since 2002, observations in 2009 permitted a model validation exercise. At three out of the four locations predicted to have outbreak risk, disease abundance was anomalously high but below the outbreak threshold. Disease abundance was low at each of the six low-risk locations.

This tool provides managers and stakeholders with the ability to target research and monitoring at the scale of individual reefs and, as it includes the coral cover threshold, does not require any external information.

Application of Tools in a Management Framework

The development of predictive tools for coral disease outbreaks has enabled the development of responsive management plans. The response framework developed by Beeden et al. (2012) has four core objectives: (1) increase understanding of the causal drivers of outbreaks; (2) enable assessment of the extent and severity of outbreaks; (3) facilitate management responses to mitigate impacts and/or enhance recovery; and (4) communicate disease threat effectively to reef stakeholders. Four components of the framework enable effective management of coral disease outbreaks: (1) early warning system; (2) tiered assessment program; (3) identified management actions; and (4) communication.

The first component is drawn from the predictive tools described above to give a pre-summer outlook and a risk assessment based on summer temperatures. The tiered approach to assessment is based upon varying levels of expertise amongst observers. Trained volunteers within monitoring networks may record the presence/absence of disease, while reef managers assess reef condition and undertake summary measurements of disease impact. Higher-level quantitative assessments occur responsively during outbreak events and also as part of longer-term research studies into disease trends. This hierarchical approach increases the likelihood of detecting disease and promotes efficient investment. Together with the predictive tools, monitoring can focus management resources across broad reef areas. Validation and refinement of predictive tools can result from new observations, therein increasing knowledge of links between disease and environmental drivers.

Direct management actions to mitigate disease involve boosting host immunity, reducing pathogen abundance and/or decreasing disease transmission rates. Beeden et al. (2012) note that while existing strategies to undertake these actions have potential for the future, they are currently experimental and prohibitively expensive on even moderate scales. However, the suggested management actions to minimize other stressors, including temporary closures (e.g., fishing, tourism) and improving local water quality, could be undertaken to support the recovery of reefs following disease events.

Communication of predicted outbreak risk and observed reef condition, along with management actions undertaken, is critical to develop/maintain the support of stakeholders (e.g., government, industry, public). Misinformation of events and responses can be harmful for relationships with industry users. Regular, intentional communication ensures accurate and timely information is provided to the broad group of interested parties (Beeden et al. 2012).

The coral disease response framework has been implemented by the GBR Marine Park Authority and is currently being used in response planning for the Papahanaumokuakea Marine National Monument (Northwestern Hawaiian Islands) as part of their rapid response contingency plan for disease outbreaks. The framework is adaptable for different scales of management effort in various reef regions.

Future Directions

Disease model development

The predictive models described above were all developed from observations of white syndromes (WS) diseases on the GBR. This was primarily due to the longevity (> 10 years) and large spatial domain (~2000 km) of the WS database compiled by the Australian Institute of Marine Science's Long-Term Monitoring Program, and because WS abundance had been identified as temperature-dependent (Willis et al. 2004). There is a clear need to evaluate predictions from existing models and potentially to develop specific relationships between temperature and disease for other regions and other disease types.

The prevalence of other diseases also appears to be related to temperature but research is required to determine if similar tools could be developed to monitor outbreak risk. Williams et al. (2010) suggested that diseases causing progressive tissue loss may be linked to temperature variation. These diseases include *Porites* and *Montipora* white syndrome (Williams et al. 2010), yellow band disease (Harvell et al. 2009), black band disease (Kuta and Richardson, 2002; Willis et al. 2004), white plague (Bruckner and Bruckner, 1997), skeletal eroding band (Willis et al. 2004) and atramentous necrosis (Jones et al. 2004). Other diseases have been shown to be temperature-independent, including growth anomalies and trematodiasis in *Porites* spp. (Williams et al. 2010). Nevertheless, thermal stress is still likely to impact host susceptibility and perhaps pathogen populations; thus temperature-based models may inform to the potential of other disease outbreaks.

Recent efforts to support testing and development of predictive tools have been initiated through the collation of historical disease observations. One such project has formulated a database of disease observations in the Hawaiian archipelago from 2004 (Sziklay et al., in prep.). Initial comparisons with satellite-derived metrics have suggested that winter temperatures play an important role in disease outbreaks there. A similar database collation has begun for the greater Caribbean region.

Other environmental parameters

Nutrients are known to increase the abundance and propagation rate of some coral diseases (Kuta and Richardson, 2002; Bruno et al. 2003; Voss and Richardson, 2006; Williams et al. 2010). Increased prevalence of multiple diseases near offshore platforms may have resulted from nutrient influx from bird guano and physical damage (Lamb and Willis, 2011), while increased rainfall and associated terrestrial runoff were implicated in outbreaks of atramentous necrosis on inshore GBR reefs (Haapkylä et al. 2011). These findings suggest potential links between large-scale patterns in water quality and coral disease prevalence.

Efforts are underway to identify potential links between remotely sensed water quality data and coral disease events. Derived from ocean colour sensors, chlorophyll-a is commonly used as a proxy for primary productivity and nutrient loading, while the diffuse attenuation coefficient (commonly Kd) is an indicator of ocean turbidity. These variables may provide further insights into the occurrence of disease outbreaks, but further development is required. Ocean colour sensors are designed for deep-water (open-ocean) measurements and there are challenges for data use in shallow waters. Several efforts are underway to calibrate ocean colour measurements near reefs (reviewed in Nim and Skirving, 2010).

Other parameters linked to water quality that should also be considered in predicting the abundance of disease include distance from terrestrial sources of nutrient input and levels of turbulence from currents and/or waves. The speed of currents may alter thresholds identified for host density, potentially through increased rates of disease transmission.

Seasonal and climate forecasting

Current disease predictions are limited to seasonal outlooks at the beginning of summer and near real-time risk based on observations. Recent development to improve the quality of seasonal prediction of SST for coral bleaching (Spillman et al. 2011; Eakin et al. 2012) could be applied to predict temperature conditions conducive to promoting disease outbreaks a season in advance. Climate change models, such as those used in the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3; Meehl et al. 2007), predict that long-term thermal stress events will become more frequent. Relationships identified between temperature and disease outbreaks can be applied to future change scenarios from global climate models. Outputs would suggest where and how often future disease outbreaks may occur, enabling assessment of potential ecosystem impacts. Such knowledge would help managers plan climate-resilient marine protected areas, targeting areas that are less exposed to temperature-induced diseases.

Acknowledgement

Financial support from the NOAA Coral Reef Conservation Program, the Great Barrier Reef Marine Park Authority and the MTSRF. The manuscript is solely the opinion of the authors and does not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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