Using the CCSM to Study Future Coral Reef Vulnerability to Temperature Change

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BACKGROUND

Vulnerability (V) of ecosystems to environmental change is most simply defined as:

$$V = f(E, S, R)$$

where: E = Exposure;
S = Sensitivity; and
R = Resilience

Over the last few decades, several major ecosystems are proving to be vulnerable to future climate changes, elevating the need for combined ecological-climatological research. One obvious ecosystem that lends itself to such research is coral reefs. Large-scale coral bleaching episodes – almost always the consequence of elevated temperature – have become increasingly common over the past 30 years (Hughes *et al.* 2004). The likelihood that increasing ocean temperatures will continue to cause mass coral reef degradation in the future is not debated, but the magnitude and regional patterns of degradation are.

QUESTIONS

Predicting the location, magnitude and severity of coral bleaching are strongly desired elements in coral reef management and long-term conservation efforts. Can we identify regions which are least vulnerable to future bleaching conditions? To do so requires the ability to predict both the future nature of SSTs (exposure), the response of coral reef ecosystems to those changes (sensitivity), and their ability to rebound following an impact (resilience).

BRIEF SCOPE OF RESEARCH

Coupled climate models such as the CCSM are the best tools for predicting future changes in ocean temperature, and the regional patterns of future changes in SST variability and extreme events. Predicting future coral bleaching events and recovery can be significantly enhanced by combining CCSM predictions with both observational data and biological models that take into account the regional variation in sensitivity of reefs to the temperature, the time-scales of adaptation, and time-scales of recovery. We propose a short (1-year) research project that will focus on future exposure and sensitivity of coral reef ecosystems to increases in sea surface temperature. This encompasses well-defined aspects of vulnerability that will the lay the groundwork for examining community resilience.

Exposure. Historical and future exposure of coral reefs to temperature change will be analyzed using a combination of observed and modeled data. These analyses will attempt to find relationships between the severity and duration of exposure, how these vary regionally and through time, and how well the models capture the observed temperature trends of the system. Comparisons of CCSM with observed data illustrates that the CCSM does capture the natural variability at many coral reef sites, particularly those in open ocean environments (Fig. 1). The analysis will also explore the natural (e.g., biologically-based) time-lags between exposure and response. There is evidence, for example, that a long-term (months to years) increase in mean temperature depresses fat storage in corals, leaving them more sensitive to elevated temperatures (Fitt et al., 2001). Several observational data sets are well suited for this analysis (e.g., HADISST, Reynolds optimally interpolated SST). CCSM model output provides temperature data that can be used directly to assess exposure of coral reefs to temperature over at least monthly time-scales, and for periods of decades to centuries.

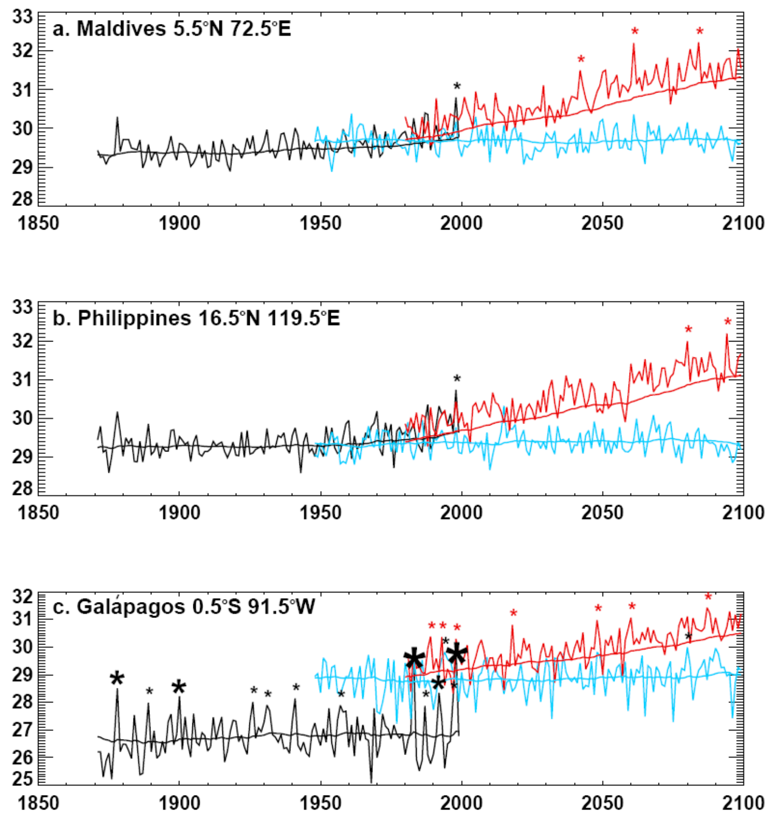

Fig 1 Comparison of observed and modeled annual maximum SSTs for three reef regions: a) Philippines, b) Bahamas, and c) Galápagos. Black solid lines for the period 1970–2000 represent annual maxima derived from the HADISST 1x1° lat/lon reconstruction of observed SSTs (Rayner et al. 2003). Blue lines show annual SST maxima for years 1948–2000 of the CCSM 1.0 CONTROL integration (atmospheric CO_2 concentration held constant at 280 ppmv). Red lines show annual SST maxima for years 1980–2100 of the CCSM 1.0 SRES B2 integration, a moderate global warming scenario. The 25-yr temperature of acclimation (sensu Ware 1997) is also shown for each SST series. Possible bleaching thresholds are indicated by stars where maximum temperature exceeds the acclimation temperature by 1.0ºC (small star), 1.5ºC (medium star) and 2.0ºC (large star). Even where absolute maximum temperatures are not duplicated by the model (e.g., for the Galápagos), a comparison between the HADISST and CONTROL data shows that the model does a good job of capturing interannual variability of maximum SSTs, which is more limiting to reefs than average maximum temperature.

Sensitivity. Once a coral reef community is exposed to elevated temperature, whether it experiences mass bleaching is determined by its sensitivity to that exposure. Sensitivity also varies regionally, as a function of such things as species composition and the pre-conditioning of corals to local temperature extremes and variability. Although the temperature threshold for coral bleaching is widely recognized as 1–2ºC above the normal summertime maximum, strong regional variations in the threshold appear to reflect the natural variability of the system rather than some absolute temperature anomaly (Figs 2 and 3; Kleypas 2006). Further analyses are needed to increase our understanding of what determines the sensitivity of coral communities, and these will entail a combination of observational data, biological data, statistical analyses, and modeling.

Resilience. Predicting resilience requires knowledge of a host of factors that characterize biological adaptation, chances of larval reseeding, probability of repeated bleaching events, etc. Although very little is known about the time-scales of biological adaptation, models can test the capacity and limits of various species to acclimate to temperature increases, or adapt over longer periods such as through natural selection. Species-species differences in response and recovery following a bleaching event could be incorporated to examine changes in community structure (which in itself is a form of adaptation) and the potential for ecosystem collapse (regime change).

Models can also be used to understand the potential role of large-scale circulation patterns in reseeding remote coral reef regions. While higher-resolution models are necessary in complex coral reef systems like the Great Barrier Reef, many open ocean atolls experience much simpler circulation patterns. The CCSM could be used, for example, to determine the time-scales necessary to repopulate open ocean atolls and coral islands. Such activities are essential in guiding future decisions in coral reef conservation, such as locating areas for protection and regulating activities that might hinder coral reef recovery following a bleaching event. Most of this research can be done using existing CCSM runs. While some ecosystem model development is desired, particularly questions regarding shifts in community structure and functioning, most of the biological responses can be addressed using statistical analyses.

In summary, the proposed research on coral reef vulnerability to future temperature increase will provide a means for identifying those reef regions that are likely to be affected the least by future temperature increases, and those which have the highest capacity for recovery.

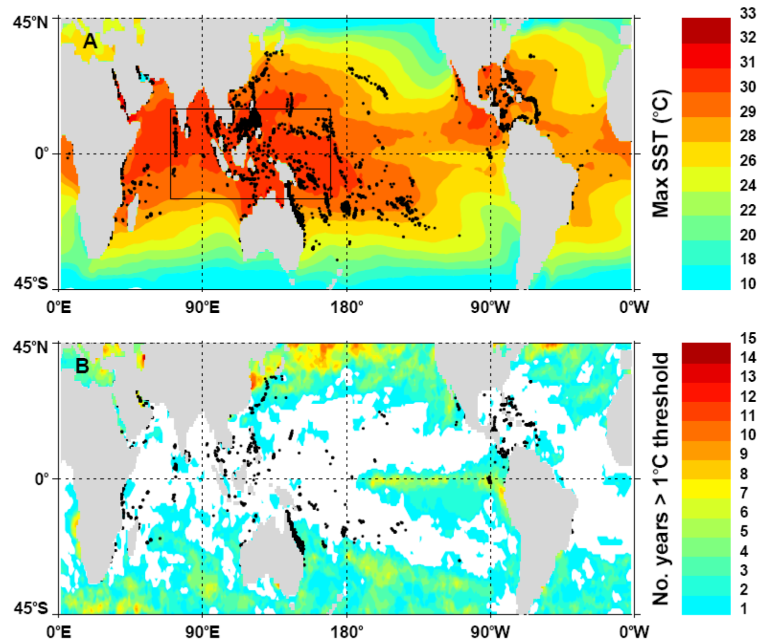

Fig 2 (A) Average annual maximum temperature calculated from a weekly sea surface temperature data set[5], for the 10-year period 1982-1991; and (B) number of years that SST exceeded the average annual maximum for the entire period of the data set (1982-2004). Locations of all coral reefs are shown in black in A; those reefs with reported bleaching are shown in B. Approximate boundaries of the western Pacific warm pool (WPWP) are indicated in A.

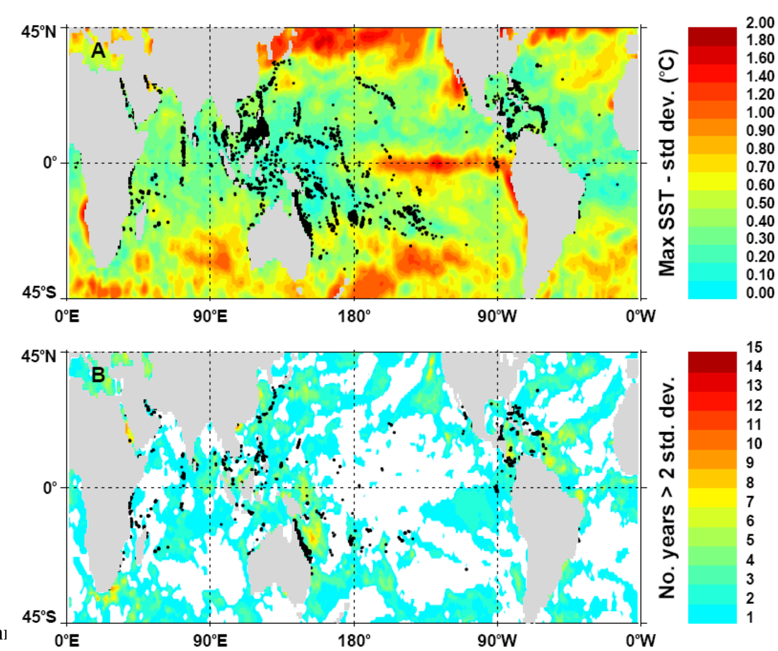

Fig 3 (A) Standard deviation of the average annual maximum temperature calculated from a weekly sea surface temperature data set[5], for the 10-year period 1982-1991; and (B) number of years that SST exceeded two standard deviations above the average annual maximum temperature, for the entire period of the data set (1982-2004). Locations of all coral reefs are shown in black in A; those reefs with reported bleaching are shown in B.

REFERENCES CITED

Fitt, WK, BE Brown, ME Warner, and RP Dunne (2001) Coral bleaching: Interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral Reefs* 20: 51–65.

Hughes TP, AH Baird, DR Bellwood, M Card, SR Connolly, C Folke, R Grosberg, O Hoegh-Guldberg, JBC Jackson, J Kleypas, JM Lough, P Marshall, M Nystrom, SR Palumbi, JM Pandolfi, B Rosen and J Roughgarden (2003) Climate change, human impacts, and the resilience of coral reefs. *Science* 301: 929–933.

Kleypas, JA (2006) Predictions of climate change in the tropical oceans, and how that should shape reef conservation efforts. Proceedings of the World Maritime Technology Conference, March 6-10, 2006, London.

Rayner, NA., DE Parker, EB Horton, CK Folland, LV Alexander, DP Rowell, EC Kent, and A Kaplan (2003) Global analyses of sea surface temperature, sea ice and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* 108: art. no. 4407.

ReefBase (2004) WorldFish Center, Penang, Malaysia, http://www.reefbase.org

Reynolds, RW, NA Rayner, TM Smith, DC Stokes, WQ Wang (2002) An improved in situ and satellite SST analysis for climate. *Journal of Climate* 15, 1609–1625.

Ware, JR. (1997) The effect of global warming on coral reefs: Acclimate or die. *Proc. 8th Intl. Coral Reef Symp.* 1:527–532.