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17D Managing bleached coral reefs

Identifying Oceanic Thermal Anomalies in the Coral Triangle Region

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Abstract. Mass coral bleaching has historically been linked to episodes of thermal stress. While location-specific time-series data have been examined, the oceanic thermal anomalies that underlie broad-scale thermal stress events are apparently unstudied quantitatively in terms of their spatial extent, temporal development, and intensity. Knowledge of the spatial and temporal parameters that characterise anomalies can be useful in understanding how bleaching-level stress develops, providing context for and a basis for modelling of future events. Here we examine historical satellite sea-surface temperature (SST) data with the goal of identifying and characterising oceanic anomalies in the Coral Triangle region. This region is of interest because it is influenced by the Indian and Pacific Oceans and is the centre of coral ecosystem diversity and significant coral reef conservation efforts. Oceanic anomalies are defined here using the HotSpot metric, which is the positive variation in temperature above the maximum of the monthly mean climatology values. This metric describes thermal stress that has been linked to coral bleaching episodes. It is proposed that the method for identifying oceanic anomalies described here be applied to datasets of varying spatial resolutions to evaluate if, and how, the characterisations are resolution-dependent. If these anomalies can be comparably identified and characterised at a coarser spatial resolution, this could open the way to examining the likely impact of oceanic thermal anomalies further back in time using historical datasets or in the future using climate models, both of which are available only at lower spatial and temporal resolutions.

Key words: Oceanic thermal anomaly, coral bleaching, sea surface temperature.

Introduction

From at least as early as 1982, widespread coral bleaching events have been regularly observed (Glynn 1984, Wilkinson 2008, Oliver et al. 2009). Also from that time, a link was first postulated and then identified between bleaching events and elevated water temperatures (Glynn 1984). While localised variations in bleaching impact do occur at the scale of individual reefs (Maynard et al. 2008), the underlying causes of mass bleaching events are oceanic thermal anomalies on the scale of hundreds to thousands of kilometres. Here we seek to identify oceanic anomalies of the intensity that has been linked to coral bleaching events, with the goal of characterising the oceanic anomalies in terms of spatial extent, temporal development and intensity. While temperature time-series have been analysed elsewhere for statistics of anomalous events, here we consider for the first time the underlying oceanic anomalies. For this study, we focus on oceanic anomalies in the Coral Triangle region, the centre of coral ecosystem diversity and a location of significant coral reef conservation efforts.

Penaflor et al. (2009) reported that the Coral Triangle region (Fig. 1) experienced an upward trend in sea surface temperature (SST) during 1985-2006. However, this warming varied significantly across the region, being greatest in the northern and eastern parts of the region and with slight cooling in some southern Coral Triangle areas. Thermal stress events, as measured using Degree Heating Weeks (DHW; Liu et al. 2003), varied similarly in space across the region. Of specific note was that much of the Pacific Ocean region off Papua New Guinea experienced thermal stress annually during the period 1996-2006.

Two significant bleaching events occurred in the Coral Triangle in recent decades. The Coral Triangle was one of several global regions affected by the widespread bleaching event during 1997-1998. Wilkinson (1998, 2000) compiled reports of variable bleaching across Southeast Asia and noted that most countries reported severe bleaching in some locations. In 2010, thermal stress and coral bleaching were again observed in parts of Southeast Asia and the Coral Triangle (Thomas and Heron 2011; Maynard et al. 2012). Reports indicated that, in some locations, the severity of bleaching was greater than that observed during the 1998 bleaching event (Tan and Heron, 2011).

While a link between coral bleaching and temperature stress has been established, this has not previously been approached from an understanding of oceanic thermal anomalies. A methodology to identify oceanic thermal anomalies using satellite temperature data is provided here and initially applied to the Coral Triangle region. A library of historical oceanic thermal anomalies can provide context for future observations of anomalies and their likely impact. Using the library to characterise the timing, extent and intensity of oceanic anomalies may provide parameters for detailing impacts from simulations of anomalies seen in climate models.

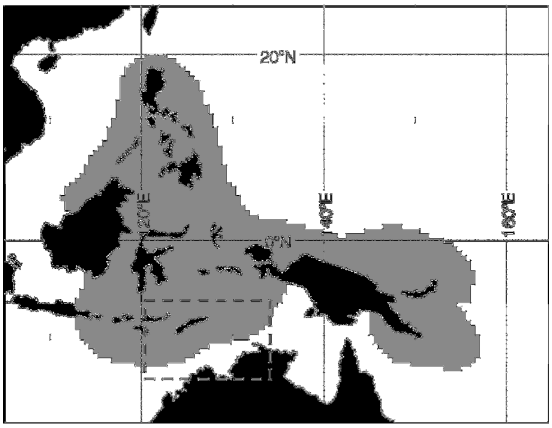

Figure 1: Definition of Coral Triangle region (grey) used in the study, after Peñaflor et al. (2009). Inset box (dash, dark grey) indicates the location of Fig. 2.

Material and Methods

For the purpose of monitoring conditions around coral reefs, NOAA's Coral Reef Watch (CRW) produces global maps of several temperature metrics at a resolution of 0.5 degree (~50 km), twice weekly in near real-time (Liu et al. 2003, 2006). The CRW suite of monitoring products including SST, SST anomaly, HotSpot and Degree Heating Weeks has been produced since late 2000.

Here we used one of these products to identify oceanic thermal anomalies of the intensity linked to coral bleaching. The HotSpot metric is a positive-only anomaly from the location-specific warmest monthly climatology value (Maximum of the Monthly Means, MMM). This metric was designed to describe the apparent level of thermal stress experienced at each location. Coral bleaching has been observed to occur when temperature exceeds the expected annual maximum temperature by 1 °C. This threshold for bleaching corresponds to a HotSpot value of 1 °C. HotSpot was chosen for this analysis because it is specifies the thermal stress observed for each twice-weekly time step.

Identification of Contiguous Patches

To understand the development of oceanic thermal anomalies of the intensity linked to coral bleaching, we needed to identify patches of warm water that were contiguous in space and time. For a specified study period, HotSpot data at each time step were read into a three-dimensional data block (dimensions of east-north-time). The threshold test ($\geq$ 1 °C) was applied to the data block resulting in a same-sized threshold block that indicated if the condition was met (value of one) or not (zero).

At each twice-weekly time step, the threshold block was examined to identify and record "contiguous patches" of adjacent 50 km pixels (including those diagonally connected in space) with HotSpot values $\geq$ 1 °C. These 2D contiguous patches represented individual oceanic anomalies at that time step.

Each 2D contiguous patch was then examined to see if it overlapped spatially with one or more contiguous patches at the subsequent time step. Any such contiguous patches were cross-referenced as being part of the same 3D patch. This represented the development (movement, growth/shrinking, combining/devolving) through time of an oceanic thermal anomaly. Contiguous patches (3D) were assigned integer labels in a three-dimensional block of the same size as the data block.

Computational Issues

While the analysis required to identify patches was fairly simple, it involved significant computational challenges. This was primarily because the sizes of contiguous patches vary and these sizes are unknown prior to their identification. Computationally, this required the use of variables that have unknown and non-constant size. While structures exist for variables of undetermined length, these are generally slower to access, which leads to longer analysis times. This analysis was undertaken using IDL8.0, within which the variable type "list" was used for variables of undetermined length. A brief pre-analysis suggested that run-time increased exponentially with the number of time steps of source data used and, related to this, the number of contiguous patches identified at each time step. The identification of contiguous patches was therefore accelerated by reducing the number of time steps through examining only periods of specific focus (e.g., historical bleaching events). However, contiguous patches at the beginning or end of the time period may have been only partially described.

A second consideration for accelerating the analysis was whether to constrain the spatial domain (from the global ocean), thereby reducing the number of contiguous patches. However, care was required to ensure that this did not lose information on contiguous patches that developed and/or devolved outside the area of interest. For example, to optimally subset the global ocean while including all contiguous patches affecting the Coral Triangle region, we first needed to know the maximal extent of the patches, which in turn meant having already identified the contiguous patches. This cyclic dilemma was overcome by using a conservative spatial subset. For this study, the domain was limited to locations within 45°S–45°N. After each contiguous patch was identified, the maximum spatial extent was compared with an extended Coral Triangle region (Fig. 1). If the contiguous patch did not overlap this region at any time then it was excluded from the library of oceanic thermal anomalies affecting the Coral Triangle.

Characterising Contiguous Patches

Once individual contiguous patches were identified, in space and through time, they were characterised in terms of timing, extent and intensity. Timing characteristics consider the onset and duration of events. For parts of the Coral Triangle region, and other reef locations that span the equator, there are two annual temperature peaks corresponding to the northward and southward relative transits of the sun. This can result in two different onset times for bleaching-level oceanic anomalies. Coral bleaching can be expected when a HotSpot of 1 °C persists for four weeks (28 days; Liu et al. 2003), making this a critical duration threshold.

As contiguous patches develop (and devolve) they can change shape and/or move (n.b., movement of thermal anomalies does not necessarily mean advection of water). The extent of contiguous patches can be considered through various measures of the location, dimension, area, density and how these change through time. The space-time volume (pixels × time) of the contiguous patch can also be useful to categorise the impact level of anomaly events.

The intensity descriptors of a contiguous patch (e.g., mean HotSpot over time and space, maximum HotSpot) were derived from the source data values. Note that the minimum intensity of each contiguous patch was 1 °C (the applied threshold value).

Results

Contiguous patches were identified and analysed using HotSpot data for two periods: 01Oct2009-01Oct2011, encompassing the most recent major bleaching year; and 01Oct2004-01Oct2006, a typical period during which thermal stress and bleaching were not widely reported in the Coral Triangle region.

An example contiguous patch from 2005 (Fig. 2) developed off the south coast of Timor in Indonesia and the thermal anomaly progressively spread across the Timor Sea towards Australia. The extent of the patch (dashed) grew through the first half of the duration and then decreased. The median position and extent did not always change between time steps.

A second example was a contiguous patch from 2010 (Fig. 3) that developed off the west coast of Thailand, wrapped around the Thai-Malay peninsula and proceeded across the South China Sea towards the Philippines and into the East China and Philippine Seas. The contiguous patch lasted for more than six months and spanned longitudes 99.5–138.5°E and latitudes 2°S–39.5°N. As the thermal stress subsided, the patch shrunk and terminated in the Gulf of Thailand. This patch of stressful temperatures was responsible for coral bleaching observed in Thailand, Malaysia, Cambodia, Indonesia and the Philippines (reefbase.org; Thomas and Heron 2011; Maynard et al. 2012).

We present here summary outputs (Table 1) from the two study periods to compare characteristics of contiguous patches from bleaching and non-bleaching periods. Filtered calculations use patches for which the duration was ≥ 28 days and at least 28 pixel-days

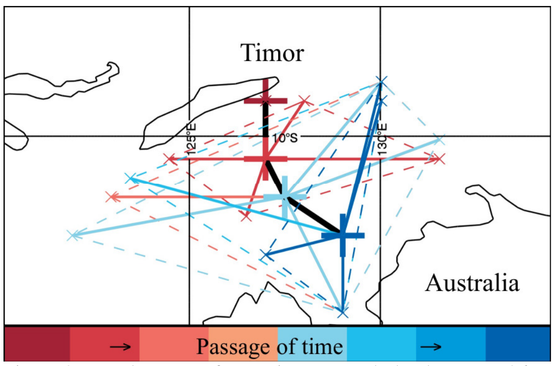

Figure 2: Development of a contiguous patch that began on 26 Nov 2005 and lasted for 90 days. Median positions (+) are connected with a black line. Passage of time is coloured from red shades to blue shades. Every third time step is shown (approx. 11 days). Patch extent at each displayed time step is indicated by dashed lines.

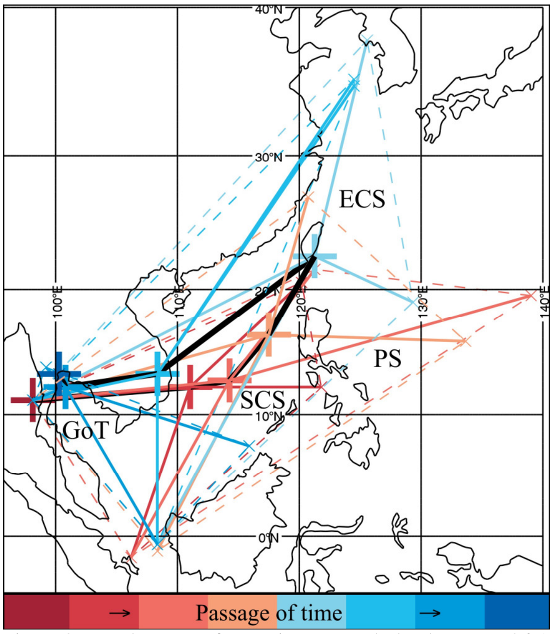

Figure 3: Development of a contiguous patch that began on 26 Apr 2010 and lasted for 196 days. Median positions (+) are connected with a black line. Passage of time is coloured from red shades to blue shades. Every seventh time step is shown (~24 days). Patch extent at each displayed time step is indicated by dashed lines. GoT: Gulf of Thailand, SCS: South China Sea, PS: Philippine Sea, ECS: East China Sea.

	2004-2006 Non-bleaching		2009-2011 Bleaching	
	All patches	Filtered patches	All patches	Filtered patches
Number of patches	143	16	151	37
Median duration, days	7	39	10	49
Mean duration, days	14.1	49.5	21.4	59.5
Mean area per time step, pixels	12.1	52.8	11.3	37.2
Mean HotSpot, °C	1.1	1.1	1.1	1.1

Table 1: Summary statistics of contiguous patches for the periods 01 Oct 2004–01 Oct 2006 (non-bleaching) and 01 Oct 2009–01 Oct 2011 (bleaching). Filtered patches are those for which duration of patch was ≥ 28 days and at least 28 pixel-days were in the extended Coral Triangle region. One pixel is ~2500 km^2.

were located inside the extended Coral Triangle region (Fig. 1). Comparisons of the summary information indicated that the periods had similar numbers of oceanic thermal anomalies, though the bleaching period had approximately twice the number of patches for which the duration was 28 days or more. Patch durations in the bleaching period were generally longer than those in the non-bleaching period. Mean HotSpot values (averaged over time and space) were the same across the two periods, for both unfiltered and filtered patches, and patch areas were similar between the two periods.

Discussion

This is the first known study of thermal stress that has focused on dynamic oceanic anomalies rather than specific reef locations. Knowledge of the characteristics of oceanic anomalies may lead to greater understanding, prediction, and management of resulting impacts (e.g., coral bleaching).

The initial analysis appears to suggest that the bleaching period had more oceanic thermal anomalies and that these events were of longer duration than the non-bleaching period. These characteristics appear most related to bleaching-level stress, the latter consistent with accumulation of stress (e.g., DHW metric). However, the extent and magnitude of stress within the oceanic thermal anomalies from the two periods were similar. This latter observation could be related to the "ocean thermostat", whereby increase of ocean temperature is limited by negative feedback mechanisms (latent heat flux, reduced heating due to cloud and ocean dynamics; Kleypas et al. 2008 and references therein). That the spatial extent of anomalies is not greater in the bleaching period is perhaps surprising, suggesting that bleaching anomalies are not necessarily larger and strengthening the link with anomaly duration. Further investigation of oceanic anomalies from these and other time periods is required to confirm these observations.

The impact of the oceanic thermal anomalies across the Coral Triangle region can be interpreted from maps of the total number of days in each period that locations (pixels) experienced HotSpots at or above the defined threshold of 1 °C (Fig. 4). The vast majority of the Coral Triangle was less exposed to thermal stress in the 2004–2006 period (Fig. 4a) than in the bleaching period 2009–2011 (Fig. 4b). There was a band of stressed locations on the south and west of the Coral Triangle in the latter period, but with very little thermal stress in the centre of the region.

The exposure to thermal stress of locations near Kimbe Bay, Papua New Guinea (150°E, 5°S) in 2009-2011 (Fig. 4b) was from four or more separate oceanic thermal anomalies (data not shown). This could be linked to the four solar peaks of the period (two in each of the two years); however, additional investigation would be necessary to confirm this. The impact on corals of four shorter thermal stress events may be less than that of one longer event.

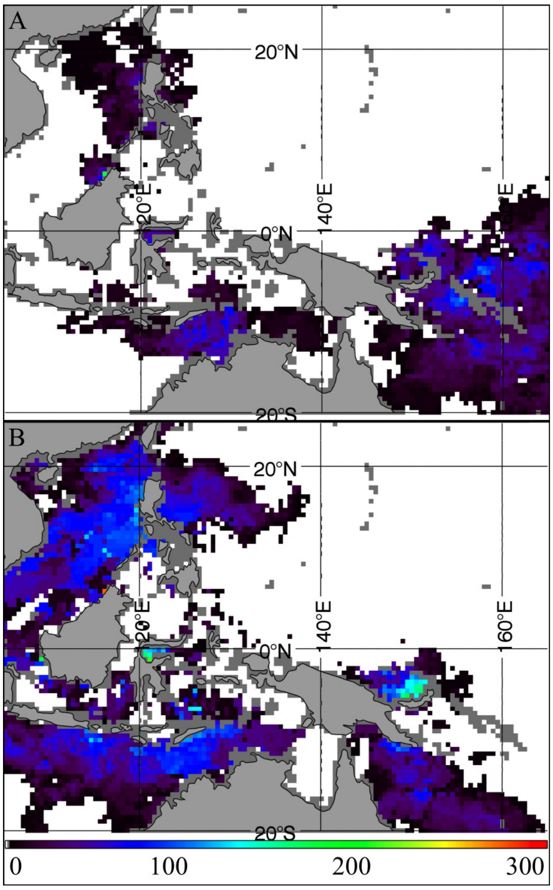

Figure 4: Total number of days exposed to HotSpot ≥ 1 °C. (a) 01 Oct 2004–01 Oct 2006 (non-bleaching), (b) 01 Oct 2009–01 Oct 2011 (bleaching). Dark grey areas are masked as land in the source (HotSpot) data

The method of identifying oceanic thermal anomalies (i.e., contiguous patches) has been successfully demonstrated for two periods. Further application includes: (1) using SST anomaly data to investigate the development of oceanic anomalies prior to their reaching bleaching intensity; and (2) evaluating the full time period to produce libraries of contiguous patches. Characterising the spatial location and temporal development of the library of oceanic anomalies and the impact on specific locations will help to inform managers of the risk to their reef sites as oceanic anomalies develop in the future.

Identifying oceanic anomalies in finer spatial resolution data would provide reef stakeholders with information at the scale of individual reefs, allowing reef-specific management response. For example, the methodology defined here could be applied to the Pathfinder 4 km SST dataset (Casey et al. 2010).

Furthermore, applying the methodology to datasets of a range of spatio-temporal resolution (4–100 km; 3-day to monthly) could lead to cross-referencing of individual oceanic anomaly events between datasets. Additional work would then be required to consider how information from the higher-resolution dataset could be applied to provide an oceanic anomaly-based downscaling in data sets from which higher-resolution data are not available. This could provide a useful method for interpreting climate model predictions (~10000 km^2) closer to the scale of management response (i.e., ~20 km^2).

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