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Remote Sensing of Sea Surface Temperatures During 2002 Barrier Reef Coral Bleaching

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Early in 2002, satellites of the U.S. National Oceanic and Atmospheric Administration (NOAA) detected anomalously high sea surface temperatures (SST) developing in the western Coral Sea, midway along Australia's Great Barrier Reef (GBR). This was the beginning of what was to become the most significant GBR coral bleaching event on record [*Wilkinson*, 2002]. During this time, NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) provided satellite data as part of ongoing collaborative work on coral reef health with the Australian Institute of Marine Science (AIMS) and the Great Barrier Reef Marine Park Authority (GBRMPA). These data proved invaluable to AIMS and GBRMPA as they monitored and assessed the development and evolution of SSTs throughout the austral summer, enabling them to keep stakeholders, government, and the general public informed and up to date.

As anomalous SSTs continued to increase off the coast of Queensland, NOAA, AIMS, and GBRMPA issued a press release on 24 January 2002 on the developing bleaching event engulfing much of the mid- and northern GBR, which later proved to be the most extensive bleaching event on record for that region.

Bleaching occurs when there is widespread loss of pigment from coral, mainly due to the expulsion of symbiotic algae [*Yonge and Nicholls*, 1931]. The algae are usually expelled in times of stress, often caused by sea surface temperatures which are higher than the coral colony's tolerance level. This may be as little as 1 to 2°C above the mean monthly summer values [*Berkelmans and Willis*, 1999; *Reaser et al.*, 2000].

The key coral bleaching products developed by the satellite monitoring and prediction component of NOAA's Coral Reef Watch (CRW) program include: SST coral bleaching "HotSpot" anomaly and "Degree Heating Week" (DHW) charts. In this article, these products will be used to describe the evolution of the anomalous SST event that caused the 2002 GBR bleaching event, which will then be contrasted with the 1998 bleaching event. The latter was the largest for the GBR region prior to the 2002 event (R. Berkelmans, Austral. Inst. of Marine Science, unpublished data, 2002).

Methodology

Beginning experimentally as early as 1997, NESDIS has been developing satellite global 50-km resolution experimental products (initially SST HotSpots and then DHW products) as indices of coral bleaching-related thermal stress. These products are the outgrowth of earlier work by *Montgomery and Strong* [1994].

The coral bleaching HotSpot is not a typical climatological SST anomaly. It is a measure of the occurrence of the hottest SST for a region; and as such, is an anomaly that is not based on the average of all SST, but on the climatological mean temperature of the climatologically hottest month (i.e., the maximum of the monthly mean SST climatology, often referred to as the MMM climatology). This climatology, derived from the Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) SSTs for the period 1985–1993, is static in time but varies in space [*Strong et al.*, 1997]. Since the HotSpot is an anomaly based on the maximum of the monthly mean SST, negative values are meaningless in this context; therefore, only positive values are displayed.

HotSpot values provide a measure of the intensity of the thermal stress, but do not measure the cumulative effects of that thermal stress on a biological system such as coral reefs. In order to monitor this cumulative effect, a thermal stress index, called a Degree Heating Week (DHW), was developed. DHW represents the accumulation of HotSpots for a given location, over a rolling 12-week time period. Preliminary indications show that a HotSpot value of less than one degree is insufficient to cause visible stress on corals. Consequently, only HotSpot values ≥°C are accumulated (i.e., if we have consecutive HotSpot values of 1.0, 2.0, 0.8, and 1.2, the DHW value will be 4.2, because 0.8 is less than one and therefore does not get used). One DHW is equivalent to one week of HotSpot levels staying at 1°C, or half a week of HotSpot levels at 2°C, and so forth.

Field observations (most of which are subjective measurements presented as informal reports) with coincident satellite data are only available for a limited number of years; these observations indicate that there is a correlation with bleached corals when DHW values of 4.0 have been reached. By the time DHW values reach 8.0, widespread bleaching is likely and some mortality can be expected. CRW has applied these DHW values for the last two years when generating satellite bleaching warnings and alerts [*Wellington et al.*, 2001].

These products have been successful in monitoring several major coral bleaching episodes around the globe [e.g., *Goreau et al.* 2000; *Wellington et al.*, 2001]. Both HotSpot and DHW charts are produced by CRW twice weekly in near-real time from composite nighttime AVHRR SST products. These products, along with descriptions of the methodologies, are Web-accessible at: http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html.

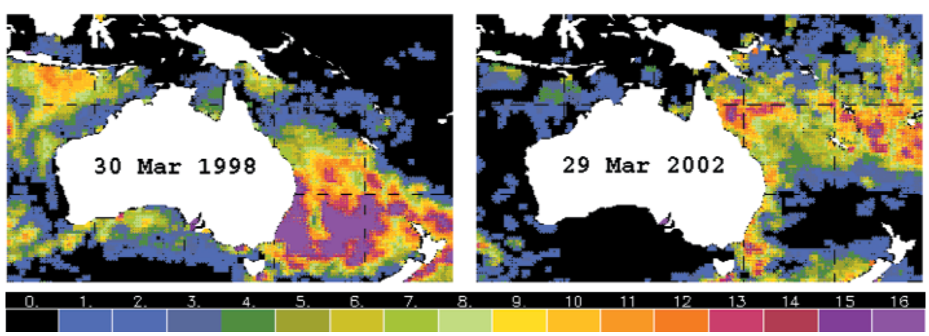

Fig. 1. DHW Chart for the end of March 1998 (left) and 2002 (right) showing the accumulation of HotSpots over the summer (December through March). Units are in °C-weeks.

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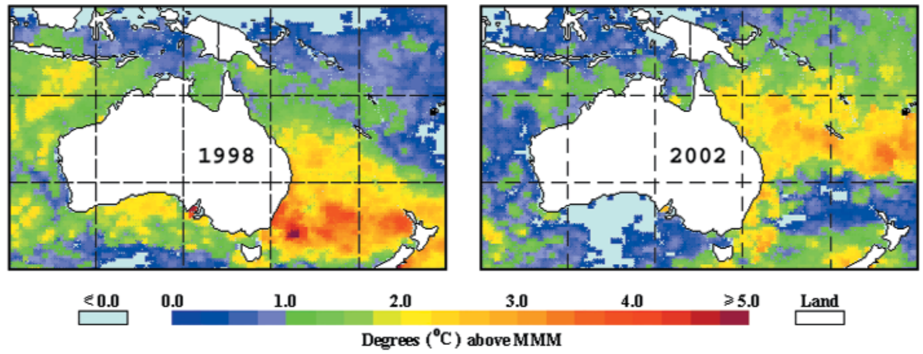

Fig. 2. Composite HotSpot charts of the summer seasons of 1998 and 2002 showing the distribution and magnitude of the maximum composite of HotSpots over the summers (January through March).

The 2002 GBR Coral Bleaching Episode

HotSpot analysis of the GBR began showing the onset of thermal stress in late December 2001 and becoming widespread by January 2002. The spatial extent and intensity of thermal stresses reached a maximum in mid-February before dissipating by mid-March. The thermal stress peaked around 11 February 2002, when widespread HotSpots over the GBR reached levels of between +2°C and +3°C.

Accumulation of HotSpot anomalies over a 12-week period (29 December 2001 through 16 March 2002) during the austral summer is captured dramatically on the DHW chart (Figure 1). Maximum accumulations for the region occurred just east of the GBR (DHW = 16), while throughout the region, DHW values exceeded 10.

Initial DHW accumulations just east of the central GBR started in mid-December 2001, reaching 4 DHWs in early January 2002, and climbing to 8 DHWs by month's end. These extreme values persisted until mid-February. The time-line of these DHW values suggests that the onset of the earliest bleaching in the region was as early as late December 2001, with some significant bleaching likely in early January, and becoming more widespread by mid-January.

Field surveys conducted by GBRMPA, AIMS, the University of Queensland, and other organizations are still being compiled. However, preliminary data are confirming that the GBR bleaching event of 2002 was the worst on record [*Wilkinson*, 2002; *Berkelmans*, 2002].

Comparison of 2002 and 1998 GBR Coral Bleaching Episodes

The 2002 coral bleaching event in the GBR was more significant than the one in 1998 in every measurable aspect: SSTs were generally higher, bleaching was more extensive, and there was more mortality [*Berkelmans*, 2002; *Wilkinson*, 2002].

Comparisons between the 1998 and 2002 satellite composite austral summer (January-March) HotSpot and DHW charts (Figures 1 and 2) reveal significant differences in the geographic distribution and pattern of the thermal stress. During the 1998 bleaching that coincided with a severe El Niño, the epicenter of the warm SST anomaly was off southeastern Australia and well south of the GBR, while in the summer of 2001–2002 (outside an El Niño), the epicenter was much closer to the GBR and centered just east of the central GBR (Figures 1 and 2). This close proximity to the GBR resulted in much higher HotSpot and DHW values over the GBR for 2002 than in 1998.

DHW charts and the composites of maximum HotSpots (Figures 1 and 2) show that the anomaly during 1998 was actually stronger than in 2002. This may be linked to the strong El Niño during that year. The position of the anomaly epicenter may also be related to the El Niño. An obvious conclusion from this comparison is that a strong El Niño is not necessarily accompanied by severe bleaching on the GBR. The cause of the 2002 GBR significant warming event remains to be investigated. In this episode, there is no apparent relationship between El Niño and this unprecedented GBR bleaching event.

Conclusions

NOAA's CRW satellite-derived, near-real-time HotSpot products successfully monitored the 2002 anomalous warming event. These products led to early warnings heralding the development of a coral bleaching episode for the GBR. This severe coral bleaching event was reported to have reached record proportions over much of the Australia's GBR during the 2001–2002 summer.

Although this recent bleaching event occurred in record proportions, judging from our experience of the aftermath of the 1998 GBR bleaching event, most corals should recover from this recent event [*Wilkinson*, 2002]. For instance, we already know that during the 2002 bleaching event, some of the most severe bleaching was experienced by the Keppel group of islands in the southern region of the GBR. Most of the reefs in this region experienced 100% bleaching; however, over 70% of these corals have since recovered [*Berkelmans*, 2002].

The key difference between the 1998 and 2002 bleaching events on the GBR lies not in the intensity of the SST anomaly that caused each event, but in the proximity of the anomaly's epicenter to the GBR. The fact that the 1998 bleaching occurred during a strong El Niño and the 2002 event occurred outside an El Niño may be an important factor in the position of this epicenter. The correlation between SST variability on the GBR and climatic events such as El Niño and the Pacific Decadal Oscillation need further investigation. The relationship between bleaching in the GBR and other relevant environmental parameters also need to be investigated to better understand potential cause-and-effect relationships. For instance, it is known that factors such as light, turbidity, salinity, pollution, etc. also cause stress and can lead to bleaching in certain circumstances [*Reaser et al.*, 2000].

SST trends from satellite and in-situ techniques are providing scientists with the tools to help understand the role of climate change on coral bleaching frequency and intensity over the GBR. However, to more accurately monitor and predict coral bleaching, satellite observations of additional environmental parameters such as wind, currents, cloud cover, and solar radiation are necessary to better relate environmental measurements and predictions to the biological response that causes coral bleaching. In addition to these, the spatial resolution and accuracy of the current data sets need to be improved. The high spatial resolution of other SST products currently in development as a joint AIMS/NOAA project [*Skirving et al.*, 2002] will help improve our capacity to understand spatial variability in this important and increasing environmental stress.

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