

Detecting and Monitoring 2001 Coral Reef Bleaching Events in Ryukyu Islands, Japan Using Satellite Bleaching HotSpot Remote Sensing Technique

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Abstract -- Widespread coral bleaching due to anomalously high water temperature was observed in the Ryukyu Islands, Japan during the summer of 2001. The U.S. National Oceanic and Atmospheric Administration's (NOAA) near real-time coral bleaching HotSpot early warning products, derived from satellite sea surface temperature (SST), showed that extraordinarily warm water started to cover the Northwest Pacific region beginning in late-June. This thermal stress continued to accumulate for over two months into early September. Coral bleaching early warnings were initially issued to the region (informally by NOAA via e-mail) early in the summer season based on the satellite observations. The comparison between the satellite SSTs and several *in situ* temperature observations in the region shows that the NOAA satellite HotSpot technique was remarkably informative in showing the onset, development, and dissipation of the warming event.

INTRODUCTION

Beginning experimentally as early as 1997, the U.S. NOAA's National Environmental Satellite, Data and Information Service (NESDIS) began developing satellite global 50km coral bleaching sea surface temperature (SST) HotSpots and Degree Heating Weeks (DHW) (called HotSpot products) as indices of bleaching related thermal stress [1,2]. Under NOAA's Coral Reef Watch (CRW), the products are produced twice-weekly at near real-time using twice-weekly composite nighttime SST derived from data received by the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA's Polar Orbiting Environmental Satellite (POES). The products are updated every Tuesday for the composite of Saturday through Monday and every Saturday for Tuesday through Friday and Web-accessible at http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html. The coral bleaching HotSpot is a type of SST anomaly showing positive anomaly (potential thermal stress) compared to a "static" bleaching threshold SST (see the references for expanded details). DHW represents the accumulation of HotSpots during the previous 12 weeks and the HotSpots have to be at least 1°C to be accumulated. One

DHW is equivalent to one week of HotSpot staying at 1°C or 0.5 week of HotSpot at 2°C, etc. This technique has been called, "the HotSpot technique." Estimation from limited years of field observations, but including the extensive 1998 bleaching event [3], shows that at 4 DHW a significant percentage of particular coral species bleach and at 8 DHW most species bleach with widespread mortality. This DHW rule has been applied in generating satellite bleaching alert. The HotSpot technique is proving to be highly successful in providing early warnings of coral bleaching on large spatial scales to the coral reef community [4,5,6].

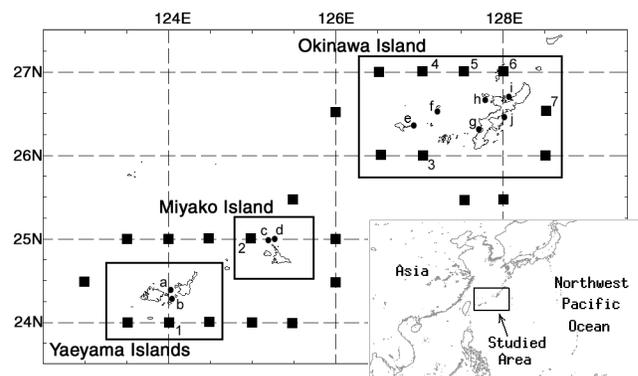


Fig. 1. Map of the central and southern Ryukyu Islands, Japan. Satellite 50km SST pixel centers (squares, some numbered (1-7)) around the islands and *in situ* stations (labeled dots, a-j) are shown.

During the summer of 2001, the Northwest Pacific Ocean experienced large-scale anomalously high SSTs. CRW's satellite coral bleaching early warning system detected and monitored the warming event and issued several alerts (on the Web site and via e-mail "Coral-list") for potential bleaching in the region. Subsequently, *in situ* observations from the Northern Mariana Islands, Palau, and Japan have revealed extensive bleaching. In Japan, the bleaching was observed in the Ryukyu Islands (Fig. 1) extending from the

Yaeyama Islands (24.4°N, 124.0°E) and Miyako Island (24.7°N, 125.4°E) in the south, through the Okinawa Island (26.5°N, 128.0°E), to the Yaku Island (30.3°N, 130.5°E, not shown in Fig. 1) in the north.

Bleaching status reports collected in the Ryukyu Islands, Japan and *in situ* water temperature observations taken around the islands during the summer of 2001 were used to verify the bleaching prediction made by CRW and to validate the differentiating capability of the bleaching early warning system. The results are presented in this paper.

SATELLITE MONITORING

In 2001, satellite HotSpots showed that anomalously high SSTs in the Northwest Pacific region initiated in the open ocean between Guam and the Philippines in late-May to early-June and evolved and expanded north and west into the Ryukyu Islands, Japan in late-June. In the Ryukyu Islands, the persistent HotSpot reached its maximum intensity (around +3°C immediately east of Okinawa) in mid-August (Fig. 2, left panel); the accumulation of DHW started in late-June and DHWs reached their maximum accumulations (> 10 DHW immediately east of Okinawa) in mid-September (Fig. 2, right panel).

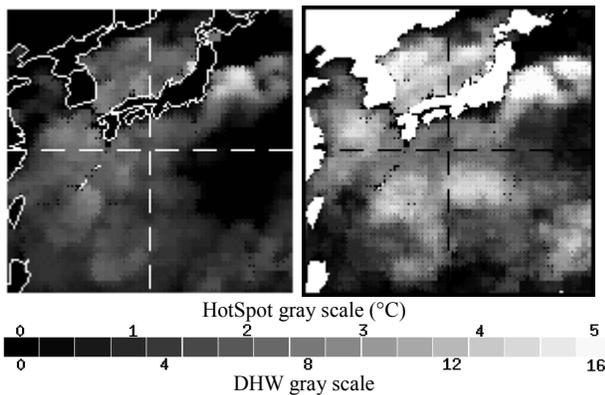


Fig. 2. Chart of composite HotSpots of 11-13 Aug 2001 (left panel) and chart of composite DHW of 15-17 Sep 2001 (right panel).

The centers of the satellite 50km SST pixels which are closest to the Yaeyama Islands, Miyako Island, and Okinawa Island are shown in Fig. 1. Each pixel box is 0.5 by 0.5 degree in size centering at either one or half degree of latitude and longitude. HotSpots appeared at these pixels in late-June, reached their maximums in early- to mid-August, and disappeared in early- to mid-September. The magnitude of HotSpot was much higher in the region around the Okinawa Island (max 2.7°C) than what was observed at the more southern Yaeyama Islands and Miyako Island (max 1.1°C), causing DHW to start accumulating much earlier in the Okinawa Island (mid-July) than the others (mid-August). 4 DHW and above were observed to reach the Okinawa Island in mid-August but never observed around the others.

Accumulation of >8 DHW was observed only at the two pixels east of Okinawa. According to the DHW rule mentioned earlier, none or minor thermally induced bleaching was expected in the Yaeyama Islands and Miyako Island with bleaching to start no earlier than mid-August, while significant bleaching was anticipated in the Okinawa Island to start no earlier than mid-July.

BLEACHING REPORTS

Bleaching status reports used for this study are provided by the International Coral Reef Research and Monitoring Center of the Ministry of the Environment, Japan and the Japanese Coral Reef Society. In the Yaeyama Islands, pale or partially bleached corals were first observed in early- to mid-July and bleaching spread throughout the area in late-July to mid-August. Severe bleaching and mortality of certain species were observed in some locations (not common) in late-August. In the Miyako Island, pale or partially bleached corals were observed from June to August and no severe bleaching was observed. In the Okinawa Island, initial bleaching was found in late-July at shallow areas and bleaching was commonly observed from late-July to early-August, with severe bleaching and mortality reported in some locations but not common. In September, typhoons struck the Ryukyu Islands and reduced the water temperature, resulting in the end of the bleaching.

The bleaching reports verified the prediction made by CRW's coral bleaching early warning system. However, the severe bleaching in the Yaeyama Islands was not predicted and the bleaching in the Yaeyama Islands and Miyako Island started much earlier than the satellite's "prediction." On the other hand, the satellite HotSpots did appear in these areas in late-June right before the reported initiation of the bleaching although the accumulation of DHW did not start then. To investigate the possible reasons for the apparent inaccuracy in the prediction, satellite SSTs were compared with *in situ* temperature observations taken around the islands. The results are presented in the next section.

COMPARISON BETWEEN SATELLITE AND IN SITU TEMPERATURES

Several *in situ* near-sea-surface temperature time series in shallow water areas (Fig. 1) were used: 2 from the Yaeyama Islands (station Kohamajima (Dot a in Fig. 1, measurement at 2 meters below the sea surface) at 24°21.1'N, 124°0.5'E and Kuroshima (b, 2m) at 24°15.935'N, 124°0.5'E, courtesy of the Ministry of the Environment, Japan), 2 from the Miyako Island (Yabiji01_st3 (c, 3m) at 24°59.7'N, 125°14.1'E and Yabiji01_st5 (d, 3m) at 25°0.8'N, 125°16.1'E, from Hirara City through the courtesy of Kenji Kajiwara), and 6 from the Okinawa Island (Kume-jima-1 (e, 2m), Aguni-2 (f, 0.5m), Ginowan-2 (g, 0.4m), Minna1 (h, 1m), Shioya-2 (i, 1m), and Ginoza-s (j, 2m), courtesy of the Coral Reef Environments in Okinawa Project [7]). Exact

latitudes and longitudes of the stations around the Okinawa Island are not available but the approximate locations are plotted in Fig. 1.

To compare with nighttime satellite SSTs, 12-hour (6:00pm-6:00am LT) averaged *in situ* temperatures were calculated from the hourly data sets. At each satellite SST pixel, “daily” nighttime SST values were constructed from CRW’s twice-weekly composite nighttime SSTs by using the same composite SST value of a twice-weekly period for each day during the period. Fig. 3 shows the *in situ* temperatures and satellite SSTs at the pixels (numbered pixels 1-7 in Fig. 1) closest to the *in situ* locations between June 15 and September 15, 2001 (a three month period).

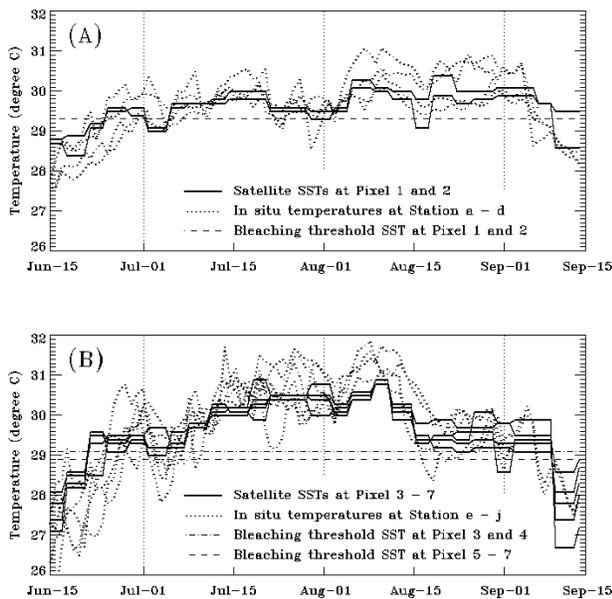


Fig. 3. Satellite SSTs (solid lines) and *in situ* temperatures (dotted lines) in the Yaeyama Islands and Miyako Island (A) and in the Okinawa Island (B) between June 15 and September 15, 2001.

The comparisons show that the *in situ* temperatures in shallow water areas were frequently warmer than the satellite SSTs at pixels near the islands. During the three month period, the mean difference between *in situ* temperatures and SSTs at the pixels closest to them ranged from $-0.55 \pm 0.51^{\circ}\text{C}$ to $0.54 \pm 0.84^{\circ}\text{C}$ with the best match of $0.19 \pm 0.35^{\circ}\text{C}$ in the Yaeyama Islands, $0.10 \pm 0.29^{\circ}\text{C}$ in the Miyako Island, and $0.02 \pm 0.49^{\circ}\text{C}$ in the Okinawa Island. Temperatures over some bleached reefs were reported staying above 30°C (even 31°C at some locations) for long periods of time in July and August. The satellite 50km SSTs taken around the islands tended to underestimate the temperatures in the shallow water areas. This is expected because during the summer season SST in these more shallow waters around the island is usually higher than SST offshore. A satellite 50km SST pixel value is an averaged value derived from AVHRR observations over an approximate 50km by 50km area which, in our case, covers

both shallow water and deep water areas or deep water areas only. Furthermore, a 50km pixel which is partially over an island is usually masked as land pixel and valid sub-pixel observations over shallow waters around the island are discarded. As a result, small spatial scale temperature variations are difficult to be detected at 50km resolution.

DISCUSSION

This study shows that NOAA CRW’s satellite 50km nighttime SST HotSpot products are capable of providing very informative prediction of onset, development, magnitude, and recovery of large-scale coral bleaching events although small-scale high temperatures in shallow water areas around islands or near coast are likely to be underestimated or missed out. However, most of widespread bleaching events are associated with large-scale warming events. The satellite can also detect and monitor the development of large-scale warming events initiated in other regions well before they evolve into shallow coral reef areas.

Under thermal stress caused by anomalously high water temperatures, the occurrence and severity of coral bleaching are also determined by other factors, such as the intensity of solar irradiation, wind speed, and tidal current. A better prediction of coral bleaching needs to incorporate the observation of these additional environmental parameters. Improvement of the HotSpot technique depends on the fine-tuning of bleaching threshold and DHW criteria. Increasing the spatial resolution of the HotSpot products will improve the capability to capture more accurately the smaller scale temperature anomalies for more accurate assessments.

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