Appendix 3

Satellite Bathymetry Use in Numerical Models of Ocean Thermal Stress

Scott F. Heron and William J. Skirving

Abstract

Techniques for deriving estimated bathymetry from satellite data are well established; however, use of this product in complex terrains is limited. Accurate bathymetry is essential in the construction of hydrodynamic models and satellite derived bathymetry is a strong candidate for use in coastal and shallow waters. A case study of Palau is presented which uses satellite-derived bathymetry as input to a hydrodynamic model. Palau underwent widespread coral bleaching during 1998, thought to be due to thermal stress, and existing satellite products observed anomalous increases in temperature. The numerical model is used to evaluate sea surface temperature patterns during such a bleaching event. Comparisons between the model and thermal indicators derived from satellite data are made, and the results used to suggest improvements for satellite monitoring of thermal stress events.

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SATELLITE BATHYMETRY USE IN NUMERICAL MODELS OF OCEAN THERMAL STRESS

S.F. Heron & W.J. Skirving

Coral Reef Watch
National Environmental Satellite Data Information Service
National Oceanographic and Atmospheric Administration
Scott.Heron@noaa.gov

ABSTRACT

Techniques for deriving estimated bathymetry from satellite data are well established; however, use of this product in complex terrains is limited. Accurate bathymetry is essential in the construction of hydrodynamic models and satellite-derived bathymetry is a strong candidate for use in coastal and shallow waters. A case study of Palau is presented which uses satellite-derived bathymetry as input to a hydrodynamic model. Palau underwent widespread coral bleaching during 1998, thought to be due to thermal stress, and existing satellite products observed anomalous increases in temperature. The numerical model is used to evaluate sea surface temperature patterns during such a bleaching event. Comparisons between the model and thermal indicators derived from satellite data are made, and the results used to suggest improvements for satellite monitoring of thermal stress events.

INTRODUCTION

Coral bleaching is the process by which a coral polyp, under environmental stress, expels its symbiotic zooxanthellae. The affected coral colony appears bleached. Severe bleaching can cause death of the coral colony. In September 1998, coral reefs across Palau were observed to be severely affected by bleaching (Wilkinson, 1998). A large proportion of the region (70-80%) underwent widespread bleaching and incurred high mortality rates; however, other regions appeared less affected.

One of the major environmental stresses that causes bleaching of corals is heightened water temperature (Berkelmans & Willis, 1999). Increased water temperatures, and hence bleaching events, are linked to weather events, which in turn may or may not be linked to climate events (e.g., El Niño). Mass bleaching occurs when there is an extended summer period of calm, sunny conditions that coincide with weak currents.

Over 98% of solar radiation energy is absorbed within the top 4 metres of the water column. This heat remains at the top of the water column unless there is a mechanism to mix it with the cooler water below. Vertical mixing occurs in regions of relatively strong horizontal currents, which can be associated with surface winds, large scale currents (e.g., North Equatorial Current) and tides. Therefore, extended periods of sustained cloudless summer days with low winds and low currents will likely induce bleaching events.

Hydrodynamic models can be used to describe oceanographic currents and from these predict SST patterns for future, severe, mass coral bleaching events. Hydrodynamic modelling can also assist in the investigation of other issues that relate to the coral reef ecosystem; connectivity with biological events (e.g., coral/fish spawning) and anthropogenic interactions (e.g., sewage outfall, pollution accidents) can be monitored and/or predicted.

One of the most important inputs to a high resolution hydrodynamic model is the bathymetry. The effect of incorrect bathymetry on computational fluid dynamic models can be significant and, as such, the accuracy of bathymetry can be crucial to the success of the numerical model (a detailed discussion is given in Gille *et al.*, 2004). For remote geographic locations, where in situ data are limited, remote sensing techniques can provide such bathymetry.

Lyzenga (1978) developed a theoretical basis for describing water depth by passive remote sensing upon which many others have expanded. Stumpf *et al.* (2003) applied this knowledge to investigate shallow regions with low bottom-albedo and variable bottom-types (e.g., sand, coral, algae, seagrass) using satellite data and developed a new algorithm for estimating water depths to 25 m and beyond.

In this work, satellite-derived bathymetry data are used as input for a numerical model to study the surface currents near Palau. From the model output, regions of vertical mixing are identified and the subsequent reduction in surface temperature for these waters is calculated. Patterns in the modelled temperature distribution are compared with satellite-derived Sea Surface Temperature (SST) data.

METHOD

Historical bathymetric data for Palau were measured primarily by Japanese ships prior to the Second World War; however, little in-situ data has been published since 1969. Newhall & Rohmann (2003) derived estimated-depths for the region surrounding Palau from LandSat imagery to use in classifying benthic habitat. The method used followed that described in Stumpf *et al.* (2003), an algorithm which is accurate to an approximate depth of 25 metres. The estimated-depth values were determined at the grid resolution of the LandSat image; i.e., 28.5 m. As the desired resolution for the numerical model was approximately 250 m, the estimated depth values were averaged across 99 points to produce a 256.5 m resolution data set. To describe the bathymetry beyond the depth-scope of the LandSat data (~20 m), the two-arc-minute-resolution data of Smith & Sandwell (1997) were interpolated to a 256.5 m grid aligned with the LandSat-derived data. Some smoothing was undertaken to combine the datasets. In addition, corrections were made to the data near to land, known coral reefs and in regions of obvious discrepancy, determined by comparison of the data with nautical charts and depth soundings (C. McLean, *unpublished data*). The corrections were incorporated by removing incorrect values, inserting replacement values where available and krigeing the data to fill any remaining gridpoints. Initial output from the computational model gave further indications of short-comings in the bathymetry, deduced by the presence/absence of observed currents, and further corrections were made.

The numerical study was undertaken using the Princeton Ocean Model (POM) as described by Blumberg & Mellor (1987). POM is a terrain-following (s-coordinate) model that has been used in a variety of oceanic and coastal applications (e.g., Chang & Isobe, 2003). The surface currents around Palau were modelled on a two-dimensional rectangular grid of 764328 points at 256.5 m resolution. Model land was defined by a 2.5 m isobath. Surface current velocities were defined at the open boundaries according to Heron *et al.* (in prep.) for the December to March season. The sea-surface elevations at these boundaries were defined as a function of tide gauge data collected in the Palau lagoon (Malakal Harbour). The boundary conditions were defined so as to reproduce the recorded elevations at the nearest model grid-point as closely as possible. No wind stress was applied in the model, as per the conditions for mass coral bleaching events. The model was ramped to the stated boundary conditions for 0.5 days and then run for 29.5 days. Model validation was performed using data collected during Aug 2002 Jan 2003, described in Steinberg *et al.* (in prep.).

The currents output from the computational model can be used to determine whether there is vertical mixing, due to bottom friction, throughout the water column. Simpson & Hunter (1974) examined the energy required for full vertical mixing and deduced a parameter to describe the position of fronts between mixed and stratified waters in the Irish Sea. This parameter (h/u^3, where h is the water depth and u is the surface velocity) was determined at each model timestep across the numerical domain. The value suggested by Simpson *et al.* (1982) for complete vertical mixing was employed here; i.e.

$$\log_{10}[\ h/u^3\ ] \leq 2.7$$

As mass bleaching events are related to temperature stress, an estimate of temperature variations, due to vertical mixing, was calculated. A vertical profile of the water temperature was determined by modelling the diurnal insolation of an initially uniform-temperature water column for a period of two weeks. The profile was then mixed from the surface to a specified depth to determine the reduction in temperature at the sea surface for a fully-mixed water column of that depth. This temperature-reduction was calculated for the range of water depths observed in the Palau lagoon, thus providing an indication of the temperature of the water column for any regions that are fully mixed. Advection of cooled waters is not presented here but will likely expand any areas cooled by the mixing mechanism. The temperature distribution across the Palau lagoon due to mixing was compared with satellite-derived Sea Surface Temperature (SST) data acquired during the widespread bleaching event in late 1998. SST values from the Pathfinder 4km SST database for the period 01 May 1998 28 Feb 1999 were examined to compare with the results from the model output. The daily data selected were for the night-time descending pass of the satellite so as to eliminate diurnal heating effects. For the region corresponding to the model domain, the quality tests imposed upon the 4km SST data discounted more than 80% of the values. The analysis of Kilpatrick *et al.* (2001) uses two tests to determine if an SST value is of sufficient quality. The first test compares the SST value with a value derived from the weekly SST data described by Reynolds & Smith (1994). Kilpatrick *et al.* (2001) indicate that this comparison may be biased in coastal zones and in regions with large SST gradients (spatial or temporal). The second discriminaton identifies pixels contaminated with cloud. Failure to meet the conditions of either of these tests causes the data to be considered as poor quality. Due to the coastal location and variable-temperature nature of this study, the "poor-quality" pixel data were also considered.

RESULTS

Surface currents derived in the Palau model during the advent of the highest high-tide of the 30-day modelled period are shown in Figure 1. The surface currents in the lagoon exceeded 1.4 m/s during the spring tides. The surface currents in the Palau region are tidally-dominated (Heron *et al.*, in prep.). As such, the currents, and therefore the vertical mixing, are maximised during times of greatest tidal range. Figure 2 illustrates the minimum value of the Simpson-Hunter parameter across the domain, corresponding to the greatest mixing that occurs for each location. From this it can be seen that very few regions of the Palau lagoon undergo complete vertical mixing. The determined mixing-induced temperature variations are referenced to a maximum temperature of 32.6°C and the resultant temperature values are shown in Figure 3. The temperature range in Figure 3 was matched to the satellite observation, discussed below, for ease of comparison.

Imagery from the Pathfinder SST 4 km dataset were examined for comparison with the modelled temperature distribution. The daily image for which the highest SST was measured (32.6°C) was selected;

the data were collected on 09 Sep 1998. This was one of only four images from the study period for which greater than 70% of the pixels passed the quality tests. In the selected image, some pixels surrounding the largest island of Palau were flagged as poor data. Examination of the quality masks indicated that the data were flagged by the first quality test described above. As this test is known to be biased against coastal regions, the "poor quality" SST values were included. The SST image for this day is shown in Figure 4, overlaid with the model land for ease of comparison. White pixels indicate land and coloured pixels indicate the SST value in degrees Celsius. The pixels with grey hash-strokes are those flagged by the quality testing as poor data. The average measured SST value (high-quality only) across the illustrated domain was 31.6°C.

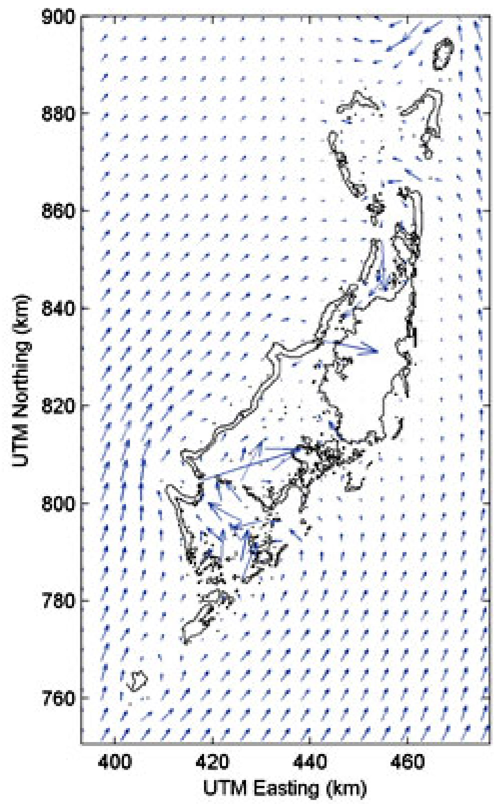

Figure 1. Currents around Palau output from numerical model. Horizontal resolution of vectors is approximately 4 km (16 gridpoints) for presentation purposes. Maximum current shown is 1.33 m/s. Axis scales in Universal Transverse Mercator (135 E) coordinates.

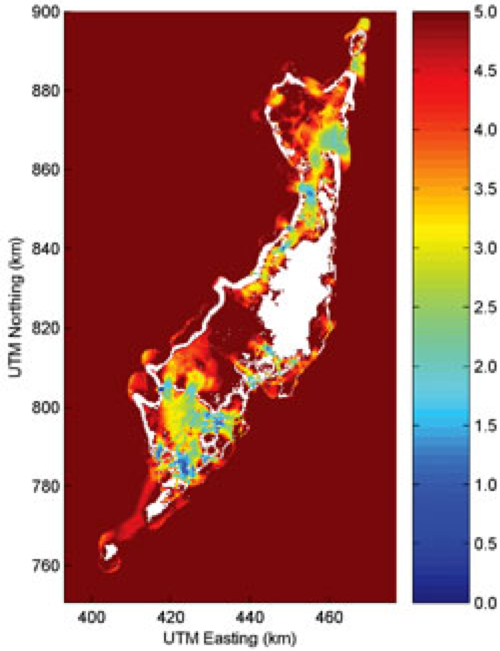

Figure 2. Minimum value of Simpson-Hunter parameter during 30 day model-run. The colour scale is in dimensionless units of $\log_{10}[h/u^3]$. A value below 2.7 indicates complete vertical mixing.

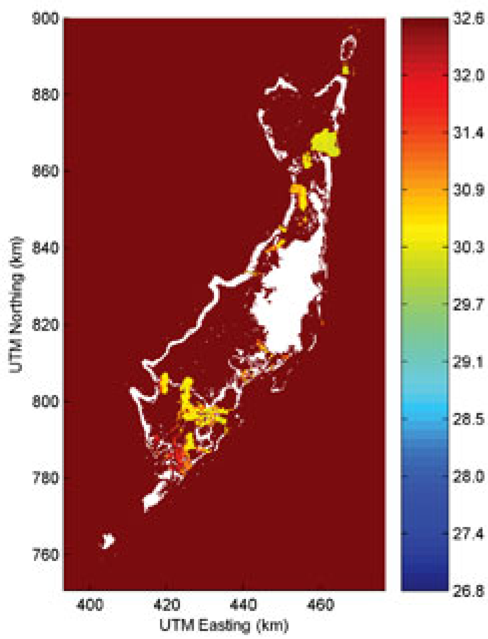

Figure 3. Modelled sea surface temperature due to vertical mixing. The values are reduced from a maximum value of 32.6°C.

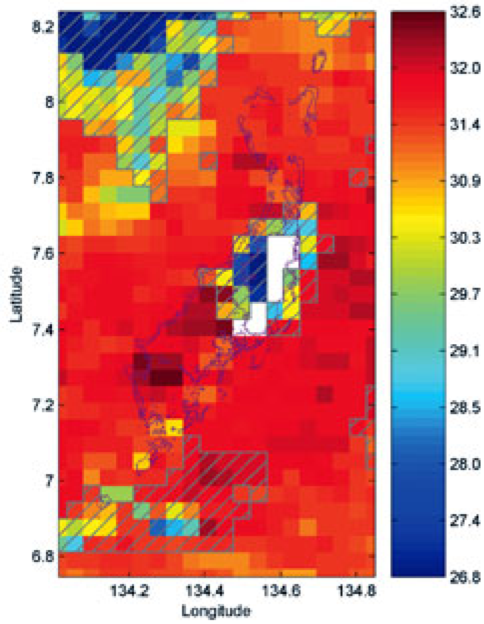

Figure 4. Pathfinder 4km SST values for the Palau region on 09 Sep 1998. White pixels represent land; coloured pixels represent SST in °C; grey hash-lines indicate data flagged as poor-quality. The model land is shown in purple for ease of comparison with previous figures.

DISCUSSION

Figure 3 shows two main areas of reduced temperature; the southern lagoon and a region in the north (near [445km E, 860 km N], known to be a grouper spawning zone (Johannes *et al.*, 1999). Comparison of the water temperatures across the lagoon is somewhat limited by the resolution of the satellite data; however, temperature patterns may be observed and discussed. The extreme low temperatures of some "poor-quality" pixels in the top-left and at the centre of Figure 4 appear to have been correctly flagged as poor; however, many of the pixels in the regions designated as poor appear to display credible temperatures.

At the locations of predicted vertical mixing (Fig. 2), slight reductions in the measured SST, compared with surrounding pixels, can be observed (Fig. 4). In the southern lagoon, two relatively-cooler pixels are observed near [134.30°E, 7.15°N] and a further two near [134.38°E, 7.23°N]. These pixels correspond with predicted locations of mixing-induced cooling. In the grouper spawning region in northern Palau, the model predicts regions of cooling. The SST data in this location are indeed cooler than those in the surrounding, non-mixed waters. However, near [134.32°E, 7.27°N], the hottest temperature pixel for the domain is located in a region for which significant mixing (and therefore cooling) was predicted.

The overall patterns in the datasets suggest that vertical mixing of water columns, and the subsequent decrease in SST, may be a significant mechanism for surface cooling in the Palauan lagoon. Further work on the model output is required to incorporate the effects of advection of cooled waters. As coral reefs are primarily located in shallow, coastal regions, improvements to the monitoring of thermal stress on corals using satellite platforms requires SST algorithms to perform with greater stability in coastal areas. Increased horizontal resolution is a first step for this; however, consistently producing data of sufficient quality in these regions is a necessity. Derivation of at-depth temperatures from satellite data will aid in further understanding of thermal impacts on corals throughout the water column.

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