Detecting 'Island Mass Effect' through remote sensing

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Abstract. Island Mass Effect (IME) refers to the enhanced production that occurs around oceanic islands in comparison to the surrounding waters. Physical factors that facilitate an IME include tidal flows that enhance vertical mixing locally and break down the pycno/nutricline, and eddies on the downstream side of the island that form in both tidal and steady currents. In some cases, runoff from the island and/or exchange with a lagoonal system can enhance nearshore production. Phytoplankon blooms in otherwise oligotrophic systems have the potential to increase nearshore zooplankton abundance. Greater availability of nearshore zooplankton may help reefs cope with stressors such as bleaching events. Palardy et al. (2008) showed that heterotrophic carbon accounted for 46% of some coral species' daily metabolic carbon requirements when healthy and 147% when bleached. Anthony et al. (2009) showed that high rates of heterotrophy could delay the onset of coral mortality by up to three weeks. We examined remote sensing data from the Aqua MODIS for three islands of the Republic of Mauritius in the Indian Ocean from 2009-2011. We found weak but predictable IME around the three islands all year round with chlorophyll-a concentration ranging from 0.047 to 2.77 mg/m^3. The peak periods of the IME occurred June through August. IME is an overlooked aspect of the biological oceanography and may have implications for reef resilience as bleaching events become chronic under global warming.

Key words: Island mass effect, Coral bleaching, Chlorophyll-a, Aqua MODIS satellite, Remote sensing.

Introduction

The term 'Island Mass Effect' (IME) was coined by Doty and Oguri (1956) to help explain observations of primary production near the Hawaiian Islands. IME refers to the enhanced primary production that occurs around oceanic islands in comparison to the surrounding waters. There are several physical mechanisms that may create an IME: (1) strong tidal mixing around the island, which acts as a stirring rod to enhance vertical mixing locally and break down the pycnocline which is often coincident with the nutricline, (2) unidirectional or bidirectional flow past the island that generates a wake often extending for several island diameters downstream, (3) freshwater runoff bringing limiting nutrients nearshore, (4) local wind shear stirring the surface layer sufficiently to cause local upwelling, (5) internal waves breaking on the island subtidal slope disrupting the thermocline, and (6) geostrophic flow and Ekman drift interacting with an island's bathymetry. IMEs generated by some of the above mechanisms have been observed around island systems as diverse as Barbados (Sander and Steven 1973), the Canary Islands (Hernández-Léon 1988, Hernández-Léon et al. 2001), the Galápagos (Palacios 2002), the Maldives (Sasamal 2006), the Marquesas (Jones 1962, Martinez and Maamaatuaiahutapu 2004), Mare (Loyalty Islands) and New Caledonia (Le Borgne et al. 1985), and the Kerguelen Islands in the Southern Ocean (Blain et al. 2001).

In oligotrophic ecosystems e.g. coral reefs, an IME event causing phytoplankton blooms may cause an increase in nearshore zooplankton abundance. This increase in abundance of food may in turn help reefs weather stress such as a bleaching event. Work by Palardy et al. (2006) and Grottoli et al. (2006) have shown that some species of scleractinian corals increase their feeding rates in the presence of increased zooplankton abundance and that some bleached corals are better able to cope with thermal stress and recover by increasing their suspension feeding. Anthony et al. (2009) report that onset of death is delayed by up to three weeks if bleached coral species are allowed to suspension feed. These findings suggest that in the presence of more food, some coral species may have greater resilience to face global climate change. Mesoscale oceanographic events like IME could mitigate bleaching severity by supplying cooler water from depth (Glynn 1993, West and Salm 2003). Here we suggest IME may be an overlooked aspect of biological oceanography influencing food supply near reefs during stressful periods that may have significant implications for reef health.

Material and Methods

IME was investigated around the islands of Mauritius (MRU),nRodrigues (ROD), and St. Brandon (SBR),

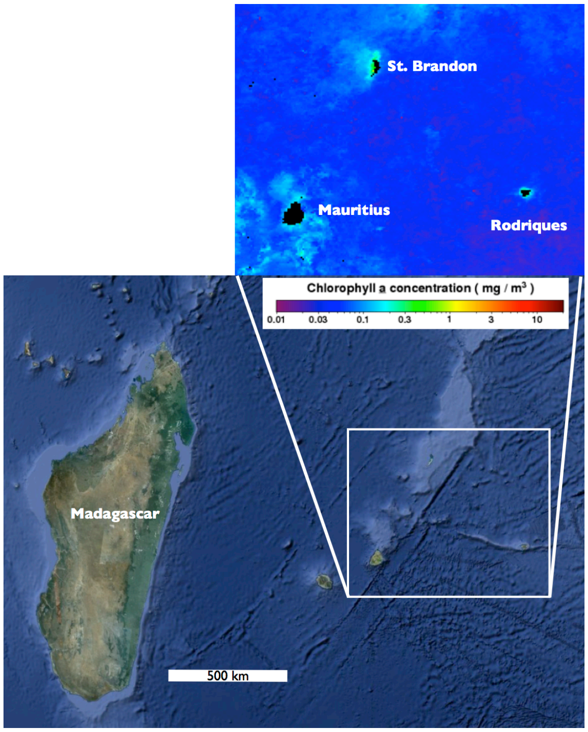

Figure 1: Geological setting of Mauritius, Rodrigues and St. Brandon on the Mascarene ridge/plateau in Indian Ocean (Google Earth). False-color composite Aqua MODIS image at top right (4.64 km pixel resolution) shows chlorophyll-a concentration from the austral summer that began in 2009. Island mass effect for chlorophyll-a concentration is visible around all three islands.

all of which are surrounded by coral reefs. These islands are found in the area bounded by 16.4 – 20.7 °S, and 57.2 – 63.8 °E in the Indian Ocean about 1000 km east of Madagascar (Fig. 1).

Sea surface temperature and chlorophyll-a concentration geophysical data were downloaded from the USA Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) for 2009, 2010, and 2011, at 4 km resolution using the Level-3 binned data products available at the NASA Ocean Color web site: http://oceancolor.gsfc.nasa.gov/. (Although the web interface lists the resolution as 4 km the actual resolution is 4.64 km.) Sea surface temperature was inferred from 11 µm wavelength daytime radiance (Brown and Minnett 1999); chlorophyll-a concentration was inferred from the sensor calibration, atmospheric corrections, and bio-optical algorithms (O'Reilly et al. 2000, Stumpf et al. 2000).

Monthly average (composed of daily means) and seasonal composite (austral winter, spring, summer, autumn) images were selected using three bounding boxes of 1.50° latitude by 1.50° longitude, each one centered on the islands of MRU, ROD, and SBR. Each bounding box covers 36 by 36 satellite data pixels (27,883 km^2). Calibrated image data were examined using the SeaDAS 6.3 data management and visualization software and the image-processing program ImageJ (Rasband 1997, Abramoff et al. 2004). Images were analyzed for mean and total chlorophyll-a, and mean and total sea surface temperature, in each image. Sea surface temperature and chlorophyll-a concentration images for a given month or season were also spatially cross-correlated to examine whether positive, neutral, or negative relationships existed near and away from reefs surrounding the study sites, using an ImageJ plugin (Chinga and Syverud 2007). Linear regression between mean chlorophyll-a concentration and sea surface temperature by month for each site was computed using the least-squares algorithm in Excel 2011, with significance tests performed in R (R Development Core Team 2010).

The possible mechanisms by which phytoplankton blooms occur around these islands were investigated. A transect across the middle latitude of each bounding box was examined for each month. Graphs were drawn to examine how chlorophyll-a concentration varied from leeward (west coast) to windward (east coast) side. Rainfall data were available for Mauritius and correlated to chlorophyll-a data to investigate its potential role in the presence of IME around the island.

Results

Detecting the Island Mass Effect

Phytoplankton blooms were detected at the three islands for the three years of this study. Maximum local values of chlorophyll-a concentration were 0.97 mg/m^3 for MRU, 2.77 mg/m^3 for ROD and 0.71 mg/m^3 for SBR. The mean minimum and maximum chlorophyll-a concentration values recorded for the entire bounding boxes were as follows: MRU, 0.053 – 0.169 mg/m^3; ROD, 0.053 – 0.129 mg/m^3; SBR, 0.069 – 0.195 mg/m^3. There is an indication of seasonal differences in the blooms. The largest and highest intensity of blooms occurred during the austral winter (June to August) for the three islands. An example is shown for SBR in Fig. 2. SBR had the highest concentration of phytoplankton blooms followed by MRU and ROD from 2009-2011.

Temperature effects on phytoplankton blooms

In general, chlorophyll-a concentration correlated negatively ($p < 0.05$) with temperature for the three islands and for the three years (Fig. 3). SBR had the steepest slopes with R^2 values 0.90 in 2009 and 0.74 for 2011. ROD had its highest R^2 value of 0.79 in 2011, which coincided with a maximum temperature of 26.9 °C. This was at least 1 °C colder compared to 2009 and 2010. MRU had an unusually high value of chlorophyll-a concentration (0.118 mg/m^3) in February 2010 (an austral summer month) when concentrations of 0.047 – 0.061 mg/m^3 are more usual.

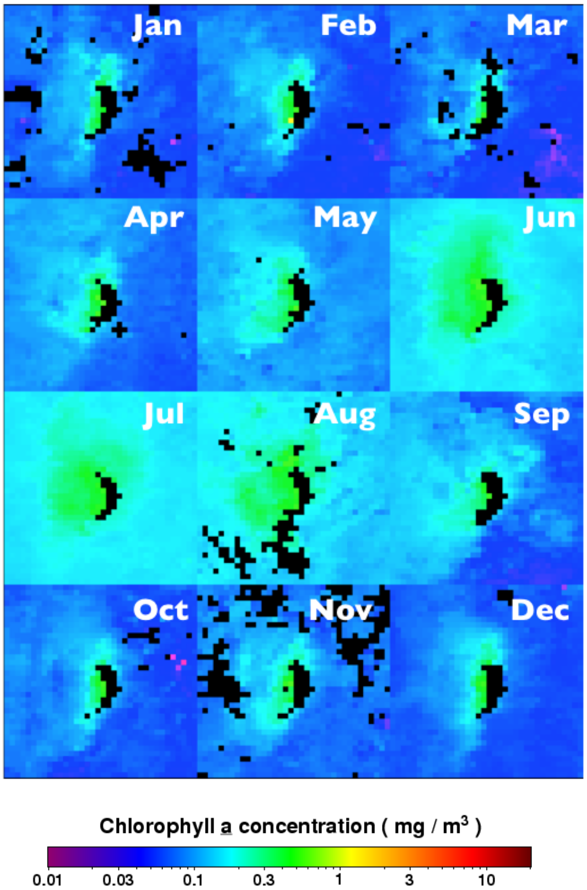

Figure 2: Monthly averages of chlorophyll-a concentration around the island of St. Brandon (SBR) in 2010 as measured by Aqua MODIS. Black pixels represent either land (crescent shape) or missing data from cloud cover.

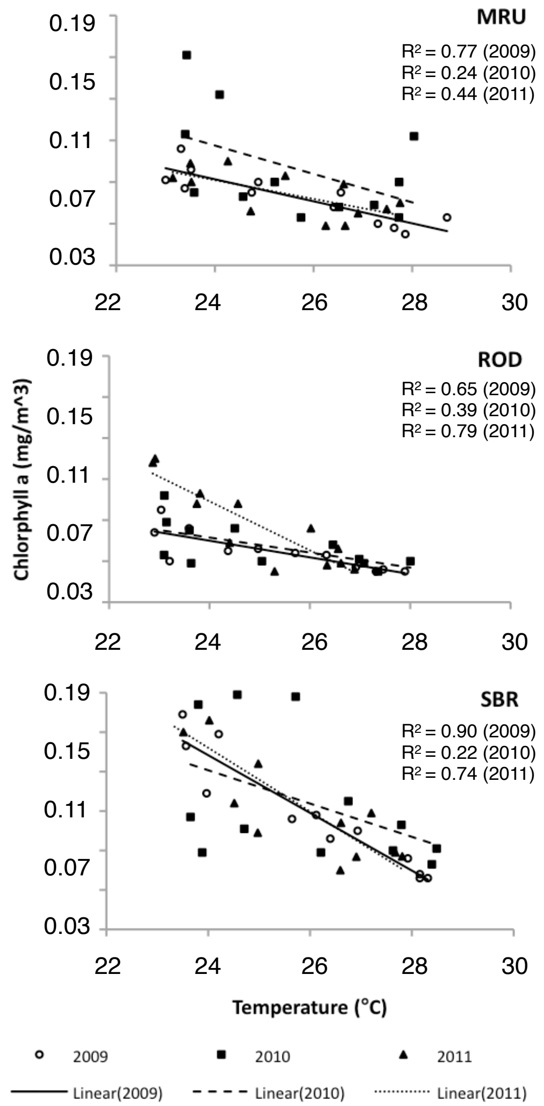

Figure 3: Correlation between mean monthly chlorophyll-a concentration and mean monthly temperature for three years for the islands of Mauritius (MRU), Rodrigues (ROD) and St. Brandon (SBR).

Mechanisms behind phytoplankton blooms

The transect data revealed that SBR had the strongest blooms of the three islands and that they were always on the leeward side (Fig. 4). This indicates that the possible mechanism of IME around SBR is the presence of strong enough currents to generate eddies on the leeward side of the island that bring cold nutrient rich waters to the surface. Peaks in concentration of phytoplankton blooms for MRU and ROD occurred both on the leeward and windward sides, but were not as strong as those seen near SBR. This suggests that the mechanism for phytoplankton blooms at these two islands may be more closely linked to the tidal regime or run-off.

There was no significant correlation between rainfall and chlorophyll-a concentration in 2009 and 2010, suggesting that run-off does not play a role at the scale of the bounding box.

Discussion

IME phytoplankton blooms that result in zooplankton increases can have significant effects on the health of organisms in higher trophic groups. In particular, coral species could benefit from this increase in food by increasing their suspension feeding (Fig. 5). Studies have shown that some coral species can increase their feeding on zooplankton when they are stressed such as during a bleaching event (Palardy et al. 2006; Grottoli et al. 2006). This would greatly increase their ability to weather stress and recover.

Enhanced primary production was observed around the islands of MRU, ROD and SBR in austral winter 2009, 2010 and 2011, thus suggesting that seasonal cycles plays an important role in the phenomenon. Temperature was the main factor that correlated negatively with the chlorophyll-a concentration, while

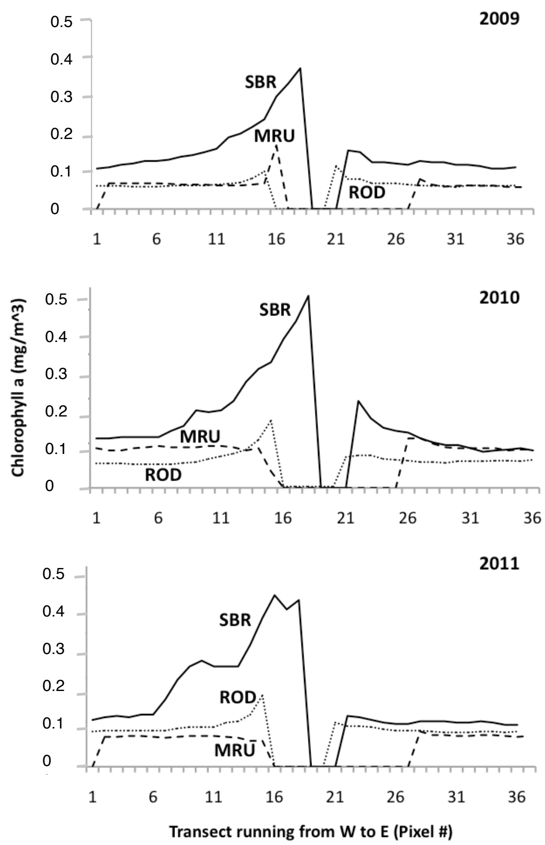

Figure 4: Mean values of chlorophyll-a concentration per pixel (4.6 km x 4.6 km) in austral winter (June-August) along a west-to-east transect for the islands of Mauritius (MRU), Rodrigues (ROD) and St. Brandon (SBR). Pixels representing land have a zero chlorophyll-a concentration. Transects were midway between the north and south tips of the islands.

rainfall did not show any significant relationships.

Of the three islands, SBR had the highest chlorophyll-a concentrations, and the peak blooms always occurred on the leeward side (west coast), contrasting with the other islands. One possible explanation for this occurrence could be a topographic upwelling. SBR is found on the shallow Carjados Carajos bank, which is part of the Mascarene Plateau, a dominant bathymetric feature of the Indian Ocean.

The whole plateau is under the influence of the South East Trade Winds and the South Equatorial Current (SEC). There is appreciable westward flow across the plateau, through gaps and channels, and some evidence of eddy formation west of the Cargados Carajos bank (New et al. 2005). The case of SBR could be similar to the Maldives Islands which are located on a submerged ridge with numerous channels. Flow through these channels causes turbulence and eddies in the wake of these islands allowing vertical mixing of stratified equatorial water (Sasamal 2006).

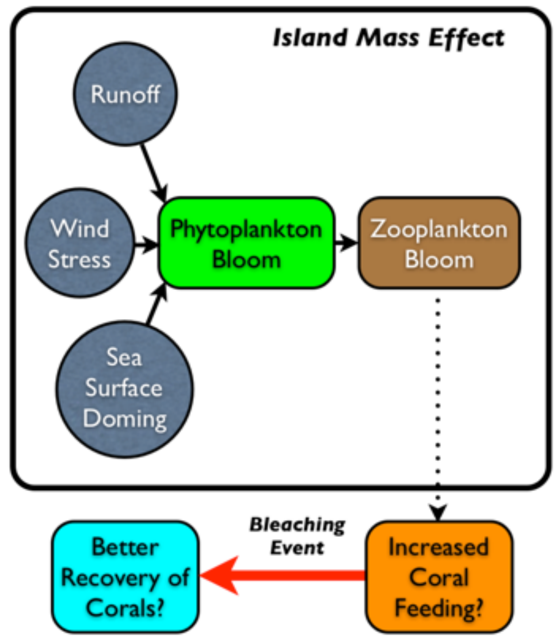

Figure 5: Conceptual diagram for why island mass effect could be important for reefs during bleaching stress.

SBR has a transient annual population of 78 people, almost no relief above the waterline, and therefore no significant run-off effects. Its tidal range is poorly known and thus it is difficult to know what role tides may play in IME events at SBR.

MRU is found on the southern tip of the Mascarene Plateau. However, the lower concentrations of chlorophyll-a as compared to SBR suggest that the currents do not create as much turbulence in the wake of the island. Of the three islands, MRU is the largest and the most highly populated. Thus run-off is an important factor to consider. However, the rainfall data did not correlate with phytoplankton blooms, indicating that runoff does not play an important role at the scale of the present study. The mean tidal range in MRU is 0.5 m (Daby 2006). Such a small range suggests that the effect of tidal mixing in creating an IME is also not likely to be significant.

ROD is found on the Rodrigues Ridge and is also influenced by the westward flowing SEC. The orientation of this ridge, along an east-west axis, does not seem to allow turbulence and upwelling to develop on the leeward side (west coast) of the island. This could explain the relatively lower concentration of phytoplankton blooms in comparison to the two other islands. The mean tidal range in ROD is 1.2 m (Daby 2006), which is more than twice that of MRU. Tidal mixing could therefore play a more important role in causing phytoplankton blooms around the ROD as compared to MRU.

Studies at a reef in the South Coral Sea (Rissik et al.

1997) and at the Canary Islands (Hernández-León 1988, 1991; Hernández-León et al. 2001) report increased abundance of zooplankton in the lee of the reef and the island that were attributed to flow disturbance and to the IME. Therefore, such physical disturbances may benefit coral species and other higher trophic organisms that rely on zooplankton directly or indirectly as a source of food. A meta-analysis found that the conversion of phytoplankton biomass to microzooplankton grazers is efficient and fast in the tropics (Calbet and Landry 2004). Further studies around MRU, ROD, and SBR are needed to determine how much of the primary production observed from space is converted to zooplankton potentially available to corals on the reefs nearby.

Global climate change is predicted to increase the frequency of bleaching events (Weeks et al. 2008). Zooplankton blooms that result from IME phytoplankton blooms near coral reefs could increase the resilience of those reefs in the face of increased stresses from warming and ocean acidification.

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