Remote Sensing of Environment 140 (2014) 596–603

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Improbability mapping: A metric for satellite-detection of submarine volcanic eruptions

Robert T. O'Malley [a], Michael J. Behrenfeld [a,*], Toby K. Westberry [a], Allen J. Milligan [a], Douglas C. Reese [b], Kimberly H. Halsey [c]

[a] Department of Botany and Plant Pathology, Cordley Hall 2082, Oregon State University, Corvallis, OR 97331-2902, USA
[b] Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331-3803, USA
[c] Department Microbiology, Oregon State University, Corvallis, OR 97331-3804, USA

ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form 10 September 2013
Accepted 24 September 2013
Available online 24 October 2013

Keywords:
Submarine volcanic eruptions
Improbability mapping index
Satellite detection

ABSTRACT

Submarine volcanic eruptions can result in both real and apparent changes in marine algal communities, e.g., increases in phytoplankton biomass and/or growth rates that can cover thousands of square kilometers. Satellite ocean color monitoring detects these changes as increases in chlorophyll and particulate backscattering. Detailed, high resolution analysis is needed to separate the optical effects of volcanic products from the response of the marine algal community. It is possible to calculate an index, which maps the magnitude of improbable change (relative to long term average conditions) following known volcanic eruptions by using low resolution, initial estimates of chlorophyll and backscatter along with an archived history of satellite data. We apply multivariate probability analysis to changes in global satellite ocean chlorophyll and particulate backscatter data to create a new metric for observing apparent biological responses to submarine eruptions. Several examples are shown, illustrating the sensitivity of our improbability mapping index to known submarine volcanic events, yielding a potentially robust method for the detection of new events in remote locations.

1. Introduction

Volcanic eruptions are among the most dramatic of all geological processes due to their explosive nature and inherent danger. Most eruptions, however, are submarine and are deep enough that they may be hidden from view by hundreds of meters of water. Shallow eruptions occurring in populated regions can be hazardous to maritime activities. The majority of these underwater eruptions, however, take place without our knowledge. Currently, detection of these events relies on reports of subaerial displays (Baker, Massoth, de Ronde, Lupton, & McInnes, 2002), surface observations (Vaughan, Abrams, Hook, & Pieri, 2007), fortuitous underwater observations (Rubin et al., 2012), seismic analyses (Schlindwein, Muller, & Jokat, 2005), or targeted hydro-acoustic array deployments (Dziak, Hammond, & Fox, 2011). If detection equipment is not in place when an eruption occurs, the assigned eruption onset times can have uncertainties of months to years (Siebert & Simkin, 2002).

Submarine eruptions are known to create hydrothermal plumes that rise hundreds of meters above the sea floor (Baker et al., 2012). Direct delivery of micro- and macro-nutrients by a volcanic eruption and subsequent venting is possible, along with additional transport of nutrients via volcanogenic upwelling (Vogt, 1989). At the same time, a volcano may further deliver large amounts of pumice and discolored water, and ongoing venting of materials may continue for weeks, potentially changing the optical properties of the sea water over large areas (Mantas, Pereira, & Morais, 2011). Careful processing of ocean color data is required to correctly separate the optical signature of volcanic products from any potential enhanced biological response. However, we propose that, irrespective of the true basis for a change, volcanic activity can result in an apparent, retrieved change in the phytoplankton population living in the surface mixed layer of the ocean that is observable with satellite imaging over large expanses of the ocean. Mechanistically, injection of nutrients from an eruption can result in a positive impact on the phytoplankton population, but contamination of the optical properties by the volcanic material can also yield false anomalies as the standard ocean color algorithms would assign the spectral changes to increased chlorophyll and particulate backscatter. Here, we use standard ocean color products to provide an initial signal for detecting submarine volcanic events. While some satellite sensors have been used to observe specific volcanic events using high resolution imagery (Urai & Machida, 2005; Vaughan & Webley, 2010), the current work investigates the sea surface expression of underwater volcanism that is spread over larger spatial scales where higher resolution images are not available, or do not cover large enough areas.

Over much of the tropical and subtropical oceans, surface plankton ecosystems are limited by nutrient availability (McClain, 2009; Sverdrup, 1955; Yoder, McClain, Feldman, & Esaias, 1993). Localized upwelling events occur when deep nutrient-rich water is physically

* Corresponding author. Tel.: +1 541 737 5289.
E-mail address: mjb@science.oregonstate.edu (M.J. Behrenfeld).

0034-4257/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.09.029

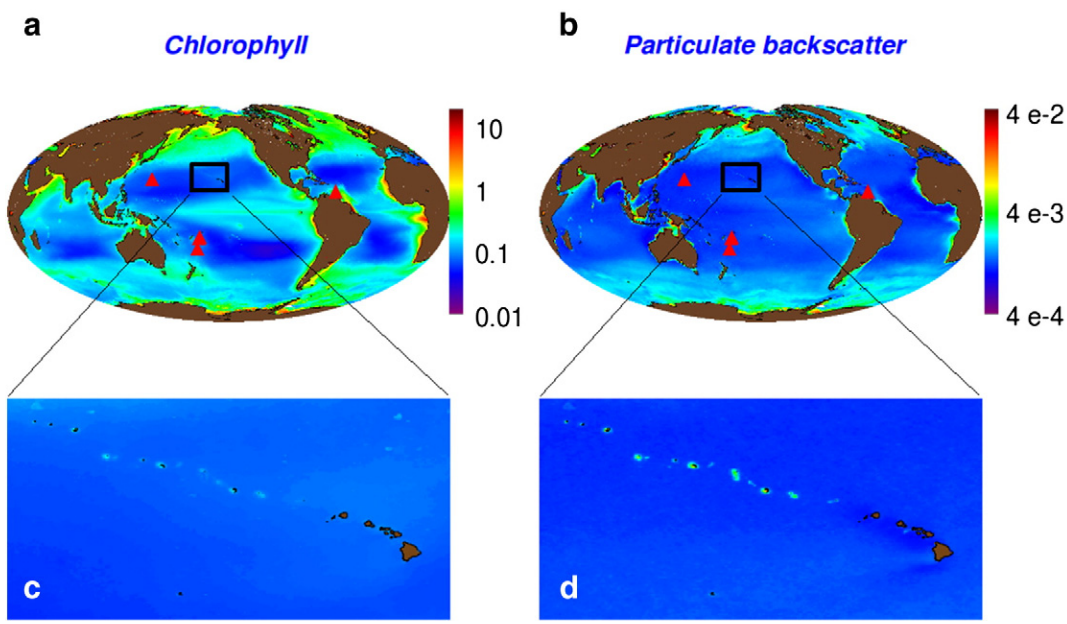

Fig. 1. Ten year average chlorophyll and particulate backscatter fields. (a) Ten year chlorophyll average (1998–2007) (mg chl m^{-3}); filled triangles represent submarine volcanic eruption sites listed in Table 1. (b) Ten year backscatter average (m^{-1}) for the same period; filled triangles represent submarine volcanic eruption sites listed in Table 1. (c) Shows average chlorophyll at the Hawaiian Island chain, while (d) shows the average for backscatter. Increases in the average levels of chlorophyll and backscatter can be found at island arcs and seamount chains due to regular delivery of nutrients over time via topographic upwelling.

transported to the surface, such as through Ekman pumping by divergent surface flows (Chavez & Barber, 1987) or eddy-driven vertical transport (Chelton, Gaube, Schlax, Early, & Samelson, 2011; Siegel, Peterson, McGillicuddy, Maritorena, & Nelson, 2011). Plankton respond to such nutrient influx by increasing their growth rates (i.e., a physiological response), standing stocks (i.e., biomass), or both. These changes can be observed by satellite images measuring variations in sea-surface-leaving radiance spectra (ocean color), which can be quantitatively related to surface chlorophyll concentrations (chl) (Fig. 1a) and particulate backscattering coefficients (b_{bp}) (Fig. 1b) (Behrenfeld, Boss, Siegel, & Shea, 2005; Stramski, Boss, Bogucki, & Voss, 2004; Westberry, Behrenfeld, Siegel, & Boss, 2008). Deep ocean currents and tidal pumping around seamounts and small islands also give rise to topographic upwelling of deep nutrient-rich water, generating local highs in chl and b_{bp} (Fig. 1c,d). Variations in ecological properties observed through satellite remote sensing of ocean color are thus responsive to nutrient delivery through a variety of water transport processes. We infer that the same effect could occur, following a submarine volcanic eruption. We note that volcanogenic upwelling is unique in that the water transport is driven by buoyant water heated by the volcanism, but what is common is the transport of nutrient rich water from below the surface mixed layer. This delivery of nutrients has the potential to generate an increase in phytoplankton growth and biomass. Thus, in eruption cases where there is minimal contamination of the optical signal by volcanic products, we may still expect detectable changes in satellite ocean color data because of associated biological response to an altered nutrient field.

To investigate apparent biological responses to submarine volcanic events, we compiled a subset of eruptions listed in the Smithsonian's Global Volcanism Program database (Siebert & Simkin, 2002) for 1998 through 2012 (Table 1). This period corresponds to ocean color measurements of the Sea viewing Wide Field-of-view Sensor (SeaWiFS), as well as the Moderate Resolution Imaging Spectroradiometer on the Aqua satellite (MODIS/Aqua). We restrict our examples to eruptions of short duration with well-defined onset times, and use these events as a test set to evaluate the ocean color signals. With the exception of *Kick'em Jenny* in the Caribbean, the selected eruptions are located in the Pacific Ocean (Fig. 1a,b). Two of our sample volcanoes have summits at ≤40 m (*Home Reef* and *Unnamed*) and three have summits between 130 and 185 m (*Ahyi*, *Monowai*, and *Kick'em Jenny*) (Table 1). The examples were chosen based on cases where cloud coverage did not restrict our ability to draw conclusions. Eruption imprints on surface ecosystems were evaluated using 8-day resolution chl and b_{bp} data at 1/12 of a degree latitudinal and longitudinal resolution (at the equator, this corresponds to pixel dimensions of 5 × 5 nautical miles, or approximately 9 × 9 km). Chlorophyll concentration responds to both physiological and biomass variability of the photosynthetic phytoplankton, while b_{bp} is a measure of particle abundance and related to total plankton carbon stocks (Behrenfeld, Halsey, & Milligan, 2008; Behrenfeld et al., 2005; Westberry et al., 2008).

Table 1
Subset of submarine volcanoes that have erupted between 1998 and 2012. Volcanoes were selected based on well defined onset times, short duration, and sufficiently cloud-free skies to not restrict the conclusions.

Test set of submarine volcanic events						
Name	Volcano number	Summit (m)	Latitude (deg)	Longitude (deg)	Start	Stop
Ahyi	0804-141	−137	20.420	145.030	04/24/01	04/25/01
Home Reef	0403-08=	−10	−18.992	−174.775	08/07/06	08/16/06*
Kick'em Jenny	1600-16=	−185	12.300	−61.640	12/04/01	12/06/01
Monowai Seamount	0402-05-	−132	−25.887	−177.188	11/01/02	11/24/02
Unnamed	0403-091	−40	−18.325	−174.365	09/27/01	09/28/01

* Stop date is uncertain.