Improbability Mapping: A Metric for Satellite-detection of Submarine Volcanic Eruptions

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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.

Keywords

submarine volcanic eruptions; improbability mapping index; satellite detection

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 et al., 2002), surface observations (Vaughan et al., 2007), fortuitous underwater observations (Rubin et al., 2012), seismic analyses (Schlindwein et al., 2005), or targeted hydro-acoustic array deployments (Dziak et al., 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 and 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 et al., 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 and Machida, 2005, and Vaughan and 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 (Sverdrup, 1955, Yoder et al., 1993, and McClain, 2009). Localized upwelling events occur when deep nutrient-rich water is physically transported to the surface, such as through Ekman pumping by divergent surface flows (Chavez and Barber, 1987) or eddy-driven vertical transport (Siegel et al., 2011, and Chelton et al., 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) (Stramski et al., 2004, Behrenfeld et al., 2005, and Westberry et al., 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 and 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 x 5 nautical miles, or approximately 9 x 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 et al., 2005, Westberry et al., 2008, and Behrenfeld et al., 2008).

2. Methods

2.1 Satellite Data

SeaWiFS was designed for global ocean color analysis (Barnes and Holmes, 1993). It was launched in August, 1997, and delivered continuous, daily coverage through the end of 2007. The six visible bands detected were at 412, 443, 490, 510, 555, and 670 nm, each with a 20 nm bandwidth. MODIS/Aqua, launched in May, 2002, detects a comparable set of visible ocean color bands (412, 443, 488, 531, 551, and 667 nm) at a narrower bandwidth (10 nm for the majority) and has a data quality similar to SeaWiFS (Franz et al, 2007). MODIS/Aqua continues to deliver daily global data, more than ten years after its launch. SeaWiFS data were regularly processed by NASA's Ocean Color Biology Processing Group to level-3 (mapped) data at 1/12 of a degree (~9 km) latitudinal and longitudinal resolution, with an 8-day averaging window (4 km and daily level-3 data are also available). MODIS/Aqua is also provided at 9 km and 4 km spacing, along with 1 km data. The chl and bbp level-3 satellite data used in this study originated from the Ocean Color MEaSUREs project at UCSB and are based on the Garver-Siegel-Maritorena inversion method (Maritorena et al., 2002; Maritorena and Siegel, 2005; Maritorena et al., 2010). Clouds are initially flagged as “no data” in these products and were later filled using the gap-fill routines at Oregon State University's Ocean Productivity site, essentially an expanding search for nearest neighbors that includes the spatial domain and looks forward and backward in time. The final, cloud-filled chl and b_{bp} data used in this study (8-day averages, 9 km resolution) can be obtained from OSU's Ocean Productivity web site (source: http://www.science.oregonstate.edu/ocean.productivity).

2.2 Probability Analysis

Our initial assumption was that a submarine volcanic eruption will cause a real or apparent increase in the biological signal detected by satellite (chl and/or b_{bp}) assuming the ejecta and/or hydrothermal plumes of the eruption are able to penetrate the surface mixed layer of the ocean (Speer, 1997). Specifically, the response to a submarine volcanic eruption is identified from spatial and temporal derivatives of chl and b_{bp}. Temporal derivatives directly show increases in time, while spatial derivatives show increases in the strength of fronts (gradients) between affected waters and unaffected areas. For chl and b_{bp}, it is sufficient to use temporal first differences as an estimate of their derivatives with respect to time. Furthermore, because these data are in regular grids, we approximated the spatial derivatives with the maximum absolute value of the spatial gradient observed between a given pixel and its eight surrounding neighbors. The gradients were calculated using spatial first differences normalized by the distance between the centers of the pixels.

The significance of the observed changes at a specific location can be assessed by converting derivatives in chl and b_{bp} into empirical probabilities of being met or exceeded at that locale (Fig. 2a). This assessment was done by directly counting how often the value observed at a given pixel was exceeded at that location over the course of the satellite record (10 years), and then dividing by the total number of observations. The joint probability of these four changes can be estimated by multiplying the individual probabilities together (Fig. 2b). While this approach provides a straight forward way of calculating the total probability of all the changes occurring at the same time, it is only accurate if the variables are independent (Wackerly et al., 2002).

A more rigorous probability estimate takes into account the potential interdependencies between chl and b_{bp}. By expanding the sample size around the pixel of interest, we allowed for a more robust estimate of the cumulative distribution function. The conditional probability was obtained by selecting a subset of data approximately equal to the observed value for one of the variables (e.g. chl). We then used the associated b_{bp} values to evaluate how often the observed b_{bp} change had been met or exceeded. The estimate of the joint probability was then obtained by multiplying these results together (Fig. 2c). More complex versions of this estimate are possible, but our interest was in the spatial patterns of probability, rather than their exact values, so the more simplified approach was sufficient.

The process of converting data to probabilities allowed multiple observations with different units to be merged into a single representation. The joint probability was then represented as an index by taking the -log10 transform of its value. The resultant metric is referred to here as the 'improbability mapping index' (IMI). Probability is unitless, as is the IMI, and the sign change in the log10 transform means that the smaller the probability, the larger the index. The IMI provides a measure of the magnitude of improbable change displayed by chl and b_{bp}. As an example, if all four inputs have a probability of 0.1, the IMI has a value of 4. If, on the other hand, the individual odds were one in a hundred (0.01), the index becomes 8. The IMI level for “average” change is 1.20, and is found by using 0.5 for all four inputs (i.e., the result of a 50% chance of occurrence for all four derivatives). The IMI was used to detect surface expressions of known submarine volcanic eruptions by seeking spatially extensive improbable increases in chl and b_{bp} following each event.

3. Results

Five specific, known submarine volcanic events were evaluated for this study: *Unnamed*, *Home Reef*, *Ahyi*, *Monowai*, and *Kick-em Jenny*. Each of these cases is discussed in the following subsections.

3.1 Unnamed

The IMI response shown in Figure 3 corresponds to a submarine volcanic eruption of an unnamed volcano (0403-091) at 18.325°S, 174.365°W in the Tonga region of the South Pacific (Table 1, *Unnamed*). This volcano has a summit depth of ~40 m and the eruption occurred between September 27th and 28th, 2001. Numerous short T-waves (seismic waves which have traveled an extended path as acoustic waves in the ocean) were detected in this period by the French Polynesian Seismic Network, along with observation of an ash-rich eruption column on September 28th (Taylor, 2002, and Smithsonian Inst., 2001b). Time series of chl, b_{bp}, and the IMI shown in Figure 3a-c include traces for the nine pixels from the 3x3 grid centered over the summit of the volcano (white outlined box), where the vertical red line indicates the day of the onset. The IMI clearly shows a strong response following the eruption (Fig. 3c), reflecting the combined responses of the chl and b_{bp} ocean color products (Fig. 3a,b). The heavy horizontal red line indicates an IMI value of average change (i.e.: $-\log10[(0.5)^4]$) and offers a baseline for comparison with the ensuing response. After the rapid IMI rise following the eruption, the index decays back to the baseline level within about two weeks. The duration of this decay period likely depends on a number of factors, including the level of venting that follows the initial eruption. The five spatial images in Figure 3d give a time-sequence of IMI values for a 2° latitude by 2° longitude area centered on the region impacted by the volcanic event, starting with a pre-eruption map. The area affected by the eruption is easily seen in map view, including subsequent transport as it moves away from the summit.

3.2 Home Reef

The second example is also a near-surface event, originating within the mixed layer with a summit of 10 m depth (Table 1, *Home Reef)*. The eruption started on August 7, 2006, and was located in Tonga at 18.992°S, 174.775°W. Satellite-detected surface expressions of the *Home Reef* eruption have previously been investigated with high-spatial resolution data (Mantas et al., 2011, Vaughan et al., 2007, and Smithsonian Inst., 2006a,b), with reports of extensive pumice rafts and discoloration of the surface water, clearly visible in both the fine scale images and the coarser MODIS data. This contamination of the biological signal with volcanic products enhances the ability of the IMI in detecting the event with uncorrected, low resolution data. Figure 4 shows how far the initially affected waters can be found away from the volcano and provides an example of a delayed IMI response at the summit. This delay and spatial transport reflect advection of material away from the summit and the sparse record of daily satellite observations going into the 8-day averages. For example, consider the second frame in Figure 4b, which corresponds to the onset of the *Home Reef* eruption. This image represents the average condition for the time period from August 5 through August 12, 2006. The eruption started on August 7 and had the remaining six days in the averaging period to impact the IMI values shown for the onset. The white outline in the second frame indicates the location of the 3x3 pixels centered on *Home Reef*, while the black box to the northeast represents the location of the Vava'u Islands. An average current of ~1/3 of a knot is required to move materials from *Home Reef* to the western edge of the Vava'u Islands over the time period of August 7 through August 12. While the pumice rafts were eventually recorded in Fiji (to the northwest) (Smithsonian Inst, 2006a) the IMI map for the onset implies that the initial trajectory was east by northeast. This trajectory is supported in the literature, with reports from the yacht, *Maiken,* that they had to head SSW from Vava'u on August 11 to avoid the pumice rafts (Smithsonian Inst., 2006a), by illustration of the pumice raft location on August 11 (see Figure 2 in Vaughan et al, 2007), and by high resolution satellite images provided by the MODIS Ocean Color team for August 5, 10, and 12 (see Figure 23 in Smithsonian Inst. 2006b, and http://oceancolor.gsfc.nasa.gov/MODIS/HTML/TongaHomeReefEruption.html). It is interesting to note the change in ocean color to the east of the pumice raft (towards Vava'u), especially when compared to the August 5 baseline image. Taken together, the pumice rafts and water discoloration are consistent with the location of the IMI maximum seen in the second frame of Figure 4b. Furthermore, with the exception of the MODIS images from August 10 and 12, the other images are mostly cloud-obscured. The result is that the 8-day "average" primarily has input from August 10 and 12, and minimal input from August 7-9. In that initial three day period of cloud coverage following the submarine eruption at *Home Reef*, the volcanic products were transported away from the summit. Because of this, no detection of an onset signal was possible at the volcano itself, resulting in the “delayed” IMI response found in the timeseries (Fig. 4a).

3.3 Ahyi, Monowai, & Kick'em Jenny

Figure 5 illustrates IMI responses for three mid-depth volcanoes (132-185 m), all with well defined eruption onsets. Our first example, *Ahyi*, erupted explosively in the northern Marianas on April 24-25, 2001, which was detected by a seismic station on Rangiroa Atoll (Smithsonian Inst., 2001c). The second example, *Monowai Seamount*, is an active volcano northeast of New Zealand in the Kermadec Island Arc, and the eruption spanning November 1-25, 2002, was again detected seismically (Smithsonian Inst., 2003). This eruption appears to be the onset of a growth cycle at the volcano, after 3+ years of seismic quiescence, and six months after an interpreted collapse event of the summit (Wright et al., 2008). The third volcano, *Kick'em Jenny*, erupted on December 4-6, 2001 in the Caribbean, with clear seismic detection (Smithsonian Inst., 2001a, and Lindsay et al., 2005). Pre- and post-eruption 2x2° surface IMI maps are provided for each event in figures 5a-c and 5g-i. The maximum IMI level on the color bar has been reduced to 5 to illustrate the before and after comparisons. Given that these eruptions originate below the mixed layer, it is not surprising that their surface impact is less extreme than the near-surface events. Circles of approximately 50 km radii are shown in the figure to indicate the most strongly affected regions. The middle panels (Fig. 5d-f) show time-series spanning the pre- and post-eruption period and, in each case, post-eruption IMI increases over baseline values for all nine pixels overlying each summit region. *Kick-em Jenny* shows a strong but delayed expression over the summit (Fig. 5f), similar to *Home Reef* (Fig. 4a), which we again take to suggest the presence of initial advection away from the summit. These three deeper examples have a more diminished and possibly more dispersed surface expression than the near-surface eruptions discussed above, but the IMI response is still present. There were no reports of observed surface discoloration or other activity at the *Kick 'em Jenny* eruption, which was well monitored and in a populated region. No direct observations were recorded for either the *Monowai* event of November, 2002, or the *Ahyi* eruption of April, 2001.

4. Discussion

Five examples are provided of improbability maps for changes in chl and b_{bp} associated with submarine volcanic eruptions of known onset times. In each case, we evaluate what (if any) improbable changes occurred in association with the event. We worked with essentially “off the shelf” low resolution global satellite ocean color products with no special processing applied. Our intent was to evaluate the usefulness of such public domain data in successfully identifying known volcanic events.

Our two examples for near-surface events (≤ 40 m depth) showed strong IMI responses, with values up to 8. For these shallow events originating within the mixed layer, it is likely that at least part of the satellite signal results from altered ecosystem conditions, including delivery of micro- or macro-nutrients. For example, in the case of *Home Reef*, after high resolution analysis was performed and volcanic contaminants were excluded, it was determined that the chl signal reached a level 17x greater than background (Mantas et al, 2011). The remaining portion of the satellite signal, however, was due to the impact of injected solids (ash or pumice) on surface optical properties, with associated water discoloration, assigned by the remote sensing algorithm to an increase in both particulate backscattering and chlorophyll. The IMI response for these cases certainly reflects changes from both volcanic materials and biological responses to the eruption. It is this combination of factors that gives rise to the large (and extensive) IMI values shown in Figures 3 and 4.

It is possible that alternative explanations exist for the IMI anomalies in Figures 3 and 4, such as topographic upwelling. However, the surface extent of high IMI values for our two near-surface examples is quite large, covering on the order of 2,000 square kilometers. Based on examination of individual examples of topographic upwelling associated with seamounts, we suggest that topographic upwelling likely impacts a smaller spatial area and would appear in IMI images more like the 4th frame of Figure 4b, rather than the 3rd frame of Figure 3d. It is also possible that an upwelling event could coincide with a submarine volcanic eruption, and fortuitous transport of impacted water could increase the resulting signal. This may be the source of at least some of the IMI response seen at Vava'u in frame 2 of Figure 4b. Upwelling in the traditional sense, however, should deliver colder bottom water along with the nutrients, and patterns of sea surface temperature could be examined to see if cold water injection matches the spatial patterns of high IMI regions. If high magnitude IMI results similar to those shown in Figures 3 and 4 are observed, then a closer examination of available high resolution data should be initiated, seeking the presence of volcanic products in the surface water. If none are found, then a subsequent analysis of sea surface temperature can test for cold water injection associated with topographic upwelling.

Our three eruption examples for summits between 132 and 185 meters depth show diminished IMI responses compared to the shallow events, but still yield detectable signals that are expanded over notably larger areas (Figure 5). These eruptions originate 100 to 165 meters below the surface mixed layer zone of the ocean, and their plumes very likely reach the density gradient at the base of the surface layer. At the time of the eruptions, the mixed layer depth for these three examples were found to be 28 m (*Ahyi*), 19 m (*Kick'em Jenny*), and 30 m (*Monowai*) (data from OSU's Ocean Productivity web site). Either their plumes were able to directly penetrate into the mixed layer, or they dispersed themselves along the base of the mixed layer zone before being incorporated into the upper layer. Once into the mixed layer, the properties would be distributed throughout the zone (Gregg and Briscoe, 1979, and Denman and Gargett, 1983). The combination of no documented reports of discolored water, pumice rafts, etc., for these events, along with the lack of a strong, localized IMI response, suggests that these may be cases where corruption of the optical signal by volcanic material was minimized, and the IMI response is predominantly biological in nature. The lack of pumice rafts is consistent with these three volcanoes being basaltic. While basaltic pumice can be formed, it is less likely to do so than dacite, which has a greater percentage of volatile gases in its magma (*Unnamed 0403-091* and *Home Reef* both released dacitic pumice rafts (Bryan et al., 2004; Mantas et al., 2011)).

For deeper volcanoes, including the three shown in Figure 5, we propose that biological response drives the IMI values, with the influence of ejected optical contaminants diminishing with increasing depth of eruption. We also propose that the biological changes are responding to dissolved micro- and macro-nutrients via the eruption, along with nutrients delivered from below the nitrocline through the process of volcanogenic upwelling (Vogt, 1989), where the nitrocline defines the base of the nutrient-depleted surface waters and the top of the nutrient-rich deep waters. It is possible that the upwelled nutrients are actually dominating the response, rather than the specific chemicals vented by the eruption.

We note that while a submarine volcano injects solids and dissolved nutrients into the water surrounding its summit, it may also introduce substances that are not beneficial to photosynthetic biology (e.g., H_2S, CO, SO_2, SO_3, HCl, and HF) (Vogt, 1989). By defining the probability measures in terms of changes which are “met or exceeded”, we have focused upon the apparent positive responses within the plankton community, not the detrimental. Any inhibiting impacts of the eruption will either act to dampen the magnitude of the observed enhancement or, if dominant, will result in mapped IMI values between 0 and 1.2 (these would be seen as dark blue pixels in our mapped products).

Consider again alternative explanations for the source of IMI increases shown in Figure 5. We must now look for processes that can drive biological changes over larger areas. Topographic upwelling would impact IMI values associated with seamount positions, but again it is difficult to imagine such processes having an impact away from the seamounts. Large frontal systems coming into the area could produce IMI changes, but would likely be associated with large scale sea surface temperature gradients as well. Another possibility is eddy systems moving through the area, which can be examined using sea surface temperature and sea surface height data. There is also the potential for temperature-induced increases in growth rates following eruptions even if nutrient conditions remain unchanged. For the test cases shown in Figure 5, it was known *a priori* that a volcanic event had taken place. If instead we only had the before and after maps shown in Figure 5, a detailed examination of alternative sources for IMI extremes would have been warranted.

In examination of our IMI images, it is also important to consider possible errors introduced as a result of using 8-day averages with cloud-filled data. These data allow for very straight-forward calculations of the derivatives and the probabilities involved, but caution must be applied. If cloud cover is sparse, then the search for nearest neighbors would fill in missing pixels with very local, average properties. As missing data area expands, however, a point is reached where the search distance exceeds the spatial correlation distance of the data (which varies from location to location). Similarly searches in time can exceed the point where the temporal correlation distance is exceeded. In those cases of extensive cloud cover with long duration, the filled data will not have local statistical properties, potentially resulting in unusually high IMI values. Any case showing extensive, high IMI results should also be examined for the presence and duration of cloud cover in the original, 8-day files. The volcanic events selected for this study (Table 1) avoided cases where cloud cover was problematic.

The evaluation of IMI responses to very deep volcanic eruptions is currently restricted by the small number of such events with well-known eruption times. The *Axial Seamount* events off the Oregon coast (January 25, 1998, and April 6, 2012) provide two possible opportunities for investigation, but extensive cloud cover in each case excluded map analysis. Nevertheless, the expectation is that an eruption plume penetrating the surface mixed layer zone from great depths is unlikely, due to the very large transfer of heat required (Speer, 1997). However, there have been reports of surface manifestations from the *South Sarigan Seamount* eruption of 2010 (Venzke et al., 2010, and McGimsey et al, 2010), where an eruption from ~200 m depth resulted in steam and ash venting into the atmosphere, along with observations of extensive pumice rafts from the deep (~1500 m caldera, -720 m summit) *Havre Seamount* eruption in 2012 (Wunderman et al., 2012). Both of these events yielded unusual surface displays from eruptions at significant depth, implying that IMI signatures may be produced by at least some deep events; in the first case by a clear breach into the surface mixed layer zone and in the second via pumice rafts and other volcanic contaminants to the optical signal.

5. Conclusions

Our aim in this study was to create a remote-sensing based index for detecting surface expressions of known submarine volcanic eruptions by seeking improbable increases in chl and b_{bp} following each event. With a test set of five known eruption locations and times, we were able to identify a pattern of IMI responses that contrast before versus after images. The spatial extent of the changes observed in chl and b_{bp} appeared to be on the order of thousands of square kilometers, expressing a maximum ocean surface response approximately within one to two weeks after the initial eruption onset. The presence of volcanic contaminants in the water (pumice rafts, ash, and discolored water) enhances our ability to detect events, as they translate directly into improbable increases in chl and b_{bp} relative to the satellite baseline history. In those cases where volcanic contaminants are possibly missing, we are left with biological responses to the submarine eruption driving the changes seen in the IMI maps. Volcanogenic upwelling of deep nutrient-rich water to the surface is suggested as a potential process influencing the biological component of the IMI response for submarine volcanic events, although micro- and macro-nutrients may also be delivered directly by the eruption proper. By tuning the IMI specifically to increases in chl and b_{bp}, we were able to detect both real biological responses to the eruptions and the apparent changes due to volcanic contaminants. This combination leads to a potentially robust method for detection of new events in remote locations, offering candidates for subsequent high resolution analysis.

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Figure Legends

Figure 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.

Figure 2: Probability calculations. (a) With two different satellite based measurements (chl and b_{bp}) and two different derivatives (temporal and spatial), there are four different variables for the probability calculations: $A = d(chl)/dt$; $B = d(b_{bp})/dt$; $C = \nabla(chl)$; and $D = \nabla(b_{bp})$. (b) If each variable is independent, we can calculate the joint probability by multiplying their individual empirical probabilities together. (c) If we take into account the possibility that chl and b_{bp} may not be independent, then we must consider this usage of conditional probabilities. This is the approach used in this analysis.

Figure 3: Satellite-detected responses to a near-surface underwater volcanic eruption from unnamed volcano 0403-091 in the Tonga region (Table 1, Unnamed, depth = 40 m). Time-series of (a) chlorophyll (mg chl m^{-3}), (b) backscatter (m^{-1}) and (c) Improbability Mapping Index (IMI). Here, all three properties in a – c show a clear response to the eruption. The

nine traces in each time-series are taken from the 9 pixels centered over the summit and are based on 8-day resolution satellite data. The vertical red line identifies the day of the eruption onset and the green box its reported duration, while the cyan lines indicate the days contributing to the averaged 8-day period overlapping the eruption onset. The days indicated in the time axis denote the mid point of the 8-day averages. The thick horizontal red line in panel c represents the IMI baseline (= $-\log10[(.5)^4]$) and is an approximation for 'average' observed change. (d) Time-series of two-dimensional map views of IMI for a 2° by 2° area (17.5 to 19.5 S latitude; 174.75 to 172.75 W longitude) encompassing the volcano. Panels from left to right represent sequential 8-day averages, with the 'before', 'during', and 'after' lines connecting panel c to the maps in panel d. The '+3 on the 'during' map indicates that the eruption was in progress for at most the last 3 days of the 8-day averaging period. Small white boxes in each panel of d shows the 3x3 grid of pixels over the summit used for the time-series plots (a-c); the black box SE of the summit indicates an area of 'no data' off a small island.

Figure 4: Improbability mapping responses to the (near-surface) *Home Reef* submarine volcanic eruption in the Tonga region (Table 1, Home Reef, depth = 10 m). Time-series of (a) Improbability Mapping Index (IMI) and (b) the associated two-dimensional map views for a 2° by 2° area (18.0 to 20.0 S latitude; 175.8 to 173.8 W longitude). The IMI time-series and maps as in figure 3. This was a very strong and well documented event, and the 'during +6' map indicates the likely advection of affected waters away from the summit in the six days that were available, and is consistent with the delayed response over the summit shown in the

time-series.

Figure 5: Satellite-detected responses to three deeper volcanic eruptions (Ahyi, Monowai, and Kick'em Jenny, Table 1, depths = 132-185 m). Time-series of two-dimensional map views of IMI for 2° by 2° areas encompassing each volcano. Left-hand and right-hand maps correspond to approximately 8 days before and after the eruption, respectively. The 9 pixels surrounding each summit are indicated by the white outlined boxes. The dark black circles have a radius of approximately 50 km, and are intended to suggest the most affected regions. Solid black squares for *Kick'em Jenny* correspond to islands. (d – f) IMI time series for the nine pixels surrounding each summit. Vertical red and cyan lines and horizontal red line as in figure 3. Horizontal green bar indicates duration of eruption.