Sadie Cwikiel
ESS 141: Remote Sensing of Oceans
Professor Kevin Arrigo
21 March 2018

Island Mass Effect and El Niño in the Northwestern Hawaiian Islands

Abstract

The island mass effect (IME) is the combination of many factors that increase nutrients near islands in otherwise oligotrophic waters, including vertical mixing, upwelling, runoff, and atoll flushing. In the vast majority of islands in the Pacific Ocean, chlorophyll-*a* concentrations increase with decreased distance from an island. In this study, the IME in the Northwestern Hawaiian Islands (NWHI) is compared to sea surface temperature (SST) changes as a result of the 2015-2016 El Niño event. Using remotely sensed monthly averages of chlorophyll-*a* and SST from 2014-2016, IME was calculated as the difference between near-island and far from island chlorophyll-*a* concentrations and compared to SST. It is apparent that the IME had a strong influence in the NWHI because for all months, the near-island chlorophyll-*a* concentrations are higher than the far from island concentrations. The maximums in strength of IME – not necessarily the highest chlorophyll-*a* concentrations – correlated with the maximums in SST. This indicates that the IME could have the most influence at higher SST. Other possible significant confounding factors not analyzed in this study include runoff due to increased precipitation and atoll flushing due to internal waves.

Introduction

It is hard to find vast communities of life thriving in the open ocean. However, the majority of remote islands are surrounded by an abundance of phytoplankton and lush coral reefs. When approaching continental margins, phytoplankton concentrations increase due to upwelling, nutrient rich runoff, and variations in salinity and other characteristics of particular waters (Doty & Oguri 1956). This increase in phytoplankton also exists when approaching island shores, but there are most likely additional explanations for this increase (Doty & Oguri 1956).

Why does an increase in phytoplankton occur around islands in the middle of oligotrophic tropical waters? Charles Darwin first pondered this phenomenon in his book *The Structure and Distribution of Coral Reefs* in response to the lush marine life around the Galapagos Islands (Sue 2016). "Darwin's Paradox" was not explained until the 1950s, when the enhancement of phytoplankton close to remote islands was described as the island mass effect (IME). Multiple factors work together near islands to reinforce each other and create positive feedback systems that retain and accumulate nutrients required to support phytoplankton and coral reefs (Fitch 2016). These factors – including anthropogenic impacts, upwelling, shape and size of the island or atoll, bathymetry, reef size and type, and runoff – impact the amount of phytoplankton surrounding islands (Fig. 1).

IME is quantified as the relationship between sea surface chlorophyll-*a* concentration and distance to the nearest island (Dandonneau & Charpy 1985). This phenomenon makes life in coral reefs possible, and can increase the near shore phytoplankton biomass by up to 86% compared to background oceanic conditions (Gove et al. 2016). In 2016, a NOAA study found that IME is a nearly ubiquitous feature among 91% of surveyed coral reef ecosystems across the central and western Pacific (Gove et al. 2016).

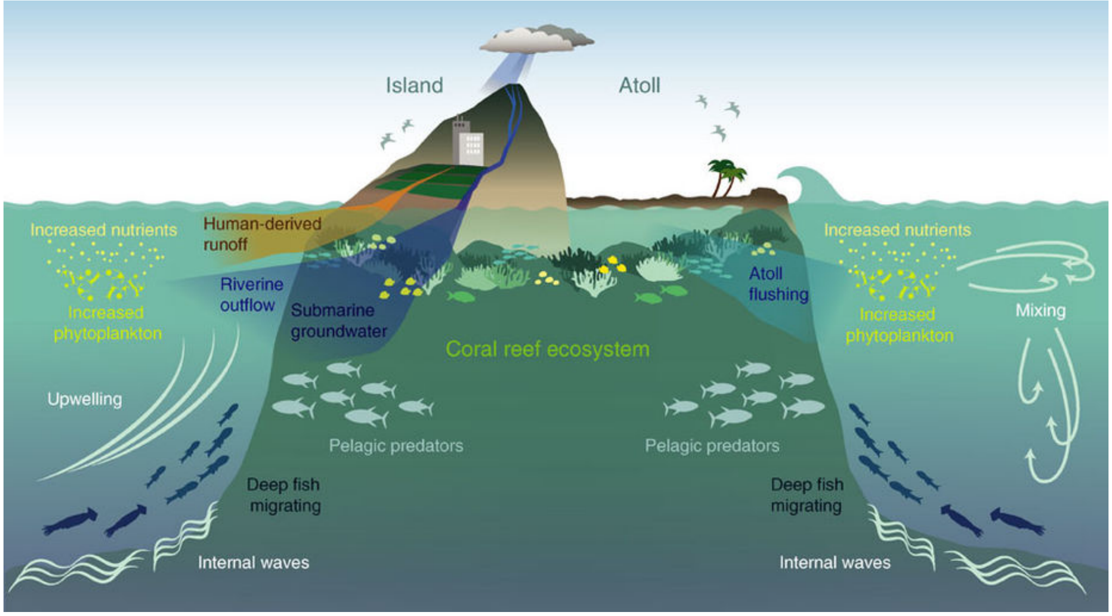


Fig. 1: The Island Mass Effect (Gove et al. 2016)

Doty and Oguri (1956) first attempted to explain the shoreward increase in phytoplankton productivity when approaching islands, even in areas with less vertical mixing than near continental margins, less runoff around low islands, and less percolated groundwater entering the system (Doty & Oguri 1956). One explanation of the IME that they suggested was that benthic algae in reef margins accumulate nutrients from the nutrient-poor waters passing by, materials from leaching of the freshwater lens, and from any runoff there may be. One way that these nutrients then become available to planktonic forms is through the consumption and excretion of the algae by benthotrophic herbivores (Doty & Oguri 1956). A 1985 study in the south tropical Pacific also agrees that a dominant process contributing to the IME could be predation by coral reef benthic communities (Dandonneau & Charpy 1985).

Another study conducted in Barbados in 1981 suggests that internal waves greatly contribute to the observed characteristics of IME, namely high levels of the standing crop of phytoplankton and increased primary production (Sander 1981). Internal waves are a dominant phenomenon that allow vertical mixing and input of nutrients from deep water into the surface mixed layer, even when continental upwelling is not occurring (Dandonneau & Charpy 1985). Wave forcing also causes atoll flushing, which is an efficient and rapid mobilization of material and nutrients out of an atoll, providing increased nutrients that could enhance near shore chlorophyll-*a* concentrations (Gove et al. 2016).

Northwestern Hawaiian Islands

In this study, I focus on investigating the island mass effect in the islands and atolls of the Northwestern Hawaiian Islands (NWHI). The NWHI span across the Pacific Ocean and connect the main Hawaiian Islands to the rest of the Emperor Seamount Chain. The chain consists of small islands and atolls that stretch for more than 1,000 nautical miles northwest of Hawaii. The area is home to some of the world's last pristine coral reef areas, and about 70% of coral reefs within United States waters are in the NWHI ("Northwestern Hawaiian Islands"). In 2006, the Papahānaumokuākea Marine National Monument encompassing the area was established, and it was expanded in 2016 ("Ko Hawai'i Pae 'Aina - Hawaiian Archipelago"). It is now one of the largest marine conservation areas in the world and is larger than all other U.S. national parks combined (Fig. 2).

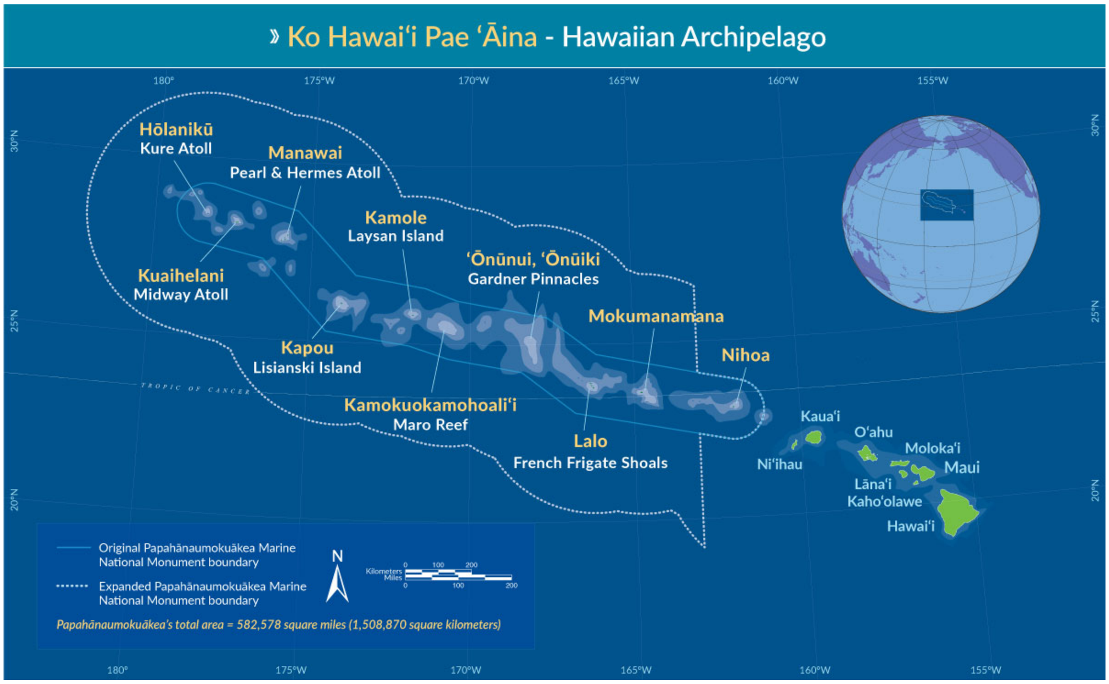


Fig. 2: Papahānaumokuākea Marine National Monument boundaries ("About Papahānaumokuākea")

Over 7,000 marine species live in the coral reefs within the conservation area, one quarter of which are endemic. 22 species of seabirds breed and nest there, 4 of which are endemic. It is also home to the endangered Hawaiian monk seal (“About Papahānaumokuākea”). The NWHI consist of important and irreplaceable habitat home to species found nowhere else in the world (“About Papahānaumokuākea”).

The NWHI are within the trade wind zone of the tropical Pacific. Seasonal changes of surface properties are relatively small (Gilmartin & Revelante 1974). The oceanic regions surrounding the NWHI and main Hawaiian Islands are relatively biologically barren with low primary production rates and small phytoplankton standing crops (Gilmartin & Revelante 1974). The chain forms a barrier across the westerly ocean currents, and channels between the larger islands provide for flow of large volumes of water, generating turbulence and eddies on leeward sides of the islands (Gilmartin & Revelante 1974). The rich volcanic soil of the islands, including those in the NWHI, would contribute to nutrient rich runoff. In a 1974 study of the IME of the main Hawaiian Islands, primary production values within 1 km of the shore were consistently higher than offshore values. Inshore areas had standing crops about twice as large as offshore, and rates of primary production were 4-5 times larger (Gilmartin & Revelante 1974).

Chlorophyll-a Concentrations and Sea Surface Temperature

Dandonneau and Charpy (1985) found that large-scale climatic features might give more variance to chlorophyll-*a* values than the presence or absence of islands. To investigate the relationship between the IME and climate forcing, I compared chlorophyll-*a* concentrations and sea surface temperature (SST) in the area surrounding the NWHI over a three-year period of time encompassing the El Niño event of 2015-2016.

In many previous studies, phytoplankton growth seems to be mostly influenced by nutrient limitation and light limitation rather than temperature (Eppley 1972). In some lab experiments however, low temperature promoted an increased assimilation (rate of photosynthetic carbon assimilation per weight of chlorophyll-*a*), which is related to the growth rate and chlorophyll-*a*:carbon ratio. This relationship was more difficult to measure in nature (Eppley 1972). Another study showed that cells require more nutrients as temperature decreases, but cell quotas and chlorophyll-*a* concentration of nutrient-sufficient cultures increased with decreasing temperature (Rhee 1981). In some cases, the degree of food limitation increased with increasing temperature (Hirst & Bunker 2003).

There was also a study conducted between 1968 and 1987 that suggests a correlation between chlorophyll-*a* concentrations and temperature across the central North Pacific Ocean. Over that period of time, a long-term sustained increase in chlorophyll-*a* was coupled with a decrease in SST (Venrick 1987). The increase in chlorophyll-*a* observed could represent an increase in organic carbon over a large area of the Pacific, and environmental fluctuations largely controlled by atmospheric forcing could have resulted in long-term changes in the carrying capacity of the surface water ecosystem (Venrick 1987). Upon review of the relevant literature, it seems as if there is variation in findings of the relationship between chlorophyll-*a* concentrations, phytoplankton growth and productivity, and SST, and it is likely that many other factors not included in this study have greater influence on IME.

Effects of El Niño in Hawaii

The main objective of this study is to investigate whether increased SST have an influence on the IME in the NWHI. One of the biggest impacts on SST in the central Pacific Ocean is El Niño, the response of the equatorial Pacific to atmospheric forcing (Wyrtki 1975). El

Niño events occur after strong southeast winds in the central Pacific intensify the Pacific gyres, increasing the sea level in the western equatorial Pacific (Wyrtki 1975). When these excessively strong southeast trade winds relax, the water that accumulated in the western Pacific flows back eastward, causing increased sea surface and subsurface temperatures in the central and eastern Pacific Ocean, as well as a depression of the thermocline (Wyrtki 1975). Because the western warm pool that is usually pushed towards the western part of the Pacific basin shifts towards the central and eastern Pacific, El Niño years are characterized by warmer than normal waters and heavier precipitation in the tropical central and eastern Pacific (Fig. 3).

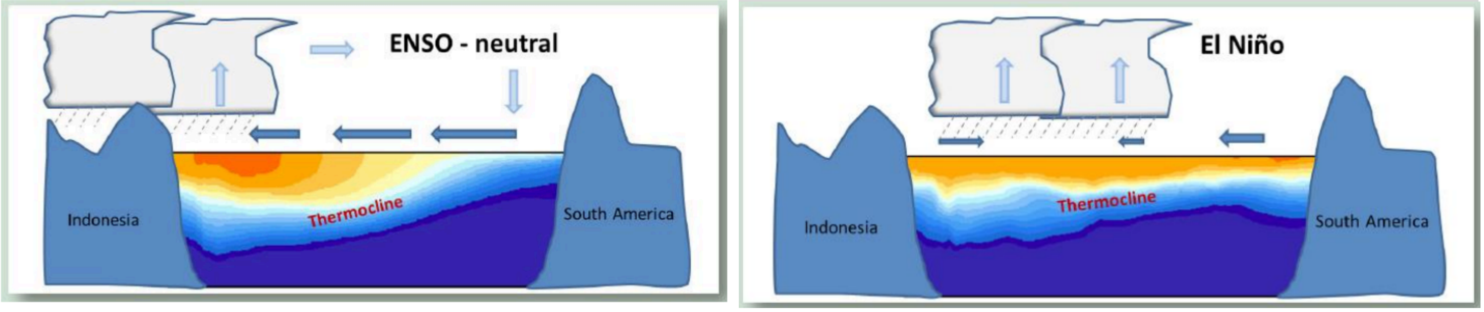


Fig. 3: ENSO-Neutral vs. El Niño conditions (“El Nino and Its Impacts on The Hawaiian Islands”)

In the area surrounding Hawaii, El Niño causes increased precipitation and a higher number of tropical cyclones. Sea levels are near or slightly higher than normal. Sea surface and subsurface temperatures increase (“El Nino and Its Impacts on The Hawaiian Islands”). The most recent El Niño event occurred in 2015 and 2016, and this is the El Niño time period studied here. According to measurements based on the Oceanic Niño Index, 2015 and 2016 were characterized by very strong El Niño events (Fig. 4). 2014 was a weak La Niña year, or conditions close to normal. Because of this, it is logical to assume that SST and precipitation in Hawaii would be higher during 2015 and 2016.

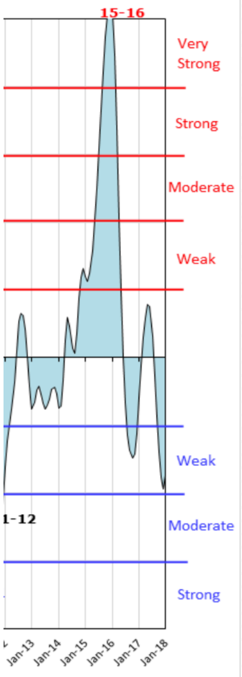


Fig. 4: El Niño strength based on Oceanic Niño Index (“El Nino and Its Impacts on The Hawaiian Islands”)

Hypothesis

I hypothesize that the IME will have an influence on chlorophyll-*a* concentrations in the NWHI, and near-island chlorophyll-*a* concentrations will be higher than far from island concentrations. Because the 2015 and 2016 El Niño events were so strong, I expect these years to have higher SST and a subsequent impact on decreased productivity measured by chlorophyll-*a* concentrations. Because vertical mixing and upwelling is usually correlated with higher productivity, I predict that this will be indicated by colder SST and will correspond with higher chlorophyll-*a* concentrations. Therefore, warmer temperatures will correspond with lower chlorophyll-*a* concentrations. I also predict that runoff and atoll flushing will have significant impacts on near-island chlorophyll-*a*, but these variables will be hard to distinguish in the data analyzed.

Methods

In order to measure chlorophyll-*a* concentrations and SST, I used remote sensing data found on the Ocean Color Web database. All data were Level 3 monthly averages, 4 km resolution, from the Aqua MODIS satellite. For chlorophyll-*a* specifically, the data was from Aqua MODIS Chlorophyll Concentration, OCI Algorithm monthly averages for 2014, 2015, and 2016 for a total of 36 images (Appendices 1, 2, & 3). For SST specifically, the data was from Aqua MODIS Monthly Sea Surface Temperature (11 μ nighttime) monthly averages for January, April, July, and October for 2014, 2015, and 2016 for a total of 12 images (Appendix 4).

Each image was cropped in the SeaDAS program onto an area confined by the coordinates 34.208° N, 178.917°W, 13.583°N, and 151.458° W, encompassing the main Hawaiian Islands and the Northwestern Hawaiian Islands. To export data for chlorophyll-*a* both at or near the islands and atolls and in the surrounding waters, two polygons were created in

SeaDAS (Fig. 5). There were seven major areas of higher chlorophyll-*a* concentrations identified by visual inspection, and these served as the "near-island" polygon (green circles in Fig. 5). The "far from island" polygon consisted of surrounding areas on all sides of the islands and atolls (purple circles on Fig. 5).

The median chlorophyll-*a* value was used from each monthly average for each polygon. The same polygons were used to extract SST data from the image. For analysis of SST, the mean temperature for both polygons was used because there was no noticeable temperature difference between the near-island and far from island measurements.

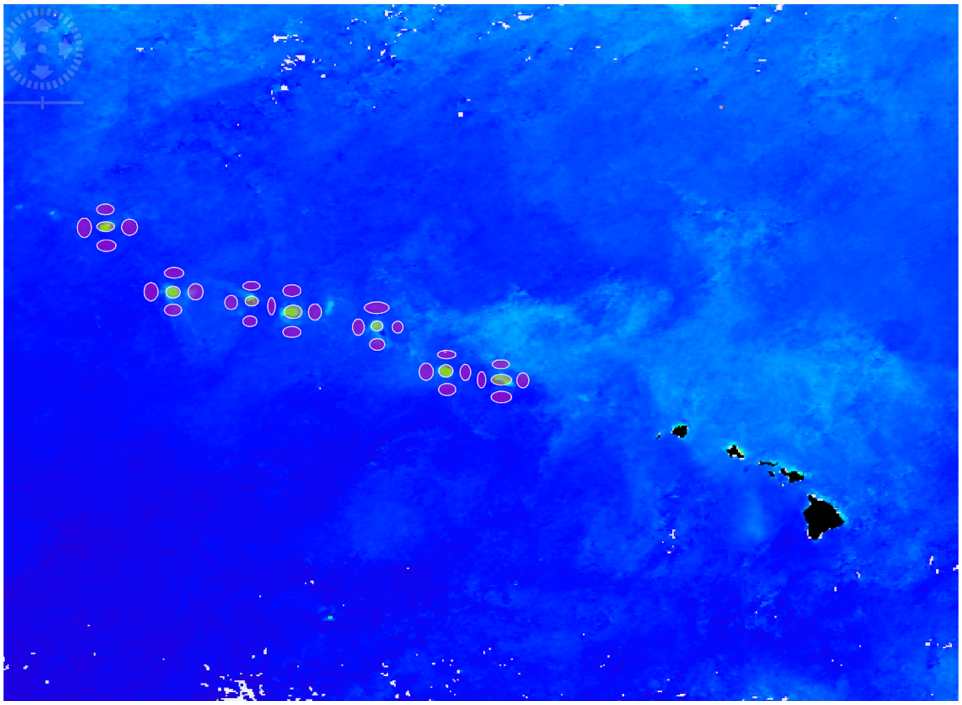


Fig. 5: Near-island (green) and far from island (purple) polygons in SeaDAS

Results

For all monthly averages from 2014-2016, the near-island chlorophyll-*a* concentrations were higher than the far from island concentrations (Fig. 6). This is evidence that the island mass effect does in fact impact chlorophyll-*a*, and therefore phytoplankton activity, in the Northwestern Hawaiian Islands.

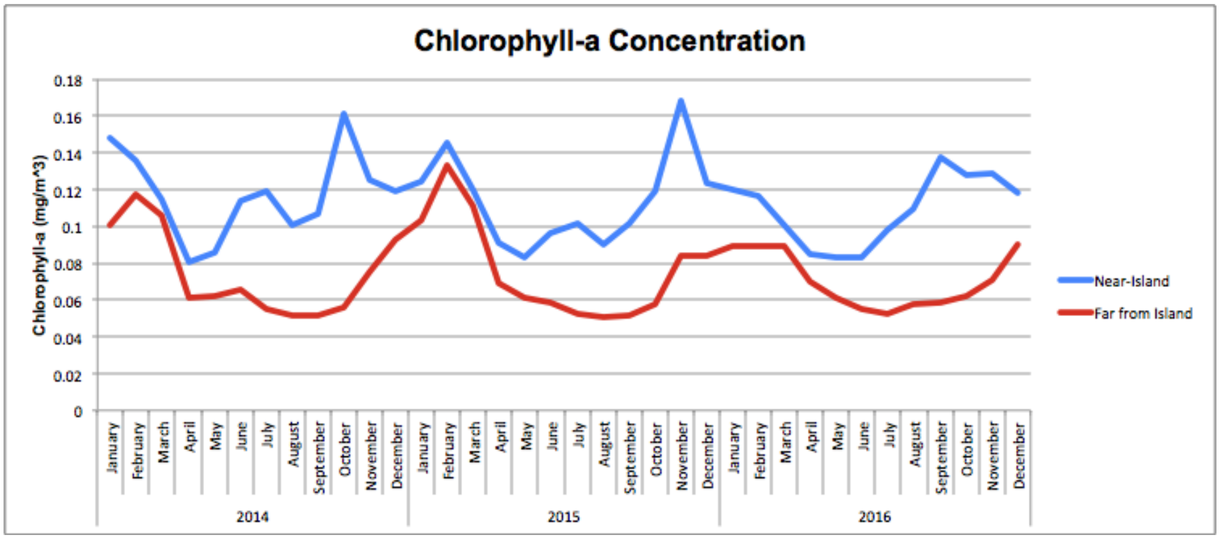


Fig. 6

The highest concentrations for the near-island chlorophyll-*a* concentrations, around 1.16 mg/m^3, consistently occur during the fall months. On the other hand, the highest concentrations for the far from island chlorophyll-*a* concentrations, ranging from 0.09 to 1.13 mg/m^3, peaked during the early spring months. There is a decrease in the highest value for near-island values in 2016, from 0.17 mg/m^3 in 2015 to 0.14 mg/m^3 in 2016. 2016 is the year when the El Niño event was supposedly strongest (Fig. 4). The highest peak in far from island chlorophyll-*a* occurred in 2015 at 0.13 mg/m^3 in February, was second highest in 2014 at 0.12 mg/m^3 in February, and lower in 2016 at 0.089 mg/m^3 in March. The lowest values for both near (0.08 mg/m^3) and far from island (0.05 mg/m^3) stay consistent from year to year, even though the maximum values decline in 2016. In March 2015, there is an anomalous peak in the near-island chlorophyll-*a* concentration at 0.15 mg/m^3 that coincides with the peak in far from island concentrations. This could have potentially been caused by another factor that occurred at this time, seeing as this peak of near-island concentration does not occur in March of 2014 or 2016.

The difference between the near-island and far from island chlorophyll-*a* concentrations was used as a way to quantify the IME. Because the near-island was always a higher value than the far from island value for all months sampled, it was possible to subtract the far from island from the near-island value. The difference between the near and far from island chlorophyll-*a* concentrations peaked in the fall, the same months where the near-island concentrations peaked. The minimum difference was in March for all three years. This was around the same time of year when the far from island concentrations peaked (Fig. 7).

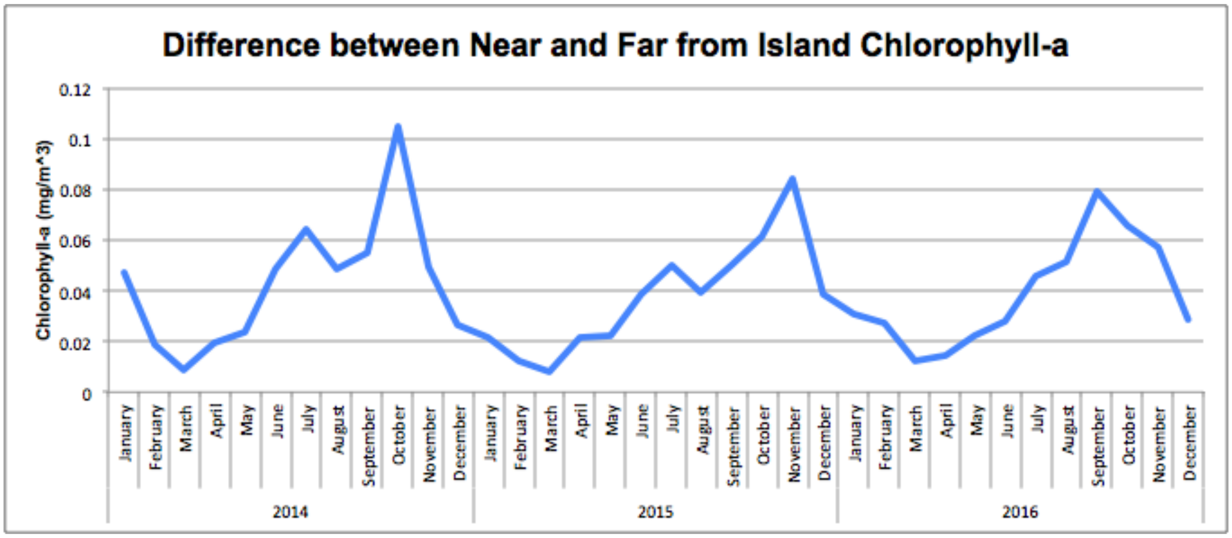


Fig. 7

The highest value of difference in near and far from island chlorophyll-*a* concentrations declines each year, peaking highest in October of 2014. The maximum in 2015 occurs in November, slightly lower than 2014. The 2016 maximum value is in September, again slightly lower. The minimum values – in March for each year – increase slightly each year.

The SST monthly averages from January, April, July, and October from 2014-2016 varied greatly, the maximum in October each year and the minimum in April (Fig. 8). Despite the fact that the El Niño event during this time period was supposedly strongest in 2016, the highest temperature was in October of 2014 at 28°C. The October 2015 temperature was 26.6°C and the October 2016 temperature was 27.1°C. The remotely sensed SST data does not correlate completely with the expectations of increasing SST due to the strong El Niño in 2016. The minimum temperatures in April of each year do not vary as much as the October maximums, only ranging from 22.3°C – 22.5°C.

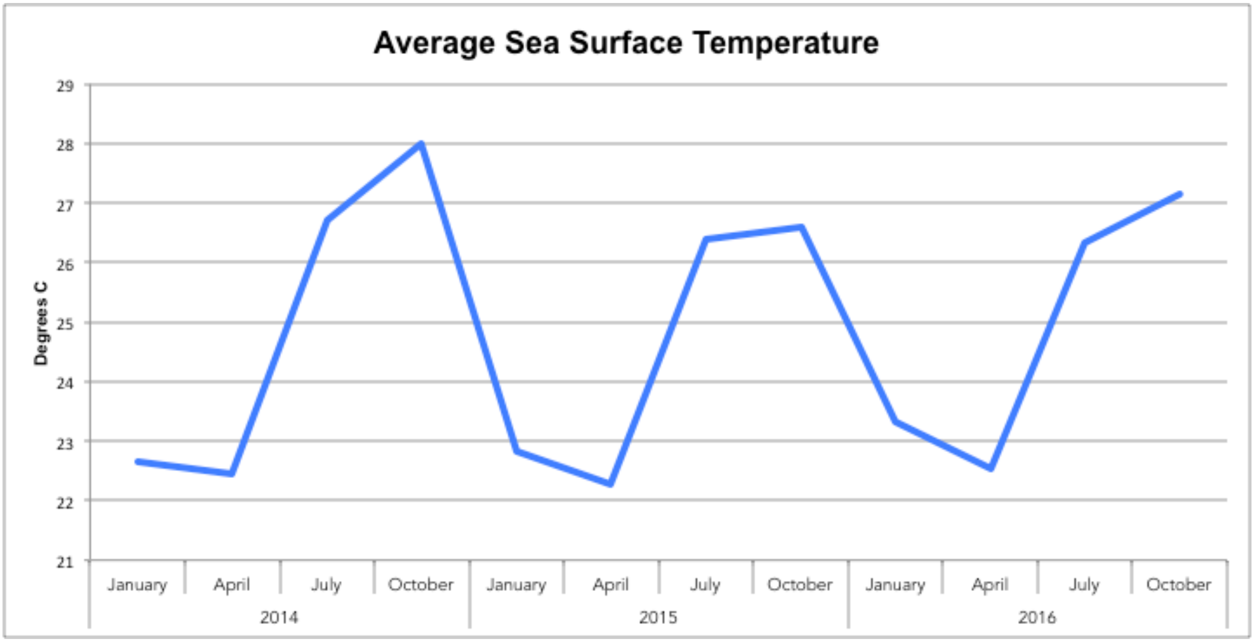


Fig. 8

When comparing the chlorophyll-*a* concentrations for both the near-island and far from island measurements to SST, there are some interesting patterns and correlations. Upon visual investigation, the highest SST values correlate with the minimum far from island concentrations and the maximum near-island concentrations (Fig. 9).

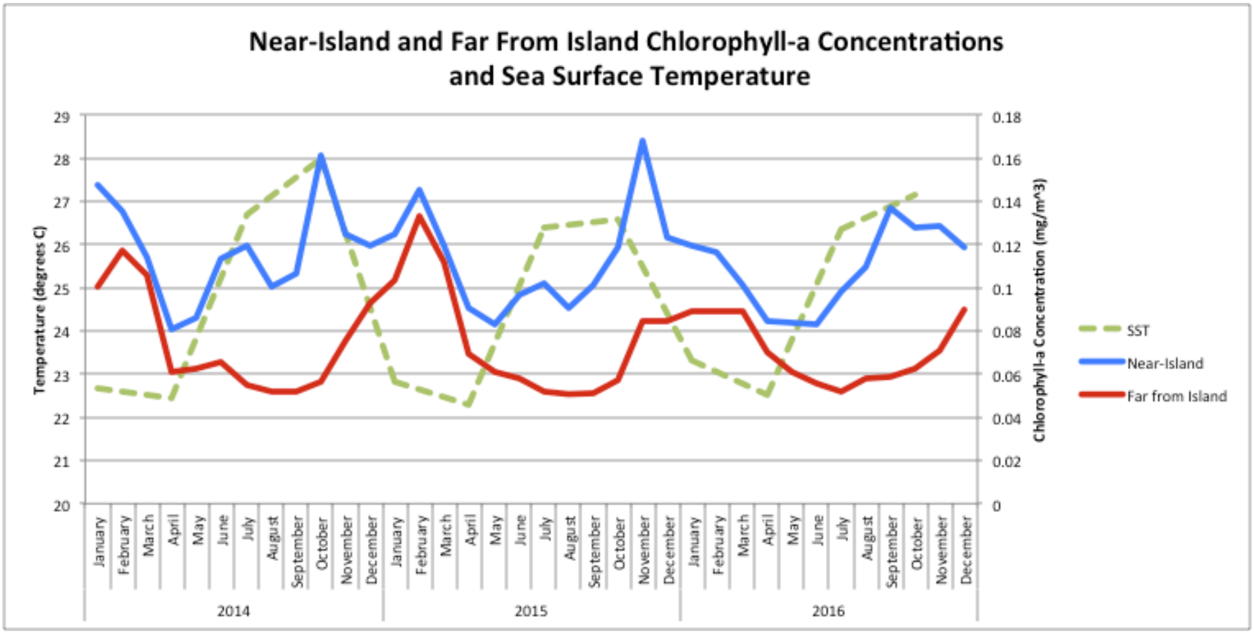


Fig. 9

It is possible that this indicates that lower SST values correlate with increased vertical mixing of colder, deep nutrient-rich water with surface water. This would increase available nutrients at the surface for phytoplankton. The start of the rainy season in fall through the colder winter months could have resulted in increased runoff and contributed to increased near-island chlorophyll-*a* concentrations (Timm & Diaz 2009).

There is a positive correlation between the highest values of the difference between near-island and far from island chlorophyll-*a* concentrations and the highest SST for all three years (Fig. 10). This could imply that the island mass effect has the strongest influence on phytoplankton activity at higher temperatures during the end of the dry summer months before the transition to the rainy season.

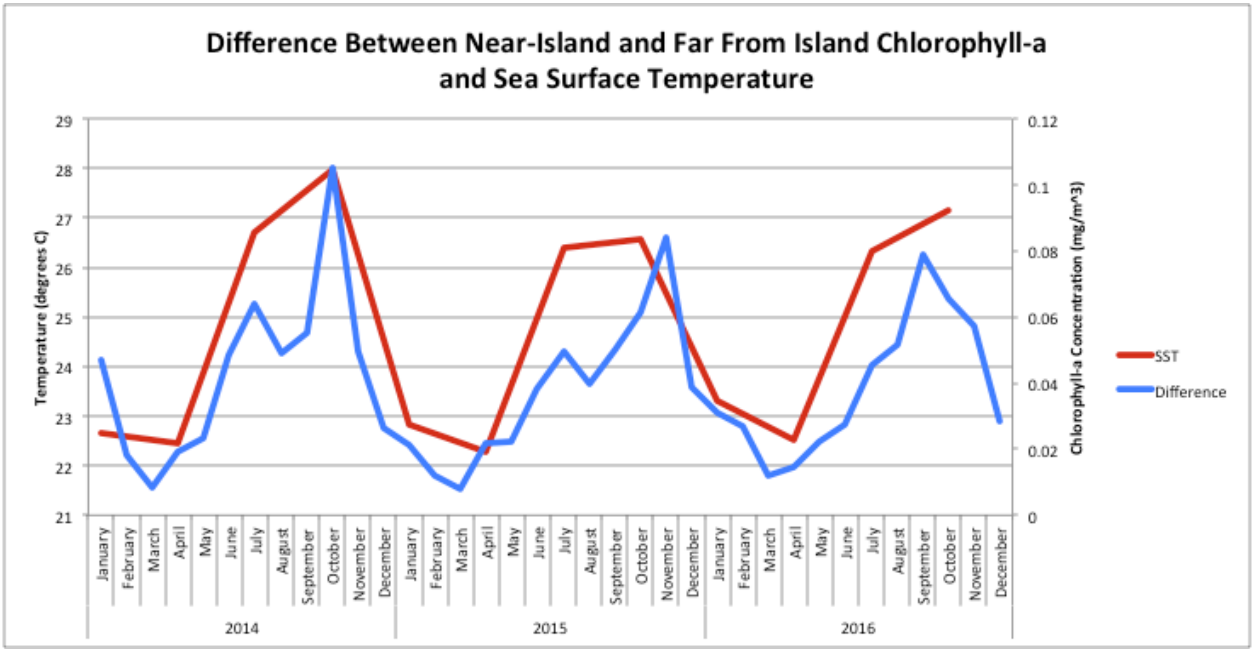


Fig. 10

Discussion

Based on these results, it is possible that the IME has a stronger influence at higher SST in the NWHI. It is important to note that the highest productivity, indicated by the highest chlorophyll-*a* values, was not necessarily at the times of stronger IME or higher SST. In fact, the far from island chlorophyll-*a* concentration was lowest at higher temperatures, probably an indication of reduced vertical mixing of colder, nutrient-rich waters. However, because the difference between the near-island and far from island concentrations occurred at higher temperatures, this is when the IME had the most impact.

Because higher productivity usually coincides with the upwelling of cold, deep, nutrient-rich water, or vertical mixing of deep channels, it makes sense that the far from island waters would be less productive when it is warmer in the fall, signaling a decrease in vertical mixing (Gilmartin & Revelante 1974). Other factors that probably influenced the phytoplankton abundance and activity at the islands and atolls are precipitation and runoff. Increased precipitation would increase runoff and nutrient inputs near the islands, increasing chlorophyll-*a* concentrations. Largely controlled by trade winds, Hawaii's rainfall is heavier during the winter months throughout the islands, and the rainy season starts near the end of the fall (Timm & Diaz 2009). The beginning of the rainy season is the time of year when near-island chlorophyll-*a* concentrations and the IME peak, indicating that runoff could have an effect on the productivity near the islands. This increased runoff probably would not have an impact on the far from island chlorophyll-*a* concentrations, contributing to the higher values of IME.

With the data available, it is difficult to identify which factor influences IME most strongly. Runoff would not have as large of an impact on lower lying islands or atolls (Dandonneau & Charpy 1985). Atoll flushing due to internal wave flushing is more influential in the atolls rather than islands of the NWHI, and this is an efficient process of moving detritus and other sources of nutrients out of the atoll and into other areas of reef surrounding it, enhancing near shore phytoplankton biomass (Gove et al. 2016). The IME is subject to many different interactions between many different factors. The findings of this study could indicate that as global ocean temperatures rise, the IME could have a stronger influence on the primary productivity near islands even if productivity farther away from islands does not increase. However, it is important to consider all of the confounding factors that influence IME not taken into account in this study.

Future Work

There are many ways to improve this study. All results and conclusions are drawn based on visual interpretation and were not analyzed statistically. Statistical analysis would improve the certainty at which conclusions are drawn. Strong correlations are visible from the original remote sensing images and the graphs of the data, but it is hard to say if the differences in values or correlations are statistically significant.

In the future with more time to expand the study, it would be useful to have monthly averages for all 12 months each year for SST. The maximums and minimums of SST could have been slightly different if data was collected for each month, and the correlation with the chlorophyll-*a* concentrations could have varied in strength or timing. It would also be meaningful to look at data and images for a longer period of time through multiple El Niño and La Niña cycles. A wider range of SST and chlorophyll-*a* patterns would help in parsing out the relationship between the IME and SST.

Additionally, because the size and shape of an island or atoll influences the IME, it would be very interesting to look at each of the seven islands or atolls separately. It would be meaningful to compare the size, shape, and bathymetry of the islands and atolls to separate near-island and far from island chlorophyll-*a* data for each. This would be an effective way to compare IME with possible runoff and atoll flushing influences in addition to temperature.

Conclusions

Even though it is hard to say which variables are most important when considering the IME, this study indicates that SST and seasonal variations in temperature do influence the difference between chlorophyll-*a* concentrations at the near-island and far from island locations. While it is unclear whether SST changes caused by El Niño have a significant impact on chlorophyll-*a* concentrations, it is possible that the IME has a stronger effect at higher SST. The IME is important when thinking about coral reef health and coastal productivity now and in a future changing climate, and it is clear from this study that chlorophyll-*a* concentration in the Northwestern Hawaiian Islands is influenced by the island mass effect.

References

"About Papahānaumokuākea." *Papahānaumokuākea Marine National Monument*, 2017, www.papahanaumokuakea.gov/new-about/.

"El Nino and Its Impacts on The Hawaiian Islands." Pacific Region Climate Office, NOAA. https://www.pacificrisa.org/wp-content/uploads/2015/11/Pacific-Region-EL-NINO-Fact-Sheet_Hawaii_2015-FINAL.pdf

"Ko Hawai'i Pae 'Aina - Hawaiian Archipelago." *Papahanaumokuakea Marine National Monument*, 2018, www.papahanaumokuakea.gov/.

"Northwest Hawaiian Islands." *Pacific Islands Benthic Habitat Mapping Center*, www.soest.hawaii.edu/pibhmc/cms/data-by-location/northwest-hawaiian-islands/.

"Northwestern Hawaiian Islands." Ocean Explorer, NOAA, 2010, oceanexplorer.noaa.gov/explorations/02hawaii/welcome.html.

Dandonneau, Yves, and Loïc Charpy. "An empirical approach to the island mass effect in the south tropical Pacific based on sea surface chlorophyll concentrations." *Deep Sea Research Part A. Oceanographic Research Papers* 32.6 (1985): 707-721.

Doty, Maxwell S., and Mikihiko Oguri. "The island mass effect." *ICES Journal of Marine Science* 22.1 (1956): 33-37.

El Nino and La Nina Years and Intensities, Feb. 2018, ggweather.com/enso/oni.htm.

Eppley, Richard W. "Temperature and phytoplankton growth in the sea." *Fish. bull* 70.4 (1972): 1063-1085.

Fitch, Chris. "Solving 'Darwin's Paradox' ." *Geographical Magazine*, Geographical, Apr. 2016, geographical.co.uk/nature/oceans/item/1605-solving-darwin-s-paradox.

Gilmartin, Malvern, and Noelia Revelante. "The ‘island mass’ effect on the phytoplankton and primary production of the Hawaiian Islands." *Journal of Experimental Marine Biology and Ecology* 16.2 (1974): 181-204.

Gove, Jamison M., et al. "Near-island biological hotspots in barren ocean basins." *Nature communications* 7 (2016): 10581.

Hirst, A. G., and A. J. Bunker. "Growth of marine planktonic copepods: global rates and patterns in relation to chlorophyll a, temperature, and body weight." *Limnology and Oceanography* 48.5 (2003): 1988-2010.

Rhee, G., and Ivan J. Gotham. "The effect of environmental factors on phytoplankton growth: temperature and the interactions of temperature with nutrient limitation." *Limnology and Oceanography* 26.4 (1981): 635-648.

Sander, F. "A preliminary assessment of the main causative mechanisms of the “island mass” effect of Barbados." *Marine Biology* 64.2 (1981): 199-205.

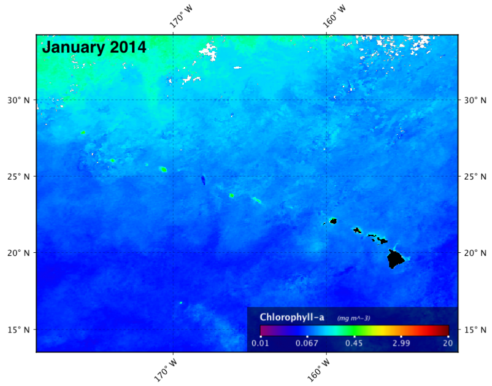
Sue, Cary L. “Scientists Solve 'Darwin's Paradox'.” *Nat Geo Education Blog*, 17 Apr. 2016, blog.education.nationalgeographic.org/2016/04/11/scientists-solve-darwins-paradox/.

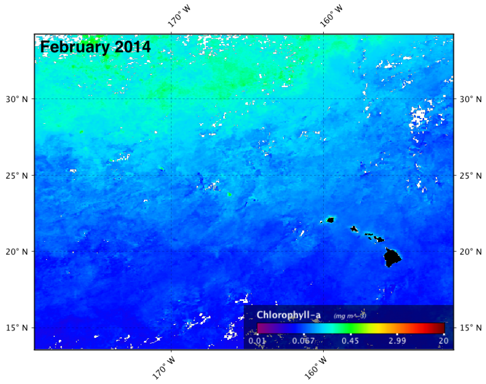
Timm, Oliver, and Henry F. Diaz. "Synoptic-statistical approach to regional downscaling of IPCC twenty-first-century climate projections: seasonal rainfall over the Hawaiian Islands." *Journal of Climate* 22.16 (2009): 4261-4280.

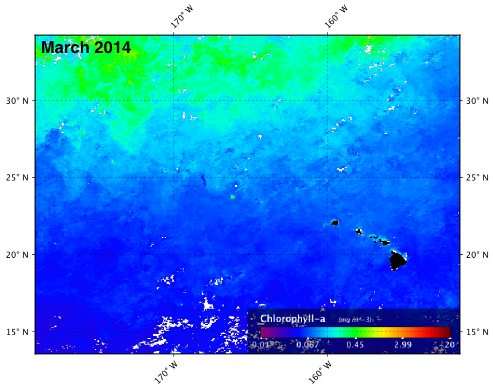
Venrick, E. L., et al. "Climate and chlorophyll a: long-term trends in the central North Pacific Ocean." *Science* 238.4823 (1987): 70-72.

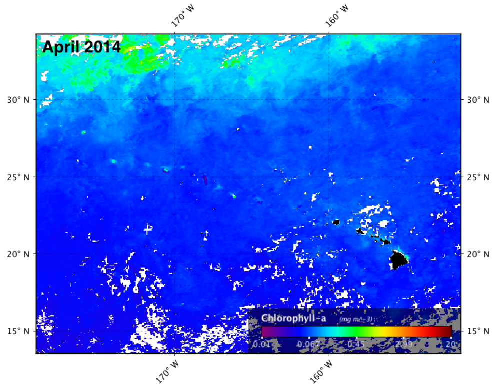
Wyrtki, Klaus. "El Niño—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing." *Journal of Physical Oceanography* 5.4 (1975): 572-584.

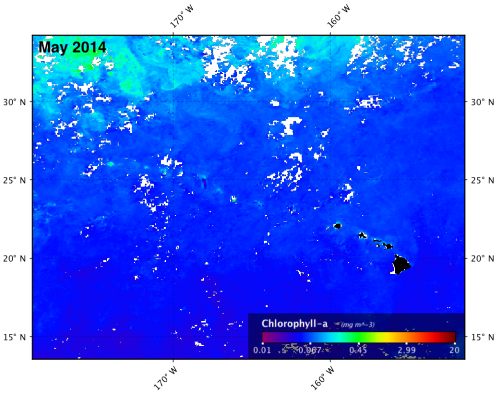
Appendix 1: 2014 Chlorophyll-*a* Concentrations

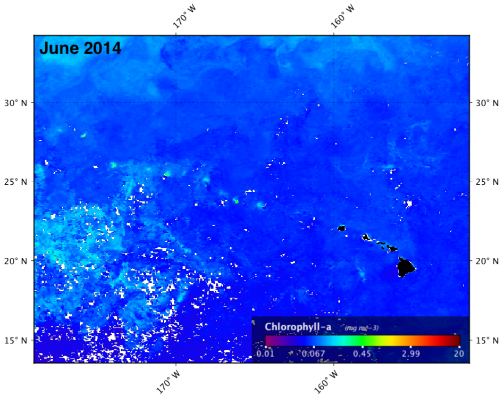


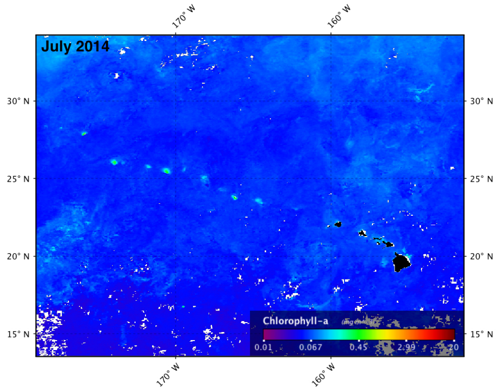


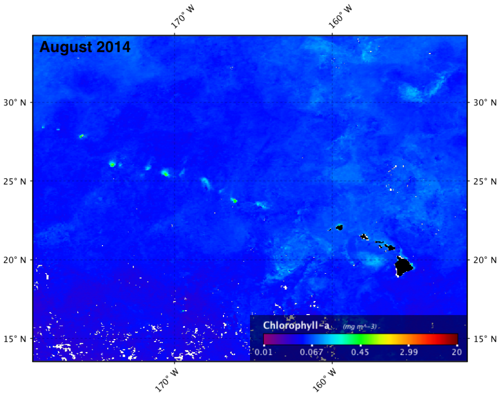


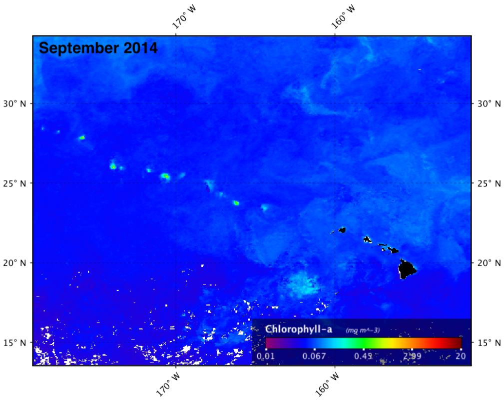


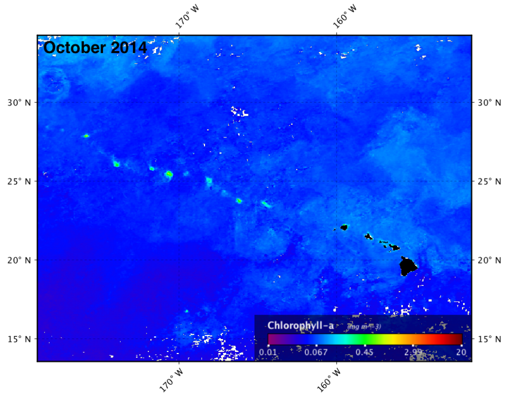


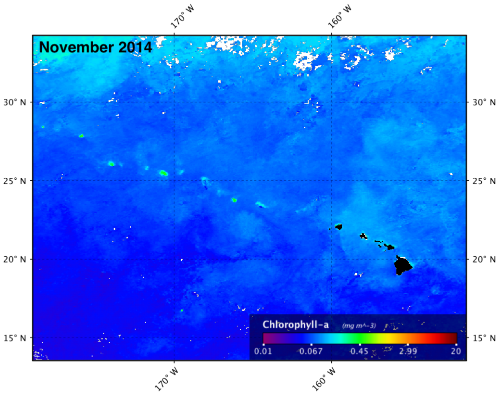


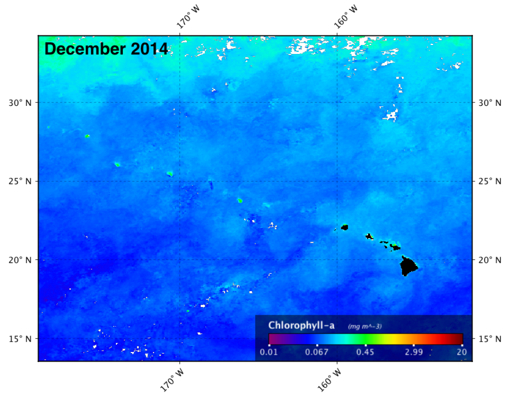




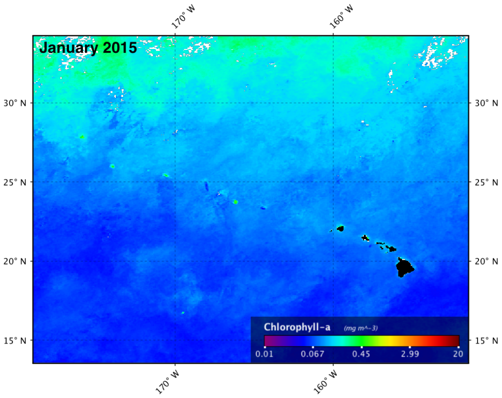


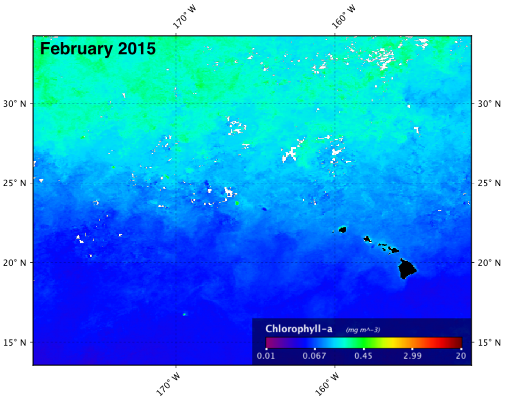


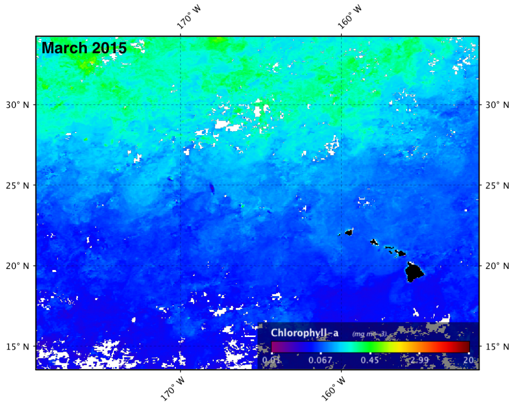


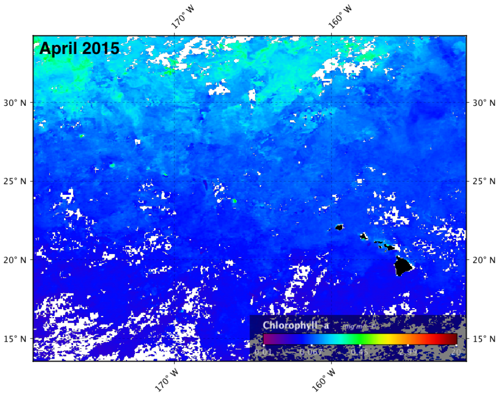


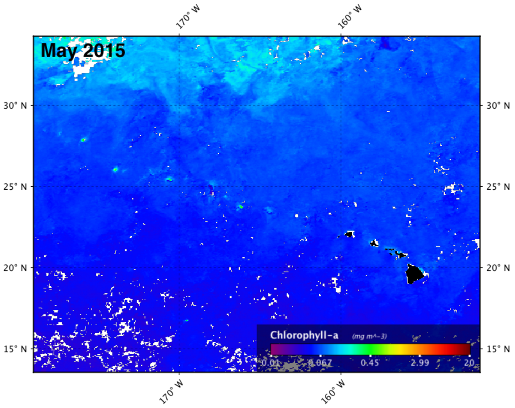
Appendix 2: 2015 Chlorophyll-*a* Concentrations

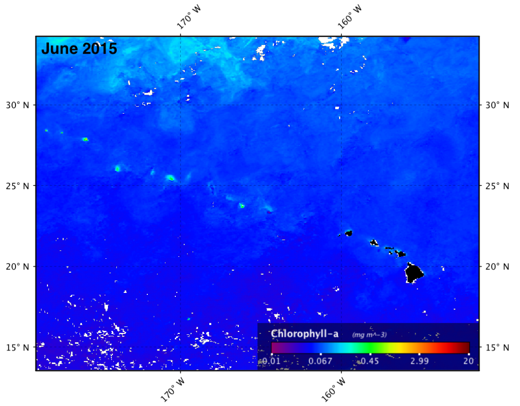


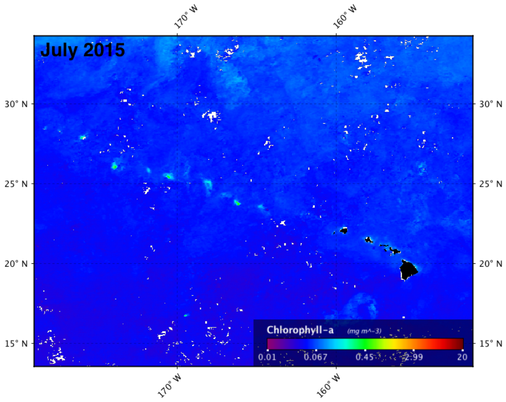


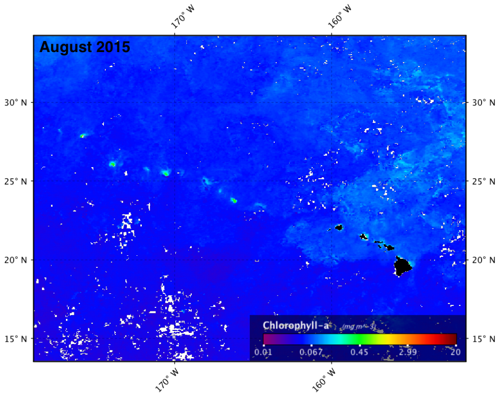


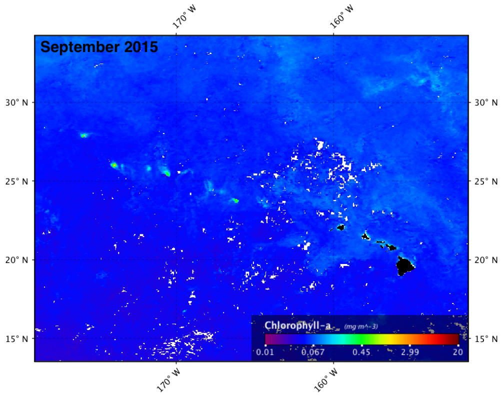


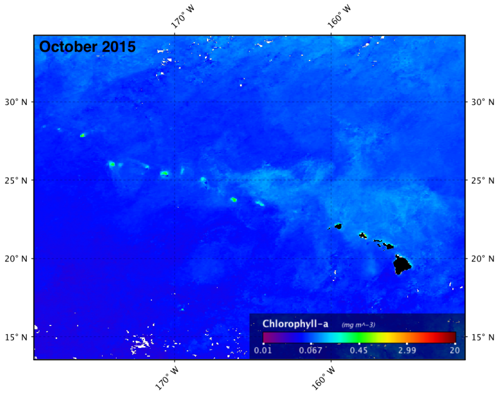


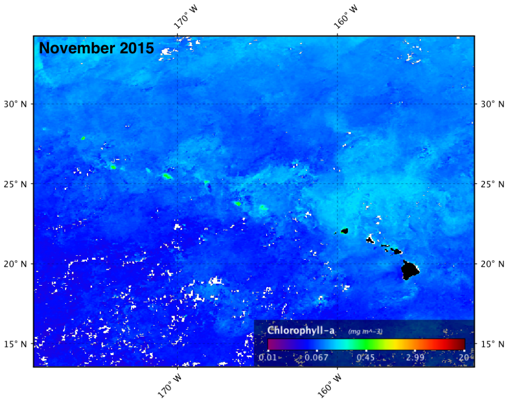


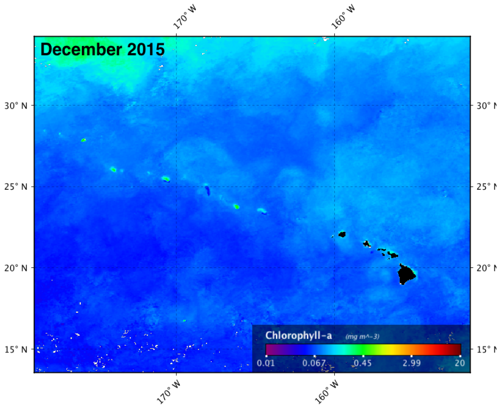




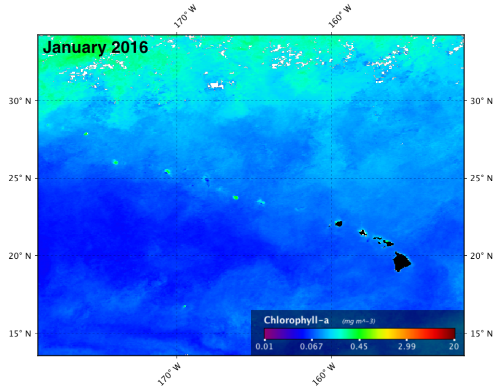


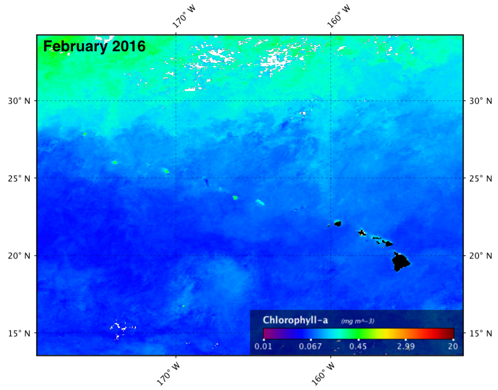


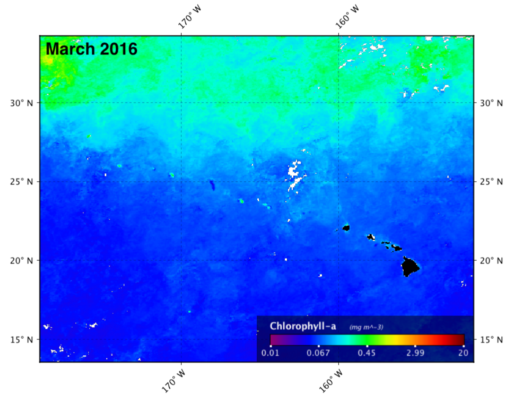


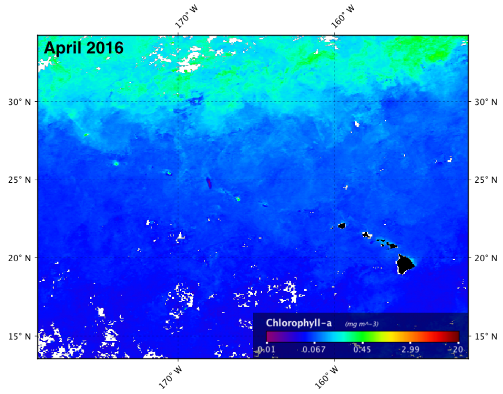


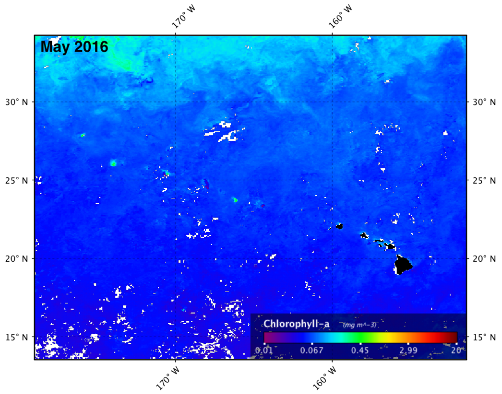
Appendix 3: 2016 Chlorophyll-*a* Concentrations

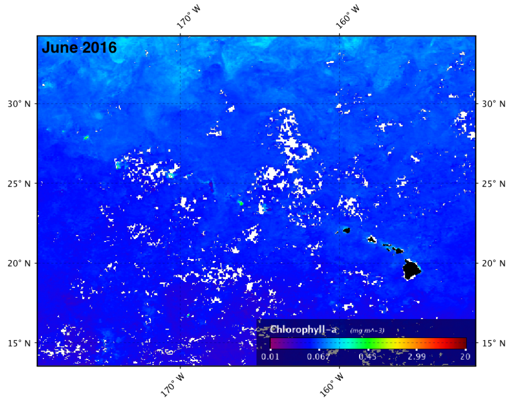


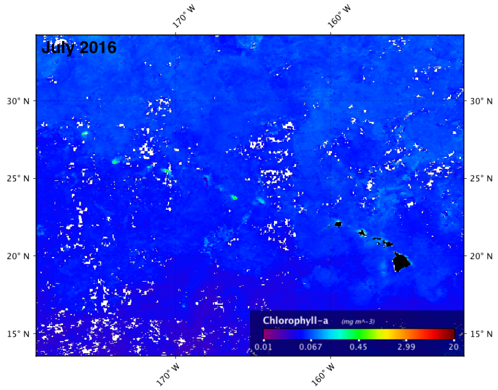


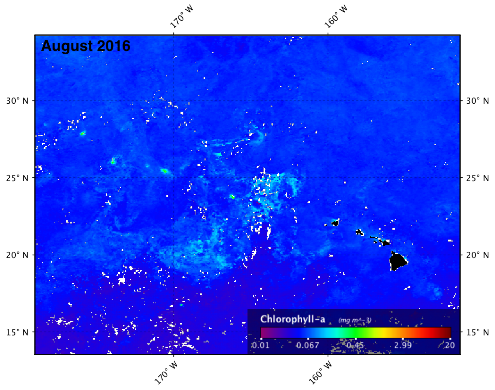


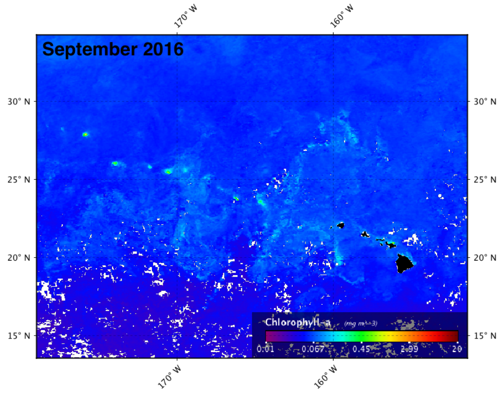


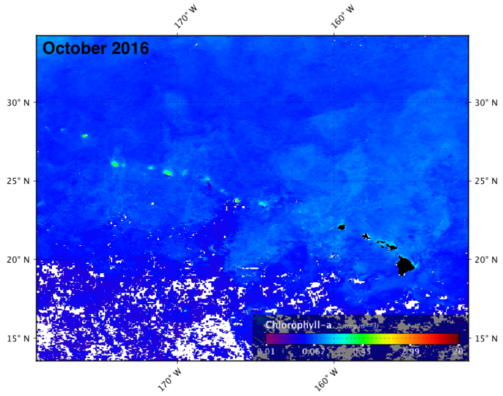


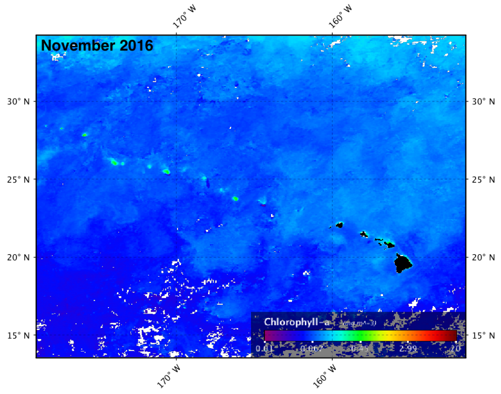


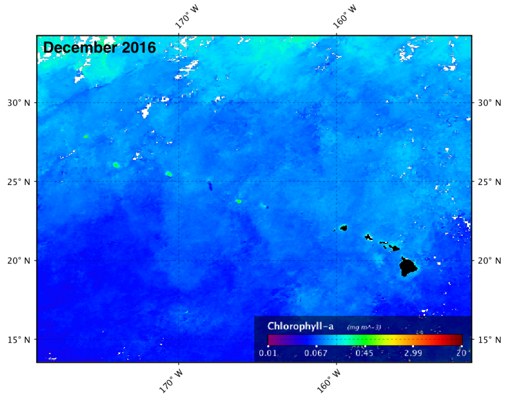












Appendix 4: Sea Surface Temperature 2014-2016