THE EFFECTS OF VOLCANIC FOG ON SeaWiFS SATELLITE IMAGERY IN THE LEE OF HAWAII

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ABSTRACT

Cyclonic and anticyclonic eddies are created by interactions between the northeasterly trade winds and the North Equatorial Current with the island of Hawaii. Of particular interest are the cyclonic eddies, also known as cold-core eddies, which vertically displace the underlying nutricline into the overlying, nutrient-deplete euphotic zone. The overall result is dramatically higher primary productivity levels, which typically corresponds to increased numbers of zooplankton and fish. SeaWiFS, or Sea-viewing Wide Field-of-view Sensor, measures chlorophyll-a concentrations over large areas of the ocean from space, thereby allowing researchers to measure how productive these mesoscale features are without having to spend the large sums of money required to travel out to an eddy and collect measurements from a ship. SeaWiFS is designed to take accurate measurements only under clear conditions, i.e. in the absence of clouds and concentrated atmospheric pollutants. The Hawaiian Islands are largely free of such atmospheric pollution except for the large and continuous quantities of volcanic fog, also known as vog, created on the island of Hawaii. It is believed that volcanic fog increases aerosol concentrations above tolerable levels, and therefore its presence will compromise chlorophyll measurements. This study investigates the effects of vog on the accuracy of chlorophyll measurements made with the SeaWiFS sensor by comparing them to *in situ* measurements. This study tests the hypothesis that the presence of vog results in over-estimations of chlorophyll-a concentrations made by SeaWiFS. Data analyses reveal an approximately linear relationship between vog thickness and errors in SeaWiFS measurements. As vog thickness increased over the study area, over-estimations in SeaWiFS measurements increased as well.

INTRODUCTION

Cyclonic eddies forming in the lee of the main Hawaiian Islands provide excellent opportunities for studying and understanding these mesoscale features. Interactions between the northeasterly trade winds and the North Equatorial Current combined with island topography create a continuous eddy field (Patzert 1969; Lumpkin 1998). These eddies are typically generated in the lee of the island on time scales of 50-70 days, although individual eddies have lasted over six months (Seki et al. 2001). The eddies average approximately 60-100 km in diameter and can form during any part of the year, but are more frequent during periods of high trade wind activity that typically corresponds to the late fall/winter months (Lumpkin 1998). The physical dynamics associated with the formation and subsequent deterioration of Hawaiian eddies have been well documented. The biological components and processes, however, are not as clearly understood. This lack of knowledge is largely due to difficulties in detecting eddies as well as, logistical technicalities in collecting *in situ* data once an eddy is detected. Ship time is expensive and difficult to obtain on short notice. The development of satellite remote sensing has

substantially improved our ability to accurately detect the formation and deterioratio[n]
around Hawaii. These technologies have also significantly improved the precision o[f]
sampling capabilities.

One such satellite sensor that is used to study these mesoscale features is SeaWiFS
viewing Wide Field-of-view Sensor. The mission of SeaWiFS is to improve the capabi
ocean color remote sensing via satellite technology. Ocean color remote sensing p
scientists with surface primary production values or chlorophyll concentrations, over lar
of the ocean. In order to measure chlorophyll levels, SeaWiFS uses bilinear gains to all
sensitivity measurements of ocean-leaving radiances and low sensitivity measurem
radiances from clouds, which are much brighter than the ocean. Basically, the more chlo
present in the surface waters the less radiant energy is reflected back to the sensor becau
of the sunlight is being used in photosynthetic processes (Kirk 1993). SeaWiFS has
important tool for identifying and studying cyclonic eddies. When an eddy forms and
levels inside the eddy increase, SeaWiFS is able to detect corresponding increases in chl
concentrations/phytoplankton abundance inside the eddy. SeaWiFS allows researc
measure how productive these mesoscale features are without having to spend the large
money required to travel out to an eddy and collect measurements from a ship.

SeaWiFS is designed to take accurate measurements only under clear conditions, i.
absence of clouds and concentrated atmospheric pollutants (Porter, personal commu
2000). The Hawaiian Islands are largely free of such atmospheric pollution except for
and continuous quantities of volcanic fog created on the island of Hawaii. The term "vo
for volcanic fog, is formed from the interaction of hot gases released from the active
Volcano, and water. Kilauea has been continuously active for years and when the northe
winds do not blow strongly, "Kona Winds" typically prevail. These winds prevent the v
being blown in the southwest direction far out to sea where it gradually dissipates
personal communication, 2000). Instead, the vog is blown west and accumulates over the
where the cyclonic and anticyclonic eddies are forming. This has caused a problem
SeaWiFS sensor that is being used to measure chlorophyll/primary production values in
cold-core eddies. The SeaWiFS sensor is calibrated to measure a standard level of atm
aerosols, but because vog is not a standard level, it is hypothesized that its prese
compromise chlorophyll estimates. As the concentration and/or thickness of vog increas
of the incoming solar radiation is scattered before it reaches the surface of the ocean res
less radiant energy being reflected back to the sensor. As a result, it is believed th
estimations of chlorophyll concentrations occur.

The goal of this project was to determine if vog causes an over-estimation in chlor
measurements made with the SeaWiFS sensor, by comparing them to *in situ* measureme
project is important for a number of reasons. It will combine knowledge and research te
from various fields including oceanography, physics, atmospheric chemistry, and mathem
will enable researchers to gain a better understanding of how local phenomena
sophisticated satellite technology. Ultimately, the importance of this project lies in advan
understanding of the cyclonic and anticyclonic eddies and how they affect offshore produ

METHODS

The first phase of data collection involved the acquisition of chlorophyll and vog t
measurements obtained during the HOT #89 cruise which took place in January of 1

HOT data were collected at Station Aloha located at 22° 45'N & 158°W (due north of the island of Oahu). Although this area is a considerable distance from Kilauea Volcano, and therefore the source of vog pollution, a significant amount of vog accumulated over Station Aloha during the HOT #89 cruise (Porter, personal communication, 2000). This research cruise provided a unique opportunity to analyze additional data sets and thereby increase the scope of this project. Chlorophyll-a measurements were collected over a three-day period using a SeaBird SBE 9/11+CTD system with a mounted fluorometer. Chlorophyll-a measurements made by the CTD unit at depths shallower than 10m were then compared to SeaWiFS level-2 Global Area Coverage chlorophyll-a measurements made over Station Aloha on the same days. The SeaWiFS data was obtained from the Goddard Space Flight Center-Distributed Active Archive Center (web address: www.http://daac.gsfc.nasa.gov/). Vog thickness was measured using the SeaWiFS sensor (band 8, tau 865nm) as well as hand-held sunphotometers over Station Aloha each day. Measurements were taken with the sunphotometers each time SeaWiFS passed overhead thereby providing groundtruthing for the SeaWiFS vog measurements.

All SeaWiFS data were analyzed using SeaDas or SeaWIFS Data Analysis System 4. software installed on a Sun Microsystems Computer. Processed data were entered into Minitab and aerosol optical thickness or vog thickness was plotted as a function of SeaWiFS chloroph measurements minus groundtruthing chlorophyll measurements. Linear regression analysis wa then performed in order to determine the relationship between vog thickness and errors i SeaWiFS.

The second phase of data collection involved the participation in a research cruise conducte by the National Marine Fisheries Service in cooperation with the University of Hawaii at Mano The cruise took place from November 15 – 20, 2000 on the NOAA RV *Townsend Cromwell*, an despite poor sea conditions during the cruise, we were able to collect sufficient amounts of dat We steamed directly down to the mature cyclonic eddy named Haulani located approximatel 140km due west of the island of Hawaii. Chlorophyll-a measurements were acquired both insid and outside the eddy using CTD-mounted WetLabs WETStar and Seapoint miniature chloroph fluorometers which were calibrated with a Turner 10-AU fluorometer (Trees et al. 2000). Whil in the center of the eddy, the CMOD-OCM bioptical drifter buoy was deployed over the stern o the ship. Once in the water, the buoy was programmed to automatically begin takin hydrographic measurements including water radiance and irradiance that chlorophyll-a wa derived from. Each day these data were transmitted via satellite to a receiving station at U Manoa where chlorophyll-a was calculated from the water radiance and irradiance values using bio-optical production algorithm (Ondrusek et al. 2000) and knowledge of *in situ* Turn chlorophyll-a distributions. Again, measurements were taken with two hand-held sunphotomete each time SeaWiFS passed overhead thereby providing groundtruthing for the SeaWiFS vo measurements. Approximately 25 measurements were taken with each sunphotometer per day.

Upon completion of the cruise, all water samples underwent HPLC pigment analys (Bidigare and Trees 2000). SeaWiFS level-2 Global Area Coverage and level-1a chlorophyll data sets corresponding to the first 19 days of drifter buoy operation were ordered from th Goddard Space Flight Center-Distributed Active Archive Center. Aerosol optical depths or vo thickness data were also ordered for these days. Again, all SeaWiFS data were analyzed usi SeaDas 4.0 software. Processed data were entered into Minitab and aerosol optical thickness o vog thickness was plotted as a function of SeaWiFS chlorophyll measurements min groundtruthing chlorophyll measurements (i.e. drifter buoy and shipboard measurements Linear regression analysis was then performed in order to determine the relationship between v ess and errors in SeaWiFS. Model II regression analyses were also applied to all the data e the independent variable, i.e. vog thickness, was not controlled in this study (Laws and , 1983). Under these conditions the Model I regression coefficient "is expected to be lower olute value than the true slope of the functional relationship" (Sokal and Rohlf, 1969).

RESULTS

ar regression analyses of HOT #89 data revealed a relationship between vog thickness rors in SeaWiFS chlorophyll measurements that approximated a linear relationship (P- 0.001, R-Sq=0.987), i.e., errors in SeaWiFS measurements were almost directly ional to aerosol optical or vog thickness. As vog thickness increased over the study area, timations in SeaWiFS chlorophyll-a measurements increased as well. Linear regression s of *Townsend Cromwell* data revealed a relationship between vog thickness and errors in FS chlorophyll measurements that approximated a linear relationship (P-value< 0.001, R- 9). This relationship, however, was not as close as that of the HOT #89 data.

data gathered by the bio-optical drifter buoy spans a total of 19 days and provided the the *in situ* chlorophyll data for this study. The drifter buoy took measurements over a four months, but after approximately the 19th day, the chlorophyll values were highly from day to day suggesting that fouling had occurred. The cause of this fouling is y under investigation. Linear regression analyses revealed a relationship between vog s and errors in SeaWiFS chlorophyll measurements that, again, approximated a linear ship (P-value<0.001, R-Sq=0.973), i.e., errors in SeaWiFS measurements were almost proportional to aerosol optical or vog thickness. A number of measurements were made e aerosol optical thickness was nearly zero, i.e. 0.001 or less. The corresponding S measurements were slightly less than the drifter buoy measurements made during the e interval. When the drifter buoy (ground truth) measurements were subtracted from the S measurements, negative values for approximately 10 data points resulted. When these ere excluded from the data set, linear regression analyses revealed a slightly closer linear hip: R-Sq values increased from 0.973 to 0.993 with a P-value< 0.001. It is possible that gative values are also responsible for the deviation in the Model II regression line. When data sets were combined and linear regression analyses performed, the resulting hip was approximately linear. Figure 1 shows aerosol optical thickness (vog thickness) WiFS chlorophyll measurements minus ground truth chlorophyll measurements. The n line shows significant correlation with a P-value< 0.001, S=0.0088, R-Sq=92.4%, R- 92.3%, and SeaWiFS-GroundT.=-0.005 + 0.501 Aerosol.

en Model II regression analyses were applied to the data and the *Townsend Cromwell* data, the change Model I regression lines was not significant. The nged from 0.446 to 0.448 and the y-intercept rom –0.0066 to –0.0067 for the HOT #89 data. The nged from 0.525 to 0.611 and the y-intercept from –0.0190 to –0.0265 for the *Townsend* . When these regression techniques were applied to r buoy data, the change in its Model I regression oticeable. The slope changed from 0.552 to 0.444 intercept changed from –0.0051 to 0.003.

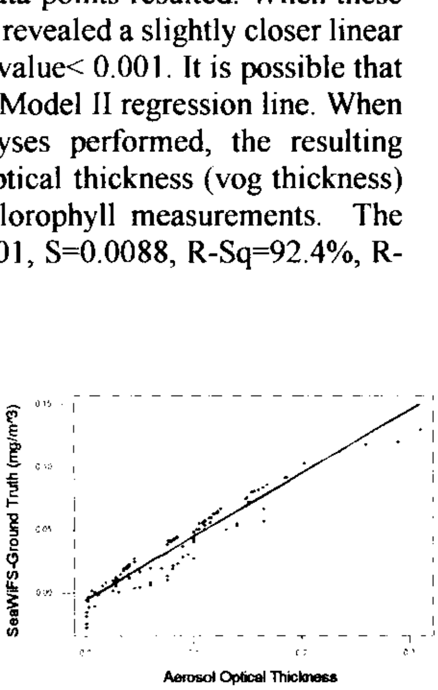

Fig 1

DISCUSSION AND CONCLUSIONS

Based upon the results of this study, it does appear that there is a clear correlation between vog thickness and overestimation in SeaWiFS chlorophyll measurements. In all three data sets, the relationship is approximately linear, and as a result, when all the data points are combined, the relationship remains approximately linear (fig.2). The differences in linear regression analysis between the data sets could be attributed to numerous factors such as changing atmospheric and sea surface conditions as well as negative data points.

The first data set shows the highest correlation between the two variables (R-Sq=0.987), but does not contain data points for a relatively large portion of the graph, i.e., between aerosol values of approximately 1.7 and 2.6. The second data set shows the lowest correlation between the two variables (R-Sq=0.890). The second data set, however, only has data points for the narrowest range of aerosol values. Furthermore, the acquisition of this data was made during rough seas, which could have decreased the accuracy of the aerosol measurements made using the sunphotometer instrument. In order to make accurate measurements, the user must line up the center of the sun in two crosshairs and then hold it there for a few seconds while the instrument takes a measurement. Taking measurements from the rolling deck of a research vessel in rough seas can be challenging. The accuracy of the SeaWiFS measurements could also have bee decreased because of the rough sea surface. Typically, when the sea surface is less uniform o calm, the reflected radiances that SeaWiFS measures are scattered to a greater extent. The thir data set shows the second highest correlation between the variables (R-Sq= 0.973), and has th largest number of data points. As previously mentioned, the negative y-axis data points, an rough sea surface conditions are most likely responsible for the lower correlation value.

The results of this study appear to show a clear correlation between the variables measure Much more data, however, is still needed before corrections can be applied to SeaWiFS erro because over the course of this study, no data were collected when vog thickness was great than approximately 0.3. It is possible that when vog thickness is greater than 0.3, errors SeaWiFS measurements will not remain linear to vog thickness, and a different type correlation/relationship will result.

The ability to correct errors in SeaWiFS measurements will also require knowledge of h various concentrations of vog or other types of atmospheric aerosols affect each individual b of SeaWiFS. The SeaWiFS sensor measures electromagnetic radiation i.e., ocean-leav radiance, over 8 discrete bands (or channels) and each band measures a specific portion of visible light spectrum. When vog is present over a sampling area, incoming solar radiatio scattered before it reaches the ocean surface. Specific wavelengths are scattered more t others, i.e., shorter wavelengths toward the blue end of the spectrum are scattered less t longer wavelengths toward the red end of the spectrum. According to Gordon et al (1994), t individual scattering characteristics must be taken into consideration when trying to devel working set of algorithms for SeaWiFS. Vog composition also varies with time and chan atmospheric conditions. The chemical constituents of vog (hydrogen sulfide gas, sulfur dio gas, and water vapor are the principal constituents) vary depending on how active the Kil Volcano is. Air temperature, barometric pressure, prevailing winds, etc. can also affect thickness and aerial coverage and must be taken into consideration when trying to correct e in SeaWiFS (Chomko 1999).

In conclusion, this study has revealed valuable insight into the questions initially a however accurate determination of the extent of and correction for the errors in SeaWiFS iire further research. I feel that this project has enabled us to gain a better understanding of local phenomena affects sophisticated satellite technology. The results obtained will oubtedly further our understanding of the cyclonic and anticyclonic eddies and how they ct offshore productivity in the lee of the Hawaiian Islands.

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