REMOTE SENSING OF VOLCANISM: EFFUSION RATES CALCULATION FOR KILAUEA VIA GOES SATELLITE IMAGES

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ABSTRACT

Remote sensing satellite images are valuable in allowing researchers to monitor volcanic activities The Geostationary Operational Earth Satellite (GOES) website is the only available source that offers near-real-time satellite images updated about every 15 minutes of various terrestrial volcanic sites Because of their rapidly moving and more extensive channelized flows, lava flows with high effusion rates are more dangerous than those with low effusion rates. For my one-semester project, the main goal is to determine if GOES data from band 2 (3.80-4.00 μm) and band 4 (10.20-11.20 μm) can be used to calculate the near-instantaneous effusion rate of Kilauea on the island of Hawaii. Using ENVI 3.2 software, 482 raw unstretched GOES Kilauea images (~ 5.3 x 4.1 km in pixel resolution) from band 2 and 4 were studied for Nov. 17-18, 1999 and Feb. 14-15, 2000. Using similar mathematical techniques to those outlined in Harris et al, 1998, the effusion rates and active lava areas were determined.

Because the difference between the corrected GOES ground temperatures and the actual field temperatures was insignificantly small (0.9 ± 1.29°C), the GOES temperatures should offer an accurate representation of the actual field dynamics. During Nov. 17-18, 1999, the GOES average effusion rate for lava at 500°C is 2.39 ± 1.45 m^3/s. For Feb. 14-15. 2000, it is 2.44 ± 1.43 m^3/s. Despite the low GOES spatial resolution, 2-3 m^3/s is very typical of the Kilauea effusion rates measured using high 30-m-pixel resolution TM data (Harris et al, 1998, and Heliker et al, 1998). In addition, the typical field lava temperatures measured using the Raytec Rayinger 3i Infrared Thermometer during April, 2000 was within the 500°C range, thus supporting the conclusion that GOES effusion rate based on band 4 data for 500°C lava flow offers a close approximation of the actual field effusion rate. Further evidence that the calculated GOES effusion rates can offer a close approximation of the actual effusion rates comes from the direct correlation between the GOES effusion rates and the R_{2volc} (having an average of 11787496.3 ± 2198122.9 W^2m/m) during Nov. 17-18, 1999. Further studies will determine an approximate mathematical relationship between band 4 GOES effusion rates and R_{2volc}. Having tested on Kilauea, the techniques from this project may be applied with some modifications to determine the near-real-time effusion rates for other terrestrial volcanic sites.

INTRODUCTION

Along with many ethical and political implications such as evacuation from danger areas, volcanism can also greatly impact our planet's atmosphere, climate, and soil fertility. The role of remote sensing in studying volcanism is significant because it allows researchers to monitor activity via satellite images. Interpretation of remote sensing images and other data obtained from terrestrial volcanoes can be applied to the geological study of other space bodies such as Venus and Io. Research on volcanism and its effects on surface features can also help us understand, explain, and provide models on the geologic history of some planets and satellites in our solar system and beyond.

GOES 8 and GOES 10 are two satellites offering remote sensing data processed by HIGP researchers on various terrestrial volcanic sites. The GOES website (http://volcano1.pgd.hawaii.edu/goes/goes.shtml) is valuable in that it offers near-real-time images updated about every 15 minutes. Most GOES images are 500 x 500 pixels in size with each resampled pixel being approximately 1 km across. The exception is the image for the Island of Hawaii which is 400 x 400 pixels in size, with each resampled pixel of ~ 0.5 km across.

In volcanic research, effusion rate (the volume of erupted lava per second) is especially useful in determining flow dynamics. High effusion rates result in faster, longer, and more extensive channelized flows that may cause greater damage than flows with low effusion rates. In Hawaii, effusion rates have also been shown to correspond with the type of flow. Effusion rates > 20 m^3/s produces quick-flowing, channelized 'a'a flows while those < 20 m^3/s, especially in the ~ 5 m^3/s range, results in slow-flowing, tube-fed pahoehoe flows (Rowland and Walker, 1990).

For my one-semester project, my purpose is to determine if GOES data from band 2 (the mid-infrared part of spectrum with wavelength of 3.80-4.00 μm) and band 4 (the thermal-infrared part of spectrum with wavelength of 10.20-11.20 μm) can be used to calculate the near-instantaneous effusion rate of Kilauea on the island of Hawaii. If a realistic approximation of effusion rate can be obtained in spite of the low resolution of ~ 4 km for Kilauea, GOES data will be able to serve as the only available near-real-time source for effusion rate measurements.

Other secondary goals for my project include (1) understanding the general flow dynamics of Kilauea (refer to Harris et al, 1997, Heliker et al, 1998, and the USGS Hawaiian Observatory Homepage at http://hvo.wr.usgs.gov for Kilauea volcanic episodes studies, summaries, and daily updates) and Pacaya volcano, Guatemala, (2) determining the error in temperature calculations for Kilauea due to atmospheric and surface characteristics, and (3) calculating the Kilauea R_{4volc} (spectral radiance of band 4) from GOES and determining if it correlates to the calculated effusion rates.

I began my project by recording from GOES characteristics of hotspot pixels including the date, time, location/description, and estimated size for the Kilauea and Pacaya regions. Pacaya is interesting in that it exhibits different types of volcanic activity. It is known to have such diverse phenomenon as effusive lava flows, strombolian eruptions, and pyroclastic events. It was especially active in late Dec., 1999 through early Jan., 2000, resulting in numerous explosive events. Kilauea, on the other hand, generally displays mostly steadily effusive basalt lava flows. During my field study in April 2000, constant lava breakouts from the tube system within the flow field were feeding many small pahoehoe toes. Surface breakouts were concentrated around Pulama pali extending to the ocean with occasional huge steam plumes that can also be seen on the GOES images.

Focusing on Kilauea, I continued my project collecting GOES data to determine the temperature calculation error, R_{4volc}, and effusion rates. Actual field temperature data recorded during my trip to Kilauea in April were also compared to the standard temperatures selected in advance for the effusion rates calculation.

METHOD

Four hundred eighty-two raw, unstretched GOES Kilauea images collected ~ every 15 minutes from band 2 and 4 were studied using ENVI 3.2 software (Environment for Visualizing Images) for Julian days 321-322 (Nov. 17-18) of 1999 and Julian days 045-046 (Feb. 14-15) of 2000. Band 2 and 4 temperatures from each of these images were recorded for the hotspot and the surrounding ambient pixels. Those images suspected of being contaminated by cloud cover were discarded from further analysis. Pixels containing the ocean surface were also rejected. The hotspot pixels were located in each band 2 image and these saturated pixels (those with temperature $\geq 320\ ^\circ K$, which ensured the presence of lava in those pixels) were highlighted.

To determine if the filtering procedures used to calculate the real surface temperature from the at-satellite temperature (contaminated by such components such as surface emissivity, atmospheric transmissivity, and upwelling path radiance) would give accurate corrected ground temperatures—the corrected temperature differences between band 2 and 4 on Nov. 17-18, 1999 from Hawaiian time 20:00-05:30 were calculated from the ambient pixels surrounding the four corners of the hotspots. (Note that night time temperatures were used here because there is no contamination from reflected sunlight at night.) Because different bands are sensitive to different components of contamination and the filteri procedures used to calculate the corrected temperature from band 2 and 4 use different basal values sui for the bands' varying sensitivities of the contamination components—an ideal difference of zero betw the corrected band 2 and 4 temperatures would mean that we have no error in our temperature correction.

The area covered by active lava in the hot pixels were needed for the calculation of the effusion r To determine the area or portion of lava inside the saturated pixel, the following equation was appli where R_{2volc} is the volcanic spectral radiance from GOES band 2, P is the portion or fraction of lava in saturated pixel, and $R_{2background}$ is the background, or ambient, band 2 radiance:

$$R_{2volc} = (P)R_{2volc} + (1\text{-}P)R_{2background}$$

To determine $R_{2background}$, the pixels surrounding the corresponding hot saturated pixel were used. Beca the pixel area is given, where the resolution is ~ 5.3 x 4.1 km—once the fraction of the pixel that conta lava was calculated, the area of lava inside the pixel could be obtained by multiplying the fraction to pixel area. Using this method, a minimum, mean, and maximum range of P's and lava areas w calculated that correspond to lava at 500-1000°C.

Using similar mathematical techniques outlined in Harris et al, 1998, the minimum, mean, maximum effusion rates based on the calculated lava area were determined. For the calculation effusion rate, band 4 data were used because band 4 is more sensitive to ambient temperature and d not saturate like band 2 temperatures. Also, the GOES R_{4volc} was determined for each image collec during Feb. 14-15, 2000. All statistical analysis was done using Microsoft Excel software. Furtherm for comparative purposes, precise temperatures were collected during the field study on the coastal side Pulama pali from April 8-9, 2000, using the Raytec Raynger 3i Infrared Thermometer.

RESULTS & DISCUSSION

For the temperature filtering correction procedure, the temperature differences obtained for Nov. 17-18, 1 between band 2 and 4 did not come out to be zero. This means that error exists in the corrected temperatures use calculate lava area and effusion rate—such that the corrected surface temperatures obtained from GOES were exactly the same as the actual ground temperature. Nevertheless, the error is small: the corrected GO temperatures used being 0.9 ± 1.29°C off from the actual field temperatures. This error is insignificant enoug offer a realistic corrected temperature, and thus should not result in calculated effusion rates that deviate much fr the actual field data. The GOES average effusion rate for the whole days of Nov. 17-18 calculated for lava at 50 is 2.39 ± 1.45 m^3/s with the average active lava area being 0.13 ± 0.08 km^2. For lava set at 1000°C, the aver

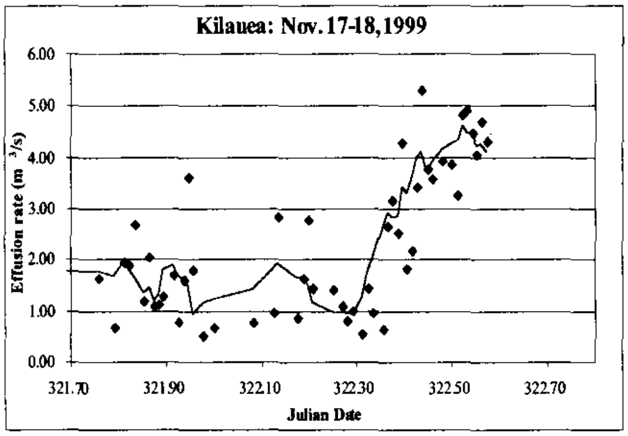

Figure 1. The mean effusion rates (dots) and the associated running mean (line) for Kilauea from Nov. 17-18, 1998 for lava at 500°C.

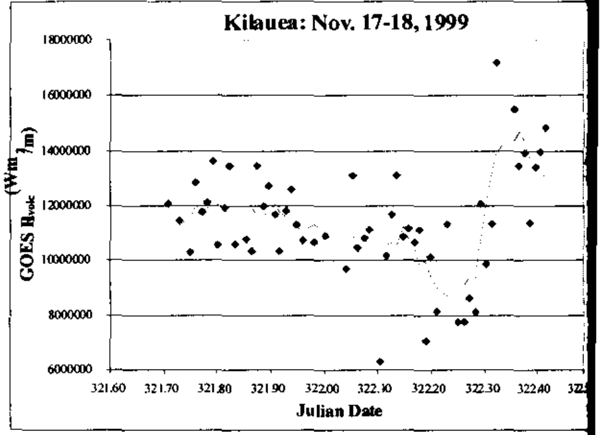

Figure 2. The R_{2volc} (dots) and the associated running mean (line) for Kilauea. Note that R_{2volc} is the spectral radiance from GOES band 2.

effusion rate is 4.00 ± 2.42 m^3/s with the average active lava area being 0.05 ± 0.03 km^2. (Note that the effusion rates for lava at 1000°C are higher than those at 500°C. This is because the effusion rates at 500°C represent older lava temperatures that are integrated over a period of 2.35 minutes while those at 1000°C is calculated almost instantaneously for lava that have just been exposed, integrated over 0.03 second.) Thus, for lava at 500°C-1000°C, the effusion rates range from ~ 2.39-4.00 m^3/s. Note that the lower range of 2.39 m^3/s is very typical of the effusion rates measured using more spatially detailed 30-m-pixel Landsat TM data for the Kupaianaha vent during 1986-1990 and other lasting Kilauea eruptions (Harris et al, 1998, and Heliker et al, 1998). This is a surprisingly good agreement given the 4 km spatial resolution of GOES.

Figure 1 illustrates effusion rates calculated for lava at 500°C for part of Nov. 17-18, 1999. The effusion rates for lava at 1000°C (not shown) are higher in value but assume the same shape as those for 500°C of lava. The running mean was obtained by averaging the two data points above and two below the central data point they surround to give a smoother trend of effusion rate. Figure 2 shows the corresponding radiance for the same days. The calculated effusion rates correspond closely to the GOES radiance. Note how the shape of the effusion rates curve dips when radiance dips and rises when radiance rises. GOES R_{2volc} was shown to be sensitive enough to allow accurate volcanic monitoring that corresponds to the actual field data (Harris et al, 1997). Since higher effusion rate results in a bigger flow and thus a higher thermal reading of radiance, the correlation between the GOES effusion rates and R_{2volc} suggests that the calculated GOES effusion rates do offer a realistic approximation of the actual effusion rates. The sensitivity and trustworthiness of GOES effusion rates are important because researchers so far do not have any means of monitoring the Kilauea effusion rates constantly every 15 minutes.

To further test the accuracy of GOES effusion rates, GOES data from Feb. 14-15, 2000 were also examined. The GOES average effusion rate for lava having a temperature of 500°C is 2.44 ± 1.43 m^3/s with the average active lava area being 0.14 ± 0.08 km^2. For lava having a temperature of 1000°C, the average effusion rate is 4.19 ± 2.80 m^3/s with the average active lava area being 0.05 ± 0.04 km^2. Figure 3 shows the range (minimum and maximum) of effusion rates for lava at 500°C. Again, the pattern is the same for lava set at 1000°C with the only difference in the higher values for higher temperature. The average R_{4volc} is 10.64 ± 8.40 $mW/m^2\text{-}sr\text{-}cm^{-1}$ (sr = steridian). However, unlike the direct correlation between GOES effusion rates and R_{2volc}, plotting R_{4volc} against effusion rate results in a random, scattered graph with no direct relationship. The most likely explanation is that band 2 and band 4 are sensitive to different components. R_{2volc} is more sensitive to the hotspot temperatures whereas R_{4volc} is more representative of the variations in the ambient surface temperatures within a pixel, meaning that R_{4volc} is not as sensitive as R_{2volc} to active lava temperatures. Thus, results of this project recommend that GOES R_{2volc} be used when studying the interdependence between effusion rates and radiance.

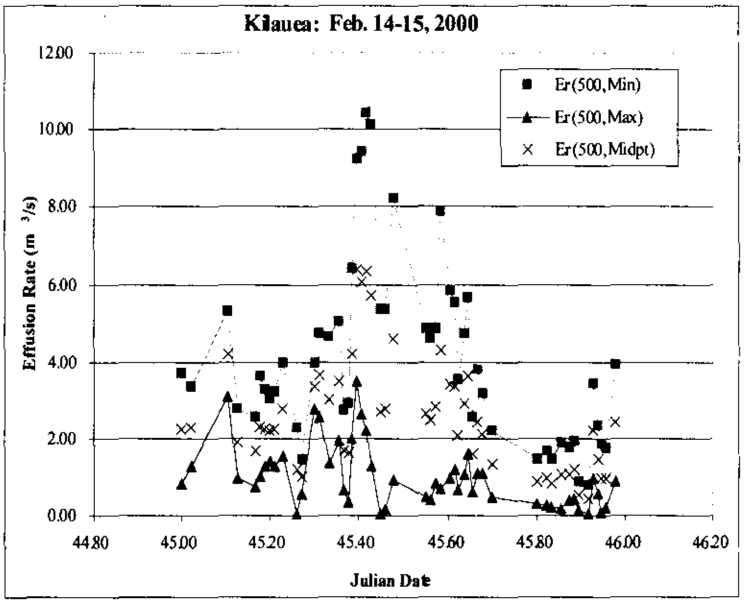

Figure 3. The minimum and maximum effusion rates (Er) and their midpoints plotted for Kilauea from Day 045-046 for lava at 500°C.

The Kilauea effusion rate calculated for 10:30 a.m. on Feb. 14, 2000 from Landsat data (which has higher resolution and is thus more accurate) is 2.6 ± 1.2 m^3/s with the active lava area at 0.176 km^2 (Harris, unpublished data, 2000). The GOES effusion rates calculated for the same time for lava at 500°C is 2.52 m^3/s with an active lava area of 0.142 km^2, and at 1000°C with an effusion rate of 0.41 m^3/s and an active lava area of 0.142 km^2. Note how closely the GOES effusion rate for 500°C lava almost equals that obtained from Landsat. This further indicates that GOES can offer realistic approximations of effusion rates for the constant monitoring of Kilauea.

During my field studies in April 2000, lava that was just exposed reached temperatures of 800-1000°C and above. However, it cooled quickly, and the more typical lava temperatures measured for the coastal area extending from Pulama pali was around the 500°C range. A representative patch of lava is shown is Figure 4. Since most of the active lava flow is closer to the 500°C range, it is not surprising to see that the GOES effusion rate calculated for 500°C lava is closer to reality compared to that calculated from 1000°C lava. This again supports that calculation set at 500°C for active lava offers the most realistic GOES effusion rates approximation for Kilauea.

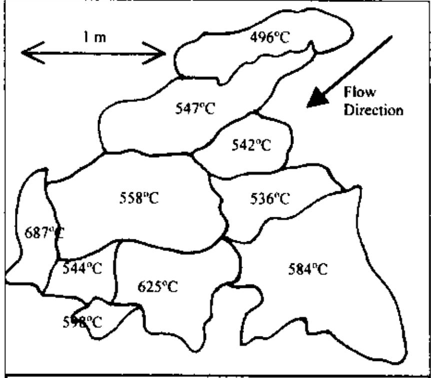

Figure 1. Lava temperature as measured by Raytec on a typical active lava patch.

CONCLUSION

Unlike the diverse volcanic activities such as strombolian eruptions and pyroclastic events evident in the Pacaya region, Kilauea most generally displays steadily effusive lava flows with occasional huge steam plumes at the ocean entry. Since the difference of 0.9 ± 1.29°C between the corrected GOES ground temperatures and the actual field temperatures is insignificantly small, the GOES temperatures can offer an accurate representation of the actual field dynamics. During Nov. 17-18, 1999, the GOES average effusion rate for lava at 500°C-1000°C ranges from 2.39 ± 1.45 m^3/s to 4.00 ± 2.42 m^3/s. For the average active lava area at 500°C-1000°C, the range is 0.13 ± 0.08 km^2 to 0.05 ± 0.03 km^2. In spite of the low GOES resolution of 4 km, 2.39 ± 1.45 m^3/s is very typical of the Kilauea effusion rates measured using more spatially detailed 30-m-pixel Landsat TM data. Further indication that the calculated GOES effusion rates can offer a realistic approximation of the actual effusion rates comes from the direct correlation between the GOES effusion rates and R_{2volc} during Nov. 17-18, 1999.

During Feb. 14-15, 2000, the GOES average effusion rate for lava at 500°C-1000°C is 2.44 ± 1.43 m^3/s to 4.19 ± 2.80 m^3/s with the average active lava area of 0.14 ± 0.08 km^2 to 0.05 ± 0.04 km^2. The average R_{4volc} is 10.64 ± 8.40 mW/m^2-sr-cm^{-1} (sr = steridian). Nevertheless, plotting R_{4volc} (unlike R_{2volc}) against effusion rate results in a random scattered graph with no direct relationship. The most likely explanation is that R_{2volc} is more sensitive to the hotspot whereas R_{4volc} is more representative of the ambient pixels. Thus, this indicates that GOES R_{2volc} is more valuable in studying the correlation between effusion rate and radiance.

A more accurate Kilauea effusion rate for Julian day 45.44 from year 2000 calculated from 30-m-pixel Landsat data is 2.6 ± 1.2 m^3/s with the active lava area at 0.176 km^2 (Harris, unpublished data, 2000). The corresponding GOES effusion rates calculated for lava at 500°C is 2.52 m^3/s with an active lava area of 0.142 km^2, and at 1000°C with an effusion rate of 0.41 m^3/s and an active lava area of 0.142 km^2. Again, the GOES effusion rate for 500°C lava almost equals that obtained from Landsat. Since the typical lava temperatures during my April Kilauea field study was around the 500°C range, this further supports that GOES effusion rates calculated based on band 4 data for 500°C lava flow offer a close approximation of the actual field effusion rates. The sensitivity and accuracy of GOES effusion rates are important because it can allow researchers to monitor the Kilauea flow dynamics constantly every 15 minutes.

The next step will be to record and analyze GOES data from Julian days 316-320 (Nov. 12-16), 1999, during which actual field data are available for comparison. This will help us further determine how closely the GOES effusion rates are to the actual field data and also determine an approximate mathematical relationship between band 4 GOES effusion rates and R_{2volc}. Having tested on Kilauea, we may well be able to apply the techniques from this project with some modifications to determine and study the near-real-time effusion rates for other volcanic sites monitored by the GOES satellites. Eventually, these techniques used for low spatial resolution GOES data may also be adapted to study and understand the flow dynamics of other space bodies (for which we also have low spatial resolution data sets) such as Venus and Io using satellite data.

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