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“Effects of Volcanoes on the Natural Environment”

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Effects of Volcanoes on the Natural Environment

Final Report

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1. Overview

The primary focus of this project has been on the development of techniques to study the thermal and gas output of volcanoes, and to explore our options for the collection of vegetation and soil data to enable us to assess the impact of this volcanic activity on the environment. We originally selected several volcanoes that have persistent gas emissions and/or magma production. The investigation took an integrated look at the environmental effects of a volcano.

Through their persistent activity, basaltic volcanoes such as Kilauea (Hawaii) and Masaya (Nicaragua) contribute significant amounts of sulfur dioxide and other gases to the lower atmosphere. Although primarily local rather than regional in its impact, the continuous nature of these eruptions means that they can have a major impact on the troposphere for years to decades. Since mid-1986, Kilauea has emitted about 2,000 tonnes of sulfur dioxide per day, while between 1995 and 2000 Masaya has emitted about 1,000 to 1,500 tonnes per day (Duffell *et al.*, 2001; Delmelle *et al.*, 2002; Sutton and Elias, 2002). These emissions have a significant effect on the local environment. The volcanic smog (“vog”) that is produced affects the health of local residents, impacts the local ecology via acid rain deposition and the generation of acidic soils, and is a concern to local air traffic due to reduced visibility.

Much of the work that was conducted under this NASA project was focused on the development of field validation techniques of volcano degassing and thermal output that could then be correlated with satellite observations. In this way, we strove to develop methods by which not only our study volcanoes, but also volcanoes in general worldwide (Wright and Flynn, 2004; Wright *et al.*, 2004). Thus volcanoes could be routinely monitored for their effects on the environment. The selected volcanoes were:

Kilauea (Hawaii; 19.425°N, 155.292°W): The on-going activity at this basaltic shield volcano has enabled many of the algorithms to be developed under our previous NASA EOS IDS activity. Ease of access to the volcano, and extensive knowledge of the history, petrology and meteorology of the volcano permits us to use Kilauea as our “field laboratory” where we can develop techniques that can then be taken to the other volcanoes of interest

Masaya (Nicaragua; 11.984°N, 86.161°W): This is a basaltic shield volcano that rises to just 635 m above sea level. Several million people live within a 30-km radius of Masaya’s caldera rim and are potentially at risk if a large eruption were to occur. In addition, a large region downwind from the volcano is adversely affected by the gas plume, making it an ideal test case for our modeling investigation. Much of the adjacent forest and crops such as coffee and citrus plants are killed yearly by the plume and people and livestock living in this zone are subject to respiratory problems.

Poás (Costa Rica; 10.20°N, 84.233°W): This is a complex andesitic strato-cone in Costa Rica rising to 2,700 m above sea level. The volcano has been continuously active throughout historical times and for much of this time there has been a warm, acidic crater lake, fumaroles and a ubiquitous shallow hydrothermal system within the summit area.

Poás supports a tropical ecosystem; and one of our goals was to search for spectral changes in foliage as one moves perpendicular to the downwind axis of the plume.

Our project goals included an integrated field, air and space-based analysis of four key aspects of the degassing of these volcanoes:

1. Thermal energy and eruption rates: Our goal here was to better understand how to interpret the thermal output of a volcano so that quantitative estimates of the magma production rate can be derived. First we intend to study high-temporal (about one measurement per second) thermal data on the ground, observe magma production rates using other field techniques (e.g., infrasonics, gravity and very low frequency radio waves), and then compare these estimates to data obtained from a variety of spacecraft (GOES, Terra, Landsat 7 and EO-1).
2. Determination of volcanic gas concentration and spatial distribution: Sulfur dioxide is the main volcanic gas of importance here, but we were also trying to develop methods for studying other gases (HCl, HF, CO etc.) using UV and FTIR techniques in order to better characterize the emissions from a volcano.
3. Aerosol optical depths and particle size distributions: The critical effort here was to understand the rate of conversion of sulfur dioxide into sulfate aerosols as they are transported downwind, and to explore how airborne and spaceborne observations (particularly from sensors such as MODIS and MISR) can be used
4. Plume structure, down-wind dispersal, and impact with the land surface: A key objective here was to develop predictive atmospheric models for the dispersion of the eruption plume. Concurrently, we intend to study the impact of this plume on the local environment, studying both the spectral properties of vegetation located downwind of the plume and the analysis of soil samples taken from

2. Meetings and Field Work:

As part of this NASA project, we had several field expeditions to collect field data at Kilauea, Masaya, and Poás volcanoes. These trips can be summarized as follows:

- 1) Field experiments to inter-compare atmospheric instruments (lidar, FTIR and Sun photometer), Kilauea volcano August 2001.
- 2) Field experiments on Kilauea volcano, October 2001. Data from numerous instruments were collected (see below), but can in general be sub-divided into two sets, focused on (a) magma production and (b) atmospheric effects of the released volcanic gases.
- 3) Field visit to Masaya and Poás, March 2002. Analysis of the degassing of these two volcanoes, and the collection of field spectra of affected vegetation.

- 4) Kilauea, November 2002. We conducted an intensive field investigation in collaboration with the U. S. Geological Survey's Hawaii Volcano Observatory. Thermal, gas, and infrasonics data for Pu'u O'o vent, open skylights and (for gas studies) the downwind dispersal of the plume were studied.
- 5) Field visit to Masaya, March 2003, to participate in the inter-comparison of gas measuring instruments.

3. Summary of Results:

One of the major accomplishments of this project was the development of two new types of field instruments for the analysis of volcanic eruptions. These instruments are informally called "DUCKS" (Harris *et al.*, 2005) and "FLYSPEC" (Williams-Jones *et al.*, in press; Horton *et al.*, in press). DUCKS is a cheap, robust, modular, real-time thermal monitoring system that was initially deployed on Kilauea, and has since been installed at ten other volcanoes, including Masaya and Poás. FLYSPEC is a UV spectrometer that is cheap and light weight that provides a measure of sulfur dioxide in the atmosphere. In collaboration with the USGS/HVO, FLYSPEC is now replacing the 1970's-era COSPEC instruments that have been the mainstay of measuring volcanic sulfur dioxide on the Big Island. We have also deployed several of these FLYSPEC instruments at one time, thereby enabling us to determine local wind speed, which is a critical parameter if total mass flux is to be determined.

The following is a summary of the other accomplishments of our project. A complete listing of the 24 peer-review publications that have been derived together with these results, is given in Section 7.

1. *InfraSound (led by Emanuele Marchetti)*

During October 2001, two digital recording stations were deployed on Kilauea volcano. This was done in order to obtain 6 days of continuous thermal, infrasonic and seismic data. Two stations were deployed: one each at the active vent, Pu'u 'O'o, and a skylight in the tub system ~1 km south of Pu'u 'O'o. The aim of the experiment was to understand any possible relationship between the degassing activity (as monitored by the thermal sensor) and the infrasonic and seismic energy release.

Our infrasonics data were collected during the entire acquisition period (October 12-18, 2001) at both stations. Results from our infrasonics experiments on Kilauea are presented in Garces *et al.* (2003).

We can summarize the results, conclusions and problems at the two stations that were obtained from this analysis as follows:

Pu'u 'O'o: 1 thermal sensor, 1 infrasonic sensor and 1 three component seismometer were deployed. The activity during the acquisition period was unfortunately at relatively low levels. Much higher levels of activity were recorded by the permanent thermal system both during the week before and the week after the experiment. During the

experiment itself, degassing episodes may be absent-to-rare. The infrasonic data appear quite noisy. This was due to bad weather conditions and strong wind, where we were unable to bury, and thus shield, the infrasonic sensor. The seismic record reveals a high tremor level. No previous results are available to which we can compare these data, although the HVO seismometers may provide some insight. An appropriate analysis and data processing are necessary. Generally, the acquisition was good and data are available for all the entire period. Only a few 15-minute-long gaps in the data are present.

Skylight downslope from Pu'u 'O'o: 1 thermal sensor and 1 infrasonic sensor were deployed. Our analysis showed some interesting trends in the signal. Considering the three days when we had continuous records, there appears to be an excellent relationship between the temperature of the gas emission and the infra-sound amplitude. The infra-sound in addition showed good low frequency high amplitude signals. Both signals show an oscillation with a time scale of several hours. Because of acquisition software problems, large gaps are present in the data set. Fortunately, however, we were able to obtain several days of continuous recording.

2. Gravity (led by Glyn Williams-Jones and Hazel Rymer):

A continuously-recording LaCoste & Romberg micro-gravity meter was installed in 2002 by the Pu'u 'O'o vent of Kilauea volcano while repeat gravity measurements were performed at a skylight in the tube system. In conjunction with thermal infrared (Andrew Harris) and infrasonic (Emanuele Marchetti) measurements, it was hoped that continuous micro-gravity measurements would show short-term variations in magma flux within the conduits or plumbing system; gravity variations may be due to changes in mass (magma intrusion/removal) or density (vesiculation/devesiculation).

At Masaya volcano, Nicaragua, there have been large gravity changes over the last number of years (> 50 micro-gal per year) in conjunction with important variations in gas emission rate. These gravity variations are likely due to changes in the thickness of a low-density, gas-rich area located immediately beneath the active craters. Furthermore, there is enticing evidence of significant (up to 40 micro-gal) gravity changes over the period of a day which may be due to rapid changes in the level of magma in the conduit; the oscillations in magma level may be related to changes in the solid Earth tide. Thus, building on the experience gained at Kilauea this year, two continuously recording micro-gravity meters (as well as thermal infrared and infrasonic instruments) were installed at Masaya between February and March, 2002. Furthermore, in conjunction with an NSF-funded project (the PI for which is Andy Harris), this experiment investigated the dynamics of puffing and magma level variations (the Harris results for Stromboli volcano were published in Calvari *et al.*, 2005).

3. Gas Studies (led by Keith Horton, University Hawaii)

In this part of our project, we collaborated with Jeff Sutton and Tamar Elias, both from the HVO. A key component of our development work of the FLYSPEC instrument for measuring volcanic gases (Horton *et al.*, in press; Williams-Jones *et al.*, in press). The reason why this development work was under-taken is two-fold: first, we were trying to produce small instruments that can either be flown on a small airplane or carried easily

into the field. The most widely used instrument at the present time is the Correlation Spectrometer (or COSPEC) which is bulky and uses late 1970's technology. Key to Keith's effort has been the development of a UV spectrometer, which we tested on Kilauea in October in conjunction with a field experiment carried out by Jeff Sutton using HVO's COSPEC.

Our new instrument is designed to measure the downwelling scattered solar spectral radiance in the UV window between 300-330 nm in which SO₂ exhibits characteristic spectral absorption features, specifically at 302.1 nm, 304.1 nm, 306.5 nm, 308.6 nm, and 310.6 nm, and where atmospheric ozone absorption is sufficiently low and SO₂ absorption is sufficiently high to provide adequate signal-to-noise. By use of SO₂ calibration cells of known concentrations and application of Lambert-Beer's law, the column abundance of SO₂ gas can be measured in ppm.

Scattered solar radiation from the sky acts as the UV radiance source. Initial field tests indicate that an integration time of approximately one second provides adequate signal without saturation of the any pixels on the detector array. The software allows the user to collect data as individual spectra in ASCII files, or automatically collect a user specified number of spectra at a user specified interval into a binary file.

Analysis of the initial field data of the Kilauea plume showed that two assumptions/corrections are required which was applied to the data in the reduction process. One correction was that the data acquisition software was not making the detector array dark subtraction correctly, as there were residual counts in the ozone absorption region (<300 nm) where there should have been no signal. The other correction was that once the spectrum was reduced to "raw" absorbance through Lambert-Beer's law, the absorbance was normalized to zero in the region of 325 nm, where there is more than adequate signal from sunlight, but little or no absorption from SO₂, in order to account for time-variations in clouds, plume opacity, etc. COSPEC data were acquired continuously at 1 sec. intervals. Mini-COSPEC data were acquired manually for this experiment, although automated data collection is an option. Other members of the Team who are working on this part of the project are John Porter, Fred Prata (CSIRO, Australia), Harold Garbeil (Univ. Hawaii).

4. Aerosol studies (led by John Porter, Univ. Hawaii)

Our goal here was to develop methods whereby we can simultaneously measure the optical properties of the plume as well as the gases being released. Led by John Porter (Univ. Hawaii), our initial aerosol work has been conducted independent of the lava flow studies, the ultimate objective is to conduct an "end-to-end" study that enables us to correlate magma flux with gas flux and aerosol properties. Other Team Members included in this work are Clive Oppenheimer (Cambridge University, England) and Keith Horton.

Four passes under the Kilauea plume were carried out August 17th, 2001, when excellent cloud-free conditions prevailed. Sun photometer measurements were carried by stopping the vehicle at various points under the plume. Lidar measurements were made

continuously as the vehicle drove under the plume. A portable GPS system and PC was used to record the position and time of the vehicle. The sun photometer used was a five channel (380, 440, 500, 675, 870 nm) handheld Microtops which is fairly small and inexpensive. Figure 1 shows the sun photometer measurements obtained on the third pass. The plume can be seen passing just over and to the south of the hairpin turn with an essential repeat along the lower leg of the road. The other passes were very similar with some shifting in the position of the plume. A manuscript describing these results was published in *Geophysical Research Letters* (Porter *et al.*, 2002).

5. *Soil Science and Vegetation Studies (led by Nancy Dise, Open University and Luke Flynn, Univ. Hawaii)*

The final link in our investigation of the impact of active volcanism on the environment is the assessment of the damage done to the ecosystem by the volcanic plumes. The steady trade winds at Kilauea are responsible for very restricted areas of intense fumigation and vegetation kill-off. An important factor at all three of the volcanoes that we studied is the influence of topography. At Masaya, the localized kill-offs are most notable in areas where the plume is in direct contact with the vegetation. Where the plume is able to decouple from the surface (e.g., in the valley between two ridges, and past the Pacaya Ridge towards the Pacific), the effect is reduced. A similar relationship is visible at Poás and Kilauea. However, further work is required to fully constrain these effects as well as the differences between the “wet” (Poás, Kilauea) and “dry” (Masaya) volcanoes. We conducted sampling of different soil horizons downwind of Kilauea volcano. Soil horizons as much as 100 km from the vent were sampled and await analysis in England.

In order to investigate the environmental effects of persistent degassing, we used Landsat ETM+ and Ikonos images with NDVI and Tassled Cap band ratio algorithms to delineate poorly vegetated areas downwind of each volcano. These data were incorporated, through GIS, with digital elevation data, as well as various ground truth data (soil pH, dry deposition rates, precipitation acidity, etc.). Extremely distinct zones of vegetation “kill off” were noted. These appear to correlate with changes in topography. It appears as if sharp topographic changes allow the gas plume to decouple or couple with the ground, hence lessening or increasing its impact at any downwind location. The integrated study of degassing at persistently active volcanoes therefore appears to be an important social issue and of importance when attempting to limit the eruption’s effects on human populations and agriculture downwind of such systems. Better land management appears to be crucial if the impacts are to be reduced.

4. **Analysis of Satellite Data Sets**

Lori Glaze (Proxemy Research) had the main responsibility for the development of theoretical models and the analysis of remote sensing data to characterize the volcanic plumes. This is one of the primary links between the field studies described above and our ultimate goal of using satellite data sets to monitor and interpret the plumes coming from volcanoes. Her work focused on three broad areas of research, namely the development of a downwind dispersal model (to supplement work being done by Steve

Businger at the University of Hawaii using the HYSPLIT 5 model), the development of techniques for validating the application of convective plume models to volcanic sources, the collection and the analysis of MISR data sets for Kilauea and Masaya volcanoes. Summaries of these efforts now follow:

- (a) *Downwind dispersal modeling*: Most of the effort here has been directed toward the development of a model that predicts the concentrations of volcanic ash and aerosols at a variety of altitude levels as a function of time. The model took as input information on ambient wind conditions, plume height and particle size distributions.
- (b) *Validation of convective plume rise models*: Significant effort was directed towards establishing several criteria for identifying when the basic plume rise model will be violated. The most important aspect of this is that, although the maximum predicted plume heights seem reasonable, rise velocity, radius of the vent and the radial velocity of the plume must also be considered. A manuscript is currently in preparation that discusses the validity of convective plume rise models in various environments.
- (c) *MISR Data*: Efforts were directed toward obtaining MISR data for both Kilauea and Masaya volcanoes, and the topographic analysis of the imaged plumes. In this regard, Harold Garbeil (Univ. Hawaii) has also contributed to this work. There have been 18 images of Kilauea obtained between June 5th, 2000 and September 28th, 2001. For Masaya, 16 scenes have been obtained over the same time period. We worked with three images (i.e., data from all nine MISR cameras) for Kilauea and one for Masaya.

5. Atmospheric Modeling

Emissions from the Kilauea volcano pose significant environmental and health risks to the Hawaiian community. In Hollingshead *et al.* (2003) we simulated the concentration and dispersion of plumes of volcanic aerosol after they emanate from the Pu'u O'o vent of the Kilauea volcano. In order to produce an accurate regional forecast of the concentration and dispersion of volcanic aerosol, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HY-SPLIT) model was used. Wind fields and thermodynamic data from the non-hydrostatic Mesoscale Spectral Model (MSM) were employed as input for the HY-SPLIT model. A combination of satellite remote sensing, aircraft, and ground-based observations collected during a field experiment was used to validate the model simulation of aerosol distribution.

The HY-SPLIT model shows skill in reproducing the plume shape, orientation, and concentration gradients as deduced from satellite images of aerosol optical depth. Comparison of the modeled and observed values suggests that the model was able to produce reasonable plume concentrations and spatial gradients downwind of the source. Model concentrations were generally less than those observed on the leeward side of the Island of Hawaii. This deficiency may be explained by a lack of (i) background concentrations, (ii) local sources of pollution and/or (iii) sea-breeze circulation in the prognostic input wind field. These results represent early progress toward the goal of

future operational application of the HY-SPLIT model to predict volcanic aerosol concentrations in Hawaii. This may help mitigate their negative impacts of plumes respiratory health, agriculture, and general aviation.

Much progress was made on the SO₂ estimation algorithm and the application that runs this algorithm, as summarized below:

a. Spatially-Variable Optimal Water Vapor Correction

Water vapor is a persistent problem in thermal infrared (TIR) remote sensing, since this gas is a strong emitter/absorber of TIR radiation and the amount of water vapor in the atmosphere can vary from pixel to pixel. The effects of water vapor are especially acute in tropical regions, such as Hawaii and Central America, where the atmosphere is humid and warm.

Previous techniques to correct for the effects of water vapor on radiance measurements were subjective, labor-intensive, and global (i.e. did not accommodate the spatial variations in water vapor). The new technique is based on the principal that a "spectrum" of ground temperatures should show no variation with wavelength. If the emissivity of the ground is known, then variations in the ground temperature spectrum can be attributed to atmospheric absorption and emission. Using radiative transfer modeling, we can iterate with different amounts of water vapor until we achieve the flattest possible ground temperature spectrum.

We can never achieve a perfectly flat ground temperature spectrum without perfect prior knowledge of the atmospheric and ground conditions. The new technique gives us the best possible, or optimal, water vapor correction relative to our imperfect knowledge of these conditions. This strategy can also be employed to correct radiance measurements for the effects of ozone.

b. 3-Slab Plume Model

This new approach models the atmosphere in three slabs: one slab describing the atmosphere below the plume, one slab describing the plume, and one slab describing the atmosphere above the plume. The term "slab" is a bit of a misnomer, since the slabs above and below the plume can still contain multiple atmospheric layers. The plume slab contains a single layer.

One benefits of this new approach is a more accurate description of atmospheric pressure, temperature, and relative humidity within the plume slab. In addition, the 3 Slab Model allows us to plug the optical depths for aerosols, ice, and ash particles into the radiative transfer calculation. The ability to plug in parameters (calculated outside of MODTRAN) is the first step towards the simultaneous estimation of the gas, aerosol, and ash content of volcanic plumes and clouds.

c. MODIS Data

A new graphic interface was developed to facilitate the input of MODIS data to the SO₂ mapping tool. Users can input MODIS Level 1B files generated at a NASA DAAC (HDF-EOS format) or at a ground station using the IMAPP software package (vanilla HDF format). All of the necessary files, TIR radiance, true color radiance, and geo-reference, are extracted from the HDF files automatically and processed to the formats required by the SO₂ mapping algorithm.

The MODIS geo-reference (latitude and longitude grid) information is used to look up the elevation of pixels in a 1-km DEM. Previous versions of the mapping tool required a DEM to be registered to the image data – a labor-intensive procedure that created a unique DEM for each data. The new approach allows the same DEM to be used for any MODIS scene that is coincident with the region covered by the DEM.

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