Concentration and dispersion modeling of the Kilauea Plume

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Abstract

The goals of this research are to develop the capability to monitor and predict the dispersion of post-eruptive plumes of volcanic aerosol as they originate from the Pu'u'O'o vent of Kilauea Volcano, and to mitigate the impact of these aerosols on respiratory health and general aviation. A combination of satellite remote sensing, aircraft and ground-based observations were used to validate model concentration and dispersion results.

The objective of the modeling component is 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 for this purpose (Draxler and Hess 1998). The wind fields and thermal data from the non-hydrostatic Mesoscale Spectral Model (MSM) were used as input for the HY-SPLIT model (Juang 2000).

The HY-SPLIT model shows skill in reproducing the plume shape, orientation and concentration gradient as deduced from SeaWiF satellite imagery processed to show aerosol optical depth. Comparison of the model simulations and MICROTOPS II sun photometer data indicate that the model is able to forecast maximum and minimum plume concentrations. These results are promising for future operational applications of the HY-SPLIT model in vog forecasting.

Keywords: Vog, sulfate, aerosol, dispersion, Kilauea Volcano

Introduction

The Kilauea volcano on the Island of Hawaii is the longest actively erupting volcano in the world. Active since January 1983, the first four years of the eruption included sensational episodes of lava fountains. During the last 14 years Kilauea has remained in a more quiescent outgassing stage. Emissions from the volcano pose significant environmental and health risks to the Hawaiian community. These emissions go through several chemical transformations after they enter the marine boundary layer. The result is a perpetual plume of thick smoke or volcanic smog that is also known as vog. The vog plume is composed mainly of water vapor and sulfate particulates. The sulfate aerosol consists primarily of sulfuric acid, ammonium bisulfate and ammonium sulfate, decreasing in acidity respectively. The size distribution of these aerosol ranges from 0.1 - 0.6 µm, in the accumulation mode. Consequently, sulfate particulates are an effective size to reach down into the human lung (Morrow 1991). In the presence of high relative humidity in the human body the aerosol can readily expand up to three times its original size to further obstruct airways (Clarke & Porter 1997).

The presence of vog has been linked to irritation of the lungs, asthma, sinusitis,
respiratory disease, lung cancer and/or chronic obstructive pulmonary disease (Worth 1995). These sulfate particulates may also dissolve in liquid water (i.e. in cloud) resulting in acid rain, which has the potential to destroy crops and leach lead from roofs and plumbing. During episodes of increased sulfate production and atmospheric stability, vog may be thick enough to create a major visibility hazard to aircraft. In summary, vog is a significant threat to the Hawaiian community and a need for a prognostic tool is evident.

SO₂ emissions from Kilauea’s East Rift Zone (Fig. 1) have ranged from 1,000 to 7,000 tons of SO₂ per day during 1992 – 1998 (Elias et al. 1998). Hawaii Volcano National Park measurements of SO₂ reveal concentrations may reach up to 1300 PPB in a single hour and on average exceed 290 PPB per hour. This far exceeds the Environmental Protection Agency’s accepted health standard of 145 PPB over a 24-hour period. During the past 14 years, SO₂ East Rift Zone emissions have reached a maximum of 32,000 tons of SO₂ per day and at present average approximately 2,000 tons per day (Elias et al. 1998). Vog dispersion is primarily a function of synoptic and local wind patterns as well as stability of the environment. As SO₂ converts to sulfate particulates near the main vent, the prevailing northeasterly trade wind flow, along with the island blocking effects and daily sea-breeze regimes, advect the vog past South Point and into the Kona region of the island (Fig. 1a). The majority of the vog pollutants are trapped within the boundary layer due to the strong trade wind inversion. The trade wind inversion is a major synoptic feature associated with the persistent subtropical high-pressure system located to the northeast of the islands. Only during occurrences of weak inversions, strong trade winds or southerly winds, associated with fronts, shearlines or kona lows, will the pollution be sufficiently advected away.

1. Objectives

The primary goal of this research is to create a prognostic tool to aid in the prediction of vog plume concentration and dispersion. Validation of simulation results will be conducted using aerosol concentrations derived from aircraft and
ground-based data, as well as satellite imagery. Satellite imagery will be used to validate plume size, shape and location.

2. Approach

A field experiment was held on the Island of Hawaii on 25 and 26 January 2000, hereafter referred to as day one and day two respectively. Several instruments and techniques were employed during this experiment. For simplicity these are sectioned into three categories, aircraft data, ground-based observations, and satellite data. Microtops II sun photometer measurements were collected on day one aboard a Seneca airplane through the open window commencing at 0000 UTC 26 Jan (1400 HST on day one) at 20.47 North and 156.22 West (Fig. 2). The pilot maintained a roughly south-southwest heading at an altitude of ~100 - 200 meters. When the pilot experienced the thickest extent of the plume, he climbed to an elevation of approximately 2400 meters, well above the trade wind inversion (Porter, Clarke and Lienert 2000).

The ground-based data consists of sun photometer measurements observed during day one and day two also using a Microtops II Sun Photometer. During both days, mobile surface measurements were taken during daylight hours with north to south transects along the southern coastal regions, for brevity, only day two’s results will be shown here (Fig. 3).

Sun photometer measurements yield aerosol optical depths. In order to compare these data with model results, data conversion from optical depth to dry mass (µg m⁻³) was necessary. Calculations assumed an optical depth corresponding to average inversion layer heights (~ 2,000 meters). Calculations also assume ambient relative humidities of 65% - 80% (using 70% as a base value) during clear sky measurements and sulfate aerosol mass values of 2.21 – 17.39 grams expressive of volcanic plume and marine derived sulfates.

Satellite data in this experiment were used to document the shape, size, location and concentration of the vog plume. The satellite data used in this research were obtained by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), which
Satellite measured radiances over the ocean consist of water leaving radiance (~10-20%) and atmospheric radiance (80-90%). In deriving ocean color products, the main charge of the SeaWiFS project, a correction is needed to remove the satellite measured atmospheric radiance. This is accomplished by deriving the aerosol optical concentration and type at near IR wavelengths (760 and 870-nm) where the ocean is near opaque (Gordon 1997). As a byproduct of this effort the aerosol optical depth (at 870-nm) can be obtained from the SeaWiFS Data Analysis System program, which is frequently used to obtain reasonable estimates of aerosol optical depths and spatial distributions (Porter and Letelier 2001).

3. Results and Discussion

Hourly concentration maps were created from HY-SPLIT model output to illustrate plume evolution. The simulation results show skill in reproducing general plume evolution based upon synoptic conditions. Animation of the hourly concentration maps (Fig. 4) show the plume experienced a southwesterly motion as it was advected off the Kue’e coast. The movement continued to the west-southwest where the plume traversed South Point. The model consistently takes the maximum concentration of the plume over South Point, leaving a relatively clear slot over the very southern tip. The Kona coast experiences little sulfate advection before 1700 UTC on day one. This is due to the spin up time necessary to advect realistic concentrations this far from the source, since background pollution is not included in the model run. Plume eddies in the lee of the mountains are distinct on day two. This dynamic effect aids in advecting aerosol across the south Kona coast (eg. Fig. 4b). However, Figs. 4c and d

![Graph showing concentration evolution](image)

*Fig. 3 Model (bold solid) vs observed (thin solid) concentration values at waypoint locations. Error bars reveal relative humidity variances between 65-80% during optical depth to concentration calculations. Inset: 2000 January 26 Waypoint locations and times.*
indicate aerosol pooling just off the Kona coast with concentrations only on the order of 0.01 - 0.1µg m$^{-3}$. 

The satellite image for day two shows a narrow plume off the southeastern coast of the Island of Hawaii, extending over Honu’apu to Hali’ipalala, just missing Keauhou Point and South Point (Fig. 5a). The satellite image also shows a more constrained plume on day two, without the well defined gradient seen the day prior. Figure 5b shows model concentration output for the time period of the satellite image. As during day one and consistent with the satellite image, the plume orientation is east-northeast to west-southwest, however, only two concentration levels are evident, 0.01 and 1.0µg m$^{-3}$. The modeled plume extends further to the north and west than the previous day. The clear slots over the Keauhou Point and South Point are in good agreement with satellite
observations. The one obvious discrepancy seems to be the northwest extent of the modeled plume. It is possible that the MSM wind fields are underestimated in the lee of the mountains. If this is the case, particles will not be advected westward sufficiently, creating a pooling effect.

Figure 3 compares sun photometer observations to model output at corresponding locations. Modeled concentration output values were produced for the latitude and longitude locations of each of the waypoints (Fig.3) for comparison. Waypoints were determined via a hand held Global Positioning System (GPS). There is a 10 - 15 meter uncertainty in GPS horizontal calculations, well within the model resolution. Sun photometer readings in the Hilo and Puna areas (waypoints 1-4) average 4.55µg m\(^{-3}\); characteristic of low background concentrations. Modeled values in this area were several orders of magnitude smaller, consistent with their upwind placement. Sun photometer values remain at a low 2µg m\(^{-3}\) from waypoint 4 to 6. Small observed values downwind of the vent are likely due to residual drainage flow off the mountain during late morning (10:00 HST), advecting the aerosol plume offshore. Modeled values at these locations experience a strong spike up to 34µg m\(^{-3}\). Sun photometer data measured the heaviest aerosol burden between waypoints 7 and 12, consistent with visual observations, whereas the model placed the greatest extent of aerosol between waypoints 5 – 8. It appears the model plume is slightly misplaced, perhaps a reflection of a lack of representation of the diurnal land-breeze in the MSM wind field.

A decreasing aerosol content is observed from South Kona to North Kona with a maximum spike of 23.9µg m\(^{-3}\) at waypoint 10. Concentrations stay relatively constant at ~ 2 - 3µg m\(^{-3}\) for the duration of the journey, with concentrations reducing slowly northward. The exception is the slight spike of 7.1µg m\(^{-3}\) at waypoint 14. This increase is consistent with visual observation of increased haze passing through the Humu'ula Saddle between Mauna Loa and Mauna Kea. The sun photometer and model output concentrations for waypoints 11 – 20 show similar trends at the same order of magnitude.

For this research, the MSM provided required momentum and thermal fields ingested by the HY-SPLIT model, which then performed vog dispersion simulations. Insofar as the reliability of the HY-SPLIT model results depends on the accuracy of the output from the MSM, deficiencies in the MSM are reflected in HY-SPLIT results. Hawai'i's complex terrain, mesoscale organization of weather systems, and lack of observational data over the central Pacific create substantial challenges for mesoscale models like the MSM. These are subjects of active research, and progress in these areas will benefit vog dispersion modeling.

Model data show that the vog plume is advected by the synoptic flow from its origin, westward, past South Point where it stagnates due to light and variable winds over ocean in the lee of Mauna Loa. The MSM surface wind fields tend to remain light and variable in the lee of the mountainous terrain, inhibiting the aerosol from intruding upon the Kona coast. Aircraft data suggest that even in the area of aerosol pooling in the lee of Mauna Loa, concentrations were under-forecast. In this study, background concentrations were not included. A reasonable explanation for the lower model concentrations near the leeward coast is the fact that the vog event in this research was unusually persistent. An
extended period of southeasterly winds caused aerosol to accumulate for a considerable amount of time, raising background concentrations prior to the field experiment.

A secondary factor in the under-forecast of concentrations in the lee of the Island of Hawaii is more likely due to the uncertainty and difficulty in representing accurate SO2 to SO4 conversion rates. Conversion rates along the plume trajectory were not included in this study. A one-time conversion of SO2 to SO4 was calculated at the vent only based upon HVO COSPEC values during the time period. The modeled curve mimicked observed trends on the leeward side quite well at the same order of magnitude yet significantly overestimated aerosol content in the thickest extent of the plume. This indicates the necessity to implement a continuous conversion process along the plume trajectory with each time step. This is intuitive as the conversion process is time dependent and must be less than 100% due to the fact that the DOH monitoring sites do record downwind SO2 concentrations, albeit small, but still arguably representative of volcanic emission.

A significant diurnal cycle in the wind field was observed during the field experiment, because of light synoptic-scale trade winds and enhanced surface heating of the island. The thermally driven circulation that results is one of the key components enhancing aerosol build-up along the Kona coast. The absence of aerosol advection onto the leeward coast in the HY-SPLIT model can be traced to the MSM wind field.

**Conclusions**

Aircraft data confirm the importance of the trade wind inversion in trapping aerosols in the boundary layer, documented by the large drop in aerosol optical depth from 0.274 to below 0.023 (no units) when climbing from 151 meters to 2452 meters (Fig. 2). Comparisons between model and ground-based data indicate that the model replicates observed trends reasonably well from North Kona to South Kona. Comparison curves tend to be slightly out of phase but within the same order of magnitude from the source point westwards towards South Point. Sun photometer measurements show an average concentration in Hilo of 4.55µg m⁻³. Since Hilo remained upwind of the vent during the field experiment, these values reflect background concentration.

The model produced plume characteristics including size, shape, orientation, and concentration gradients consistent with those observed in satellite imagery. An interesting comparative result is the success of the model to reproduce the narrower-type plume and clear slots over Keauhou and South Point on day two seen in the satellite imagery (Fig. 5). Figures 4 and 5 suggest that the model performed best over the southern portion of the island and downwind over the ocean. As the MSM had difficulty resolving sea-breeze/land-breeze circulations and complex terrain effects on the leeward side, prognoses degraded with time and distance northward along the Kona coast.

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