Modulation of Cloud Droplets and Radiation over the North Pacific by Sulfate Aerosol Erupted from Mount Kilauea

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Abstract

Mount Kilauea in the Hawaiian Islands experienced an active eruption from March until the end of December 2008 and showed a large-scale impact on aerosol, cloud microphysical properties and atmospheric radiation over the North Pacific. We analyzed the atmospheric impact of this eruption based on the satellite retrievals and 3-D global chemistry-radiation coupled transport model. We showed that approximately 1.8 Tg (±1.2 Tg) release of SO2 was estimated from this eruption, which oxidized into sulfate aerosol during transport to the northwest Pacific Ocean. The volcanic sulfate aerosol layer covering a large area (~6.5 × 106 km2) of the lower troposphere over the North Pacific for several months was confirmed from both satellite and model results. Sulfate aerosols affected the formation of cumulus water clouds by reducing the typical cloud effective radius by ~23% and increasing the cloud fractional coverage over the ocean from 9.1% to 13.4% (over the region 170°E–160°W, 10°N–20°N). The affected cumulus clouds appeared whiter than normal and thus reflected more solar radiation. Consequently, satellite observations revealed an approximately 1% increase in albedo at the top of the atmosphere in the area along main volcano plume trajectory, which induced an approximately ~5 W m−2 change in the shortwave radiation budget.

1. Introduction

Modification of cloud properties by aerosols was first described by Twomey (1977). Recent increases in anthropogenic air pollutant emissions with small aerosol particles serving as cloud condensation nuclei (CCN) can result in a decrease in cloud particle size and an increase in the cloud optical depth of the constant liquid water content. Changes in aerosols have also impacted the global radiation budget, precipitation efficiency, and characteristics of atmospheric circulation and water cycles. A number of studies have attempted to monitor these effects using satellite sensors and ground instruments (e.g., Kawamoto et al. 2006; Costantino and Bréon 2010). However, direct and clear evidence of the interaction between aerosol emission and change in cloud properties under natural conditions is still limited.

Mount Kilauea Volcano began to erupt from a new vent in the summit (Halema‘uma‘u Crater) on 19 March 2008 and continued to release large amounts of volcanic gas until the end of 2008 (Swanson et al. 2009). SO2 was a major component of the volcanic gas from Mt. Kilauea (> 85% excluding H2O and CO2). Contribution of direct injection of fine-mode aerosols (e.g., organic carbon) is generally small (e.g., Miyazaki et al. 2011). The volcanic SO2 was oxidized to sulfate aerosol. The impact of the sulfate aerosol from this eruption on cloud microphysical properties was clearly observed by satellite (see Fig. 1). Mt. Kilauea is located in a clean maritime environment characterized by the steady easterly trade wind, ubiquitous cumulus clouds and without any large anthropogenic emission sources. This condition is ideal for studying the impact of aerosol on cloud physical and radiative properties. In this paper, we report our original findings from a comprehensive analysis using multiple satellite measurements and global aerosol transport model simulations for the 2008 eruption of the Mt. Kilauea volcano and its impact on cloud properties and the atmospheric radiation.

2. Observations and experimental setup

2.1 Satellite data

The satellite-borne Moderate-resolution Imaging Spectroradiometer (MODIS/Terra) provides both aerosol and cloud measurements (Remer et al. 2005). We used the standard products of the level 3 (Collection 5.1) aerosol optical depth (AOD) at 0.55 µm, the ratio of fine-mode AOD at 0.55 µm, the 0.55/0.867 µm Angstrom exponents, and the liquid water cloud fraction. The spatial resolution of these products is 1° × 1°. We retrieved cloud microphysical properties from the MODIS/Terra 3.7-µm band measurements using the Comprehensive Analysis Program for Cloud Optical Measurements (CAPCOM) with resolution of 0.25° × 0.25° (Nakajima et al. 2010). Vertical profiles of the cloud and aerosol layers are measured by the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (Winker et al. 2007, 2010). CALIOP is a two-wavelength, polarization-sensitive backscatter lidar. In this study, the level 2 CALIOP data (version 3.01) were used. The level 2 data products provide vertical profiles of the aerosol extinction coefficient at 532 nm and cloud layer height information. To reduce observation noise, 2 months (July and August) of nighttime CALIOP data within each 10° longitudinal band were averaged and spatially smoothed to generate latitudinal and vertical aerosol distribution curves.

The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) provides SO2 vertical-column density (VCD) data with a spatial resolution of 60 km × 30 km. We used monthly averaged SO2 data at gridded coordinates of 0.25° × 0.25°. Emissions from Mt. Kilauea contained a high concentration of SO2, and the eruption plume was primarily transported in the upper part of the trade wind cumulus layer (height between 1.6 km and 3.0 km, see also Fig. 3) above planetary boundary layer, thus permitting precise estimation of SO2 concentrations (e.g., Richter et al. 2006). The SCIAMACHY level 3 data including the uncertainty information (version 1.1.3) were obtained from the Support to Aviation Control Service (SACS) data archive service (http://sacs.aeronomie.be/archive/).
2.2 Model and experiment setup

To evaluate the detailed impact of sulfate aerosol from Mt. Kilauea, we used the Spectral Radiation Transport Model for Aerosol Species (SPRINTARS), a three-dimensional global aerosol transport model (Takemura et al. 2005). This model simultaneously treats the major tropospheric aerosol components, including carbonaceous particles, sulfate, soil dust, and sea salt. In this study, the horizontal resolution of triangular truncation was set to T106 (~100 km). The model contains 20 vertical layers up to the sigma level of 0.01 (~10 hPa). Meteorological boundary conditions were taken from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data with 2.5° × 2.5° resolution at 6-h intervals. Three-hour average modeled aerosol and cloud properties were produced for use in our analyses. For the emission inventory, we used the scenario A2 estimate for the year 2000 from the Intergovernmental Panel on Climate Change (IPCC) Special Reports on Emission Scenarios (SRES) (Nakicenovic and Swart 2000).

SPRINTARS experiments were conducted for two time periods between July and September in 2007 (before the eruption) and in 2008 (during the eruption). An additional sensitivity experiment without SO\textsubscript{2} emissions from Mt. Kilauea was also performed for 2008. In the model, the SO\textsubscript{2} release height (equally distributed between the top of vent and 2600 m above sea level) was adjusted so that the best match with the MODIS AOD distribution was achieved. We estimated the SO\textsubscript{2} emission from the Mt. Kilauea eruption to be 1.8 Tg (±1.2 Tg) during the eruption based on the best match between the SCIAMACHY SO\textsubscript{2} VCD distribution and SPRINTARS simulation results (see Supplement Fig. S1). This SO\textsubscript{2} emission level corresponds to approximately 7% of the total SO\textsubscript{2} emissions from mainland China during 2008 (Lu et al. 2010) and is significant because it was released from a single point source into the remote clean maritime atmosphere.

3. Results and discussion

Figure 1 shows the MODIS measurements for August 2008. A significant increase in fine-mode AOD (maximum of 0.3) is evident in the downwind region extending from the Hawaiian Islands to the western North Pacific, with a zonal extent of 5000 km and a meridional extent of 1500 km (area of AOD increment > +0.02 after eruption). SCIAMACHY SO\textsubscript{2} VCD showed an SO\textsubscript{2} plume extending approximately 1800 km downwind from the Hawaiian Islands (inset plot in Fig. 1a and Supplement Fig. S1).

Figure 2 shows the differences between 2007 and 2008 for the AOD and the water-cloud droplet effective radius (CDR) retrieved from the MODIS measurement and SPRINTARS simulation.

We found that the agreement between model simulation and MODIS observation is good near downwind region of the Hawaiian islands along the main plume trajectory (upto 180°E), with a negative correlation between CDR and AOD. However, as the downwind distance increases, the disagreement becomes larger (especially the region south of 15°N). Major reasons of this disagreement could be due to the limitation of model resolution (both horizontal and vertical dimensions) and sub-grid scale parameterizations (e.g., cumulus cloud and wet depositions). However, our main purpose of model application is to confirm that the impact of SO\textsubscript{2} emission from Kilauea eruption covered large area of the North Pacific Ocean. In this sense, model results successfully described its impact. As long as we are restricting the detailed examination region near main plume trajectory, model results are sufficient to have a qualitative discussion.

The volcanic aerosol layer had a relatively high optical depth and persisted over a large area of the remote North Pacific, where cumulus clouds are ubiquitous. This case provides an excellent opportunity to study the possible interaction of volcanic aerosols and cumulus clouds. Trade winds are dominant around the Hawaiian Islands. Cumulus convection is active in this region because of the warm sea surface temperature (SST). Shallow cumulus layers (trade wind cumulus) are prevalent because the air near ~2 km, corresponding to the trade wind inversion, is mostly stable and dry and thus favorable for cumulus cloud formation below this altitude (Johnson et al. 2001). The trade wind cumulus distributed at 1.2–2.2 km altitudes at 155°W and 1.6–2.6 km altitudes at 175°W were observed in the latitude range of 10°N–20°N by CALIOP. We found that the aerosol layers extended vertically from the ocean surface to ~2 km in 2007, while in 2008 the top of the aerosol layers reached a height of ~3 km near Hawaii. The differences between 2008 and 2007 should be mainly due to the Mt. Kilauea eruption. The volcanic aerosol layer vertically extended for 1.4–2.0 km around 160°W (Fig. 3a) and 1.6–3.0 km around 180°W (Fig. 3b; see also Supplement Fig. S2 for 3-D view). This indicates that, although the vent of the Kilauea volcano was low (~1 km), because of plume buoyancy, volcanic gas/aerosol
was mainly transported in a height range (1.6−3.0 km above sea level) that overlaps with the upper area of the trade wind cumulus layer. At this height range, volcanic aerosols may have influenced cumulus formation. Supplement Fig. S2 also shows the 2008 and 2007 fine-mode AOD differences recorded by MODIS (horizontal plate), clearly showing that the volcanic aerosol layer impacted a large area of the northwest Pacific.

The effect of aerosol particles on the cloud radius and properties such as the cloud condensation nuclei (CCN) is known as the Twomey effect (Twomey 1977). To examine this effect, the CDR with cloud top temperatures > 273.15 K was retrieved from MODIS 3.7-µm band measurements using the CAPCOM algorithm. Figures 1 and 2 show the CDR distribution and the difference between August of average in 2003−2007 and 2008. Over the region 170°E−160°W, 10°N−20°N, the average CDR was 17.6 µm in 2003−2007 before the eruption and decreased to 13.7 µm (~23% decrease) during the eruption. Meanwhile, the averaged cloud fractional coverage increased from 9.1% (variation range by 8.2−9.9%) in 2003−2007 to 13.4% in 2008 (a relative increase of ~37%). These results suggest that the volcanic aerosol has influenced the water cloud droplet size. The aerosol index (AI), defined as the product of MODIS AOD and the Ångström exponent, is a measure of the aerosol column number concentration (Nakajima et al. 2001). We used AI as a proxy for CCN to quantify this effect. Figure 4 shows the relationship between CDR and AI for measurements in the study region. The CDR rapidly decreased as the volcanic aerosol number (i.e., AI) increased. For the smoke aerosols over the Atlantic Ocean transported from African biomass burning activities, a relationship of CDR = 5.4 AI−0.24 was estimated by POLDER and MODIS data (Costantino and Bréon 2010). Differences in the regression can be expected because of the differences in the aerosols, clouds type (stratocumulus) and satellite sensor between the studies.

Observation sites over the open ocean are limited, making it difficult to validate modeled values at the surface. Conversely, the albedo at the top of the atmosphere (TOA), an important parameter in estimating the radiation budget, is relatively easy to retrieve from satellites. The Clouds and the Earth’s Radiant Energy System (CERES) SYN1deg product provides temporally interpolated TOA fluxes. We examined change of the CERES/Aqua SYN1deg TOA albedo data between the average of August 2003−2007 and 2008, shown in Fig. 5 based on satellite measurements and modeling. Here we used Aqua data to detect a better cumulus cloud modulation study with sulfate aerosol interaction because of its suitable flyover time (13:30 LT). West of the Island
of Hawaii (170°W–155°W, 18°N–20°N), both observed and simulated results demonstrate an approximately +1% increase in albedo attributable to the change in cloud microphysics and the cloud fractional coverage. Note that the large positive anomaly in the upper left region in Fig. 5a was caused by high frequency of long-range transport of Asian pollutant in 2008 and was not related to the Mt. Kilauea eruption. Downward shortwave radiation at the TOA over Hawaii is about 440 W m$^{-2}$ (daily average), and a +1% increase in albedo will yield a ~4.4 W m$^{-2}$ change in the radiation budget. SPRINTARS simulation showed a cooling effect at the TOA of approximately ~5 W m$^{-2}$ during the August of 2008 (Fig. 5c), which is consistent with the changes expected with the increased albedo.

4. Summary and conclusions

We found that volcanic SO$_2$ produced by the eruption of Mt. Kilauea from March to late December 2008 formed a persistent, relatively thick sulfate aerosol layer with an AOD of 0.1–0.3 that extended over a large area of the central to western North Pacific. Our analyses based on multiple satellite measurements and global aerosol transport model simulations clearly reveal the entire process of SO$_2$ emission and transport, and the formation of the volcanic aerosol layer. Our results also clearly provide direct evidence of the Twomey effect, which can significantly alter the microphysical and radiative properties of cumulus clouds, consequently exerting an indirect effect on the radiation balance, which ultimately influences the oceanic environment. We also quantified the relationship between the cumulus cloud droplet size and the surrounding sulfate aerosol using a large dataset of multiple satellite measurements. The established formulation will provide an important foundational reference for climate change studies (IPCC 2007).

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Supplements

Supplement 1 describes the SO$_2$ VCD near Hawaii Islands, monthly variation of SO$_2$ VCD with error bar, and comparisons between satellite retrievals and model results of SO$_2$ VCD. Supplement 2 shows three-dimensional view of aerosol distributions over the North Pacific downwind of the Hawaii Islands.

References


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