Western Pacific Air-Sea Interaction Study

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Eruption of Mt. Kilauea Impacted Cloud Droplet and Radiation Budget over North Pacific

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Introduction

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. The volcanic SO_2 was oxidized to sulfate aerosol. The impact of the sulfate aerosol from this eruption on cloud microphysical properties was clearly observed by satellite. Mt. Kilauea is located in a clean maritime environment characterized by a 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. 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.

Methods

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 Ångström exponents, and the liquid water cloud fraction. The spatial resolution of these products is $1° \times 1°$. We retrieved cloud microphysical properties from the

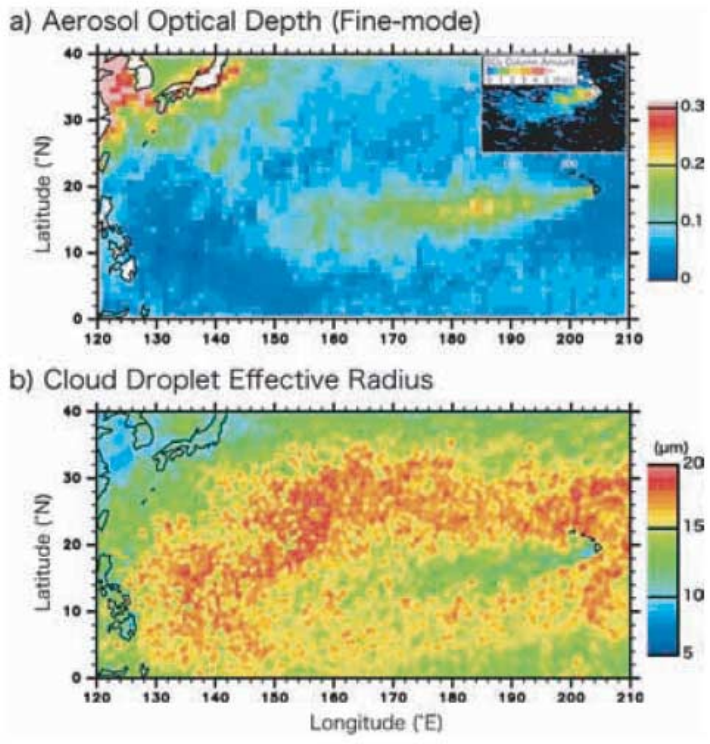

Fig. 1. (a) Fine-mode aerosol optical depth (550 nm) for August 2008 MODIS. (b) Cloud effective radius retrieved from the MODIS 3.7-μm band.

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). 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 curtains.

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). 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). 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_2 emissions from Mt. Kilauea was also per-

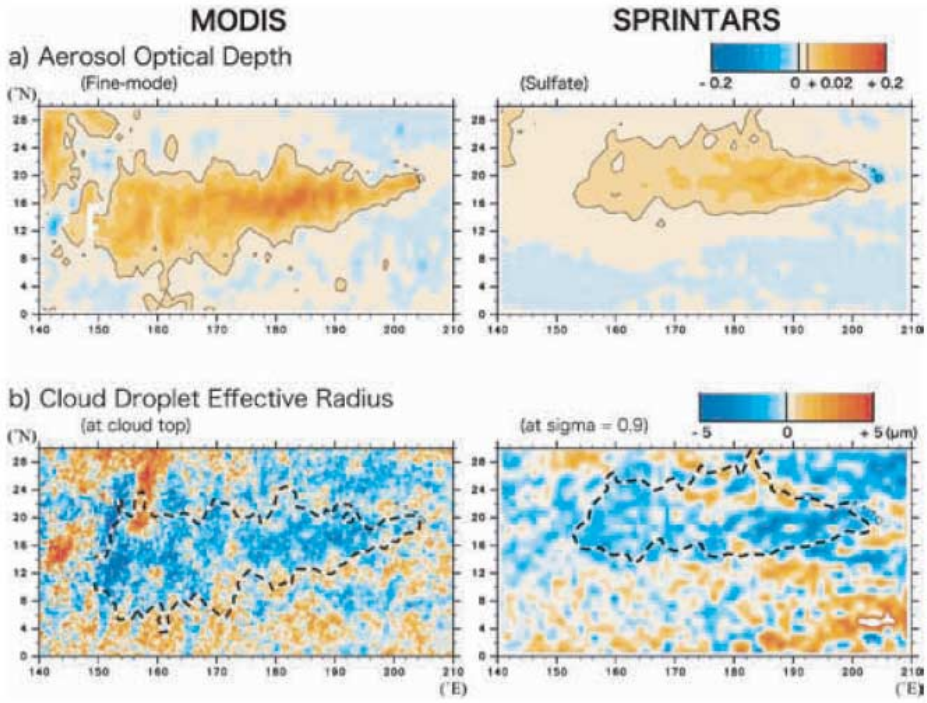

Fig. 2. MODIS (left) and SPRINTARS (right) changes between August 2007 and August 2008. (a) AOD difference, and (b) water-cloud effective radius difference.

formed for 2008. In the model, the SO_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 measured was achieved. We estimated the SO_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_2 VCD distribution and SPRINTARS simulation results. More details of model and analysis methods were already reported in Eguchi *et al*. (2011).

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). 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.

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). We found, from the

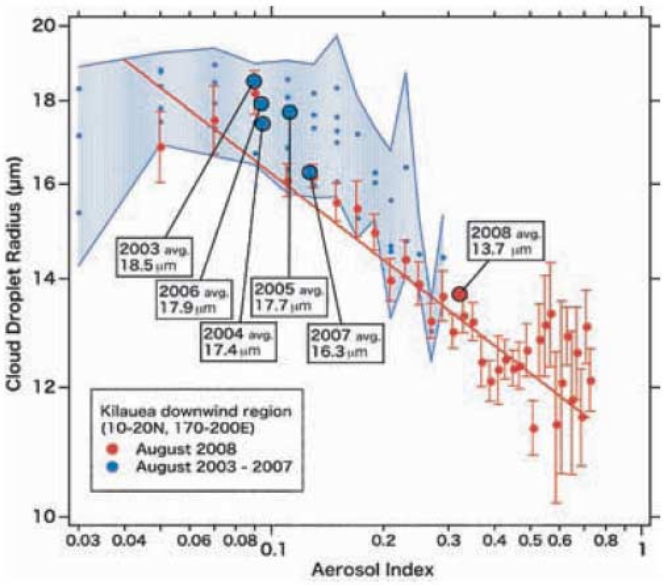

Fig. 3. Statistical relationship of the aerosol index (AI) and the water-cloud droplet effective radius (CDR) for August 2008 (red solid circles) and August 2003–2007 (blue solid circles) over the region of 170°E–160°W, 10°–20°N.

CALIOP analysis, 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 mainly be due to the Mt. Kilauea eruption. These indicate 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.

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 the August average in 2003–2007 and 2008. Over the region 170°E–160°W, 10°–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. We used AI as aproxy for CCN to quantify this effect. Figure 3 shows the relationship between CDR and AI. It can be approximated by CDR = 10.8 $AI^{-0.19}$ for measurements in the study region. The CDR rapidly decreased as the volcanic aerosol number (i.e., AI) increased.

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.

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