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Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-Train

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Abstract. Increased aerosol concentrations can raise planetary albedo not only by reflecting sunlight and increasing cloud albedo, but also by changing cloud amount. However, detecting aerosol effect on cloud amount has been elusive to both observations and modeling due to potential buffering mechanisms and convolution of meteorology. Here through a natural experiment provided by long-term degassing of a low-lying volcano and use of A-Train satellite observations, we show modifications of trade cumulus cloud fields including decreased droplet size, decreased precipitation efficiency and increased cloud amount are associated with volcanic aerosols. In addition we find significantly higher cloud tops for polluted clouds. We demonstrate that the observed microphysical and macrophysical changes cannot be explained by synoptic meteorology or the orographic effect of the Hawaiian Islands. The "total shortwave aerosol forcin", resulting from direct and indirect forcings including both cloud albedo and cloud amount, is almost an order of magnitude higher than aerosol direct forcing alone. Furthermore, the precipitation reduction associated with enhanced aerosol leads to large changes in the energetics of air-sea exchange and trade wind boundary layer. Our results represent the first observational evidence of large-scale increase of cloud amount due to aerosols in a trade cumulus regime, which can be used to constrain the representation of aerosol-cloud interactions in climate models. The findings also have implications for volcano-climate interactions and climate mitigation research.

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1 Introduction

Aerosols directly modify planetary albedo by absorbing and scattering solar radiation often referred to as the "aerosol direct effect" (McCormic and Ludwig, 1967). Increased aerosols are also expected to increase cloud droplet concentration, total droplet cross-sectional area and therefore cloud albedo for warm clouds, labeled the Twomey effect (Twomey, 1977). Moreover, increased aerosol concentration can enhance cloud macro-physical properties such as cloud amount (referred to as "cloud amount effect" here) and cloud organization (Albrecht, 1989; Stevens and Feingold, 2009; Feingold et al., 2010). Both the Twomey effect and cloud amount effect are collectively referred to as aerosol indirect effects. Aerosol direct and indirect effects constitute a strong yet still highly uncertain forcing to the climate system in a global sense (Anderson et al., 2003; Forster et al., 2007). Estimating the combined direct and indirect aerosol forcing, especially the indirect component, with sufficiently narrow error bars remains one of the largest challenges for understanding climate change.

The cloud amount effect is built upon this chain of events: enhanced aerosol loading increases warm cloud droplet number concentration and decreases droplet size (Twomey, 1977; Heymsfield and McFarquhar, 2001), an increase in droplet number decreases precipitation efficiency (Albrecht, 1989; Rosenfeld, 1999; Andreae et al., 2004), and cloud amount increases with decreasing precipitation efficiency (Albrecht, 1989). While the Twomey effect on warm clouds has been well documented, the cloud amount effect has eluded efforts of observational detection and attribution since its original proposal (Albrecht, 1989), which contributes critically to the current uncertainty. This is because a myriad of processes and factors such as entrainment, droplet sedimentation, time

scale and cloud scale dynamics can counteract the proposed chain reaction and result in unexpected changes in cloud macro-properties due to increased aerosols (Stevens et al., 1998; Ackerman et al., 2004; Bretherton et al., 2007; Wood, 2007; Feingold et al., 1996; Lu and Seinfeld, 2005; Xue and Feingold, 2006). Moreover, for observed correlations between aerosols and cloud amount, alternative explanations such as co-varying meteorology and retrieval artifacts can be proposed that do not invoke physical connections between aerosol and clouds (Brenguier et al., 2003; Mauger and Norris, 2007; Rauber et al., 2007; Loeb and Schuster, 2008; Yuan et al., 2008; Quaas et al., 2009). A multi-model comparison study also highlights the difficulty and uncertainty in modeling this effect in general circulation models (Quaas et al., 2009). Stevens and Feingold (2009) provide an excellent overview of the complexity and subtlety related to the cloud amount effect.

Most previous studies of cloud amount effect have focused on stratocumulus clouds because of their high cloud fraction and extensive coverage. Trade cumulus clouds as the other major oceanic warm cloud regime are relatively underinvestigated. However, trade cumulus can be found over larger areas as compared to stratocumulus although cloud fraction is lower (Norris and Slingo, 2009). More importantly, the cloud amount effect (or indirect effects in general) may depend on cloud regimes (Stevens and Feingold, 2009). It is thus suggested that an ideal way to study aerosol indirect effects is through the use of natural experiments focusing on a particular cloud regime (Stevens and Feingold, 2009). In this study we explore aerosol effects on trade cumulus clouds.

In this study we present results on aerosol cloud amount effect caused by a long-lasting volcanic degassing event. We will document the observed changes in cloud and precipitation properties related to cloud amount effect. The rest of the paper is organized as follows. In Sects. 2 and 3 we will describe the volcanic event, and then the data and methods of analysis, respectively. In Sect. 4, we will present results. Discussions of possible orographic effects and further evidence for aerosol effects will be presented in Sect. 5. Conclusions and final remarks will be presented in Sect. 6.

2 The natural experiment

The Halemaumau Crater of the Kilauea volcano on the Big Island of Hawaii (19°34′ N, 155°30′ W) has been active since March 2008. The volcano is actively degassing sulfur dioxide from the crater vent, located at an altitude of 1200 m. The gas is carried downwind and forms a large plume of sulfate aerosols reaching as far as 6000 km downwind as shown in Fig. 1. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) data show that the aerosol plume stays within the lowest 2 km layer.

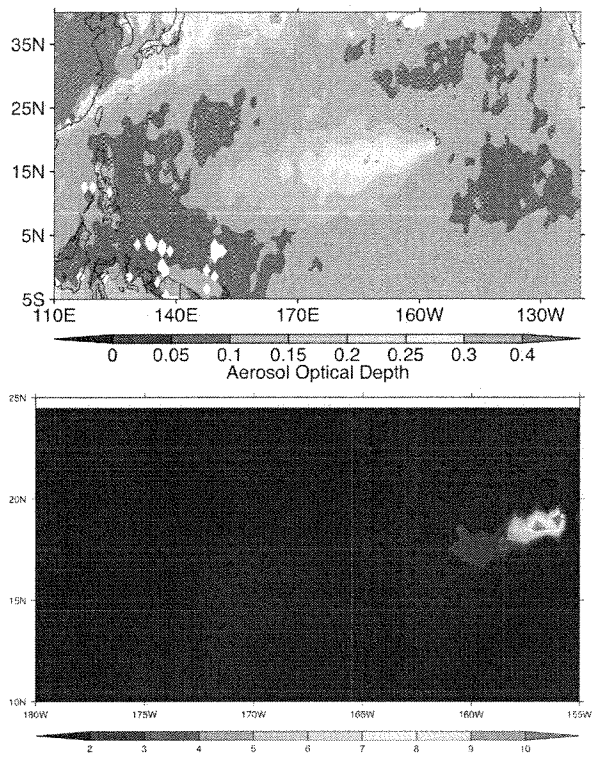

Fig. 1. The plume originating from the Halemaumau Crater of the Kilauea volcano on the Big Island of Hawaii (19°34′ N, 155°30′ W) as evidenced in **(a)** MODIS aerosol optical depth and **(b)** OMI SO_2 (in Dobson Unit) maps averaged over June, July, August 2008. The plume of aerosol optical depth extends as far as the Marshall Islands. The plume of SO_2 is less extensive presumably because of the transformation of SO_2 into sulfate particles during the course of transport.

The volcanic degassing of Halemaumau creates a natural laboratory where we can observe the consequences of adding aerosols to a relatively clean boundary layer over a broad region and during a long time period. Anthropogenic aerosols have minimal impact on this region in the summer due to the strong subtropical high-pressure system and weak source strength from Hawaii. The background aerosol loading of this region is very low (Fig. 1). The non-absorbing nature of volcanically produced sulfate aerosols avoids the complication from aerosol absorption (Ackerman et al., 2000; Koren et al., 2004; Kaufman and Koren, 2006; Feingold and Siebert, 2009). Most importantly, the volcanic activity producing the aerosol plume is entirely independent of air mass properties (Gasso, 2008). We can thus largely avoid the important problem of spurious correlation between observed aerosol and cloud properties created by the co-varying large-scale meteorology (Brenguier et al., 2003; Lohmann et al., 2006; Loeb and Schuster, 2008; Stevens and Feingold, 2009).