



# International Max Planck Research School on EARTH SYSTEM MODELLING

The Relative Influences of Volcanic and Anthropogenic Emissions on Air Pollution in Indonesia as Studied With a Regional Atmospheric Chemistry and Climate Model

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## Abstract

The regional atmospheric chemistry and climate model REMOTE has been used to study air pollution in Indonesia. The transport, deposition, and interactions between and relative impacts of emissions from volcanic, anthropogenic, and biomass burning sources have been examined.

The atmospheric loss of volcanic emissions has been shown to be dependent on meteorological conditions and the solubility in water of a given compound. The average annual mean  $\text{SO}_2$  loss rate of the Indonesian volcanoes is  $1.1 \times 10^{-5} \text{ s}^{-1}$ , or an e-folding rate of approximately 1 day. This loss rate was found to vary seasonally, be poorly correlated with wind speed, and uncorrelated with temperature or relative humidity. 53 % of the loss of  $\text{SO}_2$  is due to conversion to  $\text{SO}_4^{2-}$ , 42 % due to dry deposition, and 5 % due to lateral transport away from the dominant direction of plume travel.  $\text{PbCl}_2$  was used as a representative of highly-soluble volcanic compounds and compared with volcanic S to better understand how the solubility of volcanic emissions influences their deposition. High concentrations of  $\text{PbCl}_2$  are predicted to be deposited near to the volcanoes while volcanic S travels further away until removal from the atmosphere primarily via the wet deposition of  $\text{SO}_4^{2-}$ . The ratio of the concentration of  $\text{PbCl}_2$  to  $\text{SO}_2$  is found to exponentially decay at increasing distance from the volcanoes. In order to estimate the emission flux of compounds that are not measurable by remote sensing instruments, it is the standard experimental technique to relate remote sensing observations of  $\text{SO}_2$  flux from a volcano to the ratio of S to other compounds measured in fumarolic emissions. Assuming that the ratio between the concentrations of highly soluble volcanic compounds and  $\text{SO}_2$  within a plume is equal to that observed in fumarolic gases is justified at the distances of  $< 30 \text{ km}$  where such remote sensing observations are typically made.

The interactions of "background" anthropogenic and volcanic pollution with emissions from the catastrophic Indonesian wildfire of 1997 were studied by conducting experiments including and excluding the source of interest. It was found that the atmospheric concentrations of  $\text{O}_3$ , CO,  $\text{NO}_2$ , and  $\text{SO}_2$  were all increased above the levels generated by the fires by pollution from major cities in the region. The number of days and the distance from the fires where  $\text{O}_3$  exceeded the Indonesian hourly air quality standard were increased as a result of this urban pollution.  $\text{O}_3$  produced by the urban emissions is shown to enhance the conversion of  $\text{SO}_2$  released by the fires to  $\text{SO}_4^{2-}$ , demonstrating that pollution from different sources are actively altering the atmospheric behavior and lifetime of each other. Volcanic emissions had little influence on surface pollution during the wildfires or on fire emissions.

In order to study the effects of air pollution in Indonesia under more typical conditions than those of the extreme wildfire of 1997, the year 1999 has been examined. In this meteorologically normal year, anthropogenic S has been shown to be deposited above a critical

load value of  $0.4 \text{ g(S)}/\text{m}^2\text{-yr}$  in Java, northeastern Sumatra, and peninsular Malaysia. Volcanic S is found to be deposited below this threshold. Anthropogenic  $\text{SO}_4^{2-}$  is calculated to have an annual mean direct shortwave radiative forcing of  $-0.063 \text{ W}/\text{m}^2$  averaged over the model domain, and volcanic  $\text{SO}_4^{2-}$   $-0.012 \text{ W}/\text{m}^2$ . The forcing efficiency of anthropogenic  $\text{SO}_4^{2-}$  is found to be greater than for volcanic when averaged over ocean + land, with annual mean values of  $-328 \text{ W}/\text{g}(\text{SO}_4^{2-})$  and  $-293 \text{ W}/\text{g}(\text{SO}_4^{2-})$  respectively. Over Java, the anthropogenic  $\text{SO}_4^{2-}$  forcing efficiency is greater than the volcanic due to the enhancement of negative forcing efficiency over the ocean, as the anthropogenic sulfate is transported over the ocean while the volcanic tends to remain on land. The forcing of the total anthropogenic aerosol was calculated by assuming an external mixture of  $\text{SO}_4^{2-}$ , organic carbon (OC), and black carbon (BC), indicating an annual mean forcing of  $-0.13 \text{ W}/\text{m}^2$  averaged over the model domain. The total anthropogenic forcing is dominated by OC released by biomass burning. The influence of volcanic emissions relative to anthropogenic emissions on acid deposition and on direct radiative forcing is found to be lower in this study than in previous studies. This is attributed to an increase in anthropogenic emissions due to the simulation of the year 1999, as Indonesian anthropogenic emissions are increasing, the use of modern, realistic emission inventories, including a volcanic inventory with reduced emissions compared to earlier assessments, and the inclusion of biomass burning as an anthropogenic source.