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**Indonesian volcanic
emissions**

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Atmospheric transport and deposition of Indonesian volcanic emissions

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Abstract

A regional climate model study has been performed to investigate the transport and atmospheric loss rates of emissions from Indonesian volcanoes and the sensitivity of these emissions to meteorological conditions and the solubility of the released emissions. Two experiments were conducted: 1) volcanic sulfur released as primarily SO₂ and oxidation to SO₄²⁻ determined by considering the major tropospheric chemical reactions; and 2) PbCl₂ released as an infinitely soluble passive tracer. The first experiment was used to calculate SO₂ loss rates from each active volcano resulting in an annual mean loss rate for all volcanoes of $1.1 \times 10^{-5} \text{ s}^{-1}$, or an e-folding rate of approximately 1 day. SO₂ loss rate was found to vary seasonally, be poorly correlated with wind speed, and uncorrelated with temperature or relative humidity. The variability of SO₂ loss rates is found to be correlated with the variability of wind speeds, suggesting that it is much more difficult to establish a “typical” SO₂ loss rate for volcanoes that are exposed to inconsistent winds. Within an average distance of 69 km away from the active Indonesian volcanoes, 53% of SO₂ is lost due to conversion to SO₄²⁻, 42% due to dry deposition, and 5% is lost due to lateral transport away from the dominant direction of plume travel. The solubility of volcanic emissions in water is shown to have a major influence on their atmospheric transport and deposition. High concentrations of PbCl₂ 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 H₂SO₄. The ratio of the concentration of PbCl₂ to SO₂ is found to exponentially decay at increasing distance from the volcanoes. The more rapid removal of highly soluble species should be considered when making observations of SO₂ in an aged plume and relating this concentration to other volcanic species. An assumption that the ratio between the concentrations of highly soluble volcanic compounds and S within an aged plume is equal to that observed in fumarolic gases will result in an overestimation of the atmospheric concentration of highly soluble species.

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1. Introduction

Volcanic emissions can have significant environmental effects on local, regional, and global scales dependent on how far the emissions are transported away from source prior to deposition. Characteristics of emissions, such as chemical and physical properties (including solubility and size), as well as environmental factors, i.e. the height at which emissions are released, wind speed, and precipitation, all influence transport.

Volcanic emissions can be released continuously by passive degassing or diffusive eruptions. Emissions can also be released sporadically by more violent, and short-lived, eruptions. [Andres and Kasgnoc \(1998\)](#) have calculated that 99% of volcanic SO₂ is released continuously, while only 1% is released during sporadic eruptions. The most violent of the sporadic eruptions can inject volcanic emissions into the stratosphere: there is generally at least one such stratosphere-reaching eruption every three years ([Simkin and Siebert, 1994](#)). Stratosphere-reaching eruption clouds generally cause global surface cooling for months up to a few years by sulfate aerosol (SO₄²⁻) backscattering of incoming shortwave solar radiation (e.g. [Textor et al., 2003](#)). Compared with stratosphere-reaching eruptive emissions, volcanic emissions released into the troposphere are rapidly deposited locally and regionally. Tropospheric volcanic emissions can have a significant atmospheric impact because such emissions are frequently released continuously for long periods of time, and because volcanoes are often at elevations above the planetary boundary layer, allowing those emissions to remain in the troposphere longer than, for example, most anthropogenic S emissions. As an example of the relative significance of non-eruptive volcanic degassing, such sources may be responsible for 24% of the total annual mean direct radiative top-of-atmosphere forcing ([Graf et al., 1997](#)).

Volcanic emissions are primarily H₂O, followed by CO₂, SO₂, HCl, and other compounds (e.g. [Bardintzeff and McBirney, 2000](#)). Volcanic SO₂ has been the most monitored volcanic emission because the concentration of SO₂ within a volcanic plume is typically orders of magnitude greater in concentration than what is found in background

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ambient air. For the past few decades the majority of volcanic SO₂ observations have been performed with the Correlation Spectrometer (COSPEC), which measures the flux of emitted SO₂ (e.g. Stoiber et al., 1983). The (relatively) large number of published measurements of volcanic SO₂ fluxes is a useful tool for assessing the impact of volcanoes on the atmosphere because SO₂ is an environmentally important gas. SO₂ is readily converted, within days, to SO₄²⁻ aerosol. SO₄²⁻ is climatically significant (as described above when released explosively) and is a main component of acid rain.

Methods for observing tropospheric volcanic emissions include ground-based remote sensing, fumarolic gas sampling, and plume particle sampling. These techniques have contributed successfully to an improved understanding of the variations in time and between different volcanoes of emission compositions and strengths and, to a lesser extent, about processes occurring within volcanic plumes. There are, however, limitations to what can be accomplished in the field. For example, ground-based remote sensing measurements of volcanic SO₂ fluxes over time at one volcano can be used to observe changes in volcanic activity as an eruption prediction tool in conjunction with other volcano monitoring techniques (e.g. at Montserrat; Young et al., 2003). Remote sensing observations can detect that there is a change in the measured SO₂ flux, but cannot determine what observed variations are due to changes in the volcano itself and what are due to changing meteorological conditions. It can also be very difficult to determine what atmospheric processes are responsible for observed changes within a volcanic plume. One method of studying the loss of volcanic emissions from the atmosphere is to observe the variation of SO₂ concentration within a plume as the emissions move away from a volcano. A field-based method of characterizing this is to make measurements of atmospheric SO₂ at two distances away from a volcano, and to then relate these observations. SO₂ can be lost due to oxidation to SO₄²⁻ or dry deposition, or it can appear to be lost due to lateral transport out of the observed plume. Ground-based remote sensing observations can measure the rate at which SO₂ is lost, but cannot measure to what extent each of the potential loss mechanisms have contributed to the SO₂ loss.

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Atmospheric chemistry modeling can be a useful tool to study processes occurring in the vicinity of active volcanoes that are difficult to measure directly. For example, modeled volcanic emission transport can be analyzed in light of variable meteorological conditions while the volcanic emissions are held constant. This removes the inherent natural variability of volcanic emission rates, so as to learn about what variations in atmospheric transport are due to changing atmospheric conditions rather than due to changes in the volcanic activity. Modeling can also be used to calculate what portion of SO_2 lost from the atmosphere at increasing distances from active volcanoes is due to each of the mechanisms described above. Model experiments can further be used to study the transport and deposition patterns of volcanic emissions other than SO_2 . Volcanic SO_2 flux measurements using COSPEC are typically performed from distances of up to 30 km away from volcanic craters (for example at Mt. Etna; Weibring et al., 2002). Measurements performed at these distances are commonly used to estimate the flux rates of other volcanic compounds “X” by relating the observed concentration of SO_2 in the plume to the ratio of “X” to total S found in fumarolic gases. This method assumes that the ratio of the concentrations of “X” to SO_2 remains constant from the time the emissions are released until the plume is measured. This technique has been used, for example, to estimate the annual flux of metals from volcanoes (Hinkley et al., 1999) and to constrain the flux balances of elements at subduction zones (Hilton et al., 2002). The assumption of a steady ratio of $[\text{X}]/[\text{SO}_2]$ remains a subject of uncertainty, however. Pyle and Mather (2003), for example, have shown that $[\text{Hg}]/[\text{SO}_2]$ ratios can vary by an order of magnitude dependent on the type of volcanic activity (passively degassing vs. explosively erupting). The ratio of $[\text{X}]/[\text{SO}_2]$ can vary not only dependent on the type of volcanic activity, but can also vary in time if the two species are removed at different rates from the plume. Atmospheric chemistry modeling can be a useful tool to study the transport and deposition of multiple chemical species and how they behave relative to SO_2 . This approach can be used to gain insight onto how reasonable it is to relate observations of SO_2 concentrations in an aged volcanic plume to other compounds.

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This paper describes a regional atmospheric chemistry modeling study that has been performed to address the two questions: 1) How do variable meteorological conditions influence volcanic SO₂ concentration in the atmosphere and SO₂ loss rates? and 2) How do the transport and deposition patterns of other volcanic compounds relate to SO₂? Indonesia has been chosen as the region for study to address these two questions because it is the region of the world with the largest number of historically active volcanoes and the region has a relatively continuous emission history with 4/5 of the volcanoes with dated eruptions having erupted this past century (Simkin and Siebert, 1994).

2. Experimental setup

The regional atmospheric chemistry model REMOTE (Regional Model with Tracer Extension) (Langmann, 2000) has been used to simulate meteorological conditions for the year 1985, a climatologically “normal” year, i.e. neither “El Niño” nor “La Niña”. REMOTE combines the physics of the regional climate model REMO 5.0 with tropospheric chemical equations for 63 chemical species. The physical and dynamical equations in the model (Jacob, 2001) are based on the regional weather model EM/DM of the German Weather Service (Majewski, 1991) and include parameterizations from the global ECHAM 4 model (Roeckner, 1996). The chemical tracer transport mechanisms include horizontal and vertical advection (Smolarkewitz, 1983), convective up- and down-draft (Tiedtke, 1989), and vertical diffusion (Mellor and Yamada, 1974). Trace species can undergo chemical decay in the atmosphere or can be removed from the atmosphere by wet and dry deposition or transport out of the model boundaries. Dry deposition is dependent on friction velocities and ground level atmospheric stability (Wesley, 1989). Wet deposition is dependent on precipitation rate and mean cloud water concentration (Walcek and Taylor, 1986). 158 gasphase reactions from the RADM II photochemical mechanism (Stockwell et al., 1990) are included. 43 longer-lived chemical species are treated as predicted species and 20 shorter-lived ones as diagnosed species.

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The model was applied with 20 vertical layers of increasing thickness between the Earth's surface and the 10 hPa pressure level (approximately 23 km). Analysis data of weather observations from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used as boundary conditions every 6 h. The physical and chemical state of the atmosphere was calculated every 5 min. Background concentrations of 39 species (Chang et al., 1987), including SO₂, SO₄²⁻, O₃, and H₂O₂, were specified at the lateral model boundaries. The model domain covers Indonesia and Northern Australia (91° E–141° E; 19° S–8° N) with a horizontal resolution of 0.5° (approximately 53 km in longitude and 55 km in latitude) with 101 grid points in longitude and 55 grid points in latitude. Two experiments were performed: a) “S Experiment” – volcanic S was released as primarily SO₂ that underwent oxidation to SO₄²⁻ following the major tropospheric chemical reactions and b) “PbCl₂ Experiment” – PbCl₂ released as an infinitely soluble passive tracer.

2.1. Emission inventory

An annual inventory was established to represent maximum potential volcanic emissions within the modeled region of Indonesia. Over the past century, from 1900 to 1993, 63 volcanoes in Indonesia are known to have erupted and 32 additional volcanoes have degassed passively, for a total sum of 95 active volcanoes (Simkin and Siebert, 1994). The inventory established for this work contains both continuous eruptive and passive degassing and sporadic eruptive volcanic emissions. Continuous emissions were taken from Nho et al. (1996) as this work provides the maximum published estimate of SO₂ emissions from the Indonesian volcanoes (Table 1: 1600 Gg SO₂/yr released non-eruptively; 1900 Gg SO₂/yr eruptively; for a sum of 3500 Gg SO₂/yr continuous emissions (which is equivalent to 1750 Gg (S)/yr)). The continuous emissions were divided evenly amongst the 95 active volcanoes. This is the most reasonable assumption we could make, despite the fact that emission rates of volcanoes are highly variable in time and between different volcanoes, because only at a few of the active Indonesian volcanoes are routine SO₂ flux measurements performed. It would have been less

reasonable to have scaled the emission flux estimates for individual volcanoes based on the small number of available measurements for the active volcanoes. The result of dividing the continuous emissions evenly between all of the active volcanoes is a mean continuous SO₂ flux of 36.8 Gg SO₂/yr (100 Mg SO₂/day) for each volcano.

5 An estimate of the sporadic eruptive volcanic emissions for the region was established for this work using the [Simkin and Siebert \(1994\)](#) catalog of volcanic activity. [Simkin and Siebert \(1994\)](#) provide a compilation of the best known estimates of the date and strength for all of the known volcanic activity on Earth. Each volcanic eruption is assigned a volcanic explosivity index (VEI) strength which is an indicator of the
10 explosiveness of a volcanic event ([Newhall and Self, 1982](#)). To assemble the sporadic emissions inventory, all of the eruptions recorded in the catalog during the last century (1900–1993) for each active Indonesian volcano were summed. An index estimating the amount of SO₂ released due to each VEI has been developed by [Schnetzler et al. \(1997\)](#), the volcanic sulfur index (VSI). We multiplied the total number of eruptions of
15 each VEI by the maximum amount of SO₂ released by arc volcanoes suggested by the VSI. The SO₂ flux resulting from this multiplication was then divided by the 93 years of the record to generate an annual mean emission estimate. Averaging over 93 years removes some of the high natural short-term variability of volcanic activity. These calculations indicate 290 Gg SO₂/yr released sporadically by the Indonesian volcanoes
20 – a sum of sporadic and continuous volcanic emissions of 3800 Gg SO₂/yr (which is equivalent to 1895 Gg(S)/yr) (Fig. 1). The estimated emission fluxes for the individual volcanoes correspond reasonably well with SO₂ flux measurements of Indonesian volcanoes (Table 2).

25 The emissions of each individual volcano were released into the model layer at the actual height of each volcano. The elevations of the volcanos range from 200 m (Riang Kotang) to 3805 m (Kerinci) corresponding to the first 12 model levels.

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2.2. Experiments

The “S Experiment” was conducted to observe the transport and deposition patterns of volcanic S. The volcanic emissions from the emission inventory were released into the model as 96% SO₂ and 4% SO₄²⁻. To describe the loss of the volcanic S from the atmosphere, SO₂ loss rate calculations have been performed on the results of the “S Experiment”. SO₂ loss rate is a function of the concentration of SO₂ at two locations within a volcanic plume, the distance between these two locations, and the time of travel from the first to the second location. The calculations have been performed in a manner intended to replicate the methodology of field measurements of tropospheric SO₂ loss rates at individual volcanoes (Oppenheimer et al., 1998).

SO₂ loss rate from the model results was calculated as follows: over a given time period (year or season), the mean wind direction of each gridbox containing a volcano “V” was used to define which of the 8 surrounding gridboxes the SO₂ was most likely to be transported to: “V+1”. This was repeated a second time to define the gridbox “V+2”, a distance of 55–200 km (average 121 km) away from the volcano. The mean column burden of SO₂ at “V” and “V+2” were then related following first order kinetics (Eq. 1).

$$\Phi_{t_1} = \Phi_{t_2} e^{k_1(t_2-t_1)} \quad (1)$$

where:

Φ = Column burden at given time [kg/m²]

t_2-t_1 = time to be transported from location 1 to 2 [s]

k_1 = SO₂ loss rate [s⁻¹]

The mean wind speed and distance between the two gridboxes were used to calculate the amount of time for transport from “V” to “V+2”. The result of the calculation is the yearly or seasonal mean SO₂ loss rate “ k_1 ” for each volcano. Column burden of SO₂ was used in this calculation as opposed to single model level concentrations because column burden is a more accurate representation of the data obtained by

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ground-based COSPEC. Column burden is the total mass per area of the given species contained in the entire atmospheric vertical column (up to the top of the model, 10 hPa). For some volcanoes, the SO_2 loss rate calculation resulted in a negative or null value. A negative value indicates an increase in the concentration of SO_2 at “V+2” than at “V”. This can occur when the “V+2” grid box contains another volcano. A null value can occur when the wind direction is so variable that the emissions are predicted in the first step to be transported away from the grid box “V” and in the second step returned to it, for a net distance of 0. In both of these situations, the calculated SO_2 loss rates have been excluded from further consideration.

The “ PbCl_2 Experiment” was conducted to observe the transport and deposition pattern of PbCl_2 , a highly soluble compound released by volcanoes in relatively large concentrations (e.g. Delmelle, 2003). PbCl_2 is not among the chemicals originally included in REMOTE, however, so we included PbCl_2 in the model as an infinitely soluble passive tracer. PbCl_2 (solubility = 0.99 g/100cc) (CRC Handbook, 1993) is very soluble, and not infinitely soluble, so the modeling assumption of infinite solubility will lead to an over-prediction of the solubility of PbCl_2 . The solubility is close enough, however, that we find it a reasonable proxy. The PbCl_2 is released as a passive tracer, and as such it is transported in the atmosphere and is removed from the atmosphere by wet and dry deposition processes, but it does not react to form other chemical species. The emission inventory was established for volcanic SO_2 , so to calculate a corresponding emission flux of PbCl_2 the emissions have been scaled to the ratio of Pb to S in Indonesian fumarolic gases (Table 3).

3. Results

The results of the “S Experiment” are presented first, followed by the SO_2 loss rates that have been calculated from these results. The results of the “ PbCl_2 Experiment” are then presented.

3.1. "S Experiment" and calculated SO₂ loss rates

The modeled atmospheric distribution of volcanic S species is shown as annual mean column burden in Fig. 2 as a) SO₂, b) SO₄²⁻, and c) total volcanic S (SO₂+SO₄²⁻). The atmospheric concentration of SO₂ is much higher than that of SO₄²⁻, and dominates the sum of the two. The annual mean column burden of SO₂ ranges from 1.5–10 kg(S)/km² and SO₄²⁻ from 0–1.5 kg(S)/km². Qualitatively, both SO₂ and SO₄²⁻ show the highest concentrations near to the volcanoes, while away from the volcanoes the concentration decreases, with the dominant transport away from the volcanoes towards the east. Relatively high atmospheric concentrations of the S species is also seen at the northern boundaries of the figures. This is a result of the concentrations of SO₂ and SO₄²⁻ defined at the boundaries of the model domain and is not a result of the transport of volcanic S.

Volcanic S deposition is presented as a) the annual sum of the dry SO₂ deposition, b) dry + wet SO₄²⁻ deposition, and c) the total volcanic S deposition as the sum of the two (Fig. 3). More than 99% of SO₄²⁻ is deposited via wet deposition, so only the total SO₄²⁻ deposition is shown. SO₂ is dry deposited in large concentrations close to the volcanoes, up to 3 Mg(S)/km², but with almost no deposition away from the volcanoes. SO₄²⁻, in comparison, has a maximum annual deposition of only up to 1.25 Mg(S)/km², with much more significant deposition away from the volcanoes. Most of the volcanic S is deposited as SO₄²⁻ (83% of the total S deposition). There is an average annual sum of deposition over the entire modeled region of 45.6 kg(S)/km² SO₂ and 219.6 kg(S)/km² SO₄²⁻.

The SO₂ loss rates calculated from the model results (3.2×10^{-7} – 4.1×10^{-5} s⁻¹) agree well in magnitude with SO₂ loss rates measured at individual volcanoes in other parts of the world (1.9×10^{-7} – 5.4×10^{-3} s⁻¹) (Fig. 4) (Oppenheimer et al., 1998). There is a large variability in SO₂ loss rates measured at different volcanoes, and at Mt. Etna alone, SO₂ loss rates have been observed to vary over 3 orders of magnitude.

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Figure 5 shows a box plot of the bin wind speed over 1 m/s intervals plotted against SO₂ loss rates. The lower edge of the box represents the 25th percentile value and the upper edge the 75th. The height of each box shows the interquartile range for each season and is an indicator of the variability of the values. The line across the box indicates the median (50th percentile). Four outlayer values are shown as open circles and three extreme values as stars. The correlation between windspeed and SO₂ loss rate is weak but statistically significant ($p < 0.01$; $R^2 = 0.2$). There is a general trend of increasing wind speed associated with increased SO₂ loss rates as well as an increase in the variability of the SO₂ loss rates. Temperature and relative humidity, in contrast, demonstrate trivial and non-significant ($R^2 < 0.02$) correlation with SO₂ loss rate.

SO₂ loss rates have been calculated for each season based on the monsoonal winds: winter monsoon (December–March); spring intermonsoon (April–May); summer monsoon (June–September); fall intermonsoon (October–November). SO₂ loss rates as a function of season are shown as a box plot in Fig. 6. Three outlayer values are shown as open circles and one extreme value as a star. Excluding the outliers and extremes, winter has the lowest variability and spring the highest. The mean seasonal SO₂ loss rates for all volcanoes vary between $9.7 \times 10^{-6} \text{ s}^{-1}$ (spring) and $1.3 \times 10^{-5} \text{ s}^{-1}$ (summer). A greater variability is demonstrated between individual volcanoes than by the seasonal means over all of the volcanoes.

Loss of volcanic SO₂ from the atmosphere can be accomplished via the dry deposition of SO₂ and by oxidation to SO₄²⁻. There can also be an apparent SO₂ loss due to lateral transport outside of the measured plume (in the field) or outside of the predicted transport route (in the calculations performed on the model results). The % of SO₂ lost due to dry deposition and oxidation was calculated by dividing the daily mean dry deposition of SO₂ and the annual mean column burden of SO₄²⁻ in grid box “V” by the difference in column burden of SO₂ between locations “V” and “V+1”. The remaining lost SO₂ was attributed to lateral transport. The average for all volcanoes within an average of 69 km away from the volcanoes is 53% of SO₂ lost due to conversion to SO₄²⁻, 42% to dry deposition, and 5% lost due to lateral transport. This trend does not

continue at greater distances from the volcanoes. Between locations “V+1” and “V+2” (an average distance of 69–121 km from the volcanoes) the sum of the column burden of SO_4^{2-} and the daily dry deposition of SO_2 is greater than the loss of SO_2 .

3.2. “PbCl₂ Experiment”

5 The modeled atmospheric distribution of volcanic PbCl₂ is shown as annual mean column burden in Fig. 7. The annual mean column burden of PbCl₂ ranges from 0–3 g (Pb)/km². Atmospheric PbCl₂ is found in greatest concentrations near to the volcanoes, with only slight easterly transport. The annual sum of the wet and dry PbCl₂ deposition is shown in Fig. 8. More than 99% of PbCl₂ is deposited via wet deposition,
10 so only the sum of the two is presented. The PbCl₂ is deposited in concentrations of up to 2 kg (Pb)/km² with an average annual sum of 52 g (Pb)/km² of PbCl₂ deposited in the modeled region.

4. Model result verification

We will assess the quality of the modeling results by comparing the modeled S deposition with the concentration of S measured in peat core samples collected in the modeled region. Peat can serve as a historical record of atmospheric deposition for
15 time periods of up to thousands of years. The peat areas of Indonesia may be particularly useful recorders of the deposition of volcanic emissions because of the large number of historical and modern active volcanoes in the vicinity of peat areas (Langmann and Graf, 2003). It has been suggested in several studies that anomalous, high concentrations of S and other chemicals including Pb in peat core samples (collected outside of Indonesia) may be due to volcanic deposition (e.g. Weiss et al., 1997; Roos-Barracough et al., 2002; Kylander et al., 2005). Within Indonesia, there are two main types of peat: ombrogenous and topogenous (Page et al., 1999). Ombrogenous peat
20 receives nutrients only from atmospheric deposition while topogenous peat also re-

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ceives nutrients from groundwater. Ombrogenous peat is therefore more useful for interpreting the historical deposition of atmospheric compounds. In this work we have taken measurements of S in four ombrogenous peat areas in Indonesia for comparison with the modeled S deposition (Fig. 9; Table 4). In making this comparison, it is important to keep in mind that there are other natural sources of S additional to volcanoes, such as vegetation and sea spray, so this comparison can be only qualitative.

The average S of each sampled peat core was calculated by multiplying the average % S in each of the four peat sampling locations with the average peat dry bulk density (0.18 g/cm^3) given by Shimada et al. (2001). This value was multiplied by the minimum (1.7 mm/yr) and maximum (4.3 mm/yr) peat accumulation rates provided by Supardi et al. (1993), resulting in the presented range of values for the S deposition of each peat core. The average % S was calculated from 3–16 samples within each peat core. Each peat core had measurements of both total S as well as C_{14} ages, or were very near to another peat core where C_{14} age measurements were performed. S values from portions of the peat cores that were dated to be less than 150 years old were not included in the average as these S values may have been influenced by human activity. The modeled S deposition and the rate of S deposition measured in the peat core samples are of the same order of magnitude. The potential volcanic S contribution to the peat areas ranges from 6–72% of the S measured in the peat samples (Table 4). There is a relatively uniform concentration of volcanic S predicted to be deposited on all four peat areas ($215\text{--}285 \text{ kg/km}^2 \text{ yr}$). This is because of the distance between the peat areas and the nearest volcanoes (minimum 153 km). It would be helpful to be able to compare the model results with a peat sample collected nearer to the volcanoes, but we have not been able to find such a sample. We find the agreement in scale to be a strong indication that the modeled deposition of the volcanic S is reasonable and feel confident in interpreting the model results for the transport and deposition of volcanic emissions.

5. Discussion

We will interpret the modeling results and discuss how these results can be used to address the two questions described above: 1) How do variable meteorological conditions influence volcanic SO₂ concentration in the atmosphere and SO₂ loss rates? and 2) How do the transport and deposition patterns of other volcanic compounds relate to SO₂?

5.1. SO₂ loss rate

Temperature, relative humidity, and wind speed have been plotted against the relative % of SO₂ lost due to the dry deposition of SO₂, oxidation to SO₄²⁻, and lateral transport outside of the predicted plume pathway to see if there is any correlation between variations in the meteorological conditions and the manner in which SO₂ is lost. No such correlation was found. There is an observable seasonal cycle of SO₂ loss rates with the lowest loss rates in spring and the highest in summer. The only seasons with outlayers and extreme values are summer and winter – the monsoon seasons – which are distinguished by strong winds. The model results suggest, albeit weakly, that there may be a relationship between stronger winds and greater SO₂ loss rates. There is a stronger relationship revealed between stronger winds and greater variability of SO₂ loss rates.

The large variabilities of SO₂ loss rates measured at individual volcanoes have been attributed to variable atmospheric and plume conditions (Oppenheimer et al., 1998). The results of this study suggest a refinement of this assessment, in that the meteorological condition most significantly influencing the variability of SO₂ loss rates is wind speed. It may be more difficult to obtain a representative SO₂ loss rate for a given volcano that is susceptible to highly variable wind conditions, as opposed to a volcano that is exposed to more consistent winds. Further fieldwork-based research that considers variations in wind speed and apparent SO₂ loss rates may be able to form a more conclusive statement about the possible correlation between wind speed and

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SO₂ loss rates. If there is indeed such a relationship, it may be important to consider wind speed variations when making interpretations about changes in volcanic activity based on remote SO₂ measurements. Some variations in SO₂ flux observed over time at one volcano may be due to differences in the winds, as opposed to variations in the volcanic emissions.

5.2. Differences in transport and deposition patterns due to solubility

Both the atmospheric burden and deposition of Pb are three orders of magnitude less than that of S. In both experiments, deposition is relatively uniform with relation to distance from any given volcano and not very distinctive for individual volcanoes. This uniformity is a result of the assumption of an even distribution of the continuous volcanic emissions between the active volcanoes. PbCl₂ is rapidly deposited very close to the volcanoes, resulting in high local concentrations and a sharp decline in deposition at greater distances from the volcanoes. SO₂, on the other hand, is much less soluble in rain than PbCl₂. The less soluble SO₂ has some dry deposition, but is mostly transported away from the volcanoes prior to conversion to water-soluble SO₄²⁻. The SO₂ that is deposited, however, is deposited at heavier concentrations near to the volcanoes than the PbCl₂. Because most of the SO₂ is converted to SO₄²⁻ rather than deposited directly as SO₂, there is a much less steep gradient of S deposition at increasing distance from the volcanoes compared with PbCl₂, as well as a higher concentration of S deposition at greater distances from the volcanoes.

The influence of solubility on deposition patterns is illuminated by comparing the results of the two performed experiments (Fig. 10). The strong dependency of deposition rate on solubility has implications for the accurate extrapolation of measurements of SO₂ flux in aged volcanic plumes to other compounds. The further away from a volcano such measurements are made, the less accurate it is to assume that the concentration of volcanic SO₂ measured there has the same ratio to more soluble species as the ratio measured in fumarolic gases.

The ratio of [Pb]/[S] in the air decreases with increasing distance from the volcanoes

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as the PbCl_2 is deposited (Fig. 11). Figure 11 is a box plot with the same specifics as for Figs. 5 and 6. Four outlayer values are shown as open circles at location “V”. The interquartile range increases at greater distance from the volcanoes indicating that the variability of the $[\text{PbCl}_2]/[\text{SO}_2]$ ratio is growing at greater distances from the volcanoes.

- 5 The median $[\text{PbCl}_2]/[\text{SO}_2]$ ratio decreases exponentially at greater distances from the volcanoes with the mean exponential rate of decay of the $[\text{PbCl}_2]/[\text{SO}_2]$ ratio based on these three distances being $y=106.5e^{-0.002x}$

where:

$$y = [\text{PbCl}_2]/[\text{SO}_2] \text{ (}\mu\text{g/g)}$$

- 10 $x = \text{distance from volcanoes (km)}$.

The mean $[\text{PbCl}_2]/[\text{SO}_2]$ ratio at the three distances are: “V” = 107.7; “V+1” = 89.3; and “V+2” = 83.2 $\mu\text{g/g}$.

- 15 Based on this mean rate of decay, we estimate that calculations (e.g. based on COSPEC measurements) which assume a constant $[X]/[S]$ ratio as found in fumarolic gases will result in a 6% overestimation of the atmospheric concentration of highly soluble species at 30 km distance away from the volcano. The overestimation grows at further distances from the volcano.

6. Conclusions

- 20 This study demonstrates that realistic modeling of volcanic emissions can lead to an improved understanding of the atmospheric processes occurring in the vicinity of active volcanoes. The results of the study demonstrate that SO_2 loss rates are weakly correlated with wind speed and uncorrelated with relative humidity or temperature and that there is no correlation between these three meteorological phenomena and the relative amount of SO_2 lost due to the dry deposition of SO_2 , conversion to SO_4^{2-} , or lateral transport. A relationship is shown between increased wind speed and increased variability of SO_2 loss rates. We recommend that further fieldwork-based research be
- 25 conducted to explore the possible relationship between wind speed and apparent SO_2

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loss rates as variations in wind speed might lead to changes in SO₂ loss rates independent of a change in the state of volcanic activity.

The solubility of volcanic emissions is shown to control if they are deposited near to the volcanoes or transported prior to deposition. Highly soluble species such as PbCl₂ have high deposition rates near to the volcanoes while the relatively insoluble SO₂ is transported away from the volcanoes until it is oxidized to SO₄²⁻ and then rapidly deposited. The ratio of [X]/[SO₂], with “X” being a soluble species, decreases exponentially at greater distances from the volcanoes. We therefore recommend that the influence of different solubilities of volcanic species on atmospheric loss should be considered when relating measurements of atmospheric SO₂ to other volcanic emissions.

Acknowledgements. We thank E. Marmer, A. Heil, P. Wetzel, and P. Weis for much help and discussion and for internally reviewing the manuscript. We also thank the German Climate Computing Center (DKRZ) for computer time to run these experiments. MAP was funded by a stipend from the Ebelin and Gerd Bucerius ZEIT Foundation through the International Max Planck Research School on Earth System Modeling.

References

- Andres, R. J. and Kasgnoc, A. D.: A time-averaged inventory of subaerial volcanic sulfur emissions, *J. Geophys. Res.*, 103(D19), 25 251–25 261, 1998. [11863](#), [11884](#)
- Bardintzeff, J.-M. and McBirney, A. R.: *Volcanology*, second edition, Jones and Bartlett, 2000. [11863](#)
- Bluth, G. J. S., Casadevall, T. J., Schnetzler, C. C., Doiron, S. D., Walter, L. S., Krueger, A. J., and Badruddin, M.: Evaluation of sulfur dioxide emissions from explosive volcanism: the 1982–1983 eruptions of Galunggung, Java, Indonesia, *J. Volcan. Geotherm. Res.*, 63, 243–256, 1994. [11884](#)
- Chang, J. S., Brost, R. A., Isaksen, S. A., Madronich, S., Middleton, O., Stockwell, W. R., and Walcek, C. J.: A three dimensional Eulerian acid deposition model physical concepts and formulations, *J. Geophys. Res.*, 92, 14 581–14 700, 1987. [11867](#)

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- Lide, D. R. and Frederikse, H. P. R. (Eds.): CRC Handbook of Chemistry and Physics, CRC Press, 1993. [11870](#)
- Delmelle, P.: Environmental impacts of tropospheric volcanic gas plumes, in: Volcanic Degassing, edited by: Oppenheimer, C., Pyle, D. M., and Barclay, J., London, Geol. Soc. Lon., Special Publication, 213, 381–399, 2003. [11870](#)
- 5 Esterle, J. S. and Ferm, J. C.: Spatial variability in modern tropical peat deposits from Sarawak, Malaysia and Sumatra, Indonesia: analogues for coal, Int. J. Coal Geol., 26, 1–41, 1994. [11886](#), [11895](#)
- Graf, H. F., Feichter, J., and Langmann, B.: Volcanic sulfur emissions: Estimates of source strength and its contribution to the global sulfate distribution, J. Geophys. Res., 102(D9), 10 727–10 738, 1997. [11863](#)
- Halmer, M. M., Schmincke, D. J., and Graf, H.-F.: The annual volcanic gas input into the atmosphere, in particular into the stratosphere: A global data set for the past 100 years, J. Volcan. Geotherm. Res., 115, 511–528, 2002. [11883](#)
- 15 Heil, A., Langmann, B., and Aldrian, E.: Indonesian peat and vegetation fire emissions: Study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model, Mit. and Adapt. Strat. for Glob. Ch., in press, 2005. [11895](#)
- Hilton, D., Fischer, T. P., and Marty, B.: Noble gases and volatile recycling at subduction zones, in: Reviews in Mineralogy & Geochemistry – Noble Gases in Geochemistry and Cosmochemistry, edited by: Porcelli, D., Ballentine, C. J., and Weiler, R., 47, Washington D.C., Min. Soc. Am., 319–370, 2002. [11865](#), [11883](#)
- 20 Hinkley, T. K., Lamothe, P. J., Wilson, S. A., Finnegan, D. L., and Gerlach, T. M.: Metal emissions from Kilauea, and suggested revision of the estimated worldwide metal output by quiescent degassing of volcanoes, Earth Plan. Lett., 170, 315–325, 1999. [11865](#), [11885](#)
- 25 Jacob, D.: A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin, Met. Atmos. Phys., 77, 61–73, 2001. [11866](#)
- Kylander, M. E., Weiss, D. J., Martínez Cortizas, A., Spiro, B., Garcia-Sanchez, R., and Colesab, B. J.: Refining the pre-industrial atmospheric Pb isotope evolution curve in Europe using an 8,000 year old peat core from NW Spain, Earth Plan. Sci. Lett., in press, 2005. [11873](#)
- 30 Langmann, B.: Numerical modelling of regional scale transport and photochemistry directly together with meteorological processes, Atmos. Environ., 34, 3585–3598, 2000. [11866](#)
- Langmann, B. and Graf, H. F.: Indonesian smoke aerosols from peat fires and

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the contribution from volcanic sulfur emissions, *Geophys. Res. Lett.*, 30(11), 1547, doi:10.1029/2002GL016646, 2003. [11873](#)

LeGuern, F.: Les débits de CO₂ et de SO₂ volcaniques dans l'atmosphère, *Bull. Volcanol.*, 45(3), 197–202, 1982. [11884](#)

5 Majewski, D.: The Europa Modell of the Deutscher Wetterdienst, *Sem. Proc. ECMWF*, 2, 147–191, 1991. [11866](#)

McGonigle, A. J. S. and Oppenheimer, C.: Optical sensing of volcanic gas and aerosol emissions, in: *Volcanic Degassing*, edited by: Oppenheimer, C., Pyle, D.M., and Barclay, J., London, Geol. Soc. Lon., Special Publication 213, 149–168, 2003.

10 Mellor, B. and Yamada, T.: A hierarchy of turbulence closure models for planetary boundary layers, *J. Atmos. Sci.*, 31, 1791–1806, 1974. [11866](#)

Newhall, C. G. and Self, S.: The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism, *J. Geophys. Res.*, 87, 1231–1238, 1982. [11868](#)

15 Nho, E.-Y., Le Cloarec, M.-F., Ardouin, B., and Tjetjep, W. S.: Source strength assessment of volcanic trace elements emitted from the Indonesian arc, *J. Volcan. Geotherm. Res.*, 74, 121–129, 1996. [11867](#), [11883](#), [11884](#), [11885](#)

Oppenheimer, C., Francis, P., and Stix, J.: Depletion rates of sulfur dioxide in tropospheric volcanic plumes, *Geophys. Res. Lett.*, 25(14), 2671–2674, 1998. [11869](#), [11871](#), [11875](#), [11890](#)

20 Page, S. E., Rieley, J. O., Shotyk, Ø. W., and Weiss, D.: Interdependence of peat and vegetation in a tropical peat swamp forest, *Phil. Trans. R. Soc. Lond., B*, 354, 1885–1897, 1999. [11873](#)

Pyle, D. M. and Mather, T. A.: The importance of volcanic emissions for the global atmospheric mercury cycle, *Atmos. Environ.*, 37, 5115–5124, 2003. [11865](#)

25 Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Duemenis, L., Esch, M., Giorgetta, M., Schlese, M., and Schulzweida, U.: The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate, *MPI Rep.*, 218, Hamburg, Germany, 1996. [11866](#)

Roos-Barraclough, F., Martinez-Cortizas, A., García-Rodeja, E., and Shotyk, W.: A 14,500 year record of the accumulation of atmospheric mercury in peat: Volcanic signals, anthropogenic influences and a correlation to bromine accumulation, *Earth. Plan. Sci. Lett.*, 202, 435–451, 2002. [11873](#)

30 Schnetzler, C. C., Bluth, G. J. S., Krueger, A. J., and Walter, L. S.: A proposed volcanic sulfur dioxide index (VSI), *J. Geophys. Res.*, 102, 20 087–20 092, 1997. [11868](#)

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- Shimada, S., Takahashi, H., Haraguchi, A., and Kaneko, M.: The carbon content characteristics of tropical peats in Central Kalimantan, Indonesia: Estimating their spatial variability in density, *Biogeochem.*, 53, 3, 249–267, 2001. [11874](#)
- 5 Simkin, T. and Siebert, L.: *Volcanoes of the World*, 2nd ed., Geoscience Press in association with the Smithsonian Institution Global Volcanism Program, Tucson AZ, 1994. [11863](#), [11866](#), [11867](#), [11868](#)
- Smolarkiewitz, P. K.: A simple positive definite advection scheme with small implicit diffusion, *Month. Weath. Rev.*, 111, 476–479, 1983. [11866](#)
- 10 Spiro, P. A., Jacob, D. J., and Logan, D. J.: Global inventory of sulfur emissions with $1^\circ \times 1^\circ$ resolution, *J. Geophys. Res.*, 97, 6023–6036, 1992. [11883](#)
- Stockwell, W. R., Middleton, P., Chang, J. S., and Tang, X.: The second generation regional acid deposition model: Chemical mechanism for regional air quality modeling, *J. Geophys. Res.*, 95, 16 343–16 367, 1990. [11866](#)
- 15 Stoiber, R. E., Malinconico Jr., L. L., and Williams, S. N.: Use of the correlation spectrometer at volcanoes, in: *Forecasting Volcanic Events*, edited by: Tazieff, H. and Sabroux, J.-C., Elsevier, 1983. [11864](#)
- Supardi, Subekty, A. D., and Neuzil, S. G.: General geology and peat resources of the Siak Kanan and Bengkalis Island peat deposits, Sumatra, Indonesia, in: *Modern and Ancient Coal-Forming*, edited by: Cobb, J. C. and Cecil, C. B., Environments, Boulder, CO, Geol. Soc. Am., Special Paper 286, 1993. [11874](#), [11886](#), [11895](#)
- 20 Symonds, R. B., Rose, W. I., Reed, M. H., Lichte, F. E., and Finnegan, D. L.: Volatilization, transport and sublimation of metallic and non-metallic elements in high temperature gases at Merapi Volcano, Indonesia, *Geoch. Cosmoch. Acta*, 51, 2083–2101, 1987. [11885](#)
- Textor, C., Graf, H.-F., Herzog, M., and Oberhuber, J. M.: Injection of gases into the stratosphere by explosive volcanic eruptions, *J. Geophys. Res.*, 108(D19), 4606, doi:10.1029/2002JD002987, 2003. [11863](#)
- 25 Tiedtke, M.: A comprehensive mass flux scheme for cumulus parameterization in large-scale models, *Month. Weath. Rev.*, 117, 1778–1800, 1989. [11866](#)
- Directorate of Volcanology and Geological Hazard Mitigation of Indonesia, <http://www.vsi.esdm.go.id/mvo/mvomonitoring.html>, 2005. [11884](#)
- 30 Walcek, C. J. and Taylor, G. R.: A theoretical method for computing vertical distributions of acidity and sulfate production within cumulus clouds, *J. Atmos. Sci.*, 43, 339–355, 1986. [11866](#)

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Weibring, P., Swartling, J., Ednre, H., Svanberg, S., Caltabiano, T., Condarelli, T., Cecchi, G., and Pantani, L.: Optical monitoring of volcanic sulphur dioxide emissions – comparison between four different remote-sensing spectroscopic techniques, *Opt. Laser Eng.*, 37, 267–284, 2002. [11865](#)

5 Weiss, D., Shotyk, W., Cheburkin, A. K., Gloor, M., and Reese, S.: Atmospheric lead deposition from 12,400 to ca. 2,000 yrs BP in a peat bog profile, Jura Mountains, Switzerland, *Water Air Soil Poll.*, 100, 311–324, 1997. [11873](#)

Weiss, D., Shotyk, W., Rieley, J., Page, S., Gloor, M., Reese, S., and Martinez-Cortizas, A.: The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition, *Geoch. Cosmoch. Acta*, 66, 13, 2307–2323, 2002. [11886](#), [11895](#)

Wesley, M. L.: Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models, *Atmos. Environ.*, 23, 1293–1304, 1989. [11866](#)

15 Wüst, R. A. J. and Bustin, R. M.: Low ash peat deposits from a dendritic, intermontane basin in the tropics: A new model for good quality coals, *Int. J. Coal Geol.*, 46, 3-4, 179–206, 2001. [11886](#), [11895](#)

20 Young, S. R., Voight, B., and Duffell, H. J.: Magma extrusion dynamics revealed by high-frequency gas monitoring at Soufrière Hills volcano, Montserrat, in: *Volcanic Degassing*, edited by: Oppenheimer, C., Pyle, D. M., and Barclay, J., London, Geol. Soc. Lon., Special Publication 213, 219–230, 2003. [11864](#)

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Table 1. Estimates of Indonesian volcanic emissions.

Emission style	SO ₂ flux (Gg/yr)	Reference
continuous (non-eruptive)	120	Hilton et al. (2002)
continuous (non-eruptive)	210	Spiro et al. (1992)
continuous (non-eruptive)	1600	Nho et al. (1996)
continuous (eruptive)	1900	Nho et al. (1996)
continuous (eruptive + non-eruptive)	3500	sum from Nho et al. (1996) used in this study
sporadic (eruptive)	290	calculated for this study
continuous + sporadic (eruptive + non-eruptive)	2100–2600	Halmer et al. (2002)
continuous + sporadic (eruptive + non-eruptive)	3790	this study

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Table 2. SO₂ emissions from individual Indonesian volcanoes.

Volcano	SO ₂ flux from emission inventory (Gg/yr)	SO ₂ flux from measurements (Gg/yr)	Reference
Bromo (Tengger Caldera)	47.4	5.1	Andres and Kasgnoc (1998)
Galunggung	47.7	140.5	Bluth et al. (1994)
Merapi	55.6	240.9	Andres and Kasgnoc (1998)
		36.5	Dir. of Volcan. and Geol. Haz. Mit. of Indonesia (2005)
		51.1	Andres and Kasgnoc (1998)
Slamet	45.4	73.0	LeGuern (1982)
		21.2	Nho et al. (1996)
Tangkubanparahu	37.5	27.4	Andres and Kasgnoc (1998)

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Table 3. Pb/S ratios in Indonesian volcanic gases.

Volcano	Pb/S ($\mu\text{g/g}$)	Reference
Merapi	420	Nho et al. (1996)
Merapi	35	Symonds et al. (1987)
Papandayan	280	Nho et al. (1996)
Mean	245	the average of the above measurements was applied in this study
Global mean	190	Hinkley et al. (1999)

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Table 4.

Comparison of modeled S deposition and peat core samples.

Sampling location	Distance to nearest volcano (km)	Measured S accumulation (kg/km ² – yr)	Modeled S deposition (kg/km ² – yr)	Volcanic S (%)	Reference (% S measured in peat core)
Riau	153	398–1006	285	28–72	Supardi et al. (1993)
Batanghari River Tasek Bera	160	1744–4412	264	6–15	Esterle and Ferm (1994)
Sungai Seban-gau	258	796–2012	215	11–27	Wüst and Bustin (2001)
	396	428–1084	253	23–59	Weiss et al. (2002)

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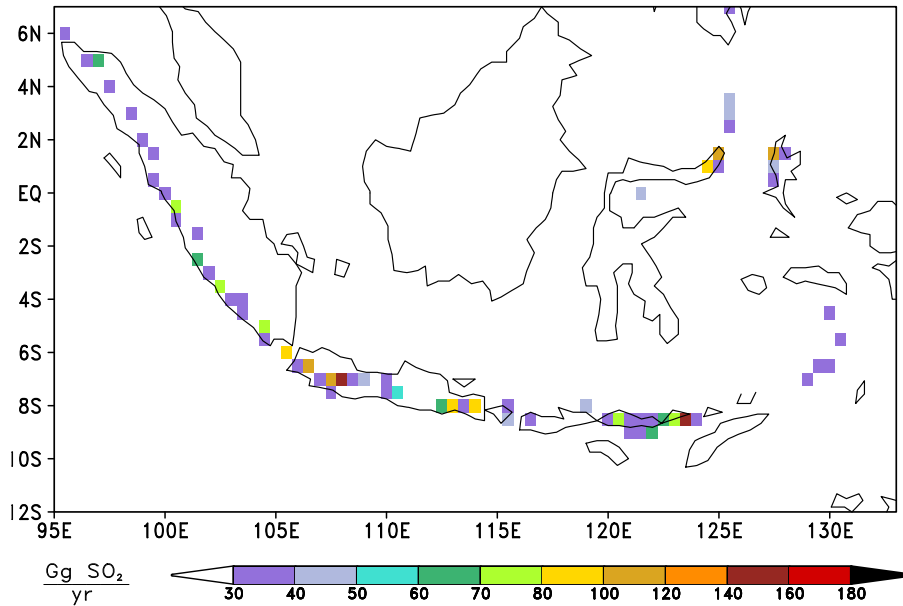


Fig. 1. Emission inventory of the annual sum of continuous (eruptive + passive) and sporadic (eruptive) volcanic SO₂ emissions.

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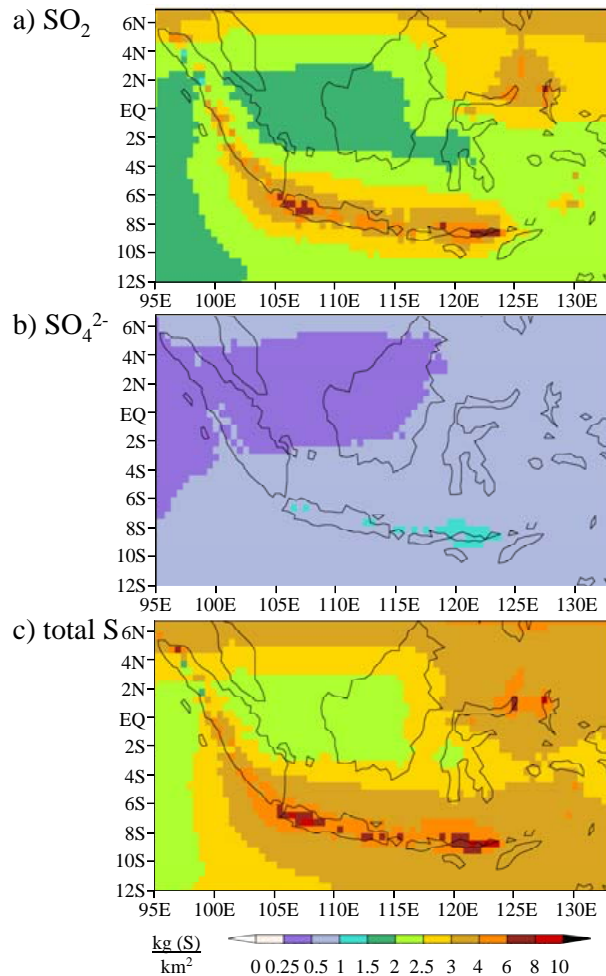


Fig. 2. Annual mean vertical column burden of (a) SO₂, (b) SO₄²⁻, and (c) total S: SO₂+SO₄²⁻ for the “S Experiment”.

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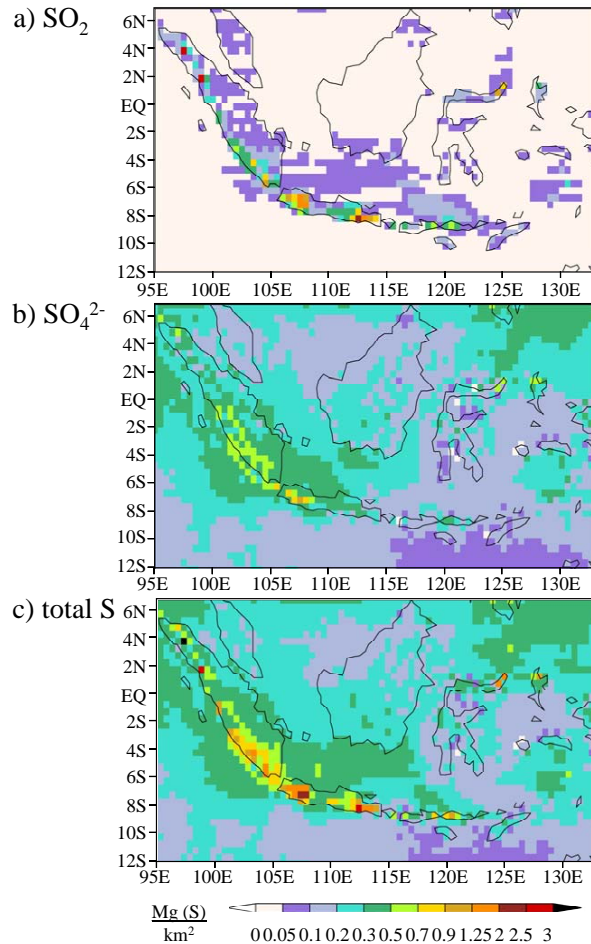


Fig. 3. Annual sum of the (a) dry SO₂ deposition, (b) dry + wet SO₄²⁻ deposition, and (c) total S: dry SO₂ + dry + wet SO₄²⁻ deposition for the “S Experiment”.

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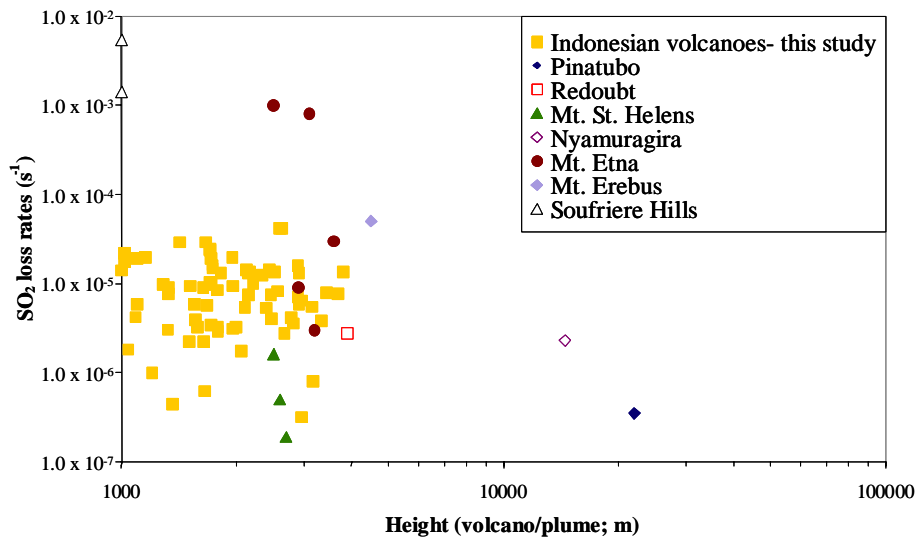


Fig. 4. Modeled SO_2 loss rates (yellow squares) are plotted against the actual height of each volcano and measured SO_2 loss rates from Oppenheimer et al. (1998) are plotted against the observed plume height.

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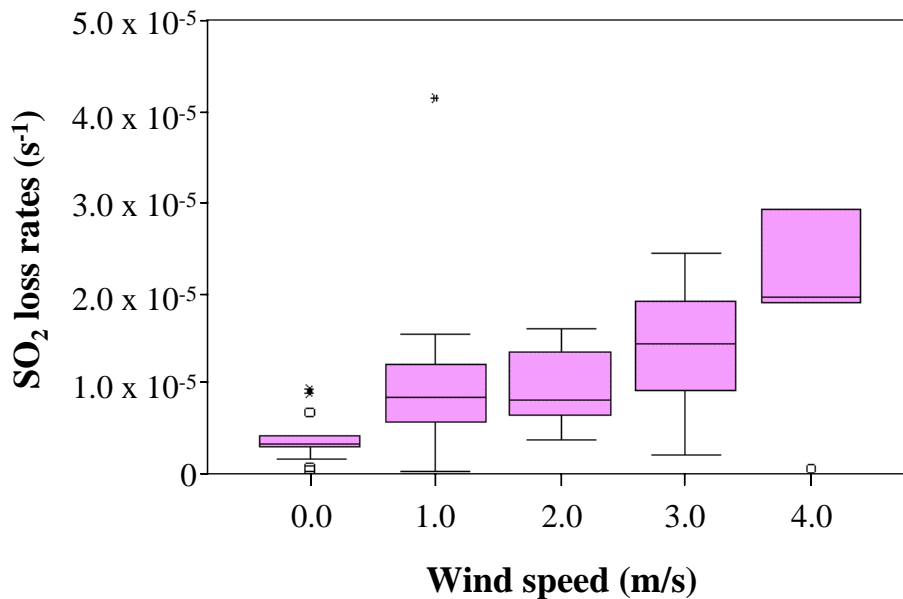


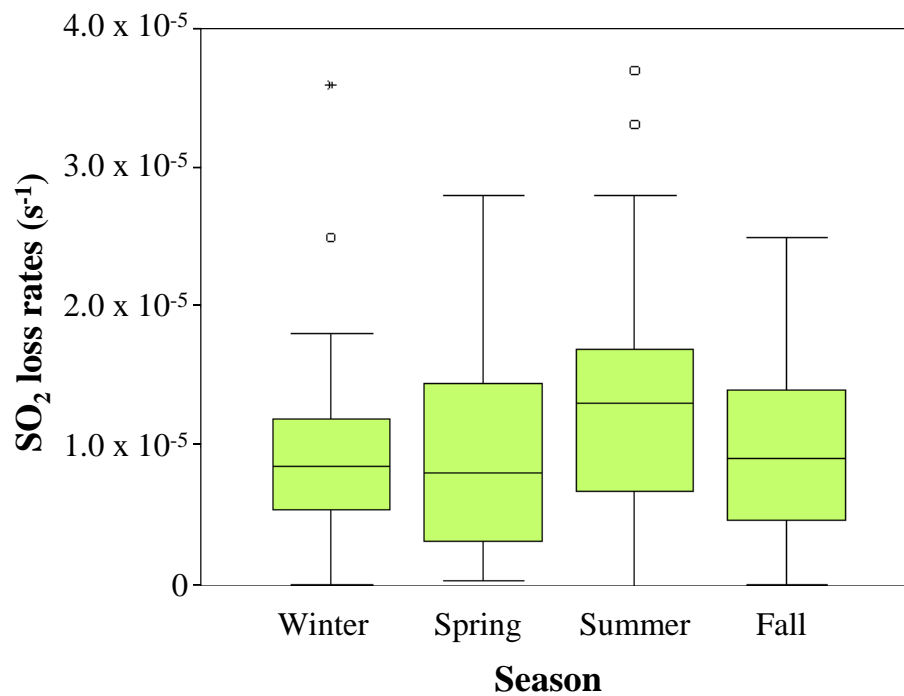
Fig. 5. Annual mean SO₂ loss rates for each modeled volcano plotted against the annual mean wind speed at the height of each volcano.

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**Fig. 6.** Seasonal SO₂ loss rates.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

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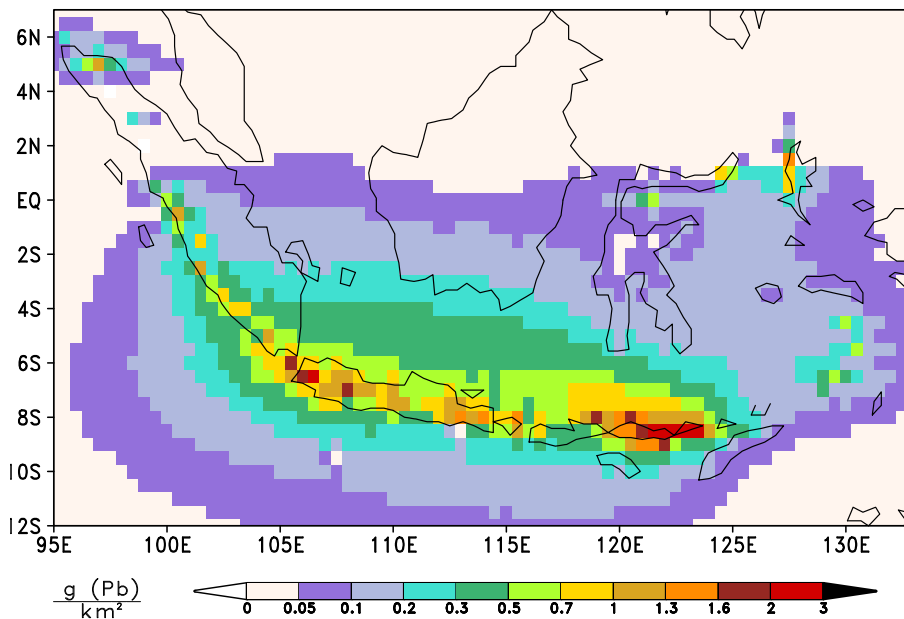


Fig. 7. Annual mean column burden of PbCl_2 for the "PbCl₂ Experiment".

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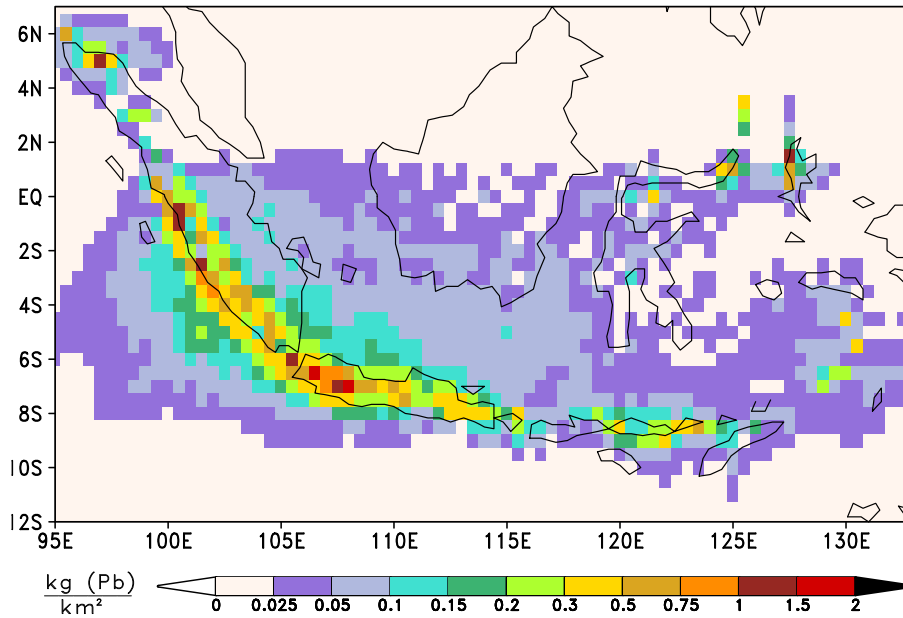


Fig. 8. Annual sum of dry + wet PbCl_2 deposition for the “ PbCl_2 Experiment”.

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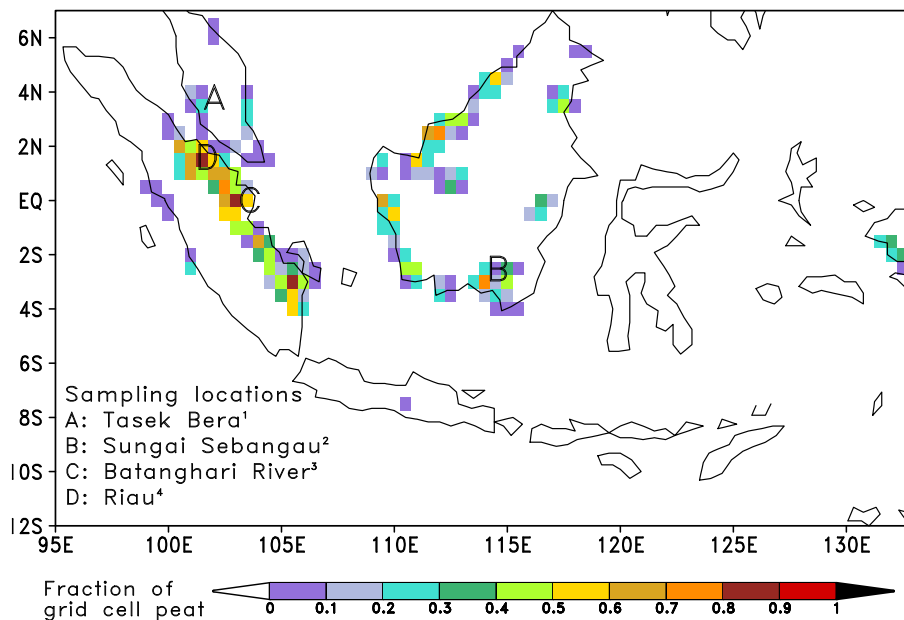


Fig. 9. Peat sampling locations on a map of the fractional peat coverage of the modeled region (after Heil et al., 2005). ¹ Wüst and Bustin (2001); ² Weiss et al. (2002); ³ Esterle and Fern (1994); ⁴ Supardi et al. (1993).

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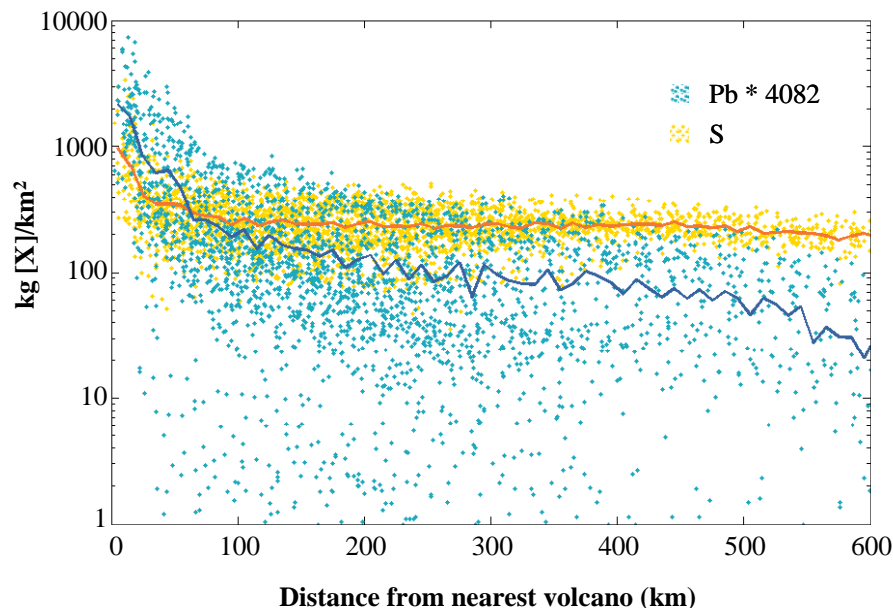


Fig. 10. Annual sum of total deposition for each modeled grid box as a function of the distance to the nearest volcano (“Passive experiment”: blue; “S experiment”: yellow). The solid lines (corresponding colors) are the bin mean over 10 km intervals.

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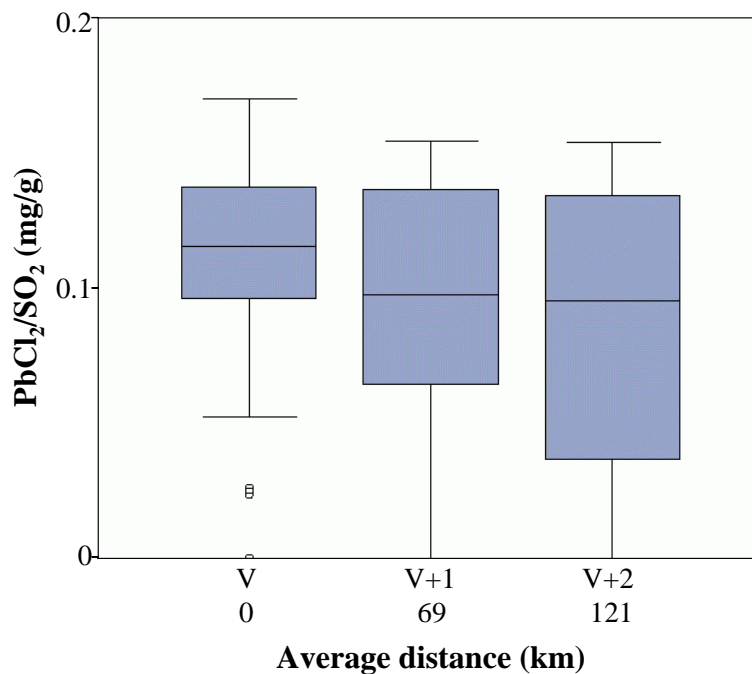


Fig. 11. Annual mean column burden of $[\text{PbCl}_2]/[\text{SO}_2]$ for all volcanoes plotted against the mean distance from each volcano (km) for locations “V”, “V+1”, and “V+2”.

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