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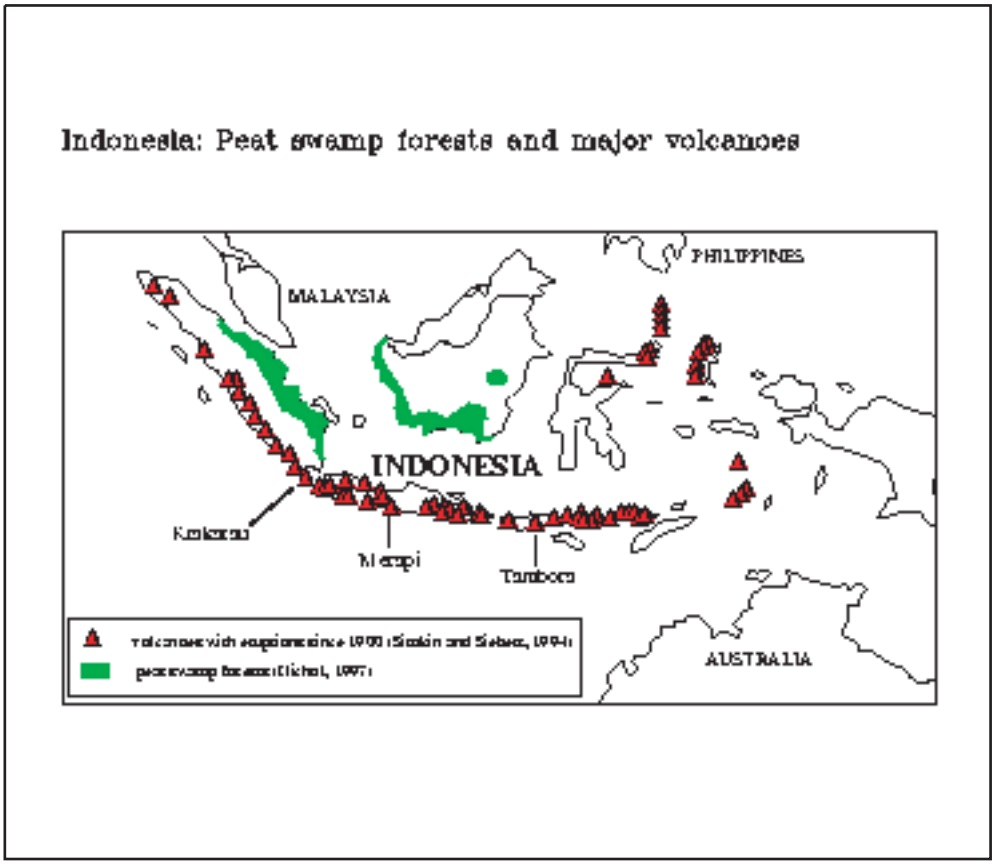

Indonesian smoke aerosols from peat fires and the contribution from volcanic sulfur emissions

by

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Indonesian smoke aerosols from peat fires and the contribution from volcanic sulfur emissions

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Abstract

The island arc volcanoes in and around Indonesia have been permanently degassing for thousands of years, thereby contributing significantly to the total emissions of sulfur species in that region. The hot and wet tropical weather conditions with high solar irradiation and regular daily precipitation during the wet season lead to efficient removal of oxidised sulfate by wet deposition. This is accumulated in the Indonesian peat areas, which serve as natural sponges, soaking up rain during the wet season and slowly releasing moisture into the atmosphere during the dry season. When peat forests are drained for land clearing purposes, the peat quickly dries out and becomes extremely flammable. When ignited, the composition of the burning peat mainly determines the fire aerosol chemical composition and microphysical properties. In this paper we investigate the contribution of volcanic sulfur emissions to wet deposition of sulfur in Indonesian peat swamp areas based on numerical simulations carried out with a global atmospheric circulation model including the tropospheric sulfur cycle. Our study suggests that the observed hygroscopicity and elevated sulfur content of the Indonesian peat fire aerosols is due to accumulated volcanic sulfur.

1. Introduction

In Indonesia, vegetation fires represent a significant source of trace gases and aerosols. During the haze episode in 1997 several measurements of the chemical composition of the fire aerosol have been performed. Most of them focus on the organic components (e.g. Fang et al., 1999; Narukawa et al., 1999, Kunii, 1999), some on inorganic material (e.g. Orlic et al., 1999, Pinto and Grant, 1999). Only a few studies exist about the microphysical properties of the fire-generated aerosols (e.g. Gras et al., 1999, Hoyningen-Huene et al., 1999, Nakajima et al., 1999). However, the knowledge of the Indonesian fire aerosol chemical composition and microphysical properties is required in detail to understand and predict their impact on climate, human health, flora and fauna.

Several studies of the Indonesian smoke haze episodes in 1997 emphasise the particular relevance of peat fire emissions (e.g. Levine, 1999, Page et al., 2002). A distinct higher sulfur content was observed in this peat fire aerosols compared to other vegetation fire aerosols (Gras et al., 1999), which could not been explained yet. In this paper we present a possible explanation by pointing out the connection between the observed sulfur enhancement in the Indonesian fire aerosol as well as in the major burning material which is peat, and quasi-permanent volcanic sulfur emissions.

2. Vegetation fires and smoke aerosols in Indonesia

Every year during the dry season land clearing fires are inflamed in Indonesia. Usually, the burning activities cease in October / November with the beginning of the northern monsoon rains. In 1997 / 1998 the strong El Nino lead to severe drought conditions. Land-clearing fires became uncontrolled particularly on Kalimantan (Borneo) and Sumatra. Reduced convective activity during August until October 1997 favours the wide spread of the vegetation fire emissions causing several episodes with intense smoke and haze heavily affecting also

Malaysia and Singapore. At Palangkaraya on Borneo and Jambi on Sumatra, both located close to the vegetation fires, up to 4,000 $\mu g/m^3$ total suspended particulate matter were measured, exceeding the Indonesian national ambient air quality standard by a factor of 15 (Heil and Goldammer, 2001).

Levine (1999) estimated the emissions released from the vegetation fires on Kalimantan and Sumatra islands between August and December 1997. Although only 20 % of the area burned is assumed to consist of peat swamp forests, they contribute about 90 % of the gaseous and particulate fire emissions. The reason is the huge storage of organic matter in the peat deposits that has accumulated over the last 5,000 to 10,000 years (Rieley et al., 1995). Suparadi et al. (1993) suggest a biomass loading of 97,500 tons/km^2 for dry peat deposits of 1.5 m thickness as representative for Indonesian peat. This is a conservative estimate since the peat is frequently 8 m in depth (Nichol, 1997). Therefore, peat bogs can burn deep under the surface and are very difficult to extinguish.

Significant differences between smoke aerosols collected by aircraft over Kalimantan and northern Australia during the 1997 dry-season fires are emphasised by Gras et al. (1999). The Indonesian fire aerosols are reported to have considerably greater light-scattering properties and hygroscopic growth factors compared to the northern Australian fire aerosols. The authors explain these differences partly by the different combustion phases: smouldering fires in Indonesian peat areas, mixed flaming and smouldering fires in the Australian savannah. But their main hypothesis is that peat deposits in the costal lowlands of Kalimantan may be enriched by Holocene sulfidic sediments which emit SO_2 when burned, providing a source of atmospheric sulfate and thus hygroscopicity for the Indonesian aerosol. Nakajima et al. (1999) report carbonaceous material with a significant sulfur content to be representative of the 1997 Indonesian forest fire aerosols. These authors carried out satellite and ground-based studies and conclude that the Indonesian forest fire aerosols are very similar to urban type aerosols

regarding their optical properties. Data published by Pinto and Grant (1999) for the mean aerosol composition in the smoke affected areas of Sumatra in 1997 (Table 1) indicate a sulfate content which is comparable to heavily polluted air at the East Coast of the USA (Philadelphia) and Central Europe (Teplice). In Kuching, Malaysia a significant increase of atmospheric SO_2 concentrations during the smoke haze episode in September 1997 was measured by Davies and Unam (1999). Maximum values of 48 ppb SO_2 are reported compared to a background level of less than 5 ppb SO_2. These findings are also supported by Balasubramanian et al. (1999) who studied the chemistry of rainwater in Singapore from July to December 1997. They found haze/non-haze rainwater ratios of nss SO_4^{2-} 1.70, K^+ 1.47, Cl^- 2.15. Sea salt does not contribute to the high sulfur load as ss SO_4^{2-} remained unchanged. Orlic et al. (1999) observed a comparable increase of several chemical species in the haze aerosol in Singapore during 1997 compared to non-haze conditions. They report haze/non-haze ratios of S 1.6 – 2.5, Cl 1.8 – 2.1, K 1.8 – 3.2. Hence, there is strong evidence that the Indonesian haze in 1997, which mostly came from the burning/smouldering peat was highly enriched by sulfur, chlorine and potassium.

3. Indonesian volcanoes and peat deposits

Sulfur, chlorine and potassium are typical for the emissions from permanent degassing also of the island arc volcanoes in and around Indonesia. Figure 1 shows the geographical position of the peat areas in Sumatra and Kalimantan (Nichol, 1997) together with the 65 volcanoes that erupted since 1900 in this region (Simkin and Siebert, 1994). 75 % of the total Indonesian peat land areas are located on Sumatra and Kalimantan, most of them in coastal lowlands within five degrees of the equator (Shimada et al., 2001). Except in the Northwest sector, these peat areas are surrounded by active volcanoes. All together there are 149 known volcanoes distributed over the Indonesian islands. Volcanism of the Sunda Arc, stretching

over 3,000 km from NW Sumatra to the Banda Sea, results from the subduction of Indian Ocean crust beneath the Asian Plate. Here 76% of the region's volcanoes are found. To the NNW, the basaltic volcanism of the Andaman Islands results from short spreading centers, and, to the east, the Banda Arc reflects Pacific Ocean crust subducted westward. North of this arc, tectonic complexity increases, with converging plate fragments forming multiple subduction zones, mainly oriented N-S, that in turn produce the Sulawesi-Sangihe volcanoes on the west and Halmahera on the east of the collision zone. 80% of the Indonesian volcanoes with dated eruptions have erupted in the 20th century.

At many volcanic sites in Indonesia high amounts of magma, ashes and gases are released into the atmosphere on short time scales, reaching occasionally into the stratosphere. Prominent examples are the explosive eruptions of Tambora in 1816, Krakatau in 1883 and Agung in 1963. Several smaller eruptions occur every year. In addition, many active volcanoes permanently emit gases into the troposphere during their non-explosive phase. Data on the emissions are available only from few volcanoes from short monitoring efforts. One example is the SO_2 emission from Merapi (Java), one of the most active volcanoes of the region (Figure 2). These data show that the degassing of a single source may vary between a few tens of metric tons SO_2 per day to several hundreds of tons with strong variations in time. If we make a simple estimate of the total emission by fumaroloic and mildly explosive activity of Indonesian volcanoes, we derive an emission of typically 1.4 Tg S per year (75 volcanoes x 100 t SO_2/d = 7500 t SO_2/d = 2,737,500 t SO_2/y = 1.4 Tg S/y). Halmer et al. (2002) determined similar volcanic emissions in the Indonesian region of 1.05-1.3 Tg S/y. Compared to global annual tropospheric volcanic sulfur emissions reported by Graf et al. (1997) of 14 Tg S/y, the Indonesian volcanoes contribute about 10 %. Given the proximity of many of the Indonesian volcanoes to the peat areas (Fig. 1) which is often within 200 to 1000 km (i.e. well within the transport distance for SO_2 or it’s oxidation product SO_4^{2-}) it is evident

that much of the sulfur from the volcanic sources may be deposited and accumulated in the peat swamps.

Graf et al. (1997) performed a numerical simulation of the fate of sulfur emissions using a global atmospheric circulation model (ECHAM-4) including a representation of the tropospheric sulfur cycle. The S containing species SO_2 and SO_4^{2-} have been tagged in this study to distinguish between anthropogenic, biomass burning, marine / terrestrial DMS and volcanic sources. A detailed description of the model and simulation set–up is given in Graf et al. (1997). Here we analyse the simulation results focussing on Indonesia. In this region the main removal process of atmospheric sulfur is wet deposition. Total wet deposition of sulfur in the Indonesian peat areas is in the order of 200-500 mg S/(m^2 y) (Fig. 3a). Maximum wet deposition of sulfur with more than 1200 mg S/(m^2 y) occurs south of the Philippines. This represents about half of the calculated yearly maximum values in the highly polluted areas of China and an amount comparable to the calculated maximum wet deposition of sulfur over Europe. According to our model simulation, 50 to 80 % of this sulfur in Indonesia originates from volcanic sources (Fig. 3b).

In total, the model calculation suggests that Indonesian peat swamp areas are enriched in sulfur by wet deposition at a rate of 200 - 500 tons S/km^2 in 1000 years. Rieley et al. (1997) report growth rates for coastal and inland peat in Indonesia of 20 cm per 100 years and 14 to 50 cm per 100 years, respectively. Assuming a growth rate of 15 cm per 100 years would produce 1.5 m peat in 1000 years with a dry peat biomass load of 97,500 tons/km^2 according to Suparadi et al. (1993). The resulting total sulfur content of the dry peat should therefore be 2-5g/kg (200 - 500 tons S/km^2 / 97,500 tons/km^2). These numbers lie in the range of the sulfur content measurements made in Switzerland by Jeker and Krähenbühl (2001). The sulfur content of the Swiss peat samples varies between 1–5 g/kg dry sample mass dependent on the

age of the peat. It shows distinct maxima in the early 1960s and 1980s, which correspond to maximum SO_2 emissions in Europe. Although tropical and mid-latitude peat systems are not directly comparable, the Swiss study supports our hypothesis of sulfur enrichment in the Indonesian peat areas. Measurements of the total sulfur content of a peat core taken in Central Kalimantan range from 1-2 g/kg dry peat (Weiss et al., 2002), which is at the lower limit of our calculation. We overestimate the total sulfur content of the peat because we did not include runoff of surface water, which removes a portion of the deposited sulfur from the peat. Additionally, it should be noted that the horizontal resolution of our model ($3.75^0 * 3.75^0$) is not representative for point measurements.

4. Summary and conclusions

In this paper we investigated a possible source of the enhanced sulfur content that has been observed in the fire aerosols in Indonesia, Malaysia and Singapore during the haze episodes in 1997. Smouldering peat swamp fires in Sumatra and Kalimantan have been recognised to release more than 90 % of the particulate carbonaceous emissions (Levine, 1999). Additionally, trace species that are removed from the atmosphere mainly by wet deposition can accumulate in the peat during its growth process (lasting up to 5000 – 10000 years) and play an important role when the peat is ignited. According to our model study, sulfur emitted from the permanently degassing island arc volcanoes in and around Indonesia contributes 50 - 80 % to the total wet deposited sulfur in the Indonesian peat swamp areas. It should be emphasised that our model study represents a typical emission situation of the 1980s including significant anthropogenic sulfur emissions. Before the 19th century, anthropogenic sulfur emissions are negligible. However, the permanent volcanic degassing of sulfur in the Indonesian area stays on similar levels since thousands of years. Our estimate of the total sulfur content of the Indonesian peat (2-5 g/kg) exceeds reported measurements (1-2 g/kg) of a single peat core taken in Central Kalimantan (Weiss et al., 2002) by a factor of two. These

differences can be related mainly to the different scales of our model and the point measurement, and the neglected surface runoff.

When the Indonesian peat is ignited, we expect a concentrated release of the accumulated sulfur because the burning rate of the peat is drastically higher than its accumulation rate was in the past. Hegg et al. (1987) draw similar conclusions when they measured enhanced sulfur emissions from a prescribed vegetation burn near Los Angeles compared to burning products in rural areas: they explained the differences by previously deposited anthropogenic pollutants.

The connection between volcanic emissions and the composition of the peat fire aerosols in Indonesia has been studied in this paper focussing on sulfur. However, permanent degassing of additional elements like Cl, K, Zn, Br, Pb, Cd, Cu from the Indonesian volcanoes is known (Nho et al., 1996). If we take into account the yearly repeating haze episodes over Indonesia even in non El Nino years like 2002 due to increased burning because of peat draining, an improved knowledge of the chemical and microphysical properties of the Indonesian peat fire aerosols is essential for the protection of human health. Furthermore, the specific character of the Indonesian peat smoke might exert a strong impact on the optical properties of the aerosol, on it's efficiency to act as cloud condensation nuclei and thus on the optical properties of clouds, their lifetime and the precipitation rate. This will affect climate on the local or even global scale. Therefore, we propose measurements of the typical volcanic elements in the Indonesian peat in different depths, the determination of the emission factors of the burning peat and measurements of the chemical and physical properties of the young and aged peat fire aerosols. Accompanying high resolution model simulations are necessary for the interpretation and assessment of the combined climate and health effects over Indonesia.

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Figure captions

Figure 1: Peat swamp forests and major volcanoes in Indonesia after Nichol (1997) and Simkin and Siebert (1994).

Figure 2: COSPEC measurements of SO_2 emissions from Merapi volcano on Java at the transition from background to active phase,
available from http://rathbun.si.edu/gvp/world/region06/java/merapi/var.htm

Figure 3: a) Wet deposition of sulfur (mg $S/m^2/y$) and b) contribution due to volcanic emissions in percent. Values derived by the ECHAM4 model.

Table 1: Mean fine aerosol ($PM_{2.5}$) composition in ng/m^3 at Palembang and Sriwijaya, Sumatra (November 1997) and in midlatitude industrialized cities (Teplice, Czech Republic, in 1993, Philadelphia, Pennsylvania, USA in 1994). The data is taken from Pinto and Grant, 1999.

	Palembang	Sriwijaya	Teplice	Philadelphia
Sulfur	11 000	6 900	10 000	3 300
Chlorine	4 500	4 600	410	26
Potassium	1 400	1 500	300	60

Figure 1:

Indonesia: Peat swamp forests and major volcanoes

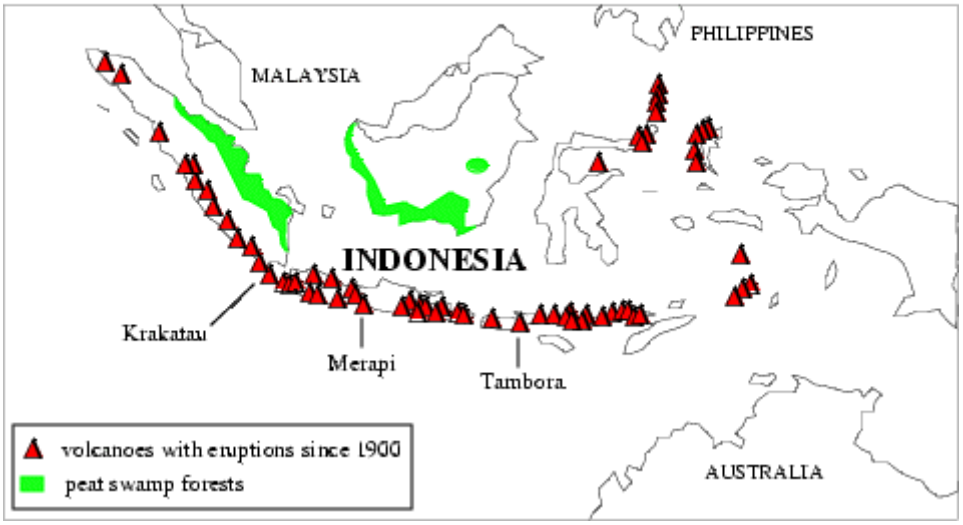
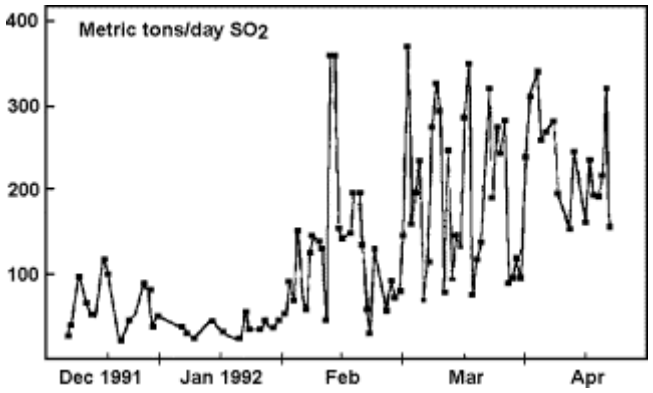


Figure 2:


Metric tons/day SO_2
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Jan 1992
Feb
Mar
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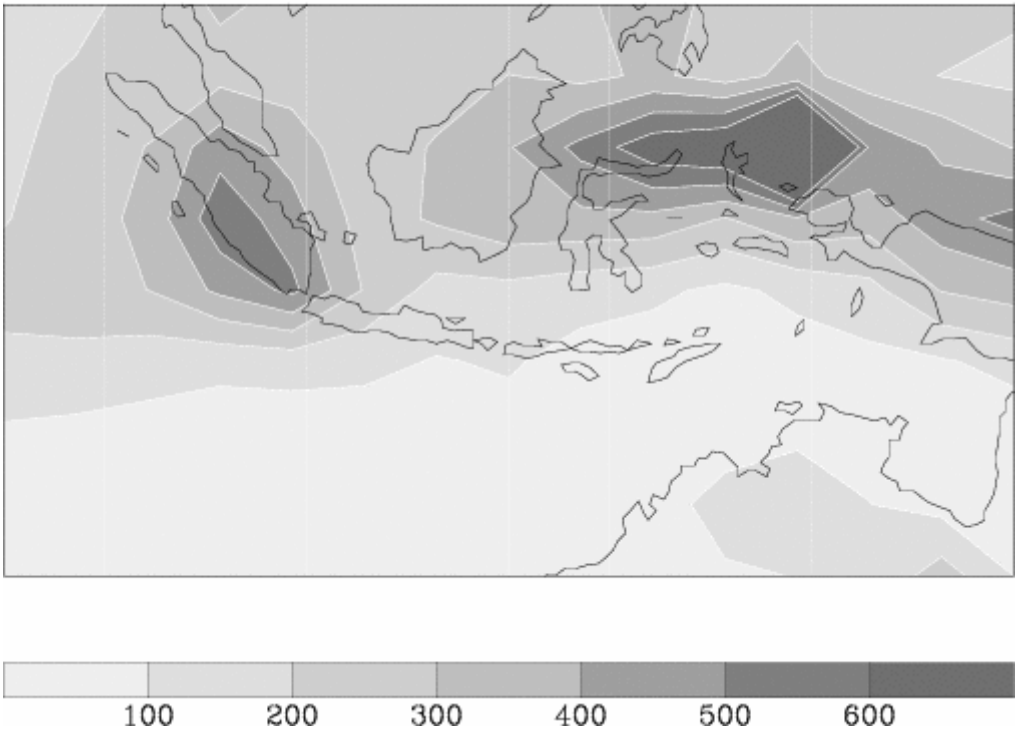
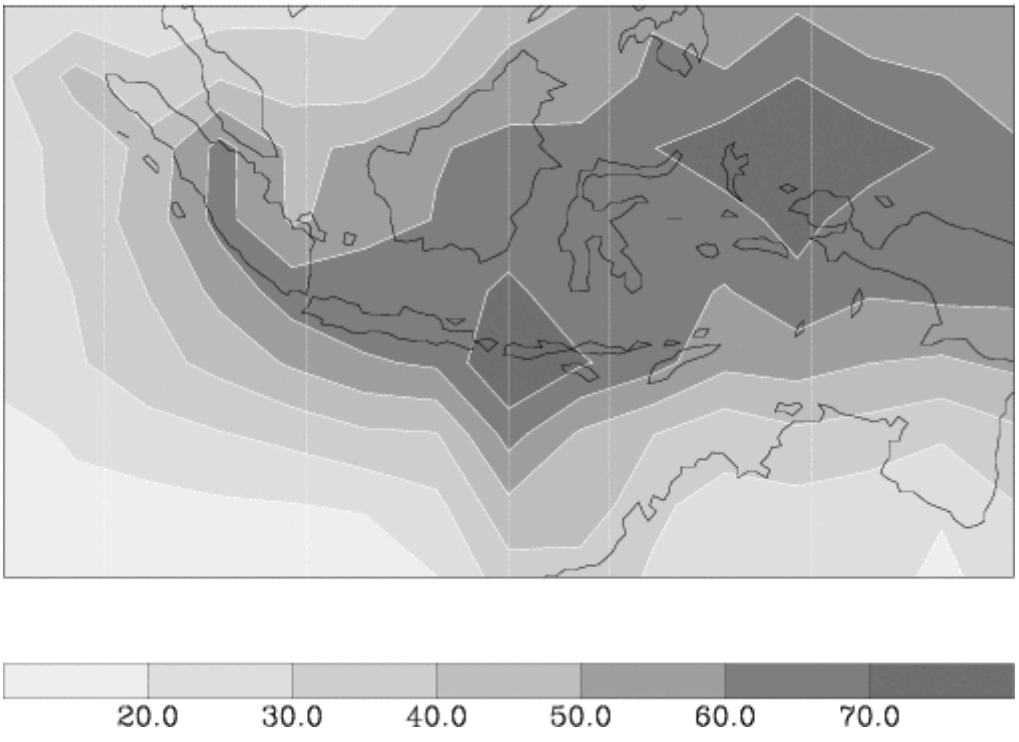
Figure 3:

a) Indonesia: Wet deposition of sulfur [mg/m2/y]



b) Indonesia: Wet deposition of volcanic sulfur [%]



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