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The impact of moderate-scale explosive eruptions on stratospheric gas injections

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Abstract Volcanic gases such as SO₂, H₂S, HCl and COS emitted during explosive eruptions significantly affect atmospheric chemistry and therefore the Earth's climate. We have evaluated the dependence of volcanic gas emission into the atmosphere on altitude, latitude, and tectonic setting of volcanoes and on the season in which eruptions occurred. These parameters markedly influence final stratospheric gas loading. The latitudes and altitudes of 360 active volcanoes were compared to the height of the tropopause to calculate the potential quantity of volcanic gases injected into the stratosphere. We calculated a possible stratospheric gas loading based on different volcanic plume heights (6, 10, and 15 km) generated by moderate-scale explosive eruptions to show the importance of the actual plume height and volcano location. At a plume height of 15 km for moderate-scale explosive eruptions, a volcano at sea level can cause stratospheric gas loading because the maximum distance to the tropopause is 15–16 km in the equatorial region (0–30°). Eruptions in the tropics have to be more powerful to inject gas into the stratosphere than eruptions at high latitudes because the tropopause rises from ca. 9–11 km at the poles to 15–16 km in the equatorial region (0–30°N and S). The equatorial region is important for stratospheric gas injection because it is the area with the highest frequency of eruptions. Gas injected into the stratosphere in equatorial areas may spread globally into both hemispheres.

Keywords Volcanic gas emission · Plume height · Atmosphere · Stratosphere · Altitude · Latitude · Tropopause

Introduction

When Mount Pinatubo (Philippines) erupted on 15 June 1991, an estimated 20×10^6 tons of sulfur dioxide and large quantities of ash particles were carried as much as 45 km high into the atmosphere (McCormick et al. 1995). The aerosol veil, composed of sulfuric acid particles, caused a negative climate forcing reducing global temperatures by 0.5 °C for almost three years. Locally, temperatures were reduced by up to 3 °C (Yue et al. 1995).

When evaluating the stratospheric impact of volcanic eruptions, several parameters need to be considered: (1) mass eruption rate, which determines the height of an eruption column, (2) latitude and (3) height of a volcano, and (4) the sulfur concentration in the magma as a free gas phase. Previous studies of the annual global gas emission into the atmosphere or stratosphere (Stoiber et al. 1987; Bluth et al. 1997; Andres and Kasgnoc 1997) did not consider some limiting factors on the gas input, such as altitude, latitude and tectonic setting of a volcano location and the season in which an eruption occurred. These factors have to be taken into account, however, when estimating gas loading of the atmosphere and especially the stratosphere.

We determined where volcanoes erupt and also the quantity of gas injected into the atmosphere/stratosphere to model historic and as well as future climate forcing caused by volcanoes. We utilize a new compilation of historic atmospheric volcanic eruptions, with possible contributions of each eruption to the stratosphere. We make use of more than 4,000 historic eruptions (Table 1) compiled by Simkin and Siebert (1994) for the time window 1900–1995. From 1996 on, we have taken the annual frequency of monitored eruptions from the Web-

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page of the Smithsonian Institute (<http://www.volcano.si.edu/gvp/>).

The parameters altitude, latitude and tectonic setting, combined with the tropopause height (9–11 km at the poles to 15–16 km at the equator, Fig. 1), significantly influence the quantity of volcanic gas emission reaching the stratosphere. The main factor controlling the input of an eruption plume is the mass eruption rate, itself a function of processes at depth such as the free gas content of rising magma columns. Further limiting factors for the volcanic plume height include the different stabilities of the atmospheric layers, and the variability of relative humidity of the ambient air surrounding the ascending eruption column. Here, we focus on limiting parameters such as altitude and latitude of 360 active subaerial volcanoes, the seasons and their effects on the tropopause height and the plume height, depending on explosive energy level.

Method

We collected data on volcanic plume heights from diverse volcanoes from different tectonic settings and with different magma compositions to compare the range of plume heights from moderate-scale explosive eruptions. Plume heights vary widely for each individual magnitude of eruption. We chose three representative plume heights for our calculation, from the range of plume heights (5 to 15 km) for moderate-scale explosive eruptions, e.g., 6, 10, and 15 km.

We determined potential stratospheric gas loading using these three different heights for a volcanic plume, indicating the significance of diverse plume heights in controlling the final stratospheric gas loading (Fig. 2). Taking into account the frequency function of volcanic plume heights, 20% of volcanic plumes rise higher than 15 km, 60% rise above 10 km, and 80% rise above 6 km.

The season significantly influences the impact of the ascending plume in two ways: (1) the tropopause height varies by several kilometers throughout the year, and (2) the relative humidity in the ambient atmosphere changes with the season. The ambient stratification of the lower troposphere varies with both season and latitude, and also often varies depending on the strength of heating and cooling. The tropopause changes asymmetrically in the hemispheres with season (Wong and Wang 2000). These variations in the stratification can significantly affect the ascent height of vapor plumes. Although this parameter is probably the most complex one, we considered the seasonal effect as a very simplified regime in our model, while including the change of water vapor in the air combined with the humidity change with the latitude in our calculation. Holton et al. (1995) discussed the stratosphere–troposphere exchange in detail.

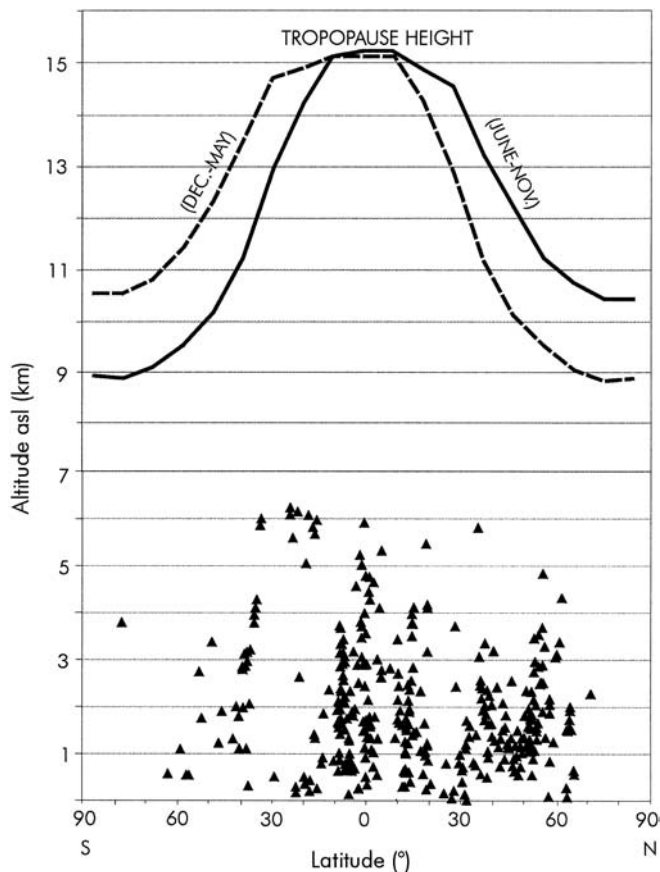


Fig 1 Latitudinal and altitudinal positions of 360 subaerial volcanoes compared to the tropopause height depending on latitude and season (tropopause height after de Brito Mendes 1998)

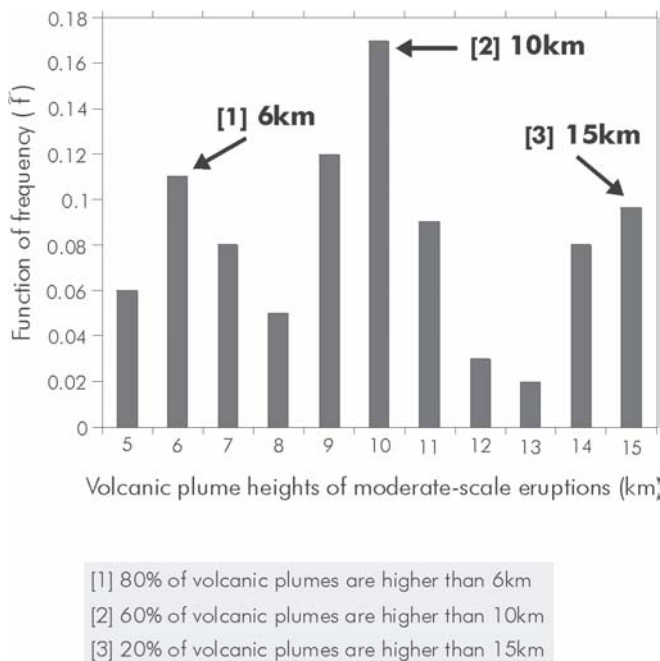
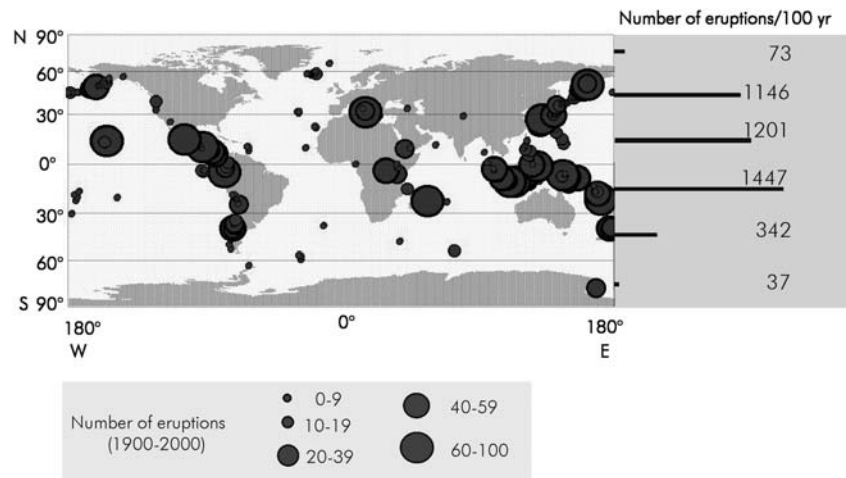


Fig 2 Function of frequency \tilde{f} of height of volcanic plumes from moderate-scale explosive eruptions based on 64 samples

Fig 3 World map showing the number of active subaerial volcanoes during the last 100 years. The different sizes of the volcanoes indicate the number of eruptions during 1900–2000



Regional distribution of volcanic gas emissions, altitudes of volcanoes and their tectonic settings

A significant feature is the high concentration of active volcanoes along the subduction zone of the Circumpacific Ring of Fire (Fig. 3). Volcanoes related to subduction zones are the major gas emitters because of the large number of very active and highly explosive volcanoes. More than 300 of the 360 active subaerial volcanoes which erupted at least once during the past 100 years are located above subduction zones, 24 in rift zones, and 22 on oceanic islands. We summarized altitudes of 360 volcanoes and determined their altitudinal range for each tectonic setting:

1. subduction zones: 2–3 km,
2. rift zones: 1–3 km, and
3. ocean islands: 1.5–2.5 km.

The mean volcano height is similar in all tectonic settings, subduction zone-related volcanoes tending to be higher as most are located on uplifted terrains. Subduction zone-related volcanoes show a “maximum” average height of 2–3 km.

The relationship of the distance between the top of a volcano and the tropopause and the varying height of the tropopause with the season is even more complex because the tropopause can vary by several kilometers, e.g., 9 km in winter to 11 km in summer at the poles (de Brito Mendes 1998). In the tropics, however, tropopause height (15–16 km) is almost constant (Table 1). Figure 1 shows the volcano heights in relation to the seasonal tropopause height.

The quantity of gas reaching the stratosphere is also significantly influenced by the altitude of a volcano. We developed a model to show the importance of determining the exact plume height of explosive eruptions. Figure 4 shows model volcanoes injecting gas into the troposphere or stratosphere, based on plume heights of 6, 10 and 15 km for moderate-scale explosive eruptions, depending on the parameters latitude, altitude and season. The seasonal

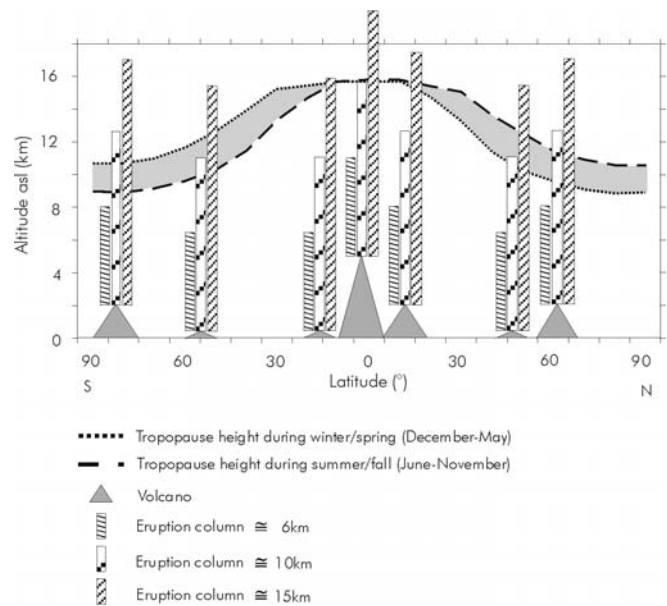
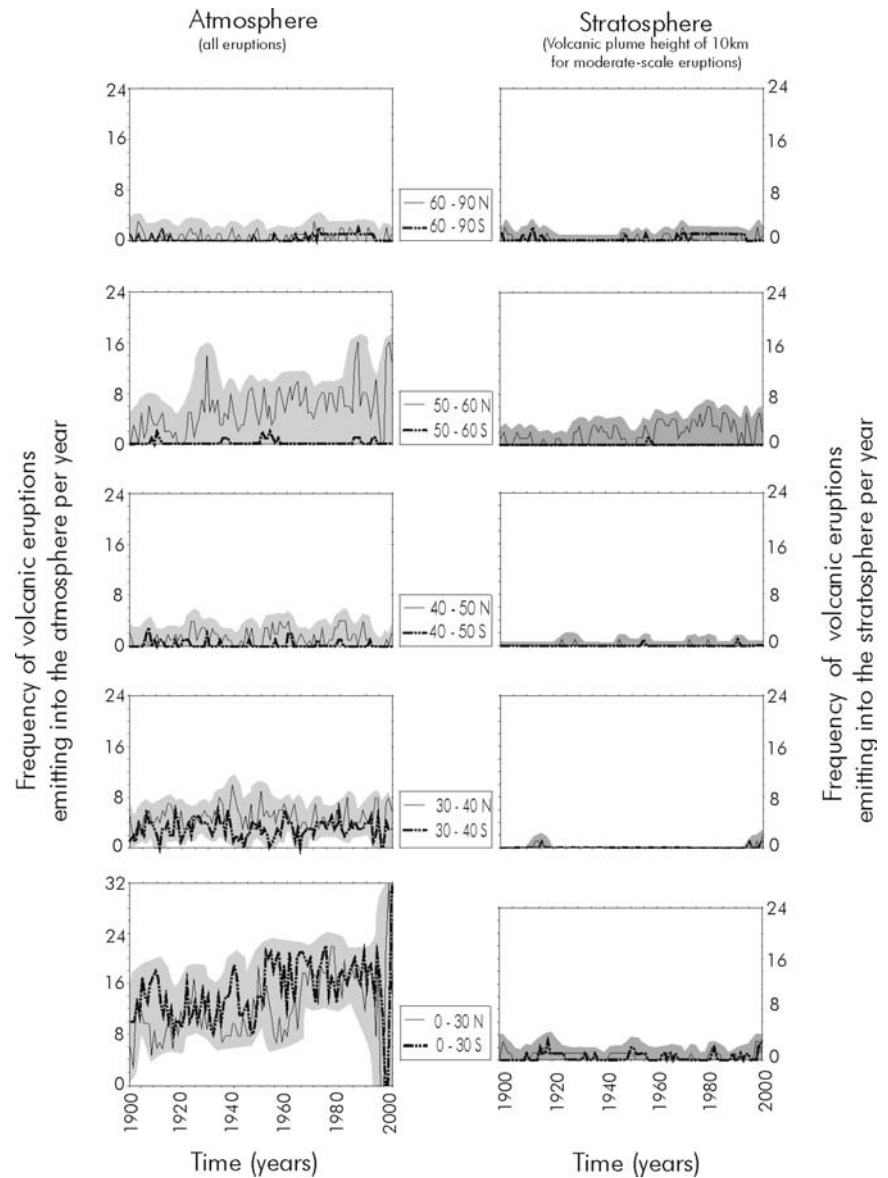


Fig 4 Model for volcanoes injecting gas into the stratosphere at different latitudinal and altitudinal positions of the volcanoes, compared to the height of the tropopause

Table 1 Annual average of the tropopause heights depending on latitude and season (based on de Brito Mendes, 1998)

Latitude	Tropopause (km)	
	(December–May)	(June–November)
Northern hemisphere		
60–90°	9	10.7
50–60°	10.3	11.5
40–50°	11.4	12.6
30–40°	13.3	13.7
0–30°	15.2	15.4
Southern hemisphere		
0–30°	15.4	14.6
30–40°	13.9	11.5
40–50°	12.7	10.4
50–60°	11.6	9.7
60–90°	10.8	9

Fig 5 Frequency of eruptions; *left side* shows total eruptions emitting into the atmosphere, and *right side* shows eruptions able to inject volcanic gas into the stratosphere (with the assumption of 10-km volcanic plume height for a moderate-scale eruption and an annual tropopause height)



variability of the tropopause height significantly influences potential stratospheric gas loading from moderate-scale eruptions at latitudes between 40 and 60°. Here, the critical height for a volcano to inject gas into the stratosphere can vary up to 2.5 km. We expanded an earlier dataset on volcanic SO₂ estimates (see Halmer et al. 2002 for further discussion) demonstrating the seasonal influence on volcanic gas input into the stratosphere, depending on the geographic location of a volcano (latitude, altitude and tectonic setting). The amount of gas reaching the stratosphere can differ significantly depending on the time of the eruption, due to the seasonal variability of the tropopause height.

We next visualized the frequency of volcanic eruptions at zonal scales for the entire atmosphere; we took 10-km plume heights for all moderate-scale explosive eruptions (Fig. 5). Our time series regarding the frequency of eruptions resulting in atmospheric gas loading is based on

the predicted variation of the tropopause height with season depending on latitude, and with 10-km-high volcanic plumes. The frequency of volcanic eruptions at 0–30° (N and S), 30–40°N, and 50–60°N is much higher than that of volcanic eruptions in other latitudinal intervals. The equatorial region (0–30°) in the southern hemisphere (SH; 107 volcanoes) shows a slightly higher frequency of eruptions compared to the northern hemisphere (NH; 95 volcanoes). Volcanic activity is low at latitudes 60–90° (N and S), 40–50° (N and S), and 50–60°S, due to the smaller number of active subaerial volcanoes (Table 1). Most eruptions (30 eruptions/year) occur at equatorial latitudes (0–30°; Fig. 5). Volcanoes between 50 and 60°N show a high annual number of eruptions reaching the stratosphere (three eruptions/year). As many as four eruptions/year reach the stratosphere from volcanoes between 0 and 30° (N and S). Volcanoes at polar latitudes 60–90°, which should have the highest

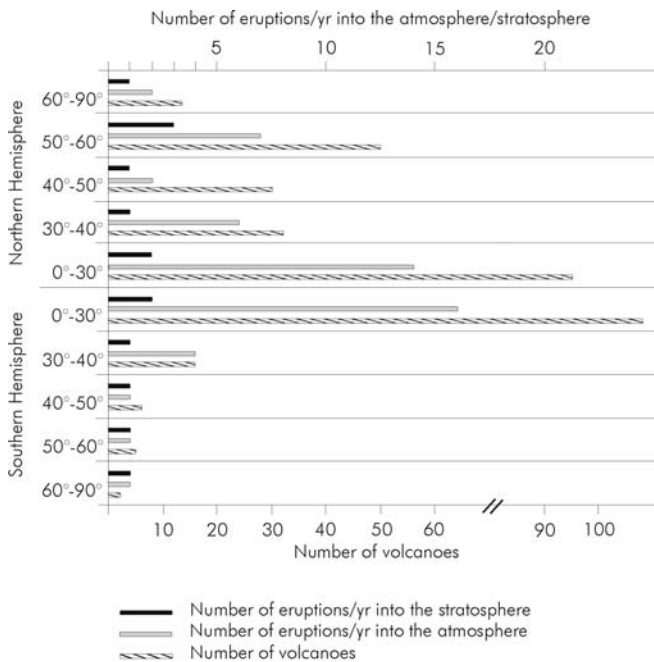


Fig 6 Average numbers of annual eruptions into the atmosphere and stratosphere based on 10-km value for volcanic plume heights of moderate-scale explosive eruptions

potential for stratospheric gas loading due to the very low tropopause height (9–11 km), contribute only two eruptions/year because only 16 active subaerial volcanoes are located at these high latitudes – 14 at 60–90°N, and two between 60 and 90°S. In brief, 54 eruptions/year inject gas into the atmosphere, and ca. 14 of these 54 eruptions/year can inject their gas into the stratosphere (Fig. 6), a much higher number than the 1–2 eruptions/year postulated by Simkin (1993).

We subdivided volcanic SO₂ emissions for the northern and southern hemispheres into five latitudinal intervals – 0–30°, 30–40°, 40–50°, 50–60°, and 60–90°. Time series were calculated in two ways, using 6, 10 and 15 km for plume heights of moderate-scale eruptions (Fig. 7). The stratospheric gas loading is obviously higher (~30% increase) when assuming a larger value for the volcanic plume height (e.g., 15 versus 10 km). Differences in stratospheric gas loading is most significant from 0 to 30° in the equatorial region, and also at 30–40° and 50–60° using 15, 10 or 6 km for plume heights of moderate-scale eruptions (Fig. 7). There is no large difference in the polar regions, due to the very low height of the tropopause. Here, moderate-scale eruptions can easily reach the tropopause when assuming a volcanic plume height of 10 km. No restriction exists between 60 and 90° for moderate-scale eruptions for the plume heights 10 and 15 km to inject gas into the stratosphere, but there is still a definite limitation for 6-km plume heights.

The final total stratospheric loading is strongly reduced compared to calculations assuming the 15-km plume heights for moderate-scale eruptions when using only the value of 10 km, or even 6 km for the past 100 years. This

shows the importance of precise determination of plume heights by different energy levels of explosive eruptions. The difference of 5 km significantly affects the quantity of stratospheric gas loading at lower latitudes because of the increasing height of the tropopause towards the equator. Volcanic activity is more frequent at low compared to high latitudes, due mostly to the larger number of volcanoes in this region (e.g., the Andes in South America; Indonesia, Africa, oceanic islands in the Pacific; Fig. 3).

Finally, we subdivided the frequency of SO₂ input into the stratosphere into the four seasons (Fig. 8). A larger amount of volcanic SO₂ reaches the stratosphere from December to February (NH winter) then during other months. The lowest quantity of SO₂ emitted into the stratosphere is from September to November (NH fall) in the SH.

Results

Active volcanoes cluster at the equatorial latitudes (0 to 30°) of both hemispheres, with volcanoes in the SH reaching heights of over 6,000 m a.s.l. The highest volcano active during the past 100 years is Pular in Chile (6,233 m a.s.l.). At temperate latitudes, however, only a few volcanoes are able to produce eruption columns approaching the stratosphere (Fig. 7). The mid- and polar latitudes (exception: 50–60°N) are unimportant areas for volcanic gas injection into the stratosphere, due to the paucity of volcanoes.

Assuming a height of an eruption plume for moderate-scale eruptions of 15 km (more reasonable in equatorial regions than in polar areas because of the rising warm air which causes an acceleration of the buoyant plume), a volcano at sea level is able to inject gas into the stratosphere. If we assume all moderate-scaled eruptions to generate volcanic plumes rising to 10 km, only few eruptions in the tropics from volcanoes higher than 5,000 m a.s.l. would transport gas into the stratosphere. Of the 360 active subaerial volcanoes, 16 are located at >5,000 m a.s.l.

The number of volcanoes located in the northern hemisphere exceeds those in the SH by 3:1, and the relation of stratospheric eruptions is 5:4. Nevertheless, an equilibrium exists between both hemispheres regarding the annual “stratospheric” eruptions based on plume heights of 15, 10 and 6 km (Fig. 5). This may be due to the fact that high mountains containing active subaerial volcanoes are more common in the SH. Volcanoes at high altitudes need a lower initial energy for their volcanic plumes to reach the stratosphere. Some of the South American Andes mountains exceed 5,000 m in height. Another factor for a higher activity of volcanoes in the SH could be caused by a higher subduction rate. In these areas, the higher volcanic activity generally depends on a higher velocity of the two colliding plates in a subduction zone, resulting in a higher magma productivity.

Fig 7. Volcanic SO₂ input into the stratosphere based on 6, 10, and 15 km for moderate-scale explosive eruptions

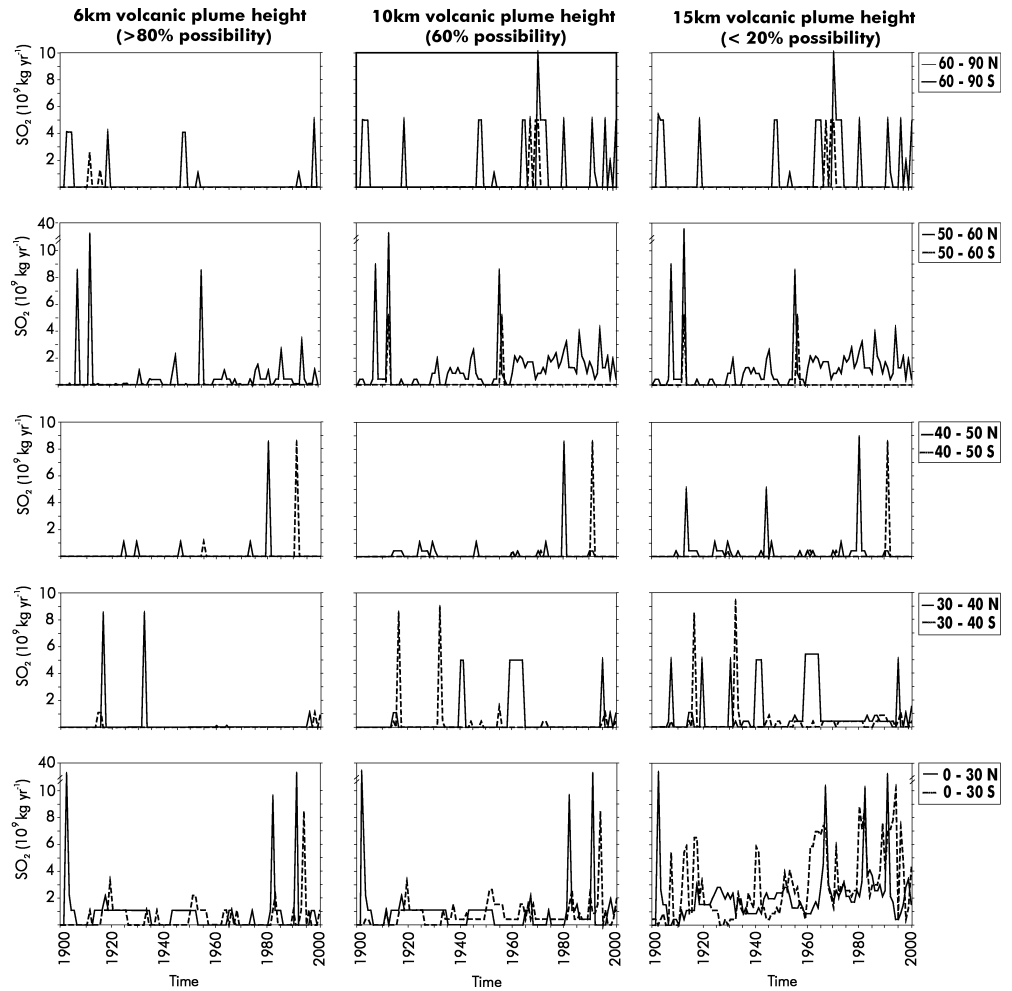
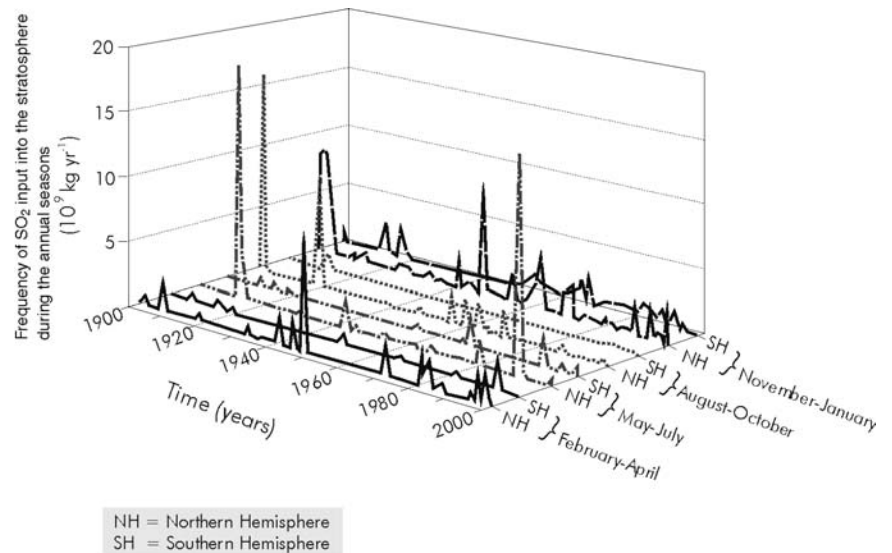


Fig. 8 Seasonal distribution of volcanic SO₂ input into the stratosphere



In addition to compositional diversity and variable supply rates, many different physical and chemical processes also contribute to the broad spectrum of subduction-zone volcanism observed. Segmentation of

volcanic chains into discrete linear belts 100–300 km long, commonly offset by zones of more intense seismicity, has been recognized in Central America, the Cascades, the Aleutian and the Andes (Carr 1984). The

geometry of the subducted slab greatly influences volcanic output. In the Andes, for example, volcanism is weak or absent above downgoing slabs inclined only gently (Simkin 1993).

Thus, the relatively high volcanic SO₂ output in the SH may be caused by higher magma supply rates. The increased frequency of eruptions at the equatorial latitudes of the SH could be partly caused by more frequent eruptions (Takada 1999). The higher frequency of eruptions for volcanoes at high altitudes – especially in the South American Andes – corroborates our conclusion that the amount of gas emitted reaching the stratosphere is higher between 0 and 30°S than in any other latitudinal interval. The quantity of SO₂ is also influenced by the fact that less explosive eruptions can potentially inject gas into the stratosphere.

Volcanic gases emitted from volcanoes at high latitudes in the NH remain mostly only in the NH for a couple of years following an eruption. Similar relations hold for the SH at high latitudes, whereas gases emitted at equatorial latitudes can spread over both hemispheres.

Cooling of the Earth's surface by volcanogenic sulfate aerosols was previously thought to be more intense for the NH where 75% of all subaerial volcanoes are located (e.g., Circumpacific Ring of Fire). Our data show, however, that stratospheric gas input from moderate-scale eruptions is about the same in both hemispheres, for a 10-km plume height. A close equilibrium seems to exist regarding the relation of gas emission caused by volcanic eruptions between the NH and the SH at equatorial latitudes (0–30°). For eruptions in the mid-latitudes and in the polar regions, a significant local/regional cooling effect on the Earth's surface is likely, a relation which needs more study.

The reported decrease in volcanic eruption frequency thought to be caused by decreased monitoring during World War I and II (Simkin 1993) is not totally corroborated by our data. In the five chosen latitudinal intervals for each hemisphere, we found no sharp decline in any of the five latitudinal intervals in the number of eruptions during 1914–1918. We even found an increase in the number of eruptions at 30–40°. There is a slight decline in the SH but a definite increase in the number of eruptions is apparent between 0 and 30°N (Fig. 5). The decline in the annual frequency of volcanic eruptions in the NH is more likely caused by a temporary decrease in volcanic activity. A decrease in the number of explosive eruptions is apparent during World War II but there is also a time interval of 2–5 years during which the frequency of eruptions still increases, and an apparent decline begins then already at the time of the war (Fig. 5). The decrease in volcanic activity in the latitudinal intervals 0–30°, 30–40°, and 50–60° is especially obvious in the NH. In the SH, there is either an increase (0–30°) or no obvious change in the number of annual explosive eruptions. An exception are the intervals 30–40° and 50–60° which show a decrease in the number of annual eruptions. However, a decadal decrease occurs in the interval 30–40°S. We think the peaks and valleys in our

time series of eruption frequencies are due to a natural variability in volcanic activity.

Conclusions

Data based on the frequency of eruptions of all monitored subaerial volcanic eruptions between 1900 and 2000 help to evaluate the impact of moderate-scale explosive eruptions associated with volcanic SO₂ emission into the atmosphere. Estimating the stratosphere input is improved by including the parameters altitude and latitude of volcanoes, the different latitudinal height of the tropopause, and the season in which eruptions occurred. These parameters need to be assessed when estimating the quantity of stratospheric gas loading. This study clearly shows how uncertainties such as the variation of plume height for a certain eruption magnitude influence the calculation of global gas input into the atmosphere and, in particular, into the stratosphere. Although we considered more parameters than previous gas studies, our study is based on very simplified assumptions with respect to plume height, variation of relative humidity of the buoyant atmosphere around the volcanic plume influenced by season, or the varying tropopause height with both latitude and season.

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