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Paper:

Measurements of Particle Distribution and Ash Fluxes in the Plume of Sakurajima Volcano with Optical Particle Counter

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Volcanic eruptions have caused very costly disturbances of international air traffic. This problem has been dealt with by simulating the formation and migration of dangerous ash plumes. However, the results of the simulations have sometimes been too safe, producing ash clouds that are too large. This was especially the case for the North Atlantic in 2010 (Eyjafjallajökull) and 2011 (Grímsvötn). Since 2012, an international cooperation team led by the Disaster Prevention Research Institute (DPRI) of Kyoto University has conducted airborne measurements of volcanic ash concentrations in the plume from Mount Sakurajima in Kagoshima Prefecture, Japan. This volcano was chosen because of its frequent but limited eruptions, which allow close observation. These measurement campaigns have provided data showing gravitational flattening of the plume, a new and previously unknown dispersion process of volcanic plumes. A new and previously unknown fallout process, called streak fallout, also has been measured. Results concerning plume flux, concentration distributions, aerosol (PM10) content of the plume, and content of very fine particles (PM2.5 and PM1) are presented, and the ways by which the observational methods can be used to produce reliable initial data and boundary values for simulations of plume dispersion are discussed.

Keywords: Sakurajima, airborne measurement, ash plume, optical particle counter

Fig. 1. Comparison of the forecasted and the actual visible ash cloud (white) on May 11, 2010. (Icelandic National Broadcasting Service).

1. Introduction

The eruptions of Eyjafjallajökull and Grímsvötn in 2010 and 2011, respectively, created great problems for commercial aviation [10] in the North Atlantic because of the large extent of the predicted ash clouds from these eruptions. Satellite images showed that the actual visible plume was much smaller than the predicted ash cloud (**Fig. 1**), and no satisfactory explanation of this discrepancy has been presented in the literature [3, 4]. Other reports showed that ash concentrations over Germany from Eyjafjallajökull were lower than predicted [15].

The need for better calibration data for simulation models was consequently clear from the start of the Eyjafjallajökull eruption in 2010. In the beginning, the efforts concentrated on better information on grain size distribution and emission rate [6]. The Spark-Mastin formula [9, 17] for the emission rate as a function of eruption column rate is one of the classic relationships in volcanology. However, this formula is very uncertain, and this is especially true for Iceland where basaltic eruptions can be quite large but not produce any significant amount of ash, as was the case for the Bardarbunga-Holuhraun event in 2014, or be subglacial and produce a lot of ash, as was the case for the Grímsvötn eruption in 2011.

Another large uncertainty is the grain size distribution in the plume. Classical research results in which the importance of fallout trajectories is demonstrated have been published by Bonadonna and Phillips [1]. It was the un-

Fig. 2. Ash deposits on Vatnajökull, a few kilometers south of the Grímsvötn crater, shortly after the eruption in 2011 (Photo courtesy of Thorsteinn Jonsson, University of Iceland).

expected large fallout (**Fig. 2**) that caused the predictions of the Grímsvötn event in 2011 to produce a cloud that was too large [3].

It is obvious that actual ash clouds have to be measured in order to gather data that can explain the forecasting problem and provide calibration for the prediction processes.

Airborne measurements of in situ concentrations of volcanic ash may be used in environmental science, volcanology, and geophysics. Obtaining airborne measurements of in situ concentrations from light airplanes is a good choice for scientists searching for a research method that provides detailed results in the shortest possible time. The target may be the properties of the plume, extent of an ash cloud, or ash flux or fallout. A lot of instrumentation for purposes other than ash concentration observation can also be included in the observation plan, and it is possible to cover a wide area.

There are two good examples of research aircraft in two different classes that have been used for volcanic ash in-situ measurement. The first class includes aircraft for overall sampling and research of atmospheric pollution. The German Aerospace Center (DLR) Falcon, DLR Falcon 2014, is a good example of such research aircraft. It is an 18 m long jet aircraft with a range of 3700 km that can fly at altitudes up to 12,800 m. It is equipped with a wide range of instruments for both in-situ and remote sensing measurements and also with telecommunication facilities for online transmission of data. It was used on one occasion to map the Eyjafjallajökull plume during the 2010 eruption [11]. In that flight, the aircraft was able to measure concentrations to some extent, but it could not remain in the plume because of its jet engines.

Another example of an aircraft in this class is the MOCCA research aircraft of the UK Met Office. This aircraft is a Cessna 412C Golden Eagle, and it is also equipped with a wide range of instruments for in-situ and remote sensing measurements and telecommunication facilities for online transmission of data. The plane and various missions are described in Taylor [13].

To use research aircraft such as these demands large financial resources, so most in-situ volcanic ash measurements have been done from less expensive aircraft with simpler instrumentation. The disadvantage of using small airplanes is of course the small payload and range and the restriction that slow flying aircraft cannot fly in strong wind. This restriction also prevents extensive use of unmanned model aircraft.

Light aircraft have been used for airborne measurements of volcanic ash in many countries in Europe [15, 16], Africa, and South America, and in several campaigns around the Sakurajima volcano in Kagoshima Prefecture, Japan. The Sakurajima campaigns were initiated in 2011 by the Disaster Prevention Research Institute of Kyoto University. From its beginning, this program was an in-house collaboration between the Research Division of Disaster Management for Safe and Secure Society and the Sakurajima Volcano Research Center. The main focus, from the start, was in situ measurement of volcanic ash plumes and Sakurajima volcano was chosen because it frequently emits several ash explosions in a single day. It is therefore a unique laboratory for airborne in-situ measurements. From 2012, the volcanic ash concentrations have been measured with optical particle counter (OPC) meters.

The measurement program produced significant results, and several presentations were made in the Scientific Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior, Kagoshima, 2013. Scientists from the University of Applied Sciences (UAS) in Düsseldorf, Germany, under the leadership of Professor Konradin Weber, participated in the program [8].

The current theory for the dispersion of ash clouds is based on advection–diffusion theory [12], which is usually referred to simply as the diffusion theory. The theory disregards all density currents due to the gravitational effects of the ash content in the plume, but the in-situ measurements of Sakurajima indicate that they should be taken into account [4]. From the Sakurajima measurements, it was also discovered that streak fallouts and gravitational spreading of volcanic plumes are processes that should be included in the simulation process [4], but this is hampered by the fact that accurate information on the density difference of the plume and the ambient air is usually not available.

In this paper, we focus on results from the Sakurajima campaign, for which the ability of the airborne measurements of volcanic clouds to measure ash flux was demonstrated.

2. Flux Capacity of Neutrally Buoyant Volcanic Plumes

A volcanic plume that is being advected through the air without any change of its altitude is neutrally buoyant. Consider a plume riding in an environment with average density ρ_{av}. Let this be the ambient air density at the same

Table 1. Examples of concentrations and fluxes in a neutrally buoyant volcanic plume.

ΔT°C	0.01	0.1	1	10	100
C mg/m^3	0.04	0.38	3.81	38.1	381
Flux kg/s	381	3,810	38,095	380,952	3,809,524

level as the center of buoyancy of the plume, and let us assume that the plume itself has an average density ρ_p. For the plume to be neutrally buoyant, we must have $\rho_{av} = \rho_p$.

If the ambient air and the ash contaminated air in the plume are assumed to be the same air mass, the ash plume needs to be hotter than the ambient air to be buoyant because of the extra weight of the ash. The necessary temperature difference between plume and ambient air required to keep the plume buoyant for various concentrations (C) is given in **Table 1**, together with the flux capacity in a 10 m/s wind. The properties of the ambient air are taken from the data for the Standard Atmosphere at an elevation of 1500 m above sea level (m asl).

The flux calculation is made for the air properties of the U.S. Standard Atmosphere Air Properties, at an altitude of 1500 m asl.[1] The width and thickness are assumed as 2000 m and 500 m, which is typical for a Sakurajima plume. The wind speed is assumed to be 10 m/s, which is not a high wind speed at 1500 m asl.

The limiting concentration for commercial jetliners is 4 mg/m^3, so the temperature difference needs to be only one degree or less for the plume to be buoyant, at altitudes where jets are allowed. In addition, the atmospheric conditions may be more complicated than **Table 1** assumes, especially if the plume is riding within stable temperature stratification. Nevertheless, we can assume that the temperature differences between the plume and the environment are not easily measureable. Actually, temperature differences commonly existing in a stratified atmosphere can be several degrees, which means that plumes normally find a stable inversion where they can be advected horizontally.

The concentrations covered in **Table 1** cover the range of likely airborne measurements. The first column shows a concentration that is too close to that of background (discussed later) ambient air to be interesting, and the last column has concentration and temperature values that are too high to be measureable using light aircraft.

3. Results of Airborne Measurements and Volcanological Observations

3.1. Measurement Series and Eruption Event of Feb. 13, 2015

We now examine a measurement series of a plume from Sakurajima recorded on Feb. 13, 2015. The aircraft used was a Cessna 172 from the New Japan Aviation (NJA) company. The weather in Kagoshima City (31°33.3′N, 130°32.8′E) was sunny with a 9 m/s wind. The measurement period on this day was 15:35:08–16:29:35 local time (local time is also used in the forthcoming, and the sampling frequency was 1 s. The instruments were a Dust-Mate OPC provided by DPRI counting in 4 bins and a Grimm SkyOPC, provided by the University of Applied Science, Düsseldorf, Germany, counting in 32 bins. Positioning was done by GPS.

Figure 3 shows on the left a photograph of Sakurajima with the plume behind it. On the right, the figure shows the estimate of the explosion strength from the Sakurajima Volcano Research Center (SVRC). This estimate is based entirely on volcanological observations independent of the airborne measurements and is therefore used only for comparison.

The output rate of the volcanic eruption is very uneven, which is normal behavior of the Sakurajima crater. This characteristic was seen clearly in visual observations of the eruption and is apparent in the output diagram in **Fig. 3**. The time series plot of **Fig. 4**, which is of the entire series, also reveals this. The highest concentrations, above 3000 μg/m^3, are cut off for better separation of the different grain size series. It must be noted that raw data maxima are not significant due to the large fluctuations [5].

The output (**Fig. 3**) starts with a single puff at 15:25. This puff was measured at 15:36 some 3 km downwind of the crater (see **Table 2**). Three minutes after the first puff, the output diagram in **Fig. 3** shows what looks like a continuous puff lasting from 15:28 to 15:40; the concentrations measured during 15:36–16:26 are from this puff. Its average strength according to **Fig. 3** (right) is 300 kg/s. The measurement of this output required approximately one hour flying along a zig-zag route through the plume. The route is displayed in **Fig. 6**.

Figure 5 shows the concentration values, density corrected with the factor of 1.7, which corresponds to an ash sample in loose packing. The vertical scale in **Fig. 5** is logarithmic, for better separation of the four series. The series consists of values filtered with an F-16 filter [4].The F-16 filtering, which eliminates the random fluctuations of the concentrations and separates them [5], was necessary because of the natural fluctuations in the OPC results.

The series shown in **Fig. 5** is divided into traverses, and the times until the end of the first nine traverses are shown by the blue bars at the bottom of the figure, together with an exact number for the endpoint of each traverse. The traverses are used in the following flux analysis.

Table 2 shows the four grain size bins. It is noteworthy that the total suspended load (TSP) is considerably higher than the PM10 in the high concentrations of the tops in **Fig. 5**, but similar in between.

There are also elevated values of PM2.5 and PM1 in the tops. These very fine particles are dangerous for the lungs, as described by Hillman et al. (2012) [7]. The concentrations of the ambient air, found between the observed tops, are however within health limits.

Table 2 shows the average SkyOPC data. The effect

1. Taken from http://www.engineeringtoolbox.com/standard-atmosphere-d_604.html

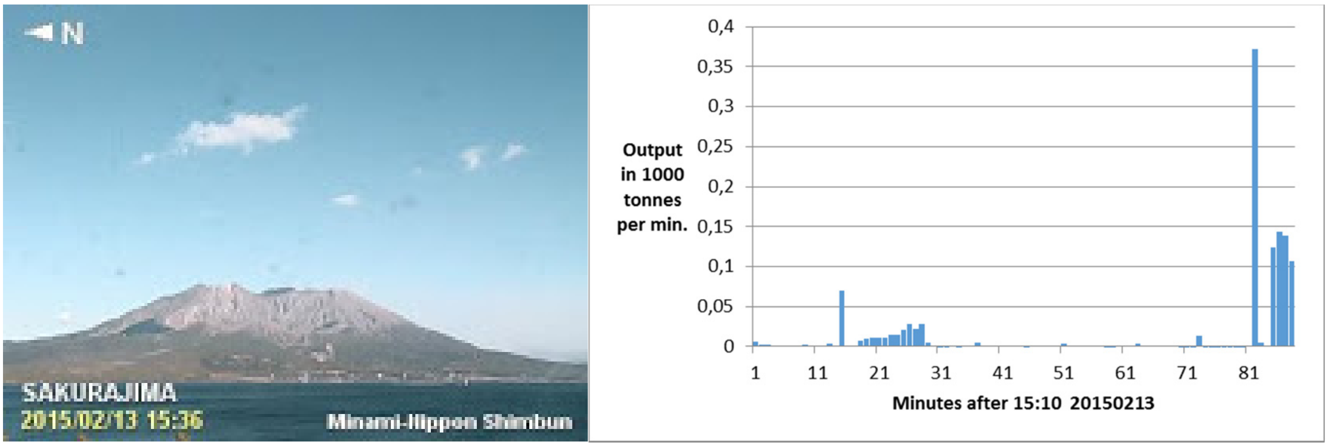

Fig. 3. Photograph of Sakurajima at 15:36 (left) and output estimate by SVRC (right).

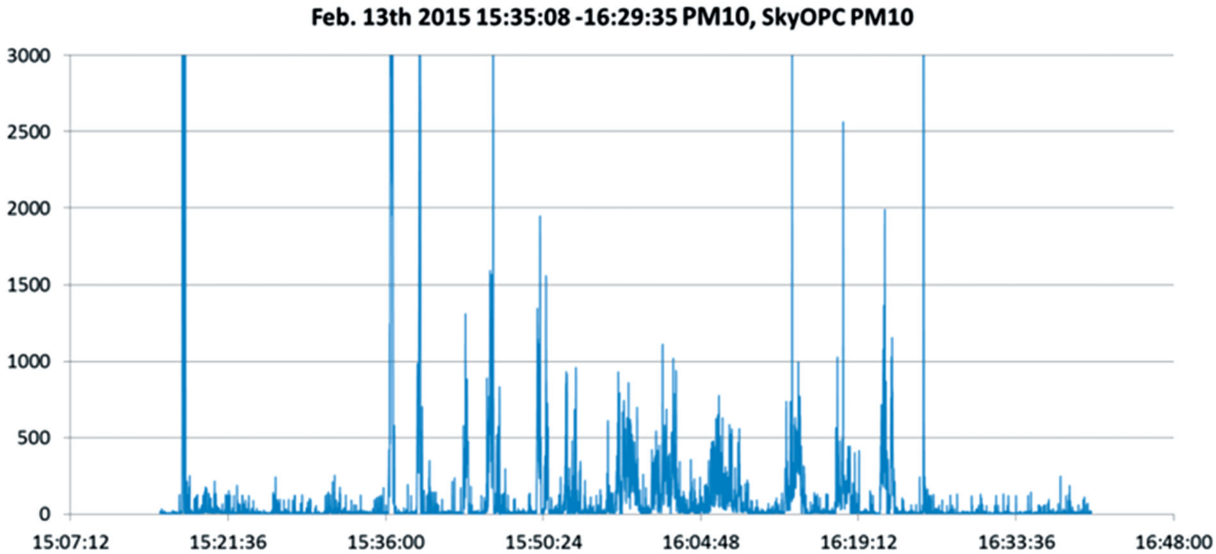

Fig. 4. Plot of the raw data in μg/m^3 measured with the SkyOPC optical particle counter.

Table 2. SkyOPC data.

	SKYOPC DATA Density corrected and F-16 filtered except maxima							
	TSP	PM10	PM2.5	PM1	TSP	PM10	PM2.5	PM1
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	%	%	%	%
Average	282.4	128.8	15.9	4.7	100	46	6	2
St. Deviation	658.3	366.7	32.8	4.1				
Maximum	8287.0	5817.7	433.4	57.3				

of the filtering can be appreciated from the fact that the values of 658.3 and 8287.0 in **Table 2** would be 1028.8 and 26457.3, respectivel, without filtering, so the fluctuations would dominate these values. The average amount of PM10 material is 46% of the whole. Due to the logarithmic scale in **Fig. 5**, the low values in between the tops are very visible. These are background values, which may be dust from previous explosions or dust from distant sources independent of any Sakurajima eruption. Concentrations in the observed spikes in **Fig. 5** are much higher than the background values between them, so the 46% value is very similar to the average value for all the tops in **Fig. 5** because the ambient air between them is background concentration that carries very little weight in the grand average. However, the TSP/PM10 ratio in the ambient air is close to 1. The information that ambient air around Sakurajima tends to contain PM10 and finer particulates may be of value for scientists and public health officials studying the adverse effects of Sakurajima ash on the population.

3.2. Visual Display in Google Earth

If the average diameter of the grains larger than 10 μm is estimated to be 25 μm, the terminal fallout velocity of this grain size would be about 5 cm/s, according to com-

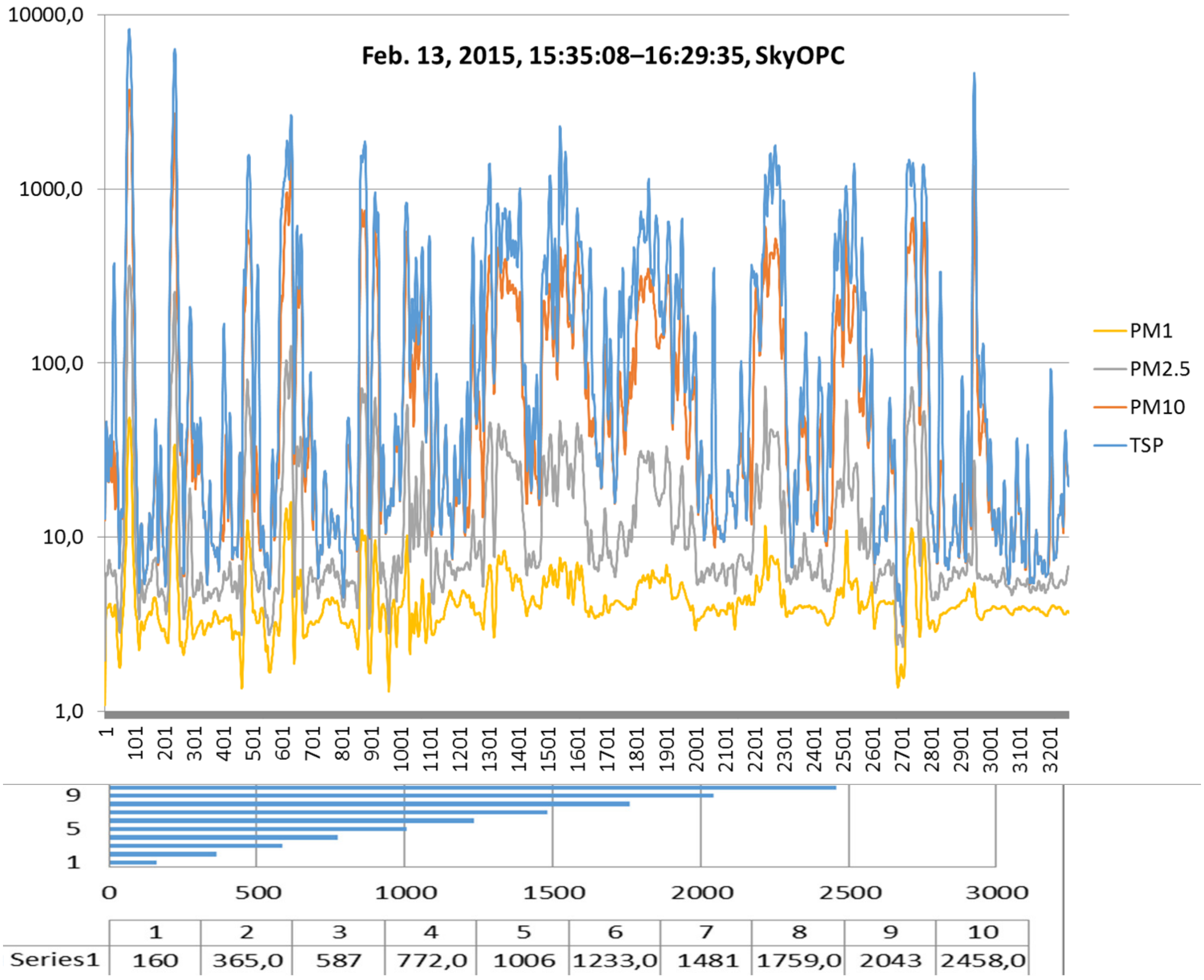

Fig. 5. Time series plot of F-16 filtered SkyOPC data in μg/m^3 in log scale. Horizontal axis: Number of points from 15:35:08 on Feb 13, 2015. Blue bars: End point numbers of traverses 1–9. Bottom numbers: Accurate lengths of the traverses in seconds. One point is one second.

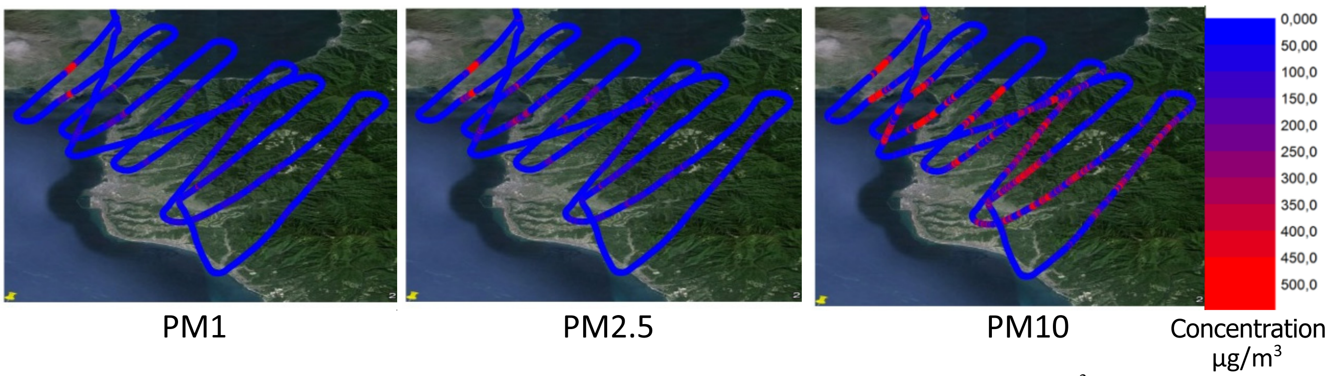

Fig. 6. Concentrations plotted along track on Google Earth (PM1, PM2.5, PM10, μg/m^3).

monly used formulae for the terminal velocity of spherical particles [1]. This would mean a half-life in the plume of about 10 h for this grain size. In a 9 m/s wind, this would result in a mean travel distance of about 250 km, assuming an initial height of 1000 m. Thus, it may be concluded that conventional fallout from the plume is negligible for grain sizes of 25 μm and smaller in the measurement area, as it stretches only 20 km downwind.

3.3. Traverse Analysis

Figure 6 shows PM1, PM2.5, and PM10 in the plume. The concentration scale is on the right, and the blue color shows the background concentration that is expected around Sakurajima. The red color shows elevated concentrations. The rightmost picture shows several tops with ambient air in between, just as **Figs. 4** and **5** indicate.

The Google plot (**Fig. 6**) shows the general direction of migration of the plume. The highest concentrations are

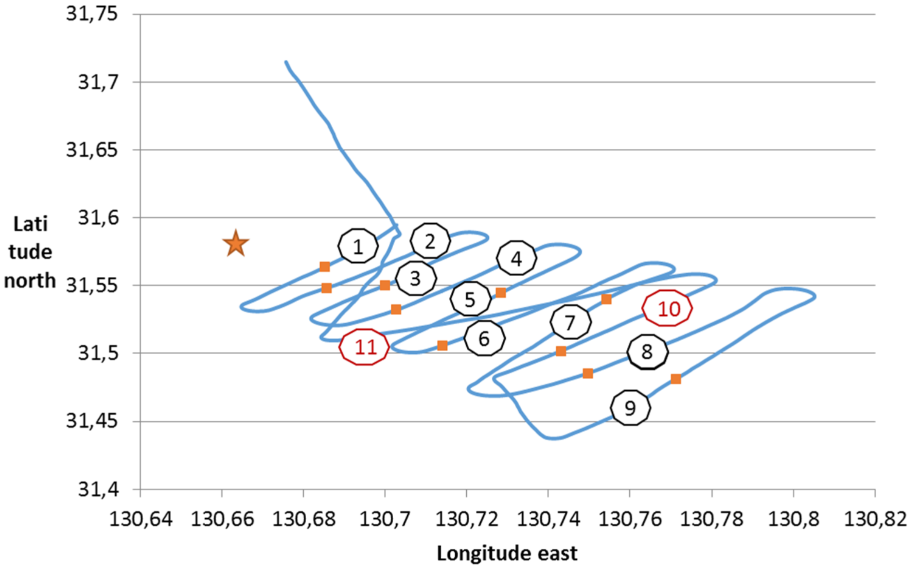

Fig. 7. Traverses. Yellow star: Sakurajima crater. Yellow squares: Position of the maximum concentration in each traverse. Black numbers: Number of the traverse, increasing with distance from the crater. Red numbers: Return flight.

Table 3. Flux calculation for TSP.

	Time	Traverse	Crater	Tsp				
		width	distance	Sum	Average	Backg	Volcano	Flux
		m	m	$\mu g/m^2$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	kg/s
1	15:35:08	6477	3087	123535	829	12	817	19
2	15:37:38	6377	4331	79429	389	14	375	9
3	15:41:03	6607	5116	30221	137	14	122	3
4	15:44:45	7520	6745	73457	399	9	390	11
5	15:47:50	6388	7674	54023	232	26	206	5
6	15:51:44	8908	9740	30378	134	26	108	3
7	15:55:31	10353	10082	84248	341	23	319	12
8	15:59:39	10071	13571	95751	346	24	322	12
9	16:04:17	9182	15290	82848	293	10	283	9
10	16:09:01	9573	11777	98771	239	10	229	8

not always in the middle of the plume but migrate from left to right. This indicates a horizontal undulation of the plume in the wake of the Sakurajima mountain top.

Figure 4 was used to define the traverses, and **Fig. 7** is a schematic picture of the traverses with their numbering. The flux through each traverse is

$$Q_f = \int_{H_{\min}}^{H_{\max}} C(Y,Z)dZ \int_{Y_{\min}}^{Y_{\max}} dY$$
$$= \int_{Y_{\min}}^{Y_{\max}} H_{\text{eff}} C(Y)dY \quad \ldots\ldots\ldots \quad (1)$$

where Q_f is the flux through the traverse in kg/s in the downwind direction, C is the measured concentration in excess of the background concentration in kg/s, Y is the horizontal coordinate perpendicular to the downwind direction X, Z is the elevation, and H_{eff} is the effective vertical thickness of the plume with respect to the measured excess concentration. H_{eff} is estimated to be 400 m, and wind speed is taken as 9 m/s.

Table 3 shows the flux estimation for TSP. **Table 4**, showing similar values for PM10, is provided for comparison. The values for the nine traverses and a tenth traverse (a traverse on the flight back) are listed.

The TSP flux is everywhere less than 20 kg/s, or about 7% of the estimated strength of the puff (**Fig. 3**). The PM10 flux is everywhere less than 10 kg/s and is close to half the TSP flux everywhere. Similar results were obtained in another Sakurajima campaign [4].

The mass flux is lower than 10% of the total erupted mass (puff strength). Many estimations of erupted mass in volcanic eruptions are done by estimating the ash deposits on the ground [2]. However, this result indicates that these measurements are sufficiently accurate (the small part of the total erupted mass that remains in the air is within the expected estimation accuracy). This also means that the total erupted mass and the mass in the ash clouds are not comparable.

In these circumstances, it is very difficult, if not impossible, to estimate the flux in the plume by starting with an estimation of the total erupted mass. The expected error of the estimation would be huge.

Table 4. Flux calculation for PM10.

	Time	Traverse	Crater	PM10				
		width	distance	Sum	Average	Backg	Volcano	Flux
		m	m	μg/m^2	μg/m^3	μg/m^3	μg/m^3	kg
1	15:35:08	6477	3087	58521	393	12	381	9
2	15:37:38	6377	4331	36698	180	15	165	4
3	15:41:03	6607	5116	14021	63	15	48	1
4	15:44:45	7520	6745	38092	207	10	197	5
5	15:47:50	6388	7674	27167	117	26	90	2
6	15:51:44	8908	9740	18488	82	23	59	2
7	15:55:31	10353	10082	38289	155	21	134	5
8	15:59:39	10071	13571	41553	150	17	133	5
9	16:04:17	9182	15290	39333	139	10	129	4
10	16:09:01	9573	11777	38507	93	10	83	3

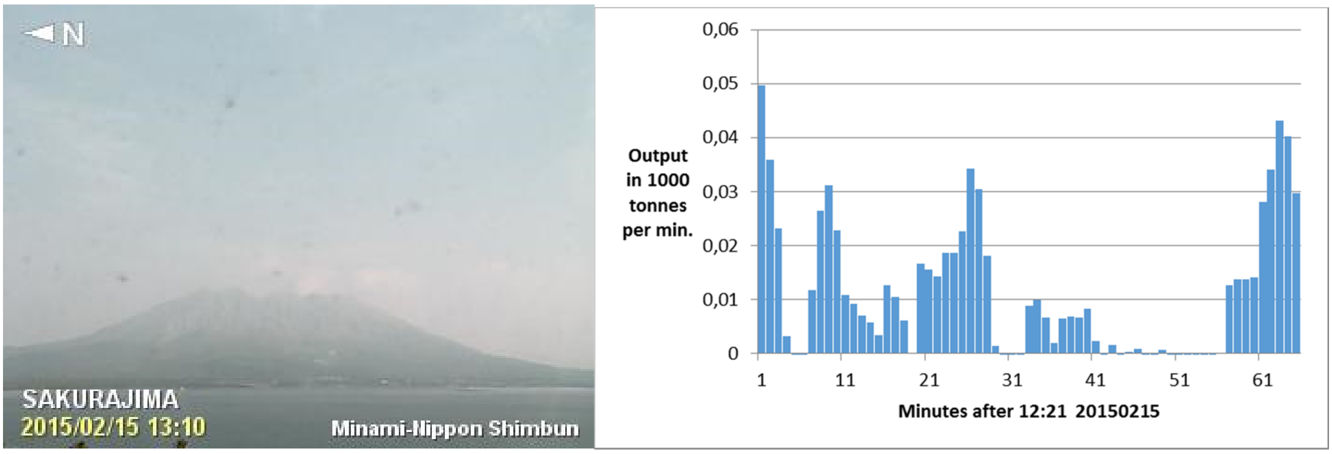

Fig. 8. Photograph of Sakurajima at 13:10 (left) and output estimate by SVRC (right).

The flux is highly variable as the output of the crater is very uneven in time. In order to see how well the stationary diffusion–advection model fits the plume, the PM10 flux (last column in **Table 4**) and the traverse width (third column in **Table 3**) can be used to find the linear regression formula, also called the trend line, for the dependence of these values on downwind crater distance (fourth column in **Table 4**). For the plume width we obtain the following:

Plume width versus distance in *m*: $y = 0.3386x + 5185.9$. Correlation coefficient: $R = 0.84$.

The correlation coefficient is high enough that this regression formula is a significant approximation of the width–distance relationship. This result can be used to find the diffusion coefficient in the diffusion advection model. For this purpose, formula C15 in Elíasson et al. [4] can be used. Another possibility is to use a logarithmic regression formula (relate $\ln(y)$ to x) and then use formula A7 in the same paper to estimate T_p, the time constant of the gravitational plume spreading in the formula A7.

However, the wake effect, discussed in section 3.3, together with the uneven eruption rate, indicate that mixing of ambient air into the plume is taking place on many scales in place and time. The results of such calculation would not be representative for a continuous plume, but both the regression and the formulae quoted do presuppose a pseudostationary wind and output, i.e., slowly varying eruption rate, wind speed, and direction.

PM10 flux versus distance in *m*: $y = -0.0001x + 4.9158$. Correlation factor: $R = 0.19$.

The $-0.0001x$ term indicates a fallout factor $k = 10^{-4}$ kg/s/m. The average concentration of PM10 in the plume is 129 μg/m^3, and the width of the plume in its beginning stage is 5.2 km, so the average fallout velocity is 0.15 cm/s. This is far too high to be an average terminal fallout velocity of the ash grains falling out from the plume, so streak fallout is the dominant fallout process. This result is the same as those found in earlier campaigns at Sakurajima [4], and this result may be significant, because fallout is not as sensitive as mixing rate to variations in eruption rate, wind speed, and direction.

3.4. Measurement Series and Eruption Event of Feb. 15

This measurement series is very similar to the one for Feb. 13 and shows similar eruption output, **Fig. 8**.

The aircraft used in the acquisition of this series was a Cessna 172 from the New Japan Aviation (NJA) company.

Table 5. SkyOPC data.

	SKYOPC density corrected (1.7)							
	TSP	PM10	PM2.5	PM1	TSP	PM10	PM2.5	PM1
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	%	%	%	%
Average	1015	446	94	46	100%	44%	9%	5%
St. Deviation	6876	2653	283	25				
Maximum	218158	86500	9457	630				

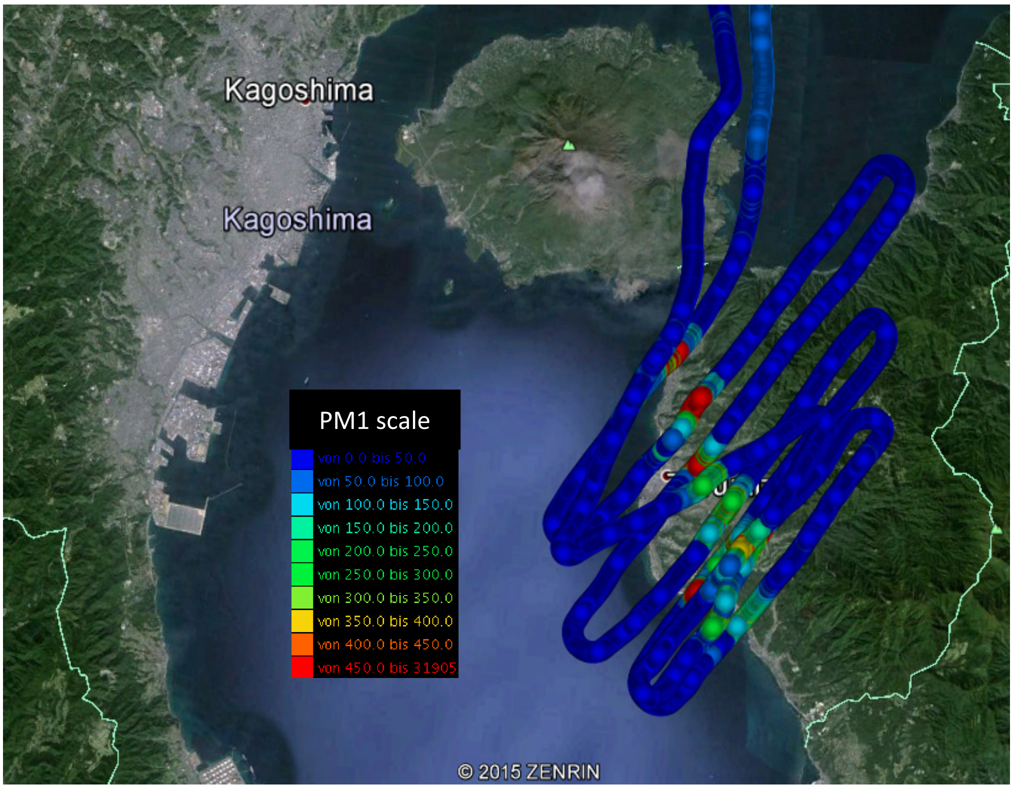

Fig. 9. Google plot of PM1 in μg/m^3. Blue color: Background values. Other colors: Elevated values.

The weather in Kagoshima City (31°33.3′N, 130°32.8′E) was sunny with a 5 m/s wind. The measurement period on this day was 12:22:00–13:20:19. The sampling frequency and instrumentation was the same as that used before.

3.5. Visual Display of the Measurement on Feb. 15

The average output estimate of SVRC is 240 kg/s, and the output is more continuous in time than it was on the Feb. 13, but still unsteady.

Comparing **Tables 2** and **5**, we see that the averages at this time are higher, which is partially due to lower wind speed and a thinner plume. The average explosion strength is similar, but explosions are not as concentrated as on Feb. 13. This means that the explosions are distributed over a longer time, so each one is weaker than on the 13$^{\text{th}}$. This may also indicate that the plume is thinner and lower. The average plume height is only 15–200 m, and the effective plume thickness is 200 m.

The percentage of fine grains in the two tables is very similar, especially for PM10. This is a somewhat unexpected result considering the unsteadiness of the Sakurajima eruptions.

The data in **Table 5** are not filtered. This affects the standard deviation and the maxima, as mentioned in the discussion of **Table 2**. **Fig. 9** shows elevated values of the finest fraction in the plume, PM1. Areas with elevated values are narrow. This can also be seen in **Fig. 10**, which displays the measurement as one series.

In **Fig. 10**, the TSP is displayed by the brown color behind the blue color showing the PM10. There are 10 blue tops, corresponding to the 10 areas with elevated values shown in **Fig. 9**. Seven areas and the flight path through them are used in the traverse analysis in **Table 6**.

The plume has a rather narrow effective width that increases with time. This is sometimes called pancaking when the effective thickness of the plume is getting smaller at the same time. Most of the measurement shows ambient air, where PM10 is lower than 100–200 μg/m^3. The measured concentration jumps from this value to several thousand when a puff of new ash is penetrated (**Fig. 9**). In **Fig. 9**, there is ambient air where the TSP

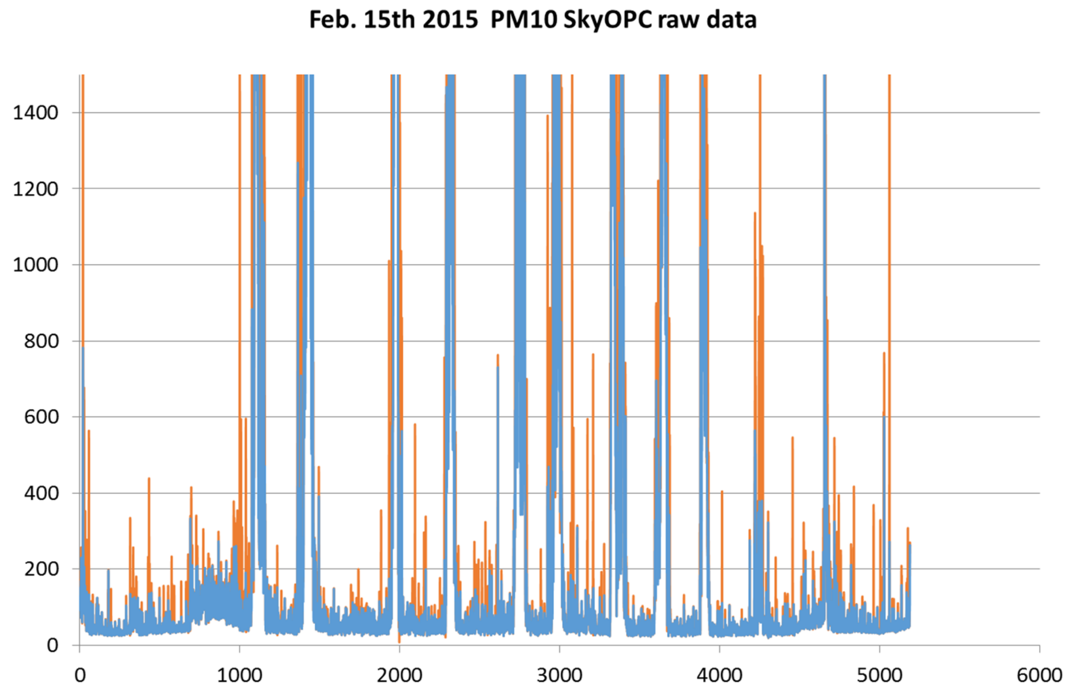

Fig. 10. Comparison of PM10 (blue) and TSP (brown behind the blue). Values are truncated at 1500 μg/m^3. The horizontal axis is measurement point number.

Table 6. Fluxes on Feb. 15, 2015, SkyOPC result.

Average TPS	Av. PM10	Av. PM2.5	Av. PM1	Flux TSP	Flux PM10	Flux PM2.5	Flux PM1
μg/m^3	μg/m^3	μg/m^3	μg/m^3	kg/s	kg/s	kg/s	kg/s
2578	983	151	50	18.9	7.2	1.1	0.4
4132	1624	218	52	60.4	23.7	3.2	0.8
1346	527	100	42	16.5	6.4	1.2	0.5
802	338	79	41	10.3	4.3	1.0	0.5
1665	674	120	46	14.8	6.0	1.1	0.4
922	378	86	42	9.3	3.8	0.9	0.4
979	558	110	43	9.2	5.2	1.0	0.4

and PM10 are equal, so we see only the blue color in this figure. Where new ash exist, the TSP values may be an order of magnitude higher than the PM10, which may be studied in **Fig. 10**.

3.6. Traverse Analysis and Flux Calculation

The fluxes display values very similar to those found on Feb. 13. The only exception is a high value of 60.4 kg/s in one traverse. The average flux is 18.4 kg/s, or about 8% of the total estimated strength of the puff (**Fig. 8**). The fluxes, concentrations, and TSP/PM10 ratio display very much the same properties, on average, as those displayed on the 13th. This is quite remarkable because the eruption activity was very unsteady.

4. DustMate Measurements

The flying in and out of cloud puffs creates enormous variability that causes the high standard deviations in **Tables 2** and **5**, and it should not be misinterpreted as instrumental error. The standard deviations of the finer particles, PM2.5 and PM1, show that there is much less of these fractions in the ejected ash compared to the PM10 and coarser fractions. This result may be of interest to researchers concerned about public health, as mentioned previously.

The DustMate measurements were always lower than the SkyOPC. However, they confirm the overall properties of the plumes described thus far, see **Fig. 11**.

The DustMate was too often saturated, which caused trouble in the present measurement but did not do so previously during lower concentrations in other campaigns. DustMate and SkyOPC compared very well in the lower concentrations of previous campaigns [4]. Detailed calibration and comparison in a wind tunnel test confirmed this result [15].

The reason for the discrepancy in this campaign is unclear, but it shows clearly the importance of having two meters in the aircraft for quality control.

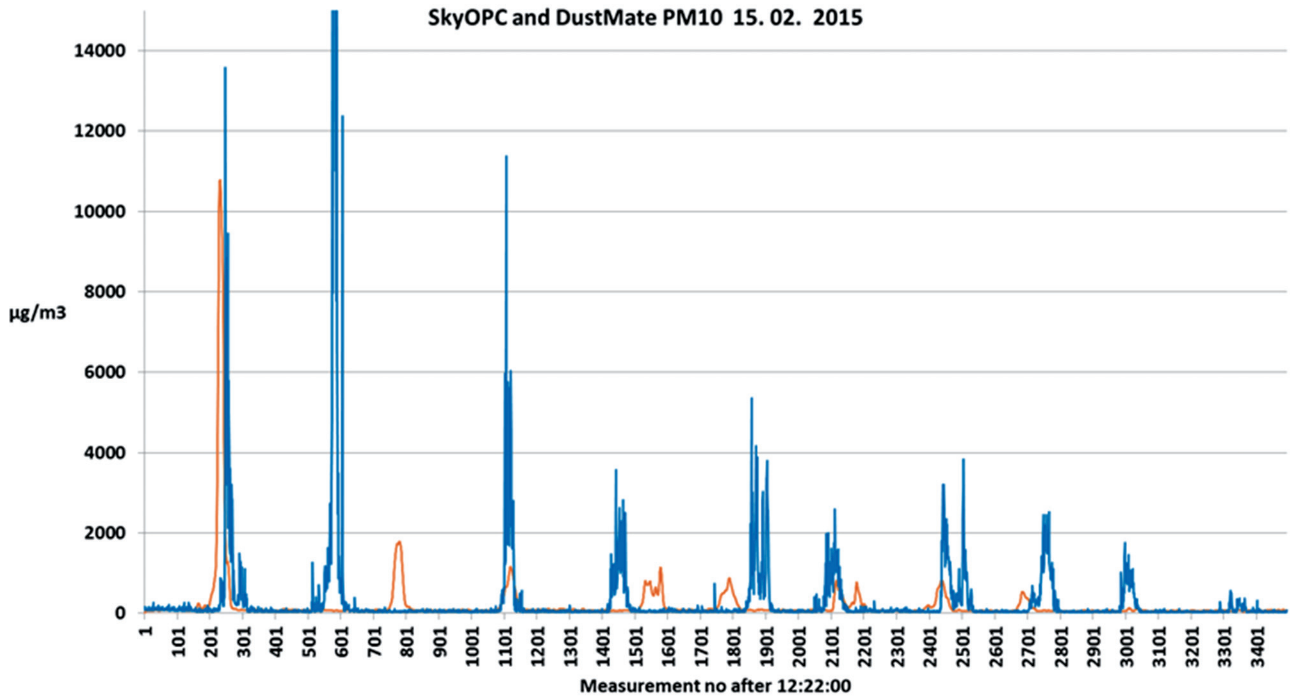

Fig. 11. Comparison of the PM10. SkyOPC shown in blue and DustMate shown with brown. Density correction is 1.7.

5. Conclusions

The Sakurajima airborne measurement campaigns provide a very detailed picture of the volcanic ash plumes and present scientists with an opportunity to investigate the properties of volcanic plumes, test theories, and improve older methods.

This campaign produced the following important results.

1 Concentrations were higher than in previous campaigns.

2 The estimated fluxes were 7–8% of the total output estimates of SVRC.

3 This confirms that estimations of the total output of volcanoes made by measuring the ash deposits are accurate.

4 Estimation of the ash concentration in the cloud using the estimates of the eruptive material as an input to conventional dispersion models is not possible.

5 PM10 was 45% of the total transport. Thus, a great part of the emitted tephra would have fallen straight down almost immediately, another part would have flowed down to the ground in streak fallouts, and there would also have been ordinary gravitational fallout of particles larger than PM10.

6 The fluxes may require updating as the wind velocity used was the wind velocity at low altitude at Kagoshima. Ideally, a free flow wind velocity value at 1000–1500 m altitude over the mountaintop should be used.

7 The plume had an altitude lower than 1000–1500 m on all of the campaign days. In all of the photographs of Sakurajima available for February 13 and 15, no plume is seen at altitudes higher than the mountain and all measurements were at 1100 m or lower. This means that the measured plumes were in the wake of Sakurajima's mountain top, where the wind velocities would have been lower than the free flow value. If information on the ratios of wind velocities in the free stream and the wake can be obtained, the flux values should be updated.

The following recommendations for further research are suggested.

A scheme for better determination of plume thickness and gridding of data to produce initial boundary data for plume simulation are needed. This is easy to do for stationary plumes, but a special method must be devised for unsteady plumes. Further investigation of the streak fallout process is a very important research object. Another important research objective is to discover how large a part of the total output estimate can be assumed to be in the PM10 category, as the ash that can travel a long distance from the mountain and disturb air traffic is mainly in this category.

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