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Ground-Level Concentrations of Volcanic SO_2 at Miyakejima Island, Japan

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Abstract

Miyakejima volcano violently erupted during the summer of 2000, initiating enormous ejections of volcanic sulphur dioxide (SO_2) and forcing residents to evacuate the island. Residents have been able to return to their homes since February 2005, but high SO_2 concentrations are still transported downwind from the vent to low-lying, populated coastal areas. This study investigates the occurrence of concentration events exceeding 1 ppm in such areas, focussing upon October 2005 as a case-study of highly changeable wind conditions. During this period, high concentration events fluctuated between the hazardous east and south-west zones over a matter of days, in response to strong westerly and north-easterly winds generated by alternating low and high pressure systems over mainland Japan. In addition, a Pacific typhoon directly to the south amplified north-easterly winds, causing abnormally high SO_2 concentration measurements in the south-west. Results demonstrate a direct link between the occurrence of high SO_2 concentrations at the foot of Miyakejima volcano, and the overall meteorological situation for the Izu islands area. Findings have important implications for hazard mitigation at degassing volcanoes, as everyday weather forecasts can be used as a useful educational tool, particularly at the onset of a new volcanic crisis or where little funding is available for expensive warning systems.

Key Words: gas dispersion, sulphur dioxide, volcanic gas, volcanic hazard

Introduction

Miyakejima volcano, an island about 160 km south of Tokyo along the Izu island chain (Fig. 1), has been ejecting enormous amounts of sulphur dioxide (SO_2) from its summit crater since the large eruption of mid-August 2000. Initial emission rates were in the order of tens of thousands of tonnes per day (td^{-1}; Kazahaya *et al.* 2004), forcing a complete evacuation of the inhabitants in September 2000. Seven years later, emissions have gradually reduced to around 1000-4000 td^{-1} (JMA 2008a), and people have been allowed to return since February 2005.

However, volcanic gas remains a major hazard, as prevailing wind conditions

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still cause high concentrations of SO_2, up to several parts per million (ppm), to blow down to low-lying coastal areas. SO_2 is highly irritant when inhaled and the Japanese Ministry of the Environment describes hourly SO_2 concentration levels of 0.1 ppm and above as dangerous to human health (MOE 2007). H_2S is also detected, but at comparatively very low levels, and is therefore of lower concern to the local authorities. Ground-based air quality stations, measuring the concentration of SO_2 at 14 locations (Fig. 1b), are therefore extremely important for the island's hazard mitigation program. Data not only form the basis for warning the island's population about where high concentrations are occurring, but also offer a unique time series for investigating gas dispersal.

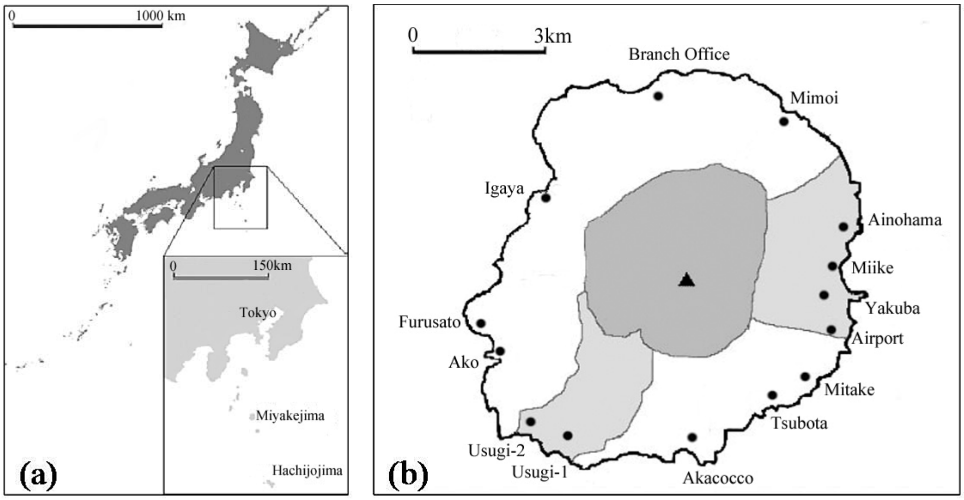

Fig. 1. The location of Miyakejima (a) and the location of 14 gas monitoring stations (b). The black triangle in (b) is the active vent of Mt. Oyama (775 metres above sea level), and the dark grey area surrounding it is the exclusion zone covering the flank of the volcano. The two light grey areas to the east and south-west are the predominant downwind gas hazard zones. (b) is based on the hazard map issued by Miyake Village Office.

Low-altitude gas dispersion has been studied at a variety of volcanic settings across the world, including Etna and Vulcano volcanoes in Italy (Graziani *et al.* 1997, Pareschi *et al.* 1999), Masaya volcano in Nicaragua (Delmelle *et al.* 2002) and Sakurajima in Japan (Kawaratani and Fujita 1990, Kinoshita *et al.* 2004). Indeed, the regional impact of sulphur gas dispersal can be compared to the pollution generated by anthropogenic sources (Graf *et al.* 1998). At Sakurajima SO_2 concentration measurements around the volcano have been linked to observations of plume behaviour (Kinoshita 1996, Kinoshita and Togoshi 2000, Kinoshita *et al.* 2004). Firstly, during strong winds (greater than 10 ms^{-1}), high concentrations occur downwind due to the downdraft of gas in a narrow direction, often accompanied by a mountain lee-wave. In contrast, light winds invariably allow the plume to rise, transporting gas away from the locality of the volcano.

The same mechanism has since been observed at Miyakejima (KINOSHITA *et al.* 2003), showing good agreement with dispersion modelling results (SEINO *et al.* 2004). In addition, the long-term trend of high ground-level SO_2 concentrations also correlates with the prevailing wind characteristics of each season (IINO *et al.* 2004a, Table 1). The hazardous zones to the east and south-west (Fig. 1b) correspond to dominant westerly winds throughout the year, particularly during winter, and a secondary north-east wind direction, usually peaking in autumn, respectively.

Table 1. Summary of typical seasonal meteorological conditions over mainland Japan, and resulting wind characteristics at Miyakejima. (Based on IINO *et al.*, 2004a.)

Season	Weather system (mainland Japan)	Wind conditions (Miyakejima)	High SO_2 concentration
winter (typically Nov-Feb)	low pressure system (anticlockwise circulation of air), associated with westerly monsoon	strong, westerly	eastern stations
spring (typically Mar-May)	periodical high/low pressure systems	variable	variable
summer (typically June-Aug)	Pacific high pressure system (clockwise circulation of air)	relatively weak, southerly	fewer events
autumn (typically Sept-Oct)	periodical high/low pressure systems, with possibility of typhoons	variable (northerly/westerly)	variable (eastern and south-western stations)

However, during the summer (and spring), calm wind conditions allow the plume to rise and SO_2 concentrations at low-lying stations are therefore low; instead, gases have been observed 100-400 km downwind of the volcano (e.g. KINOSHITA *et al.* 2003) and can be transferred to the ground surface by atmospheric mixing during warm and sunny days (IINO *et al.* 2004b), even causing long-term vegetation damage on mainland Japan (IWASHITA *et al.* 2006). Recently, declining summer concentrations in the hazardous south-western zone allowed residents to return during July and August in 2007.

This study presents the latest data analysis from April 2004 until February 2008, encompassing the period since all 14 stations have been operational. Although there is a general decrease in average ground-level concentrations at Miyakejima (IINO *et al.* 2007), specific meteorological conditions are still able to produce "extreme" events, particularly to the east and south-west. Specific high concentration events are therefore discussed for these areas, with respect to daily or twice-daily changes in wind characteristics. The return of inhabitants to previously "dangerous" zones means such short-lived events are especially important to understand.

Description of Datasets

SO_2 concentration measurement

The Tokyo Metropolitan Government began installing SO_2 (and H_2S) measurement stations on Miyakejima in November 2000, now maintained by the Miyake Village Office since October 2005. The number of stations has progressively expanded from an initial three locations to ten, and finally, as mentioned in the introduction, to 14 in April 2004 (Fig. 1b). Atmospheric SO_2 concentration is recorded using standard gas sampling instruments, originally designed for monitoring air quality near to industrial and traffic emissions. Automated measurement occurs every five minutes and is typically recorded down to 0.01 ppm (where 1 ppm-volume of SO_2 is equivalent to 2.7 mgm^{-3} at standard surface temperature). However, due to the large amount of data, only 1-hour average values equal or greater than 1 ppm are considered for this study. Daily or bi-daily trends can be interpreted from the hourly data, while ground concentrations exceeding 1 ppm ('>1ppm') are representative of extreme SO_2 events, dangerous for residents and of most concern to local authorities.

Meteorological conditions

Wind measurements are not available from the summit of Miyakejima volcano itself, but meteorological conditions are observed twice a day (at 09:00 and 21:00 Japanese Standard Time (JST = UTC + 9 hours)) by the Japanese Metorological Agency (JMA) using radiosonde measurement at neighbouring island Hachijojima (JMA 2008b). It has a similar geographical location also being an isolated island, 110 km to the south-south-east of Miyakejima (Fig. 1a), and as the sole source of radiosonde data along the island chain, measurements provide an estimation of the overall wind field across the Izu islands area. Upper wind data (direction and speed) from Hachijojima at 925 hPa can be applied, as the summit height of Mount Oyama (775 metres above sea level) is close to the average corresponding altitude of 830 metres and within the range of 706-869 metres (variable according to atmospheric pressure conditions), recorded during October 2005. Previous studies have justified the use of such data, demonstrating that upper air stability conditions at Hachijojima are representative of the surrounding region, including Miyakejima (Iino *et al.* 2003).

Reference is also made to ground wind measurements, recorded hourly around Miyakejima, particularly when the time resolution of upper wind data cannot fully explain SO_2 concentration events. Three JMA meteorological stations are located close to the Branch Office, Mitake and Ako SO_2 monitoring sites in Fig. 1b, with elevations of approximately 20-36 m.

In addition, daily meteorological charts are printed monthly in the Journal of the Meteorological Society of Japan (Tenki), providing a summary of weather conditions over Japan every 24 hours (at 09:00 JST). The locality of contrasting pressure systems provides a good indication of synoptic wind conditions over Miyakejima.

Results

Occurrence of high SO_2 concentration events in 2004-2008

The monthly occurrence of hourly SO_2 measurements exceeding 1 ppm from April 2004 to February 2008 is summarised in Fig. 2. Stations with a similar long-term trend are presented as north, east, south and south-west (refer to Fig. 1b for locations). For northern and southern stations (Fig. 2a and 2c), the proportion of high concentration events is consistently below 5% for the whole period. Even prior to 2004, high concentration values were rarely recorded (Iino *et al.* 2007). However, events are clearly more common at stations in the east (Fig. 2b), peaking around 15-35% during the winters (invariably November to February/March) of 2004 and 2005, although less clear for the remainder of the period. The northernmost location, Ainohama, in fact peaks in summer, but rarely above 10% and records fewer events overall. In the south-west (Fig. 2d), events are more numerous for the Usugi stations, clearly peaking during the autumn months (5-20%), with a secondary increase during spring 2004 and 2005, and again in January 2008.

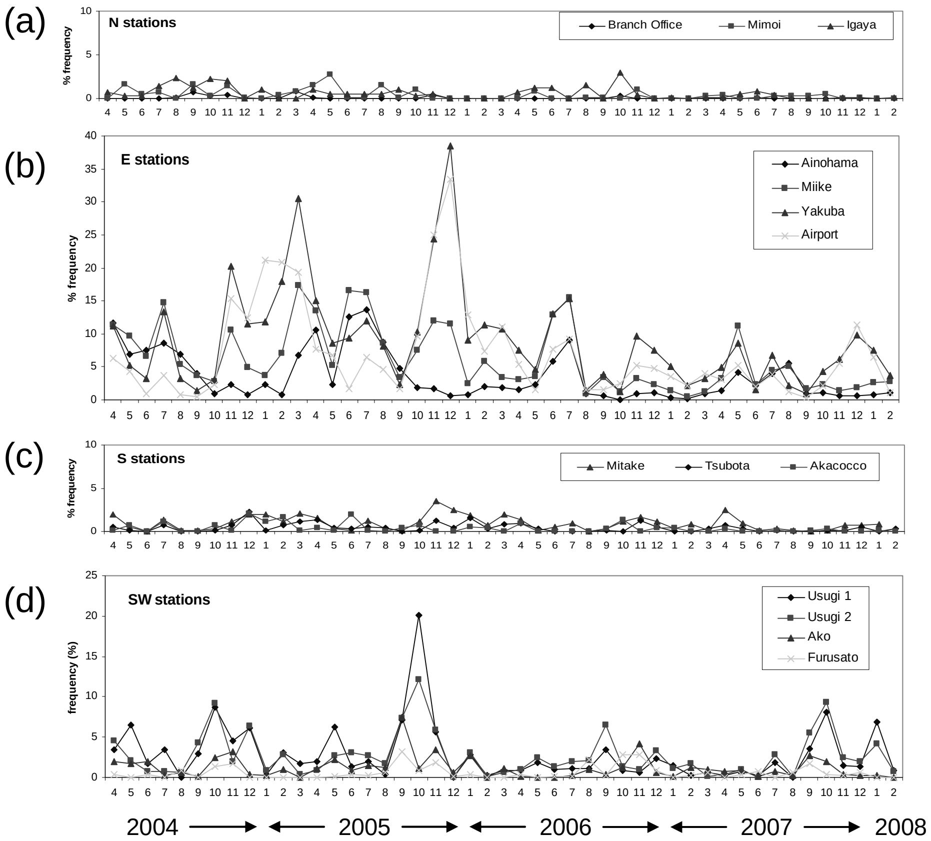

Fig. 2. The monthly occurrence (%) of 1ppm (or greater) SO_2 concentration events for northern (a), eastern (b), southern (c) and south-west (d) stations for April 2004 to February 2008.

Most notably, the largest peak in the percentage of events occurs in October 2005. Compared to typical autumn values of 5-10%, peaks at around 20% and 13% for Usugi-1 and Usugi-2 respectively, are unprecedented considering the general decline in SO_2 emissions from the volcanic vent (flux rate averaged about 4,000 td^{-1} during 2005 compared to around 6,000-7,000 td^{-1} in 2003/2004; JMA 2008a). An increase in concentrations also occurs at the eastern stations, signalling the start of a peak in winter. This unique event is analysed closer with respect to highly changeable wind conditions.

SO_2 concentrations and upper wind during October 2005

12-hour wind direction and wind speed measurements at Hachijojima during October 2005 are summarised in Fig. 3. Clearly, both west and north-east winds were most common (around 15%; Fig. 3a), whilst north-easterly winds were also the strongest (about 13-17 ms^{-1}; Fig. 3b). High SO_2 concentrations in both the south-west and east of Miyakejima are therefore understandable according to the prevailing wind.

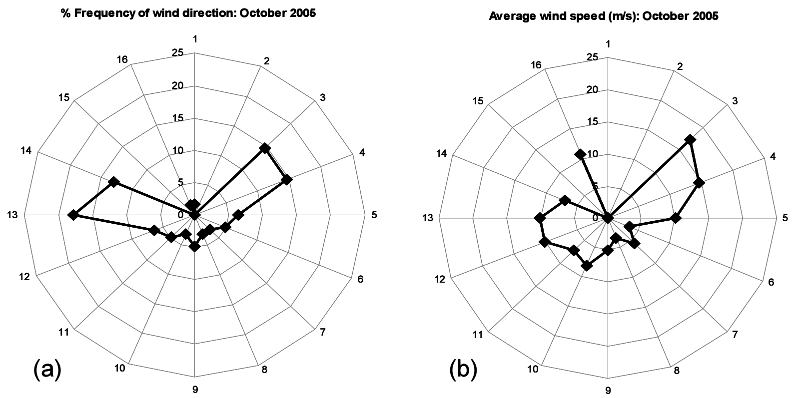

Fig. 3. Summary of 12-hour wind measurements at Hachijojima during October 2005. (a) Frequency (%) of occurrence of each wind direction. (b) Average wind speed (ms^{-1}) for each direction. Direction points 1-16 correspond to the compass points, where 1 is N, 2 is NNE, 3 is NE etc.

The daily pattern of concentration measurements (Fig. 4), although difficult to discern between individual stations, reveals two periods of high concentration: at the beginning and end of the month at eastern locations (Fig. 4a), and a more prolonged episode during the middle for the Usugi stations (Fig. 4b). In both cases, peak concentrations exceed 4 ppm, even surpassing 5 ppm for individual measurements, and link well with the prevailing wind conditions (Fig. 4c). Strong north-eastern winds clearly correlate extreme SO_2 concentrations in the south-west during October 9-14 and 17-21, whereas eastern events equally reflect western wind directions. To investigate these events further, meteorological conditions are examined during individual time periods.

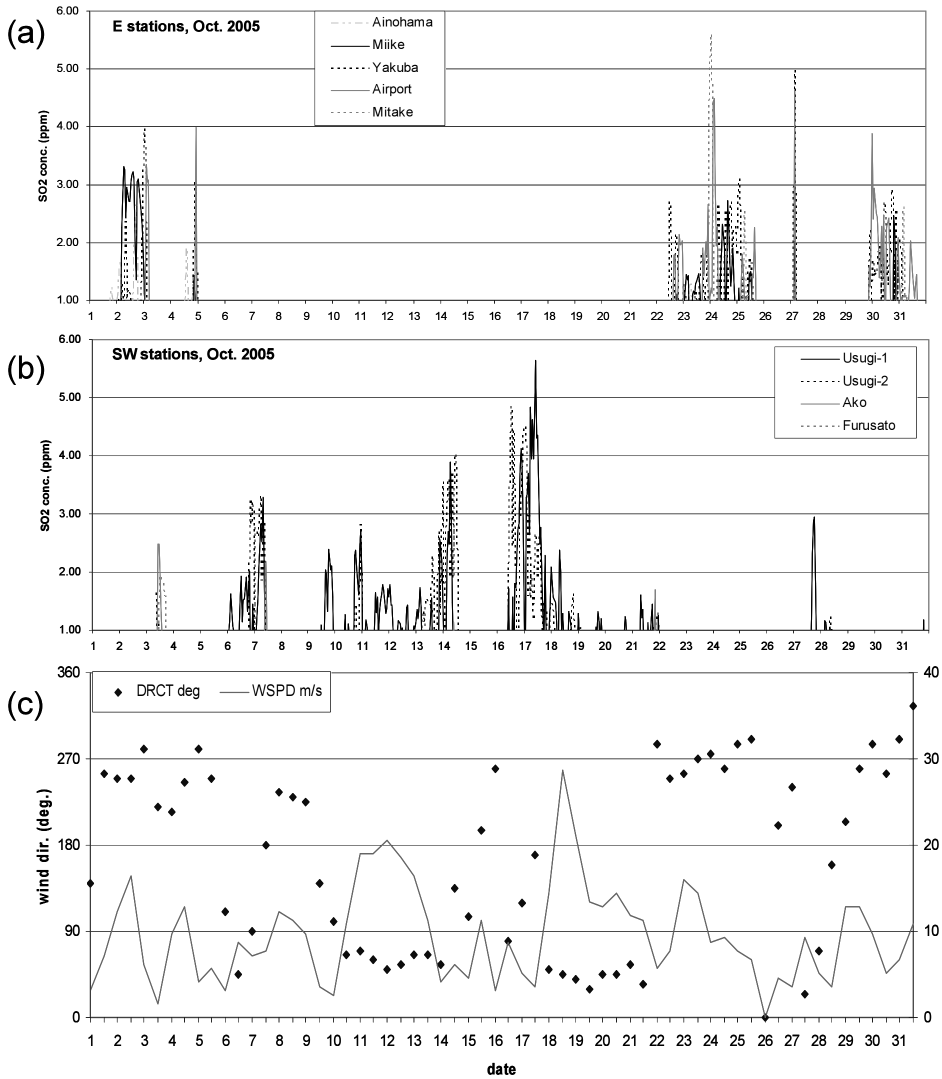

Fig. 4. Hourly SO_2 concentration measurements greater than 1 ppm at (a) eastern stations (including Mitake) and (b) south-western stations during October 2005. (c) is upper wind direction and wind speed for October 2005, recorded twice daily at Hachijojima (925 hPa height). Wind direction axis (left) refers to compass direction ($0^{\circ}/360^{\circ}$= north, 90°= east, 180°= south, 270°= west).

1-5 October

Initially during 2-3 October, high SO_2 concentrations are detected in the east (Fig. 4a) as the result of an occluded front moving eastwards, associated with a low-pressure to the north of Japan (Fig. 5). Westerly winds were generated with a velocity of about 5-15 ms^{-1} over the period (Fig. 4c). Following this, high-pressure conditions developed over the island on 3 October, accompanied by a clear decrease in wind speed to less than 2 ms^{-1}. However, despite no clear shift in the wind direction (Fig. 4c), from late morning until the evening, high SO_2 concentrations, even exceeding 2ppm, were instead detected in the western stations of Usugi-2, Ako and Furusato (Fig. 4b). Under calm conditions it is difficult to determine the cause of SO_2 transport as observations indicate the gas plume is more likely to rise (KINOSHITA *et al.* 2003). Instead, the day-time convection within the lower atmosphere may have occurred, as weather conditions over Miyakejima were likely to have been clear with little cloud, and accompanied by high temperatures (as inferred from the weather chart in Fig. 5). Further research, ideally with additional data at greater spatial resolution, is necessary to clarify the situation.

Fig. 5. Surface weather conditions over Japan during October 2-4 (09:00 JST), 2005. Black triangle indicates the relative position of Miyakejima.

The formation of a second occluded front during October 4 (Fig. 5) regenerated westerly (south-westerly) winds and caused concentrations of almost 4 ppm during the late hours at the Airport and nearby stations (Fig. 4a). No events were recorded the following day, but on October 6 high-pressure conditions reformed again, resulting in high SO_2 concentrations (1.5-3.5 ppm) at Usugi and Ako to the south-west.

6-21 October

High SO_2 concentrations (up to 4 ppm) occurred at south-west stations during 6-14 October (Fig. 4b) due to predominantly north-easterly winds (Fig. 4c). Only from the evening of October 7 to the morning of October 9 is there a break in concentration events, due to a change in the wind towards the south/south-west direction (Fig. 4c). On October 9 a high-pressure system formed over mainland Japan to the north of Miyakejima, and there was a clear decrease in wind speed (Fig. 4c). On the same day, the Japan Meteorological Agency began issuing warnings for a tropical depression south-east of Okinawa. During October 10-12, north-easterly winds were generated once again, and initial SO_2 concentration measurements at the Usugi stations were consistent at around 1.5-2.5 ppm (Fig. 4b). On October 12 the tropical depression was upgraded to a typhoon (named Kirogi), coinciding with the first of two large concentration peaks on October 13-14. At this time, unusually high SO_2 concentrations exceeding 4 ppm were recorded at the Usugi stations, which correlate well with strong north-easterly winds up to around 20 ms^{-1} (Fig. 4c). It is suspected that easterly winds generated by clockwise air movements from the high-pressure system to the north, was amplified by anticlockwise motions associated with the development of the typhoon almost directly to the south.

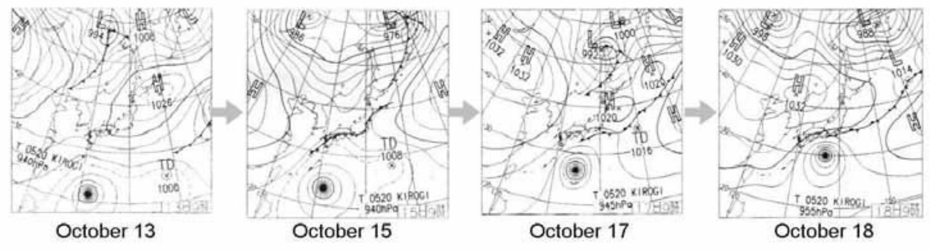

Fig. 6. Surface weather conditions over Japan during 13, 15, 17 and 18 October (JST 09:00 hours), 2005.

Remarkably, there was a clear decrease in SO_2 concentrations during October 14 and no high concentration events occurred on the island again until around midday on October 16 (Fig. 4b). During this time wind speed decreased to around 5-10 ms^{-1} and the wind direction was scattered (Fig. 4c; also indicated by ground-level data (JMA 2008b)), indicative of the high-pressure conditions over Miyakejima, limiting atmospheric circulation. It is unlikely that SO_2 emissions from the volcano ceased between two large concentration events, so it is probable that the gas plume rises and transports SO_2 away from the island.

Wind speed remained low (<10 ms^{-1}) and in scattered directions until October 18 (Fig. 4c). However, despite no change in wind measurements, extremely high SO_2 concentrations are once again recorded at the Usugi stations from October 16, lasting for two days and peaking at 5.65 ppm at 11:00 on October 17 (Fig. 4b). In fact, Hachijojima measurements at 09:00 on October 17, closest to the peak SO_2 value, only recorded a wind speed of 5.14 ms^{-1}, originating from the south-east (120°; Fig. 4c). Wind speed values measured at ground-level also remained less than 10 ms^{-1}, but for each of the weather stations the wind direction consistently originated from the north and north-east (JMA 2008b). It is therefore suggested that despite the complicated meteorological conditions - typhoon Kirogi continued to slowly approach Miyakejima from the south, but the wind field was affected by neardy low-pressure system to the east (TD in Fig. 6) - again there was a strong tendency for plume transport towards the south-western stations.

On October 18, strong north-eastern winds increased once again due to the proximity of the typhoon south of the island, and the development of a large high-pressure system from the north-west (Fig. 6). Wind speed peaked at around 29 ms^{-1} at 21:00, and remained above 10 ms^{-1} for around four days (Fig. 4c). High SO_2 concentrations continued to be detected, but were less extreme ranging around 1.3-2.3 ppm (Fig. 4b). On October 19, the typhoon was declared extra-tropical and a clear reduction in high concentration events in the south-west is also observed. High pressure over Japan maintains north-easterly winds until October 21, after which only a few concentration events occurred.

22-31 October

From 22 October until the end of the month, a series of depressions to the north produced predominantly westerly winds over Miyakejima (Fig. 4c). High SO_2 concentrations were consistent for eastern monitoring stations (Fig. 4a), indicating the start of the winter weather regime, characterised by low-pressure systems (Table 1) and is reasonably well understood (e.g. IINO *et al.* 2004a). Measurements peak above 5.5 ppm on October 24 at Mitake, not located in the hazardous zone (Fig. 1b), but included because a local deviation towards strong north-westerly winds must have occurred. High concentration levels are only interrupted during 26-29 October when high-pressure conditions and calm winds allowed the gas plume to rise. North-easterly winds on October 27 also briefly transported SO_2 to the south-west (Fig. 4b).

Discussions

SO_2 emission rate

Ground-level SO_2 concentrations can be linked to emissions from the volcanic vent at Mount Oyama. An increase in SO_2 output from the volcano, combined with strong winds, is likely to cause abnormally high concentrations downwind, and therefore could have been a major factor in October 2005. However, SO_2 emissions data suggests volcanic activity and degassing remained at normal levels through the month. 12 measurements over three days averaged 3,550 td^{-1}, close to the average emission rate of around 3,900 td^{-1} recorded regularly for the whole of 2005 (JMA 2008a). This is also comparable to the previous and following years, as average SO_2 flux values for October in the years 2004, 2006 and 2007 ranged 2,025 - 3,750 td^{-1} (JMA 2008a).

Comparison of with October data with other years

The possibility of abnormal meteorological conditions during October 2005 must also be considered. Average SO_2 concentrations recorded at south-western stations during October 2005 are noticeably larger than in October 2004 , 2006 and 2007 (Fig. 2), suggesting that north-easterly winds were more frequent in 2005, and/or stronger. Initial comparison between Fig. 3 and Fig. 7 suggests that the general distribution of wind in 2005 was more constrained to western and north-easterly directions. Direct north-easterly winds were also more frequent (14%), perhaps accounting for high SO_2 concentrations at the Usugi stations directly to the south-west. North-easterly winds were similarly frequent in October 2007, but there was a wider spread of weak north-easterly and easterly winds. In addition, east-north-easterly winds were more common in 2004 and 2006 than in 2005. During October 2005 the frequency of east-north-easterly winds was 15%, whereas frequencies in 2004 and 2006 were 18% and 24% respectively. This correlates with relatively high concentrations at Ako and Furusato (which lie in the path of east-north-easterly winds), but the overall number of events is still far fewer than in 2005. However, average wind conditions alone do not provide a clear explanation for increased SO_2 concentration levels at south-western stations in October 2005.

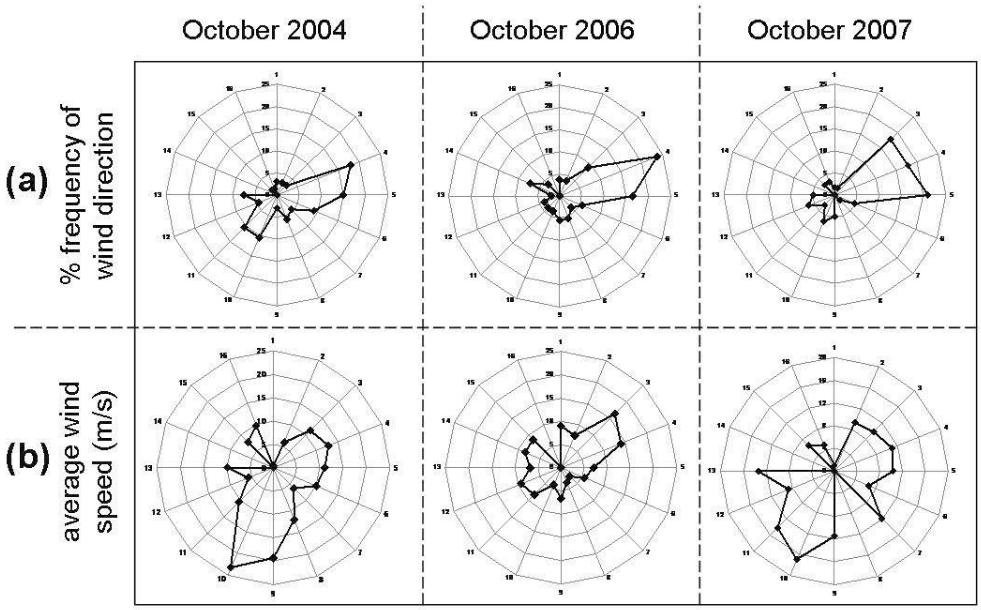

Fig. 7. Summary of wind measurements recorded at Hachijojima in October 2004, 2006 and 2007. (a) Frequency (%) of occurrence of each wind direction. (b) Average wind speed (ms^{-1}) for each direction. Direction points 1-16 correspond to the compass points of N, NNE, NE etc., as in Fig. 3.

Although during each period scattered concentration events in the south-west and east can be correlated with strong north-easterly and westerly winds, meteorological conditions can be investigated beyond interchanging high and low-pressure systems over mainland Japan.

Most notably, the month of October, and the autumn season in general, is characterised by typhoon events and the migration of such weather systems in relation to particular regions of Japan can be important for generating variation within the wind field. Firstly, three typhoons migrated to the west of Miyakejima during October 2004, generating very strong southerly winds up to 30 ms^{-1} (average wind speed is indicated in Fig. 7b). Only minor SO_2 concentrations were recorded at northern and north-eastern stations during this time (generally, southern winds are rare and SO_2 directed to the north/north-east may have been undetected due to the lack of stations compared to the south (Fig. 1b)). This contrasts with October 2005, when typhoon Kirogi approached Miyakejima directly from the south, generating north-easterly winds and thus causing high SO_2 concentrations in the south-west. Fig. 8 illustrates the difference in the location of typhoon landfall. In both 2004 and 2005, each typhoon was generated from tropical depressions to the south-west of the chart, but a different approach towards Japan can lead to significantly different wind directions at Miyakejima. Incidentally, only minor SO_2 concentrations were recorded at northern stations during typhoon events in October 2004. Generally, southern winds were rare and SO_2 directed to the north may well have gone undetected due to the lack of stations compared to the south (Fig. 1b). However, SO_2 emissions from the vent were similar to October 2005 (3,480 td^{-1}, compared to 3,550 td^{-1}; JMA, 2007), so there was still the potential for many concentration events. It is therefore possible that fewer events may also be attributed to high altitude plume transport away from the island.

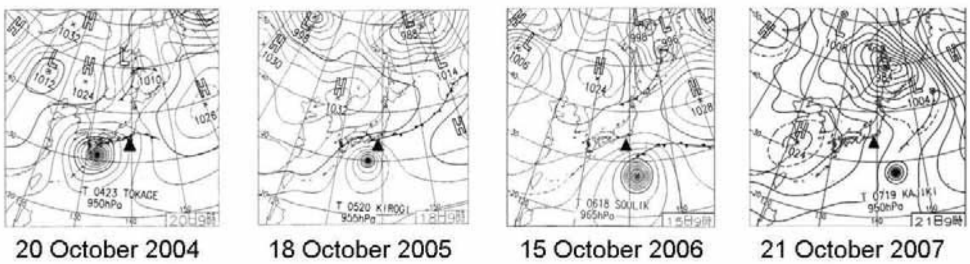

Fig. 8. Landfall positions of typhoons in October 2004 and October 2005, and final position of the October 2006 and October 2007 typhoons. Black triangle indicates the relative position of Miyakejima.

In October 2006 and October 2007, only specific high-pressure systems to the north of Miyakejima generated north-easterly winds, causing a few, isolated high concentration events to the south-west (1.5-3.5 ppm). High-pressure conditions remained directly over the island through much of the month, so most SO_2 emissions were likely to have been transported away by a rising gas plume. Typhoons, although linked to strong easterly winds (around 15-25 ms^{-1}) at Hachijojima, did not cause high SO_2 concentrations to the south-west as it appears to have passed too far south to influence the wind field at Miyakejima. In addition, the typhoon did not make landfall in Japan and was two categories weaker than typhoons in October 2004 and 2005.

Meteorological conditions during October 2005 were therefore favourable for south-western high concentration events. High-pressure systems to the north, over mainland Japan, clearly generate north-easterly winds on Miyakejima, but the movement of typhoon Kirogi directly to the south during October 9-21 also appears to have intensified the wind field. A deviation in the movement of typhoons in October 2004, 2006 and 2007 however, failed to produce the same effect. In addition, east-north-easterly winds were more frequent during these months (Fig. 7a), thus passing to the north of the directly south-west Usugi stations.

Plume dispersal and wind data

1-hour SO_2 concentration measurements exceeding 1 ppm allow for a clear comparison between extreme events in the east and south-west sectors of Miyakejima island. The severity (how concentrated) and duration of such events can clearly be related to 12-hour upper wind measurements, representative of conditions at the summit of Mount Oyama and the overall meteorological situation over the Izu islands at the time.

However, a closer comparison of SO_2 concentrations between neighbouring stations in both the east and south-west (Fig. 4a and 4b) shows there is further variation over just a matter of hours. In the east from 22-25 October 2005, for instance, a number of concentration peaks can be detected for individual stations, varying from about 1.5 ppm and exceeding 5.5 ppm (Fig. 4a). Treating the data as a whole, the high concentrations are clearly the result of westerly winds, as mentioned before (Fig. 4c; related to a low pressure system to the north), but for investigating the variation between neighbouring stations, 12-hour resolution wind data is obviously insufficient. Peaks only last for a few hours and also suggest that the main gas plume (indicated by SO_2 concentrations exceeding 1 ppm) rarely disperses beyond the width of two stations. For example, Miike and Yakuba stations are only about 800 m apart (refer to Fig. 1b for locations), thus suggesting that the main gas plume is both remarkably narrow and is transported in a highly specific, but changeable direction. The same is true for stations in the south-west (Fig. 4b), but as there are fewer stations, clear variation is limited to measurements between the Usugi stations, about 1 km apart (Fig. 1b). North-easterly winds correlate with high concentrations at both stations (Fig. 4b), but hourly fluctuation between the two is difficult to distinguish.

Surface wind data collected by JMA on Miyakejima, provides a greater time resolution. Fig. 9 correlates hourly SO_2 concentration peaks for the 22-25 October 2005 period with hourly wind measurements from the nearest JMA station, close to the Mitake SO_2 monitoring site (Fig. 1b). Close examination shows there is some association between individual SO_2 peaks at Mitake and north-west/west-north-west winds - most notably at 23:00 on 23 October and 05:00 on 25 October. The occurrence of other individual peaks can also be correlated with a specific wind direction, but this is inconsistent and there is no obvious link to wind speed, despite a possible diurnal pattern (wind strength is greater during the daytime; Fig. 9b). The large peaks for Mitake and Airport stations during the night of 23-24 October are particularly curious, but the deviation of the wind must have been sufficient enough to transport larger quantities of SO_2 during this time. A clear interpretation of the dispersal pattern between adjacent monitoring stations cannot be confirmed.

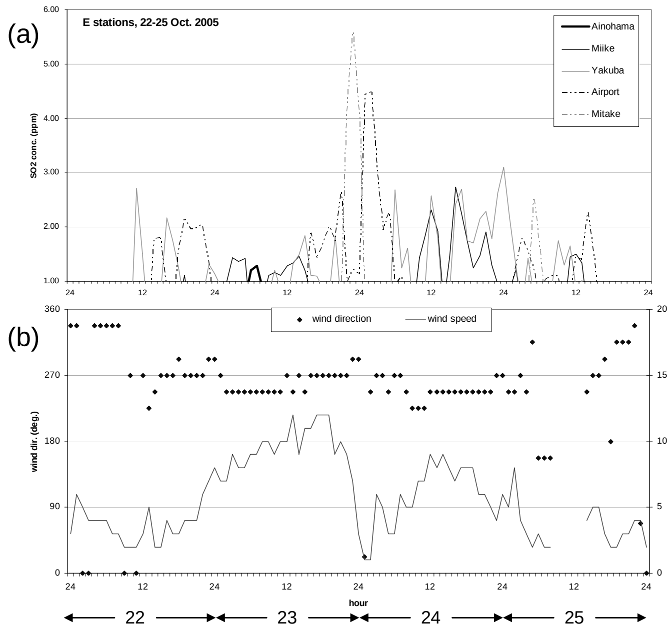

Fig. 9. Hourly SO_2 concentration measurements greater than 1 ppm for eastern stations (including Mitake; a) compared with hourly ground-level wind direction and wind speed (b) for 22-25 October 2005. Ground-level wind measurements recorded at the meteorological station close to Mitake SO_2 monitoring site. Wind direction axis (left of (b)) refers to compass direction ($0^\circ/360^\circ$= north, 90°= east, 180°= south, 270°= west).

In general, surface wind data provides additional insight where upper wind measurements are limited. However, due to the location of the three meteorological stations outside the hazardous zones - close to the Branch Office, Mitake and Ako SO_2 monitoring sites in Fig. 1b - a full analysis of plume dispersion in the east and south-west is still prevented. Unlike wind measurements at the height of Mount Oyama, localised factors such as topography influence the path of the gas plume. For example, a topographic barrier exists to the north of Usugi-2, acting as a natural boundary for the south-west restricted zone. Therefore, as an indication of synoptic wind conditions at Miyakejima, upper air measurements from Hachijojima remain the most reliable option, and indeed the easiest to interpret.

Implications for hazard mitigation

The direct correlation of the large-scale wind field over the Izu island area with the occurrence of high SO_2 concentrations at the foot of Miyakejima has notable implications for managing gas hazards in volcanic crises. Despite the efficient warning system currently in place on Miyakejima, these data show that simple reference to daily weather forecasts can provide the public with an idea of where on the island high concentrations of gas are likely to occur. Severe weather warnings, such as those for typhoons, could also be incorporated. While the public have access to real-time ground-level measurements, one is also able to make informed decisions about possible events the following days based on television or radio weather information. This would be especially important during the onset of a new volcanic gas crisis. When the vent at Mt. Oyama initially began to emit vast quantities of SO_2 in 2000, although useful dispersion simulations were later provided by SEINO *et al.* (2004), little was known about the fate of grounded gas emissions. The education of the local populace with respect to understanding daily meteorological forecasts is therefore a useful, and low-cost, option for hazard mitigation at persistently degassing volcanoes. Such a practice would be appreciated where little funding is available for warning systems: for example, at Ambrym and Yasur volcanoes, Vanuatu, in the South Pacific, where local islanders are constantly exposed to airborne emissions, but little relief is available (BANI and LARDY 2007).

Conclusions

Gas plumes from Miyakejima volcano, containing large concentrations of SO_2, are regularly transported by strong winds down to low-lying coastal areas around the island. Although SO_2 emission rates have been constantly decreasing since the initial degassing in 2000, dangerously high levels of SO_2 are still regularly detected at ground-level. This paper builds upon our initial understanding of dispersion patterns on the island with respect to seasonal meteorological conditions, by comparing ground-level SO_2 concentrations exceeding 1 ppm, with daily and 12-hour upper wind measurements. Findings focussed on October 2005 as a period of highly changeable wind characteristics with respect to the large-scale meteorological situation:

Ground-level SO_2 concentrations are directly linked to alternating low and high-pressure systems over mainland Japan. Resulting strong westerly and north-easterly winds vary over just a matter of days, causing high concentration events in the east and south-west respectively.

SO_2 concentration values at south-western stations are also influenced by typhoon activity to the south. During 12-18 October 2005, Typhoon Kirogi moved directly south of Miyakejima, amplifying strong north-westerly winds. However, different typhoon pathways observed in October 2004 and 2006 failed to produce similar concentration events.

The correlation of surface SO_2 concentration events with upper wind measurements, and the corresponding regional meteorological situation, has useful repercussions for hazard mitigation at persistently degassing volcanoes. The interpretation of television or radio weather forecasts means that the local population are able to make informed decisions about where high gas concentrations are likely to occur. Such a practice would be particularly useful in educating local people about the gas hazard, either at the onset of a new volcano crisis, or where funding is limited for expensive warning systems.

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