NOTES AND CORRESPONDENCE

Development of a Dispersion Model for Volcanic Gas over Miyake Island

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(Manuscript received 3 September 2001, in revised form 25 April 2002)

Abstract

A very fine mesh dispersion model was developed for volcanic gas over Miyake Island. The model consisted of a meteorological prediction part and a dispersion part. The multi-nesting method was used for the meteorological prediction part to express the field, depending on synoptic weather pattern in this study. The grid size of the innermost model was 100 m. The days when the observed SO₂ concentration was comparatively high were chosen for the verification of the model. Four cases of 24-hour numerical simulations were conducted. We try to reproduce the SO₂ concentration in each situation. Following results were derived. The effect of the advection was dominant as compared with other physics, so the volcanic gas moved leeward. Even the slight change of the wind direction largely varied the concentration. The volcanic gas spread widely, in case of weak wind at night, because of the mountain breeze. Although there were some cases of time-lags of the peaks, and some degrees of overestimation, or underestimation, each situation was almost well reproduced.

1. Introduction

Miyake Island is located about 180 km to the south of Tokyo on the Pacific Ocean. Mt. Oyama, which is placed at almost the center of Miyake Island, has been in eruption since 8 July 2000. The volcano has spouted out several tens of thousand tons poisonous SO₂ gas every day, so all the residents evacuated from Miyake Island have not been able to return. Our group started the development of the SO₂ dispersion model to help in the judgment of whether the residents can temporally return to the Island or not. The volcano emitted many kinds of gas, e.g., SO₂, H₂S and water vapor. The dispersion of only SO₂ gas was handled in this study, considering its poisonousness and the reliability of the observation.

The long-range transport model was developed by Kimura and Yoshikawa (1988) in the Meteorological Research Institute (MRI). They simulated the spread of the radioactive pollutants using the global model. Satomura et al. (1994) used the regional model for simulating the dispersion of the radioactive pollutants from the accident at the Chernobyl nuclear power plant. Sato et al. (1999A) developed the long-range sulfur transport model to evaluate the acid deposition in East Asia. The grid intervals of those models exceeded 100 km. However, the diameter of Miyake Island is about 10 km, so those models are far from expressing the dispersion of SO₂ over the Island. We adopted 100 m for the grid size of the innermost model, and it was fine enough to express the topography of Miyake Island. The way that the homogeneous wind was given for initial and boundary conditions had been often used for expressing the small scale meteorological field. The multi-nesting method was, however, used for the meteorological model to express the field depending on the synoptic weather pattern in

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Fig. 1. The nesting model system used in these experiments. The RSM with 10 km grid interval is nested in the GANL. The three NHMs whose grid sizes are 2 km, 400 m and 100 m are nested one after another.

this study. The days when the observed SO_2 concentration was comparatively large were chosen for our numerical experiments. The 24-hour calculations of the SO_2 dispersion on those days were conducted, and their results were compared with the observation. It took about 60 hours for CPU time in one case, by using the Hitachi SR8000 whose calculation speed was 8 G Flops, so we could not conduct many experiments. Thus, only four cases are introduced in this study.

This paper is constructed as follows. In Section 2, the model structure is briefly described. The results of numerical simulations are compared with the observation in Section 3. Concluding remarks are in Section 4.

2. Model description

The model used in this study consists of two parts; one is a meteorological prediction

part and the other is a dispersion part. Multi-nesting method was used for the meteorological part, as seen in Fig. 1. The global analysis (GANL) data set was used for the outermost model. The GANL was developed by the Numerical Prediction Division (NPD) in the Japan Meteorological Agency (JMA). Its grid size is 1.25° in both longitude and latitude. The Regional Spectral Model (RSM) was nested in the GANL. The RSM was also developed by the NPD, to use operationally for weather forecast around East Asia. The transformed grid interval of the original version was 20 km, but we modified it to 10 km in this study. Moreover, the nonhydrostatic model (NHM), which was developed in the MRI and NPD, was nested three times. The details of the NHM can be found in Saito et al. (2001). The horizontal grid intervals of the nested NHM are 2 km, 400 m and 100 m. We adopted the same grid point

numbers for all three NHMs. There are 102×102 grid points horizontally and 38 layers vertically. The diameter of the Miyake Island is somewhat smaller than 10 km, so the island just fits to the innermost model.

The Lagrangian particle method is used for the dispersion part. One thousand particles are emitted per one second. The particles are moved through the process of advection and diffusion. The random walk procedure is used for the horizontal and vertical diffusion. More details about the dispersion model can be found in Satomura et al. (1994) and Sato et al. (1995, 1999A, 1999B).

There was not enough information about the condition of the source emission, so we made several assumptions about it. The volcanic gas was emitted from the crater with a certain initial vertical velocity. The velocity of the gas is maximal at the center of the plume, and decreases apart from the center. We set the following distribution for the initial velocity of the gas,

$$w(r) = \frac{w_c}{1 - e^2} (e^{-2(r^2/r_0^2)} - e^{-2}) \quad r \leq r_0, \quad (2.1)$$

where r_0 is the radius of the plume and w_c is velocity at the center of the plume. In this study, we used r_0 was 200 m and w_c was 4.5 m/s, in accordance with survey by aircraft.

As time passed from the emission, the velocity gradually decreases through the entrainment process. Thus we set the time dependency of the velocity as follows,

$$w(t) = w_0 / (1 + w_0 \times c \times \Delta t),$$

$$c = 0.2/b, \quad (2.2)$$

where w_0 is the initial vertical velocity, Δt is the elapsed time from the emission time, c is the entrainment coefficient and b is the vertically averaged radius of the SO_2 plume.

There were some fumaroles in the crater, and each of those was sub-grid scale. Thus, we assumed the normal distribution for the initial concentration of the SO_2 gas as follows,

$$f(r) = \alpha e^{-2(r^2/r_f^2)} \quad r \leq r_f,$$

$$r_f = \left(1.0 + \frac{K_V}{3.0}\right) r_0, \quad (2.3)$$

where K_V is the vertical diffusion coefficient.

The assumption of emission velocity, and concentration of volcanic gas stated above, greatly influences the evaluation of the SO_2 gas distribution. However, we did not have enough information about the state of the SO_2 emission. These assumptions have to be modified to improve the accuracy of the simulation through additional information of SO_2 emission, and comparing it with the observed SO_2 concentration data.

The calculated concentration is proportional to the amount of emitted SO_2 , so the precise amount is required for estimation of the concentration. The amount fluctuated day by day, and hour by hour, depending on volcanic activity, so it is difficult to estimate it. It is assumed that the amount of SO_2 emitted from the volcano was 30000 tons per a day in this study for simplification. We considered that the amount was almost reasonable from observed data (JMA's volcanic information).

3. Observation and results of numerical simulations

The major residential areas on Miyake Island are Okubo, Tsubota and Ako (see Fig. 1). There are a couple of SO_2 monitoring stations in each area. One is operated by the JMA the other by the Tokyo Metropolitan Government. There was not a large difference between the data observed by the JMA and the Tokyo Metropolitan Government. We used the JMA data in this study, because it was easy to get. The observation points operated by the JMA are shown on the topographic map in Fig. 1.

The minimum concentration that the model can express depends on the number of emitted particles. It takes much CPU time when a lot of particles are emitted. In this study, the model cannot express the concentration less than about 1 ppm. Thus, the days when the observed concentration was comparatively large were searched in the data described above. The high concentration of SO_2 was not found at Okubo and Ako, but at Tsubota in the data from November 2000 to April 2001. We chose four cases for our numerical experiments to investigate the performance of the model; (1) from 09 JST 3 to 09 JST 4 December 2000, (2) from 15 JST 5 to 15 JST 6 December 2000, (3) from 09 JST 18 to 09 JST 19 February 2001, (4) from 21 JST 15 to 21 JST 16 April 2001.

3.1 The case from 09 JST 3 to 09 JST 4 December 2000

Figure 2a is the weather chart around Japan at 21 JST 3 December 2000. The trough that was located at the Japan Sea passed to the

east. The wind direction around Miyake Island was southwest at 09 JST 3 December. It slowly rotated clockwise and became west at 15 JST. The wind became weak at night and the direction changed to northeast the next morning.

Fig. 2. a) The weather chart around Japan at 21 JST 3 December 2000. b) The time sequence of the calculated and observed SO₂ concentration at Tsubota monitoring station from 09 JST 3 to 09 JST 4 December 2000. A closed circle is observed concentration and open circle is calculated one. c) The horizontal distribution of ground level SO₂ concentration and surface wind calculated by the 100 m grid size NHM at 16 JST 3 December 2000. The values of the contour lines are 1, 10 and 50 ppm from the outermost line and the intervals from the next line are 50 ppm. d) Same as Fig. 2c, but for 21 JST 3 December 2000.

Figure 2b is the time sequence of the calculated, and observed SO_2 concentration at Tsubota. The observed concentration was detected from 15 JST. There were two peaks of the concentration during this period; one was about 10 ppm at 16 JST, and the other was about 25 ppm at 20 JST. After the later peak, the concentration gradually faded out.

Figures 2c and 2d is the horizontal distribution of SO_2 calculated by using the meteorological field of the 100 m grid size NHM at the lowest level (10 m from the surface). The emitted SO_2 gas was transported toward northeast by the southwest wind at 09 JST 3 December (not shown). The band shaped concentration distribution shifted to the east. The calculated SO_2 concentration was also detected from 15 JST, same as observed. At 16 JST, the plume stretched to the east-southeast direction (Fig. 2c), and the concentration reached the first peak. The calculated value at the peak was almost the same as observed. At 17 JST, the southerly wind, which was blowing around the island, became strong near Tsubota. Thus, the plume temporally shifted to the east-northeast and the concentration at Tsubota became thin (not shown). After that, the wind gradually became weak, and the calculated SO_2 gas spread to a wide area of the southeast part of the Island, at night (Fig. 2d). The calculated concentration reached the peak again (21 JST), one hour later than the observed, and the value was rather low, compared with the observed.

3.2 The case from 15 JST 5 to 15 JST 6 December 2000

Figure 3a shows that the weather pattern was a typical winter type around Japan. The winter monsoon wind was blowing, and the wind direction was the west-northwest (10~15 m/s) around Miyake Island. The SO_2 concentration at Tsubota station was found from 19 JST 5 December (Fig. 3b). The SO_2 concentration, maximum value about 29 ppm, was observed next morning at 07 JST. After that it decreased, but still remained about 15 ppm during this period.

The emitted SO_2 gas was transported leeward. The distribution stretched from west to east like a band shape. Figure 3c is the SO_2 distribution at 15 JST 5 December. The SO_2 gas did not reach Tsubota at this time. The

band slightly fluctuated north and south, and its width also changed over. The calculated SO_2 concentration was detected from 20 JST. It was one hour later than the observed (Fig. 3b). Both the calculated and observed concentration reached their peak at 00 JST. From 01 JST to 04 JST, both of them progressed at a low value. The calculated concentration again reached the peak at the same time as observed (07 JST). The calculated maximum concentration (20 ppm) was about 10 ppm less than the observed. The band of the SO_2 concentration at the peak time (Fig. 3c) was slightly shifted to the south, as compared with that at 15 JST (Fig. 3d). In this way, a slight shift of the band seriously affected the SO_2 concentration at Tsubota. After that, both the concentrations gradually decreased. The model could not exactly express the slight change of wind direction. It was supposed to be the cause that the calculated concentration was over estimated before 03 JST, and after that it was underestimated.

3.3 The case from 09 JST 18 to 09 JST 19 February 2001

The band shaped anticyclone, stretched east and west, was located to the south of Miyake Island (Fig. 4a). The westerly wind whose velocity was several m/s was blowing during this period. The observed SO_2 concentration was detected from 10 JST, and reached its peak at 12 JST (Fig. 4b). It gradually became low, and approximated to zero from 15 to 18 JST. It was detected again at 19 JST, and increased slowly. The maximum value (17 ppm) was observed at 06 JST.

The model could not express the first peak at 12 JST (Fig. 4b). The phase of temporal fluctuation after 19 JST was almost well reproduced. The value of the calculated peak at 05 JST was equivalent to the observed value at the peak, however the time was one hour earlier than the observed one. Figure 4c is the calculated SO_2 distribution at 15 JST, when SO_2 was not detected at Tsubota and Fig. 4d is that at 05 JST when the calculated concentration at Tsubota was at peak time. The emitted SO_2 gas was transported to the east, and the plume slightly fluctuated north to south. The difference of the angle of the plume axis, between Fig. 4c and Fig. 4d, was only less than 20 degrees. The

Fig. 3. a) Same as Fig. 2a, but for 09 JST 6 December 2000. b) Same as Fig. 2b, but for from 15 JST 5 to 15 JST 6 December 2000. c) Same as Fig. 2c, but for 15 JST 5 December 2000. d) Same as Fig. 2d, but for 07 JST 6 December 2000.

Tsubota monitoring station was located at the southern edge of the plume. Thus, the concentration at Tsubota was seriously affected by the slight fluctuation of the wind direction. Figures 4e and 4f were cross sections of the east and west direction. At 15 JST, the particles located at a high place. On the other hand, the particles flowed along the mountain slope the next morning. The atmosphere became stable in the early morning, and the particles stayed in the

low layer. Thus, the surface concentration at 15 JST was lower than that at 05 JST on the following day.

3.4 The case from 21 JST 15 to 21 JST 16 April 2001

The center of a migratory anticyclone passed through Miyake Island at 09 JST 16 April (Fig. 5a). The weak westerly wind was blowing during this period. The observed concentration was

Fig. 4. a) Same as Fig. 2a, but for 21 JST 18 February 2001. b) Same as Fig. 2b, but for from 09 JST 18 to 09 JST 19 February 2001. c) Same as Fig. 2c, but for 15 JST 18 February 2001. d) Same as Fig. 2d, but for 05 JST 19 February 2001. e) The cross section of the east and west direction at 15 JST 18 February 2001. f) Same as Fig. 4e but for 05 JST 19 February 2001.

Fig. 5. a) Same as Fig. 2a, but for 09 JST 16 April 2001. b) Same as Fig. 2b, but for from 21 JST 15 to 21 JST 16 April 2001. c) Same as Fig. 2c, but for 03 JST 16 April 2001. d) Same as Fig. 2d, but 12 JST 16 April 2001.

detected from 00 JST, and went out at 06 JST (Fig. 5b). There were two peaks at 01 and 03 JST. Both observed values were about 12 ppm.

The calculated concentration was overestimated from 21 JST 15 to 11 JST (Fig. 5b). The SO₂ gas was transported toward Tsubota at 03 JST (Fig. 5c). The wind was blowing along the slope of the mountain, since the atmosphere was stable at night. Thus, a lot of SO₂ gas was transported along the slope. The

concentration at Tsubota became high. Weak westerly wind transported the SO₂ gas toward the east at 12 JST (Fig. 5d). After that, SO₂ was hardly detected in both the observation and calculation.

4. Concluding remarks

We developed a very fine mesh dispersion model to simulate the volcanic gas distribution over Miyake Island. The multi-nesting method

was adopted for the model, and its grid size was 100 m in the innermost model. The days when the observed SO₂ concentration was comparatively high were chosen for the verification of the model. The four cases of 24-hour numerical simulations were conducted to reproduce the SO₂ concentrations.

Four cases chosen for the numerical experiments in this study were as follows; (1) from 09 JST 3 to 09 JST 4 December 2000, (2) from 15 JST 5 to 15 JST 6 December 2000, (3) from 09 JST 18 to 09 JST 19 February 2001, (4) from 21 JST 15 to 21 JST 16 April 2001. These four cases were different from each other in their synoptic weather pattern. The following results were obtained. It was common in all cases that the effect of the advection was dominant as compared with other physics. The concentration at the Tsubota station was seriously affected by the slight fluctuation of the wind direction. The concentration at the early morning was apt to be dense. The SO₂ gas spread widely in the case of weak wind at night, because of the mountain breeze. Although there were some cases of time-lags of the peaks, and some degrees of overestimation or underestimation, the time sequence of SO₂ concentration at Tsubota was almost well reproduced in each case.

Two main causes were considered for the bad score cases. One of them was due to the meteorological reproducibility. The best way to estimate the reproducibility of the meteorological model is to compare the calculated field with the observation data. There was not, however, an observation network that was fine enough to be compared in the 100 m scale. The model performance was showed by other experiments (Kato et al. 1998), but the scale was different from our experiments. We could also suppose the meteorological field was almost well reproduced, since the concentration was approximately simulated. When the wind was strong, the plume became narrow and the slight change of the wind direction largely affected the concentration. The meteorological model did not have the ability to express such a slight change of wind direction. We have to evaluate the reproducibility of the meteorological model and improve it to get better the performance of the dispersion model.

Another cause of the bad score case is the

shortage of source information. The uncertainty of the emission rate of SO₂ also became a cause of the underestimation or overestimation of concentration. We did not know the exact daily amount of SO₂ emitted from the volcano. Amount of emitted SO₂ gas has a direct influence on the calculated SO₂ concentration. In this study, it was assumed that the value was 30000 tons per a day. However, the JMA observed that the values were 20000~30000 tons in case (1) and (2), about 40000 tons in case (3) and about 20000 tons in case (4). Thus, there was a possibility that the case (3) was underestimated and the case (4) was overestimated. It was difficult to estimate the accurate value of the emitted SO₂. In addition to that, the value changed day by day depending on the activity of the volcano. The same emission value was adopted for all cases for simplicity. It was one of the reasons why the model well reproduced the SO₂ concentration qualitatively but not quantitatively.

There was not enough information about emission of SO₂ gas, so we used several assumptions about the daily amount of emitted SO₂ gas, e.g. initial vertical velocity, and distribution of the SO₂ gas. They also largely affect the ground level SO₂ concentration. The validity of the assumptions should be considered through doing a lot of numerical experiments and observation of volcanic gas emission. We would like to carry out more experiments of various situations, and then improve the model for having a better correspondence with observation.

Acknowledgements

We thank Dr. Kazuo Saito for useful advice of using the MRI/NPD-NHM. We also thank the members of the Seismological and Volcanological Department in the JMA for using observed data. This study is conducted by using the ARGO super computer system in the MRI.

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