

Numerical Simulation of Volcanic Ash Plume Dispersal from Kuchinoerabujima on 29 May 2015

Hiroshi L. TANAKA¹ and Masato IGUCHI²

1: Center for Computational Sciences, University of Tsukuba
Tsukuba 305-8577 JAPAN

2: Sakurajima Volcano Research Center
Disaster Prevention Research Institute, Kyoto University
Kagoshima 891-1419 JAPAN

(Received: Sep 9, 2016 Accepted: Nov. 2, 2016)

Abstract

In this study, airborne ash dispersal from the eruption of Kuchinoerabujima Volcano in Japan on 29 May 2015 is simulated using the volcanic ash tracking PUFF model. A major eruption occurred at 9:59 am local time (0:59 UTC), and the ash plume reached 9 km above the ground. According to MTSAT-2 satellite monitoring, the ash plume with a mushroom-shaped distribution drifted in the east-southeast direction. The observed ash fallout over Yakushima Island is in the order of 100 g/m². Using this observational fact, we estimated that a particle in the numerical model represents 60 tons of ash mass. Based on this number, total emissions are estimated to be 600,000 tons for this event. The result suggests that the ash concentration in the air can also be estimated by this method. According to the aviation safety report, an ash density of 4 mg/m³ and above is considered as a danger zone for commercial airliners. The PUFF model simulation shows that the core region of the plume front at 9 km in height indicates 100 mg/m³ of airborne ash density even for the plume 250 km from the erupting volcano. The satellite images show the exact location of the ash plume. The PUFF model simulation can therefore estimate the airborne ash density over a much wider diffused area to identify the danger zone for aircraft.

Keyword: PUFF model, Kuchinoerabujima Volcano, aviation safety, airborne ash density, ash dispersion

1. Introduction

A major volcanic eruption occurred on Kuchinoerabujima (657 m) at 9:59 am local time (0:59 UTC) on 29 May 2015. Kuchinoerabujima Volcano is an active volcano of the Ryukyu Island arc, Japan. The island is located at 30.44° N / 130.22° E, which is about 100 km south of the southern tip of Kagoshima Prefecture in Japan. A tall mushroom ash plume reached 9 km above sea level within 10 min. The initial radius of the circular anvil cloud was about 10 km for the first 20 min. The phreatomagmatic eruption from the vent of Mount Shindake, the island's main peak, generated a pyroclastic flow that reached the shoreline of the island. The Japan Meteorological Agency (JMA) raised its volcano alert to the highest level of 5 at 10:07 am (01:07 UTC). Fortunately, there were no reports of injuries or damage owing to the immediate evacuation. Kuchinoerabujima Volcano then erupted on 18 and 19 June, but no eruption has been observed since 19 June 2015. (JMA Website for Ash Fallout Prediction, 2015: <http://www.jma.go.jp/jp/ashfall/>).

According to the high resolution MTSAT-2 satellite imagery at 2:10 UTC (see Fig. 1), the ash cloud appeared over Yakushima Island in a dark color while ordinary clouds appeared in white by the newly installed color imagery of MTSAT-2.

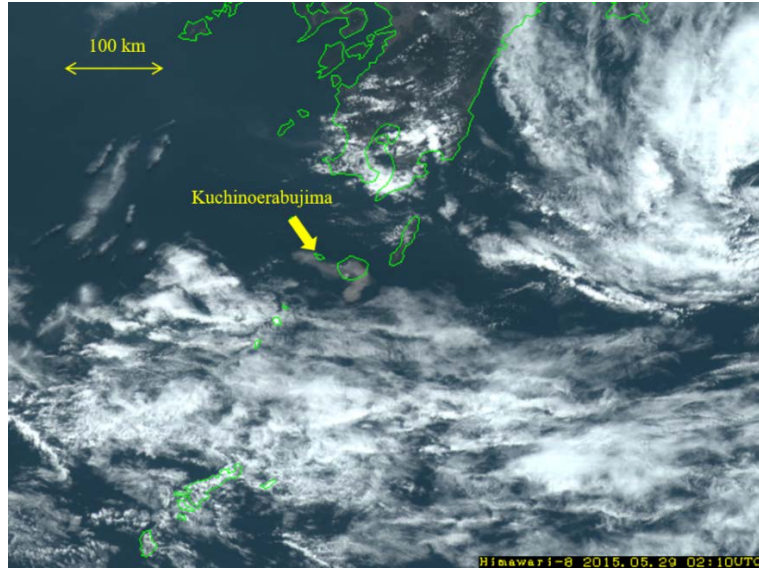


Fig. 1 MTSAT-2 (Himawari-8) satellite imagery of the volcanic ash plume from Kuchinoerabujima erupted at 0:59 UTC on 29 May 2015. Dark ash cloud is seen over Yakushima Island at 2:10 UTC (animation provided by JMA Web: <http://www.jma-net.go.jp/sat/data/web89/himawari8-sample-data.html>).

We can clearly identify the ash cloud by viewing a high-speed animation of the cloud movement. The movement of the volcanic ash plume is traced in Fig. 2 using the MTSAT-2 satellite data. The plume top of 9 km in height soon spread in an east-west direction from the volcano. The elongated shape of the plume top started to drift toward Yakushima Island. By 11:00 am local time (2:00 UTC), the ash front had reached Yakushima Island located 20 km east of Kuchinoerabujima. The front edge of the ash plume over Yakushima Island was elongated in the north-south direction while the tail of the ash plume was connected to the vent of the volcano. At 11:40 am (2:40 UTC) the front edge of the ash plume had passed Yakushima Island, and clear mushroom head distribution appeared for the ash plume in the north-south direction on the satellite image. There was a tail from the ash plume head connected to the erupting volcano. The lower part of the ash plume drifted westward while the upper part of the ash plume moved in the east-southeast direction.

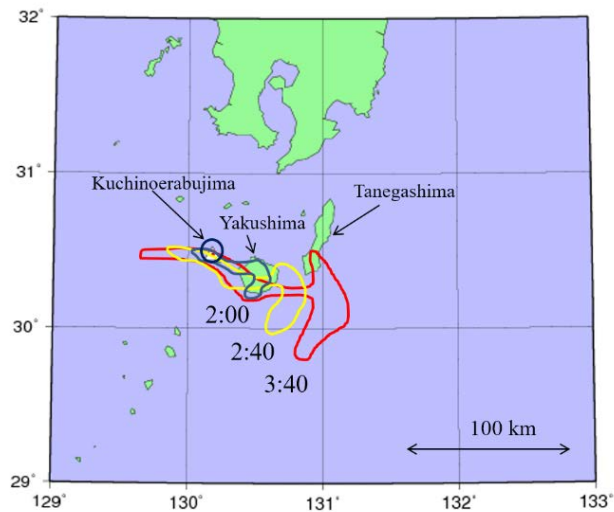


Fig. 2 Distribution of volcanic ash plumes from Kuchinoerabujima (black circle), traced from the satellite images for 2:00 (blue), 2:40 (yellow), and 3:40 (red) UTC.

The wind direction at the boundary layer was opposite to that of the upper level, as confirmed by the movement of ordinary clouds in different vertical levels. At 12:40 pm (3:40 UTC), the mushroom head distribution of the ash plume expanded further in the north-south direction, reaching Tanegashima Island, and the tail of the ash plume was connected to the volcano. The lower part of the ash drifted further westward due to the strongly sheared air flows near the volcano. By 3 hours after the eruption, the front edge of the ash plume top drifted east-southeast over the North Pacific at 100 km from the volcano.

Ash plumes that flow and travel in the air, especially those of the Plinian type, are danger to aviation safety even for the aircraft that are far from an erupting volcano. The first well known report of a serious encounter with an airborne ash plume was that concerning the incident of a KLM jumbo jet approaching Anchorage International Airport from Europe in December 1989. At that time, the aircraft was flying over Mt. McKinley, and Redoubt Volcano was erupting and ejecting a large amount of ash into the upper troposphere and travelled 300 km from Redoubt Volcano. All four engines stopped due to the dense ash that melted and jammed the engines. The aircraft stalled lost power and dropped to 10,000 feet above the ground (Hobbs et al., 1991; Casadevall, 1994). Fortunately, one of the engines recovered due to the cooling and removal of the jammed ash from the engines. After this incident, the International Civil Aviation Organization (ICAO) established Volcanic Ash Advisory Centers (VAAC) at 9 sectors in the world, including the Tokyo VAAC established in 1997 (see Onodera 1997). However, similar incidents of commercial airliners encountering volcanic ash have occurred many times since then.

In order to avoid volcanic hazards, especially for aviation safety purposes, a number of ash plume dispersion models have been developed under the VAAC activities. For volcanic hazard and aviation safety, refer to the comprehensive review by Onodera (2013). Among those dispersion models, Tanaka (1994) developed a real-time volcanic ash plume tracking model, called the PUFF model, at the Geophysical Institute, University of Alaska Fairbanks. The PUFF model here is a Lagrangian model tracking ash particles, and is different from the conventional puff-plume model of air pollution study. The PUFF model was applied to volcanoes in the northeastern Pacific Rim by Searcy et al. (1998), and has been operational under Alaska Volcano Observatory since the eruption of Redoubt Volcano in 1990 (Tanaka, 1991; Kienle et al., 1991; Dean et al., 1993). The PUFF model was transplanted to the US Geological Survey, US National Weather Service, Japan Airlines, Japan Weather Association, and University of Tsukuba, Japan. The performance of the volcanic ash tracking PUFF model has been examined for Alaskan volcanoes (Tanaka et al., 1993; Akasofu and Tanaka, 1993), for Usu Volcano (Tanaka and Yamamoto, 2002), and for many actual eruptions occurring throughout the world, including Kelud Volcano in Indonesia (Tanaka et al. 2016).

By comparing the ash fallout using the PUFF model with the dense observation network around Sakurajima, the discharge rate of the ash mass from the crater was estimated by empirical formulae using seismic monitoring and ground deformation data (Iguchi, 2012; 2016). The combination of the real-time PUFF model simulation with the real-time seismicity, tilt and strain monitoring enables us to establish a quantitative evaluation of the airborne ash density as well as the distribution of ash fallout on the ground. The PUFF prediction system is now applicable to any volcano. According to the assessment of aviation safety by ICAO, an ash density of 4 mg/m³ and above is considered a the danger zone for commercial airliners (Kelleher 2010). Estimation of the airborne ash density by the PUFF model offers useful information for aviation safety.

The purpose of this study is to simulate the volcanic ash plume dispersal from Kuchinoerabujima Volcano, which erupted on 29 May 2015, using the PUFF model. In this study, the 3D distributions and time variations of airborne ashes are simulated quantitatively, based on the ground observation of ash fallout at Yakushima Island.

The PUFF model simulation is expected to identify the location and spread of the danger zone for aviation control in a major eruption of Kuchinoerabujima Volcano in Japan.

2. Description of the PUFF model

The PUFF model for a real-time volcanic plume prediction was constructed by Tanaka (1991; 1994) and

reported in detail by Searcy et al. (1998) and by Tanaka et al. (2016). The model is based on the three-dimensional (3D) Lagrangian form of the fluid mechanics. We assume a vertical column of initial ash particles that are transported and diffused by winds and turbulence in a 3D space. In the Lagrangian framework, material transport is conducted by the fluid motion, and diffusion is represented by a stochastic process of random walk (e.g., Chatfield, 1984). Here, the plume dispersion model is constructed by a sufficiently large number of random variables $r_i(t)$, $i = 1 \sim M$, representing the position vectors of M particles from the origin of the volcanic vent. The gravitational fallout is superimposed on the process of diffusion and transportation.

With a discrete time increment Δt , the Lagrangian form of the governing equation may be written as

$$\begin{cases} r_i(0) = S, & i = 1 \sim M, & \text{for } t = 0, \\ r_i(t + \Delta t) = r_i(t) + V\Delta t + Z\Delta t + G\Delta t, & i = 1 \sim M, & \text{for } t > 0, \end{cases} \quad (1)$$

where $r_i=(x, y, z)$ is a position vector of the i -th particle at time t , $V=(u, v, w)$ is the local wind velocity to transport the particle, $Z=(c_h, c_h, c_v)$ is a diffusion vector containing diffusion speeds generated by Gaussian random numbers, and $G=(0, 0, -wG)$ is the gravitational fallout speed approximated by Stokes Law. Note that diffusion Z depends on the direction, and gravity settling G depends on the particle size.

For computation of the transportation, wind velocity V is obtained from the real-time Grid Point Values (GPV) data provided by the Japan Meteorological Agency (JMA). The GPV data contain initial and predicted wind data up to 168 hours in the weather forecast by the global spectral model (GSM). The GPV data with 6-hour intervals are first interpolated to the model's time step of 5 minutes by a cubic spline method (see Burden et al., 1981). Then, the wind velocity at an arbitrary spatial point is evaluated using the 3D cubic-splines from the nearby gridded data of 1.25° longitude-latitude intervals and 16 vertical levels from the surface up to 10 hPa. For the real-time PUFF model prediction, the forecasted wind data are used. However, for the simulation in the past eruption event, the forecasted wind data have been replaced by a sequence of initial data provided by the analysis-forecast cycle. The diffusion speed and gravitational settling are described in detail by Tanaka et al. (2016). This paper can be referenced for details of the model description. In this study, the particle size is given by the mean of -3.5 and standard deviation of 1.0 in a log-normal distribution. The radius of enhanced diffusion is set at $r_0=70$ km. All remaining parameters are the same as those used in Tanaka et al. (2016).

As the source of ash plume S , the number of particles released at every time step may be adjusted in order to draw optimal statistical information from the model products. In this study we generate $M_0=5000$ particles uniformly in time by a uniform random number over time step Δt , which scales the emission rate. Particles are converted from the time coordinate to the vertical column from vent z_1 to plume top z_2 considering the buoyancy. In the present case, $z_1=657$ m for the vent, and plume height z_2 reached 9 km, and the discharge was assumed for 10 min from the initial explosion. Since there is no reliable information for the emission rate for this event, we must assume a uniform emission rate during the 10 min.

The governing model equation is integrated in time and the distribution of the particles in the atmosphere is presented in various mapping projections. The total number of plume particles M in the atmosphere increases by every time step. When the particles fall to the ground, the fallout locations are recorded. Likewise, when the particles have moved out from the prescribed computing domain, they are removed from the computation. The distribution of the ash fallout amount is computed by counting the total number and total mass of the ashes at a unit area on the ground. The emission rate is then scaled in reference to the ground observation at Yakushima Island (NIED 2015). Likewise, the distribution of the airborne ash density is computed by counting the total number and total mass of the ashes at a unit volume in the atmosphere. The output product of the map projections is drafted using Generic Mapping Tools (GMT) software (Wessel et al. 2013).

3. Results of the model simulation

The performance of the PUFF model simulation of the ash dispersal relies totally on the accuracy of the wind data provided by JMA/GSM. The output from GSM with 1.25° longitude-latitude grids is coarser than that of the meso-scale numerical weather prediction models. However, as it has the advantage of covering the entire world, the PUFF model is applicable to any erupting volcano on the planet.

Figure 3 shows the wind vectors at 1000 hPa and 400 hPa levels at the time of 9:00 am (0:00 UTC) on 29 May 2015. The real-time GPV data is provided by the Japan Meteorological Agency by way of the portal site at the Center for Computational Sciences, University of Tsukuba. The 400 hPa map shows that a strong west-northwesterly wind of 14 m/s blows over Kuchinoerabujima at an altitude of 7.5 km. The air moves 50 km/hour to the east-southeast, which is consistent with the satellite imagery in Fig. 2. The wind near the surface at the 1000 hPa level is in the opposite direction to the wind at the 400 hPa level.

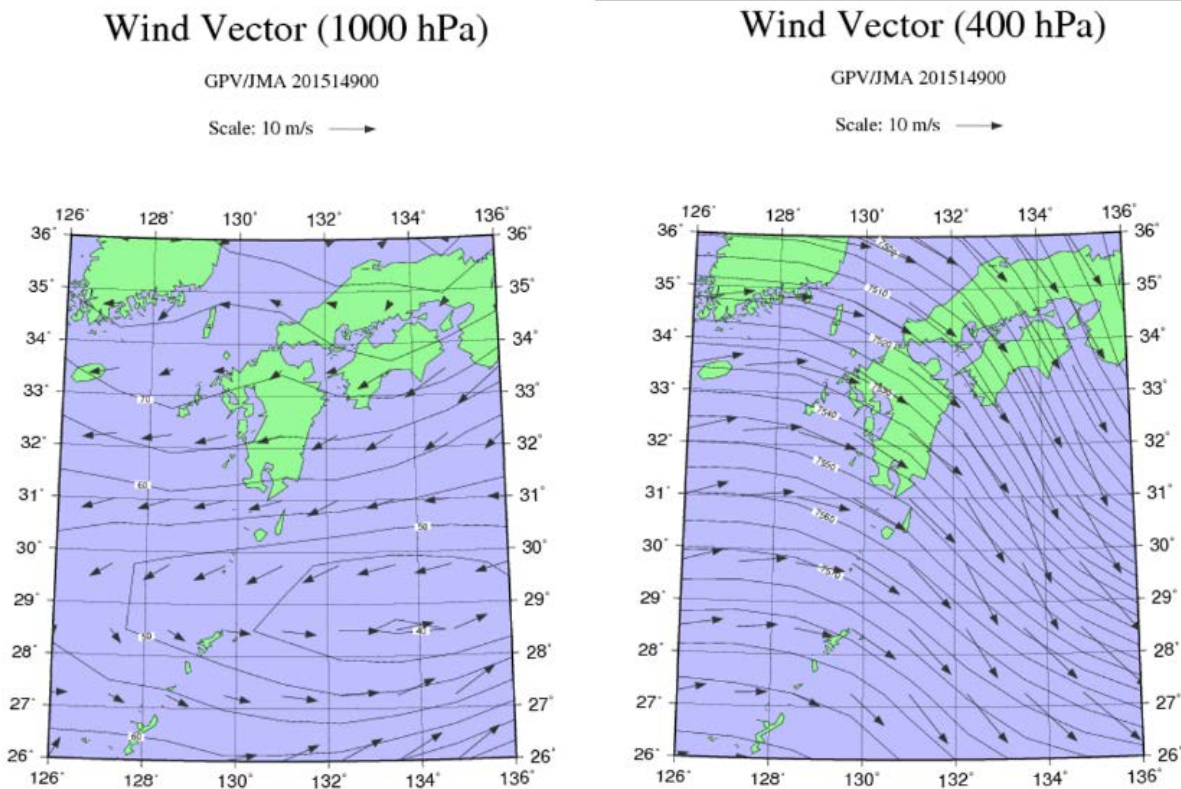


Fig. 3 Wind vectors at 1000 hPa (near surface) and 400 hPa levels (about 7.5 km) at 00:00 UTC on 29 May 2015. The real-time GPV data is provided by the Japan Meteorological Agency by way of the Center for Computational Science, University of Tsukuba.

Figure 4 illustrates the results of the PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 9:00 UTC on 29 May 2015. The figure is for 8 hours after the beginning of the eruption. The colors of particles indicate a different plume height, and the projection onto the ground is marked by black dots. Since the plume top reached 9 km, the strong west-northwest wind transports the ash plume in the east-southeast direction. The plume tilts eastward with respect to height. As shown by the 1000 hPa level winds in Fig. 3, the lowest level particles move in the opposite direction to the upper level particles.

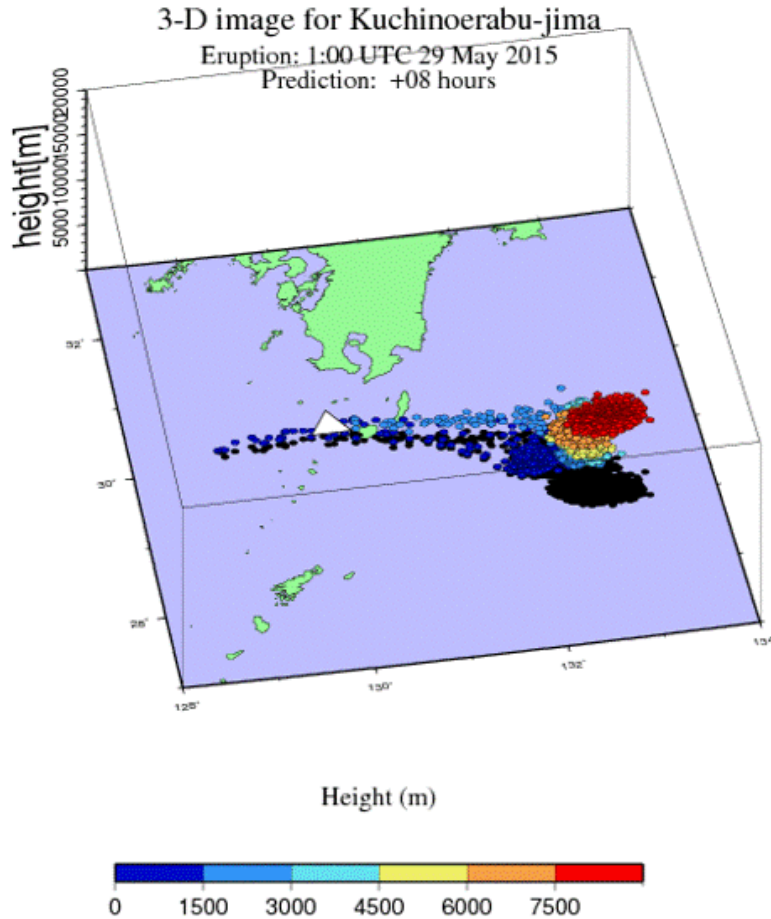


Fig. 4 The 3-D perspective image of the volcanic ash plume dispersal from Kuchinoerabujima Volcano at 8 hours after the eruption. The colors of particles indicate different plume height, and the projection onto the ground is marked by black dots.

Figure 5 illustrates the results of horizontal distributions of the ash plume dispersal for 2, 4, 6, and 8 hours after the eruption set at 1:00 UTC. The colors of particles indicate different plume heights in feet. At 2 hours after the eruption, there is a circular-shaped plume top (red) by the horizontal diffusion. The location of the ash plume agrees with the satellite imagery in Fig. 2. However, details of the ash distribution and plume shape are rather different. In Fig. 2, the ash over Yakushima indicates a hook shape, but the simulated ash indicates a circular shape. The wind data with 1.25° longitude-latitude grids is insufficient for simulating details of the plume structure. Yet, the location of the simulated ash clouds agrees well with the satellite observation.

As seen at 4 hours after the eruption, the ash plume has drifted in the east-southeast direction by the strong west-northwest wind at an altitude of 7.5 km. Note that the low-level ash drifts westward (blue). The result is consistent with the satellite observation in Fig. 2. At 6 hours, there is further drift of the plume top (red) to the southeast. The plume is the highest at the front edge of the movement, and the height decreases at the source region. Interestingly, the lower part of the plume (blue) continues moving westward. At 8 hours after the eruption, the plume top (red) is at 132.5° E, which is about 250 km from the volcano.

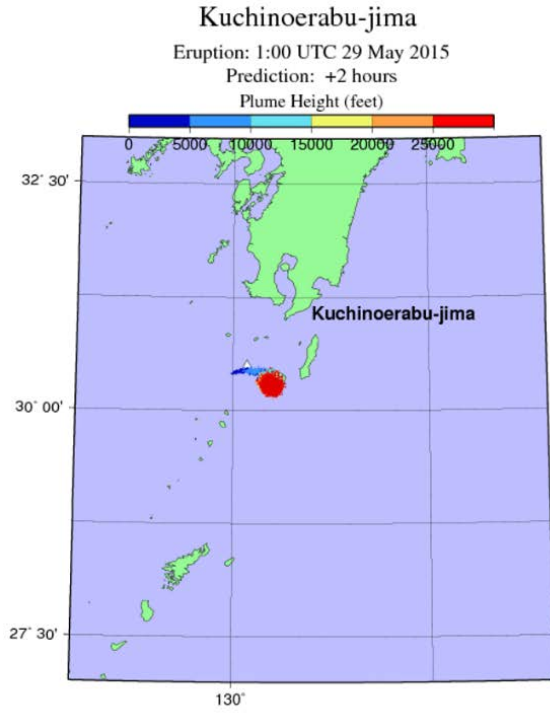


Figure 5(a)

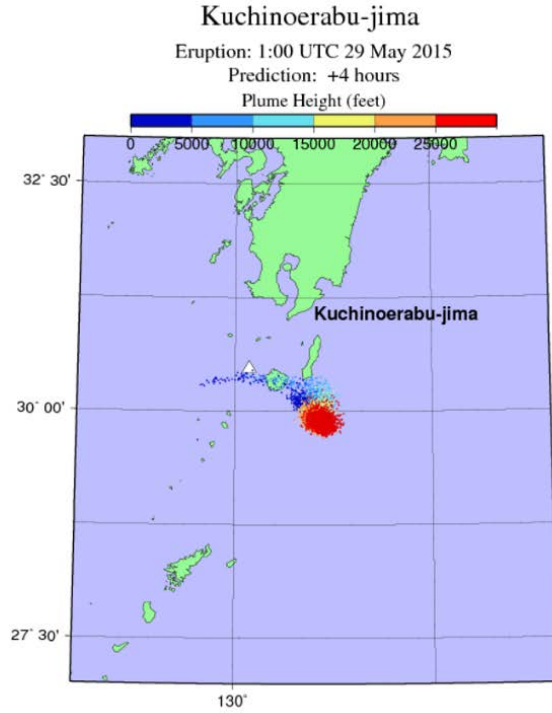


Figure 5(b)

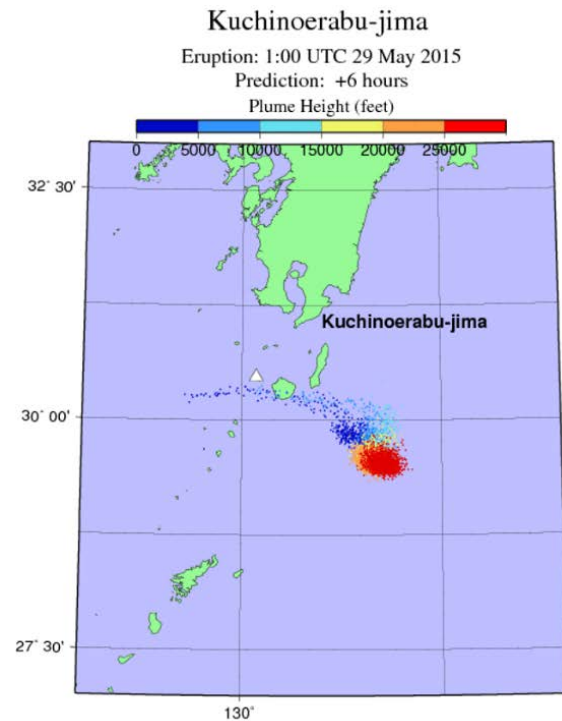


Figure 5(c)

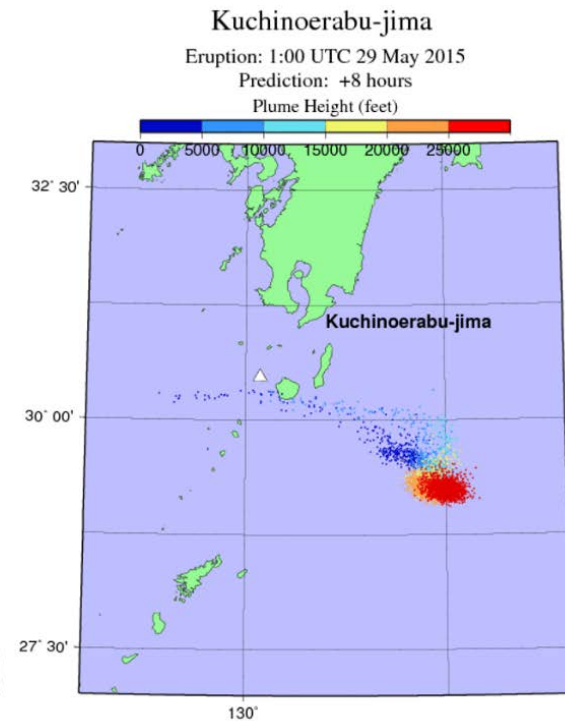


Figure 5(d)

Fig. 5 PUFF model simulation of the ash plume dispersal for (a) 2 hours, (b) 4 hours, (c) 6 hours, and (d) 8 hours after the eruption set at 1:00 UTC. The colors of particles indicate different plume heights.

Figure 6 depicts the vertical cross sections of ash plume dispersal for longitude-height and meridional-height sections for every 1 hour starting from the eruption. The plume shape for the first 1 hour shows a structure with minor spread at the plume top near 9 km both in the X-Z and Y-Z sections. The result of the X-Z section shows a flat plume top extending eastward by the upper air wind. A minor counter flow is seen at the lowest level by the counter flow in the boundary layer. Simulated animation shows there are many particles falling from the anvil clouds at the east side. The result of the Y-Z section shows anvil clouds extending south from the volcano forming a reverse triangle from the vent. The upper level plume extends southward indicating a wedge shape.

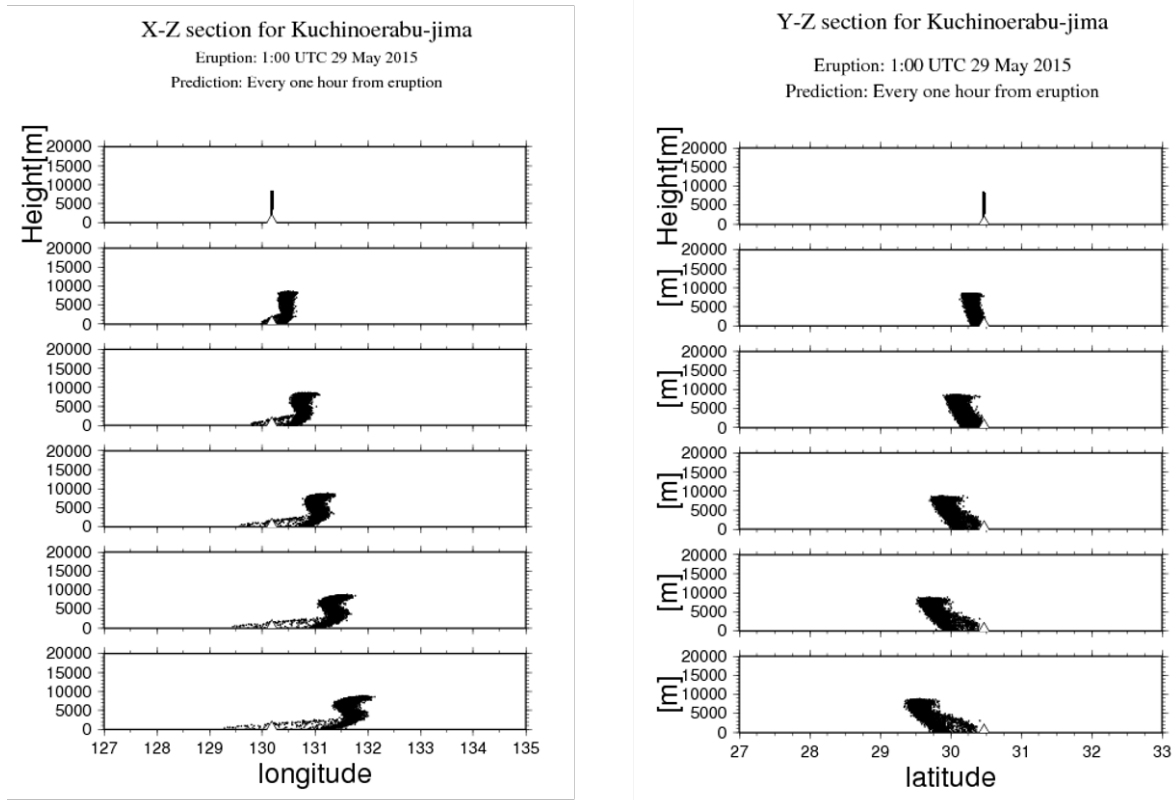


Fig. 6 Vertical cross sections of ash plume dispersal for longitude-height and meridional-height sections for every 1 hour starting from the eruption set at 1:00 UTC.

Figure 7(a) plots the particle distribution for ash fallout accumulated during the 9 hours following the eruption. The fallout covers almost the entire Yakushima Island extending in the southeast direction. According to the in-situ observations of ash fallout over Yakushima Island (NIED 2015), a maximum of 400 g/m² of ash was reported at the western end of Yakushima Island, and 100 g/m² of ash in the middle of the island.

Figure 7(b) plots the ash fallout distribution evaluated from Fig. 7(a) in the units of g/m² with a common log-scale, i.e., 2 denotes 100 g/m². The contours of the PUFF model simulation are roughly calibrated in reference to the in-situ observations to match each other. By this calibration, it is possible to assign a mass to the particle in the model. According to the result, we find that one particle in the model represents 60 tons of mass for the emission rate of 5000 particles in 5 minutes. Based on this number, the emission rate is estimated as 60,000 tons per minute, and total emissions are estimated as 600,000 tons for 10 minutes of eruption in this event. Once a mass estimation is given to the particle, it becomes possible to assess the ash concentration in the air.

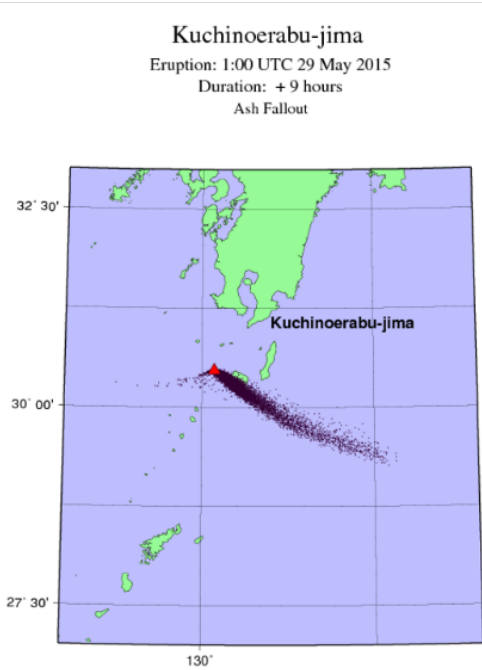


Figure 7(a)

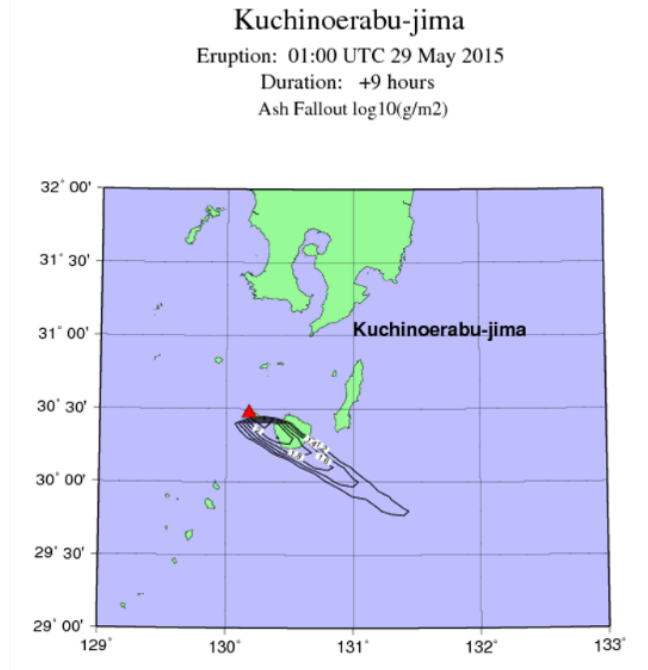


Figure 7(b)

Fig. 7 (a) Particle distribution of ash fallout during 9 hours after the eruption, and (b) the estimated concentration of ash fallout (g/m^2) in common log-scale, i.e., 2 denotes $100 \text{ g}/\text{m}^2$.

Finally, Fig. 8 plots the distributions of airborne ash density (mg/m^3) for 2, 4, 6, and 8 hours after the eruption. The values are in common log-scale, i.e., 2 denotes $100 \text{ mg}/\text{m}^3$. As a result, the values of the highest density in the vertical column are projected onto the ground.

At 2 hours after the eruption, a circular-shaped ash plume is clearly identified. In the core region, there is a contour of $100 \text{ mg}/\text{m}^3$ over Yakushima Island. The contour of 0.6 represents the ash density of $4 \text{ mg}/\text{m}^3$. This area is recognized as a danger zone for commercial airliners. It seems that the diffusion is in good agreement in the present simulation compared with the satellite imagery in Fig. 2. At 4 hours after the eruption, the core area with $100 \text{ mg}/\text{m}^3$ is maintained. The area with $4 \text{ mg}/\text{m}^3$ extends 150 km east from the volcano. The area of ash density with $4 \text{ mg}/\text{m}^3$ covers most regions of Yakushima Island and the southern edge of Tanegashima Island. At 6 hours after the eruption, the contour $100 \text{ mg}/\text{m}^3$ has moved in the southeast direction around 132.0° E and 29.5° N . The area with $4 \text{ mg}/\text{m}^3$ appears widely around 131.5° E and 29.5° N , but Yakushima Island and Tanegashima Island are now out of the danger zone. Finally, at 8 hours after the eruption, the area with $4 \text{ mg}/\text{m}^3$ has moved further to the southeast around 132.5° E and 29.3° N .

Although the satellite image in Fig. 2 shows the exact location of ash plume detectable by the satellite, there is the possibility of a wider spread of thinner ashes as simulated by the present model. The airborne ash density simulated by the PUFF model provides useful and quantitative information about the possible danger zone for the eruption event of Kuchinoerabujima Volcano in May 2015.

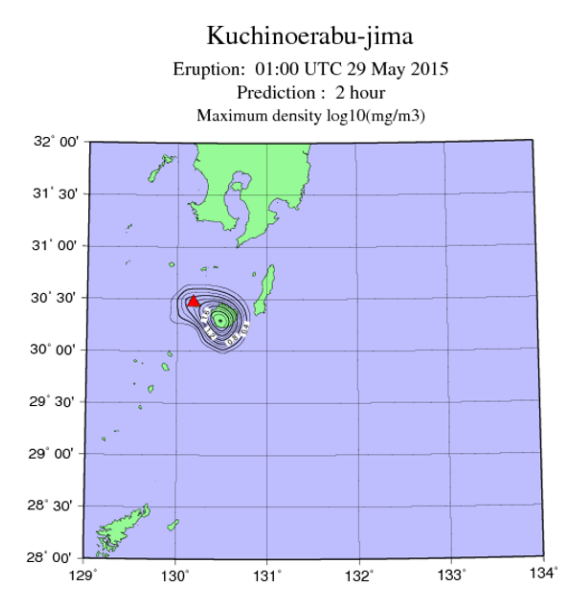


Figure 8(a)

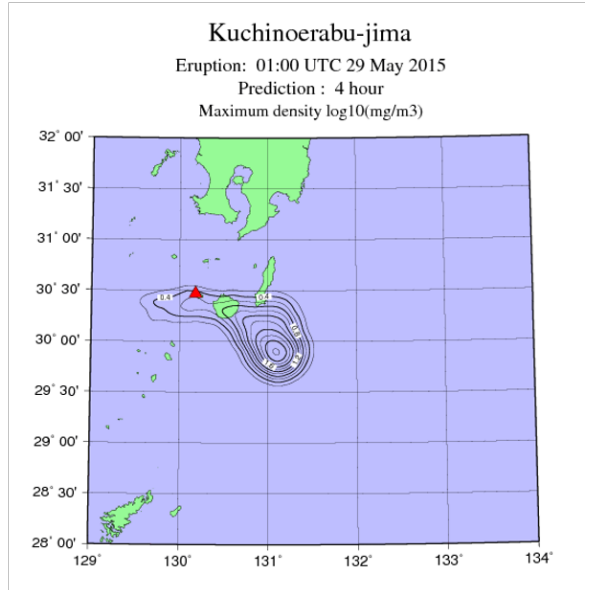


Figure 8(b)

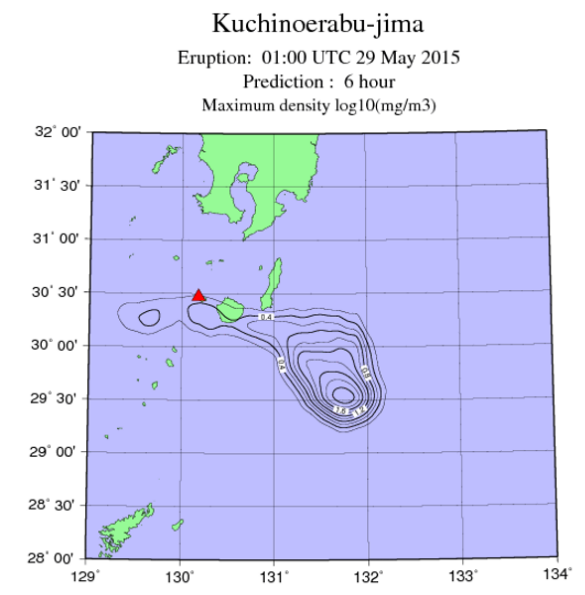


Figure 8(c)

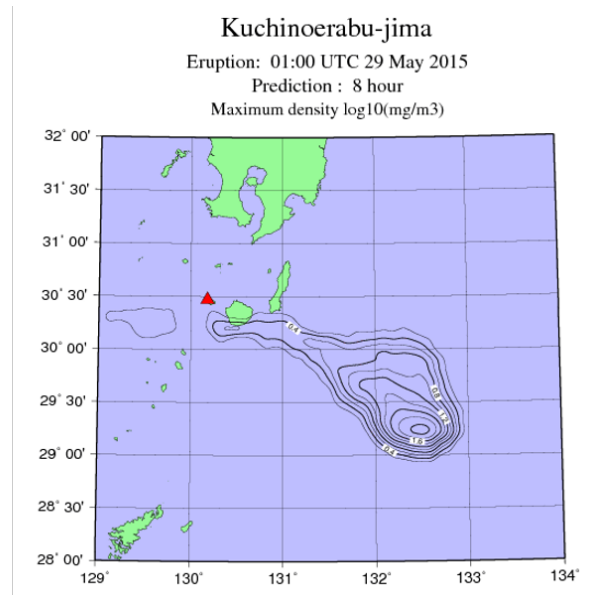


Figure 8(d)

Fig. 8 Distribution of airborne ash density (mg/m^3) for (a) 2 hours, (b) 4 hours, (c) 6 hours, and (d) 8 hours after the eruption. The values are in common log-scale, i.e., 2 denotes $100 \text{ mg}/\text{m}^3$.

4. Conclusion

A major eruption occurred at Kuchinoerabujima Volcano at 9:59 am local time (0:59 UTC) on 29 May 2015. The ash plume reached 9 km above the ground. According to the MTSAT-2 satellite monitoring, the plume top approximately 9 km in height drifted in the east-southeast direction. The ash plume showed a mushroom-shaped distribution heading in the east-southeast direction according to the satellite image. The plume top drifted with a gradual spread by diffusive mixing. By 8 hours after the eruption, the center of the

plume top had drifted in the east-southeast direction by 250 km. In this study, the sequence of airborne ash dispersal from Kuchinoerabujima Volcano was simulated using the PUFF model. A steady emission rate from the vent was assumed for 10 min.

The horizontal distribution of ash fallout was estimated by the model simulation and compared with the ground truth observation in Yakushima Island. The ash fallout over Yakushima Island was in the order of 100 g/m². After some calibrations with this number, the mass of an ash particle in the model was quantified to have 60 tons of ash mass. The result suggests that the ash concentration in the air can be estimated by this method.

According to ICAO, ash density of 4 mg/m³ and above is considered a danger zone for commercial airliners. The result of the PUFF model simulation suggests that the anvil cloud of ash top at 9 km maintains sufficiently high ash density for 8 hours after the eruption. According to the result of the PUFF model simulation, the core region of the plume front shows the airborne ash density of 100 mg/m³ even at 250 km from the volcano.

Although the satellite images show the exact location of the ash plume, the simulation result indicates a large diffused area of the danger zone for aircraft. The model prediction can provide information for thin ash dispersal at a long distance, which the satellite data cannot detect. However, the accuracy of the model prediction relies totally on the wind data by the numerical weather prediction models. The accurate wind data and emission rate are the most important items for the improvement of the ash dispersal model. In this study, the emission rate was scaled in reference to the ground observation at Yakushima Island. The particle size and fallout speed are important to calibrate the emission rate with a few ground observations. Further improvement is required for the PUFF model simulation by accumulating comparisons for the observations and simulation outputs.

Acknowledgments

We are grateful for the support of Dr. H. Nakamichi of DPRI, Kyoto University and Mr. Mamoru Izumi of SATREPS for their technical assistance. The MTSAT-2 satellite imagery was provided by the Japan Meteorological Agency. This research was supported by the SATREPS research project and by Grant-in-Aids (15H05794) of the Japan Society for the Promotion of Science (JSPS).

References

- [1] Akasofu, S.-I., and H. L. Tanaka, 1993. Urgent issue of developing volcanic ash tracking model, *Kagaku Asahi*, No.5, 121-124 (in Japanese).
- [2] Casadevall, T. L., 1994. The 1989-1990 eruption of Redoubt volcano, Alaska: Impacts on aircraft operations, *J. Volcanol. Geotherm. Res.*, 62, 301-316.
- [3] Chatfield, C., 1975. *The analysis of time series: An introduction*, Chapman and Hall, 286 pp.
- [4] Dean, K. G., S. I. Akasofu, and H. L. Tanaka, 1993. Volcanic hazards and aviation safety: Developing techniques in Alaska, *FAA Aviation Safety Journal*, Vol. 3, No. 1, 11-15.
- [5] Hobbs, P. V., L. F. Radke, J. H. Lyons, R. J. Ferek, D. J. Coffman, and T. J. Casadevall, 1991. Airborne measurements of particle and gas emissions from the 1990 volcanic eruption of Mount Redoubt, *J. Geophys. Res.*, 96, 18735-18752.
- [6] Iguchi, M., 2012. Prediction of volume of volcanic ash ejected from Showa crater of Sakurajima Volcano, Japan, *Disaster Prevention Research Institute, Annual Report B, University of Kyoto*, 55, 169-175.
- [7] Iguchi, M., 2016. Method for real-time evaluation of the discharge rate of volcanic ash: Case study on intermittent eruptions at Sakurajima Volcano, Japan, *J. Disaster Res.* 11, 1, 4-14.
- [8] Kelleher, R., 2010. Atlantic conference on Eyjafjatljokutl and aviation, UK volcanic ash safety regulation, Keflavik Airport, Iceland.
- [9] Kienle, J., A. W. Woods, S. A. Estes, K. Ahlnaes, K. G. Dean, and H. L. Tanaka, 1991. Satellite and

- slow-scan television observations of the rise and dispersion of ash-rich eruption clouds from Redoubt volcano, Alaska, *EOS*, Vol. 72, 2, 748-750.
- [10]NIED Report, 2015. Report on ash fallout at Yakushima Island for volcanic eruption of Kuchinoerabujima on 29 May 2015, National Research Institute for Earth Science and Disaster Resilience (NIED) on 5 June 2015, <http://www.bosai.go.jp/saigai/2015/pdf/20150605-01.pdf> (in Japanese).
- [11]Onodera, S., 1997. Volcanic activity and flight operations, *Aviation Meteorological Notes*, 45, 13-30.
- [12]Onodera, S., 2013. A study on the prevention of aircraft encounter with volcanic ash in the proximity area between airways and active volcanoes, Dissertation for Ph. D., Life and Environmental Sciences, University of Tsukuba, 272 pp.
- [13]Searcy, C., K. Dean, and B. Stringer, 1998. PUFF: A volcanic ash tracking and prediction model, *J. Volc. and Geotherm. Res.*, 80(1-2), 1-16.
- [14]Tanaka, H. L., 1991. Development of a prediction scheme for the volcanic ash fall from Redoubt volcano, First Int'l. Symp. on Volcanic Ash and Aviation Safety, Seattle, Washington. U.S. Geological Survey, Circular 1065, 58.
- [15]Tanaka, H. L., K. G. Dean, and S. I. Akasofu, 1993. Predicting the movement of volcanic ash clouds, *EOS*, Vol. 74, No. 20, 231-231.
- [16]Tanaka, H. L., 1994. Development of a prediction scheme for volcanic ash fall from Redoubt volcano, Alaska, Proc. First International Symposium on Volcanic Ash and Aviation Safety, U.S. Geological Survey, Bulletin 2047, 283-291.
- [17]Tanaka, H.L., and K. Yamamoto, 2002. Numerical simulations of volcanic plume dispersal from Usu Volcano in Japan on 31 March 2000, *Earth, Planets and Space*, 54, 743-752.
- [18]Tanaka, H.L., M. Iguchi, and S. Nakata, 2016. Numerical simulations of volcanic ash plume dispersal from Kelud Volcano in Indonesia on February 13, 2014, *J. Disaster Res.* 11, 1, 31-42.
- [19]Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe, 2013. Generic Mapping Tools: Improved version released, *EOS Trans, AGU*, 94, 409-410.