Developing an airport-wise volcanic early warning system for aviation preparedness

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A VEI 4 eruption of Eyjafjallajökull in 2010 April paralyzed European airspace for almost a week, making it the costliest disruption to aviation in history. Until now, Japan has never experienced a severe aviation disruption from volcanic ash, but Japan can never take it lightly. It is only a matter of time before the Sakurajima volcano on Kyushu island erupts massively. However, Japan does not have a volcano alert level system for aviation nor a detailed volcanic hazards mitigation plan. In acknowledgement of weaknesses of current aviation volcanic hazard management, we teamed up with stakeholders from airlines, Civil Aviation Bureau, volcano observatories and university researchers from multiple disciplines to explore new strategies to enhance the aviation section's level of preparedness. In this joint early warning research, we innovatively developed an airport-wise volcanic alert level system for aviation preparedness. Unlike traditional volcanic alert level systems, our system issues alert levels to each airport, not the volcano itself. To make the airport-specific system practical, we incorporated the alert level system into deliberately divided airport groups so that phased responses become achievable. We supposed that phased responses are critical to the success of our aviation volcanic early warning system, which could utilize the ash travel time to mitigate the uncertainty. We hope our work can assist airliners to mitigate volcanic hazards risks timely, proactively, effectively and can be extended to other stakeholders in the future.

Key words: *Risk governance, crisis management, aviation, volcanic hazards, early warning*

1. Introduction

Volcanic hazard can lead to significant disruptions to aviation business, even life-threatening crises in extreme cases. In April 2010, the explosive eruption of the Eyjafjallajökull volcano in Iceland (called E2010 thereafter) paralyzed European airspace for one week, around 10 million passengers were affected, and cost airlines $ 1.7 billion in revenue [1),2)]. Even though the impact could have been predicted, the response were entirely reactive and therefore less effective than it could have been [3)]. Dating back further, overwhelmed air-ground communication almost resulted in casualties: a Boeing 747 experienced engine failure in Indonesia due to volcanic ash encounter in 1982; in 1989, a Boeing-747 nearly crashed after encountering volcanic ash from the Redoubt volcano eruption, and a total of 129 encounters of aircraft with volcanic ash were reported from 1953 through 2009 [4),5)]. Following these haphazard responses to volcanic risks, several instrumental patches have been introduced. The International Civil Aviation Organization (hereafter called ICAO) established International Airways Volcano Watch (hereafter called IAVW) in 1987 [6)]. Likewise, the European Aviation Crisis Coordination Cell (EACCC) was established in May 2010, which is co-chaired by the European Commission (EC) and Eurocontrol [7)]. Both institutions were established in a bid to smooth communication and cooperation between stakeholders from member states when circumstances beyond the normal environment of operation manifest themselves.

As an applied science, disaster management learns from the past. Atypical wind, extraordinarily fine ash particles, imprecise modeling, and ill-prepared response were all blamed for the costly E2010 [3]. Unsurprisingly, to prevent the E2010-like nightmare from happening again, aviation communities are actively developing solutions to mitigate these exposed weaknesses. Besides the aforementioned institutional changes, researchers have also called for changes in practice. The large-scale volcanic eruption has a low recurrence rate, which indicates that employee turnover can easily lead to loss of gained knowledge. As a result, a volcanic ash exercise (VOLCEX) is conducted roughly once a year in Europe, focusing on the air traffic response at the onset of a volcanic eruption [8]. As a matter of fact, the onset of eruption is widely recognized as the most dangerous stage. In the United States, the US Geological Survey developed a color-coded multi-level level system as part of their solution to volcanic risk in the aftermath of the 1989-1990 Redoubt volcano eruption, a revised version of which was later endorsed by ICAO, to enhance communication of volcanic risk to pilots-in-command especially at the onset and during eruption stages [9,10]. This color-code system indicates volcanic activity but not risk, nor distal ash status [9]. By far, both long-term (like institutional reform) and imminent (communication at the very onset) issues have been extensively studied, however, we noticed a missing piece: short-term aviation volcanic risk management. We may already have a tested and trained-upon communication plan, but the response plan remains reactive and ad hoc. Through dedicated design and management, we could defy uncertainty and act earlier, in a proactive manner.

Worryingly, Japan has not taken serious steps towards volcanic hazards in aviation, probably due to a “normalcy bias” [11,12]. The last time the Sakurajima volcano, the most active volcano in Japan, erupted massively was in 1914, many years before the jet era. However, Japan is home to 110 active volcanoes, many of which are showing worrying signs and thus being closely monitored [13]. For example, scientists predicted that Sakurajima volcano is on course to produce another Taisho-like large-scale eruption, probably within 30 years [14]. Japan is home to three of the ten most populous volcanoes in the world. Volcanic hazards for local populations have been regarded as a serious issue by both Japanese government and the public, we just need to expand that effort to include aviation [15].

This paper addresses the early warning of ashfall hazards for aviation communities, including risk knowledge, communication and dissemination, and response ability [16]. As we have mentioned before, most previous research focuses on more dangerous phases: at the very onset and after initiation of an eruption, and we argue here that it is equally worthwhile to reshape the current ad hoc approach of response planning into a well-planned one. To fill in the gap, that is, short-term contingency planning, we present our work in the fashion of an early warning system for aviation preparedness: a decision-making support tool from early precursory signs to response actions. We begin our research with a focus on Sakurajima. Firstly, Sakurajima is the most active volcano in Japan. Secondly, Sakurajima is widely acknowledged as one of the most monitored volcanoes in the world [17]. We believe such an established monitoring network is a good starting point for us.

The following section briefly introduces the plan of this study. Then, obstacles towards a prepared response and highlights of our early warning system are introduced. Next, we present the design of the system and how the system enables phased responses, including airport groupings, trigger events and recommend actions. We also discuss which institution is best positioned to manage the system. Finally, we conclude our study and discuss implications for both system development and practice.

2. Objectives

We initiated this project to facilitate a well-prepared volcanic hazard response among the aviation community. However, as we will see in this paragraph, a traditional design will certainly fall short of our expectation, we need innovative mitigation strategies and conceptual design to fulfill the leap from ad hoc response to well-planned.

(1) Evacuation

Aircraft is vulnerable to volcanic ash, even only traceable amount of ash could severely damage the aircraft. Thus, our policy on volcanic ash hazard management is avoid when possible. Of course, disaster managers can seal the aircraft when ashfall is predicted to onset, and honestly speaking we advise airlines mandate sealing materials on their inventory lists. However, firstly, sealing critical parts of the aircraft such as jet engines is not enough, abrasive ash particles can also damage the fuselage skin. Secondly, airports with ashfall presence will be paralyzed for a prolonged period of time, costing airlines time and money. Thirdly, even if appropriately sealed, the aircraft still have to go through an extensive safety check procedure if ashfall at the stationing airport is confirmed. Fourthly, aircraft checkup and maintenance center is located at Tokyo airport, since this is the only maintenance center in Japan, many aircraft may have to wait for a prolonged length of time to be checked. Thus, sealing should be a plan B when evacuation is impossible. Evacuation is always the recommended response in the heat of crisis and our early warning system should be designed to navigate the whole process from situation awareness through evacuation.

(2) Nighttime standby

Most airports in Japan does not operate in the night while the volcano is no less likely to erupt. As a result, we need to include a trigger for nighttime standby. You might ask why airlines do not evacuate their aircraft before the airport closure when above-normal volcanic unrests manifest. However, situations are not that simple. Because of inherent uncertainty, there exists a 'dilemma zone' where chances of ashfall impact is heightened but not significant enough. If aircraft are evacuated and nothing happens, then flights in the following morning will be avoidably disrupted; if aircraft are not evacuated and the airport is covered by ash, then ashfall will inflict severe damage on aircraft. So, if this dilemma zone stretches into after-hours, stakeholders should standby for emergent evacuation.

(3) Airport-wise

Because not all airports in Japan are threatened by volcanic ashfall hazards, nor will they be affected at the same time, the new volcanic alert level system should be able to reflect the heterogenous nature of ashfall hazards. The traditional event-specific volcanic alert system is not applicable to this project because an alert level system assigned to the volcano can by no means indicate the risk of a distant airport. As a result, our system should make a great stride from the tradition, from event-specific to location-wise, in this study, airport-wise to be specific.

(4) Phased response

Another benefit derived from airport-wise early warning system is phased response. As we have mentioned before, the airports are not affected at the same time in the heat of crisis. For distant airports, it would take the wind field several hours to disperse volcanic ash over hundreds of kilometers to affect their operation. And an evident fact is that uncertainty decreases with time especially after the onset of the eruption. In other words, for airports proximal to the volcano, we are forced to make uneasy decisions while the level of uncertainty remains high; for distant airports, we are much relieved from dilemmas. As such, it is desirable to impose restrictions on airports phase by phase, based on the projected length of lead time.

For a given airport, we should also impose restrictions phase by phase, for example, airlines can impose restrictions on riskier arrival flights first, then with the elevating volcanic unrest, the restrictions can later be expanded to all flights. Phased response is a necessary step towards a balance between the safety of aircraft and the level of uncertainty.

(5) VALS parallel

Many countries refrain from implementing a VALS for aviation for fear of interference with ground hazard-targeted VALS. We admit that the hazards on residential area should be of primary concern to scientists and disaster managers because a large-scale explosive eruption could instantaneously put thousands of lives under dire situation. Many lives on ground have been lost to volcanic hazards while no deadly ash encounter in air has happened.

In this study, we will deal with this problem, the incompatibility of ground hazards and aviation hazards is by no means insurmountable. One possible solution is to pool trigger events for airport-targeted VALS from alert levels in ground hazard-targeted VALS.

See Fig. 1 for illustration of conceptual prototype which incorporates aforementioned highlights of airport-wise, phased response and VALS parallel.

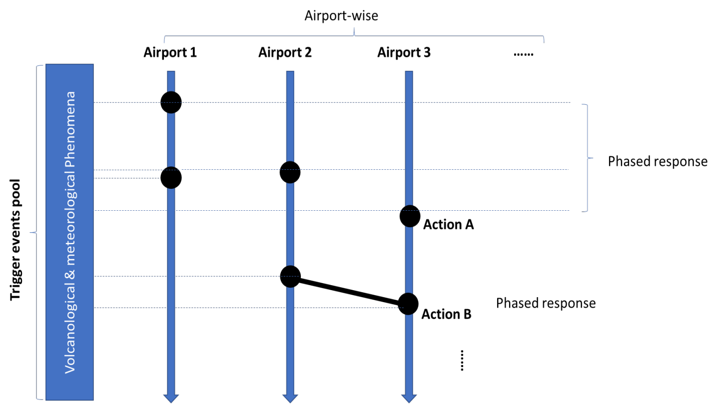

Fig.1 *Illustration of conceptual which incorporates aforementioned highlights of airport-wise, phased response and VALS parallel.*

3. Methods

Early warning system spans risk knowledge, monitoring, communication and response capability, and in this study, we are especially interested in the interlinkages between disaster information and end-

user's perception and behavior. As a result, we launched our program as an interdisciplinary research bridging the gap between science and practice. The host of this research project first reached out to representatives of All Nippon Airways, the largest airline in Japan by revenue and passenger numbers, to have a general understanding of airline's interest. We believe the airline's insight is a good starting point for our early warning system project. Through multiple rounds of face-to-face open and in-depth discussions, we learned that apart from the safety of en-route aircraft, airlines are also concerned with the safety of on-ground aircraft, given the fact that most airports in Japan do not operate 24 hours. In other words, early warning is all but necessary.
Then, we initiated a joint working group of disaster managers, volcanologists, ash dispersal modelers, and aviation operation researchers to design an early warning system. From the beginning, we decided to create an alert level system based on response action. After rounds of open, inclusive, and fruitful discussion, participants reached a consensus that phased response can utilize relative ashfall commencement time between airports and meanwhile mitigate the uncertainty of volcanic hazards. To realize phased responses, we broadly reviewed papers on early warning systems for other kinds of natural hazards like flood and landslide, then we innovatively came up with an idea of building an airport-wise volcanic alert level system as the core component of our volcanic early warning system. In other words, each airport has its own level of alert during a crisis. To link a trigger event to a level of alert, we first categorized all airports in Japan into four groups both by likelihood of ashfall impact based on "scenario bank" by (Rahadianto et al 2020) and estimated relative ash arrival time based on historical eruptions. Then, trigger events were pooled from JMA's Volcanic Alert Level System (called VALS Ground Hazard thereafter) and Volcanic Ashfall Forecast (called VAFF thereafter). For each airport group, we deliberatively assigned a trigger event to each level of alert. In this study, airports in the same group will flag the same alert level upon a certain trigger event, thus indicating the same response strategy, but we do allow improvised adjustment in the heat of the crisis. The grouping of airports is a concession between the phased response requirement and system simplicity.

Finally, the joint working group reach out to the airline again and bring the newly created early warning system prototype to an open discussion. We comprehensively presented our prototype, including every detail, to the airline in a coherent and logical manner. The airline was satisfied with our system design. With feedback from the airline, we made further updates and the system is agreed by all participants ready to be implemented by the aviation community.

4. Results as of now

As of this writing, we have finished airport grouping, alert level design and assignment of trigger events and indicated actions.

(1) Four airport groups

All airports in Japan are categorized into four different groups by urgency of evacuation. To begin with, let us explain the threshold of nighttime standby: for a given airport i, if the duration of ash transportation is shorter than the duration of airport downtime in the night in combination with necessary time to evacuate from airport i, then we can assume that the airport i requires standby in the night when extraordinary volcanic unrests manifest. In other words, if the eruption started right at the time when the airport is closed, the worst timing for a volcano eruption, and consequently the airline operators do not have enough time to evacuate aircraft safely from the airport in the following morning, then we assume the airport should incorporate a nighttime standby option into the contingency plan.

Airport grouping is conducted by the following rules. The first group, Group A, consists of airports that are located so close to the Sakurajima that airlines are not allowed enough time to evacuate after the onset of the eruption, even if without delay. In other words, for aircraft stationing at Group A airports, a decision to evacuate must be made before the onset of eruption. Needless to say, these airports require nighttime standby if elevated volcanic unrests beyond normal manifest. Group B contains airports which are allowed enough time to initiate evacuation after the onset of the eruption but still require nighttime standby (in following section, we finetune trigger events to further divide Group B into three sub-groups.). Group C includes airports that are located far enough from the volcano that nighttime standby turns unnecessary. It is noteworthy that some airports operate 24 hours, we will discuss the classification of those 24-hour airports in section 4.3.2. Lastly, Group D comprises airports that are "safe": less than 3% likely to suffer an ashfall of 0.2mm and above, according to (Rahadianto et al. 2020)'s scenario bank. We suppose airports belonging to Group D are well positioned to shelter evacuated aircraft during a Taisho-like crisis. Please also refer to Table 2 for description of Group A, B, C and Table 1 for variables used therein.

Table 1. Glossary of variables used to define airports groupings

Definition of variable	Symbol (hr)
Necessary time to evacuate from airport $\boldsymbol{i}$	y_i
Ash travel time from volcano to airport $\boldsymbol{i}$	a_i
Duration of downtime in the night at airport $\boldsymbol{i}$	dt_i
Desired buffer time for flight cancellation	x

The ash travel time is governed by wind field and distance. Because of the linear wind speed gradient in the troposphere, ashfall onset consumes about twice as much time as ash dispersal in the stratosphere [18]. Put it simply, if ash arrives at airspace over the airport in the stratosphere in 4 hours, then ashfall at this airport should commence roughly another 4 hours later. To ensure the evacuation is not affected, ash travel time in this study refers to the length of time from the onset of the eruption to the time when airspace over the airport is contaminated, not the ashfall commencement. Recaps on historical eruptions of Sakurajima revealed that volcanic ash was dispersed in the stratosphere at a speed ranging from 20 m/s to 40 m/s, fastest along the axis. In this study, we tentatively set the ash travel speed at 100 km/h, which means the ash travel time is calculated by dividing the distance by speed of 100 km/h.

Table 2. Thresholds to define Group A, B, C

Group	Thresholds	Brief Explanation
A	$a_i < y_i$	The necessary time to evacuate from **airport** $\boldsymbol{i}$ is longer than ash travel time
B	$a_i < dt_i + y_i$ and $a_i > y_i$	Ash travel time is shorter than downtime + necessary time to evacuate from **airport** $\boldsymbol{i}$ The necessary time to evacuate from **airport** $\boldsymbol{i}$ is longer than ash travel time
C	$a_i > dt_i + y_i$	Ash travel time is longer than downtime + necessary time to evacuate from **airport** $\boldsymbol{i}$

Airports business hours are retrieved from the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT). In this step, we tentatively set the necessary time to evacuate from each airport, which is subject to updates during the final validation process. Normally, pilots arrive at the airport 1h~2h before the take off. In this study, we suppose pilots will be able to arrive at the airport 1h after receiving the call in emergency situations. The traffic volume of the airport also affects the required length of time. Kagoshima airport has around 15 aircraft on ground concurrently at its peak: nighttime. We assume Kagoshima airport need half an hour to evacuate these 15 aircraft. As for other airports, currently we do not have precise data on number of overnight staying aircraft at each airport, so we can roughly estimate the necessary evacuation time based on annual aircraft movements as reference to Kagoshima airport. We assume Haneda airport will need 2 hours, airports that approximate Kansai, Fukuoka and Narita airport in size will require 1.5 hours, Chubu and Itami 1 hour, Kagoshima-sized airports 30 minutes, and all other small airports are assigned 12 minutes.

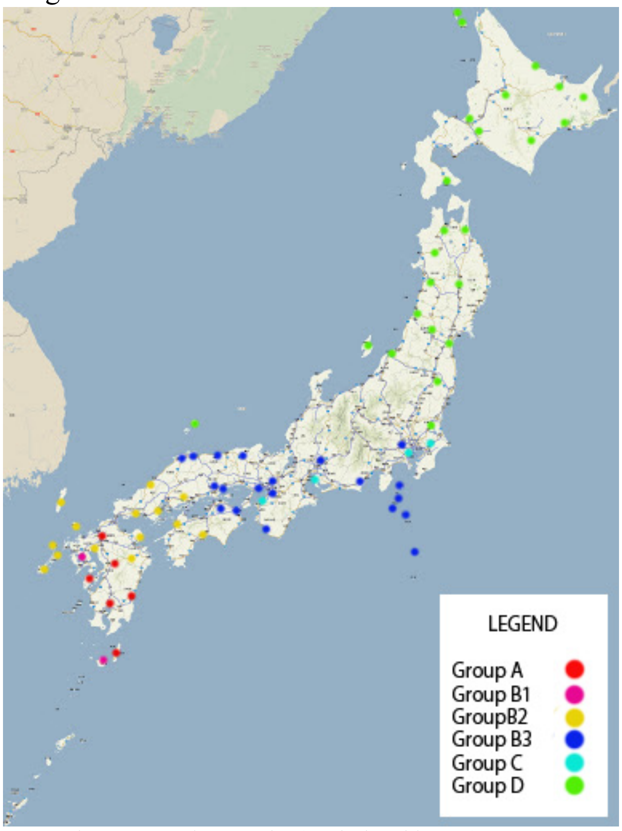

Fig.2 Airport grouping results (exclude Okinawa).

Finally, with assumed values and defined thresholds, we group Kyushu airports mainly in Group A, west Honshu airports mainly in Group B and airports in east Honshu, Okinawa and Hokkaido in Group C and D. Fig. 2 illustrates the airport grouping results with subgroups in Group B. Also see Appendix A for details on time variables and airport grouping results.

(2) Levels and indicated actions

We divided our alert level system into four levels, increasing from green to yellow, then orange, finally red, by urgency of the situation. We purposefully selected colors instead of numbers to prevent confusion with VALS Ground Hazard. Also, we decided to name our alert level system VALS Airport to highlight the linkage to, as well as differences with, the existing VALS Ground Hazard. The visual presentation of the alert level system can be found in Fig. 3.

Volcanic Alert Level System for Airport

Alert Level	Expected Response Action
RED	Restriction advices on DEPARTURES and ARRIVALS in effect; evacuation advised
ORANGE	Restriction advices on ARRIVALS in effect
YELLOW	Attention required; After-hours standby on offer
GREEN	No attention required

Levels may **NOT** move in sequence as volcanic unrest and meteorological conditions can change rapidly

Refer to airport announcement for detailed information on response actions, especially effective time of restrictions.
When destination is on YELLOW, although no restrictions in effect, we advise airlines make plan for disruptions.
Air traffic controllers may also initiate restrictions on airspace in response to volcanic hazards, see NOTAM for further information.

Fig. 3 Volcanic Alert Level System for Airport

Level Green indicates that the airport is not under potential threat of being covered by ash and there is no need for airport operators, airline schedulers, or pilots-in-command to pay special attention to the volcanic activities. If the airport moves up to Level Yellow, it indicates that the airport may face a potential threat from ashfall in the near future, stakeholders should exercise additional attention to the volcano activities, make contingency plans for possible widespread disruptions, and regularly check announcements from the volcano observatory (VONA). For airports in Group A and B, nighttime standby should also be considered on Level Yellow.

When Level Orange prevails, we advise airports to announce warnings to arriving flights; detailed warning information varies by groups and also within the group. When at Level Orange, no warning information to departure flights is yet in effect. If, unfortunately, the level of alert moves to the top level: Level Red indicating that airports are now under imminent ashfall threat, warning information to both departures and arrivals is advised. At Level Red, the airport enters evacuation mode, aircraft still on the ground should consider evacuation in this situation. Again, detailed information varies by airport groups and within the group. We purposefully separate arrival flights from departure flights in recognition of the effect of flight duration. For a given airport at a given time, en route arrival flights are more vulnerable than on-ground departure flights because an in-air ash encounter could cost lives, and evacuation can only be carried out after the aircraft arrives, meaning extra time. As a result, we proposed that airlines should restrict inbound flights prior to outbound flights. However, the earlier airlines act, the higher level of uncertainty they must tolerate.

(3) Trigger events and recommended response actions

In this research, we proposed phased responses through our deliberate designation of trigger events. We pegged trigger events in our system to alert levels of VALS Ground Hazard, in other words, alert levels of VALS Ground Hazard are trigger events in VALS Airport, and reasons are summed up as follows: firstly, VALS Ground Hazard is a mature and effective volcanic warning system designed and maintained by the JMA and we are confident that JMA's VALS Ground Hazard is capable of translating scientific phenomena into actionable information. Secondly, as we have mentioned before, human lives are and should be primary concerns for scientists and disaster managers. Our linkage implies that VALS Airport is subordinate to VALS Ground Hazard. We briefly unveil the idea of phased response here before we navigate into details: in our system, a certain level of VALS Ground Hazard has different implications for each airport group. In essence, the closer the airport is located to the

Table 3 Trigger events and recommended actions for airports in Group A

Alert Level	Trigger	Actions	
Yellow	Level 4	Nighttime standby Attention to further information on volcanic activities	
Orange	Level 4 & VAFF(s)	Departures:	No restrictions.
		Arrivals:	Cancel on-ground flights that are scheduled to take off in x hours.
Red	Level 5	Departures:	Cancel flights which are scheduled to take off in y_i hours and later.
		Arrivals:	If ETA later than $y_i$hours, divert, return (in-air) or cancel (on-ground)
		Evacuations:	Initiate evacuation of cancelled departures and arrivals aircraft.
		ATC:	Airspace restriction (radius of 8 NM)

Table 4. Thresholds to define Group B1, B2 and B3

Group	*Thresholds*	*Brief Explanation*
B1	$a_i > y_i$ $a_i < 0.5 + y_i$	*The necessary time to evacuate from* ***airport i*** *is shorter than ash travel time.* *Detailed VAFF is not feasible.*
B2	$a_i > 0.5 + y_i$ $a_i < x$	*Detailed VAFF is feasible.* *Buffer time is not viable for departure cancelation*
B3	$a_i > x$ $a_i < dt_i + y_i$	*Detailed VAFF is feasible.* *Buffer time is viable for departure cancelation*

volcano, the lower level of uncertainty we tolerate. Conceivably, during a crisis, the alert level of VALS Airport propagates from airports close to the eruption source to peripherals.

In the next section, we will introduce trigger events and corresponding recommended actions for each group separately. Before we discuss details, we must underline a condition applicable to all groups: the decision to initiate a nighttime standby can only be made before airport closure, if the trigger events for nighttime standby are reported during the night, stakeholders should heighten their level of attention, assess the situation and response appropriately as soon as possible the following morning.

a) Tigger events for airports in Group A

Trigger events and corresponding actions for group A are listed in Table 3. The trigger events for Yellow are Level 4 in VALS Ground Hazard. When JMA issues a Level 4 alert, airports in group A will automatically move to Yellow alert; we recommend airports work collaboratively with airlines to initiate nighttime standby, pay close attention to further information regarding volcanic activities and make contingency plans for possible disruptions.

In the meantime, we also keep airports updated with Volcanic Ashfall Forecasts (VAFF), if any of the scheduled VAFFs (VAFF is offered in three formats, refer to [19] for details) suggest that the airport will be affected by ashfall, then this airport enters the Orange stage. At level orange, there are no restrictions applied to departure flights, at least temporarily. As for arrival flights, the airport operator will advise airlines to cancel flights that are scheduled to take off in x hours, allowing for a buffer time. We introduced a buffer time here to rein in the chaotic outcome of abrupt cancellations. However, VAFF only simulates small-scale eruptions in line with normal plume height for the Sakurajima volcano. We need a trigger for notifications of large-scale eruptions. Fortunately, the ash volume of Sakurajima can be nowcasted. The Sakurajima Volcano Observatory developed a "linear combination method" equation using an empirical relationship between seismological and deformation data as: $M_T = c_1A + c_2V + c_3$ to monitor the volume of ejectable ash, where M_T is the material weight (in tons), A is the seismograph spectrum sum between 2-3 Hz, V is the pressure source volume change sum (in cubic meters). The values for the parameters were calculated ($c_1 = 3.8 \times 10^{-5}$, $c_2 = 2.6$, $c_3 = -1.3 \times 10^5$) with regression analysis. If the M_T increases above $1.2 \times 10^9\ t$ (threshold of a VEI-4 eruption: $0.1\ km^3$, and a density of $1200\ kg\ m^3$), JMA should initiate simulations of large-scale VAFF instead of normal-scale VAFF. This not only benefits airlines but also residents since it represents the actual situation at the volcano (see

Table 5. Trigger events and recommended actions for airports in Group B1

Alert Level	Trigger	Actions	
Yellow	Level 4 & VAFF(s)	• Nighttime standby • Attention to further information on volcanic activities	
Orange	Level 5 & VAFF(s)	Departures:	No restrictions.
		Arrivals:	Cancel on-ground flights with STA less than y_i hours to ashfall (assume eruption), please be noted, for in-air flights, no restriction until Red alert.
Red	Eruption & VAFF(p)	Departures:	Cancel flights which are scheduled to take off after the estimated ash arrival time.
		Arrivals:	• If ETA later than y_i hours to ash arrival time, divert, return (in-air) or cancel (on-ground). • Put on-ground arrivals on hold while waiting for VAFF.
		Evacuation:	Initiate evacuation of canceled departures.
		ATC:	Airspace restriction in accordance with VAA

[20] for details of an ash volume nowcast; see [19] for information on VAFF).

If Level 5 is reached, indicating that a large-scale eruption is imminent, we recommend airports in group A move up to Level Red. When at Red, airports will recommend that airlines cancel and evacuate departing flights that are scheduled to take off in y_i hours and later. As for arrivals, airlines should consider canceling arriving flights that have not taken off. For en-route arrival flights, airlines should consider landing, return, and diversion, as they have planned when the alert level was at Yellow. Since Level 5 indicates a large-scale eruption is imminent, air traffic controllers (ATC) should also precautionarily draw a danger zone as a circle with a radius of 8 nautical miles from the vent [21]. At Level Red, we decided not to include the scheduled VAFF in consideration of the significant error of the ashfall forecast prior to eruption [22].

b) Trigger events for airports in Group B

Group B contains airports which are not too close or too far from the volcano: aircraft at these airports can evacuate after the eruption, but these airports must implement a nighttime standby. In this section, we further subdivided Group B into three subgroups, namely B1, B2, B3 (Table 4). Trigger events vary slightly among the three subgroups. We subdivided Group B based on whether airlines have enough time to wait for detailed VAFF (we assume a 30 minutes latency for detailed VAFF) and whether ash travel time is longer than x hours. See Appendix A for details on airport group results.

Table 5 sums up trigger events and corresponding recommended actions for airports in group B1. If any of the scheduled VAFF suggest ashfall at the airport, and concurrently Level 4 is in effect, this airport is issued a Yellow alert. Recommended actions remain the same as Yellow for airports in group A: the airport initiates a nighttime standby, stakeholders should pay close attention to further information on volcanic activities and make plans for a possible ashfall hazard. It is worth noting that the threshold for large-scale VAFF mentioned in the previous section is also valid here.

If Level 5 is issued, and any of the scheduled VAFFs shows that the airport is likely to be covered by ash, this airport enters the Orange stage, but remains Yellow otherwise. When at Orange, no restriction on departure flights is currently in effect. For arrivals, we first assume the eruption has just started (which in fact it has not in reality), then we estimate an approximate ash arrival time (time when the airspace over the airport is contaminated by ash), and if the scheduled time of arrival (STA) is less than y_i hours to ash arrival time, then we advise the pilots and airlines operator to cancel the plan. Speaking of which, if the scheduled time of departure (STD) of the flight which meets the cancelation condition lies more than x hours later, we recommend the airline operator temporarily put the cancelation on hold. By the time the STD is in less than x hours, we then cancel it.

When the eruption is confirmed by the observatory, the aviation community should quickly refer to the preliminary VAFF, which is expected to be available about 5 minutes after the onset of the eruption [19]. If VAFF shows that the airport is likely to be covered by ashfall, we cancel departing flights which are scheduled to take off after the estimated ash arrival time. Subsequently, these canceled flight aircraft should be evacuated to safe airports. For arriving flights, if the estimated time of arrival (ETA) is less than y_i hours to ash arrival time, we recommend that airline operators and pilots-in-command consider diversion or return, or, if the aircraft is still on-ground, then it should be canceled. Since the eruption has already started, air traffic controllers (ATC) should recommend a detour to avoid contaminated airspace in line with volcanic ash advisories (VAA) and in-air reports from pilots.

Table 6. Trigger events and recommended actions for airports in Group B2

Alert Level	Trigger	Actions	
Yellow	Level 4 & VAFF(s)	Nighttime standby Attention to further information on volcanic activities	
Orange	Level 5 & VAFF(s)	Departures:	No restrictions.
		Arrivals:	Cancel on-ground flights with STA less than y_i hours to ashfall (assume eruption), please be noted, for in-air flights, no restriction until Red alert.
Red	Eruption & VAFF(d)	Departures:	Cancel flights which are scheduled to take off after the estimated ash arrival time.
		Arrivals:	If ETA later than y_i hours to ash arrival time, divert, return (in-air) or cancel (on-ground). Put on-ground arrivals on hold while waiting for VAFF.
		Evacuation:	Initiate evacuation of canceled departures.
		ATC:	Airspace restriction in accordance with VAA

Table 6 summarizes trigger events and recommended actions for airports in group B2. Trigger events and recommended actions for Level Yellow and Orange in this group are identical to Group B1. However, for Level Red, the trigger event becomes detailed VAFF. If this airport is predicted to be covered by ashfall through detailed VAFF, then this airport is issued a Red alert. Recommended actions remain identical to Red in Group B1.

Table 7 summarizes trigger events and recommended actions for airports in group B3.

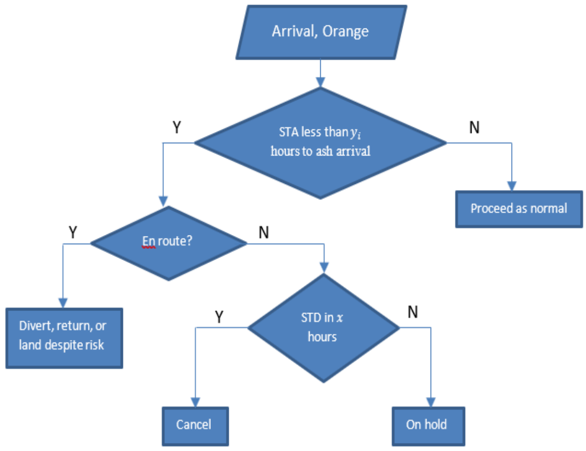

Fig.3 Flow chart of decision making on Arrival flights at Orange Level. STA: Scheduled time of arrival. STD: Scheduled time of departure

Trigger events and recommended actions for Level Yellow in this group are identical to Group B1 and B2. Level Orange is confirmed upon the occurrence of a large-scale eruption and detailed VAFF suggesting that this airport will be affected. Recommended actions are slightly changed because the eruption has been confirmed. In this case, pilots-in-command should consider diversion, return or land despite risk if their flights are forecasted to be affected.

For Level Red, since the airport is located more than x hours from the volcano by ash dispersal, we can wait to cancel departing flights with ETD in x hours and later when the ashfall is estimated to commence in x hours.

In fact, as we will find out in Group C, all trigger events and recommended actions for Group B3 are identical to Group C except for a nighttime standby issue. For Group B3, nighttime standby is required while for Group C, there is no need to contemplate nighttime standby.

c) Tigger events for airports in Group C

Group C includes airports that are located far enough from the volcano that nighttime standby is rendered unnecessary, and airports which operate 24 hours and do not belong to Group D. Trigger events and recommended actions are also summarized in Table 7. Different from Group A and B, Level Yellow for Group C airports does not recommend nighttime standby because the relatively long distance remits airline operators sufficient time to maneuver after the airport reopens. However, even if the nighttime standby is not required, we still advise stakeholders not to take the situation lightly, and keep themselves updated with the latest hazard information.

The trigger event for Level Orange in VALS Airport for group C is the onset of a large-scale eruption and detailed VAFF showing that the airport is about to be covered by ash, which should be published 25-30 minutes after the onset of the eruption by JMA. If the detailed VAFF excludes the airport from the ashfall area, this airport remains at Yellow. If the airport moves to Orange, no restrictions are applied to departures, at least temporarily. For arrivals, since the eruption has already been confirmed, we can roughly estimate an ash arrival time. Subsequently, airlines can cancel flights with an STA of less than y_i hours to ash arrival and an STD in x hours and earlier. If the STA of the flight is less than y_i hours to ash arrival, but the flight is already en route, the

Table 7. Trigger events and recommended actions for airports in Group B3, C

Alert Level	Trigger	Actions	
Yellow	Level 4 & VAFF(s)	Nighttime standby (B3 only) Attention to further information on volcanic activities	
Orange	Eruption & VAFF(d)	Departures:	No restrictions.
		Arrivals:	Cancel on-ground flights with STA less than $y_i$hours to ashfall, please be noted, for in-air flights, no restriction until Red alert. en route flights with STA less than $y_i$hours to ashfall should consider diversion, return or land despite risk.
Red	x hours to ash arrival time	Departures:	Cancel flights which are scheduled to take off in x hours and later.
		Arrivals:	If ETA later than $y_i$hours, divert, return (in-air) or cancel (on-ground). Put on-ground arrivals on hold while waiting for VAFF.
		Evacuation:	Initiate evacuation of canceled departures.
		ATC:	Airspace restriction in accordance with VAA

airline should consider returning, diversion or landing despite the ash threat. Like we did in group B, for flights with STD more than x hours later, we advise airline operators to put them on hold temporarily, and wait until the STD is in x hours, we cancel the flight if the alert level has not been downgraded. See Fig. 4 for flow chart of decision making on Arrival flights at Orange Level.

When time remains only x hours to ash arrival, the airport enters Level Red Alert. For this level, departures which are scheduled to take off in x hours and later, cancelation and evacuation are advised. For arrivals which are estimated or scheduled to arrive within y_i hours before the estimated time of ash arrival, the advice remains almost the same: cancel, divert or return flights, whichever suits best.

Above is our detailed explanation of trigger events and recommended actions. Fig. 5 illustrates the trigger events for all airports contributing to the phased response. Intuitively, this propagation of alert levels from proximal airports to peripheral airports is what we have referred to as "phased responses".

Finally, it might seem self-evident, but we think it is still worth noting that a flight for which the recommended actions are contradictory or inconsistent, we recommend following the stricter advice. For instance, if the departing airport raises no restriction but the arriving airport suggests cancelation, then the airline operator and pilots-in-command should follow the cancelation advice

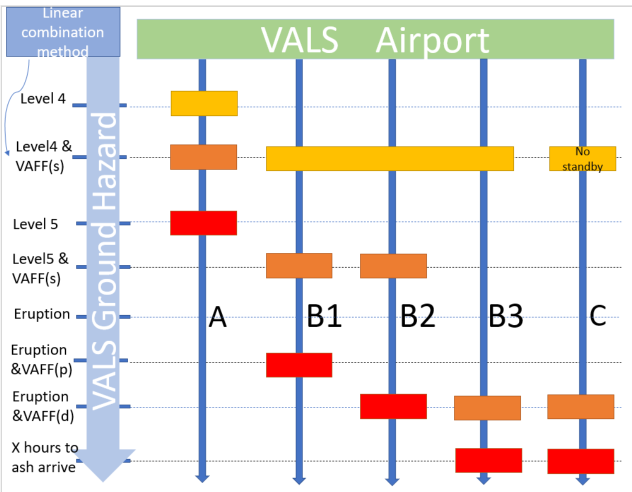

Fig.4 Trigger events in VALS Airport in parallel with VALS Ground Hazard. Before the issuance of Level 4, all airports are at Level Green. Text on the left hand side lists alert levels in VALS Hazard Ground and ashfall risk at given airport confirmed through VAFF (s: scheduled; p: preliminary; d: detailed). Each color bar stands for timing of issuing corresponding alert level in VALS Airport.

rather than the all-clear signal from the departure airport as the foundation of their decision making.

(4) Management of the VALS Airport

We must also designate an established institution to manage the VALS Airport. This manager should be responsible for the maintenance of the system during normal times, including maintain social relationships with stakeholders and organize regular training, issuance of alert levels during crises, and assume the role of the primary source of information on airport vulnerability. After careful consideration, we propose the VAAC Tokyo to have responsibility for the VALS Airport. The factors that make the VAAC Tokyo the best candidate for this job are summarized as follows: firstly, VAAC Tokyo is responsible for volcanic ash dispersal simulation and information dissemination. As a result, VAAC Tokyo has a long history of dealing with stakeholders from aviation communities during volcanic crises and such pre-existing relationships are a benefit for cultivating mutual trust in a new project [23]. Secondly, VAAC Tokyo is an institution under the leadership of JMA. In our model design, we pegged the VALS Airport to VALS Ground Hazard, which is managed by JMA. The subordination of VAAC Tokyo to JMA would facilitatively eliminate barriers and distrust in practice. Fourthly, we refrained from proposing JMA to directly manage the VAAC Airport in order to prevent potential conflicts of interest. At first glance, JMA is even a better candidate for VALS Airport management because JMA produces VAFF which serves as the foundation of the VALS Airport. However, alert levels of VALS Ground Hazard are used as trigger events in VALS Airport, which means any adjustment to alerts to residents will also affect aviation communities. Previous research has shown that induced actions could affect scientist's decision making, we aim to prevent induced aviation actions to avoid repercussions on JMA's decision making on VALS Ground Hazard [24]. Lastly, VAAC Tokyo has dual accountability on both sides, i.e., scientific communities and aviation communities. C J Fearnley and Beaven (2018) first applied the Cash et al. (2003) boundary theory to research on volcanic crisis communication. following their footprints, we would like to point out that a VAAC-managed VALS Airport also satisfies dual accountability, one of the three fundamental elements of an effective "boundary organization" in the Cash et al. article. On the one hand, VAAC Tokyo is accountable to JMA, which is Japan's organization in charge of volcano monitoring, forecasting, and warning. On the other hand, VAAC Tokyo is also accountable to the aviation community. The aviation community is the sole end-user of VAAC products, and VAAC should be exclusively committed to enhancing the continuity of aviation business and safety of aviation operation.

The warning information should also be presented in an easily readable way, as plain and direct as possible. For example, for red alert for Group C, our recommended action for arrival flights is: If ETA is less than y_i hours to ash arrival, divert, return (in-air) or cancel (on-ground). If this were the information in use, it would be hard for end-users to consume. In contrast, exact time should be used. Here is a sample: “Flights to RJTT: Red Level in effect at RJTT. If the ETA is later than 15:30, please consider cancelation, diversion or return”

5. Discussions

As of this writing, we have conceptualized a prototype for VEWS Airport. Airlines are strongly motivated to implement an early warning system because they are aware of the potential huge impact volcanic hazards can inflict on their business, and by ICAO codes, airlines and pilots-in-command are responsible for operation [27]. In summary, airlines are highly motivated to participate in the VEWS project. On the other hand, the attitude of aviation bureau who controls the operation of airports in Japan is subtle. In general, it has the obligation to assist the airlines with respect to aviation safety issues. However, since nighttime standby will not produce any extra benefit on airports, airport operators are less incentivized than airlines to react based on uncertain information. As a result, we argue that aviation bureau needs a higher level of trust in scientific communities than airlines to initiate early-stage response. However, this is an untested claim which needs further examination. The design of VEWS Airport is also an effort to build common languages among stakeholders. Stakeholders do not naturally have a common language. Apart from different jargons they daily use in their own disciplines, stakeholders may also perceive the volcanic risks differently, for instance, government is likely to pay significantly more attention to safety of residents proximal to the hazardous volcano, airport authority may emphasize on ashfall hazards to facilities while airlines are more concerned with safety in air and timely evacuation from risky airports. We need a set of simple but effective language rules to bring stakeholders together to tackle volcanic hazards on aviation communities while do not deviate them from their primary jobs, namely safety of residents for government. VEWS Airport is such a common language tool to facilitate risk communication with an intuitive design of color-coded alert levels and clearly defined recommended actions at each level.

We plan to quantitatively analyze how our proposed system would benefit the airlines, how many aircraft would be saved in the worst-case scenario, comparing with the outcomes if without any preparation in the next step and hold a joint workshop with stakeholders from airline business, Sakurajima observatory and university aviation operation research to validate the drafted early warning system model. Even though airlines already have an established timeline for typhoon, we cannot validate our timeline to that for typhoon through analysis of the historical issuance of volcanic alert levels because last time Sakurajima volcano erupted massively was in 1914, while JMA only officially started issuing volcanic warnings and forecasts on 1 December 2007 [28]. 1914 Taisho eruption is also the latest VEI-4 eruption in Japan, in other words, we do not have historical cases to analyze. As a result, we argue that an open, inclusive and deliberative workshop which walks through all aspects of volcanic hazards preparedness and response is the most viable way to validate the model design. Face-to-face workshop is also conducive to trust-building and common language cultivation. We will especially focus on the following points:

Firstly, we will validate the necessity of differentiating arrivals and departures. We suppose the arrivals are more vulnerable than the departures because for arrivals, their take-offs happen earlier. As a result, we argued that decisions on arrival flights should be made earlier to hedge the higher level of risk. In doing so, airlines have to tolerate higher level of uncertainty. We are wondering is such design practical. We will elaborate our design to the airline company, the airline company will evaluate our proposal and give us a feedback, then we can update the prototype model based on the feedback.

Secondly, we will work with volcanologists to realize the proposal of a large-scale VAFF. Currently, the VAFF only covers daily small-scale eruption. We argue that JMA could utilize the ejectable volume of ash derived through linear combination method as the indicator of producing large-scale eruption. Still, technical details remain to be worked out.

Thirdly and most importantly, the timeline must be validated with all stakeholders, i.e., volcanologists, airline representatives, VALS modelers, aviation operation researchers and authorities. Numerous factors affect the timeline, for instance, the necessary time to produce large-scale VAFFs, the probable time to eruption at Level 4 & 5, the speed of ash dispersal in air, and the necessary time to completely evacuate an airport. As a matter of fact, the necessary time should vary with number of on-ground aircraft and for most airports especially hubs, we suppose nighttime is the time when they have most aircraft on apron.

Fourthly, we have to designate sheltering airports as destinations for aircraft evacuation. As of this writing, we plan to designate hub airports in Group D such as Shin-Chitose, Naha and Sendai airport to be sheltering airports. If capacity provided by these three airports is not enough to shelter all evacuated aircraft from risky airport, then we can add other Group D airports to the standby list. If the capacity provided by all suitable airports in Group D still falls short of demand, then we can designate Group B and Group C airports which are cleared by VAFF to be sheltering airports.

Lastly, how could airlines implement nighttime standby. We developed the prototype model from the perspective of airport. However, the airport nighttime standby alone is not enough, airlines should also work out a plan to implement the nighttime standby strategy. Possible limitations include pilots availability, flight hours cap and so on could hinder the implementation of nighttime standby.

APPENDIX

https://drive.google.com/file/d/1lS89fEJAC6J6j6ur0RQdRBsuV42xZ8ot/view?usp=sharing

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