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An investigation of changes to commercial aircraft flight paths during volcanic eruptions

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Abstract

Volcanic eruptions can inject ash into the atmosphere, which is then advected by meteorological winds, potentially affecting large volumes of airspace. Volcanic Ash Advisory Centres (VAACs) issue volcanic ash advisories (VAAs) when airspace is likely to contain ash above a concentration threshold. Much research has been done to improve operational ash forecasts of volcanic ash location in the atmosphere, but until now the paths of aircraft around erupting volcanoes and when VAAs have been issued, and the impact these routes have on flight schedules and diverted aircraft's fuel consumption, have not been closely examined. Here, we investigate the behaviour of commercial aircraft during times of volcanic ash emissions as reported in VAAs. We use publicly available flight trajectory data during several ash-rich eruptions at Etna, Sakurajima, Marapi, Sheveluch, Klyuchevskoy and Ubinas volcanoes in 2022 and 2023. We examine a range of geographic locations and eruption sizes. Flight trajectories during periods when VAAs were issued are compared with flight trajectories during periods when no VAAs were issued. We find that the aircraft largely avoided the air space shown to be affected by ash by VAAs, indicating that they adopt a range of strategies to avoid ash. We also find that, in general, by avoiding ash aircraft also avoided volcanic SO_2 plumes. Our results confirm that the greater the volume of airspace affected by volcanic ash the greater the deviation of aircraft from their usual flight paths. Rerouted aircraft may travel significantly further distances to avoid ash, which results in longer air travel time and delays, suggesting greater fuel consumption and carbon emissions. Further long-term systematic studies of the impact of volcanic eruptions on flight routes and timing would help to characterise ash-related aircraft disruption over time. Air traffic is likely to grow in the coming years and VAAC advisory strategies will also evolve so understanding how such changes affect disruption trends may be useful.

Keywords Volcanic Ash Advisory Centres (VAACs), Volcanic ash hazard, Eruption

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Introduction

Aircraft interaction with volcanic ash can in some circumstances cause serious problems such as engine failure and damage to avionic systems (Golewski & Sadowski, 2016). Ash melting temperatures are lower than that of a jet engine's combustion chamber, therefore if ingested into the engine, ash can melt and accumulate on cooler turbine blades (Song et al., 2019). This reduces air flow, impacting engine efficiency and, in the worst cases, cause engine failure. Between 1953 and 2009, 129 ash-aircraft incidents were reported (Guffanti et al., 2010), including 9 severe events, consisting of in-flight engine power loss requiring an emergency landing. One such notable incident occurred following the 1991 Pinatubo eruption when an aircraft lost engine power after twice flying through dilute ash 500 km from the volcano (Guffanti et al., 2010). This highlights how even dilute ash at great distance from the source volcano can lead to engine failure. During the 2010 Eyjafjallajökull eruption, 92 aircraft reported encountering ash (Christmann et al., 2015).

Given the potential consequences of ash – aircraft interactions, restrictions to air travel through ash-affected airspace are advised by the International Civil Aviation Organisation (ICAO) (ICAO, 2012). Such restrictions, even if advisory in nature, can have significant impacts on the global economy due to flight diversions, delays and cancellations (Eurocontrol 2010; Ellertsdottir 2014). For restrictions that are only advisory in nature, there is flexibility within the decision-making process and so airlines can choose to employ a cost-benefit analysis where they will need to balance the risk of encountering ash plumes with costs arising from cancellations or rerouting. As a result, much research has been conducted on detecting ash plumes (Prata 1989; Prata and Grant 2001) and understanding the processes controlling ash injection into the atmosphere and its dispersal (Poulidis et al., 2018). Such studies help in producing increasingly accurate forecasts (Capponi et al., 2022; Crawford et al., 2022; Beckett et al., 2024) and advisory information to aircraft on ash hazard (Witham et al., 2012; Beckett et al., 2020; Mastin et al., 2022; Lau et al., 2024).

Operational organisations such as Volcanic Ash Advisory Centres (VAAC) use this research and monitoring data to improve their observation and forecasting outputs. There are 9 VAACs covering airspace around the world (Fig. 1).

Mechanisms for informing aircraft of the presence of volcanic ash

Volcanic ash dispersion is carefully monitored worldwide and multiple steps are taken to warn aircraft of the potential location of ash in the atmosphere (Fig. 2) (Lechner et al., 2018). The key steps in alerting civil aviation to atmospheric ash are as follows and are shown

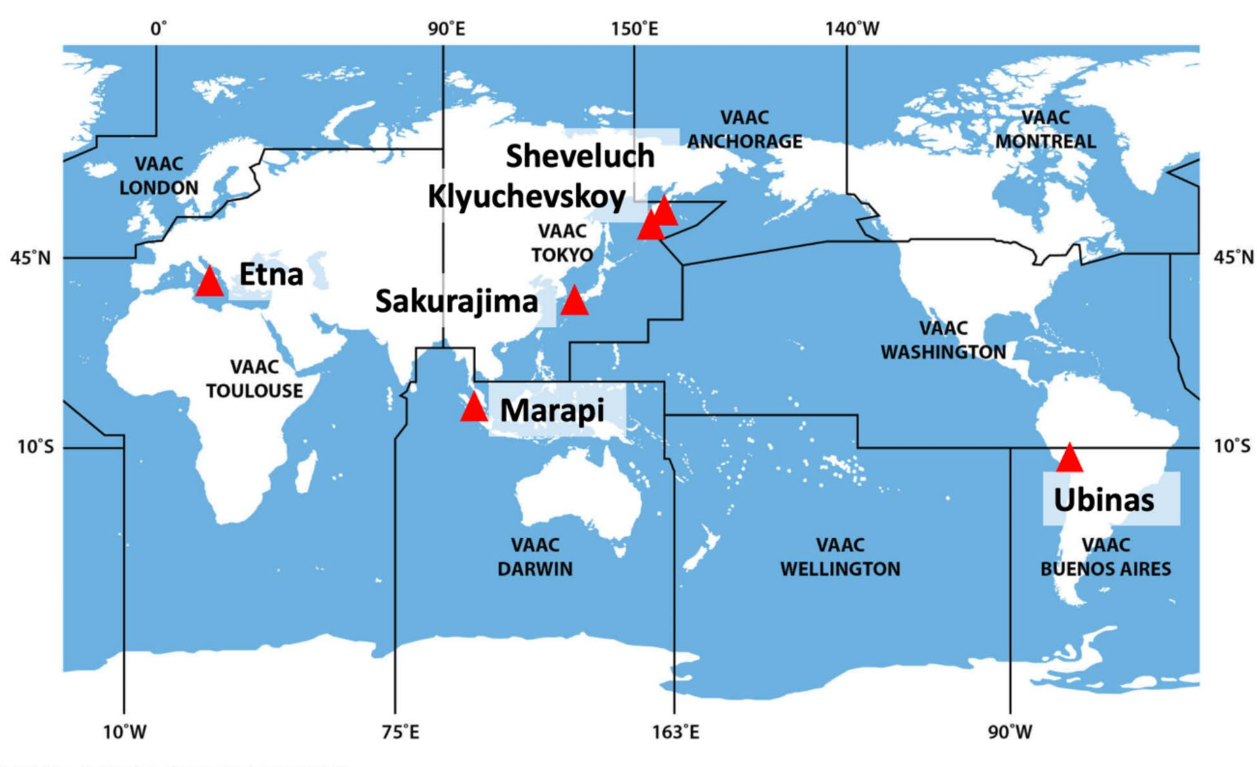

Fig. 1 The Volcanic Ash Aviation Centre areas of responsibilities and the location of volcanoes used in this study (Modified from the Civil Aviation Authority of New Zealand - http://vaac.metservice.com/index.html)

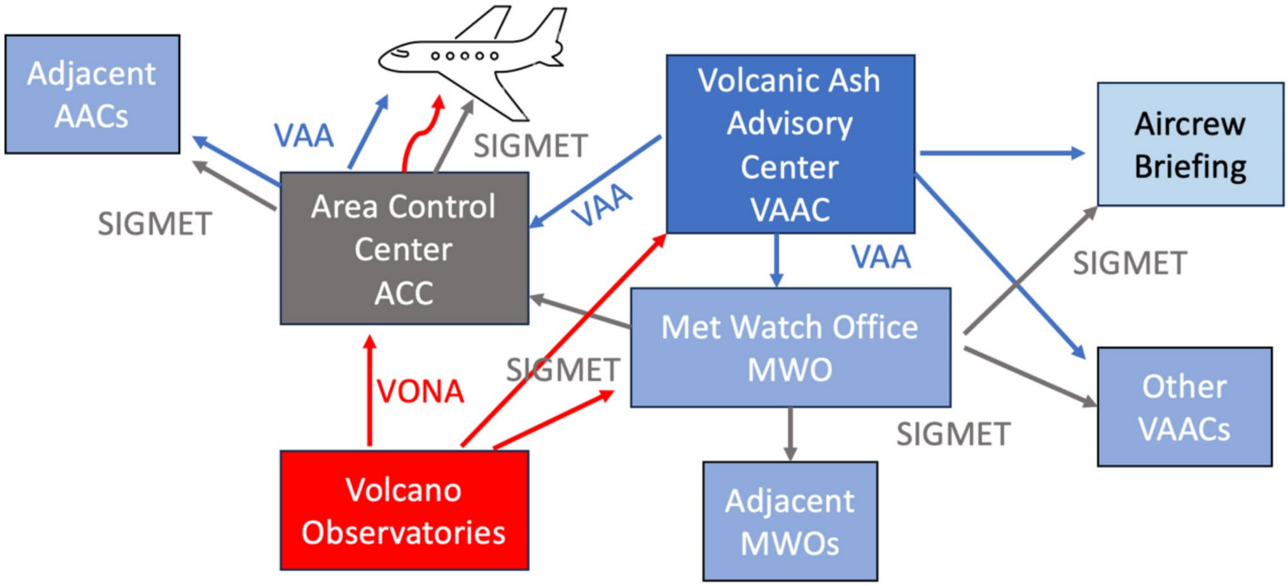

Fig. 2 Information flow between different organisations involved in response to volcanic emissions for providing hazard information to aviation Modified from the Guidance for State Volcano Observatories: The International Airways Volcano Watch 1st Edition (2009)

Table 1 Volcano level of alert colour codes for aviation (extracted from ICAO Doc 9766 (Second Edition), Table 4-4) (ICAO, 2004)

Level of alert	Status of activity of volcano
Green	Volcano is in normal, non-eruptive state. *or, after a change from a higher alert level*: Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.
Yellow	Volcano is experiencing signs of elevated unrest above known background levels. *or, after a change from a higher alert level*: Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
Orange	Volcano is exhibiting heightened unrest with increased likelihood of eruption. *or* Volcanic eruption is underway with no or minor ash emission. *[specific ash-plume height if possible]*.
Red	Eruption is forecasted to be imminent with significant emission of ash into the atmosphere likely. *or* Eruption is underway with significant emission of ash into the atmosphere. *[specific ash-plume height if possible]*.

schematically in Fig. 2. Where present, a volcano observatory monitors volcanoes for signs of a potential eruption. Many volcano observatories release a Volcanic Observatory Notice for Aviation (VONA) to the responsible Air Traffic Management Area Control Centre (ACC), the Meteorological Watch Office (MWO) and VAACs when there is significant unrest, an eruption starts, or when there is a change in eruptive activity. The VONA contains information on the status of the eruption, a colour code – the Aviation Colour Code (ACC; Table 1) – and key observation information that can be used by the relevant VAAC to initiate the numerical models used to issue ash dispersion forecasts. VAACs use this information alongside resources including satellite imagery, (such as from HIMAWARI-8 (Tokyo VAAC), HIMAWARI-9 (JMA and Darwin VAACs), GOES-16 (Washington VAAC), and GOES-E (Buenos Aires VAAC)) and web cameras to determine ash location, estimate plume height and apply models to forecast the ash cloud movement (Engwell et al., 2021). At the onset of an eruption, or when ash is detected in the atmosphere, and at 6 hourly intervals thereafter, the responsible VAAC issues a VAA and a Volcanic Ash Graphic (VAG) which include information on the possible location of ash as well as an ash dispersal forecast for 6, 12 and 18 h after the advisory is issued. This comes in the form of polygons delimiting areas of airspace which are believed to contain ash. This information is sent to the MWOs and the Air Traffic Management ACCs. Finally, the MWOs, located at airports, generate a SIGnificant METorological (SIGMET) report containing hazard information, in this case regarding ash, and the ACC produces a NOTices to Air Men (NOTAM) which is sent out to airlines. This information is used by airlines to plan their flight paths. Ultimately, a pilot can make real-time decisions should they encounter an SO_2 (ICAO, 2004) or ash plume if they deem it necessary to exit/avoid the plume.

Volcanic ash advisories (VAA)

It is not obligatory for airlines to take VAA information into consideration when planning routes (ICAO, 2012). Any decision to reroute an aircraft needs to take into account the risk associated with the aircraft encountering an ash plume, the cost of significantly rerouting a flight, and the potential for the flight to encounter other hazards, for example significant turbulence or dust.

Eruptions, data source and SO_2 exposure

The aim of this study is to investigate whether volcanic eruptions or issuance of VAAs results in changes to flight routes of commercial aircraft. The period of study was limited to a little more than 12 months as any flight trajectory data older than one year from the current date is deleted. Priority was given to those eruptions which were associated with a red ACC from the volcano observatory. However, for some eruptions, ACC information was not accessible and so in those cases, volcanoes with ash emissions affecting a large area were chosen. Volcanoes close to airports (e.g., Etna, Sakurajima, Marapi) were prioritized as these have the most potential to disrupt air traffic. We focused on the period from 21st November 2022 to 11th December 2023, providing 386 days of data. In this period information from VAAs issued in relation to eruptions from Etna, Sakurajima, Marapi, Sheveluch, Klyuchevskoy and Ubinas were analysed in combination with flight trajectory information to identify whether flight paths change during periods of heightened eruptive activity. A volcano can be erupting for years but this does not mean that the volcano emits ash or gas continuously throughout the eruption. In this paper heightened eruptive activity or eruptive activity refer to an event occurring during an eruption, meaning ash and/or gas is being emitted. Changes to flight routes associated with VAAs are examined with reference to their normal flightpaths. This provides key insights into how VAA information is used worldwide. During the period of investigation VAAs were issued for volcanoes in the area of responsibility (AoR) of 6 out of the 9 VAACs.

In addition to our primary aim, we also investigate whether as avoidance also led to the avoidance exposure of volcanic SO_2. Ash and gas may separate in volcanic plumes (Primulyana et al., 2019), so it's not automatic that ash-avoidance results in SO_2 avoidance. SO_2 exposure may also have long-term detrimental impacts on engine performance (Song et al., 2019).

Etna

Etna volcano is a frequently erupting volcano located on the island of Sicily, Italy. It is monitored by the Osservatorio Etneo dell'Istituto Nazional di Geofisica e Vulcanologia (OE-INGV) and falls under the AoR of Toulouse VAAC (Fig. 1; Table 2) (https://vaac.meteo.fr). Catania airport is situated 32 km southeast of Etna, and the prevailing winds are towards the southeast, making Catania airport highly vulnerable to ash emissions from Etna. Here we focus on an eruptive activity at Etna which started in May 2023 (Global Volcanism Program| Etna, May 2023). The particular emission analysed here is typical of this volcano and occurred on the evening of 13th August 2023 at 19:30 UTC and ended on the morning

Table 2 Summary of volcanic eruptions, responsible VAAC, whether Aviation Colour Code (ACC) issued, airports and airlines

Volcano	Country	Date (dd/mm/yyyy)	VAACs the plume enters	Departure airport	Arrival airport	Airlines
Etna	Italy	13/08/2023, 14/08/2023	Toulouse	Malta, Milan, Rome, Bologna	Catania	AirMalta, easyJet, ITA Airways, Neos, Ryanair, WizzAir
Sakurajima	Japan	21/11/2022, 03/12/2022, 07/12/2022, 08/12/2022, 14/12/2022, 24/12/2022, 27/12/2022	Tokyo	Osaka, Kikai, Nagoya, Tanegashima, Okinoerabu, Tokyo, Yakushima, Amami, Tokunoshima	Kagoshima	Japan Airlines, All Nippon
Marapi	Indonesia	04/12/2023, 05/12/2023, 06/12/2023	Darwin	Padang	Kuala Lumpur	AirAsia, Super Air Jet
Sheveluch	Russia	10/04/2023, 11/04/2023, 12/04/2023, 13/04/2023, 14/04/2023, 15/04/2023	Tokyo, Anchorage, Montreal, Washington,	Anchorage	Tokyo, Seoul, Hong Kong	Nippon Cargo, Korean Air, Asian, FedEx, Polar Air Cargo, UPS, Atlas Air, Cathay Pacific, Alaska Airlines, All Nippon Airways
Klyuchevskoy		31/10/2023, 01/11/2023, 02/11/2023	Tokyo, Anchorage			
Ubinas	Peru	26/08/2023, 27/08/2023, 28/08/2023, 15/09/2023, 16/09/2023, 11/12/2023	Buenos Aires	Lima	São Paulo	Latam Airlines

of 14th August 2023 (with ash having reached 8.5 km a.s.l. (Global Volcanism Program| Etna, 2023)). Over this period, OE-INGV issued 7 VONAs (https://www.ct.ingv.it/index.php/monitoraggio-e-sorveglianza/prodotti-del-monitoraggio/comunicati-vona). OE-INGV issued a red ACC assigned in a VONA on 13th August 2023 at 20:41 UTC. This was reduced to orange on 14th August 2023 at 05:54 UTC and further reduced to green at 12:17 UTC of that same day. The eruption led to closure of the airport on 15th August 2023 (euronews, 2023).

Sakurajima

Sakurajima volcano is located in south Japan within the Aira caldera. It falls under the AoR of Tokyo VAAC (Fig. 1; Table 2) (https://www.data.jma.go.jp/vaac/data/index.html) and is monitored by the Japan Meteorological Agency (JMA). Sakurajima started erupting in March 2017 and has been continuously erupting since. The heightened eruptive activity used for this paper is typical of this volcano's ongoing eruption. The events studied here occurred on 21st November, 3rd, 7th, 8th, 14th, 24th and 27th December 2022 (Global Volcanism Program| Aira, 2022). On 21st November 2022, information from the VAAs state that heightened eruptive activity started at 04:34 UTC and by 11:50 UTC the ash had dissipated (Table 3). On 3rd December 2022, VAAs state that ash was first detected at 06:34 UTC and was last detected at 14:20 UTC. On 7th December 2022, a VAA stated that eruptive activity increased again at 03:04 UTC and continued until 9th December 2022. On 13th December 2022, VAAs describe another eruptive activity at 20:15 UTC with ash dissipating according to satellite imagery by 05:50 UTC the next day. On 24th December 2022, heightened eruptive activity started at 10:54 UTC and the ash had dissipated according to analysis of satellite imagery by 23:50 UTC. Finally, the last event analysed started on 27th December 2022 at 12:31 UTC and by 17:50 UTC, the ash was not identifiable on HIMAWARI-9 satellite imagery. JMA does not provide ACCs for its volcanoes (Table 2), and therefore are not available for this example.

Table 3 Time and date of activity, when ash dissipated and was no longer visible by satellite (Japan Meteorological Agency 2022)

Date	Eruptive activity start time	Ash dissipation time
21 November 2022	04:34 UTC	11:50 UTC
3 December 2022	06:34 UTC	14:20 UTC
7 December 2022	03:04 UTC	9 December 2022
13 December 2022	20:15 UTC	14 December 2022 05:50 UTC
24 December 2022	10:54 UTC	23:50 UTC
27 December 2022	12:31 UTC	17:50 UTC

Marapi

Marapi volcano is located on the island of Sumatra, Indonesia and is monitored by Pusat Vulkanologi Dan Mitigasi Bencana Geologi (PVMBG). It falls under the AoR of Darwin VAAC (Fig. 1; Table 2) (http://www.bom.gov.au/aviation/volcanic-ash/). Marapi erupted in December 2023 and is continuously emitting ash plumes at the time of writing (January 2025). The eruption of interest started on 3rd December 2023 (Global Volcanic Program| Marapi 2023). PVMBG released a VONA and relayed it to Darwin VAAC (https://magma.esdm.go.id/vona). A red ACC was assigned on 3rd December 2023 at 07:54 UTC and this was changed to orange on 4th December 2023 at 01:22 UTC in the VONA released by the volcano observatory. Observed ash extent polygons were last reported in VAAs for 5th of December, identified at 06:00 UTC.

Sheveluch

Sheveluch volcano is located in Kamchatka, Russia and is monitored by the Kamchatka Volcanic Eruption Response Team (KVERT). It falls under the AoR of Tokyo VAAC (Fig. 1; Table 2) (https://www.data.jma.go.jp/vaac/data/index.html). Sheveluch's current activity (as of January 2025) started in August 1999. The eruption is usually characterised by short periods of heightened eruptive activity (Global Volcanic Program| Sheveluch 2023) such as from 10th to 16th April 2023 (Global Volcanic Program| Sheveluch 2023). KVERT is responsible for issuing VONA for this region (http://www.kscnet.ru/ivs/kvert/van/index). The Sheveluch heightened eruptive activities started at 13:10 UTC with ash reaching 15 km altitude and a red ACC was issued thereafter. The ash spread first to the west, then south and 24 h after the eruption began, started dispersing east. The ash entered the Anchorage VAAC jurisdiction on 12th April 2023 at 11:57 UTC. The ACC was lowered to orange on 12th April at 20:52 UTC since the intensity of the eruptive activity had decreased. The ACC remained orange throughout the 4 days analysed. The ash spread across the North Pacific, into Anchorage VAAC (https://www.weather.gov/vaac/), Montreal VAAC (https://weather.gc.ca/eer/vaac/index_e.html) and Washington VAAC (https://www.ospo.noaa.gov/products/atmosphere/vaac/index.html) AoR. The ash dispersed from Anchorage VAAC to the Washington VAAC AoR on 13th April at 15:48 UTC. The eruption ended on 16th April 2023 by 11:50 UTC. As is common practice during events that affect the AoR of multiple VAACs from eruptive activity in over the North Pacific, Tokyo VAAC issued VAAs, which were then referred to by the VAACs of other affected regions. No known airports were closed however, several flights to and from the Canadian province of British Columbia were cancelled (CityNews Vancouver 2023).

Klyuchevskoy

Klyuchevskoy volcano is also located in Kamchatka, Russia and is also monitored by KVERT and falls under the AoR of Tokyo VAAC (https://www.data.jma.go.jp/vaac/data/index.html). Klyuchevskoy has been erupting since June 2023, characterised by lava fountaining and small ash and gas emissions. In late October to early November 2023 eruptive activity increased according to ground observations and satellite thermal imagery, with ash plume heights reaching 14 km a.s.l. Heightened eruptive activity occurred on 31st October to 2nd November 2023 (Global Volcanic Program| Klyuchevskoy 2023). The ash spread over the Anchorage VAAC AoR (https://www.weather.gov/vaac/). KVERT raised the ACC to red on 31st October 2023 at 02:34 UTC and reduced it to orange on 2nd November 2023 at 21:24 UTC, with the VONA stating that "danger to international and low-flying aircraft remains". Only the heightened eruptive activities of those three days are analysed here.

Ubinas

Ubinas volcano is located in Peru and falls under the AoR of Buenos Aires VAAC (Fig. 1; Table 2) (https://ssl.smn.gob.ar/vaac/buenosaires/inicio.php?lang=en). This volcano has been erupting almost continuously from June 2023 to December 2023 with eruptive activity was characterised by earthquakes and ash plumes rising to 1–2 km above the crater. The Instituto Geofísico del Perú, in coordination with the Peruvian Corporación Peruana de Aeropuertos y Aviación Comercial S.A. (CORPAC), issued a VONA which was then used in Buenos Aires VAAC's report. We analysed eruptive events from 26th to 28th August, 15th to 16th September and 11th December 2023 (Global Volcanism Program| Ubinas, 2023).

Methodology

Selection of eruptive events and flight routes

Flight trajectories were taken from flightradar24.com, which provides data on the latitude, longitude and altitude of aircraft throughout their flight. Eruptive events from Etna, Sakurajima, Marapi, Sheveluch, Klyuchevskoy and Ubinas were chosen as detailed in Sect. "Eruptions, data source and SO_2 exposure". Once the volcano was chosen and the closest airport identified, the most frequent flight routes from that airport were selected for analysis. The most frequently operating airlines were chosen, maximising the amount of flight trajectory data and enabling comparison of data when the nearby volcano was erupting or quiescent. Eruptive events where the ash expanded beyond the country of origin and on busy air traffic routes (e.g., Sheveluch and Klyuchevskoy) but far from an airport were also chosen. Finally, smaller eruptive events associated with limited ash dispersion (<50 km from volcano) and far from airports (e.g., Ubinas) were included to understand the impact of persistently active volcanoes on aviation. In the last two cases, the airlines chosen were those that operate frequently on this route, again in order to compare flight routes with those on days when no ash emission occurred.

Polygons communicating airspace containing volcanic ash are taken from VAAs issued by the responsible VAAC (e.g., Toulouse VAAC for Etna). VAAs contain information on both the observed and forecast location of ash but here only the observed volcanic ash cloud polygons are extracted. This is because forecast locations can be prone to more uncertainties than observed polygons. For example, the eruption could stop or become more intense which changes the ash dispersion. In addition, forecasted ash location is given in 6-hour increments for the next 18 h, but further advisories are typically released less than 6 h after the first advisory, particularly when there has been a change in eruptive activity. This means there are often observed ash locations available before the time of the forecasted polygon is reached. Ash cloud polygons are presented as a series of latitudes and longitudes based on geographical coordinated datum WGS84.

Flight trajectories and VAA polygons from the same time were plotted on a map and the data compared. The flight trajectories from days when eruptions occurred, and days of quiescence were also compared to determine whether any difference in flight route could be identified. We also examined the likely impact on fuel consumption arising from the difference in distance travelled during an ash emission and during a "normal" flight, i.e., a flight which occurred when there was no emission. This was carried out for a Boeing 747–8 F, Flight 5X62 during eruptive events at Sheveluch and Klyuchevskoy. The travel time was calculated using the data available from flightradar24. Fuel consumption data was taken from Hendry (2023).

As a preliminary step to determine whether the aircraft analysed in this study encountered volcanic SO_2, we looked at satellite imagery for the Sheveluch and Marapi eruptive events as these were the only ones with available and detectable SO_2 emissions. SO_2 satellite retrievals were taken from TROPOMI (Tropospheric Monitoring Instrument) on board Sentinel-5P. The Vertical Column Densities, which show the amount of SO_2 particles (in Dobson Unit - DU) along a vertical line, were superimposed on the VAAC ash polygons.

Results

Etna (August 2023)

During heightened eruptive activity from Etna, flights from Malta, Milan, Rome and Bologna to Catania were analysed (Fig. 3). These included 4 flights from Air Malta, 5 flights from easyJet, 21 flights from ITA airways, 19

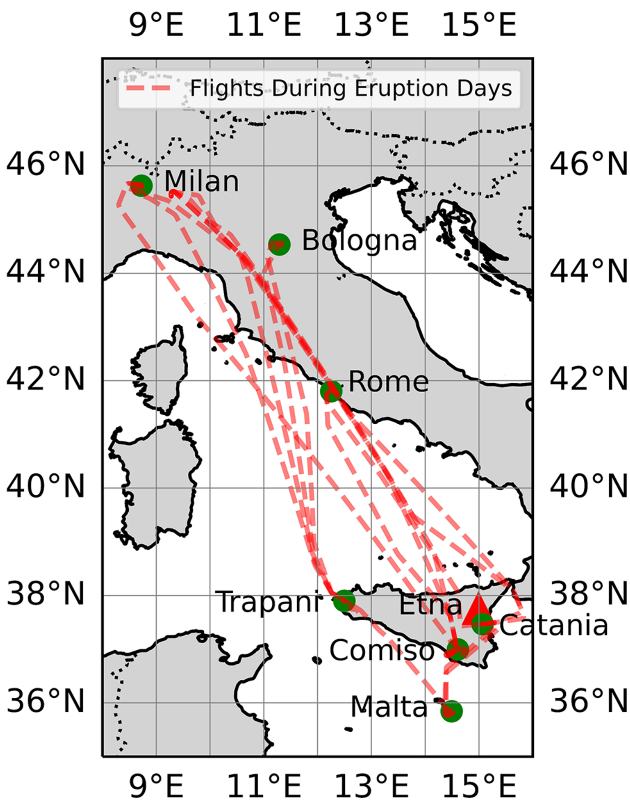

Fig. 3 Location of Etna volcano flight routes during the eruption and origin and destination airports

flights from Ryanair and 10 flights from WizzAir. The number of flights on 13th August, before the first eruptive event of our study period, was 27 (Table 4). These flights all landed in an easterly direction, south of the volcano (Fig. 4A and C). On the first day of heightened eruptive activity, the number of flights reduced to 14 (Table 4; Fig. 3). Throughout the heightened activity, which lasted less than 24 h, 3 flights were on time (2 Ryanair and 1 ITA Airways), 7 were late (1 each from Air Malta, easyJet, ITA Airways and Wizz Air and 3 from Ryanair) and 14 were cancelled. There are also two airlines which diverted aircraft: ITA Airways to Comiso airport (6 diversions) and Ryanair to Trapani airport (4 diversions) – both located elsewhere on Sicily. Five of the ten diversions occurred after the ACC was reduced to green by the volcano observatory marking the end of the eruptive activity. It is important to note that even though eruptive activity may have ended, ash may still be present and detectable in the atmosphere, and therefore VAAs are still issued to communicate the presence of this ash (Engwell et al. 2021). Flights by other airlines were not diverted.

During the period VAAs were issued for this event, flights landed in a westerly direction rather than the usual easterly direction which suggests that this deviation in approach direction was to avoid the ash. A 2-D birds eye view shows 5 aircraft entering the ash polygon. However, when altitude is considered, 4 of these aircraft fly under the ash polygon before landing. Flight FR395 briefly enters the ash polygon but quickly reduces altitude (Fig. 4D): it enters the ash polygon at 22:56:41 UTC and exits it from below at 22:57:26 UTC, less than a minute after entering it.

Sakurajima (November and December 2022)

For the eruptive events at Sakurajima mentioned in Table 2, flights from Osaka, Kikai, Nagoya, Tanegashima, Okinoerabu, Tokyo, Yakushima, Amami and Tokunoshima to Kagoshima were analysed (Fig. 5). These included 40 Japan Airlines flights and 19 All Nippon airlines flights. The distance between Kagoshima airport and Sakurajima is 25 km. During periods of volcanic quiescence, 62% of flights go around the east side of the volcano and land in an easterly direction (Fig. 6A and C). During periods of heightened eruptive activity, all flights except for 3 Japan Airlines flights were on time and none were cancelled. One flight flew west of the volcano (Fig. 6B).

During this activity, only three aircraft were delayed, two of which took off 20 and 21 min before the eruptive activity occurred. Since there is no clear sign flights were rerouted, we are uncertain whether this delay was caused by perceived hazard of volcanic ash. There was on average no delay recorded for these flights. Very few aircraft showed signs of detour, however, one aircraft made a clear deviation from the typical flight paths of the previous day as it approached the volcano during the eruption (Fig. 6D), which could be due to the presence of volcanic

Table 4 Number of flights on 13/08 and 14/08, before and during activity at Etna volcano

Airlines	No. flights planned during heightened eruptive activity	13/08/2023 & 14/08/2023 Actual no. flights during heightened eruptive activity	No. flights cancelled
Air Malta	3	1	2
easyJet	2	1	1
ITA Airways	10	5	5
Ryanair	8	6	2
Wizz Air	5	1	4

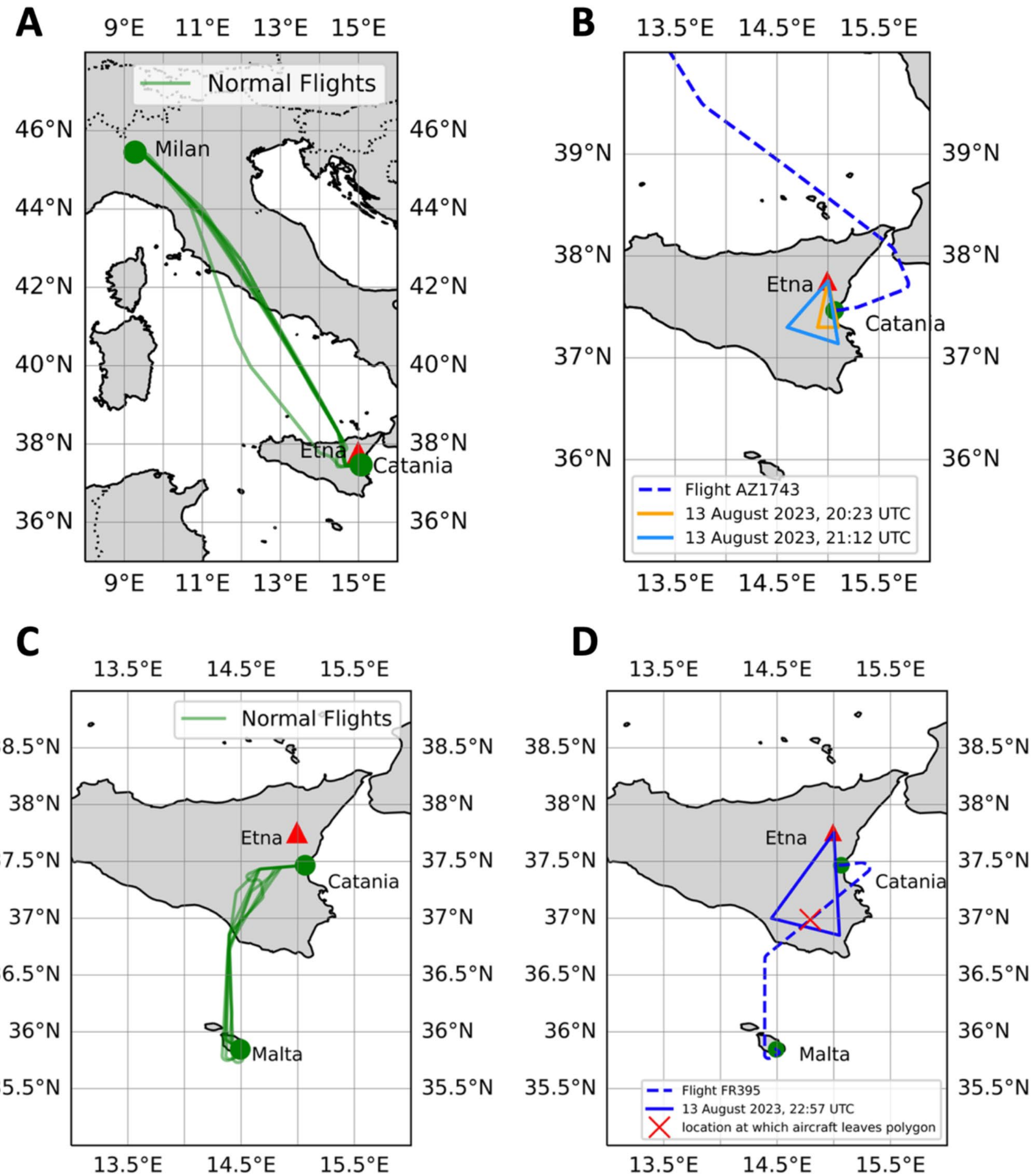

Fig. 4 (**A**) Flight AZ1743 (ITA) – flight paths for 7 flights between Catania and Milan airports before heightened eruptive activity. (**B**) Flight AZ1743 which took place during the time period covered by VAAs (20:32 and 21:12 UTC) shown in blue. (**C**) Flight FR395 (Ryanair) – flight paths for 7 flights between Catania and Malta airports before heightened eruptive activity. (**D**) Flight FR395 which took place during a time period covered by an advisory (22:57 UTC shown in solid blue line). The aircraft momentarily entered the ash polygon but exited it in less than one minute by dropping in altitude

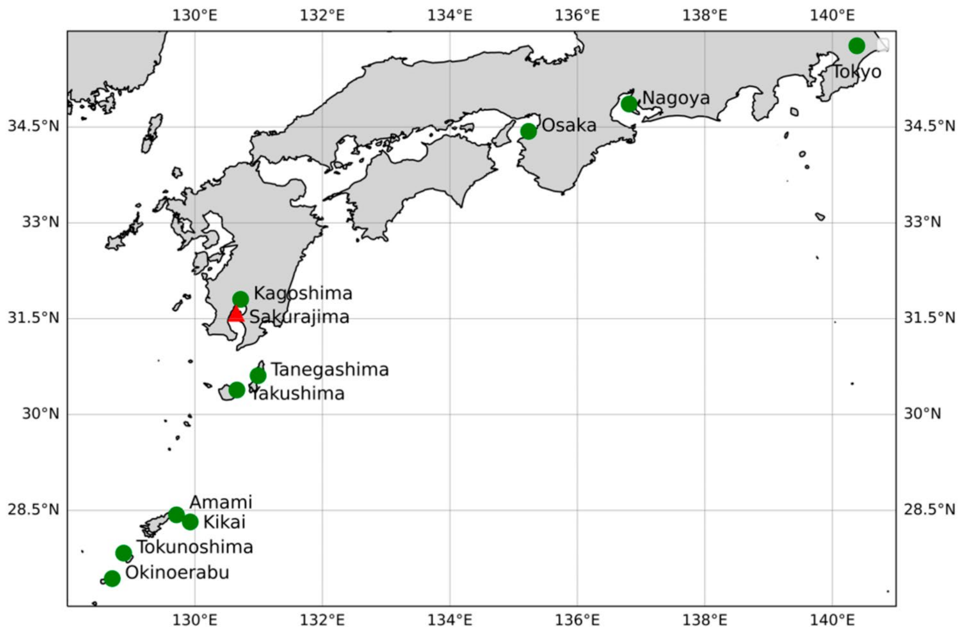

Fig. 5 Sakurajima volcano and airports analysed

ash. It could also be due to orographic effects associated with the high topography due to the volcano.

Marapi (December 2023)

For the Marapi eruption flights from Kuala Lumpur, Malaysia to Padang, Sumatra were analysed (Fig. 7). These included 5 aircraft: 3 AirAsia and 2 Super Air Jet aircraft. These flights operate between Kuala Lumpur and Padang. Marapi volcano is located approximately 60 km from Padang airport.

Two flights during quiescence and one during the time an orange ACC was issued fly north of the volcano, the rest fly south of the volcano before landing at Padang. There is a high variability in flight trajectory even on days of quiescence (Fig. 7A). These observations suggest that there are not designated routes for times of quiescence and times of volcanic unrest.

Sheveluch & Klyuchevskoy (April 2023 & October-November 2023)

For Sheveluch's heightened eruptive activity, flights from Anchorage, USA to East Asia (Tokyo, Seoul and Hong Kong) were analysed (Fig. 8). This included 19 flights, 17 cargo flights (from Nippon Cargo, Korean Air, FedEx, Polar Air Cargo and UPS) and 2 commercial flights (from Atlas Air and Cathay Pacific). The distances between Sheveluch volcano and the airports are 2816 km (Anchorage), 2801 km (Tokyo), 3253 km (Seoul) and 5359 km (Hong Kong). During periods of volcanic quiescence, these flights operate along the same route. During the heightened eruptive activities and plume dispersion, no flights were diverted or cancelled. Out of 19 flights, 11 landed late and 8 landed on time. From a bird's eye view, it appears that flight 5X62 on 12th April 2023 entered the ash polygon. However, when looking at the cross section, the aircraft flew over the ash plume. There were no noticeable differences in diversions for passenger and cargo flights for both volcanoes.

For Klyuchevskoy's heightened eruptive activities 16 flights were analysed, 13 cargo flights (from UPS, Atlas Air, Nippon Cargo, Polar Air Cargo and Fedex) and 3 commercial flights (from All Nippon) (Fig. 10). The distances between Klyuchevskoy and the airports are approximately the same as for Sheveluch as these two volcanoes are only separated by about 80 km. Similar to the Sheveluch data, during periods of volcanic quiescence, these flights operate a route that is very similar. During the heightened eruptive activities, one plane on its way to Seoul was diverted to Narita International airport in Tokyo, Japan and 6 aircraft were delayed. The rest arrived at their destinations on time.

As the ash plume developed and dispersed the flight paths increasingly deviated from their routes. The location of the aircraft at the time of the publication of the VAA can be traced, providing an idea of the location of the aircraft compared to that of the ash plume (Fig. 9). It is clear that the aircraft avoided the ash, staying on the usual trajectory for as long as possible until rerouting. This could be so the aircraft can take the shortest and quickest route before having to reroute or it could also be to avoid encountering aircraft flying in the opposite direction. Similar trends can be observed when analysing flight routes during heightened eruptive activity at Klyuchevskoy. Flights during heightened eruptive activity

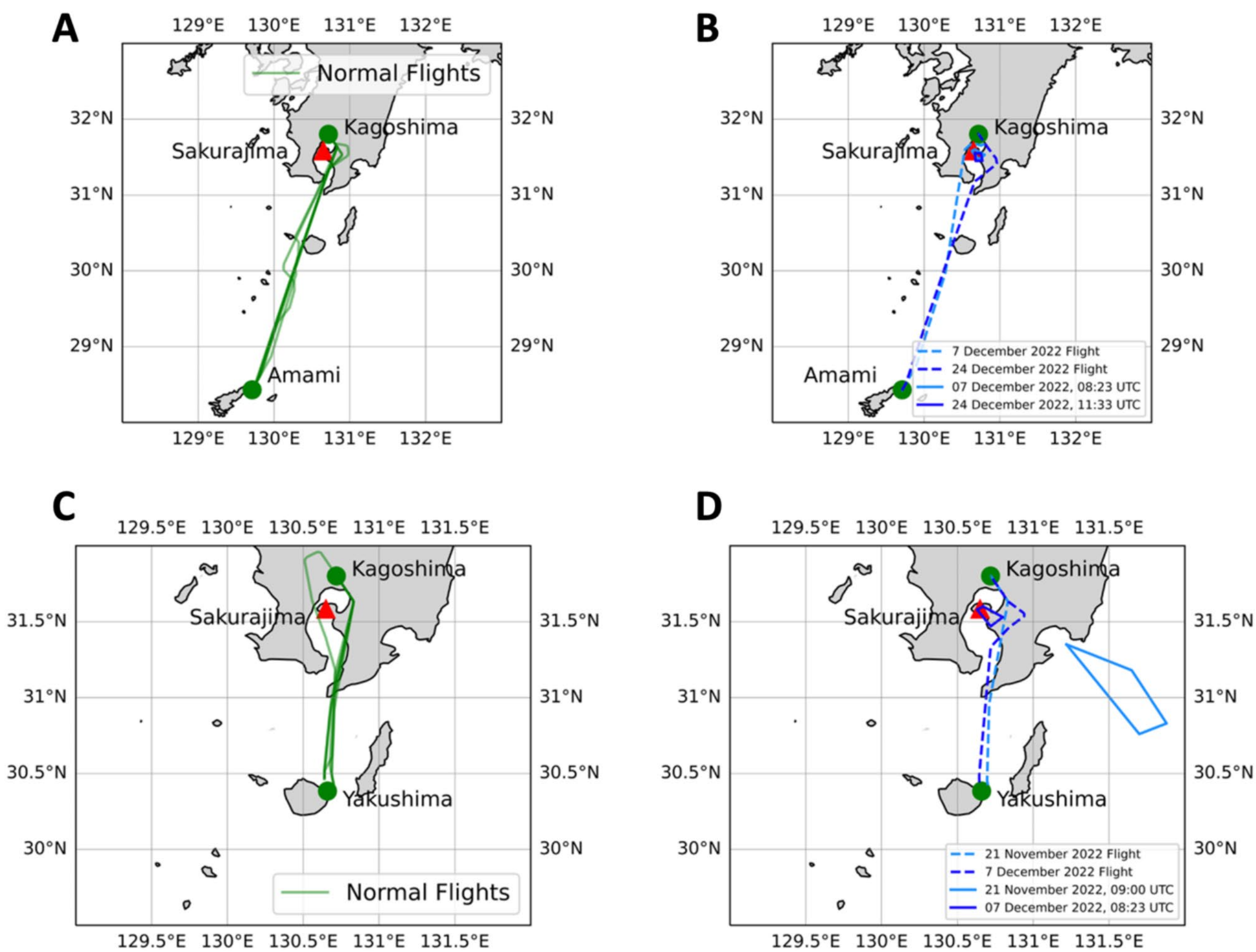

Fig. 6 (**A**) Flight JL3738 (Japan Airlines) – flight paths for 7 flights between Kagoshima and Amani airports before first heightened eruptive activity. (**B**) Two flights JL3738 which took place during a time period covered by two advisories (7 December 2022 at 08:23 UTC and 24 December 2022 at 11:33 UTC). (**C**) Flight JL3756 (Japan Airlines) – flight paths for 7 flights between Kagoshima and Yakushima airports before the heightened eruptive activity. (**D**) Two flights JL3756 which took place during a time period covered by two advisories (21 November 2022 at 09:00 UTC and 7 December 2022 at 08:23 UTC)

were rerouted to the south and avoided the ash cloud (Fig. 10).

Ubinas (2023)

For eruptive events at Ubinas, the flight routes of 6 Latam Airlines flights from Lima to São Paulo airports were analysed (Fig. 11). The distance from the departure airport, Lima Airport to the volcano is 814 km. During periods of volcanic quiescence, this flight route falls either north or south of the volcano. Out of the 16 normal flights studied, 8 flew north of the volcano and 8 flew south (Fig. 11C). During the period when VAAs were issued, 3 flew north of the volcano and 3 flew south (Fig. 11B). One flight was delayed while the rest landed on time. As seen in Fig. 11A and B, the trajectory direction is either south then east, passing just south of the volcano, or travelling in a more direct line (south-east), flying north of the volcano. The flight trajectories show aircraft travel along these routes during periods of quiescence; however they can also follow a trajectory very close to the volcano (Fig. 11C). It is important to note however, that this case study relates to relatively small eruptive activity (maximum of 7 km ash plume altitude a.s.l.) compared to the other case studies analysed above and the volcano is far from both the departure and the arrival airports.

Rerouting effects on fuel usage

Some of the delayed planes during the Klyuchevskoy and Sheveluch heightened eruptive activities was a UPS Flight 5X62, a Boeing 747–8 F, diverted and arriving late on the three flights which occurred when ash was observed in the atmosphere. This Boeing 747 – 400 has a fuel capacity of 216,840 L (Hendry 2023). The four engines burn approximately 4 L every second and about 10 to 11 tonnes of fuel per hour at cruising altitude. During the heightened eruptive activities, a UPS Flight 5X62, another Boeing 747–8 F was diverted and arrived late on the three flights which occurred when ash was observed in the

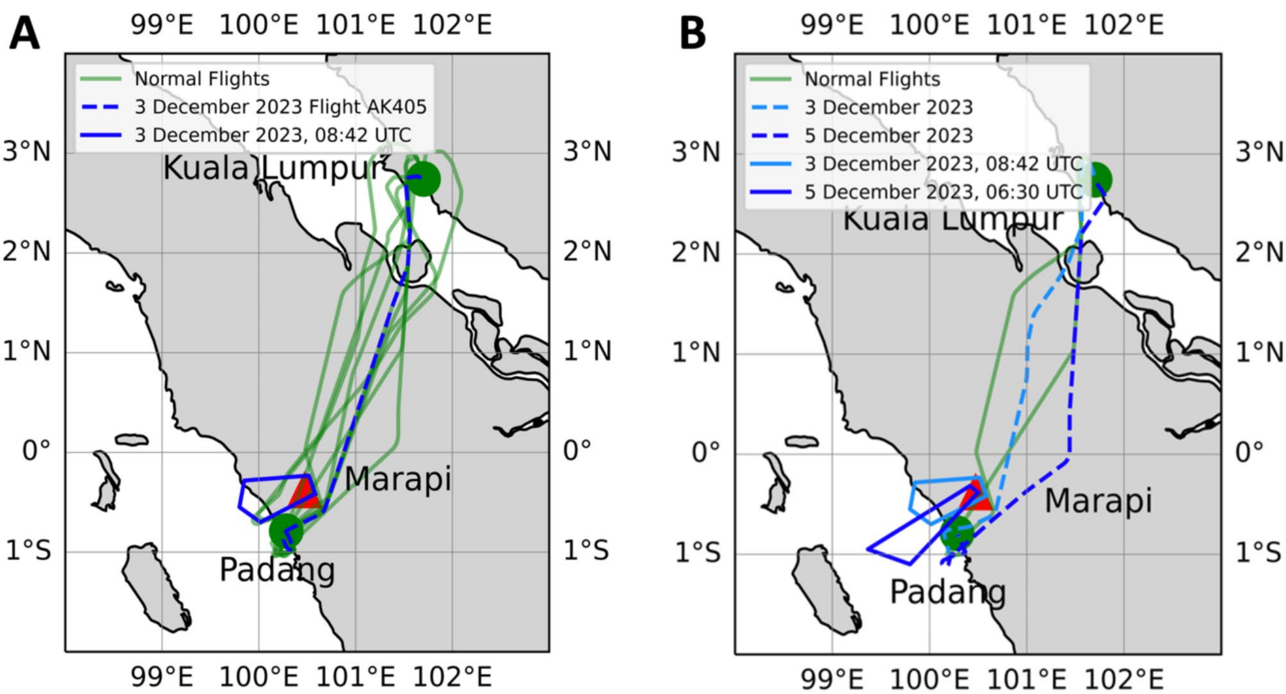

Fig. 7 (**A**) Flight AK405 (AirAsia) flight trajectories during quiescence and those during release of VAA with ash polygon on 3rd December 2023 at 08:42 UTC. (**B**) Flights IU185 (Super Air Jet) normal flight trajectories and flights during release of VAA with ash polygons on 3rd December 2023 at 08:42 UTC and 5th December 2023 at 06:30 UTC

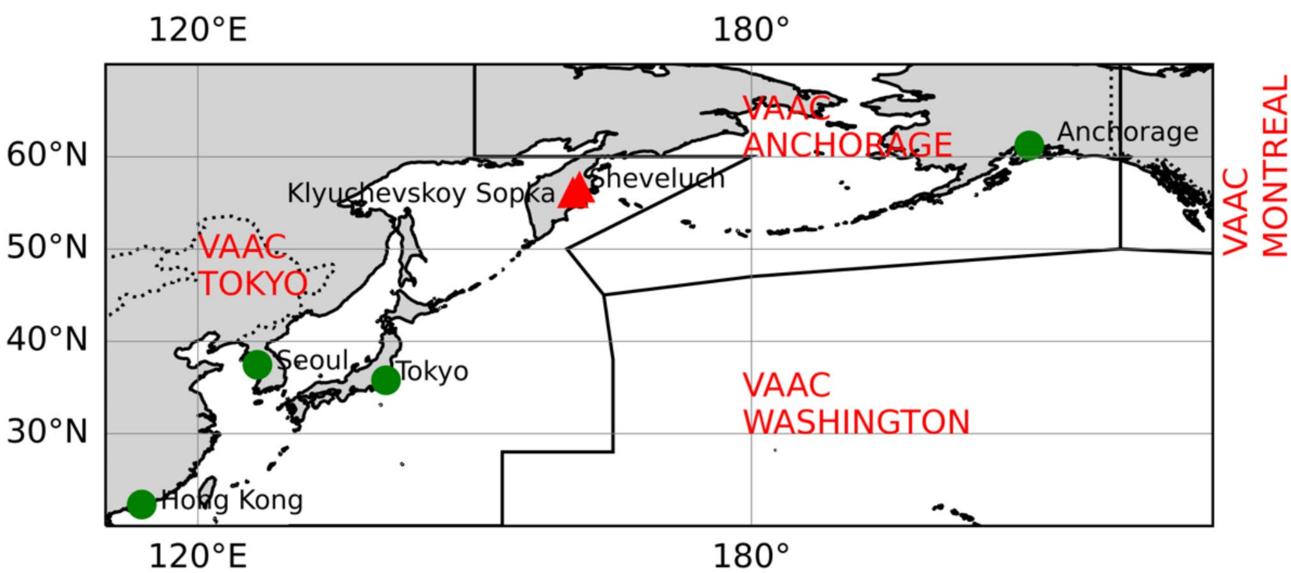

Fig. 8 Sheveluch and Klyuchevskoy volcanoes and airports analysed with the VAAC areas of responsibility

atmosphere. The fuel capacity for this plane is roughly 230,000 L, equivalent to about 188 tonnes of kerosene (Airport Technology 2024). Fuel burnt during flights that occurred when no ash was present were compared with those during the Sheveluch and Klyuchevskoy heightened eruptive activities which had emitted ash (Fig. 12). During periods of no ash, the travel time for these flights ranges from 10 to 13 h. When considering this time range with the 10 to 11 tonnes of fuel consumed per hour, this gives roughly 100 to 143 tonnes of fuel burnt per flight. A clear oscillation in the amount of fuel burnt per flight is visible in Fig. 12. This is probably caused by a change in wind patterns and the location of the jet stream throughout the year which affects the flight duration. During the eruptions studied here, the travel time ranged from 11.5 to 13.6 h (equivalent to approximately 115 to 150 tonnes

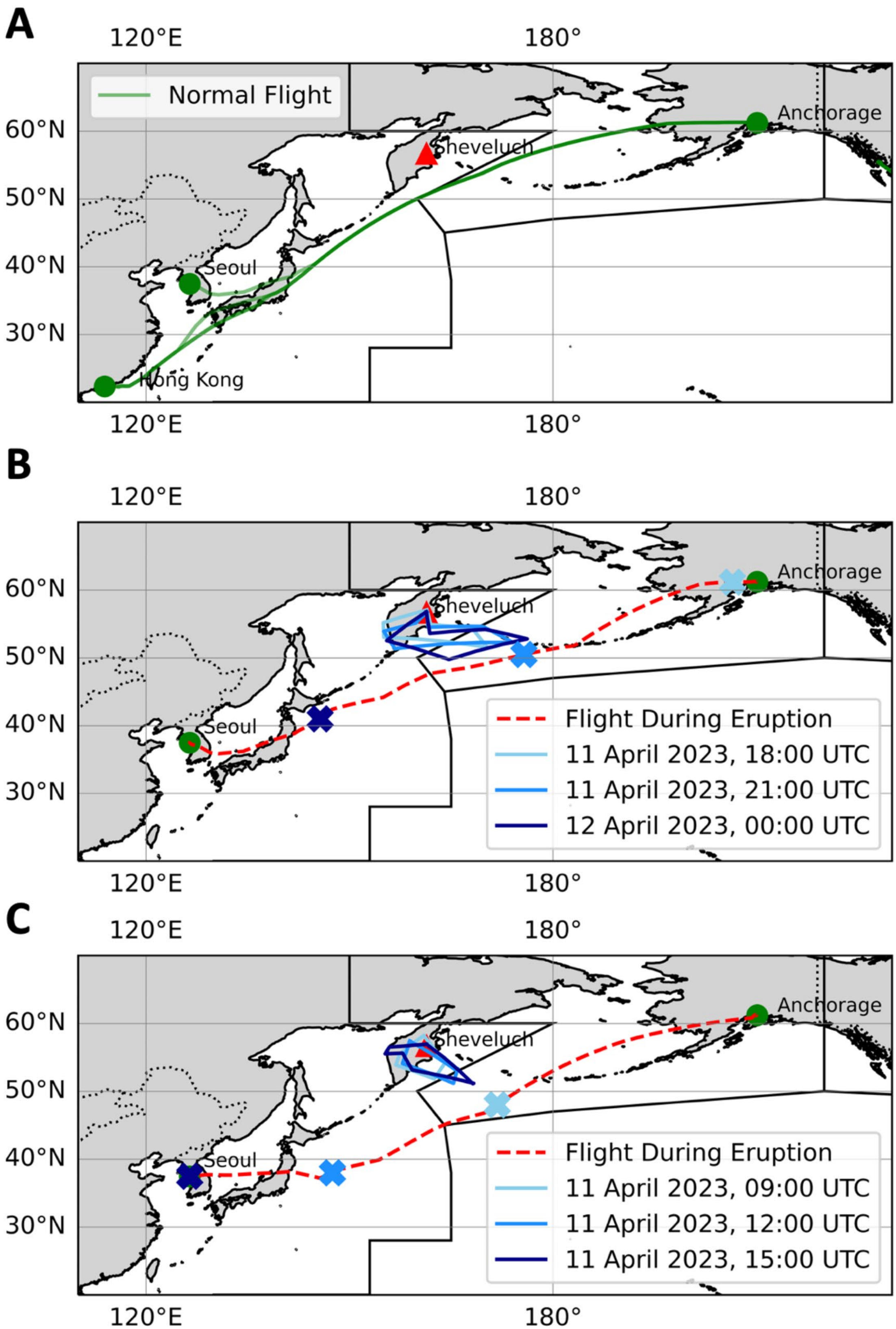

Fig. 9 (**A**) 9 normal flights from studied airlines (**B**) Flights 5X64 (UPS) and (**C**) 5Y537 (Atlas Air) during the Sheveluch 11th to 15th April 2023 heightened eruptive activity. Ash outlines become darker with passing time (time of ash location in legend). The location of the aircraft at the times of the ash outlines are shown by the X and their colour match those of the ash outlines. The black lines outline the different VAAC areas of responsibility

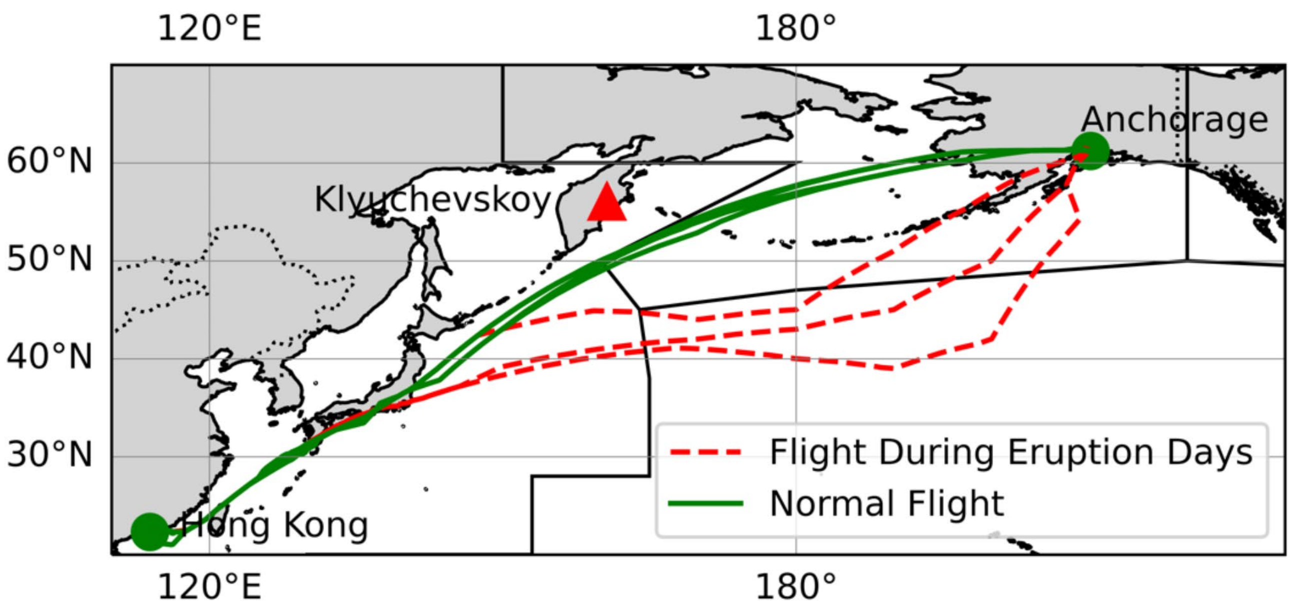

Fig. 10 Flights 5X62 (UPS) during the Klyuchevskoy heightened eruptive activity (dashed red line) and during times of volcanic quiescence in the region (green). The black lines outline the different VAAC areas of responsibility

of fuel burnt). While below the fuel capacity of the engine these results show that some flights during the eruptions studied here clearly consume more fuel than during normal conditions.

SO_2 plumes

A preliminary study on whether aircraft encounter SO_2 plumes was also carried out. Only two eruptions were analysed as the rest of the eruptions either did not have SO_2 data available or no SO_2 was detectable. For 10th–15th April 2023 heightened eruptive activity at Sheveluch, the ash and gas are broadly co-located (Fig. 13) so in this case, the aircraft did not fly into volcanic SO_2. The other eruption where SO_2 was visible was the Marapi December 2023 eruption. The SO_2 and ash were co-located, and since the aircraft avoided ash, they also avoided the SO_2 (Fig. 14). There was no apparent occurrence of ash and SO_2 separation based on satellite detection/observation.

Discussion

The comparison between flights during periods when VAAs are issued and periods when they are not is described below. The potential reasons for aircraft deviation are then highlighted, followed by the overall behaviour of the aircraft in all the studied regions during the various eruptions.

Aircraft behaviour in the presence vs. absence of ash

Comparison between flights during times when VAAs were issued for the air traffic regions compared to times of volcanic quiescence sometimes showed flights clearly deviating from their normal flight pattern. The two Kamchatkan volcanic eruptions led to significant rerouting of aircraft. Kamchatka is a highly active volcanic region, meaning affected airlines must often account for volcanic activity. The Sakurajima, Ubinas and Marapi events showed aircraft trajectories with no clear differences between flight paths during times when VAAs were issued compared to during periods of quiescence. For the Sakurajima eruptive events, two flights deviated slightly from the usual flight path and we interpret that this was to avoid ash in the atmosphere (Fig. 6C and D), but the other flight paths remained similar during eruptive activity and times of quiescence. Aircraft that did not show distinct modifications to their flight routes still avoided the areas identified in the VAA suggesting that, given the frequency of activity at this volcano, flight routes already account for potential for ash in the atmosphere near the volcano and further responses are not necessary.

Reasons for ash avoidance

Differing reactions to volcanic emissions by the airlines are caused by multiple factors. An ash plume may be very widespread or very contained around the volcano and airline and/or pilot decisions are not expected to be the same in these two instances. Furthermore, the ash cloud top height matters: if it is much lower than cruising altitude, flying over the ash plume may be possible. This was the case for the eruption of Ubinas (maximum plume altitude of 7 km a.s.l). In the case of Sheveluch, Klyuchevskoy and Marapi, ash altitudes reached 16 km, 14 km and 15 km a.s.l., respectively, impacting cruising altitude. As for Sakurajima and Etna, ash reached a maximum altitude of 3 km and 8.5 km a.s.l., respectively.

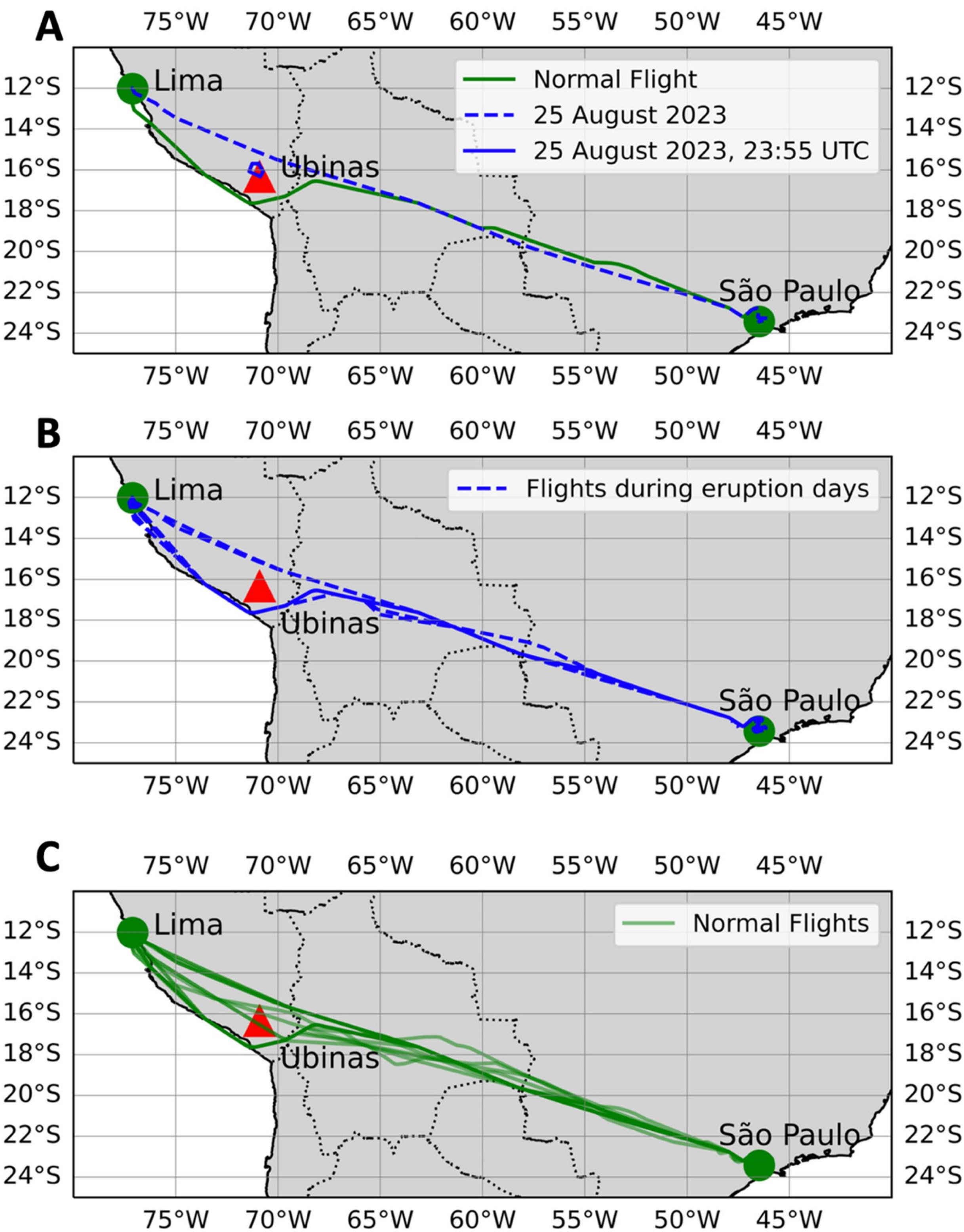

Fig. 11 Flights from Latam Airlines from Lima, Peru to São Paulo, Brazil during heightened activity at Ubinas volcano. (**A**) Heightened eruptive activity on the evening of 25th August 2023. The green line represents a flight on 25th before the heightened eruptive activity. The blue line around the volcano (red triangle) represents the ash cloud contour described in the first VAA report of 25th August 2023 at 23:55 UTC. The dotted blue line represents flight during heightened eruptive activity. (**B**) Flight trajectories during heightened eruptive activities from Ubinas. (**C**) Flight trajectories during periods of no emissions from the volcano

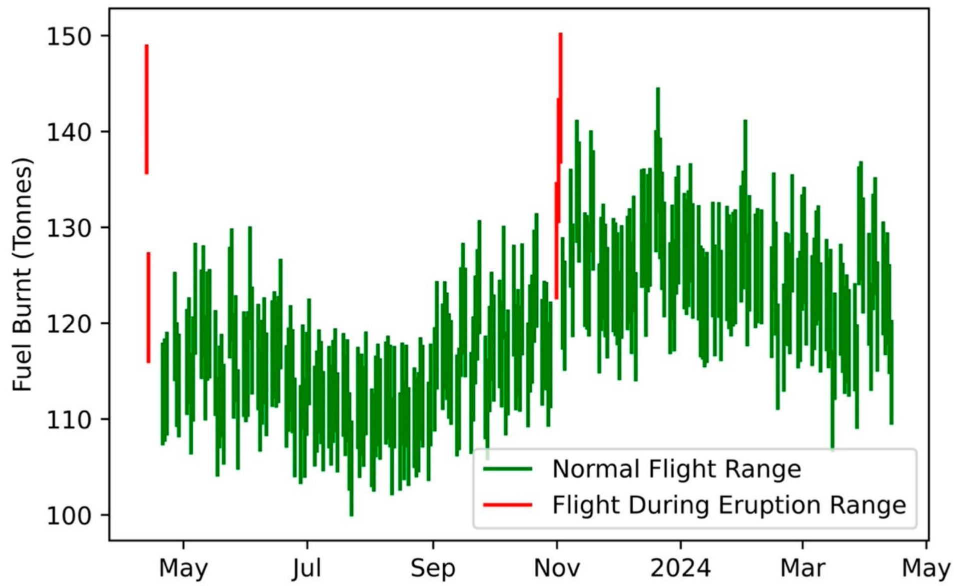

Fig. 12 Fuel burnt range during flight 5X62 throughout the year and when ash was present in the atmosphere. Each vertical line represents the range of fuel burnt for one flight

These are below cruising altitude but since the volcanoes are close to airports, this can impact landing and takeoff for aircraft.

When flight trajectories pass by volcanoes such as Etna and Sakurajima that are located close to airports, the avoidance of volcanoes may also be related to orographic effects associated with topographic highs, making meteorology, in particular wind, more variable in these areas. There were no cancellations of flights to Kagoshima and very few delays during the time of activity at Sakurajima, whereas there was a lot of disruption due to the Etna eruptive activities for all companies (except Neos which didn't have planned flights on the eruption days in the first place).

Weather and wind patterns are not the same along all flight paths around the world. In some cases, storms, strong winds or turbulence could be considered more hazardous than volcanic ash to an aircraft. This means that we cannot solely rely on differences in flight routes to how decisions were made about flight routing and the risk posed by different hazards, including volcanic ash, in the flights analysed during this study. Furthermore, some flights analysed were significantly shorter than others. For example, flights over the North Pacific were approximately 10–13 h, meanwhile the flights over Indonesia and Malaysia were 1 h. In some instances, the ash emissions affected aircraft in the middle of their route (North Pacific and South America) while others were affected close to takeoff and landing (Italy). Finally, some ash plume emissions reached greater altitudes (Sheveluch – approx. 16 km a.s.l.) than others (Ubinas – 7 km a.s.l.) impacting the amount to which flight routes needed to change to avoid areas potentially containing ash. All flights avoid ash in different ways, some because their normal flightpath naturally avoids the ash, some by rerouting or diverting to other airports and others by cancelling flights.

SO_2 plumes

Only two examples where SO_2 information is available were used in this study and more case studies are needed to conclude whether aircraft may enter separate SO_2 plumes when avoiding detected ash plumes. SO_2 dispersion information is not currently communicated in the same way as volcanic ash in VAAs, and the challenges in doing so are discussed in detail in Kristiansen et al. (2024).

Overall statistics

A total of 28% of all flights analysed were delayed (Table 5) but this was probably not due to rerouting as the flight durations were broadly the same. Rather the delay occurred due to delayed takeoff, as was the case during the Marapi eruption when 52% of the flights analysed were delayed. These takeoff delays could be due to concerns about the volcanic eruption or other factors

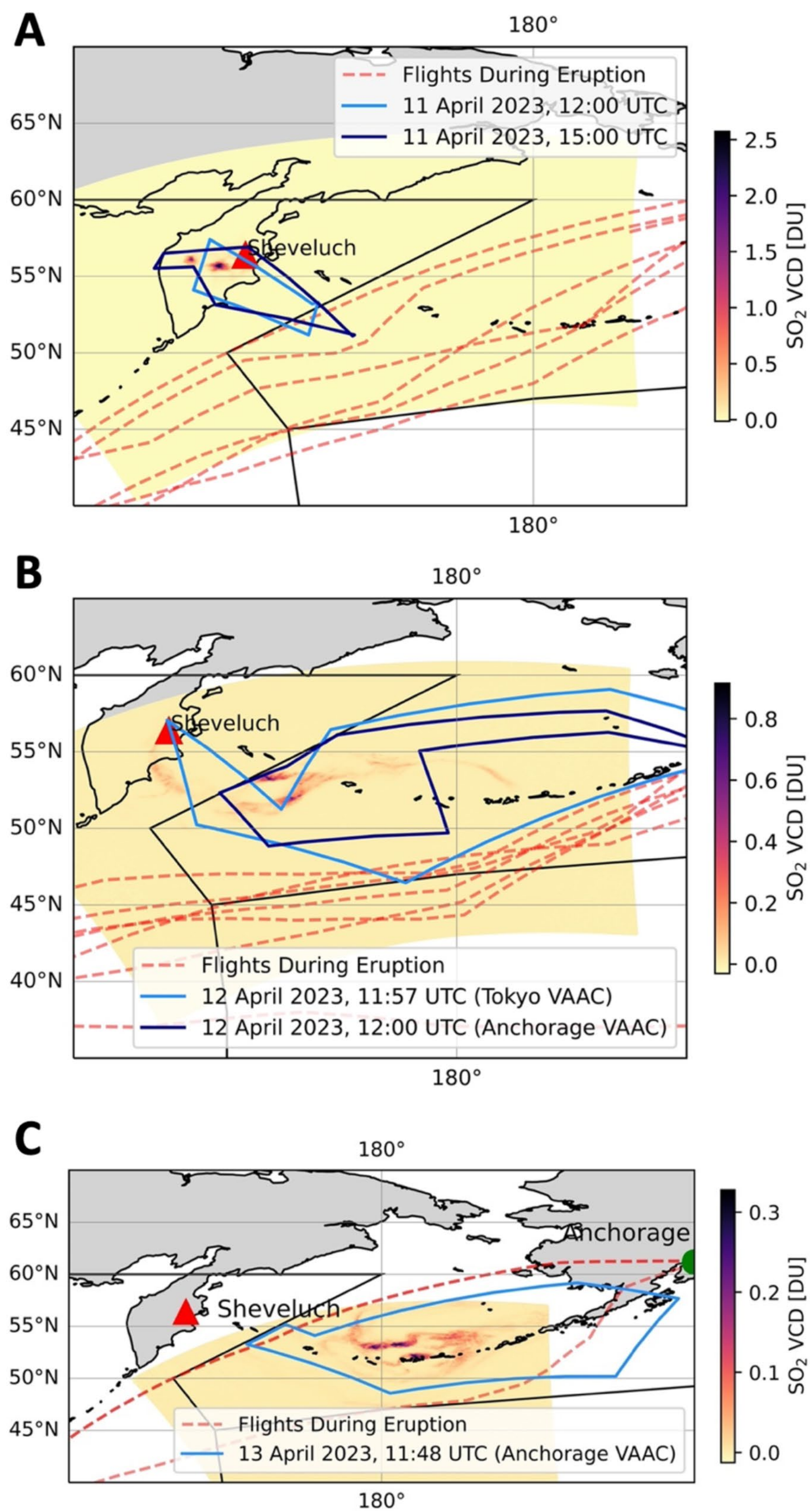

Fig. 13 TROPOMI-derived SO_2 and ash location with flights from the same day—11th to 13th April 2023. (**A**) 11th April with Tokyo VAAC ash outlines. (**B**) 12th April with Anchorage and Tokyo VAAC ash outlines. (**C**) 13th April with Anchorage VAAC ash outlines. The black lines outline the different VAAC areas of responsibility

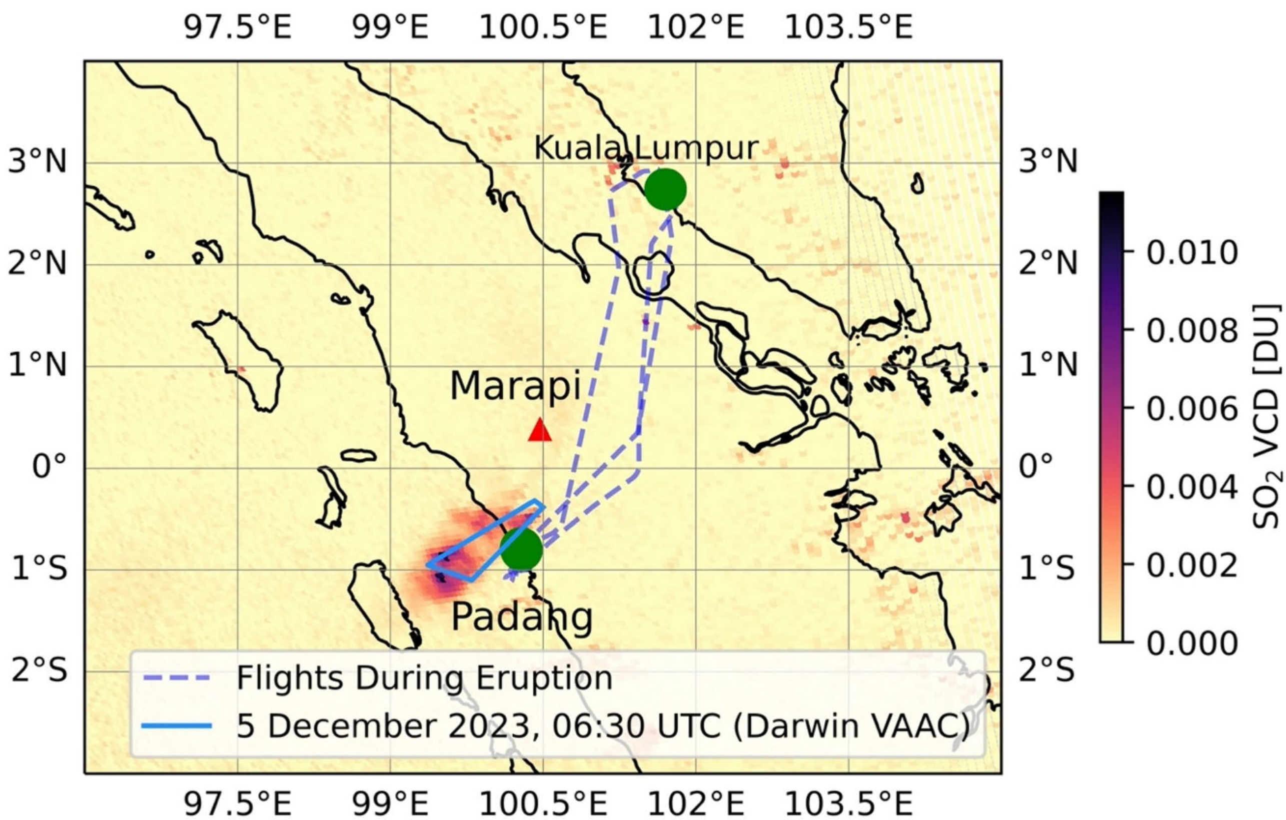

Fig. 14 5th December 2023 SO_2 and ash (solid blue line) location with flights (dotted line) during eruption

unrelated to the eruption. The exceptions are Sheveluch and Klyuchevskoy where rerouting resulted in delays to 58% and 63% respectively of flights during the time when ash was reported to be in the atmosphere using VAAs. The low number of significant delays due to rerouting could be because (1) the ash emission was small and so easily avoided (as was the case for Ubinas – only one flight out of the 6 was delayed, and before takeoff) (2) volcanic ash is not a factor accounted for when planning the route and (3) these are frequently active volcanoes, and flight routes already take potential eruptive activity into account. However, this could mean that aircraft that are rerouted (as is the case with the Sheveluch and Klyuchevskoy ash emissions) are consuming more fuel.

Table 5 Summary of flight information for the different heightened eruptive activities

Volcano	Etna		Sakurajima		Marapi		Sheveluch		Klyuchevskoy		Ubinas		Total	
	Raw No.	%	Raw No.	%	Raw No.	%	Raw No.	%	Raw No.	%	Raw No.	%	Raw No.	%
No. Flights	61		58		23		19		16		6		183	
Entering polygon	1	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	1	**0.5**
No noticeable deviation	51	**83**	58	**100**	23	**100**	3	**16**	1	**6**	6	**100**	142	**78**
Noticeable deviation	10	**16**	0	**0**	0	**0**	16	**84**	15	**94**	0	**0**	41	**22**
Cancellations	14	**-**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	14	**-**
Flights diverted to another airport	10	**16**	0	**0**	0	**0**	0	**0**	1	**6**	0	**0**	11	**6**
Delay 15–30 min	4	**7**	Unknown		5	**22**	Unknown		1	**6**	0	**0**	10	**5**
Delay 30+mins	11	**18**	Unknown		7	**30**	Unknown		9	**56**	1	**17**	28	**15**
Delay Total	15	**25**	3	**5**	12	**52**	11	**58**	10	**63**	1	**17**	52	**28**

Conclusions

Analysis of volcanic ash emissions versus flight routes demonstrates that the impacts on flight rerouting are related to the extent of the ash dispersal: rerouting was more visible during emissions with greater air space affected. Very few flights flew through areas thought to contain ash according to VAA polygons. In some cases, rerouting was clear and led to delays, whilst in other cases there were no clear signs of rerouting. For those events where both ash and SO_2 location information was available (Sheveluch and Marapi), where airlines rerouted to avoid ash, post-eruption analysis of satellite imagery showed they also avoided the co-located SO_2 plumes. More research is needed to determine whether the avoidance of both ash and SO_2 during eruptions is common. The investigation of pilot reports and individual airline policies regarding volcanic ash avoidance as well as communicating directly with pilots and airlines would provide further insight into how and when decisions are made regarding ash avoidance.

Abbreviations

ACC	Aviation Colour Code
AoR	Area of Responsibility
JMA	Japan Meteorological Agency
MWO	Meteorological Watch Office
NOTAM	NOTices to Air Men
SIGMET	SIGnificant METeorological report
TROPOMI	Tropospheric Monitoring Instrument
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Centre
VAG	Volcanic Ash Graphic
VONA	Volcanic Observatory Notice for Aviation

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Author contributions

JD conceived and designed the analysis, created the codes, analysed the imagery and drafted the manuscript. MB, SE, BE and CH supervised the project. SE aided with the interpretation of the data. All authors reviewed the manuscript.

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Data availability

Ash data from the figures can be found on the VAAC websites or on figshare. SO_2 data has been deposited on figshare. https://doi.org/10.6084/m9.figshare.27620793; https://doi.org/10.6084/m9.figshare.27630096; https://doi.org/10.6084/m9.figshare.27641022; https://doi.org/10.6084/m9.figshare.27641028; https://doi.org/10.6084/m9.figshare.27641037; https://doi.org/10.6084/m9.figshare.27641043; https://doi.org/10.6084/m9.figshare.27641049; https://doi.org/10.6084/m9.figshare.27642159. Flight trajectory data is available on https://flightradar24.com with a subscription.

Declarations

Competing interests
The authors declare no competing interests.

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