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RESEARCH ARTICLE

The European Volcano Observatories and their use of the aviation colour code system

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Abstract
Volcano observatories (VOs) around the world are required to maintain surveillance of their volcanoes and inform civil protection and aviation authorities about impending eruptions. They often work through consolidated procedures to respond to volcanic crises in a timely manner and provide a service to the community aimed at reducing the potential impact of an eruption. Within the International Airways Volcano Watch (IAVW) framework of the International Civil Aviation Organisation (ICAO), designated State Volcano Observatories (SVOs) are asked to operate a colour coded system designed to inform the aviation community about the status of a volcano and the expected threats associated. Despite the IAVW documentation defining the different colour-coded levels, operating the aviation colour code in a standardised way is not easy, as sometimes, different SVOs adopt different strategies on how, when, and why to change it. Following two European VOs and Volcanic Ash Advisory Centres (VAACs) workshops, the European VOs agreed to present an overview on how they operate the aviation colour code. The comparative analysis presented here reveals that not all VOs in Europe use this system as part of their operational response, mainly because of a lack of volcanic eruptions since the aviation colour code was officially established, or the absence of a formal designation as an SVO. We also note that the VOs that do regularly use aviation colour code operate it differently depending on the frequency and styles of eruptions, the historical eruptive activity, the nature of the unrest, the monitoring level, institutional norms, previous experiences, and on the agreement they may have with the local Air Transport Navigation providers. This study shows that even though the aviation colour code system was designed to provide a standard, its usage strongly depends on the institutional subjectivity in responding to volcano emergencies. Some common questions have been identified across the different (S)VOs that will need to be addressed by ICAO to have a more harmonised approach and usage of the aviation colour code.

Keywords Aviation colour code · State Volcano Observatories · Europe · Exercises · IAVW · ICAO

Introduction

Volcano observatories (VOs) are entities or institutions responsible for monitoring and surveillance activities at specific volcanoes. The VOs study and monitor these volcanoes, inform about volcanic activity, and warn authorities and/or the public about impending eruptions and their associated hazards. At the international level, their job definition, responsibilities, and structure differ significantly from country to country, depending primarily on cultural, political, and economic factors (Pallister et al. 2019; Lowenstern et al. 2022a, 2022b). Some VOs have personnel working in operational service; others rely on academic institutions and provide service when called for. Some have specific mandates from their governments and are functional within a predefined

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response plan in the event of a volcanic crisis; others are not part of any specific operational plan. Some are designated by their State as a "State" Volcano Observatory (SVO) within their International Civil Aviation Organization (ICAO) region's Air Navigation Plan (Volume I, Table MET I-1 *State Volcano Observatories*—all available via icao.int[1]) and as such are approved to issue information into the aviation system.

This ambiguity in responsibility and role is reflected in an objective difficulty in counting how many VOs are in the world. Some contacts are currently listed in the World Organization of Volcano Observatories (WOVO) webpage (https://wovo.iavceivolcano.org/observatories); others are counted in the recent publication by Lowenstern et al. (2022a, 2022b). One additional list is accessible through the Handbook on the International Airways Volcano Watch (IAVW - ICAO 2019). Initiatives are currently ongoing to regulate and harmonise the concept of a VO and identify the official institutions embracing this role. In particular, it is worth mentioning the effort conducted by the leadership of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) to rejuvenate the WOVO commission and reshape it into a network with clear objectives and mandates (IAVCEI Newsletter 2019), as well as the ongoing work within the ICAO on updating the IAVW Handbook with the current list of institutions in the world that may be able to support and inform the aviation sector about volcanic activity, whether or not they are designated as SVO.

Despite the lack of centralised coordination amongst VOs and the numerous types of VO entities in the world, within the aviation community, the identity of a SVO is relatively well defined as it is stated within the Annex 3 to the Convention on International Civil Aviation: "State volcano observatory: A volcano observatory, designated by regional air navigation agreement, to monitor active or potentially active volcanoes within a State and to provide information on volcanic activity to its associated area control centre/flight information centre, meteorological watch office and volcanic ash advisory centre" (ICAO 2019).

In this paper we define VOs as those institutions in Europe that have (or are expected to have soon) a legal mandate to conduct the volcanological surveillance through a real-time monitoring service, to maintain a 24/7 alert system, and that are the official contact for volcanological advice to civil protection authorities.

[1] European SVOs are usually designated in the European Air Navigation Plan Vol I and/or the North Atlantic Air Navigation Plan Vol I, but may be designated in other Air Navigation Plans for territories further afield.

The establishment of the IAVW and requirements from ICAO

The IAVW was established by ICAO in coordination with the World Meteorological Organization (WMO) in the late 1980s, with the nine Volcanic Ash Advisory Centres (VAACs), each with a defined geographic area of responsibility, being implemented in the early 1990s (ICAO 2021). It was created to coordinate actions across the volcanological and meteorological communities to mitigate the volcanic ash risks to aviation (Lechner et al. 2017). The triggering event occurred on 24 June 1982 when a British Airways B747 lost power at all four engines when flying between Kuala Lumpur (Malaysia) and Perth (Australia) because it flew into an ash cloud originating from Mt. Galunggung in Indonesia (Casadevall 1993; Guffanti et al. 2010). This new threat needed a proper coordinated response. Through recommendations and guidelines, ICAO finally adopted and published new standards in warning issuances and reporting on volcanic activity in 1987 (ICAO 2017). That set of instructions created the basis for establishing the framework of IAVW. This system is currently an operational programme binding on all ICAO member States (countries) through the Chicago Convention (Lechner et al. 2017) and it relies on three main components: observing, advisory, and warning. SVOs play a role within this programme as information providers and, herein, their roles and responsibilities are well set. By designating a VO as a *State* Volcano Observatory, ICAO is ensuring that there is one responsible organisation providing volcanic activity advice into the aviation system, thereby reducing the risk of conflicting information for aviation users. As part of this structured service, described in the Annex 3 of the Convention on International Civil Aviation (ICAO 2010) and further in the IAVW Handbook as well as the Guidance for SVOs, SVOs must provide information to aviation on volcanic activity and it is suggested they utilise the aviation colour code and disseminate the information about the ongoing volcanic activity through a Volcano Observatory Notice for Aviation (VONA; ICAO 2019). More specifically, the aviation colour code is cited to be "a key component of the global standardisation of information provided by volcanological agencies to aviation users" (ICAO 2019). It is expected that the use of colour code and VONA will become a *recommended practice* in Annex 3 from November 2025 (ICAO 2018, 2021). The system currently relies on four levels, each characterised by a colour,

Table 1 The Aviation Colour Code system as defined and provided by the International Civil Aviation Organisation (ICAO) to be used by Volcano Observatories (VOs) to inform the civil aviation community on volcano activity level and potential threat in the presence of an (imminent) eruption. It is published on the World Organization of Volcano Observatories' website (https://wovo.iavceivolcano.org/volcanic-alert-levels?layout=edit&id=15)

AVIATION COLOUR CODES DEFINED BY THE INTERNATIONAL CIVIL AVIATION ORGANIZATION	
GREEN	Volcano is in normal, non-eruptive state. or, after a change from a higher 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 higher 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 [specify ash-plume height if possible]
RED	Eruption is forecast to be imminent with significant emission of ash into the atmosphere likely. or, Eruption is underway with significant emission of ash into the atmosphere [specify ash-plume height if possible]

which corresponds to different levels of activity at the volcano (Table 1). A fifth level, defined as "unassigned", will be added from November 2025 for those volcanoes that are considered under-monitored or not monitored at all (Paula Acethorp, personal communication). Despite the large debate about the usage of general Volcano Alert Level Systems (VALS) and the difficulties in defining categories for describing the level of volcanic activity and reflecting in a way both the uncertainty and the uniqueness of each volcanic setting (Papale 2017; Fearnley and Beaven 2018), there are reports of efficient and extended usage of the aviation colour code system in the past decades (Guffanti and Miller 2013; Potter et al. 2017).

Building a European community of Volcano Observatories

The European project EUROVOLC, which was active in the period 2018–2022 (http://eurovolc.eu), offered a unique opportunity for many VOs in Europe to work together in harmonising procedures, comparing standards, and identifying good practices. One of the tasks was dedicated to deliver information about monitored volcanoes and their hazards in a common and unified format. The result is the European Catalogue of Volcanoes (accessible online at http://volcanoes.eurovolc.eu), which represents the first step toward a pan-European database on active volcanoes. A second task focussed on revisiting the current communication strategies in place between VOs and VAACs for identifying improvements, reinforcing connections, and sharing practices. An initial workshop was held in January 2019, in Exeter (UK), to gather European VOs and VAACs representatives. A second one was held in November 2021, only virtual, and extended the audience including people from the aviation sector (industries, agencies, airlines), all the European VOs and their VAACs of reference. During both workshops, attention was given to the current procedures in place to maintain connection between VOs and VAACs in quiet and crisis time. VAACs identified priorities in the type of information they would need to execute their dispersal forecast models and VOs showed the level of capabilities to monitor, observe, and quantify volcanic eruptions (IAVCEI Newsletter 2022). These workshops represented a milestone in the process of linking European VOs and VAACs for a coordinated response to mitigate the potential disruptions caused to aviation by volcanic eruptions. A major theme related to the use of the aviation colour code by European VOs. This included when and how colour code decisions are made, and how information about the colour code is delivered to stakeholders.

This paper is the first inclusive overview describing the European VOs, their area of responsibility, their monitoring setup, and the way they inform aviation sector on volcano status, volcanic eruptions, and, in general, on volcanic hazards posed to air traffic. It reports on real cases and exercises, current

procedures, and ongoing challenges. It also widens the discussion bringing attention to complementary alert levels, such as ground-based VALS, aimed at informing about hazards affecting the surrounding of a volcano and the people in its vicinity.

In September 2023, the 2nd European Volcano Observatories workshop took place in Catania (Italy) in the framework of the Aristotle ENSHP project (Aristotle's website 2023). The main objective was to formalise the collaboration between VOs through the establishment of a European network for strengthening the collective planning, preparedness, and response capability to volcanic emergencies, at local, national, and European level (INGV's website 2023).

The European Volcano Observatories

Thirteen institutions are currently the reference entities for operational volcano monitoring of volcanoes in Europe and its overseas territories (OT) as shown in Fig. 1. Amongst those, nine are officially recognised as SVO(s) with defined responsibilities towards the aviation community, offering a 24/7 surveillance service. These nine are listed in the updated IAVW Handbook, which will be published online in 2025 and are highlighted in bold in Table 2. Four institutions are in the process of defining the role through their governing State agreements and progress has been made towards the formalisation of responsibilities.

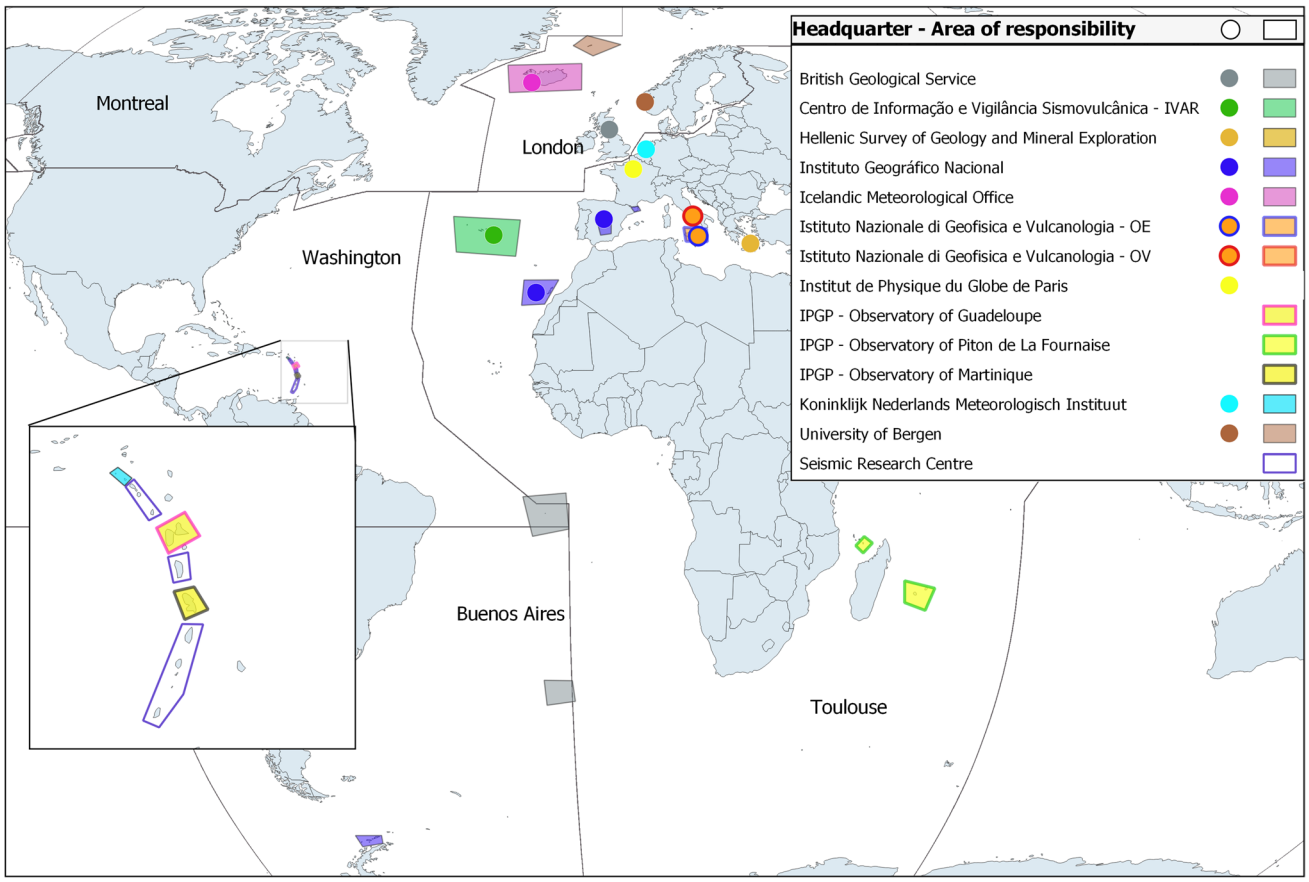

Fig. 1 Map showing the location of European Volcano Observatories (VOs) (large, coloured points) and the respective volcanoes/volcanic areas they are responsible for (coloured polygons). The inset image shows the islands of the Lesser Antilles where different territories are monitored by different institutions. For the sake of clarity, the list also includes the Seismic Research Centre (SRC) based in Trinidad which is responsible for earthquake and volcano monitoring in the English-speaking Eastern Caribbean but does not belong to European VOs. Straight black lines identify the zonation of different VAACs responsibilities (as retrieved from https://gis.icao.int/portal/home/item.html?id=4a65882574b44ecca159fa6429d03fd6)

Table 2 The table summarises key information for the European VOs, including the level of service, whether they are listed in the International Aviation Volcano Watch (IAVW) Handbook, whether they are a designated State Volcano Observatory, whether the Aviation Colour Code (ACC) system is used and where it is possible to find the information on ACC (and VONA)

Institution	Level of service	Area of responsibility	IAVW contact	Usage of aviation colour code	Usage of ground-based alert level (VALS)	SVO designated (regional air navigation plan the designation is in)	Link to aviation colour code and VONA webpage	VAAC of reference	# of VONA released between 2018-2022 [exercises]
CIVISA-IVAR—Azores	24H	Azores	YES	YES	YES (http://www.ivar.azores.gov.pt/sjorge/Paginas/alertas-vulcanicos.aspx)	YES (NAT)	http://www.ivar.azores.gov.pt/sjorge/Paginas/comunicados.aspx	Toulouse	2 [16]
IGN—Spain	24H	Spain, Canary islands, Deception island	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (EUR)	Not public yet	Toulouse	29 [7]
INGV-OE—Italy	24H	Etna, Stromboli, Vulcano	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (EUR)	Etna volcano: https://www.ct.ingv.it/index.php/monitoraggio-e-sorveglianza/prodotti-del-monitoraggio/comunicati-vona	Toulouse	462 [1]
							Stromboli volcano: https://cme.ingv.it/bollettini-e-comunicati/messaggi-vona-stromboli		28 [0]
							Vulcano volcano: https://cme.ingv.it/bollettini-e-comunicati/messaggi-vona-vulcano		1 [0]

Table 2 (continued)

Institution	Level of service	Area of responsibility	IAVW contact	Usage of aviation colour code	Usage of ground-based alert level (VALS)	SVO designated (regional air navigation plan the designation is in)	Link to aviation colour code and VONA webpage	VAAC of reference	# of VONA released between 2018-2022 [exercises]
INGV-OV—Italy	24H	Vesuvius Campi Flregrei Ischia	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases (https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-web)	YES (EUR)	https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/vona	Toulouse	0 [24]
IPGP-OVPF—France	24H	Piton de la Fournaise	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (AFI)	Not public yet	Toulouse	82 [0]
IPGP-OVSG—France	24H	La Soufrière de Guadeloupe	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (CAR/SAM)	Not public yet	Washington	0 [3]
IPGP-OVSM—France	24H	Martinique	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (CAR/SAM)	Not public yet	Washington	0 [1]
IPGP-REVOSIMA—France	24H	Mayotte	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	NO	Not public yet	Toulouse	0 [0]

Table 2 (continued)

Institution	Level of service	Area of responsibility	IAVW contact	Usage of aviation colour code	Usage of ground-based alert level (VALS)	SVO designated (regional air navigation plan the designation is in)	Link to aviation colour code and VONA webpage	VAAC of reference	# of VONA released between 2018-2022 [exercises]
IMO—Iceland	24H	Iceland	YES	YES	No, but scientists advice is considered within the Civil Protection emergency levels/phases	YES (NAT)	https://en.vedur.is/earthquakes-and-volcanism/volcanoes/vona-notifications/	London	39 [52]
BGS—UK	Working hours	Ascension, Tristan de Cunha	NO	NO	No, but scientists advice is considered within the Civil Protection emergency levels/phases	NO	NA	Buenos Aires (Toulouse) + Washington	0 [0]
HSGME—Greece	24H	Santorini	YES (ISMOSAV)	NO	No, but scientists advice is considered within the Civil Protection emergency levels/phases	NO	NA	Toulouse	0 [0]
KNMI—The Netherlands	24H	Caribbean Netherlands	In progress	YES	YES (https://www.knmidc.org/volcanoes/?Alert-Levels)	In progress	https://www.knmidc.org/volcanoes/?Alert-Levels	Washington	0 [1]
University of Bergen—Norway	Working hours	Jan Mayen	NO	NO	NO	NO	NA	London	0 [0]

Centro de Informação e Vigilância Sismovulcânica dos Açores - Instituto de Investigação em Vulcanologia e Avaliação de Riscos (CIVISA-IVAR)—Azores (Portugal)

The institution and area of responsibility—Azores archipelago

The Centro de Informação e Vigilância Sismovulcânica dos Açores (CIVISA) is a private non-profit association of two partners: the Autonomous Region of the Azores and the University of the Azores. It was created in 2008 with the aim of implementing an integrated service for the permanent monitoring and assessment of geological hazards in the Azores region and it corresponds to the operational branch of the Instituto de Investigação em Vulcanologia e Avaliação de Riscos (IVAR) of the University of the Azores. CIVISA-IVAR is responsible for monitoring all islands of the Azores archipelago and the surrounding underwater area (Fig. 1 (green area) and Fig. 2). In its area of responsibility, there are 50 seismogenic zones and 26 active volcanoes and volcanic systems, 18 of which are subaerial, in all islands of the Azores except in Santa Maria, where volcanism is considered extinct. The other eight volcanic systems are submarine.

Monitoring capabilities and observatory operations

CIVISA manages a multiparametric monitoring system composed of several permanent networks (seismic, gas geochemistry, GNSS, and meteorological and hydrometric) spread over the different islands of the archipelago. All data are transmitted in real- or near real-time to the Data Acquisition Centre (CAD) (Fig. 2) in CIVISA's headquarters, located at the IVAR premises in the University of the Azores in Ponta Delgada, São Miguel Island. The CAD staff guarantees monitoring activities 24/7 through shifts of 8 h. Data acquired by the permanent networks are complemented by regular monitoring campaigns (gas and water sampling, GNSS observations, kinematics of unstable slopes, etc.) and, if necessary, temporary stations installed during periods of increased seismic or seismo-volcanic activity. The Emergency Operations Centre (COE) (Fig. 2) is responsible for the integration of all information acquired by the multiparametric monitoring system and ensures communication with Azores regional civil protection and local

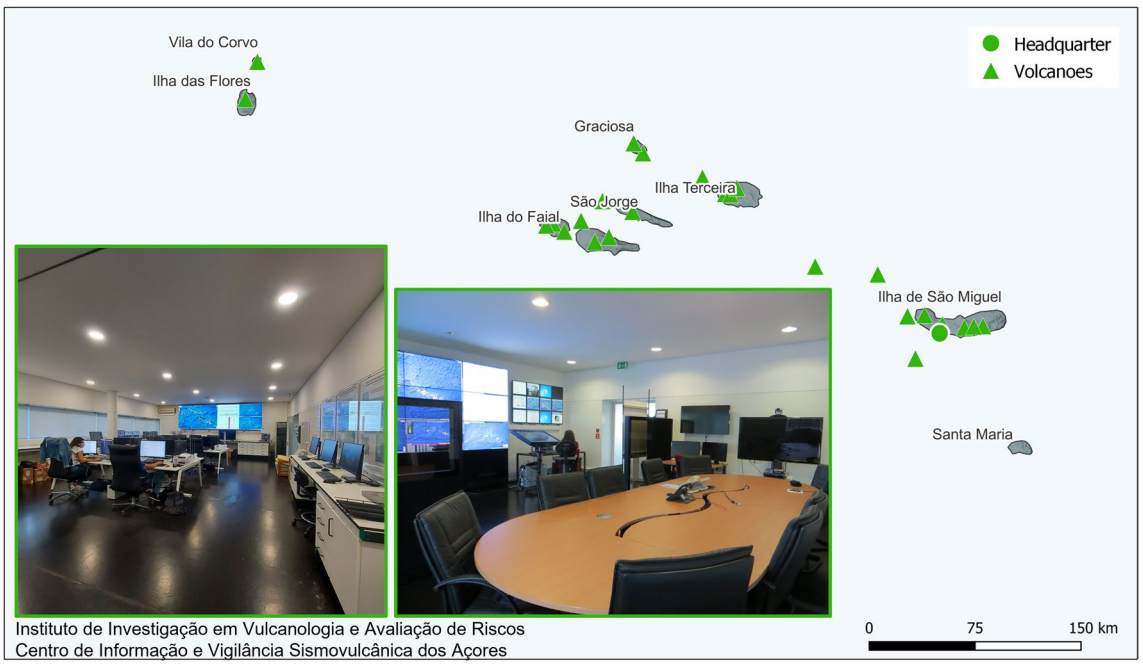

Fig. 2 CIVISA's area of responsibility and its monitoring room, the Data Acquisition Centre (CAD), on the left, and the Emergency Operations Centre (COE) on the right

civil protection authorities, as well as national and international entities, such as Toulouse VAAC. It also maintains an integrated GIS platform that supports crisis management and emergency planning. The COE staff works 24/7 remotely in quiet periods, and 24/7 in person during periods of unrest.

CIVISA comprises seven Operational Scientific Units (Hydrogeology, Hydrometeorology, Gas Geochemistry, Infrasound, Seismology and Geodesy, Volcanology, and Crisis Management and Response Mechanisms) and a Crisis Office, which is activated in response to emergency situations.

Usage of alert level systems

The aviation colour code system is in place at CIVISA-IVAR and has been regularly trained in joint exercises with Toulouse VAAC, Santa Maria Area Control Center and Meteorological Watch Office (Instituto Português do Mar e da Atmosfera (IPMA)). In the past 15 years, CIVISA-IVAR participated in 16 exercises at both national and international levels (VOLCAZO and VOLCEX exercises, respectively). In all exercises, VONAs were issued, gradually changing the aviation colour code from green to red, with the aim of simulating increasing volcanic unrest that culminates in the explosive eruption of selected volcanoes. Over the years, these exercises were focused on the trachytic central volcanoes of the archipelago, because they are considered the most hazardous for air traffic: Sete Cidades (Pimentel 2021a), Água de Pau (also known as Fogo, Pimentel 2021b), and Furnas, on São Miguel Island; Caldeira on Faial Island; and Santa Bárbara on Terceira Island.

CIVISA-IVAR also operates a scientific alert level reflecting the state of a volcano or volcanic system in the Azores region (see Table 2). This scale includes seven alert levels, ranging from V0 when the volcano is in normal, quiet state to V6 for the case of a paroxysmal eruption. The change of scientific alert level is based on the integrated analysis of the monitored parameters (geophysical, geodetic, and geochemical), as well as on the correlations between them. The increase in alert level may occur over timescales of years or months, or just a few hours, depending on the rate at which the unrest escalates. In real unrest situations, the change of the alert level and the aviation colour code is decided by the Crisis Office, a collegial body composed of a group of experts, which comprises the President of the Board of Directors and the coordinators of the seven Operational Scientific Units. The Crisis Office is responsible for assessing the unrest episodes, based on the analysis of all available information.

Since 2008, CIVISA-IVAR issued only two real VONAs changing the aviation colour code for São Jorge Island in 2022 due to an ongoing seismo-volcanic crisis. Before that, the state of Azorean volcanoes or volcanic systems did not justify the change of the aviation colour code, despite several episodes of higher seismic activity. A more detailed description of São Jorge unrest management is provided in Section "Experiences in operating the aviation colour code".

Instituto Geográfico Nacional (IGN)—Spain

The Institution and area of responsibility—Canary Islands, Iberian Peninsula, and Deception Island

The Instituto Geográfico Nacional (IGN) is the centre in charge of volcano monitoring and volcanic alerts in Spain since 2004. The IGN's area of responsibility in volcanology covers the entire national territory, the Canary Islands being the only area with historical volcanic activity (Fig. 1 (blue area) and Fig. 3). In the Iberian Peninsula, there are two areas that according to dating could be considered active: La Garrotxa (Girona, Zafrilla et al. 2021a) and Campos de Calatrava (Ciudad Real). In the framework of the Spanish Polar Committee, the IGN was appointed in 2020 to be responsible for volcanic monitoring and warning on Deception Island (South Shetland, Antarctica).

Monitoring capabilities and observatory operations

Currently the monitoring group consists of about 35 people and the surveillance is guaranteed through a 24/7 shift plan, which is mainly dedicated to seismic monitoring, but during eruptions, also to volcano monitoring (Fig. 3). The monitoring network deployed by IGN is mainly focused on the Canary Islands archipelago and consists of a geophysical, geodetical, and geochemical system plus observational cameras, magnetometers, and gravimeters.

Canary Islands is an active volcanic area with a rather low eruptive frequency: about three eruptions per century (based on historical eruption data). Because of this, the experience in instrumental monitoring of eruptive processes in Spain is limited to two cases: the submarine eruption of Tagoro volcano on the island of El Hierro in 2011–2012 (López et al. 2012) and the recent eruption of 2021 on the island of La Palma (Del Fresno et al. 2023). Of these two cases, only in the latter one was ash emitted into the atmosphere.

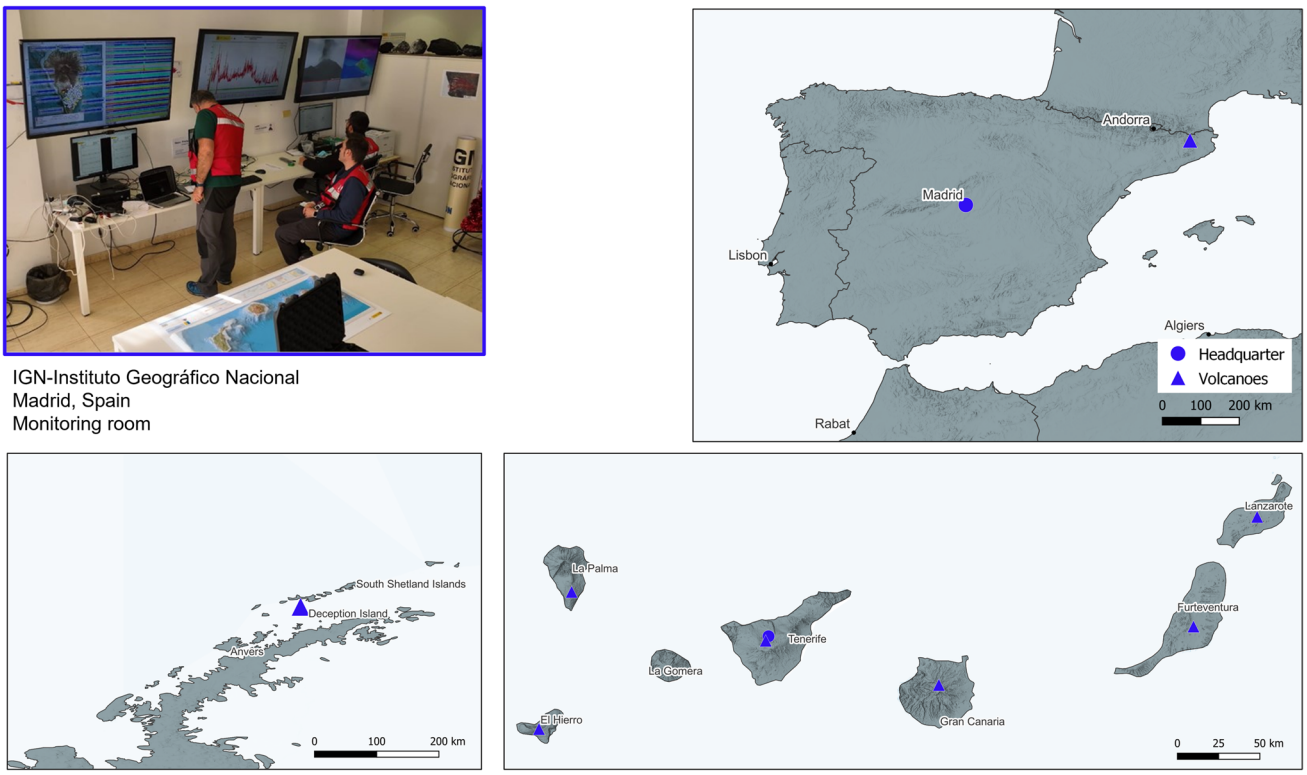

Fig. 3 IGN's area of responsibility and the monitoring room at La Palma during 2021 eruption

Usage of alert level systems

IGN's knowledge about the aviation colour code system was based on ICAO documentation and the experience transmitted by staff from other VOs both in VOLCEX preparatory meetings and VAAC-VO workshops organised by the EUROVOLC project. In November 2022, a Spanish volcano (Teide, Zafrilla et al. 2021b) was for the first time the target volcano within the European exercise VOLCEX22. Moreover, no exercises were ever held at a national level to practise response to a volcanic unrest/eruption. Unfortunately, the exercise planned by IGN and VAAC Toulouse for 2020 had to be cancelled because of the COVID-19 pandemic. Therefore, when the 2021 eruption in La Palma started, almost no member of the team in charge of measuring the height of the eruptive column and for issuance of VONAs had previous experience or training in the use of the aviation colour code. During the 2021 eruption, the decision to change the colour code was taken by consensus of a small group of 3–4 scientists and technicians, in which there was always at least one person present on the island of La Palma. A more detailed description of La Palma eruption management is provided in Section "Experiences in operating the aviation colour code".

The emergency plan for volcanic risk in the Canary Islands (PEVOLCA) includes the adoption of volcano alert levels to address the potential effects and consequences of a volcanic eruption on the population (Canary Government 2018). The decision whether to change the volcano alert level, structured over four tiers, is taken by the authorities in charge, but always after consultation with the scientific committee which IGN belongs to.

Icelandic Meteorological Office (IMO)—Iceland

The institution and area of responsibility—Iceland

The Icelandic Meteorological Office (IMO) was officially designated as SVO in 2011 by the Icelandic Transport Authority (ITA) and it was given the responsibility of reporting on volcanic unrest and volcanic eruptions in Iceland to the London VAAC, and other VAACs if necessary. This appointment was done in the aftermath of the volcanic eruption in Eyjafjallajökull in 2010 and as soon as the Grímsvötn eruption started in 2011. IMO has responsibility for monitoring, forecasting, and warning of almost all natural hazards in Iceland, including volcanic unrest and eruptions at any of the 33 volcanoes and volcanic systems in the country (Fig. 1 (pink area) and Fig. 4). IMO is also the Meteorological Office responsible for issuing SIGMETs for eruptions originating from

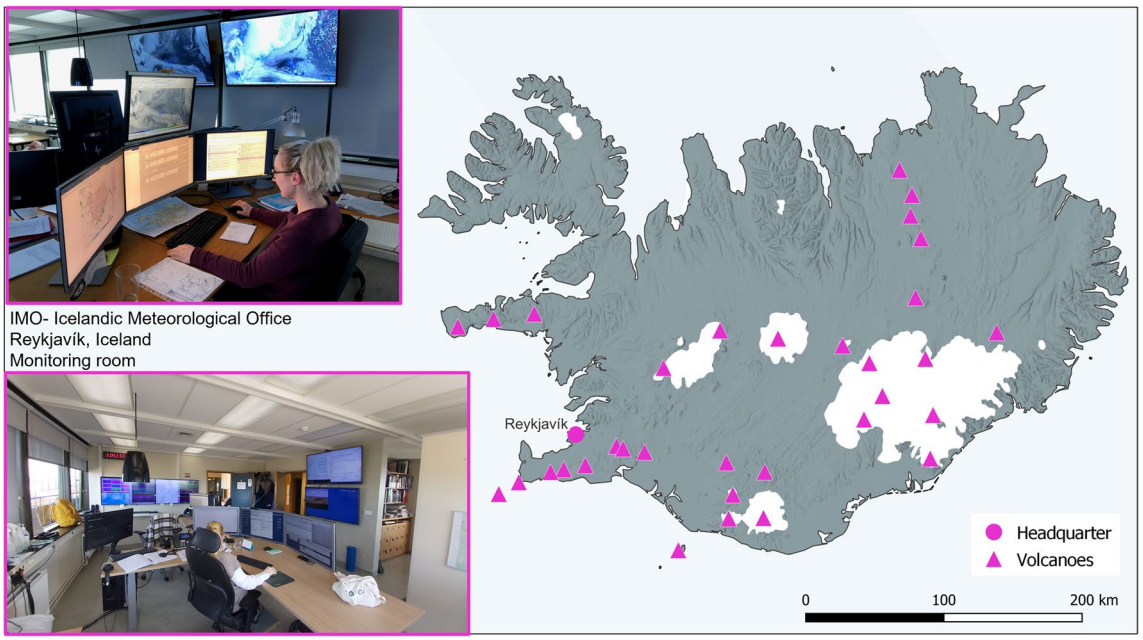

Fig. 4 IMO's area of responsibility and its monitoring room (the meteorologist on duty on the top and the natural hazard specialists room on the bottom)

Beerenberg volcano in the Norwegian island of Jan Mayen (see University of Bergen section).

Monitoring capabilities and observatory operations

In the monitoring room, there are four experts on duty during the day (two natural hazard specialists and two meteorologists), which reduce to two during the nighttime (Fig. 4). The natural hazard specialist (NHS) monitors the real-time data coming in from the seismic (90 stations), geodetic (50 stations), geochemical (two MultiGAS and one DOAS) and hydrological (105 stations) networks, and integrates, in a multidisciplinary way, the information to assess any impending hazards. Additional monitoring sensors and instrumentation include ground-temperature probes, 1 tiltmeter, 4 strain-meters, calibrated cameras, 5 meteorological radars and a variety of satellite imageries. Contingency plans exist to activate internal personnel through a call down list and to guarantee fast communication with key stakeholders including the local Civil Protection, the London VAAC, and the Icelandic navigation service provider (ISAVIA). The work in the monitoring room is supported by a group of scientists (seismologists, geophysicists, geochemists, volcanologists, hydrologists) who help with evaluating ongoing events, by processing monitoring data and interpreting them in light of background knowledge.

Usage of alert level systems

Since its implementation in Iceland in 2012, in the aftermath of the Eyjafjallajökull in 2010 and Grímsvötn in 2011 eruptions, the aviation colour code has been used to report about the status of nine volcanoes, including Bárðarbunga (2014-2015), Eldey (2015), Katla (2016–2017), Öræfajökull (2017–2018), Reykjanes (2020 and 2022), Grímsvötn (2020, 2021 and 2022), Krýsuvík (2021 and 2022), Fagradalsfjall (2023), and Askja (2021). A simple procedure has been set up to make the issuance of VONA fast and comprehensive as part of the official contingency plan for the NHS on duty. A template, prefilled in some fields, is edited with the additional information regarding the ongoing event. As such the VONA, broadcasting the change in aviation colour code, is sent out via e-mail to a list of addresses, the colour code is automatically changed on the online map on IMO's website as well as in the Catalogue of Icelandic Volcanoes (https://icelandicvolcanoes.is//), and in less than 5 min, the VONA is made available on the web (see Table 2). In most situations, for example, at the beginning of a volcanic unrest phase, a group of scientists is responsible for deciding on changes of the aviation colour code, whereas when it is needed to react quickly, a smaller group (or just the NHS) would take the decision.

The experience gained from operating the aviation colour code at IMO suggests that a separate VALS should be

developed and implemented to inform other stakeholders and end users about ground-based hazards associated with the changed status of a volcano. The eruption in Bárðarbunga in 2014–2015 was an eye-opening event as the hazard posed to the aviation sector was minimal, but the hazards on the ground were highly time dependent and critical to assess the safety around the eruption site (Barsotti et al. 2020). Work is in progress at IMO to develop and introduce such a system. Scientists from IMO, along with specialists from other agencies, belong to the Scientific Advisory Board which gives advice to the Icelandic Civil Protection who eventually decides on operational emergency levels (Barsotti et al. 2020).

Istituto Nazionale di Geofisica e Vulcanologia (INGV)—Italy

Both the Osservatorio Etneo (INGV-OE) and Osservatorio Vesuviano (INGV-OV) are part of the Istituto Nazionale di Geofisica e Vulcanologia, the institution in charge of the seismic and volcano monitoring and surveillance in Italy supporting the Italian Civil Protection Department (DPC).

INGV-OE—Etna and Aeolian Islands, Sicily

The institution and area of responsibility

Monitoring of the Sicilian active volcanoes dated back to the early 1900 by the University of Catania, and then over the decades across the Istituto Internazionale di Vulcanologia in the 70s (IIV-CNR), and in 1999 by the Geodynamics Observatory of Sicily, POSEIDON. Since 2000, both the IIV-CNR and POSEIDON migrated and merged to INGV-OE, which was appointed by law to carry out monitoring and surveillance activities of the Sicilian active volcanoes (Fig. 1 (orange area with blue contours) and Fig. 5). Eventually, 7 years later, the Etna Volcano Observatory was appointed as SVO. Mt. Etna is one of the most active volcanoes in the world (e.g. Bonaccorso et al. 2004, Branca 2021), with a wide range of eruptive activity, spanning from effusive to more than one hundred lava fountain events produced in the last 10 years. These explosive events produced high plumes, rising to 15 km above sea level, and notably affected the population and aviation operations (Barsotti et al. 2010; Scollo et al. 2013).

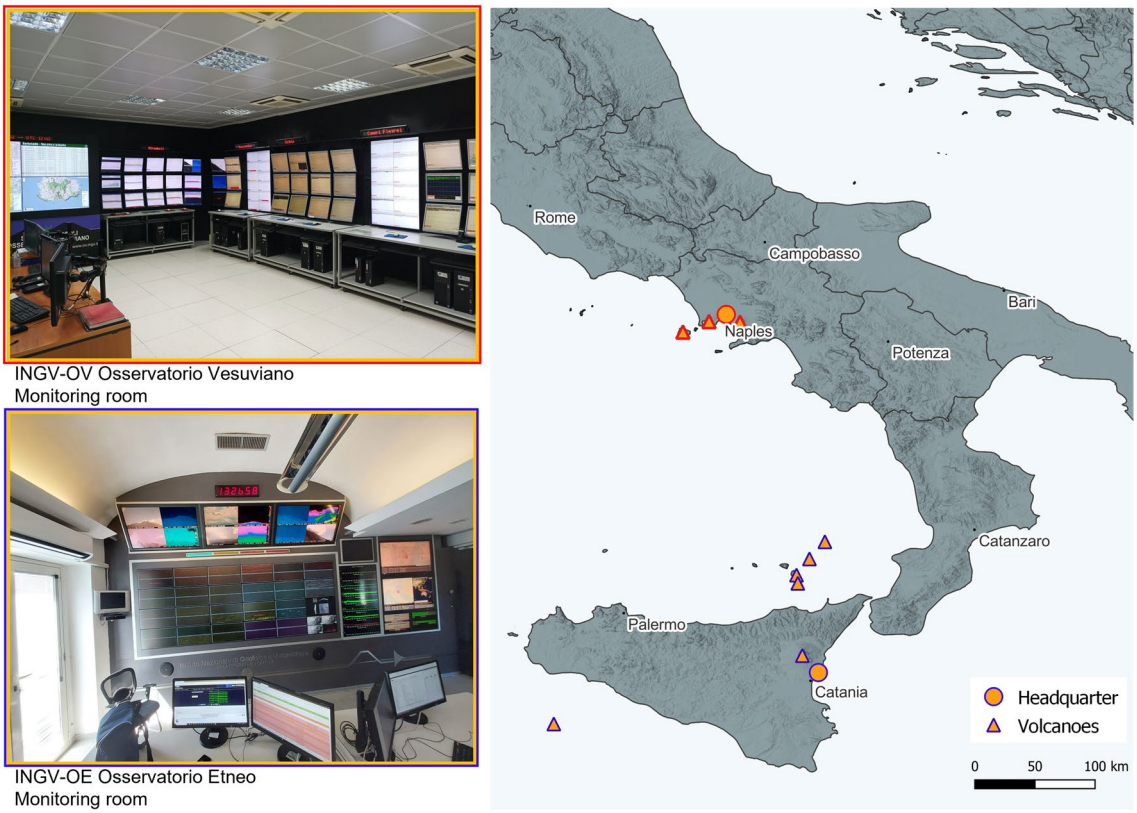

Fig. 5 INGV's area of responsibility: contoured in orange and red are those volcanoes monitored by the INGV-OV and contoured in orange and blue those monitored by INGV-OE. Operation room at INGV-OV is marked with red contour and in blue the INGV-OE monitoring room

Table 3 Overview of the criteria adopted by INGV-OE for operating the aviation colour code at Etna volcano. P1 is a no-fly area defined as a circle centred on Etna summit having a radius of 1.0 NM

ACC	Volcano Status	Description of volcanic activity for Etna volcano
Green	Normal	Quiescent, no eruptive activity
Yellow	Unrest	Pre-eruptive state with possible weak ash emission confined within the P1 no-fly area
Orange	No ash emission	Eruption with no or weak ash emission confined within the P1 no-fly area
Red	Ash emission	Eruption with strong ash emission up to the P1 area

Monitoring capabilities and observatory operations

The Mt Etna monitoring and surveillance activities conducted by the INGV-OE are based on a 24/7 Operational Room and a multidisciplinary monitoring system, which consists of ~160 stations, most of them multi-parameter. The 24/7 surveillance activity in the OE Operations Room is carried out through a set of tools and procedures based on a comprehensive multidisciplinary observation of the recorded data, the scientific advances achieved, and on the expert staff weekly on call shifts from various disciplines (volcanology, deformation, seismology, ground deformation, IT technology). The service towards authorities is modulated by specific procedures according to decision-making grids and timings which are rigidly codified in the agreement with the Civil Protection Department. Since June 2014, the Operations Room has issued the VONA messaging for aviation authorities. VONAs are compiled and issued by the volcanologists on call. Since 2006, INGV-OE has been running a volcanic ash forecasting system for Mt. Etna (Scollo et al. 2009). The system, tuned for fixed eruptive scenarios, automatically downloads daily data from meteorological weather forecasts, runs models of tephra dispersal, and produces hazard maps of volcanic ash dispersal and deposition. Products are sent in real time to DPC (Scollo et al. 2009). The system has been continually improved thanks to the extensive use of remote sensing systems ranging from radar (Freret-Lorgeril et al. 2018; Giammello et al. 2022; Mereu et al. 2022), lidar (Scollo et al. 2012), and cameras (Scollo et al. 2014). Observations of plume height with visual calibrated images and satellite data are also available in the 24/7 operational room (Scollo et al. 2019; Corradini et al. 2018) supporting the activities of the Volcanologist in drafting the VONA and communications. Since April 2022, the ETNAS (ETna iNtegrated Alert System) Early Warning system for both explosive and intrusive eruptions has been operational. Developed as a pilot in the framework of DPC funds, ETNAS is a digital platform that aggregates multiple independent warning subsystems, individually based on different models and/or geophysical and geochemical data.

Usage of alert level systems

Following the IAVW's directives and the procedure of ENAC, the Civil Aviation National Authority of Italy,[2] INGV-OE developed a semi-automatic system to edit the VONA messages. The system automatically sends the VONA but in order to ensure its successful communication, the receipt of the message needs to be confirmed by a call by 24/7 operational room. The aviation colour code changes are mainly based on the video-surveillance system, geophysical instrumental data, and/or on the information given by the INGV-OE volcanologist on field. Green and yellow aviation colour codes are issued in VONA messages when the volcano activity is in normal background or in an unrest phase, respectively. Orange aviation colour code is issued during eruptive activity with no ash emission or when there is a weak ash emission with a dispersal limited to a circle centred on Etna summit having a radius of 1.0 NM (the so-called P1 no-fly area). Finally, red aviation colour code is issued when there is a strong ash emission or a significant change of the eruptive style (e.g. Strombolian vs kava fountains). Afterwards, when a significant variation of the altitude of the eruption column is observed, another VONA is issued keeping the red aviation colour code. Table 3 summarises the procedure used to change the aviation colour code at INGV-OE.

INGV-OV—Vesuvius, Campi Flegrei, and Ischia

The institution and area of responsibility

INGV-OV manages seismic and volcano monitoring and surveillance in the Neapolitan area, which include Vesuvius (Di Vito 2021), Campi Flegrei (Di Vito and Doronzo 2021), and Ischia Island (Fig. 1 (orange area with red contours) and Fig. 5). Although not erupting recently, the volcanoes in the Neapolitan area are considered high risk due the possibility of high-energy eruptions and the intense urbanisation. The last eruption of Vesuvius occurred in 1944, showing both effusive and explosive eruption styles. Campi Flegrei has been in an unrest state

[2] GEN 04A 19/12/2013 updated to GEN 04C 15/04/2020 (https://www.enac.gov.it/la-normativa/normativa-enac/circolari/serie-gen/gen-04b)

("Attention Level" issued by DPC) since 2012 because of the continuous uplift observed in the area (Italian Dipartimento Protezione Civile (DPC) website 2023). Ischia produces very shallow earthquakes (less than one km) with catastrophic consequences (the last earthquake in 2017 caused two fatalities and more than 2600 persons to become homeless).

Monitoring capabilities and observatory operations

INGV-OV has a 24/7 Operation Room (Fig. 5), hardware and software infrastructure for the acquisition, storage, and real-time analysis of multi-parametric data. The 24/7 surveillance is ensured by the presence of two shift workers and by three other units of highly specialised staff on call: a seismologist, a volcanologist/geochemist, and a computer scientist. INGV-OV has developed a volcanic ash forecasting system, which is able, using automatic procedures (Folch et al. 2008), to download daily data from meteorological weather forecasts, run a model of tephra dispersal for Vesuvius (three scenarios) and Campi Flegrei (one scenario) (Folch et al. 2020), and store the ash loadings for off-line analysis of the impact on buildings and infrastructures (Zuccaro et al. 2008).

Usage of alert level systems

VONA messages have been issued during aviation exercises, VOLCITA and VOLCEX, in 2017, 2018, and 2019. The volcanologist on duty oversees sending the VONA messages and of changing aviation colour code on the basis of the volcanic activity. Since the Neapolitan volcanoes have been quiet for many years, no VONA has been issued outside the national or international exercises.

Institut de Physique du Globe de Paris (IPGP)—France

Institution and area of responsibility

The Institut de Physique du Globe de Paris is a major public institution for higher education and research. It is associated with the CNRS and is a component of Université Paris Cité. The IPGP oversees national observation services in volcanology, seismology, magnetism, gravimetry, and erosion. Thus, IPGP is responsible for observation and monitoring of French overseas active volcanoes and their geodynamic setting and it contributes to the Intergovernmental Coordination Group on the tsunami alert system in the Caribbean. Based on instrumental alerts and off-site voluntary duty personnel on shifts, IPGP maintains operational VOs in the French overseas territories of La Réunion (Piton de la Fournaise), Guadeloupe (Soufrière de Guadeloupe), and Martinique (Montagne Pelée). The overseas observatories are coordinated by the Paris-based Observatoires volcanologiques et sismologiques office at IPGP where several researchers, engineers, technicians, and administrative staff collaborate. IPGP leads the National service for observation in volcanology (SNOV, CNRS-INSU) in co-leadership with the Observatoire de Physique du Globe of Clermont-Ferrand (OPGC), which provides a complementary expertise with operational capabilities for satellite remote sensing and ground-based plume radars as well as with additional fields in volcanology. The VOs are run 24/7 and they use instrumental alerts and off-site voluntary duty personnel on shifts to perform the monitoring of different geographical areas. This strategy is reinforced to shift duty during seismic swarms or potentially eruptive unrest, sometimes with watch duty remotely undertaken by IPGP personnel from Paris via the WebObs platform. Since the major submarine eruption started in 2018 offshore from Mayotte island (Mozambique channel, Indian Ocean) a new national infrastructure, REVOSIMA, has been established in 2019 with the mission of the long-term operational monitoring network and observation system for volcanic and seismic activity in Mayotte and the surrounding region.

Off-site contributions and operational interaction between all French VOs are possible in real time owing to the implementation in each observatory of an integrated web-based platform (WebObs; Beauducel et al. 2020) for monitoring, data processing, dissemination, and network management. Since 2015, IPGP observatories are required to send a VONA for each change in the activity of the volcanoes for which they are responsible in overseas territories (La Réunion, Guadeloupe, Martinique) (Fig. 1 (yellow areas), Fig. 6, and Fig. 7). Recently, steps are being taken to add the Mayotte volcanic zone (France, Fig. 6) to this protocol. Official volcano crisis response plans (ORSEC *Dispositif spécifique*, organisation of civil security response) and protocols for volcano crises management (volcano unrest and eruption) are in place and operational, under the responsibility of the Préfectures (the local authority representing the state of France). Along with warnings to the local authority in charge of changing the alert level for the volcano, these protocols include the issuance of a VONA as the highest priority duty for the local VO in case of unrest and/or eruption or return to baseline activity level. VONA messages are still not fully public, as the French IPGP office is working on creating a webpage to store and distribute the different types of reports published by their observatories.

The French National service for observation in volcanology (SNOV) involves 44 researchers, largely from IPGP and OPGC for a total of about 12 researchers full-time equivalent (FTE) persons for observation/monitoring duties (excluding research and teaching), 42 engineers for a total of 27 FTE

Fig. 6 IPGP-OVPF and REVOSIMA area of responsibility in the Indian Ocean. The monitoring room in La Réunion Island is marked with a yellow and green contour

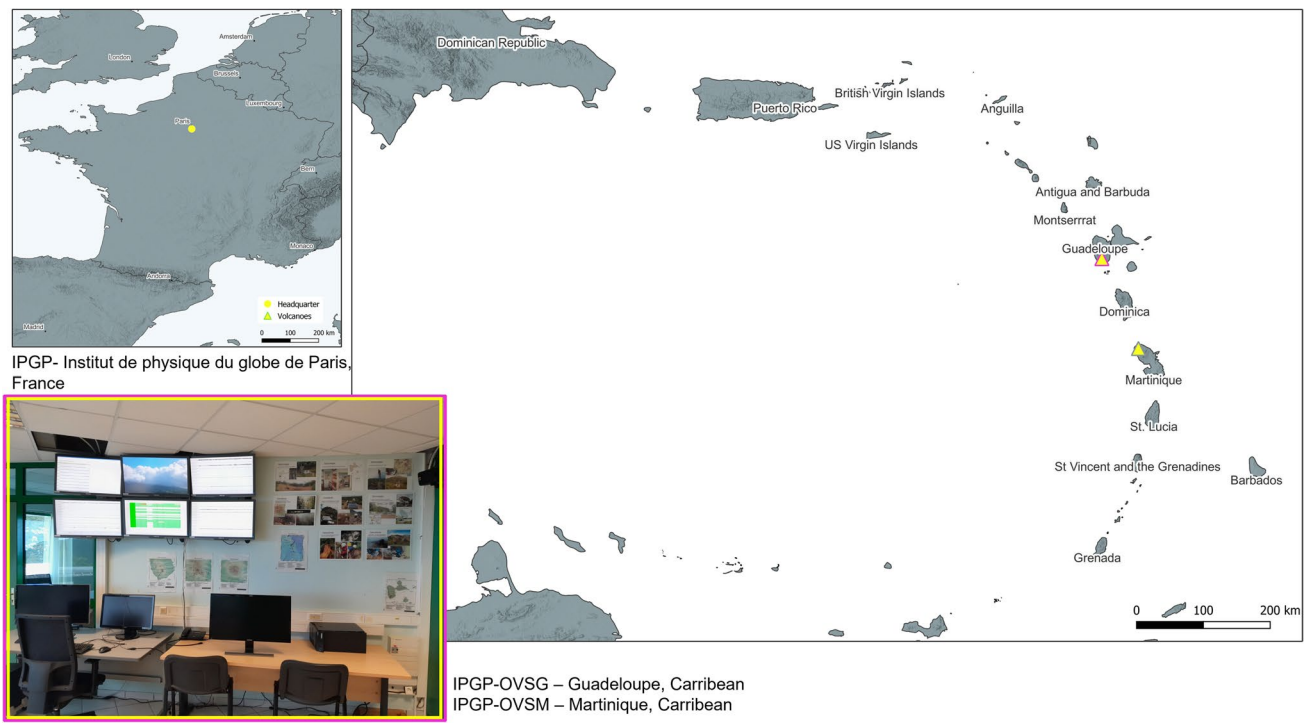

Fig. 7 IPGP-OVSG and IPGP-OVM area of responsibility in the Caribbean. The monitoring room of OVSG is marked with a yellow and violet contour

persons, 10 technicians for a total of 5 persons FTE, and 9 administrative staff for a total FTE of 7 persons FTE. On 30 September 2023, the SNOV thus involves 105 persons for a total of 52 persons FTE (44 at IPGP and 7 at OPGC) excluding collaborators in the research community, nationally, and internationally.

IPGP-OVPF—Piton de la Fournaise (La Réunion)

Monitoring capabilities and observatory operations

The Piton de la Fournaise volcano observatory (IPGP-OVPF; Fig. 6) on-site permanent staffs include, as of 2023, six researchers, nine engineers or assistant engineers, and one administrative staff (total of 16 staff). The observatory operates a geophysical and geochemical network of 43 seismic stations, 26 GNSS (Global Navigation Satellite System) stations, 10 pairs of tiltmeters, three extensometers of 3 components, three Max-DOAS NOVAC stations, four soil CO_2 gas station, and one MultiGAS station, which transmit their data in real or near real time. In addition, the observatory periodically reoccupies 82 sites including 72 GNSS sites and 10 portable MultiGAS surveys. IPGP-OVPF also maintains meteorological stations that provide key environmental parameters to the volcanological data.

Usage of alert level system

In the protocol of the ORSEC "volcan du Piton de la Fournaise" volcano emergency response, OVPF-IPGP is responsible for providing up-to-date information on activity at Piton de la Fournaise, and for advising Préfecture of La Réunion over change the alert level when necessary. As of November 2022, IPGP-OVPF had issued 82 VONAs since October 2015 (date of implementation of the procedure), in response to 20 eruptions and eight intrusion phases. The VONAs were sent to Toulouse VAAC, as well as London VAAC for redundancy, and Météo-France (the reference meteorological office). The general criteria to respond to the different phases of volcano activity in La Reunion are summarised below:

1. Alert level 1 (imminent eruption): a VONA is issued with a yellow aviation colour code.
2. Alert level 2 (ongoing eruption): a VONA is issued either with orange or red aviation colour code, depending on confirmation of ash production (since the procedure was implemented in 2015, only VONA with orange aviation colour code have been issued).
3. Safeguard level (end of the eruption): a VONA is issued to go back to green colour code.

The decision of when to declare the beginning of an eruption at Piton de la Fournaise (Peltier and Di Muro 2021) is taken with respect to the onset of eruptive tremor signals. As soon as the tremor stops, the eruption is then declared over (Peltier et al. 2021). In that instance, VONA and bulletins are immediately sent—with parallel calls—in La Réunion to the local Civil Protection authorities (Préfecture) and other stakeholders, as well as to the Toulouse VAAC and the Meteorological Watch Office.

IPGP-OVPF occasionally rehearses with the local Civil Protection. Two exercises have been held in the last 5 years dedicated to practice response to eruptions with direct impacts on inhabited areas. However, during such exercises, VONAs were not sent out as the procedures are well established and tested several times each year given the frequency of eruptive activity at Piton de la Fournaise. The high rate of eruptions also allows IPGP-OVPF to maintain very regular interactions with the Toulouse VAAC and Météo-France.

IPGP-OVSG—Soufrière (Guadeloupe)

Monitoring capabilities and observatory operations

The Observatoire volcanologique et sismologique de Guadeloupe (IPGP-OVSG; Fig. 6) on-site permanent staffs include, as of 2023, three researchers, six engineers or assistant engineers, two technicians, and one administrative staff (total of 12 staff). The observatory operates a continuous geophysical and geochemical network of 53 seismic stations, 21 GNSS stations, one radar extensometers, one MultiGAS station, one webcam, two tide gauges (part of the monitoring network of the Intergovernmental Coordination Group on the tsunami alert system in the Caribbean), and one fumarole temperature sensor which transmit their data in real or near real-time. In addition, the observatory reoccupies periodically 329 sites including 50 GNSS sites, 15 1-D extensometry sites, 2 3-D fissurometers, 35 gravimetry sites, 10 thermal springs, 2 fumaroles, 10 portable MultiGAS surveys, 103 soil CO_2 passive soil degassing sites, and 103 ground temperature sites. IPGP-OVPF also maintains meteorological stations that provide key environmental parameters to the volcanological data. As part of a new experiment, an optical ocean-bottom seismometer is operational in Les Saintes and linked to the coast by optical fibre where the data is transmitted to the OVSG-IPGP. As a member of the consortium of the French accelerometric network (RAP), the OVSG-IPGP oversees 26 strong motion stations in Guadeloupe. The observatory uses a modern seismic data acquisition system and calls upon most recent machine-learning-based algorithms for earthquake monitoring, as well as automatic processes to model deformation source, like those used in other

IPGP VOs. The OVSG-IPGP also has several trained drone pilots who operate visual, multispectral, and thermal observation flights and photogrammetric surveys. The facilities of OVSG-IPGP include a chemistry laboratory where the composition of hydrothermal and magmatic gases and thermal waters from La Soufrière volcano have been routinely analysed for more than 40 years. The OVSG-IPGP works in close partnership with the OVS general headquarters in Paris, and with the Observatoire de Physique du Globe of Clermont-Ferrand (OPGC), which provides complementary expertise in all fields of volcanology and contributes to volcanic monitoring. These off-site contributions and expertise sharing are possible in real-time owing to the implementation in each observatory of an integrated web-based system (WebObs) for monitoring and network management.

Usage of alert level system

In the protocol of the ORSEC volcano emergency response, the Observatoire Volcanologique et Sismologique de Guadeloupe (OVSG-IPGP) (Préfet de Guadaloupe 2018) is responsible for providing up-to-date information on activity at volcanoes in Guadeloupe (Fig. 1 (yellow areas with pink and brown contours) and Fig. 7). Information is delivered to the Piarco (Trinidad and Tobago) Air control centre, the Port of Spain (Trinidad and Tobago) Meteorological Watch Office, to the Washington VAAC, and in parallel to the local Civil Protection authorities. Within the ORSEC response plan, different phases and alert levels are identified and are coordinated in consultation with scientists of the OVSG-IPGP. These phases are structured over four levels, which are, respectively, green (no alert), yellow (vigilance), orange (pre-alert), and red (alert).

IPGP-OVSG occasionally rehearses with the local Civil Protection. IPGP-OVSG had exercises in 2019, 2021 and 2023 dedicated to practising the response to eruption crises with direct impacts on inhabited areas. During the exercises VONAs were only sent locally to the Civil Protection authorities but not to the VAAC.

However, on 29 June 2021, a VONA protocol exercise was carried out for the two French VOs (OVSG and OVSM) together with the Washington VAAC, the Piarco (Trinidad and Tobago) Air control centre, and the Port of Spain (Trinidad and Tobago) Meteorological Watch Office (MWO). Given the permanent state of unrest at La Soufrière (vigilance level, yellow, ORSEC plan) since 1999 and the present lack of an imminent risk of ash emission, yellow level VONA associated with increased unrest at the volcano has not been issued as these would not be practical. Hence, although the alert level for Soufrière de Guadeloupe is vigilance, yellow, the VONA colour level remains green at the time of writing. As of 10 October 2023, real-crisis VONAs have never been issued for Soufrière of Guadeloupe.

IPGP-OVSM—Observatoire volcanologique et sismologique de Martinique

Monitoring capabilities and observatory operations

The Observatoire volcanologique et sismologique de Martinique (IPGP-OVSM; Fig. 6) on-site permanent staffs include, as of 2023, one researcher, four engineers or assistant engineers, five technicians, and two administrative staff (total of 12 staff). The observatory operates a continuous geophysical and geochemical network of 37 seismic stations, 13 GNSS (Global Navigation Satellite System) stations, 2 borehole inclinometers, 3 AFM lahar detection stations, 1 tiltwire lahar detection station, one webcam, 1 well physico-chemistry station, and 1 pluviometer which transmit their data in real or near real time. In addition, the observatory periodically reoccupies 23 sites including 16 GNSS sites, 4 thermal springs, 3 wells for geochemistry, and 1 submarine fumarole. IPGP-OVPF also maintains meteorological stations that provide key environmental parameters to the volcanological data. As a member of the consortium of the French accelerometric network (RAP), the observatories are in charge of 19 strong motion stations in Martinique. The observatory uses a modern seismic data acquisition system and calls upon most recent machine-learning-based algorithms for earthquake monitoring, as well as automatic processes to model deformation source, similar to those used in over IPGP VOs. The OVSM-IPGP also has several trained drone pilots who operate visual, multispectral, and thermal observation flights and photogrammetric surveys. The facilities of OVSM-IPGP include a chemistry laboratory where the composition of thermal waters from Montagne Pelée volcano can be analysed and a new marine monitoring platform with sensors such as a 300-m depth multibeam echosounder, a small ROV that can be mounted on a small opportunity boat, and a fixed multi-parameter oceanographic buoy. The OVSM-IPGP works in close partnership with the OVS general headquarters in Paris, and with the Observatoire de Physique du Globe of Clermont-Ferrand (OPGC), which provides complementary expertise in all fields of volcanology and contributes to volcanic monitoring. These off-site contributions and expertise sharing are possible in real time owing to the implementation in each observatory of an integrated web-based system (WebObs) for monitoring and network management.

Usage of alert level system

In the protocol of the ORSEC volcano emergency response, the Observatoire Volcanologique et Sismologique de Martinique (OVSM-IPGP) (Préfecture de la Martinique 2022) is responsible for providing up-to-date information on

activity at volcanoes in Guadeloupe (Fig. 1 (yellow areas with pink and brown contours) and Fig. 7). Information via VONA messages (green, yellow, orange, red) is delivered to the Piarco (Trinidad and Tobago) Air Control Centre, to the Port of Spain (Trinidad and Tobago) Meteorological Watch Office, to the Washington VAAC, and in parallel to the local Civil Protection authorities. Within the ORSEC response plan, different phases and alert levels are identified and are coordinated in consultation with scientists of the OVSM-IPGP.

IPGP-OVSM occasionally rehearses with the local Civil Protection with its first volcano crisis response exercise on 7 December 2022 dedicated to training some elements of the response to an eruption crisis (e.g. escalating unrest, preventive evacuation of two test towns, small phreatic eruption during the evacuation) with direct impacts on inhabited areas. On 23 March 2023, the CaribeWave23 exercise simulated a partial edifice flank collapse of Montagne Pelée and the genesis of a tsunami affecting Martinique and possibly the Caribbean region. The OVSM-IPGP was actively part of this exercise and decided to practise the VONA with the civil protection authorities by issuing a yellow, orange, and red VONA as part of the crisis scenario. During these exercises, VONAs were only sent locally to the civil protection authorities and to IPGP crisis response teams but not to the VAAC. However, on 29 June 2021, a VONA protocol exercise was carried out for the two French VOs (OVSG and OVSM) together with the Washington VAAC, the Piarco (Trinidad and Tobago) Air Control Centre, and the Port of Spain (Trinidad and Tobago) Meteorological Watch Office (MWO).

Given the recent long-lasting state of unrest at Montagne Pelée (vigilance level, yellow, ORSEC plan) since 2020-12-04 and the present lack of an imminent risk of ash emission, yellow level VONA associated with increased unrest at the volcano has not been issued as these would not be practical. Hence, although the alert level for Montagne Pelée is vigilance, yellow, the VONA colour level remains green at the time of writing. As of 10 October 2023, real-crisis VONAs have never been issued for Montagne Pelée (Martinique).

IPGP-REVOSIMA—Mayotte active volcanic zone

Monitoring capabilities and observatory operations

The REVOSIMA is responsible for (a) developing scientific knowledge on volcanic and seismic phenomena, (b) identifying and communicating early-warnings to civil protection authorities on the observed phenomena, and (c) regularly disseminating information to all stakeholders and the population. REVOSIMA is coordinated and managed by the IPGP (OVPF) and BRGM (BRGM Mayotte). Operational monitoring of seismo-volcanic activity in the Mayotte volcanic zone (Fig. 6) is carried out by the IPGP (OVPF), jointly with BRGM. REVOSIMA relies on a close scientific and technical partnership with Ifremer and CNRS and a large consortium of institutional and academic national scientific partners in France including the OPGC that contribute to data acquisition. Given the exceptional situation of this major eruptive reactivation of the Mayotte volcanic zone and implementation of a new observatory service on France's new and 4th active volcanic zone, funding for this national monitoring infrastructure was earmarked especially by the French government outside of the budget for the other three overseas VO. Given the exceptional onset of this new volcanic activity, the French government opened 6 new full-time positions (2 researchers, 4 engineers) at IPGP and 1 full-time position at BRGM Mayotte. However, about 30–50 additional researchers, engineers, and technicians dedicate part of their time on a regular but fluctuating basis to the REVOSIMA across the different French institutions.

Currently, the ground-based network on Mayotte island consists of nine seismic stations, eight GNSS stations, and one soil CO_2 gas station, which transmit their data in real or near real-time. This permanent network is completed by regular offshore scientific campaigns.

Usage of alert level system

At the time of writing, there is no official volcano crisis response plan in place for this active volcanic zone. The Préfecture authorities from Mayotte are currently in the process of developing this response plan for Mayotte. However, temporary operational procedures are being followed by the REVOSIMA and the IPGP-OVPF. Analogous to Piton de La Fournaise, VONA procedures for Mayotte involve parallel calls to the local Civil Protection and Toulouse VAAC. Volcanic activity in Mayotte would also be immediately reported to authorities in La Réunion, such as the Air Traffic Control/Flight Information Centre, the Meteorological Watch Office, and the local Civil Protection.

British Geological Survey (BGS)—UK

Institution and area of responsibility—Ascension Island and Tristan da Cunha

The British Geological Survey (BGS) provides objective and authoritative geoscientific data, information, and knowledge to help society manage environmental change and be resilient to environmental hazards. BGS is part of United Kingdom Research and Innovation (UKRI) and is a research centre under the Natural Environment Research Council (NERC). UKRI is a non-departmental public body sponsored by the

Department for Science, Innovation and Technology (DSIT) and NERC is the driving force of investment in environmental science in the UK. The BGS works closely with the UK Met Office (London VAAC) and other UK scientific institutions as part of the "Natural Hazards Partnership" and the "North Atlantic Volcanic Hazards Partnership" (e.g. Beckett et al. 2023). The UK (England, Scotland, Wales, and Northern Ireland) has no active volcanoes. Three populated British Overseas Territories (or UK Overseas Territories) have active volcanoes (Montserrat, Ascension Island, and Tristan da Cunha). BGS is not a SVO for the British Overseas Territories but discussions about roles and responsibilities for the populated active volcanic islands of the South Atlantic are underway.

The combined territory of "St Helena, Ascension Island and Tristan da Cunha" has a UK-appointed Governor who is the head of government, and Ascension Island and Tristan da Cunha each have an Administrator advised by elected Island Councils (Fig. 1 (grey area) and Fig. 8). The last eruption of Tristan da Cunha was in 1961 (Baker et al. 1964).

Monitoring capabilities and observatory operations

BGS has since prepared a preliminary hazard assessment for Tristan da Cunha (Dunkley 2002), responded to the offshore eruption of a seamount near Tristan da Cunha in 2004 by deploying campaign seismic instruments (O'Mongain et al. 2007), and interdisciplinary research has been completed on the eruption history, hazards, and participatory approaches to disaster risk reduction (Hicks et al. 2012, 2014). BGS staff have organised citizen science initiatives (such as a school seismometer project) and an ongoing study of landslides will include installation of a GNSS receiver. There is no dedicated volcano monitoring network, but BGS staff review data from two seismometers on the island installed by the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO) and there are plans for a dedicated seismic network. Recent research on Ascension Island has established an eruption history (e.g. Preece et al. 2018) and although there is further work to do, three basaltic eruptions are thought to have occurred in the last 2000 years, and a geological map is also in progress. BGS has

BGS, British Geological Survey, Edinburgh, United Kingdom

View of Sister's Peak, the most recent site of eruptive activity, from the south on Ascension Island © UKRI.

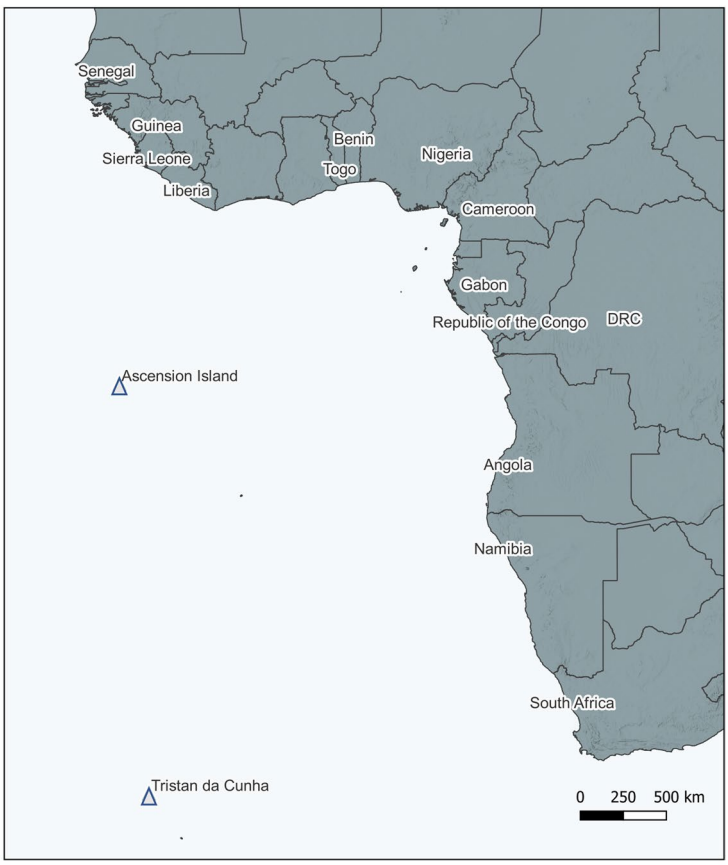

Fig. 8 BGS's areas of responsibility. The photo shows a view of Sister's Peak, the most recent site of eruptive activity, from the south on Ascension Island © UKRI

developed preliminary scenario-based volcanic ash fall hazards assessments and carried out campaign monitoring (seismic and CO_2 soil gas). There are plans for a dedicated seismic monitoring network.

BGS was involved in the multi-national, multi-institutional establishment and running of the Montserrat Volcano Observatory (MVO) from 1995 to 2008 (e.g. Aspinall et al. 2002), investing in training, capacity building, and infrastructure; however, Montserrat has its own elected government that Montserrat VO reports to. The Seismic Research Centre based at the University of the West Indies in Trinidad and Tobago leads the MVO team, under contract to the Government of Montserrat.

Usage of alert level system

BGS does not yet operate alert level systems for the volcanic area of pertinence.

Hellenic Survey of Geology and Mineral Exploration (HSGME)—Greece

Institution and area of responsibility—Santorini

Santorini Volcano Observatory is the only VO institution in Greece (Fig. 1 (gold area) and Fig. 9). The Institute for the Study and Monitoring of the Santorini Volcano (ISMOSAV) is a non-profit organisation founded in the summer of 1995, whose primary aim is to continue to maintain the operation of the Santorini VO and the monitoring networks, which were established under a research program funded by the EU (1993–1995). ISMOSAVs main target is the promotion of volcanological research on the island, more specifically how to achieve the most accurate assessment possible regarding volcanic phenomena and to increase the ability to precisely forecast future volcanic eruptions. ISMOSAV is not an officially mandated institution to respond to volcanic crises. In Greece there is no such mandated institution.

Monitoring capabilities and observatory operations

Santorini VO runs a complete monitoring system consisting of eight seismic and five GNSS stations, satellite imagery analysis, physico-chemical near real-time monitoring of the temperatures, and the CO_2 soil flux as well as periodic complete chemical analysis of the fumarolic gases. Each system is under the supervision of a responsible scientist that has the role of checking its functionality, but also, as members of the scientific committee at Santorini VO undertakes the responsibility of disproving any false statements or rumours regarding the state of the volcano. The Santorini VO runs on a 24/7 basis, with three telemetered, real-time monitoring networks: seismic (nine stations), ground deformation (four GNSS stations),

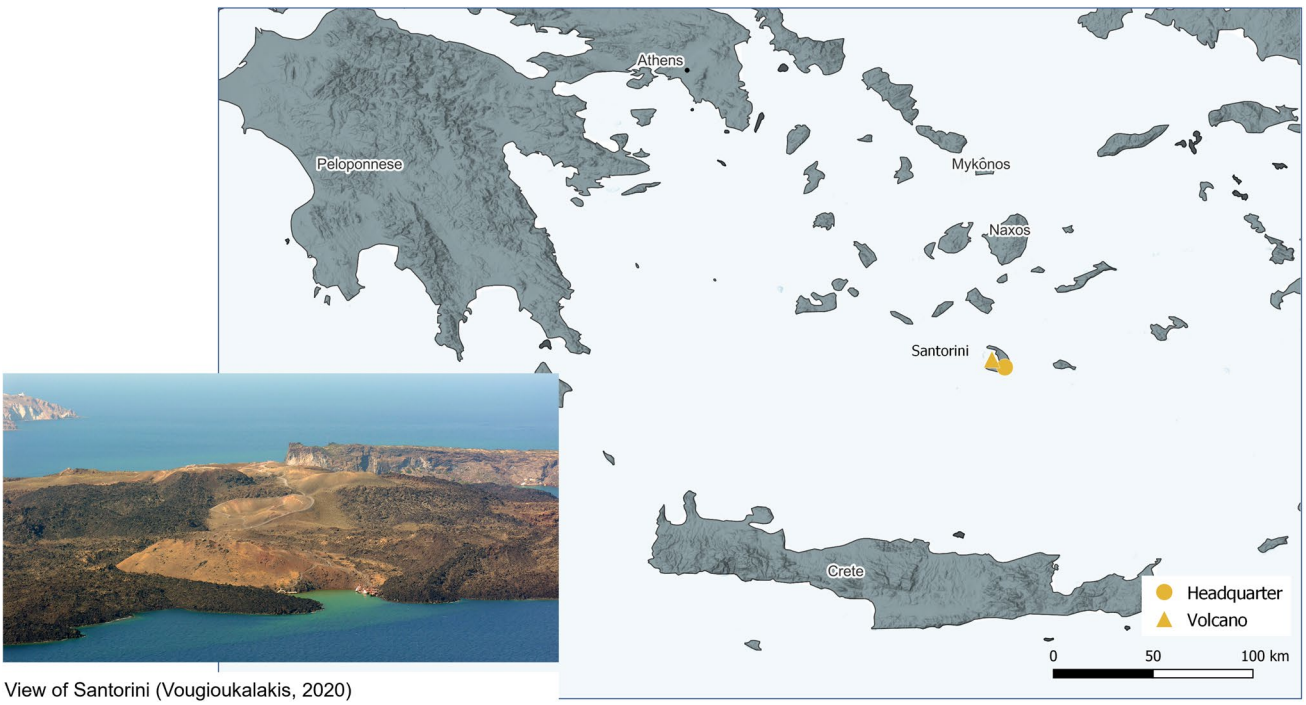

Fig. 9 HGSME's area of responsibility and a view of Santorini volcano

and thermal-chemical (two stations). Periodic measurements are also performed for thermal and chemical monitoring of the hot springs and fumaroles, CO_2 flux, and the radon content in soil gasses. Ground deformation is also continuously evaluated with InSAR satellite images. Scientists responsible for these activities are permanent staff of the Hellenic Survey of Geology and Mineral Exploration (HSGME), the Aristotle University of Thessaloniki, and other education and research institutions from Greece and abroad. Apart from Santorini (Kameni and Kulumbo active volcanic centres) which are fully monitored, basic precursory parameters are also monitored on Methana, Milos, and Nisyros.

Usage of alert level systems

There is a National Committee of experts, under the Earthquake Planning and Protection Organization (EPPO) and the Civil Protection umbrella, which is responsible for evaluating the state of the active volcanic centres in Greece, defining the colour code of each volcano and advising the Civil Protection for any anomalous event, but the committee does not have any monitoring networks. ISMOSAV scientific committee members participate in the National Committee.

The volcano alert colour code in use for Greece has been defined in the Civil Protection "TALOS" plan, which concerns the emergency planning and the actions to undertake in case of a Santorini volcano reactivation. In this plan, the 4-colour alert code scale proposed from ICAO has been accepted. Only during the 2011-2012 Santorini volcano unrest, the Santorini VO has been involved in a process of a colour code definition or change. At that time it was proposed in the National Committee to classify the Santorini volcano at a "yellow" colour code. Santorini VO has never been involved in any process of providing a VONA or any other information for the VAACs, as no volcanic event has occurred at Santorini volcano since 1950 (Vougioukalakis 2021).

Koninklijk Nederlands Meteorologisch Instituut (KNMI)—The Netherlands

The institution and area of responsibility—Caribbean islands of Saba and St. Eustatius

In 2010, the Caribbean islands of Saba and St. Eustatius became special municipalities of the Netherlands. Each island hosts an active volcano, Mount Scenery on Saba and The Quill on St. Eustatius (Fig. 1 (cyan area) and Fig. 10). The Royal Netherlands Meteorological Institute (KNMI) is responsible for the timely warning for geophysical phenomena, including volcanic eruptions or unrest. KNMI is not a SVO. No eyewitness accounts exist of historic eruptions of Mount Scenery and The Quill. However, volcanic deposits on both islands testify to

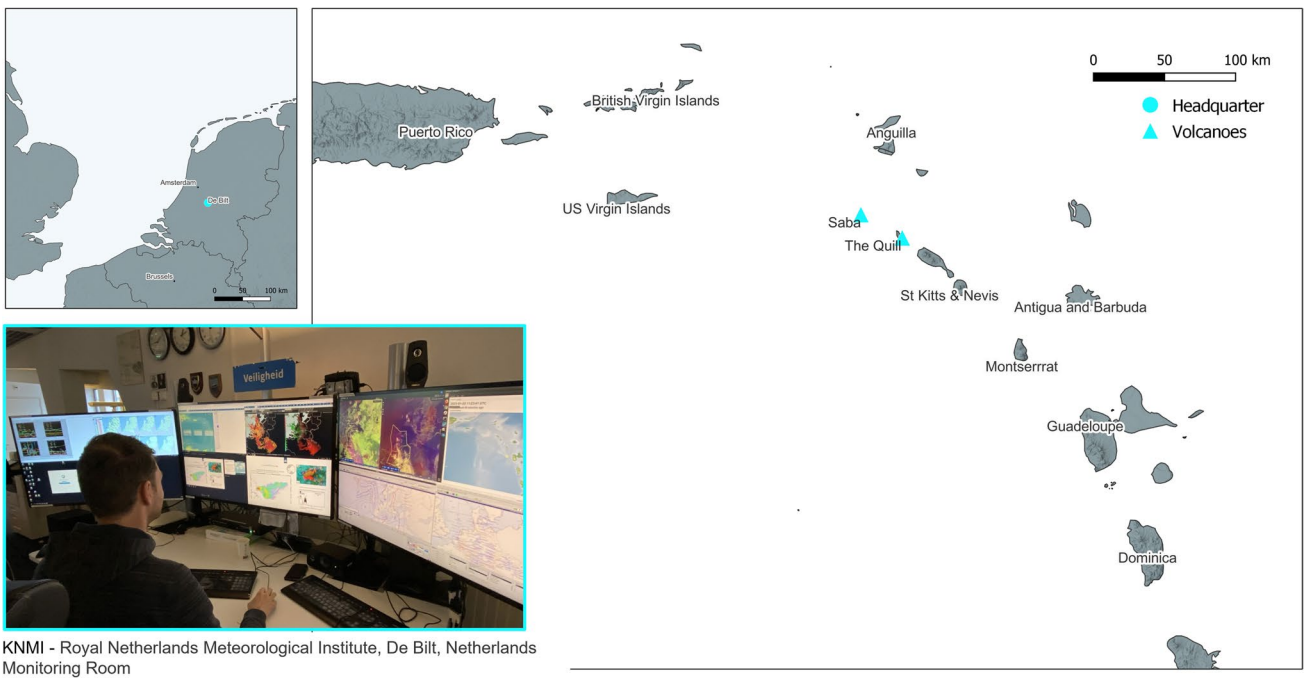

Fig. 10 KNMI's area of responsibility. The monitoring room in De Bilt, Netherlands, is marked with cyan contour

their explosive past. The most recent eruption on Mount Scenery took place around 1640 and at The Quill around 400 CE.

Monitoring capabilities and observatory operations

Since 2006, KNMI has been building a multi-sensor monitoring network (de Zeeuw-van and Sleeman 2018) on the islands. This work is carried out by a team consisting of a volcanologist, a seismologist, and technical support. By the end of 2022, the monitoring network consists of ten broadband seismometers, eight continuous GNSS instruments, and two temperature sensors. Seismic and GNSS data are transmitted to KNMI 24/7 using (i) leased lines, (ii) 4G mobile technology, and (iii) satellite communication. At KNMI, the data are processed automatically and monitored by a 24/7 duty officer (Fig. 7). In acute potentially hazardous situations, a protocol is followed with KNMI informing (i) the local authorities on the islands and (ii) the departmental crisis coordination centre of the Ministry of Infrastructure and Water Management as soon as possible by phone and e-mail. Responsible agencies on the islands can take further action if needed, assisted by the crisis coordination centre. In the case of volcanic unrest, activity reports will be issued to describe the recent changes. During periods of quietness, a status report is issued 1–2 times a year giving a general overview of the monitoring activities.

Usage of alert level systems

A four-tier system corresponding to Volcanic Alert Level and Aviation Colour Code is in place consisting of the following tiers: NORMAL, green; ADVISORY, yellow; WATCH, orange; and WARNING, red. So far, KNMI has never needed to change the aviation colour code. A change in the colour code would be based on the evaluation of available parameters such as seismic data, GNSS data, satellite observations, local observations, and hot spring temperature measurements. A team from KNMI, led by the KNMI volcanologist, would make the decision to change the colour code if deemed necessary. Clear criteria for a change do not exist since very little, to nothing, is known about the eruption behaviour of these volcanoes. The tasks of KNMI can be divided into data acquisition, data analysis and interpretation, and communication of findings to stakeholders. The communication line is in place for volcanic unrest but also functions for regional earthquake and tsunami warnings. A regional annual exercise, CARIBE WAVE, is in place to validate and advance tsunami preparedness efforts in the Caribbean. During this yearly exercise, the protocol is tested and updated when applicable. In 2019, during the EU exercise Caribbean Coast, a volcanic eruption scenario was followed on Saba, including aviation colour code changes.

University of Bergen (UiB)—Norway

Institution and area of responsibility—Beerenberg (Jan Mayen Island)

Beerenberg is the active volcano on the Norwegian island Jan Mayen that is situated about 600 km northwest of Iceland (Gjerløw 2021) (Fig. 1 (brown area) and Fig. 11). It is located along the Jan Mayen fracture zone that connects the Kolbeinsey and Mohns ridges and regularly produces large earthquakes (Rodríguez-Pérez and Ottemöller 2014). Most recently, flank eruptions occurred on Beerenberg in 1970 (Gjelsvik 1970; Siggerud 1972) and 1985 (Imsland 1986; Havskov and Atakan 1991) releasing clouds of steam and ash in both cases. Both eruptions were accompanied by earthquake activity, and for 1985, it was reported that earthquakes preceded the onset of eruption (Havskov and Atakan 1991). The northern part of Jan Mayen is not visible from the settlement Olonkinbyen as Beerenberg is towering in between preventing early visual detection of an eruption. But shaking from frequent earthquakes felt at the settlement, if different from large earthquakes in the Jan Mayen fracture zone, is quite likely an indication of an eruption.

Monitoring capabilities and observatory operations

Jan Mayen has been seismically monitored in collaboration between the Norwegian Armed Forces and University of Bergen (UiB) since 1962. Initially, the monitoring was done with a single station that sadly missed the 1970 eruption as it was down due to maintenance. However, the eruption made it clear that seismic monitoring is required, and a three-station network became operational in 1972. This network recorded the 1985 eruption and remains in place today. Central recording equipment has changed several times, but a major upgrade of the seismic and data transmission equipment was only done in 2018 with infrastructure funding through the EPOS-Norway project. Today, the network has three high-quality broadband seismometers and data is digitally transmitted to the base in Olonkinbyen. The data are received in real time at UiB and processed as part of the Norwegian National Seismic Network (NNSN) operations (Ottemöller et al. 2018). GNSS receivers are installed at two of the sites and data are processed by the Norwegian Mapping Authority as daily chunks.

Near real-time monitoring of Beerenberg currently relies on the seismic data and the processing at UiB during working hours. However, the data are also available to the residents on Jan Mayen who can contact UiB staff at any time.

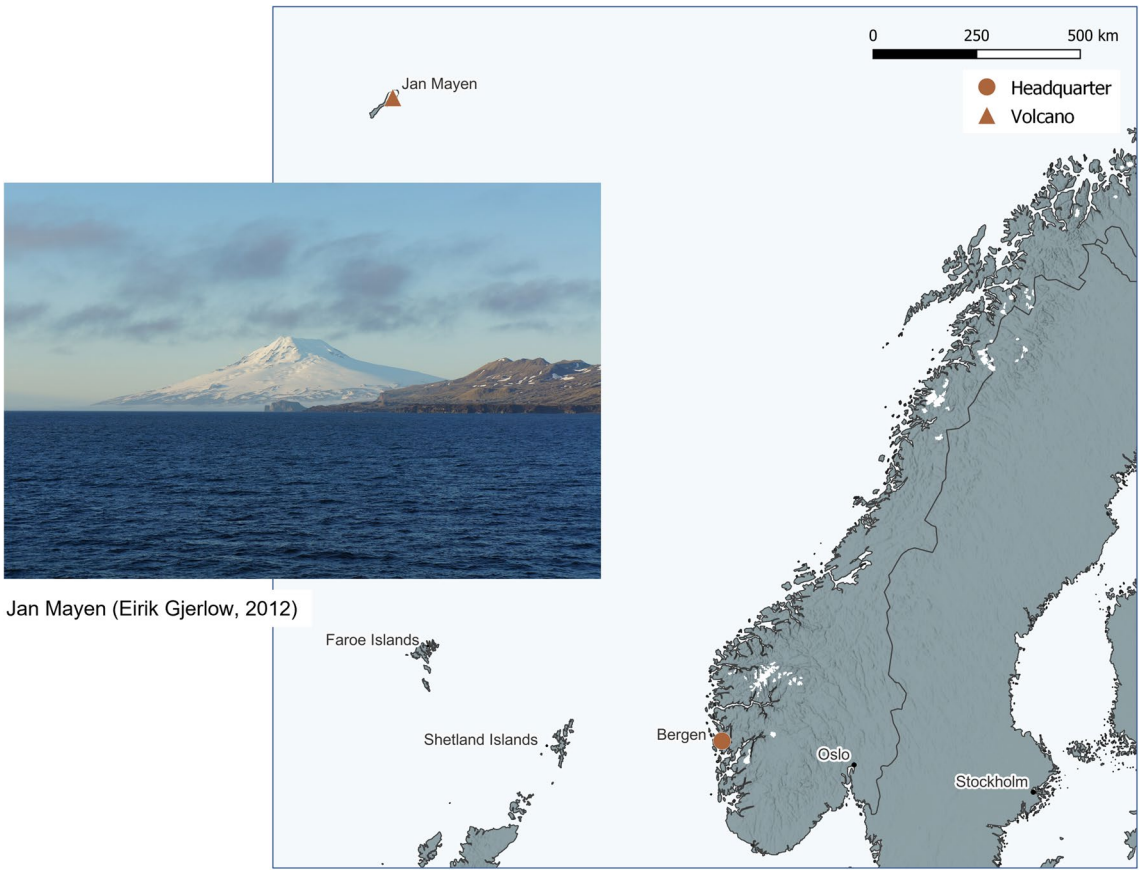

Fig. 11 UiB's area of responsibility and a view of Jan Mayen

Improvements to the monitoring system are possible by implementing automated warning and utilising the GNSS data. Satellite data are monitored by the Norwegian Meteorological Institute (MET Norway), which has the mandate to alert the IMO in case of a suspected ash cloud caused by a Beerenberg eruption. The IMO has then the responsibility to issue SIGMET (SIGnificant METeorological information) messages for the region including Jan Mayen Island (Titos et al. 2022).

Usage of alert level systems

UiB does not yet operate alert level systems for the volcanic area of pertinence.

Experiences in operating the aviation colour code at European Volcano Observatories

The frequency of usage of the aviation colour code, the ability of sending VONA, and the possibility of having them publicly accessible varies significantly amongst VOs. Some already publish VONAs on their websites (see Table 2), whereas others are still working on making them easily accessible. When the number of VONAs issued by each VO is compared, a huge discrepancy is evident. Figure 12 shows the number of times a decisional process has been undertaken for changing the aviation colour code (both during increasing and decreasing activity trends) at each VO over the period 2018–2022. The figure shows the activations that required issuance of a VONA during real cases of unrest or volcanic eruptions (in blue) as well as exercises (in red). INGV-OE and IPGP-OVPF have released the largest number of VONAs for real cases, due to the high frequency of volcanic eruptions at Mt. Etna (452 VONA) and Piton de la Fournaise (82 VONA), respectively. IMO issued a total of 39 VONAs for eight different Icelandic volcanoes. IMO also rehearses on a monthly basis, resulting in a large number of VONAs issued for exercise purposes (52). CIVISA-IVAR also practises often, with 42 VONAs issued during exercises and two VONA for real cases. IGN issued a total of 29 VONAs for real situations and five in one exercise. IPGP-OVSG practised over three exercises. Several VOs did not issue VONAs very often in the past years, neither for real cases nor for exercises (HSGME and KNMI). University of Bergen never had the chance to practise the procedures for

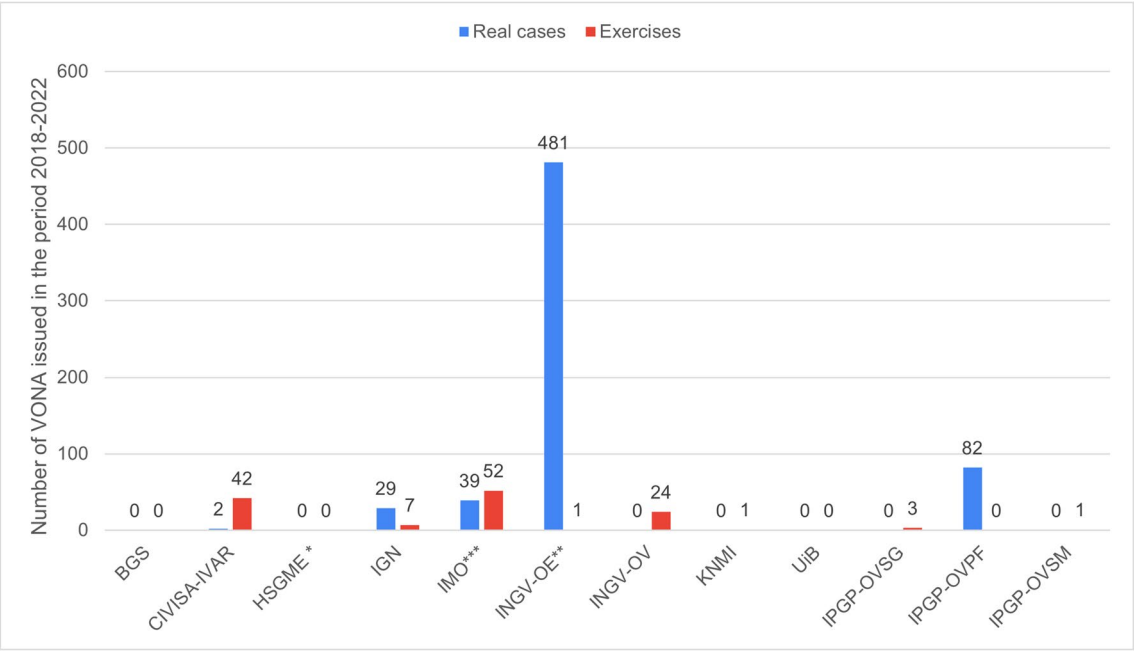

Fig. 12 Number of times a VONA was issued per VO over the past 5 years (2018–2022). In blue are the reported real cases, in red the practices done during exercises. (*) Please note that the case here refers to the only time the ACC was changed for the unrest in Santorini in 2011–2012; (**) these numbers count the changes done for Etna, Stromboli and Vulcano in total; (***) the total number of real usages includes volcanic crises at eight different volcanoes

operating the aviation colour code and issuing VONAs in recent years, and the same applies to BGS.

We report on three recent key events, which raised some aspects to consider for a wider discussion: (1) La Palma eruption in Canary Islands in 2021, (2) São Jorge seismo-volcanic unrest in the Azores in 2022, and (3) Fagradalsfjall eruption in Iceland in 2021.

La Palma eruption in 2021, Canary Islands, responded by IGN

During the La Palma volcanic eruption, 29 VONAs were issued, seven of which involved a change in the aviation colour code (see Fig. 13). During that period, the height of the eruptive column/ash cloud reached up to 8500 m asl (being the topographic height of the emission centre about 1130 m asl when the new volcanic cone was fully developed). The first VONA issued during the event was on 16 September, 3 days before the start of the eruption, with the aviation colour code changing from green to yellow. On 19 September, the eruption started, and the colour code changed from yellow to orange as the emission of ash was not very significant and no clear eruptive column had developed. The first red colour code was issued on 23 September, when an ash-rich sustained eruptive column of 5000 m asl height developed. Five days later, on 27 September, the magma emission stopped for about 7 h (probably due to a collapse in the volcanic conduit), and the aviation colour code was lowered to orange. The next day, with the magma emission restored, the explosive activity reached a maximum height of 7000 m asl, with a large amount of ash, so the colour code was raised to red again and remained there until the end of the eruption during the night of 13 December. On 15 December, the aviation colour code was lowered to yellow due to 24 h without ash emission. On 25 December, the eruption was declared officially over, and the colour code was finally lowered to green.

Throughout the eruption, IGN volcanologists not only issued VONAs, but also met almost daily with personnel from different aviation agencies (air traffic controllers, air navigation providers, aviation safety personnel, meteorological watch officers, military aviation representatives) to communicate the status of the eruption and the expected short-term scenarios. The feedback received from the aviation community was very positive, highlighting that the information received on volcanic processes facilitated their decision-making.

São Jorge seismo-volcanic unrest in 2022, Azores, responded by CIVISA-IVAR

The unrest episode at São Jorge started abruptly on 19 March 2022 at 16:05 (local time, UTC-1), with a sharp

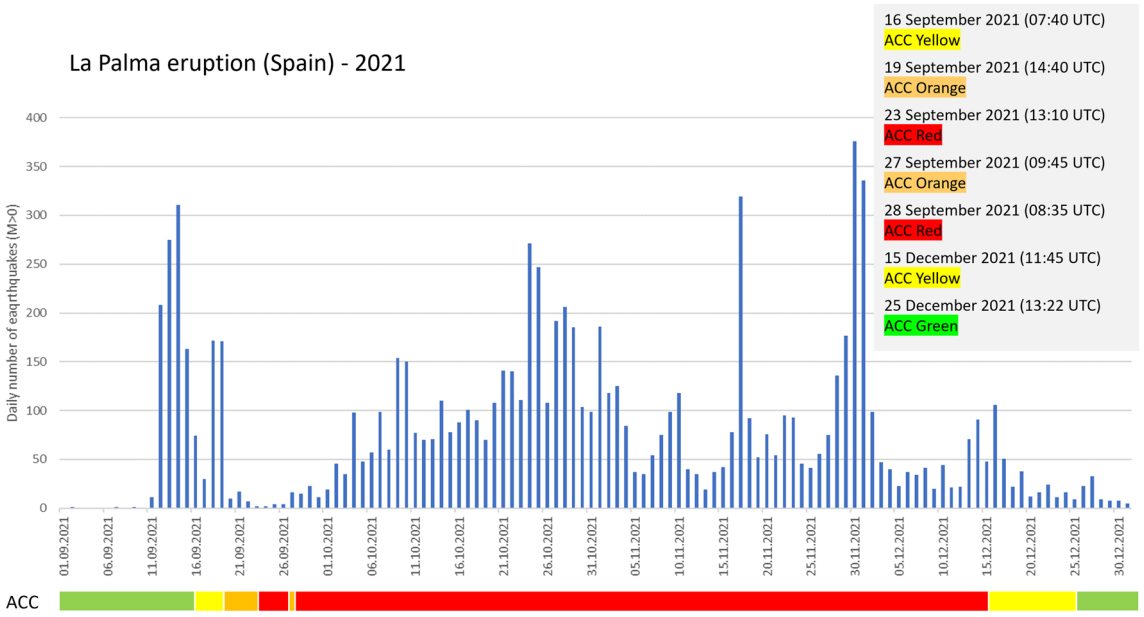

Fig. 13 Timeline of seismicity during La Palma eruption in 2021 and the related change in the aviation colour code operated by IGN

increase in seismic activity in the central part of the island, namely in the Manadas Fissure Volcanic System, where the historical eruptions of 1580 and 1808 took place (see Fig. 14). The seismic swarm quickly escalated on 20 March, leading CIVISA-IVAR to raise the scientific alert level from V0 (volcano in normal, quiet state) to V3 (signs

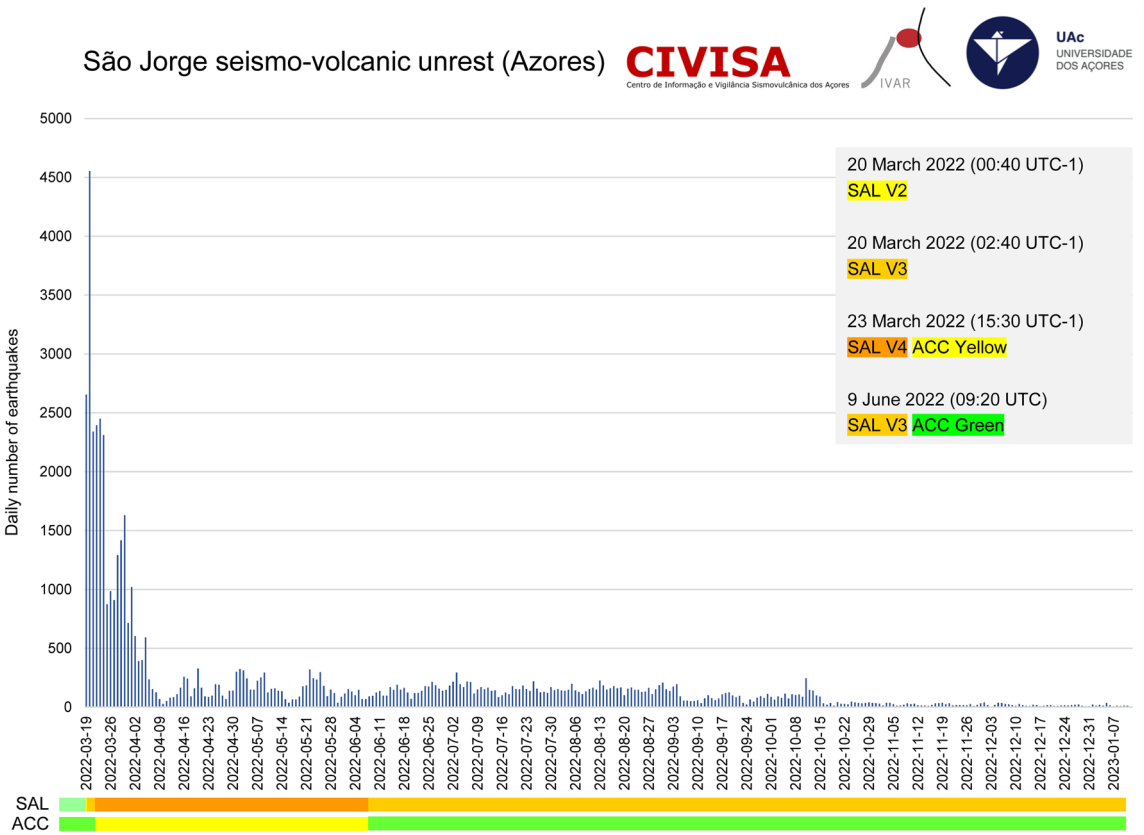

Fig. 14 Timeline of seismicity during Sao Jorge volcanic unrest in 2022 and the related change in the aviation colour code operated by CIVISA-IVAR

of elevated activity, confirmation of reactivation of the system) in less than 12 h. In the following days, seismic activity continued at very high levels and InSAR data confirmed ground deformation in the central part of the island compatible with a dyke intrusion at depth. This prompted CIVISA-IVAR to increase the alert level to V4 (signs of pre-eruptive activity, threat of a volcanic eruption) on 23 March, which was followed by the issuing of a VONA to Toulouse VAAC (and London VAAC for backup) to change the aviation colour code from green to yellow. Seismic activity continued at elevated levels during the following months, with low-magnitude earthquakes (up to M3.8) extending for approximately 20 km along a WNW-ESE-trending strip, from the central part of the island to the western tip. At the end of May and early June 2022, seismic activity showed a decreasing trend, although sometimes interrupted by short periods of higher hourly frequency and/or release of energy. The decrease in seismic activity, together with the absence of other anomalous indicators, related to ground deformation, gases, or waters, led CIVISA-IVAR to lower the scientific alert level from V4 to V3 on 9 June. Accordingly, a new VONA was issued changing the aviation colour code for São Jorge from yellow to green. Nearly 10 months after the onset of the unrest, at the time of writing of this document, the seismic swarm was still ongoing. Until 12 January 2023, more than 56,000 earthquakes were recorded, of which at least 343 were felt by the population.

Fagradalsfjall eruption in 2021, Iceland, responded by IMO

A small effusive eruption commenced at Fagradalsfjall on the Reykjanes peninsula on 19 March 2021 and lasted for 6 months (Barsotti et al. 2023) (Fig. 15). The eruption was preceded by long precursors dated back to December 2019. However, it was not until 24 February 2021, when an earthquake of magnitude M5.7 struck in the unrest area, that the aviation colour code for the Krýsuvík volcanic system was elevated to yellow. After a few days, InSAR images and GNSS data revealed evidence of deformation caused by a likely magmatic intrusion in the area (Sigmundsson et al. 2022; Parks et al. 2023). The aviation colour code was elevated further to orange on 3 March when seismic tremor was detected at several stations on the peninsula, suggesting that magma was travelling at depth. On the evening of 19 March, the eruption started at Fagradalsfjall and the aviation colour code was changed to red. The red colour was maintained for 11 h until a lack of ash was confirmed by a surveillance flight and monitoring observations, causing the aviation colour code to be moved back to orange. This level remained unchanged until 18 October, 1 month after the seismic tremor dropped and no fresh lava was detected at the crater. The eruption was eventually declared over in December 2021; however, the aviation colour code remained yellow as the seismic activity and the deformation level in the peninsula never went back to normal conditions.

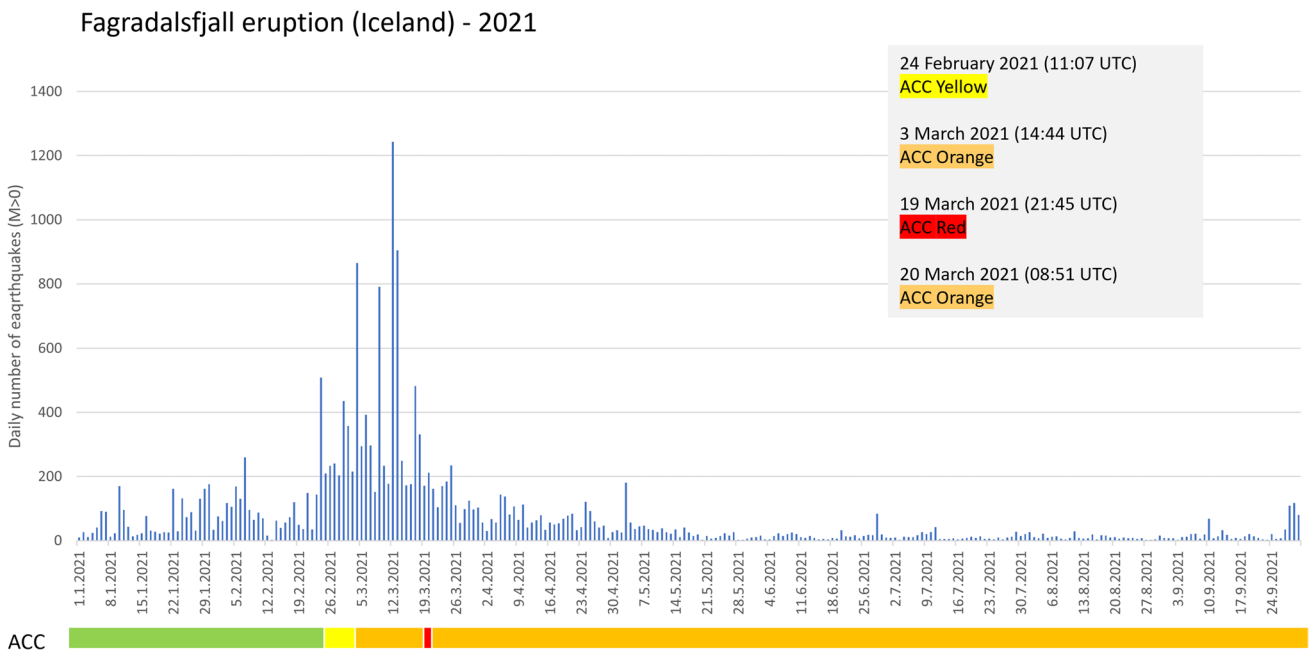

Fig. 15 Timeline of seismicity during Fagradalsfjall eruption in 2021 and the related change in the aviation colour code operated by IMO

The Krýsuvík volcanic system was moved back to aviation colour code green (i.e. normal status) when there was confirmation of no further deformation occurring in the area for several months. As soon as the activity started escalating again in July 2022, the colour code was changed to yellow (30 July) and red when the eruption started again on 3 August. The aviation colour code was moved back to orange after 1.5 h when observations confirmed the lack of release of ash into the atmosphere. This eruption (as well as the two following in 2022 and 2023) clearly showed how the aviation colour code alone is not exhaustive in informing about impending and ongoing volcanic hazards. Even though the aviation colour code was maintained orange for most of the eruption duration, gas pollution, lava flows, ballistics, and grass fires were the main hazards which required a full activation and a proper prolonged response.

Discussion

The following section is structured around four main discussion points, which arise from the data presented and are intended to address some relevant questions that are common to all the European VOs.

1. *When to change the aviation colour code*

Frequently erupting volcanoes facilitate the definition of clear and automatic response procedures, which make the decision of changing the aviation colour code relatively easy, fast, and consistent. The person on duty refers to criteria to move across the different aviation colour code levels and assign it to the current volcano activity. This is the case for Etna in Italy and Piton de la Fournaise in La Réunion. Indeed, both INGV-OE and IPGP-OVPF have already established operational procedures, which rarely need additional scientific advice.

Unrest phases at infrequently erupting volcanoes need to be treated differently, as often these are volcanoes that have not been erupting in modern times and for which the monitoring data have never been used to track unusual activity. However, it is possible to identify some procedures and decisional criteria in common amongst most European VOs. Independent of the variety of volcanological settings, monitoring capabilities, and frequency of activations, these VOs rely on a group of experts to decide on the need for changing the aviation colour code and to choose the appropriate level. This was the case for Fagradalsfjall, São Jorge, and La Palma unrest phases. In all three cases, the yellow aviation colour code was based on the evidence of unusually high level of seismicity and ongoing ground deformation. Both geophysical parameters were considered and analysed before the decision was made to elevate the aviation colour code. In general, the timeline of the volcano therefore often dictates the need for expert advice, with short-term decisions taken by a smaller group of people (often only those on duty) when the unrest escalates, and the likelihood of an eruption increases.

In all cases, the VOs declare that the usage of the aviation colour code is intended to be dynamic and to quickly reflect the changes in volcano status or eruption activity. However, from theory to practise is a big step where it is easy to fall into inconsistencies. In accordance with the European VOs and previous experiences, some questions are raised.

- ***Elevating the aviation colour code to red***

The experiences reported above demonstrate how differently the VOs use the red aviation colour code. IMO changed to red in the beginning of the eruption in Fagradalsfjall even though it turned out to be effusive, but the colour code was not downgraded to orange until the absence of ash in the atmosphere was confirmed (took about 11 h). On the other hand, IGN changed the aviation colour code to red 4 days after the beginning of the low-explosivity eruption in La Palma, as in their assessment, this was the day when the eruption started posing a serious threat to aviation.

INGV-OE is so experienced with explosive eruptions that it moves the aviation colour code to red only for volcanic plumes that are dispersed beyond the P1 no-fly area, in all cases when a significant change of the eruptive style (Strombolian vs lava fountains) occurs, in particular when there is no visibility due to bad weather. In this case, an eruption can evolve suddenly even if a volcanic ash plume in the atmosphere is not detected but values of geophysical parameters (seismic tremor and Doppler radar signal, in particular) are high. In such an uncertain phase, VOs might tend to keep the aviation colour code at red, but occasionally they may face pressure from external partners (like airport, ATS), which would require a release of the restriction imposed by the red alert. IPGP-OVPF on Piton de la Fournaise, in the absence of explosive plumes over the recent period, the aviation colour code was never switched to red. The change to red would be done only if ash release in the atmosphere would be observed (last time in 1961 and to a lesser extent during the caldera collapse in 2007 when the plume was only a few 100 m high).

Based on what was previously stated the following question is raised:

Are VOs expected to raise the aviation colour code to red at the beginning of any eruption (both effusive and explosive) and downgrade it only with respect to the considerations of safe conditions for aviation?

- ***Moving the aviation colour code back to green***

Different approaches are used when changing aviation colour code from higher to lower levels. This is the case for the end of an eruption. As there are no clear criteria to adopt to declare the end of an eruptive episode, VOs might prefer to wait before declaring an eruption over as the volcano might be experiencing just a halt or a temporary pause; misinterpreting the end of an eruption caused the loss of lives during the event of El Chichón volcano in 1982 (Tilling 2009). So, for example, IMO maintained the yellow aviation colour code for 3 more months after the last fresh lava was extruded from the main vent in Fagradalsfjall (however, a much shorter delay was applied to the last eruptions in 2022 and 2023 when the eruptions were declared over 2 weeks after the volcanic tremor dropped to normal level). Similarly, INGV-OE keeps the red aviation colour code at least 4 h after the end of the strong volcanic ash emission. On the contrary, IPGP-OVPF, which relies on seismic tremor, immediately declares the end of an eruptive episode when the tremor ends. Moreover, INGV-OE declares the end of the eruption and the return to green aviation colour code only when direct observations are available, because geophysical data can be ambiguous when there is a pause in the eruption and, for example, lava emission could occur even without any increase in gas emission, seismic swarms, seismic tremor, or seismicity or ground deformation changes (Bonaccorso et al. 2006).

Based on what was previously stated the following question is raised:

Should the aviation colour code reflect the presence of ongoing activity at a volcano and be moved back to "normal level" as soon as possible or should a minimum period, characterised by absence of activity, delay the change?

- ***Long-lasting volcanic unrest***

Another issue that is common across a few VOs relates to the usage of aviation colour code during long-lasting volcanic unrest. This is the case (at the time of writing) for Askja (Iceland), Campi Flegrei (Italy), La Soufrière de Guadeloupe volcano and Montagne Pelée (French Antilles), and São Jorge (Azores). All five volcanoes have recently been showing elevated trends in several geophysical parameters for months/years. Just on 9 November 2022, IMO decided to move the aviation colour code for Askja volcano back to green, after having it set to yellow for more than a year since the beginning of fast uplift in the inner part of the caldera in August 2021 (IMO's website 2021; 2022). The decision of moving it back was based on the lack of other geophysical and geochemical parameters over such a long time window. However, a level of "Uncertainty" issued by the Icelandic Civil Protection is still in force for Askja volcano. Campi Flegrei has officially been in unrest state since 2012 because of continuous uplift (approximately 9 cm/year since January 2012, with slight acceleration), and increase of seismicity and gas flux from the fumaroles (Tramelli et al. 2022). The alert level "Attention" (yellow) was declared by DPC in December 2012. INGV-OV produces regular bulletins of surveillance every week and a summary every month (see Table 2). Every 6 months, the DPC convenes the "Commissione Grandi Rischi - Settore Rischio Vulcanico" (the scientific Commission in charge of the evaluation of the status of the Italian volcanoes) for an update. In the last 10 years, no changes in the current alert level were proposed by the Commission. No VONAs are issued by INGV-OV while Campi Flegrei is in this status of slow uplift. French volcanoes in the West Indies have been in a state of moderate unrest for extended periods of times lasting many years (Soufrière de Guadeloupe, yellow level—vigilance of the ORSEC volcano emergency response plan for 31 years since 1992; Montagne Pelée, yellow level—vigilance of the ORSEC volcano emergency response plan for 2.5 years since December 2020). This has rendered the decision to change the aviation colour code very challenging. The IPGP-OVSG and IPGP-OVSM have not decided to change the aviation colour code during these prolonged unrest periods on the grounds that there was no clear multiparameter evidence that the unrest was escalating or that indicated the probability that the unrest could lead to an explosive eruption in the short-term future with production of ash in the atmosphere. Matching the ORSEC Yellow - Vigilance alert level with the issuance of VONA yellow level message would be counterproductive and is unfeasible for such extended periods of times. In retrospect, it is possible to argue that a yellow VONA notice could have been issued in April 2018 during a short-duration phase of escalating unrest at La Soufrière de Guadeloupe that produced, on 27 April 2018, the largest magnitude M4.1 (depth 2.3 km) volcano-tectonic earthquake at La Soufrière de Guadeloupe in 30 years (Moretti et al. 2020). Given the lack of any clear-cut migration of earthquake activity to shallow levels directly below the summit active fumaroles and of any escalating near-field deformation signals, the aviation colour code was not changed to yellow, and the ORSEC volcano alert level was maintained at yellow—vigilance level. Retrospective analysis of the full data set, once gas sampling was possible on the summit fumaroles after the M4.1 earthquake, led experts to interpret the escalating April sequence of unrest culminating in the M4.1 earthquake as an aborted deep-sourced phreatic eruption whose overpressured hot fluids did not propagate to the superficial hydrothermal system but were drained by relatively deep hydrofracturing along an existing tectonic discontinuity 2 km Northwest from the summit and at a depth of about 2.3

km (Moretti et al. 2020). Despite the non-eruptive outcome, this complex situation could, given the uncertainties, have warranted a change of the aviation colour code to yellow for a short time. The decision was indeed challenging. The seismo-volcanic unrest at São Jorge (Azores) is still ongoing more than 1 year after it started in March 2022, but seismicity has decreased significantly over time. At the moment, CIVISA-IVAR still maintains a scientific alert level V3 (signs of elevated activity, confirmation of reactivation of the system) as the seismic activity is still above "normal" levels, i.e. has not yet returned to the pre-unrest situation. However, the aviation colour code has been green since 9 June 2022, following the lowering of the scientific alert level from V4 to V3 (and no new VONAs have been issued since then) (see Fig. 14).

Based on what was previously stated the following question is raised:

Is a prolonged yellow aviation colour code of any utility or should it be recommended to adopt the aviation colour code only for short-term changes in the volcano? How should a long lasting unrest be communicated to aviation users?

Using aviation colour code along with ground-based alert level systems

An additional issue concerns the usage of different alert level systems for addressing separately ground-based hazards and those which might threaten aviation with the conviction that they do not necessarily need to be raised (lowered) at the same time. In some countries, both systems are operated; in some instances, the VO is in charge of managing both (e.g. CIVISA-IVAR, KNMI), and in others, an operative alert system is controlled by Civil Protection authorities in light of VOs and volcanologists' advices (e.g. INGV, IPGP, IGN, IMO, and HGSME). IMO reports from its experience the lack of such system to warn also on hazards impacting and affecting the local population, visitors, and infrastructure at the ground (Barsotti et al. 2020). The recent effusive eruptions in the Reykjanes peninsula revealed again the aviation colour code to be an inadequate resource for informing about volcanic hazards impacting the surrounding of an eruption and the need for developing a complementary system, which would be used for warning about local hazards, for example, lava flows, jökulhlaup, and gas pollution (Barsotti et al. 2018). In the case of the São Jorge seismo-volcanic unrest, the usage of both systems by CIVISA-IVAR worked well and did not lead to misunderstandings by the end-users as the targets for the different messages are different. The changes in scientific alert levels were communicated directly to the Azores regional civil protection, while the change of the aviation colour code was communicated to Toulouse VAAC via VONA.

The frequency of issuing VONA

Even though the IAVW Handbook offers a valid guidance on how to operate the aviation colour code and the associated issuance of VONAs, it currently leaves some freedom regarding the frequency of the issuance, stating that a VONA must be delivered each time the aviation colour code is changed or when, within the same level, there is a change in the volcanic activity. However, reality is often more complex and variable than what we can imagine and drawing clear lines is often difficult. The main questions arise in the presence of an eruption that is ongoing but poses minimal or no hazard to aviation (e.g. purely effusive eruptions as well as low-plume explosive eruptions). In the past, long low-intensity eruptive phases of Mt. Etna triggered numerous requests for information and clarification from the pilots of the aircraft in transit in the Catania Control Traffic Region. In agreement with ENAC, INGV-OE now reiterates once per week the message contained in the VONA with the orange aviation colour code, even if the previous one is still valid, or if it contains only small variations. During the last eruption in Fagradalsfjall in 2023, IMO also maintained the aviation colour code to orange for several weeks and issued weekly VONA to restate the lack of hazard to the aviation. In this way, it is ensured that air traffic controllers remain aware that an eruptive phenomenon, which does not impact air traffic but can be a source of apprehension for a pilot in transit, is still ongoing.

It is a fact, though, that VOs operate differently, and the consensus is that general guidelines would help in refining plans and responses. The European VOs express their recommendation so that the official documentation reporting on the usage of the aviation colour code and the VONA can clarify and help resolve these open questions, which are raised transversely across all European VOs.

Based on what was previously stated the following question is raised:

How often do VOs have to issue VONAs in such conditions? Is this left to the discretion of VOs themselves?

During the 8th International Workshop on Volcanic Ash, held in Rotorua (New Zealand) in February 2023 (https://community.wmo.int/en/activity-areas/aviation/workshops/iwva-8), it was communicated that the updated version of the IAVW Handbook will contain detailed suggestion on the frequency for issuing the VONA.

Exercises

The analysis conducted in this paper also demonstrated how different is the habit or chances of running exercises. For some VOs, it is already a well-established procedure to practice regularly. For other, very few, if any, exercises have ever

been practiced. The utility of exercises is well recognised in several fields (Witham et al. 2020) and one of the elements reported in the roadmap document published within the EUROVOLC project (https://eurovolc.eu/wp-content/uploads/2020/05/EUROVOLC_D4.4.pdf) recommends the participation of all European VOs in yearly European VOLCEX yearly exercises (Witham et al. 2020; Reichardt et al. 2019). However, for those VOs with weak relationships with their aviation counterparts, it could be difficult to make contact and be involved in practices and common rehearsals. In this perspective, the European VOs envisage the need for a more coordinated activity across the aviation authorities in Europe (e.g. European Aviation Crisis Coordination Centre, National Air Service Providers, Civil Aviation Authorities) and the institutions in charge of providing information during volcanic eruptions. Such activity could be organised and planned through regular workshops, formal working groups and a wide distribution of information, in general.

Conclusions

The absence of an overarching entity coordinating the work performed by the different VOs leaves space for some inconsistencies on how VOs operate in response to volcanic eruptions and unrest phases. The analysis conducted herein amongst European VOs reveals several differences in operating the aviation colour code system as well as in how the VONAs are issued. At the same time, the analysis identifies clear questions that the entities in charge (i.e. ICAO and related commissions) should try to address. This could be done by implementing clearer instructions to harmonise the way different VOs act and react during volcanic activity, with respect to informing the aviation community on possible impending hazards. These questions specifically refer to (1) when to raise the aviation colour code to red, (2) when to lower it to green, (3) how to treat long-lasting volcanic unrest via aviation colour code, and (4) how often to issue a VONA for eruptions that do not pose direct hazard to aviation.

There is a general agreement on the inappropriateness of the aviation colour code as a tool for informing about volcanic ground-based hazards; therefore, an alpha-numeric system to be adopted alongside the aviation colour code is considered necessary. It is recognised such a tool should be built within a consensus by all the different stakeholders, with the aim of avoiding misunderstanding and confusion to the end-users.

Finally, the European VOs recognise the importance of participation in exercises, both at national and European level, e.g. VOLCEX exercises which are held each year, in order to activate and facilitate the connection, which sometimes is lacking, between VOs and the corresponding Air Transport Navigation providers and VAACs.

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Declarations

Conflict of interest The authors declare no competing interests.

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