Bulletin of Volcanology (2024) 86:39
https://doi.org/10.1007/s00445-024-01728-6

RESEARCH ARTICLE

A fast compilation of the VONA messages using a computer-assisted procedure

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Received: 26 September 2023 / Accepted: 29 February 2024
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Abstract
Mt. Etna, in Italy, is one of the most active volcanoes in the world, producing several explosive events in recent years. Those eruptions form high eruption columns that often reach the top of the troposphere (and sometimes even the lower part of the stratosphere) and create several disruptions to air traffic, mainly to the Fontanarossa International Airport in Catania, which is about 20 NM (~37 km; NM = Nautical Miles) away from the summit craters and is located in the main wind direction. In Italy, the institution responsible for volcano monitoring is the Istituto Nazionale di Geofisica e Vulcanologia (INGV). In 2007, the INGV, Osservatorio Etneo (INGV-OE) in Catania was appointed as "State Volcano Observatory" (SVO) and, in 2014, sent the first Volcano Observatory Notice for Aviation (VONA) message. Since that moment, several VONA messages have been sent, mainly due to the high frequency of Etna activity. In order to facilitate and speed in the generation and the dispatch of the VONA messages, a computer-assisted procedure has been designed and built to help the work done by the volcanologist on duty and by the two shift workers of the 24/7 Control Room of INGV-OE. Consequently, information on the explosive activity can be quickly provided to the Volcanic Ash Advisory Center (VAAC) in Toulouse and national air traffic offices, reducing risks to aviation operations. In this work, we describe how the computer-assisted procedure works, addressing the main advantages and possible improvements. We retain that a similar approach could be easily applied to other volcano observatories worldwide.

Keywords Etna volcano · Monitoring activity · VONA messages · Computer-assisted procedure · Hazard mitigation

Introduction

During explosive eruptions, a great amount of particles is ejected in the atmosphere. Whereas particles from hundreds of micrometres to millimetres can fall on densely populated areas causing copious tephra fallout (e.g. Biass et al. 2017; Cioni et al. 2003; Scollo et al. 2013), fine volcanic ash can be easily transported by winds reaching very long distances (Guffanti and Tupper 2015; Prata and Rose 2015). It is well known that fine ash can have a strong impact on aviation operations (Casadevall 1994; Guffanti et al. 2010). The eruption of Eyjafjallajökull in 2010, caused huge economic losses to airlines, estimated at around 299 million dollars a day. After this event, the need to provide air users with information on the presence in the airspace of volcanic ash in quantities exceeding the threshold of possible damage to aircraft, was evident (ICAO 2023). However, this is not an easy task because quantitative information is possible only integrating data from different remote sensing methods (e.g. Scollo et al. 2019; Freret-Lorgeril et al. 2021; Mereu et al. 2022) and/or performing simulations which use ensemble techniques and applying multi-model strategies (Osores et al. 2020; Witham et al. 2007).

The "List of Volcanoes of the World for VAAC Use" published by the Smithsonian Institution (https://volcano.si.edu/projects/vaac-data/) identifies 13 active or potentially active volcanoes on Italian territory. These volcanic systems are considered able to produce eruptions in the short or medium term, as they have shown activity for the past 10,000 years. In the Enroute (ENR) section of the Aeronautical Information

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Publication (AIP), published by ENAV (the Italian joint-stock company which operates as the exclusive provider of civil air navigation services in the Italian airspace), only five volcanoes are classified dangerous for air traffic and they are Etna, Stromboli, Vulcano, Vesuvio and Campi Flegrei. Amongst them, Etna and Stromboli (Fig. 1) are characterised by a persistent activity because they give rise to several eruptive events only separated by short periods of rest (Andronico et al. 2021; Calvari et al. 2021). Moreover, since 1986, Etna has shown an evident increase in the explosive activity, with hundreds of episodes (ranging from violent Strombolian to Lava Fountains) mainly at the summit craters such as the recent eruptive crisis of December 2020–February 2021 which produced a sequence of 66 episodes of lava fountain at the South East crater (Calvari et al. 2022a, b). In general, those events generated eruptive columns rising up to 15 km above sea level (a.s.l.) and volcanic plumes that extend until, in some cases, also hundreds of km away from the volcano (Azzopardi et al. 2013; Scollo et al. 2013; Amiridis et al. 2023).

In some cases, volcanic activity causes the total interdiction of airspace and the interruption of operations at Catania Fontanarossa Airport (LICC), which is only 30 km from the summit craters. Those events encouraged the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE), in Catania, responsible for monitoring of the Sicilian volcanoes, to perform several actions aimed at preventing and reducing the hazard from volcanic ash dispersal and fallout. Moreover, in October 2007, the INGV-OE was appointed as "State Volcano Observatory" (SVO) and has hence the duty to send, as soon as possible, the Volcano Observatory Notice for Aviation (VONA) as reported in the ICAO Doc 9766 Handbook on the International Airways Volcano Watch (ICAO 2023). In 2008, the Etna Volcanic Report (EVR) was structured to define the VONA compliant messages for communication of Etna's eruptive activity through the 24/7 Control Room to the national air traffic offices. Following the aeronautical agreements with the Ente Nazionale Aviazione Civile (ENAC), Meteorological Watch Office (MWO) Italy, Area Control Centre in Rome (ACCR) and Volcanic Ash Advisory Center (VAAC) Toulouse, the first VONA message was issued by INGV-OE on 06/07/2014 at 00:21Z. Since that message and until 16/08/2023, a total of 694 VONA have been issued, 52 of which GREEN type (T) Alert Terminate (see section 3 for VONA type used at INGV-OE), 117 YELLOW (76 of which type (A) Alert and 41 of type (G) eruption Gone), 308 ORANGE (167 of which of type (N) No ash emission and 141 of type (F) ash emission Finished) and 217 RED, 167 of which of type (E) ash Emission and 50 of type (C) ash Cloud.

During Etna explosive activity, volcanological observations are carried out using data from different ground based and

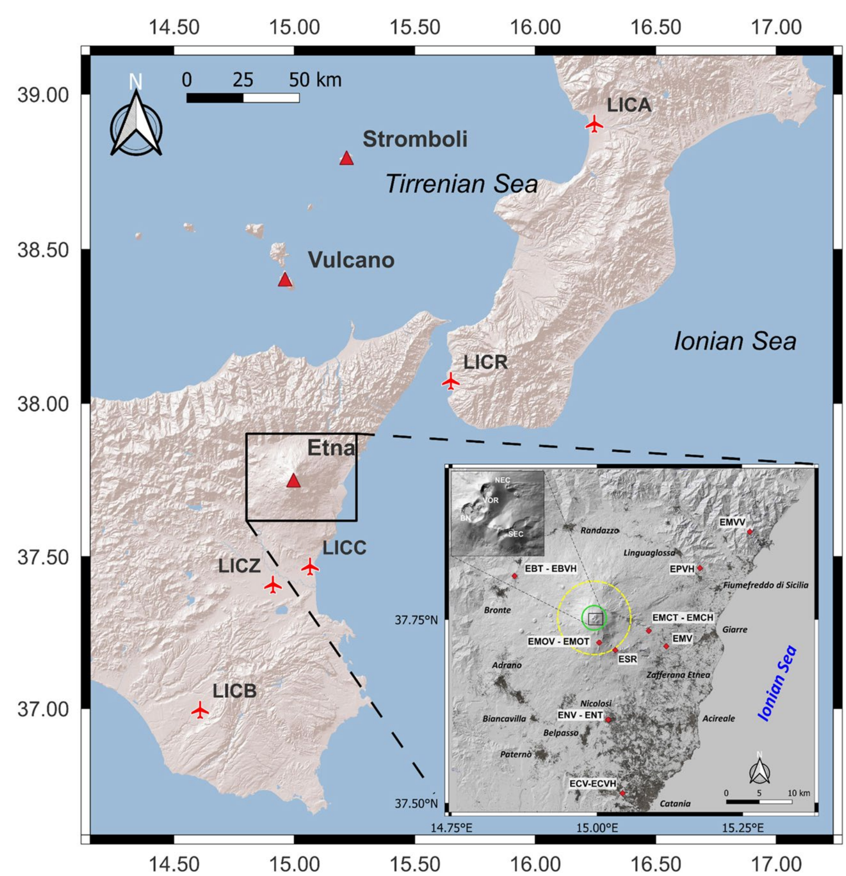

Fig. 1 Map of the Sicilian Volcanoes monitored by INGV-OE including the main airports (LICA = Lamezia Terme; LICB = Comiso; LICC = Catania; LICR = Reggio Calabria; LICZ = Sigonella military). around those volcanoes. In the panel, the map of Etna volcano and the summit craters (NEC = North East Crater; VOR = Voragine Crater; BN = Bocca Nuova Crater; SEC = South East Crater). Red diamonds: video surveillance network cameras (ECV-ECVH Catania CUAD; EBT-EBVH Bronte thermal and visible; EMCT – EMCH Monte Cagliato thermal and visible; EMV Milo visible; EMOV – EMOT Montagnola visible and thermal; ENV – ENT Nicolosi Visible and thermal; ESR Schiena dell'asino visible; EMVV Monte Veneretta visible; EPVH Piedimonte visible). The maps were created using the open source software QGIS, Coordinate Reference System WGS84; EPSG:4326

satellite remote sensing systems. As an example, after 2019, data on column heights of Etna, obtained analysing images of the visible calibrated cameras and satellite (Scollo et al. 2014), are also available to shift workers of the 24/7 Control Room and to the volcanologists on duty (Scollo et al. 2019; Corradini et al. 2018). This has improved the capability of INGV-OE to give detailed information on explosive activity but also increased the number and quality of the messages sent to aviation authorities. In fact, when there is a significant variation of column height with time, a new VONA is usually sent. Considering that Etna shows different eruptive styles, a high number of the VONA messages are usually issued by INGV-OE. Furthermore, it is worth noting that the Fontanarossa Airport in Catania exceeded ten million passengers in 2022, being amongst the busiest European airports (Fig. 1). For all those reasons, a semi-automatic procedure has been implemented in the 24/7 Control Room to write and send the VONA messages quickly.

The paper is structured as follows: the "The VONA messages at INGV-OE" section explains the main structure of the VONA messages; the "The computer-assisted procedure" section explains the computer-assisted procedure; in the "Instruments which support the drafting of the VONA messages" section, we describe some of the instruments running in near real time aimed at assisting the volcanologist on duty in drafting the VONA messages. Moreover, in the "Application to eruptive events at Etna" section, we will show two examples of VONA sent during two different Etna volcanic crises (Lava Fountain versus Effusive Activity) and discuss our results in the "Discussions" section.

The VONA messages at INGV-OE

All VONA messages issued by INGV-OE can be downloaded at the following link:

https://www.ct.ingv.it/index.php/monitoraggio-e-sorveglianza/prodotti-del-monitoraggio/comunicati-vona. The VONA message format is extracted from the ICAO Doc.9766-AN/968 "Handbook on the International Airways Volcano Watch (IAVW)" and the main structure is shown in Fig. 2. There is a brief summary of volcanic activity including the main observations of volcanic ash emission. The VONA message should have "synthetic" sentences suitable for describing the eruptive phenomena

The VONA structure

(1) VOLCANO OBSERVATORY NOTICE FOR AVIATION — VONA

(2) Issued: Universal (Z) date and time (YYYYMMDD/HHMMZ).

(3) Volcano: Name and number (per Smithsonian database at http://www.volcano.si.edu/)

(4) Current Aviation Colour Code: **GREEN, YELLOW, ORANGE, OR RED** in upper case bold font

(5) Previous Aviation Colour Code: Lower case font, not bold

(6) Source: Name of Volcano Observatory (volcanological agency)

(7) Notice Number: Create unique number that includes year

(8) Volcano Location: Latitude, longitude in NOTAM format (N or S deg min W or E deg min)

(9) Area: Regional descriptor

(10) Summit Elevation: nnnnn FT (nnnn M)

(11) Volcanic Activity Summary: Concise statement that describes activity at the volcano. If known, specify time of onset and duration (local and UTC) of eruptive activity. If the eruption is ongoing at the time of VONA release, indicate "eruption and ash emission is continuing".

(12) Volcanic Cloud Height: Best estimate of ash-cloud top in nnnnn FT (nnnn M) above summit or AMSL (specify which). Give source of height data (ground observer, pilot report, radar, etc.). "UNKNOWN" if no data available or "NO ASH CLOUD PRODUCED" if applicable.

(13) Other Volcanic Cloud information: Brief summary of relevant cloud characteristics such as colour of cloud, shape of cloud, direction of movement, etc. Specify if cloud height is obscured or suspected to be higher than what can be observed clearly. "UNKNOWN" if no data available or "NO ASH CLOUD PRODUCED" if applicable.

(14) Remarks: Brief comments on related topics (monitoring data, observa-tory actions, volcano's previous activity, etc.)

(15) Contacts: Names, phone numbers (voice and fax), email addresses.

(16) Next Notice: "A new VONA will be issued if conditions change significantly or the colour code is changes." Include URL of Web site where latest volcanic information is posted.

Fig. 2 Main structure of the VONA message issued by INGV-OE. The structure is taken from the ICAO Doc.9766-AN/968 "Handbook on the International Airways Volcano Watch (IAVW)"

Table 1 Activity Colour Codes (ACC) used by INGV-OE during Etna explosive activity

Number	Color Code	Volcano status	Description
1	GREEN	Normal	Normal or quiescent state, no unrest activity observed
2	YELLOW	Unrest	Pre-eruptive activity with possible weak ash emission confined within the P1 zone
3	ORANGE	No-Ash Eruption	Effusive or strombolian eruptive activity with reduced emission of ash confined within P1 zone
4	RED	Ash Eruption	High ash emission beyond P1 zone produced by a paroxysmal phenomenon, strong intra crateric activity, crater collapse

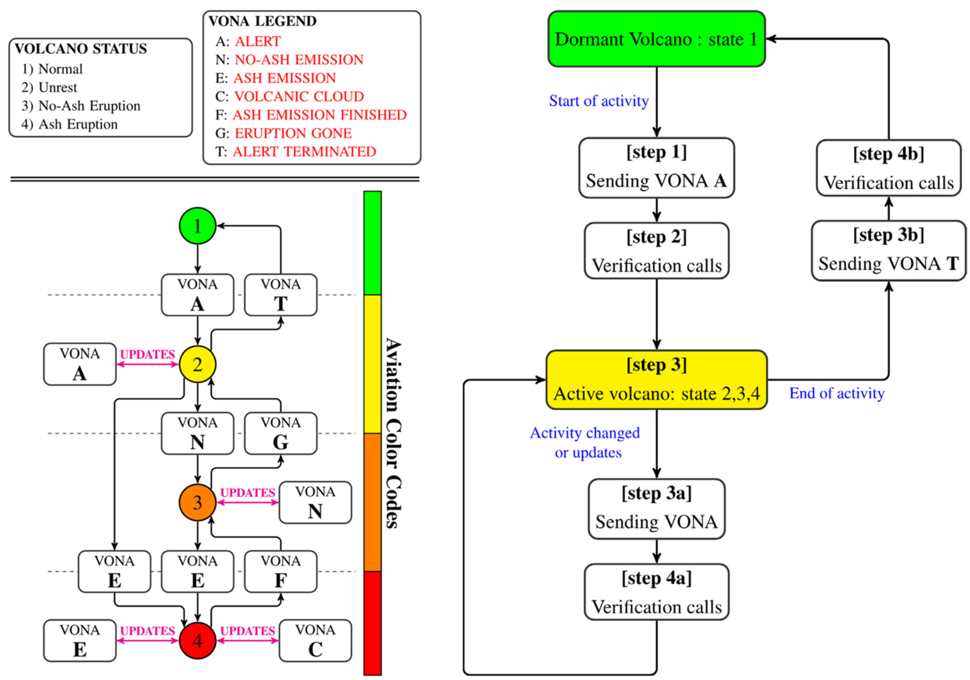

Fig. 3 On the left, the VONA state machine and related messages; on the right, outline of the operating procedure described in Table 2

but avoiding the use of technical terms. Moreover, the message must be provided as soon as possible (< 5–10 min since the first observation of a volcanic event) expeditiously to minimise harm to passengers and avoid risks to air traffic. Considering the Sicilian volcanoes, the VONA messages for Etna have been available since 2014, whilst for Stromboli and Vulcano volcanoes have been available since 2019 and 2021, respectively. The Stromboli volcano does not present long periods of quiescence but only of minor activity, the effects of which are, as a rule, limited to the prohibited zone (LI P200) above the volcano and manifest themselves with effusive activity and with the fallout of short-range pyroclastic material; therefore, these manifestations do not represent a significant predictive signal of the possibility of an explosive eruption, nor of the possibility of ash being released into the atmosphere. Consequently, the concept of pre-eruptive activity, as defined and described in ICAO Doc. 9766 associated with the alert level identified with the YELLOW code "YELLOW ALERT: Volcano is experiencing signs of elevated unrest above known background levels" currently, it is not directly applicable to the activity of the Stromboli volcano.

A better and more responsive description of the state of normal activation of the Stromboli volcano is achieved

Table 2 Steps of the internal procedure used to send the VONA messages at INGV-OE. As required by ICAO Doc. ICAO 9766, INGV OE immediately communicates available information to ACC/FICs, MWOs and associated VAACs by telephone to verbally inform them of significant activity, and then follows up with a Volcanic Aviation Observatory Notice (VONA) sent by e-mail

STEP-1	If the volcano activity is starting (unrest condition) send VONA message A and other alert communications to Civil Protection authorities [go to step 2]
STEP-2	Make the verification calls to verify that the recipients received the message correctly [go to step 3]
STEP-3	Following the following sub steps
	a) if there is a change in the activity or for weekly communication send the relevant VONA message [go to step 4a]
	b) if the volcanic activity is terminated send VONA message T [go to step 4b]
STEP-4a	Make the verification calls to verify that the recipients received the message correctly [go to step 3]
STEP-4b	Make the verification calls to verify that the recipients received the message correctly [go to step 1]

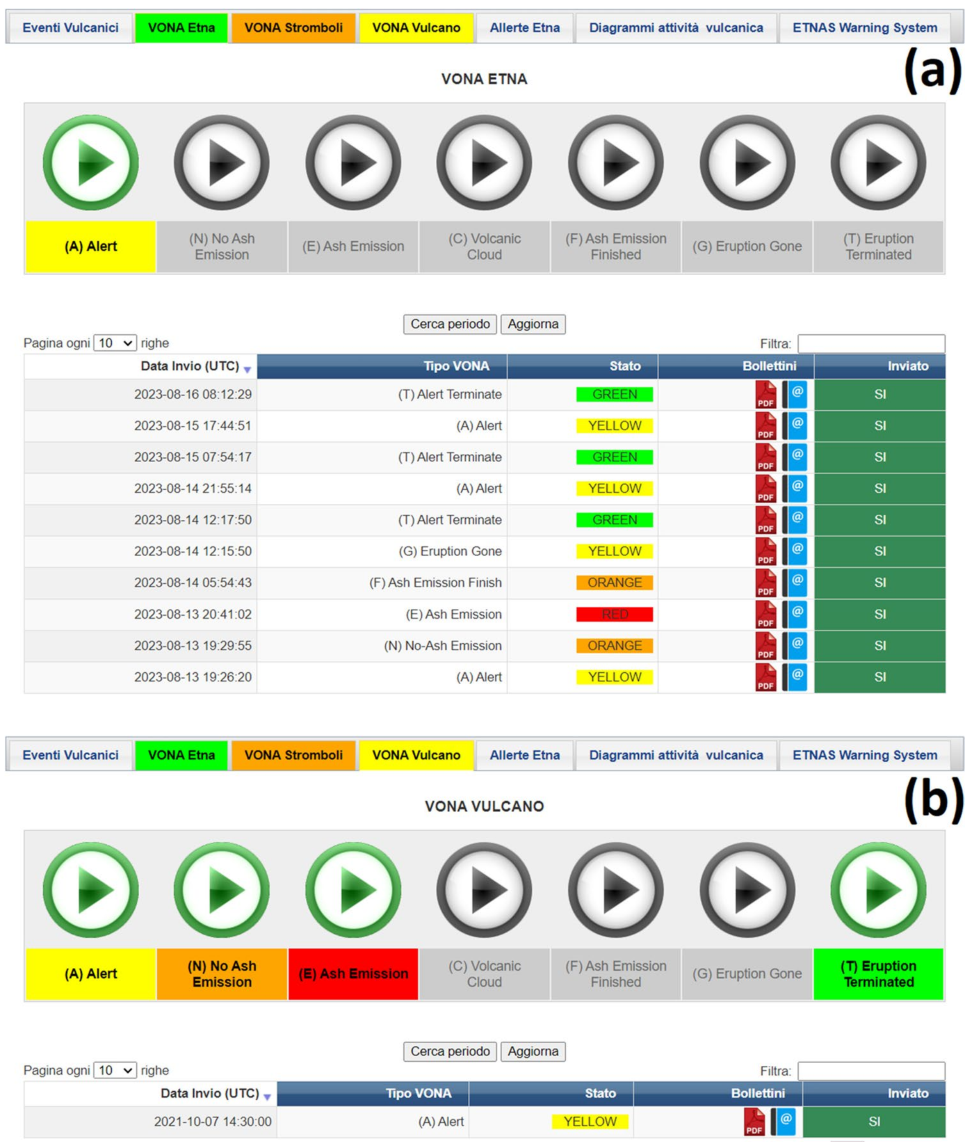

Fig. 4 The WEB interface of the VONA message software tool. **a** An example of the dashboard configuration for Etna when the current ACC = green. **b** An example of the dashboard configuration for Vulcano, when the current ACC = yellow (in this case)

by attributing the colour code ORANGE to the Stromboli volcano corresponding to continuous eruptive activity, not necessarily associated with the release of volcanic ash into the atmosphere (ORANGE – NO OR MINOR ASH EMISSION).

The VONA messages issued at Etna

Mt. Etna (Italy) is located in the East of Sicily (Fig. 1). It involves the airspace of the Flight Information Region (FIR) of Area Control Center of Rome Ciampino and the

Control zone (CTR) managed by Sigonella military airport. During Etna explosive eruptions, volcanic plumes can affect mainly the airports of eastern Sicily (Catania, Sigonella and Comiso). An area (LI P1, where LI is the ICAO country code for Italy) around the summit area of Etna has been established and represents the portion of the airspace in which air traffic is always prohibited, with the exception of state flights, air ambulances and aircraft directly involved in operations authorised by the Italian Civil Protection Department. In detail, the LI P1 is a circular area centred on 37°44′55″N 015°00′02″E, with a radius of 1 NM (~1.85 km) when the activity colour code is green and 3 NM (~5.56 km) when the Activity Colour Code (ACC) is yellow. It extends—vertically—from the surface (SFC) to FL195 (about 6000 m a.s.l.). Therefore, the volcanic activity which occurs within this area is not considered dangerous for air traffic. On Etna the ACC (Field 4 in the VONA message) is based on a scale of four different colours defined by ICAO (Table 1).

For Stromboli and Vulcano, a similar procedure is applied. As for the Etna volcano, at Stromboli a prohibited area has been defined (LI P200). It is a circular area centred on 38°47′39″ N 015°12′40″ E with radius 0.3NM and extending vertically from the surface (SFC) to FL50 AMSL (about 1500 m). For Vulcano, no forbidden area has been defined yet. Note that, for the Stromboli volcano, the first VONA message was issued on 10 July 2019 and, since a persistent Strombolian activity occurs, the VONA is always "orange". Since this first message and until 16/08/2023, 44 VONAs have been issued, most of them to communicate the

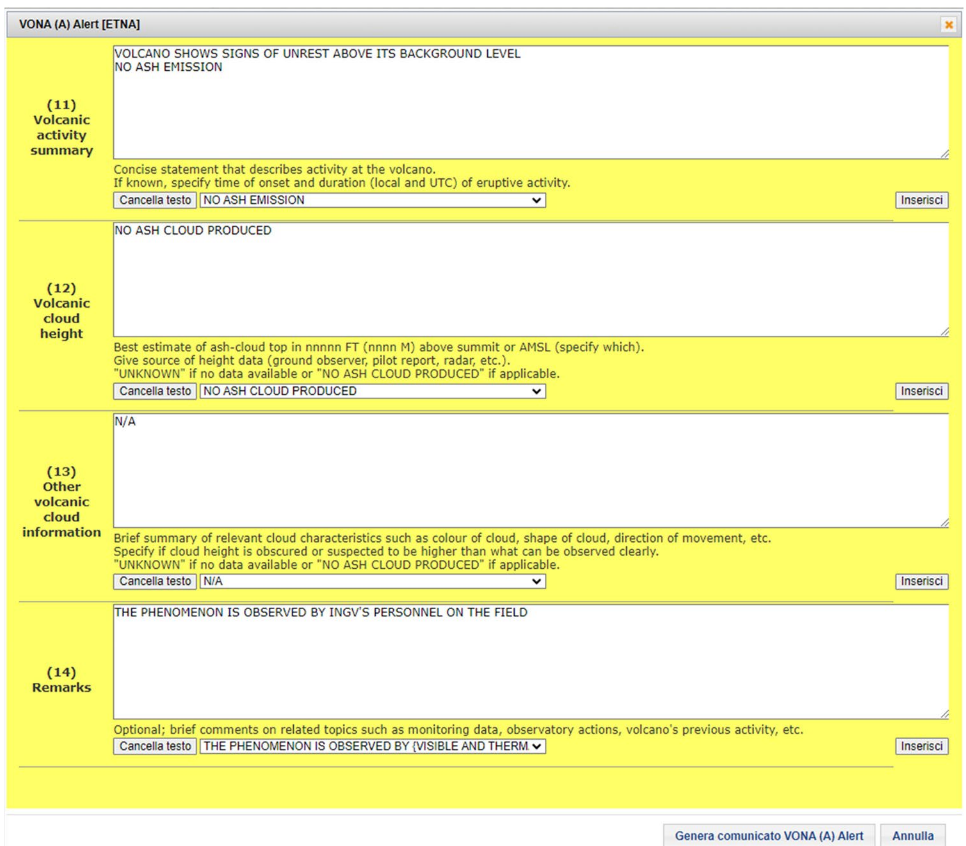

Fig. 5 Wizard of the descriptive fields of the VONA messages

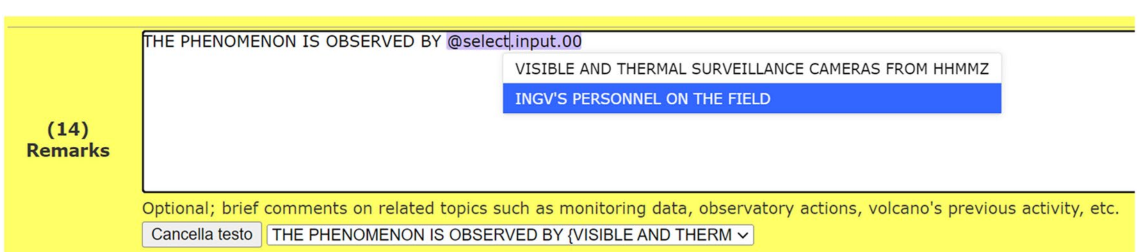

Fig. 6 List of sentence portions proposed by the system to replace tags (*@select.input.XX*)

occurrence of summit effusive activity; the only RED message was sent on 28 August 2019 during a paroxysmal event which formed an eruption column of 4 km a.s.l. (Giordano and De Astis 2021). Finally, for the Vulcano volcano, only one VONA message has been sent on 7 July 2021, at the onset of the unrest phase which has been observed since 2021 and still ongoing (Federico et al. 2023).

The computer-assisted procedure

In the VONA messages, the ACC is also associated with a number from 1 to 4 (Fig. 3 and Table 1) to maximise the use for 24/7 shift workers who could have colour discrimination deficits. Figure 3 shows the flow diagram of the VONA messaging (or state machine) on the left. Circles represent the volcano states (see VOLCANO STATUS legend) and are coloured according to the relative ACC. Arrows express the transitions between them and are accompanied by rounded rectangles representing the type of VONA sent for the transition (see the VONA LEGEND). On the right of Fig. 3, the operating procedure starting from a quiet state of the volcano is shown.

Starting from a normal state (dormant volcano (state 1), aviation colour code = green), the procedure consists of the following steps, described in Table 2.

The shift workers must send the VONA messages with every change in the state of activity of the volcano. In order to facilitate the compilation of those messages and minimise the errors, a software tool has been created. The tool is a web application, and the code was written in PHP (server-side) for data management and in Javascript (client-side) for interface management. It is fully integrated into the software environment used by shift workers for the regular execution of the workshift (Cassisi et al. 2016) allowing to the following: (i) ensure the consistency of the VONA state machine; (ii) help the shift workers to follow the right operating procedure; (iii) simplify the compilation of the descriptive fields; and (iv) ensure the correct compilation of the VONA messages. Given the potential interest this application might have amongst other SVOs, we plan to rewrite the code to make it self-consistent and share it with the worldwide SVO community.

Figure 4 shows the WEB interface of the software tool. The tab background colour reproduces the current ACC. The interface consists of only 7 buttons (dashboard). Each button is associated with a specific type of the VONA message. The dashboard helps to select the right VONA type according to the current ACC. If a button is enabled, the background of the caption is coloured with the ACC that the system will assume once the VONA message will be sent, otherwise the background colour is grey and then such transition is

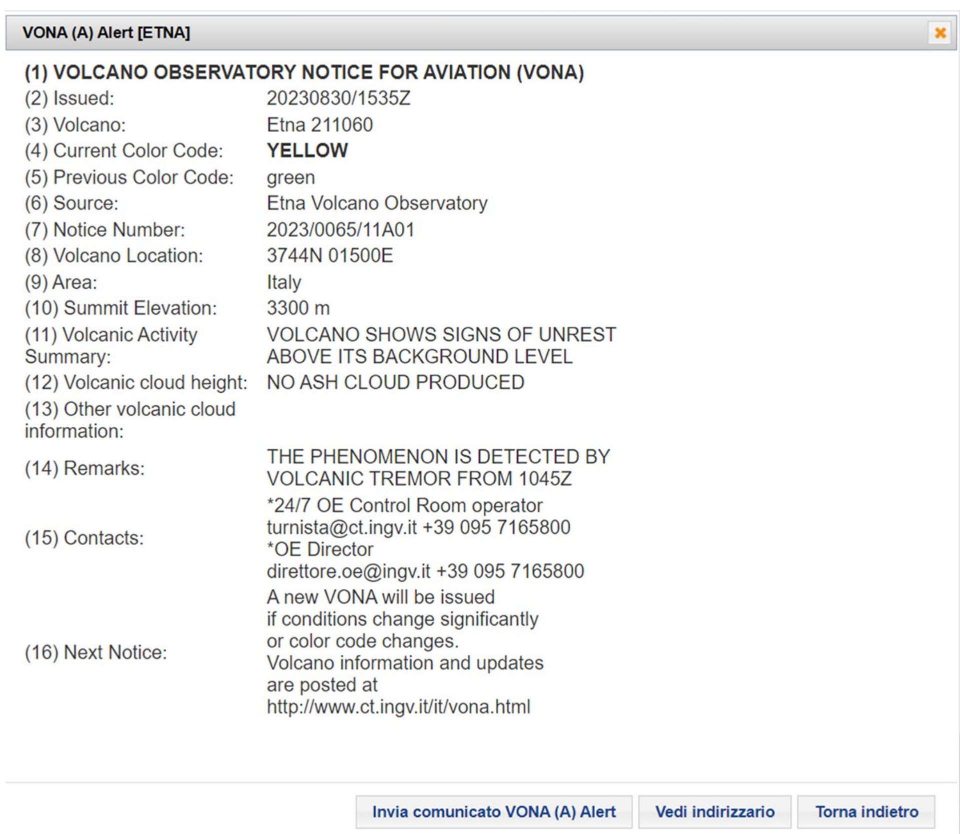

Fig. 7 Preview of the VONA message, generated before sending

not allowed. Figure 4 (a) shows the example of Etna having the current ACC = green, where only the VONA type A is enabled for the transition to the ACC = yellow. In (b) the example of Vulcano having the current ACC = yellow, where VONA types A, N, E and T are enabled for the transition to the ACC = yellow, orange, red and green respectively, according to flow diagram shown on the left of Fig. 3. Once the shift worker has selected the VONA message (click on the button), a wizard will be displayed to assist editing the descriptive fields. Figure 5 shows instead the interface of the wizard. Also in this case the interface background colour is informative and represents the ACC that the system will assume once the VONA message will be sent.

The wizard interface contains 4 editable areas, corresponding to the sections from 11 to 14 of the VONA message's structure (see Fig. 2). Depending on the type of message, some fields can be filled automatically with default sentences, otherwise the shift worker would have to fill a new text of the field under the leadership of the volcanologist on duty. For each field, there is a drop-down box that contains pre-edited messages making the VONA compilation easier. In fact, the shift worker can select a parametric pre-edited message from the list and insert it in the text area using the *Insert* (it. label "Inserisci") button. Once inserted the message, it can be modified by acting on the interactive portions. The editing engine also provides interactive fields for numerical values (time, geographical coordinates, altitudes and distances) and portions of text. The engine simplifies the input method, taking care of converting the result into the correct format foreseen in the VONA messages. Moreover, the system proposes a list of sentence portions that can be inserted in place of suitable tags (*@select.input.XX*). The user clicks on the tag, selects the most relevant phrase and the tag will automatically be replaced by the new phrase. Figure 6 shows an example of this interaction with a sentence list defined by plain text included in curly braces, separating the single options by a vertical bar (*{sentence 1|sentence 2|...}*). Figure 7 shows the interface before the VONA submission.

The other Sects. (1–10; 15–16) of the VONA message are compiled automatically from the system. Once all the fields have been filled in, pressing the "*Generate VONA message*" button (it. label "Genera comunicato VONA", Fig. 5) will display a preview interface showing the VONA message (Fig. 7). In this way the shift worker can check the content of the message, send it or return to the editing interface modifying the content of the VONA message. It is worth noting that, with the exception of the initial VONA (GREEN to YELLOW), the VONA messages have to be compiled by the shift worker only with the support of the volcanologist on duty. All the sentences used in this procedure can be visible in the Supplementary Information.

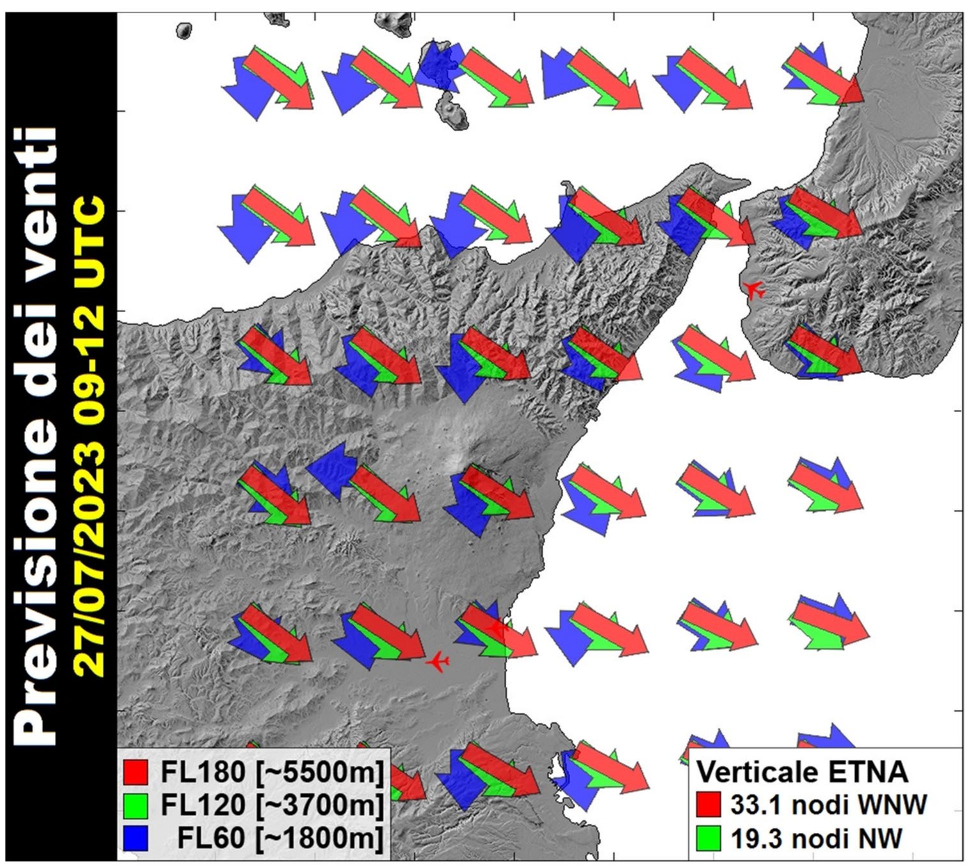

Fig. 8 Wind forecasts available at the 24/7 Control Room of INGV-OE on 27/07/2023

Instruments which support the drafting of the VONA messages

Hereafter, we briefly describe the main instruments used by the volcanologist on duty in the drafting of the VONA messages for Etna volcano. These include wind forecasts, volcanic tremor signals, the video surveillance system and satellite images from the SEVIRI satellite.

INGV-OE daily receives the weather forecast from the Italian Air Force Meteorological Office (in Italian acronym CNMCA) in Rome and from the hydrometeorological service of ARPA in Emilia Romagna (ARPAE, https://www.arpae.it/it/temi-ambientali/meteo). Weather forecasts are covered for 48 h and have an area which covers most of Sicily and have 22 isobaric levels (Scollo et al. 2009). Meteorological data at three different levels are available to the 24/7 Control Room and help the volcanologist to estimate the main wind direction of the volcanic plume during an eruption (Fig. 8) when volcanic ash is present in the atmosphere (orange or red ACC). The file is transferred every day early in the morning. The main direction is hence added in the VONA message, also taking into account the height of the eruption column.

Another important parameter is the seismic background volcanic tremor, which plays a key role in the surveillance of Etna. Since 2006, a multi-station alert system has been established in the INGV-OE Control Room exploiting the ratios between two different stations (D'Agostino et al. 2013). When the volcanic tremor is high and the summit craters are not visible (e.g. bad weather conditions) the VONA can be moved to the RED by the volcanologist on duty only based on geophysical signals (Field 14). New updates of this system have been recently made but they are in a test phase.

The video-surveillance system has been continuously improved at INGV-OE and now, around Etna, there are several thermal and visible cameras located around the summit crater and covering almost all the direction. The system is formed at the time of writing of 14 cameras which operate continuously on Etna. All images are sent in real time, through dedicated transmission systems, to the INGV Control Room in Catania (Fig. 9). The analysis of those images, together with the observation of personnel in the field, is very useful to describe the state of eruptive activity in the bulletins and communications. Moreover, they can be used to estimate qualitatively the amount of volcanic ash in the atmosphere.

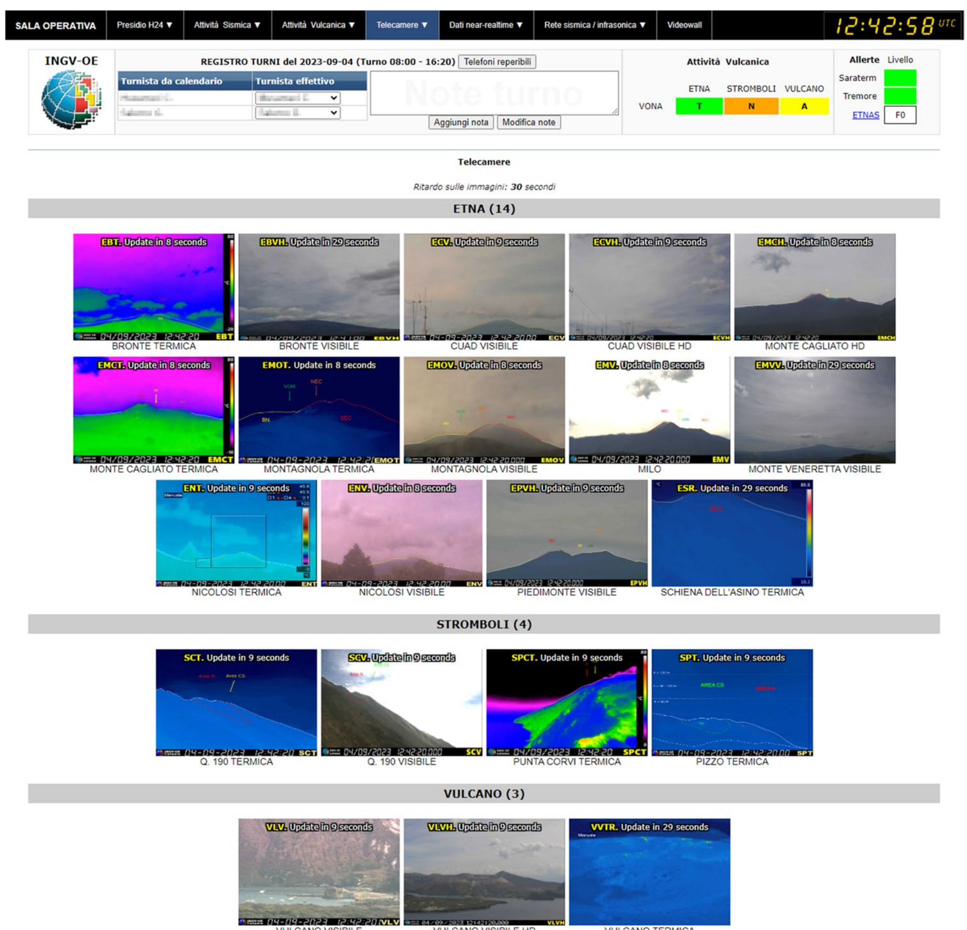

Fig. 9 Screenshot of the webcamera available in the 24/7 Control Room

The estimation of the eruption column height in real time is carried out by analysing the images from two visible cameras and the images acquired from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) MSG satellites. Two cameras, located in Catania (ECV) and Bronte (EBVH) in the south and west volcano flank (Fig. 1), with a 1/2.5″ progressive CMOS image sensor and a maximum resolution of 2560 × 1920 are used. The field-of-view is 33°–93° (vertical), 24°–68° (horizontal) and 40°–119° (diagonal). Both cameras were calibrated following the approach described in Scollo et al. (2014). The uncertainty of the column height is + / − 500 m. Moreover, the SEVIRI images are also sent by file transfer protocol (FTP) from INGV in Rome to INGV-OE in Catania (Scollo et al. 2019). Satellite images are hence analysed in near real time to estimate the column height taking into account the temperature of most opaque pixels above the summit craters and comparing it with the atmospheric temperature profile extracted from the weather forecasts around the volcano (Corradini et al. 2018). The error for Etna is generally less than 10% in height and is set equal + / − 500 m also for satellite data. Example of the method is in Fig. 10. Figure 10.a shows the output of the SEVIRI data processing, at the top left is shown the estimate of the volcanic plume height (9051.24 m) above the summit crater. The image processing output of the ECV camera is shown in Fig. 10b. Finally, Fig. 10c shows a frame captured by the EBVH camera installed on the northwest slope of the volcano.

Application to eruptive events at Etna

In this section, we describe the application of this procedure during two eruptive events that occurred in the past but that can represent the most common activity at Etna: the lava fountain and lava flow emission. For lava fountains we took as an example the activity of 12 March 2021 when Strombolian activity produced from the South East Crater began at about 03:35 UTC followed by lava fountains formed between 06:40 and 09:45 UTC (Calvari et al. 2022a, b). During this event, the volcanic plume rose up to about 10 km above sea level (Fig. 11). The first VONA message was issued at 06:18 UTC, indicating Strombolian activity and a volcanic plume high about 4 km a.s.l. (Fig. 11a). Then another VONA message was sent at 07:49 UTC when a lava fountain was observed and a column height of 6 km was estimated using images of visible calibrated cameras (Fig. 11b). Furthermore, a new VONA was issued by INGV-OE at 08:44 UTC because the column reached the height of 9 km and the volcanic plume moved towards the east direction (Fig. 11c). Although the lava fountain and, consequently, the presence of an eruption column ended at about 09:45 UTC, the VONA message was moved from red to orange at 12:32 UTC (Fig. 11d), because volcanic ash was no longer visible around the summit craters and the geophysical parameters came back to almost the background level.

On 27 November 2022 starting at about 17.00 UTC, the video surveillance cameras observed an effusive vent at the north-eastern base of the SEC, at an altitude of about 2800 m a.s.l., from which a small lava flow was emitted and slowly advancing in the direction of the Valle del Leone (Fig. 12a). Observations via cameras were very difficult due to cloud cover. The first VONA Yellow—A (Alert) message is issued at 18:48Z to signal the unrest in progress, and is followed at 21:44Z by the VONA orange—N (No ash emission) message which communicates the presence of a lava flow in the summit area and the absence of ash cloud.

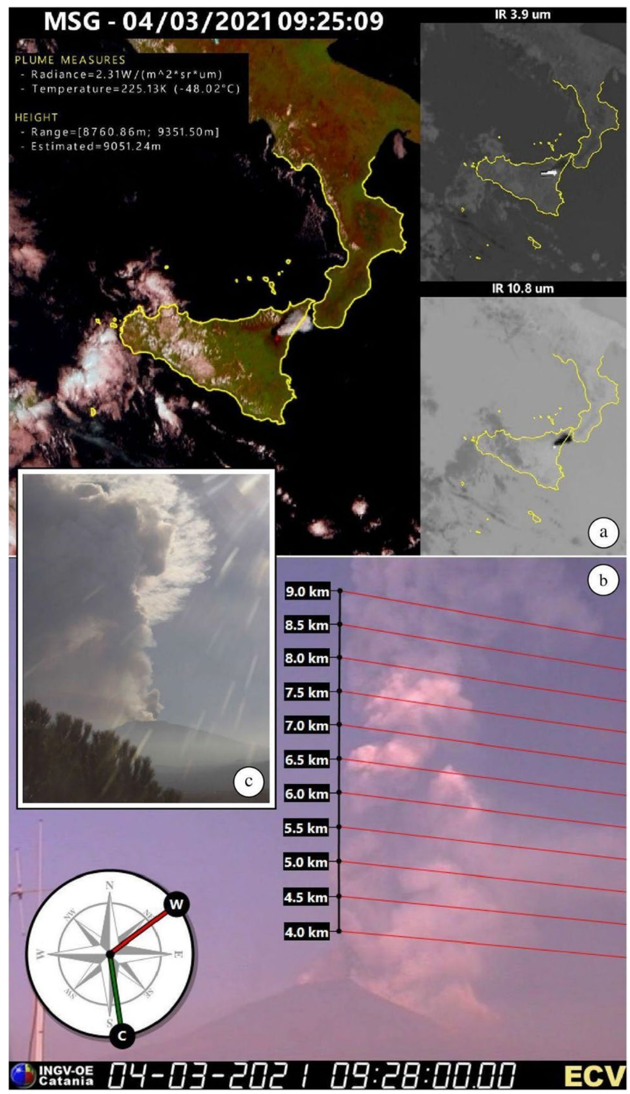

Fig. 10 **a** Etna volcanic plume seen by the SEVIRI data processing on 4 March 2021; visible calibrated image of the ECV camera located in Catania for the same day; **c** visible calibrated image of the EBVH camera installed on the northwest slope of the volcano near Bronte

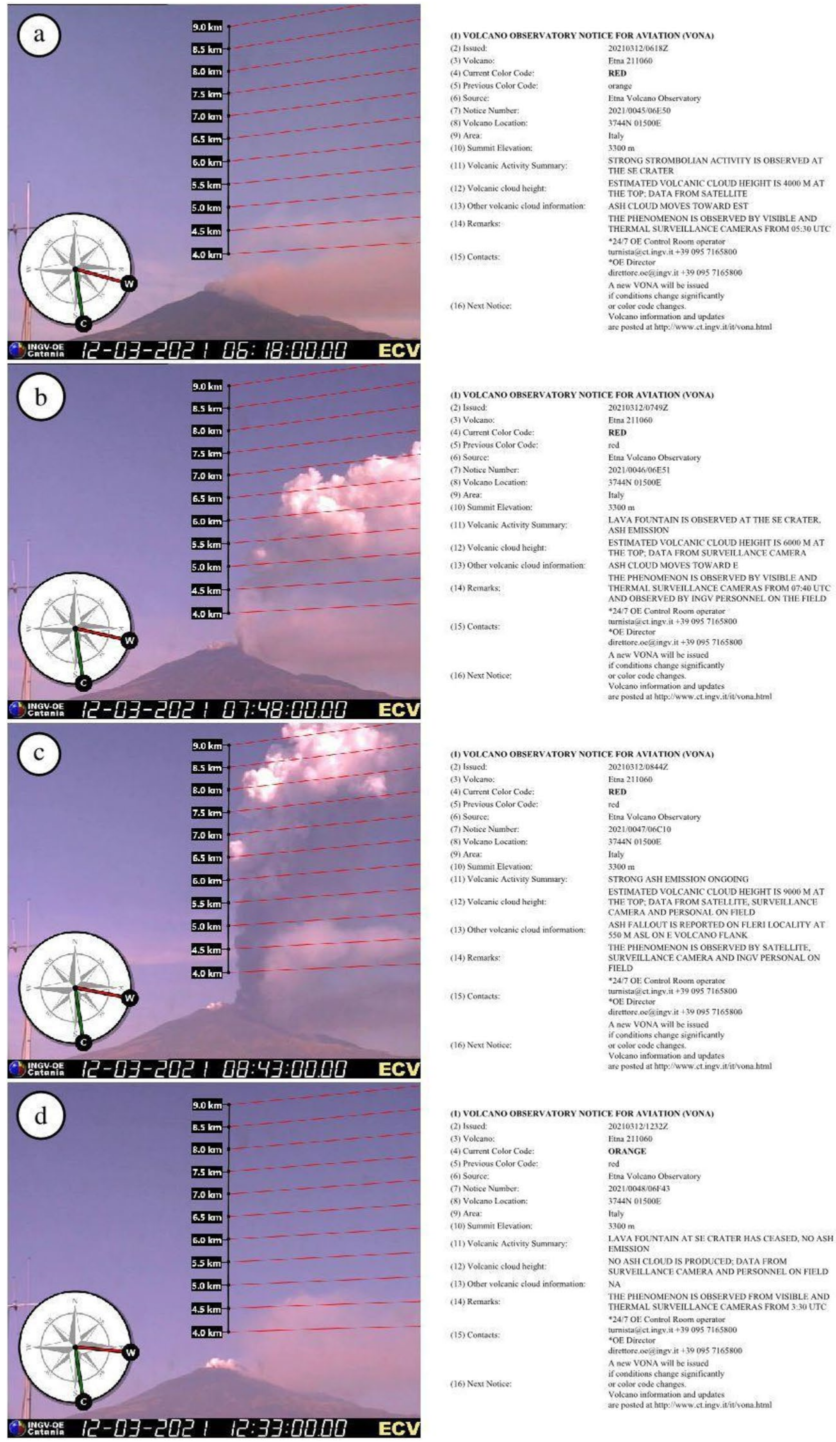

Fig. 11 Image of the eruption column from the visible calibrated camera of INGV-OE and the VONA messages were issued by INGV-OE. **a** 06:18 UTC, Strombolian activity and volcanic plume high about 4 km a.s.l.; **b** 07:49 UTC, lava fountaining and an eruptive column height of 6 km; **c** 08:44 UTC, the eruptive column reached the height of 9 km and the volcanic plume moved towards the east direction; **d** 12:33, the lava fountain ended at 09:45, but the VONA orange message was sent at 12:33, when the volcanic ash was no longer visible around the summit craters and the geophysical parameters came back to almost the background level

The activity continues for over two months, with a very low effusion rate, which produces an advance of the lava front of a few hundred metres in the Valle del Leone and on the western wall of the Valle del Bove (Fig. 12b). The eruptive vent also fed other small flows which partially overlapped the main one (Fig. 12c). During this phase, three VONA updates (orange – N – No ash emission) were issued, on 17, 25 and 31 January 2023. Starting from the afternoon of 4 February 2023, the effusive activity shows a progressive decrease and is no longer fueled. The lava field in the Valle del Leone area and on the western wall of the Valle del Bove (Fig. 12d) appeared to be cooling. In the final phase of the activity, the SEC showed a fumarolic outgassing of variable intensity accompanied by frequent glows visible during the night, rarely associated with thermal anomalies and modest diluted ash emissions rapidly dispersed in the summit area

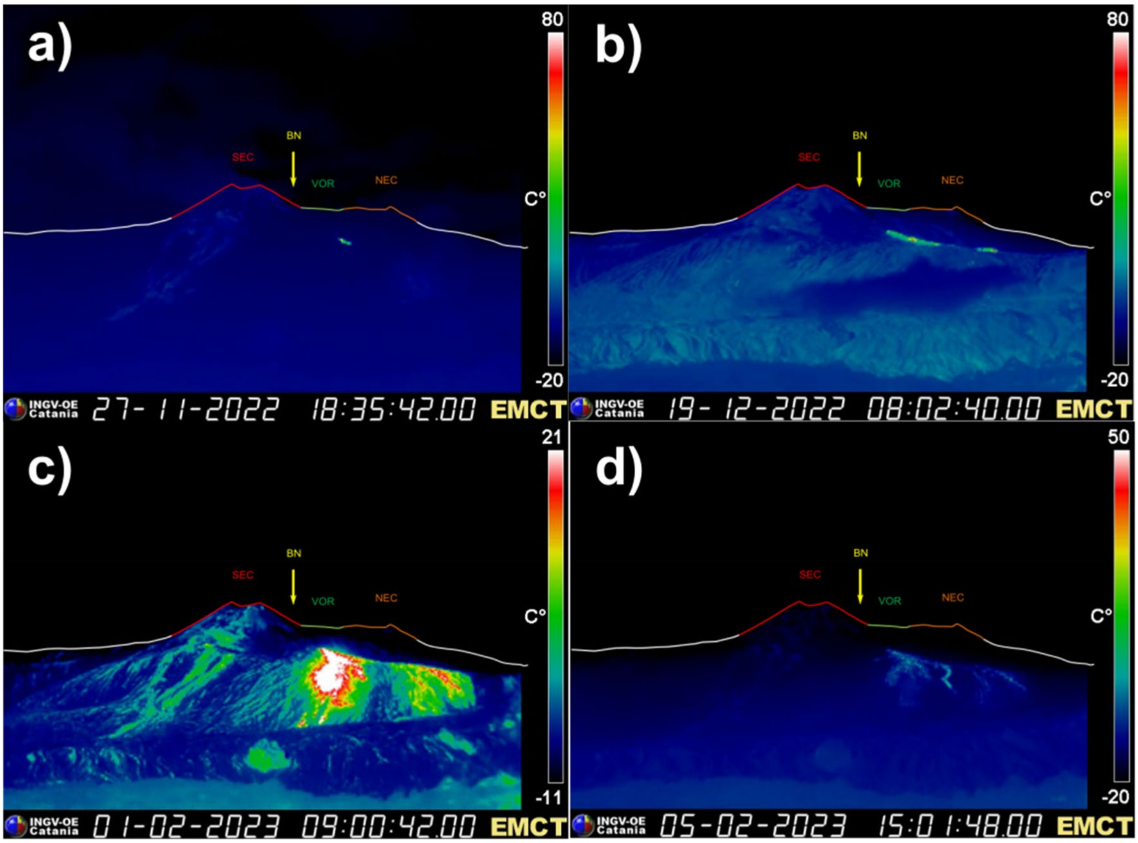

Fig. 12 Images of the different phases of the lava flow emission seen by the thermal camera of Monte Cagliato (EMCT), on the eastern slope of the volcano. **a** 27–11-2022: effusive vent at the north-eastern base of the SEC and a small lava flow that slowly advances towards the Valle del Leone; **b** 19–12-2022: the lava front slowly advances in the Valle del Leone and on the western wall of the Valle del Bove; **c** 01–02-2023 small lava flows partially overlap with the main one in Valle del Bove; and **d** 05–02-2023: the lava field in the Valle del Leone area and on the western wall of the Valle del Bove appeared to be cooling. For references to VONA messages issued by INGV-OE, see the text

by high-altitude winds. The VONA Yellow—G (eruption Gone) message was hence issued on 7 February 2023. When the activity ended on 14 February 2023, the VONA green—T (alert Terminate) message was issued.

Discussions

In this paper, we show a computer-assisted procedure aimed at preparing and sending the VONA messages as soon as possible. The procedure is running at INGV-OE but it can be easily applied to other volcano observatories worldwide. The efficiency of this procedure mainly depends on data available in real time at the volcano observatories. Whereas the geophysical parameters such as the analysis of volcanic tremor (D'Agostino et al. 2013) can be very useful to define the unrest state (VONA from green to yellow), remote sensing systems from ground to satellite can help to estimate, even if only qualitatively, the amount of volcanic ash in atmosphere and address the volcanologist on duty on the transition from orange to red and vice versa.

We mark that one of the most critical points is to define the amount of "significant" ash emission and its dispersal which could cause problems to aviation operations. Although some progress has been made in the Etna case, defining when the volcanic plume crosses the P1 area is a difficult task. It still requires improving the instrument capability and retrieval because few remote sensing systems are able to quantify the volcanic ash concentration in the atmosphere in real time. In fact, very useful instruments such as lidars need an operator and cannot be used in real time (Scollo et al. 2012). Moreover, although recent studies on volcanic plumes produced during powerful lava fountains address the capability of radar systems to estimate the volcanic ash concentration in the atmosphere (Freret-Lorgeril et al. 2021; Giammello et al. 2022; Mereu et al. 2022), those instruments could not detect weak ash emissions far from the vent that, however, can cause problems to aviation operations (Scollo et al. 2020). Perhaps, in the near future, the P1 area could be estimated visually only with the support of the video-surveillance systems that in our opinion remain a powerful and low cost tool for volcano monitoring. New progress on AI techniques, already applied to satellite images (Romeo et al. 2023) could help to automatically quantify the area covered by the volcanic plume and the amount of volcanic particles ejected in the atmosphere, also during weak ash emission.

The computer-assisted procedure described here is only applied to the VONA messages. It is northworthing that, during the volcanic crisis the INGV-OE sends to the DPC different communications which include more information on the description of the volcanic activity, of geophysical and volcanological measurements, and of the associated hazard. Similarly to the VONA, those messages are added in the INGV-OE web-page and available at: Bollettini Multidisciplinari (ingv.it). In general, the developed computer-assisted procedure makes it possible to speed up the production of messages and standardise their content to be easily understood by air traffic controllers who are not volcanologists, by using a predefined set of sentences agreed amongst the volcanologists on duty. Furthermore, since all VONA messages are stored in a relational database, the interface is able to query the database for analytics, as well as assist the user in correctly following the VONA state. The time for compiling the VONA messages could be further reduced by allowing the volcanologist on duty to compile and send them directly without the support of the 24/7 Control Room. At this time, this feature has not been implemented yet but we hope that, in future, updates of the system described here could drastically reduce time in the VONA message compilation at INGV-OE. Since it is a web interface and therefore usable also through a remote device, we trust that such functionality can be implemented quickly by adopting the appropriate security measures.

Finally, it is important to mark that improvements in writing the VONA messages were also carried out thanks the participation of INGV-OE in ad hoc meetings with national and international authorities, including the VAACs, exercises (e.g. VOLCEX) and projects (e.g. Eurovolc, Eudanics and e-shape). INGV-OE is an active part in the discussions and improvements of the systems because, as State Volcano Observatory, we have the obligation to send detailed information as soon as possible. Whereas scientific collaboration can improve the instruments and data analysis, national and international meetings with the authorities that are responsible to take decisions during volcanic crises are an essential step towards the growth of the volcano observatories worldwide.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00445-024-01728-6.

Acknowledgements We would like to thank all the scientists, technologists and technicians from INGV-OE who work in the 24/7 Operative room and who take care of the maintenance of all instruments and software. We are also very grateful to the two anonymous reviewers, whose helpful and constructive comments and suggestions contributed significantly to the improvement of the manuscript.

Funding Open access funding provided by Istituto Nazionale di Geofisica e Vulcanologia within the CRUI-CARE Agreement. This paper is funded by the Convenzione attuativa per le attività di servizio in esecuzione all'accordo-quadro tra il Dipartimento della Protezione Civile e l'Istituto Nazionale di Geofisica e Vulcanologia per le attività di cui alle lettere A), relativamente alla valutazione dei rischi e della pericolosità, nonché C), D), ed E) del comma 1 del decreto-legislativo 29 Settembre 1999,-N. 381 (periodo 2022—2025).

Declarations

Conflict of interest The authors declare no competing interests.

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