**Natural Hazards
and Earth
System Sciences**

Monitoring and forecasting Etna volcanic plumes

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Abstract. In this paper we describe the results of a project ongoing at the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The objective is to develop and implement a system for monitoring and forecasting volcanic plumes of Etna. Monitoring is based at present by multispectral infrared measurements from the Spin Enhanced Visible and Infrared Imager on board the Meteosat Second Generation geosynchronous satellite, visual and thermal cameras, and three radar disdrometers able to detect ash dispersal and fallout. Forecasting is performed by using automatic procedures for: i) downloading weather forecast data from meteorological mesoscale models; ii) running models of tephra dispersal, iii) plotting hazard maps of volcanic ash dispersal and deposition for certain scenarios and, iv) publishing the results on a web-site dedicated to the Italian Civil Protection. Simulations are based on eruptive scenarios obtained by analysing field data collected after the end of recent Etna eruptions. Forecasting is, hence, supported by plume observations carried out by the monitoring system. The system was tested on some explosive events occurred during 2006 and 2007 successfully. The potentiality use of monitoring and forecasting Etna volcanic plumes, in a way to prevent threats to aviation from volcanic ash, is finally discussed.

1 Introduction

Volcanic ash causes damages to infrastructure and telecommunication, contamination of crops and water supply (Blong, 1984; Casadewall, 1994). It may create serious health problems such a respiratory diseases and illness (Horwell and Baxter, 2006) and is extremely dangerous for air traffic (Casadevall, 1994). Threats as ruin to windscreens, fuselage surfaces and landing lights are documented in detail (Miller and Casadevall, 2000; Guffanti and Miller, 2002; Salinas, 2004). The most dangerous threat is the engine total failure.

In fact, volcanic ash has a fusion temperature lower than modern jet engine operating temperatures, and consequently may melt in the hot section and re-solidify in the colder parts of the engine as nozzle guide vanes and turbine blades, causing the degraded engine performance (Guffanti et al., 2005). The first famous case of such accidents occurred on 24 June 1982 when a British Airways Flight 9, a Boeing 747-200 flying at an elevation of 11 470 m from Kuala Lumpur, in Malaysia, to Perth, in Australia, encountered volcanic ash after passing over Krakatau volcano. All four engines failed but luckily, at about 3650 m, the pilot was able to restart three engines and make an emergency landing at Jakarta, in Indonesia (ICAO, 2004).

One of the early reported incidents of an airport impacted by volcanic activity was during WWII, when the 1944 Vesuvius eruption destroyed 88 B-25 bombers of the US 340th Bombardment Group based in Naples. Another important effect of ash on aviation is the airport operation. Guffanti et al. (2004) reported 108 incidents since 1944 due to eruptions of 34 volcanoes that involved 75 airports. Tephra fallout causes in fact disruption due to slippery runways and reduced visibility, deposition of ash on parked planes and buildings, remobilization of deposited ash by machinery, aircraft, and wind, and contamination of various ground-support facilities, including ATC computer systems. Consequently, airports located near active volcanoes are often forced to close to prevent similar disasters.

In 1987, the International Civil Aviation Organization (ICAO) established the International Airways Volcano Watch (IAVW) commission that defines international protocols for the monitoring and provision of warnings to aircrafts in presence of volcanic ash in the atmosphere (Romero, 2004). Information on volcanic ash to aircraft is given through SIGMETs and NOTAMs issued by the Meteorological Watch Offices (MWOs) and Aeronautical Control Centres (ACCs) through their NOTAM Offices (NOFs) (Romero, 2004). To assist MWOs on drafting the SIGMETS nine volcanic ash advisory centres (VAACs) were established at Anchorage, Washington, Buenos Aires, Montreal, London, Toulouse, Tokyo, Darwin and Wellington with the aim to provide

advisories on the plume dispersal and act like an interface between MWOs, traffic control centres, and volcano observatories (Webley and Mastin, 2008). These are essential in forecasting because i) they know the time at which an eruption column is forming; ii) they may collect all information needed for initializing models using monitoring systems and iii) they may verify the reliability of model results by comparing the computed data with the observed cloud trajectory and tephra deposit.

One of the most active volcanoes in the world is Mt. Etna, in Italy, characterized by explosive activity ranging from mild strombolian to sub-plinian. Activity occurs from the central craters (NEC, SEC, VOR, BN-1 and BN-2) (Fig. 1) and/or from fractures opened along the volcano flanks. In the last two decades the number of explosive events has increased (Branca and Del Carlo, 2005) and, because the volcanic plumes remained in the atmosphere from several hours to days, they forced several times the closure of the International Airport in Catania, only 30 km far from the volcanic vent. The most reported damages to aviation in Italy are, in fact, due to Etna's eruptions (Table 1, courtesy of M. Guffanti). On 3 August 1979, the airport of Catania had to close due to the large amount of ash fallout produced during an eruption from SEC (Romano and Sturiale, 1982; Chester et al., 1985). Major inconvenience occurred also on 24 September 1986, when NEC formed an eruption column of 10–13 km a.s.l. (Romano et al., 1986), and on 22 July 1998, when the eruption column reached 12 km a.s.l. (Andronico et al., 1999). Between 26 January and 24 June 2000, SEC produced 64 lava fountains forming weak plumes up to 6 km a.s.l. (Alparone et al., 2003). In particular, on 26 April 2000 an Airbus 320 taking off from Catania to Milan encountered volcanic ash and was forced to flight back to Catania (lieutenant colonel F. Colombo of Italian Air Force, personal communication; BGVN, 2000). The next year, an eruptive fracture opened at 2570 m a.s.l. producing a weak plume rising up to 5–6 km a.s.l. between 21 and 24 July that caused the cancellation of flight operations of Catania and Reggio Calabria airports (Scollo et al., 2007). Tephra fallout was also a significant phenomenon during the 2002–2003 Etna eruption (Andronico et al., 2005). Weak plumes having heights between 2.5 and 7 km a.s.l. (Andronico et al., 2008a) were almost continuously present between 27 October and the end of the explosive activity in December 2002. The International Airport of Catania was often forced to close to avoid accidents, causing considerable economic losses and inconveniences to the south-eastern population of Sicily. The airport was forced to close again on 24 November 2006 because ash fallout covered the SE flanks of the volcano.

In this context there was the demand to improve the monitoring and forecasting of the volcanic plume dispersal and tephra deposition during Etna explosive eruptions in a way to give precise warns to the aviation authorities via Italian Civil Protection, the national service for the emergency management in Italy, and to assist the work of VAACs. The ac-
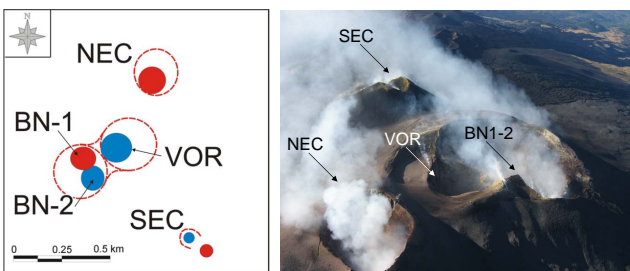
Fig. 1. Left: schematic map of the central craters of Etna volcano: North East crater (NEC), Voragine (VOR) and Bocca Nuova (BN-1, BN-2) and South East crater (SEC). The outline lines represent the crater rim (photo courtesy of INGV-CT). Right: photopicture taken from D. Andronico on August 2007 during the monitoring activity of INGV-CT by helicopter surveys.

Table 1. Damages to aviation due to the volcanic ash in Italy.

Eruption Date	Volcano	City/Airport
22 Mar 1944	Vesuvius	Naples/Terzigno
3 Aug 1979	Etna	Catania/Fontanarossa
24 Sep 1986	Etna	Catania/Fontanarossa
22 Jul 1998	Etna	Catania/Fontanarossa
5 Jun 2000	Etna	Catania/Fontanarossa
5 Jun 2000	Etna	Catania/Sigonella
21–30 Jul 2001	Etna	Catania/Fontanarossa
27 Oct 2002–28 Jan 2003	Etna	Catania/Sigonella
27 Oct 2002–28 Jan 2003	Etna	Reggio Calabria
27 Oct 2002–28 Jan 2003	Etna	Catania/Fontanarossa
24 Nov 2006	Etna	Catania/Fontanarossa

tions for reducing the hazard from tephra fall were developed during an ongoing specific project, the FIRB Italian project "Sviluppo Nuove Tecnologie per la Protezione e Difesa del Territorio dai Rischi Naturali" funded by Italian Minister of University and Research. The project leaded by the Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania (INGV-CT), the managing institution for the surveillance of Etna, has the aim to provide accurate and fast information on the evolution of the volcanic plumes during explosive eruptions of Etna.

In this paper we describe the approach used for monitoring and forecasting Etna volcanic plumes. Monitoring (Sect. 2) is carried out by using remote sensing systems for detecting the plume dispersal and the particle fallout. Forecasting (Sect. 3) is performed by combining four different models of tephra dispersal that were previously validated comparing simulations with field data collected during the monitoring activities of INGV-CT (e.g. Andronico et al., 2009). Automatic procedures, described here, were developed and made operative at INGV-CT since the end of 2006, when several explosive eruptive episodes occurred at SEC of Etna. Daily reports, edited during the activity, were very useful to the

Italian Civil Protection for supporting their decisions during the emergencies. Finally, we address some future developments (Sect. 4) needed for improving the system.

2 Monitoring system

Timely volcanic plume observations may improve the forecast greatly. In fact, an efficient real time monitoring is crucial for aviation safety because it may evaluate input parameters needed for simulating tephra dispersal correctly and reduce the uncertainty of model outputs drastically. Real-time monitoring can be performed using both ground-based observations, located far or near the volcanic vent, and satellite images. Examples of near and far ground based observations are UHF wind profile applied for the first time at Etna between 11 and 12 October 1998 (Dubosclard et al., 1999, 2004), portable FM-CW radar used to evaluate the velocity of the explosions (Hort and Seyfried, 1998), acoustic instruments recently used to analyze sub-plinian plumes at Shishaldin volcano in Alaska (Vergniolle et al., 1996), meteorological radar systems (Harris et al., 1981; Lacasse et al., 2004; Rose et al., 1995), detectors of volcanic lightning (Mather and Harrison, 2006) and electric fields (Butter et al., 2000), visual, thermal, NIR cameras (Andò and Pecora, 2006). Geostationary or polar satellites are widely used to retrieve microphysical and morphological properties of volcanic ash plumes from satellite data (Prata and Grant, 2001). Actually, the instrumentation used at INGV-CT consists of four cameras, one thermal camera, multispectral infrared measurements from the Spin Enhanced Visible and Infrared Imager on board the Meteosat Second Generation geosynchronous satellite (SEVIRI) and three continuous wave X-band disdrometers (PLUDIX).

Four cameras are available at INGV-CT for surveillance purposes. They are located in Catania, Nicolosi, Milo and Schiena dell'Asino (at about 27, 15, 11, and 5 km far from the vent). Further, one thermal camera located at Nicolosi is able to detect the presence of volcanic ash during the night. Surveillance cameras are very useful for detecting the height of eruption columns and analyze the style of explosive activity. Analysis of these images is used routinely at INGV-CT during Etna explosive activities (Alparone et al., 2007; Andronico et al., 2008a, b; Scollo et al., 2007).

Since August 2006 INGV-CT receives multispectral infrared measurements from EUMETSAT (European Organization for the Exploitation of Meteorological Satellites), an intergovernmental organization founded in 1986 and supported by 20 different European states. At present, EUMETSAT has five satellites, belonging to second generation meteorological satellites, being the most recent METEOSAT 8 and its backup METEOSAT 9. Each satellite has 12 spectral channels and delivers data with a temporal resolution of 15 min. The spatial resolution of SEVIRI is 3 km for all channels except the HRV (High Resolution Visible) channel

which is 1 km. Although they have a lower resolution with respect to polar satellites (e.g. AVHRR), the high time resolution of geostationary satellites is more suitable for tracking plume purpose and sometimes used for providing quantitative information (e.g. height of eruption column). Just recently, a quantitative analysis was performed during the November 2005 eruption of Karthala volcano by using five infrared channels of SEVIRI centred at 6.2, 7.3, 8.5, 11 and 12 μm (Prata and Kerkmann, 2007). The analysis of these IR images allowed to detect, for the first time, the separation between SO_2 and volcanic ash. In addition, AVHRR images are elaborated by INGV, CNT-LABTEL of Rome for monitoring Etna volcanic plumes (Spinetti and Buongiorno, 2007) and delivered to INGV-CT every day.

Finally, three continuous wave X-band disdrometers (PLUDIX) are used to detect the ash fall rate. PLUDIX is a rain gauge disdrometer that detects the signal backscattered by hydrometeors and consists of a sensor, a signal processor and data communications unit. The sensor is a low power (10 mW) Continuous Wave (CW) Doppler radar operating at a frequency of 9.5 GHz (Prodi et al., 2000). PLUDIX was tested for the first time during 2002–2003 Etna eruption and was able to measure terminal settling velocity of volcanic particles falling above the radar (Scollo et al., 2005). The instrument was considered as a helpful tool for the real-time monitoring because it can evaluate the particle fall rate and eventually the total grain-size distribution using inverse modelling. Two instruments are installed in Catania and Nicolosi, respectively at about 25 and 15 km from Etna volcanic vents, along the axes toward the Airport. The third instrument is used for performing measurements during explosive events.

3 Forecasting plume dispersal and particle fallout

Here we describe the automatic procedure used for forecasting ash dispersal and tephra deposit at INGV-CT. A good forecast need of: i) high-resolution meteorological data; ii) validated tephra dispersal models; iii) well-defined eruptive scenarios; iv) hazard map production by means of an automatic procedure. In the following sections each of these points is analyzed in detail.

3.1 Meteorological data

Weather data furnished by meteorological models are needed to forecast plume dispersal and tephra deposit correctly. Meteorological models are classified in *Global* when their domain is the Earth, *Regional* or *Limited-Area* models when instead they cover part of the Earth. Examples of Global models are GFS (Global Forecast Service), developed by NOAA (National Oceanic and Atmospheric Administration) in USA, NOGAPS, developed by US Navy in USA, or ECMWF developed by the European Centre for Medium-Range Weather. Examples of regional models

are MM5, developed in cooperation between the Pennsylvania State University (Penn State) and the University Corporation for Atmospheric Research, LAMI (Limited Area Model Italy) developed by the European Consortium for Small-Scale Modelling (COSMO). Metereologists tipically use an international public format GRIB (GRIdded Binary) standardized by WMO (World Meteorological Organization) packed in a binary format for increasing the storage efficiency.

Daily, INGV-CT receives weather forecasts from the Italian Air Force Meteorological Office (in Italian acronym CN-MCA) in Rome and from the hydrometeorological service of ARPA in Emilia Romagna (ARPASIM). CNMCA furnishes the GRIB files every 24 h in 16 files having a time step of 3 h; therefore the weather forecasts are covered for 48 h. The CN-MCA grid covers an area from 12.5° and 18.5° E and 34.5° and 40.5° N, with 101×101 points stepped by 0.06° and has 13 isobaric levels. Instead, the ARPASIM GRIB files are given every 12 h with a time step of 1 h and the weather forecasts are given until 72 h. The ARPASIM grid covers an area rotated with respect to the Equator that is moved to the medium latitudes. It spans from 1° to 7.25° E and from –23° to 17.65° N and has 22 isobaric levels. The GRIB files are formed from 101×101 points stepped by 0.0625°. Every hour an ftp application logins automatically at CNMCA and ARPASIM ftp web-sites for downloading the GRIB files which are then stored at INGV-CT. If the connection closes accidentally, the application preserves the date of the last file that was downloaded, in a way to reconnect to the same file in the next connection. The data are plotted automatically on a monitor at INGV-CT operative room where two operators watch for the activity of Sicilian volcanoes on 24/7 and alert Italian Civil Protection authorities in case of eruption. The forecast of wind direction and speed, cloud cover, temperature, precipitation are visualized in a desktop by the VISUALGRIB software developed at INGV-CT within this project (Fig. 2).

3.2 Tephra dispersal models

Tephra dispersal models solve the advection-diffusion equation by using different approaches and may be grouped in two main categories: Lagrangian and Eulerian. In the Lagrangian approach particle motion is considered to consist of two terms, i.e. a deterministic part due to the wind transport plus a random walk process which describes diffusion due to turbulence. The plume dispersion is evaluated applying a statistical analysis on the trajectories of a large number of particles. Instead in the Eulerian description the movement of the plume is observed on specific points in the space through which the plume moves. The advection-diffusion equation can be also solved by using analytical methods (providing exact solutions) under appropriate approximation or by using numerical methods (providing instead approximate solutions of the full differential equation). In Volcanology, Lagrangian

models are used to forecast tephra dispersal for aviation operation applications (Barsotti and Neri, 2008; D'Amours, 1998; Heffter and Stunder, 1993; Searcy et al., 1998). Eulerian models are used to analyze the turbulent dispersion and deposition of particles in a wind field (e.g. Armienti et al., 1988; Glaze and Self, 1991, Carey and Sparks, 1986; Woods et al., 1995), or to analyze the large-eddy sedimentation from plume margins combined with gravity-driven intrusion at the neutral buoyancy level (e.g. Bursik et al., 1992a, b; Koyaguchi and Ohno, 2001a, b; Bonadonna and Phillips, 2003). Under simplifying assumptions the equation for the mass conservation describing the plume dispersion, admits an analytical solution obtained as a Gaussian distribution (the simplified analytical Eulerian models are known as Gaussian models). These models have been extensively used to make probability maps of the tephra fallout (Bonadonna et al., 2005; Cioni et al., 2003; Macedonio et al., 2008) because they allow performing a great number of simulations fastly and hence make reliable the statistical analysis.

Four different tephra dispersal models are run at INGV-CT daily. They are HAZMAP (Macedonio et al., 2005), TEPHRA (Bonadonna et al., 2005), PUFF (Searcy et al., 1998) and FALL3D (Costa et al., 2006). HAZMAP is a two dimensional dispersal model that solves semi-analytically the advection-diffusion equation. The model was previously applied to evaluate the tephra fallout risks at Vesuvius (Barberi et al., 1990) and the hazard assessment associate with dome-collapses and the vulcanian explosions on Montserrat (Bonadonna et al., 2002). HAZMAP was also used by Pfeiffer et al. (2005) to reconstruct the 79 AD plinian eruption of the Vesuvius and by Scollo et al. (2007) to model the dispersal of the weak and long-lasting plume formed between 21 and 24 July 2001 at Etna. TEPHRA (like HAZMAP) is an advection-diffusion model based on several theories (Armienti et al., 1988; Bonadonna et al., 1998, 2002; Bursik et al., 1992a; Connor et al., 2001; Suzuki, 1983) and written for parallel computing on a Beowulf cluster. The model has been already calibrated on two explosive Etna eruptions occurred on 22 July 1998 and between 21 and 24 July 2001 and used to perform the hazard assessment from tephra fall of Etna volcano (Scollo et al., 2006). PUFF is a Lagrangian model (Searcy, 1998). The model requires 3-D atmospheric data and the DEM of the area affected by the fallout. PUFF is able to locate at any time the position of thousands particles that are released from the volcano and then advected, diffused, and settled within the atmosphere. An example of the model application to Etna is presented by Aloisi et al. (2002) in which the 22 July 1998 plume is simulated and compared with SEVIRI images. Finally, FALL3D (Costa et al., 2006; Folch et al., 2009) is a 3-D Eulerian model for the transport and deposition of volcanic ash which is coupled with global and mesoscale meterological models and uses the gradient transport theory for the turbulent diffusion and buoyancy plume theory for the eruption column. FALL3D runs at INGV-CT, inside the APOLLO platform (Folch et al.,
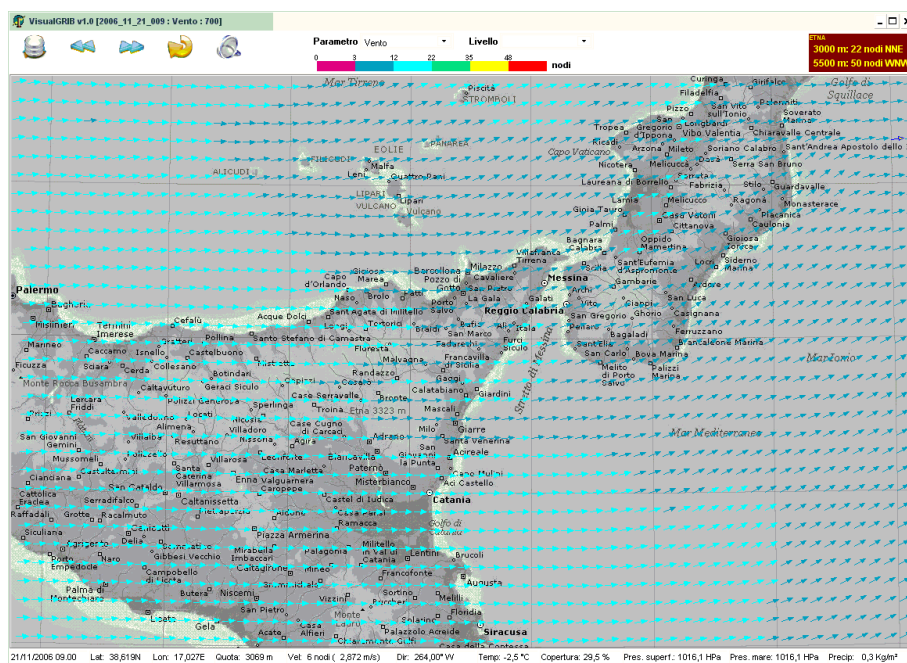
Fig. 2. VISUALGRIB software able to plot the forecast of wind direction and speed, cloud cover, temperature and precipitation for two days.

2008a), platform-independent procedure designed to generate data input for all models installed in the platform, run these and plot their results with equal isomass curves for a user-friendly analysis. FALL3D has been already validated successfully comparing the computed deposit with field data of 2001 Etna eruption (Costa et al., 2006), amongst several other eruptions worldwide.

3.3 Eruptive scenarios

Tephra dispersal models require the following input parameters: erupted mass, column height, total grain-size distribution and particle shape. The constrain of these parameters is usually given by analysis of field data collected during the monitoring activities of INGV-CT (Alparone et al., 2007; Andronico et al., 2009). However, two different typologies of explosive activity have been identified at Etna (Scollo, 2006): one producing strong and short-lasting plumes and another producing weak and long-lasting plume. Forecast of the plume dispersal is based on simulations of different Etna eruptions, each belonging to one of these two typologies: the eruption of 22 July 1998 (Andronico et al., 1999), of 21–24 July 2001 (Scollo et al., 2007), and finally of 2002–2003 (Andronico et al., 2008a).

Scenario 1 was chosen similar to the eruption occurred on 22 July 1998. During 22 July 1998 Etna formed an eruption column rising 12 km a.s.l. (Fig. 3) and a tephra deposit covering the SE flanks of the volcano. Wind direction was almost constant toward SE for altitudes up to 10 km (about 140 from the north). Wind speed ranged between 4 and

Fig. 3. Eruption column produced during the activity of 22 July 1998. Photo courtesy of M. Pompilio.

$6 \, \text{m s}^{-1}$ at about 1 km a.s.l. and between 9 and $11 \, \text{m s}^{-1}$ at about 16 km a.s.l. (Aloisi et al., 2002). After the eruption, Andronico et al. (1999) collected 35 samples on the SE flanks and classified the eruption as sub-plinian according to

the analysis of the deposit. They estimated a total erupted mass of 1.3×10^9 kg using the method by Walker (1973). The total grain-size distribution was instead evaluated using the Voronoi's method (Bonadonna and Houghton, 2005) as a Gaussian distribution peaked at $2.3 \pm 1.5\phi$ (Scollo et al., 2008a).

Scenario 2 is similar to the 21–24 July 2001 eruption. During 21–24 July 2001 a weak and long-lasting plume produced by a phreatomagmatic activity (Fig. 4) rose up to 5–6 km a.s.l. from a volcanic vent opened at 2570 m on the S flank of the volcano. 46 samples were collected in this case on the SE flanks and analyzed in detail by using both field data standard analysis and modelling (Scollo et al., 2007). The total mass was equal to 2.3×10^9 kg using the Power law's method and a total grain-size distribution at $2.0 \pm 1.5\phi$ using Voronoi's method (Bonadonna and Houghton, 2005).

Finally *Scenario 3* was chosen similar to the 2002–2003 eruption. The 2002–2003 Etna eruption was amongst of the most explosive events of the last centuries. The explosive activity began on 27 October 2002 (Fig. 5) and persisted up to 20 December while the eruptive activity ended definitely on 28 January 2003. The heights of eruption columns, estimated by combining barometrical altimeter data during over-flights with the analysis of images and videos, ranged from 3.3 to 7 km a.s.l.. Tephra sampling carried out on 27, 28, 31 October and 4 November allowed to estimate a total erupted mass of 4.4×10^{10} kg and a total grain-size distribution of 0.5ϕ (Andronico et al., 2008a). Simulations showed that the E flanks of the volcano were mainly affected from the tephra fallout and that also basaltic volcano as Etna can produce a huge amount of volcanic ash (Andronico et al., 2008a).

Input parameters for modelling (Table 2) were obtained by the analysis of the deposits collected after few hours from the eruptive event. Only the duration was modified being 5 min for *Scenario 1* and three hours (like the time step of the wind forecast data) for *Scenarios 2* and *3*.

3.4 Hazard map production

We implemented an automatic procedure for publishing hazard maps of plume dispersal and particle fallout for the considered scenarios. The system is supervised by a "scheduler", software developed in this project (Fig. 6) which checks if each process has run correctly in the right sequence, and ended regularly; otherwise it sends an e-mail to alert that some errors have occurred. The scheduler makes the acquisition of meteorological data, and decides also which of the two weather forecasts is used to run simulations. When all the GRIB files are downloaded, an application converts these files in ASCII and NetCDF formats to be readable by TEPHRA and PUFF models, respectively. The APOLLO platform (Folch et al., 2008a) reads directly from the GRIB files; consequently we only set inputs to run with both the CNMCA and ARPASIM files. Every 3 h, volcanic ash dispersal and tephra fallout occurring from the *Scenarios 1, 2*

Fig. 4. Eruption column produced during the activity of 24 July 2001. Photo taken during the monitoring activity of INGV-CT.

Fig. 5. Eruption column produced during the activity of November 2002. Photo taken during the monitoring activity of INGV-CT.
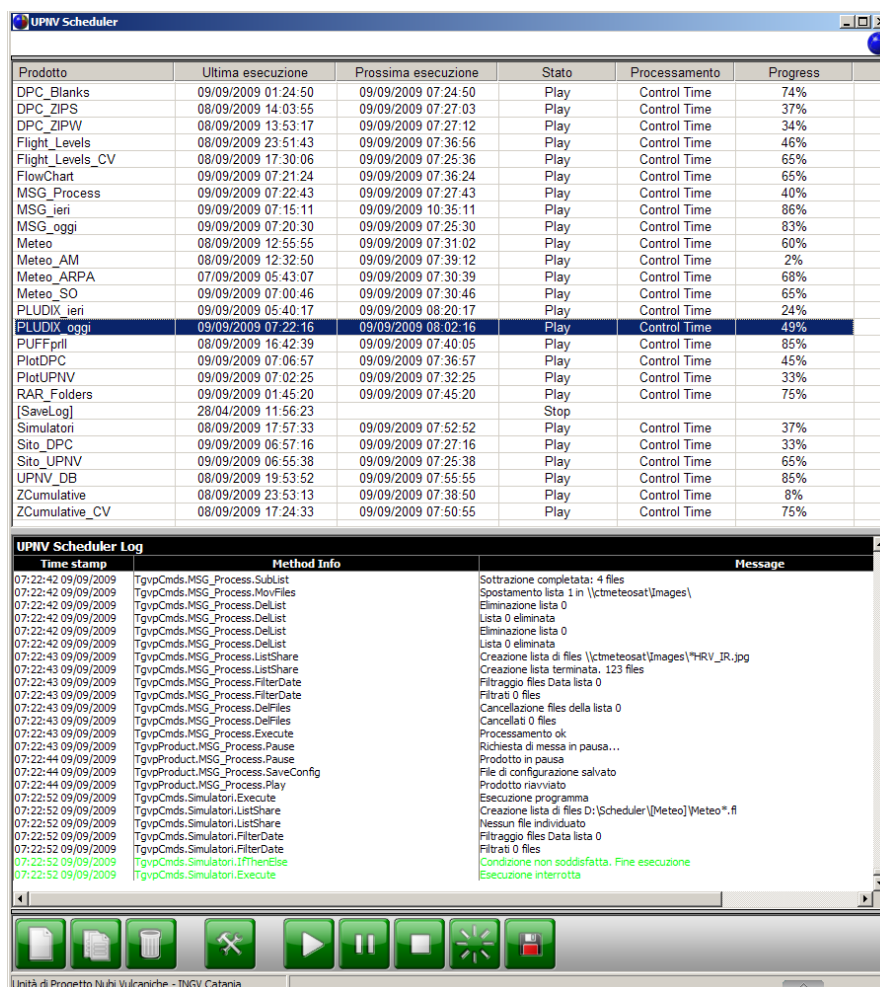
Fig. 6. Software which controls the processes of monitoring and forecasting at INGV-CT.

and 3, are simulated. All codes run on a Beowulf cluster composed by 24 Opteron bi-processor nodes, and the results of TEPHRA, PUFF, HAZMAP, FALL3D are plotted on geo-referenced maps in the air and on the ground automatically. Finally, the scheduler publishes them into two websites, one visible only by Italian Civil Protection (Fig. 7), in which SEVIRI and AVHRR (given from INGV, CNT-LABTEL of Rome) images are plotted together with hazard maps of TEPHRA and PUFF, and one in which hazard maps of different simulators are plotted together for studying their differences and helping for a better quantification of the uncertainties associated with a forecast (this work is in progress with INGV, sezione di Napoli, and INGV, sezione di Pisa).

4 Application to Etna

Although the project was at an early stage, the occurrence of several explosive events at Etna since 2006 forced us to make operative the previously described system. The result was

Table 2. Input parameters of *Scenarios 1, 2* and *3* used for forecasting plume dispersal and tephra deposit at INGV-CT; MER is for Mass Eruption Rate, CH for Column Height, TGS for Total Grain-Size distribution.

Eruptive scenarious	Duration	MER (kg/s)	CH (km)	TGS (ϕ)	(σ)	Etna eruption
Scenario 1	5 min	1.E+06	8	2	1.5	1998
Scenario 2	3 h	5.E+03	2	2	1.5	2001
Scenario 3	3 h	1.E+05	4	0.5	1.5	2002–2003

the production of several reports on the forecasting and the detection of volcanic plumes available on-line at http://www.ct.ingv.it. These reports were very useful to the Italian Civil Protection which from that time requires these hazard maps from INGV-CT daily. This work gave us the opportunity to estimate the reliability and accuracy of the system from the beginning of the project and suggested future improvements.
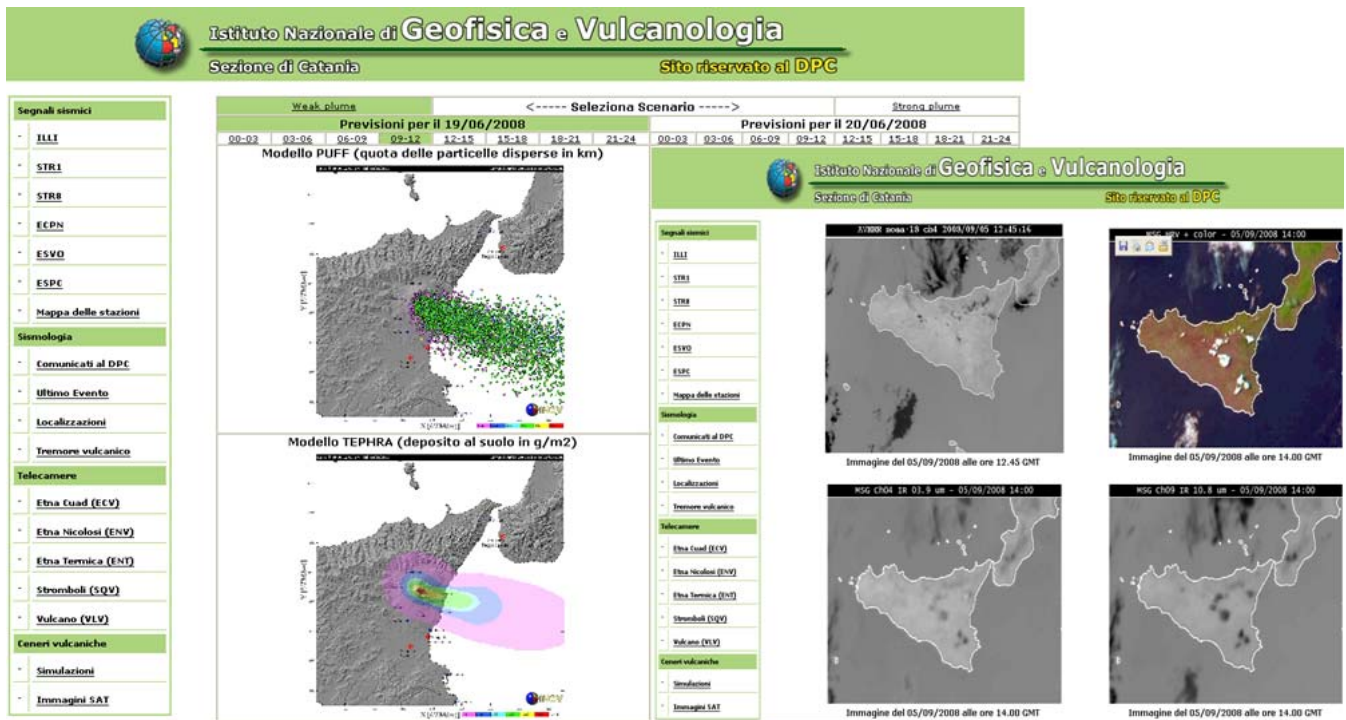
Fig. 7. Web-site dedicated to the Italian Civil Protection in which the satellite images and ash forecasting are visualized.

We report two examples in which the system was applied successfully, 24 November 2006 and 4–5 September 2007.

On 24 November, SEC produced one of the most relevant paroxysms of 2006. A weak plume started at 02:19 GMT and lasted for about ten hours. Bombs and blocks reached heights up to 200 m (De Beni et al., 2006) and tephra fallout affected mainly the south-east volcano sector between Giarre and Siracusa (Andronico et al., 2007) causing the closure of the international airport of Catania. The plume moved from SE toward SSE at about 11:30 GMT due to the variation of the wind direction, action confirmed by the HRV images of SEVIRI. Figure 8 shows the plume dispersal as retrieved by SEVIRI, in good agreement with the FALL3D and HAZMAP simulations for *Scenario 2*. Further, it is notable as the shift from SE towards SSE was also computed by the numerical simulation (e.g. TEPHRA forecasting in Fig. 9).

During 4 September 2007 a powerful lava fountain started at 14:00 GMT from SEC producing a volcanic plume, about 5 km a.s.l. in high that kept the same direction for almost 12 h (Andronico et al., 2008b). The associated tephra deposit covered the E flanks of the volcano between Piedimonte to the N and Sarro and Guardia Mangano to S. The deposit was analyzed in detail by Andronico et al. (2008b) who estimated a total volume of 3.9×10^8 kg and a total grain-size distribution peaked at 0ϕ. The TEPHRA and PUFF simulations for *Scenario 2* computed the plume dispersal and tephra deposit toward E as confirmed by satellite images (Fig. 10). In this case, flights landed from NW, the opposite side of the plume, and the International Airport of Catania did not have to close.

5 Future developments and conclusions

Three pre-defined eruptive scenarios run daily at INGV-CT (corresponding to the 1998, 2001 and 2002–2003 Etna eruptions). However, it is evident that a new eruption could differ from these scenarios significantly and, consequently, the simulations may differ from the real dispersion. Recent studies have shown that due to the high variability of Etna explosive activity (Andronico and Scollo, 2008) the use of predefined scenarios could be limiting. However, the number of scenarios can not be increased because of high time for computing the model outputs even using computing techniques. Otherwise, several typologies of eruptions could be studied in detail extracting input parameters for tephra dispersal models. Hence, the volcanologist on duty could choose, on the base of information obtained by the monitoring system, input parameters belonging to a given typology with similar features of the ongoing eruption.

Techniques of data assimilation could be also used. In fact, recent parametric studies have shown that the output of models can be strongly sensitive to the uncertainties on input parameters (Connor and Connor, 2006; Scollo et al., 2008a, b). For giving a reliable ash forecasting, mass eruption rate, column height, distribution of the mass along the column and grain-size distribution should be well constrained. Because many of these parameters are lacking during an eruption, a possible approach could be to simulate the event using semi-quantitative volcanological input parameters based
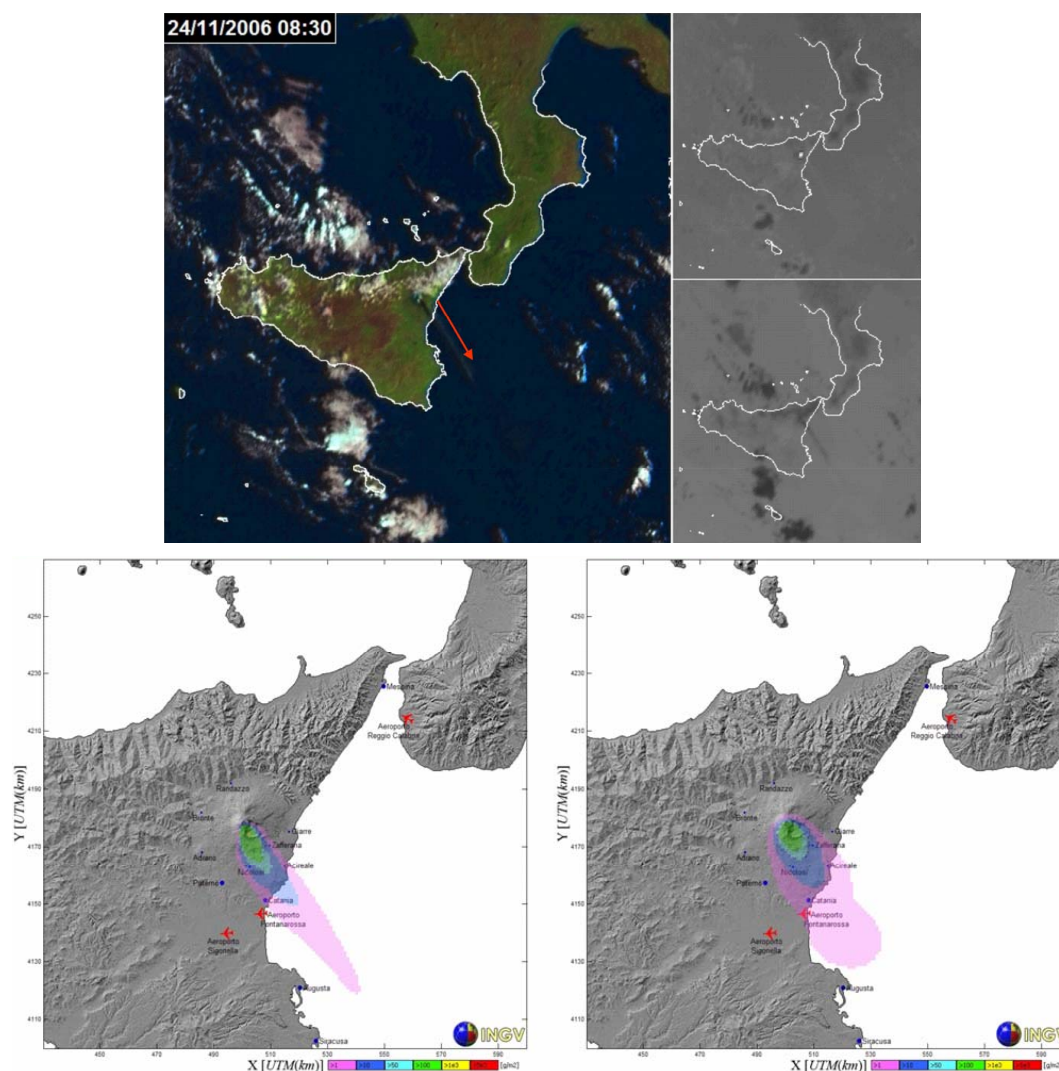
Fig. 8. SEVIRI images showing the plume dispersal toward SE on 24 November 2006 at 08:30 GMT and FALL3D and HAZMAP simulations of *Scenario 2*.

on the first eruption reported data. This method was applied by Folch et al. (2008b) to forecast tephra dispersal during the May 2008 Chaitén eruption. In this case, mass eruption rate was evaluated from the column height (available from several reports) and kept constant during the simulation (this approach led to an overestimation of the erupted mass). They used a 1-D radially-averaged Buoyant Plume Theory model for the distribution of the mass along the column and a grain-size distribution representative of a sub-plinian eruption. Due to several assumptions on input parameters, this strategy has to be considered as a first order semi-quantitative approach, as also highlighted by Folch et al. (2008b). The forecasting system described in this paper can be also considered semi-quantitative due to the use of defined scenarios. However, note that this static approach is the only method able to furnish fast information on the plume dispersal and tephra fall-out. Afterward, it is evident as the future developments in

volcanic ash forecasting should be addressed to collect data from the monitoring instruments, transform them into input parameters for tephra dispersal models in a way to make more reliable simulations. This could be carried out using techniques of data assimilation already widely used in meteorological fields. New instruments and/or techniques able to detect the key parameters for models should be developed and make operative in observatories like INGV-CT. All models available in this project have already been tested and validated on data collected during the 2001 Etna eruptions (e.g. FALL3D, Costa et al., 2006). However, these studies have showed the need of reducing the model uncertainty by improving the modelling of some processes still now unknown (e.g. influence of particle shape, aggregation processes, and rain scavenging). Since the last years techniques of ensemble forecasting have been recently developed for analyzing the limitation imposed by the uncertainties in the prediction and
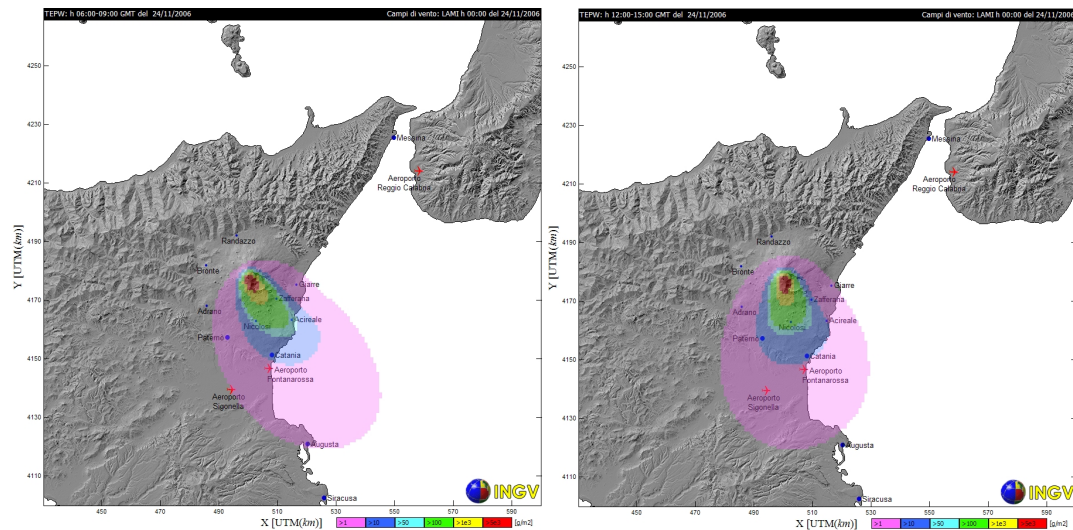
Fig. 9. Shift of the volcanic plume modelled by TEPHRA reflecting the changing of the wind direction from SE to SSE.
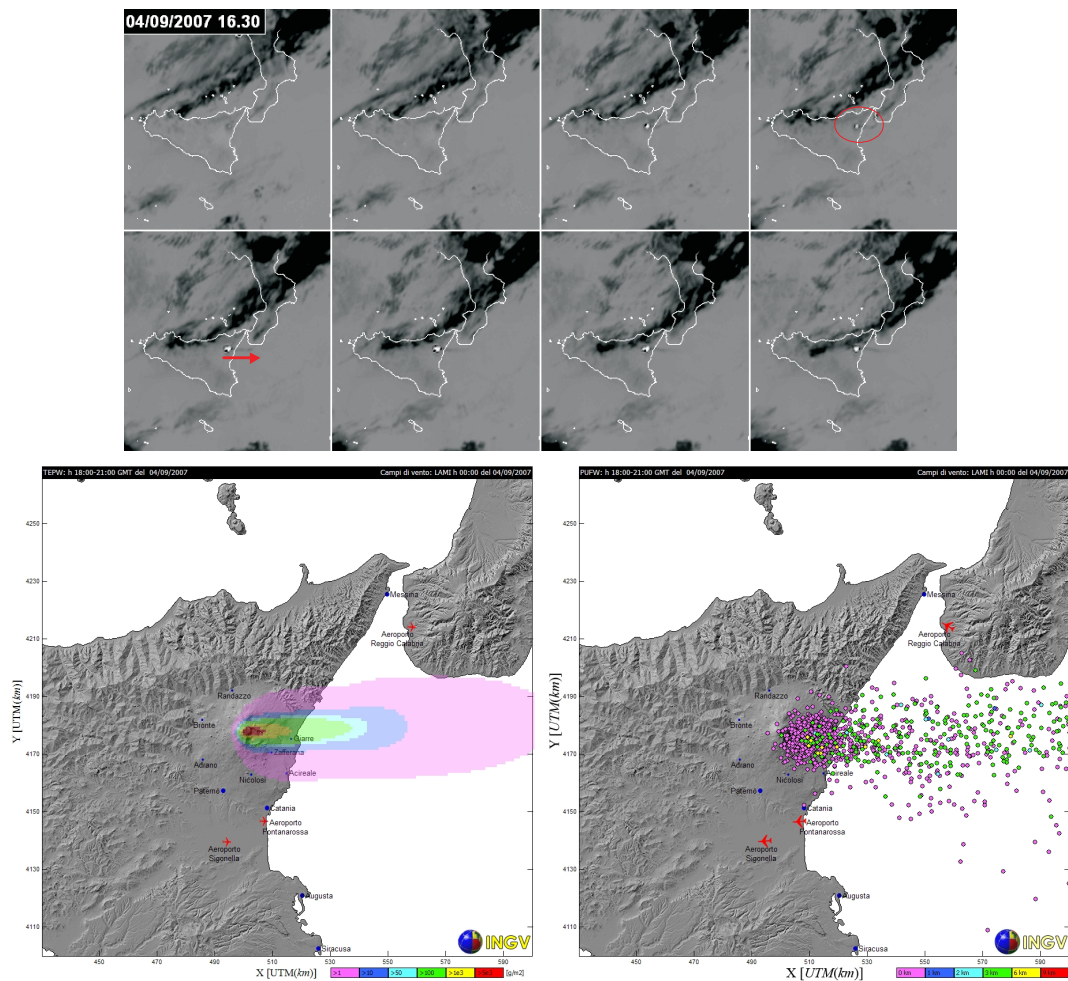
Fig. 10. SEVIRI images from 16:30 to 18:15 GMT of 4 September 2007 with steps of 15 min showing the ash plume toward E and TEPHRA and PUFF simulations of *Scenario 2*.

estimate quantitatively the probability density of the state of atmosphere at a specific time (Leutbecher and Palmer, 2008). At the moment we are beginning to compare the results of five dispersal models (this work is going on with the collaboration of INGV, sezione di Pisa, and INGV, sezione di Napoli). The same technique could be used in forecasting ash dispersal in a way for example to evaluate the probability density that volcanic ash is found in a specific space and time during an explosive eruption.

In summary, the forecasting and monitoring system developed at INGV-CT can be described as following: weather forecast data are downloaded from ARPA-SIM and CNMCA daily and four tephra dispersal models (FALL3D, HAZMAP, PUFF, TEPHRA) using input parameters for three predefined eruptions at Etna every three hours. Finally hazard maps are plotted and uploaded to web-site. The forecasts are validated using data from visible and thermal cameras, SEVIRI images and PLUDIX instruments. Further, the use of the field data collected after the explosive event is also crucial to evaluate the reliability of the simulations.

This paper shows that multidisciplinary approaches are needed to improve any type of forecasting. In fact, only the use of instruments able to detect different aspects of the same eruptive phenomena combining with advanced tephra dispersal models available in literature can give useful information on the presence of volcanic ash in the air and on the ground and consequently to prevent damages and airport disruptions.

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