Study over volcanic ash contamination conditions of Romanian air space-Etna

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Abstract: *This study is focused on finding the hypothetical conditions under of which the Romanian air space could be affected by a volcanic ash-like pollutant originating from Etna Volcano. We describe the plume transport behaviour, on its way to Romania, using the mass loading distribution displayed by the HYSPLIT (Hybrid Single Lagrangian Integrated Trajectory) model output. From the WLK (Wetterlagen-klassifikation) catalogue we have specific day sequences showing more than three days of a south-western circulation with a wet anticyclonic pattern over Romania. The resulting 24 cases in a period spanning more than a decade (2004-2014) displayed that the chances of contamination would be better for a quiescent environment around Etna's summit. There were found ten cases in quiescent atmosphere and only four cases in windy atmosphere with Romanian air space contamination. Although it was not possible to determine the effective concentration of the fine ash pollutant it was possible to isolate the mass loading distribution in time. As the study cases displayed one order of magnitude difference between mass loading distributions it became obvious that the behaviour of the mass loading distribution in time has a directly dependence on the environmental stratification of the Etna's summit atmosphere.*

Key Words: *volcanic ash, trajectories, mass loading distribution, air space contamination*

1. INTRODUCTION

Volcanic ash hazard is a threat mostly for northern parts of Europe. Increasing frequency in eruption is observed over the last 1100 years and about 80% of the verified eruptions were from the East Volcanic Zone of Iceland, including the most active volcanic systems: Grimsvötn, Bardarbunga-Veidivötn, Hekla and Katla [1]). For the last years this topic became increasingly important for the scientific community linking several disciplines related to aviation, volcanology, software development and meteorology.

Ejyafjallayökull demonstrated that we know very little in volcanic ash monitoring and transport. It also showed that such conditions make the entire air space vulnerable, rather than affecting airports in particular.

Initially 200 micrograms per cubic meter concentration was adopted as threshold for flight recommendation or permission.

Afterwards it has been raised at 2000 micrograms/ cubic meter and remained established as being damaging for the air traffic at 2000 micrograms per cubic meter.

Enhanced procedures are recommended with limited flying taking place in zone of 2000 to 4000 micrograms per cubic meter concentration level [2]; [3]).

Area of High Contamination was defined as "an airspace of defined dimensions where volcanic ash may be encountered at concentrations equal or greater than $4x10^{-3}$ grams on cubic meter, or areas contaminated airspace where no ash concentration is available" having a 60 NM (111km) interdiction zone [2]).

Although Romanian airports are not numbered amongst the airports as ones that are affected by the volcanic activity, this is not a hazard that can be entirely ignored.

Study of eruption dynamics and eruption plume estimation, tracking and practical interpretation are recently introduced among competencies and responsibilities assigned to volcanology and meteorology departments of civil aviation organizations [3]. Two major sources should be taken into account as most threatening for the east-central Europe: Iceland volcanic apparatus and Italian Mediterranean volcanic zone. Etna Volcano is very active volcano with explosive activity causing most of the reporting activity sourced of the Italian aviation [4]).

Etna's explosive activity is increasingly hazardous by its proximity to the Sicilian most important airport, Catania-Fontanarossa. Therefore, since 1980, there is a multidisciplinary approach to its surveillance system [2], as its eruptive activity shows anomalous eruptive style during last two decades, with more explosive pattern [5].

In this context there is a demand on considering the eruptive scenarios more catastrophic and longer than that on April 2010 [3] this being the reason for that the study is thought to consider the situation of a large eruption.

Therefore in this work it was considered necessary to think simulations scenarios of the Vesuvius and/ or Etna eruptions, tracking and analyzing the plume and the volcanic ash cloud emphasizing the entering regime in the Romanian air space in order to explore the possible contamination pattern.

The eruption parameters, the trajectories source data and the methods used to determine the quantity of pollutant and the trajectory of the volcanic ash cloud are displayed in Section 2. In Section 3 there are presented the results obtained regarding the dominant circulations accordingly to the WLK catalogue of weather types and the most favoring circulations for the Etna's plume trajectory towards Romania and also the dispersion and the transport of the volcanic ash cloud results. Section 4 is reserved for summary and concluding remarks.

2. METHODOLOGY USED TO SIMULATE VOLCANIC ASH TRANSPORT TOWARD ROMANIA

2.1 Short considerations

The methods used to obtain trajectories of the volcanic ash cloud towards Romania and the pollutant quantity distribution in Romanian air space are based by exploring the relationship between ash column height, air circulation pattern and transport of the volcanic ash. The trajectories are determined using HYSPLIT (Hybrid Single Lagrangian Integrated Trajectory) model. To apply this model, we used three steps: (a) it was simulated ash column using the Plume Rise web-tool; (b) the dominant air circulation for pollutant plume transportation over Romanian air space was analyzed using the WLK Catalogue [6] and selected the most frequent south-western trajectory classes; (c) the first and second steps results were used to obtain the trajectories of the plume with HYSPLIT, a hybrid Euler-Lagrange, transport model [7].

Etna Volcano is a very active stratovolcano, characterized as a 'M' volcano category with mafic, basaltic and ultramafic composition of the erupted material [8]. It has a wide range of the explosivity behavior ranging from mild strombolian to sub-plinian with an increasing tendency of the explosive activity [5]). The geographical coordinates required for HYSPLIT model input usage are: latitude 37.43 deg. north; longitude 15.00 deg. east and an elevation of 3320m AMSL (Average Mean Sea Level) (Fig. 1).

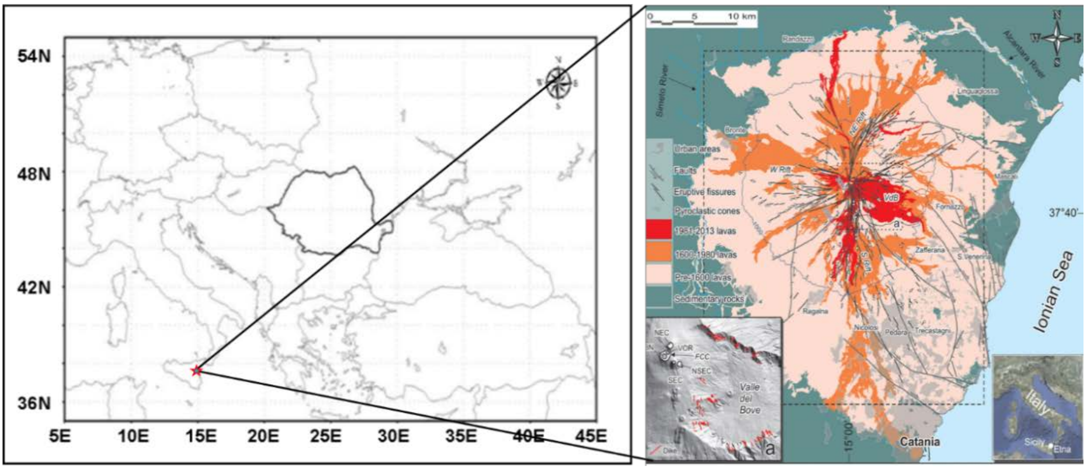

Fig. 1 Location of Etna Volcano (right side) within atmospheric circulation types domain (left side)

2.2 Data used for each step of the study

Data used are either observational and/ or modelled. The observational data is incorporated into Reanalysis meteorological model Global Data Assimilation-National Centers for Environmental Prediction/National Center for Atmospheric Research (GDAS-NCEP/ NCAR).

These data are used in HYSPLIT trajectories calculation and for the WLK Catalogue, generating maps (2.5^0 lon by 2.5^0 lat) – global grid resolution with 28 vertical levels.

In order to isolate the specific days of south-westerly circulation with strong wind presence over Etna location there have been used the online archived maps of METEOCIEL.fr web site [9].

This is an web site which provides maps of different meteorological data fields created departing from the NCEP/ NCAR Reanalysis meteorological data (*) and we used the 300 hPa wind field for Jet Stream.

The modelled data used are as follows: the output from PlumeRise web tool as plume height and solid mass fraction, both at neutral buoyancy, are used as input data for HYSPLIT model in the "release top" field and as fine ash mass fraction of the source.

The model used is a HYSPLIT subsection: Real-time Environmental Applications and Display sYstem (READY) Website (http://www.ready.noaa.gov), [10]).

The output of the HYSPLIT model is used to determine the mass loading vertical distribution at specific time during the plume's transport for specific dates with/or without Jet Stream presence at Etna's location.

In this study there was one major assumption made in order to model the plume's trajectories: at the neutral buoyancy height the solid mass fraction values obtained from PlumeRise runs represents "the fine ash mass fraction" or *m63* [8]) values required by the HYSPLIT input fields.

For the first step, (a), in order to predict the movement of the volcanic ash cloud it is necessary to use a source minimal dataset: the height of the erupted column (the level at neutral buoyancy in a stratified atmosphere) and the mass flux of material released during the eruption [11]).

Unfortunately, the source mass flux could not be directly measured. But the mass flux is straight related to the ash column height in the stratified atmosphere [12]):

$$H = 3.76 Q_T^{1/4} N^{-3/4} \tag{1}$$

where Q_T is enthalpy flux (J/s) and N is Brünt Väïsäla frequency.

This equation led to inversion methods and permitted to calibrate a quarter-power relationship between plume height at neutral buoyancy, eruption duration and total erupted mass or mass flux of the source ([13]; [14]; [15]; [8]). For instance Mastins's fit to estimate the source mass flux is:

$$H = 0.304 Q^{0.241} \tag{2}$$

PlumeRise uses an integral model [16]) to obtain a more realistic simulation of the ash column physical proprieties. The model takes into account the heat content of the erupting material, heat exchange between particles and entrained air, expansion of gases, density variation, atmospheric stratification, different entrainment rates in jet and volcanic plume region.

Because volcanic plumes are strongly affected by strong wind [11], [17]) in this study we used the web-tool "PlumeRise" as this web-tool is designed to model a volcanic ash column in a windy and moist atmospheric environment.

This plume model is applicable for large explosive eruptions and it incorporates the influence of the solid pyroclasts on the bulk plume properties as density and heat capacity [11]. As the dispersion models generally over predicts the reduction of the plume rise height for a specified source mass flux when compared to the observations [11]), we decided to use as input for trajectories simulations the height of the plume obtained at neutral buoyancy.

For the second step, (b), the WLK circulation types were determined by using cost733class software [18]), for a spatial domain (Fig. 2 – left side) centered over Romania [19]).

The WLK catalogue developped by Dittman et al. in 1995 [6] uses information from three basic tropospheric levels: 925, 700 and 500 hPa, and information on the precipitable water content over the entire atmosphere column (for depiction of water content of the air mass: dry-D, wet-W).

Geopotential fields at 925hPa and 500hPa are used in order to establish the cyclonicity (C) or anticyclonicity (A), while the U and V components of wind at 700hPa are to establish the dominant direction of the flow (southwestern-SW, northwestern-NW, northeastern-NE, southeastern-SE and undefined). Daily data sets presented above were extracted from NCEP/

NCAR data archive[20]) between 2004 and 2014 with a spatial resolution of 2.5 by 2.5 degrees for the spatial domain considered in this study.

For the final step, (c), the several trajectories of a modeled ash plume cloud accordingly to selected meteorological conditions that satisfy the condition of a south-westerly circulation over Romanian territory were simulated.

The HYSPLIT model uses a Lagrangian method for advection and diffusion and a Eulerian framework (fixed grid) for concentrations (Draxler et al., 1998 [7].

The modelled data used are as follows: the output from PlumeRise web tool as plume height and solid mass fraction both at neutral buoyancy are used as input data for HYSPLIT model in the “release top“ field and as fine ash mass fraction of the source. The output of the HYSPLIT model is used to determine the mass loading vertical distribution at specific time during the plume’s transport.

3. RESULTS AND DISCUSSIONS

Initially, multiple runs were tested on PlumeRise, varying the column speed at the vent, the vent’s radius and the temperature in the ash column.

The pyroclastic density was kept at 1200 kg/m^3 while the wind entrainment coefficient was 0.9 as it is recommended by Woodhouse et al., 2013 [11] and no-wind entrainment coefficient was 0.09 [21].

Gas mass fraction was varied between 0.01 and 0.1. For the final outcomes used as input for HYSPLIT runs it was established at 0.01 as “strong plume” (Table1).

The temperature of the column was established at the value of 1000 K and the speed of ejected material at source as 275m/s following [22] simulations for a “strong” plume parameters.

Table 1. PlumeRise data used for HYSPLIT simulation.

PlumeRise (strong plume) inputs: **Gas mass fr.=0.01; T=1000K; Pyroclasts density=1200kg/m^3; V=275m/s**			
Strong wind **V** ≥50m/s Wind entrainement coeficient=0.9		**Weak** wind **V** <50m/s No Wind entrainement coefficient=0.09	
Top	Neutral buoyancy	Top	Neutral buoyancy
Htop= 23757m	Hnb=13216m	Htop= 29736m	Hnb=21302m
Solid mass fraction=0.02	Solid mass fraction=0.028	Solid mass fraction=0.08	Solid mass fraction=0.09

Consequently, assuming that the values of the particle diameter at the neutral buoyancy are less than 63 µm, the HYSPLIT model runs in this study with release height at neutral buoyancy at 13216 m and solid mass fraction *m63* =0.028 (dimensionless) for jet stream presence cases; for non-jet stream presence cases it was used height at 21302 m and solid mass fraction *m63* =0.09 (dimensionless) (Table 1).

In order to identify the days with Romanian air space contamination most favorable conditions we evaluated the WLK catalogue results in terms of southwestern circulations, affecting Romania for the 2004-2014 time period.

We found that for the period 2004-2014 southwestern circulation had a 26% of contribution to the entire period from which anticyclonic-wet (AAW) ones had a 29% followed by a cyclonic-wet (CCW) circulation representing 26% from the total number of southwestern circulation days of the time period (Fig. 2).

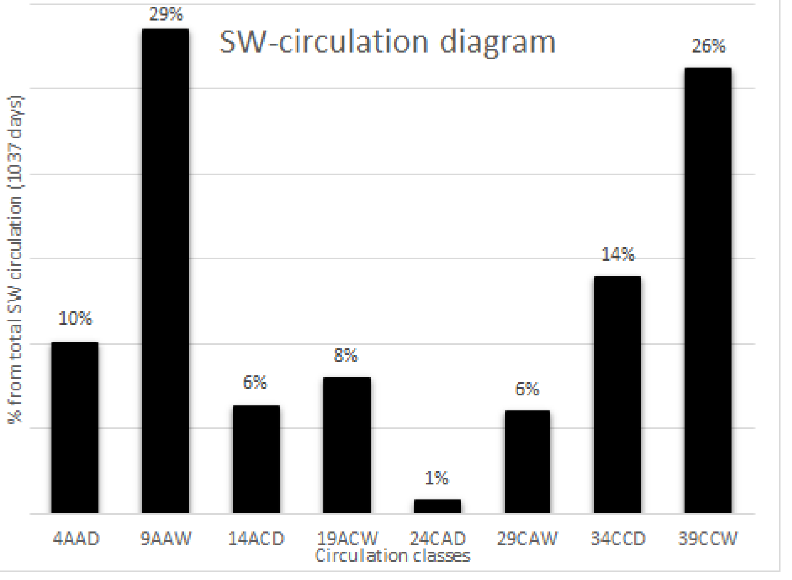

Fig. 2 South-westerly circulation diagram (occurring percentage) over Romanian territory during ten years (2004-2014)

We isolated from WLK catalogue (example Fig. 3) all the cases with the time period of south-westerly circulation and the specific days with wet anticyclonic pattern having more than three days persistence (see the Annex, Table 2) and obtaining a number of 24 study cases. Eight cases from 24 were having a jet stream while fifteen were on non-jet stream. In one case study there was no way to decide the jet stream presence. One of them was undefined.

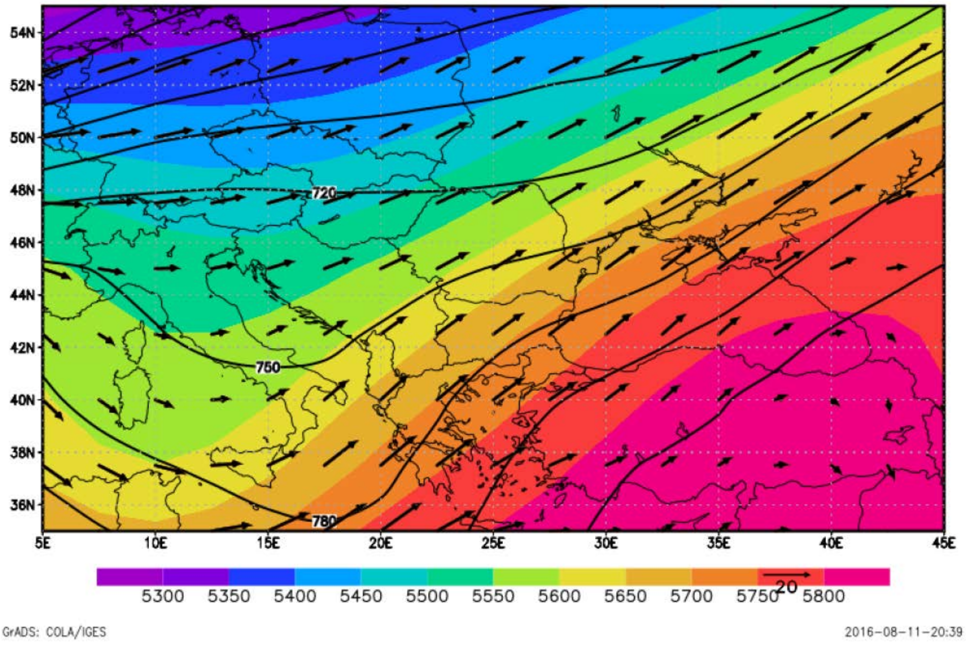

Fig. 3 South-western anticyclonic wet (9AAW) circulation pattern; the geopotential height (mgph) at 500 hPa level is colored; the contours represents the geopotential height (mgph) at 925 hPa level; the arrows represents the wind vector at 700 hPa level

In order to explore the contamination patterns for Romanian air space we analyzed the simulated trajectories of the volcanic ash using HYSPLIT model (volcanic ash quantitative). In figures 4 and 5 there are represented the plume trajectories for the two situations, turbulent (Fig. 4) and quiescent (Fig. 5) atmosphere over Etna Volcano.

One can note that for turbulent atmosphere were obtained only four cases of the Romanian air space contamination: 11 April 2004; 28 September 2004; 11 November 2010; 11 December 2011 (Fig. 4).

Ten cases for a quiescent environment displayed contamination behaviour: 16 December 2006; 5 Mars 2008; 28 October 2008; 6 June 2009; 12 June 2010; 27 November 2012; 29 October 2013; 25 December 2013; 6 November 2014; 14 December 2014 (Fig. 5).

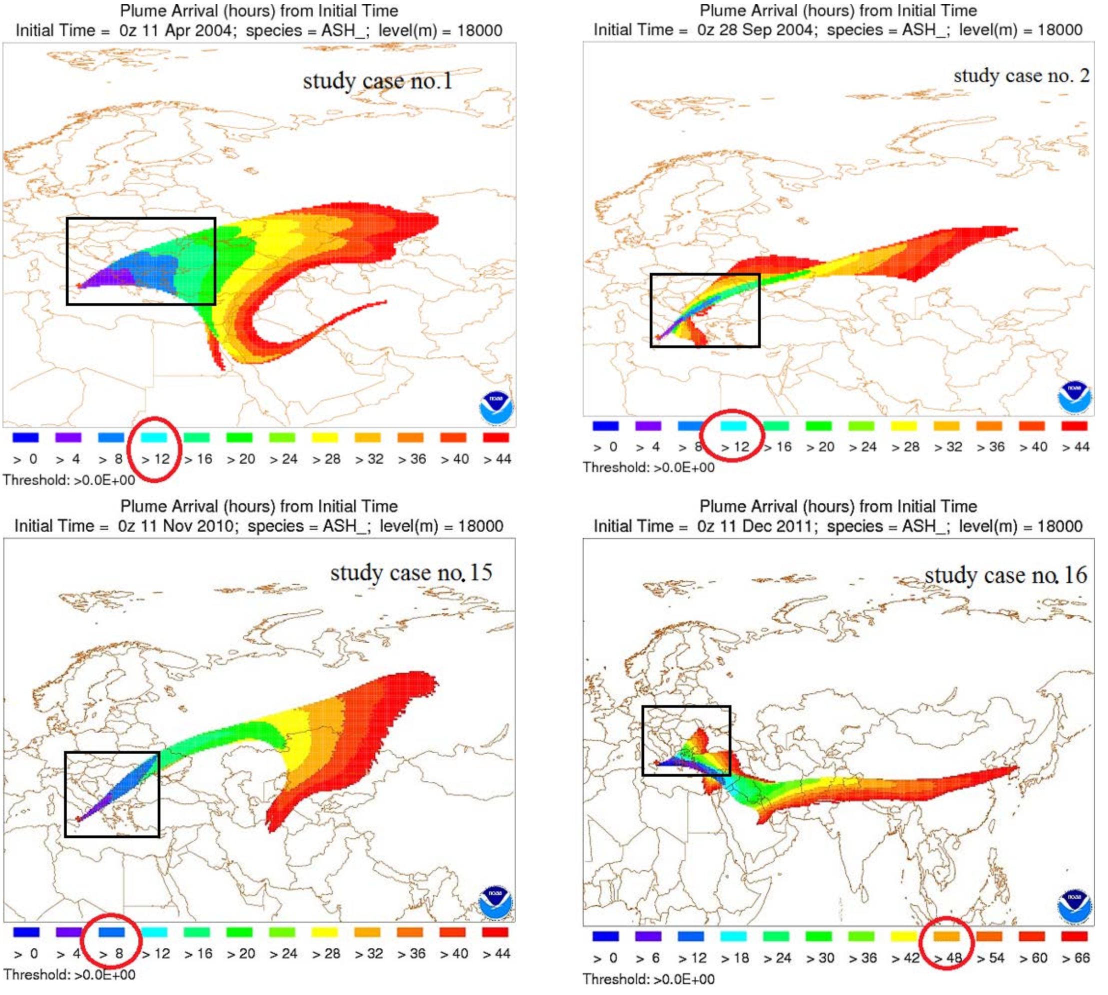

Fig. 4 HYSPLIT output maps illustrating the plume trajectories timing for the jet situations. Circled in red is the time step of the model when the plume is simulated to enter the Romanian air space

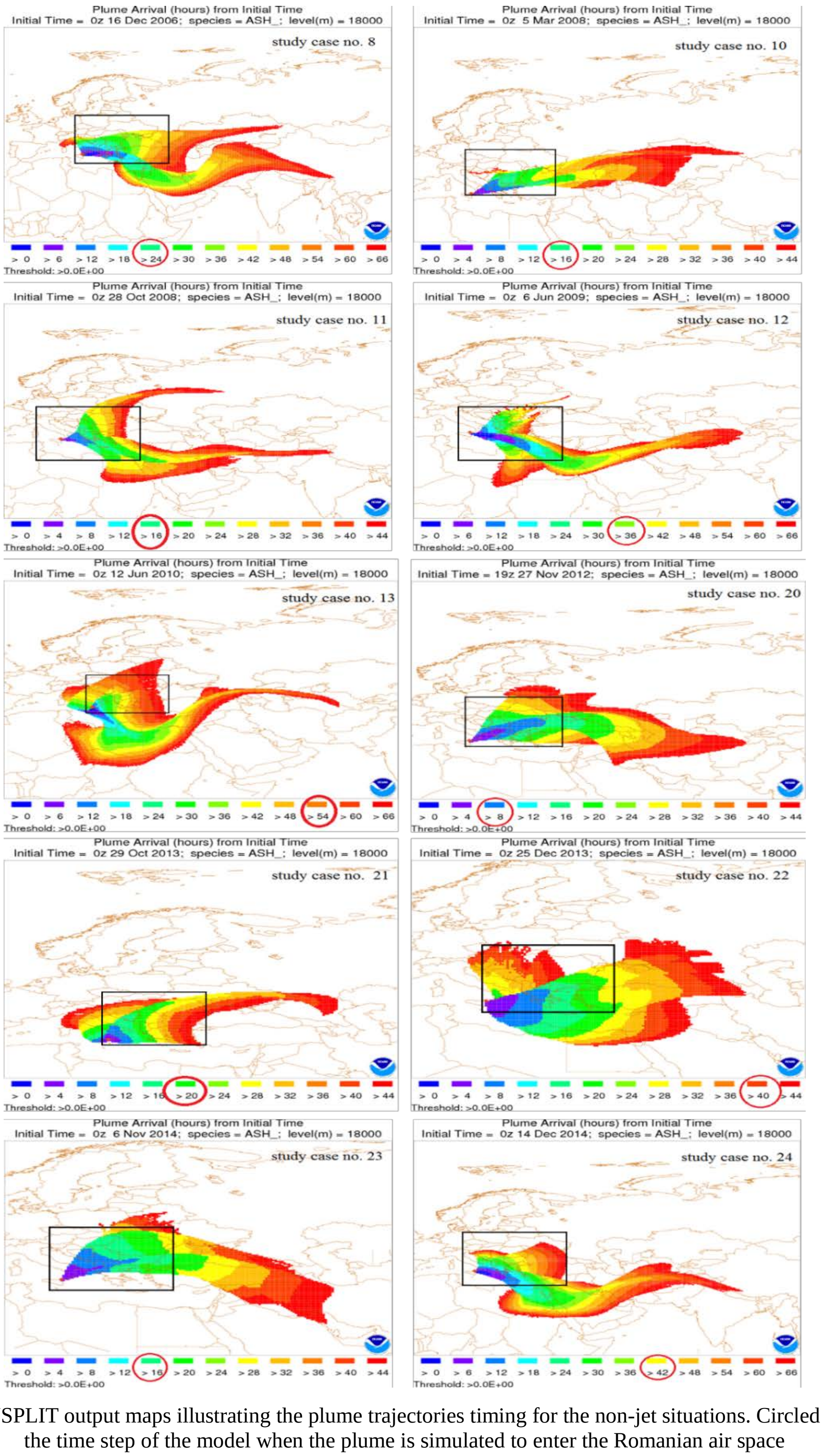

Fig. 5 HYSPLIT output maps illustrating the plume trajectories timing for the non-jet situations. Circled in red is the time step of the model when the plume is simulated to enter the Romanian air space

For a better understanding of the behaviour of the solids fragments mass loading during the plume's transport it we have performed the extraction of the mass loading distribution for every 6 hours, beginning with the estimated time of the eruption.

In figures 6 and 7 are displayed the distribution of ash (m63) mass loading with height for the jet and non-jet cases.

All cases were selected for the situations when the plume had "touchdown" on the Romanian air space.

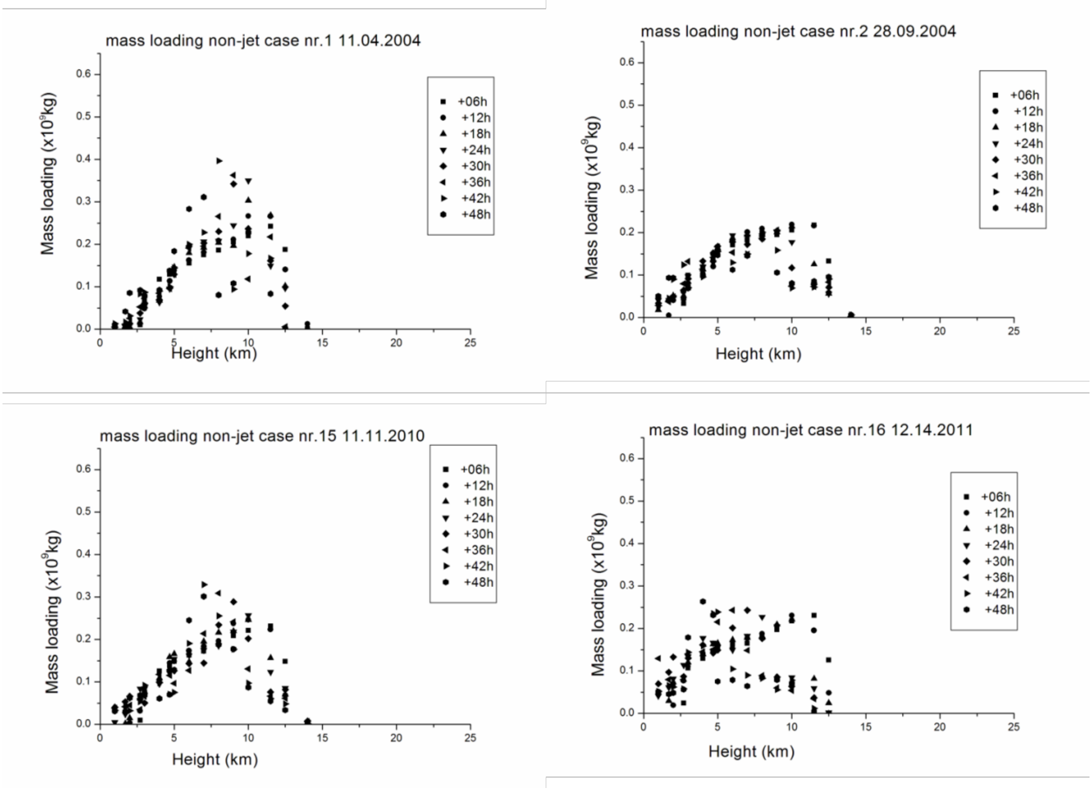

Fig. 6 Simulated fine ash (m63) mass loading values on height distribution for every day of south-western circulation class (namely anticyclonic wet- AAW) in a turbulent environment over the Etna's summit. Data were extracted from HYSPLIT MESSAGES outputs file for the Romanian air space contamination case

It can be seen that, generally, in case of a turbulent atmosphere over Etna Volcano the mass loading distributions is Gaussian accordingly to atmospheric dispersion of pollutants. The HYSPLIT model displays maximum values of mass loading (0.210^9-$0.3\ 10^9$ kg) between 5 and 10 km height.

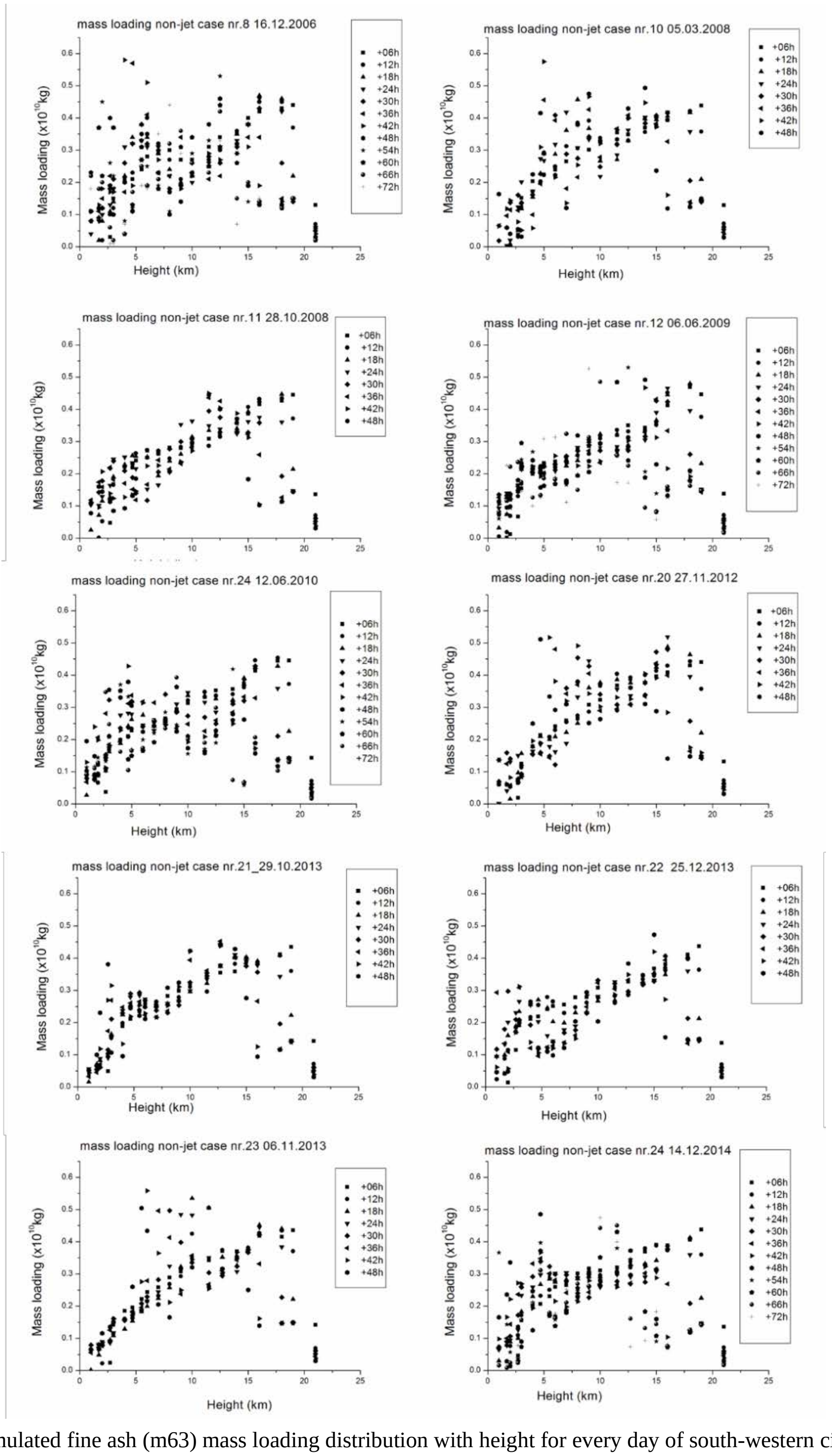

Fig. 7 Simulated fine ash (m63) mass loading distribution with height for every day of south-western circulation class (namely anticyclonic wet -AAW) non-set Stream over the Etna summit for 2004-2014. Data extracted from HYSPLIT MESSAGES outputs files for the Romanian air space contamination case

The results of HYSPLIT runs for a calm atmosphere over Etna's peak show that the values of mass loading are greater than in turbulent atmosphere and the maximum values were shifted to larger values of height (7-15 km).

It is interesting to note that for some cases mass distribution has two peaks at 5 km and 12 km; this may be explained by the presence of disturbances in the horizontal air flow.

The comparison between the mean values of mass loading distribution in time in the four jet cases and the eight non-jet cases are shown in Fig. 8.

The average of mass loading decreases in 48 hours for jet cases and in 72 hours for non-jet cases.

In addition, the decreasing rate is $0.18\cdot10^7$ kg/h (at 99.99% confidence level) for presence of jet and $1.9\cdot10^7$ kg/h (at 99.99% confidence level) for the static stability cases. The explanation, as expected, is that the difference is due to atmospheric state which controls dispersion of volcanic ash.

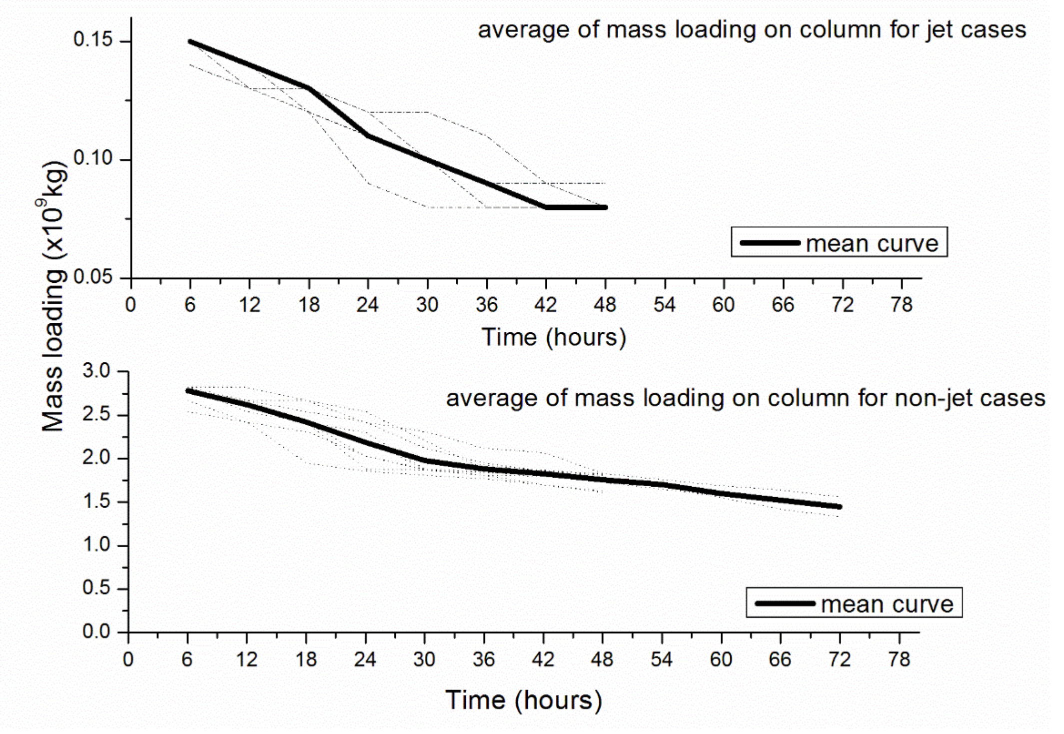

Fig. 8 Comparison between the mass loading average on column for Jet Stream cases and non- Jet Stream cases. Different dash-dot lines represent the average of the mass loading on column for each study-case while the solid ones are the mean of the average of mass loading on column

Because the most used layer on cruise flight is between 9 and 11.5 km altitude, we tested the model for the mass loading average between these two levels (Fig. 9).

One can note the same rapidly decreasing of mass loading for the jet-cases as in previous figure and a constant average mass loading for non-jet cases, however for each case the trend is different.

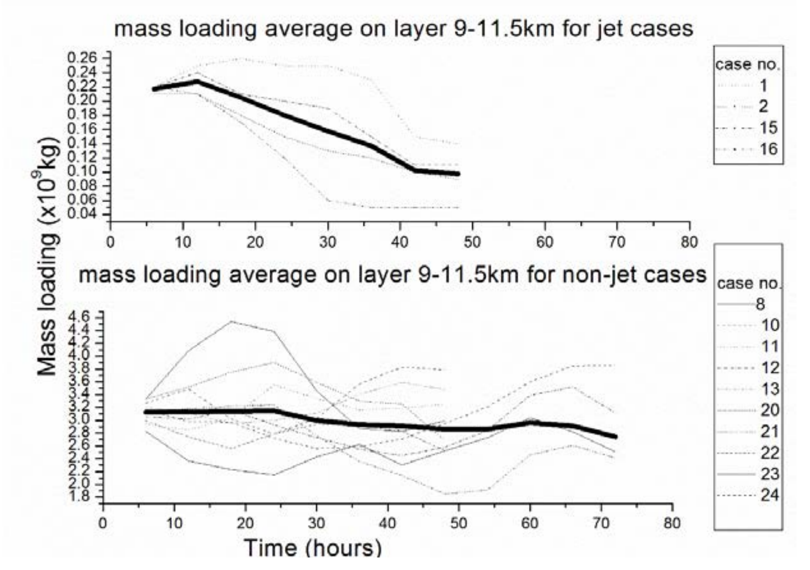

Fig. 9 Comparison of the mass loading (x10^{9}kg) averaged on layer 9-11.5 km. Mass loading average on upper panel is referred to a turbulent environment at the source, while on the lower panel the mass loading average is for the quiescent environment cases

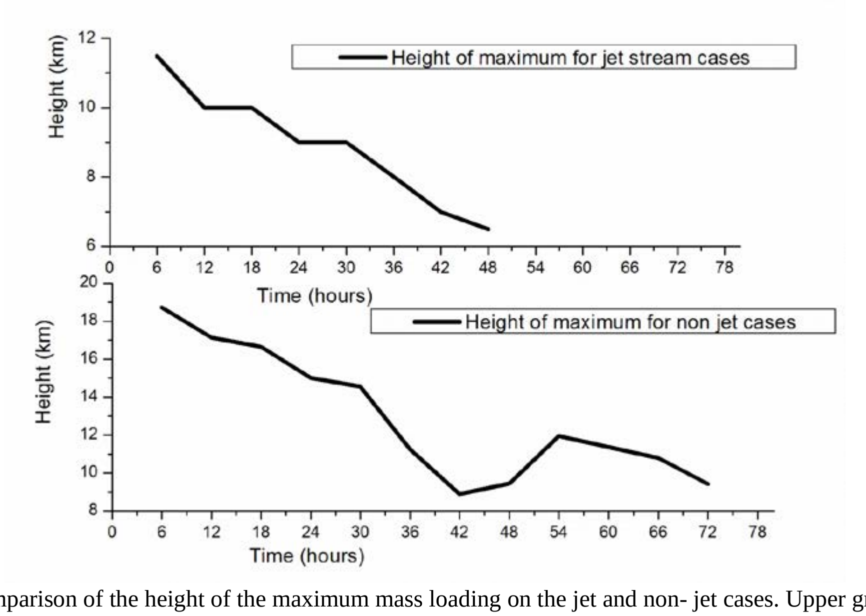

Fig. 10 Comparison of the height of the maximum mass loading on the jet and non- jet cases. Upper graph is the evolution of the level of the maximum mass loading on column accumulated in time while the lower graph shows the height of maximum mass loading on column in the quiescent environment

4. SUMMARY AND CONCLUDING REMARKS

Running HYSPLIT model for volcanic ash contamination using the input data obtained with the PlumeRise web-tool output parameters provided an interesting and useful evaluation about the behaviour of a virtual volcanic ash event threatening Romanian air space safety. The study was focused on the 2004-2014 time interval and within this period there were found two predominant air circulation classes favoring volcanic ash transport from Etna towards Romania. Using HYSPLIT model for volcanic ash facilities enabled us to study the virtual trajectories of the plume.

The results of the study have shown:

From a wet anticyclonic air circulation class there were obtained 24 cases of virtual trajectories from Etna to Romania. For turbulent atmosphere over Etna's summit were found eight cases with four them displaying Romanian air space contamination and fifteen cases for calm atmosphere over Etna's summit from which ten cases had contaminating trajectories.

The mass loading vertical distribution is directly linked on the atmosphere stratification over the Etna's summit; the case studies displayed one order of magnitude difference between jet and non-jet mass loading distribution. This is consistent with recent findings as the ash column rising in a strong wind field displays a strong bending over shape and thus having a significantly reduced height at the source than a plume in a quiescent atmosphere [11].

HYSPLIT runs performed for jet case-presence displayed a short time period of the plume suspension contaminating the Romanian territory, less than 12 hours (Fig. 4); as for the non-jet-presence cases, the study showed that the Romanian air space is contaminated after 18 hours or more after the simulated eruption (Fig. 5). In conclusion, the atmospheric state remains a deciding factor for the volcanic ash pollutant plume not only for the source ash column but also for the plume dispersion and trajectory.

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