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Volcanic Eruptions in South Europe and the Change of Carbon Dioxide Concentration – Case Study: "Moussala" Basic Environmental Observatory

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Abstract

The volcanic eruptions are one of the most characteristic natural sources of CO_2 in the atmosphere (IPCC, 1990, 2007). In order to study the effect of volcanic eruptions on the increased levels of CO_2, we have used data from the Basic Environmental Observatory (BEO) "Moussala", Bulgaria, for the period comprised between July 2007 and March 2015. The Carbon dioxide is not a health hazard gas and there is no established limit concentration by the Bulgarian and international law. In this study, we have accepted as extremely high values the values that exceed the 95th percentile of the distribution of the daily average values for the studied period. The days with exceeding CO_2 concentration were analysed in terms of volcanic activity (Etna), which could affect the investigated area with the spread of air pollutants and also CO_2. The simulations developed by the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model are used in order to describe the trajectory and dispersion of pollutant and products from eruptions of Etna in the atmosphere. A synchrony between the occurrence of days with extreme high concentration of CO_2 in the atmosphere in the region of BEO "Moussala" and eruptions of Etna volcano was established in most of the investigated cases.

The analysis of the results from BEO "Moussala" confirms the impact of the volcanic eruptions and Etna volcano, in particular, for the increasing of CO_2 concentration in the atmosphere. On the other side, it was established that the activity of Etna is not the only factor which has impact on the concentration of CO_2. More detailed analyses concerning not only natural, but also anthropogenic factors have to be done in the future in order to clarify the reasons for the increasing concentration of CO_2 in the atmosphere (IPCC, 2014).

Keywords: *carbon dioxide, Etna volcanic eruptions, Bulgaria, HYSPLIT Model*

Erupţiile vulcanice din Europa şi modificarea concentraţiei de dioxid de carbon din atmosferă. Studiu de caz: Observatoriul de Mediu *Moussala*

Rezumat. Erupţiile vulcanice reprezintă una din sursele principale de CO_2 din atmosferă (IPCC, 1990, 2007). Pentru a studia efectul erupţiilor vulcanice asupra nivelurilor crescute de CO_2, s-au utilizat datele de la observatorul de Mediu *Moussala* (BEO) din Bulgaria pentru perioada cuprinsă între iulie 2007 şi martie 2015. Întrucât dioxidul de carbon nu este considerat un gaz cu risc pentru sănătate, nu este stipulată nicio limită pentru concentraţia acestui gaz în legistaţia bulgărească sau internaţională. Pentru acest studiu, am considerat ca volori foarte mari cele care depăşeau cu 95% valorile medii zilnice pentru perioada studiată. Zilele în care s-au înregistrat depăşiri ale concentraţiei de CO_2 au fost analizate din persectiva activităţii vulcanice (Etna), care ar fi putut afecta aria luată în analiză datorită răspândirii poluanţilor aerieni, inclusiv a CO_2. Simulările elaborate cu ajutorul Modelului *Hybrid Sincle Particle Gagrangian Integrated Trajectory* (HYSPLIT) sunt folosite pentru a descrie traiectoria şi dispersia poluanţilor şi particulelor expulzate de vulcanul Etna în atmosferă. În majoritatea cazurilor, s-a stabilit o sincronizare între zilele în care s-au înregistrat concentrări extrem de mari de CO_2 în atmosfera din apropierea BEO *Moussala* şi erupţiile vulcanului Etna.

Analiza rezultatelor de la BEO *Moussala* confirmă impactul erupţiilor vulcanice în general şi al vulcanului Etna în particular asupra concentraţiei de CO_2 din atmosferă. Pe de altă partă, s-a stabilit că activitatea vulcanului Etna nu este singurul factor cu impact asupra concentraţiei de CO_2. Pe viitor, trebuie întreprinse analize detaliate privind nu numai sursele naturale de CO_2, dar şi cele antropice pentru a putea clarifica motivele pentru creşterea concentraţiei de CO_2 din atmosferă (IPCC, 2014).

Cuvinte-cheie: *dioxid de carbon, erupţiile vulcanului Etna, Bulgaria, modelul HYSPLIT*

Introduction

Natural sources of CO_2 are mainly volcanic eruptions and large forest fires. Volcanic activity can inject large quantities of gases and aerosols into the atmosphere both during and between eruption breaks (Pareschi et al., 1999). Depending on the power of the eruption and the speed of the wind, the ejected CO_2 in the atmosphere can be transported over long distances. That is why several gases, CO_2 included, could be registered thousands of kilometers from the volcano itself.

The gases exuded in volcanic eruptions from magma at a certain depth, as well as during the cooling of lava in the lava flow, form gaseous clouds. Their composition is predominantly of sulfur compounds, carbon dioxide, nitrogen, hydrogen, methane, chlorine and compounds of boron and argon, water vapor. The greatest amount of CO_2 is contained in the gases which have a temperature below 100°C. These are the so called mofette. Volcanic ash that is released during eruptions contains lava particles, mica, volcanic glass, gases and water vapor (Kanev, 1983). Etna is one of the largest contributors of magmatic gases, CO_2

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included (Allard et al., 1991; Francis et al., 1998; Williams et al., 1992). Etna is an active stratovolcano, as the cone of the volcano is formed by alternating eruptions in which lava masses alternate with tuffs (Kanev, 1983). Its height is variable, i.e. amended by volcanic eruptions. Currently, the altitude of Etna is 3330 m. a.s.l. which makes it the highest active volcano in Europe. It covers an area of 1,190 sq km in Eastern Sicily, between the African and Eurasian continental plates. The volcano is one of the most active in the world and it is almost constantly in a state of activity (Global Volcanism Program, 2013).

The high mountain station BEO Moussala is located in Rila National Park at an altitude of 2,925 m a.s.l. and it is far from major industrial pollutants and other human activities (Angelov et al., 2013). Therefore, human influence is limited to a minimum. Periodic increases in CO_2 concentration are mainly due to natural sources such as volcanoes and summer forest fires. Depending on the wind speed and its direction, increased levels of CO_2 in some cases may also be registered due to human activity, especially ventilated emissions from the activity of central heating. Because of the lack of data about more significant human activity, this aspect has not been examined in this study.

Methodology

Through comprehensive research approach and application of mathematical, statistical and analytical methods, monthly and seasonal concentrations of CO_2 in the air and meteorological parameters are calculated and trends in chronological changes are analyzed. The causal relationships between the changes in the concentration of CO_2 in the air and the natural factors (weather parameters and volcanic activity) have been established.

Tracking the movement of volcanic ash and gases which are ejected into the atmosphere from Etna volcano was done through simulations of the course of volcanic ash made by NOAA HYSPLIT model (http://www.arl.noaa.gov/HYSPLIT_info.php, accessed 30 November, 2013). This model is a system for tracking the trajectories of different air pollutants, including CO_2. In addition to determining the trajectory, the model is used in various simulations representing the deposition of pollutants on the ground. HYSPLIT model could be used also for tracking and forecasting of radioactive elements, gases from forest fires, dust and volcanic ash. For the purposes of this study, the transport of volcanic ash from Etna is used, because the greatest synchronicity was established between the occurrences of days with extremely high CO_2 concentrations in the air and moments of eruption of the volcano.

The HYSPLIT model is managed interactive online and enables tracking the emitted volcanic ash at a given period of time. The date of the volcanic eruption has to be used as input data for the simulation. The initial information about the eruptions of the volcano was obtained from the Volcano Discovery database (http://www.volcanodiscovery.com, accessed 30 November, 2013), where the daily state of active volcanoes on the planet is published. A period of 28 days (December 17, 2013 - January 13, 2014) is used in the present study in order to analyze the impact of volcanic eruptions on the concentration of CO_2 in the air. The choice of this period is determined by the greatest number of days (18 days) with increased concentration of CO_2 in the atmosphere, according to the data from BEO "Moussala".

Results

Chronological changes and seasonal course in CO2 concentrations in the air

The data for monthly values of CO_2 from BEO "Moussala" were used for the analysis of annual and seasonal distribution of this indicator during the period comprised between July 2007 and March 2015. The seasonal values are defined as the average of monthly concentrations, as follows: for winter - December, January and February; for spring - March, April and May; for summer - June, July and August; for autumn - September, October and November.

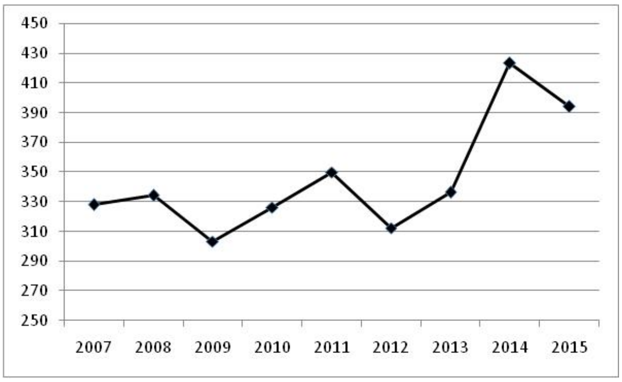

Fig. 1: Average annual CO_2 concentrations in the air (in ppm)

The highest annual concentration of CO_2 in the air is established in 2014 - 423.37 ppm (Fig. 1). The year 2014 is one of the years with the highest volcanic activity in the world and this led us to the hypothesis that the increased concentration of CO_2 in the air at the BEO "Moussala" is due to the volcanic activity.

The analysis of the average seasonal concentrations of CO_2 in the air for the period 2007-

2015 shows a clear seasonality in the course - the highest concentrations of CO_2 measured in BEO "Moussala" are registered during summer (360.81 ppm) and the lowest are registered during autumn (315.77 ppm) and winter (332.1 ppm) (Fig. 2).

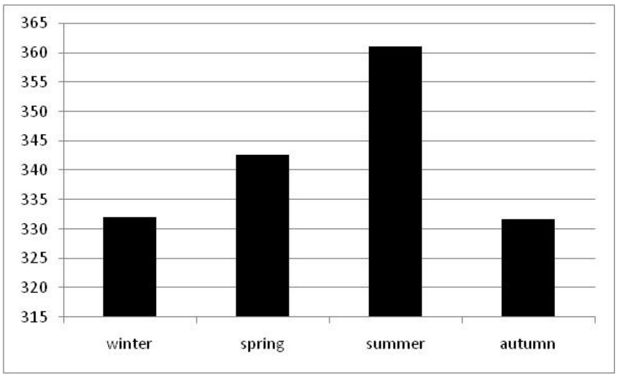

Fig. 2: Seasonal distribution of CO_2 concentration in the air (in ppm) at BEO Moussala (2007-2015)

As for the cold season in the region of Moussala peak, a relatively small amount of precipitation, few days with fog, reducing the air temperature and increasing of vertical stability of the atmosphere are characteristic and this could have caused the reduction of CO_2 concentrations for this period.

Seasonal distribution of CO_2 concentrations measured at BEO "Moussala" refers mainly to the natural factors, such as the impact and regime of the main climatic elements - air temperature, humidity, atmospheric pressure, speed and direction of the wind, as well as volcanic eruptions in the Southern European region.

CO2 concentration in the air in the region of BEO "Moussala" and its relation to the eruption of Etna volcano

In order to show the relation between volcanic eruption and CO_2 concentrations, the data during the period comprised between December 17, 2013 and January 13, 2014 is used for the purposes of this study. This period is characterized by intensification of Etna volcano activity. The analysis of the daily concentrations of CO_2 shows that during 18 days of this period, the daily concentration of CO_2 was above 95 percentiles of the empirical distribution for each month, for the investigated period (Table 1). These days were accepted as days with extremely high CO_2 concentration.

The correlation between the increased CO_2 concentrations in the air and the activity of Etna volcano was investigated in connection with data about direction and speed of the wind measured at BEO "Moussala" (Table 2). The extreme high values of CO_2 concentration exceeded 500 ppm, but this is below the safety thresholds recommended for human health (Granieri et al, 2014; Aerias, 2005). The most typical examples are described below.

Table 1: Days with extreme CO_2 concentrations

Year	Months	Days
2013	December	17, 19, 20, 21, 22, 27, 29, 30, 31
2014	January	1, 3, 4, 6, 8, 9, 10, 11, 13

According to the Volcano Discovery database for December 2013, the first releases of volcanic ash in the atmosphere from the northeast part of the volcano were registered on December 17, 2013. The track of the volcanic cloud, followed by HYSPLIT model, shows that it is very likely to exist a relation between the activation of Etna volcano and the increasing values of CO_2 concentration. The data from Volcano Discovery show an increasing volcanic ash in the atmosphere on December 22, 2013. The prevailing winds are west-northwest and their speed is over 2 m/s. The cloud of volcanic ash is observed in the Western part of the Bulgarian territory. The results obtained from the model showed a cloud of volcanic ash in West of Bulgaria. On December 23, 2013, a release of volcanic ash and gases with considerable power is observed in the atmosphere. The prevailing wind direction is southwest (Table 2). The HYSPLIT model shows that on the same date, the cloud of volcanic ash completely covers the airspace of Bulgaria (Fig. 3).

During the next few days, the state of Etna volcano varies from calm to quite active. The CO_2 concentrations in the air measured at BEO "Moussala" kept high levels and reached extreme or close to extreme values (Table 2).

On December 29, 2013, a loud explosion in the southeast part of Etna volcano is reported and an ejection of large amounts of volcanic ash and gases in the atmosphere is observed. Daily average concentration of CO_2 measured in the atmosphere at the region of "BEO Moussala" rose to 497.15 ppm which is above 95 percentiles of the data for December. Prevailing winds are southeast and an average speed of over 4 m/s (Table 2). The model results show cloud of volcanic ash in the airspace of Bulgaria was moving from southeast (Fig. 4).

An ejection of lava, volcanic ash and gases from the southeastern part of Etna volcano continues on December 30, 2013 (Volcano Discovery). The resulting models clearly show covering of all airspace of Bulgaria by the cloud of volcanic ash emitted from Etna volcano on December 31, 2013.

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Table 2: Daily concentration of CO_2 in the air, wind direction and wind speed for the period 17 December 2013 – 13 January 2014

** In Italic, bold, are the days with the extreme high CO_2 concentration*

Date	CO_2 (ppm)	Wind direction	Wind speed (m/s)
17.12.2013	***498.39***	***E-NE***	***10.09***
18.12.2013	*460.39*	*E-NE*	*9.93*
19.12.2013	***499.93***	***E-SE***	***4.54***
20.12.2013	***500.47***	***S-SE***	***2.50***
21.12.2013	***514.91***	***W-NW***	***3.07***
22.12.2013	***539.15***	***W-NW***	***2.72***
23.12.2013	*490.04*	*SW*	*3.32*
24.12.2013	*477.99*	*SW*	*8.94*
25.12.2013	*481.97*	*S-SW*	*4.14*
26.12.2013	*490.71*	*S*	*5.73*
27.12.2013	***499.45***	***S-SE***	***5.50***
28.12.2013	*461.59*	*E*	*3.37*
29.12.2013	***497.15***	***SE***	***4.98***
30.12.2013	***500.00***	***SW***	***2.24***
31.12.2013	***505.11***	***E-SE***	***1.40***
1.1.2014	***504.65***	***S-SE***	***3.05***
2.1.2014	*477.33*	*E-NE*	*2.23*
3.1.2014	***521.94***	***W-SW***	***4.10***
4.1.2014	***512.89***	***S-SE***	***4.66***
5.1.2014	*495.74*	*SW*	*6.75*
6.1.2014	***517.56***	***E-SE***	***3.52***
7.1.2014	*467.63*	*E-NE*	*5.37*
8.1.2014	***522.66***	***E-SE***	***3.52***
9.1.2014	***527.18***	***S-SW***	***4.18***
10.1.2014	***529.38***	***S-SW***	***5.55***
11.1.2014	***521.71***	***S-SW***	***5.98***
12.1.2014	*481.47*	*SE*	*5.13*
13.1.2014	***506.07***	***E-SE***	***4.88***

The CO_2 concentrations in the atmosphere at the region of "BEO Moussala" continued to rise and its daily average value reached 500.00 ppm. The prevailing wind is southwest and had a relatively low average speed of over 2 m/s (Table 2).

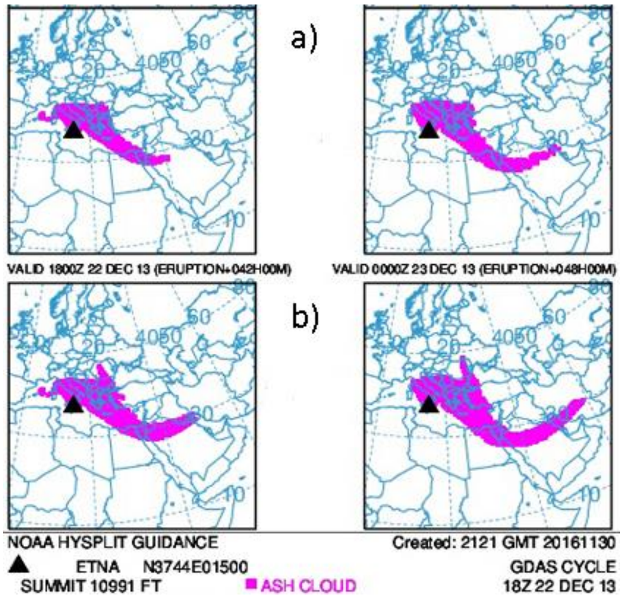

Fig. 3: Spread of volcanic ash from Etna volcano after eruption of December 22, 2013

a) at a height between the earth surface and 20,000 feet (6,096 m)
b) at a height between the earth surface and 55,000 feet (16,764 m)

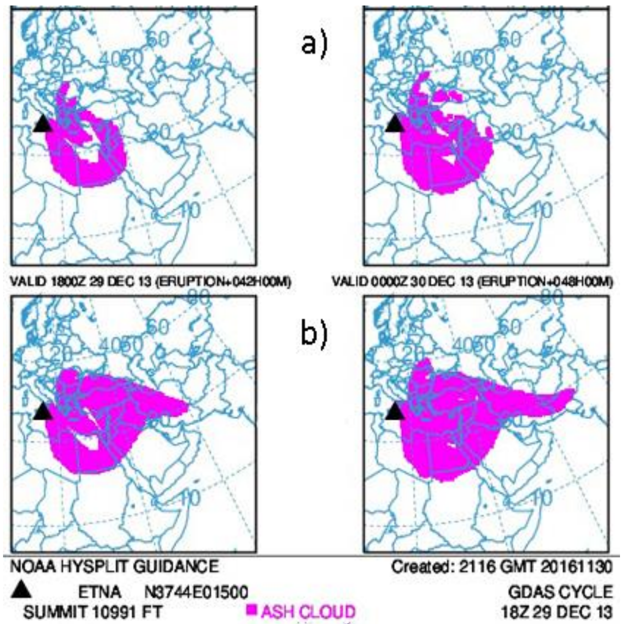

Fig. 4. Spread of volcanic ash from Etna volcano after eruption of December 28, 2013

a) at a height between the earth surface and 20,000 feet (6,096 m)
b) at a height between the earth surface and 55,000 feet (16,764 m)

In most cases, the days with extremely high concentrations of CO_2 in the atmosphere are not observed during the days of volcano activation, but some days later. The Volcano Discovery database shows that during the period comprised between 3 and 7 January, 2014 the activity of Etna volcano decreased, but on January 4, 2014, the wind direction had a southern component and high levels of CO_2 concentration in the air were established. This is probably a consequence of active ejection of volcanic ash and gases from the volcano in the previous days. The trace of the cloud of volcanic ash is described by the results of the model HYSPLIT (Fig. 5). The analysis of the model results allows us to assume that increased CO_2 concentration is associated with the spread of volcanic ash from eruptions of Etna volcano at the end of 2013 and at the beginning of 2014.

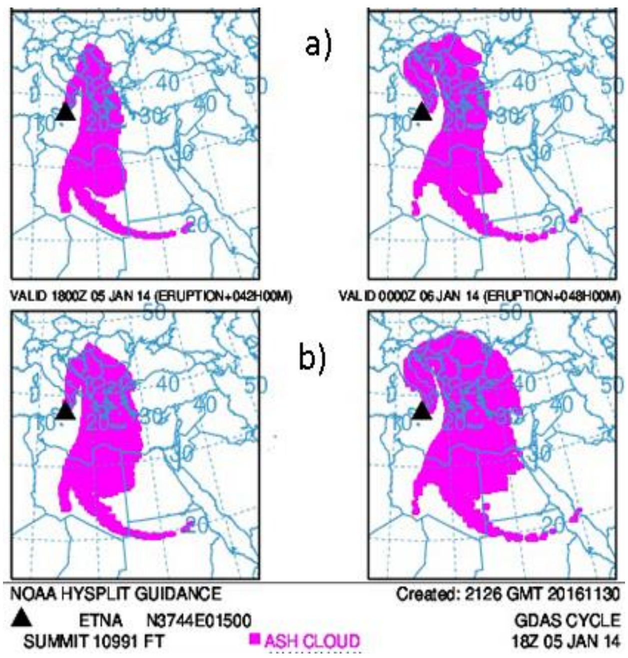

Fig. 5: Spread of volcanic ash from Etna volcano after eruption of January 4, 2014

a) at a height between the earth surface and 20,000 feet (6,096 m)
b) at a height between the earth surface and 55,000 feet (16,764 m)

The disposal of volcanic ash in the atmosphere from the northeast side of Etna continues on January 11, 2014 (Volcano Discovery). Volcanic ash is transported by the movement of air masses in the southeast and covers areas south of the territory of Bulgaria. The average daily CO_2 concentrations reported in the air were above 500 ppm. The wind speed was 5.98 m/s with the prevailing southwest direction (Table 2).

The analysis of large-scale circulation processes in the European region shows that during the days of Etna volcano activity and increased CO_2 concentration, the centers of low pressure are established in the region of northeastern Europe and Iceland, while Southern Europe is in an area of high pressure. According to the air pressure field, the main air transport is from southern Europe, including the area of Etna volcano to the Central or Eastern Europe through the territory of Bulgaria (Fig. 6).

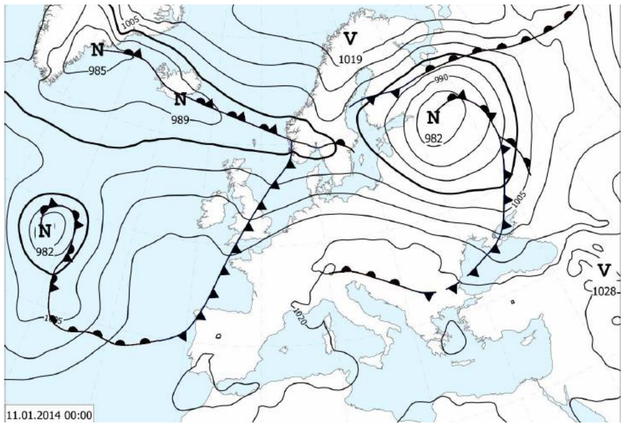

Fig. 6: Situation of air pressure centers in the European region on 11.01.2014. (*Source: Bulletin Meteorologia a Klimatologia, 2014*)

The location of air pressure centers in the atmosphere of the European region and determined by this factor transport of air masses confirm the role of activity of Etna volcano for the increased CO_2 concentrations in the atmosphere measured at the region of BEO Moussala, which reached extremely high levels.

In 15 cases of the above shown 18 days with extremely high concentrations of CO_2 the wind had a southern component and in 7 cases – a western component (Table 2). (The amount is more than the total number of days with extremely high concentrations, because in some of the days the wind had both southern and western components). It should be noted that the data about wind direction and speed given from the monitoring of BEO "Moussala" indicate the specific conditions in the region and considerably reflect local characteristics of the wind in relation to the nature of the relief. That is why there are other factors which contribute to the increasing CO_2 concentration in the studied period.

Conclusion

The data provided by BEO "Moussala", INRNE BAS, which are the basis of this study, show a rising trend in average monthly CO_2 concentrations in the air for the period comprised between 2007 and 2015, which is driven mainly by significant increases in 2013-2015.

The analysis of the results obtained from the database of BEO "Moussala" and NOAA HYSPLIT model clearly shows the influence of the natural factor (the eruption of Etna volcano) as a cause for the increasing CO_2 concentration in the atmosphere. For the period December 17, 2013 - January 13, 2014, 18 days with extreme high concentration of CO_2 are registered. In this period, Etna volcano emits volcanic gases and ash, a part of which are transported by the movement of air masses to the airspace of Bulgaria and an increasing in the concentration of CO_2 in the air at the BEO "Moussala" is registered.

The analysis shows that the activity of Etna volcano is not the only factor for the increased CO_2 concentration in the air. Regarding to this, more detailed analyses in this area would be made in subsequent studies.

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