Pre-earthquake chain processes detected from ground to satellite altitude in preparation of the 2016-2017 seismic sequence in Central Italy.

Dedalo Marchetti[1], Angelo De Santis[1,3], Serena D'Arcangelo[2], Federica Poggio[3], Alessandro Piscini[1], Saioa A. Campuzano[1], Vinicius Werneck[4]

(1) Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, Rome 00143, Italy

(2) Univ. Complutense de Madrid, Facultad Física, Avd. Complutense, s/n. – Madrid 28040, Spain

(3) Università Gabriele D'Annunzio – Chieti, Italy

(4) Observatório Nacional – Rio de Janeiro , Brazil

Corresponding Author: Angelo De Santis (angelo.desantis@ingv.it)

Abstract

This work is based on the retrospective analysis of several geophysical observations to search for possible lithosphere-atmosphere-ionosphere coupling effects in the preparatory phase of the central Italy seismic sequence 2016-2017. The major seismic events occurred on 24 August 2016 (Mw 6.0 Amatrice earthquake), 30 October 2016 (Norcia mainshock, Mw6.5) and on 18 January 2017 (four M5+ events close to Campotosto).

The work consists of a multi parametric approach over different observables from ground and space: the geomagnetic field (from satellites and observatories), atmospheric chemical / physical composition, with the comparison with other already published results from chemistry of groundwater and seismicity.

In particular, we investigated the vector magnetic data from INGV ground L'Aquila and Duronia magnetic Observatories and ESA Swarm three-satellite constellation. In addition, we searched for anomalies in physical/chemical composition of the atmosphere using MERRA-2 climatological dataset over central Italy before the start of the seismic sequence.

Two anomalous conditions anticipating the seismic sequence by about 275 and 85 days from geomagnetic Observatories and by about 240 days from satellite have been found. Furthermore, two highly perturbed periods in atmosphere chemical/physical composition that precede by 200 and 150 days the start of seismic sequence have been discovered.

A comparison with also other published papers' results to validate and integrate our findings is finally presented. We find a chain of some quasi synchronous anomalies and propose a global point of view demonstrating that the earthquake preparation phase affects the equilibrium of the Earth system producing anomalies from around a year in lithosphere, atmosphere and ionosphere.

1 – Introduction and seismological context.

From 24 August 2016, a very long seismic sequence has been hitting Central Italy Apennines. The first earthquake of the seismic sequence occurred at 01:36 UTC, with a magnitude Mw 6.0 at 8 km depth. The mainshock of the seismic sequence occurred on 30 October 2016 at 6:40 UTC, 5 km North-East from Norcia (Perugia, Italy). The Italian Institute of Geophysics and Volcanology (INGV) have localized more than 85000 events during the seismic sequence (from the 24 August 2016 until January 2018) with some aftershocks still under way. Unfortunately, the first earthquakes destroyed Amatrice, Accumoli and other smaller towns causing about 300 fatalities.

It is noted that from 1 January 2015 to just before the start of seismic sequence on 24 August 2016, no significant earthquake was recorded in central Italy (see Figure 1), so any typical seismological approach to cope with the problem of the precursors is not possible or rather difficult (see the quiescence found by Gentili et al. 2017). In this paper, we resort to the analysis of some other geophysical parameters in the same period of study.

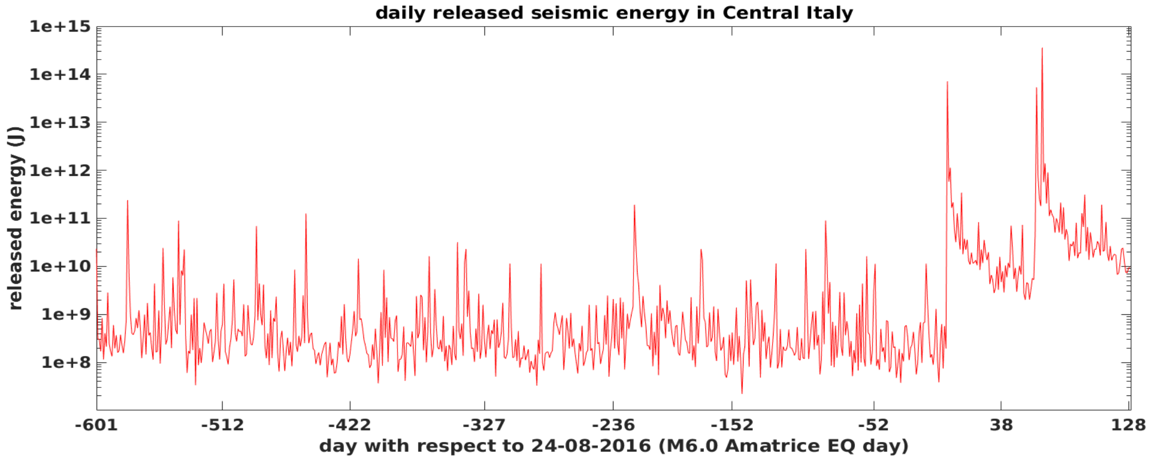

Figure 1 Daily released seismic energy in central Italy (41° N < latitude < 45°N and 11° E < longitude < 15° E) in 2015 and 2016

Some geochemical, seismic and atmospheric precursor "candidates" have been already published, respectively, by Barberio et al. (2017), Gentili et al. (2017), Piscini et al. (2017) and De Luca et al. (2018) about this seismic sequence and they will be taken deeply into account in this paper together with our new results.

The possible existence of seismic precursors has been analyzed extensively in the past (e.g. Cicerone et al. 2009). Unfortunately, no reliable working precursor has been yet discovered, although some seem of valuable consideration (e.g. Piscini et al. 2017). The current idea is to consider the earth-atmosphere and ionosphere system as a whole and therefore to privilege a multi-parametric approach to identify perturbations of the geophysical system rather than look for a single precursor (De Santis et al., 2015).

The idea that the atmosphere and the ionosphere can be altered during the preparation phase of important seismic events is supported by theoretical models that take the name of LAIC (Lithosphere Atmosphere Ionosphere Coupling). Different models were proposed by Freund (2011, 2013), Pulinets and Ouzounov (2011) and by Kuo et al. (2011, 2014) to theoretically explain LAIC effects.

In these models, a leading role is taken also by electric and magnetic precursors (e.g. Hattori 2004; Vallianatos et al. 2004). For this reason, in this paper we analyse several geophysical and atmospheric parameters, including magnetic field data from ground and satellite, for looking at potential pre-earthquake anomalies and a possible chain of precursory processes that can help us to understand the LAIC phenomenology and its possible evolution.

In the next section, we introduce the types of datasets and, then, the applied methods of analysis, together with the results. In the final section, we discuss the main results and propose some conclusions.

This work intends to be the ideal continuation and extension of another one (Marchetti et al. 2018), mainly dedicated to the satellite data analysis of magnetic field and electron density preceding the seismic sequence.

2 - Datasets

First, we analysed magnetic data from ground Observatories and European Space Agency (ESA) Swarm satellite constellation.

Ground magnetic data are acquired by two INGV observatories in L'Aquila and Duronia. L'Aquila geomagnetic observatory is located in 42.383° N, 13.317° E at 682 m above sea level (a.s.l). Duronia geomagnetic observatory is located in 41.650° N, 14.467° E at 918m a.s.l. Each observatory measures the geomagnetic field components X, Y and Z simultaneously by two independent triaxial fluxgate magnetometers and the total intensity of the magnetic field by an Overhauser scalar magnetometer (for more information about these observatories see:

http://roma2.rm.ingv.it/it/unita/1/osservatori_geomagnetici_e_rete_magnetica_nazionale).

In order to analyse magnetic field in ionosphere we have used the ESA Swarm satellite mission, which is monitoring the Earth's magnetic field since its launch on 22 November 2013. The Swarm mission is composed of two satellites, Alpha and Charlie, placed at a lower altitude of about 460 km and a higher orbit satellite (Bravo) at about 510 km above mean sea level. The three satellites are identical and they host on board the same instrumentation. In particular, in this work we focused on data provided by the Vector Field Magnetometer (VFM), a fluxgate three-component magnetometer with a Compact Spherical Coil magnetic field sensor. Data of this instrument are provided via FTP server (ftp://swarm-diss.eo.esa.int) in Level1B at two sampling frequencies: 50 Hz (HR, high resolution) and 1 Hz (LR, low resolution), in two reference systems: instrument frame and NEC (X North, Y East and Z Vertical) frame. For our purposes, we analysed the LR data in NEC frame.

To investigate the state of the atmosphere, we analysed MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2). MERRA-2 is a climatological model of atmospheric chemical composition developed by NASA (Gelaro et al. 2017). It contains an atmospheric model that starts on 1980 and it is updated in present time with one / two months of delay. The space resolution is 0.5 degrees in latitude and 0.625 degrees in longitude. The time resolution is one hour. Although MERRA-2 is a model, it is firmly based on real data and well represents the real state of the atmosphere.

From MERRA-2, M2T1NXAER version: 5.12.4 subset, we investigated in this paper TOTEXTTAU: the Aerosol Optical Thickness (AOT) [at a wavelength of 550 nm], DMSSMASS: the Dimethylsulphide Surface Mass Concentration in kg/m^3, and SO2CMASS: the SO_2 Column Mass Density in kg/m^2. We considered these atmospheric parameters since we could expect they would be affected by LAIC processes.

3 – Methods of data analysis

Different methods of data analysis have been used, according to the type of analyzed data. The various techniques are described below.

3.1 Ground magnetic data

The data of the Italian geomagnetic Observatories are available with sampling rate at minute and second. For this work, the highest resolution (1Hz) data have been considered in order to detect any short seismic electromagnetic signals. The analysis is based on the Observatories of L'Aquila and Duronia as the former is near the epicentral area (distance between Amatrice Mw6.0 EQ epicenter and L'Aquila Observatory: 36.6 km) and the latter, being farther, was taken as a reference (distance between Amatrice Mw6.0 EQ epicenter and Duronia Observatory: 178.2 km). The idea is to search for some uncorrelated signal between the two Observatories that could be produced by some mechanism during the preparation phase of the seismic sequence under investigation.

Correlation analysis is based on the estimation of the correlation coefficient r in a 20-minute moving window between the datasets of two Observatories (after a simple check of simultaneous availability of both data). Then only windows with the correlation coefficient less than a given threshold (e.g. $r \leq 0.3$) will be taken into account, because we expect that any electromagnetic emission, possibly produced in the epicentral area, would reach more easily L'Aquila than Duronia Observatory.

Similarly to the other methods, a graph with the cumulative number of uncorrelated windows was computed to look for possible significant increases before the start of the seismic sequence.

3.2 Satellite magnetic data

To analyse the Swarm satellite magnetic data we propose an alternative method to that described in De Santis et al. (2017). In this case, it is extended to two Swarm Satellites and applied to a very longer period before the start of seismic sequence: more than 600 days before 24 August 2016. The method consists in considering a couple of satellites, such as Alpha and Bravo, which have very different position over the globe. Then we looked at Alpha satellite selecting only those tracks that pass through the Dobrovolsky circular area, with radius as defined in Dobrovolsky et al. (1979). Then we make a correlation analysis between Alpha and Bravo satellite magnetic data, almost analogous with the previous one applied to the two Italian Observatories. The method then is extended to the other two satellites every time considering one far from the other, so we use Alpha for comparison of Bravo data and Bravo for Charlie Swarm satellite. The correlation was made excluding the polar regions: |geomagnetic latitude| ≤ 50 ° and avoiding disturbed times. In order to align in geomagnetic latitude both satellites, we considered the correlation between points at the same latitude and same track. Then we defined an anomaly in the first satellite when the absolute value of the correlation coefficient r was less than or equal to 0.01. In addition, a graph with the cumulative number of uncorrelated windows was computed, analogously with the previous ground Observatories analysis.

3.3 Atmospheric climatological data

The selected parameters (AOT, SO_2 and DMS) of MERRA-2 atmospheric chemical/physical model have been extracted in a square area with a side of 3 degrees (i.e. smaller than Dobrovolsky area) and centered on the epicenter of Norcia M6.5 30-Oct-2016 earthquake. The algorithm selected the data at local midnight (i.e. for Italy is 23 UTC) to avoid possible disturbance of solar irradiation over the day. For each day from 1980 the spatial average is computed. The historical time series is constructed excluding the years under investigation, so, for example, the mean value and standard deviation of all the first of January of 1980, 1981, … 2014 are computed in terms of the historical mean value and its variance for the specific day. If, in a year, a parameter has a too big value (i.e. greater than 10 times the standard deviation of the typical value for the studied region), it is excluded from the historical time series, and the statistics is recomputed.

The year under investigation is then superposed to the historical values and compared to the daily historical values plus or minus their 1.0, 1.5 and 2.0 standard deviations, σ.

4- Analysis results

Ground data from geomagnetic Observatories of L'Aquila and Duronia for 2015 and 2016 have been systematically analysed using the technique described in the previous section. We analysed these data using a moving window of 15 minutes and 20 minutes with thresholds in *r* correlation coefficient less than (or equal to) 0.1, 0.2, 0.3 and 0.5. By changing these parameters the results are consistent and do not vary substantially. Figure 2 shows the analysis with correlation coefficient |*r*|≤ 0.3 and a 20-minute moving window. The color of each dot identifies the geomagnetic conditions, defined using the geomagnetic indices Dst and a_p: green for quiet (|Dst| ≤ 10 nT and a_p ≤ 10 nT), orange for medium-quiet (10 nT <|Dst| ≤ 20 nT and a_p ≤ 10 nT) and red for geomagnetically disturbed conditions (|Dst| > 20 nT or a_p > 10 nT). On the same graph, some published anomalies from other papers are reported (details in the caption).

We analysed with particular attention the Y magnetic field component, since it is considered the geomagnetic component that is less affected by external magnetic disturbances (e.g. Pinheiro et al. 2011). In the Y component we note a significant increase of the number of anomalies around 275 days before the first strong earthquake. This period was properly checked in the original data to exclude any sort of problems in the acquisition system.

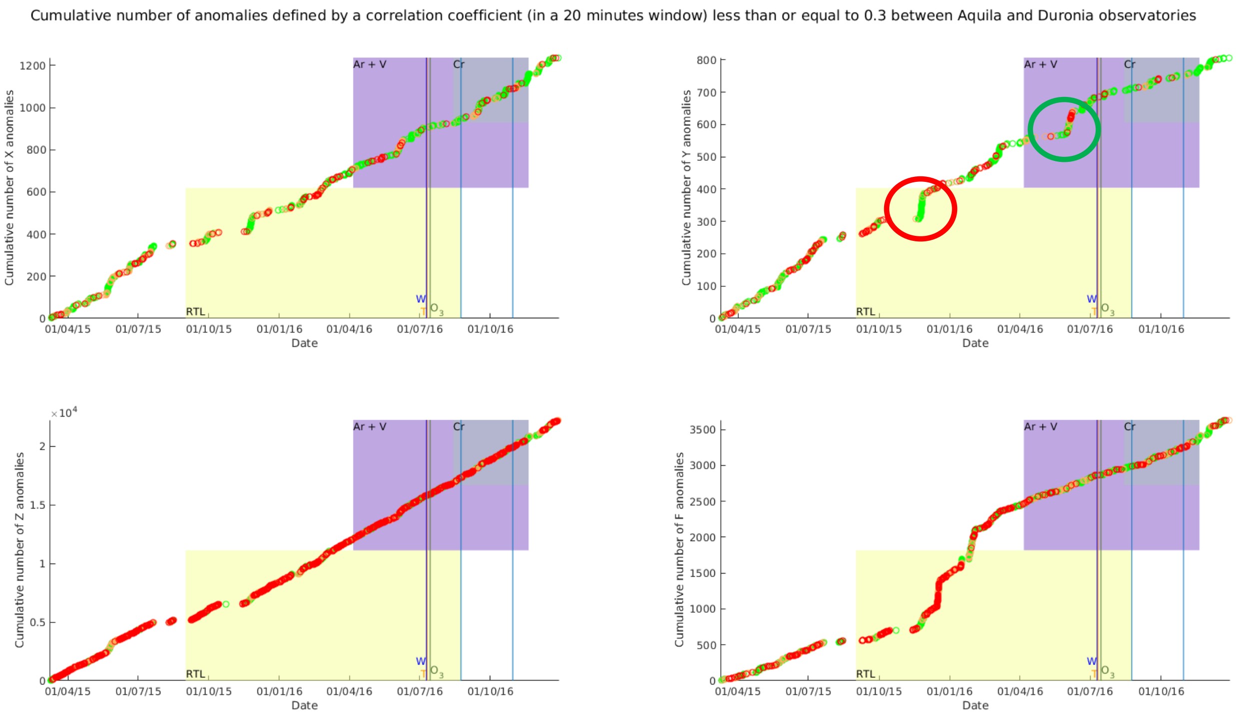

Figure 2 Cumulative number of ground magnetic anomalies in X, Y, Z and F for 2015 and 2016 defined as the 20-minute windows that have a correlation coefficient |r|≤ 0.3 between L'Aquila and Duronia observatories. The two blue lines are the time of occurrence of M6.0 Amatrice (24 August 2016) and M6.5 Norcia (30 October 2016) earthquakes. The color of each dot identifies the geomagnetic conditions: green for quiet (|Dst| ≤ 10 nT and a_p ≤ 10 nT), orange for medium-quiet (10 nT <|Dst| ≤ 20 nT and a_p ≤ 10 nT) and red for geomagnetically disturbed conditions ((|Dst| > 20 nT or a_p > 10 nT). Yellow time is the anomaly found by Gentili et al. 2017 in seismic quiescence. Purple and grey regions are the anomalous time for geochemical concentration (Arsenic Ar, Vanadium V and Chrome Cr), in water analyzed by Barberio et al. 2017 (notice that as the sample rate is about one sample for month a ±15 days of uncertainty is considered). The dark blue, orange and green lines are respectively the total column water vapour W, skin Temperature T and total column ozone O_3 anomalies found by Piscini et al. 2017. At about 275 days (Feb-March 2016) and 85 days before the first shock, there are two significant increases of anomalies in Y indicated by red and green circles in the plot.

Figure 3 shows the cumulative number of Swarm anomaly tracks in X,Y,Z components and F total intensity of satellite magnetic field in 2015 and 2016 inside Dobrovolsky area for M6.5 Norcia earthquake. The anomalies are defined by a correlation coefficient |r|≤0.01 between two far Swarm satellites magnetic data at the same geomagnetic latitude (but different time). The two blue lines are the time of occurrence of M6.0 Amatrice and M6.5 Norcia earthquake, respectively. At about 235 days (January 2016) before the first shock, there is a significant increasing of anomalies in Y.

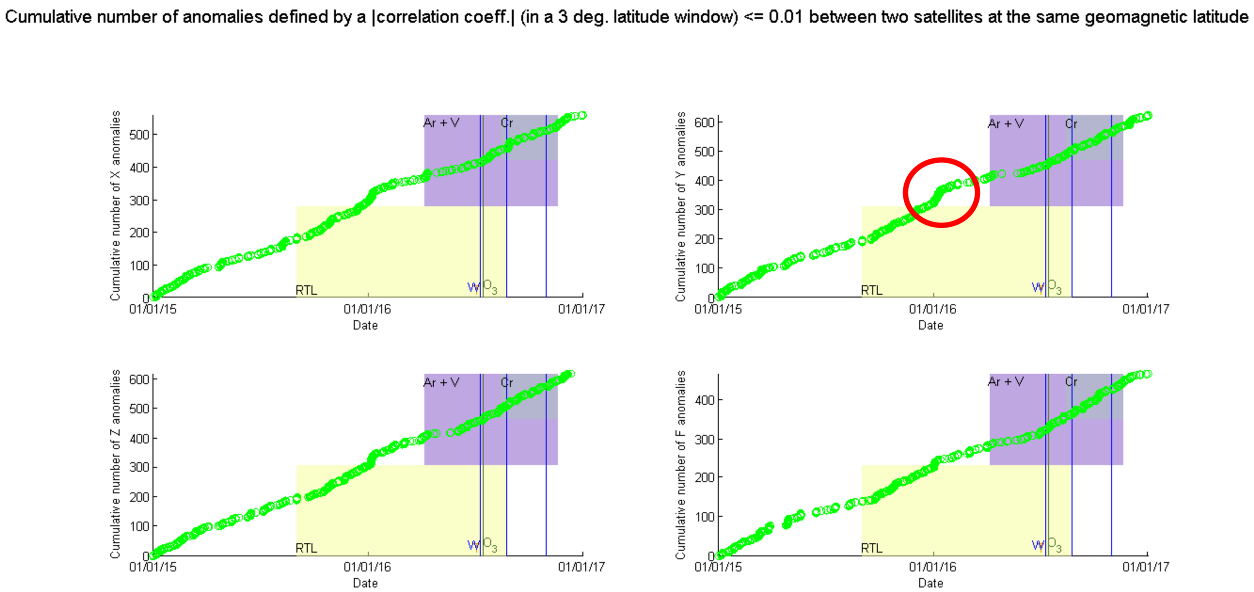

Figure 3 Cumulative number of Swarm anomaly tracks in X,Y,Z and F in 2015 and 2016 inside Dobrovolsky area for M6.5 Norcia earthquake. The anomalies are defined by a correlation coefficient |r|≤0.01 between Alpha and Bravo satellites magnetic data at the same latitude (but different time). The two blue lines are the time of occurrence of M6.0 Amatrice and M6.5 Norcia earthquake, respectively. At about 235 days (January 2016) before the first shock, there is a significant increasing of anomalies in Y indicated by a red circle in the plot.

Figure 4 shows the behavior of atmospheric Total Aerosol Thickness compared with the historical mean between 1980 and 2015 and the corresponding 1.0, 1.5 and 2.0 standard deviations. For each day, we computed the geographical mean inside a 3° width square area centred in Norcia M6.5 earthquake. Some years (1981-1989, 1991, 1992, 1994-1996, 1998, 1999, 2002-2004, 2013, and 2014) have been excluded automatically from the analysis because they presented too high values (that could be spurious values or due to other geophysical reasons). In the figure, a seasonal trend is presented and clearly visible, but this does not affect the result since the historical average and standard deviation of each parameter is estimated independently for each day.

It is particularly interesting that the most anomalous values occurred from around 150 to 110 days before the earthquake occurrence, with a value of AOT highly above two standard deviations of the historical mean.

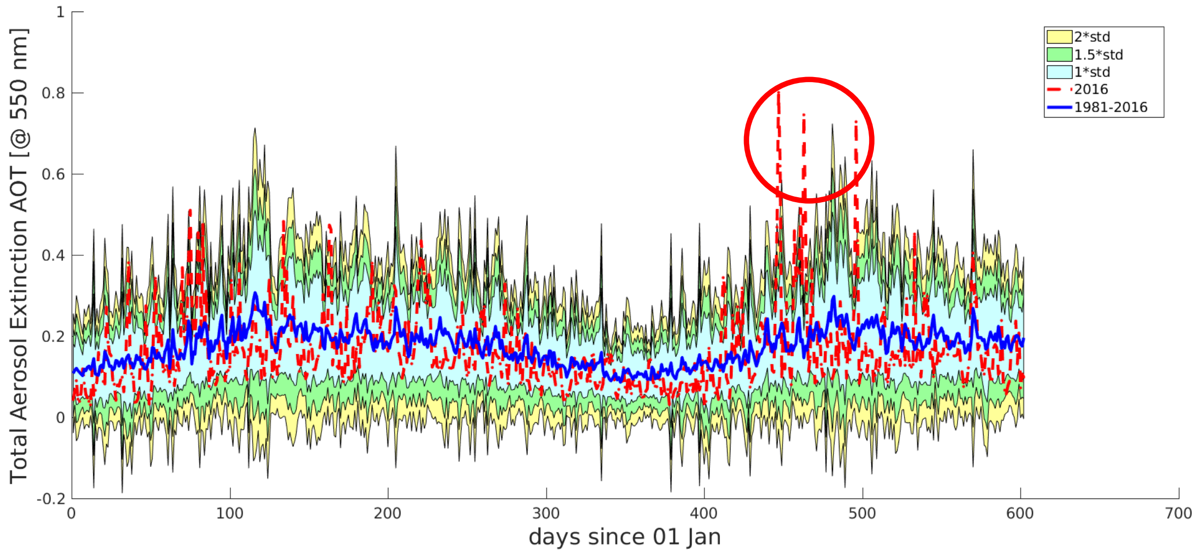

Figure 4 Climatological analysis for the Total Aerosol Thickness in atmosphere considering a rectangular area large 11° latitude by 11° longitude centred on Norcia M6.5 earthquake. Blue line is the historical mean, light blue, green and yellow b ands are 1.0, 1.5 and 2.0 standard deviations, respectively. Red dashed line is the AOT values from 1 January 2015 until 24 August 2016. From 150 and 110 days (May 2016) before the first major shock, there are three significant increasings of anomalies indicated by a red circle in the plot.

The results given by DMS and SO_2 parameters are analogous to those obtained by AOT. They all will be considered together by applying the procedure detailed below.

In order to compare each other the above different atmospheric (AOT, DMS and SO_2) parameters, the value in σ exceeding the chosen threshold has been extracted. Therefore, the quantity *G* has been calculated for the days that exceed two standard deviations:

$$G(d) = \frac{P_y(d) - (P_h(d) + 2 \cdot \sigma_{P_h(d)})}{\sigma_{P_h(d)}}$$

Where $P_y(d)$ is the value of the geochemical parameter for the y year under investigation, $P_h(d)$ is the historical mean and $\sigma_{P_h(d)}$ is its standard deviation, for a given day *d*.

Cumulating the number of the anomalous (i.e. positive) *G*(*d*) for SO_2, DMS and AOT in atmosphere, we obtain the graph of Figure 5. It is possible to see a clear increment of the trend at 420 days (red circle) and at 470 days (green circle) after 1 January 2015, that correspond respectively to about 200 and 150 days before the M6.0 24 August 2016 earthquake.

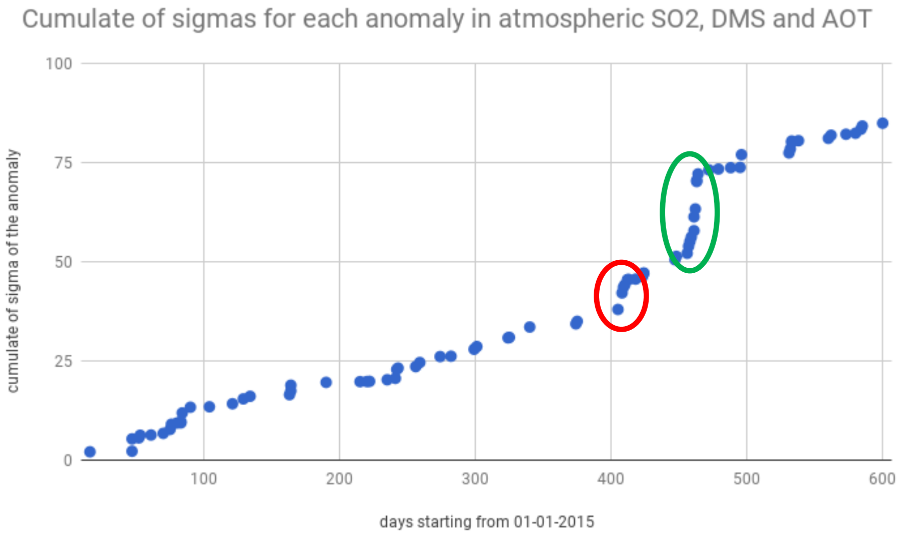

Figure 5 Cumulative number of the sigma values of anomalies in atmospheric SO_2, DMS and AOT. All days are counted from 1 January 2015. The day of M6.0 Amatrice earthquake is 602. At about 200 and 150 days (April 2016) before the first major shock, there are two significant increasings of anomalies, indicated by red and green circles in the plot.

5 – Discussion and Conclusions

Comparing the different analyses carried out in this work and comparing them with other already published works, we find a synergy, a coherence and a convergence towards the Amatrice-Norcia 2016-2017 seismic sequence starting.

Figure 6 reports a summary of all detected anomalies compared with the works of Gentili et al. 2017, Barberio et al. 2017, Piscini et al. 2017 and De Luca et al. 2018. Analyzing about two years of data (starting from January 2015), the first anomaly is found at about one year before the first major earthquake, when the seismic quiescence starts (Gentili et al. 2017). Right after around 4 months, the ground and satellite magnetic anomalies are found. We notice a little delay of around 1 month between ground and satellite anomaly increases, so supporting some slow diffusion process instead of electromagnetic wave propagation.

After this, a first increment of anomalies in chemical composition of atmosphere is detected about 200 days before the Amatrice earthquake. A second is more conspicuous and precedes the earthquake by 150 days. This latter increment of anomalies in atmospheric SO_2, DMS and AOT occurs in April 2016; it coincides with the start of the increase of Arsenic and Vanadium in groundwater as published by Barberio et al. (2017). In addition, Chrome element starts to increase in April, but its value is significantly greater only in the samples acquired between the M6.0 Amatrice earthquake and M6.5 mainshock. The great difference between the analysis of geochemical concentrations in the water wells and those of chemical concentrations in the atmosphere is the persistence of the anomalous concentration. Concerning the anomalous concentration in atmosphere presented in this paper, they persist only for few days, while the anomalous concentrations in water wells persist for some months until the mainshock. The much shorter persistence in atmosphere could be due to the weathering phenomena that could move and mix the substances released from underground into the atmosphere.

The time-closest precursory anomalies in the studied parameters are the geomagnetic anomalous behavior in Observatories about 85 days before the beginning of seismic sequence and the ground/atmospheric climatological anomalies in skin temperature, total column water vapour and total column ozone about 40 days before the start of seismic sequence (Piscini et al. 2017). Please note that a recent work (De Luca et al. 2018) found some anomalies in hydraulic pressure and electrical conductivity in Gran Sasso borehole, which are practically contemporary to the skin temperature, total column water vapour and total column ozone anomalies, starting about 40 days before the M6.0 Amatrice earthquake (and also another most evident five days before the M6.0).

The picture of the phenomenon that emerges from the all above resulting anomalies is that the earthquake preparation phase evolves with different stages, some still confined in the lithosphere, others in the above atmosphere. First, it starts with some anomalous seismic behavior (quiescence), then, according to LAIC models (Freund 2011, Pulinets and Ouzounov 2011), there is the release of some electric charges or radon that changes the conductivity of the bottom of atmosphere, and perturbs first the magnetic field at the surface and then the state of the ionosphere. After a while, some changes occur in the physical properties of the lower atmosphere and in the underground water and/or rocks, with different times of persistence, depending on the heterogeneous interactions with the surrounding environment.

Panza et al. (2017) highlight the particular motion of two plates along a transept that passes from Amatrice with a clear difference in velocity pattern comparing the region before and after the first major earthquake. This only information alone does not provide a "precise" timing of the earthquake, but it could be very important if it is compared to the other precursory anomalies for a future earthquake forecast platform.

We think that the detection of a chain of quasi-synchronous perturbations from very different points of view (seismological, satellite, atmospheric and underground in-situ measurements) is very important and a confirmation of a possible perturbation due to the preparation phase of the seismic sequence that let lithosphere coupling with the above neutral and charged atmosphere.

Our work confirms the great advantage to combine a multi parametric study from different points of view. It also confirms that the preparation of the earthquake produces a chain of processes, involving a complex system composed of lithosphere, atmosphere and ionosphere and culminating with the major earthquakes, in what is called "the synergy of earthquake precursors" by Pulinets (2011). Therefore, our results would support the idea that the larger earthquakes are the final product of a critical process mechanism (De Santis et al. 2015, 2017).

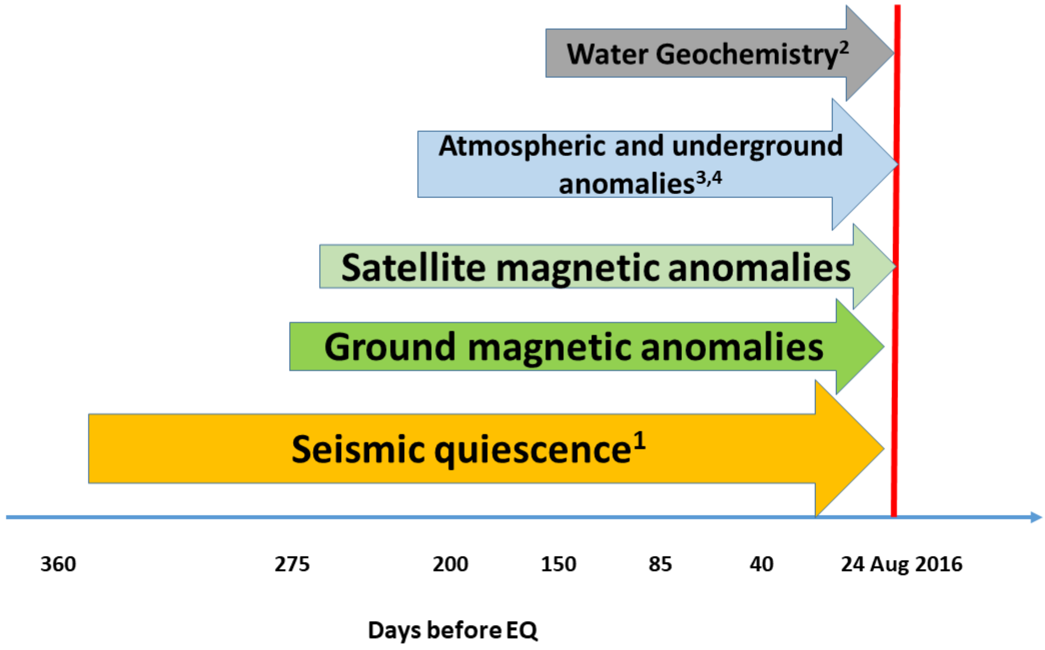

Figure 6. Resume of all anomalies and comparison with some other published works (1- Gentili et al. 2017, 2- Barberio et al. 2017, 3- Piscini et al. 2017, 4- De Luca et al. 2018). The vertical red line is the occurrence of the 24 August 2018 Amatrice earthquake, the first major shock of the seismic sequence.

Acknowledgements

This work was undertaken in the framework of the ESA-funded project SAFE (Swarm for Earthquake study), and under the LIMADOU-Science project, funded by the Italian Space Agency (ASI).

References

Barberio, M. D., Barbieri, M., Billi, A., Doglioni, C., Petitta, M. (2017). Hydrogeochemical changes before and during the 2016 Amatrice-Norcia seismic sequence (central Italy). Scientific Reports, 7, 11735. doi:10.1038/s41598-017-11990-8.

Cicerone, R.D., Ebel, J.E., Britton, J. (2009). A systematic compilation of earthquake precursors. Tectonophysics 476, 371–396.

De Luca G., Di Carlo G., Tallini, M. (2018). A record of changes in the Gran Sasso groundwater before, during and after the 2016 Amatrice earthquake, central Italy. Scientific Report, 8, 15982. https://doi.org/10.1038/s41598-018-34444-1

De Santis A., De Franceschi, G., Spogli, L., Perrone, L., Alfonsi, L. Qamili, E., Cianchini, G, Salvi S., Filippi E., Pavón-Carrasco F.J., Monna S., Piscini A., Battiston R., Vitale V., Picozza P.G., Conti L., Parrot M., Tao D. (2015). Geospace perturbations induced by the Earth: the state of the art and future trends, Phys. & Chem. Earth, 85-86, 17-33.

De Santis, A., Balasis, G., Pavon-Carrasco, F. J., Cianchini, G., and Mandea M. (2017). Potential earthquake precursory pattern from space: The 2015 Nepal event as seen by magnetic Swarm satellites. Earth and Planetary Science Letters, 461, 119-126.

Dobrovolsky, I.P., Zubkov, S.I. & Miachkin, V.I. (1979). Estimation of the Size of Earthquake Preparation Zones. *PAGEOPH*, 117: 1025. doi:10.1007/BF00876083

Freund F. (2011). Pre-earthquake signals: Underlying physical processes, Journal of Asian Earth Sciences, 383–400

Freund F. (2013). Earthquake Forewarning – A multidisciplinary Challenge from the Ground up to Space, Acta Geophysica, 61, 4, 775–807 DOI: 10.2478/s11600-013-0130-4

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L, Randles, C. A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S.D.c, Sienkiewicz, M., Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), American Meteorological Society - Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) special collection.

Gentili S., Di Giovambattista, R., Peresan, A. (2017). Seismic quiescence preceding the 2016 central Italy earthquakes. Physics of the Earth and Planetary Interiors, 272, 27-33, Doi:10.1016/j.pepi.2017.09.004

Hattori K. (2004). ULF geomagnetic changes associated with large earthquakes, TAO, 15, No.3, 329-360.

Kuo, C. L., Huba, J. D. Joyce, G. and Lee L. C. (2011), Ionosphere plasma bubbles and density variations induced by pre-earthquake rock currents and associated surface charges, J. Geophys. Res., 116, A10317, doi:10.1029/2011ja016628.

Kuo, C. L., Lee, L. C. and Huba. J.D. (2014). An improved coupling model for the lithosphere-atmosphere-ionosphere system. J. Geophys. Res. Space Physics, 119, 3189-3205, DOI: 10.1002/2013JA019392

Marchetti D., De Santis A., D'Arcangelo S., Poggio F., Jin S., Piscini A. and Arquero-Campuzano S. (2018). Magnetic field and electron density anomalies from Swarm satellites preceding the major earthquakes of the 2016-2017 Amatrice-Norcia (Central Italy) seismic sequence, Pure and Applied Geoph., submitted.

Panza, G.F., Peresan, A., Sansò, F. et al. (2017). How geodesy can contribute to the understanding and prediction of earthquakes, Rend. Fis. Acc. Lincei, pp. 13. https://doi.org/10.1007/s12210-017-0626-y

Pinheiro, K. J., A. Jackson, and C. C. Finlay (2011). Measurements and uncertainties of the occurrence time of the 1969, 1978, 1991, and 1999 geomagnetic jerks, *Geochem. Geophys. Geosyst.*, 12, Q10015, doi:10.1029/2011GC003706.

Piscini A., De Santis A., Marchetti D. and Cianchini G., (2017). A multi-parametric climatological approach to study the 2016 Amatrice-Norcia (Central Italy) earthquake preparatory phase, *Pure appl. Geophys.*, 174, 10, 3673-3688.

Pulinets S., (2011). The synergy of earthquake precursors, Earthquake Science 24(6):535-548.

Pulinets S, Ouzounov, D. (2011). Lithosphere‐Atmosphere‐ ionosphere coupling (LAIC) model‐an unified concept for earthquake precursors validation, J. Asian Earth Sci, 41(4–5):371–382.

Vallianatos F., Triantis D., Tzanis A., Anastasiadis C., Stavrakas I. (2004). Electric earthquake precursors: from laboratory results to field observations, Phys. & Chem. Earth, 29, 339-351.