A Multiparametric Investigation of an Earthquake by a Jupyter Notebook: the Case Study of the Amatrice-Norcia Italian Seismic Sequence 2016-2017

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Abstract. We present a Virtual Research Environment (VRE), developed in the form of a Jupyter Notebook, devoted to a multidisciplinary and multiparametric analysis of an earthquake. In particular, the VRE retrieves and analyses lithospheric, atmospheric and ionospheric parameters from various sources. Among them, we selected the Open Data of the European Plate Observing System (EPOS) for the earthquake catalogue, integrated with the atmospheric climatological archive MERRA-2 provided by NASA, and the satellite magnetic data of the Swarm mission produced by ESA. The open-source code and friendly environment of Jupyter Notebook allow future users to personalise the research parameters (e.g., investigated time, area of interest) and apply the same VRE to other earthquakes. The VRE is designed for the 2016 seismic sequence that affected Central Italy, characterised by the Mw = 6.0 earthquake near Accumoli and Amatrice on August 24, 2016, and the Mw = 6.5 earthquake near Norcia on October 30, 2016. The Jupyter Notebook performs: 1) seismological investigations such as the calculus of cumulated Benioff strain and released energy weighted for the distance of the target event; 2) extraction of typical atmospheric values and identification of possible anomalies and 3) searching for small oscillations of magnetic field not likely related to geomagnetic activity. Finally, a graphical comparison of all the investigations is provided to search for possible interactions among the different geo-layers. In the context of studying the preparation phase of the 2016-2017 Italian Seismic Sequence, we provide a tool for exploiting and integrating multiparametric EPOS data with other datasets.

Keywords: Jupyter Notebook; lithosphere; atmosphere; ionosphere; pre-earthquake signals.

1 Introduction

Here, we introduce the European Plate Observing System (EPOS), the Jupyter notebook, and the Italian Amatrice-Norcia 2016-2017 seismic sequence, as well as multiparametric studies of the preparation phase of the earthquake, investigating possible lithosphere-atmosphere-ionospheric anomalies.

1.1 EPOS and Jupyter Notebooks

The European Plate Observing System (EPOS ERIC) was conceived in 1997 as a European Research Infrastructure Consortium (ERIC) [1] in order to provide a research infrastructure in Solid Earth Sciences at the pan-European level. EPOS is in continuous evolution and already hit several milestones: in 2015, it started the implementation phase; in 2018, EPOS-ERIC was established; in 2020, it started the Pilot Operational Phase, and it became completely operational in 2023. One of the most important tools provided by EPOS is the Data Portal (https://www.epos-eu.org/dataportal), which is a multiparametric platform collecting datasets from multiple sources [2].

The Data Portal is populated by several services managed by Thematic Core Services (TCS) communities. The data are linked and not copied to EPOS after homogenisation and quality check through metadata harmonisation to facilitate the development of multidisciplinary studies and also the final user that can access from a common interface. Ten TCS communities representing specific disciplines are present nowadays in EPOS Data Portal: Seismology [3], Near-Fault Observatories [4], GNSS Data and Products [5], Volcano Observations [6], Satellite Data [7], Geomagnetic Observations [8], Anthropogenic Hazards [9], Geological Information and Modelling [10], Multi-Scale Laboratories [11], and Tsunami [12].

The integration of more than 300 interoperable multidisciplinary services in the EPOS central hub system is based on a microservice-based architecture [13]. EPOS Data Portal is distributed under a GPL license as open-source software (https://epos-eu.github.io/epos-open-source/) and complies with the FAIR Principles [14], encouraging interdisciplinary cooperation and technological development in Earth sciences and beyond. Considering the intrinsic multidisciplinary and multiparametric nature of the research on the preparation phase of the earthquakes in the view of Lithosphere Atmosphere and Ionosphere Coupling [15], the EPOS infrastructure can provide crucial support to implement and improve these analyses.

We used a Jupyter Notebook to implement and share our Virtual Research Environment (VRE). Jupyter Notebook was developed a few years ago to provide an easy way to share code among different researchers and communities, being executable, including results and explanations [16]. Jupyter Notebook generally uses a Python kernel, but also others are available and integrable. For example, we first developed the VRE in Matlab code, and a version in Python is under development.

1.2 Italian Amatrice-Norcia 2016-2017 Seismic Sequence

On 24 August 2016 at 1:33 Universal Time (UT), an earthquake of moment magnitude Mw = 6.0 hit Central Italy close to the towns of Accumoli and Amatrice. Furthermore, a very long seismic sequence started, and a larger event occurred after more than two months, on 30 October 2016, close to the town of Norcia. The location of the seismic sequence was in the Central Apennine chain, which is mainly characterized by an extensional tectonic setting. The mainshock was the largest magnitude event in Italy in the previous thirty-five years, following the Irpinia earthquake in 1980 [17].

Several studies have been done in order to study the preparation phase of the Italian seismic sequence 2016-2017. Piscini et al. [18] investigated three atmospheric parameters: skin temperature, total column water vapour and total column ozone. They were retrieved from the European Center for Medium-range Weather Forecast (ECMWF) from different datasets: ERA-Interim, a climatological archive and an operational Integrated Forecasting System (IFS). The climatological archive data provided historical trends starting from 1979 with Worldwide coverage, while the operational one delivered updated data every three hours. The authors identified a sequence of atmospheric anomalies that started with water vapour and skin temperature followed in a few days by an increase of Ozone in Central Italy preceding about 40 days the start of the seismic sequence. Marchetti et al. [19] analysed the ionospheric magnetic field, identifying interesting anomalous tracks about 3.5 days before the two larger shocks in Central Italy (Amatrice and Norcia events). Fidani et al. [20] installed several electromagnetic ground observatories in Central Italy, and they identified possible anomalous electrical and magnetic field signals on the ground possibly related to the 2016 seismic sequence. The analysis of the variations of the permanent GNSS positions provided useful indications to understand possible anomalous tectonic movements before the earthquake, as reported by Panza et al. [21]. Finally, a chain of lithospheric, atmospheric and ionospheric anomalies was proposed by Marchetti et al. [22], suggesting that they could be induced by the accumulation of stress in preparation for the 2016 seismic sequence of central Italy.

1.3 The Possible Lithosphere Atmosphere Ionosphere Coupling before the Earthquake Occurrence

The possible Lithosphere Atmosphere Ionosphere Coupling (LAIC) before the earthquake occurrence was proposed about 30 years ago [23]. It aims to explain several phenomena recorded before the earthquake occurrence, especially the electromagnetic signals. Several authors recorded anomalous geomagnetic field signals or electromagnetic variations of the bottom layer of the ionosphere in preparation for earthquakes in the USA, Indonesia, Japan and other countries [24–26]. However, recording an anomaly before an earthquake does not necessarily imply a causal-effect relationship. It's necessary to provide some more pieces of evidence and a theory that may explain how the accumulation of stress in a fault with an impending earthquake can generate anomalies. The topic is so controversial that there is still no definitive conclusion [27]. Nevertheless, understanding that some phenomena would be linked to the preparation phase of an earthquake does not mean that we are able to predict such an earthquake. So, the present research is devoted to finding signals possibly related to the preparation phase of earthquakes but not to predict them directly. In principle, this could seem a contradiction, but it can be considered a step necessary but not sufficient for the prediction of an earthquake. As an example, a sign of the accumulation of stress on a fault could underline the activity and even nucleation of an earthquake but not provide information about the incoming time, so not finally, a prediction which requires defining at least position, time, magnitude, percentage of confidence to be scientific reliable [28].

Several theories have been proposed to explain the detected phenomena before the earthquakes and, more in general, the possible LAIC. A milestone theory is the one called "dilatancy" proposed by Scholz [29] in the early seventies. He proposed that the preparation phase of an earthquake is composed of different phases, and their duration is proportional (in logarithm scale) identification to the magnitude of the incoming event. The latter hypothesis was also empirically identified in different types of pre-earthquake signals by Japanese seismologist Rikitake [30]. Recently, such a relationship between the anticipation time and magnitude of the incoming earthquake was confirmed even for magnetic anomalies detected by the satellite constellation Swarm [31, 32]. The different stages of preparation for an earthquake can be identified by noticing variations of seismological parameters (e.g., the ratio Vp/Vs of the primary over the secondary speed of seismic waves), followed by underground fluid movements and reduction of electrical resistivity of the crust. The underground fluid movements could transport trace gases on Earth's surface as radon [33]. The radon introduced in the atmosphere decays, and the alpha-radiative particles can ionise atmospheric molecules, producing alterations in atmospheric and even ionospheric electric fields. In addition, the accumulation of charges in the atmosphere may induce a chain of phenomena, such as the hydration of aggregation molecules, increase of aerosol, drop of relative humidity and emission of outgoing longwave radiation [34, 35]. Other theories proposed a more direct mechanism for the generation of electromagnetic anomalies, such as the one by Molchan and Hayakawa [36], based on the separation of charges at fault level due to stress increase. An innovative theory was proposed by Freund [37, 38]. He proposed that the stress increase can break some peroxy-links of the minerals in the rocks at the fault level, releasing positive charges called p-holes. The p-holes could accumulate on the Earth's surface and induce electrical anomalies in the atmosphere and ionosphere as modelled (analytically and numerically) by Kuo et al. [39]. They showed that electron density anomalies could propagate up to about 2000 km altitude from the accumulation of electrical charges on Earth's surface. However, other authors argued some mistakes [40] in the simulation regarding the electrical conductivity of the atmosphere. A response from the original authors was provided, showing that the results in the ionosphere can also be confirmed with the suggested correction [41]. Nonetheless, the contrast underlines a difficult conclusion on the topic. A recent Special Issue on this topic is available as Open Source in [42].

2 Data

The Virtual Research Environment (VRE) was developed in the form of a Jupyter Notebook. The general idea is shown in Fig. 1. The VRE collects data from different sources, elaborates the data, and, whenever possible, integrates them together. A list of the data and analysed parameters is reported in Table 1 and a specific description of them is provided in the following subsections.

Table 1. List of the analysed datasets and parameters.

Geo-layer	Dataset	Parameters	Type of analysis
	EMSC-CSEM	Earthquake catalogue	• Time series of number of events

	(by EPOS)		• Cumulative Benioff stress • ES (Energy weighted for distance)
Litho-sphere	SGO-EPND (by EPOS)	GNSS Weekly Positions Time series	• Time series of variations along transects • Maps of rate of positions drift
Atmos-phere	MERRA-2 (by NASA)	Surface Air Temperature SO_2 Dimethyl Sulphide Aerosol Optical Thickness CO Surface Latent Heat Flux Relative Humidity	• Historical time series (1980-2024) characterization compared with the year of the earthquake
Iono-sphere	Swarm satel-lites (by ESA)	East component of the magnetic field measurement	• Selection of data above epicentral area and track detrending to analyses residuals.

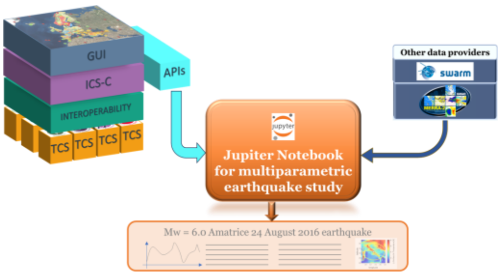

Fig. 1. Sketch of the VRE. The core of the VRE is the Jupiter Notebook. It retrieves most data (e.g., the earthquake catalogue) from the EPOS platform via APIs and integrates it with other external data sources, such as Swarm satellite geomagnetic data. It provides an output report with information on the Italian Seismic sequence 2016, graphs, and analyses of the retrieved data.

2.1 Datasets for Lithosphere Atmosphere and Ionosphere

In order to investigate the lithosphere, the earthquake catalogue and the GNSS positions were selected. For the earthquake catalogue, we selected the EPOS "Parameters of modern earthquakes (1998-present) - FDSN event" provided by Thematic Core Service (TCS) Seismology of EPOS Data Portal [3]. This earthquake catalogue ingests several data providers contributing to the European Mediterranean Seismological Centre (EMSC-CSEM). INGV (Italian National Institute of Geophysics and Volcanology) is the data provider for the Italian territory (i.e., the area of this study). Consequently, the earthquake catalogue analysed in this case study was originally created by INGV, and it's also available in the ISIDE repository [43]. However, the advantage of downloading from EPOS infrastructure is that the same research environment can be easily applied to any other earthquake in Europe and the Mediterranean area.

The area of research is the Dobrovolsky's circle defined by its radius "R_{Dob}":

$$R_{Dob}\,[km] = 10^{(0.43 \times M)} \tag{1}$$

where “M” is the earthquake's magnitude (preferably moment magnitude). This area was proposed by Dobrovolsky [44] as the one where we can expect to record signs of the seismic event preparation. The earthquake catalogue was downloaded in a larger area (a square with a side length of 2 times R_{Dob} + 10° for latitude and longitude, as visible in Fig. 2. Nevertheless, the following analyses will select only the events inside Dobrovolsky’s circular area.

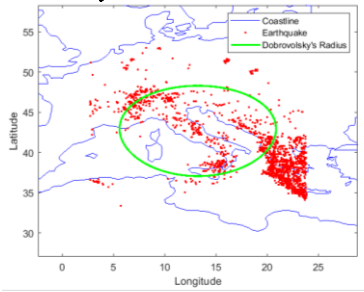

Fig. 2 Maps of the downloaded seismic events from the EPOS earthquake catalogue in the 8 months before the start of the Amatrice-Norcia Italian seismic sequence 2016-2017.

With regards to the Global Navigation Satellite System (GNSS) network, this VRE automatically makes two calls to the EPOS Data Platform: the first one is to retrieve the list of the stations in the area of interest, while the second one is to download the time series of GNSS positions. The data are provided by the TCS-GNSS of EPOS [5]. The area of interest of GNSS data analysis was reduced with respect to the full Dobrovoslky’s area, as we expect the tectonic deformations closer to the incoming seismic event and not in other tectonic systems. Consequently, the square inscribed into Dobrovolsky’s circle was the research area for GNSS data. The map of the available GNSS stations is shown in Fig. 3.

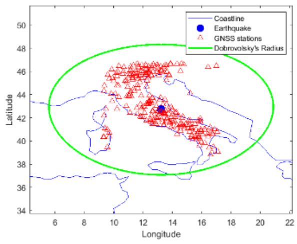

Fig. 3 Map of the GNSS stations available in the EPOS network within the research area (square inscribed in Dobrovolsky's circle).

The weekly time series were retrieved for the selected GNSS stations, and further selection was made for the specific investigation. In fact, the analysis has been conducted on each couple of stations whose direction is along a transect of the fault of the target earthquake (in this case, Amatrice/Norcia) or using all the stations at a certain time and calculating the rate of variation of the three components (North-East-Up) from one measurement to the next one.

The geo-layer of the atmosphere was investigated using the data from the climatological archive Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) provided by NASA [45]. It contains an estimation of several physical and chemical atmospheric parameters from 1980 to the present on a regular grid in space and time. The resolution is 0.5° latitude, 0.625° longitude and 1 hour in time. It is updated monthly, and it ingests data from ground, airborne, and satellite sources. Then, it fits over a physical/empirical atmospheric model. Data are open with a free account in the EarthData portal. Here, we retrieved seven parameters: Surface Air Temperature, Sulphur Dioxide (SO_2), Dimethyl Sulphide (DMS), Aerosol Optical Thickness (AOT), Carbon Monoxide (CO), Surface Latent Heat Flux (SLHF) and Relative Humidity (RH).

The ionosphere was studied by analysing the European Space Agency (ESA) magnetic data recorded by the three-identical satellite mission Swarm. It's the state-of-the-art monitoring of the Earth's magnetic field from space. It's been in orbit since November 2013 [46]. ESA provides the data openly by dissemination server (swarm-diss.eo.esa.int) by https browser or ftp with EarthObservation ESA free credentials. The data are organised in daily files, which contain all orbits with a resolution of 1 Hz (Low Rate) that we selected for this work (50 Hz is also available).

3 Methods and Results

The above dataset has been analysed by a general workflow illustrated in Fig. 4 and described in the following lines. The description is divided in:

3.1. Lithosphere – investigation of the earthquake catalogue
3.2. Lithosphere – investigation of the GNSS position data
3.3. Atmosphere – investigation of the climatological data
3.4. Ionosphere – investigation of the satellite magnetic data
3.5. Summary view

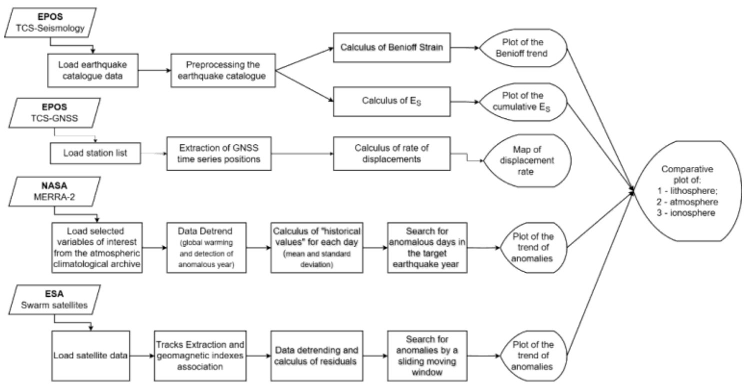

Fig. 4 Workflow of the developed VRE to study the lithosphere, atmosphere and ionosphere with a multiparametric and multidisciplinary study.

3.1 Lithosphere – Earthquake Catalogue Investigation

The earthquake catalogue was first filtered for several constraints: minimum earthquake magnitude, maximum hypocentral depth and distance from the target earthquake epicentre. The selection of these constraints applied to the seismic catalogue is based on seismological settings. In particular, the minimum magnitude is the "Completeness magnitude" (Mc) of the earthquake catalogue, i.e., the minimum magnitude that is surely detected. Events of lower magnitude can be present in the catalogue (for example, shallow earthquakes close to a seismic station), but not all earthquakes of that magnitude [47]. The maximum distance is set to Dobrovolsky's radius. The maximum depth was fixed at 50 km, according to previous studies [32].

Using the selected events, the Benioff cumulative strain was computed according to the original formulation [48]. Firstly, for each (i-th) seismic event, the earthquake energy "E_i" was estimated using its magnitude "M" by Gutenberg-Richter law:

$$E_i\ [J] = 10^{(1.5 \times M + 4.8)} \tag{2}$$

Then, the cumulative Benioff Strain S(t) was estimated as the sum of the square root of the energy of the i-th seismic events up to time t:

$$S(t) = \sum_{i \le t} \sqrt{E_i} \tag{3}$$

The VRE then provides two graphs with the cumulative number of events and the Cumulative Benioff Strain in the selected period, like the ones reported in Fig. 5.

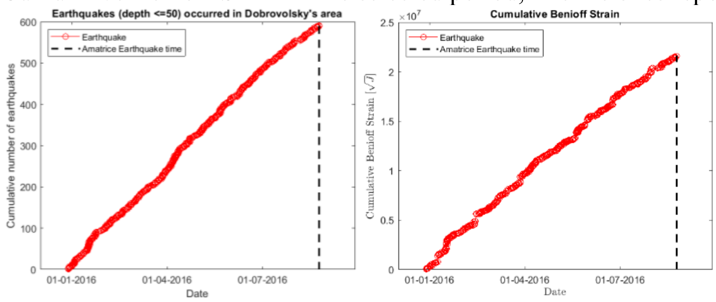

Fig. 5. The cumulative number of earthquakes (left panel) and cumulative Benioff strain (right panel) occurred in the eight months before the start of the Amatrice-Norcia Italian seismic sequence 2016-2017

In addition to Benioff cumulative strain, the second parameter, "E_S", related to the seismicity, was estimated. Prof. Katsumi Hattori introduced this parameter to understand if the area surrounding a monitoring station (e.g., magnetic observatory) was seismic active or not [49, 50]. It was calculated using the distance of the seismic event from the monitoring station. Here, the distance "r" is computed from the target earthquake. The E_S is then calculated daily (i.e., summing all i-events that occurred on the same day):

$$E_S = \sum_i \frac{E_i}{r^2} \tag{4}$$

The result is shown as a time series of daily values of E_S as well as a cumulative trend as reported in Fig. 6.

3.2 Lithosphere – GNSS Data Investigation

GNSS data investigation was explored using two different approaches: a time series of a couple of stations along the transects of the seismic fault or mapping the rate of position variations.

The transect is the perpendicular direction with respect to the fault. We focused on the analysis of variations of GNSS positions along the transect, considering the interesting results obtained by Panza et al. [21]. However, here, we are developing a new method without necessarily reconstructing or replicating their results. One important difference is that in [21], the authors used several GNSS stations aligned along the transect, while here, we used only two stations whose direction is along a transect of the main fault of the target event.

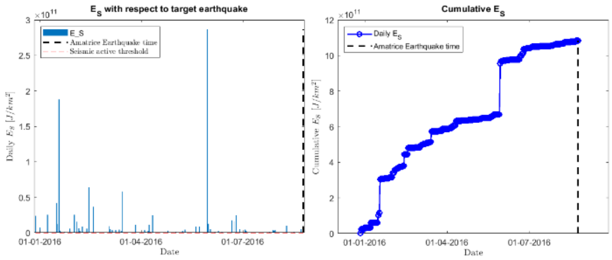

Fig. 6. Daily (left panel) and cumulative trend (right panel) of the ES parameter (earthquake energy weighted for squared distance from the target earthquake).

The first step was to divide the GNSS stations that were on the footwall by the ones on the hanging wall of the main fault. We achieved this by calculating the angle of the GNSS station with respect to the target earthquakes and then considering this angle with respect to the Strike of the fault (one of the input parameters of the VRE). A graphical map shows the stations after this division with two different colours, as reported in Fig. 7 (left panel). We would underline that such a division on the footwall and hanging wall regards only the direction of the main fault but not the real extension of the fault. Consequently, a GNSS station marked on the hanging wall (footwall) could be on another fault system but not on the target event's footwall (hanging wall).

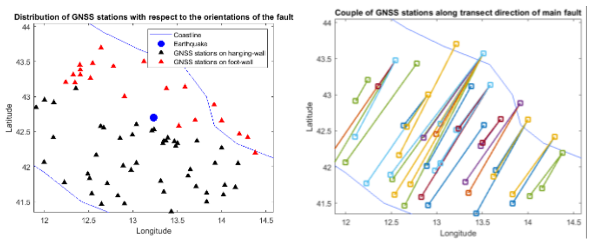

Fig. 7. Maps of the GNSS stations. Left panel: GNSS stations are divided into the ones that are on the footwall and on the hanging wall of the main fault of the target event. Right panel: Couple of GNSS stations along the transects of the main target fault.

To search all the couple GNSS stations on the transects, each one on the hanging wall was selected, and the angle with respect to the GNSS stations on the footwall was calculated. If such an angle was perpendicular to the strike of the main target fault, the couple of stations were selected as belonging to one transect. All the detected couples of stations along a transect of the main fault are reported in the right panel of Fig. 7 .

Then, for each couple of GNSS stations, the two time series of the three positions displacements (North, East, Up) were selected, and after resampling the second stations on the same time step of the first one, the differential position was calculated:

$$\begin{vmatrix} \Delta N(t_i) \\ \Delta E(t_i) \\ \Delta U(t_i) \end{vmatrix} = \begin{vmatrix} North_{station1}(t_i) - North_{station2}(t_i) \\ East_{station1}(t_i) - East_{station2}(t_i) \\ Up_{station1}(t_i) - Up_{station2}(t_i) \end{vmatrix} \tag{5}$$

The results visible in Fig. 8 were plotted firstly in a two-dimensional graph with a vertical axis, the differential displacement for each component, and the horizontal time. Secondly, a three-dimensional graph was realised, calculating the transect's distance to the target earthquake's epicentre.

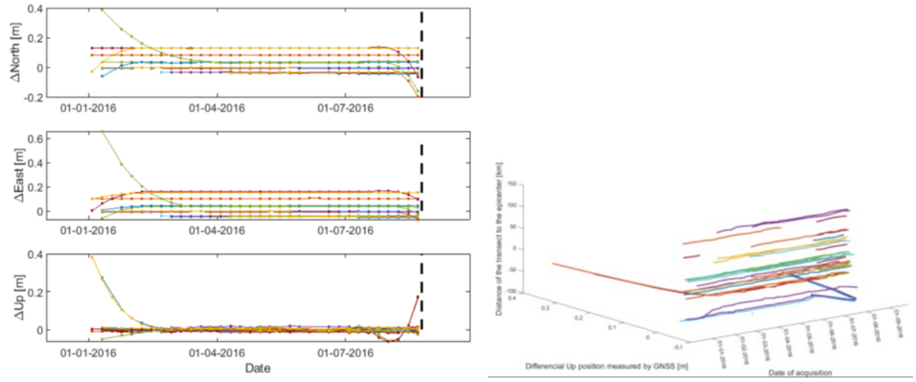

Fig. 8 Time series of differential displacements of couple of stations along the transects of the main fault.

A second approach to investigate the GNSS data was carried out producing maps of variation of the recorded positions in Central Italy. We firstly homogenised the data in a tensor with dimensions of time, station and the three recorded positions. The space was first filled with available data. The values were interpolated with the previous and following measurements for the time steps without measurements at one station. If one or both were not available, the value was not used. Then, the differences of the two consecutive timesteps for each GNSS were computed and divided for the time intercurred from among the two steps, i.e., estimating the variation rate of the measured positions at all available stations. With all the available data, a map was then interpolated for each timestep (weekly). An example is provided in Fig. 9.

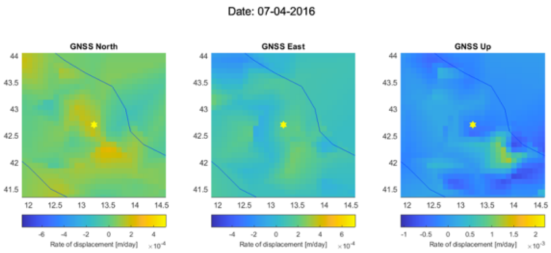

Fig. 9. Rate of variation of the positions measured by GNSS stations in Central Italy.

3.3 Atmosphere – Investigation of the Climatological Data

For the investigation of the atmospheric climatological data, we applied an approach similar to the Climatological Analysis for seismic PRecursor Identification (CAPRI) algorithm developed by Piscini et al. [18]. A similar algorithm that is the one inserted in this VRE is called ''MErra-2 ANalysis to search Seismic precursors'' (MEANS) [51]. The MEANS analysis steps for each atmospheric parameter "P" are the following:

1. Calculus of spatial average of P;
2. Calculus of mean value of P for each year;
3. Calculus of multi-year trend of parameter P from 1980 to present with corresponding plot and linear fit;
4. The slope of the linear fit is removed in order to take into account possible global warming (i.e., a multi-year trend) not related to the earthquake;
5. Each year is then checked for possible outlier values, and eventually, the year with an outlier is removed. For example, SO_2 could be high during a volcanic eruption, compromising the average;
6. Calculus of mean and standard deviation "std" of P for each specific day (e.g., mean(P) and std(P) of 1 Jan., mean(P) and std(P) of 2 Jan. and so on);
7. Comparison of the value of the earthquake with the average ones and if the specific day is greater (or lower for humidity) of mean plus two standard deviations is computed as an anomalous day;
8. The cumulative plot of the anomalies as a function of time is carried out.

3.4 Ionosphere – Investigation of the Satellite Magnetic Data

The magnetic data were investigated using an approach similar to the one of the MAgnetic Swarm anomaly detection by Spline analysis (MASS) algorithms, successfully applied to specific earthquakes (e.g., Nepal 2015 [52]; Indonesia 2018 [53]) and statistical worldwide correlation with M5.5+ earthquakes [31, 32].

In order to extract eventual anomalous magnetic signals in ionosphere, the algorithm applies the following steps to ESA Swarm data:

1. Select the satellite tracks that crossed the research area (Dobrovolsky's circle) during the investigated time, preserving the full tracks within -50° and +50° geomagnetic latitude.
2. Estimate the first derivative, "FD", by calculating the first differences (sample-by-sample) divided for the time between the two samples.
3. Fitting a smoothing spline to the FD and subtracting it from FD. This

produces the track residual, as shown for ten random tracks in Fig. 10.

4. Using a moving window of 3° latitude, search for possible anomalies, i.e., windows with root mean square larger than “threshold” multiplied by the root mean square of the whole track. In this example, the threshold was set to 4.0, but the user can run the VRE by selecting another threshold.
5. Calculating and plotting the cumulative trend of anomalies as a function of the time.

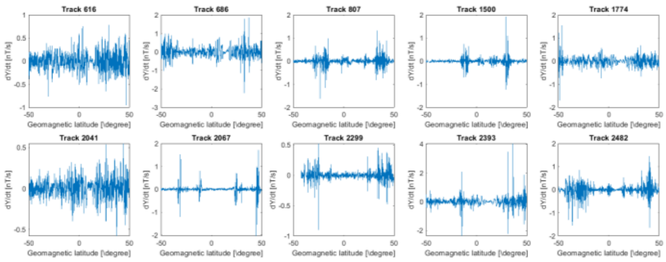

Fig. 10. Examples of ten tracks residuals of the East component of the magnetic field.

3.5 Summary View

Finally, the VRE provides a summary of the analyses in the form of a common view reported in Fig. 11. Here, the calculated time series of lithospheric, atmospheric and ionospheric data are reported together with a common horizontal time axis. The target earthquake time is marked by a vertical black dashed line. This picture allows the researcher to identify possible common trends (e.g., an increase of anomalies) that may suggest an interaction between the geo-layers, i.e. a coupling, as identified in previous studies [53, 54].

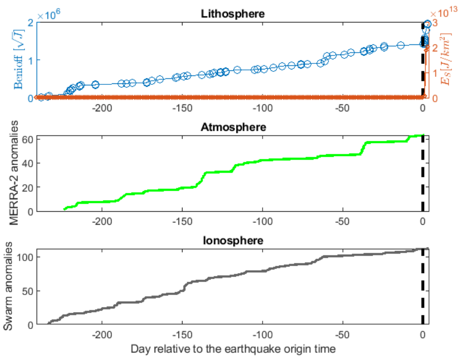

Fig. 11. Summary view of the multidisciplinary and multiparametric investigation of the preparation of the Italian seismic sequence Amatrice-Norcia by visualising time series of lithospheric atmospheric and ionospheric data.

4 Discussion and Future Perspectives

From the lithosphere investigation, it was interesting to note the cumulative trend of E_S

parameter presented in Fig. 6. In fact, two timeframes of higher seismic activity during the 8 months preceding the start (on 24 August 2016) of the Italian Amatrice-Norcia 2016-2017 seismic sequence within the Dobrovolskys's area:

1. About 225 days before the start of the seismic sequence
2. About 60 days before the start of the seismic sequence

However, the E_S parameter shows a very much higher value for the second event. This is due to the closeness to the target event. It was an earthquake of magnitude Mw = 4.4 that occurred on the North side of Bolsena Lake in Central Italy on 30 May 2016 (see Fig. 12). This seismic event was about 104 km from the 24 August 2016 Amatrice earthquake and 95 km away from the 30 October 2016 Norcia earthquake. Nevertheless, the involved faults are very far and not directly connected.

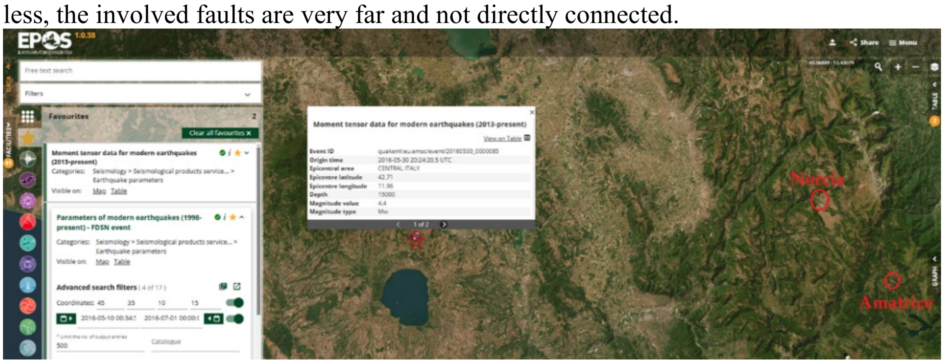

Fig. 12 Localization of the Mw = 4.4 earthquake occurred on 30 May 2016. Positions of the towns of Amatrice and Norcia are marked.

From the analysis of GNSS positions recorded in Central Italy in the 8 months before the seismic sequence, it was possible to identify an interesting trend in the North time series (see Fig. 8). However, from the detailed plot considering the distance of each transect from the epicentre, the interesting profile is far from the epicentre, so it's probably not connected with the preparation for the earthquake. Still, some of the maps of the rate of variation of GNSS positions present interesting patterns, as the one reported in Fig. 9. It's worth noting that at this time, other anomalies were recorded and reported: here, the atmospheric trend shows an increase that followed such days (see green trend in Fig. 11 at about day -140) and Barberio et al. [55] detected an increase in heavy metals in water wells close to Sulmona town in April 2016. However, our main object of this present work is to present a flexible environment, and we leave the scientific discussions to other works, for example [22].

Finally, the Jupyter Notebook allows the user to easily integrate new data and features to expand the present research framework. Furthermore, the analysis of another earthquake is very easy as most of the part of the Notebook automatically downloads the necessary data, calculate the region of interest automatically, and replots all the output according to the new input parameters. Regarding the region of the World that can be analysed, some limitations are provided if a dataset is focused only on a specific region (for example, local earthquake catalogue). However, some ongoing work on the EPOS platform is devoted to a wider integration with other open-source similar platforms that can overpass even such limitations. In conclusion, the developed VRE provides a tool that any researcher can use to verify the obtained results independently and to reuse, modify the parameters, or analyse other case studies (earthquakes, volcanic eruptions, or other natural or anthropogenic hazards). Such an open approach can also help the advancement of understanding of the preparation phase of the earthquake, facilitating cooperation and exchanges among several researchers of the World, hopefully improving the knowledge.

Software repository. The VRE described in this paper is available at: https://github.com/dedalomarchetti/VRE_Amatrice (DOI: 10.5281/zenodo.15365530).

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