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ARTICLE

Weather Events Associated with Strong Earthquakes and Seismic Swarms in Italy

Valentino Straser[1*], Daniele Cataldi[2], Gabriele Cataldi[2]

[1] *University Makeni Department of Agriculture, Fatima Campus, Makeni, 00000, Sierra Leone*

[2] *Group Radio Emissions Project, Lariano, Rome, 00076, Italy*

ABSTRACT

This study discusses the possible relationship between potentially destructive seismic events, earthquake swarms, and intense weather events occurring in the same epicentral zone at time intervals ranging from one day to a few weeks. The objective of the present study is, therefore, to analyze the interaction between the lithosphere, atmosphere, and ionosphere in order to propose, prospectively, a new hydro-climatic model to be applied not only in Italy, where this research was carried out. The study concerns some of the most intense Italian earthquakes starting from 1920, with the destructive event in Lunigiana, in North Western Apennines, until the recent earthquake swarm that hit the Emilia-Romagna region followed, as in the cases analyzed in this research, by strong atmospheric disturbances. The recurrence associating seismic events with atmospheric precipitation allows us to propose some hypotheses about the triggering mechanism. In tectonically stressed areas, during pre-seismic and seismic phases, the release of gases from the ground and electrical charges near active faults is known. It is hypothesized that water condensation nuclei are carried by radon gas on atmospheric gases, also originating from cosmic rays in the upper atmosphere, generated by air ionization.

Keywords: Extreme hydro-climatic events; Earthquakes; Radon gas; Earthquake swarms; Atmospheric precipitation

1. Introduction

The dramatic nature of hydro-climatic events that have affected various parts of the Planet makes it possible to consider various triggering mechanisms according to a holistic principle [1-3], that is, consid-

*CORRESPONDING AUTHOR:
Valentino Straser, Department of Agriculture, University of Makeni, Makeni, 00000, Sierra Leone; Email: valentino.straser@gmail.com

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ering both anthropogenic impact and geophysical events, without excluding the influence of radiation from the cosmos [4-6]. This mode of investigation is facilitated by technological advances, including satellite data retrieval and the development of new models and interpretation of natural processes by scientific teams. Italian chronicles from the last century and others around the world report the correspondence between potentially destructive seismic events and precipitation, such as rain or snow. Following are some excerpts from news reports.

Earthquake May 6, 1976, Friuli, magnitude 6.5: "After the disastrous telluric events of May 6, September 11 and 15, 1976, winter opened with a cold and snow event of the rare kind for Friuli Venezia Giulia. Here is the account experienced firsthand by yours truly in Udine during that exciting two days that brought over 15 cm of snow to the capital of Friuli" (http://www.centrometeo.com). Earthquake April 6, 2009, L'Aquila, magnitude 6.3: "After last night's tremors that brought back fear among the population of L'Aquila, since the first light of dawn it has been raining continuously on the whole area" (Abruzzo amid bad weather and new tremors—La Stampa. https://www.lastampa.it/cronaca/2009/04/21). Earthquakes of August 24 and October 30, 2016, a magnitude of 6.5 and a swarm of January 18, 2017, with a maximum magnitude of 5.5 in central Italy: "Strong earthquake tremors hit central Italy, already tested by the seismic events of August and October and the copious snowfall in recent days" (https://www.ilsole24ore.com). May 20, 2012 earthquake, magnitude 5.8 with epicentre in Emilia: "May 20, 2012—as early as late morning rain hit the towns affected by the quake and is not expected to subside until at least Monday morning" (https://www.ilfattoquotidiano.it 2012/05/20). "Exacerbating the situation came violent rain that has been falling since the early morning hours on the earthquake-affected municipalities" (https://www.gazzettadimodena.it). On a larger scale, examples of this between minimum depression and potentially destructive earthquakes include the Islands of Greece, or strong earthquakes, such as the Kumamoto earthquake in Japan in 2016. In this case, the main shock was followed by other earthquakes associated with intense precipitation, as Kazunori Miura (personal communication) pointed out with the superposition of seismic tail hypocenters with meteoric events [4]. Similar studies have been carried out by V. Strasser, where recurrences of the link between seismic activity and baric variations, with even intense precipitation, two days before or two days after in the epicentral zone of the earthquake have been shown. The production of ions in seismically active zones [7,8] and the release of gases into the atmosphere, which can generate water condensation nuclei, and thus create a link of the interaction between lithosphere and atmosphere, have been discussed by both Sergey Pulinets [9], Sergey Pulinets and Kirill Boyarchuk [10]. Indeed, studies conducted by Nigel Marsh and Henrik Svensmark have shown that cosmic rays influence Earth's climate, through comparisons of changes in cloud cover and the flux of cosmic rays reaching the troposphere [11]. Ions are associated with nanoparticles and filamentous structures of various origins, caused by the combination of meteoric phenomena and ions in the air as reported by Marie-Agnès Courty and Jean-Michel Martinez, which would underlie hydro-climatic triggers [12,13].

2. Method, data, and limits of this research

Data retrieval does not contemplate detailed information on bad weather or weather conditions, especially in years prior to 2010. In this case, the presence of rainfall, drought or frost is mentioned, with no time reference. This has led to many problems in finding weather data to be associated with seismic data.

Meteorological data, to be superimposed on seismic swarm data are highly variable, due to the duration of the seismic swarm. So, if we want to indicate unambiguous meteorological data, regarding a swarm that lasts several months is, as we understand, very difficult and scientifically invalid. In this regard, it was decided to consider the weather data prior to the triggering of the swarm, that is, the date of the beginning of the seismic tremors.

In some cases, the data did not cover weather conditions, and the duration of weather phenomena such as torrential rains, intense thunderstorms and adverse weather phenomena are not available. It was only possible to indicate when these occurred, where possible, before the seismic shock or the onset of the earthquake swarm.

When we talk about a seismic swarm, we must mention a geographical area (GPS data), but it is known that seismic swarms especially if they are long-lasting can encompass very large areas geographically and here express themselves from a seismic point of view. So, another limitation was precisely to indicate a geographical point where the seismic swarms occurred and there calculate the meteorological condition. The method used in this study was to compare data found on the website.

2.1 Origin of pre-seismic electromagnetic phenomena

Pre-seismic radio emissions (also called "Seismic Electromagnetic Precursors" or SEPs) are a natural phenomenon described for the first time in a scientific publication in 1890 by British geologist John Milne [16]. At present, the scientific community agrees that these radio emissions are generated by the piezoelectric effect caused by the accumulation of tectonic stress on fault edges [17] (**Figure 1**). Laboratory experiments conducted on rock fragments have found that during the creation of fractures in rocks under mechanical stress, they emit radio waves induced by piezoelectricity. This phenomenon is observed when crystals are applied on some of the mechanical stress in certain crystallographic directions: the opposite sides of the crystals were loaded instantly [18,29].

The creation of experimentally induced microfractures in the rocks was demonstrated for the first time through triaxial compression tests [18-21].

The characteristics of the tectonic stress, the geometric characteristics of the fault (irregularities) and the typology of minerals included in it determine the creation of microfractures which has different orientations: This determines the reaction of non-isotropic electromagnetic sources [22-24].

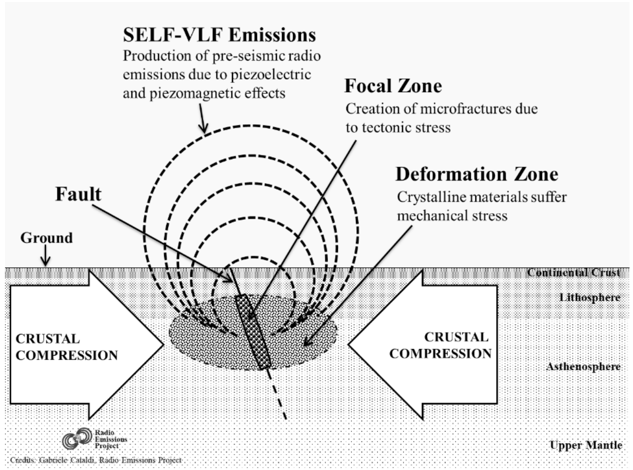

Figure 1. Pre-seismic radiofrequency is generated through the phenomenon of piezoelectricity. In the image above the geodynamic mechanism responsible for the pre-seismic radiofrequency emission has been represented. Credits: Gabriele Cataldi, Radio Emissions Project.

Other studies have shown that the volume of the earth's crust involved in the creation of microfractures is 24-520 times larger than the earthquake preparation zone [25].

The amplitude of the electromagnetic signals caused by the formation of microfractures of the rocks subjected to tectonic stress in the earthquake preparation area mainly depends on the density of the microfractures and their size; the morphology of the electromagnetic field depends on the orientation of the microfractures; on the other hand, the period of oscillation of the electromagnetic field (temporal modulation) depends on the geological characteristics of the fault and on the characteristics of the tectonic stress that determine a growth of the microfractures that does not proceed linearly [26].

According to T. Lay and T. C. Wallace only 1-10% of the energy and seismic moment contained in earthquake zones preparation is converted into seismic waves and it is therefore conceivable that the 90% (or more) of this energy, or part of it, can be converted to radiofrequency. Taking as a reference an earthquake of magnitude 5, this has an energy and a seismic moment between 10^{12} and 10^{18} Nm [27].

Considering that it is not possible to quantify the energy losses of the system in terms of thermodynamic efficiency and the efficiency of energy conversion tectonic in other forms of energy, we assume that only 50% of the energy residual theorized by T. Lay and T. C. Wallace can be converted to radiofrequency [27].

2.2 Radon as a seismic precursor

The Radon gas is a chemical element that has been used for the first time as a seismic precursor in 1927 [28], but the first real recording that has had an important echo within the scientific community was realized following the Tashkent earthquake in 1966 [29]. Although the ICEF (International Commission on Earthquake Forecasting) has stated that it is obviously no significant correlation between the radon gas increases and seismic events; in our case the monitoring of the flow Rn_{222} has provided guidelines that were deemed correct, as confirmed by the RDF electromagnetic monitoring.

Certainly, the opinion ICEF does not contemplate the use of RDF technology confirming the creation of fractures in the subsurface, and this confirms that when using new media research, you can get unexpected results.

According to the authors, encouraging data about the use of radon as an imminent seismic activity indicator have been obtained, for example, against Radon gas flow measured before the M7.2 earthquake that was recorded in Kobe (Japan) on January 17, 1995 [1] (**Figure 2**).

Allegri and his team [31] and Pulinets and Boyarchuk [32] analyzed the flow of gas Radon in central Italy between 1979 and 1980 in the sites of Rome and Rieti experiencing between June and November 1980, an increase of +25% of the Radon flux and +170% of the baseline level, which preceded the M6.5 earthquake that was recorded in Irpinia (southern Italy) November 23, 1980 (**Figure 3**).

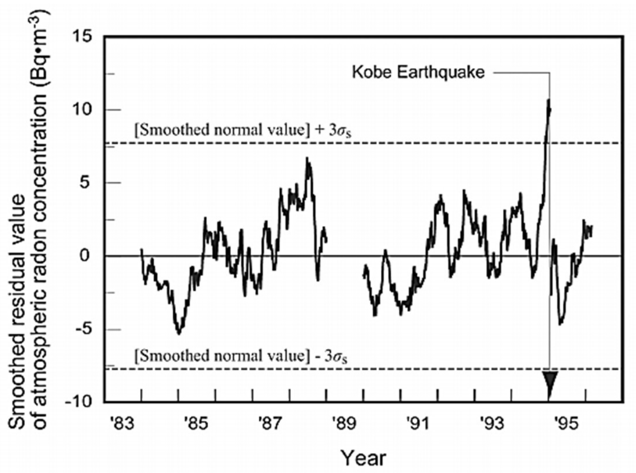

Figure 2. Radon gas concentration related to the M7.2 earthquake which was recorded in Kobe on January 17, 1995. In the graph above it is possible to observe the variation of the Radon gas concentration which preceded the M7.2 earthquake which was recorded in Kobe in 1995. Credits: Air radon concentration vs. time (by Kobe Pharmaceutical University) before the M = 7.2 Kobe earthquake of January 17, 1995 [29,30].

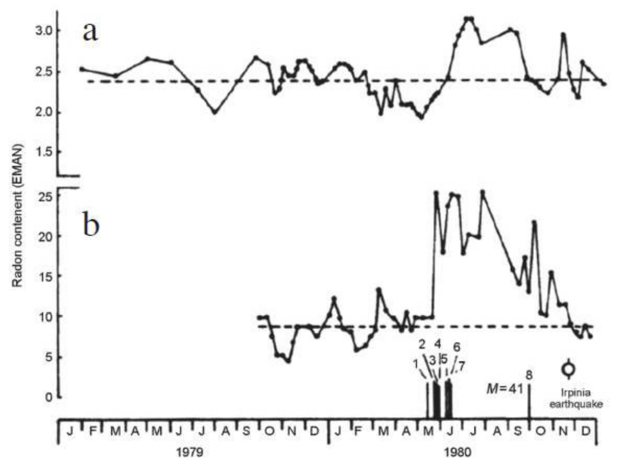

Figure 3. Radon gas concentration related to the M6.5 earthquake which was recorded in Irpinia (southern Italy) on November 23, 1980. In the graph above it is possible to observe the variation of the Radon gas concentration that preceded the M6.5 earthquake which was recorded in Italy in 1980. The 1979-1980 series of the groundwater radon content at: a) Rieti station, b) Rome station. The vertical bars in the bottom panel show the seismic shocks. The length of the bars is proportional to the magnitude (modified from Pulinets and Boyarchuk [10]).

3. Results

A total of 36 events occurred in the last century in Italy, that is, since 1920, were considered for the present research. The data are summarized in **Tables 1 and 2** and are broken down into 17 earthquake swarms and 19 earthquakes, of which 17 were destructive **Table 1**:

Below are the maps of the geographical areas

Table 1. Comparison of seismic swarms and intense weather events considered in Italy since 1927 and their respective occurrence intervals.

N.	Date of swarms start	Lat.	Long.	Main shock magnitude (Mw)	Area	Interval between earthquake and precipitation (in days) in the same area	Duration of meteorological events (days)
1	1927-1928	44.538584	9.648097	5.30	Bedonia, Alta Valterno, Italy	0	0
2	18/01/1990	39.115505	16.853912	4.00	Calabria, Crotone, Italy	0	2
3	26/09/1997	42.819109	13.184194	5.70	Appennino Umbro-Marchigiano, Italy	0	0
4	21/08/2000	44.889056	8.399895	4.90	Quattordio, Italy	0	0
5	18/11/2003	38.147984,	13.394317	5.60	Palermo, Italy	0	2
6	09/10/2004	39.904635	16.186023	4.20	Pollino, Italy	0	20
7	16/10/2008	42.387694	13.397661	4.60	L'Aquila, Italy	0	15
8	20/05/2012	44.826673	11.212160	6.10	Emilia Romagna, Italy	0	15
9	24/08/2016	42.497640	13.408839	6.00	Appennino Centrale, Italy	0	90
10	18/01/2020	42.625285	13.287986	4.20	Amatrice, Italy	0	20
11	24/05/2020	37.748736	15.007888	4.60	Etna, Italy	0	0
12	18/01/2021	37.766478	15.011280	4.10	Etna, Italy	0	15
13	31/07/2021	44.061205	12.601903	2.20	Rimini, Italy	0	0
14	22/03/2022	43.291692	12.318422	4.30	Umbertide, Italy	0	0
15	18/03/2022	40.842690	14.138801	2.00	Campi Flegrei, Italy	0	2
16	09/11/2022	43.503222	13.320910	5.70	Ancona, Pesaro, Macerata, Italy	7	15
17	28/05/2023	37.724041	15.118004	4.00	Milo, Italy	0	0

where the seismic swarms listed in **Table 1** occurred. Of these maps, one of the seismic swarms that occurred between 1927 and 1928 is missing, because this data, although witnessed, is not present in the archives of the INGV—National Institute of Geophysics and Volcanology, an archive where the data on the earthquakes in question have been extrapolated (**Figures 4-19**).

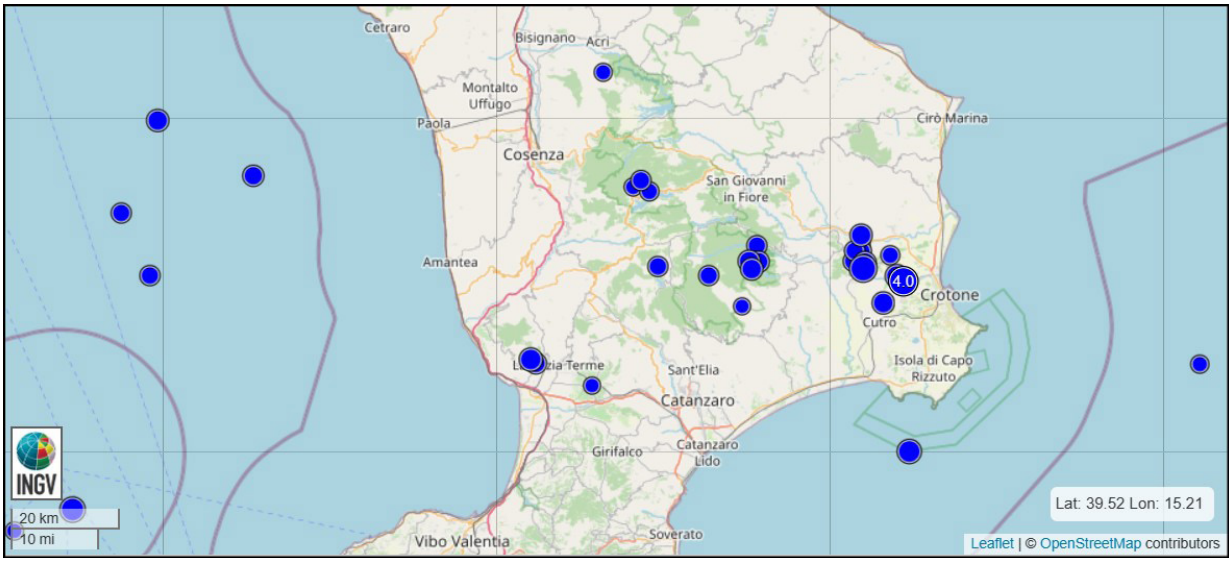

Figure 4. Earthquake swarm of January 18, 1990.

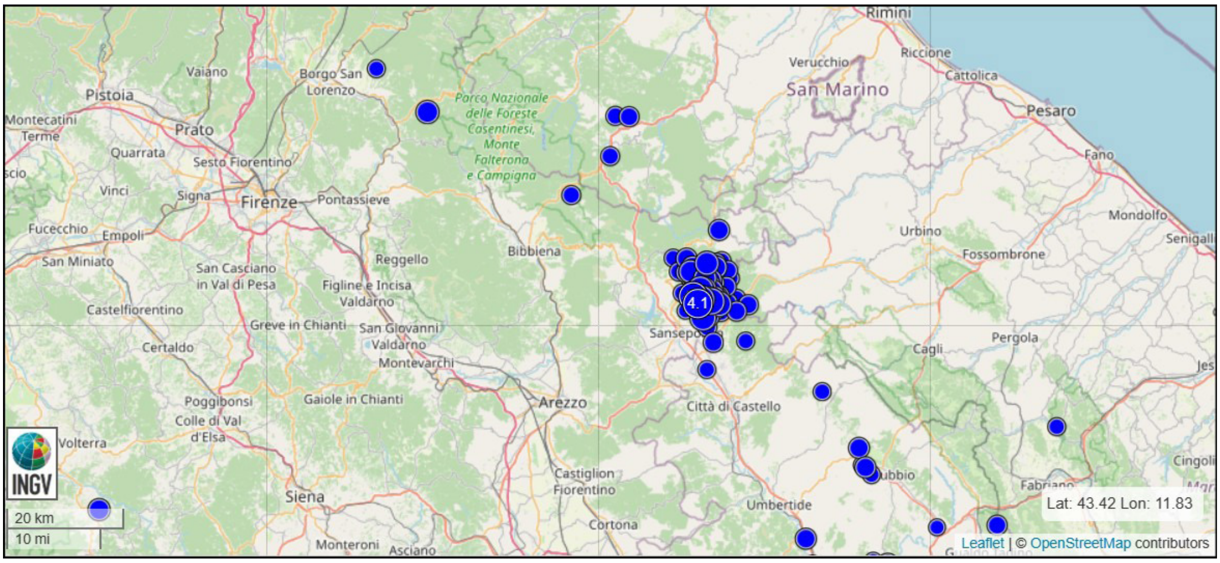

Figure 5. Earthquake swarm of September 29, 1997.

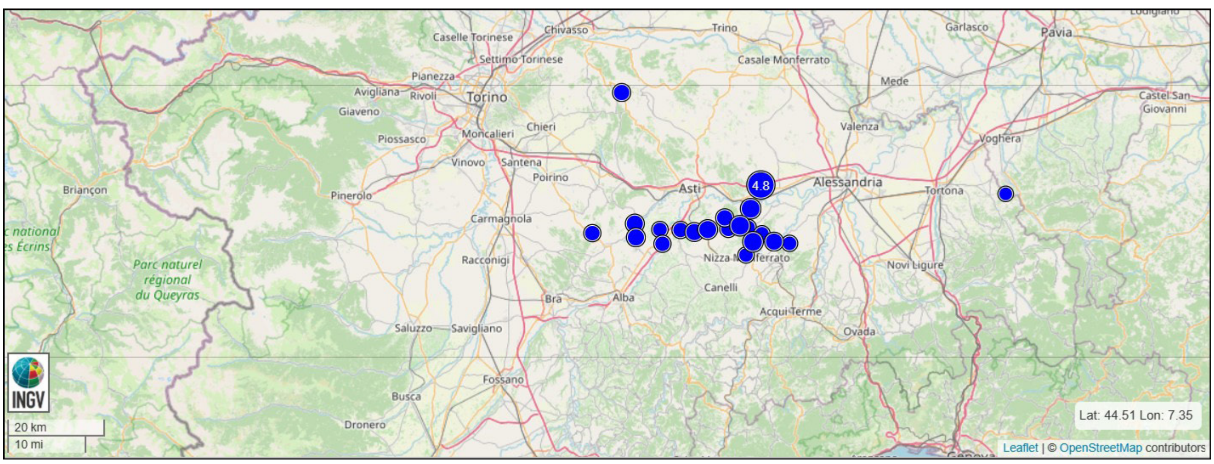

Figure 6. Earthquake swarm of August 21, 2000.

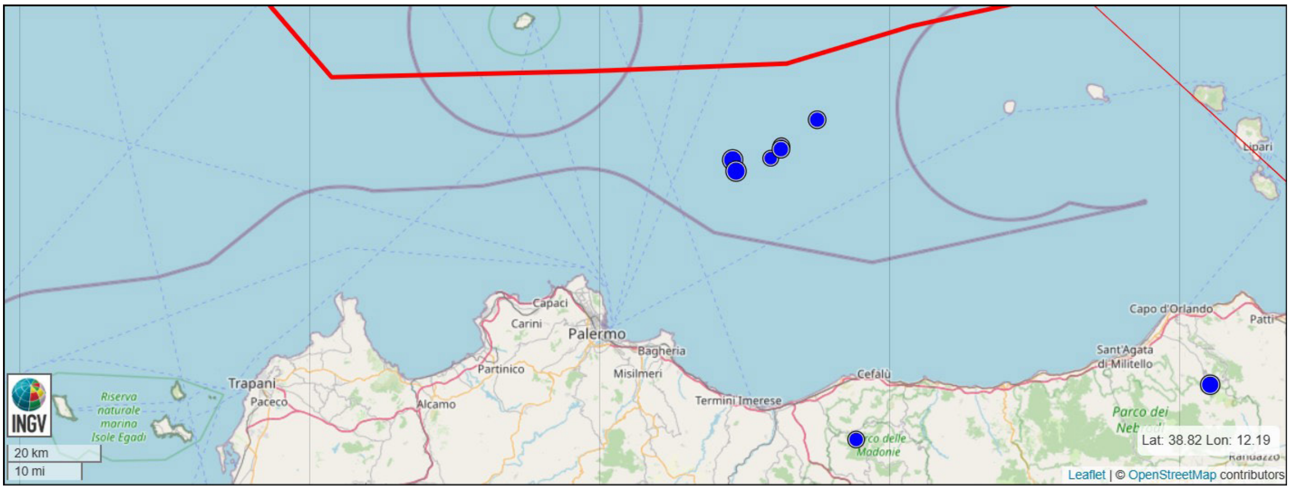

Figure 7. Earthquake swarm of November 18, 2003.

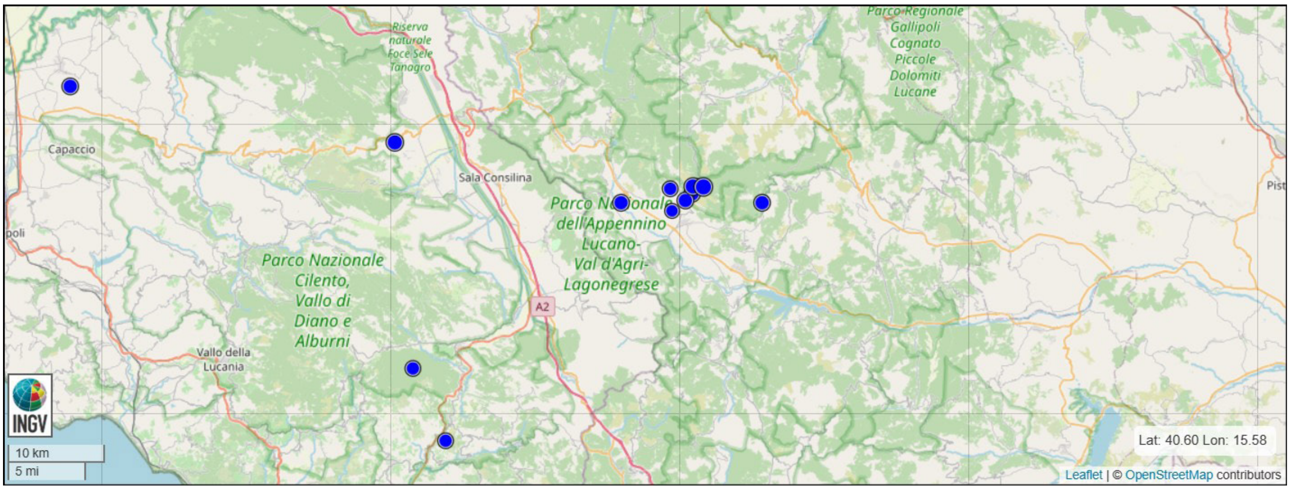

Figure 8. Earthquake swarm of October 9, 2004.

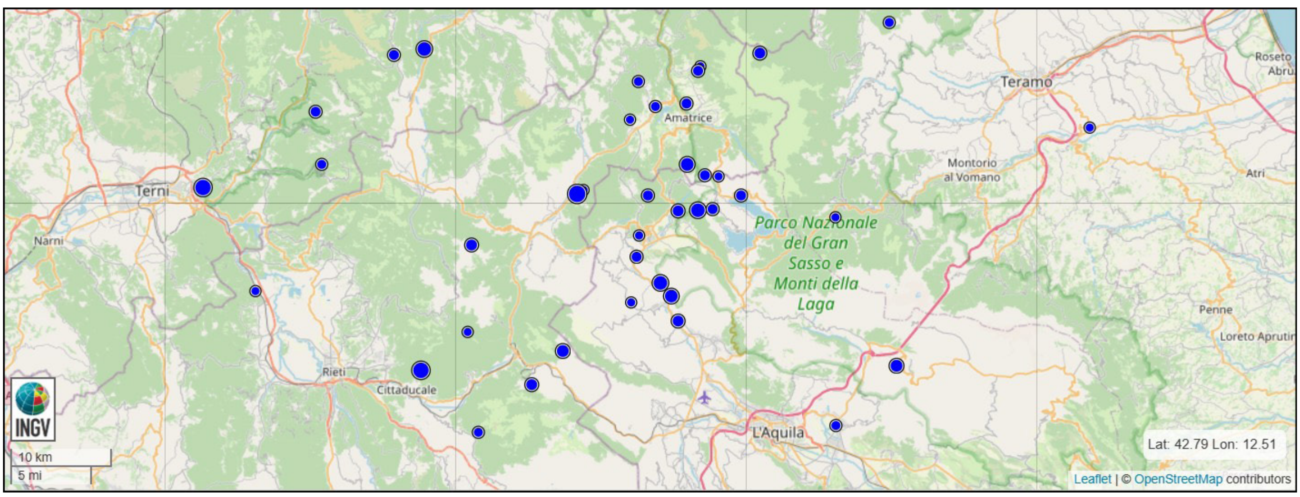

Figure 9. Earthquake swarm of October 16, 2008.

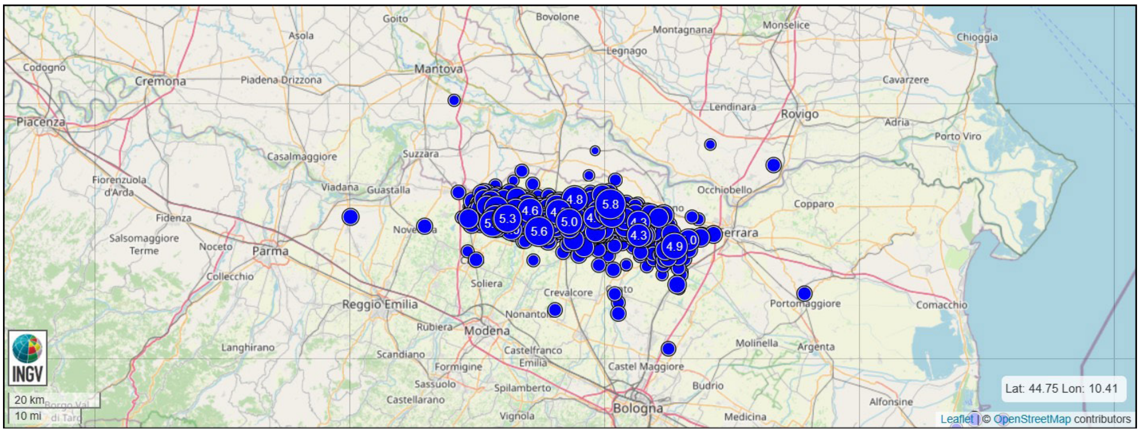

Figure 10. Earthquake swarm of May 20, 2012.

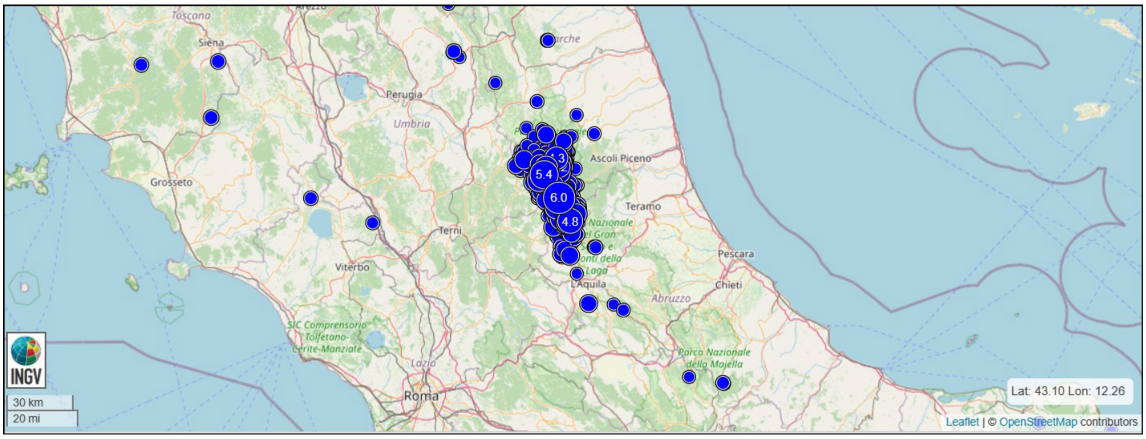

Figure 11. Earthquake swarm of August 24, 2016.

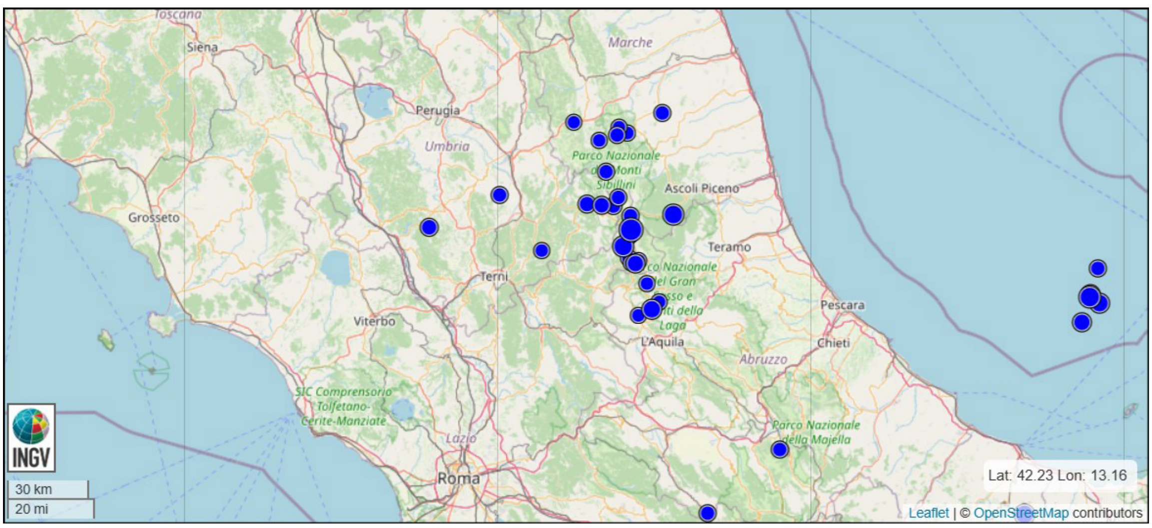

Figure 12. Earthquake swarm of January 18, 2020.

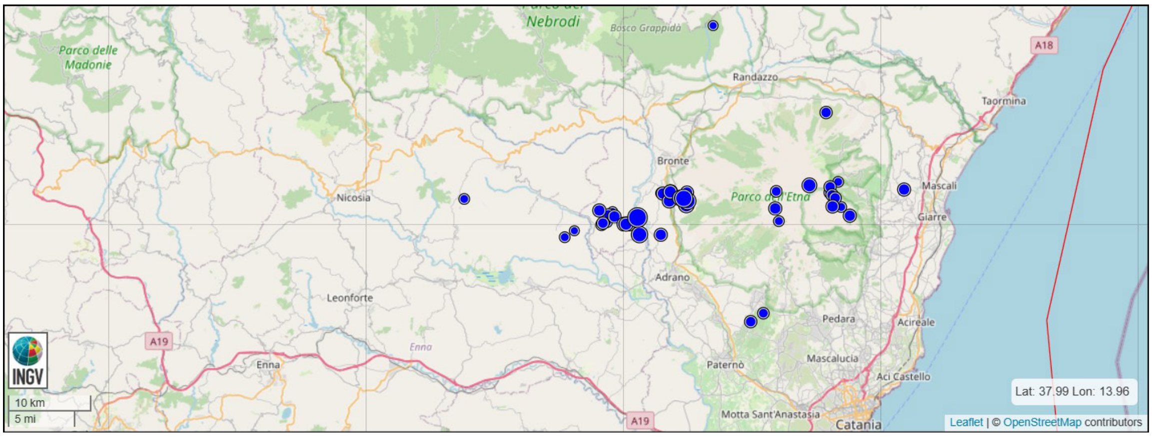

Figure 13. Earthquake swarm of May 24, 2020.

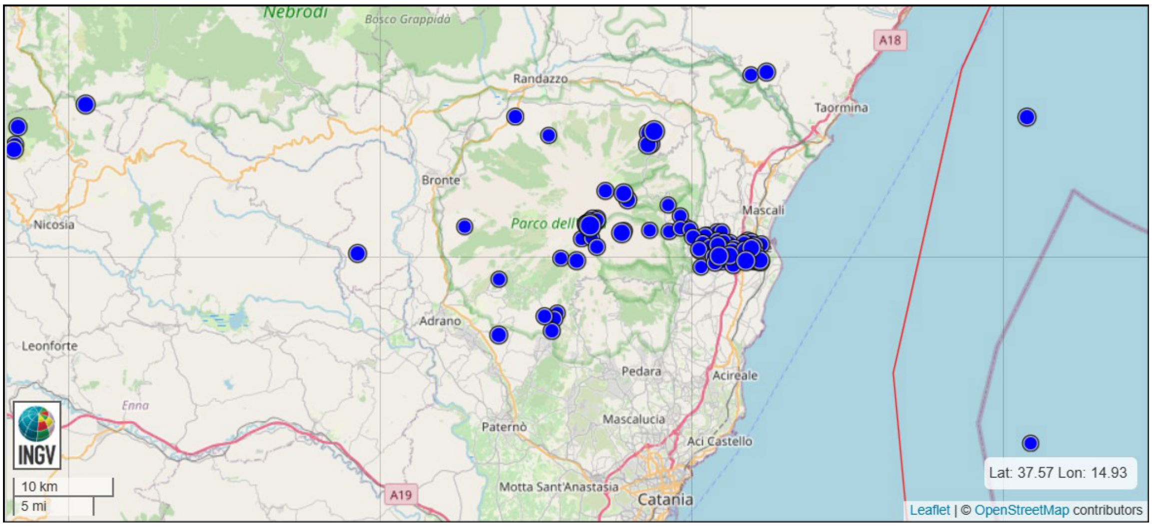

Figure 14. Earthquake swarm of January 18, 2021.

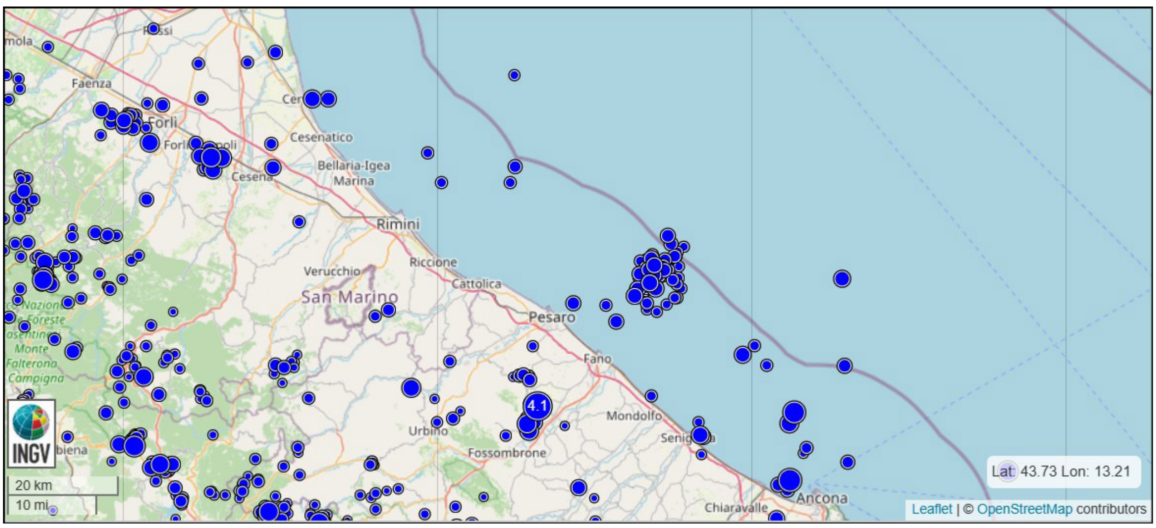

Figure 15. Earthquake swarm of July 31, 2021.

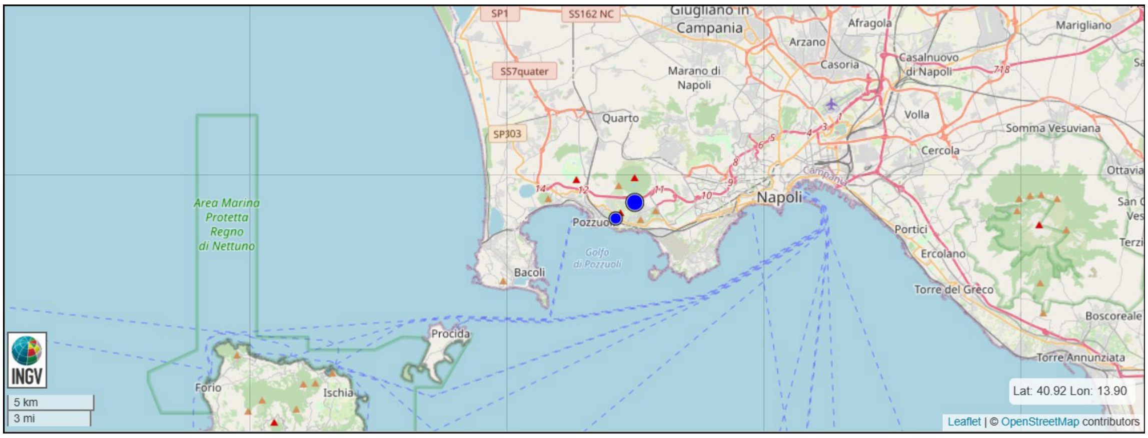

Figure 16. Earthquake swarm of March 18, 2022.

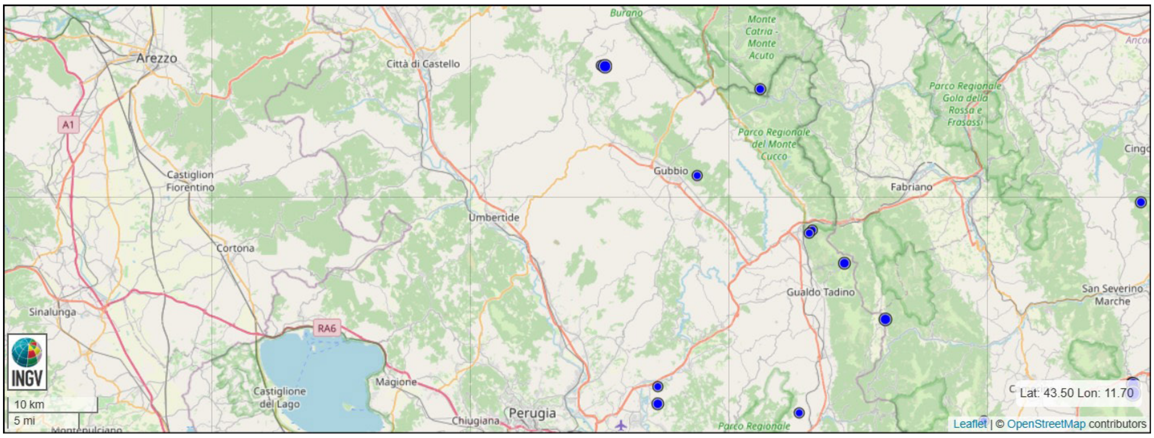

Figure 17. Earthquake swarm of March 22, 2022.

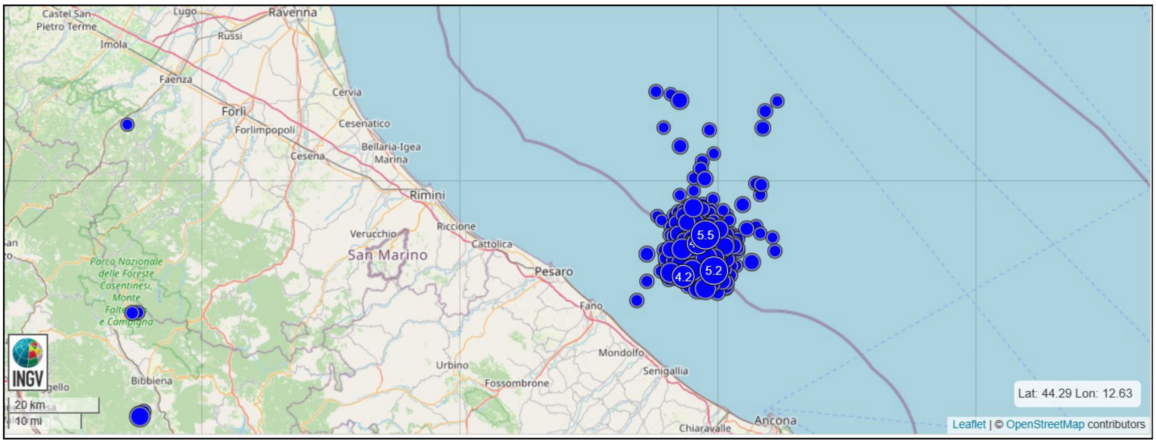

Figure 18. Earthquake swarm of 9 November, 2022.

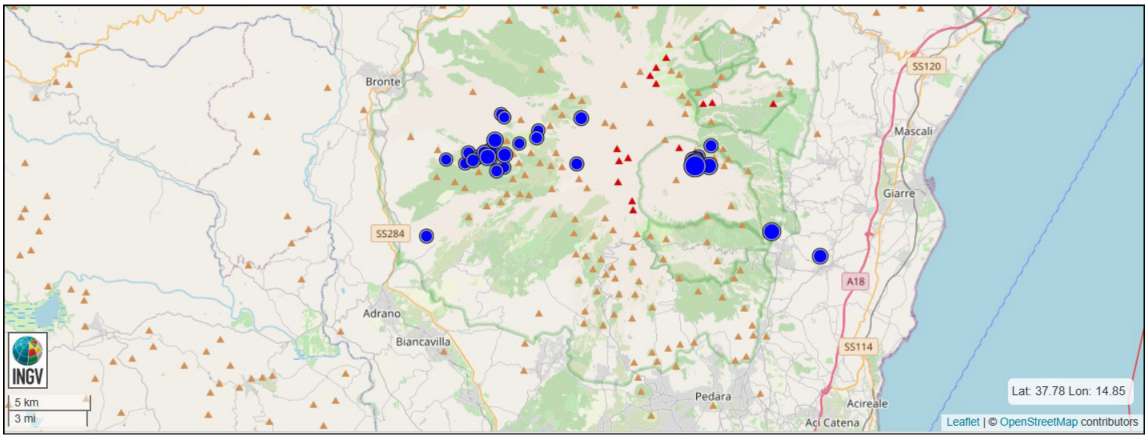

Figure 19. Earthquake swarm of May 28, 2023.

Table 2. Comparison of destructive earthquakes that have occurred in Italy since 1920 the duration of meteoric events and their respective intervals of occurrence.

N.	Swarms start	Lat.	Long.	Main shock (Mw)	Zone (Italy)	Interval between earthquake and precipitation (days)	Meteorological events (days)
1	08/09/1920	44.058	10.395	6.3	Molazzana	0	10
2	23/07/1930	40.980	25.341	6.6	Bisaccia Nuova	0	10
3	21/08/1962	41.175	15.009	6.2	Montecalvo Irpino	0	10
4	19/07/1963	43.343	08.153	6.3	San Lorenzo al Mare	0	10
5	19/07/1963	43.344	08.278	6.1	San Lorenzo al Mare	0	10
6	15/01/1968	37.745	12.997	6.0	Salaparuta	0	3
7	06/05/1976	46.356	13.275	6.5	Prato	0	10
8	17/06/1976	46.162	12.864	6.1	Lestans	0	10
9	15/09/1976	46.302	13.197	6	Isola	0	0
10	23/11/1980	40.914	15.366	6,9	Cairano	0	0
11	26/09/1997	43.084	12.812	6	Nocera Umbra	0	0
12	06/09/2002	38.381	13.701	6	Santa Flavia	0	1
13	06/04/2009	42.334	13.334	6.3	Sassa	2	1
14	20/05/2012	44.890	11.230	6	Massa Finalese	2	1
15	27/05/2012	44.814	11.115	6.3	Medolla	0	0
16	17/01/2016	41.558	14.603	7	Campobasso	0	1
17	24/08/2016	42.723	13.187	6.2	Accumuli	2	15
18	26/10/2016	42.956	13.066	6.1	Visso	0	1
19	30/10/2016	42.862	13.096	6.6	Preci	0	1

In **Figures 4-19**, the extensions of seismic swarms concerning the Italian territory can be observed.

4. Discussion

Italian chronicles from the past century, as well as others around the world, report earthquake events generally followed by various types of precipitation, such as rain, snow, or hail, even with repeated occurrences for weeks, as shown in **Tables 1 and 2**. **Figures 20 and 21** display the association between the two events; generally, on a time scale, physical shaking occurs first and then precipitation occurs. At least in the cases considered in Italy.

In the first case, seismic swarms were considered (**Table 1**), and considering that swarms are characterized by a succession of earthquakes of varying magnitude without depending on an earthquake of greater energy and lasting even months, as in the case of the seismic crisis that affected the Northwest Apennines, between 1927 and 1928 [35]. In this context, it is therefore very difficult to indicate the duration of the meteorological event and the time interval between it and the seismic event since we are talking about the succession of earthquakes lasting several days and, in some cases, several months. Thus, we referred to the date of onset as opposed to the total duration of the earthquake swarm, which extended up to a maximum time interval of 90 days. Within these limits, the interaction between lithosphere and atmosphere, discussed in this study was respected for all earthquakes analyzed.

The second case examined destructive earthquakes that occurred in the last century in Italy. The data are summarized in **Table 2** and report single earthquake events of potentially destructive magnitude. In this analysis, reference is made, to general weather conditions, in which storms, rain, drought, cold/freeze or stable conditions can be found, with respect to the date of occurrence of the main quake. The reference period is represented by the date of the event itself and its geographical location. In the discussion of the data (**Figure 21**), we have considered the areal extent of weather events, as their geographical extent sometimes extends beyond the geographical limits of the epicentres of the earthquake events examined.

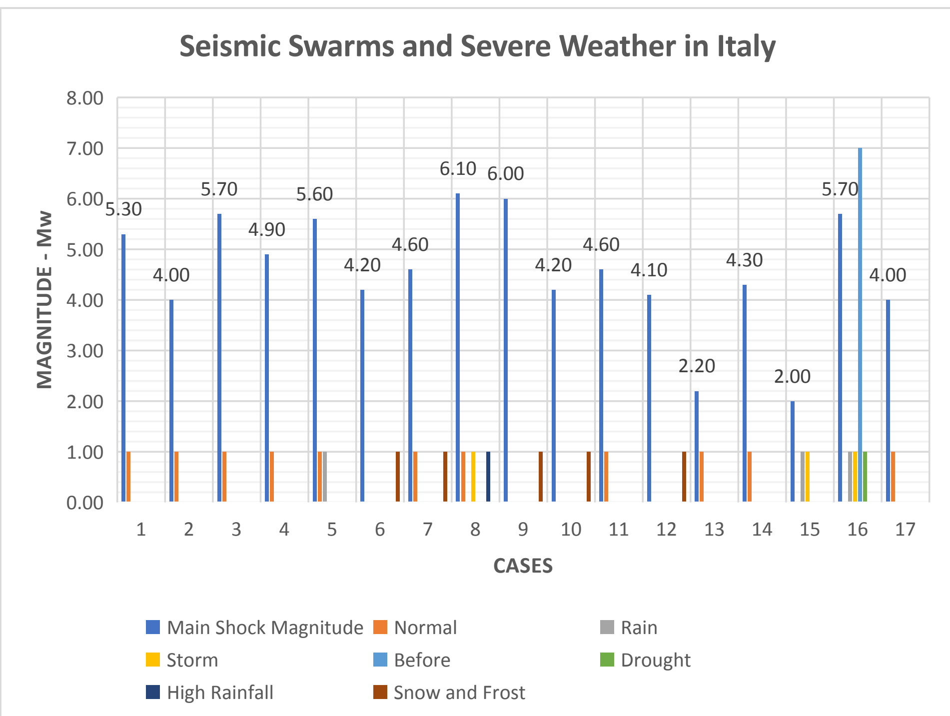

Figure 20. Comparison of seismic swarms and meteoric precipitation of various kinds that have occurred in Italy since 1927 (see **Table 1**).

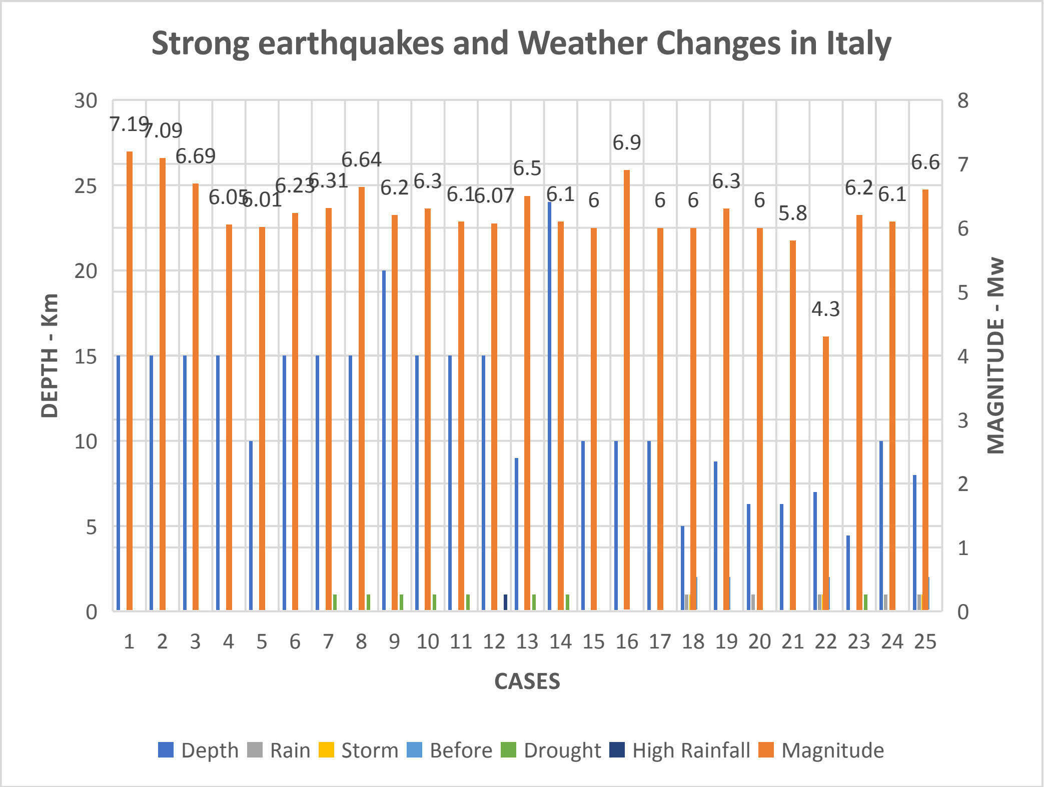

Figure 21. Meteoric events of various kinds and different intensities are associated with earthquakes of magnitude 6 or greater, except for two cases of magnitude 5.8 and 4.3, which have occurred in Italy since 1920 (see **Table 2**).

The recurrence between geophysical and hydro-climatic events, whether earthquake swarms or destructive earthquakes, allowed us to advance, at the level of hypothesis, the potential link between the two phenomena.

The first mechanism involves water condensation nuclei. They are transported by both radon gas, released from the ground in the pre-seismic and seismic phases on atmospheric gases, and cosmic rays in the upper atmosphere, generated by air ionization [34-37]. Radon gas, trapped in the lithosphere, is released in pre-seismic phases and during the main shaking in areas under tectonic stress. The release of the gas into the atmosphere increases its ionizing effect in the air, in agreement with the model proposed by Pulinets et al. [1].

A second mechanism not yet fully understood in the troposphere has been studied by Wu in recent work, concerning "jet streams" [38]. According to the author, these atmospheric streams would be influenced by the charges released from the subsurface and intercept in the pre-seismic phases the area of the area of the future epicentre a few days before the main shock [39-42].

5. Conclusions

The question we have tried to answer in this paper is whether there can be a direct relationship between earthquakes, precipitation, and extreme weather events, and what common denominator connects them. The answer is affirmative. The potential candidate is tectonic stress with which is associated the release of charges in fault zones close to rupture, responsible for the formation of water cores. Interdisciplinary studies may or may not confirm the repetition of extreme hydro-climatic events in other parts of the world to make long-term predictions. In fact, today, thanks to modern instruments, the use of satellites and interdisciplinary teamwork, the analysis of hydro-climatic phenomena can be assessed with a holistic approach, that is, considering anthropogenic impact, geophysical events, and radiation from space. The outcome of this study, which associates earthquakes and seismic swarms with even extreme weather events and vice versa, can be considered in agreement with those of other authors who have analysed the interaction between the two physical and geophysical phenomena in various seismically active areas of the world [43-47].

Author Contributions

Valentino Straser has the main responsibility, and initiative based on several years of study of seismic precursors, especially in the electromagnetic field. The co-authors supported the present study with data collection.

Conflict of Interest

The author and co-authors declare that they have no conflicts of interest.

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