Statistical precursors of a strong earthquake on April 6, 2009 on the Apennine Peninsula

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HIGHLIGHTS

• New method is proposed for determining the precursors of upcoming earthquakes.
• Based on measurements of the critical frequency of the ionosphere, the statistical phenomena that accompanied the preparation of the earthquake were considered.

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ABSTRACT

The article discusses the possibility of formulating a conclusion about the transition in early April 2009 to an exceptional state of the geophysical system in an area with a radius of about several hundred kilometers from Rome. This fact preceded the tragic earthquake on April 6, 2009, which led to large casualties in the Italian city of L’Aquila. This conclusion was obtained based on an analysis of the statistics of the critical frequency of the ionosphere. In the course of calculations, in particular, phenomena with a high degree of determinism that preceded the specified seismic event were detected. The fact of their existence with a high probability indicates the occurrence of an exclusive state of the regional geophysical system in the period of about several days before this event. It was depicted that the identified phenomena precede a significant number of seismic events. Based on the analysis of variations in the statistics of the critical frequency of the ionosphere in the Apennine region in 2007–2011, including those preceding the earthquake near the city of L’Aquila on April 6, 2009, an algorithm was formulated to detect a significant probability of transition to an exclusive state of the corresponding local segment of the geophysical system. The approach proposed in the article can be used to compile a short-term forecast of the existence of a significant probability of the occurrence of seismic events of large magnitude in various regions of the world.

1. Introduction

Earthquakes may release bursts of electrical energy that can be felt in the ionosphere, kilometers above Earth. The abundance of charged particles means the ionosphere reacts to electric and magnetic fields, something other regions of the atmosphere generally do not do. The ionosphere includes four broad regions: D, E, F, and the top. These regions are composed of several layers such as F1 or F2 (F region above about 150 km in which the important reflecting layer, F2, is found). The apparent (“virtual”) height is recorded instead of the true height, since radio pulses propagate in the ionosphere more slowly than in open space. The virtual height tends to infinity for frequencies approaching the maximum plasma frequency in the sheath, since the pulse must travel a finite distance with virtually zero velocity. Such frequencies are called critical frequencies. The values of virtual heights (h’E, h’F, h’F2, etc.) and critical frequencies (foE, foF1, foF2, etc.) of each layer are scaled by ionograms. The obtained numerical values and original ionograms are archived at five World Data Centers for Ionosphere [www.ngdc.noaa.gov].

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The effectiveness of the technologies of ionosphere monitoring in ionospheric precursors detection was demonstrated in many researches worldwide. Among them we should mention the vertical ionospheric sounding by ground-based ionosondes (Pulinets et al., 2004; Liu et al., 2006). The publications devoted to the seismo-ionospheric effects initiated the series of international projects aimed to the effect validation. The INSPIRE project studied the physical processes and their effects in the ionosphere, which can be identified as earthquake precursors, with a detailed description of the methodology for determining ionospheric preseismic anomalies (Pulinets et al., 2021). Subtle fluctuations in Earth’s ionosphere, a region of charged particles high above the surface, preceded the Baja California earthquake (Liu et al., 2022).

In this paper, using the example of the April 6, 2009 earthquake in L’Aquila (Italy) (Vittori et al., 2011; Blumetti et al., 2010; Amoruso and Crescentini, 2009), the problem of detecting short-term precursors of approaching high-magnitude earthquakes is considered. The applied technique is reduced to the assessment of the relative changes in the level of chaos (entropy parameters) for the statistics of measured data in a mode close to real time (Kogan, 2015; Kogan et al., 2021; Volvach et al., 2022).

The corresponding measurements can refer to any physical (or biophysical) fields associated with processes in seismically active regions. A fundamentally important property of the approach used is the weak dependence of the results obtained on the permanently present stationary components of the background noise of an arbitrary nature. In particular, as applied to the measuring equipment itself, this means the possibility of neglecting the randomness introduced by the variations of its parameters, provided that they are relatively constant over a time interval of the order of three to four months.

Thus, the measurements contain a large amount of information about the development processes of an earthquake. In order to identify them, as can be seen from the calculations presented below, allows the detection of the effect of the “final preparation” process of seismic events in near real time.

Moreover, an essential feature of the proposed method of determining the fact of the occurrence of a high probability of the final stage of the preparation process for a strong seismic event there is a fairly easy-to-implement condition on the comparability of the effective width of the probability distribution associated with such a process (or with some nonlinear transformation from the measurement results) with several units of the minimum realizable discreteness interval of the measuring equipment. This means a high sensitivity of the applied approach, which allows us to assume the possibility of its wide use in geophysical problems. This conclusion, in particular, is illustrated by the calculations given below.

In Section 2 we describe the data and mathematical apparatus used in solving the objective. Analysis of the properties of functional corresponding to measurements of the ionosonde Rome of the values of the critical frequency of the ionosphere for a time interval of the order of two years before the event of April 6, 2009 is given in Section 3. Additional justification of the obtained results are presented in Section 4. Specifically, in Section 5 we consider a possible algorithm for formulating a conclusion about the occurrence of an exclusive state of a local segment of the geophysical system and its relation with a high probability of approaching a seismic event. In Section 6 discussion of the results are presented. Finally, in Section 7 we provide a summary of our findings and conclusions.

2. The data and mathematical apparatus used in solving the objective

The critical frequency data were collected from NOAA’s (National Oceanic and Atmospheric Administration) NGDC (National Geophysical Data Center) site. In this article, the calculations were carried out using measurements of the Rome ionosonde (RO 041) located in Italy, near Rome, in the period of March 26, 2007–September 11, 2009 (Section 2) and March 26, 2007–April 5, 2011 (Section 3).

As well as in (Kogan, 2015; Kogan et al., 2021; Volvach et al., 2022) let us assume that any physical or geophysical fields \( x = x(t) \) which is measured in seismically active zones can be submitted as sum of two variables:

\[
 x(t) = x_1(t) + x_2(t).
\]

Here \( x_1(t) \) is a background noise which is determined by the population of random events that are not related to the upcoming earthquake. Whereas the second term \( x_2(t) \) (obviously, almost always \( |x_2(t)| \ll |x_1(t)| \) is completely determined by the processes caused by the influence of the approaching seismic event.

As in (Kogan et al., 2021), to identify short-term precursors of earthquakes, the article will use a statistical functional of the form:

\[
 L(n) = \frac{A}{M} \sum_{k=-M+1}^{n} |\mathcal{F}_k|, \quad \mathcal{F}_k = \sum_{m=0}^{n-1} (-1)^m P_{m,1}.
\]

In (2) \( M = 100, A = 1000 \) (this factor allows you to go to a more convenient range of values). Any coefficient \( P_{m,1} \) is the probability that the values of the function \( F(x(t)) = \sin(x(t)) \) (see Kogan et al., 2021) fall into the cell number \( m \) of the distribution of the corresponding range of values:

\[
 x_{\text{min}} + mh \leq \sin(x(t)) < x_{\text{min}} + (m + 1)h, \quad 0 \leq m \leq N - 1.
\]

In (3) the index \( l \leq l \leq N_{\text{real}} \) is the number of the corresponding implementation segment. Value \( x_{\text{min}} \geq -1 \) is least value of function \( F(x(t)) \) for the corresponding interval of realization. Discretization interval width is equal to \( h = 0.01 \) that is why total number \( N = 200 \). The total duration of any implementation segment is defined as \( N_{\text{real}} = 96 \) consecutive intervals of \( J = 15 \) min each, which in total is 24 h. Each such 15-minute time interval is juxtaposed with either one value of the measured physical quantity, or a hardware failure. In the presence of the latter, the number of measurement counts in the dataset, over which the distribution (3) is constructed for the corresponding segment of the implementation, becomes less than \( N_1 \) by the number of specified failures. Taking into account the measurement gaps (that is, the time intervals for which there are no data at all, including in the form of messages about measurement failures), the number of daily implementation intervals considered below is \( N_{\text{real}} = 848 \) in section 2 and \( N_{\text{real}} = 1448 \) in section 3 of this article.

For clarification, we note that the probability density \( \rho(w) \) of the sum of two independent random variables \( X_{1,2} \) can be written using an integral convolution of the form

\[
 \rho(w) = \int_{-\infty}^{\infty} \rho_1(w - w_1) \rho_2(w - w_2) \, dw.
\]

Further, we assume that for the discrete interval \( h \) in (3) the condition \( \sigma_1 \geq (2 \div 3)h \) is true, where \( \sigma_1 \) is the standard of fluctuations of the values of the random process \( X_2(t) \). In this case, small-scale fluctuations of the empirical probability density \( \rho(w) \), corresponding to the considered interval of implementation number \( l \) and corresponding to a finite volume of measurements, will significantly decrease as a result of averaging when performing the specified convolution (both in its continuous and discrete versions) (Kogan, 2015; Kogan et al., 2021; Volvach et al., 2022). Thus, the appearance in (1) of the term \( x_2(t) \), which is associated with the process of preparing an approaching earthquake and does not depend (or weakly depends) on the background noise \( x_1(t) \), plays the role of a natural regularizing factor. Its action leads to a decrease in the deviation of the random function \( \rho(w) \) from some unknown “ideal” probability density, which would correspond to an infinite number of samples.

Obviously, such a difference in the properties of the dependence \( \rho(w) \), in the presence and in the absence of the independent term \( x_2(t) \) in (1) can be quite simply detected when, for example, using a mathematical apparatus like the Fourier transform. In (1) there is a factor \((-1)^{n} = \)
exp(iπm). Therefore (without taking into account the transition to the consideration of the random variable \( \sin(x) \) instead of the directly measured field \( x \)), the functional \( L(n) \), up to a constant coefficient, can be considered as the averaging of the indicated transformation from the probability density (that is, the characteristic function) at the value of the Fourier variable equal to \( \pi \).

Actually, the transition to the study of statistics \( \sin(x) \) is connected with the existence of an integrable singularity of the form \( \sim (1 - w^2)^{-1/2} \) for the probability density \( p_{\text{ran}}(w) \). When \( w \to \pm 1 \), its influence leads to a significant change in the amplitudes of small-scale variations of the random dependence \( p(w) \). As a result, the difference in the properties of the functional \( L(n) \) increases in the cases of existence and, conversely, the absence of the process of preparing an approaching earthquake at the corresponding time intervals. Thus, the function \( \sin(x) \) plays the role of a kind of “magnifying glass” that allows one to study in more detail the indicated changes in the statistics of the measured field \( x(t) \).

The critical frequency of the F2 layer of the ionosphere (measured in megahertz) is considered below as a random variable indicated changes in the statistics of the measured field \( x(t) \).

Figure 1 shows seismic fault lines in the Mediterranean region indicating the coordinates of the considered earthquake.

3. Analysis of the properties of functional (2) corresponding to measurements of the ionosonde Rome of the values of the critical frequency of the ionosphere for a time interval of the order of two years before the event of April 6, 2009

In Figure 2 shows the dependence \( L(n) \) for the interval March 26, 2007–September 11, 2009 (the point of origin is shifted by 100 days compared to March 26, 2007, taking into account the preliminary averaging performed in (2) over a 100-day interval). In Figures 2 and 3, as and in all figures in this article, the immediate moment of the earthquake in L’Aquila with a magnitude of 6.3 (its beginning occurred at 1 h 32 min UTC on April 6, 2009) is marked with a vertical solid red line (aftershocks close in time were not considered). Hereinafter, UTC time is used; the corresponding moments in the figures are always marked with an accuracy of \( \Delta n/2 \), that is, up to half of the 15-minute measurement interval. In Figure 3 (it will be the main one in the analysis) shows in detail the most informative section of Figure 2, where, as will be commented below, there are graphical phenomena with a high degree of determinism.

By this concept, we mean the ability to determine the value or properties of the dependence \( L(n) \) at future values of \( n \) with an accuracy not less than a given one, on the basis of knowledge of the previous properties of this function, as well as almost complete coincidence of a number of numerical “graphic” parameters at key points the curve \( L(n) \) in the Cartesian plane \( (n, L(n)) \).

Note also that in order to avoid cluttering with symbols in Figure 2, the number of key points of the \( L(n) \) curve and other designations marked with letters is less than in the more detailed Figure 3 (also, as in Figure 4) from the next section of the article. The indicated dependence is constructed for discrete values of \( n \) corresponding to points \( (n, L(n)) \) of the Cartesian plane. Straight lines 1’ and 2’ in Figures 2 and 3 are parallel to straight lines 1 and, respectively, 2 and illustrate the degree of closeness of their directions. The abscissa unit in all cases corresponds to one day of continuous operation of the indicated ionosonde.

As follows from Figure 3 (see also Figure 2), at point \( a \), which corresponds to 0:00 on October 26, 2007, there is the deepest minimum of the \( L(n) \) dependence over the entire considered time period. Taking into account the statistical meaning of functional (2) (Kogan, 2015; Kogan et al., 2021; Volvach et al., 2022), such a minimum with a high probability corresponds to the largest width of the probability density of a “weak” random process \( x_1(t) \), which is independent (or weakly dependent) of the background noise \( x_1(t) \) and is caused by seismic phenomena in the local sector of the geophysical system, including the Apennine Peninsula. In other words, this minimum most likely corresponds to the largest range of variations in tectonic compression of lithospheric plates (The authors consider it legitimate to state that the amplitude of this variation is proportional to the effective magnitude of the specified compression; in this article, this assumption is not used.)

Further, as can be seen from Figure 3, the curve \( L(n) \) turns out to be bounded from below by the straight line 1 drawn directly through the points \( h(00:00, 20.01.2008) \) and \( f(00:00, 17.12.2008) \). As a designation, we will call a quasi-tangent straight line any straight line drawn through two points of the dependence \( L(n) \) at \( n = n_1 \) and \( n = n_2 \) and almost exactly, that is, with a relative deviation along the vertical axis.
Figure 2. Dependence $L(n)$ on the interval 26.03.2007–11.09.2009.

Figure 3. Dependence $L(n)$ in the area of the existence of graphic phenomena with a high degree of determinism.

Figure 4. The dependence of $L(n)$ on the interval 26.03.2007–05.04.2011.
touching on the interval \( n_1 < n < n_2 \) at least three more points of this curve without other possible intersections with the line of the considered dependence \((2)\). The value of the relative deviation \(\delta\) is defined as the ratio of the modulus of the vertical difference between the quasi-tangent line and the closest point of dependence \((2)\) to the value of \(L(n)\) at this point. In this case, either the horizontal or vertical length of such a segment of the curve \(L(n)\) should be

\[ n_2 - n_1 \geq 50 \]

The number of days along the horizontal axis and, accordingly

\[ |L(n_2) - L(n_1)| \geq 50 \]

units along the vertical axis. With regard to straight \(1\), this definition is fully satisfied, see Figure 3. Indeed, in the section between \(b\) and \(f\), this straight line also passes near the minima of the dependence \(L(n)\) at points \(c\) \((00:00 01/27/2008)\), \(d\) \((00:00 02.07.2008)\) and \(e\) \((00:00 04.27.2008)\) with maximum relative deviation

\[ \delta < 0.1\% \]

satisfying \((4)\). This fact, which means the long existence of an effective linear boundary from below for the values of \(L(n)\), we consider to be a manifestation of the determinism of the processes under study. Then, at the point \(g\) \((04:00 04.03.2009)\), which is 32 days before the earthquake in question along the horizontal axis (horizontal coordinate \(g\) is determined with an accuracy of \(\pm 0.5\%\)) to the value of \(L(n)\) at point \(i\) \((00:00 02.04.2009)\).

By way of explanation, let us point out that points \(a\), \(b\), \(c\), \(d\), \(e\) and \(i\) are minima of different scales for the \(L(n)\) dependence. It is defined for discrete values of the argument \(n = 100...N_{radio}\) and, as is easy to understand, only one integer value \(n\) can correspond to any extremum of this curve. Hence, it follows that each listed point is matched exactly with the time “00:00” of the beginning of the corresponding day. Whereas the “intermediate” points, like \(g\) and \(j\) in Figure 3, arbitrary values of the horizontal coordinate can be assigned. The meaning indicated in Figure 1 of the region \(h\), marked with a violet contour and associated with additional measurements, will be discussed below. As mentioned above, the immediate moment of the earthquake in L’Aquila is marked with a vertical solid red line. It was also drawn with a time accuracy of the order of \(1\%\) and, its intersection at point \(j\) with the curve \(L(n)\) is indicated by an orange arrow in Figure 3.

Note that in Figures 2 and 3, straight line 2 passing through points \(a\) and \(i\) of the key extrema, limiting the values of the functional \(L(n)\) from below, turns out to be almost strictly parallel to straight line \(1\); the angle \(\delta\) of the divergence between their directions approximately equal to \(1\%\) (that is, it does not exceed 0.05 units of the vertical axis per day). The degree of this parallelism, as noted above, is illustrated by straight lines \(1’\) and \(2’\). In accordance with the definition introduced above, we also assume this fact to be a manifestation of both the determinism of the ongoing processes and evidence of the special importance of the moment in time corresponding to point \(i\) (see Figure 3). In which, among other things, four days before the moment of this earthquake, the dependence \(L(n)\) reaches an exclusively low level. Indeed, in Figure 3 horizontal dashed line 3 connects points \(i\) and \(c\) corresponding to the same levels \(L(n)\). In other words, the value \(L(n) = 109.7905\) reached at point \(i\) was previously accepted by this functional more than fourteen months earlier, at point \(c\), with \(n = 306\), that corresponds to January 27, 2008. This fact of the coincidence of the \(L(n)\) values at two topologically significant extrema can also be interpreted as an additional confirmation of the determinism and exclusivity of the phenomena that occurred several days before the considered earthquake in Aquila.

Thus, as follows from the calculations, before the event of April 6, 2009, the following exclusive facts took place, the totality of which can be interpreted as the accumulation of the phenomena of determinism of the processes under study, preceding a strong earthquake.

1. Four days before the event under consideration, functional \((2)\), the value of which with a high probability depends on the range of tectonic pressure variations, takes an extremely low value at point \(i\) (see Figure 3), which was previously recorded for one year and more than two months up to this point.

2. Starting from January 20, 2008, a linear boundary appears (quasi-tangent straight line \(1\) in the section \(bf)\), which effectively limits the variations of the dependence \(L(n)\) from below. This boundary has existed for more than a year, until 32 days before this earthquake, as follows from Figure 3, the curve \(L(n)\) does not intersect it at the point \(g\).

3. Straight line 2, drawn through points \(a\) and \(i\) of two extrema, which are the deepest minima of the dependence \(L(n)\) for the period of fourteen months preceding point \(i\), with high accuracy turns out to be parallel to straight line \(1\). In this case, the achievement of the curve \(L(n)\) of point \(i\) of the second indicated minimum took place four days before the considered earthquake.

4. Thus, point \(i\) simultaneously corresponds to both the achievement of the value \(L(n)\), which was not previously recorded for a long time, and the formation of the lower boundary of the “channel” from straight lines 1 and 2 (further, if necessary, for such graphic phenomena we will use the designations of the form “channel 1–2” or just “1–2”).

As a result, we come to the conclusion that either the emergence of new or the termination of the existence of the former deterministic phenomena on the Cartesian plane \([n, L(n)]\) took place before this earthquake.

In addition to what has been said, let us take into account that starting from March 29, 2009, that is, no more than seven days before this seismic event, a group of Italian scientists led by D.D. Giuliani recorded a repeated increase in radon content in the vicinity of L’Aquila (Giuliani et al., 2009). According to (Pulinets et al., 2015; Pulinets, 2011; Pulinets and Boyarchuk, 2004; Firstov et al., 2017; Gufeld and Novoselov, 2016), such a method for short-term forecasting of impending earthquakes is very promising. From a physical point of view, it is associated with an increase in the release of radon and a number of other gases in the preparation of the upcoming earthquake. This phenomenon is caused by a sharp increase in the seismic stress of tectonic plates in the zone of the epicenter of the approaching event. As a result, in addition to the physical squeezing of gases from the rock, a web of cracks piercing it occurs. Taken together, these two processes can lead to the indicated increase in the release of the gaseous component from the earth’s crust. Special attention to radon is associated with considering this radioactivity, the presence of which facilitates both the measurement of the concentration of this gas in the air and the recording of famous effects (associated with the effect of ionization under the influence of radon radiation), such as the appearance of linear cloud structures in the area of preparation for an impending event (Pulinets, 2011; Pulinets and Boyarchuk, 2004). Provided that false alarms are filtered, which, in particular, is possible when using the methodology proposed in this work, these phenomena can be considered as precursors of an approaching seismic cataclysm.

According to (Giuliani et al., 2009), after March 29, 2009, two days before the earthquake in question, there was a strong increase in radon concentration in the Aquila region. In Figure 3, the curve segment from March 29, 2009 to April 4, 2009 is highlighted by a purple outline \(h\). Unfortunately, a specially created commission of the Ministry of Emergency Situations of Italy considered these facts insignificant. This verdict was most likely based on the sufficient frequency of their previous repetition in this seismically active region, which was not accompanied by any serious consequences. With the prognostic methods that existed at the time of the earthquake in L’Aquila, such a statement was the most probable and did not contradict the entire volume of accumulated data.
4. Additional justification of the obtained results

In order to substantiate a sufficiently high probability of occurrence of the detected graphical phenomena marked on the Cartesian plane \( \{n, L(n)\} \), we will additionally perform calculations that are not directly related to the earthquake of April 6, 2009 in the city of L’Aquila. Figure 4 shows the dependence (2) for a more complete time interval 26.03.2007–05.04.2011, constructed according to the data of the same Rome ionosonde (RO 041). The vertical lines \( E_1 \) and \( E_2 \) denote the moments of earthquakes with a magnitude of 5.3 points (12.17.2008, 21.57 UTC, N39.240, E15.461) and 5.2 points, respectively (11.03.2010, 18.13 UTC, N40.030, E13.257), and the straight line \( E_2 \) corresponds to the seismic event studied above on 6.04.2009 with an epicenter near the city of Aquila. The \( E_1 \) and \( E_2 \) earthquakes were selected according to the USGS catalog for consideration as events that occurred during the specified time period in an area with a radius of 450 km from Rome, whose magnitudes exceed 5 points. As and for the \( E_2 \) earthquake, for events \( E_1 \) and \( E_2 \) aftershocks close in time were not considered.

The meaning of the notation for lines \( L_1, L_2, L_3 \), and points \( a, b, d, e, f, g \) and \( i \) in Figures 2 and 3 is the same as in Figures 2 and 3. It is particularly significant that the moment of the earthquake \( E_1 \) corresponds directly to the point \( f \) of the topologically important extremum. For convenience of analysis, Table 1 shows the calendar dates corresponding to all considered points of the dependence \( L(n) \) in Figure 3, as well as the interval from the time points of these points to the day of the earthquake.

As can be seen from Figure 4, point \( f \) simultaneously serves as the intersection of straight lines \( L_1 \) and \( L_4 \). The latter is drawn through points \( q \) and \( s \) and is a quasi-tangent line. Indeed, for straight line \( 4 \), there is a deterministic phenomenon in the form of the actual tangency of the curve \( L(n) \) at three intermediate (between \( q \) and \( s \) ) points with the explicit fulfillment of (4). Therefore, line \( 4 \), in accordance with the definition of Section 2, is assumed to be an essentially deterministic object. Thus, to the point \( f \) corresponding to the moment of the earthquake \( E_1 \), we can associate more than one graphic phenomenon with a high degree of determinism (Note that drawing the quasi-tangent line \( 1 \) precisely through the points \( a \) and \( f \), and not through \( b, c, d \) or \( e \), see Figure 1b is associated with minimizing the value of the coefficient \( \delta \), see (7)).

We come to a similar conclusion for the event \( E_3 \). See Figure 4. It follows from this figure that this earthquake occurred twelve days after the simultaneous exit at the point \( w \) of the dependence \( L(n) \) from the inner regions of channel 5–7 or the “narrow” channel 6–7 (see Figure 4). The degree of parallelism of their boundaries with each other, as well as with respect to the quasi-tangent \( 4 \), is demonstrated by the straight lines \( 4'–7' \), the meaning of which is similar to the lines \( 1' \) and \( 2' \). The maximum angle \( \delta_1 \) of the divergence of the directions of any of the straight lines \( 4–7 \) does not exceed 0.15 units of the vertical axis per day. This angle in Figure 4 is about 1° between straight lines \( 4 \) and \( 5 \) and substantially less than 0.5° between straight lines \( 5, 6, \) and \( 7 \). The fact of a high degree of parallelism of these lines is considered a manifestation of the determinism of the processes under study and at the same time confirmation of the exclusivity of the time when the curve \( L(n) \) reaches the point \( w \).

Consequently, the moment of the earthquake \( E_3 \) is also preceded by several significantly deterministic graphical phenomena. In this case, determinism is associated both with the revealed quasi-parallelism of these lines, and with the very fact of the existence of a quasi-tangent (7), the time of intersection of which with the curve \( L(n) \) is quite close to the event \( E_3 \). As a result, we find that the statistical effects of a high level of determinism noted in relation to the studied earthquake \( E_2 \) in L’Aquila are not rare or exceptional, but are quite common phenomena. We also point out that the straight \( 8 \) drawn through the points \( e \) and \( i \) in Figure 4 also concerns the other two global minimums when performing (4). The existence of this tangent can be an argument in favor of the hypothesis that the seismic process, which resulted in the catastrophic earthquake in L’Aquila, acted up to the moment when the curve \( L(n) \) reached the point \( p \) (21.12.2010).

5. A possible algorithm for formulating a conclusion about the occurrence of an exclusive state of a local segment of the geophysical system and its relation with a high probability of approaching a seismic event

In accordance with the obtained results we can describe a possible algorithm for formulating a conclusion about the statistically significant probability of an approaching large-magnitude earthquake. The basic principle of the algorithm is proof of the occurrence of an exclusive state in the local geophysical system, which is based on the detection of the accumulation over a short period of time of a population of rarely occurring or deterministic phenomena.

1. Sign of transition to an exclusive state is the fact that a measured (or calculated from the results of measurements) parameter reaches a value that has not been previously noted for a long time. According to computations carried out, such a parameter is most simply determined when using a functional of the form (2) applied to any of the measured physical or biophysical fields. Such a property is due to the statistical meaning of the statistical operator \( L(n) \) which can suppress background components of the received signal and amplify the influence of components associated with new independent processes that arise in the system under investigation. The most likely such “independent” phenomenon is the process of the breaking of lithospheric plates, which, as a rule, is weakly related to the population of “ordinary” phenomena that make up the usually accepted background noise (Kogan, 2015; Kogan et al., 2021). As a result, there is a possibility of detecting an exclusive (that is, an unusual, rare, “strange”) state of the system. It should be pointed out that the use of the proposed methodology is reduced to the elements of conducting a Fourier analysis of the corresponding statistical series.

2. Any graphical phenomena on the Cartesian plane \( \{n, L(n)\} \), characterized by a high degree of determinism, can be seen as a sign of the emergence of an exclusive state of the system. At the same time, the moment of completion of the corresponding graphic phenomena, or, conversely, the time of their occurrence, require special attention. In the role of such phenomena, quasi-tangent lines of the form \( I \) can be considered, see Figures 2 and 1b, or \( 4–7 \), see Figure 3. These lines should be tangent with high accuracy (see (4)) the curve \( L(n) \) on a section of a sufficiently large horizontal or significant vertical length. The moment of termination of the existence of such a limiting line is very important. In relation to the Aquila earthquake, this occurs at point \( g \) (see Figure 3) one month before April 6, 2009.

3. Another essentially deterministic phenomenon, which should also be interpreted as a sign of the transition of the system to an exclusive state, may be the appearance of a “channel” with almost parallel “shores”, drawn through the points of two topologically significant extremums. In the case of the event of April 6, 2009, such an object is represented by two lines of the form \( 1 \) and \( 2 \), see Figures 2 and 3, where the second boundary (line 2) passes through the points of the two deepest minima of the curve \( L(n) \). In this case, the determinism

| Graph point | \( a \) | \( b \) | \( c \) | \( d \) | \( e \) | \( f \) | \( g \) | \( i \) |
|-------------|------|------|------|------|------|------|------|------|
| Date        | 26.11.2007 | 20.01.2008 | 27.01.2008 | 07.02.2008 | 27.04.2008 | 17.12.2008 | 04.03.2009 | 02.04.2009 |
| Time until the earthquake on April 6, 2009, days | 496 | 441 | 434 | 423 | 343 | 109 | 32 | 4 |
consists in the fact that the “shores” of the channel under consideration are almost completely parallel. With regard to channel boundary, the moment of especial attention is an inception of second the extremum, through which the line 2 (from Figure 3) passes (in this case, this takes place four days before the event). As in Figures 2 and 3, both corresponding maximum or minimum should belong to the most significant number and only be reached over a long time interval. Also, the moment of entry of the curve $L(n)$ into the channel or, conversely, the time of exit from it requires special attention.

4. An essential sign of the emergence of an exclusive state of a local segment of a geophysical system is the fact that two (or more) of these signs are performed simultaneously, as is the case with respect to point $i$ in all figures or for points $f$ and $w$ in Figure 4 (At point $w$ there is a simultaneous exit of the $L(n)$ curve from channels 5–7 and 6–7.)

5. A situation in which several signs corresponding to the algorithm under consideration are fixed in a compressed time interval requires special attention. So, before the earthquake in question in Aquila, four of these signs were actually implemented within one month. This includes the achievement of the extreme (maximally small over an interval of more than one year) value of the functional (2) at point $i$ for the first time in more than one year, the termination (at point $g$) of the action of the long-existing lower boundary of the curve $L(n)$ in the form of a straight line 1, the formation of the second boundary of the channel in the form of a straight line 2 passing through the minimum at point $i$. The latter means that, as noted in the previous paragraph of the algorithm, several criteria for the occurrence of an exclusive state are simultaneously fulfilled at this point.

6. If there are facts noted either in all the previous paragraphs, or at least in one of them, then special attention should be paid to any other phenomena indicating a possible exclusive (special, anomalous) state of local seismic processes. This may be a changed groundwater level, unusual animal behavior, the appearance of large-scale elongated quasi-linear cloud structures of a great extent, and so on. Of course, in such a situation, a significant sign of a significant probability of the process of “final preparation” of a high-magnitude earthquake may be a significant increase in the concentration of radon, as was the case before the tragic events in Aquila.

7. The implementation of the above points can become a factual basis for justifying the conclusion about the high probability of a strong earthquake at a fairly close time.

6. Discussion of the results

Based on the analysis of variations in the statistics of the critical frequency of the ionosphere in the Appennine region in 2007–2011, including those preceding the earthquake near the city of L’Aquila on April 6, 2009, an algorithm was formulated to detect a significant probability of transition to an exclusive state of the corresponding local segment of the geophysical system. In combination with additional facts, the occurrence of which can be interpreted as local signs of seismic activity (animal behavior, groundwater level, variations in radon concentration, etc.), the statement of this state means a significant probability of the approach of a high-magnitude earthquake.

We also note that, as shown by a large number of additionally performed calculations, which cannot be presented in this work, taking into account the limited scope of its volume, that the above-considered local in time linear boundaries of dependences of the form (2) and other deterministic phenomena found in the analysis of graphical objects in the given in the article figures are a widespread phenomenon preceding seismic events. They correspond to a wide variety of physical (and biophysical) fields. At the same time, the mechanisms of the occurrence of these phenomena remain not entirely clear. It is quite possible that this is a consequence not only of the complexity of the issue of drawing up an adequate physical model, but also of the weak mathematical elaboration of the problem of the properties of the probability distributions of an “anti-Gaussian” sum of a large number of simultaneously occurring and strongly dependent random processes. Such a set of nonlinearly related and intensely interacting phenomena usually accompanies high-magnitude earthquakes. Consideration of such questions is the subject of further research.

We also point out that seismology as a science has a rigid ethical component. There is a known problem related to the impossibility of announcing an alarm at every suspicion of an approaching seismic event. This means a high probability of missing the start of a real earthquake. A possible way out of this kind of contradiction can be reduced to the regular publication of a set of data, similar to those given in this work, on the unusual (exclusive, “strange”) state of the seismic system of the corresponding region. In order to provide the population with information for an independent assessment of the situation that has arisen.

7. Conclusions

Based on the analysis of the results of long-term measurements of the critical frequency of the ionosphere, the statistical phenomena that accompanied the preparation of the earthquake on April 6, 2009 in L’Aquila (Italy) were considered in the article. In the course of calculations, in particular, phenomena with a high degree of determinism that preceded the specified seismic event were detected. The fact of their existence with a high probability indicates the occurrence of an exclusive state of the regional geophysical system in the period of about several days before this event. It was depicted that the identified phenomena precede a significant number of seismic events. In order to generalize the results obtained, a possible algorithm for formulating a conclusion about the possibility of a strong seismic event in a short time interval is proposed.

Declarations

Author contribution statement

A.E. Volvach, L.P. Kogan, K.H. Kanonidi, I.T. Bubukin, V.B. Shtenber, L.N. Volvach & Biazitov D.T.: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data associated with this study has been deposited at the Rome ionosonde station RO 041 and NOAA’s (National Oceanic and Atmospheric Administration) NGDC (National Geophysical Data Center).

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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