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The Changes in Distribution of Total Ozone over the Kamchatka Region and Hazardous Endogenous Geological Phenomena, That Occurred Here in 2016-2025

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KEYWORDS

kamchatka region;
total ozone content;
dangerous endogenous geological phenomena;
hydrogen degassing;
response;
frequency

ABSTRACT

A pressing problem in aerology, geophysics and emergency safety is the identification of links between changes in average daily values of total ozone content (hereinafter referred to as TO) over the Kamchatka region, as well as hazardous endogenous geological phenomena occurring there (volcanic eruptions and earthquakes). Such connections may be causal in nature, since the mentioned phenomena result in a significant activation of degassing of the earth's interior, which leads to an increase in the flow of hydrogen entering the stratosphere. Since hydrogen is one of the catalysts for ozone destruction reactions, the phenomenon in question can lead to a decrease in the TO over the corresponding region. A hypothesis has been put forward that during the phenomena under consideration, a significant decrease in TO over some points in the Kamchatka region occurs more frequently than in the intervals between them. The aim of the work is to test it for the period 2016-2025, in which the indicated phenomena in the region occurred almost annually. To achieve this goal, information obtained using the OMI instrument (artificial Earth satellite AURA (NASA)) was analyzed. It was established that a significant decrease in TO over many points in the region for all the phenomena under consideration was observed with a delay of several days in relation to their onset dates. The frequencies with which this decrease occurs during periods of volcanic eruptions and earthquakes are significantly greater than in the intervals between them. The values of these frequencies are increased over areas close to the epicenters of the mentioned cataclysms. Significant decreases in TO over the region in the period under consideration occurred before the onset of the studied phenomena. This allows the identified features to be used in long-term earthquake forecasting.

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1. Introduction

The Changes in the state of the ozone layer over any region of the world significantly affect variations in the flow of biologically active ultraviolet radiation affecting its population and wildlife [1-3]. Even with its partial destruction, the primary incidence of life-threatening forms of oncological diseases among the population of any region increases significantly [4-5].

The duration of the accumulation cycles of combustible material on its territory and its thermal regime also change [6], which affects the dynamics of fire hazard [7]. Therefore, identifying the features of the influence of various natural factors on changes in the state of the ozone layer is a pressing problem in aerology, geophysics and safety in emergency situations.

The solution to this problem is of greatest interest for regions in the atmosphere over which the frequency of occurrence of negative ozone anomalies is increased.

In Russia, one of them is the Kamchatka region, the conventional boundaries of which can be considered to be the meridians 155 east longitude and 163 east longitude, as well as the parallels 49 o north and 62 o north.

Another significant feature of the Kamchatka region is the presence of 28 active volcanoes. Among them, the most active is Klyuchevskaya Sopka (4750 m) with coordinates 56°04′ N 160°38′ E – the highest volcano in Eurasia [8-9].

Eruptions of this volcano in the last decade alone occurred: - from 3.04 to 6.11.2016; - from 1.11.2019 to 3.07.2020; - from 18.02 to 20.03.2021; - in November 2022; - from 23.06.2023; - from 30.07.2025.

The Shiveluch volcano (3283 m), with coordinates 56°38′ N 161°19′ E, has also been very active in the last decade [10].

This volcano erupted several more times during the period 2016-2025. Ash column emissions were observed: - 10.01.2016 to a height of 7 km; - 29.01.2016 - 10 km; - 24.02. 2017 - 5 km; - 15.06.2017 - 12 km; - 17.03.2019 - 4 km.

The most powerful eruption in the last decade was the one that began on 11.04.2023. The volcano also began to show activity on 14.07.2025.

On 3.08.2025, the Krasheninnikov volcano (54°35′36″ N 160°16′24″ E) began to erupt for the first time in the entire history of observations.

Another feature of the Kamchatka region is the increased frequency of powerful earthquakes [11]. The mentioned phenomena have been repeatedly recorded over the last decade.

Three earthquakes can be considered the strongest.

The epicenter of the first, which had a magnitude of 8.5 and occurred on February 3, 1923, was located on the bottom of the Pacific Ocean, in the area with coordinates 53°00′ N 161°00′ E. The second, with a magnitude of 6.9, occurred on June 5, 2023. Its epicenter was on the bottom of Avacha Bay, 64 kilometers from Petropavlovsk-Kamchatsky.

The most powerful earthquake was the third one, with a magnitude of 8.8. It occurred on July 30, 2025. The epicenter was also located on the bottom of the Pacific Ocean, at a point with coordinates 52°30′36″ N 160°15′40″ E. On the same day, the Klyuchevskaya Sopka volcano began to erupt, and on August 3, 2025, the Krasheninnikov volcano also began to erupt.

As follows from the above, all hazardous endogenous geological phenomena (hereinafter referred to as HGP) registered in the region for 2016-2025 occurred in the sector, the boundaries of which are the meridians 160°00′ E and 161°19′ E.

Many of them were accompanied by the release of significant energy and various substances that can influence the formation of negative ozone anomalies over the region.

According to existing ideas about the causes of ozone layer destruction, one of them is the occurrence of ozone elimination reactions in the atmosphere, in which hydrogen or hydroxyl OH participates as a catalyst[6-7,12-14].

The greater the reaction flows of such catalysts, the more intensively, all other things being equal, ozone is eliminated, which leads to a decrease in its total content (hereinafter TO).

Taking this into account, V.L. Syvorotkin established that one of the consequences of the activation of hydrogen degassing of the earth's interior, as a rule, is the formation of local negative ozone anomalies over the areas in which it occurs [8,15-17].

They have repeatedly noted the occurrence of such anomalies over regions where volcanic eruptions and powerful earthquakes have occurred, including over the Kamchatka region. At the same time, it has been established that such ozone anomalies can also occur in the atmosphere for other reasons.

At the same time, the probability with which negative ozone anomalies are formed during HGP in the Kamchatka region, as well as in other periods of time, has not been previously assessed. This does not allow for such consequences of HGP to be adequately taken into account when developing appropriate measures to protect the population from them.

The detection of the ozone anomalies under consideration is complicated by the fact that during an HGP, hydrogen from the earth's interior is mainly released not into the stratosphere, where ozone is mainly located, but into the troposphere. It can only enter the stratosphere directly when sufficiently high ash columns are emitted.

In the troposphere, the rise of hydrogen released into it, as well as its migration into the stratosphere, are significantly affected by circulation processes, many components of which change randomly. As a result, the areas of the earth's surface, over which a decrease in TO is observed after the HGP, do not always correspond to the points, where these HGP occurred.

Cyclones, monsoons, and the Pacific jet stream, the northern periphery of which is located above its southern regions, have a significant impact on the rise of hydrogen released from the surface of the Kamchatka region into the stratosphere.

Since the speed of this current can reach 25 m/s and more, its influence can lead to a decrease in the TO over areas of the earth's surface that are hundreds of kilometers away from the point where degassing occurred. Consequently, as a result of volcanic eruptions, two TO minima may form, differing in time.

After a powerful earthquake, the formation of one minimum of the TO, lagging behind it by a large amount, is more likely.

The directions and speeds of air flows in the troposphere and stratosphere are very variable, as are the reaction flows of substances participating in the destruction of stratospheric ozone.

Over time, the intensity of hydrogen degassing may also change unpredictably. As a result, changes in the TO over a particular area of the earth's surface should be considered as a random variable, the characteristics of which depend on the coordinates, month, and year.

One of the informative characteristics of this value can be the frequency with which the average daily TO over a certain area of the earth's surface in a certain month decreased below a certain level.

As follows from the above, it is permissible to assume that during periods of occurrence of HGP in the Kamchatka region, the values of the specified characteristic over some of its areas are on average significantly greater than in the intervals between them.

The hypothesis put forward is not trivial, since the reasons for the decrease in the TO, as noted above, can also be other processes. An example of them is landscape fires, during which the temperature of the underlying surface increases significantly.

As a result of the latter, thermal convection is activated, carrying pyrogenic substances into the upper layers of the troposphere, from where, as a result of the action of certain air exchange mechanisms[1,14], they can penetrate into the stratosphere and participate in the destruction of stratospheric ozone.

Ground monitoring of changes in TO over the Kamchatka region is carried out at the Petropavlovsk-Kamchatsky ozonometric station (53°01′ N 158°39′ E), located in the city of Petropavlovsk-Kamchatsky [18].

Remote measurements of this indicator over all areas of the earth's surface (including the region under study) are carried out using instruments installed on some artificial Earth satellites belonging to NASA (USA).

The most advanced of these instruments is the OMI (Ozone Monitoring Instrument), which was developed jointly by the Dutch Aerospace Agency, the Finnish Meteorological Institute, and NASA. Since 2004, it has been used to conduct daily monitoring of the TO over all areas of the Earth's surface measuring 0.25o x0.25o.

The OMI instrument measures and compares the spectral characteristics of sunlight scattered in the atmosphere and reflected from the Earth's surface in the wavelength range of 270-500 nm, with a spectral resolution of 0.5 nm and a spatial resolution of 13x24 km/1 pixel.

Comparison of these spectra allows us to obtain information about the distribution of ozone concentration in the atmosphere, which absorbs and scatters solar radiation with the corresponding wavelengths. Based on this information, the value of the TO, expressed in Dobson Units (Du), is calculated [19-20].

Information obtained by the OMI instrument for the period from October 2004 to the present, with a lag of about two days, is available on the EarthDATA GES DISC website.

The OMI instrument is installed on the AURA artificial Earth satellite, launched by NASA as part of the EOS (Earth Observing System) program on July 15, 2004, into a virtually circular orbit with the following parameters: eccentricity - 0.0002062, apocenter - 710 km, pericenter - 707 km, inclination - 98.1°, orbital period 98.82 min.

However, the validity of the proposed hypothesis has not been previously tested. Therefore, the purpose of this work was to test the proposed hypothesis using the example of changes in the TO that occurred over the Kamchatka region in the period 2016-2025.

To achieve this, the following tasks were solved:

1. Estimation of the delay times of the dates of occurrence of the nearest and main TO minima over different areas of the Kamchatka region, in relation to the date of the onset of the HGP.

2. Determination of the frequencies with which, in a certain month related to the studied period of time, the average daily TO over a particular point in the region decreased below the corresponding levels.

2. Factual Material and Research Methodoligy

To achieve the stated goal, as a source of information on changes in TO over the Kamchatka region, information [21] obtained using the OMI instrument (artificial Earth satellite AURA) for the period from 01.01.2016 to 31.08.2025 for all points in the region corresponding to the nodes of the coordinate grid with a step of 1o was used.

The admissibility of using the specified information as factual material has been confirmed by testing it, using information on the values of the TO measured at standard times at the Petropavlovsk-Kamchatsky ozonometric station.

An analysis of the factual material showed that information on average daily TO values over certain points in the region is missing from the specified source for many dates.

As an example, information on the number of omissions of such information in the specified factual material corresponding to 2020 for a particular month, as well as for some points in the region, is presented in Table 1.

Table 1. Number of omissions in information on the TO contained in [21] for some months of 2020 and points in the region located on the meridians 155° E and 161° E.

155ºE								
Latitude (ºN)	62	60	58	56	54	52	50	At all latitudes
January	13	3	2	4	4	7	6	78
February	0	0	0	2	4	4	5	30
March	0	0	0	2	4	6	6	36
April	0	1	1	4	5	5	7	46
May	0	0	0	2	4	4	6	32
June	0	0	0	2	3	4	6	30
July	0	0	0	2	5	5	6	36
August	1	0	1	2	4	5	6	38
September	0	0	0	2	4	4	6	32
October	0	0	0	2	4	4	6	32
November	5	9	6	2	5	4	6	74
December	28	4	7	6	7	6	6	128
Total	47	17	17	32	53	58	72	
161ºE								
Latitude (ºN)	62	60	58	56	54	52	50	At all latitudes
January	11	3	0	2	7	7	8	76
February	0	0	0	2	3	6	8	38
March	0	0	0	2	3	4	8	34
April	0	1	1	2	5	4	6	38
May	0	0	0	2	3	4	8	34
June	0	0	0	2	4	4	7	34
July	1	0	0	2	5	4	6	36
August	1	0	1	1	4	4	8	38
September	0	0	0	2	3	3	7	30
October	0	0	0	2	4	5	7	36
November	2	5	4	5	5	4	7	64
December	28	2	2	4	8	9	10	126
Total	43	11	8	28	54	58	90	

As we can see from Table 1, for December and January the number of gaps in the information under consideration is significantly greater than for other months.

The number of gaps is also increased in points located near the northern and southern borders of the region.

In other years, the distribution of gaps within the studied region has similar features. Therefore, the factual material can be considered quite reliable for the months from February to November and for latitudes from 55°N to 60°N.

Taking into account the specified features of the factual material, the frequency value of the studied event for a given month was calculated as the ratio of the number of days during which it was detected in that month to the total number of days in that month for which information on the TO values is presented in [21].

In solving the first problem, the time dependences of the average daily TO values for the entire period under study were considered, corresponding to all the points of the Kamchatka region taken into account. For each section, the time intervals were determined between the date of occurrence of a particular HGP and the dates on which the closest (c) and greatest (g) decrease in TO over it occurred.

The solution to the second problem was carried out in two stages.

At the first stage, threshold levels were determined, which were then used to evaluate the frequencies under study.

If the changes in any month of the average daily TO over different points in the region were samples of a normal random process, then their main statistical characteristics would be the mean value (m) and the standard deviation (σ).

In this case, the following levels could be considered as thresholds: X1 = m - σ; as well as X2 = m - 2σ, the probability of a decrease below which in the average daily TO would be 0.07 and 0.028.

It was assumed that in 2024, in which the HGP did not occur in the Kamchatka region, for any month the statistical properties of the TO changes are close to the properties of a normal random process.

In accordance with the Pearson criterion, such an assumption can be considered valid if the frequencies with which the TO for the corresponding point of the Kamchatka region and the month of 2024 (in which the TO was not recorded) are close to the specified values.

If in reality the actual values of the frequencies under consideration turn out to be significantly different, then the assumption about the normality of the process under study is incorrect, which, however, does not prevent the use of the selected levels X1 and X2 when solving the second problem.

At the second stage of its solution, for each month and each point, the frequency with which the average daily TO was below levels X1 and X2 was calculated.

The values of the frequency of decrease in the total atmospheric pressure for the months following the onset of a particular acute gas event occurring over areas of the region's surface close to its epicenter were compared with similar indicators for other areas and months.

The probability was assessed that the points and months in which the acute gas incidents occurred correspond to the maximum frequency of occurrence of the indicated events.

It is easy to see that the presented methodology allows for each section of the studied region, as well as for each month, to estimate the frequency with which the hypothesis put forward for them in the period 2016-2025 was fair. Therefore, it allows achieving the goal of this work.

It should be noted that the estimates of the studied frequencies obtained using it are inaccurate, since the information on the values of the TO, which were used to calculate them, do not correspond to any dates from the studied period, and the number of their omissions for a particular month in different years is different.

Therefore, it is advisable to consider the conclusions that this method allows to obtain as qualitative in nature.

3.Research Results and Their Analysis

Using the described methodology, for each period of the HGP and each point of the Kamchatka region, time shifts were determined between the start date of the corresponding process, as well as the dates on which the average daily TO values over it reached their minimums (the closest to the HGP date (c) and the main one (m)).

As an example, let us consider the time dependence of the average daily values of TO (Du) in the period before and after the Kamchatka earthquake of July 30, 2025, over points in the Kamchatka region located on the meridians of 155°N, 160°N and 163°N, as well as parallels from 49°N to 62°N with a step of 1°.

The time interval under consideration was chosen because a powerful earthquake occurred in the region during this period (July 30, 2025) and two volcanoes began erupting (Klyuchevskaya Sopka - July 30, 2025 and Krasheninnikova - August 2, 2025). As a result, the above-mentioned OGNs had a cumulative effect on the ozone layer over the Kamchatka region, the response to which could have been more noticeable.

The meridians under consideration, 155°E and 163°E, correspond to the western and eastern boundaries of the Kamchatka region, and the meridian 160°E is located near the epicenter of the mentioned earthquake and the craters of both erupting volcanoes.

The time dependences of the average daily values of TO (Du) in the period before and after the Kamchatka earthquake of 2025 over points in the Kamchatka region located on the indicated meridians and parallels are shown in Fig. 1

As can be seen from Fig. 1, the time dependences of the average daily values of TO (Du) in the period before and after the Kamchatka earthquake of 2025 over all the considered points of the Kamchatka region have the character of complex oscillations.

Directly on the date of 30.07, corresponding to this earthquake, as well as the beginning of the eruption of the Klyuchevskaya Sopka volcano, the minimums of the total atmospheric pressure were detected in some areas located directly near the points where the indicated HGP occurred (see Fig. 1e, 1f). Similar extremes in various points of the region were detected both before and after this date.

It is obvious that the response to any HGP can be the minimums of the TO that arise only after its onset. The question of whether the minimums of the TO that precede the onset of the HGP, can serve as its precursors requires additional study.

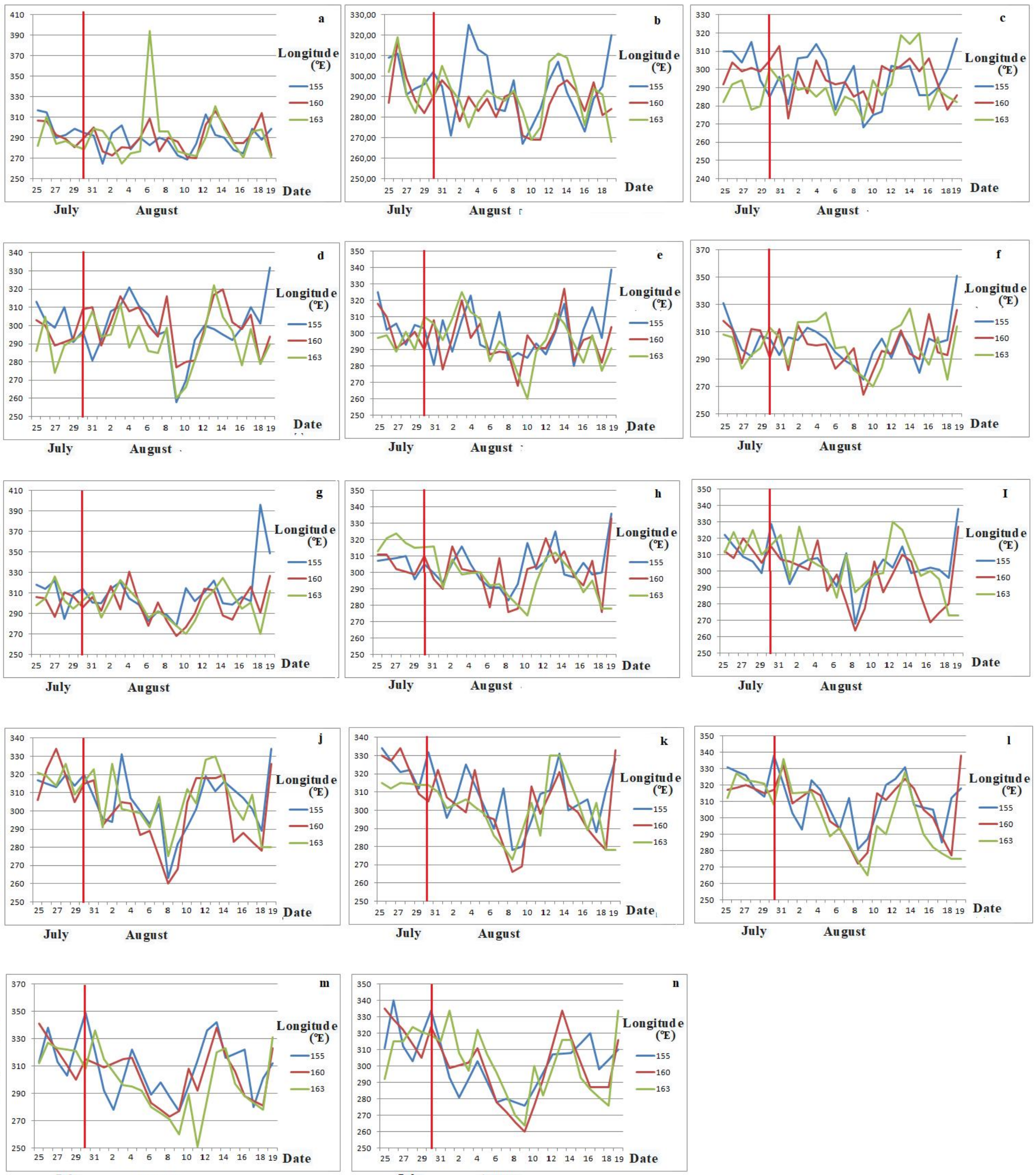

Fig. 1. Dependences on time of average daily values of TO (Du) in the period before and after the Kamchatka earthquake of 2025 over points of the Kamchatka region located on some meridians, as well as parallels:

a) 62° N.; b) 61 ° N; c) 60 ° N; d) 59°N; e) 58°N; f) 57°N; g) 56°N; h) 55°N;
i) 54°N; j) 53°N; k) 52°N; l) 51°N; m) 50°N; n) 49°N.

The vertical red line indicates the date 30.07.2025.

Immediately after 30.07.2025, one or another decrease in TO over all points in the region was observed on dates that were 2-3 days behind the indicated date. On such (nearest) dates, TO minima were detected at points located at parallels 56°-61°N. and 53°N.

Fig. 1b-1n indicate that the lowest TO values in the region for the period under consideration for most of its points correspond to August 8-10, 2025. Such a negative ozone anomaly occurs with a delay of 9-11 days in relation to the onset date of the HGP.

It is easy to see that the closer a certain point is to the epicenter of an earthquake or the mentioned volcano, the smaller the delay of the date corresponding to such a minimum of the TO in relation to 30.07.2025, and the absolute value of such a decrease in the TO is greater. This allows us to consider the identified anomalies as consequences of the HGP that occurred.

The formation of both minima of the TO with the indicated delays in relation to the moment of the onset of the HGP is possible, since the hydrogen released during these processes can enter the ozone layer (at altitudes of 23-28 km) only after some time.

As noted above, the eruption of the Klyuchevskaya Sopka volcano on July 30, 2035, began with the emission of a column of ash and volcanic gases to a height of 5-6 km above its summit (the height of which is 4750 m).

It is obvious that during this event, some of the hydrogen contained in the gases mentioned penetrated directly into the stratosphere. This hydrogen apparently reached the ozone layer over the region in 2-3 days, which led to the formation of the nearest minimum of TO.

A significant portion of the hydrogen that entered the troposphere during this eruption could have partially mixed with the air there. Therefore, it could have crossed the tropopause only with some delay.

The hydrogen released into the atmosphere during the earthquake, as well as during the subsequent eruption of the same volcano, apparently did not form such a powerful and consolidated stream, but entered the stratosphere as a result of the action of other, less rapid air exchange mechanisms [1, 14]. This is probably why the most significant decrease in TO over the region could have occurred later (August, 8-10).

The rise of hydrogen released from the earth's surface into the stratosphere was certainly influenced by the dynamics of the troposphere, to which, as is known [22-23], multi-scale turbulence makes a significant contribution.

At different moments in time, air currents existing in the troposphere above the region carried hydrogen released from its surface in different directions. The latter, apparently, led to the formation of the indicated responses to the HGP under consideration in the ozone layer over almost the entire Kamchatka region.

Similar features were revealed in all other above-mentioned HGP that occurred here for the period from January 2016 to August 2025.

Table 2. Values of delays in the dates of the onset of the nearest (c) and main (m) TO minima over points in the Kamchatka region located at different latitudes, which arose after the formation of some HGP in it.

Start date HGP	3.02.23		11.04.23		5.06.23		30.07.25	
latitude north	б(days)	г (days)	б (days)	г(days)	б (days)	г(days)	б (days)	г (days)
62°	4	4	4	8	6	19	3	11
61°	4	4	4	11	6	19	3	11
60°	4	4	4	8	3	19	2	10
59 °	4	4	3	11	3	30	2	10
58 °	4	4	3	18	3	30	2	10
57 °	4	4	3	18	3	30	2	10
56 °	4	4	3	7	3	30	2	9
55 °	4	4	3	16	3	31	2	9
54 °	4	4	3	16	3	33	2	9
53 °	4	4	3	16	4	32	2	9
52 °	11	11	3	16	4	31	5	9
51 °	3	3	3	15	4	34	2	10
50 °	3	3	3	15	6	19	5	9
49 °	3	3	3	15	6	19	2	10

As follows from Table 2, during the HGP that arose in the Kamchatka region in the summer months (with the dominance of the summer monsoon and cyclones over it), the response to them was the formation of two TO minima, lagging behind the dates of the corresponding events by units of days and units of weeks.

When the HGP form here in the winter months (during the period of dominance of the Siberian anticyclone periphery over the region), the nearest minimum of TO over all points of the region coincides in time with the main minimum, which is apparently explained by the indicated feature of atmospheric circulation.

When solving the second problem, for each point in the Kamchatka region and each month related to 2024 (in which the HGP was not registered), the average values and standard deviations of the average daily TO were determined, which were used to determine the threshold levels of TO X1 and X2.

The Examples of the values of the indicated levels corresponding to certain months for points in the region located on the 161st meridian (near which the HGP occurred) and at various latitudes are given in Table 3.

Table 3. Examples of the values of X1 and X2 for different months and for points in the region located on the meridian of 161°E, as well as on some parallels.

	X_1(Du)						X_2(Du)					
Latitude (°N)	62	57	56	55	52	49	62	57	56	55	52	49
January	429,3	416,4	408,5	409,1	411,2	408,2	392,4	374,5	363,7	365,8	374,4	379,6
February	468,9	459,8	453,5	455,3	453,9	426,3	434,8	416,2	407,1	405,5	408,4	381,4
March	419,1	431,7	436,6	439,5	435,1	441,8	388,1	402,6	410,9	413,4	402,7	410,4
April	415,3	401,1	392,9	388,8	391,5	385,7	382,2	365,3	355,1	349,5	351,9	346,1
May	389,7	385,9	380,7	378,9	366,3	359,7	363,4	353,3	345,1	342,1	321,1	316,9
June	364,7	373,0	373,3	372,9	367,4	363,3	340,5	355,5	355,3	353,7	344,3	336,4
July	322,4	319,1	322,4	321,0	329,5	311,8	299,1	295,6	300,9	297,6	304,4	278,3
August	312,9	304,0	301,3	301,4	289,0	274,5	293,5	284,9	281,9	283,2	269,7	252,2
September	302,1	305,2	306,7	306,6	300,2	292,4	276,2	276,7	278,1	275,5	270,9	263,6
October	325,6	310,9	303,6	298,8	279,7	264,8	299,7	283,2	276,4	271,3	247,7	232,4
November	350,3	352,4	353,6	354,4	349,5	339,3	310,2	323,9	327,8	329,2	323,5	313,8
December	395,4	400,1	397,7	400,1	389,6	386,6	366,6	372,3	367,9	370,7	356,5	358,8

It has been established that for the months of 2024, the frequencies of the decrease in the average daily TO below the levels X1 and X2 for all the points in the Kamchatka region under consideration are significantly higher than 0.07 and 0.028. Consequently, in reality, the probability distribution of TO for such points and months differs significantly from Gaussian.

Also, for each month related to the period January 2016 - August 2025 and each point of the Kamchatka region, the frequency of the event was determined in which the average daily value of TO decreased below levels X1 or X2.

As an example, Fig. 2 shows the time dependence of the frequency of an event in which the average daily value of the TO over points located at parallels 56°N and 49°N, as well as at the meridian 161°E, decreased below the X1 levels.

From Fig. 2 it follows that the dependences of the frequencies of the event under consideration on time for points in the Kamchatka region located at parallels 56°N and 57°N, as well as at meridians 157°Eh, 161°E and 163°E have significant similarities.

Even without taking into account the maxima that occur in December and January of each year, it follows from Fig. 2 that the maxima that do not correspond to the beginning of any HGP constitute before to 75% of their total number. “Before” because active hydrogen degassing of the earth’s interior with varying intensity occurred not only in the months in which the eruptions began, which could also lead to the formation of some maxima.

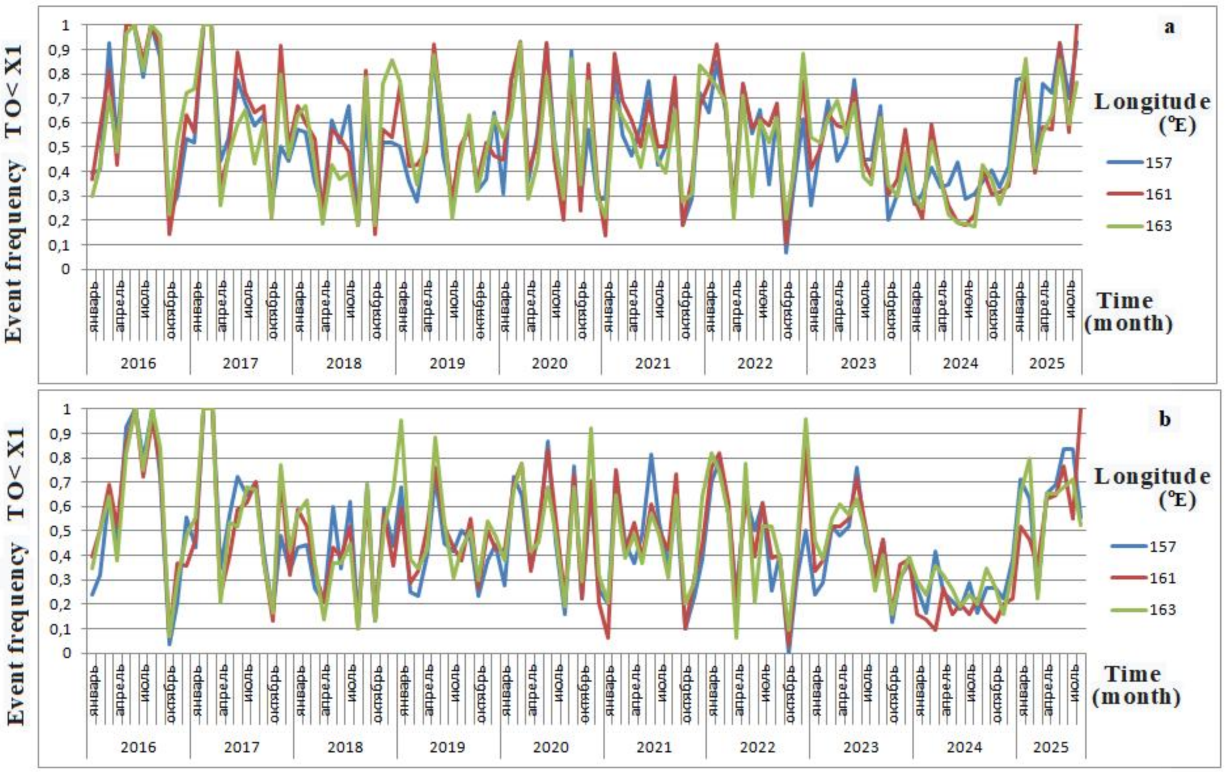

Fig. 2. Time dependences of the frequencies of decreases in average daily TO values below the X1 levels that occurred during the period from January 2016 to August 2025 for points in the Kamchatka region located on the indicated meridians and parallels:

a) 56°N; b) 57°N.

At the same time, the graphs presented in Fig. 2 contain maxima that fall on periods when the previous HGP, according to available data, has ended, and the next HGP has not yet begun.

For example, in 2025, the maximums of the indicator in question occurred not only in August (immediately after the Kamchatka earthquake of July 30 and the beginning of the eruption of the Klyuchevaya Sopka and Krasheninnikov volcanoes), but also in January and June.

If the maximum corresponding to January can be considered as a consequence of a significant number of gaps in the initial data (of which there were 11), then the existence of the maximum corresponding to June is beyond doubt. Therefore, such events require an explanation.

An analysis of similar dependencies corresponding to all 126 points of the Kamchatka region under consideration made it possible to identify such "advancing" maxima for all powerful earthquakes detected in it in 2016-2025.

It is also clear from Fig. 2 that the absolute majority of maxima and minima of the dependencies under consideration, corresponding to points, located on different parallels and meridians, coincide in time. The same coincidences were also found for other points in the region.

It follows from this that changes in the TO over all points of the Kamchatka region are caused by the action of the same factors.

One of these factors here, as in other regions of the world, is probably variations in the characteristics of atmospheric circulation due to the change of seasons, but there may be others. The latter may include changes in the intensity of hydrogen degassing of the earth's interior that are occurring in the Kamchatka region.

To confirm the presence of a connection between the identified "advancing" maxima and the HGP, the time dependences of the frequency values with which the decrease below the X1 levels of average daily TO occurred over various points in the Kamchatka region were compared for the months corresponding to the onset of any HGP, and for the months advancing them by 2 months.

As an example, Fig. 3 shows the dependences on longitude of the frequency values with which the average daily TO for August and June 2025, over points in the Kamchatka region located on some parallels, decreased below the X1 levels.

As can be seen from Fig. 3a, in the northern part of the Kamchatka region (at parallels 60°N - 62°N), in August 2025, the average daily TO decreased below the X1 levels most often at points located at the meridians 160°E - 162°E. The frequency of such events was 1. At other points in the region located at the same parallels, its values were within the range of 0.79 - 0.95.

It is evident from Fig. 3b that for June 2025, no maxima of the frequency of the events under consideration were detected on the same parallels and on the meridians 160th - 162nd. Moreover, the minima of the dependencies under consideration correspond to the meridian 161st.

From Fig. 3c it is clear that at the parallels 56°N–57°N, the event in question occurred in August with a frequency of 1 at points located on the meridians 161°E–162°E. For points located on other parallels, the values of the indicator in question were 0.5–0.92.

As follows from Fig. 3g, in June 2025 the same event occurred with a frequency of 1 at points located on the meridians 161°E - 162°E.

Fig. 3d shows that at the parallels 52°N - 54°N the highest values of the studied frequency (0.8 and 0.85) in August were achieved at the meridians 160°E and 163°E.

Fig. 3e allows us to establish that for June the studied event on the same parallels was recorded with a frequency of 1 on the meridians 155°E-157°E, 160°E, 161°E and 163°E, and on other meridians with a frequency of no less than 0.85.

From Fig. 3f it follows that on the parallels 49 °N - 51°N the maximum values of the considered frequency (0.78 - 0.82) were achieved on the meridians 159°E and 160°E.

From Fig. 3g it is easy to conclude that on the same parallels the values of the studied frequency, which correspond to points located on any meridians, did not decrease below 0.85.

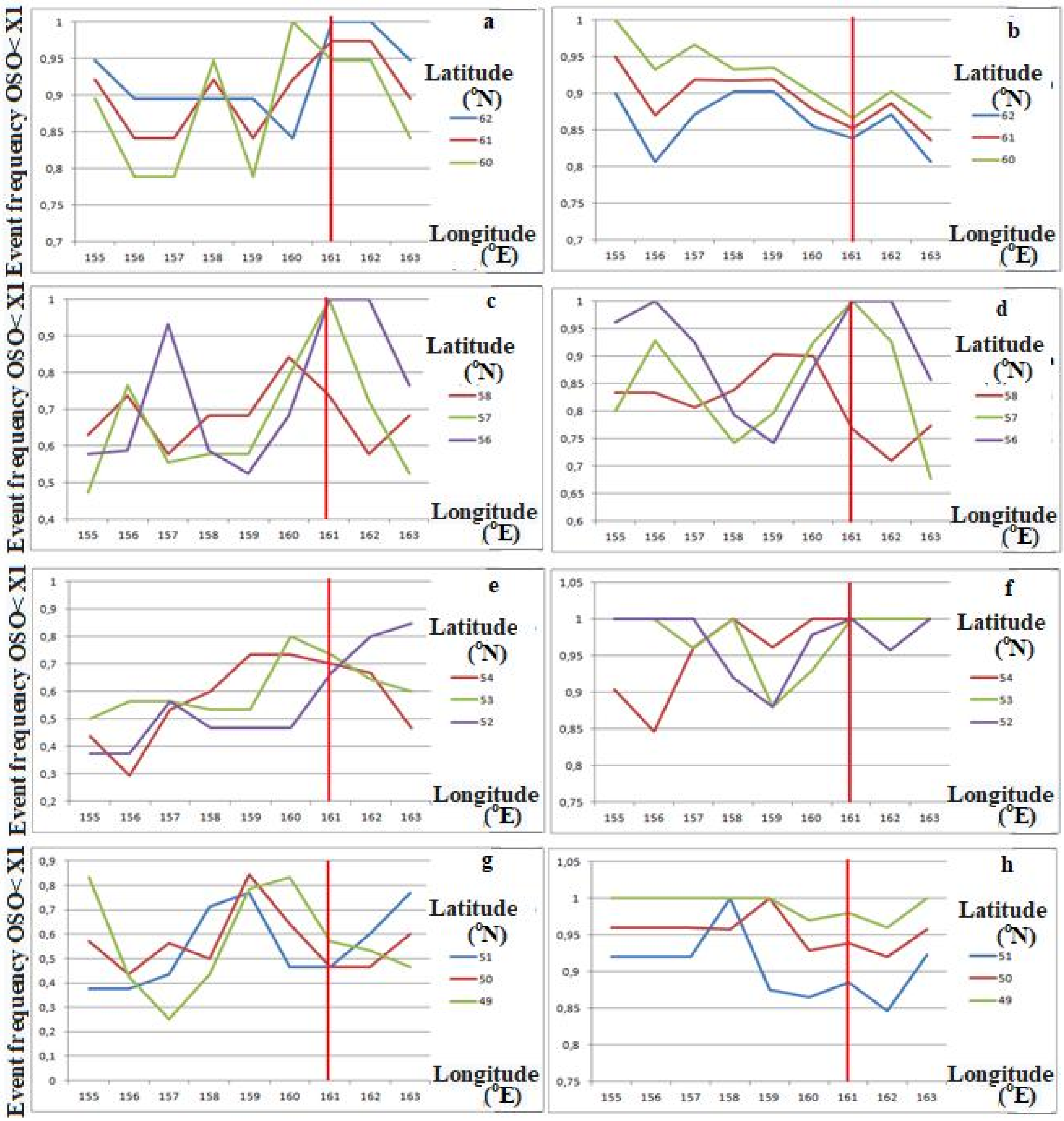

Fig. 3. Longitude dependences of the frequency values with which the average daily TO decreased below the X1 levels for points in the Kamchatka region located on the parallels:

for August 2025, for June 2025.

a) 60°N, 61°N, 62°N, b) 60°N, 61°N, 62°N

c) 56°N, 57°N, 58°N., d) 56°N, 57°N, 58°N,

e) 52°N, 53°N, 54°N, f) 52°N, 53°N, 54°N,

g) 49°N, 50°N, 51°N, h) 49°N, 50°N, 51°N.

Thus, from Fig. 3 it is obvious that in the entire Kamchatka region, both in June and in August 2025, the average daily TO decreased below the X1 levels most often at points located on meridians close to 161°E (near which are the craters of both awakened volcanoes and the epicenter of the earthquake).

Figure 4 shows the dependences of the frequency with which the average daily TO for August 2025 and June 2025 over points in the Kamchatka region located on some meridians decreased below levels X1 or X2.

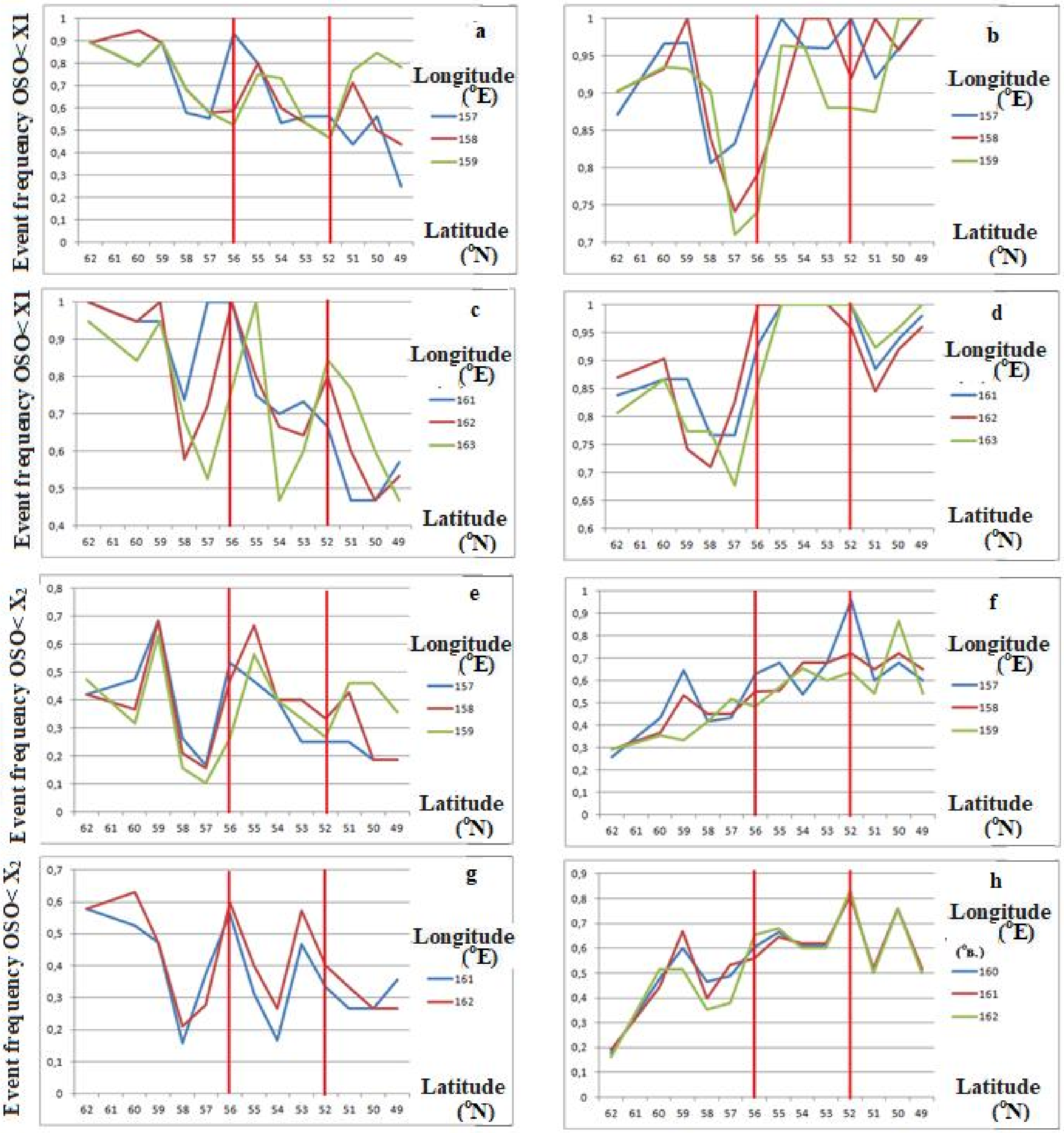

Fig. 4. Dependences on latitude of the frequency with which the average daily TO for August and June 2025, over points in the Kamchatka region located on some meridians, decreased below the levels:

August 2025: a) and c) X1; e) and g) X2.

June 2025: b) and d) X1; f) and h) X2.

Red lines show the parallels near which erupting volcanoes and the earthquake epicenter are located.

As follows from Fig. 4, on all the meridians under consideration, the highest values of the frequency of the studied events for August correspond to the parallels 55°N - 57°N, as well as the meridian 161°E, near which the Klyuchevskaya Sopka and Krasheninnikov volcanoes are located.

For June, the frequency maxima of the same events correspond to the 52°N parallel, near which the epicenter of the Kamchatka earthquake is located.

Fig. 4a shows, that on the same parallels, for the meridians 157 ° E -159 ° E, the frequency maxima of the same event are 0.75-0.92.

From Fig. 4b it is clear that for June, on the same parallels and meridians, the frequency values of the event in question are greater than in August, and on the parallel of 52°N. this indicator is equal to 1.

As can be seen from Fig. 4c, for the indicated parallels and meridians 161°E - 163°E, the value of the frequency of the decrease in the total ozone for August 2025 below the X1 level is equal to 1.

The same values are reached by the frequency under consideration at the parallels 62°N - 60°N (however, the number of gaps in the initial data for these parallels is greater, as a result of which the given estimate is obviously less accurate).

As follows from Fig. 4e, for the same parallels and meridians, the value of the frequency of the decrease of the TO below the level X1 is also equal to 1.

From Fig. 4d it is evident that the highest value of the frequency of decrease in the TO corresponding to August, below the X2 level, was revealed for points of the Kamchatka region located on the meridians 157°E - 159°E and parallels 55°N and 56°N.

Fig. 4f shows that for June 2025 the maximum of the same indicator, equal to 0.95, corresponds to the parallel 52°N and the meridian 157°E.

Fig. 4g shows that for August 2025 the frequency maxima of the event under consideration correspond to parallels 56°N and 53°N and meridians 161°E and 162°E.

From Fig. 4h it is clear that for June of the same year the frequency maxima of the event under consideration correspond to points in the Kamchatka region located on the 52°N parallel north latitude on the 160°E and 162°E meridians. The values of the studied indicator corresponding to the indicated maxima are equal to 0.8.

From Figs. 3 and 4 it is evident that the identified maxima of the frequency of decrease in TO, corresponding to August, below the level of X1 and X2 for points in the Kamchatka region located on meridians and parallels close to the coordinates of the Klyuchevskaya Sopka and Krasheninnikov volcanoes, correspond to existing ideas about the influence of active hydrogen degassing on the destruction of stratospheric ozone [8,15-17].

At the same time, the established existence of a similar maximum for June, corresponding to points located near the epicenter of the Kamchatka earthquake, is an unexpected fact.

As the analysis of similar dependencies corresponding to previous years showed, the identified patterns also appear for other earthquakes in the region.

This is confirmed by Fig. 5, which shows the time dependence of the frequency of decrease below the X1 levels of the average daily values of the TO over points located at different parallels and on the meridians 155°E, 160°E and 161°E, for the period January 2023 – August 2025.

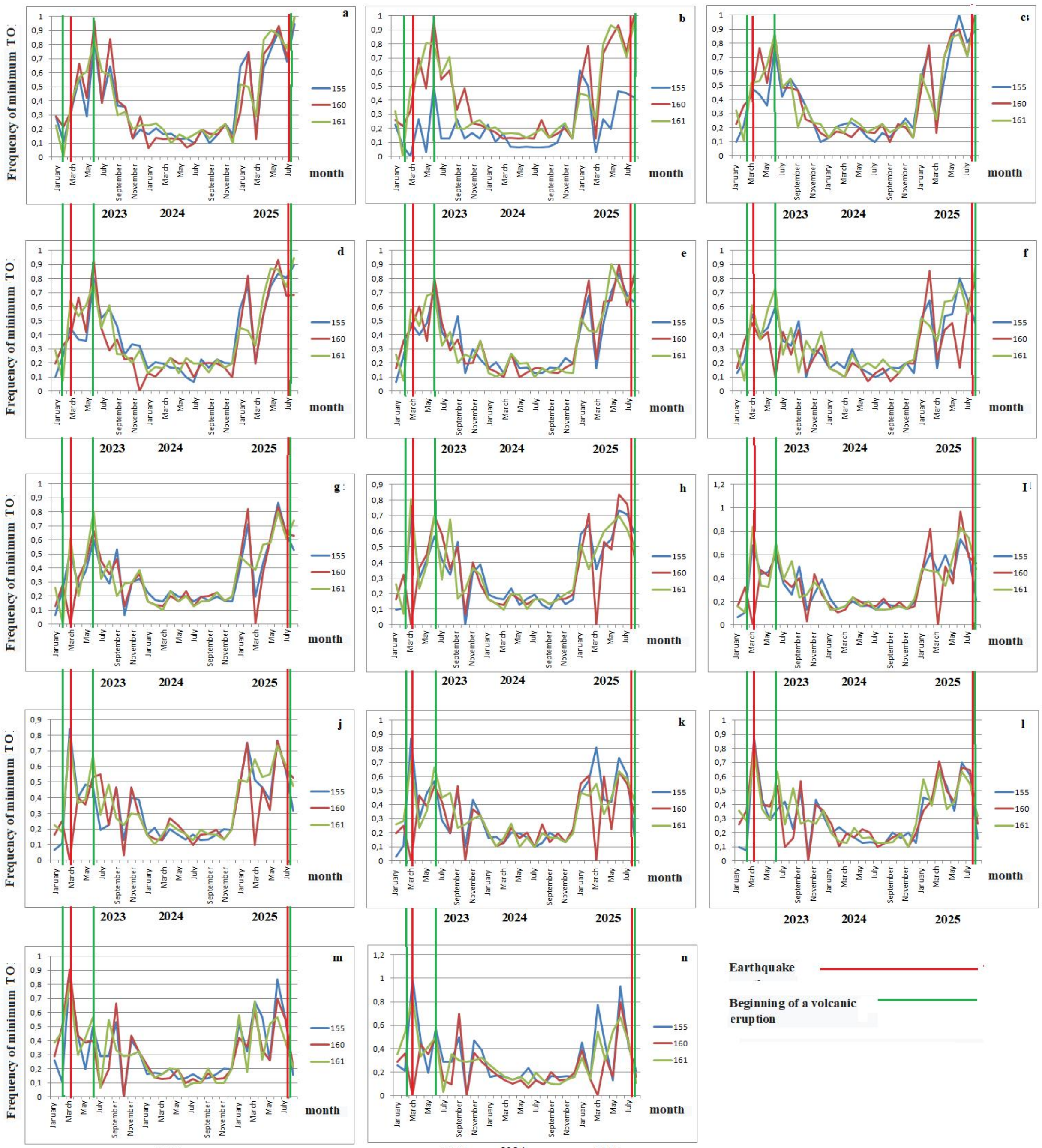

Fig. 5. Time dependences of the frequency of decrease below level X1 of average daily TO over points of the Kamchatka region located at latitudes

a) 62N; b) 61N; c) 60N; d) 59N; e) 58N; f) 57N; g) 56N; h) 55N;

i) 54N; j) 53N; k) 52N; m) 51N; m) 50N; n) 49N.

As can be seen from Fig. 5, for all points in the Kamchatka region located on the meridians and parallels under consideration and for any month of 2024, the frequency of decreases in the average daily TO below the X1 level is significantly less than for the months of 2023 and 2025, in which the HGP under consideration occurred.

At all the parallels under consideration located to the south of 57°N, the studied dependencies contain maxima that coincide in time with the months for which the earthquakes of 2023 and 2025 occurred in the Kamchatka region.

Maxima corresponding to the April 2023 eruption of Shiveluch volcano and the July 2025 eruptions of Klyuchevskaya Sopka and Krasheninnikov volcanoes were also identified.

Maxima, which are 2 months ahead of the Kamchatka earthquake (2025), were found at parallels located south of 55°N, by 7 months (January) at all parallels.

Maxima, which precede the earthquake of 2023 by 2 months, were also found at parallels 55°N - 57°N (the reliability of this conclusion is reduced, since there were many gaps in the information on the TO for January). Similar maxima, which precede it by 7 months, were found for all parallels. Maxima, which precede the onset of volcanic eruptions, were not found.

Thus, the validity of the proposed hypothesis is confirmed, and the goal of the study is achieved.

4. Discussion of the Results Obtained

It follows from the results obtained that, in general, they confirm the validity of the conclusions [8,15-17] about the role of hydrogen degassing of the earth's interior in the ongoing changes in the state of the ozone layer. At the same time, some of the established facts are scientifically novel. These include:

1. Estimates of the time shifts between the dates on which the HGP occurred in the Kamchatka region, as well as the dates of the formation of a negative ozone anomaly over it.
2. Estimates of the frequencies with which a decrease in average daily TOC values below selected levels occurred over various areas of the Kamchatka region's surface in certain months of 2016–2025, confirming the idea that in a year when OHS did not occur here, the mentioned events occur less frequently.
3. Locations of areas of the Kamchatka region over which, when the considered HGP occur, the frequency of decreases in average daily TO values below the selected levels increases significantly.
4. Along with the maxima of the mentioned frequencies, for the months in which the beginnings of the considered HGP occur, which allow for interpretation as responses of the ozone layer to the process of hydrogen degassing of the earth's interior in the region, there are also their maxima, which precede the earthquakes occurring here by 2, and possibly by 7 months. In such months, the highest values of the frequencies under consideration were found for the same areas of the region where similar maxima occur immediately after earthquakes that occurred in it.

The reasons for the existence of "advancing" maxima require additional study. The established facts allow us to assume that the occurrence of a negative ozone anomaly over a region may serve as a harbinger of the occurrence of a powerful earthquake on the corresponding section of its surface.

5. Conclusions

Thus, experimental confirmation has been obtained of the validity of the idea that one of the reasons for the emergence of a negative ozone anomaly over the Kamchatka region is the increased intensity of hydrogen degassing of the earth's interior, which occurs during volcanic eruptions and powerful earthquakes that occur here.

1. It has been established that the response of the ozone layer to the indicated events in the Kamchatka region is, with high probability, a significant increase in the frequency with which the decrease in average daily values of the total ozone content occurs, not only directly above their epicenters, but also above many other areas.

2. During volcanic eruptions and earthquakes in the region that occur in the summer months, two "waves" of stratospheric ozone destruction occur over most areas of its surface. The first lags behind the date of the event by 2-4 days, and the second by 8-30 days. In the winter months, with the same phenomena, as a rule, only one such "wave" occurs.

3.Changes in the distribution of total ozone content over the Kamchatka region, occurring before the onset of powerful earthquakes in it, have statistical properties that allow them to be considered as precursors of such events, preceding their onset by a certain time and approximately indicating the area in which they may occur.

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Competing Interest

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