ISSN 0016-7932, Geomagnetism and Aeronomy, 2018, Vol. 58, No. 4, pp. 548–553. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © G.A. Mikhailova, O.V. Kapustina, Yu.M. Mikhailov, S.E. Smirnov, 2018, published in Geomagnetizm i Aeronomiya, 2018, Vol. 58, No. 4, pp. 567–572.

Features of the Atmospheric Temperature Variations Prior to Strong Earthquakes in Kamchatka and Their Relation to the Fluxes of Outgoing Infrared Radiation

G. A. Mikhailova[a], O. V. Kapustina[a], Yu. M. Mikhailov[a, *], and S. E. Smirnov[b, **]

[a] *Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, the Russian Academy of Sciences (IZMIRAN), Moscow, Troitsk, 1008840 Russia*

[b] *Institute of Space Physics Research and Radio Wave Propagation, Far Eastern Branch of the Russian Academy of Sciences, Paratunka, 684034 Russia*

**e-mail: yumikh@izmiran.ru*

***e-mail: sergey@ikir.ru*

Received May 25, 2017; in final form, March 20, 2018

Abstract—The temperature variations of the near-surface atmosphere in Kamchatka at Paratunka observatory and fluxes of outgoing infrared radiation prior to strong Kuril earthquakes (November 15, 2006, $M = 8.3$; January 13, 2007, $M = 8.1$) have been analyzed. It is shown that the radiation fluxes at ground level, as measured on satellites above the epicenter of earthquakes and above a remote observatory, coincide with each other, both in magnitude and in the feature of their time variations. The temperature measured directly at the observatory and the temperature at surface level estimated from satellite observations differ in magnitude, but they coincide in the feature of their time variations. The detected temperature increase (despite the negative regular trend at this time of year) is caused by the appearance of an additional heat source entering in the near-surface atmosphere. This result, together with the studies of variations of various geophysical data before strong earthquakes performed earlier in Kamchatka, led to the conclusion that the additional heat source is in the Earth's crust.

DOI: 10.1134/S0016793218040096

1. INTRODUCTION

Unusual variations of various geophysical data prior to strong earthquakes (EQs) with a magnitude of $M \geq 7$ in Kamchatka were occasionally observed relatively long ago and were considered an EQ precursor. For example, unusual variations of the quasistatic electric field were recorded a few days before the strong EQ on November 13, 1993, $M = 7.0$ (Rulenko et al., 1996); December 5, 1997, $M = 7.7$ (Buzevich et al., 1998); November 15, 2006, $M = 8.3$; January 13, 2007, $M = 8.1$; January 30, 2016, $M = 7.2$ (Smirnov et al., 2017). These signals have the time form of large intensity oscillations typical for conditions of a local thunderstorm activity (Smirnov, 2008; Mikhailova et al., 2010). These studies also noted the increasing of natural electromagnetic radiation of a pulsed pattern at frequencies $f = 1.2$ kHz (Rulenko et al., 1996); $f = 0.6$ kHz (Buzevich et al., 1998); $f = 0.45$ kHz (Gavrilov et al., 2007), which is caused by local thunderstorm activity. An increase in the volumetric activity of radon and thoron in subsoil gas and in the air near the surface was detected prior to of the EQs of December 5, 1997, $M = 7.7$ (Buzevich et al., 1998) and March 11, 2011, $M = 9$ (Rulenko and Kuzmin, 2015). Anomalous phenomena were also observed in hydrodynamic processes. For example, a decrease in groundwater levels was recorded in two self-extinguishing wells before the EQ of December 5, 1977 (Kopylova and Boldina, 2012). Taking into account the data from GPS stations, it was shown that the effect was caused by expansion of the volumes of water-bearing rocks in the process of crack formation. Similar effects of lowering well-water levels were also registered prior to of the EQs on June 21, 1996, $M = 7.0$ (Tronin et al., 2004), November 15, 2006, $M = 8.3$ (Gavrilov et al., 2007), and before a series of strong EQs (Kopylova and Serafimova, 2007).

Particular attention should be paid to variations in meteorological data (temperature, pressure, air humidity, and wind speed) that directly affect electrical and electromagnetic processes in the near-surface atmosphere. For example, a sharp increase in atmospheric temperature to $T \sim 0°$ C (at an average seasonal level of -15 to $-18°$) and the precipitation of heavy rainfall was observed in (Buzevich et al., 1998) with three-hour values recorded at a local meteorological station two weeks prior to the EQ. Since these processes developed against a powerful chromospheric flare, the authors believed that it was its action that led to the redistribution of global atmospheric circulation and the intensification of cyclonic activity. In another case (Rulenko and Kuzmin, 2015), prior to a strong EQ, there were high levels of temperature and relative humidity and strong variations in atmospheric pressure, which the authors associated with the transit of a cyclone.

In simultaneous measurements of air temperature, temperature, and water flow rate in the wells prior to the EQ on June 21, 1996, $M = 7.0$ (Tronin et al., 2004), the water temperature gradually increased two weeks prior to it, reached a maximum before, and fell abruptly to the original level at the time of the EQ. During this time, the water flow rate changed insignificantly, but it increased dramatically at the time of the EQ. The feature of the water temperature change coincided with a thermal anomaly of the atmosphere on the Earth's surface, which was estimated from satellite measurements of infrared radiation fluxes.

A more complete study of the variations of electrical and meteorological parameters in Kamchatka prior to strong EQs was performed by Smirnov et al. (2017). The present work is a continuation of this research and is devoted to a detailed study of the features of temperature variations and their relation to variations in the fluxes of outgoing infrared radiation measured on meteorological satellites.

2. ORIGINAL EXPERIMENTAL DATA

Below, we consider the diurnal variations in the near-surface atmospheric temperature measured by a WS-2000 digital weather station with a time resolution of 10 min at the Paratunka observatory of the Far Eastern Branch of the Russain Academy of Sciences (φ = 52.97° N; λ = 158.25° E) prior to two strong Kuril EQs with a magnitude of $M > 8$ in 2006 and 2007.

Data obtained at the Earth System Research Laboratory (ESRL) of the Physical Sciences Division (PSD) in NOAA (https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html) were used to compare these values with the fluxes of outgoing infrared radiation. Examples of the daily mean values of radiation flux and temperature at ground level in the range of latitudes 40°–60° N and longitudes 150°–170° E are shown in Fig. 1a and 1b, respectively. It is known that the thermal radiation detected by meteorological satellites includes the heat flux coming directly from the ground, from the lower layers of the atmosphere, and from the clouds. Spatial and temporal variations of this radiation are of the greatest interest for its connection with seismic activity. For this purpose, we read the flux and temperature values from Fig. 1 for each day at the epicenters of EQs and in the remote observatory. Below, we consider in detail the relationship of these values to the temperature variations measured directly in the Paratunka observatory.

1. EQ on November 15, 2006: $t = 1114$ UT; $M = 8.3$; h = 30.3 km; φ = 46.614° N; λ = 153.23° E ($R = 10^{0.43M} = 3707$ km, $r \sim 800$ km, where R is the radius of the seismically active zone in the Earth's crust prior to the EQ (Dobrovolsky et al., 1979); r is the distance from the observatory to the epicenter. The epicenter was located on the island slope of the central zone of the Kurile-Kamchatka Trough, 170 km from the Simushir Island of the Kuril Chain. Figure 2a shows that the radiation fluxes measured in the epicenter (points) and in the observatory (crosses) coincide both in magnitude and in the form of temporal variations, despite their spatial separation. This result indicates a large spatial scale of the phenomenon, thus confirming the conclusions of Dobrovolsky et al. (1979). Figure 2b shows the diurnal temperature variations in the observatory measured with a time step, $\Delta t = 10$ min (curve *1*), the daily average values in November (averaged over 2009–2016, curve *3*), and the daily average values at ground level (curve *2*) estimated from satellite data. It can be seen that a regular diurnal variation with a maximum at the local noon (0130 UT) and a minimum before the sunrise is observed on curve *1* in the period from November 2 to November 7 under "fair weather" conditions (see Smirnov et al. (2017)). This diurnal variation began to be violated on November 7, and the temperature subsequently increased further on from 0° to 6°C until November 16 (the moment of the main shock of the EQ), despite the negative trend at this time of year (www.gismeteo.ru). The positive temperature trend observed during this period is apparently caused by the inclusion of an additional heat source that continued to operate for some time and after the EQ on November 16. "Fair weather" conditions then occurred in the near-surface atmosphere. Simultaneously, a similar positive trend was also observed for temperatures estimated at the observatory level from satellites (curve *2*).

2. EQ on January 13, 2007: $t = 0423$ UT; $M = 8.1$; $h = 10$ km; φ = 46.48° N, λ = 154.07° E ($R = 3041$ km, $r \sim 850$ km). Figure 3 shows a sequence of plots similar to those in Fig. 2. The fluxes of outgoing infrared radiation in the epicenter (points) and in the observatory (crosses) coincide with each other, both in magnitude and in the feature of temporal variation, but they differ from the previous case. The time variations in the temperature are also close in feature in this combination of quantities (curves *1* and *2*). On January 3 and 4, there were "fair weather" conditions in the atmosphere with a regular daily temperature change from –15°C at the maximum to –27°C at the minimum. On January 5, an additional heat source appeared; it operated until January 13. As a result, the temperature rose to –10°C and then reached a maximum of 0°C 6 days prior to the EQ. Unlike the previous case, the temperature changes were less regular in time relative to the daily average curve estimated for the period 2009–2017.

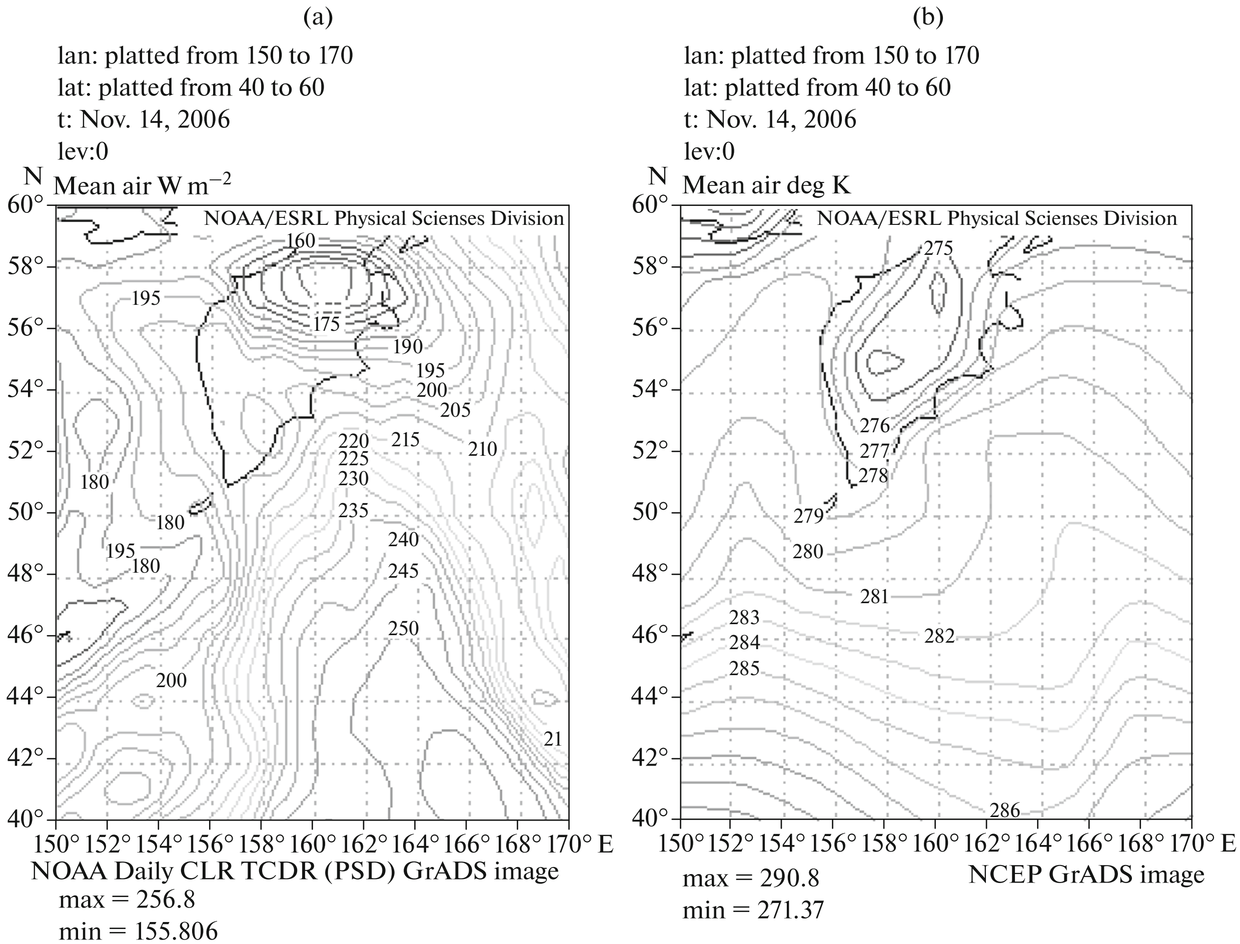

Fig. 1. (a) Daily average flux of outgoing infrared radiation and (b) temperature near the Earth's surface in the range of latitudes 40°–60° N and longitudes 150°–170° E above the epicenter of EQs and over the Paratunka observatory.

3. RESULTS DISCUSSION AND CONCLUSIONS

The Kamchatka Peninsula has its own characteristic features of geological structure: high seismic activity, the presence of active volcanoes and geothermal sources. The studied processes have been proceeding against this background. Analysis of the temporal variations in the temperature and humidity of the atmosphere showed that an additional heat source was initiated a few days prior to strong EQs. This source significantly changed their diurnal variation: a high atmospheric humidity occurred during the period of increased temperature, contrary to its regular diurnal variations (Smirnov et al., 2017). As a result, conditions of local thunderstorm activity formed in the near-surface atmosphere. It manifested itself in temporal variations of the quasistatic electric field and in increasing of the natural electromagnetic radiation of impulse nature in the range of extremely low-frequency waves (see references in the Introduction). However, the natural thermal energy coming from the Sun is clearly not enough for initiation of thunderstorm processes in November and January. Therefore, the presence of an additional heat source is required. This source can be cyclones, which are known to carry warm air masses and dense clouds, and, when they collide with a mass of cold air, can cause frontal thunderstorms. In our case, these were local thunderstorms. Moreover, during cyclone development, negative trends in the pressure and temperature of the near-surface atmosphere are observed (Matveev, 1965). In our case, as shown by Smirnov et al. (2017), conversely, a positive temperature trend was observed at a fairly stable pressure except for short-term deviations caused by thunderstorm activity. This difference in the character of the processes, with consideration of their time relative to the shock of EQ, allowed us to reject the cyclonic nature of the additional heat source in the near-surface atmosphere in the considered cases.

In the development of the assumption on the different nature of an additional source of heat, special attention should be paid to the results of studies in

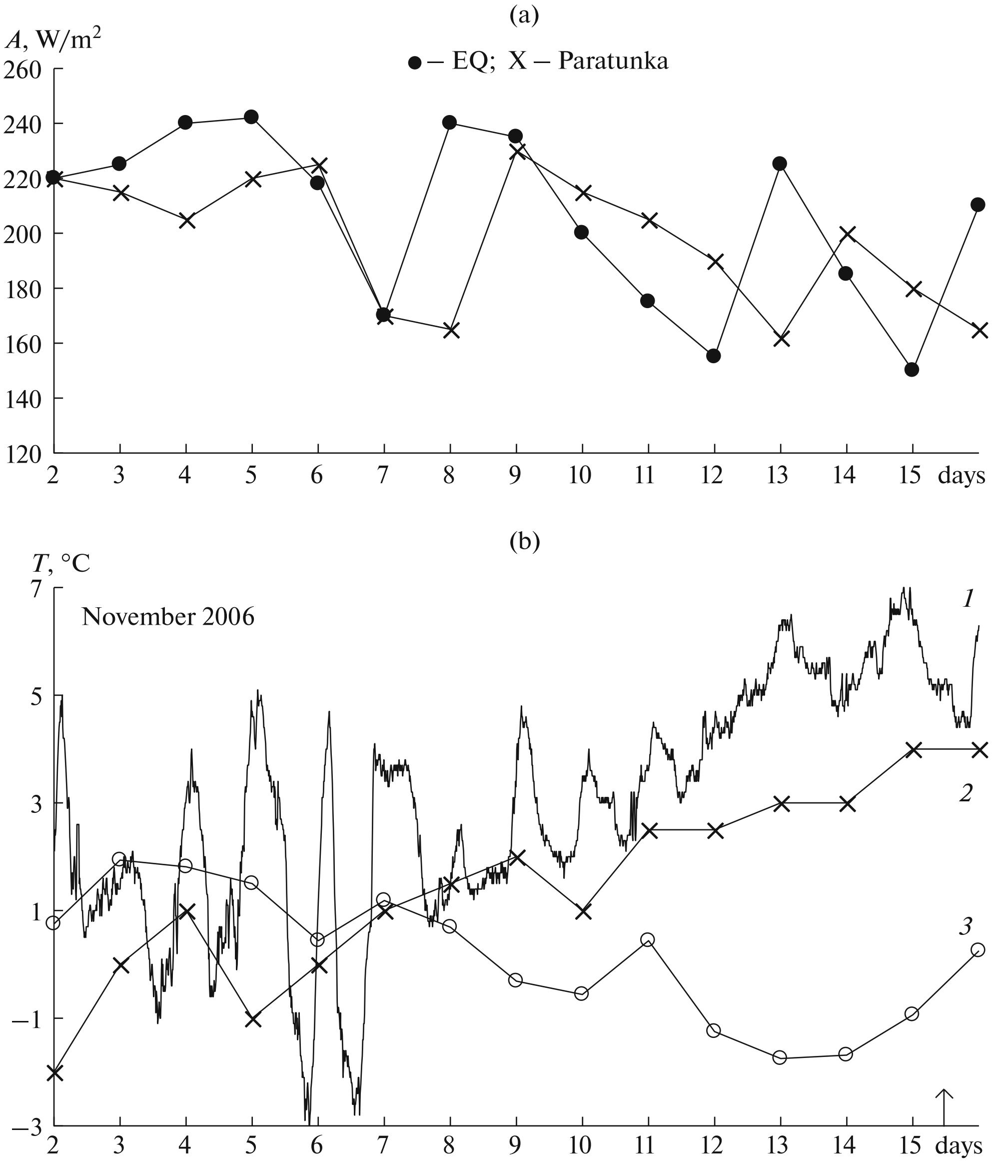

Fig. 2. EQ on November 15, 2006. (a) Daily mean fluxes of outgoing infrared radiation measured over the EQ epicenter and above the observatory, and (b) temperature variations measured in the observatory (*1*), estimated from the satellite data (*2*), and daily mean values averaged over the period 2009–2016 (*3*). The arrow indicates the shock of the EQ.

Kamchatka on hydrophysical phenomena prior to strong EQs. It so happened that the measurements of the level and density of well water were performed just prior to the EQ on November 15, 2006, in the Karymshino obs. (20 km to the south of the Paratunka city) (Gavrilov et al., 2007). These values decreased two weeks before the EQ. A similar effect was also noted in other papers (see the Introduction). This result indicates the active formation of cracks and the expansion of the volume of rock aquifer layers. The decreased water density was attributed by the authors to an increase in water temperature. Indeed, the rise in well-water temperature was previously detected by Tronin et al. (2004) two weeks prior to a major EQ. Moreover, an increase in the volume activity of radioactive constituents in subsoil gas (Buzevich et al., 1998) and, simultaneously, in subsoil gas and in near-surface air (Rulenko and Kuzmin, 2015) was observed prior to strong EQs. The rise in the groundwater temperature and the increased convection of radioactive gases indicate the release of heat in the depths of the Earth with the active formation of cracks.

Thus, analysis of the entire set of results of studies of the characteristics of variations of various geophysical data prior to strong EQs in Kamchatka allowed us to conclude that an additional heat source, found on the example of two EQs, is concentrated in the Earth's

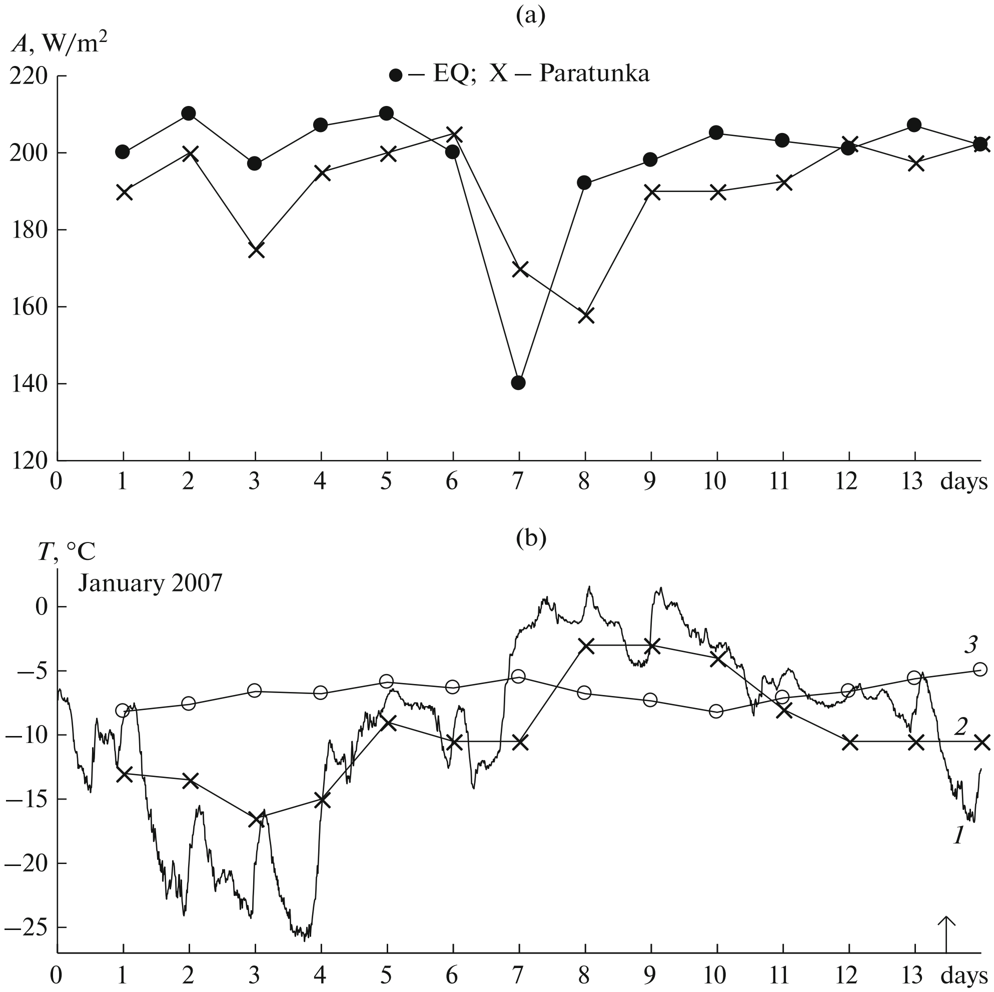

Fig. 3. The same as in Fig. 2 but for the EQ of January 13, 2007.

crust. However, the mechanism of these temperature changes prior to EQs is still not clear. Several possible models have been proposed in literature. For example, it is assumed (Geng et al., 1998; Tronin et al., 2004; Freund et al., 2007) that an increase in subterranean temperature is associated with strong tectonic pressure, along with active crack formation in rocks. At the same time, in the mechanism proposed by Pulinets et al. (2006), a source in the Earth's crust is excluded, and it is assumed that additional heat is released directly in the atmosphere. A critical analysis of the proposed mechanisms, perhaps an incomplete one, is beyond the scope of the article.

ACKNOWLEDGMENTS

The authors thank the Earth System Research Laboratory of the Physical Sciences Division, NOAA, Boulder, Colorado for the opportunity to use their data on the website (https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html).

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Translated by I. Ptashnik