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The Lower Ionosphere and Tectonic Processes on Earth

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Abstract—The subject of our study is the possible relationships between the state of the lower ionosphere and tectonic events on Earth during episodes of high solar activity. There is evidence that during such episodes, electrical interactions between the lower ionosphere (layers D and E), the Earth's surface, and the lithosphere can play an important role in triggering seismic or volcanic events, if the geological objects involved are close to the near-critical state. As examples, we consider three strong earthquakes that occurred during solar cycle 24 (SC24 according to the Zurich classification) and the possibility of their initiation by strong solar flares and related events (sudden ionospheric disturbances, SIDs): 1. The Mexican earthquake (M = 8.1) on September 7–8, 2017; 2. The Chilean earthquake (M = 8.1) of April 1, 2014, and 3. The Japanese earthquake of November 3, 2011. The possibility of using indirect data to study solar flare–ionospheric triggers of large earthquakes that occurred after 1874 A.D. is discussed. This indirect information refers to the areas of sunspot groups, their morphology types, and apparent locations on the solar disk for the corresponding dates. The Chirpan earthquake of April 14, 1928 is given as an example. The inverse piezoelectric effect is one of the most possible physical mechanisms to explain the identified patterns. The possibility of using SID monitor (VLF) data to study these phenomena is briefly discussed.

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1. INTRODUCTION

In recent years, evidence has emerged that, to a large extent, the physical channels of the triggering influence of solar activity on Earth's tectonic processes (earthquakes and volcanic eruptions) consists in electrical interactions between the lithosphere and the atmosphere. Some of these interactions appear to be carried out via geomagnetic activity caused by high-speed coronal mass ejections (CMEs), which cause fluctuations of solar wind parameters near the Earth. The time constant for such relationships is about 1.5–2 days. The existence of such relationships between solar activity and strong earthquakes with magnitude M ≥ 5.6 is indirectly indicated by the recent results obtained by Martichelli et al. (2020).

A systematic delay, of the order of 1–2 days, of the main phases of the activation of the Pinatubo volcano in 1991 with respect to the most powerful manifestations of X-ray solar flare activity during this period was reported in our previous works on this subject (Komitov and Stoychev, 2011; Komrtov and Kaftan, 2022). One of the most probable physical mechanisms of solar triggering the volcanic focus is considered to be solar proton events (SPEs), which usually accompany M5 solar flares or higher. In this regard, the high class of the solar flares considered in the studies should be noted, most are ≥X9.0, i.e., so-called mega-flares. It should also be said that in thiss case the role of geomagnetic activity accompanying solar flares cannot be ruled out.

Analyzing their results with respect to the relationship between solar activity and strong earthquakes, Marticelli et al. (2020), as well as Komitov and Kaftan (2022) for volcanic activity, suggested that one of the important and very likely causes of the observed triggering relationships is the inverse piezoelectric effect. It occurs due to variations in the electric field strength between the Earth's lithosphere and ionosphere, which occur during solar flares, subsequent solar proton events, and changes in geomagnetic activity. It is taken into account that in the lithosphere free electric charges occur in volcanic focuses (Smith et al., 2011) and in zones of active tectonic faults (Martichelli et al., 2020).

Physical channels should also not be excluded or underestimated, where these trigger effects of solar activity on the Earth's tectonic processes are based on the direct influence of powerful X-ray solar flares, causing so-called *sudden ionospheric disturbances* (SIDs). This can lead to a significant reduction in the time constant of the trigger effect.

The possible presence of relationship between ionospheric and lithospheric sources of electric field causes the potential possibility of ionospheric disturbances as a result of tectonic phenomena, i.e., manifestation of a trigger effect in the opposite direction.

It should be noted that the first observational evidence of the existence of a relationship between VLF fluctuations of the ionosphere and terrestrial current systems followed by strong earthquakes occurred in the mid-1970s (Kamogawa, 2006, and references therein). At the beginning of this century, the number of studies increased significantly. The results will be discussed in more detail in Section 4 (DISCUSSION).

The possibility of identifying relationships between the parameters of the lower ionosphere and powerful tectonic events is the main subject of the present study. As examples, the reported relationships between active phenomena on the Sun, in the lower ionosphere, on the Earth's surface, and strong earthquakes during several episodes of active space weather during the previous 11-year solar cycle 24 (SC24) are used. As an additional example of the identification of possible triggering effects of solar-ionospheric origin on major tectonic events on the basis of detailed daily data on the sunspot and geomagnetic activity in the more distant past, the circumstances concerning the series of Chirpan earthquakes in Southern Bulgaria in 1928 are discussed. The used data are presented in Section 2. The events themselves are described in Section 3. A detailed discussion of the described facts and the possibility of using observations of VLF radio signals reflected from the lower ionosphere to identify solar triggers of the tectonic activity on Earth is presented in Section 4.

2. THE DATA

This article uses information from three mega-earthquakes that occurred between 2011 and 2017. Their characteristics were published in the Earthquake Hazards Program (EHP) database of the American Geophysical Union at https://earthquake.usgs/earthquakes. The data relate to the March 11, 2011, Tohoku earthquake in Japan ($M_w = 9.1$), the April 1, 2014, Chilean earthquake ($M_w = 8.2$), and the September 7–8, 2017, earthquake on the Mexican Pacific Coast ($M_w = 8.2$). They refer respectively to the ascending, near maximum, and descending phases of SC24. Archived data on the Chirpan earthquakes in Southern Bulgaria (April 14–18, 1928) were copied from the mentioned database. In connection with these events, newspaper articles and testimonies of adult eyewitnesses were used.

All the helio-geophysical data related to the mentioned seismic events were obtained from the ftp-server of the US National Geophysical Data Center (ftp://ftp.ngdc.noaa/STP) and the site of the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration (Boulder, Colorado, United States, http://swpc.noaa.gov). Archived data on sunspot activity between April 10 and 20, 1928, including the apparent location on the solar disk and the sunspot group area and type, were obtained from the USAF/NOAA Sunspot Database (Royal Observatory, Greenwich, https://solarscience.msfc.nasa.gov/greenwch.shtml). For their textual and graphical visualization, special software developed by the authors was used.

We also used data on the level of reflected observed very-low-frequency (VLF) radio signals at 24 kHz obtained at the Public Astronomical Observatory (Stara Zagora, Bulgaria) for the 2012–2018 period.

3. EXAMPLES OF PROBABLE "SPACE WEATHER–LOWER IONOSPHERE–TECTONIC ACTIVITY" RELATIONSHIPS

This section presents evidence for possible relationships between several mega-earthquakes and space weather manifestations (solar flares, solar proton events, SID events in the lower ionosphere, and geomagnetic activity). Events are presented not in chronological order but by the amount of information and the possibility of physical interpretation.

3.1. The Mega Solar Flare (X9.3) of September 6, 2017 and Related Geophysical Phenomena

One of the more striking examples related to the subject of this article is the mega solar X-ray flare of September 6, 2017. It can be considered the most powerful eruptive event during the 11-year SC24. It reached its maximum phase at X9.3 at 1203 UT. The source of this event was the solar active region AR12973 (no. 2673) (Figs. 1a and 1b). However, in the preceding 48 h, this region also generated two other large flares: the moderately strong M5.5 and the strong X2.2 flares. These flares were associated with solar proton events, which caused a radiation storm lasting more than 48 h. It began around midnight on September 5 as a weak flare (S1) but then reached medium strength (S2) and weakened slightly afterwards. However, the X9.3 flare caused the radiation storm to intensify. It reached S3 (strong) around midnight on September 7–8. At about 2100 UT on September 7, the solar coronal mass ejection (CME) reached the Earth, and a very strong geomagnetic storm ($Kp = 8$) began. At 2349 UT, there was a strong earthquake ($M_w = 8.1$) with an epicenter near the Pacific coast of Mexico. Eyewitnesses reported a weak glow near the Earth's surface in the near-surface atmospheric layer at a height of several meters. It appeared shortly before the main shock and lasted until the moment of the earthquake.

Around the same time, the glow was also observed at a location ~12000 km away from Mexico. Figure 1c shows an amateur photo taken by a smartphone in the early evening at ~2000 UT local time (~1700 UT) in a locality in Bulgaria on September 7, 2017, i.e., about 15 h after the X9.3 mega solar flare and about 4 h

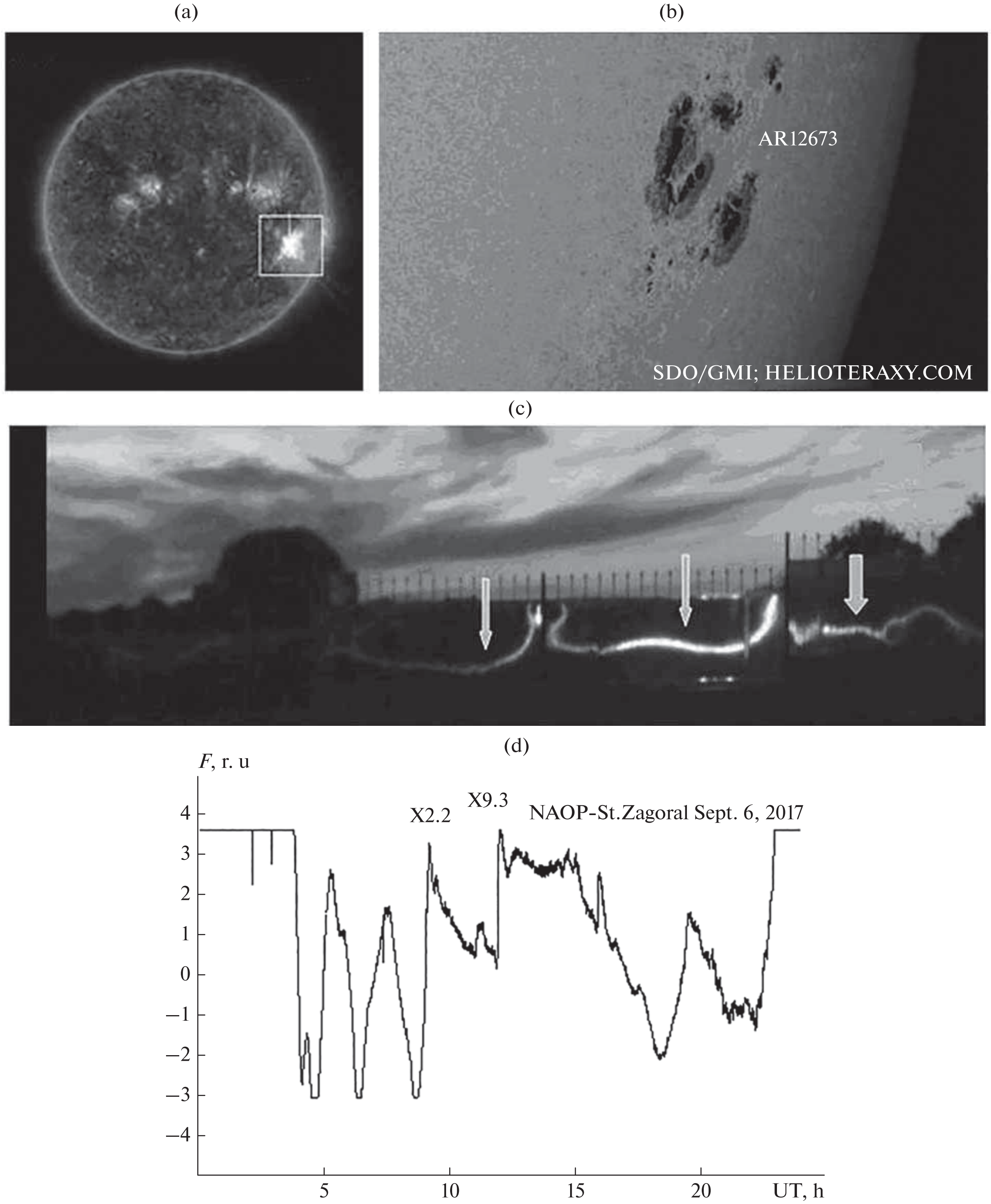

Fig. 1. The mega Solar X-ray flare (X9.3) on Sept. 6, 2017, and presumably related optical effects near the Earth's surface: (a) X9.3-flare near the maximum phase in UV ($\lambda = 131$ Å) (https://sdo.gsfc.nasa.gov); (b) solar active region AR12673 in white (https://sdo gsfc.nasa.gov); (c) corona discharge-type glow in the Bulgarian locality during the evening twilight of Sept. 7, 2017 (d) diurnal variation plot of the VLF signal at the frequency $f = 24$ kHz recorded by the SID monitor at the Public Astronomical Observatory (Stara Zagora, Bulgaria) on Sept. 6, 2017.

before the geomagnetic storm. The gray arrows show a glow near the Earth's surface, apparently of the corona discharge type that is sometimes observed on power lines. An electric field with a strength of the order of $E \geq 500$ volt/m is necessary for this type of glow to appear. Meteorologically, the weather was calm and clear. In our opinion, this phenomenon has nothing to do with the geomagnetic storm (which began later). Most likely, it was formed due to fluctuations in the parameters of the lower ionosphere as a result of the solar flare and the increased flux of high-energy solar protons ($E \geq 10$ MeV). It should be noted that in contrast to the Pacific coast of Mexico, the corresponding region of Bulgaria is characterized by relatively low seismicity. Significant factors when such light effects occur could be the electrical conductivity, mineral composition and structure of the near-surface soil, and geological structures close to the earth's surface, including metal ores or metallic objects. It can also be assumed that the moisture content of the near-surface atmospheric layer also plays a significant role in this process. This large and very specific set of conditions can explain why such optical phenomena are exceptionally rare.

Cases of the appearance of such a glow in the same area were registered earlier, before 2017. Relatively more complete information is available about the event of May 6, 2015. It was photographed and coincided in time with the intensification of space weather, namely the M1.9 solar flare. Information from the EHP data archive showed that there were no strong earthquakes ($M > 5.5$) in the period May 5–8, 2015. In our opinion, in this case, too, the surface glow indicates a significant increase in the strength of the electric field between the ionosphere and the Earth's surface due to the solar flare. The conditions for such a glow could probably arise in other regions of the Earth, where there were no prerequisites for the manifestation of the corresponding trigger effect. Apparently, in this particular time interval, near-critical conditions were not formed in areas of tectonic faults, which could take place in connection with the intensification of the "ionosphere–ground surface–lithosphere" current system.

3.2. Space Weather and the Big Chilean Earthquake of 2014

One of the strongest earthquakes since the beginning of the 21st century is the mega-earthquake in northern Chile. It occurred on April 1, 2014, in the northern part of the country near the city of Iquique. The main shock of the earthquake with a magnitude of $M_w = 8.2$ occurred on April 1 at 2346 UT. Until April 3, 2014, it was followed by four more strong aftershocks, the strongest of which had a magnitude of $M_w = 7.7$.

In the aspect of our study, this earthquake is a good illustration of the reversibility of the relationship between the lower ionosphere and lithosphere. The sequence of ionospheric–lithospheric triggering effects appears to have begun on March 29 with a large X1.0 solar flare (Fig. 2a). Its maximum was reached at 1754 UT. The source of this event was the active solar region AR12032 (beta-gamma magnetic class). It was observed in the southeastern quadrant of the solar disk. The flare was impulsive and lasted for ~13 min. As a result, it produced neither a coronal mass ejection (CME) nor a solar proton event. Nevertheless, the flare formed a very clear trace in the ionospheric D layer. This sudden ionospheric disturbance was detected with an VLF radio wave detector at $f = 24$ kHz (SID monitor) at the Public Astronomical Observatory in Stara Zagora (Fig. 2a). It could destabilize the electric field system between the lower ionosphere and the lithosphere over vast regions of the Earth.

However, in our opinion, another phenomenon detected by the same instrument on the next day, March 30, 2014, could also lead to such an effect. Around noon (~1220 UT), a change in the reflected signal was detected, which by all apparent signs was similar to an SID event caused by a medium- or high-power solar flare of M and X classes (Fig. 2c). Nevertheless, such an event was not recorded in the GOES-15 database. On the other hand, there were coincident detections of SID events at several other observation stations in different regions of the Earth. For the time interval from March 29 to April 3 only a few weak C-class events can be found in the solar flare database. This could be due to a technical omission. This event (for brevity, we denote it by the symbol H) could also be a source of influence on the electrical interaction between the ionosphere and the lithosphere.

An interesting pattern of the VLF-signal was obtained on the next day, on March 31, 2014 (Fig. 2d). It is absolutely atypical for the usual diurnal variations of the reflected radio signal at a frequency of 24 kHz. Its "dip" in the first half of the day approximately between 0900 and 1200 UT can be clearly seen. The most probable explanation for this behavior is a sharp drop in the electron concentration in the ionospheric D layer. This episode ended with two series of short oscillations unrelated to variations in the solar X-ray flux. It is likely that this anomalous behavior of the diurnal variations is related to nonstationary events in the lithosphere in areas of some tectonic faults. Potential triggers could be either the SID event caused by the X1.0 solar flare, or the H event, the assumed source of which was a "lost" medium- or high-power solar flare, or both of these events.

Finally, on October 31 around 1730 UT an M1.4 medium-power X-ray flare occurred on the Sun. The resulting SID event could be observed over the Western Hemisphere. It can be assumed that this finally triggered the $M_w = 8.2$ mega-earthquake in Chile around midnight March 31–April 1.

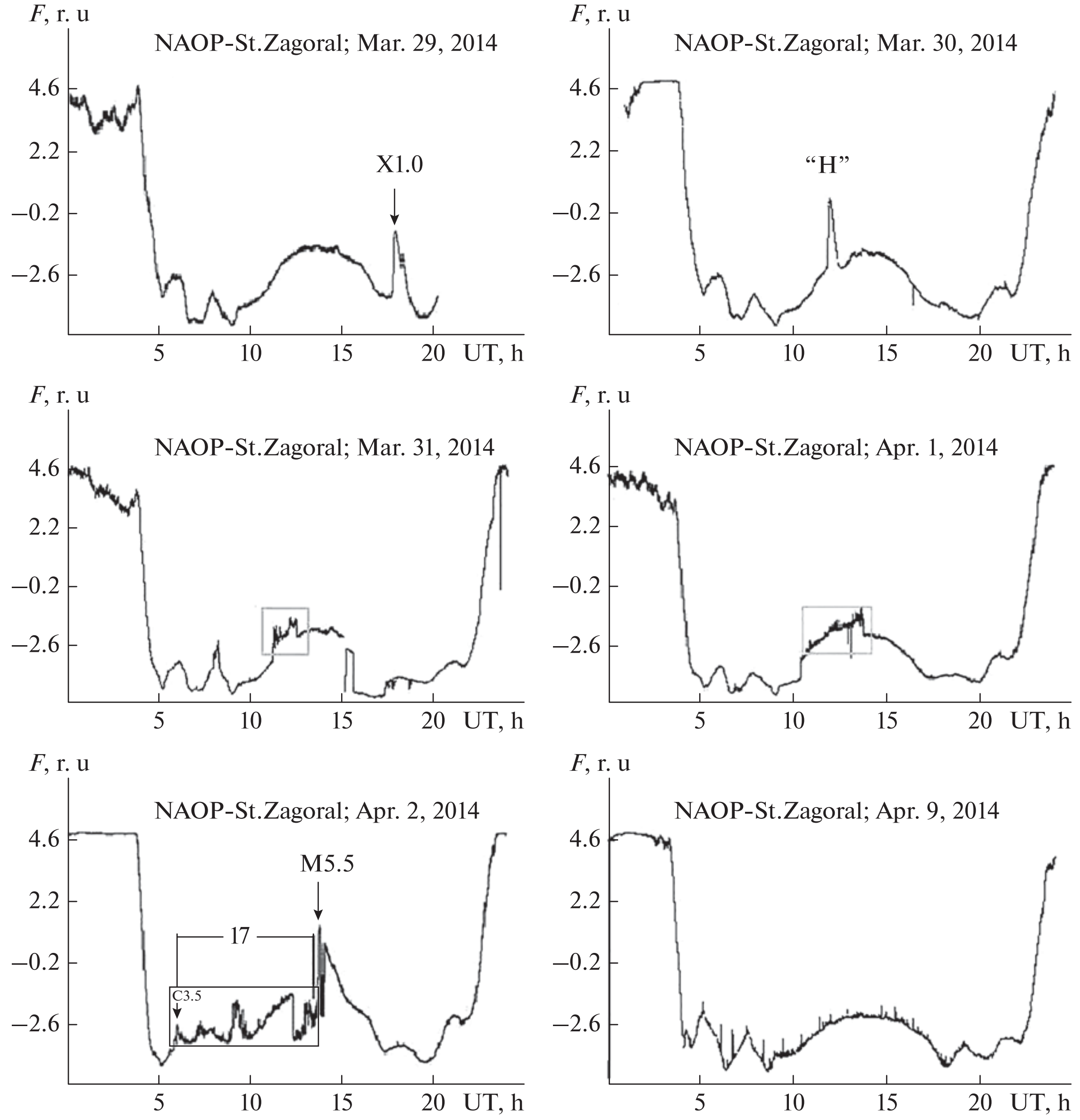

Fig. 2. The daily variations of the radio signal reflected from the lower ionosphere (layers D and E) at a frequency of $f = 24$ kHz detected by the SID-monitor at the Public Astronomical Observatory (Stara Zagora, Bulgaria) during the period from Mar. 29 to Apr. 9, 2014. The last plot of Apr. 09 refers to quiet conditions.

During April 1 and 2, 2014, there were some strong aftershocks of the Chilean earthquake with a magnitude of $M_w = 6.0–7.7$. On the VLF-signal graphs of the SID monitor in Stara Zagora their atypical behavior was detected again, which could be caused by processes in the lithosphere near the Pacific coast of Chile (Figs. 2d and 2e). Of particular interest is the nature of changes in the graph from April 2, 2014 (Fig. 2e). Again, there was a "dip" of the signal (Figs. 2d and 2e) due to a decrease in the electron concentration in the ionospheric D layer. It quickly recovered due to the SID event caused by the moderately powerful M5.5 solar flare.

3.3. Space Weather and the March 11, 2011, Japan Earthquake

A number of articles were written on the relationship between the Tohoku (Japan) March 11, 2011 mega-earthquake and ionospheric processes, for example, (Heki, 2011). We focus only on the changes in space weather that could be potential triggers of this seismic event. These were three moderate strong and strong solar flares (two M1.7 and one X1.5), which took place on March 9, 2011, in the interval of 30–45 h before the earthquake. A planetary geomagnetic disturbance $Kp = 4$ was associated with them, whose beginning coincided with the main shock $M_w = 9.1$ at 0545 UT.

3.4. Chirpan Earthquakes (April 14–18, 1928)

Sufficiently complete, regular, and standardized data on SID phenomena are available only since the second half of the 1950s. We used data from the web archive of the US National Geophysical Data Center (ftp://ftp.ngdc.noaa/STP). As for data on X-ray solar flares, this series is much shorter than that for SID phenomena. Continuous X-ray flare observations have been carried out since 1976 by the GOES satellites. Even earlier observations from the SolRad space mission program cover the 1968–1974 interval. On the other hand, regular instrumental observations of earthquakes have been carried out in many countries of the world since the late 19th–early 20th centuries. Reliable observational information on strong volcanic eruptions with VEI ≥ 5 for most of the Earth's surface has been available since at least the mid-18th century, and relative reliable data since the mid-16th century (Komitov and Kaftan, 2022).

The question arises as to whether it is possible to use indirect data on space weather from which conclusions can be drawn about possible SID phenomena and triggering effects on tectonic processes in the past and if so, over what time interval.

We believe that such indirect information can be obtained from the database of diurnal data on the apparent position on the solar disk, the morphological class, and area of sunspot groups when comparing their changes in successive days. On this basis, we can make some assumptions about their magnetic class, eruptive potential, and flare activity. Such data can be obtained from the USAF/NOAA Sunspot Database created and maintained by Dr. David Hathaway at http://solarcyclescience.com/activeregions.html. The database is based on the Greenwich Observatory Sunspot Group Catalog for the 1874–1976 period, with its extension up to the present. As additional material, we can use daily data of the geomagnetic AA-index, which have a continuous series since 1868. For the graphical visualization and digitization of data from the relevant information, software developed by the authors was used.

The information about greatest earthquakes of the 20th century on the territory of Bulgaria, at Upper Thracian (Chirpan–Plovdiv), on April 14–18, 1928, was used as an example. It had two main shocks with magnitudes of $M_w = 7.0$–7.1, respectively, in the areas of Chirpan and Plovdiv. The first (Chirpan) shock occurred on April 14, 1928, around 1120 local time and the second (Plovdiv), on April 18, 1928.

As can be seen from Fig. 3, several groups of sunspots were observed on the solar disk during the second decade of April. In our opinion, the most likely potential candidate for the excitation of powerful solar flares is the area of the sunspot group bounded by a square. The area of this region is proportional to the area of the sunspot group; the red color indicates the morphological type 6 of the sunspot-forming center according to the Greenwich Nomenclature. This corresponds to a group including two large sunspots and many small ones located linearly between them. Therefore, we can assume that this group had at least a standard bipolar structure (magnetic class beta), but it is possible that the magnetic class was higher. On the other hand, the total area of the sunspot group increased continuously for several days until April 14–15, 1928. At that time, it was at its maximum (~1000 millionths of the solar disk) and was visible to the naked eye. Its eruptive potential was at its maximum; this was when the probability of generating powerful X-ray flares from this region was highest. After April 15, the area of the group dropped, which corresponds to the hypothesis that powerful solar flares in the specified region occurred around April 14–15.

Such flare activity apparently took place on the morning of April 14. It led to at least one SID event, which in turn destabilized the electric field between the ionospheric D layer and the lithosphere, and acted as a trigger for the first major seismic shock around noon. Indirect evidence of the electrical nature of the excitation of this earthquake is found in the behaviors of animals in the area of Chirpan. Living witnesses of this event relate that about 1.5–2 h before the earthquake animals (cats, dogs, and farm cattle) were very restless.

As can be seen from Fig. 3, the potential trigger excitation on April 14 was a purely ionospheric (SID event) and has nothing to do with the subsequent geomagnetic activity, which took place in the following days. Nevertheless, a weak geomagnetic storm in the second half of April 16 could be related to the second strong shock on April 18, 1928.

4. DISCUSSION

Cases of observations of a surface glow at individual stations during episodes of active space weather are very rare. Their manifestation is certainly connected not only with it but also with additional factors (surface characteristics, mineral and rock composition, structure of the local lithosphere, meteorological conditions, etc.). Therefore, it can only rarely be observed during trigger-activated tectonic events and not necessarily in tectonically active areas. Most likely, these are concomitant phenomena of solar-tectonic triggering effects. However, cases of surface glow, in our opinion, are indicators of the occurrence or intensification of electric fields between the Earth's surface and lower ionosphere during the intensification of space weather. This can happen due to changes in the D and/or E layer parameters due to X-ray solar flares or solar proton events. This would lead to changes in the electric potential between them and the Earth's surface. If this

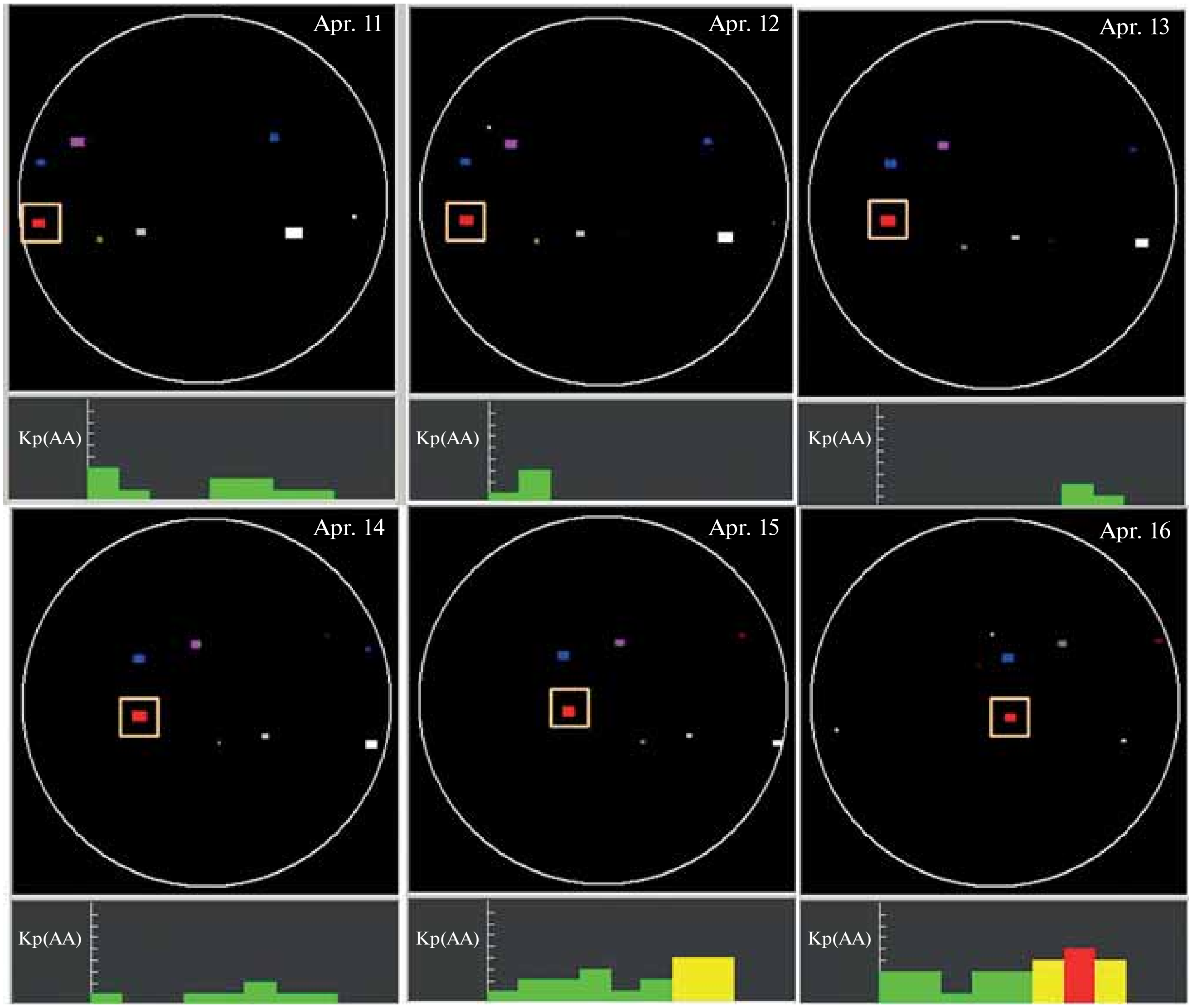

Fig. 3. Maps of sunspot groups on the disk of the Sun on Apr. 11–16, 1928.

region is characterized by a block structure of the lithosphere and a near-critical potential energy is accumulated there, the destabilization of the electric field between the ionosphere and the Earth's surface could play the role of a trigger for an earthquake or volcanic eruption.

The analysis of the situation during the 2014 Chilean earthquake presented in our work shows that the nature of the ionospheric–lithospheric interaction can be very complex and ambiguous. In some cases, the trigger effect can manifest itself from the ionosphere to the lithosphere and in others, vice versa. This is due primarily to the presence of two sources of electric field: in the ionosphere and in the lithosphere. Bearing in mind the fact that there are aerosol condensation nuclei with electric charges in the atmosphere, the structure and variations of electric fields between the ionosphere and lithosphere can be very complex and specific for separate cases. Therefore, it is difficult to assume that at this stage studies of ionospheric–lithospheric interactions could be used, e.g., for predictive purposes. However, these studies are useful for improving the understanding of the factors of tectonic activity.

It should also be recalled that in this article we focus on the influence on tectonics of only one group of characteristics of space weather, those associated with active processes on the Sun. The maximum level of their influence takes place in the epochs of solar cycle maxima. On the other hand, there are phenomena of space weather whose influence on the environment occurs during the epochs of solar minima. The main primary source of such influence is the flux of galactic cosmic rays (GCRs). Its intensification during solar minimum epochs leads to an increase in the formation of ion–electron pairs in the stratosphere and troposphere, which in turn contributes to the active formation of aerosol nuclei (Swensmark and Friiz-Christiensen, 1997; Yu, 2002). On the other hand, this additional GCR contribution to the ionization processes of the middle and lower stratosphere is actually an additional contribution to the electric field strength in the ionosphere–lithosphere system and leads to an increased probability of volcanic or seismic events, but in this case during epochs of low solar activity. This explains the second main peak in the frequency of strong volcanic eruptions during epochs of low solar activity; except for the peak that occurs during epochs of high solar activity (Stotchers, 1989; Komitov and Kaftan, 2022). An increase in volcanic activity through the emission of dust and acid gases additionally forces the formation of aerosols and their condensation nuclei.

A similar effect of increasing the frequency of strong earthquakes near solar minima was found in (Rogozhin and Shestopalov, 2007).

One of the most probable physical mechanisms of such a triggering process could be a reverse piezoelectric effect (Komitov and Kaftan, 2019, 2022; Martichelli et al., 2020). In this case, two factors can be distinguished. The first is the relative abundance of the mineral quartz (SiO_2) in the upper layers of the lithosphere, especially in continental areas. Second, the structure of the lithosphere itself in the form of blocks and tectonic plates, resembling giant plates.

In view of the nature of the phenomena that are the subject of research, we believe that one very useful source of information for detailed analysis is the database of SID phenomena within the data archive of the US National Oceanic and Atmospheric Administration (ftp.ngdc.noaa.gov/STP/space-weather/ionospheric-data/sids/reports). It contains observational data from several dozen stations recording the absorption or reflection of VLF radio signals from the lower ionosphere in the 5–50 kHz range. These cover the 1958–2014 interval. Observational data obtained for the 24 kHz frequency on the SID monitor of the Public Astronomical Observatory (Stara Zagora, Bulgaria) for the 2012–2017 period should be used as an additional source.

The analysis of the situation with the Chirpan seismic events presented in this study shows that the use of indirect data on space weather events, such as from the Greenwich Observatory Sunspot Group Catalog, namely, the modern extended version of the Hathaway's database (http://solarcyclescience.com/activeregions.html), is useful for identifying potential trigger events from the more distant past. Nevertheless, the effectiveness of this method should be proved by comparing the results of recent decades obtained by this method with those based on actual observations of solar flares and SID phenomena in the lower ionosphere. This indirect method can be useful for obtaining estimates of possible trigger effects during powerful volcanic eruptions during the last ~150 years.

5. CONCLUSIONS

(1) Based on the comparison of the data set for three of the strongest earthquakes in the 21st century (in Japan in March 2011, in Chile in April 2014, and in Mexico in September 2017), there is reason to believe that all of these seismic events were excited by space weather intensification associated with high power X-class solar flares. This leads to the conclusion that a certain part of the strongest earthquakes were activated by some trigger related to solar flares of X class and in some cases of M class. This effect is most probably associated with the influence of solar flares on the Earth's ionosphere (first of all, on its lower D layer) by increasing the electronic concentration in form of sudden ionospheric disturbances (SIDs).

(2) SID events cause changes in the strength and structure of the electric field between the ionosphere and the Earth's surface/upper lithosphere. In extreme cases, specific meteorological conditions, as well as mineral composition and structure of the nearest to the surface Earth layers, possibly contribute to the appearance of the corona discharge-type glow. Changes in the electric field can serve as a trigger in tectonically active regions, where the mechanical potential energy of deformation or pressure of volcanic magma reaches near-critical levels. The presence of a significant amount of free electric charges in the magma of volcanic sources, as well as in areas of tectonic faults, generally forms an additional source of excitation of the electric field between the ionosphere and the lithosphere (lithospheric dynamo) (Kuo et al., 2013; Martichelli et al., 2020).

(3) The most likely candidate for the trigger effect is the reverse piezoelectric effect, which is possible in conditions of fragmentation of the Earth's lithosphere in areas of tectonic faults, as well as due to the relatively high content of SiO_2 and other minerals with piezoelectric properties in the upper lithosphere.

(4) Solar proton events (SPEs), which often accompany powerful X-ray flares, are very often sources of additional ionization in the middle and low atmosphere of the Earth. Therefore, they can make their own contribution to changes in the electric field between the ionosphere and the lithosphere. Another source of electric field destabilization is geomagnetic storms and disturbances originating from high-speed coronal mass ejections (CMEs). Their sources are medium- and high-power solar flares. As can be seen from the example of the Mexican earthquake of September 2017, in such cases, the trigger effect seems to be a combined process of a set of factors of extreme space weather, which act in a very short time interval of the order of 1–2 days after the solar flare.

(5) The principal possibility of the use of the database of average daily observational parameters of sunspot groups based on the Greenwich Observatory Sunspot Group Catalog (1874–1976) to identify pos-

sible trigger excitations of tectonic events in the last ~150 years, since 1874, was shown.

(6) Given that the nature of the studied relationships is very often specific to each particular tectonic event and is reversible, we believe that at this stage, and for the foreseeable future, there is no reason to hope for predictions of tectonic events based on their interactions with space weather.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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