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RESEARCH ARTICLE

Response of the Turkish Ionosphere to Geomagnetic Storms During the 24th Solar Cycle

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ABSTRACT

The Earth's ionosphere, a haven for charged particles within the atmosphere, is susceptible to energetic excitations from space weather. When geomagnetic storms erupt, triggered by solar activity, a cascade of charged particles rushes towards our planet. These charged particles, among other factors, have dynamic and disruptive effects on Earth's ionosphere. The foremost among these effects are significant fluctuations in the ionospheric electron density during geomagnetic storms. This study investigates the effects of 54 geomagnetic storms of different magnitudes on the Turkish ionosphere during the 24th Solar Cycle using the differential rate of total electron content (DROT) method. The study was conducted for the TUBITAK station. The results indicate that both medium- and large-scale traveling ionospheric disturbances (TIDs) occurred in the Turkish ionosphere during these geomagnetic storms. However, it was also observed that no ionospheric disturbances occurred during some geomagnetic storms. The study demonstrates that the DROT method requires careful application in detecting ionospheric disturbances.

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1. INTRODUCTION

The ionosphere is a region of the Earth's upper atmosphere that extends from approximately 50 km to about 1000 km in altitude, encompassing the mesosphere and thermosphere regions. It is named the ionosphere primarily due to the high abundance of ions and free electrons generated by the ionization of atmospheric gases, largely caused by intense ultraviolet (UV) radiation from the Sun [1-4].

The ionosphere is divided into several layers, each named according to the primary ionizing substance present in the layer. Layers from the lowest to highest altitudes are the D, E, and F layers (which are further subdivided into the F1 and F2 layers). The layers where molecular ions dominate and chemical processes are important are the D and E regions, respectively. Although the D region has a complex structure in terms of water ions, ternary reactions, and positive and negative ions, the E region is not complex in terms of its chemical structure. In the F1 region, ion-atom transformations and transport dominate, and in the F2 region, ionization is seen to increase as a result of transport and chemical losses in the plasma [2, 5].

The ionosphere plays a crucial role in the propagation of radio waves by reflecting certain frequencies back to the Earth, thus enabling long-distance communication via radio signals. Due to its significant role, continuous monitoring of the ionosphere is necessary, and measures must be taken to ensure uninterrupted radiowave and satellite communications. To achieve this, it is important to detect ionospheric disturbances and take measures to mitigate them [6 - 12].

Traveling ionospheric disturbances (TIDs), which are ionospheric disturbances that occur in the ionosphere, are variations in electron density that spread horizontally along the ionospheric plasma. These disturbances are often associated with changes in the neutral atmosphere, including atmospheric gravity waves, and can have significant effects on radio wave propagation. TIDs can affect radio wave propagation in the ionosphere. Changes in electron density caused by TIDs can cause scintillation in radio signals, affecting the quality and reliability of communication and navigation systems. Understanding and monitoring TIDs are crucial for predicting and mitigating these effects [13 - 17].

TIDs in the ionosphere are typically generated by atmospheric gravity waves originating from the lower atmosphere, especially the troposphere and stratosphere. As these waves propagate upward, they can induce changes in ionospheric electron density. TIDs can travel over large distances and at different speeds depending on their sources and the characteristics of the neutral atmosphere. They exhibit a frequency range and various periods ranging from a few minutes to several hours [13 - 19]. Shorter periods are associated with gravity waves originating from the lower atmosphere, while longer periods may be linked to solar-induced variations. TIDs can be influenced by space weather events such as solar flares and geomagnetic storms. During geomagnetic storms, there is an intense energy input from the magnetosphere to the Earth's upper atmosphere. This energy input causes ionospheric disturbances such as temperature, wind, and density. The increased magnetospheric flux energy during the geomagnetic storm period creates ionospheric disturbances that expand toward the equator [20-21]. Changes in ionospheric conditions due to TIDs can impact satellite communications, GPS navigation, and other ionosphere-dependent technologies.

TIDs are evaluated in two groups according to the characteristics of the oscillations. Large-Scale Traveling Ionospheric Disturbances (LSTIDs) and Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) (Francis 1974). Both LSTIDs and MSTIDs have been observed to travel thousands of kilometers and reach speeds of hundreds of kilometers per hour [22 - 24].

Scientists use various observation techniques to study TIDs in the ionosphere. Ground-based instruments, such as ionosondes and radar systems, can provide valuable data on the vertical and horizontal distribution of the electron density. Global Navigation Satellite System (GNSS) receivers, which use signals from satellites, are also used to detect TIDs by monitoring fluctuations in received signals [11, 25-28].

In this work, the response of the Turkey ionosphere, located in the mid-latitude region, to geomagnetic storms occurring during the 24th solar cycle is investigated using the differential rate of total electron content (DROT) method commonly employed in many studies in the literature. The total electron content (TEC) data from the TUBI station of the Turkey National GNSS Network (TUSAGA-Aktif) are utilized for this purpose. TEC data was obtained using the IONOLAB-TEC software provided by the Hacettepe University Engineering Faculty.

2. MATERIAL AND METHOD

2.1. Obtaining Ionolab-Tec Data

IONOLAB-TEC (I-TEC) values were obtained for the coordinates of the TUBI station at temporal resolution, i.e., 30 s, through the IONOLAB-TEC/STEC software, which can be downloaded as *.exe from the website www.ionolab.org, on geomagnetically disturbed days [29, 30]. The IONOLAB service has been used and mentioned in many studies in TEC estimation and modeling. This service with a graphical interface provides comfortable use. This unique application can be accessed online by registering for free and downloading IONOLAB-TEC forecasts for different stations with appropriate files [31].

This model calculates STEC, the line integral for electron density along the raypath between the receiver and satellite station, using the IONOLAB - STEC/TEC algorithm. VTEC is obtained from STEC due to its reflection at the Ionosphere Pierce Point (IPP) in the ionosphere model consisting of a single layer (SLIM) [32]. While STEC symbolizes total activity along a single raypath between the global positioning system satellite and earth-based receiver, I-TEC combines all variability in the local zenith direction because of the different orbit positions of various satellites. IONOLAB-TEC and

IONOLAB-STEC provide reliable, accurate, and robust GPS-TEC (G-TEC) estimates for any high-latitude, mid-latitude, or equatorial global positioning system station for both disturbed and quiet days [30].

2.2. Difference of Rate of TEC (DROT)

In this work, the response of the Turkey ionosphere to a total of 54 geomagnetic storms that occurred during the 24th solar cycle was investigated using the Differential Rate of Total Electron Content (DROT) method, as detailed below. The DROT method is a proposed technique for automatically detecting ionospheric disturbances and scaling the intensity of these disturbances for further investigation. DROT is a sensitive method for amplitudes that exhibit wave behavior. In a study where the DROT method was applied to STEC data of disturbed days in the mid-latitude, it was recorded that the disturbances were detected in almost real time, even if 15-minute data were taken from the GPS station [19, 27].

Let the G-TEC values for receiver u on day d be represented as follows:

$$x_{u,d} = \left[x_{u,d}(1) + \cdots + x_{u,d}(n) + \cdots + x_{u,d}(N)\right]^T \quad (1)$$

Here, N represents the total number of G-TEC values for receiver u on day d, and T is the operator. The temporal variation of the TEC values can be observed in Figure 1-a.

One of the most commonly used methods to investigate the temporal variability of the ionosphere is the rate of TEC (ROT). The ROT method is typically used to evaluation of ionospheric perturbations. The change rate of TEC and ROT in a unit time interval is equivalent and the unit of ROT is TECU/s. In this work, the temporal derivative ROT is calculated from the TEI data as follows:

$$ROT_{u,d}(n) = \frac{\left(x_{u,d}(n+1) - x_{u,d}(n)\right)}{\Delta t} \quad (2)$$

Here, Δt represents the time interval of the samples, which is 30 s in this study. Then, we can express the obtained ROT values as follows:

$$ROT_{u,d} = \left[ROT_{u,d}(1) + \cdots + ROT_{u,d}(n) + \cdots + ROT_{u,d}(N)\right]^T \quad (3)$$

The temporal variation of the ROT values for a sample storm is shown in Figure 1-b. These values are then subjected to a median filter to address the linearity problem. Nonlinear digital filtering technique commonly used to remove or smooth noise in an image or signal is defined as median filter in Digital Signal/Image Processing. Median filters are useful in reducing random noise when the probability of noise amplitude has large tails and periodic patterns [19]. Performing operations with the help of a sliding window on the signal or image is called median filtering. To apply the median filter with the DROT method, two sliding windows of different lengths, t_f1 and t_f2, are first determined and applied to the data. In this study, the first filter of length t_f1 was applied to correct noise data due to factors unrelated to ionospheric parameters, such as signal processing, global positioning system antenna phase problems and instantaneous loss, and abrupt changes or interruptions, such as power ratios or Signal-to-Noise Ratio (SNR) or low Signal-to-Carrier Ratio (SCR). Therefore, the first filter of median is used for ROT as follows:

$$Y_{u,d} = medfilt(ROT, t_{f1}), \quad (4)$$

The median time filter of the second sliding window, t_f2, in predicting the behavior of the TEC structure is as follows and:

$$\widehat{Y_{u,d}} = medfilt\left(Y_{u,d}, t_{f2}\right) \quad (5)$$

The temporal variation of $Y_{u,d}$and $\widehat{Y_{u,d}}$ values for a sample storm is shown in Figure 1-c.

Equation (6) shows the ROT variation, indicating that this nonlinear trend filter can correct all other potential perturbations with durations shorter than 15 minutes and longer than 4 hours [19, 27].

In reducing TEC variability that does not contribute to the ionosphere, the first falling window in the median filter length was chosen as , t_{f1}=25 to correspond to 12,5 minutes. This value corresponds broadly to the quiescent period of the mid-latitude ionosphere, as discussed by Sayin et al. (2010), Erol and Arıkan (2005) [33, 34]. The length of the second sliding window filter, , t_{f2}=504, was selected as 504, corresponding to 4,2 hours. The difference in the second level for the DROT algorithm can be obtained from Equations (4) and (5) as follows:

$$D_{u,d} = Y_{u,d} - \widehat{Y_{u,d}} \quad (6)$$

Finally, the ratio of equation (7) to equation (5) gives the DROT values in the third step. Thus;

$$DROT_{u,d} = \frac{\sqrt{\sum_{n=1}^{N}\left[D_{u,d}(n)\right]^2}}{\sqrt{\sum_{n=1}^{N}\left[Y_{u,d}(n)\right]^2}} \times 100 \quad (7)$$

an expression is derived. The temporal variation of $DROT_{u,d}$ values for a sample storm is shown in Figure 1-d.

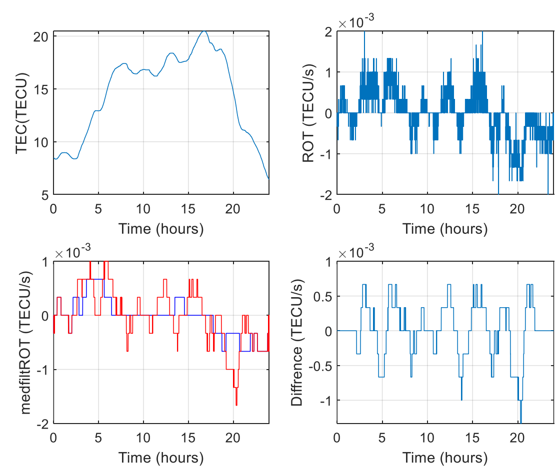

Figure 1. Temporal variations of parameters obtained using the DROT method during the geomagnetic storm on August 04, 2010. (a) Shows the variation of normalized TEC values, (b) represents the variation of ROT values, (c) shows the temporal changes of the red line $Y_{u,d}$ value and the blue line $\widehat{Y_{u,d}}$ value, and (d) shows the temporal variation of the differential rate of TEC (DROT) value.

3. RESULTS AND DISCUSSION

In this study, the response of the Turkish ionosphere to a total of 54 geomagnetic storms occurring during the 24th solar cycle was investigated using the DROT method. The Kp and Dst indices were used as geomagnetic storm indices in the study. The storms considered for this solar cycle and their relevant values are shown in Table 1. The IONOLAB-TEC values obtained from the TUBI station in the Turkey National GNSS Network were used to examine changes in the ionosphere in Turkey. The values obtained from the application of the DROT method to these IONOLAB-TEC values from this station are depicted in Figure 2.

When examining the obtained results, it can be stated that both medium-scale (MSIDs) and large-scale (LSIDs) traveling ionospheric disturbances occurred in the Turkish ionosphere during geomagnetic storms according to the DROT method. The highest disturbance, with a value of 101,95%, was observed during the geomagnetic storm on 28 May 2017. On this storm day, the Kp value reached 7, and the Dst value reached a value of -125 nT. Similarly, the lowest value obtained, with a percentage of 31,91%, occurred during the geomagnetic storm on March 17, 2013. During this storm, the Kp value was 6.7, and the Dst value was -132 nT. Studies proposing the DROT method in the literature suggest that when this value is between 50% and 70%, MSIDs occur, when it exceeds 70%, LSIDs occur, and when it is below 50%, no ionospheric disturbance occurs. Therefore, it can be stated that there was no response of the Turkish ionosphere to some of the geomagnetic storms examined in this study. This is because, respectively, for the storms on October 24 and 25, 2011, March 15, 2012, October 8, 2012, March 17, 2013, February 19, 2014, September 12, 2014, August 15, 2015, and September 20, 2015, the DROT values were 34.59, 34.95, 39.73, 38.84, 31.91, 44.97, 35.9, 44.96, and 48.95.

Table 1. Representation of Kp and Dst values and DROT values for geomagnetic storms occurring during the 24th solar cycle.

No	Day of storm	Kp max	Dst-max	DROT	No	Day of storm	Kp max	Dst-max	DROT
1	10/11/2008	6,3	-54	76,26	28	06/22/2015	8,3	-114	61,33
2	04/05/2010	7,7	-61	68,15	29	06/23/2015	7,7	-198	58,91
3	08/03/2010	6,7	-72	55,91	30	08/15/2015	6,3	-71	44,96
4	08/04/2010	6,3	-74	79,65	31	08/27/2015	6,3	-103	81,83
5	05/28/2011	6,3	-80	54,14	32	09/07/2015	6,3	-75	63,02
6	08/05/2011	7,7	-96	62,11	33	09/11/2015	7	-87	60,27
7	09/26/2011	6,3	-118	61,39	34	09/20/2015	7	-79	48,95
8	10/24/2011	7	-79	34,59	35	10/07/2015	7,3	-130	54,45
9	10/25/2011	7,3	-147	34,95	36	12/20/2015	6,7	-166	93,76
10	03/09/2012	8	-145	61,03	37	12/21/2015	6,7	-159	62,83
11	03/15/2012	6,3	-88	39,73	38	05/08/2016	6,3	-95	77,67
12	04/24/2012	6,7	-120	51,48	39	10/13/2016	6,3	-110	64,34
13	07/09/2012	6,7	-78	68,94	40	10/25/2016	6,3	-65	94,92
14	07/15/2012	7	-139	57,22	41	03/27/2017	6,3	-70	87,56
15	07/16/2012	6,3	-113	56,45	42	05/28/2017	7	-125	101,95
16	10/01/2012	6,7	-122	75,18	43	09/07/2017	7,7	-68	68,45
17	10/08/2012	6,3	-99	38,84	44	09/08/2017	8,3	-122	89,33
18	10/09/2012	6,7	-109	60,16	45	09/27/2017	6,3	-44	85,39
19	11/14/2012	6,3	-108	65,89	46	09/28/2017	6,7	-56	87,68
20	03/17/2013	6,7	-132	31,91	47	11/07/2017	6,3	-71	83,77
21	06/01/2013	7	-124	72,47	48	11/08/2017	6,3	-73	59,33
22	06/29/2013	6,3	-101	72,77	49	08/26/2018	7,3	-175	80,65
23	10/02/2013	7,7	-72	58,25	50	08/27/2018	3,3	-71	91,39
24	02/19/2014	6,3	-119	44,97	51	05/11/2019	3,7	-50	81,38

25	06/08/2014	6,3	-37	78,77	52	05/14/2019	6,3	-65	80,78
26	09/12/2014	6,3	-88	35,9	53	08/05/2019	5,3	-53	92,91
27	03/17/2015	7,7	-234	56,12	54	09/01/2019	5,3	-52	96,2

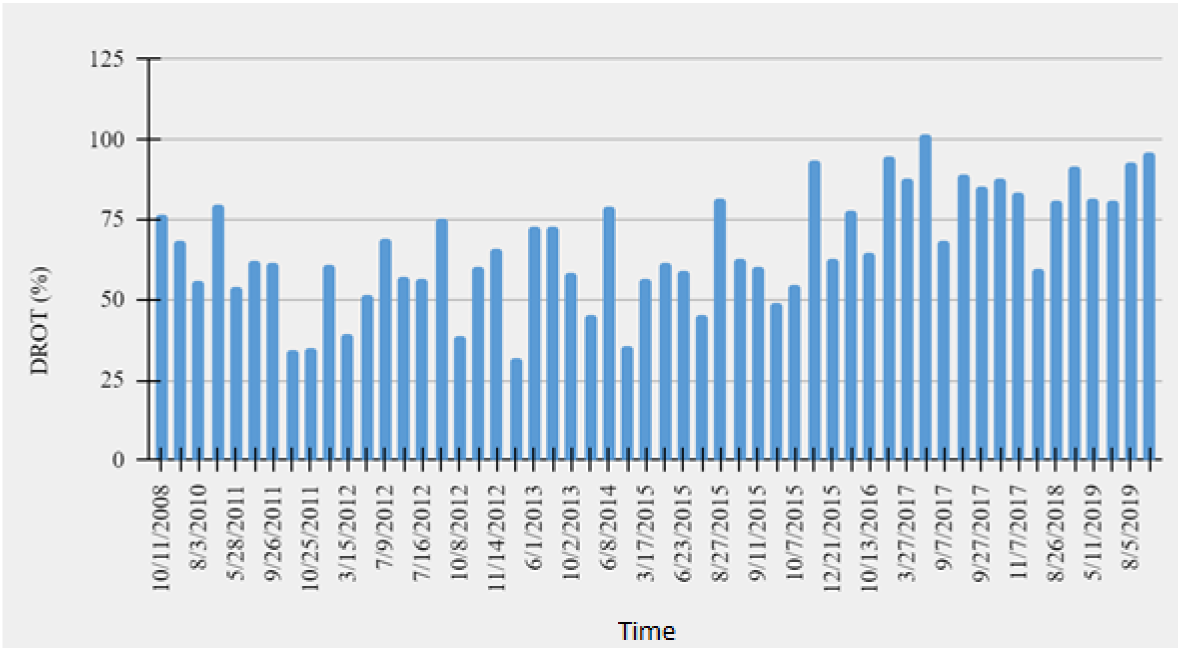

Figure 2. Temporal variation of DROT values depicting the ionospheric response to the 54 geomagnetic storms that occurred during the 24th solar cycle.

In the literature, research regarding geomagnetic storms occurring during the 24th solar cycle has indicated the presence of ionospheric responses. A study by Song, Ding et al. (2013) investigated the response of the Chinese ionosphere to a moderate geomagnetic storm on 28 May 2011, and stated that large-scale traveling ionospheric disturbances occurred in the Chinese ionosphere [35]. Another study by Berényi, Heilig et al. (2023) examining the ionospheric response to geomagnetic storms on November 14, 2012, and March 17, 2015, found a significant decrease in the critical frequency of the F region (foF2) and the total electron content (TEC) [36]. In another study by Mansilla (2018), a global response to the geomagnetic storm on 22 June 2015 was investigated, revealing both increases and decreases in ionospheric TEC values globally [37]. Many other studies have indicated various disturbances in the ionosphere due to geomagnetic storms [8, 38-43].

Furthermore, the occurrence of traveling ionospheric disturbances during geomagnetic storms has been expressed in the literature. Cherniak and Zakharenkova (2018) stated the occurrence of large-scale ionospheric disturbances during a geomagnetic storm on December 19-21, 2015 [44]. The DROT values obtained for the same storm on December 20, 2015 (93,76) in this study match the previous study. In another study by Kishore and Kumar (2023), it was mentioned that large-scale ionospheric disturbances occurred during geomagnetic storms on March 17, 2015, and June 23, 2015 [15]. However, in this study, it can be noted that medium-scale traveling ionospheric disturbances occurred during both storms. Zhang, Nishimura et al. (2022) indicated the occurrence of medium-scale traveling ionospheric disturbances during geomagnetic storms on August 25, 2018, September 7-8, 2017, and May 28, 2017, over the American continent [17]. The results obtained with the DROT method during the same storm periods in this study indicate the occurrence of large-scale traveling ionospheric disturbances over the Turkish ionosphere, except for the storm on September 7, 2017 (DROT=68,45).

3.1. Evaluation of the DROT Method

The DROT method has been defined as a technique proposed by Efendi and Arikan (2017) and used by the authors to automatically detect ionospheric disturbances and scale the intensity of these disturbances for further research [27]. This method has been employed in various studies to attempt to detect ionospheric disturbances [19, 27, 45]. Among these, Karatay (2020) attempted to classify ionospheric disturbances by applying this method to vertical TEC (V-TEC) values. In this study, the same method has been used to detect ionospheric responses to geomagnetic storms.

As expressed in the results section above, it was found that during certain geomagnetic storms, no ionospheric disturbance occurred over the Turkish ionosphere using this method. In particular, the absence of any ionospheric disturbance during severe geomagnetic storms (Dst < -100 nT) casts somewhat doubt on the results of this method. However, during the geomagnetic storm on 17.03.2013, ionospheric responses were investigated for the stations svtl (60,53 D, 29,78 K) and zamb (15,43 D, -28,31 G), located almost in the same longitude, and medium-scale traveling ionospheric disturbances were found to occur with DROT values of 59.80% and 54.95%, respectively. Furthermore, during the same storm, DROT values were calculated for two different stations in Turkey, and for these two stations, DROT values were obtained as ankr (33.20%) and ista (35.80%). These results suggest that, while no disturbance was detected in the Turkish ionosphere according to the DROT method, medium-scale ionospheric disturbances may have occurred in other regions. Karatay (2020) stated in their study that the ability of the DROT method to detect disturbances depends on the magnitude, frequency, and duration of the data. To clearly express the ionospheric response to different forces, Karatay (2020) examined the amplitude and frequency variations of synthetic data. As a result, moderate-scale ionospheric disturbances were predicted to occur when the amplitude of these data ranges between 1.5 A0 and 2A0 and the frequency is low, while large-scale ionospheric disturbances occur when the amplitude exceeds 2.5 A0 and the frequency is lower. Here, A0=1.08 TECU. This analysis may explain why the Turkish ionosphere did not respond to some severe geomagnetic storms in this study, as the amplitude variation of the data may not have reached a sufficient magnitude. In this sense, the inability to obtain ionospheric responses during certain storms in this study could be attributed to the data not reaching a sufficient magnitude of change. It can be suggested that the DROT method may be suitable for detecting ionospheric disturbances that reach sufficient amplitude due to parameters such as geomagnetic storms, solar events, the Earth's magnetic field, and cosmic events. In the future, if this method can be integrated into ionospheric research tools, it may also be useful for detecting possible disturbances that may occur in the radio wave propagation in the ionosphere. As a result, although this method can be used for processing data above a certain magnitude, it may not be appropriate for use below a certain magnitude threshold.

4. CONCLUSION

The response of the Turkish ionosphere to 54 geomagnetic storms of varying scales during the 24th solar cycle was investigated using the DROT method applied to IONOLAB-TEC values. The research revealed that medium- and large-scale ionospheric disturbances occurred in the Turkish ionosphere during these 54 geomagnetic storms. The results obtained are consistent with those reported in the literature for some storms, while they are not consistent for others. In general, large-scale TIDs are expected to occur during severe geomagnetic storms, according to the literature. However, in this study, it was found that medium-scale disturbances occurred during some severe geomagnetic storms using the DROT method, while large-scale TIDs occurred during some moderate and low intensity geomagnetic storms. This discrepancy with the literature may arise from the fact that the ionospheric response to geomagnetic storms depends on various parameters, including latitude and longitude. Furthermore, these results highlight the importance of knowing the fundamental properties of the data, such as frequency and magnitude, for detecting ionospheric disturbances using the DROT method. Examining TIDs in the ionosphere contributes to our understanding of the dynamic and complex nature of the upper atmosphere of Earth. This information is crucial to improving ionospheric models, enhancing space weather forecasts, and developing strategies to mitigate the impact of ionospheric disturbances on various technological systems.

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