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Effects of Tropical Cyclones in the Ionosphere from Data of Sounding by GPS Signals

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Abstract—The problems of recording the ionospheric response to tropical cyclones (TCs) and the possibilities for detecting such a response using GPS (Global Positioning System) signals are discussed. Investigations of ionospheric effects of tropical cyclones with the use of different geophysical methods and technologies of GPS application for remote diagnostics of the ionosphere are reviewed. The results of investigating the action of tropical cyclones on the Earth's ionosphere on the basis of measurements of variations in the total electron content at the global network of ground-based double-frequency GPS receivers are presented. It is shown that (a) the recording of tropospheric effects in the ionosphere is associated with the difficulties of detecting weak disturbances and their identification against the general background of variations and with the problems of identification of sources of such disturbances; (b) geomagnetic storms mask the effects of tropospheric disturbances in the upper ionosphere; and (c) when identifying the ionospheric effects of tropical cyclones, one must pay the bulk of attention to the search for the enhancement of the intensity of disturbances in ionospheric parameter variations.

Keywords: ionosphere, tropospheric disturbances, tropical cyclone, satellite navigation systems, GPS.

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INTRODUCTION

Investigation of the interaction of the ionosphere with the underlying atmospheric layers is one of the most important directions in geophysics. The propagation from the bottom upward of internal atmospheric waves (IAWs) of different scales can serve as the mechanism of such an interaction (Danilov et al., 1987; Hocke and Shlegel, 1996; Kazimirovsky et al., 2003; Lastovicka, 2006): planetary waves (with periods of several days), tidal waves (with periods of several hours), and gravity waves (with periods of 1–150 min). The search for meteorological effects in the ionosphere usually consists in the establishment of correlations between variations in parameters of the ionosphere and troposphere. The overwhelming majority of investigations in this field are devoted to the study of large-scale (with periods from several hours to 30 days) disturbances in the ionosphere associated with planetary and tidal waves (Danilov et al., 1987; Hocke and Shlegel, 1996; Kazimirovsky et al., 2003).

At the same time, it was repeatedly suggested that powerful meteorological disturbances (cyclones, thunderstorms, tornadoes, etc.) must serve as sources of gravity waves of different types, which, under favorable conditions, can penetrate to ionospheric heights and manifest themselves there as traveling ionospheric disturbances (TIDs) (Danilov et al., 1987; Hocke and Shlegel, 1996; Kazimirovsky et al., 2003; Lastovicka, 2006). In addition, according to theoretical models, electric fields arising over regions of strong synoptic disturbances can lead to the generation of irregularities in ionospheric plasma (Pulinets et al., 1998; Sorokin et al., 2005). The influence of tropospheric structures on the overlying layers can be also exerted through the redistribution of minor constituents (for example, ozone) associated with ejections of charged and neutral particles from the cyclone zone (Vanina-Dart et al., 2007a, b; Danilov et al., 1987).

As the experience of long-term investigations showed, the lower ionosphere is more sensitive to meteorological actions (Danilov et al., 1987; Kazimirovsky, 2003; Lastovicka, 2006). Meteorological disturbances can lead to substantial (by one to two orders of magnitude) changes in the electron concentration *Ne* in the *D* and *E* regions of the ionosphere. Analysis of the databank of the rocket-borne sounding in the Tumba research area over 1985 and 1988 (Vanina-Dart et al., 2007a, b) revealed the *Ne* decrease in the *D* region during the 8501-01B tropical cyclone and showed that the electron concentration at heights of 60–80 km on days with TCs is lower than on days without them. The largest *Ne* decrease is observed at levels of about 70 km. At heights exceeding 80 km, the TC action is insignificant. The TC effects in the lower equatorial atmosphere are recorded at distances of up to 8000 km from the cyclone trajectory.

Ionospheric disturbances associated with the TC action on the upper ionosphere (*F* region) were detected in most cases by measurements of the Doppler frequency shift (DFS) or the Faraday rotation of the polarization plane of a sounding signal (Bertin et al., 1975; Hung and Kuo, 1978; Huang et al., 1985; Xiao et al., 2007). The response of the *F* region had the form of wave like TIDs with periods of 20–90 min (Bertin et al., 1975; Hung and Kuo, 1978), 13–14 min (Huang et al., 1985), and about 20 min (Xiao et al., 2007). The trajectory calculations performed in (Bertin et al., 1975) showed that the TID generation zones, most probably, were located in the troposphere in cyclone formation regions. Horizontal distances of probable sources from TID recording places were 1000–2000 km. It was also established that all of the recorded TIDs propagated in the direction opposite to the neutral wind direction in the *F* region of the ionosphere. Therefore, the theoretical estimates (Hocke and Shlegel, 1996; Sorokin et al., 2005) according to which the neutral wind in the ionosphere serves as a filter for wave TIDs were confirmed. The statistics of observations of the ionospheric response are ambiguous. In (Huang et al., 1985), the response of the *F* region was detected only for two events (typhoon Andy of July 22–30, 1982, and typhoon Wayne of July 23–25, 1983) of 12 typhoons considered in the period 1982–1983. Xiao et al. (2007) recorded TIDs in the *F* region during 22 of 32 typhoons which occurred in 1987–1992. In this case, eight typhoons coinciding in time with magnetic storms and solar flares were excluded from consideration.

Chernigovskaya et al. (2008) and Perevalova and Polekh (2009) reported recording an enhancement in the intensity of oscillations with periods of 2–6 h in ionospheric parameter variations from data of the oblique (Chernigovskaya et al., 2008) and vertical (Perevalova and Polekh, 2009) soundings of the ionosphere in the eastern Asia region during the fall of 2005. The growth of intensity was observed under quiet geomagnetic conditions and could be related to the TC action on the atmosphere in the northwestern part of the Pacific Ocean.

The first experiments on recording the ionospheric response to a TC using GPS signals are described in (Afraimovich and Perevalova, 2006; Afraimovich et al., 2007, 2008; Bondur et al., 2008b). Afraimovich and Perevalova (2006) and Afraimovich et al. (2007, 2008) note a certain enhancement of disturbances in the ionosphere during the TC action and specify geophysical factors which can impede the identification of the TC action. Bondur et al. (2008b) fixed the electron concentration increase at the maximum of the *F* layer over the center of hurricane Katrina on September 28, 2005, which was caused, in the opinion of the cited authors, by the penetration of the electric field generated by the hurricane into the ionosphere.

On the whole, experimental investigations support the idea that the passage of a powerful cyclonic front is accompanied by the excitation of IAWs which can reach the ionosphere, as well as propagate to horizontal distances of hundreds and thousands of kilometers. However, theoretical models of the IAW propagation do not always agree with experimental data. The theoretical calculations performed in (Kunitsyn et al., 2007a) showed that acoustic-gravity waves (AGWs) with periods of several minutes must be observed over the place of a local disturbance of the atmosphere. Internal gravity waves (IGWs) with periods of tens of minutes to two to three hours will be recorded at large horizontal distances from a local source in the atmosphere. This phenomenon is associated with the fact that AGWs rapidly attenuate owing to the viscosity and heat conductivity of the atmosphere. At the same time, Huang et al. (1985) and Xiao et al. (2007) report that AGWs with periods of 10–20 min are recorded in the *F* region at horizontal distances up to 2000 km from a TC.

To summarize the review of experimental works on recording the TC ionospheric effects, we should admit that facts of reliable recording of the ionospheric response to TCs are of occasional character. Isolated measurements and short data series presented in papers do not provide full certainty that the detected effects are caused precisely by TC action, and many authors conclude that further systematic investigations in this field are necessary.

This work discusses the possibilities of the GPS satellite radio navigation system for remote diagnostics of the ionosphere and presents the results of investigations of TC action on the ionosphere of the Earth obtained by us from the data of measurements of variations in the total electron concentration at the global network of double-frequency GPS receivers.

GPS POSSIBILITIES FOR RECORDING TC IONOSPHERIC EFFECTS

The GPS satellite radio navigation system is a unique tool for investigations of the ionosphere. At present, the ionosphere of the Earth is transilluminated by thousands of GPS receiver–satellite rays with different positions of receivers. The largest volume of measurement data with the time resolution from 1 to 30 s is obtained from ground-based GPS receivers and is accessible on the Internet. At present, the global network (http://sopac.ucsd.edu) and a number of regional (in Japan, in California, on Kamchatka, etc.) networks of double-frequency ground-based GPS receivers are operating in the world. The total number of registered ground-based receivers exceeds 3000.

Navigation measurements in the GPS are conducted at one f_1 (single-frequency measurements) or at two f_1 and f_2 (double-frequency measurements) carrier frequencies ($f_1 = 1575.42$ MHz; $f_2 = 1227.60$ MHz). For determining the distance between the satellite and the receiver (pseudorange), the measured parameter is either the time of signal propagation (code pseudorange measurements) or the carrier phase delay (phase pseudorange measurements). The accuracy of phase measurements (0.001 m) is substantially higher than that of code measurements (0.3–3 m) (Hofmann-Wellenhof et al., 1992).

During their propagation in the ionosphere, radio signals experience a delay, whose value is proportional to the total electron content (TEC) along the propagation direction. This circumstance makes it possible to determine the TEC from navigation measurements of a GPS receiver. The TEC can be calculated from both code and phase navigation measurements at two frequencies, as well as by combining code and phase measurements at one or two frequencies (Afraimovich and Perevalova, 2006; Hofmann-Wellenhof et al., 1992). In the practice of ionospheric investigations, double-frequency measurements are used the most often, as they are more accurate. The generally accepted measurement unit for the TEC is TECU (total electron content unit) equal to 10^{16} m^{-2}.

The use of double-frequency code measurements and the combination of code and phase measurements make it possible to reconstruct the absolute TEC value. However, the noise level at such a TEC determination is rather high. If the TEC is calculated from double-frequency code measurements, this level is, on average, 30–50% (i.e., several TECUs) (Kunitsyn et al., 2007b), whereas in the TEC determination from code–phase measurements, the noise level is about 0.1 TECU (Afraimovich and Perevalova, 2006). A high noise level substantially impedes the identification of TEC disturbances and makes it possible to record only fairly strong variations. A number of technologies for the GPS diagnostics of the state of ionospheric plasma were developed on the basis of combined code–phase measurements. The technology of constructing the GIM (Global Ionospheric Maps) maps of the absolute vertical TEC (Mannucci et al., 1998) was developed. The standard global GIM maps have the time resolution of 2 h. The spatial resolution of the GIM maps is 2.5° in latitude and 5° in longitude. Regional TEC maps with a higher spatiotemporal resolution (1°; 0.5–1 h) have been published recently. The method for reconstructing the height profiles $Ne(h)$ from TEC measurements was developed in (Smirnov, 2001, 2007; Bondur and Smirnov, 2005). The total electron concentration profile $Ne(h)$ is reconstructed under the assumption of a local spherically layered ionosphere in the height interval of 100–1000 km with the maximum ionization. It is shown that a good accuracy of the $Ne(h)$ profile reconstruction is attained if the accuracy of pseudorange measurements is not worse than 0.2–0.3 m (Smirnov, 2001, 2007). In this case, the rms error of the $Ne(h)$ reconstruction does not exceed 0.02×10^6 el/cm^3, and the Ne value at the maximum of ionization is determined to an accuracy not worse than 2% (Smirnov, 2001, 2007; Bondur and Smirnov, 2005). In other situations, this method can be used for estimating the electron concentration alone at the maximum of ionization (Smirnov, 2001). In spite of technical difficulties, the GPS tomography of the ionosphere is intensely being developed (Kunitsyn et al., 2007b). The GPS tomography methods make it possible to obtain four-dimensional (three spatial coordinates and time) distributions of the electron concentration Ne. The resolution of such distributions depends on the network density of GPS receivers. At present, the horizontal and vertical resolutions of the Ne distributions obtained with the aid of the GPS tomography are, on average, about 100 km; the time resolution varies from 20 to 60 min (Kunitsyn, 2007b). Therefore, the methods based on code–phase measurements make it possible to control the electron concentration level and ensure the possibility of studying large-scale ionospheric structures and processes.

Phase measurements at two frequencies yield a high (up to 0.01 TECU) accuracy of recording TEC variations; however, the absolute TEC value remains unknown (the so-called "ambiguity of phase measurements") (Afraimovich and Perevalova, 2006; Hofmann-Wellenhof et al., 1992). The sensitivity of phase measurements in the GPS system makes it possible to detect disturbances with a time scale up to 5 min and amplitude up to 10^{-3} of the background TEC value (Afraimovich and Perevalova, 2006; Hofmann-Wellenhof et al., 1992).

The recording of satellite signals at spaced GPS receivers makes it possible to determine spatial parameters of irregularities and characteristics of their motion. In this connection, the calculation of TEC variations from double-frequency phase measurements is widely used for the recording of ionospheric disturbances from different sources (solar flares and eclipses, geomagnetic storms, earthquakes, explosions, rocket launches, etc.). A great number of publications are devoted to the methods and results of detecting ionospheric disturbances using double-frequency phase GPS measurements. A generalized review of these publications is made in the monograph (Afraimovich and Perevalova, 2006). The use of double-frequency phase GPS measurements is most preferable for the search for ionospheric manifestations of gravity waves generated by tropical cyclones and for the recording of electron concentration irregularities resulting from the penetration of electric fields over TC zones into the ionosphere.

IONOSPHERIC EFFECTS OF TROPICAL CYCLONES FROM GPS DATA

To detect ionospheric TC manifestations, we used the data on TEC variations obtained at the global network of ground-based double-frequency GPS receivers (http://sopac.ucsd.edu), as well as the GIM maps (ftp://cddisa.gsfc.nasa.gov/pub/gps/ products/ionex)

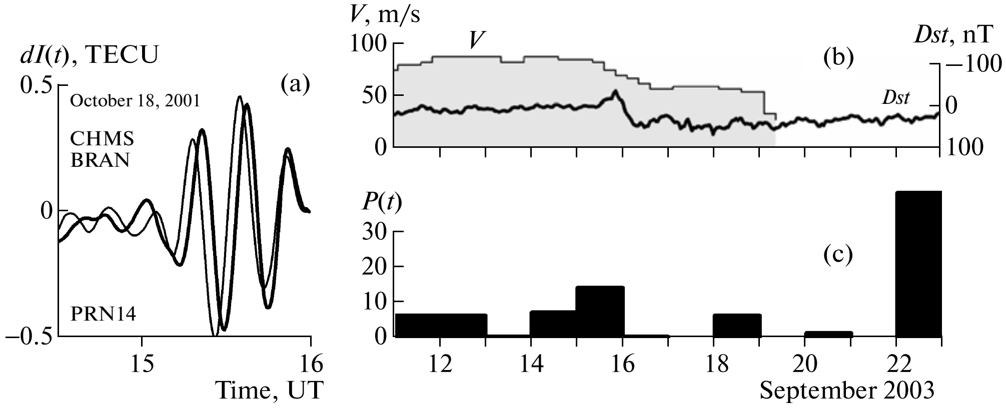

Fig. 1. (a) Example of TWPs in filtered TEC variations. (b) Behavior of the geomagnetic activity index *Dst* and the wind velocity in the Isabel cyclone of September 11–22, 2003. (c) Distribution of the number of TWPs recorded in the period of September 11–22, 2003.

and the regional TEC maps (http://www.ngdc.noaa.gov/stp/IONO/USTEC). For the analysis of data of GPS receivers, we chose continuous series of TEC variations $I(t)$ at least 2.5 h long. Variations in the required range of periods were identified through data filtering with a suitable time window.

The state of the magnetic field of the Earth was controlled by variations in the geomagnetic activity indices *Kp* and *Dst* (http://swdcwww.kugi.kyoto-u.ac.jp; http://clust1.wdcb.ru/spidr). The information about TCs is obtained from the Geoinform-TTs geoinformation system of global tropical cyclogenesis (Pokrovskaya and Sharkov, 2006) and on the site http://www.solar.ifa.hawaii.edu.

TC Isabel (September 6–21, 2003; Atlantic Ocean)

Our first experience in the use of GPS data for the search for ionospheric effects of TCs is associated with the investigation of a special class of medium-scale TIDs—traveling wave packets (TWPs). TWPs represent quasiperiodic TEC oscillations with periods of 10–20 min and packet duration of about 1 h (Afraimovich and Perevalova, 2006). An example of TWPs in the filtered TEC series $dI(t)$ recorded on October 18, 2001, at the CHMS and BRAN stations (PRN14 satellite) in California (USA) is presented in Fig. 1a. According to our data, AGWs propagating in a heterogeneous nonisotropic medium acquire the character of wave packets and can manifest themselves as TWPs (Afraimovich and Perevalova, 2006). Tropical cyclones were considered as a possible source of TWPs. The data of the GPS network in the region of California, the Caribbean Gulf, and southeast Asia related to 18 TCs in the period of 1998–2003 were processed. TC Isabel, which passed during the period of September 6–21, 2003, near the eastern coast of the United States, proved to be the most significant. The largest wind velocity $V = 87$ m/s in the cyclone was fixed on September 11–14 (Fig. 1b). The geomagnetic situation on September 11–14 was rather quiet, and, according to *Dst* variations, a weak magnetic storm was observed on September 15–19 (Fig. 1b). The distribution $P(t)$ of the number of TWPs recorded during the period of September 11–22, 2003, is presented in Fig. 1c. A certain increase in the number of TWPs (up to 15 realizations per day) compared with other periods of Isabel's existence (no more than seven realizations) was fixed in the period of the largest TC development (September 11–14), under quiet geomagnetic conditions. Similar results are obtained for the remaining 17 TCs. Note that the largest number of TWPs (42 realizations) was observed twenty-four hours after the total destruction of the Isabel cyclone (on September 22). However, it has not been established whether this event was related to the Isabel cyclone.

TCs in the Northwestern Part of the Pacific Ocean (September 2005)

The period from September 17 through November 30, 2005, was characterized by a quiet geomagnetic situation and the absence of large magnetospheric storms. Owing to this, the specified period was most favorable for investigating the response of the upper atmosphere to tropospheric disturbances. Nine large TCs were recorded in the northwestern part of the Pacific Ocean during September–November 2005. The time of action of each cyclone is marked by arrows in Fig. 2a. Thick lines indicate the periods when the cyclones were in the stage of a hurricane. The end of September, when three powerful cyclones acted simultaneously, is most interesting for investigations. All three cyclones reached the stage of a hurricane after September 22.

Figure 2b shows the geometry of measurements and the trajectories of motion of the three TCs at the end of September. Thick lines on the trajectories indicate the stages of a hurricane. The positions of the cyclone centers at 00:00 UT are marked by triangles.

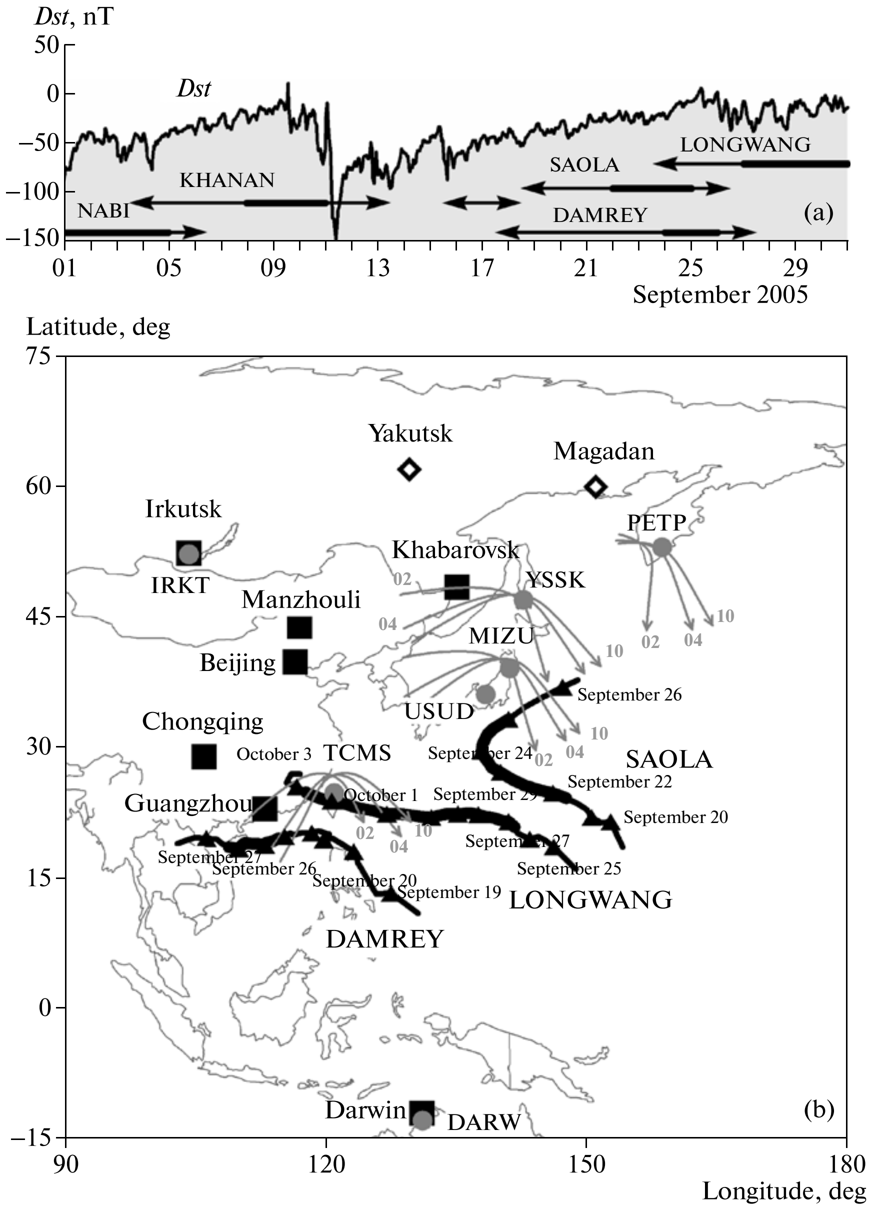

Fig. 2. (a) Behavior of the geomagnetic activity index *Dst* and the times of action of TCs in September 2005 (thick lines indicate the periods when cyclones were at the stage of a hurricane). (b) Geometry of measurements and trajectories of motion of three TCs at the end of September 2005.

Gray dots indicate the GPS receivers whose data were used for the study of the ionospheric response to TCs. Arrows show the trajectories of ionospheric points of the three GPS satellites which were located in the zone of radio visibility of the receivers in the nighttime at the largest angles of the place (numerals designate the numbers of the GPS satellites).

The disturbances possibly associated with the TC action were identified only in the records of TEC variations related to night hours of local time, which once more supports the idea about the predominant influence of solar radiation on the ionospheric plasma. We compared the TEC response in the period from September 20 through October 3, 2005, at the stations located in the immediate vicinity to the TC trajectories (for example, the TCMS station) and at the remote receivers (for example, the YSSK station). Figure 3 shows the TEC variations *dI* obtained at the YSSK (Figs. 3a–3e) and TCMS (Figs. 3f–3j) stations (PRN02, PRN04, and PRN10 GPS satellites) and filtered in the range of periods of 20–90 min.

In the entire period under investigation, TEC disturbances with characteristic time scales of 60–90 min were observed at the stations close to the TC trajectories (TCMS station, Figs. 3f–3j). The amplitude of these disturbances exceeded by more than a factor of two the level of background TEC fluctuations for the given range of periods (Afraimovich and Perevalova, 2006). The amplitudes of TEC variations periodically decreased (on September 23, 2005, and September 28, 2005; Figs. 3g, 3i). As a rule, the amplitude decrease was recorded when no active cyclones were located near the station (September 28, 2005; Fig. 3i). According to our observations, the amplitude of TEC disturbances increased at the moment when the cyclone encountered the coast (September 20, 2005; Fig. 3f). However, this fact must be checked.

At remote stations (YSSK station, Fig. 3a–e), on the whole, we observed an analogous pattern of the TEC behavior with one distinction. The intense disturbances were recorded after one to three days: noticeable TEC disturbances appeared at the YSSK station on September 21. The delay increased at stations more remote from the zone of TC action.

The results of GPS sounding can be complemented with the analysis of data of the vertical sounding of the ionosphere in the East Siberian and Far East regions of Russia, in China, and in Australia, which was performed in (Perevalova and Polekh, 2009) for September–November 2005. At the end of September 2005, the enhancement of the intensity of variations with periods of 2.5–6 h under quiet geomagnetic conditions was fixed nearly at all of the considered ionospheric stations (these stations are marked by squares in Fig. 3b). In most cases, such enhancements coincided in time with periods of TC action. The growth of intensity of variations was, as a rule, accompanied by substantial deviations of the critical frequency and the lower boundary of the *F* ionospheric layer from their median values. In October–November 2005, the response of the *F* region to TCs was considerably weaker than in September. This was, probably, due to the fact that the cyclonic activity in October–November was lower. Our results agree with the data presented in (Chernigovskaya et al., 2008), which reported that the growth of the intensity of variations in the maximum observed frequencies with a period of 2 h was recorded on the Magadan–Irkutsk path of oblique sounding.

Cyclone Katrina (August 23–31, 2005; Atlantic Ocean)

TC Katrina arose on August 23, 2005, in the northwestern part of the Atlantic Ocean. On August 25, the cyclone reached the stage of a hurricane; on August 26, it passed over the Florida Peninsula and appeared in the Gulf of Mexico; and on August 31, it was destroyed over US territory. The cyclone's trajectory is shown in Fig. 4a by the thick black line. The positions of the cyclone's center at 00:00 UT are marked by triangles. Two powerful magnetic storms were recorded when the cyclone was active (Fig. 5a): on August 24–26, 2005 (the *Dst* index dropped to −216 nT; *Kp* = 9), and in the period of August 31–September 5, 2005 (*Dst* = −131 nT; *Kp* = 7). Bondur et al. (2008a) showed that the storm of August 24–26, 2005, could affect the intensity and trajectory of the Katrina cyclone owing to the Forbush reduction of the flux of cosmic rays and the temperature variations at the tropopause level associated with it. In the period of the maximum cyclone development (August 27–30), the geomagnetic situation was fairly quiet (*Dst* index exceeded −50; *Kp* index was no more than 3). Such a situation, in principle, made it possible to record the ionospheric response to the cyclone but required that the geophysical conditions be carefully taken into account.

The cyclone's trajectory passed near the region of action of the equatorial anomaly of ionization, which forms in afternoon hours of local time on both sides of the magnetic equator (Bryunelli and Namgaladze, 1988). Analysis of the GIM maps of the TEC distribution over Central America showed that the reorganization of the equatorial anomaly started on August 25. Such reorganization usually accompanies large magnetospheric storms (Astafyeva et al., 2007). Under quiet conditions, the northern crest of ionization was located at the latitudes 8°–10° N. On August 25, it began to shift northward and reached about 20° N by August 31. Figure 4a shows an example of the TEC map for 20:00 UT, August 28, 2005 (which corresponds to 14:00 LT at −90° E). In the period of August 25–31, in daytime hours of local time, the region of action of the Katrina cyclone fell into the zone of large TEC gradients on the slope of the northern crest of the anomaly, where the probability of generation of heterogeneous ionospheric plasma was high. At night, the anomaly vanished, and TEC spatiotemporal variations along the Katrina cyclone's trajectory were weak (Fig. 4b).

In order to analyze the TEC behavior, the initial series $I(t)$ were filtered in two ranges of periods: 2–20 min and 20–50 min. Continuous data series encompassing several days were formed for each GPS station. Owing to the satellite motion, the duration of an individual series of observations in the GPS receiver is, on average, 5–6 h. At the same time, at least four GPS satellites are permanently present in the visibility range of the receiver. The joining of individual filtered TEC series $dI(t)$ obtained in consecutive time intervals on receiver–satellite rays with highest elevation angles made it possible to form a continuous series of TEC variations several days long for each GPS station. As an example, white lines in Fig. 4a indicate the sites of trajectories of ionospheric points for several GPS satellites whose data were used for constructing continuous series of TEC variations at the KYW1 and MOB1 stations. The filtered series $dI(t)$ at the KYW1 and MOB1 stations, which were located in the immediate vicinity of the trajectory of TC Katrina, are presented in Figs. 5b–5e. In these panels, the time of activity of the equatorial anomaly is shown in gray. An enhancement of the intensity of TEC variations with significant outbursts on some days was recorded in the period from August 24 to 31. The majority of outbursts coincided with the periods of

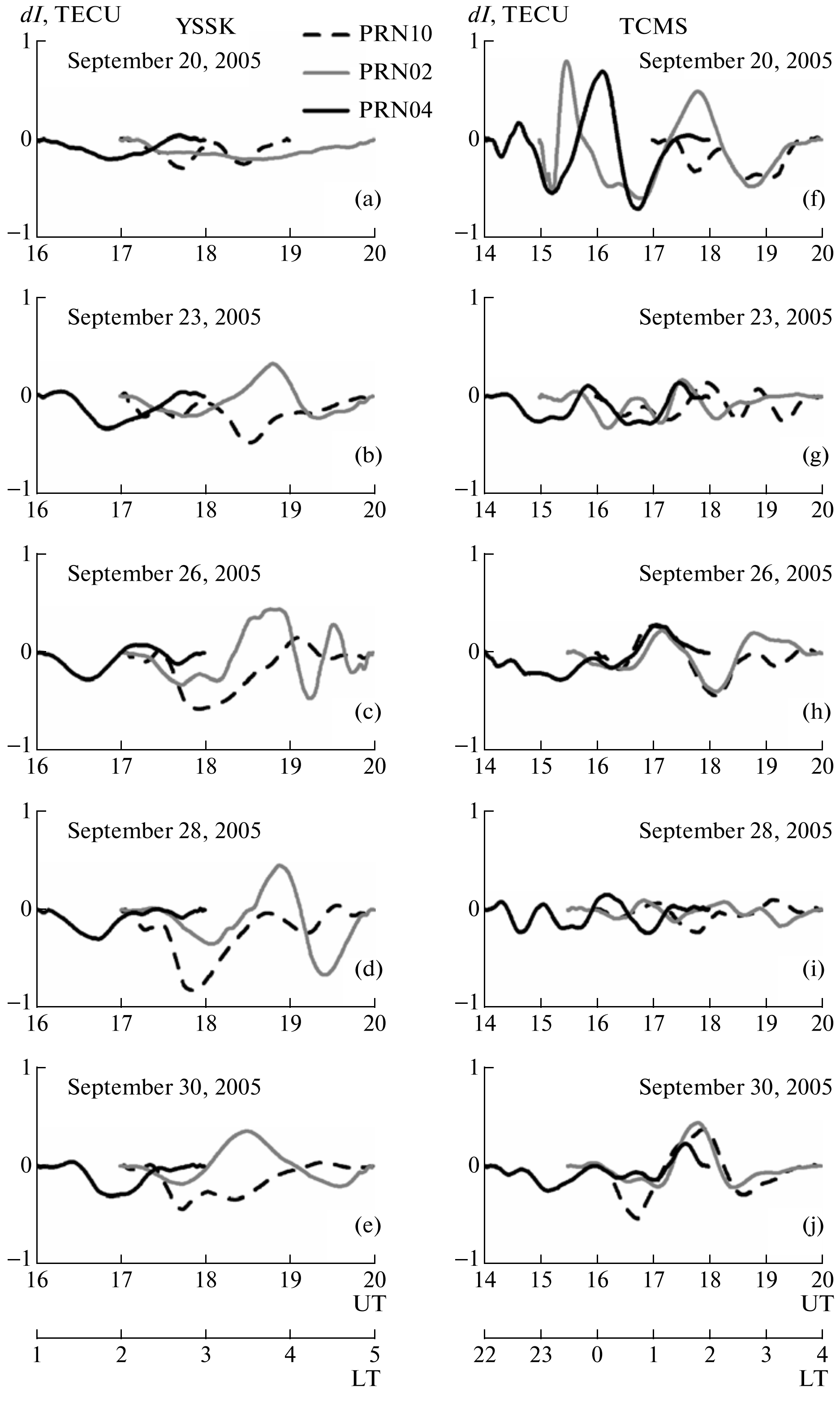

Fig. 3. Filtered TEC variations obtained at the (a–e) YSSK and (f–j) TCMS stations and for the PRN02, PRN04, and PRN10 GPS satellites in September 2005. The LT scales for these stations are shown below.

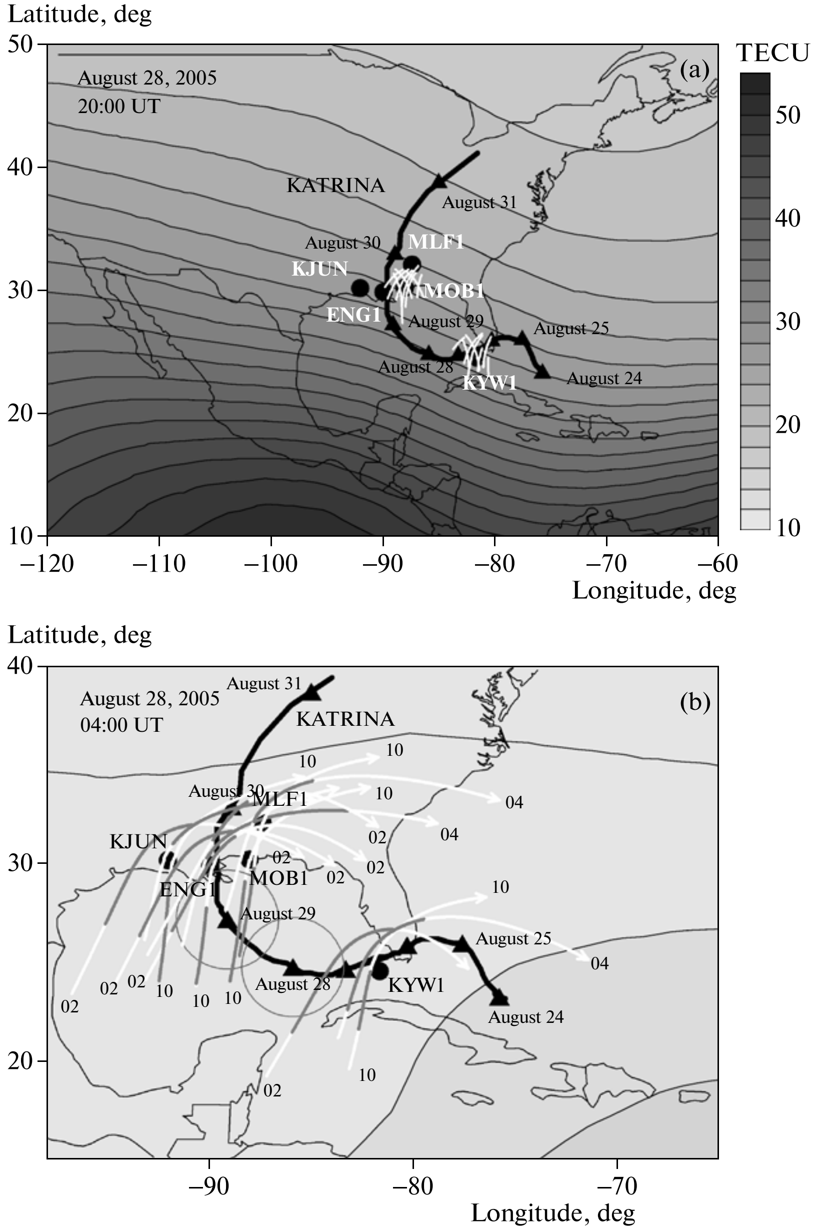

Fig. 4. Maps of the TEC distribution (GIMs) over Central America on August 28, 2005, for two time moments: (a) 20:00 UT and (b) 04:00 UT. The thick black line shows the trajectory of motion of TC Katrina. Triangles mark the positions of the TC center at 00:00 UT. Large dots mark the positions of GPS stations; white lines indicate the trajectories of ionospheric points.

activity of the equatorial anomaly and, most likely, were caused by disturbances of ionospheric plasma resulting from its motion. The response of the ionosphere to the onset of magnetic storms was clearly pronounced on August 24, 2005, at night hours of local time and on August 31, 2005, in the daytime (the largest disturbance of the equatorial anomaly was also observed on this day). We observed an analogous situation during the Saomai cyclone (Afraimovich et al., 2008): the ionospheric effects of the cyclone were suppressed by the actions of the magnetic storm and equatorial anomaly. Therefore, geomagnetic storms seriously impede the recording of ionospheric responses to TCs.

However, the enhancement of the intensity of TEC variations, unrelated, to all appearance, either to the equatorial anomaly dynamics or to the magnetic storms and coinciding with the period of the highest activity of the Katrina cyclone, when the wind velocity in the wall surrounding the hurricane eye exceeded 40 m/s, was recorded on August 27–28 during night hours of local time (Fig. 5a). The TEC variations at night hours of August 27–28 were investigated in greater detail. Figure 6 shows examples of the TEC variations filtered in the ranges of periods of 2–20 and 15–40 min which were obtained during the local night at the KYW1 and MOB1 stations (PRN02, PRN04,

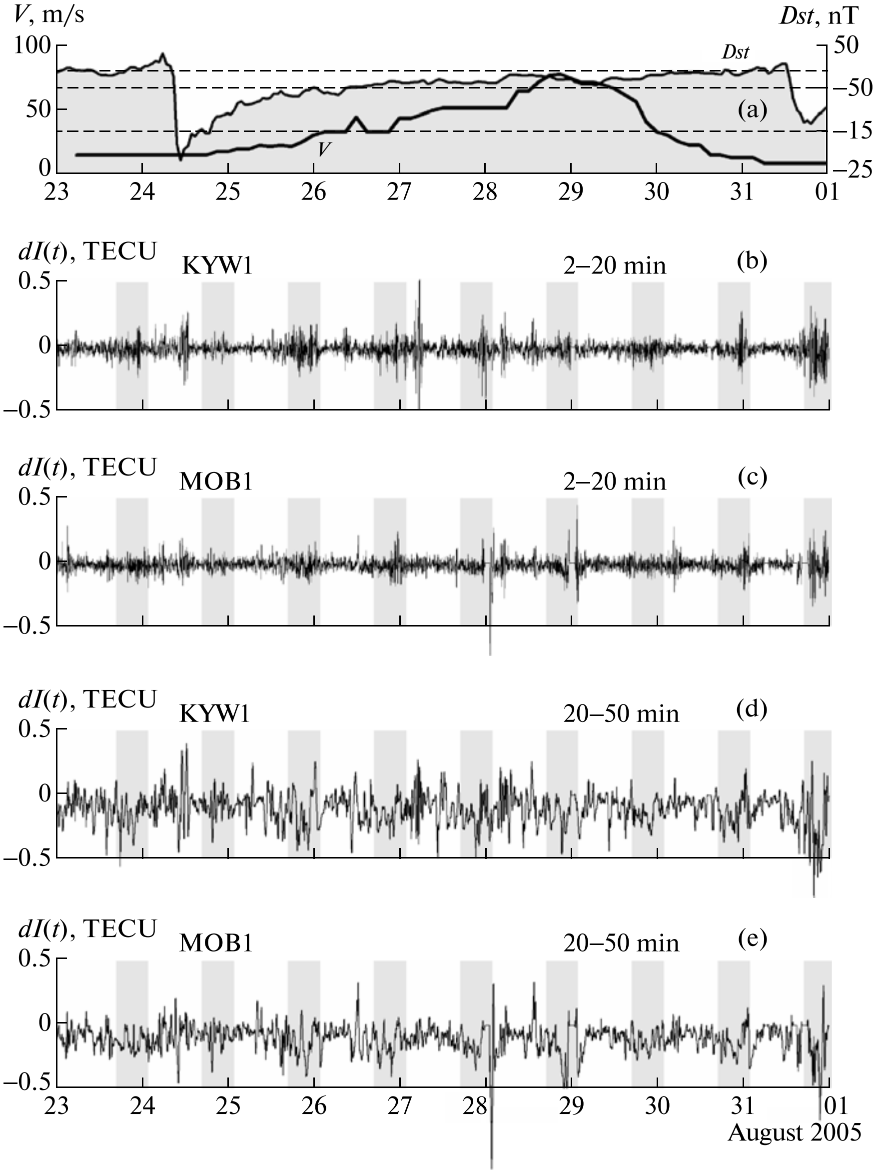

Fig. 5. (a) Behavior of the geomagnetic activity index *Dst* and the wind velocity in the Katrina cyclone of August 23–31, 2005. TEC variations at the KYW1 and MOB1 stations filtered in the ranges of periods of (b, c) 2–20 min and (d, e) 20–50 min. Periods of activity of the equatorial anomaly in the region (–120° to –60° E) are shown in gray in panels (b–e).

and PRN10 satellites) on August 28 and 30, 2005. A considerable intensification of TEC variations in both ranges of periods was recorded in the interval 03:00–07:00 UT (21:00–01:00 LT at longitude –90° E) on August 27, 28, and 29 at five GPS stations (KYW1, MOB1, ENG1, KJUN, and MLF1). As a rule, the intensity of variations was higher on the receiver–GPS satellite rays, which were the nearest to the center of the hurricane, i.e., the KYW1–PRN02 and MOB1–PRN10 rays (Figs. 6a, 6c). It can also be noted that the intensity of variations on August 29 (when TC Katrina shifted northward) at the KYW1 station was considerably lower than at the MOB1, ENG1, KJUN, and MLF1 stations, and on August 30, virtually no TEC disturbances were observed at the KYW1 station. At the remaining stations, small TEC disturbances could be identified on August 30; however, their amplitude was substantially smaller than on August 27–29. The quiet geophysical situation, the time of appearance, and the behavior of TEC disturbances give grounds to believe that the recorded disturbances are caused by the action of the Katrina cyclone on the ionosphere.

White arrows in Fig. 4b show the trajectories of ionospheric points of the receiver–GPS satellite rays for the PRN02 (in the interval 02:00–08:00 UT), PRN04 (in the interval 03:00–09:00 UT), and PRN10 (in the interval 05:00–10:00 UT) satellites which were observed at the KYW1, MOB1, ENG1, KJUN, and

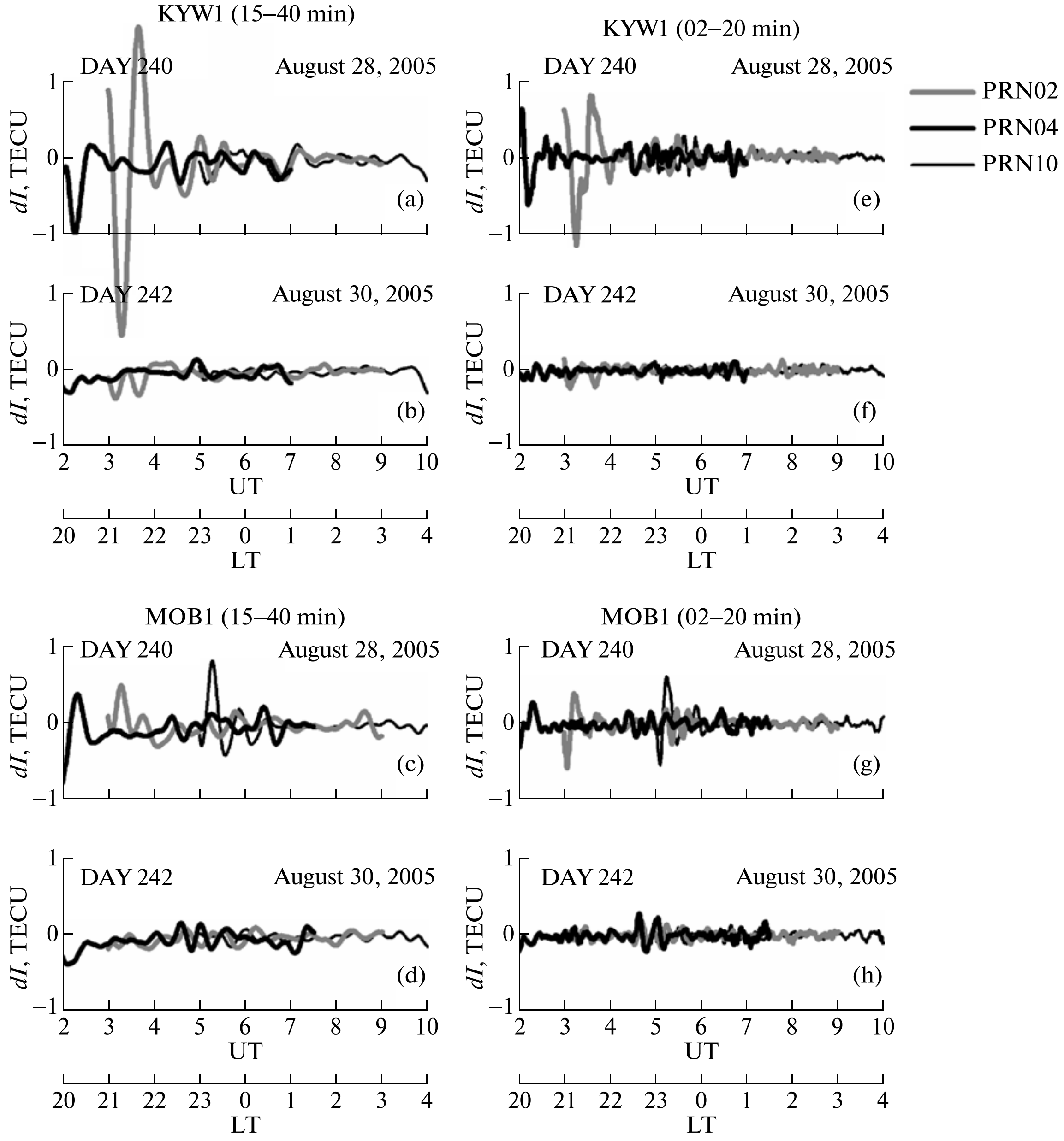

Fig. 6. TEC variations filtered in the ranges of periods of (a–d) 15–40 min and (e–h) 2–20 min obtained on August 28 and August 30, 2005, at the KYW1 and MOB1 stations for the PRN02, PRN04, and PRN10 GPS satellites. The LT scales are shown for the longitude –90° E.

MLF1 stations on August 28, 2005. The periods when the enhancement of the intensity of TEC variations was observed are shown in gray on the trajectories. Circles indicate the region encompassed by the cyclone in the troposphere. We estimated the size of this region from the photograph of cloudiness on board the GOES satellite for 17:45 UT of September 28, 2005 (http://maps.csc.noaa.gov/hurricanes/reports.jsp). If the recorded TEC disturbances were caused by the Katrina cyclone, the spatial distribution of responses indicates that a region of ionospheric plasma irregularities existed over the hurricane's trajectory at heights of the ionosphere. This region forms when a cyclone reaches the stage of hurricane, has a horizontal dimension of about 1500 km, and travels behind the cyclone.

CONCLUSIONS

The recording of the response of the ionospheric *F* region to tropospheric disturbances is one of the complex problems in ionospheric investigations, which is associated with difficulties of detecting weak ionospheric disturbances and their identification against the general background of variations, as well as with the problems of identification of sources of such disturbances.

We believe that, in the study of the TC influence on the ionosphere, it is necessary to take into account the following aspects.

(1) Solar and geomagnetic activities are the dominating factors which control the behavior of the ionosphere (especially the upper ionosphere). Magnetic storms mask the effects of tropospheric disturbances in the upper atmosphere, and responses of the *F* region to TCs can be sought only under quiet geomagnetic conditions. In the identification of the ionospheric response to the passage of a cyclone, it is necessary to take into account, apart from variations of geomagnetic activity, the effects of other possible sources (solar flares, the equatorial anomaly, the solar terminator, earthquakes, etc.).

(2) Changes in the electron concentration and temperature, the formation of irregularities and wave disturbances in ionospheric plasma, variations in electric and magnetic fields, infrasonic oscillations, and optical emissions are possible TC manifestations at ionospheric heights. The question concerning the distance at which the response of the ionosphere to a TC is recorded calls for special attention. It should be taken into account that, at large distances from the cyclone trajectory, the observed effect can be caused by local sources of disturbances rather than by the TC action.

(3) A TC acts for a fairly long time (several days). If during this time it is a source of IAWs, this must increase the intensity of the entire spectrum of variations or its individual regions. On the other hand, time variations in ionospheric parameters, even under quiet conditions, represent a mixture of wave and aperiodic disturbances of various time scales. Taking into account these features, in the identification of the ionospheric effects of TCs (especially at large distances), the main attention should be given to the search for enhancements of the intensity of disturbances in ionospheric parameter variations rather than to the recording of individual wave disturbances.

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