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Regional Features of Atmospheric Manifestations of Tropical Cyclones according to Ground-Based GPS Network Data

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Abstract—Using statistically significant data, we show that the GPS observation method is efficient for revealing the response of the upper atmosphere to global synoptic processes with the help of correlation techniques.

The wave structures detected with the help of GPS interferometry in the given observational network were found to be geographically associated with places of orographic disturbances. For example, disturbances of acoustic gravity waves may arise along coastlines from typhoon-captured airflows. The excitation of these wave structures is most efficient at large rates of increase or decrease in the typhoon intensity. In this case, there occurs a sharp change in the structure (namely, the spectrum roll-off factor of wavelike disturbances). Our analysis revealed no statistically significant correlation between the emergence of wave structures and the core (eye) of a typhoon or cyclone.

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1. INTRODUCTION

The upper atmosphere and ionosphere of the Earth are affected by different groups of processes proceeding in both the near-Earth space and the lower atmosphere (in the lithosphere–atmosphere system). The mechanisms of transfer of atmospheric effects or responses to ionospheric heights from atmospheric phenomena have obviously been investigated poorly. No coherent theory exists; there are a number of physically justified (and, in some cases, experimentally verifiable) suppositions. In this regard, wave energy transfer is probably the most effective, but not the only, mechanism that considers internal atmospheric waves propagating upward from the Earth's surface and generated by certain sources. The wave response of the ionospheric–thermospheric system to external forces (Danilov et al., 1987; Kazimirovskii and Kokourov, 1979; Hocke and Schlegel, 1996) can also be associated with a variety of rather large atmospheric phenomena, such as thunderstorm activity, tropical cyclones, typhoons, hurricanes, tornadoes, etc. The detection of ionospheric disturbances is generally based on the separation of electron concentration disturbances, which researchers associate with meteorological or other disturbances.

In terms of "slow" or quasi-stationary ionospheric manifestations of atmospheric processes, Vanina-Dart et al. (2007) considered the electron concentration decrease over a tropical cyclone at heights of ~70 km and revealed no cyclonic effect at altitudes of the $F2$ layer maximum. However, Bondur et al. (2008) revealed an increase in the electron concentration at the $F2$ layer maximum during the passage of the infamous KATRINA hurricane, which, according to the authors, is due to the influence of the electric field induced by the hurricane.

The azimuth and horizontal velocity of some wavelike traveling ionospheric disturbances (TIDs) of meteorological origin were calculated in (Bertin et al., 1975). The authors claim that the generation areas of the recorded TIDs are probably located in the troposphere and coincide with areas of low atmospheric pressure in the cyclone formation regions, while the wave structures themselves have periods in the range from 20 to 110 min. In (Huang et al., 1985), an array of Doppler instruments was used to study the TID parameters during 12 typhoons (1982–1983); in this case, the authors were only able to detect two events with ionospheric responses as quasi-periodic variations with a characteristic period of around 15 min, which is close to the periods obtained from microbarographic data. However, a later work (Xiao Zuo et al., 2007) analyzed the records of meteorological parameters of 24 (twice the number of events considered in the previous study) strong typhoons in 1987–1992 and compared them with the corresponding data on the ionospheric high-frequency Doppler shifts. It was shown that the typhoons were often characterized by medium-scale TIDs, especially when a strong typhoon landed or was close to the coast.

A number of experimentally observed phenomena generally agree with the linear theory of propagation of internal acoustic gravity waves (AGWs) in the atmosphere (Lighthill, 1970; Kunitsyn et al., 2007). Thus, typhoons (hurricanes) can be generally taken as one of the key ground-based sources of wavelike disturbances in the troposphere.

Table 1. Biggest Atlantic hurricanes (considered in this paper) in 2004–2008 and their characteristics

No.	Name	Date	Storm area, km	$P_{\min}$, mbar	*V*, km/h	*Kp*/*Dst*
1	IVAN	(2–24).09.2004	680	910	270	5.5/–50 and more
2	KATRINA	(23–30).08.2005	780	902	280	9/up to –216 nT 24.08
3	RITA	(17–24).09.2005	750	895	285	Less than 4/–50 and more
4	WILMA	(15–26).10.2005	680	882	295	Less than 4.5/More than –40, up to +30
5	DEAN	(13–23).08.2007	600	905	280	Less than 1.5/More than –15, up to +15
6	IKE	(1–14).09.2008	900–1450*	935	230	3.5/more than 50 nT

Notes: The table indicates the minimum pressure ($P_{\min}$, mbar) and maximum recorded wind velocity. The rightmost column gives the maximum values of planetary indices *Kp* and *Dst* (nT), respectively, separated by a slash. The asterisk (*) indicates that different estimates were used.

In the last fifteen years, technologies for remote diagnostics of the ionosphere using signals of the GPS satellite radio navigation system have been developed actively. The ideology of this monitoring was proposed rather long ago (Hoffmann-Wellenhof et al., 1992). The technique has been developed and improved in a number of works (Ho et al., 1996; Afraimovich and Perevalova, 2006; Zakharov and Zienko, 2007; Zakharov et al, 2008). The new opportunities offered by the ideology of spatial GPS detectors can be used for detecting ionospheric disturbances of meteorological origin in a given region of the Earth. The technique for the analysis of data obtained from networks of navigation signal receivers was tested to identify various ionospheric phenomena (Ho et al., 1996) associated with solar eclipses, explosions and earthquakes, geomagnetic storms and solar flares (Afraimovich and Perevalova, 2006; Zakharov and Zienko, 2008), etc. However, the efficiency of the use of GPS technologies in studying the ionospheric responses to meteorological phenomena has remained open. Indeed, an analysis of integral maps of the total electron concentration obtained from GPS data revealed no direct response to a typhoon itself (Afraimovich et al., 2008); however, the above-mentioned paper (Bondur et al., 2008) observed a large-scale change in the electron concentration over the area of a powerful tropical hurricane.

One of the latest (relative to the time of the preparation of this paper) studies (Perevalova and Ishin, 2010) describes the difficulties of using the GPS technology and points to the "instability" associated with revealing the cyclonic effect on the ionosphere by methods of spectral analysis of variations in the total electron content determined by GPS data. Also, the following obvious and expected conclusion was made: "the record of tropospheric effects in the ionosphere is connected with difficulties associated with detecting small disturbances, selecting them on the general background of variations, and with problems of identifying the source of these disturbances, for example, on the background of disturbances associated with the geomagnetic situation." However, as shown in another study by almost the same team of authors (Ishin et al., 2009), ionosondes make it possible to rather confidently separate the integral ionospheric responses to large-scale atmospheric processes.

The aim of this paper is to use the capabilities of the GPS satellite radio navigation system for remote diagnostics of the ionosphere, namely, using the method of GPS interferometry, to detect the atmospheric and ionospheric wave manifestations of several major Atlantic hurricanes acting on the Atlantic coast of the United States in 2004–2009 (IVAN, KATRINA, RITA, WILMA, DEAN, and IKE). This paper provides a detailed analysis of the geophysical and heliophysical conditions during the action of these cyclones to separate their manifestations in the atmosphere from the manifestations associated with the phenomena under consideration.

2. EVENTS UNDER CONSIDERATION ARE THE LARGEST ATLANTIC HURRICANES

This paper analyzes the ionospheric manifestations of some of the biggest (with respect to certain parameters) tropical hurricanes observed in the Atlantic over the last 5 years. The data on these events were taken from the Internet (http://weather.unisys.com, http://stormpulse.com; http://en.wikipedia.org (here, a more detailed bibliography can be found)) and are presented in Table 1 for convenience of discussion. Figure 1 shows the trajectories of the hurricanes. All events belong to the highest category (category 5) of the Saffir–Simpson scale (http://en.wikipedia.org/wiki/Saffir-Simpson_Scale). An exception is hurricane IKE, acting on September 1–14, 2008. Its existence was characterized by the largest (over the entire (rather short) history of systematic GPS observations) recorded size of air vortices entrained into the hurricane (i.e., the diameter of the hurricane). In this case, this size was almost twice the "normal" values for similar phenomena. It is because of this size that IKE is second only to KATRINA in terms of the damage caused to the United States.

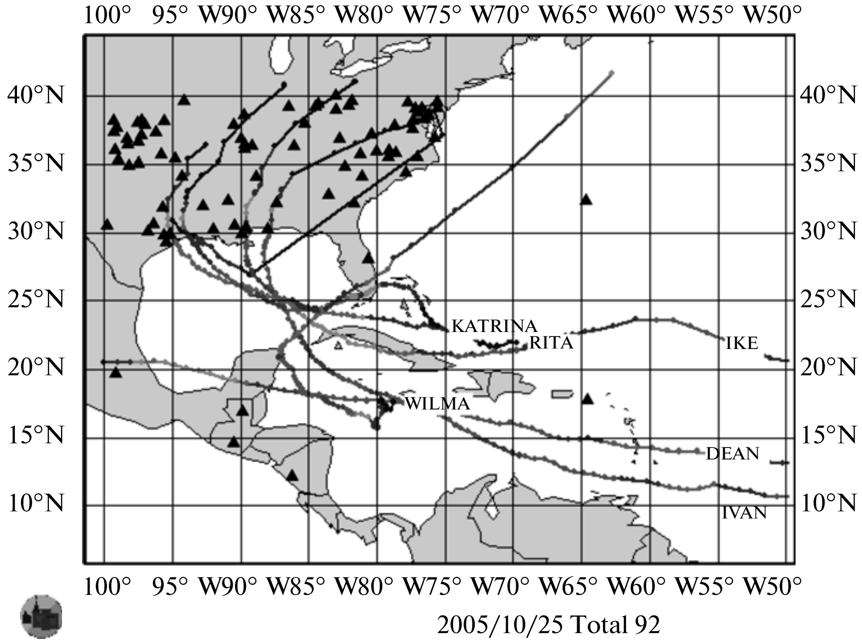


Fig. 1. Distribution of observation stations (triangles) in the region and tracks of all events—the biggest hurricanes of 2005–2009 with their tracks shown on the map.

The above-mentioned hurricanes are remarkable by the fact that all of them put some synoptic "records" and have unique characteristics even in their own category.

For example, the duration of hurricane IKE constituted 19 days, which is almost twice as much as usual. Hurricane RITA was characterized by wind gusts with a speed of up to 380 km/h, while the hourly average wind speed in it reached ~285 km/h. Hurricane WILMA set a record drop in atmospheric pressure during its passage: it dropped by 90 mbar over 12 h with a more than twofold increase in the wind speed (from 120 to 270 km/h) over 16 h.

Hurricane DEAN, which has "mediocre" indicators among other category 5 hurricanes, appeared on the land at its peak intensity. It is unique in terms of the rate of precipitation on the territory of the United States in the history of GPS observations. Additional details regarding each of the hurricanes will be given when considering individual events.

As we will discuss the possible influence of the biggest tropical hurricanes (cyclones) described in Table 1 on the ionosphere, the observed ionospheric effects should be interpreted with regard to heliogeophysical conditions and their effects on the ionosphere. These consolidated data from http://www.spider.ngdc.noaa.gov/ are presented in the last column of Table. 1. Our analysis shows that, except for hurricane KATRINA, all events proceeded on the background of moderately or weakly disturbed geomagnetic conditions, and, therefore, the sharp changes in the properties of ionospheric irregularities registered in the given time periods cannot be explained, as far as is currently known, by variations in solar and geomagnetic conditions alone.

3. GPS DATA PROCESSING AND ANALYSIS TECHNIQUE

In the last fifteen years, technologies for remote diagnostics of the ionosphere using signals of the GPS satellite radio navigation system have been developed actively. The ideology of this monitoring was proposed rather long ago (Hoffmann-Wellenhof et al., 1992). Emerging global observational GPS networks provide new possibilities for detecting ionospheric disturbances of meteorological origin in a given region.

Indeed, the use of GPS signals makes it possible to separate disturbances in the ionosphere on the background of regular changes in this environment on the basis of phase measurements (Hoffmann-Wellenhof et al., 1992; Ho et al., 1996; Afraimovich and Perevalova, 2006) recorded by observational GPS networks. The idea of the method is to combine the L_1 and L_2 recorded phases at two operating frequencies in the form

$$L_I \equiv L_1 - L_2 \sim S\mathrm{TEC} + \mathrm{err}_I,$$

where STEC is the slant (along the sounding beam) integral of the total electron content (TEC) calculated with error err_I.

The slant TEC (I) measured in TEC units is defined as

$$I = \frac{1}{40.308}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}[L_1\lambda_1 - L_2\lambda_2 + \delta L + \text{const}],$$

where $L_1\lambda_1$ and $L_2\lambda_2$ are the increments of the phase path (in meters) at the corresponding operating frequencies f_1 and f_2 with wavelengths λ_1 and λ_2; δL is the error of phase measurements; and const means the uncertainty of the phase difference between observations at different frequencies. The data obtained by different researchers (Hoffmann-Wellenhof et al., 1992; Ho et al., 1996; Afraimovich and Perevalova, 2006) show that the GPS error in determining the TEC changes under quiet geomagnetic conditions does not exceed 1% (for an undefined initial value). The time resolution of most records is 30 s, which makes it possible to study atmospheric processes of relevant periods. TEC series are filtered out to obtain the deviations from average values. The value of the filter window is chosen experimentally and usually constitutes 5 min.

In our work, we also used the derivative of the recorded frequency phase L_1 because it has less phase noise and the amplitude of the GPS signal emitted at that frequency is more than at the second operating frequency. This technique has proved its efficiency (Zakharov and Zienko, 2007; Zakharov et al., 2008).

Thus, based on correlation processing in a navigation signal, one can determine the response of inhomogeneous structures in media. We emphasize that this concerns inhomogeneous (fluctuating) structures and parameters of media motion (velocity direction and vector), rather than their regular parameters. Since noise fluctuations mask the "useful signal" of an ionospheric response and the amplitude of the given signal is comparable with the amplitude of background noise oscillations, it is extremely important to develop special techniques for analyzing and filtering useful signals at the level of noises, including the presence of signal failures (Zakharov and Zienko, 2007).

So, to identify the structure of a wave and determine its parameters within the widespread approach (Afraimovich and Perevalova, 2006), it is proposed to use statistical techniques that have obvious limitations for regional monitoring of large areas because the separation of wave structures by GPS interferometry methods is of aspect character. In this paper, we identify the wave structures using cluster analysis, which has often and quite successfully been used in modern geophysics for data structuring with respect to given criteria (Duran and Odell, 1977; Gvishiani and Dubois, 2002; Zakharov and Budnikov, 2012). In our case, the criteria for the structures to be separated are the localization of a wavelike disturbance (more exactly, the coordinates of the projection of the intersection of the wave vector of the structure with the plane located at the height of the F2-layer maximum) and the direction of the structure motion. The criteria for clusters are associated with the potential accuracy of our technique and constitute approximately ±0.5° by geographic coordinates and ±15° by direction. The further processing is as follows. If some number of structures separated in the course of the preliminary analysis are clustered around a center with the characteristics specified above, they are considered to be a single structure with its geographic coordinates defined as the coordinates of the center of gravity of all wave structures involved in this cluster and its motion parameters are the result of statistical processing (for example, the average value and variance of the structure velocity vector are determined). In fact, the use of clustering algorithms in our case makes it possible to perform an efficient multidimensional data filtering by setting the level (the number of structures included in a cluster).

4. REGIONAL MONITORING NETWORK OF THE GULF OF MEXICO

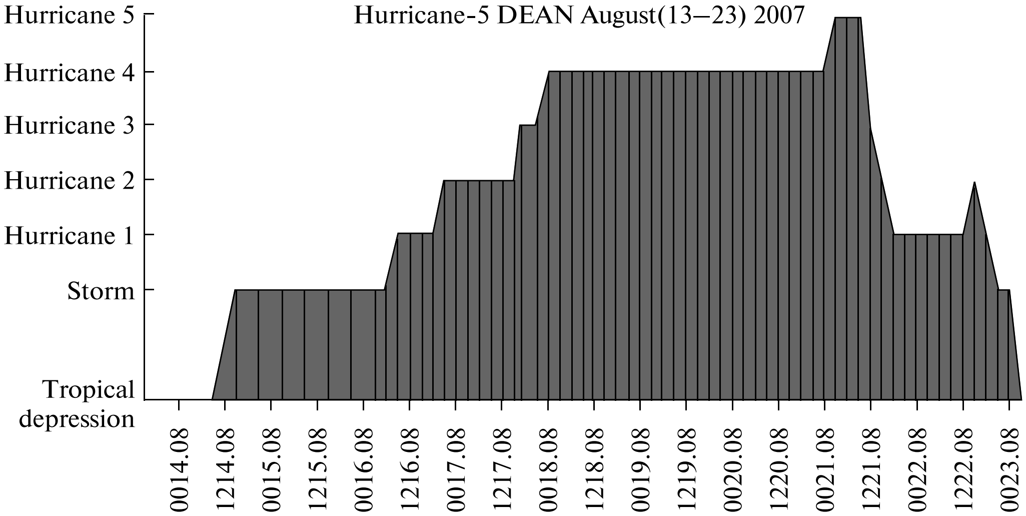
The idea of GPS observation networks (Afraimovich and Perevalova, 2006; Zakharov et al., 2008) is in the selection of stations that cover a monitored area quasi-uniformly. For atmospheric phenomena usually emerging and developing over oceans, this approach has obvious difficulties.

In our work, the monitored area has a size of more than 30° × 30° and covers a territory of over 5 million km^2 in area. We have selected and analyzed data from 92 stations of the IGS network (http://www.sopac.ucsd.edu) (see Fig. 1), which are geographically located around the Gulf of Mexico and to the north of it (in the territory of the United States). The geographical location of these stations is such that some of them are on the Florida peninsula, some are on the Latin American coast of the Gulf of Mexico, and the remaining ones are on the north coast of South America. The distribution of the stations in the region is extremely nonuniform; there were repeated malfunctions during the passage of hurricanes, or the stations failed to provide data at all. To obtain statistically significant estimates for the parameters of wave structures from more than 30 measuring cells, we processed redundant data. The term "statistical estimates" is used not accidentally: in some cases, we have to use measuring cells with large bases and obtain estimates for the parameters of wave structures.

5. MAIN RESULTS

The chosen configuration of the monitoring network makes it possible to obtain information regarding the location and motion parameters of wave structures. The analysis was based on data with a total length of 75 days, i.e., ~140000 h of phase observations with an interval of 30 s (more than 33 million individual readings of phases at both frequencies). As

(a)



Hurricane-5 DEAN August(13–23) 2007

(b)

DEAN August(13–23) 2007

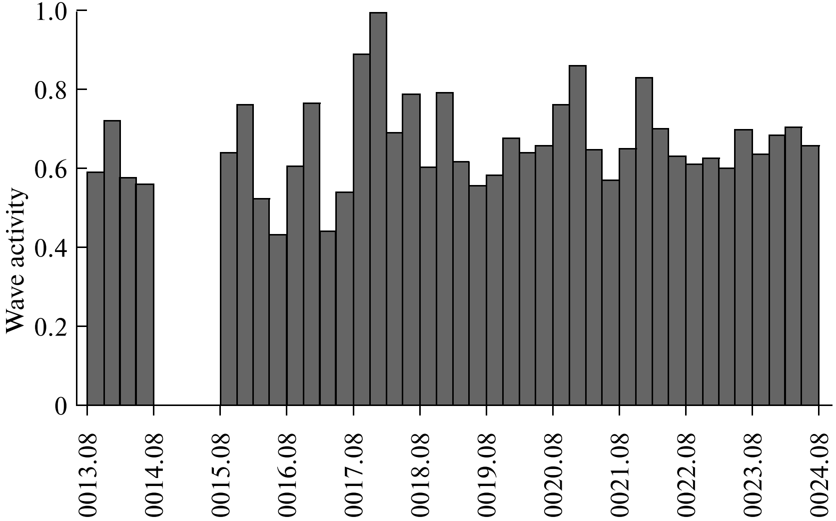


Fig. 2. (a) Evolution of hurricane DEAN, and (b) relative wave activity during the action of hurricane DEAN. The omissions point to a lack of data; normalization to the maximum value is used.

a whole, these results are statistically significant, despite the failures at some stations in the period of hurricanes with increased intensities. The results and conclusions described in the further discussion reflect a number of common trends in the manifestation of atmospheric disturbances at ionospheric heights.

(1) Figure 2a shows the development of hurricane DEAN. It can be seen that on August 17, 2007, the hurricane sharply grows from category 2 to category 4. By wave activity, we call the ratio of wavelike structures observed at a given time period (taken to be 6 h in this figure) to the maximum value over the total observation period (here, this corresponds to the time from 0600 to 1200 on August 17, 2007). Our analysis of the dynamics of the emergence of wave structures shows that on August 17 the wave activity increases by almost ~20% compared to the next day (see Fig. 2b; the omissions here point to a lack of data) and more than 30% relative to the mean value between August 13 and 24, 2007.

We note that the wave structures generated by a cyclone often have a velocity component coinciding with its eastwest direction of motion, while this area is usually characterized by detected wave structures with northsouth and north-southeast directions. The direction from east to west coincides with the motion of the terminator, but time analysis allows us to identify the velocity component associated with the motion of the atmospheric phenomenon itself.

Moreover, a detailed analysis of the spectra of the separated AGW structures shows that it is during the passage of a hurricane with an increasing or decreasing

Fig. 3. Evolution of the wave spectrum roll-off factor during the action of hurricane DEAN on August 13 to 24, 2007: *1* is the area with a lack of data. The dashed lines denote the variance deviation from the average value (bold solid line).

intensity that the α roll-off factor of the spectrum $S(k) \sim k^{\alpha}$, where $k = 2\pi/\lambda$ (where λ is the characteristic size of the disturbance parameter), varies (Gershman et al., 1984).

For hurricane DEAN, we obtained (see Fig. 3) that α reached a numerical value of –2.8 against the average value of –1.27 from August 13 to 24. This deviation is much greater than the variance for the given time period (0.24). In other words, during a sharp increase in a tropical hurricane, the ionosphere has wave structures differing from the "equilibrium, background" conditions and, as a rule, these structures have a higher (up to 2 times) velocity, reaching 1.2–1.5 km/s.

These results are not related to geomagnetic activity: in the period between August 13 and 23, 2007, the absolute *Dst* value was less than 20 nT and the value of the *Kp* index did not exceed 1.5.

The behavior of wavelike structures was somewhat different for hurricane IVAN. In English-language literature, this event is often called "IVAN the Great" owing to its intensity and duration. The hurricane began on the night of September 2, 2004, with a tropical depression, which turned into a storm by 0200 on September 3. The hurricane rapidly (in less than 15 h) intensified to category 4 (at 0000 on September 6). Then, it dropped to category 2 (on September 7) and subsequently grew to category 5 (on September 9). From September 9 to 17, the hurricane intensity was between categories 4 and 5. Then, the hurricane rather quickly (in less than 20 h) terminated and degenerated into a tropical depression.

When the hurricane reached category 4 or 5, the wind speed was up to 90 m/s and the pressure dropped to 910 mbar. For comparison, the wind speed at the phase of tropical depression did not exceed 15–20 m/s. The temporal drops in pressure and wind speed constituted from –12 to 5 mbar/h and ±5 m/s^2, respectively.

An analysis of the wave spectra of the separated structures has shown here an abrupt change in the behavior of the α parameter from August 15 to 18, reaching –1.9 against the average value of –1.2 at a variance of 0.12; i.e., the average value was exceeded by almost 1.6 times (see Fig. 4). This time interval corresponds to the decay of the hurricane from category 5 to a tropical depression. This period was characterized by small geomagnetic variations; i.e., the *Dst* value was no more than –40 nT. At the same time, the *Kp* index was moderately disturbed and there were no significant solar disturbances (http://www.spider.ngdc.noaa.gov). In other words, the observed behavior of wave structures is most probably caused by the hurricane.

Finally, we consider the α parameter during the development of hurricane IKE (see Fig. 5). Although this is the only hurricane of category 4 among all the hurricanes considered by us, the size of its synoptic vortex (the storm area) is 1.5–2 times larger than the similar values for other hurricanes in 2004–2009.

Our analysis also shows that in this case the value of the α parameter during the hurricane changes dramatically (see Fig. 6) in the range from –1.45 to –0.8 with an average value of –1.06 and a variance of 0.11. We emphasize that the geomagnetic situation in this period was moderately disturbed, which also allows us to associate the resulting variations in the spectrum of wave structures with the action of the hurricane.

(2) For convenience of comparison, all the results obtained from the analysis of the spectrum of wave structures are combined in Table 2. It can be seen that all the events under consideration are characterized by

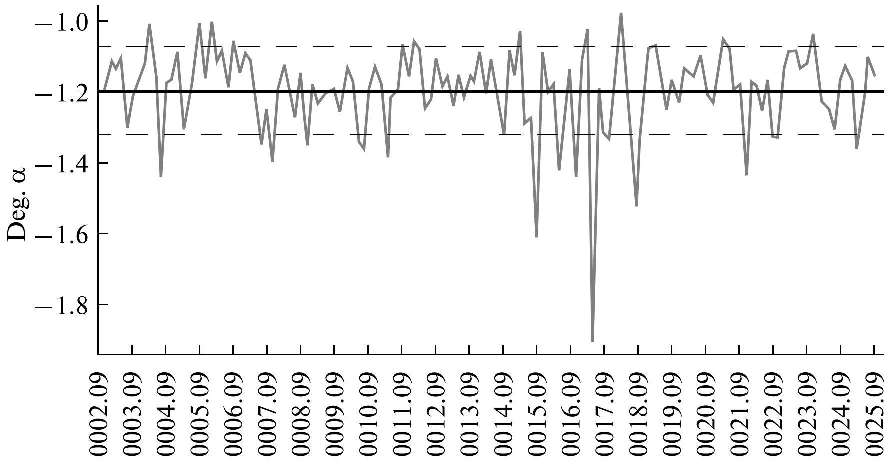


Fig. 4. Evolution of the wave spectrum roll-off factor during the action of hurricane IVAN on September 2 to 25, 2004.

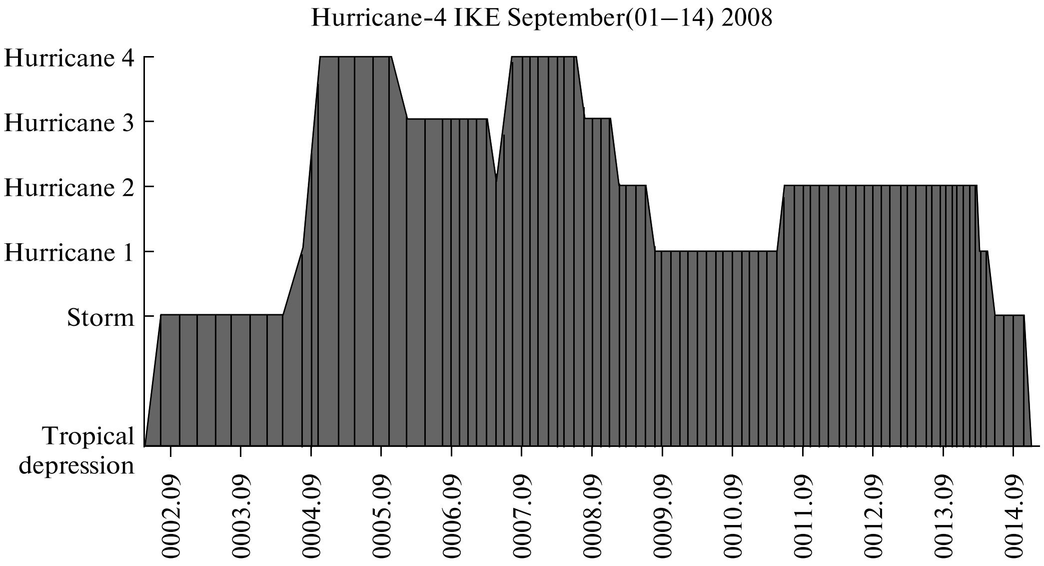


Fig. 5. Evolution of hurricane IKE.

a sharp decrease in the α parameter just during the action of the hurricane or with the most sharp changes in its intensity (increase or decrease). The variations in α with respect to its average value during the action of the hurricane and 5 days before and after it constituted 1.3 to 2.2 times, which significantly exceeds the variance of variations with respect to the average value. For the five events considered, the geomagnetic activity during the action of the hurricanes was low or weakly disturbed. An exception is KATRINA: this hurricane is characterized by strongly disturbed geoheliophysical conditions, which complicates the unambiguous interpretation of the resulting variations in α, as in this case too exceeds its average value more than twice and has the above-described features of the behavior of α.

It should be noted that this behavior of the specified parameter is generally similar to the manifestations of magnetic storms in the spectrum of ionospheric inhomogeneities (Zakharov et al., 2008). In both cases, there occurs a sharp change in the spectrum roll-off factor; i.e., the effect actually leads to a changed rate of transition to turbulence in the medium. We believe that this is related to the wave energy transfer into the upper atmosphere, despite the different energy sources of this effect, which are located in the Earth's lower atmosphere and magnetosphere, respectively.

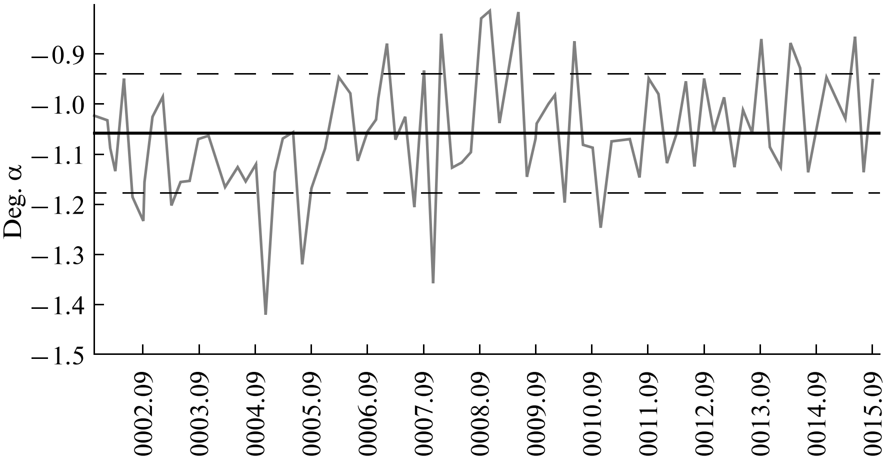


Fig. 6. Evolution of the wave spectrum roll-off factor during the action of hurricane IKE on September 2 to 15, 2008.

(3) Now, we turn to the analysis of the geographic fixation of wave structures; i.e., we locate the source of the AGW disturbances recorded at ionospheric heights. We note that the methodical accuracy of the localization of the subionospheric points of wave structures is usually no less than 50–100 km for measurement cells with dimensions of up to 100 km (Afraimovich and Perevalova, 2006).

Figure 7a shows maps of the geographic location of subionospheric points for clusters of wave structures (single points) separated during the action of hurricane KATRINA (its trajectory is represented by a solid line). One can see the binding between the structures and orographic disturbances along the hurricane trajectory (the islands and mountain ranges). For example, on the island of Cuba, which turned out to be in close proximity to the eye of the hurricane, the large number of ionospheric disturbances, as shown by the analysis, is due to the Sierra-de-Trinidad mountain range in the center of the island (the highest peak is Mount San-Juan, 1156 m). The situation is also similar for the coast of Honduras, where the disturbance sources are identified as the coastal edge and mountain range in the southern part of the country (on the border with Nicaragua). A sufficiently large number of signals were recorded from the Bahamas, which were in close proximity to the eye of the hurricane.

We note that Fig. 7b shows a close-up view of the map of the coast and the southern part of Honduras. On the shaded map, the beam length is proportional to the average velocity of structures in the corresponding cluster, and the direction coincides with the direction of motion of the given structure. Comparing our map with a topographic map of the region, one can clearly see that the structures separated by cluster analysis are bound to the coast and mountain ranges.

A similar situation is also observed in other cases (see Figs. 8a–8d). So, the disturbance sources for hurricanes DEAN, IKE, and WILMA are the island of Cuba, the Bahamas Islands, and the coastal edge of the Yucatan Peninsula. Hurricane IVAN yields a clearly expressed area of the coast and mountain range

Table 2. Wave spectrum roll-off factor during the biggest Atlantic hurricanes in 2004–2008

No.	Hurricane	Date	$\alpha_{av} \pm \sigma_\alpha$	α_{min}	Period
1	IVAN	(2–24).09.2004	−1.20 ± 0.12	−1.9	Transition from category 5 to depression
2	KATRINA	(23–30).08.2005	−1.05 ± 0.11	−2.15	Time of action
3	RITA	(17–24).09.2005	−1.26 ± 0.15	−1.64/−0.85	Growth from a storm to category 3
4	WILMA	(15–26).10.2005	−1.28 ± 0.11	−1.72	Time of action
5	DEAN	(13–23).08.2007	−1.24 ± 0.12	−2.8	Growth from category 2 to category 4
6	IKE	(1–14).09.2008	−1.08 ± 0.12	−1.42	Time of action

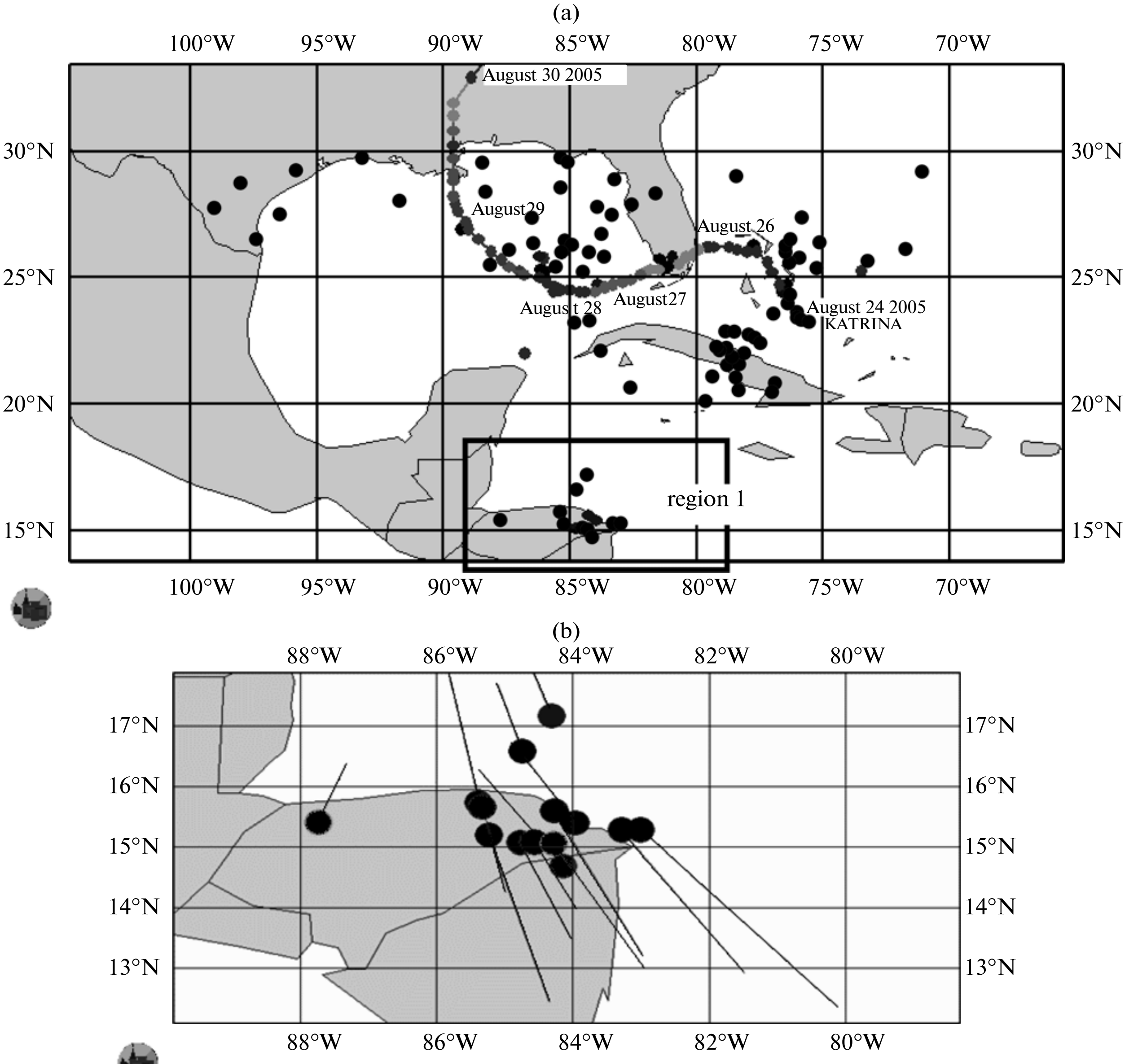


Fig. 7. (a) Location of the subionospheric points for the clusters of wave structures emerging during the action of hurricane KATRINA. The solid line denotes the hurricane trajectory. (b) Same as for (a), except for enlarged area *1*. The beam length is proportional to the velocity, and the beam direction specifies the motion of the detected structure in a cluster.

in Honduras and shows no disturbances from the island of Cuba.

Our analysis shows that not every mountain structure creates orographic disturbances at ionospheric heights. Indeed, in all the cases considered, we did not manage to associate the localization of subionospheric points of perturbations with the mountain range on the island of Haiti, the height of which is more than twice the height of the mountain range on the island of Cuba (which was treated by us as a source of atmospheric disturbances). It is noteworthy that in all cases (except for hurricane IVAN), the source of atmospheric disturbances is confidently localized in the shallow-water area of the Gulf of Mexico (east of the Florida Peninsula).

These results revealed that it is statistically insignificant whether wave structures emerge directly from the core (eye) of a typhoon or cyclone.

The revealed facts have a quite simple qualitative explanation.

Wavelike disturbances arise when air flows moving with a hurricane flow around orographic disturbances; here, their excitation is effective at sudden changes in the hurricane intensity (its growth or decay), which is

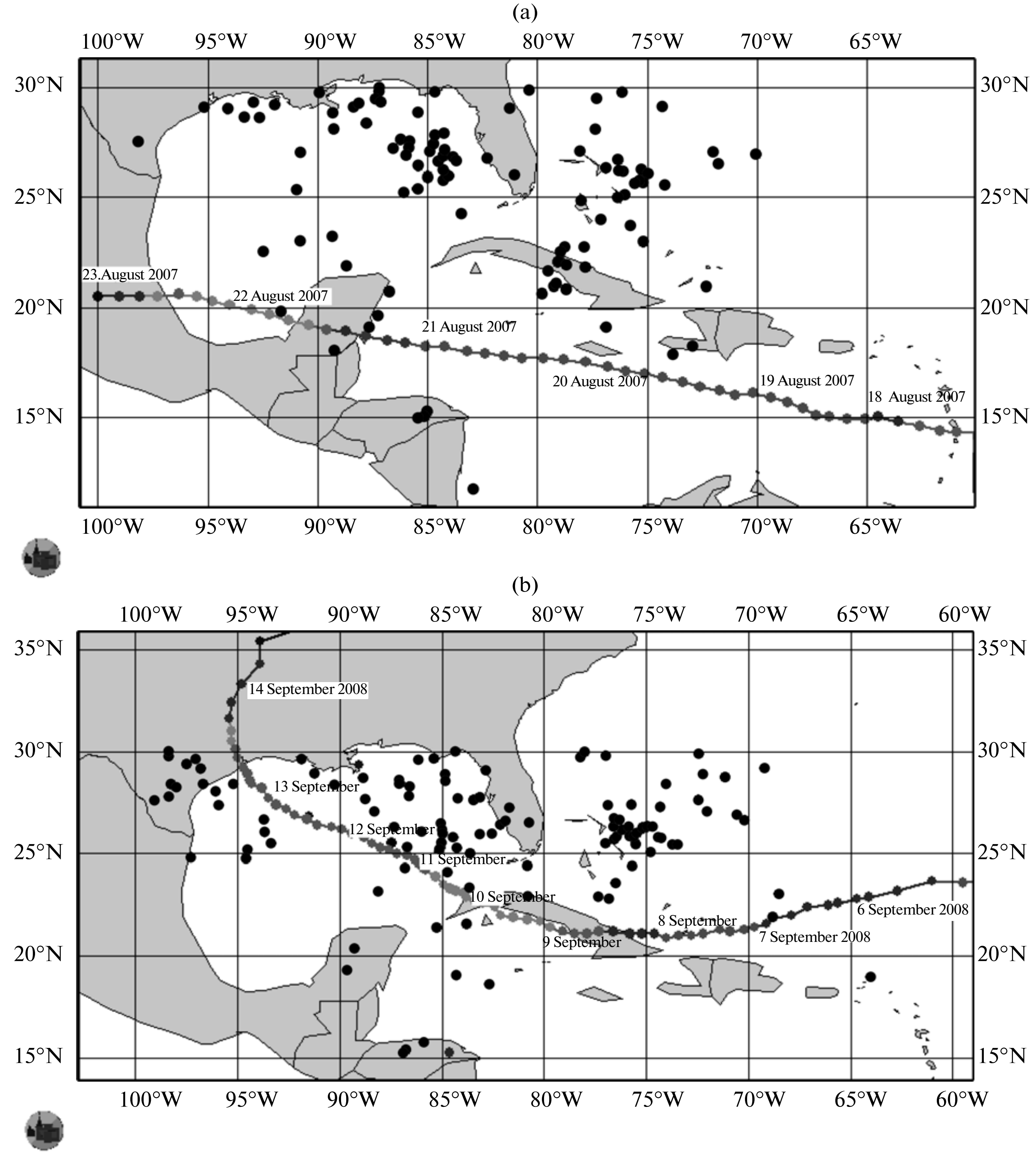


Fig. 8. Geographic location of the sources of acoustic gravity disturbances detected by GPS interferometry methods during the action of big Atlantic hurricanes: (a) IKE, (b) DEAN, (c) IVAN, and (d) WILMA. Cluster analysis was used to classify the disturbances.

generally expected. The emergence of generation areas associated with the coastal edge has also been observed earlier, although without the use of GPS techniques (Bertin et al., 1975). The stable generation of waves in this case is probably related to the emergence of vortex structures in the atmosphere in the area of airflow of orographic obstacles. Obviously, propagating wave structures must have frequencies coinciding with the natural frequencies of internal oscillations in the free atmosphere, i.e., correspond to periods from several minutes to several hours, which makes it possible to use data of GPS observations with a duration of up to 4 h for their identification. The region of stable generation of disturbances in the shal-

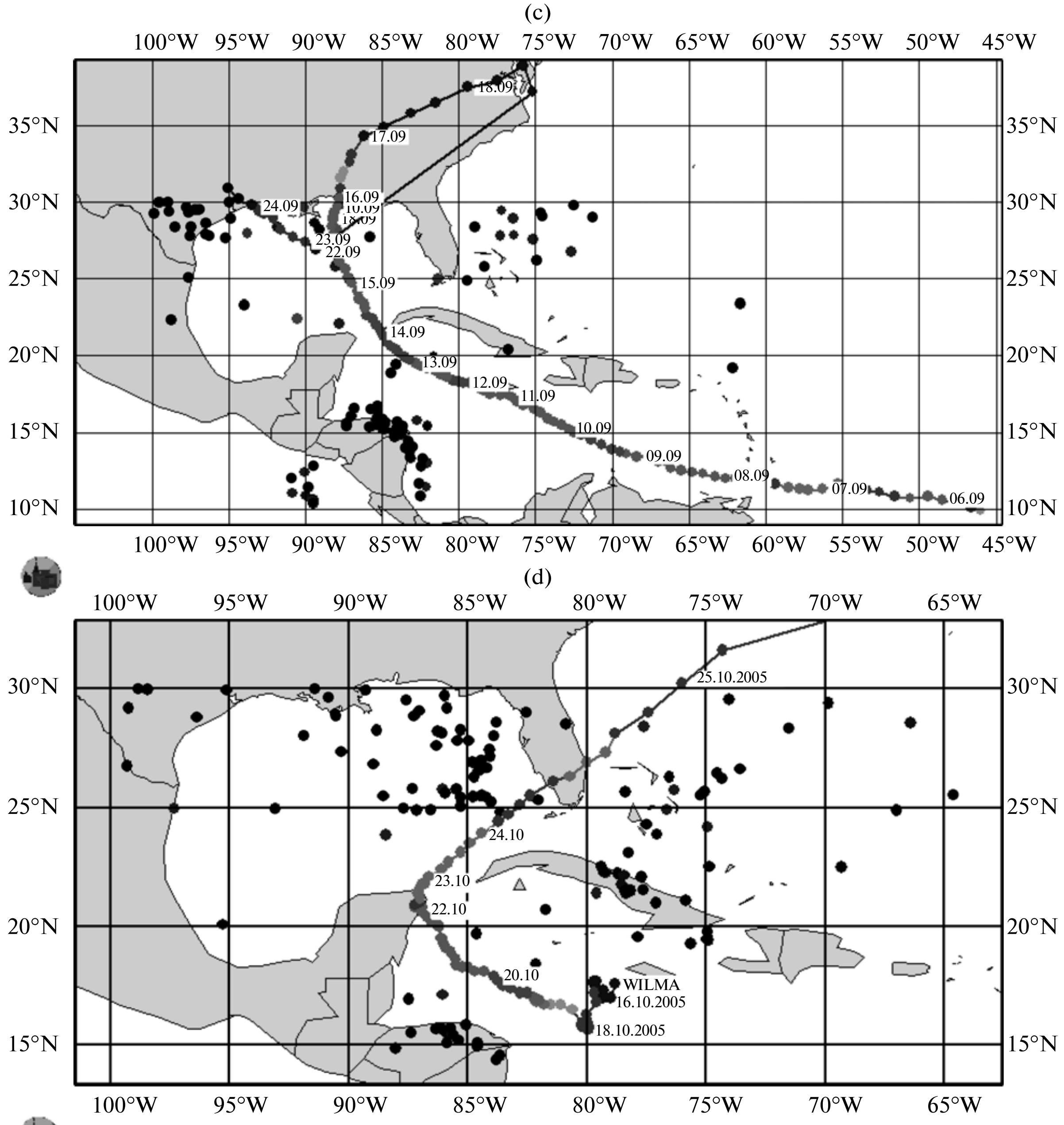


Fig. 8. Contd.

low-water area of the Gulf of Mexico is probably connected with tide phenomena phenomena and shallow-water waves, as well as flow or interaction with these hurricane-induced typically topographical formations.

6. CONCLUSIONS

Using statistically significant unique data, we show for the first time that the technique of GPS observations with correlation methods is efficient for revealing the response of the upper atmosphere to global synoptic processes.

We found that the wave structures detected by the method of GPS interferometry in a given observation network are geographically associated with places of orographic disturbances. For example, AGV disturbances may arise along coastlines from typhoon-captured airflows. The excitation of these wave structures was found to be most effective at high rates of typhoon growth or decay. This leads to a dramatic change in the structure, namely, the spectrum roll-off factor of wave disturbances. The nature of this factor is generally similar to the manifestations of magnetic storms in the spectrum of ionospheric inhomogeneities (Zakharov et al., 2008), which is primarily caused by the wave nature of the ionospheric effect in both cases, despite the different energy sources of this effect, located in the Earth's atmosphere and magnetosphere, respectively.

Our analysis revealed no statistically significant correlation between the emergence of wave structures and the core (eye) of a typhoon or cyclone.

Cyclone-induced wave structures often have a velocity component coinciding with the direction of its motion. Indeed, this region usually involves detected wave structures with the northsouth and north-southeast directions. During the development of a hurricane or cyclone, the northern and eastern components of the velocity vector of wave propagation arise, and some disturbances are strictly northward or eastward. The observed eastwest direction coincides with the motion of the terminator, but time analysis allows us to identify the velocity component associated with the motion of the atmospheric phenomenon itself.

So, it was found that cyclones significantly affect the modes of generation and propagation of wave structures in the ionosphere, and the use of GPS networks makes it possible to reveal this effect. The observed phenomena may be related to the excitation of internal and acoustic gravity waves in the lower atmosphere and their propagation to ionospheric heights. The frequencies of excited oscillations coincide with the natural frequencies of atmospheric free oscillations, and this fact certainly complicates both their separation and interpretation of the results obtained on the background of "proper" (or equilibrium) wave structures in the system of geospheres. However, the use of correlation methods of processing in some cases allows us to overcome this difficulty.

From the methodological point of view, the use of the capabilities of the GPS satellite radio navigation system for detecting the atmospheric and ionospheric wave manifestations of major hurricanes can be regarded as a fundamentally important and efficient technique.

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REFERENCES

Afraimovich, E.L. and Perevalova, N.P., *GPS-monitoring verkhnei atmosfery Zemli* (GPS Monitoring of the Earth's Upper Atmosphere), Irkutsk: SO RAMN, 2006.

Afraimovich, E.L., Voeykov, S.V., Ishin, A.B., Perevalova, N.P., and Ruzhin, Yu.Ya., Variations in the Total Electron Content during a Powerful Typhoon of August 5–11, 2006, near the Southeastern Coast of China, *Geomagn. Aeron.*, 2008, vol. 48, no. 5, pp. 703–708 [*Geomagn. Aeron.* (Engl. transl.), 2008, vol. 48,, pp. 674–679].

Bertin, E., Tesud, Y., and Kersley, L., Medium Scale Gravity Waves in the Ionospheric *F*-Region and Their Possible Origin in Weather Disturbances, *Planet. Space Sci.*, 1975, vol. 23, pp. 493–507.

Bondur, V.G., Pulinets, S.A., and Uzunov, D., Studying the Effect of Large-Scale Atmospheric Turbulent Processes on the Ionosphere, Using the Katrina Hurricane as an Example, *Issled. Zemli Kosmosa*, 2008, no. 6, pp. 3–11.

Danilov, A.D., Kazimirovskii, E.S., Vergasova, G.V., and Khachikyan, G.Ya., *Meteorologicheskie effekty v ionosfere* (Meteorological Effects in the Ionosphere), Leningrad: Gidrometeoizdat, 1987.

Duran, B. and Odell, P., *Klasternyi analiz* (Cluster Analysis), Moscow: Statistika, 1977.

Gershman, B.N., Erukhimov, L.M., and Yashin, Yu.Ya., *Volnovye yavleniya v ionosfere i kosmicheskoi plazme* (Wave-Like Phenomena in the Ionosphere and Space Plasma), Moscow: Nauka, 1984.

Gvishiani, A. and Dubois, J.O., *Artificial Intelligence and Dynamic Systems for Geophysical Applications*, Berlin: Springer, 2002.

Ho, C.M., Mannucci, A.J., Lindqwister, U.J., Pi, X., and Tsurutani, B.T., Global Ionosphere Perturbations Monitored by the Worldwide GPS Network, *Geophys. Res. Lett.*, 1996, vol. 23, no. 22, pp. 3219–3222.

Hocke, K. and Schlegel, K., A Review of Atmospheric Gravity Waves and Traveling Ionospheric Disturbances: 1982–1995, *Ann. Geophys.*, 1996, vol. 14, pp. 917–940.

Hoffmann-Wellenhof, B., Lichtenegger, H., and Collins, J., *Global Positioning System: Theory and Practice*, New York: Springer-Verlag Wien, 1992.

Huang, Y.-N., Cheng, K., and Chen, S.-W., On the Detection of Acoustic-Gravity Waves Generated by Typhoon by Use O: Real Time HF Doppler Frequency Shift Sounding System, *Radio Sci.*, 1985, vol. 20, pp. 897–906.

Ishin, A.B., Voeykov, S.V., Perevalova, N.P., Zalizovskii, A.V., and Sopin, A.A., Variations in the Ionospheric Parameters Observed during Powerful Hurricanes in 2005 near the USA Atlantic Coast, *Recent Probl. Remote Sound. Earth Space* 2009, vol. 6, no. 2, pp. 274–279.

Kazimirovskii, E.L. and Kokourov, V.D., *Dvizheniya v ionosfere* (Motions in the Ionosphere), Novosibirsk: Nauka, 1979.

Kunitsyn, V.E., Suraev, S.N., and Akhmedov, R.R., Modeling the Propagation of Acoustic Gravity Waves in the Atmosphere for Different Surface Sources, *Vestn. Mosk. Gos. Univ., Ser. 3, Fiz. Astron.*, 2007, no. 2, pp. 59–63.

Lighthill, M. J., *Nelineinaya teoriya rasprostraneniya voln* (Nonlinear Wave Propagation Theory), Moscow: Mir, 1970.

Perevalova, N.P. and Ishin, A.B., Hurricane Effects in the Ionosphere according to the Data of Sounding Performed Using GPS Satellite Signals, *Issled. Zemli Kosmosa*, 2010, no. 3, pp. 49–61.

Vanina-Dart, L.B., Sharkov, E.A., and Pokrovskaya, I.V., Studying the Interaction between the Equatorial Lower Ionosphere and Hurricanes according to the Data of Remote and Rocket Sounding, *Issled. Zemli Kosmosa*, 2007, no. 1, pp. 1–9.

Xiao Zuo, Xiao Sai-guan, Hao Yong-qiang, and Zhang Dong-he, Morphological Features of Ionospheric Response to Typhoon, *J. Geophys. Res.*, 2007, vol. 112A, pp. A04304/1–A04304/5.

Zakharov, V.I. and Zienko, A.S., Method Used to Statistically Analyze Wavelet Spectra of GPS Ionospheric Signals, *Vestn. Mosk. Gos. Univ., Ser 3, Fiz. Astron.*, 2007, no. 2, pp. 44–49.

Zakharov, V.I., Zienko, A.S., and Kunitsyn, V.E., GPS Signal Propagation at Different Solar Activity, *El.-Magn. Volny Elektron. Sist.*, 2008, no. 8, pp. 51–57.

Zakharov, V.I., Budnikov P.A., The Use of Claster Analysis for the GPS Interferometry Data Processing, *Vest. Mosk. Gos. Univ., Ser. 3, Fiz. Astron.*, 2012, no. 1, pp. 25–32.

http://en.wikipedia.org/wiki/Category:Tropical_cyclon_meteorology

http://weather.unisys.com/hurricane/

http://www.sopac.ucsd.edu

http://www.spider.ngdc.noaa.gov

http://www.stormpulse.com