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Effect of Mesoscale Atmospheric Vortex Processes on the Upper Atmosphere and Ionosphere of the Earth

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Abstract—The mechanisms of incipience and intensification of dangerous atmospheric vortex processes such as tropical cyclones (TCs) and their interaction with the Earth's ionosphere are considered. Different models of TCs are analyzed, including models taking into account the ionization processes. The mechanisms taking into account the spiral field of velocities during TC formation are analyzed, as are the physical mechanism that explains the statistical correlation between short-term variations in galactic cosmic rays (Forbush decreases) and the frequency of incipience and the intensification of TCs. It is shown that such an effect is conditioned by a decrease in the ion-production rate during Forbush decreases against the tropopause and, hence, a decrease in the temperature upon the top of the ionosphere altitude because of a decrease in the latent heat release due to water-vapor condensation on the newly formed ions. This process leads to an increase in the temperature difference between the ocean surface and the top level of TCs and, respectively, to the intensification of vertical convection, which results in cyclone intensification. It is concluded that the study of these mesoscale vortex processes requires taking into account not only the hydrodynamical features of these formations, but also their thermodynamical and electrodynamical properties. The results are important for the organization of studying and monitoring TCs with the use of spaceborne techniques.

Keywords: mesoscale atmospheric processes, tropical cyclones, vortex formations, atmosphere, ionosphere, space monitoring

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INTRODUCTION

The theory of incipience and intensification of tropical cyclones (TCs) was formed first within the classical atmospheric hydro- and thermodynamics [Golitsyn, 1973; Shuleikin, 1978]; the simulation was carried out with the use of preset input atmospheric parameters, which are not always known at the instant of TC incipience. Elements of nonlinear simulation were introduced later [Yaroshevich and Ingel, 2004; Erokhin et al., 2007]. The possibility of choosing the parameters of the generalized nonlinear model allowed an analysis of the temporal dynamics of a vortex, including the length of TC life cycle stages, maximal wind velocity, and so on. The use of mesoscale atmospheric models provided for a significant increase in the quality of TC dynamics forecasts [Hoffman et al., 2006; Kafatos et al., 2006], including variations in their motion directions in the presence of spatial anisotropy of a temperature field. The role of ionization on the Earth's surface (natural Earth radioactivity) [Karelin, 2009; Bondur et al., 2009] and in the tropopause (galactic cosmic rays) [Bondur et al., 2008a; 2009] is of growing interest.

Experimental results from flights of airborne laboratories inside TCs, from the space monitoring of these natural disasters, and from simulation make it possible to introduce the concept of atmospheric motion helicity and the development of a nonlinear theory of inverse cascade (the formation of large-scale structures from those of a smaller scale) to describe the dynamics of the development of these natural disasters [Levina and Montgomery, 2010].

In this work, we try to consider the problems of TC dynamics on the basis of results of earlier studies and the authors' works on the study of the TC effect on the Earth's atmosphere and ionosphere with the use of space data [Bondur et al., 2008a, b; 2009; Bondur and Vasyakin, 2011; 2012; Pulinets et al., 1998; Pulinets and Lui, 2004; Pulinets et al., 2006].

CLASSICAL THEORIES OF TROPICAL HURRICANES

Mathematical models for calculating the parameters of temporal dynamics of TCs were developed in earlier works (see, e.g., [Shuleikin et al., 1978]) on the

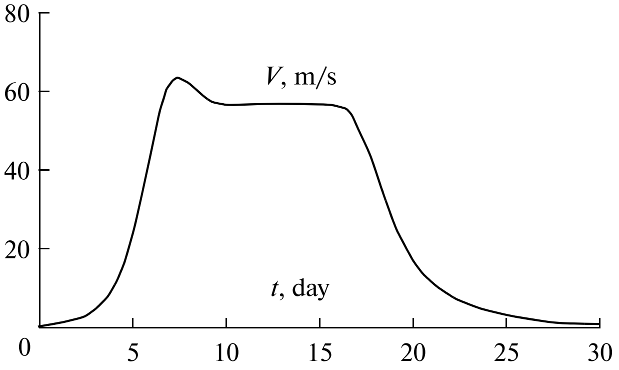

Fig. 1. Dynamics of variations in the wind velocity with account for the TC decay phase.

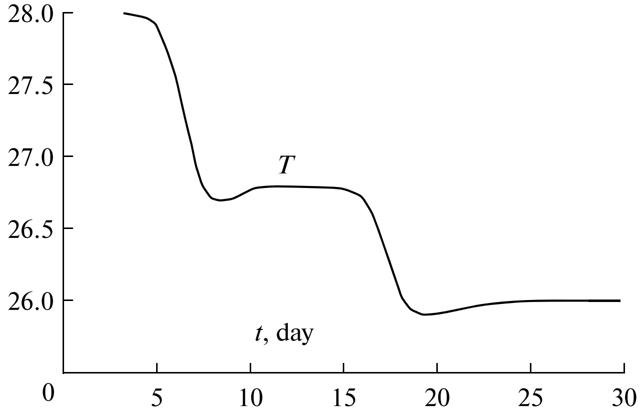

Fig. 2. Dynamics of the ocean surface temperature with account for the hurricane decay phase.

basis of experimental observations. These models were based on the equation

$$dV/dt = (T - T_{th})V - \sigma V^2,$$

where T is the ocean surface temperature in the TC region; T_{th} is the threshold value of this temperature above which disturbances intensify; and σV^2 is the term determining the energy loss due to dissipative processes, which increase with the vortex intensity.

The efficiency of transformation of the thermal energy into the energy of air motion in a preset direction is usually accepted equal to [Golitsyn, 1973]

$$\Delta p/p,$$

where Δp is the accelerating pressure gradient and p is the total pressure on the ocean surface.

By analogy with lasing models, a nonlinear model of TC development was suggested in [Yaroshevich and Ingel, 2004], which takes into account the energy pump in the ocean–atmosphere system, the threshold conditions for strong vortex formation, and its interaction with the environment.

This model was developed in [Erokhin et al., 2007]; it allows a description of the TC decay stage, which is connected with the arrival of a TC to land or its displacement to a colder region of the ocean surface. For this, the time dependence was introduced in one of the environmental parameters determining the conditions for vortex generation. Correspondingly, a decrease in this parameter below the threshold value resulted in TC decay.

Figure 1 shows variations in the wind velocity in a TC, and Figure 2 shows variations in the ocean surface temperature while accounting for the decay according to the modified nonlinear model [Erokhin et al., 2007]. As is seen from these figures, the introduction of free (variable) parameters in the model allows one to control the description of TC generation and decay processes. The solar–terrestrial interaction effects can be introduced as free parameters; their role as one of the factors of regional tropical cyclogenesis has been statistically ascertained [Pérez-Peraza et al., 2008].

USE OF MESOSCALE NUMERICAL MODELS OF THE ATMOSPHERE FOR TC SIMULATION

The MM5 NCAR mesoscale model is the most commonly used in numerical calculations of atmospheric processes [Grell et al., 1994]. This assimilative model allows almost the online introduction of experimental observation data in calculations. The model covers an area of 3000 × 4000 km^2 at ten levels in the pressure range from the land surface to 50 hPa.

The 4D-VAR technique is successfully being used; it allows calculations of the TC dynamics within the MM5 model by means of introduction of small finite variations in parameters, including time [Hoffman et al., 2006]. Using this technique, the most sensitive parameters affecting the TC dynamics were determined. In particular, the role of the high temperature of the ocean surface in the Gulf of Mexico in the sharp intensification of Hurricane Katrina was shown in [Kafatos et al., 2006] with the use of MM5 calculation results. The simulation results are confirmed by the experimental data obtained in [Bondur and Vasyakin, 2011; 2012] from satellite data.

TC SIMULATION WITH ACCOUNT FOR IONIZATION PROCESSES

An attempt to substantiate a need (in the presence of a certain ionization level) for the formation of a sufficient number of condensation centers was made in [Karelin, 2009]. The model calculations that used a modified Shuleikin equation [Shuleikin, 1978] as the initial one have shown that no intense TC develops (the wind velocity is higher than 60 m/s or 200 km/h [Shuleikin, 1978]) in ordinary conditions at a low atmospheric ionization rate independently of the initial velocity and environmental temperature, even at high relative air humidity. However, the wind velocity sharply increases with the ionization level, as well as with the surface temperature (see Fig. 3). This shows a need for considering the processes of atmospheric boundary layer ionization when simulating TC incipience and development.

The role of ionization is also significant at high altitudes, near the cloud top-edge. The physical mechanism of TC intensification, which is connected with variations in the ionization level at the tropopause altitude during a short-term decrease in the galactic cosmic ray flux when a magnetic storm is developing (Forbush decrease), is described in [Bondur et al., 2008a]. The effect of variations in the cosmic ray flux on the TC intensity in the Atlantic has been ascertained by a statistical analysis of a long-term data series [Pérez-Peraza et al., 2008]. The TC intensification is connected with a decrease in the temperature at the tropopause altitude due to a decrease in the latent evaporation heat release and a corresponding increase in the temperature gradient between the ocean surface and tropopause, which results in vertical convection intensification.

Figure 4 shows variations in the atmospheric parameters during a magnetic storm that occurred in the end of August 2005 and resulted in the intensification of Hurricane Katrina [Bondur et al., 2008a; 2009].

Thus, we have ascertained that an ionization level near the ocean surface and in the upper part of a hurricane should be considered when simulating the TC dynamics, since thermodynamic processes connected with the ionization affect the hurricane energy.

HELICITY IN TROPICAL CYCLOGENESIS

Scientific research into the role of helicity in tropical cyclogenesis is being actively developed. The restructuring of large-scale convective instability under the action of small-scale helical turbulence is studied. This instability is called the instability of inverse cascade in nonlinear physics; it is developed due to the joining of small-scale helical convective structures and results in the generation of larger and more intensive spiral vortices.

No attention has been paid to spiral properties of the velocity field when studying TC until recently. Now, more and more researchers believe that deep cumulonimbus convection in the tropics with a characteristic horizontal scale of 2–20 km, which transfers explicit and latent heat from the underlying surface throughout the troposphere, is a basic intensification mechanism preceding the generation of mesoscale (~200 km) cyclonic circulation and its transformation into a hurricane [Emanuel, 2003]. However, there is no single opinion about the scenario of this transformation and the physical mechanisms participating in it now.

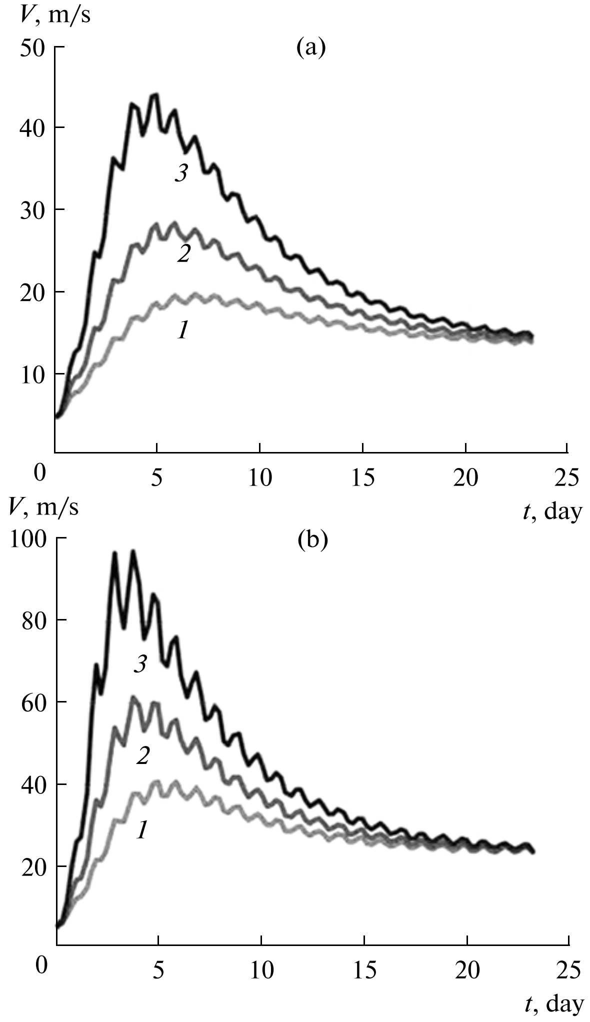

Fig. 3. (a) Wind velocity as a function of time at $V_0 = 5$ m/s, $H = 95\%$, $T_g = 18°C$; (b) wind velocity at $T_g = 28°C$ and the maximum ionization velocity $f_I = 26$ (*1*), 52 (*2*), and 104 cm^{-3} s^{-1} (*3*).

Numerical experiments on the estimation of the role of helicity in TC development carried out on the basis of the Regional Atmospheric Modeling System (RAMS), Colorado State University (United States), are described in the work [Levina and Montgomery, 2010]. It is shown that the helicity symmetry (left and right helicity) is violated during hurricane development. The integral helicity is zero during the first 15–17 h of the modeling time under the action of small-scales vortices. In about 18 h, the helicity becomes significantly positive and growing. In this case, the analysis of vertical velocity and vorticity fields shows that positive helicity is caused by the prevalence of local cyclonic upward movements. Nonzero helicity indicates violence of the mirror symmetry of atmospheric turbulence and decreases the possibility of generating large-scale vortex instability.

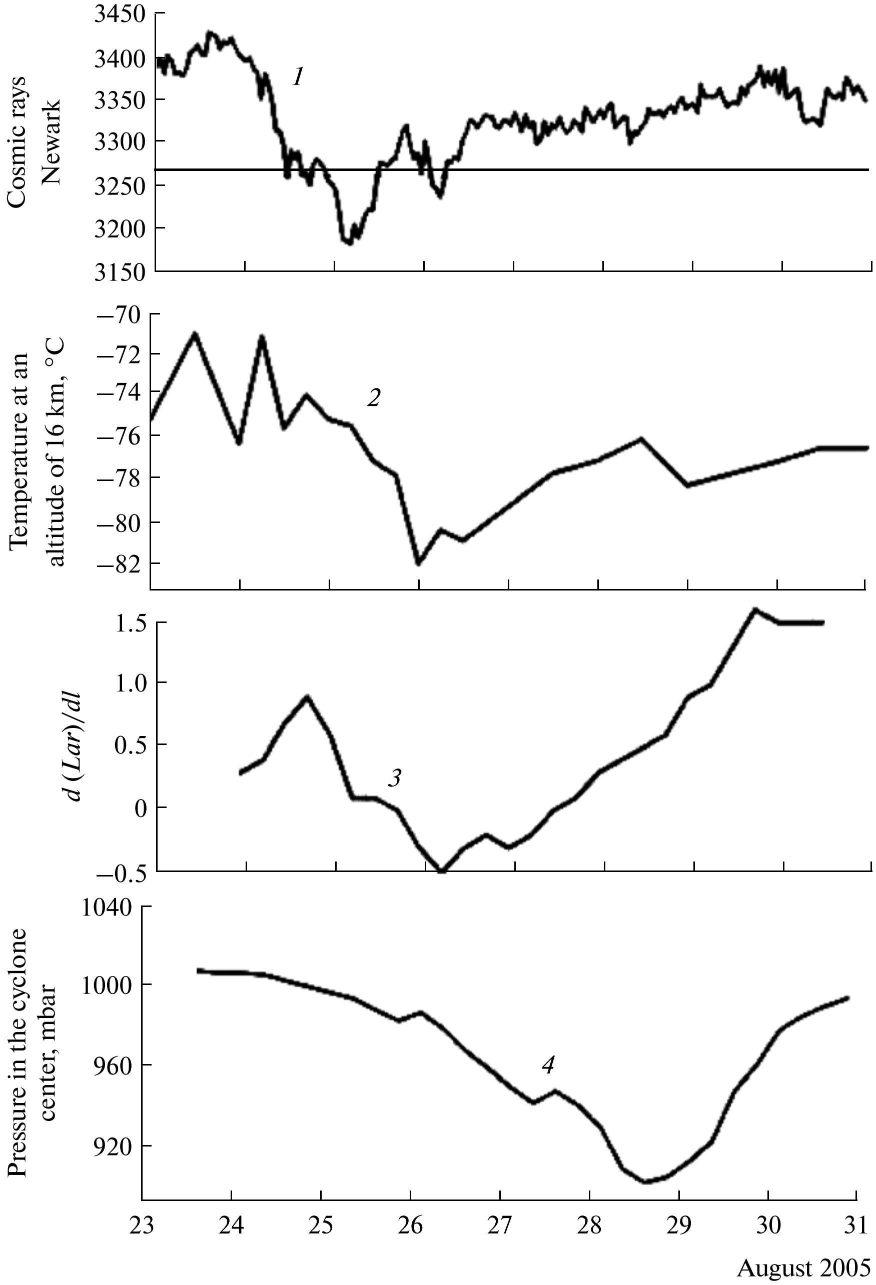

Fig. 4. Variations in the cosmic ray flux according to the Newark station data, United States (curve *1*); the air temperature at an altitude of 16 km (curve *2*); the rate of geographic latitude of the Hurricane Katrina position (curve *3*), and the pressure in the hurricane center (curve *4*).

We consider the fact that helicity monitoring (including satellite) can be a reliable indicator of TC development as the main result of this work.

NATURE OF HOT TOWERS AND ELECTROMAGNETIC PROPERTIES OF HURRICANES

As was noted in the work [Levina and Montgomery, 2010], vortex columns crossing the troposphere play the main role in the joining of convective vortices in a TC. They were called vortex hot towers. In particular, they were revealed from space (TRM satellite, United States) in Hurricane Katrina (see example in Fig. 5 [Young, 2005], the color insets).

A question arises about the nature of formation of such towers and their difference from another part of hurricanes that are nonstructured in the form of towers. The fact that their temperature is higher than the ambient medium temperature implies an idea about a

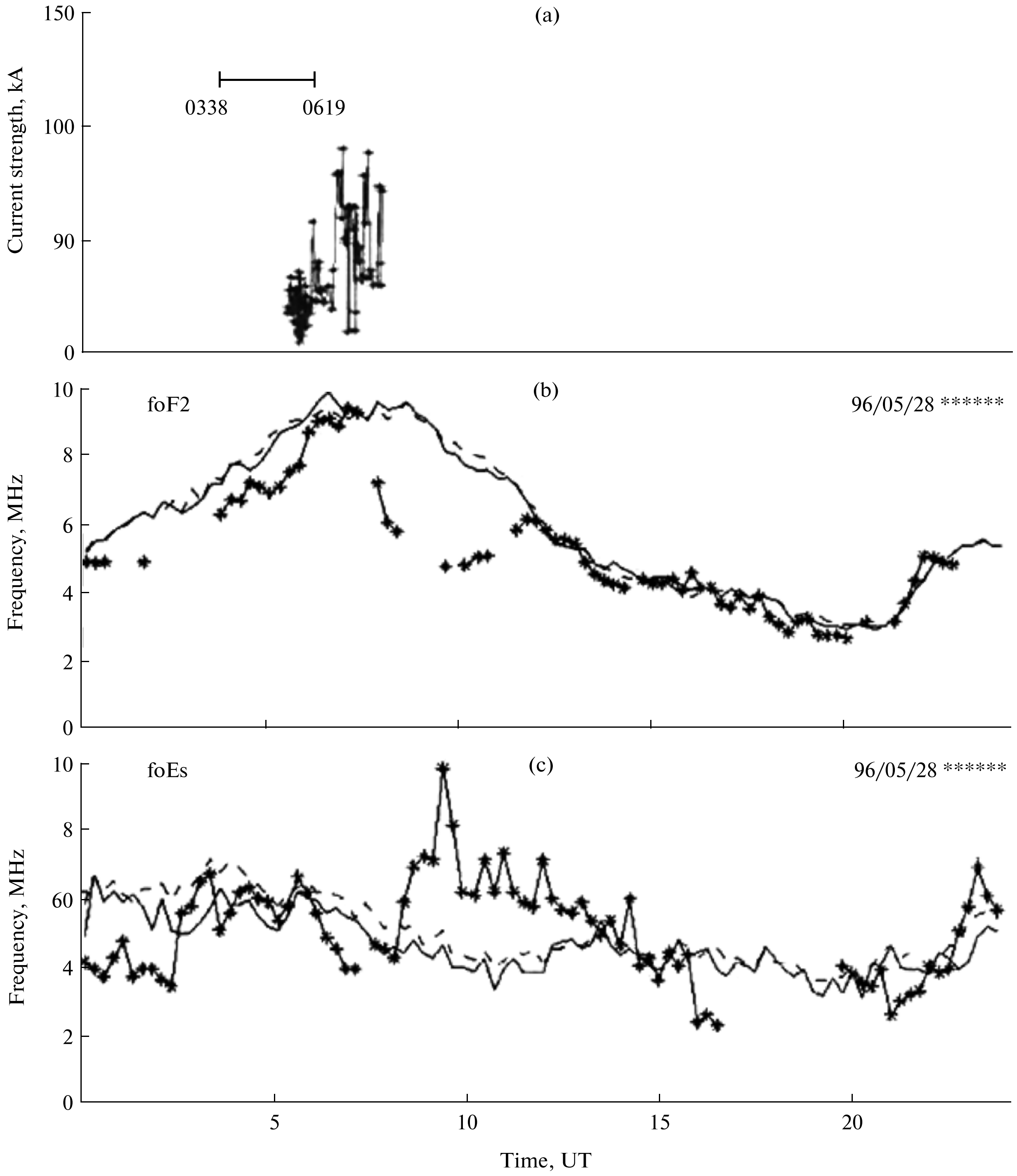

Fig. 6. Ionospheric effects recorded in Taiwan during the thunderhead passage over the ionospheric station: (a) time period when reflections from thunderstorm clouds were observed using a radar (the horizontal line); thunderstorm discharges recorded with a lightning detector (crosses); (b) variations in the penetration frequency foF2 (solid curve shows the month median, and crosses show data during the thunderstorm passage); (c) variations in the penetration frequency of a sporadic layer (solid curves shows the month median and crosses show data during the thunderstorm passage).

heat-release mechanism inside a tower different from the TC thermodynamics. This can be latent heat release during moisture condensation on ions, as was described in works [Bondur et al., 2008b; Pulinets et al., 2006].

As was mentioned above, the ionization processes play an important role in TC development. There are two ionization sources: natural radioactivity of the Earth and galactic cosmic rays. One more ion source should be taken into account: thunderstorm activity.

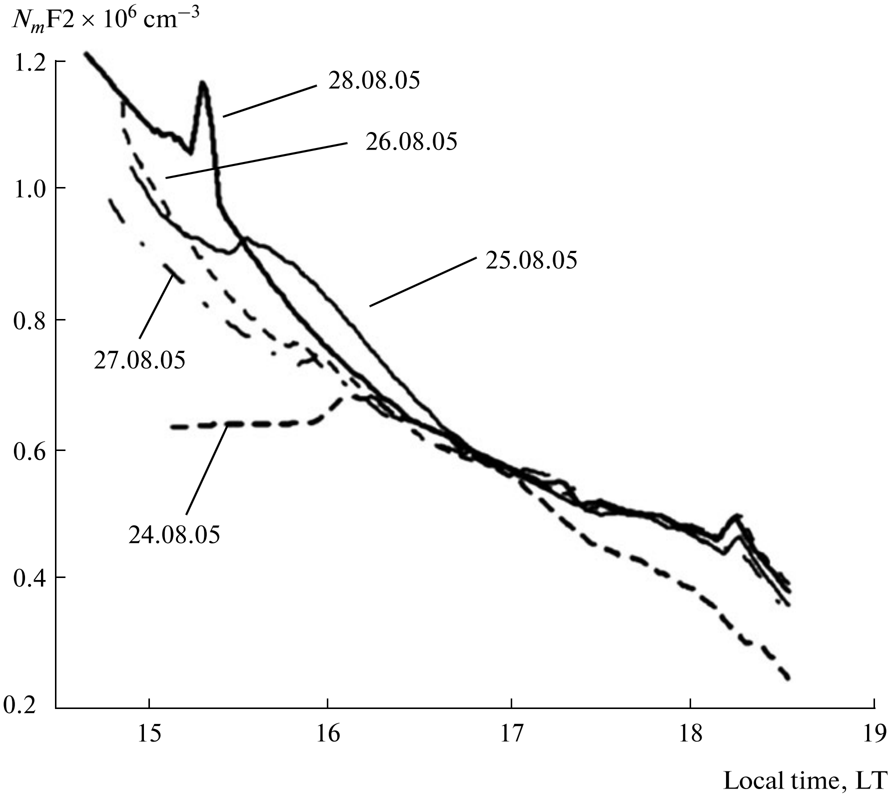

Fig. 8. Variations in the electron concentration N_mF2 over Hurricane Katrina according to data from GPS satellite no. 19 for the period from August 24 to 28, 2005 [Bondur et al., 2008b].

As is known, TCs are formed from depressions where thunderstorms develop that are capable of causing intense ionization by lightning discharges. It is interesting to note that regions with hot towers are notable for increased thunderstorm activity.

Other ionization mechanisms have been suggested recently, connected with the development of a corona discharge on water drops [Karelin, 2010] and an avalanche process resulting in a breakdown (with the possible participation of cosmic rays as a trigger) [Gurevich et al., 2009].

In view of this, the following hypothesis about the nature of hot towers can be suggested: they are regions with increased ion concentrations and thunderstorm activity. A high ionization rate results in an increased release of latent evaporation heat due to moisture condensation on ions and increased tower temperature when compared with the ambient medium.

In this case, another circumstance is of interest: the increased ion concentration in these formations requires a consideration of electromagnetic forces, in particular, the Lorentz force. Lines of force of the geomagnetic field are almost horizontal and directed along a meridian near the geomagnetic equator and in polar latitudes; therefore, horizontal winds involve charged clusters in the motion and thus result in their vertical movements. This causes the charge separation and formation of a layered electric structure of clouds. The vertical movements due to convection result in horizontal movements of ions. Thus, electromagnetic forces promote the violation of helicity caused by hydrodynamic motions and, probably, contribute to zero integral helicity during hurricane development.

IMPACT OF HURRICANES ON THE IONOSPHERE

The penetration of an electric field about 10 kV/m in strength from the upper part of a hurricane is the most evident reason a TC will impact the Earth's ionosphere. The penetration of an electric field from a thunderstorm cloud in the ionosphere has been estimated by many authors, e.g., [Hegai et al., 1990]. In this work, the formation of a zone of decreased electron concentrations in the ionospheric E region was considered. Later studies of electric field penetration in the ionosphere [Pulinets et al., 1998] have shown that sporadic layers can be formed in the E region under the effect of a strong electric field penetrating from the Earth's surface (or a thunderstorm cloud). Experimental measurements with the use of vertical sounding allowed one to reveal a decrease in the electron concentrations in the ionospheric F region simultaneously with the formation of sporadic layers in the E region [Pulinets and Liu, 2004].

Figure 6 shows the ionospheric effects recorded in Taiwan during the passage of a thunderhead over the ionospheric station. Thunderstorm clouds were also recorded using radar (the horizontal line in Fig. 6a); the results recorded with a lightning detector are shown by crosses.

Strong electric fields were recorded above tropical hurricanes from the KOSMOS-1809 satellite [Isaev et al., 2002]. Their strengths corresponded to the fields recorded during a strong geomagnetic storm (about 8 mV/m).

The TC impact on the ionosphere was studied in [Bondur et al., 2008b] using the example of Hurricane Katrina with the use of GPS data received from the region of TC passage; a specially used data-processing technique allowed the authors to determine the electron concentration distribution and the position of the F-layer maximum altitude, as well as the modification of vertical profiles of the electron concentration.

The position of F2-layer electron concentration maximum altitude over the region of Katrina passage is represented in 3D in Fig. 7 for August 28, 2005 [Bondur et al., 2008b] (see the color inserts). A decrease in the altitude of the maximum of electron ionization of the ionospheric F2 layer over Hurricane Katrina was accompanied by a peak in the electron concentration (shown in Fig. 8) [Bondur et al., 2008b].

Similar peaks in the electron concentration above hurricanes were also recorded by the KOSMOS-1809 satellite [Belyaev et al., 2010]. The authors of this work interpret the observed increase as a result of the upward carryover of ions. In this case, plasma quasineutrality is supported by the mobility of electrons longitudinally along the magnetic field. The fine structure of the peak in zenith over a hurricane shows that an ion flux stops at an altitude of about 1500 km.

The study of the impact of the hurricane on the ionosphere and analysis of the results proves the presence of correlations between the Earth's troposphere and ionosphere and the existence of complex electromagnetic processes in large-scale vortex structures. The lowering of the ionosphere over a hurricane, as was revealed in [Bondur et al., 2008b], and an increase in the electron concentration over the eye of the storm confirm this correlation.

CONCLUSIONS

The analysis of problems of TC generation and their interaction with the Earth's atmosphere shows that the helicity of cyclogenesis should be considered when simulating these phenomena, as should the electromagnetic properties of these structures due to processes of ionization from different sources: on the underlying surface (natural radioactivity) and outside (cosmic rays) and inside of a hurricane (thunderstorm activity, corona discharges on drops, and breakdown on escaping electrons). Electromagnetic forces inside a TC can affect its dynamics, in particular, the development of inverse cascade instability. Ionization results in increased heat release in regions of intense ion formation, which apparently causes the formation of hot towers inside a hurricane with high thunderstorm activity.

The effective charge separation inside a vortex structure results in the formation of a strong electric field on the top edge of a hurricane penetrating into the ionosphere and producing local inhomogeneities in the ionospheric E and F regions. A difference in the tropospheric conductivity inside a TC and outside it can be a source of ionospheric anomalies, resulting in a change in ionospheric potential over it.

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