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GEOPHYSICS

Role of Variations in Galactic Cosmic Rays in Tropical Cyclogenesis: Evidence of Hurricane Katrina

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Based on the analysis of experimental data on vertical temperature profiles in the propagation region of Hurricane Katrina and variations in fluxes of galactic cosmic rays (hereafter, cosmic rays), we established an interrelation between temperature variations at the tropopause level and variations in the level of atmosphere ionization by cosmic rays. We found that variations in temperature and its spatial gradient related to the Forbush depression of cosmic ray flux induced by a magnetic storm could lead to variation in the direction of the meridional component of velocity and the intensification of Hurricane Katrina.

INFLUENCE OF COSMIC RAYS ON THE CLOUD COVER

In recent studies of global climate variations, researchers have paid significant attention not only to anthropogenic factors, but also to the role of natural causes of climate formation, including variations in cosmic rays [1]. The presence of meteorological effects caused by cosmic rays was found long ago [2]. However, significant attention has been paid to this factor only recently. For example, the author of [1] revealed a correlation between variations in the cosmic rays and global cloud cover during cycles 21–22 of solar activity. The ions formed in the atmosphere due to impact ionization by high-energy particles of the cosmic rays become centers of water vapor condensation as a result of hydration, which finally leads to cloud formation [3]. The investigations of the correlation between the fluxes of cosmic rays and the cloud cover were continued by different authors. In particular, the authors of [4] studied the correlation between variations in the cosmic rays and cloud cover for a longer period than in [1]. The correlation coefficient for the period from 1983 to 2001 was 99.5%. The modulation of the fluxes of cosmic rays by solar activity allows us to distinguish different time periods in weather variations starting from the 11-yr-cycle of solar activity and finishing with short-period variations during magnetic storms (Forbush effect of cosmic rays). An increase in the density of solar wind plasma and the interplanetary magnetic field during active events on the Sun leads to scattering of cosmic rays and decrease in their flux on the Earth's surface, especially at low latitudes [5].

The author of [6] found short-period variations in the cloud cover during the Forbush depression. The cloud density decreased considerably in the regions with a thick cloud cover and increased over the ocean with a cover of lesser density.

Thus, we established a correlation between variations in the cosmic ray flux (including short-period ones) and the cloud cover. This effect can be used for the analysis of variability of tropical cyclones.

POSSIBILITY OF THE INFLUENCE OF COSMIC RAYS ON TROPICAL CYCLONES

Can short-period variations in the cosmic ray flux influence such atmospheric formations as tropical cyclones? The authors of [7] present a detailed statistical analysis of the possibilities of the correlation between variations in solar geomagnetic activity and cosmic rays, on the one hand, and cyclonic activity in the Pacific and Atlantic basins near the Mexican coast. Based on analysis of 119 typhoons and hurricanes in these regions over a time interval of 55 yr, they found the following regularity: for seven hurricanes of category 5, the Forbush depression of cosmic rays was recorded two days before the cyclone reached the level of category 1 hurricane. The author of [8] suggested that Hurricane Katrina was generated by the magnetic storm on August 24, 2005. The main mechanism was an increase in the baric contrast in the illuminated hemisphere and a pressure decrease at tropical latitudes. We can agree that the magnetic storm might have influenced the development of Hurricane Katrina. However, the forcing mechanism suggested by the author of [8] requires more detailed elaboration.

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The results obtained in the cited publications and the present work give grounds to correlate variations in the hurricane development dynamics with variations in the cosmic rays during magnetic storms.

Let us consider in more detail the possible mechanism of the influence of cosmic rays on the dynamics of tropical cyclones. In addition to the nucleation processes related to the formation of new ions due to ionization and the consequent formation of clouds, we should focus attention on the thermodynamics of these processes. Up to the present time, researchers considered that cosmic rays played the role of a factor modulating the amount of nucleation centers. The thermal effects caused by the bonding of water molecules and ions were not taken into account.

We should pay attention to the fact that variation in the flux of latent evaporation heat is caused by the processes of phase transition: condensation and evaporation of water play the main role in the evolution of tropical cyclones. The authors of [9] demonstrated that an increase/decrease in the number of ions, which are the products of atmosphere ionization, can cause strong variations in the flux of latent evaporation heat. Heat release during hydration of ions leads to simultaneous temperature increase in the surrounding air and variations in the relative humidity and pressure. Thus, sharp variations in the ionization level would lead to distortions in the thermodynamic balance within the hurricane in the entire altitude range.

Is this process effective? One proton with energy $E_p \sim 10^{15}$ eV (mean energy of cosmic rays) at the ionization energy of the main atmospheric gases within $E_i \sim 10$–20 eV can generate 10^{13}–10^{14} ion-electronic pairs. Laboratory experiments and measurements on aerostats showed that one ion can attach more than 100 water molecules [10]. In the investigation of the formation of large particles due to atmospheric ionization by cosmic rays based on an aerostat-borne mass-spectrometer, positive ions were detected in the upper troposphere with a molecular mass of 2500 [10]. It is not difficult to show that the energy released in this case as the flux of latent evaporation heat exceeds $\sim 10^4$ times the energy of the proton, which is the ionization source.

We measured the concentration of aerosol particles (giant ion clusters formed as a result of ionization and subsequent hydration of ions) and found that the spectral maximum of the newly formed particles is located close to 1000 nm, which gives an efficiency of the ionization process (ratio of the released thermal energy to the ionization energy) exceeding 10^8 [9].

Thus, even insignificant variations in the density of the cosmic ray flux can lead to notable effects in the atmosphere, as was noted in the investigations of the density of the Earth's cloud cover [3, 4, 6]. Although the authors of [9] estimated only the heat release during increase in the ionization level, one can suppose that a decrease in the heat energy release caused by weakening of the ionization source would have the same efficiency.

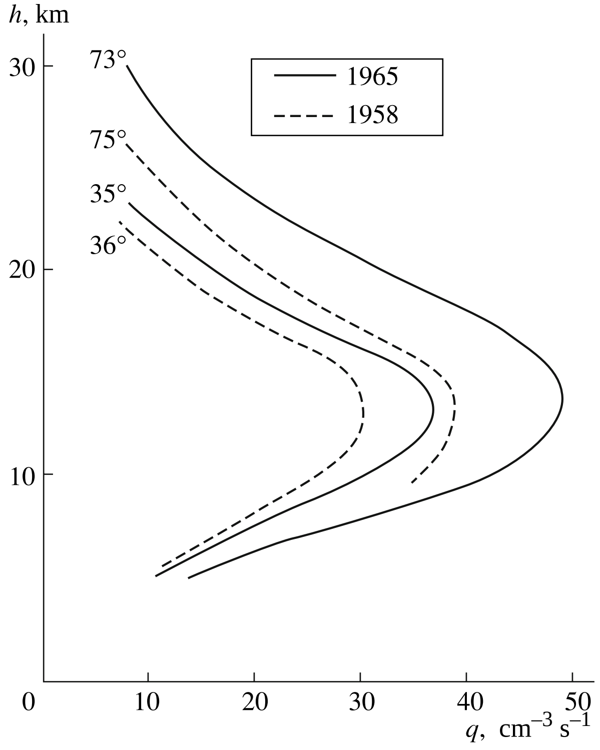

Fig. 1. Altitude profiles of ion generation at different latitudes in the maximum (1958, dashed line) and minimum (1965, solid line) periods of solar activity based on [10].

Taking the aforesaid into account, we can expect a temperature decrease at altitudes of the maximal generation of ions when the cosmic ray flux drops during the Forbush depression.

Figure 1 demonstrates experimental profiles of ion generation at different latitudes for the period of maximum (dashed line) and minimum (solid line) solar activity [11]. One can see that the maximal effect can be expected at $h \sim 12$–16 km.

ANALYSIS OF EXPERIMENTAL DATA ON HURRICANE KATRINA

Let us consider the specific case of tropical cyclone Katrina (August 23–30, 2005). Figure 2 shows the hurricane trajectory based on the GOES-11 data. One can see that tropical cyclone Katrina strongly changed its direction of motion during the time period from August 24 to August 27, 2005. The meridional velocity component of Hurricane Katrina on August 25–26, 2005, changed from the northern direction to a southern one. Owing to this fact (while the zonal velocity component was constant and directed to the west), the hurricane displaced from the western part of the Atlantic to the Gulf of Mexico (Fig. 2). The following question is put forward: what factor could have influenced this sharp

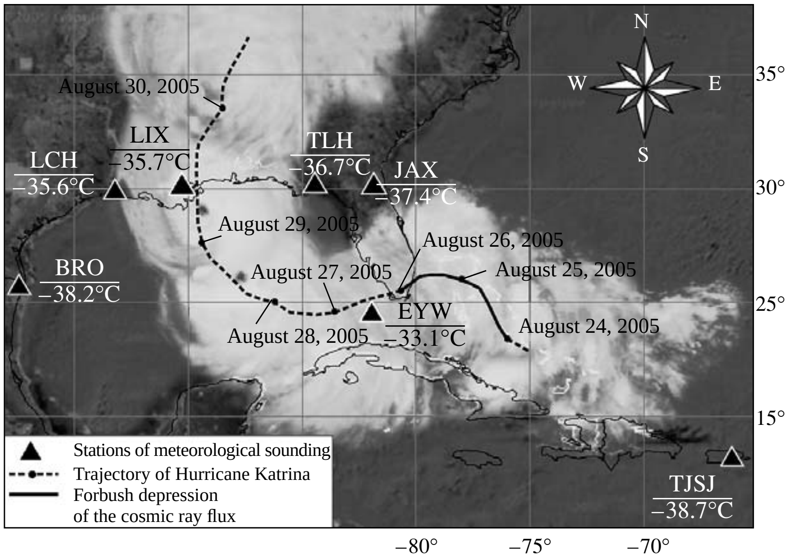

Fig. 2. Trajectory of Hurricane Katrina based on GOES-11 data and locations of meteorological sounding stations. Temperatures at an altitude of 10 500 m measured at 12:00 LT on August 26, 2005, are indicated near each station.

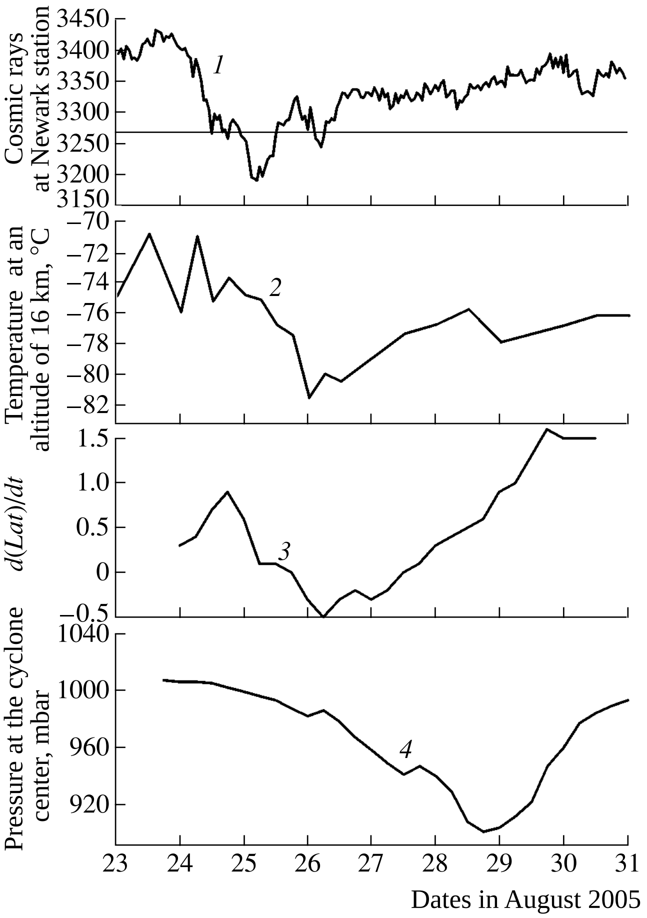

Fig. 3. (*1*) Variations in the cosmic ray flux based on the Newark station (United States) data; (*2*) air temperature at an altitude of 16 km; (*3*) derivative of the latitude of Hurricane Katrina location; and (*4*) pressure at the center of Hurricane Katrina.

change in the motion trajectory of the tropical cyclone Katrina?

The analysis of the geophysical situation showed that a strong magnetic storm occurred on August 24–25. The equatorial index D_{st} during the main phase of the magnetic storm was equal to –216 nT. The storm started suddenly: the index of the magnetic storm D_{st} changed from an unperturbed value of 3 nT to –216 nT during a period of only 3 h. The development of the storm led to a sharp decrease in the cosmic ray flux. On August 24–26, 2005, a minimum of the Forbush effect was observed (Fig. 3, curve *1*).

Thus, attenuation of the ionization source due to variation in cosmic rays should lead to a decrease in heat release and the consequent temperature decrease in the region of maximal ion generation (Fig. 1).

In order to confirm this effect, we analyzed altitude temperature profiles obtained from meteorological balloons [13] launched from the stations located near the trajectory of Hurricane Katrina (Fig. 2).

The analysis of experimental data from meteorological balloons (Fig. 4) showed that the maximal temperature decrease was observed on August 26, 2005, at the level of the tropopause at an altitude of ~16 km.

Figure 3 (curve *2*) shows variations in air temperature at an altitude of ~16 km. It also shows a clear minimum with a time lag of ~20 h relative to the minimum in the intensity of cosmic rays. It is clearly seen from curve *2* (Fig. 3) and the comparison of profiles shown in Fig. 4 that the temperature at an altitude of ~16 km on August 26, 2005, decreased by ~9°C as compared to August 25, 2005. Such a temperature drop led to an increase in the altitude temperature gradient and intensification of convection. As a result of stronger convec-

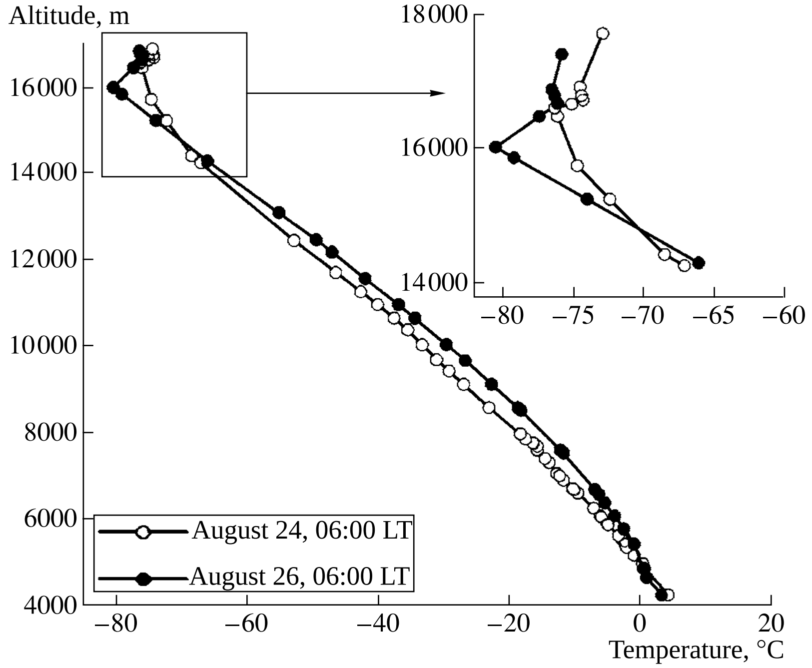

Fig. 4. Altitude profiles of temperature based on the data of meteorological sounding at station EYW (24° N, 81.75° W) measured on August 24 and 26, 2005.

tion, warmer air layers ascended and the temperature at altitudes from 5 to 14 km increased by ~2°.

In order to show variations in the trajectory of tropical cyclone Katrina, we calculated the diurnal increment of the latitude of the hurricane center shown in Fig. 3 (curve *3*). The change in the meridional velocity component from the northern direction to southern one on August 25, 2005, also produced a minimum on the curve of the hurricane position on August 26, 2005 (curve *3*). The lag of the maximum southern component of hurricane velocity relative to the minimum of the cosmic ray flux is approximately one day (Fig. 3, curves *1* and *3*). It is worth noting that despite the small time resolution, the local minima on the curve of cosmic rays are reflected in the local minima of the derivative of hurricane latitude.

The analysis showed that the correlation coefficient between the variations in the cosmic rays and temperature at an altitude of 16 km is ~0.75 with a time lag of 20 h, and the correlation coefficient with the location of the hurricane is ~0.8 with a time lag of 24 h.

Let us consider the issue of the correlation of the observed temperature measurements with the degree of convection that determines the intensity of the hurricane. Figure 4 presents vertical temperature profiles obtained with a radio sounding balloon over station EYW with coordinates 24° N, 81.75° W (Fig. 2) before the beginning of the change in the cosmic ray flux on August 24, 2005, and after the Forbush effect on August 26, 2005.

How can temperature variation influence the cyclone dynamics? In order to answer this question, we can use the results of mathematical modeling. The authors of [14] investigated the possibility of influence on a hurricane and determination of the key parameters of such influence on the basis of the system of variation assimilation of the measurements of the atmospheric and hydrophysical parameters during the propagation of two destructive tropical hurricanes (Iniki and Andrew) in 1992 in the Atlantic Ocean. They found that the variations in the air temperature, which leads to the appearance of the horizontal temperature gradient (spatial anisotropy) in the upper part of the hurricane, can change its trajectory, while a temperature increase in the upper part of the hurricane can lead to a decrease in its intensity.

Two effects were manifested in the case of Hurricane Katrina: variation in temperature at different altitudes and appearance of a horizontal temperature gradient. This was caused by the fact that the cosmic ray fluxes are characterized by spatial anisotropy, which leads to spatial anisotropy of the thermal effect appearing as a result of ionization. This was observed in our case. Figure 2 shows the temperatures at time moment 12:00 LT on August 26, 2005, based on the data of seven meteorological sounding stations used in our study. It is seen that the scattering of temperatures at an altitude of 10.5 km exceeds 5°C (the maximum value is –33.1°C at station EYW). At the same time, on August 24, 2005 (12:00 LT), the scattering did not exceed one degree at temperatures ranging from –36 to –37°C [13]. As was discussed above, a temperature decrease at the level of the tropopause caused an increase in the convection and intensification of Hurricane Katrina.

In the analysis of the evolution of Hurricane Katrina, one should keep in mind the role of ocean surface temperature. The authors of [15] showed that a higher temperature level in the Gulf of Mexico facilitated intensification of Hurricane Katrina on August 27, 2005, when the hurricane propagated to the gulf after changing the trajectory. Figure 3 (curve *4*) shows the diurnal evolution of the atmospheric pressure at the center of Hurricane Katrina. It follows from the analysis of the curve that intensification of the hurricane, which was manifested in the pressure decrease at the center of the cyclone, can be divided into two stages: (i) initial intensification that was likely caused by the influence of cosmic rays on August 24–27, 2005, with two local minima corresponding to the minima in the intensity of the cosmic ray flux and (ii) a sharp intensification of the hurricane on August 28, 2005, when it displaced to the Gulf of Mexico.

Thus, the analysis of the data on the vertical temperature profiles in the region of propagation of Hurricane Katrina together with the data on the cosmic ray flux allows us to conclude that variations in the cosmic rays during the magnetic storm on August 24–25, 2005, influenced the intensity and trajectory of the hurricane motion.

CONCLUSIONS

(1) Variations in the cosmic rays (including short-period variations) are an important factor in the formation of the cloud cover and heat balance of the upper tropospheric layers.

(2) A decrease in the cosmic ray flux during magnetic storms as a result of the Forbush effect leads to a decrease in the air temperature at the level of the tropopause and to an increase in the vertical temperature gradient, which can cause variations in the characteristics of tropical cyclones.

(3) Variations in the characteristics of Hurricane Katrina based on our analysis can be presented as follows:

(i) as a result of a decrease in the cosmic ray flux on August 24–26, 2005, during the development of a magnetic storm, the temperature decreased by 9°C at an altitude of the tropopause of 16 km, which led to intensification of convection and corresponding intensification of the hurricane; local minima on the pressure curve at the hurricane center reflect the minima on the curve of the cosmic ray flux with a time lag of ~1 day (Fig. 3);

(ii) the spatial temperature gradient found from the experimental data caused variation of the hurricane trajectory and its displacement from the Atlantic Ocean to the waters of the Gulf of Mexico across the Florida Peninsula; and

(iii) propagation of the hurricane to the south and west to warmer waters of the Mexican Gulf on August 27, 2005, led to an increase in the temperature contrast and further intensification of the hurricane (pressure decrease at the hurricane center).

Thus, we established a mechanism of the influence of variations in the cosmic rays on the variation of characteristics of tropical cyclones (intensity and trajectory of their propagation).

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