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THE EARTHQUAKES AND IONOSPHERE PHYSICS COUPLING

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Abstract
The monograph on the earthquakes and their connection with the physics of the upper atmosphere are considered. The book consistently presents ideas about the structure of the environment for the generation of earthquakes (the lithosphere), the causes of their occurrence (movements of the lithospheric plates in areas of the tectonic faults), and the impact of earthquakes on all layers of the near-Earth envelope. The physics of this medium, methods of observing its variations and methods of mathematical modeling of these variations caused by both solar and seismogenic sources are discussed. The important role of the network of geostationary satellites is noted, which supply the Internet with the values of the total electron content (TEC) along the vertical above the earthquake epicenter, determined by the electron density in the main ionospheric maximum. The properties of TECs during the periods of preparation of large earthquakes and their using for attempts of mathematical modeling and forecasting of the latter are described.

THE BOOK CONTENT
The analyzed **monograph** [1] consists of seven chapters.

Chapter 1 is introductory. It indicates the sources and authors of the research papers on which this book is based. The monograph "Physics of the ionosphere" [2], published in 1988 in Russian, is noted and the co-authors of the articles used in writing the current monograph are listed.

Chapter 2 considers the Earth and its surroundings as a **single environment**, formed in the process of the emergence of the solar system with the Sun at its center. The parameters of the elliptical orbit of the Earth rotated around the Sun according to Keppler's laws are described. The shape of the Earth is considered as a magnetic ball rotated around its geographic axis, inclined relative to the plane of the ecliptic and pointing with its north pole to the North Star. The intrinsic magnetism of the globe is created by currents flowing inside it, and has the character of a magnetic dipole field (a coil with a current or a uniformly magnetized ball) with an axis that does not coincide with the geographic axis of rotation.

Most of the Earth's surface is in the liquid phase (oceans and seas), lying on a solid (continental) basis. Above the surface, the near-Earth medium is in the gaseous phase and is called the atmosphere, which consists of several parts: the neutral atmosphere, the ionosphere, the plasmasphere, and the magnetosphere. The absence of sharp boundaries between the mutually penetrating parts of the near-Earth environment is noted. Such boundaries are introduced conditionally for the convenience of mathematical modeling.

Chapter 3 is devoted to the **lithosphere** and its perturbations (earthquakes). The internal structure of the Earth, tectonic plates floating on the molten substance, their faults and movements, leading to collisions of parts of the plates, collisions with one another, crumbling of the edges of the plates, accumulation of elastic deformation energy and its explosive releases (earthquakes) are discussed. The earth consists of several spherical shells, differing in their chemical and deformation properties. The uppermost shell is the lithosphere, it is located at depths of 5 – 200 km from the surface and includes the crust at depths of 5 – 10 km, the upper mantle is located deeper at depths of 35 – 60 km, followed by the mantle (35 – 890 km), asthenosphere (100 – 200 km), upper mantle (35 – 660 km), lower mantle (660 – 890 km), outer core (2890 – 5150 km), inner core (5150 – 6371 km). The position of these layers was determined from the propagation time of seismic waves generated by earthquakes.

Seismic measurements show that the core consists of an outer liquid part and an inner solid part. The thickest layer of the earth is the mantle, the boundary between it and the crust is called the Mohorovichic section, on which the speed of seismic waves increases sharply. There are two fundamentally different types of crust: continental, older, and oceanic (not older than 200 million years). It is in constant motion: horizontal and oscillatory. Some lithospheric plates are composed entirely of oceanic crust (such as the largest of them, the Pacific), while others are composed of pieces of continental crust welded to the oceanic. The plate movements leading to earthquakes are the movements of the fragile lithosphere over the viscous asthenosphere, the convection of which causes the edges of some plates to sink under others. This is due to the entrainment of plates by convective currents in the asthenosphere. The subsequent violation of the balance between the elastic force of compression and pressure leads to the breaking of the plate and the explosive release of the accumulated energy, that is, to an earthquake.

Chapter 4 is about the **neutral atmosphere**. Its altitudinal regions related to the lower, middle and upper atmosphere (troposphere, stratosphere, mesosphere, thermosphere, exosphere) are discussed, in which the weather and climate are formed, and the ionosphere is born. The dominant processes in a neutral atmosphere are discussed (photochemical reactions with a predominance of oxygen components, dissociation, geostrophic winds, interaction with charged components, ionic and viscous friction, turbulent and molecular diffusion, mixing, hydrostatic equilibrium under the action of gravity forces and pressure gradients, winds from solar and high-latitude sources, tides, acoustic-gravity and planetary waves, thermal regime). The dominant role of changes in the neutral composition in the formation of ionospheric disturbances is noted.

Chapter 5 is the longest in the monograph and discusses the **ionosphere** as a propagation medium for radio waves used for radio communications, radar and radio navigation.

The fundamentals of **plasma physics** are outlined. The motion of a charged particle in a magnetic field is studied, various types of **drifts** under the action of the Lorentz force are considered, including taking into account the inhomogeneity of the magnetic field.

The concepts of **hydrodynamic description** of plasma are introduced, such as quasi-neutrality, plasma frequency, Debye radius, collisions, current in plasma, magnetic pressure, influence of boundaries, plasma diamagnetism, **Ohm's law**.

Waves in plasma, Fourier and Laplace transformations, concepts of dispersion, refractive index, group and phase velocities, cutoffs and resonances, wave equation, plasma permittivity, dispersion equation, wave polarization are considered.

The **magnetoion theory**, the Appleton-Hartree formula, quasi-longitudinal and quasi-transverse approximations, oblique propagation, radio wave paths, radio wave absorption, Faraday rotation, electrostatic waves, Boltzmann's kinetic equation, anomalous collisions are described.

Section 5.3 deals with **ionospheric measurements** (vertical sounding, oblique sounding, back-tilt sounding, overhead sounding, absorption measurements, riometric measurements, TEC measurements, partial reflection method, cross-modulation method, radar studies, incoherent scatter method, satellite and rocket measurements).

Section 5.4 is devoted to **mathematical modeling**, including transport equations, coordinate systems, integration over drift trajectories, initial and boundary conditions, and numerical methods.

Section 5.5 describes **the Sun and the magnetosphere**, solar and magnetic activity, auroras, the solar wind and the formation of the magnetopause, the structure of the magnetosphere, and the electric field.

Sections 5.6 – 5.8 consider **ionospheric processes** and all types of **quiet and disturbed variations** of ionospheric parameters. As ionospheric processes, the processes of ionization and recombination, photochemical reactions, vibrationally excited molecular nitrogen, a simplified photochemical model, quadratic and linear laws of electron losses, lifetimes and transport times, magnetized single-ion plasma (altitudes of 200 – 500 km), ambipolar diffusion, wind entrainment, the role of vertical transport processes in the formation of the F2-layer, ionospheric-protonospheric flows, static distribution of electrons in the multicomponent outer ionosphere, diffusion in the multicomponent outer ionosphere, the role of ionic inertia, stationary polar wind, non-stationary processes of filling and emptying power magnetic tubes, transfer of charged particles in the E and F1 regions of the ionosphere and its influence on the altitude profiles of the ion and electron density, the effects of three-dimensional transfer of charged particles, the thermal regime of charged plasma components.

Section 5.7 describes **regular ionospheric variations** in different latitude zones. The latitudinal zoning of the ionosphere is considered: its division into the mid-latitude, equatorial, high-latitude and subauroral ionosphere in accordance with the features of the geomagnetic field. In each of these zones, regular (daily, seasonal, semi-annual and annual, as well as solar-cyclic) variations of parameters in each of the high-altitude ionospheric regions (D, E, F1, F2, plasmasphere) are considered. Particular attention is paid to the region of the main ionospheric trough (observations and physical interpretation).

Section 5.8 deals with **ionospheric disturbances**. The types of ionospheric disturbances, the channels of energy transmission from the Sun, the general morphological picture and the physical scheme of the development of ionospheric disturbances are described. Sudden ionospheric disturbances and absorption in the polar cap are considered as ionospheric effects of wave and corpuscular radiation of solar flares. The ionospheric effects of precipitation of energetic particles from the magnetosphere (auroral absorption, absorption at middle latitudes, the effect of precipitation on the E and F regions of the ionosphere) are described, and the ionospheric effects of magnetospheric electric fields and magnetospheric ring current are considered. As effects of thermospheric disturbances, the effects of internal gravity waves (traveling ionospheric disturbances) and the effects of large-scale disturbances of thermospheric circulation are studied. The superposition of effects from various sources is considered. The influence of taking into account the movements of the north magnetic pole on calculations for the auroral and subauroral ionosphere is studied. The influence of geomagnetically induced currents on the environment is described. Active methods for studying the ionosphere (artificial impact on the ionosphere) are considered.

Chapter 6 describes Lithospheric-Atmospheric-Ionospheric Coupling (**LAIC**), its mechanisms and modeling. Methods for detecting the impact of lithospheric disturbances (earthquakes) on the atmosphere and ionosphere of the Earth are considered by using various geophysical measurements (geomagnetic, ionospheric, satellite), which are hindered by the locality of earthquake sources and the suddenness of their activation, as well as by the insufficient density of the ionosonde network. The most effective in recent years has been the use of a network of geostationary satellites that provide the Internet with information about variations in the total electron content (TEC), measured along the lines connecting satellite transmitters with ground-based receivers of their signals, and proportional to the electron concentration in the main ionospheric maximum. TEC variations observed before the onset of earthquakes in the vicinity of their epicenter are called their **precursors**; they are usually observed as well in the magnetically conjugated region. Their horizontal dimensions are about a thousand km in latitude and several thousand in longitude. The amplitudes of the precursors reach 40 – 100% of the background values. They are slightly mobile in the horizontal direction. Increases in TEC prevail, but negative precursors of earthquakes are often observed.

Numerical modeling of TEC variations in front of strong EQs is presented by the results of model calculations for closed geomagnetic field lines, performed using the global numerical models such as the **Global Self-Consistent Model of the Thermosphere, Ionosphere and Protonosphere** [3] and UAM (**Upper Atmosphere Model**) [4]. Both models numerically integrate the continuity, motion, and heat balance equations for atomic oxygen and hydrogen ions, the sum of molecular oxygen and nitric oxide ions, and electrons, as well as neutral particles (oxygen and hydrogen atoms, and oxygen and nitrogen molecules). Necessary approximations for small neutral components are used. In the region above 200 km, the equation for the electric potential is also solved. The initial and boundary conditions are described. The geomagnetic field is considered to be dipole in the region of closed field lines and open to vacuum on the polar cap field lines. The geographic and geomagnetic axes do not coincide.

Calculations using GSMTIP show that the main physical factor in the formation of earthquake precursors in TEC variations is the vertical electromagnetic drift of the ionospheric plasma under the action of a zonal electric field of seismic origin [5], which is most effective in the equatorial region, where it acts similarly to the case of an equatorial anomaly. The required values of the seismogenic electric field are about 1 – 3 mV/m in low latitudes and 5 –10 mV/m in middle latitudes.

In model calculations using UAM, the seismogenic electric field was switched on not by setting the potentials at the western and eastern boundaries of the generation area, but by setting the vertical electric currents that generate the electric field. The appearance of these currents is similar to lightning electricity and is associated with the vertical movement of aerosols over the area of their emanation, due to the compression of solid rocks. The dependence of TEC variations on the position of these currents at different latitudes and relative to the geomagnetic meridian passing through the earthquake epicenter has been studied. TEC variations reach the highest intensity at a latitude of 30 degrees. A change in the sign of the current changes the symmetry of the effect in the TEC along the latitude relative to the geomagnetic meridian of the epicenter. The influence of return currents of various configurations on the TEC structure was considered, but it did not turn out to be significant.

EQ precursors are easier to detect under geomagnetically quiet conditions, when there are no other sources of disturbances such as geomagnetic storms and substorms. An attempt was made to consider the joint action of the seismogenic electric field and geomagnetic sources on the TEC. For this purpose, the behavior of the TEC was studied in the period from December 20, 2015 to January 6, 2016, when 3 global geomagnetic disturbances took place and a low-latitude earthquake took place in India with epicenter coordinates of 15° mag. lat., 165° mag. long near the northern crest of the equatorial anomaly, which had a significant impact on the ionosphere. Model calculations for this period were carried out using the UAM, in which the sources of geomagnetic disturbances of the ionosphere were the field aligned ionospheric-magnetospheric currents of zones 1 and 2, and the sources of seismogenic disturbances were vertical currents in the vicinity of the epicenter. Calculations showed that both types of perturbations were clearly revealed both in calculations and in observations, being of the same order of magnitude. The significant role of the electric field of dynamo origin, which is generated by the equatorial winds, is noted.

Chapter 7 summarizes what has been said in the previous chapters and discusses the issue of earthquake prediction. For the reasons already mentioned (the limited number and quality of observations, first of all), this issue is very difficult from a practical point of view, so many researchers consider it simply impossible to solve it in the foreseeable future [6], especially taking into account the need to involve and coordinate specialists from completely different directions, both experimental and theoretical, such as geology, hydrometeorology, geophysics, radiophysics, plasma physics, space physics, solar physics, etc. Nevertheless, the movement towards understanding the essence of phenomena and methods for their study based on observations and physical and mathematical modeling cannot be stopped. The authors hope that the monograph under consideration will be of assistance to those involved in this movement, both novice and experienced researchers.

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