Global Electric Circuit: Solar Wind, Magnetosphere, Ionosphere, Atmosphere

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Accepted : 23 September 2019

Abstract The aim of this paper is to investigate the global electric circuit and processes of solar wind-magnetosphere-ionosphere-atmosphere interaction. Also, I discuss the question as to how the magnetospheric energy source feeds the ionospheric current system. It is shown that a consistent application and further development of our structurally adequate magnetospheric model makes it possible to solve the magnetosphere-ionosphere coupling problem in regard to the formation of auroral electrojets by bulk currents generated in the geomagnetosphere. If there is a mechanism for the magnetospheric disturbance effect on meteorological processes in the atmosphere, it supposes a more complicated series of many intermediates, and is not associated directly with the energy flux that arrives into the ionosphere during storms.It is concluded that the whole of the complicated magnetospheric 'structure' only acts to redistribute, in space and time, currents and energy fluxes, which must be supplied by external sources to feed the dissipative processes in the ionosphere and in the atmosphere.

Keywords: solar wind-magnetosphere interaction; magnetosphere-ionosphere coupling; lower atmosphere; power aspects.

1. Introduction

A magnetospheric storm is a 1-3 day long phenomenon spanning all the magnetosphere regions, and it features sharp depressions in the magnetic field. During storms and substorms, the ionosphere undergoes rather significant Joule heating with a great power of precipitating energetic particles. Huge energy increases the ionosphere temperature, causes large-scale ion drifts, and neutral winds.

In the **description** of magnetospheric processes for many years was reached the significant progress (e.g. (Ruohoniemi, Baker, 1998), (Milan et al., 2000), (Vasyliunas, 2001), (Forster et al., 2008) etc). There are a lot of useful books for undergraduates, graduates and researchers in plasma physics, space physics (e.g. (Baumjohann, Treumann, 1996), (Bothmer, Daglis, 2007)). Also here appeared a lot of models, scenarios, simulations, which reflect the true time, place and scale of the developing magnetosphere events in the function of solar wind parameters, created, however, on the empirical or semiempirical basis (Akasofu, 1980.), (Kan, 1993), (Lui, 1996), (Baker et al., 1996), (Waters, et. al., 2001), (Brautigam, 2002), (De Zeeuw, et. al., 2004), (Solovyev, 2003), (Lyons et al., 2009), (Wolf et al., 2009). According to their tasks models are divided into two types. The first type models task is the maximally accurate description of the outcome parameters relation with the income ones. Such models are created as a combination of the regression equations, which coefficients present the model's content. The coefficients are determined on the basis of the teaching extracts, for which are known the income and outcome parameters. Such models correctly reflecting the system functions should be named as functionally adequate. The other model's type has in its basis the physics equations, which describe the real physical processes happening in the system. They more or less can form the physical structure of the object. That's why they should be called as structurally adequate models.

The concept of magnetic field line reconnection was formulated in 1961 (Dungey, 1961). The assumption that an effective conductivity exists in the region of magnetotail which is the basis for this concept. This coefficient is proportional to a certain length, which has the sense of a pair collision mean free path. Since the mean free path in the magnetosphere during pair collisions with a Coulomb interaction considerably exceeds the extents of the magnetosphere, it is customary to assume that the magnetospheric plasma is collisionless. However, collective processes resulting in a momentum and energy exchange between particles can exist in the plasma. Exchange proceeds through waves, which should have an energy spectral density sufficient for maintaining an adequate exchange rate (quasi-collisional regime). Thus, the consistency of the concept is reduced to the problem of searching for plasma instabilities capable of maintaining a quasi-collisional regime. This problem has not yet been solved.

At present, there have been created several functionally adequate models that describe the magnetosphere behavior well, if the input parameters are located within the properly provided learning sample (e.g. (Akasofu, 2003), (Akasofu, 2013) etc). The case with structurally adequate models is quite different. It is as follows. If the functionally adequate model is allowed not to rest upon the knowledge of certain physical processes and can be made only formally, then, for the structurally adequate model, setting real physical mechanisms is the work content.

The book (Herman, Goldberg, 1978) is particularly welcome at a time at which many astronomers, space scientist, geophysicist, and meteorologists are entering the field of Sun-weather/climate investigation. This book provides an excellent opportunity for a scientist considering this new field to get an overall view of the present status of the subject in its many disciplinary aspects. The existing correlations provide a strong suggestion that some physical mechanism exists linking the variable Sun and the weather and climate, but the details of such a mechanism or mechanisms are quite unknown.

Statistical correlations were found between geomagnetic activity, atmospheric pressure and temperature (Bucha, 2009), (Palamara, 2004). Authors of (Haigh, et al., 2005) suggested that the observed climate response to solar variability is brought about by a dynamical response in the troposphere to heating predominantly in the stratosphere.

It is known that a tropical cyclogenesis may be "a mechanism for effective discharge of the surplus heat in the atmosphere under the conditions when the routine mechanism effect becomes insufficient" (Sharkov, 2005). Between the solar-terrestrial disturbance parameters, on the one hand, and the cyclogenesis characteristics, on the other, various researchers endeavor to trace hard-to-detect statistical communications associations. The revealed coincidence between the time of origin and evolution of the 23-24 Aug 2005 Hurricane Katrina with the powerful geomagnetic storm main phase also boosted the research in this trend.

The issue of the reality and the physical mechanism for solar-terrestrial couplings has rather a long history. Many geophysicists were most decisive in rejecting the idea about a solar activity effect on the lower atmosphere condition as absolutely unacceptable. And, first of all, the matter was that the power of atmospheric processes exceeds the solar-wind input energy flux into the near-Earth space enormously. Due to this, it seems most unlikely that solar activity could significantly affect the lower atmosphere condition. However, the research done over the last years allowed us to find a clue to overcoming this inconsistency. The main objection to a possibility of the solar activity effective influence on the condition of the lower atmosphere and weather, based on insufficient power of the solar wind, appears quite surmountable; see e.g. (Pudovkin, 1996). Also, like the computations in (Pudovkin, 1996) show, the energy necessary to create the atmospheric optical screen (cloud layer) is incomparably lower than the amplitude of the variation in the screen-induced solar energy flux arriving in the lower atmosphere.

According to (Pudovkin, 1996), a noticeable variation in the chemical composition and contents of small components, as well as in the atmosphere transparency, is caused by variations in the atmospheric ionizing radiation flux observed during geomagnetospheric disturbances. The main types of such variations are (Pudovkin, 1996): 1) the galactic cosmic ray intensity short-term depressions observed during geomagnetic disturbances (Forbush decreases) caused by dispersion of energetic charged particles by the magnetic fields transported from the solar atmosphere by the solar wind high-velocity streams; 2) solar cosmic ray flux bursts caused by solar flares.

The link between the enhanced solar wind (geomagnetic) forcing, the North Atlantic Oscillation (NAO) and changes in the troposphere was suggested in (Crowley, et al., 1989) showing that the strengthening of thermospheric winds generates vertical downward winds in the aurora.

In (Mansilla, 2011) author examined the possible connection between atmospheric parameters measured at low and middle altitudes and geomagnetic storms occurred in 2000 and 2003. The results presented in (Mansilla, 2011) may show evidence to support, that atmospheric parameters at heights of the troposphere and lower stratosphere could be possibly related to geomagnetic storms.

Cloud layers play an important role in Earth's radiation balance (Tinsley et al., 1989), (Tinsley et al., 1993), affecting the amount of heat from the Sun that reaches the surface and the heat radiated back from the surface that escapes out into space.

According to (Troshichev, Janzhura, 2004) temperature alterations Antarctic ice sheet initiated by the disturbed solar wind. The interplanetary electric field influence is realized through acceleration of the air masses, descending into the lower atmosphere from the troposphere, and formation of cloudiness above the Antarctic Ridge, where the descending air masses enter the surface layer. The cloudiness results in the sudden warming in the surface atmosphere, because the cloud layer efficiently backscatters the long wavelength radiation going from ice sheet, but does not affect the process of adiabatic warming of the descending air masses. Influence of the interplanetary electric field on cloudiness has been revealed for epochs of the solar activity minimum, when Forbush decreases effect is absent. The acceleration of the descending air masses is followed by a sharp increase of the atmospheric pressure in the near-pole region, which gives rise to the katabatic wind strengthening above the entire Antarctica. As a result, the circumpolar vortex around the periphery of the Antarctic continent decays and the surface easterlies, typical of the coast stations during the winter season, are replaced by southerlies. It is suggested that the resulting invasion of the cold air masses into the Southern ocean leads to destruction the regular relationships between the sea level pressure fluctuations in the Southeast Pacific High and the North Australian –Indonesian Low, since development the El-Nino event strongly follows anomalous atmospheric processes in the winter Antarctica.

The results of the paper (Lockwood et al., 2018) are the first physics-based quantification of the space weather conditions in both the Dalton and Maunder minima. These authors think that the weakening of Earth's magnetic moment means that the terrestrial disturbance levels during a future repeats of the solar Dalton and Maunder minima will be weaker and we here quantify this effect for the first time.

The objective of this paper is to investigate the global electrical processes coupling the solar wind and magnetosphere, the magnetosphere and ionosphere, and the ionosphere and lower atmosphere.

2. Solar wind-geomagnetosphere-ionosphere-atmosphere interaction.

Blast-wave shocks can arise during CME formation. The difference from piston shocks is that a blast-wave shock originates from the explosions that frequently accompany CME formation, and further propagates freely without any CME piston effects. Earth's bow shock (BS) is a piston shock. The front of the Bow Shock (BS) is the region where the parameters of the Solar Wind (SW) undergo strong changes, especially in the "nose" part. The particle number density and the intensity of the tangential component of the magnetic field increase approximately by a factor of 4 behind the front, the normal velocity component decreases by the same factor (according to data of well-known satellite missions – GEOTAIL, CLUSTER-II, THEMIS). If almost all SW energy before the front is concentrated in the progressive motion, then behind the front it is concentrated in the energy of compressed plasma and magnetic field. At the bow shock the kinetic energy of the solar wind also is converted to the thermal energy. The bow shock front is the main converter of solar wind kinetic energy into electromagnetic energy (Ponomarev et al. 2006). When passing hrough the bow shock front, the intensity of the tangential component of the SW magnetic field and the plasma density increase several fold. Therefore, among other things, the BS front is a current sheet. This current is diverging in this layer, that is the front is the generator of the current. Since plasma with magnetic field passes through the front, electric field arises in the front reference system. Thus, the BS front is a source of electric power. There is a potential difference between the BS front and the magnetosphere, unequivocally (since the Transition Layer (TL, or magnetosheath) magnetic field is determined by the SW magnetic field) associated with the velocity of the transition layer plasma flow. Thus, the magnetopause potential is functionally related to SW parameters (Sedykh, 2011; Sedykh, 2014(a, b)). The solar wind energy also feeds the ion acceleration process, the generation of waves in the region of bow shock, and the energy necessary to build up the foreshock. it is clear that the primary energy source for magnetospheric processes is the solar wind, but the process of energy transfer from the solar wind into the magnetosphere, or rather, to convecting magnetospheric plasma, appears to be rather complicated.

The power consumed by the magnetosphere is spent on the compressor work and consists of active and reactive power. The active part covers losses in the ionosphere (ohmic, primarily), the reactive part returns to the magnetospheric compressor (structurally adequate model – (Sedykh, Ponomarev, 2012; Sedykh, 2015)).

Let us address the problem of the extraneous electric field penetration into the Earth's magnetosphere. The penetration of the electric field and the current into the geomagnetosphere is a two-stage process, and may be presented as follows. Let an electric current component towards the magnetosphere appear at instant T. A potential value will be established at the magnetopause segment. In the thin near-side layer of the thickness $d \sim 2\pi c/\omega_{pp}$

(where ω_{pp} is proton plasma frequency, c is the speed of light) the charge division process will start, and the displacement current $\mathbf{j^*} = (\varepsilon/4\pi)\times\partial\mathbf{E}/\partial t$ will appear. Also, there will appear Ampere force $\mathbf{F} = [\mathbf{j^*}\times\mathbf{B}]/c$ that will start accelerating plasma. The only force that withstands the Ampere one is the inertia force. Under the conditions of a homogeneous medium, the inertia force is $\rho\partial\mathbf{v}/\partial t$: $\rho\partial\mathbf{v}/\partial t = [\mathbf{j^*}\times \mathbf{B}]/c = (\varepsilon/4\pi c)\times[\partial\mathbf{E}/\partial t \times \mathbf{B}]$. Taking into account that $\varepsilon=c^2/V^2_A$, where V_A is the Alfven velocity, upon integrating we will have: $\mathbf{v} = c[\mathbf{E}x\mathbf{B}]/B^2$ that is the classic equation for the electric drift velocity (it is important for us to express the dynamic process in this case). When the plasma is accelerated in the layer d up to the **VxB** drift velocity (and it happens during the gyroperiod), then there will be no field in the plasma coordinate system, and it appears at the boundary between the moving and stable plasmas in a stable coordinate system. The boundary moving velocity separating the moving plasma from the stable one will be, consequently, $V_\phi \sim d\omega_B/2\pi$, where ω_B is the proton gyrofrequency. Taking the values d and ω_B into the equation for the phase velocity, we see that it is the Alfven velocity like we expected. Thus, the external electric field penetrates into the magnetosphere without any limitations of the Alfven-wave type, and the electric current penetrates only in a form of the displacement current. The electric current flows through the system under consideration only when there is a transitive process. In the stationary regime, there is no electric current. If the magnetic field is inhomogeneous according to an axis X, then the plasma pressure gradient will be originated independently due to the flow nonuniformity. The electric field establishment time in the system here is $\tau_E = L/V_\phi$, and the current establishment time is $\tau_I = L^*/V_c$, where L is the system size, V_ϕ is the phase velocity for the electromagnetic signal propagation across the system, $L^* = (B/\nabla B)$, V_c is the plasma convection velocity. An approximate estimate applied to the magnetosphere gives the time of the electric field establishment to be hundreds of seconds, and the electric current establishment time to be about an hour. Thus, the electric current penetration into plasma is a two-stage process. Initially, the polarization field that penetrates into plasma “layer by layer” is produced. Or, to be more exact, the momentum corresponding to this field penetrates into plasma. Here, if the system is inhomogeneous, the flow can redistribute pressure so that an electric current arises in plasma because of the appearance of gradients. This electric current is necessary to maintain plasma convection in the magnetosphere (Sedykh, 2015).

The equations of the two-fluid or one-fluid magnetohydrodynamics with isotropic or anisotropic pressure are as a rule applied to describe collisionless magnetospheric plasma. In this case any dissipative processes in the system are considered inessential. This statement is usually valid for ohmic loss and loss by radiation. However, particles (and energy) also escape from the magnetospheric plasma into the atmosphere through open ends of flux tubes. This type of loss can be very substantial and should be taken into account. Combined action of plasma convection and pitch-angle diffusion of electrons and protons lead to the formation of plasma pressure distribution in the magnetosphere. Specifying the initial pressure at the boundary, we can find the resultant pressure at any point on the flux line (fig.1a).

In such a way, the field of plasma pressures in the entire magnetosphere is calculated (Sedykh, Ponomarev, 2012). In the course of the electric drift, the plasma tube moves from one flux tube to another tube without excess and deficiency, if magnetic field lines are equipotential. Let us imagine for definiteness that electric drift proceeds toward increasing magnetic field. In such a case, the plasma tube volume constantly decreases ($\sim L^4$), and this means that pressure increases by a factor of $L^{4\gamma}$ at a uniform adiabatic compression (hereafter, L is the McIlwain parameter, and γ - is the adiabatic exponent). The process of magnetic flux tube depletion due to particle escape into the loss cone (into the ionosphere) is superposed on the above process. Thus, the mapping (projection) of the plasma pressure relief onto the ionosphere corresponds to the form and position of the auroral oval. This projection, like the real oval, executes a motion with a change of the convection electric field, and expands with an enhancement of the field. Steady bulk currents are connected to distribution of plasma pressure. The divergence of these bulk currents brings about a spatial distribution of field-aligned currents, i.e. magnetospheric sources of ionospheric current systems (Sedykh, Ponomarev, 2012).

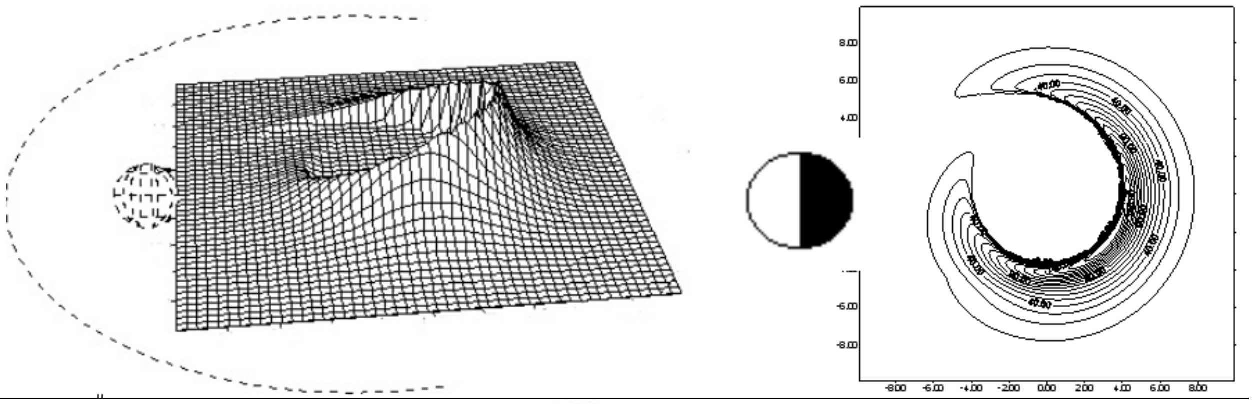
Let us now address the question about power supply of the ionospheric current system as exemplified by auroral electrojets (fig.1b). The source region of electrojets in the magnetosphere is on the earthward slope of the gas pressure peak. The transversal current in the magnetosphere near the equatorial plane has two components: $j_R \sim -\nabla_\lambda p_g$ and $j_\lambda \sim \nabla_R p_g$, where R, λ, φ are spherical coordinates. The latitude φ is calculated from the magnetic equator; the longitude λ, from the midday meridian counter-clockwise. The presence of the positive gas pressure gradient on the earthward slope of the gas pressure peak p_g is associated with particle losses by precipitation. This gradient $\nabla_R p_g$ produces the counter-clockwise current j_λ. Its possible competitor is a drift current of clockwise energetic protons. The current j_λ is closed in remote parts of the magnetosphere through the current segments shown in fig. 1b as radial. The $j_\lambda E_\lambda$ product and $j_R E_R$ are negative.

This suggests that both j_λ and j_R can work when branch off to the ionosphere. There is a component of the Poynting vector directed into the ionosphere: $S_\varphi = -(J_R E_R + J_\lambda E_\lambda)$, where J_R and J_λ are j_λ and j_R currents integrated with respect to the current-carrying layer thickness.

It is known that auroral electrojets are dominantly Hall currents flowing between two 'curtains' of field-aligned currents, which flow into the ionosphere to the south of the electrojet at dusk, to the north of the electrojet at dawn and flow out to the north of the electrojet at dusk and to the south at dawn (for the northern hemisphere). Besides, as is seen from fig. 1b, the westward current can also be closed through the ionosphere. The proton DR-current has $j^{DR}{}_\lambda E_\lambda > 0$, therefore it is a power consumer and cannot do work upon the ionosphere. It takes away a portion of the j_λ current for itself. This suggests that the gas pressure of fast protons in the DR-current favours a decrease in $\nabla_R p_g$.

The situation changes radically when the boundary conditions are time dependent. Knowing the distribution of the plasma pressure, we can determine the places of MHD-compressor and MHD-generators location in the geomagnetosphere. We have demonstrated (Sedykh, Ponomarev, 2012) that magnetospheric regions that operate like an MHD compressor, where plasma is compressed under the action of Ampere’s force $[\mathbf{jxB}]/s$, satisfy the condition $\mathbf{V}\cdot\boldsymbol{\nabla}p_g > 0$, and regions where gas dynamic forces acts on electromagnetic forces, i.e. regions of MHD generators, satisfy the condition $\mathbf{V}\cdot\boldsymbol{\nabla}p_g < 0$. If the B_z-component of IMF is less than zero, the direction of external current is such that, by closing through the magnetospheric body, it produces there Ampere’s force capable of acting to pushing magnetospheric plasma earthward, toward an increase of magnetic and plasma pressure. Thus, the MHD compressor lie in this region (located mostly at 5Re<L<10Re on the nightside, Re=6371 km, i.e. before the plasma pressure maximum). Consider a situation arising in the region of the dusk electrojet, using a circuit from fig.1b. For simplicity, in this figure the current systems supplying electrojets are divided. The radial current along with the radial electric-field component supplies the 'curtain' structure of field-aligned currents. It is evident that $j_R E_R < 0$ in the magnetosphere, i.e. there is a source of electric power, whereas in the ionosphere $j^I{}_R E^I{}_R > 0$, i.e. there is a consumer of electric power. The Poynting vector is directed everywhere to the ionosphere.

A.



B.

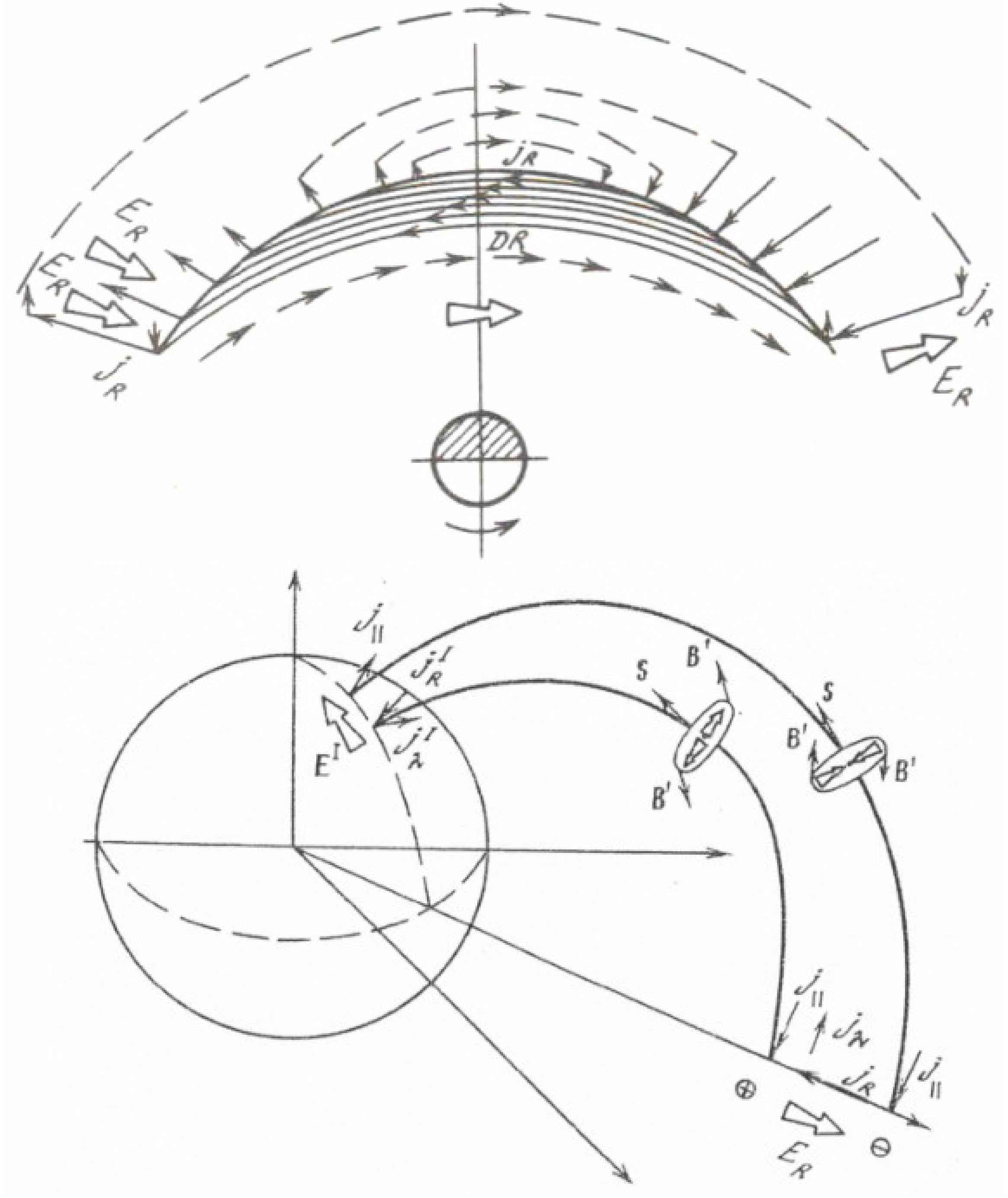


Fig. 1. A. The plasma pressure relief under the stationary boundary conditions. The projection (mapping) of the plasma pressure "hump" onto the ionosphere corresponds to the form and position of the auroral oval. This projection, like the real oval, executes a motion with a change of the convection electric field, and expands with an enhancement of the electric field.
B. The scheme of location of electric fields and currents in the equatorial plane of the geomagnetosphere (according to the section of the plasma pressure relief).

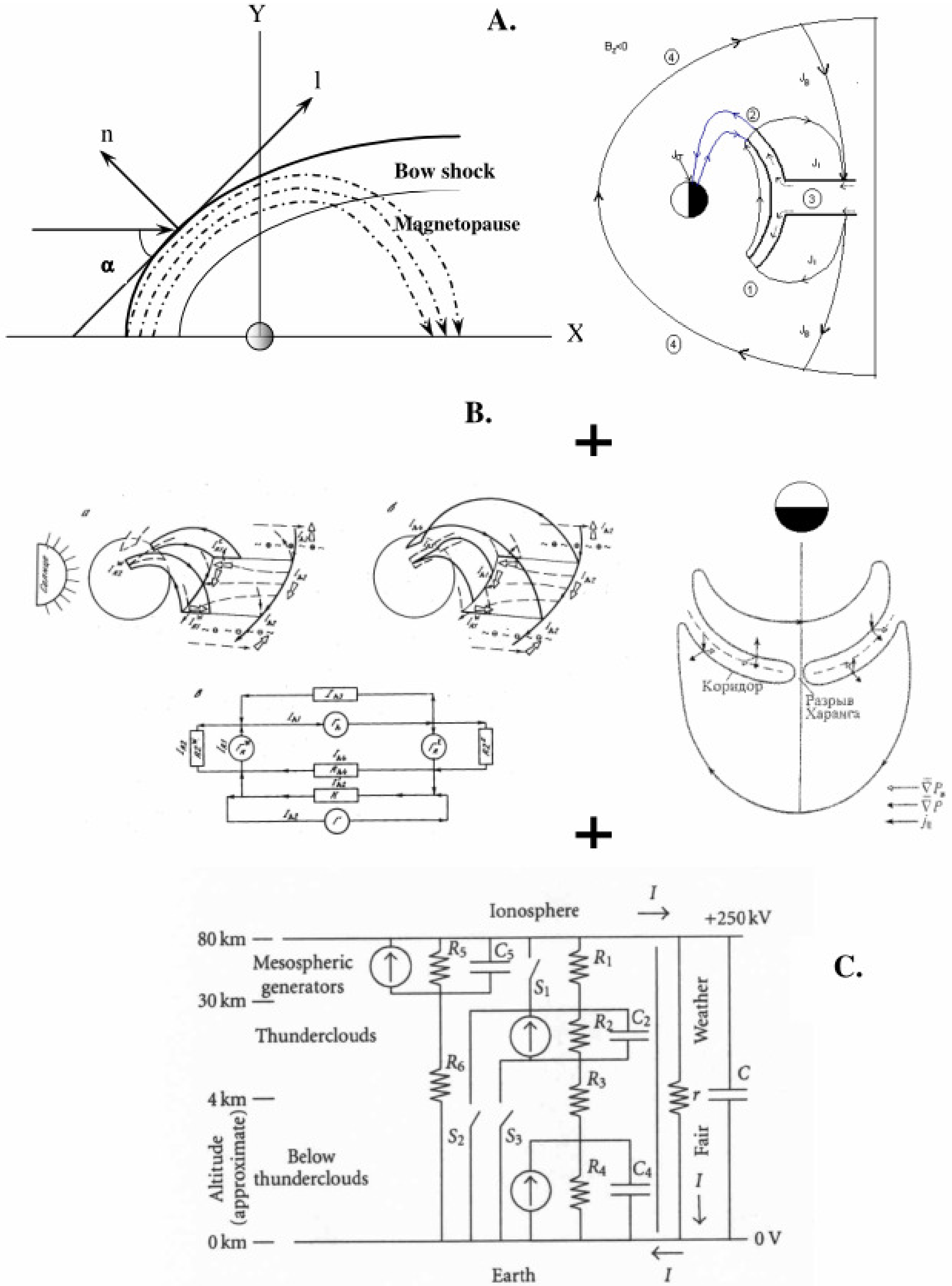


Fig. 2. The scheme of locations of functional blocks in the magnetosphere - structurally adequate model (A); (B) schematic spatial location of the magnetospheric-ionospheric currents (Sedykh, Ponomarev, 2012); (C) the diagram showing equivalent electric circuit for atmospheric scheme (Rycroft, 2006).

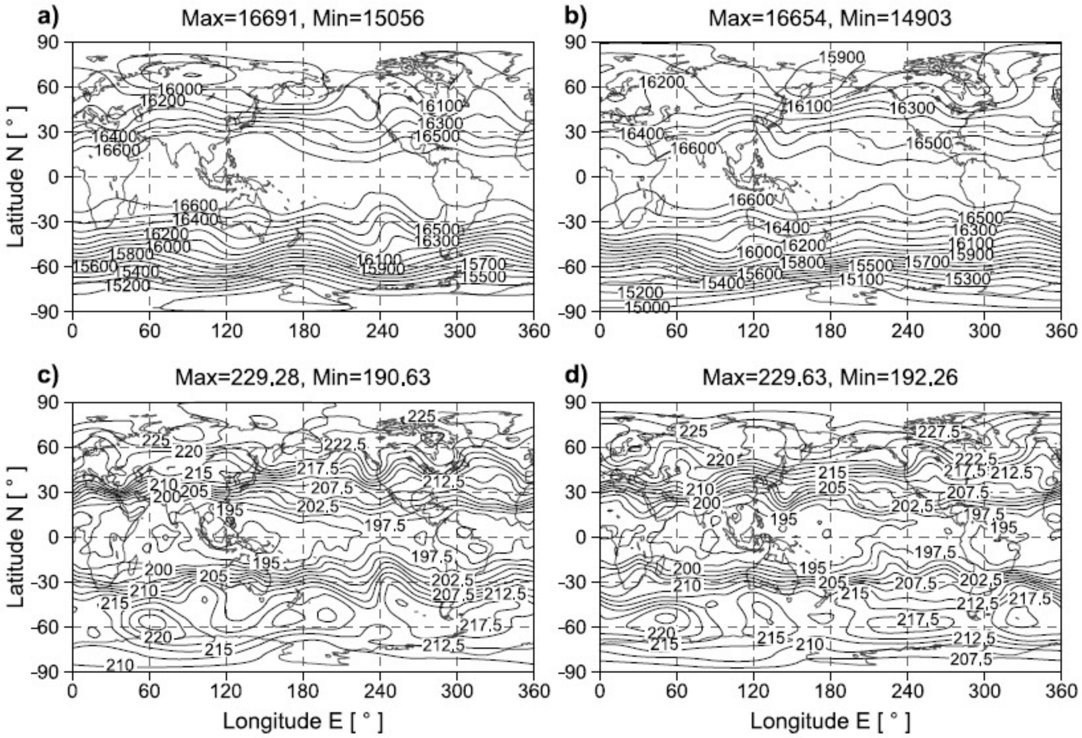


Fig. 3. The NCEP/NCAR reanalysis examples: **a)** and **b)** height of an isobaric surface at the level 100 hPa (averaged per day, values in m) for the event of 3 May 1986 and for the geomagnetic quiet day 3 May 1985 (*AE* ≤ 100 nT), respectively; **c)** and **d)** averaged temperature (values in K) at the level 100 hPa for the event of 3 May 1986 and for the geomagnetic quiet day 3 May 1985 (*AE* ≤ 100 nT), respectively (Sedykh, Lobycheva, 2013).

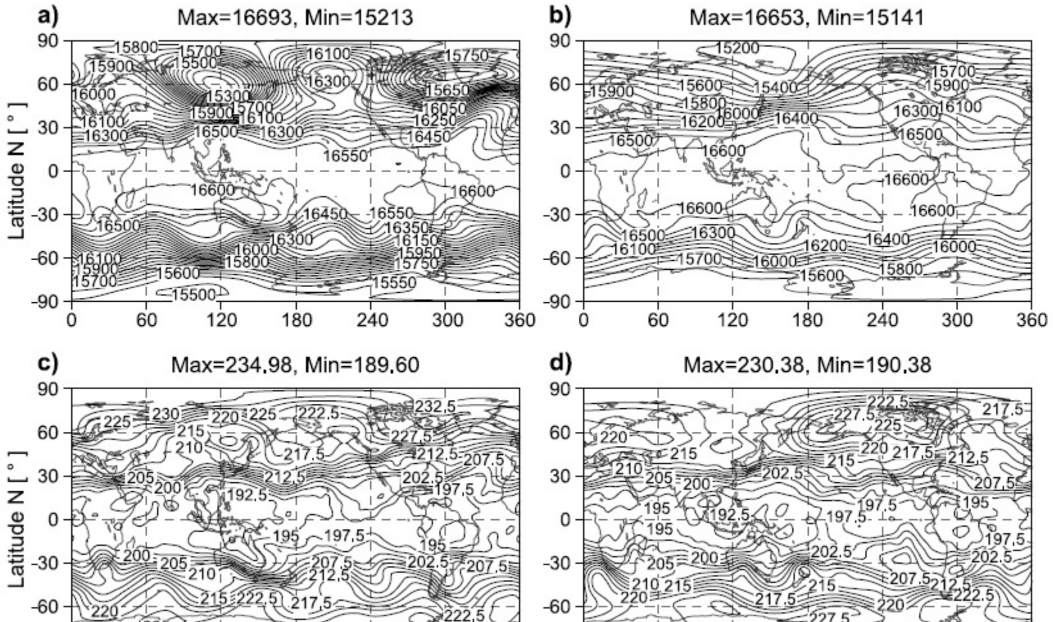


Fig. 4. The NCEP/NCAR reanalysis examples: **a)** and **b)** height of an isobaric surface at the level 100 hPa (averaged per day, values in m) for the event of 13-14 March 1989 and for the geomagnetic quiet day 14 March 1985 (*AE* ≤ 100 nT), respectively; **c)** and **d)** averaged temperature (values in K) at the level 100 hPa for the event of 14 March 1989 and for the geomagnetic quiet day 14 March 1985 (*AE* ≤ 100 nT), respectively (Sedykh, Lobycheva, 2013).

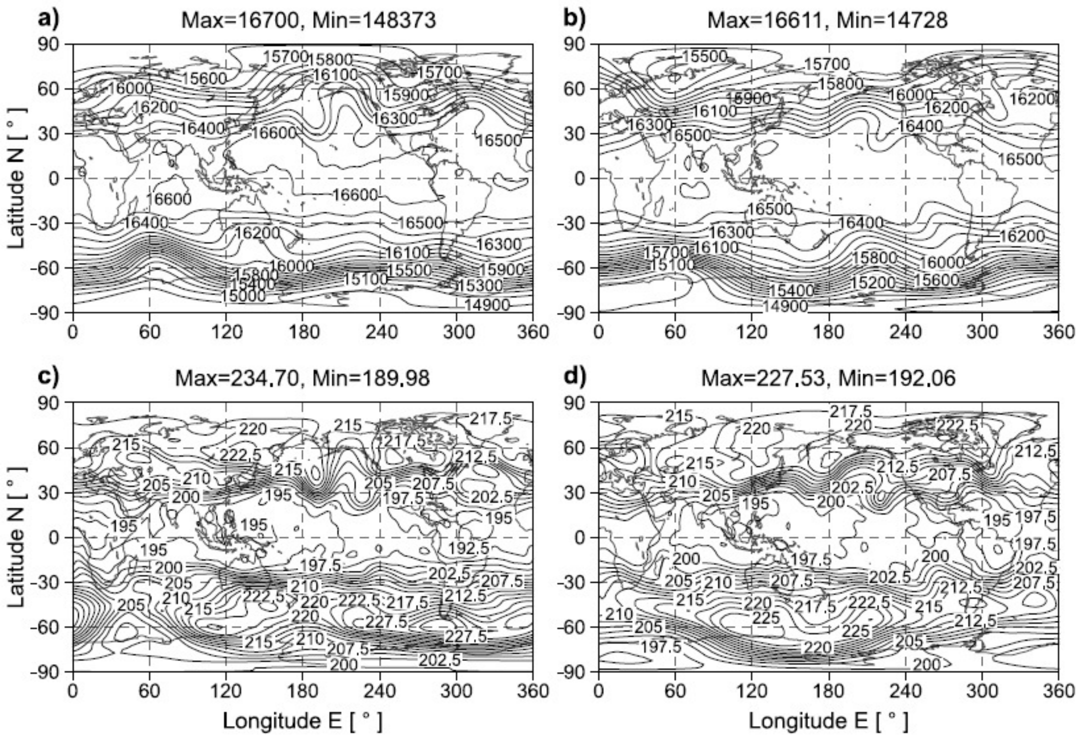


Fig. 5. The NCEP/NCAR reanalysis examples: **a)** and **b)** height of an isobaric surface at the level 100 hPa (averaged per day, values in m) for the event of 30 October 2003 and for the geomagnetic quiet day 30 October 1985 ($AE \leq 100$ nT), respectively; **c)** and **d)** averaged temperature (values in K) at the level 100 hPa for the event of 30 October 2003 and for the geomagnetic quiet day 30 October 1985 ($AE \leq 100$ nT), respectively (Sedykh, Lobycheva, 2013).

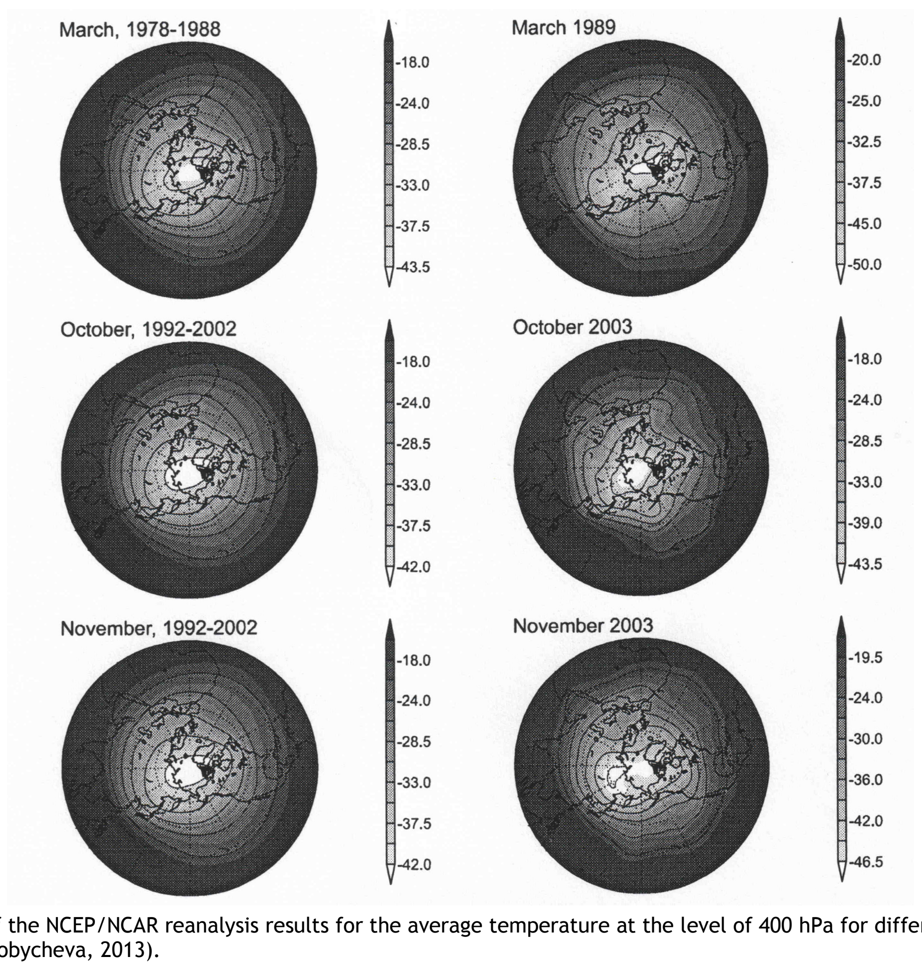


Fig.6. Comparison of the NCEP/NCAR reanalysis results for the average temperature at the level of 400 hPa for different periods and days (Sedykh, Lobycheva, 2013).

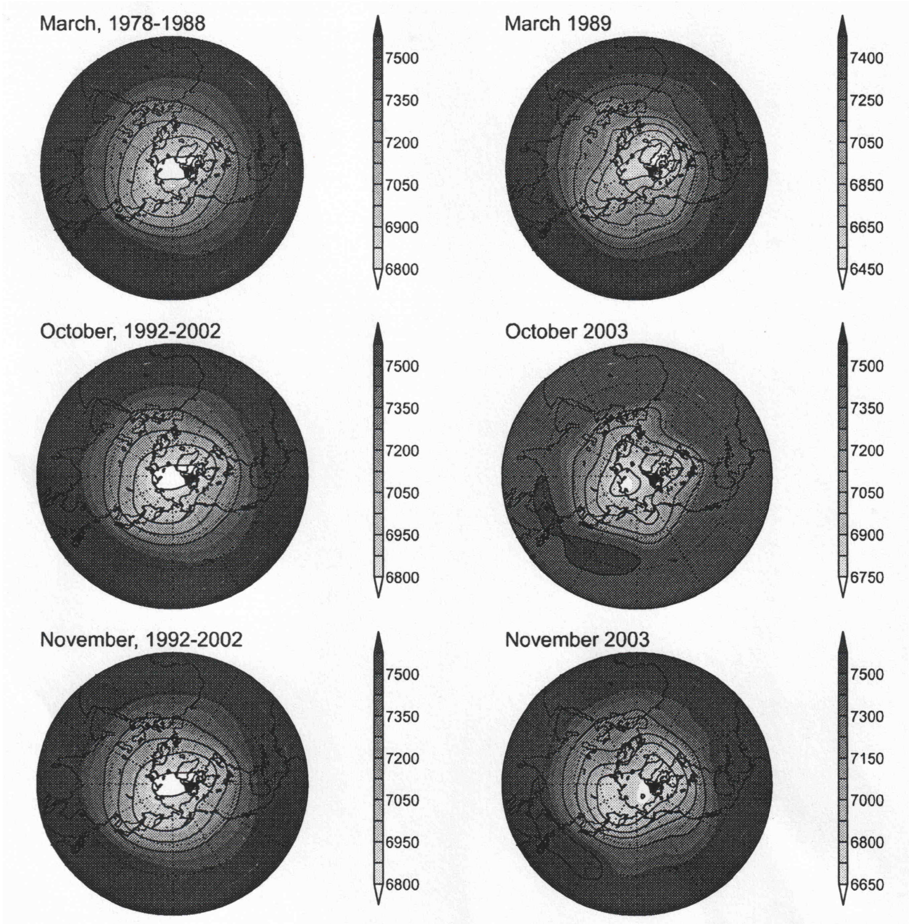


Fig. 7. Comparison of the NCEP/NCAR reanalysis results for the average geopotential heights at the level of 400 hPa for different periods and days (Sedykh, Lobycheva, 2013).

The work upon electric forces in the magnetosphere is done by the gas pressure falling in the direction of convection velocity, therefore $\mathbf{V\nabla P_g}$ <0. The spatial and equivalent power-supply circuits for ionospheric currents are also given in fig.1b.

Auroral electrojets are supplied by four magnetospheric generators comprising a fairly complex power system. The generators feed the current systems of Birkeland-Bostrom (BB) of the first and second types. Three of them, referred to as secondary, work due to the pressure gradient of compressed plasma. The MHD-compressor is powered partly by the primary generator and partly by the back electric current of secondary generators. The value of the back electric current depends on the load intensity largely determined by resistance of the ionosphere in the auroral zone. Intensification of auroral electrojets produces changes in currents of the magnetotail (see in details (Sedykh, Ponomarev, 2012).

The cross section of this spatial pattern along any intermediate contour line is shown in fig. 2b. Figure 2b indicates that the field-aligned currents are directed oppositely on both sides of the corridor. Since the sign of the p_g gradient changed and that of the p_B gradient remained unchanged, the double "curtain" of field-aligned currents is formed, which is a characteristic feature of auroral electrojet feeding. The corridor is shown in a way, in which it is stretched along the lines B=const under the small corner, that's why the time of plasma tube devastation τ can be considered the constant quantity. The plasma flow in a corridor also happens under a small angle to its axis. Field-aligned currents (FACs) connect the magnetosphere and the ionosphere into a uniform electric circuit.

The atmospheric process power incomparably exceeds energy flux from the solar wind into the geomagnetosphere, and the power of extremely strong magnetospheric disturbances. The energy flux from the magnetosphere into the atmosphere during the strong storm was about 1.5×10^{19} (erg/s) $\times24\times3600=1.2\times10^{24}$ ergs/day, which is by 2-3 orders of magnitude less than the atmospheric process power whose values are in (Pudovkin, Babushkina, 1992).

In the frame of the global electric circuit concept, thunderstorms act as a "meteorological" generator and create a potential drop of $U_{int} \approx 270$ kV between the ionosphere and the Earth's surface. It is considered that this potential is identical at all points of the ionospheric shell. In the high-latitude ionosphere, U_{int} is superposed by the potential from the magnetospheric source (U_{ext}). Distribution of U_{ext} corresponds to the ionospheric plasma convection, which is directly related to plasma convection in the geomagnetosphere. Therefore, how the electric field is transferred from the solar wind to the geomagnetosphere, and magnetospheric plasma convection generation, are very important issues.

Indeed, there is no simple global electric circuit via which a sharp increase in the solar wind electric field during magnetospheric disturbances would be possible. The solar wind electric field penetration process is complex and non-linear.

The atmospheric conductivity sharply declines between the polar ionosphere and the layer at h~10 km.

A realistic model of equivalent circuit with capacitors, resistors, and switches is presented and is shown in fig. 2c (Rycroft, 2006). The electrodynamic coupling between the Earth's atmosphere and the ionosphere is very complex and may be described by the global electric circuit (Rycroft, 2006).

3. Discussion and conclusions

The global atmospheric electric circuit is connected through a high-altitude ionosphere, and magnetospheric disturbances can effect on the stationary and changes of an atmospheric electric field. Process of electric field penetration from the solar wind is complicated; this phenomenon is nonlinear. A generation of plasma convection in the geomagnetosphere is associated with processes at the bow shock front. A combined action of plasma convection and pitch-angle diffusion of electrons and protons lead to the formation of plasma pressure distribution in the magnetosphere. As it is known, bulk currents are associated to plasma pressure distribution in the magnetosphere. Divergent of these bulk currents gives a spatial distribution of FACs, i.e. magnetospheric sources of ionospheric current systems. Field-aligned currents (FACs) connect the magnetosphere and the ionosphere into a uniform electric circuit. The suggested equivalent electric circuit scheme of the interaction (fig.2) may be analyzed for understanding of the mechanism of geomagnetic activity effect on complex nonlinear system of atmospheric processes.

The geomagnetospheric disturbance effect on the troposphere is weak compared with a multitude of other factors affecting it (see **fig. 3-7**). However, the existing works on a high correlation between tropical cyclones and magnetic storms may evidence either the existence of another mechanism for the effect (that was not addressed in this study), or a random coincidence rather than a physical essence (Sedykh, Lobycheva, 2013). A very interesting mechanism suggested by Troshichev and Janzhura (2004) needs further considering and improving. Authors in the paper (Troshichev, Janzhura, 2004) noted that the solar wind dynamic pressure effect on the cloud layer would be opposite to that of the interplanetary electric field. Thus, now we can note that, probably, there is some connection between processes at the bow shock front region and meteorological processes at the lower atmosphere, because the magnetospheric plasma convection generation is associated with processes at the bow shock front.

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