Model of solar activity action on the climatic characteristics of the Earth's troposphere

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The problems are discussed in the paper that may have a fundamental importance for understanding and estimation of possible role of solar activity in climatic variations in the past and the future. Particular attention is paid to the mechanism of solar activity influence on the climatic characteristics of the atmosphere through the tropospheric electricity. The principal causes of significant variations of the electric field in the Earth's atmosphere over polar latitudes during the events of helio-geophysical disturbances are analyzed. Those are the solar cosmic rays, protons, and electrons precipitating from the magnetosphere during geomagnetic disturbances and enhancement (disturbances) of magnetospheric convection during the geomagnetic storms. It is proved that this mechanism works efficiently in the high-latitude regions, favoring the formation of extra cloudiness in the regions with sufficient moisture content. We also present the estimations of temperature, pressure and radiation balance variations in the high-latitude regions, in which water vapor phase state changes due to the influence of helio-geophysical factors. It is shown that the greatest and unique influence of solar activity on the state of climatic system is observed in the absence of incoming radiation (high-latitude regions in winter), as in this case any cloudiness causes a decrease of the energy losses by the climatic system. In the framework of the model and mechanism of solar-terrestrial connections proposed, the results of investigation of manifestation of solar flares and interplanetary magnetic field structure in the thermobaric characteristics of the troposphere are systematized and generalized.

Introduction

At present, a particular attention is paid to the studies of global warming, its manifestations in the planetary regions, and to the forecasts of the climatic variations. Three possible causes of these phenomena are discussed:

1. Natural variability of the terrestrial climatic system (variations in the circulation of the atmosphere and ocean).
2. Anthropogenic impact connected with human activity.
3. Influence of solar activity.

In a series of papers,[1–7] solar variability is considered as a possible cause of the global warming. The comparison of variations in the climatic and solar activity characteristics on large time scales shows their close behavior in time. In particular, there are certain grounds to consider that cold and warm periods have been strictly related to solar activity variations, at least in the XX century. Nevertheless, in spite of the numerous studies, in which the trustworthy, statistically significant connections between various indices of helio-geophysical activity and weather and climate characteristics have been established, the problem of significant contribution of solar activity to the climate variations is still debated. In addition, in a series of papers (see, for example, Ref. 8) the idea of solar activity influence on the lower atmosphere state and climate is rejected as completely unacceptable.

The question on to what degree the global warming occurring during the past decades was of the anthropogenic origin, in contrast to the natural origin (due to the solar activity or owing to the natural variability of the global climatic system, or because of the volcanic activity, etc), is of fundamental importance both for understanding the character of the Earth's climate change in the past and in the future, as well as for planning those human activities, which can influence the climatic system of the Earth.

In this connection, the question on the solar activity contribution to the observable climatic variations becomes especially urgent. It is supposed in the overwhelming majority of papers devoted to the studies of solar activity influence on weather and climate that energy necessary for causing the changes in the climate characteristics of the troposphere should come from outside. However, it is known, that the solar activity variations cause only extremely small variations in the energy flux reaching the lower troposphere as compared with the energy reserve of the stratosphere and troposphere or even with the energy of an atmospheric formation (for example, an isolated cyclone). Regardless of these facts, the reconstructed characteristics of solar activity are, as usual, converted into the power (W/m^2) quantities at consideration of helio-climatic connections, especially for the long-term periods. On the part of the majority of climatologists and meteorologists, it meets a categorical (in our opinion, proved) objection against a significant influence of solar activity on the Earth's climate.

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In the framework of our model,[9–12] it is the basic idea of the concept of solar activity influence on the Earth's climate that the external factors affect the climate system by regulating the energy flux outgoing from the Earth to space. In this case, energy necessary for the regulation of this flux can be small enough being of no principal importance.

In this paper, the following problems are considered:

• Basics and the concept of the electro-optical mechanism of the solar activity effect on the climatic characteristics of the troposphere.

• Some results of the analysis of observations showing the manifestation of solar cosmic rays (SCR) and magnetospheric disturbances in parameters of atmospheric electricity and in the thermobaric field.

• The model of helio-geophysical factors effect on the climatic characteristics of the troposphere is formulated and validated.

• The contribution is estimated of the solar activity to the heat content variation of the Earth's climate system.

Electro-optical mechanism

In our papers[9–12] we have proposed an electro-optical mechanism of the solar activity influence on the climate characteristics and atmospheric circulation through the atmospheric electricity.

The main idea of the mechanism proposed is as follows: the enhancement of helio-geophysical activity (fluxes of solar cosmic rays, disturbances of solar wind and interplanetary field, geomagnetic storms and substorms) leads to an increase in the potential difference between the ionosphere and the Earth. The potential difference increase is accompanied by the growth of the vertical electric field, which leads to redistribution of charged condensation nuclei over heights in the troposphere (to the rise of the negative charged aerosols up to high altitudes). Thus in the regions with the earlier low concentration of these nuclei while with high enough water vapor content, the water vapor condensation and cloud formation take place. Cloud formation is accompanied by the emission of latent heat and by the change of the radiation balance. According to Ref. 9, this mechanism should most efficiently influence on the radiation balance and the tropospheric thermobaric field in the high-latitude regions when no radiation flux is coming from the Sun (high-latitude regions in winter period). In this case, any cloudiness will lead to the temperature rise due to reduction of the radiation cooling of the atmosphere over the high-latitude regions.

Let us consider the effects produced according to the mechanism proposed and its efficiency in the real atmosphere. For this purpose, let us carry out analysis of the results of observations of the electric and thermobaric fields in the troposphere.

Influence of variations of the tropospheric electric field on aerosols

The electric field variations in the troposphere can affect the charged particles in the troposphere and, hence, cause redistribution of the aerosol particles over height, which can be condensation nuclei in the atmosphere. At the magnitude of the electric field variations ΔE = 10–100 V/m observed in the lower troposphere (1–3 km) the strongest effect undergo, according to Ref. 11, the charged aerosol particles of 0.1 to 0.5 μm in size. In Fig. 1 the distribution densities of aerosol particles concentration over size taken from Ref. 13 are presented.

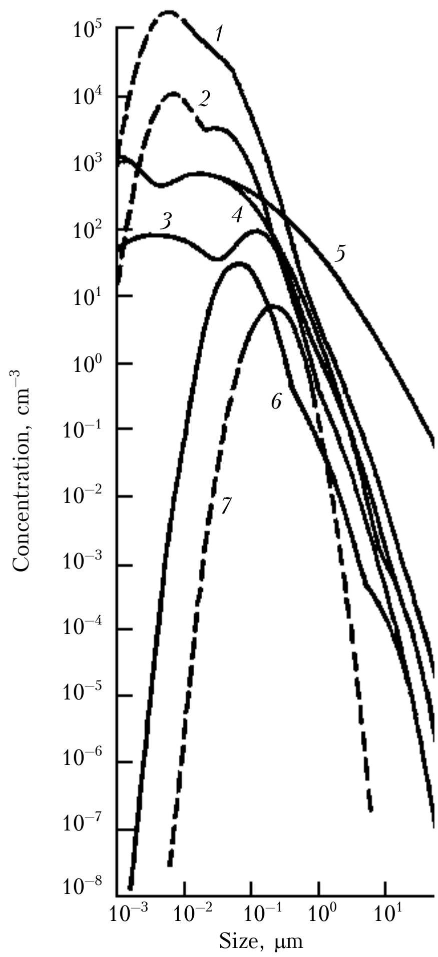

Fig. 1. The distribution of aerosol particles concentration over size[13]: urban (*1*); industrial (*2*); background (*3*); remote continental (*4*); dust storms in deserts (*5*); polar (*6*); stratospheric (*7*) aerosols.

According to data of observations presented in Fig. 1, just the particles of these sizes make up the maximum in the aerosol size-distribution, in the atmosphere. Note that aerosol particles of these sizes are termed meteorological particles; they most actively influence on the water vapor condensation in the atmosphere.[14]

The data of high-altitude measurements[15] under clear sky conditions reveal quite close correlation between the height distribution of the condensation nuclei and the strength of the atmospheric electric field (Fig. 2).

It is necessary to take into account that the state of the troposphere and such meteorological characteristics, as cloud cover, wind, humidity, and others, essentially influence both the distribution of condensation nuclei over height and the atmospheric electric field. Therefore, the global electric field variations would necessarily modify the vertical profile of the electric field and thus cause the corresponding redistribution of the condensation nuclei over height but only under clear sky conditions.

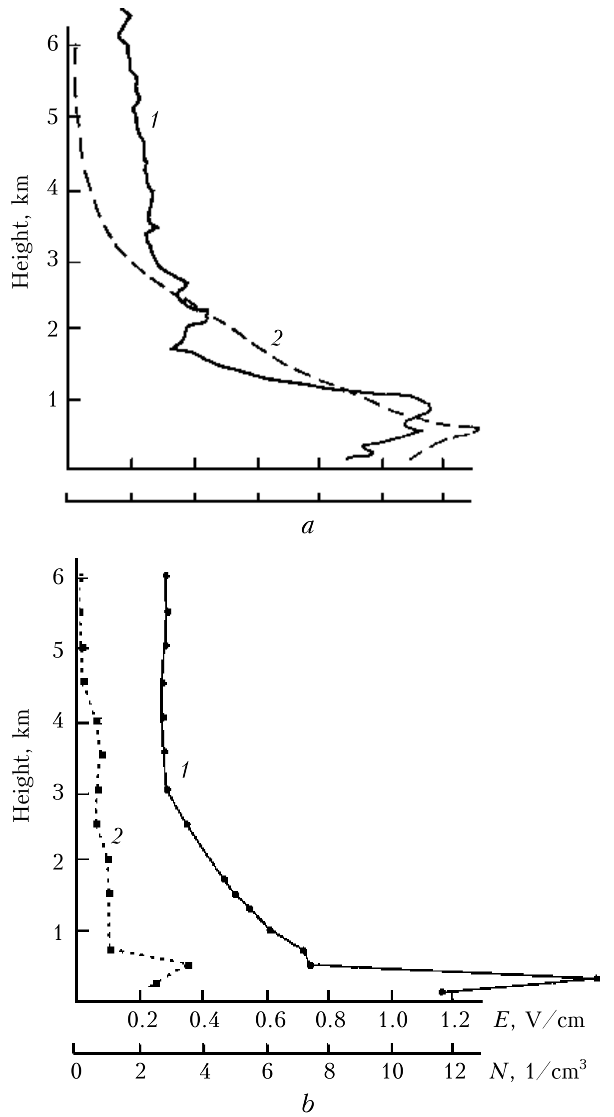

Fig. 2. Variations of height distribution of the condensation nuclei (*N*-curves *2*) at the electric field variations (*E*-curves *1*).[15]

Manifestations of the helio-geophysical effects in the troposphere should depend on time of the day, season, and atmospheric conditions in the given region, namely on the vertical profile of moisture content and temperature, and on the initial distribution of the condensation nuclei over height at the moment the disturbance takes place.

Let us consider, how and which helio-geophysical properties influence the electric potential between the ionosphere and the Earth and consequently the distribution of the condensation nuclei over height.

Influence of the solar cosmic rays and magnetospheric disturbances on the atmospheric electricity

In Ref. 10 theoretical aspects of the SCR influence on the parameters of atmospheric electricity have been considered. According to measurement data in polar regions, the ionosphere–Earth electric current increases approximately twice during the invasion of strong fluxes of solar cosmic rays. Figure 3 shows the measurement data on the atmospheric current over Apatity and on the flux of protons with the energies above 100 MeV according to the data acquired with the Geos-10 satellite during the proton event on April 15, 2001.[16]

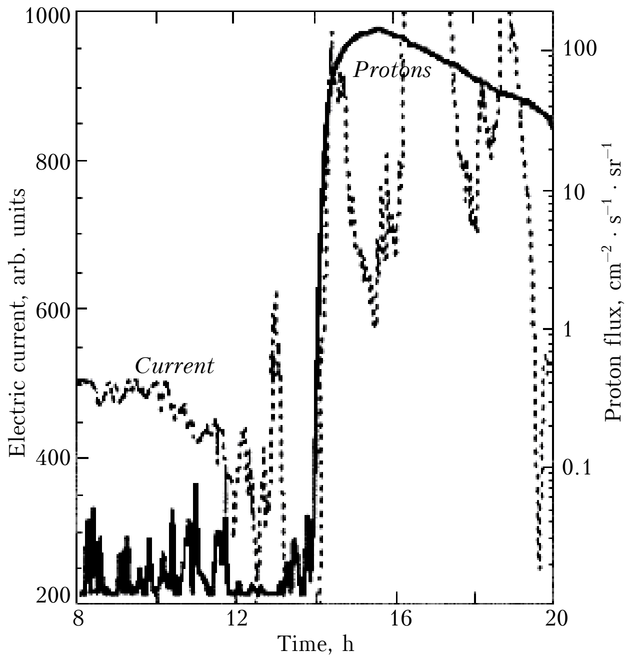

Fig. 3. Variations of the ionosphere – Earth electric current density in a polar region in period of increased flux of the solar cosmic rays on April 15, 2001.[16]

Similar manifestations are observed not only at polar, but also at the high-latitude stations. In the Ref. 17 according to the parametric measurements of atmospheric electricity at the Zugspitze mountain observatory it was shown by the method of superposed epochs that after solar flares, the electric current and the field strength increase on the average by about 1.5 times (Fig. 4).

Similar reaction of the tropospheric electric field over the polar regions is observed not only during the periods of solar cosmic rays invasion, but also during the geomagnetic disturbances[18–21] accompanied by the enhancement of magnetospheric convection and the particles' outburst (of protons and electrons) from the magnetosphere into the high-latitude regions.

Let us point out that measurements of ground electric field, and the ionosphere–Earth electric current correspond to the so-called "fair-weather" conditions.

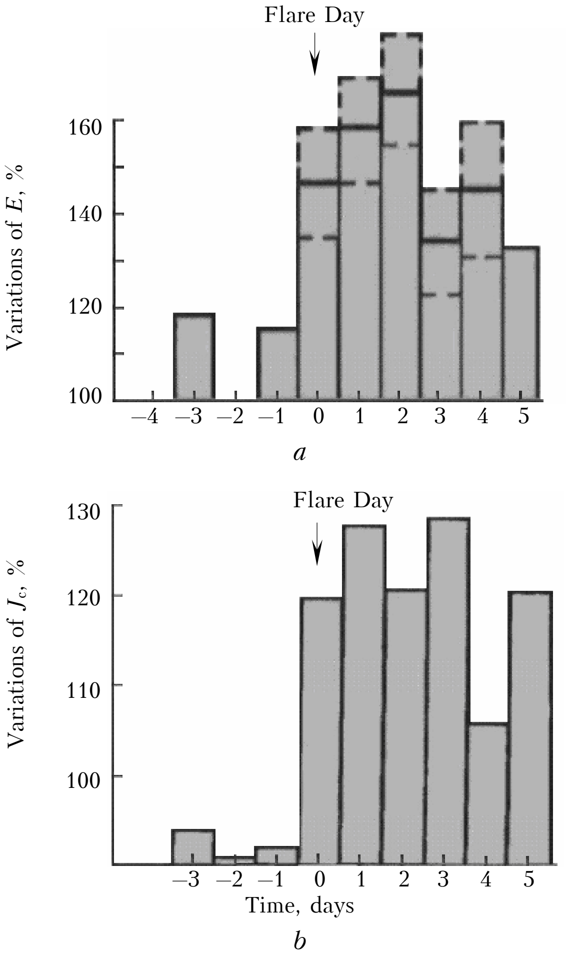

Fig. 4. Parametric variation of the atmospheric electricity, obtained at the Zugspitze observatory in the periods of solar flares, which were processed by the method of superposed epochs as related to the moments of solar flares in H_α line[17]: the electric field strength E (a); the density of the ionosphere–Earth electric current J_c (b). The dashed lines denote the level of statistical significance.

Thus, there are three causes of the essential changes in the electric field of the atmosphere in the polar latitudes during the helio-geophysical disturbances:

- solar cosmic rays;
- enhancement (disturbances) of magnetospheric convection during the geomagnetic storms;
- outbursts of protons and electrons from the magnetosphere during the geomagnetic disturbances.

Manifestations of the solar flares in thermobaric characteristics of the troposphere

High-power solar flares are, as a rule, accompanied by the SCR generation and the coronal plasma outbursts, responsible for geomagnetic disturbances.

After helio-geophysical disturbances and the corresponding changes in the electric field of the high-latitude atmosphere, first, we have to expect relevant changes in the vertical profile of temperature due to the release of the latent heat at water vapor phase transition followed by cloud formation in those high-latitude regions, where the corresponding conditions are met. The clouds formed change the radiation balance, reduce radiation cooling, and smoothen the variations of the tropospheric thermobaric field. Thus, the air temperature below the newly formed clouds rises and it drops down in the atmosphere above the clouds.

It is possible to estimate temperature variations in those atmospheric regions where water vapor condensation takes place. For this purpose we shall assume, that all the heat released at the water vapor condensation, warms up the air in the condensation field. In this case, the temperature rise will be described by the expression:

$$\Delta T = 2.7 \cdot 10^3 (E_v / P)[(\alpha - 100\%)/100\%],$$

where ΔT is the temperature change; E_v is the vapor saturation pressure; P is the air pressure in the condensation field; α is the degree of water vapor supersaturation expressed as a percentage. For estimations, the standard atmospheric characteristics were used, and the latent heat of the evaporation was taken to be equal 500 cal/g, the specific air heat is 0.15 cal/(g · deg).

Estimations for the 500 hPa level show that the temperature rise at heights of cloud formation is about 2 to 5°C, depending on meteorological conditions, such as the vertical profile of moisture content and temperature, distribution of condensation nuclei over height at the moment the disturbance took place. At the same time in the regions above the cloudiness, the temperature should drop down. Most clearly, this will be manifested at night in the high-latitude regions during winter when radiation flux coming from the Sun is absent.

Thus, it is necessary to expect natural temperature variations in the regions of cloud formation as a response to the external impacts. Besides, change of radiation balance caused by the clouds formed will lead to a more significant variation of temperature, and consequently, of pressure and circulation.

In Fig. 5 the measurement data on vertical temperature profile are presented obtained for Murmansk observatory, for dates from February 15 until February 18, 1984 (Ref. 22) including the period of solar cosmic rays invasion on February 16, 1984. It is obvious, that the observed variations of temperature profile completely correspond to the expected ones, according to the model.

A convincing confirmation of the solar flares' influence on meteorological characteristics of the atmosphere was obtained also in Ref. 23. The authors of Ref. 23 established that after solar flares, variations of the pressure and temperature above the oceans and in the coastal zones were observed in the latitude zone from 40 to 60°N.

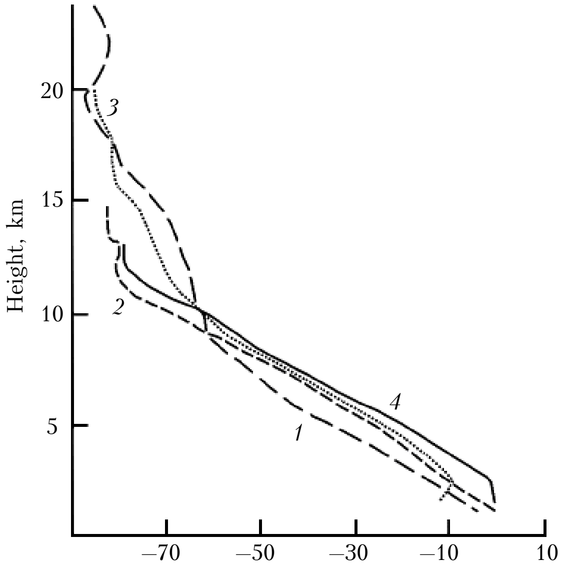

Fig. 5. Variations of the temperature vertical profile after the SCR intrusion into the high-latitude region in the period of February 15–18, 1984: before the solar cosmic rays invasion (*1*); after the SCR invasion (*2–4*).

In Fig. 6 average differences are shown between temperatures on the constant-pressure surfaces before and after the solar flare events above the Northern Atlantic. The maximum temperature rise is observed at 500 hPa level, and the maximum temperature drop at the 200 hPa level.

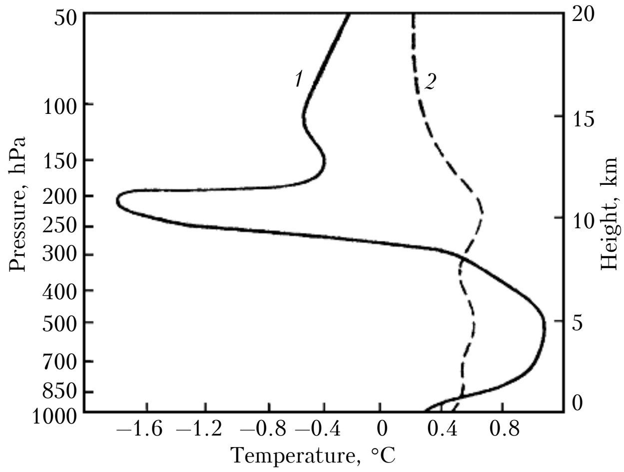

Fig. 6. Variation of the vertical profile of temperature after solar flares[23]: the average differences between temperatures on the constant pressure surfaces before and after solar flares above the Northern Atlantic (*1*); the standard error of the average (*2*).

Reaction of the tropospheric thermobaric field to various helio-geophysical disturbances was considered in numerous papers. In analyzing the long-term correlations, Wolf numbers are usually used as an indicator of the solar activity (direct observational data since 1700 or the reconstructed data). In the short-term analysis, the solar flares and magnetic storms are used. Generalization of the results on the correlation between solar activity and meteorological phenomena can be found in some reviews (see, for example, Refs. 1 to 3).

According to the electro-optical mechanism of the solar-terrestrial relationship, the reaction of atmospheric pressure in the high-latitude regions to invasion of strong SCR fluxes (see Refs. 9 to 12) has been considered.

Analysis of thermobaric field variations of the atmosphere during the invasion periods of the anomalously strong SCR fluxes in August 1972 and in July 2000[9–11] has shown, that the most expressed response is observed at the height of the 500 hPa level in the some high-latitude regions of the Southern hemisphere (local winter) in the latitude zone of 50–70°S. The maximum effect is observed in 3–5 days after the event. In the Northern hemisphere, analogous manifestations, however, less pronounced are also observed. According to Ref. 12 variations in the height of the constant pressure surface of 500 hPa over vast high-latitude zones occur synchronously, what means, that these are governed by helio-geophysical factors, and not by natural synoptic processes.

As an example, the results obtained by the method of superposed epochs from the pressure data for the Earth's surface (Reanalysis data) in the periods of the SCR invasion in some most sensitive areas of the Northern and Southern hemispheres are shown in Fig. 7. It is obvious, that identical regularities in the pressure behavior are observed over certain areas, in different hemispheres. The maximum lowering is observed on the 5th or 6th day after the SCR invasion.

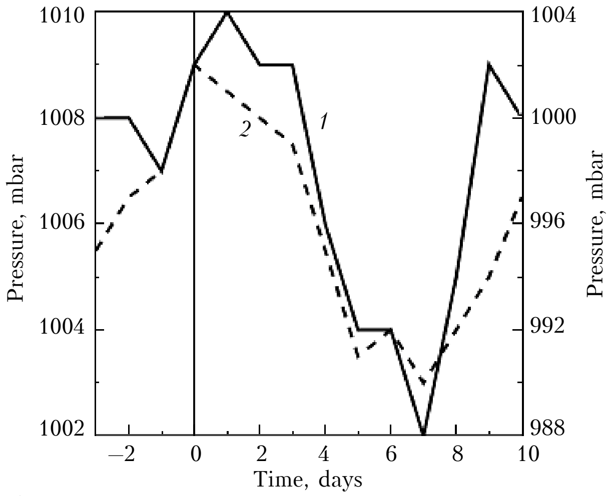

Fig. 7. Atmospheric pressure variation at the Earth's surface after the SCR invasion in some regions of the Northern (*1*) and Southern (*2*) hemispheres obtained by the method of superposed epochs. Zero is the day corresponding to the moment of the SCR invasion. Scale on the left is the pressure in the Northern hemisphere.

In many papers, the reaction of atmospheric pressure to geomagnetic disturbances (see, for example, Ref. 24) has been revealed by the method of superposed epochs. In Ref. 25, a relation of the ionospheric disturbances, discovered by observing the auroral emissions (in X-rays), and pressure variations at the sea level above the Arctic regions (Fig. 8) was found.

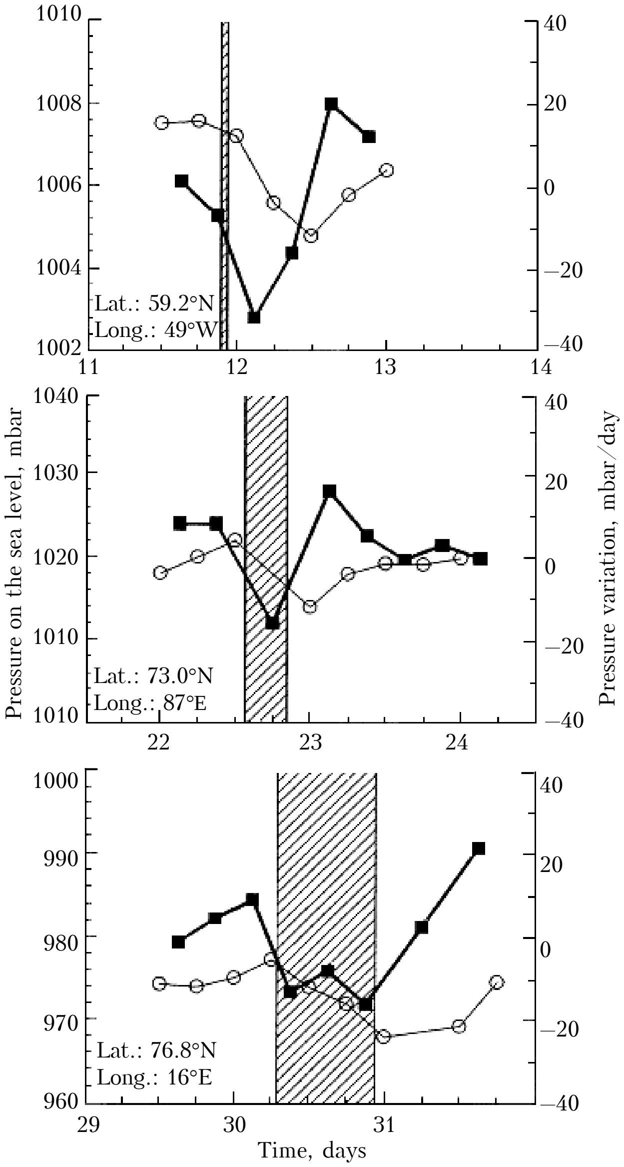

Fig. 8. Relation of the atmospheric pressure behavior to the ionospheric disturbances in January 2000.[25] The pressure variations at the sea level (○); the variations of its derivative with respect to time (■). Periods of ionospheric disturbances observed in the X-rays are shown by shadow area.

Atmospheric pressure variation directly under the area of particles shower, causing the ionospheric disturbances was investigated. Particular attention has been paid to the pressure behavior before the disturbance. In Ref. 25 it was shown, that the reaction of atmospheric pressure depends on the initial conditions. However, in all cases, except for two very powerful atmospheric formations, the lowering of atmospheric pressure at the sea level after the ionospheric disturbances was recorded what completely agrees with the mechanism proposed.

Thus, analysis of the given observations referring to different blocks of the electro-optical mechanism for the real atmosphere completely confirms its validity and allows one to generalize it as a model of helio-climatic relationship.

Model of the solar activity influence on the Earth's troposphere

In Fig. 9 a model block diagram of the solar activity action on the Earth's climatic system is presented based on the above-stated influence mechanism of helio-geophysical factors on the electric field, radiation balance, and thermobaric field of the Earth's troposphere in polar regions.

As shown above, it is possible to point out three causes of the variation of the ionosphere–Earth electric potential.

Variation of the electric potential in high-latitude regions results in the corresponding changes in the strength of the electric field in the troposphere thus causing the changes in the height distribution of charged aerosol particles. In the regions where the electric potential increases, the negatively charged aerosol particles move aloft thus increasing the particle concentration at the heights of cloud formation.

As a result, any of the above factors, may affect the cloud formation in the corresponding regions of the polar troposphere. In the process of cloud formation, during the phase transition of water vapor, release of the latent heat should occur that must cause a slight increase of temperature of the ambient air.

The electro-optical mechanism works most efficiently in the high-latitude regions (in the auroral oval zone during the period of magnetospheric disturbances and in the polar "cap" field during the SCR invasion), leading to the supplemental cloud formation (in the areas with sufficient water vapor concentration) above the oceans in the coastal zones.

Cloud formation in the high-latitude regions leads to corresponding change in the radiation balance there. In the presence of radiation coming from the Sun (local summer, light time of the day) the influence of clouds on the radiation balance is too complicated and essentially depends on the cloud type.

During dark time of the day or on polar night any cloud would lead to the temperature rise below the clouds and to its drop above the clouds, owing to the decreasing of radiation cooling, which is the most essential component of the radiation balance in this period.

Thus, at the increase of solar activity, a decrease of energy losses by the Earth's climatic system occurs, mostly in the high-latitude regions, as a result of the above-mentioned mechanism.

For this reason, an altitude temperature profile changes that leads to the change of the general circulation and to a decrease of the heat outflow from the middle-latitude and equatorial regions. Because of the rearrangement of both local and general atmospheric circulation, the thermobaric field of the troposphere, in its turn, will change on a global scale.

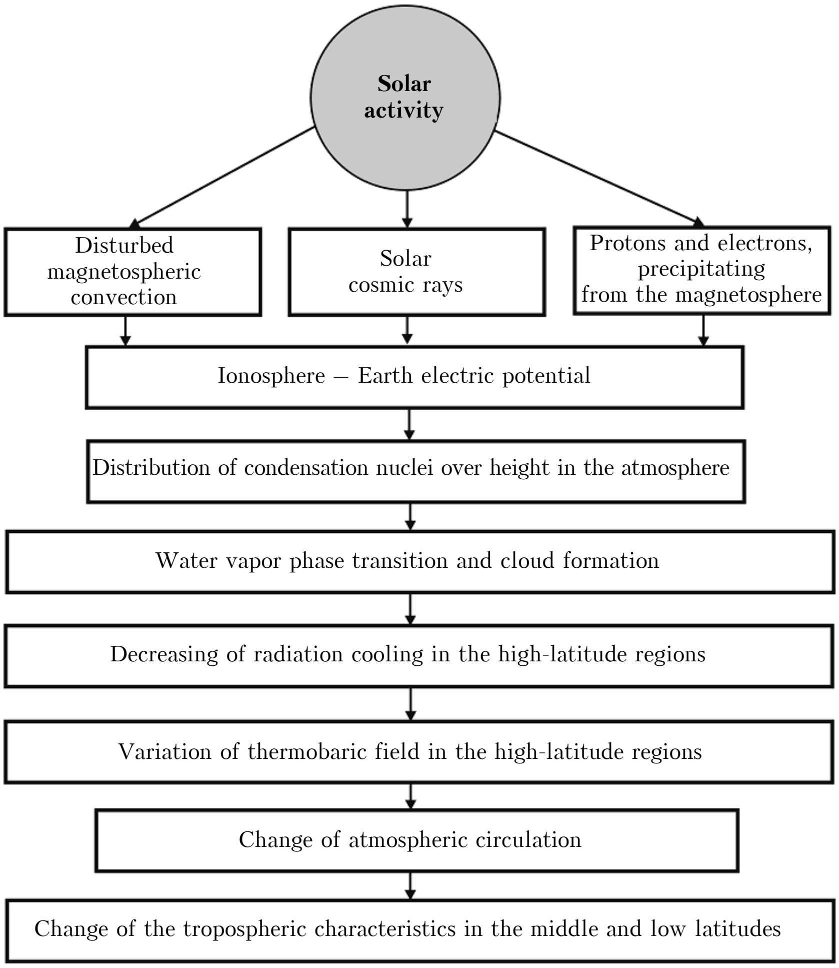

Fig. 9. Schematic model representation.

Since there is significant ice cover in the polar regions, it is possible to qualitatively expect (quantitatively – the computations in the framework of global climatic model are necessary) that a significant part of the "stored" heat will be consumed by the phase transition (ice thawing), at only slight increase of the near ground air temperature. While the decrease of the heat outflow from the middle latitudes can lead to the appreciable increase in the near ground air temperature at midlatitudes, especially on the continents.

Thus, a reduction of energy losses by the Earth's climate system and the increase of the heat content of the climate system can occur in the prolonged periods of high solar activity according to the mechanism proposed.

According to the model proposed at the increase of solar activity, air temperature will rise, especially in the high-latitude regions. Besides, this model forecasts a more intense temperature rise at night, than in daytime. Therefore, at the increase of solar activity both daily and annual temperature variation will decrease, and this decrease will be most pronounced in the high-latitude regions.

In the prolonged periods of low solar activity (more than 10 years), the opposite process will occur – the increase of radiation cooling in polar regions and the corresponding decrease of the heat content of the Earth's climate system. It is necessary to note, that computations of manifestations of the solar activity in the global temperature variations are to be done within the framework of the global climatic model. The ocean and ice mass of Arctic and Antarctic Regions exert a significant stabilizing (inertia) effect on this processes.

Contribution of the electro-optical mechanism to energy variations of the Earth's climate system

Let us estimate the efficiency of this mechanism (within the frameworks of the model proposed) in relation to energy variation of the Earth's climate system. Let us also assume that the mechanism has started to work with the beginning of the growth of a helio-geophysical disturbance in the beginning of the past century. In so doing, we shall consider possible variations of the energy balance in the Earth's climate system caused by local winter of polar latitudes.

The change in radiation cooling (change of the total radiation losses) in the high-latitude regions in local winter at an increase of geomagnetic disturbance can be presented in the following way:

$$\Delta Q = (e_0\uparrow - e_1\uparrow)SK_1K_2. \quad (1)$$

where ΔQ is the total change of radiation losses; $e_0\uparrow$ is the outgoing thermal radiation of the Earth and the atmosphere (density of the energy flux) which the system loses in he absence of clouds; $e_1\uparrow$ is the same quantity in the presence of clouds; S is the effective area above which the mechanism is active.

Let us introduce some correction factors to limit time and area of the helio-geophysical factors action, which take into account:

– area (longitude and latitude);

– "favorable" atmospheric conditions;

– duration of the disturbance:

thus K_1 is the coefficient allowing for the probability that some external factors are present (periods of enhanced geomagnetic activity and invasion of the SCR ($K_1 = 0.3$ and its value varies within the interval from 0.05 to 0.6); K_2 is the coefficient accounting for the probability of occurrence of conditions favorable for the mechanism action in the atmosphere ($K_2 = 0.3$ and its value varies within the interval from 0.2 to 0.6).

$$S = 4\pi R_E^2(1 - \sin\varphi)K_3, \quad (2)$$

where R_E is the Earth's radius; φ is the latitude; K_3 is the coefficient describing the longitudinal fraction of the area sensitive to the external actions ($K_3 = 0.3$ and its value varies within the interval from 0.2 to 0.4).

According to data of actinometric sounding of the atmosphere with radiosondes in Antarctic,[26] the effective radiation at tropopause level under cloudy conditions makes up 60 to 70% of that under clear sky, and $e_0 - e_1$ is 45 to 65 W/m^2. Assuming the proposed mechanism to be valid, the estimated difference between of the integrated radiation energy losses of the Earth's climate system in the periods of low and high geomagnetic activity only in the polar regions is equal to (1 to 2) $\cdot 10^{14}$ W. This corresponds to the warming rate of 0.2 to 0.4 W/m^2 for the entire Earth's surface. This is only an estimate of the possible energy-saving resource caused by the solar variability. The question is whether such variations can noticeably affect the Earth's climate or not?

Let us compare the obtained estimations with the observed change in the enthalpy of the Earth's climate system for the period of global warming in the second half of the XX century.

In Ref. 27 one can find data on the change of the Earth's climate system enthalpy observed between 1955 and 1996. These data allow for the increase of the World ocean enthalpy by $18.2 \cdot 10^{22}$ J, the increase due to ice and snow phase transition (in Antarctic Region, on land, and in the Arctic Region) of $1.25 \cdot 10^{22}$ J, and the increase of the atmospheric enthalpy by $0.66 \cdot 10^{22}$ J. Thus the total increase of the enthalpy for 40 years Q_Σ makes up $2 \cdot 10^{23}$ J. Assuming, that these changes occurred uniformly over the considered time interval, the rate of enthalpy variation, or source power, which provided such a variation is:

$$W = Q_\Sigma/t = 2 \cdot 10^{23}/1.26 \cdot 10^9 = 1.6 \cdot 10^{14} \text{ W},$$

that corresponds to the warming rate of 0.3 W/m^2 for the total Earth's surface.

Thus, it turns out that the observed change in the enthalpy of the Earth's climate system in the XX century corresponds to the above-mentioned estimates of possible contribution of the solar variability through the mechanism considered above.

Let us point out, that only quasi-periodic variations of solar constant were observed in the considered time interval and no significant trend occurred. This enables one to draw a conclusion that the observed change of the enthalpy of the Earth's climate system has been caused by reduction of the energy flux outgoing from the Earth to space.

Thus, in the framework of the electro-optical mechanism considered the estimate of the solar variability contribution to changes in the energy of the Earth's climate system shows that variations caused by solar variability are comparable with the observed variations of the climate system in the XX century.

Conclusions

A physical mechanism has been proposed and validated of solar activity influence on the weather and climate. This mechanism is reduced to the regulation (modulation) of the energy flux outgoing from the Earth to space in the high-latitude regions. It works like a valve regulating the radiation balance in the atmosphere over high-latitude regions. The radiation balance of polar regions depends on the level of helio-geophysical activity, which exerts a significant influence on the vertical electric current and on the ionosphere–Earth electric potential.

Three causes have been revealed of significant variations of the electric field in the atmosphere of the Earth's polar regions during the helio-geophysical disturbances: 1) SCR; 2) particles precipitating from radiation belts; 3) disturbances of the magnetospheric convection.

A quantitative estimate of the solar activity contribution to the change in the enthalpy of the Earth's climate system has been made in the framework of the mechanism proposed. It is shown, that one can explain naturally the climatic anomalies in the past century by this mechanism, as well as a significant part of the global warming in the XX century.

Acknowledgments

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