Radiation budget of the atmosphere and climatic manifestations of solar variations

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The results of a combined analysis of long-term variations of radiation budget elements, global cloudiness, intensity of galactic cosmic rays, near-surface air temperature, and characteristics of solar activity are presented. Satellite and ground-based data on variations of cloudiness and solar irradiance are summarized. Most data indicate that total cloudiness increases, on average, for the last century or, at least, last decades. The energy budget of the Earth's climatic system is calculated, and changes in the heat content of the World Ocean and the atmosphere for the last 50 years are estimated. According to the estimates, only a minor part (~ 0.1%) of the incident energy is spent for changing the heat content of the atmosphere and the ocean. Possible effects of changes in the solar constant on the energy budget of the atmosphere are discussed. The analysis of experimental data shows that, on the one hand, the radiative flux coming to the Earth decreases and, on the other hand, the heat content of the World Ocean, land, and atmosphere obviously increases. This suggests that the most significant factors for the Earth's energy budget are variations of the outgoing longwave radiation, rather than variations of the net energy flux coming to the Earth. Possible mechanisms of the sun–climate relations, which can play an important role on both short and long time intervals, are discussed. The roles of cosmic rays and the electric field of the atmosphere, which, on the one hand, are subject to solar variations and, on the other hand, can influence considerably the radiation budget of the atmosphere by affecting the atmospheric distribution of cloud condensation nuclei, phase state of water in the atmosphere and cloud cover, are considered.

Introduction

Of the highest priority are now the investigations of global variability of the atmosphere, climate, and environment. A particular attention is given to the study of the global climate warming (GCW), its manifestations in different regions of the planet, and predictions of climate changes for the nearest decades. This is a basic issue, which is of not only theoretical and practical, but also of political and economic importance. The estimate of the anthropogenic contribution (intensification of the greenhouse effect caused by the human activity) to the global warming in the past decades in contrast to the natural contribution (for example, the solar activity, natural variability of the global climatic system, volcanic activity, etc.) is of primary significance for the understanding of the character of the Earth's climate change in the past and in the future. Unfortunately, model calculations of the CO_2 quantitative contribution to the observed and predicted global warming based on up-to-date climatic models predict the global temperature increase in a very wide range: from 1 to 5° (Ref. 1). This makes impossible to draw an unambiguous conclusion that the warming in the 20th century is caused exclusively by the anthropogenic factors and, particularly, that only CO_2 is responsible for the observed global warming.

At the same time, the most ponderable and justified argument casting doubts on such a conclusion is the absence of the answer to the question what were the causes for warm and cold periods in the past millennium. The observed correlations of long-term changes in the global temperature and CO_2 do not mean that just CO_2 causes the global warming, because the increase in the ocean temperature (which is really observed) also leads to the increase of CO_2 in the atmosphere, that is, the increase of CO_2 may be a consequence, rather than a cause of the global warming.[2]

1. Radiative budget in the Earth's atmosphere

One of the key parameters, determining the global climate, is the radiation balance at the top of the atmosphere for the whole earth surface, which characterizes the energy exchange between the earth's climatic system and the space. A perturbation of this balance leads to climate changes.

The shortwave radiation flux incident on the atmospheric top is well known: it is the solar constant (SC). According to the data of satellite measurements from 1978 to 2002 (Ref. 3), which are shown in Fig. 1, the SC changed by no more than 0.15%.

Are more significant changes in the solar radiation influx possible? According to some estimates,[3] the changes in the solar irradiance during the Maunder Minimum could be as high as 0.3%. The energy flux of the solar wind and the interplanetary magnetic field (IMF), solar and galactic cosmic rays, whose variations are more significant in the solar activity cycle, makes

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up 10^{-6} of the solar constant variations. Note that almost all their energy, as well as the variable part of the solar constant, is absorbed by the upper atmosphere: magnetosphere, ionosphere, and stratosphere.

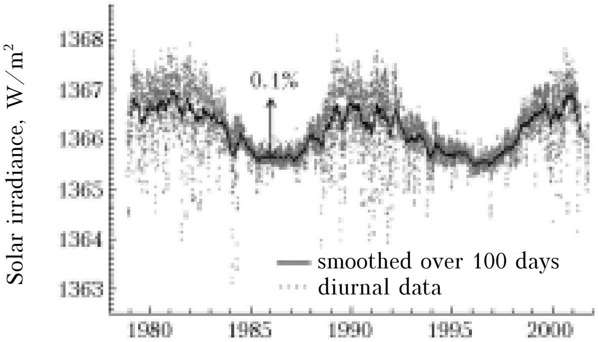

Fig. 1. Solar constant variations according to satellite radiometric measurements from 1978 to 2002 (Ref. 3).

As to the outgoing flux of shortwave (cloud and surface albedo) and longwave radiation, emitted by the Earth's surface and the atmosphere, to estimate it from satellite measurements is a complicated problem, because the instrumentation capabilities do not allow the energy balance to be determined with the needed accuracy.[4] The quantitative estimate of the disbalance, averaged for long periods, can be obtained to a rather high accuracy from the measurements of the heat content of the Earth's climatic system, whose variations for the period from 1955 to 1996 can be found in Refs. 5 and 6. These data show an increase in the heat content Q of the World Ocean by $18.2 \cdot 10^{22}$ J, the increase of Q caused by the phase change of ice and snow (Antarctic, land, Arctic) by $1.25 \cdot 10^{22}$ J, and the increase of atmospheric Q by $0.66 \cdot 10^{22}$ J. The total increase Q_Σ for 40 years is $2 \cdot 10^{23}$ J. Assuming that these changes proceeded uniformly in the period under consideration, the rate of change in Q or the power of the source, which provided for the change Q, is

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

This is an approximate estimate. The real power is somewhat higher, because the change in the heat content of the land is not taken into account. It is interesting to compare this estimate with the energy incoming from the Sun. It is well-known that the solar constant is 1366 W/m^2.

The solar irradiance power at the atmospheric top is $1.7 \cdot 10^{17}$ W. Consequently, about 0.1% of the incident solar energy is consumed for the change in the heat content of the Earth's climatic system for the past 40 years. If the variations of the solar constant are assimilated by the climatic system with the same efficiency, then the observed changes in the thermal conditions of the atmosphere and, correspondingly, the global warming cannot be explained by the observed variations in the solar influx. Taking into account the above estimates of the radiation balance efficiency, on the assumption that the radiative (transfer) characteristics of the Earth's climatic system for this epoch vary insignificantly at small influx variations (less than 1%), even such changes in the solar constant cannot influence considerably the heat content of the Earth's climatic system and the Earth's climate. Thus, the variable part of the external influence cannot directly provide for the change in the energy of the Earth's climatic system.

Thus, it can be concluded that the Earth's climatic system is quite stable and only slightly reacts to changes in the energy influx, but it is more sensitive to variations of the parameters, controlling the outflux. Consequently, it can be believed that the observed changes in the heat content of the Earth's climatic system both in the 20th century and in the past millennium are caused by the changes in the energy, emitted by the Earth's climatic system into the space.

Thus, no less important, and even of primary importance is the change in the energy flux, emitted by the Earth and the atmosphere into the space, and the key role in regulation of this flux belongs to the cloudiness and minor gaseous constituents, such as CO_2, H_2O, O_3, methane, and others.

2. Manifestations of heliogeophysical characteristics in tropospheric weather and climate parameters

The study of the solar activity influence on the weather and climate has a long history (see Refs. 7–13). Most authors point out a similarity in the behavior of the climate and the solar activity, especially, on long time scales. The historical data indicate that not less and, possibly, more significant changes can be caused by solar cycle variations.

There are strong evidences that the cooling and warming cycles, at least in the Middle and Ancient Ages, were connected with variations of the solar cycle. The long-term variations of the solar activity in comparison with the climatic characteristics are illustrated in Fig. 2.

It can be seen that for the last 1000 years the global climate underwent changes, rather accurately corresponding to solar activity variations: in the 11–13th centuries, when the solar activity was high, a warm period was observed ("Medieval Climate Optimum"), and two pronounced temperature decreases in the Little Ice Age (16–17th centuries) correspond to the Maunder and Sperer minima. Once the Maunder Minimum ended, a general increase of the solar activity level started, causing the world climate warming for the most part of this period.

Robertson et al.[14] present the data on the temperature and solar activity, which also show that, apart from temperature anomalies connected with powerful volcanic eruptions, the changes in the global temperature of the Northern Hemisphere mostly follow the solar activity variations (Fig. 3).

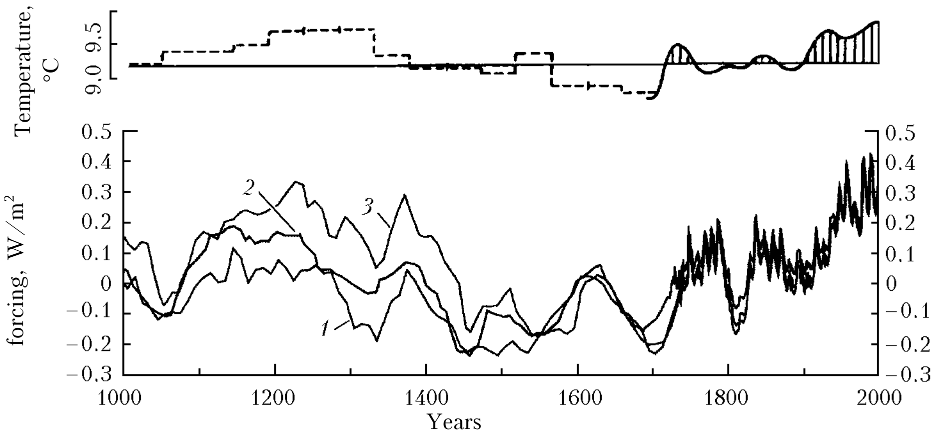

Fig. 2. Long-term variations of the solar activity by direct and indirect data: C14 resid/Lean splice (*1*), Be10/Lean splice[8] (*2*), and C14 Bard/Lean splice (*3*) in comparison with anomalies of the surface air temperature (SAT).

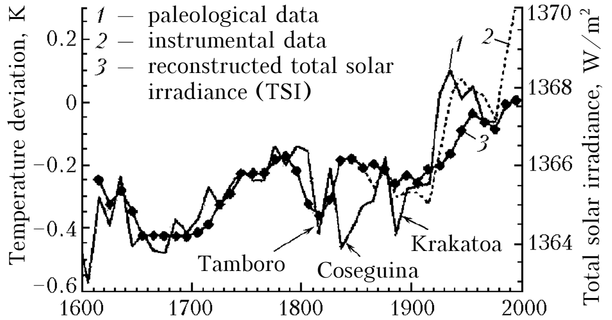

Fig. 3. SAT anomalies in the Northern Hemisphere and solar radiation (reconstructed and observed) for the period 1600–2000 (Ref. 14).

The long-term changes in 11-year moving averages, obtained from the instrumental findings,[11] are shown in Fig. 4.

All the curves obviously have similar long-term trends. Nevertheless, the question about the existence of the above-mentioned relationship is still open. The point is that at short time intervals the relationship often appears ambiguous. In some regions it is positive, while being negative or fully absent in others; sometimes the sign of the relationship alternates.

Numerous correlations between various heliogeophysical characteristics and the weather and climate can be divided into two categories: long-term ones, attributed to the climate, and short-term ones, corresponding to weather or synoptic processes. When considering the long-term relationships, the solar activity is usually characterized by the sunspot number, Wolf number, duration and intensity of the 11-year solar cycle, and AA index of geomagnetic activity. When considering short-term manifestations of the solar activity in weather characteristics, the reference dates are usually the instants of solar flares, intersections of sector boundaries of the interplanetary magnetic field, Forbush decreases in the cosmic ray intensity, and the main phase of geomagnetic storms. In some papers,[7–10] it was supposed that the atmospheric electricity may be a link between solar activity variations and tropospheric parameters.

Below we present indirect evidences of the influence of heliogeophysical processes on variations of different atmospheric characteristics, possibly caused by this mechanism. To reveal the influence, the epoch superposition method is used, as a rule.

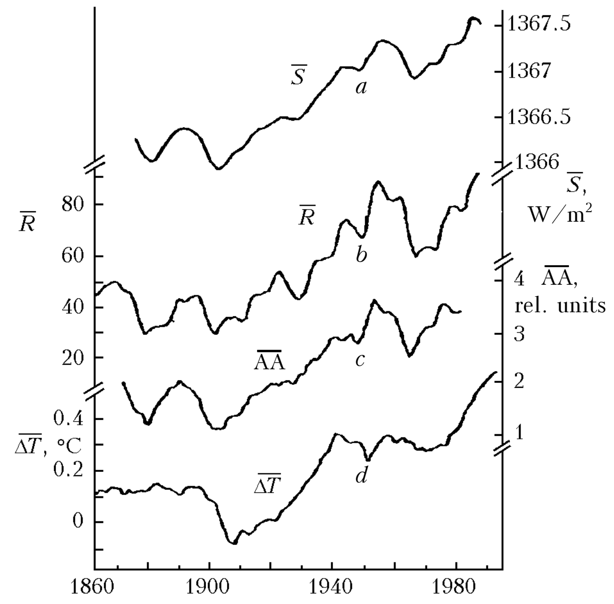

Fig. 4. Long-term changes of the solar radiation (*a*), Wolf number (*b*), geomagnetic AA index (*c*), and SAT anomalies (*d*) [Ref. 11].

The sector structure of the interplanetary magnetic field reflects the global solar magnetic field, transported by the solar wind and forming a deformed current layer in the heliosphere. The period of revolution of the sector structure around the Earth is 27 days. To the north of the current layer, the IMF direction is antisunward, and to the south it is sunward. The IMF polarity alternates every 11 years, approximately, within 2 years after the maximum of the 11-year cycle.

It was established in numerous works that different heliogeophysical characteristics change in a regular way upon intersection of the sector boundary.

Certainly, the current layer itself cannot cause some marked effects, but it is only a reference, indicating regular changes of physical conditions on the Sun, in particular, the configuration of large-scale magnetic fields and their dynamics, which determine parameters of the solar wind and IMF.

Figure 5 shows the distribution of the index of geomagnetic disturbance K_p with respect to some sector boundary, corresponding to zero day. It can be seen that the minimum of geomagnetic disturbance takes place one day ahead of crossing the sector boundary, and then the geomagnetic activity increases and slowly decays for 3–4 days. Figure 6 shows the variation of the cosmic ray intensity in positive and negative sectors of the interplanetary magnetic field found by the epoch superposition method. These regular variations within a sector, significantly depending on the sector sign, are obvious. Their minimum is observed within 2–3 days after intersecting the sector boundary and corresponds to the maximum of the geomagnetic activity.

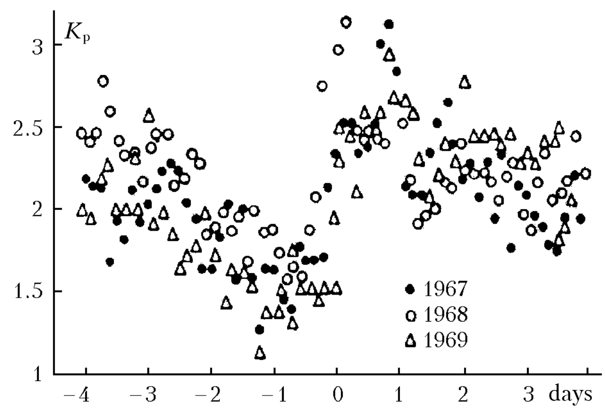

Fig. 5. Variation of the K_p index with respect to sector boundaries of the interplanetary magnetic field (the boundary passes the Earth at the zero day).

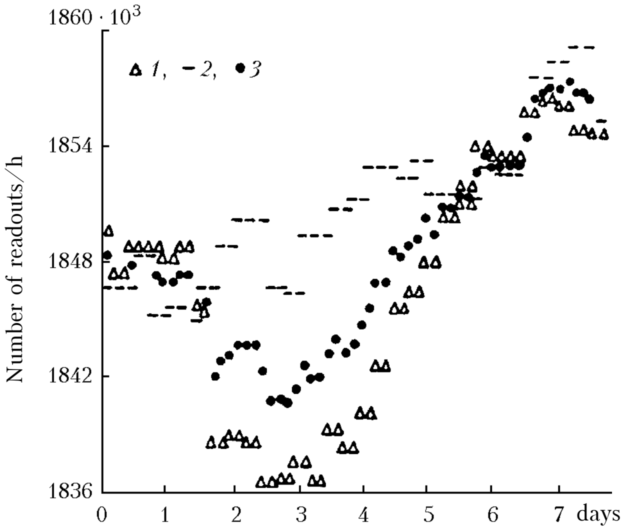

Fig. 6. Variation of the galactic cosmic ray intensity in the positive and negative sectors of the interplanetary magnetic field: antisunward field (*1*); sunward field (*2*); regardless of the field direction (*3*).

The ionosphere–Earth electric potential and, consequently, the conduction current also depend on the sector structure. Figure 7 shows the electric field distribution with respect to intersections of the sector boundaries. It turned out that many characteristics, in particular, the Vorticity Area Index (VAI), characterizing the total area occupied by cyclonic formations in the Northern Hemisphere, change upon the passage through the sector boundaries.

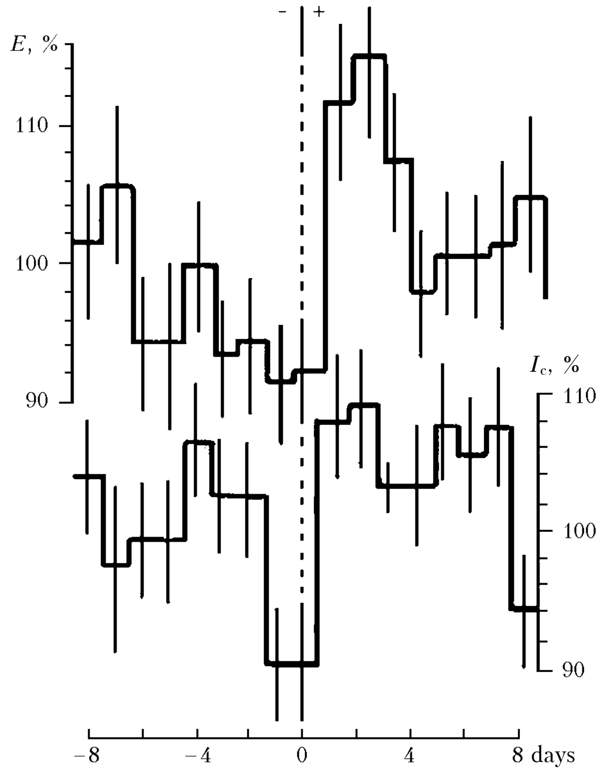

Fig. 7. Variations of electric field strength and the current density relative to sector boundaries. The results of analysis by the epoch superposition method of the electric field strength E at Zugspits at a fine weather and the Earth–atmosphere current density I_c.

The regular VAI changes, when passing the sector boundaries, can be seen in Fig. 8 [Ref. 7].

A significant increase of VAI is observed two days before the intersection of the sector boundary, then VAI decreases and achieves the minimum within one day after the intersection of the boundary. It is important to note that the effect considerably intensifies for the sector boundaries, which are accompanied by proton fluxes with the energy of tens to hundreds MeV (Ref. 7). Since the atmospheric electric field depends on the flux of solar cosmic rays, this effect indirectly confirms the hypothesis that the solar activity influences tropospheric parameters. One of the serious arguments, confirming the real influence of the solar variability on the weather, is a significant worsening of the prediction of VAI (Ref. 7) for one to two days after the Earth intersects the sector boundary of the interplanetary magnetic field.

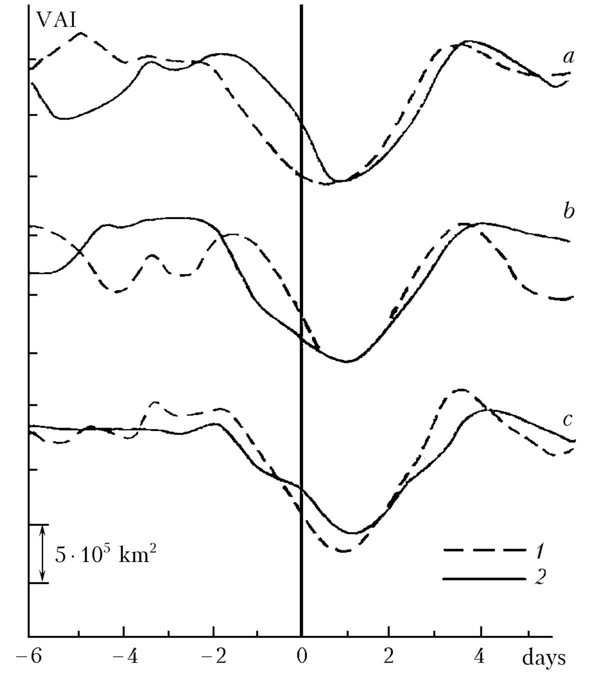

Fig. 8. Variation of the Vorticity Area Index (VAI) before and after intersecting the IMF sector boundaries: (*a*) alternation of sectors: from positive to negative (*1*), from negative to positive (*2*), 24 cases; (*b*) winter season: the second half of the winter (*1*), 22 cases, the first half of the winter, 32 cases (*2*); (*c*) periods: 1967–1970 (*1*), 1964–1966 (*2*).

Figure 9 shows the results of statistical analysis of the reaction of atmospheric pressure characteristics to geomagnetic disturbances.

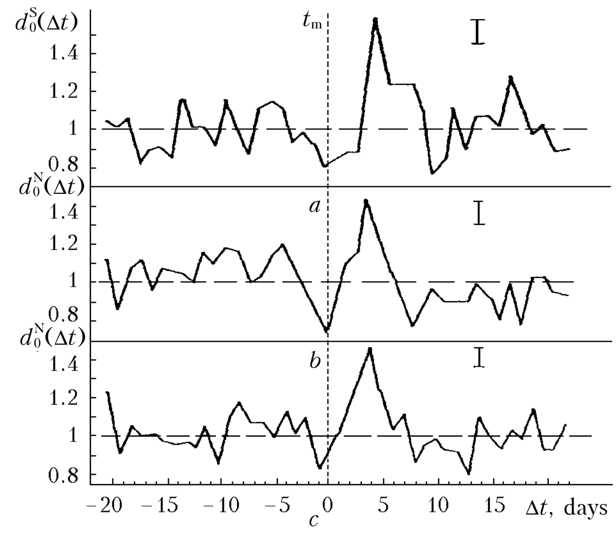

Fig. 9. Normalized variance of diurnal pressure differences during the geomagnetic storm for (*a*) the Southern Hemisphere and (*b*, *c*) the Northern Hemisphere (t_m is the start moment of the geomagnetic storm, I is the standard deviation).[15]

The response to a geomagnetic storm obviously manifests itself almost identically in the both hemispheres. The regions of the strongest increase of tropospheric instability are located over the oceans in the regions of the increased atmospheric instability, near the auroral zone. In these regions, the time of the tropospheric reaction is four to five days, and the amplitude is 50–60% (Ref. 15).

A high correlation between the duration of solar cycles and the temperature in the Northern Hemisphere (Fig. 10) was established in Ref. 16.

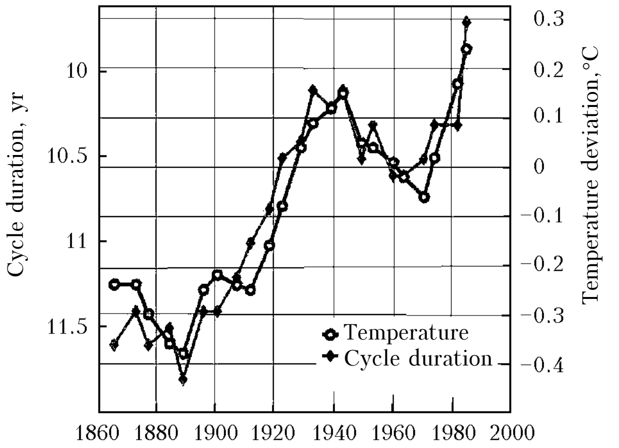

Fig. 10. Variation of temperature in the Northern Hemisphere in comparison with the solar cycle duration.

These results are indicative of real climatic influence of helio-space factors and cast doubts upon the concept that the observed warming is mostly caused by the anthropogenic factor. Thus, they stimulate further investigations of relationships between the solar activity and the Earth's climate. The close correlation between the variations of the global air temperature in the Northern Hemisphere and the solar cycle duration ($r = 0.95$) [Ref. 16] indicates that one of the key climatic characteristics is not connected with the anthropogenic factor. However, this conclusion should be treated with a particular care. The point is that the global surface air temperature (SAT) is known to be closely related to the characteristics of the World Ocean, and, consequently, is too inertial.

Most experts attribute the warming to the greenhouse effect. The model calculations show that in this case the most significant changes should be expected in the continental regions of Eurasia. The Baikal region, lying in the central part of the continent, thus falls within the zone of intense climatic and ecological changes. For SAT at the center of large continents, the smoothing role of the World Ocean is less significant, while the interannual variations are quite considerable. Therefore, to reveal reliable trends, the averaging over long time periods is necessary. At the central part of the continents, the SAT is especially sensitive to the global warming. Thus, the study of peculiarities of long-term SAT variations in the Baikal region is of particular interest.

The relationship between SAT in the Baikal region and different characteristics of the solar activity has been studied in Refs. 17 and 18. It turned out that SAT in the Baikal region is closely related to the mean power of the solar cycle, rather than to its duration. Figure 11 shows the SAT in the Baikal region, averaged over the solar activity cycles and their mean power.

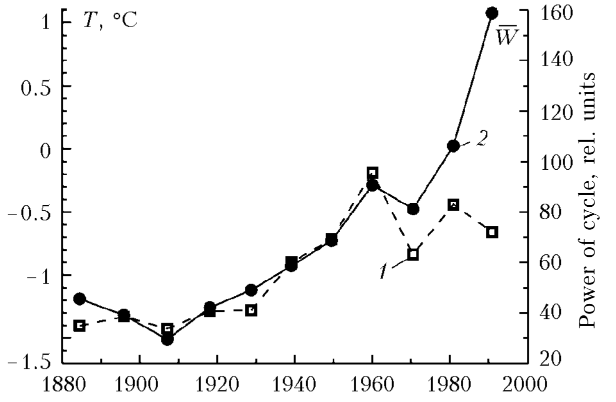

Fig. 11. Comparison of the mean power $\bar{W}$ of the solar cycle (*1*) with variations of the surface air temperature in Irkutsk (*2*), averaged over the solar cycle.

It is obvious that, as in Ref. 16, the main significant variations of the air temperature in the region for the period 1881–1960 are caused by the solar variability. However, from the 1960s and to now, at a constant influence of the solar variability, we observe an evident influence of another factor, whose role increases continuously and already exceeds that of the solar variability in the last decade.

A correct description of feedbacks, which can either intensify or suppress the initial perturbation, is the most sensitive and important in any climatic model. The key role is played by the change of the atmospheric water vapor content and the cloud–radiation relationship. Analysis of observations of global SAT changes, as well as calculations by global climate models (GCMs), show that it is impossible to reconstruct the observed climate changes taking into account only natural factors. The calculations by various current GCMs are indicative of the considerable contribution of anthropogenic factors to SAT trends in the last decades.[19]

However, it should be emphasized that the observed increase of CO_2 may be a consequence from the increase of the ocean temperature, rather than a cause for the increase of the global temperature.[2]

Thus, a significant contribution of the solar variability is obvious in the SAT variations in the Baikal region, as well as in the global SAT variations. However, in contrast to global SAT, the amplitude of SAT variations in the region is much higher. The main SAT changes in the Baikal region in the 20th century occurred mostly in the winter–spring period and practically without a marked lag behind the power of the solar cycle. It is important to note that the temperature in the region under study in the last half of the 20th century increased against the background of the decreasing net solar influx.[20,21] So high and stable correlation of climate variations and parameters of solar activity is connected with the fact that some additional factors, intensifying this correlation, are likely present in the continental regions. In particular, such factor is the Siberian (Asian) High, present in the Baikal region, and its sensitivity to changes in the global atmospheric circulation, which, in its turn, is sensitive to changes in the atmospheric thermal balance, caused by both the solar activity and the anthropogenic factor. All variations of the thermal conditions in the region under study, as well as the long-term trends, are obviously connected, in some or other way, with changes in the general atmospheric circulation.

The main factor, which casts doubts upon the real and significant influence of the solar activity on the weather and climate, is the absence of a reliable physical mechanism, capable of explaining exhaustively the numerous correlations between various heliogeophysical indices and climatic characteristics of the troposphere.

One of the main problems in the consideration of the mechanism, through which the solar activity influences the weather and climate, is the fact that the changes in the energy influx achieving the troposphere due to the solar activity, are negligibly small as compared to the energy stored in the stratosphere and troposphere or even to the energy of one cyclone. It is clear that the energy of solar variability is insufficient to exert a significant direct effect upon the tropospheric processes. In addition, almost all investigators, studying the influence of the solar variability on the climate, face the problem of separation of the external signal against the background of internal powerful perturbations in the atmosphere–ocean system. It is apparent that the influence of the solar activity on the weather is not identical and even unambiguous in different regions of the Earth. The role of the atmospheric circulation seems to be very important, especially, for high latitudes.

3. Cloudiness, cosmic rays, climate

Figure 12 shows a generalized scheme of possible sun–climate relationships, which illustrates possible mechanisms, through which solar processes can influence the weather and climate. The elements, which, in our opinion, are of particular importance at both short and long time intervals, are marked out. They are the solar radiation, cloud cover, greenhouse gases, aerosol field of the atmosphere, cosmic rays, condensation nuclei, and the atmospheric electric field.

The cloudiness and the water vapor content in the atmosphere are known to play the decisive role in the energy balance of the Earth's climatic system. The influence of cloudiness on thermal conditions of the atmosphere is determined by two opposite effects: reflection of shortwave radiation and absorption of longwave radiation. A prevalence of one of them can lead to either cooling or heating of the atmosphere. The balance depends on the cloudiness characteristics. It is commonly accepted that an increase of the low-level cloudiness leads to the cooling of atmosphere, while the increase of the upper-level cloudiness leads to its heating.

Any cloudiness decreases the energy loss by the climatic system, whereas in the presence of the radiation influx the influence of cloudiness on the climatic system proves to be very complicated and ambiguous.

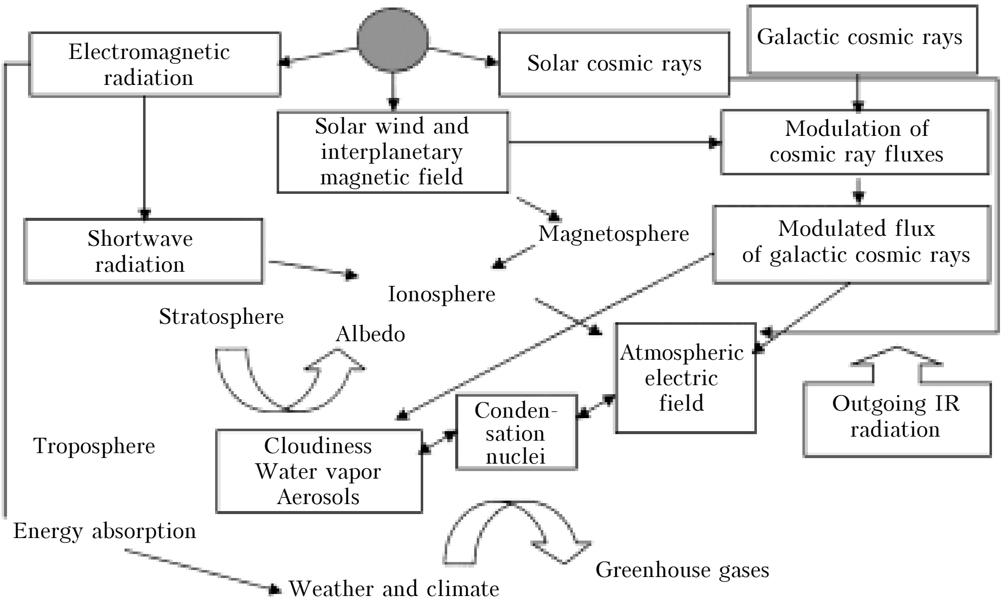

Fig. 12. Scheme of sun–climate relationships.

This requires a description of complex and ambiguous feedbacks in global climate models. The feedbacks either intensify or suppress the initial perturbation in the climatic system. In addition, changes in the general atmospheric circulation exert a considerable influence on the model results. Therefore, despite a significant progress in the mathematical simulation of the Earth's climatic system with the use of modern global climate models, the description of feedbacks and, consequently, sensitivity to minor external actions is still an open problem.[1]

The possibility of modulation of the Earth's albedo by changes in cloudiness, caused by variations of the galactic cosmic rays (GCR), was mentioned in Ref. 22. Cosmic rays can affect the cloud formation through ionization of tropospheric air. Since the flux and the spectrum of cosmic rays are modulated by the interplanetary magnetic field, subject to the strong effect of the solar magnetic field, the cosmic rays can serve as a link between the solar activity and the global climate. This mechanism became particularly attractive after a strong correlation was found between the factor of cloudiness over ocean in mid-latitudes and the cosmic ray flux for the period 1980–1995 (Fig. 13) [Ref. 23].

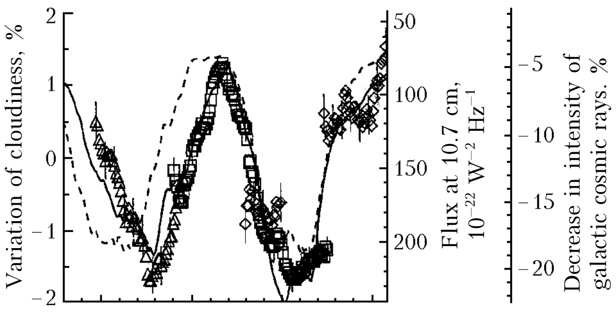

Fig. 13. Comparison of total cloudiness, variations of galactic ray intensity, and the radio flux at 10.7 cm.

Unfortunately, when more complete experimental data were included in the analysis of correlation between the cosmic rays and cloudiness, significant contradictions were revealed.[24,25] The level and even the sign of the correlation depend on the latitudinal zone, character of the surface (land, ocean), and the height of the cloud cover. Up to 1991, the cosmic ray flux correlated quite well with the total cloudiness in mid-latitudes, but after 1991 the character of the correlation has changed. The direct correlation with variations of the cosmic ray flux is now characteristic of the low-level cloudiness, which after 1991 changed in the anti-phase with the variation of the total cloud amount. This is illustrated in Fig. 14, which shows the data on the variations of the total and low-level cloudiness, as well as the flux of galactic cosmic rays. The close correlation between the cosmic ray flux and the total cloudiness obviously kept true in 1983–1991, but then the curves diverge. Thus, with allowance for the data of 1992–1994, the new data series appears to contradict the previous results concerning the total cloudiness. To the contrary, the cosmic rays turn out to correlate closely with the low-level cloudiness.

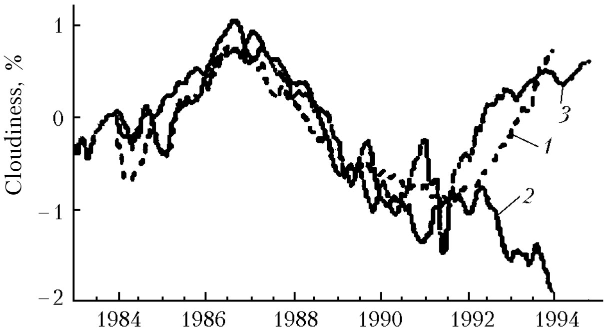

Fig. 14. Variation of low-level cloudiness (*1*) and total cloudiness (*2*) by the satellite data in comparison with the intensity of galactic cosmic rays (*3*).

Of particular interest and significance is the comparison of cloudiness and the galactic ray intensity for long observation series. Using the observations of total cloudiness from Ref. 26, we have compared the total cloudiness variations with variations of the galactic cosmic ray intensity for the period of 1950–2000 (Fig. 15). First of all, to be noted is the evident presence of the 11-year variation in all data series. However, the global cloudiness and the intensity of galactic cosmic rays anticorrelate. This contradicts the main hypothesis about the influence of cosmic rays on the cloudiness. This contradiction disappears, if we assume that the global and low-level cloudiness also anticorrelate, and the decrease of the low-level cloudiness is accompanied by more effective (in area) increase of the upper-level cloudiness and, correspondingly, the global warming. The phase shift between the intensity of galactic cosmic rays and the global cloudiness has no physical meaning and rather confirms the absence of physical relationship between them.

In addition, it should be noted that for the winter period the influence of galactic cosmic rays in the polar regions is opposite to that in the low latitudes, that is, the increase in the GCR intensity leads to the warming in these regions.

Thus, there are some reasons to believe that galactic cosmic rays influence the cloud formation. However, despite the attractiveness of the mechanism of GCR influence on cloudiness and, correspondingly, on the weather and climate, this hypothesis still was not supported by somewhat convincing quantitative estimates.[12,24,25] Unfortunately, the satellite data series cover only the last decades, therefore, the data on the sunshine duration can be used as an additional information. However, these data give no information about the type of cloudiness. The sunshine duration is known to be an indirect characteristic of total cloudiness. The comparison of the obtained series with the satellite data for July 1983 – August 1994 has shown that the variations of cloudiness over Ireland are, in general, similar to those over the North Atlantic and the mid-latitudinal oceanic regions. It can be assumed that the trend had the same character over the whole Northern Hemisphere. However, the cosmic ray flux decreased in this period. According to the found correlations, this should lead to a decrease of, at least, low-level cloudiness. The contradiction is removed, provided the upper-level cloud amount increased simultaneously.

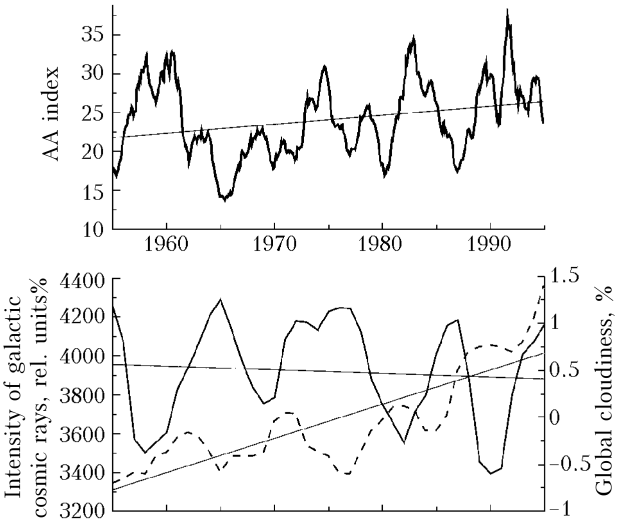

Fig. 15. Comparison of global cloudiness[26] with variations of the intensity of galactic cosmic rays and the AA index of geomagnetic activity.

The satellite and ground-based data on the variations of cloudiness and the solar radiation influx for the last 40 years (Ref. 26), generalized in the Table, indicate the increase of the cloud amount and the decrease of radiation. The latter can be connected with the change of not only the cloud amount and their height distribution, but also the amount of atmospheric aerosol.

Many papers postulate that the variations of the solar radiation, incoming directly to the Earth, are the most important climate-forming factor. However, this postulate is not fully correct and fails to find a confirmation in the analysis of observation data.

Observations	Total cloudiness	Low-level cloudiness	Upper-level cloudiness	Period
	Ground-based data			
Sunshine in Ireland (decrease)	Increase of cloudiness	–	–	1881–1998
Sunshine in Israel (decrease)	Increase	–	–	1979–1995
Synoptic cloudiness over CIS	Increase	Decrease	Increase	1936–1990
Synoptic cloudiness over oceans	Increase	Increase	–	1952–1995
Synoptic data (Australia, North America, India, Europe, etc.)	Increase	–	Increase	1900–1990
Ground-based observations of solar radiation	Increase	–	–	1960–2000
	Satellite data			
ISCCP C2	Stable	–	Increase	1983–1991
ISCCP D2	Stable	Decrease	Stable	1983–1994
DMSP (water clouds over oceans)	Increase	–	–	1988–1998
HIRS (only cirrus clouds)	–	–	Increase	1989–1996

The point is that the increase of any cloudiness results in a decrease of the energy, coming to the Earth. Nevertheless, this does not mean that the cooling should be observed. The situation depends on whether upper-level or low-level cloudiness changes. This is confirmed by the analysis of long-term variations of elements in the radiation budget of the atmosphere according to the data obtained at the network of stations.[26] For the last 50 years, the statistically significant decrease of the direct and net solar irradiance is observed.[20,21,27–29] At the same time, despite the decrease in the solar radiation coming to the Earth, the global warming is observed.

Certainly, the cosmic rays are not the only link in this relationship. It is impossible to explain the tropospheric reaction to geomagnetic disturbances using the cosmic rays, as was shown in numerous papers by Mustel with co-authors.[15] Below we present indirect evidences of the effect of heliogeophysical processes on variations of different atmospheric characteristics. As a rule, the effect is revealed using the epoch superposition method.

It is quite obvious that since the change in the energy flux reaching the lower troposphere due to solar activity variations is negligibly small as compared to the energy stored in the stratosphere and troposphere, and if the influence of the solar activity on the climatic characteristics of the troposphere is significant, then the physical mechanism of the relationship can be realized through variation of parameters, controlling the balance of energy fluxes incoming to the Earth's atmosphere and outgoing into the space.

4. Variations of solar irradiance

The elements of the radiation budget of the atmosphere, measured at the stations of the Baikal region of Eastern Siberia and at the network of other stations in the last 50 years, have been analyzed in Refs. 20 and 21. It was found that, at the overwhelming part of the territory, the statistically significant decrease of the direct and net solar radiation, amounting to 6.3% on average and 2.5% for 10 years, was observed. The rates of the direct solar radiation decrease are illustrated in Fig. 16, which shows the variations of the annual mean values of the diurnal sums of direct solar radiation at the Irkutsk station.

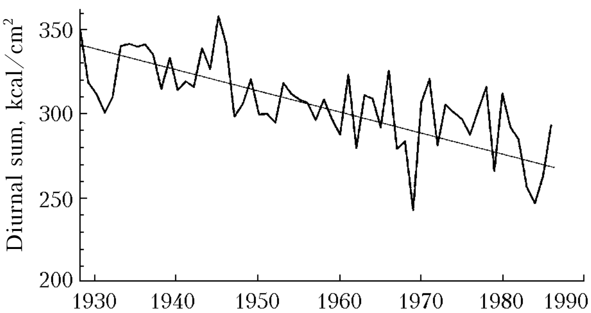

Fig. 16. Variations of the annual mean diurnal sums of the direct solar radiation at the Irkutsk station.

The long-term variations of the diffuse radiation have a quite different character. Figure 17 depicts the map of variation of the diffuse radiation at the Irkutsk station, having a long series of observations (more than 50 years).

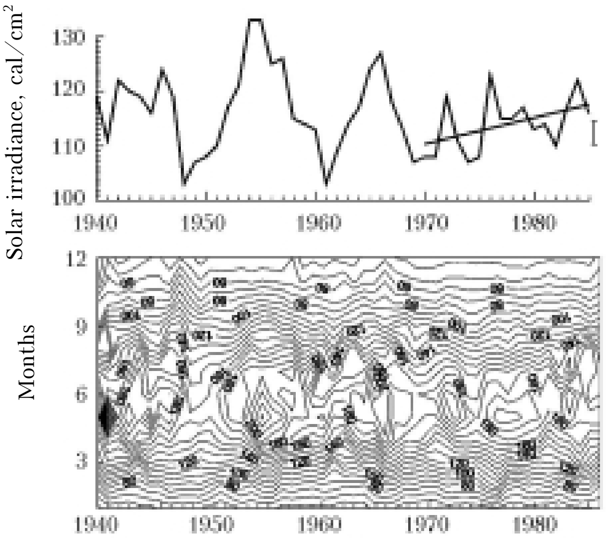

Fig. 17. Variations of the annual behavior of the diffuse radiation in Irkutsk for the period 1939–1986.

Apart from the natural seasonal variation, the 11-year cycle is clearly seen in the radiation distribution before the 1960s. The peaks of the diffuse radiation are most pronounced in the spring–summer period and correspond to the solar activity minima. Starting from the 1960s, this correlation breaks, the amplitude of variations of the diffuse radiation decreases, and the minimal values of the intensity increase simultaneously with the decrease of the maximal values. The same 11-year periodicity was also found in variations of the atmospheric transmittance.[30,31]

5. Mechanism of influence of the solar variability on electric characteristics of the troposphere

In some papers,[7,22,32–35] it was hypothesized that the atmospheric electricity may be a link between the variations of the solar activity and the tropospheric parameters. The detailed overview of the relationship between the parameters of atmospheric electricity and the solar variability, as well as the role of atmospheric electricity in polar latitudes, can be found in Refs. 10 and 36.

It should be emphasized that almost all papers, devoted to the influence of cosmic rays on parameters of atmospheric electricity, consider their influence on the atmospheric conductivity, variation of the ionosphere–Earth current, and the corresponding variations of the vertical electric field. However, the conductivity variations caused by the variations in the cosmic ray intensity fail to explain the observed short-term changes of the potential V and the electric field strength E in the lower troposphere of the polar latitudes.[35]

According to Ref. 10, the change of the total ionosphere–Earth resistance during the Forbush decreases is no higher than 10%, which leads to the decrease of E near the ground by roughly 10% as well. At the time of arrival of solar cosmic rays (SCR), the conductivity changes significantly at high altitudes, while the total resistance changes only slightly. This is connected with the fact that, in the most cases, the solar proton events are characterized by very soft energy spectrum and restricted to the energy lower than 500 MeV. The particles with such energies are absorbed at sufficiently high altitudes in the atmosphere (above 15 km) and, in spite of the significant increase of ionization at these altitudes, the resistance of the atmosphere–Earth circuit changes by no more than 5% in the regions of SCR intrusion and only in high latitudes due to the effect of geomagnetic cutoff, that is, only in the region of geomagnetic latitudes higher than 60°.

Anomalous events of arrival of SCRs with the energies up to 10 GeV are extremely rare, and their duration is no longer than 1–2 hours. Thus, for the overwhelming majority of SCR arrival events, as well as for the periods of particle precipitation from radiation belts during geomagnetic disturbances, the total ionosphere–Earth resistance remains practically unchanged. Consequently, the significant (more than 100%) increase of E near the ground, observed in the polar latitudes,[34–37] cannot be explained by the changes in the resistance. According to the measurements of atmospheric electrical parameters, the current almost doubles during the arrival of anomalously high fluxes of the solar cosmic rays.

In Ref. 34, it was shown based on the data obtained in Zugspits that the current and the electric field strength increase, on average, 1.5 times after solar flares. The change in the conductivity due to the SCR arrival cannot provide for such values of the observed effects.

In Ref. 38, it was shown that the SCR influence on the atmospheric electrical characteristics at high SCR fluxes is not confined by only the change of the conductivity (inherent in GCR), as it is treated in the most papers, but induces principally different effects, caused by the intrusion of charged particles into the atmosphere and, in particular, the injection of a charge depending on the SCR energy and intensity.

6. Mechanism of influence of atmospheric electricity on climatic characteristics of the troposphere

Possible influence of the galactic cosmic rays and interplanetary magnetic field on the tropospheric circulation through the electric field of the atmosphere was considered in Refs. 39–41. These papers proposed a mechanism, through which the changes in the solar activity can lead to large-scale changes in the atmospheric circulation. According to this mechanism, the solar wind modulates the galactic cosmic rays and the magnetospheric convection. This leads to changes in the ionospheric potential and the ionosphere–Earth current, to increase of the polarization of clouds with large horizontal dimensions, and to accumulation of positive charges on droplets near cloud tops. Charged drops (crystals) sharply increase the rate of drop (crystal) growth, and the latent heat is released. The heat release leads to changes in the thermobaric field of the troposphere and the atmospheric circulation.

However, despite some appeal of this mechanism, it seems to be rather complicated and, what is more important, its influence on the climate changes has not been quantified yet.

A mechanism of influence of electric field variations on the atmospheric characteristics was proposed in Ref. 38. The data of the profile measurements at fine weather are indicative of the close correlation between vertical distribution of condensation nuclei and the electric field of the atmosphere. Therefore, changes of the global electric field will necessarily lead to changes in the vertical profile of the electric field and the corresponding vertical re-distribution of condensation nuclei.

The mechanism consists in the following: the vertical distribution of charged condensation nuclei in the troposphere is governed by the vertical ionosphere–Earth electric potential. In the absence of heliogeophysical disturbances, this potential is determined by tropical thunderstorms and the intensity of galactic cosmic rays.

In the periods of heliogeophysical disturbances in high latitudes, the disturbed magnetospheric convection, flows of charged particles precipitated from radiation belts, and solar cosmic rays contribute considerably to the ionosphere–Earth potential.

The vertical re-distribution of condensation nuclei upon the increase of the atmospheric electric field can lead to water vapor condensation in zones, where earlier the concentration of these nuclei was low and the water vapor content was sufficient. This process is accompanied by changing the total latent heat (phase transition of water vapor) and the appearance of clouds, which leads to the change in the radiation budget, decrease of radiative cooling, and change of the thermobaric field of the troposphere.

The changes of the electric field will affect charged particles in the troposphere and, consequently, lead to the vertical re-distribution of aerosols, which can serve as condensation nuclei in the atmosphere. It is easy to estimate what charged aerosols will markedly displace in the vertical direction due to changes of E in the Earth's field of gravity from the condition of equality of the gravity and electric forces, acting upon an aerosol particle:

$$mg = qE,$$

where $m = \rho\frac{4}{3}\pi r^3$ is the particle mass; q is the particle charge.

For really observed changes of the electric field in the lower troposphere (1–3 km) E = 10–100 W/m, charged aerosols (as well as ions) with particle sizes smaller than 0.5 μm will subject to the considerable effect. According to the experimental findings, just such aerosols correspond to the maximum in the aerosol particle size distribution in the atmosphere. Aerosol particles of such a size are referred to as meteorological, and they affect most actively the process of water vapor condensation in the atmosphere.

The manifestation of heliogeophysical effects in the troposphere will depend on the time of day, season, and the state of the atmosphere in the given region, namely:

a) on vertical profiles of the water content and temperature;

b) on the initial vertical distribution of condensation nuclei at the time of disturbance;

c) on the vertical turbulent mixing.

This mechanism will exert the strongest effect on the state of the climatic system in the periods, when there is no incoming energy (high-latitudinal areas in winter). In this case, any cloudiness decreases the energy loss by the climatic system. In the presence of the incoming energy flux, the influence of the cloudiness on the climatic system appears to be very complex and ambiguous. Its description involves a consideration of complex and ambiguous feedbacks in global climate models. These feedbacks either intensify or suppress the initial disturbance of the climatic system. A change of the global atmospheric circulation also significantly affects the model results.

7. Analysis of the tropospheric thermobaric field during an anomalous heliophysical event

Variations of the thermobaric field of the atmosphere for the periods of intrusion of anomalously high fluxes in July 2000 have been studied in Ref. 38 based on the Reanalysis data (Fig. 18).

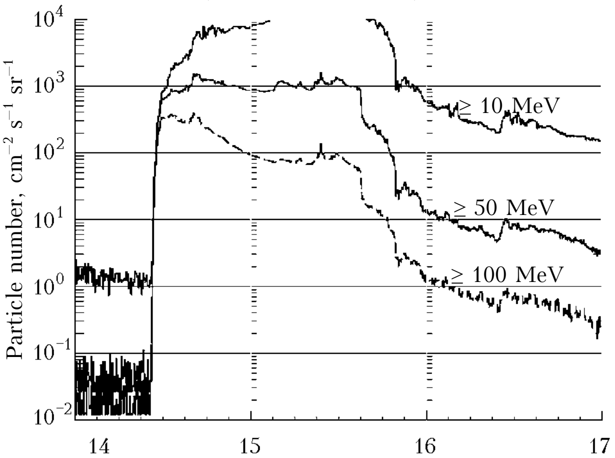

Fig. 18. Variations of fluxes of solar protons with the energy of 10, 50, and 100 MeV according to GOES-8 data in July 14–17 of 2000.

The height of the 500 hPa level turned out to be most sensitive to the particle intrusion. The effect of SCR intrusion was most pronounced in the Southern Hemisphere (local winter) in the 50–70° latitudinal zone. The maximal effect was observed on the 3rd–5th days. Figure 19*a* maps the dynamics of the 500 hPa isobaric surface from July 14 to 23 of 2000, that is, from the time of intrusion to the time of maximal changes. For comparison, Fig. 19*b* depicts a similar map in the absence of heliogeophysical disturbances (minimum of the solar activity in August, 14–23, 1987).

It is clear that the changes of the 500 hPa level of the isobaric surface occur synchronously in vast high-latitude zones, located quite far from each other along the longitude. This indicates that such changes are controlled by heliogeophysical factors, rather than natural synoptic processes.

It is well known that during geomagnetic disturbances the charged particles (electrons and protons) precipitate from the radiation belts. This also leads to changes in the ionosphere–Earth potential. As a result, according to the above mechanism, charged aerosols are re-distributed over the altitude, causing the formation of clouds in areas with a sufficient water vapor content. The formed clouds influence the radiation budget, decreasing the flux of the outgoing longwave radiation, and cause changes in the thermobaric field.

The observations fully confirm this scenario. In Ref. 42, a relationship between ionospheric disturbances and pressure variations at the sea level over the Arctic was established, and it was found that the reaction could be weaker or stronger depending on the initial conditions.

Within the framework of the proposed mechanism, it is possible, in principle, to understand and explain the revealed relationships between different characteristics of the solar and geomagnetic activity and the tropospheric parameters, namely,

– the change in the structure of the surface pressure field after geomagnetic storms;

– the influence of low-energy (E = 100 MeV) solar cosmic rays;

– the relationships of distribution of different heliogeophysical characteristics with respect to the intersection of the sector boundary of the interplanetary magnetic field with the Vorticity Area Index (VAI), etc.

Conclusions

There is a significant correlation between the low-level cloudiness (according to the modern satellite data) and the flux of galactic cosmic rays. However, the array of these data is not sufficiently large, and therefore many ambiguities arise in the reconstruction of the long-term trend of cloudiness.

The physical mechanism, providing for the influence of the solar activity on the weather and climate, reduces to the regulation (modulation) of the energy flux, outgoing from the Earth into the space. This is a sort of a valve, determining the conditions of radiation balance in the atmosphere and affecting the global circulation.

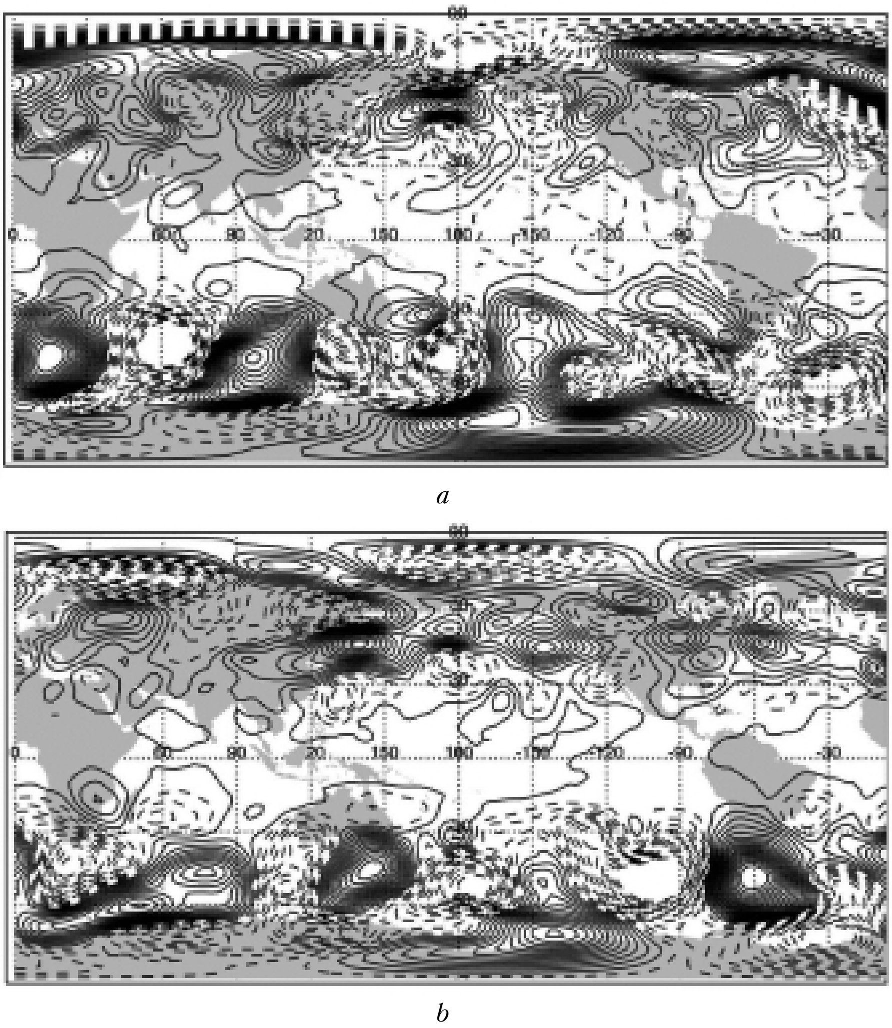

Fig. 19. Dynamics of the 500 hPa isobaric surface from July 14 to 23 of 2000 (*a*) and on August 14–23 of 1997 (*b*).

A significant part of warming in the past century can be attributed quantitatively to the effect of the solar variability. However, starting from the 1960s till now, with the effect of the solar variability kept true, we observe the clear effect of some other factor, whose role increases continuously and in the last decade already exceeds the contribution of the solar variability.

The cosmic rays and the atmospheric electric field serve a link in the sun–troposphere relationships. These factors are subject to the influence of the solar variability and exert a significant effect on the radiation budget of the atmosphere by affecting the atmospheric distribution of condensation nuclei, the phase state of water in the atmosphere, cloud cover, and, finally, the radiation budget and the atmospheric circulation.

The contribution of the variations of cosmic rays and the parameters of atmospheric electricity to the radiation budget, global atmospheric circulation, and, consequently, the weather and climate is still to be quantified.

There are strong grounds to believe that in the nearest few decades (about 40 years) the influence of helio-space factors on the climate will become weaker on both global and regional scales and partly compensate for the possible anthropogenic impact on the climate. At shorter time intervals, the behavior of these characteristics will probably diverge.

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