SOLAR ACTIVITY, COSMIC RAYS AND CLIMATE CHANGE (ON THE 75TH ANNIVERSARY AND IN MEMORY OF PROF. M.I. PUDOVKIN)

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Abstract. A review of the research activity of M.I.Pudovkin, his co-workers and followers in solving the problem of the solar activity influence on atmospheric processes and climate change is presented, the roles of cosmic ray variations and changes in cloudiness are emphasized. The problems that still remain unresolved in this field are outlined.

1. Introduction

M.I. Pudovkin was an outstanding scientist-geophysicist famous for remarkable achievements in solar-terrestrial physics. He was a founder of a scientific school at St.Petersburg (Leningrad) State University. Under his guidance about 50 candidate and doctor theses were defended. The team formed by Prof. Pudovkin still occupies one of leading positions in this area of science in Russia. It is the first at St.Petersburg University by the citation indexes of the works [Krivovichev, 2008].

M.I. Pudovkin's scientific interests were extremely versatile. The subjects of his investigations were magnetic storms and substorms, ionospheric disturbances, auroral processes, the formation and dynamics of the radiation belts, simulation of the structure and dynamics of the magnetosphere, boundary processes associated with the solar wind - magnetosphere coupling, the structure and dynamics of the solar wind, etc. Considerable attention was given to the study of the influence of solar activity on the processes in the lower atmosphere and climate parameters. The goal of this paper is to briefly review the main achievements of M.I.Pudovkin and his team in the investigations of this problem.

2. Influence of solar activity and cosmic ray variations on the lower atmosphere state and climate parameters in the studies of M.I. Pudovkin and his followers

The first paper devoted to this subject was published by M.I. Pudovkin in "Geomagnetism and Aeronomy" in 1989. Its title was "Manifestation of solar and magnetic activity cycles in the air temperature variation in Leningrad" [Pudovkin and Lubchich, 1989]. The most popular concept in the interpretation of the solar activity – climate links at that time was "the Sun – solar wind – magnetosphere – ionosphere – a trigger mechanism of atmospheric disturbances". The main problem in this interpretation was a considerable difference between the energies of the processes in the magnetosphere-ionosphere and the lower atmosphere. The energy of atmospheric processes exceeds the energy of the magnetosphere-ionosphere ones by a factor of 10^3-10^4 [Pudovkin and Raspopov, 1992; Pudovkin and Babushkina, 1992a]. Pudovkin put forward the hypothesis that there had to be an agent related to solar activity and able to affect directly the lower atmosphere by changing its thermal state. There were two candidates: the first was variations in solar irradiance, including the ultra-violet part of the spectrum, and the second was variations in the cosmic rays (CR), with the intensity modulated by solar activity, which affect optical parameters of the atmosphere (aerosol concentration etc.), cloud cover and the global electric circuit.

The ~10-year data of satellite observations (NIMBUS 7, SMM etc.) of the total solar irradiance (TSI) available to the moment the paper was published indicated that the solar irradiance changed only slightly (~0.1 % of the mean TSI) during the 11-year solar cycle (Fig.1) [Frölich and Lean, 2004]. For this reason M.I.Pudovkin came to the conclusion that cosmic rays, both solar and galactic, could be the main agent transferring the solar activity influence to the lower atmosphere. So, right from the start, M.I.Pudovkin and his co-workers began to develop this concept, looking for experimental data confirming the idea of cosmic ray effects on the atmospheric processes. The first paper of Pudovkin and Lubchich [1989] also reported the ~11-yr and ~22-yr periodicities coinciding with the main solar cycles revealed in the near-ground temperature in Leningrad. It is known that the 22-yr solar magnetic cycle manifests itself very weakly in the sunspot number variations, but it is pronounced in the geomagnetic activity and galactic cosmic ray (GCR)

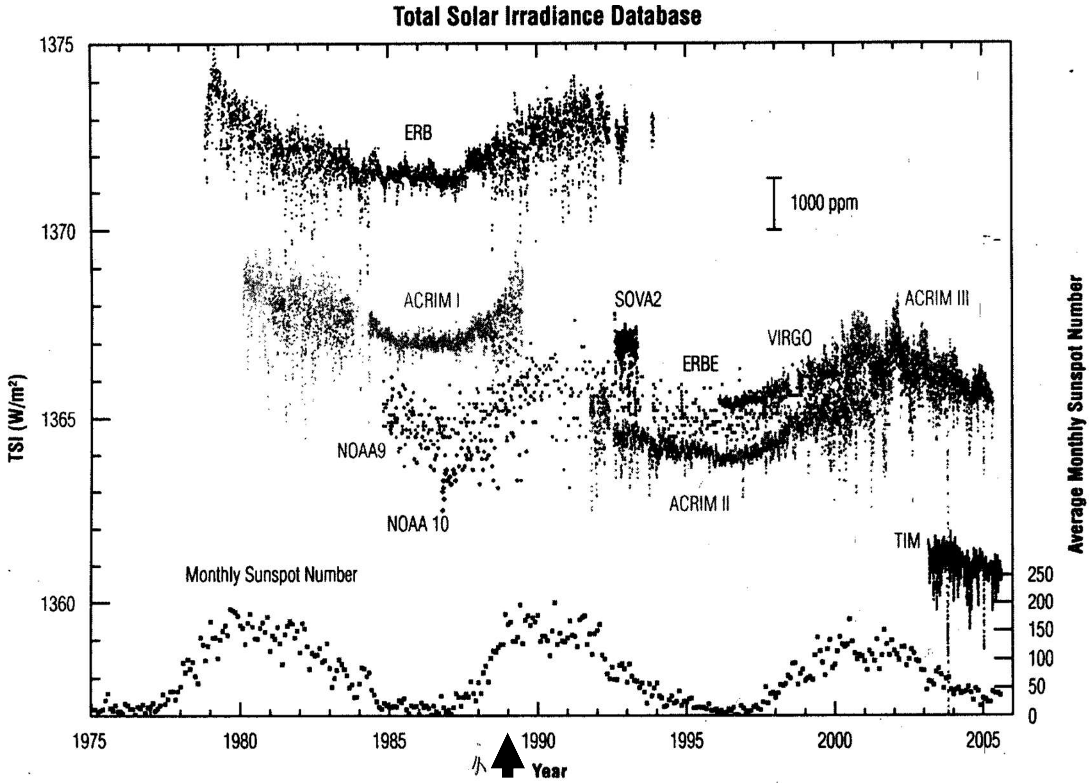

Fig.1. Results of total solar irradiance measurements at the different satellites [Frölich and Lean, 2004]. The arrow indicates the year of the first publication by M.I. Pudovkin on the problem of solar-climate relationships.

variations. By now the 22-yr periodicity has been revealed in the concentration of cosmogenic ^{10}Be isotope in Greenland ice cores [Veretenenko et al., 2005] whose production in the atmosphere is due to cosmic rays. Thus, the result obtained by M.I. Pudovkin in 1989 is confirmed by modern data.

In further investigations M.I. Pudovkin and his co-workers focused attention on the atmosphere response during sharp decreases of CR fluxes associated with geomagnetic storms (Forbush-decreases of GCR) and also during the CR increases – solar proton events (SPE). New important results were obtained in the studies of variations in the zonal circulation in the lower atmosphere at middle latitudes [Pudovkin and Babushkina, 1992a]. It was found that an intensification of zonal circulation took place due to the CR increases (SPE), whereas its weakening was observed during decreases of CR fluxes (Forbush-decreases of GCR) (see Fig.2 according to [Veretenenko and Pudovkin, 1993; Pudovkin and Veretenenko, 1996]). The energy necessary for the changes in the atmospheric circulation to occur was estimated to be ~5.10^{26} – 2.10^{27} ergs [Pudovkin and Babushkina, 1992a; Pudovkin and Raspopov, 1992].

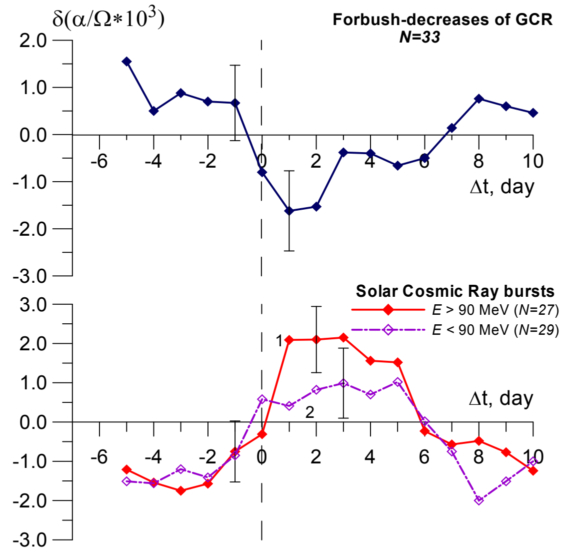

Fig.2. Superposed epoch analysis of the variations of the zonal circulation indices $\alpha/\Omega\cdot10^3$ (α is angular velocity of the zonal flow at middle latitudes, Ω is the angular velocity of the Earth's rotation) associated with cosmic ray variations. Moment Δt=0 corresponds to the day of the event onset; N is the number of events.

The study of meridional profiles of zonal atmospheric pressure during intense geomagnetic disturbances, including periods of SPE and Forbush-decreases of GCR (Fig.3), revealed that the observed variations in zonal circulation were due to the atmospheric processes at subpolar and polar latitudes (φ > 55°N), i.e., they were characterized by a latitudinal dependence [Pudovkin and Babushkina, 1992a]. The latitudinal dependence of the zonal pressure spoke in favor of the hypothesis that CR variations were the most probable link between solar activity and the lower atmosphere. Later studies of short-period effects of CR variations in meteorological characteristics

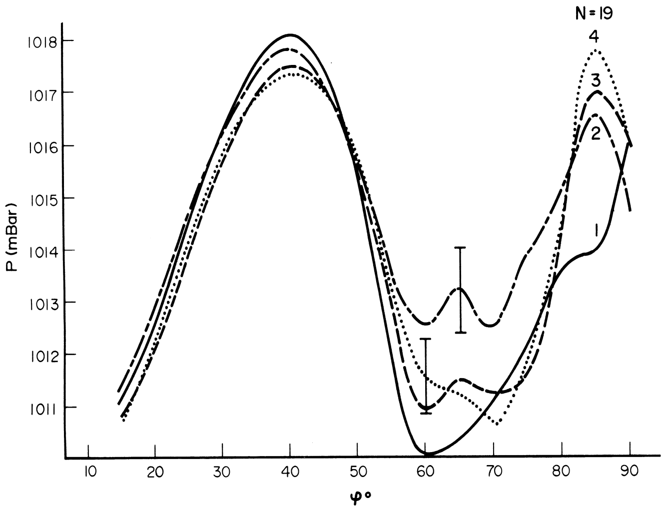

Fig.3 Meridional profiles of zonal pressure at different stages of geomagnetic disturbances (*N* =19). Moment Δt=0 corresponds to the day of the disturbance onset: *curve 1*– Δt= –1 day (flare effect); *curve 2* – Δt= +4 days (Forbush-decrease effect); *curves 3* and *4* – Δt= –4 and –5 days (quiet days).

of the high-latitude atmosphere (Sodankylä station, Finland) carried out by Pudovkin's team confirmed once more an important role of the variations in cosmic ray fluxes associated with solar activity in the disturbances of tropospheric circulation [Pudovkin et al., 1996, 1997]. Note that by now the correlations between the atmospheric circulation and CR flux variations have been revealed not only at a short time scale, but also for the ~200-yr solar periodicity (de Vries cycle) [Meeker and Mayewski, 2002; Delmonte et al., 2005; Raspopov et al., 2007].

The next step in the studies of the CR influence on the lower atmosphere carried out by M.I.Pudovkin and his colleagues was analysis of variations in the atmospheric transparency during Forbush-decreases of GCR, for which the actionometric data of ground-based stations were used. It was shown that during these events a significant increase in the atmosphere transparency took place in auroral and subauroral zones and caused an increase in the solar radiation input by ~10-13% at these latitudes [Pudovkin and Veretenenko, 1992; Pudovkin and Babushkina, 1992b]. According to the quantitative estimates, the additional income of solar energy to the lower atmosphere during the period of a Forbush-decrease of GCR may reach ~10^{27} ergs. This value exceeds the energy coming to the magnetosphere from the solar wind (~10^{23} ergs/day) by a factor of 10^3-10^4, and it is comparable to the energy necessary for the changes in the zonal circulation associated with solar activity phenomena. According to Pudovkin's ideas, the changes in the atmosphere transparency associated with Forbush-decreases of GCR, solar cosmic ray bursts, and intense geomagnetic disturbances and, hence, the changes in the amount of the solar energy coming to the lower atmosphere must give rise to variations in the atmospheric temperature and pressure. Simulation of possible changes in the high-latitude temperature and pressure due to the transparency variations associated with solar cosmic ray bursts was carried out by Pudovkin and Morozova [1997, 1998].

The most remarkable achievement of M.I.Pudovkin and his team was establishment of the relationships between variability of cosmic ray fluxes and cloud cover formation. It was found that the total cloud cover decreased in the auroral and subauroral zones during Forbush-decreases of GCR [Veretenenko and Pudovkin, 1994; Pudovkin and Veretenenko, 1995]. Variations in the cloud amount averaged over the ground-based actinometric stations of Russia in the latitudinal belts φ ≈ 65-68°N and 60-64°N are shown in Fig.4 for the period including the development of GCR Forbush-decreases. It can be seen that a rather sharp decrease in the cloud cover (on the average, by 5-8% of the total sky area relative to the undisturbed level) occurs on the +1/+2 day after the event onset. The total cloudiness variations associated with Forbush-decreases of GCR were revealed at all the stations involved, the frequency of occurrence of clear-sky days at some stations was found to increase by a factor of 2 during these events (Fig.5). Thus, the conclusion was made that a decrease in the GCR fluxes resulted in a decreasing cloudiness, mainly at the latitudes that

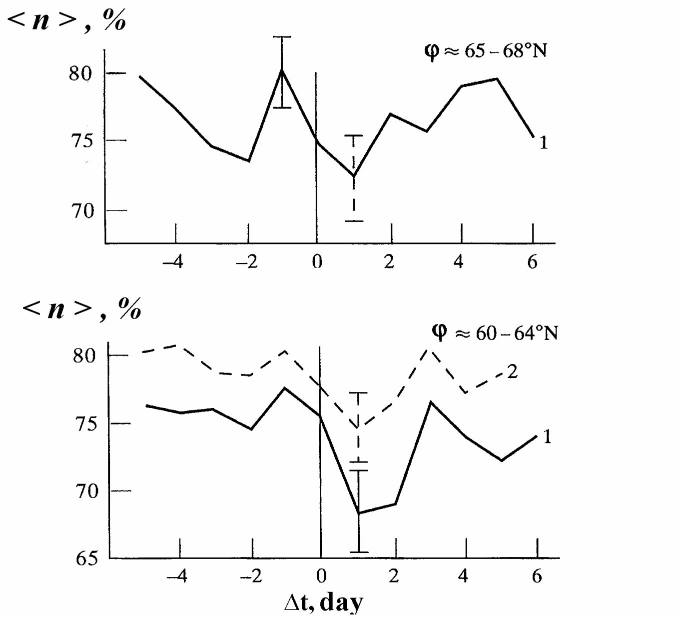

Fig.4. Mean variations of the total cloud amount (in per cent of total sky area) averaged over the stations in the auroral (φ≈65-68°N) and subauroral (φ≈60-64°N) zones during Forbush-decreases of GCR. Moment Δt=0 corresponds to the day of Forbush-decrease onset: *curve 1* – winter events (number of events *N*=42); *curve 2* – summer events (*N*=21).

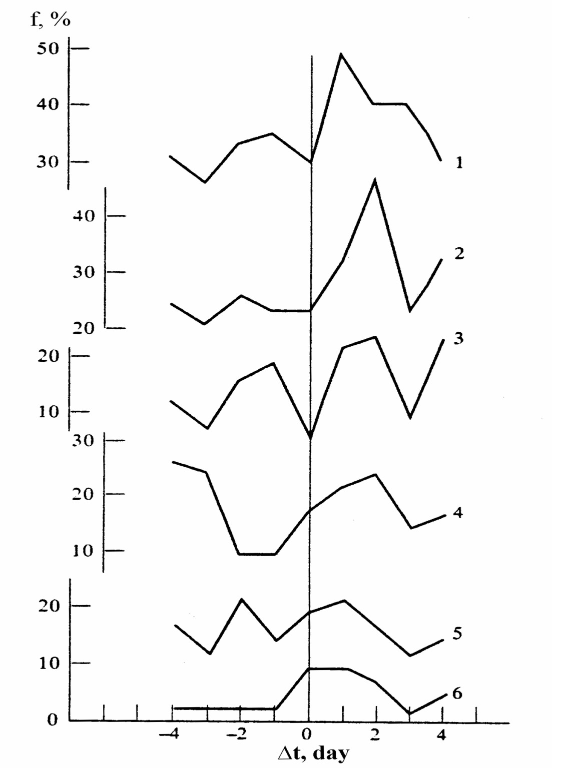

Fig.5. Frequencies of occurrence *f* (%) of clear sky days (i.e. days with the total cloud amount $n \leq 20\%$ of total sky area) during Forbush-decreases of GCR at the stations in the latitudinal belt φ≈60-64°N: *curve 1* – Okhotsk, *curve 2* – Oimyakon, *curve 3* – Vanavara, *curve 4* – Voeykovo, *curve 5* – Yakutsk, *curve 6* – Aleksandrovskoe.

Further studies of the total solar radiation input to the lower atmosphere during Forbush-decreases of GCR confirmed that cosmic rays affected the cloud cover state. The total radiation fluxes are defined as the sum of both direct radiation coming directly from the Sun's disk and the scattered radiation coming from the remaining area of the sky. Both the total and direct radiation decrease as the cloudiness increases. A statistically significant increase in the daily sums of the total radiation that provides evidence for a cloud cover decrease was detected at the stations at the latitudes φ >60°N in the first days after the Forbush-decrease onsets [Veretenenko and Pudovkin, 1997]. It was found that the changes in the solar radiation input could reach $2{\cdot}10^5$–$5{\cdot}10^5$ J/m^2 (Fig.7). Thus, not only the CR effects on the cloudiness state were confirmed on the basis of new experimental data, but also quantitative estimates of changes in the solar radiation input were obtained.

The influence of GCR on the cloud cover state and the total solar radiation input were considered for the 11-year solar cycle as well [Veretenenko and Pudovkin, 1999]. A negative correlation between the half-year sums of the total radiation and GCR intensity, which pointed to an increase in the cloud could be reached by cosmic particles with the energies from about several hundred MeV to several GeV. The variations in the cloud cover during the bursts of energetic solar cosmic rays, i.e., those associated with the increases of CR fluxes, were analyzed in the next paper [Veretenenko and Pudovkin, 1996]. The results of this study are shown in Fig.6 for four stations in the latitudinal belt 61°-69°N, the zero moment Δt = 0 corresponding to the day of the SCR burst onset. One can see that the SCR increase is accompanied by increasing cloud cover at all the stations under study. The effect was found to grow with increasing latitude.

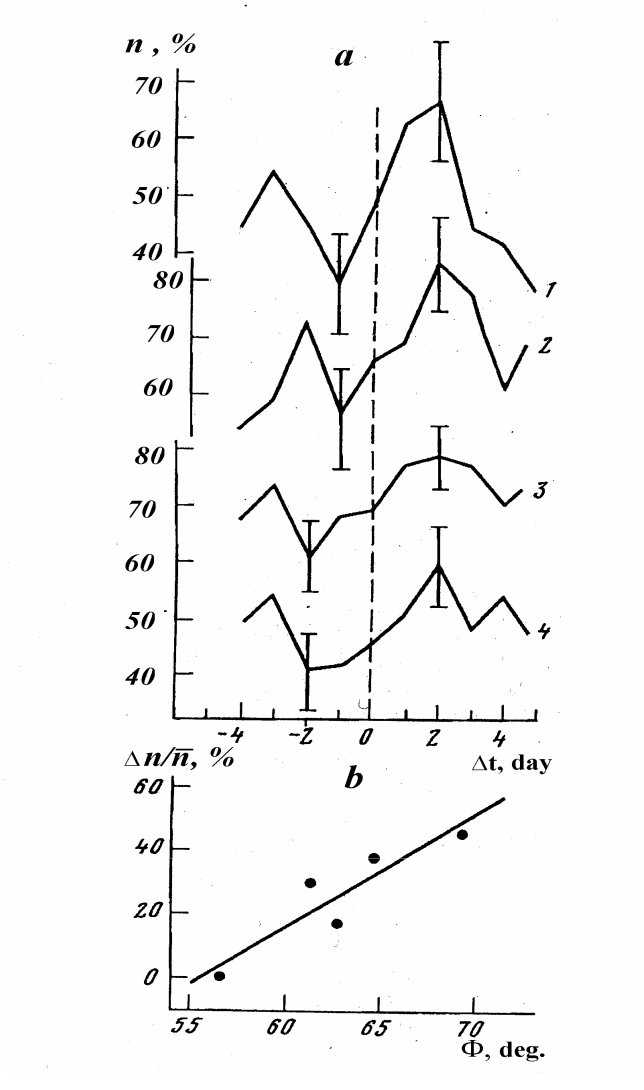

Fig.6. Variations of cloud cover associated with SCR bursts (E > 90 MeV). Moment Δt=0 corresponds to the day of the burst onset:
a) Mean variations of cloud amount (in per cent of total sky area) at the high-latitude stations: *curve 1* – Kotelny island (Φ=69.3°, *N=15*); *curve 2* – Chetyrekhstolbovy island (Φ=64.6°, *N=18*); *curve 3* – Olenek (Φ=62.8°, *N=30*); *curve 4* – Verkhoyansk (Φ=61.3°, *N=40*).
b) The amplitude of SCR effects $\Delta n/\bar{n}$ ($\bar{n}$ is the mean level of cloud amount before the event onset, Δn is the deviation from the mean level) vs. geomagnetic latitude of the stations.

cover with increasing GCR at solar activity minima, was revealed at high-latitudinal stations both during cold and warm periods. In addition, it was shown that the flare activity of the Sun as well as the auroral activity could also exert a considerable influence on the cloudiness state and the solar radiation input. The changes in the solar radiation input in the 11-year solar cycles were found to amount to ±4-6%, so they could be regarded as a possible energy source of long-term disturbances of the atmospheric circulation associated with solar activity.

In later years M.I. Pudovkin and his group concentrated their attention on analysis of regional climatic responses to solar activity phenomena in the North Atlantic region and Central Europe [Morozova et al., 2002].

Thus, M.I. Pudovkin and his group carried out thorough complex investigations that indicated that cosmic ray fluxes exerted a considerable influence on the processes in the lower atmosphere. The experimental data were supported by the quantitative estimates that showed that the changes in the solar radiation in the lower atmosphere due to the CR variations provided a sufficient amount of energy for intensification of dynamic processes.

It is important to note that the first papers of Pudovkin and Veretenenko [1994, 1995] devoted to the correlation between the cloud cover and GCR variability were published 2 and 3 years before the paper of Svensmark and Friis-Christensen [1997] on a possible influence of GCR fluxes on cloudiness state appeared. Thus, the priority of Pudovkin's group in these investigations is evident though these groups of investigators used different data: Pudovkin and Veretenenko employed ground-based observations of the cloud cover and solar radiation input, while Svensmark and Friis-Christensen used satellite data.

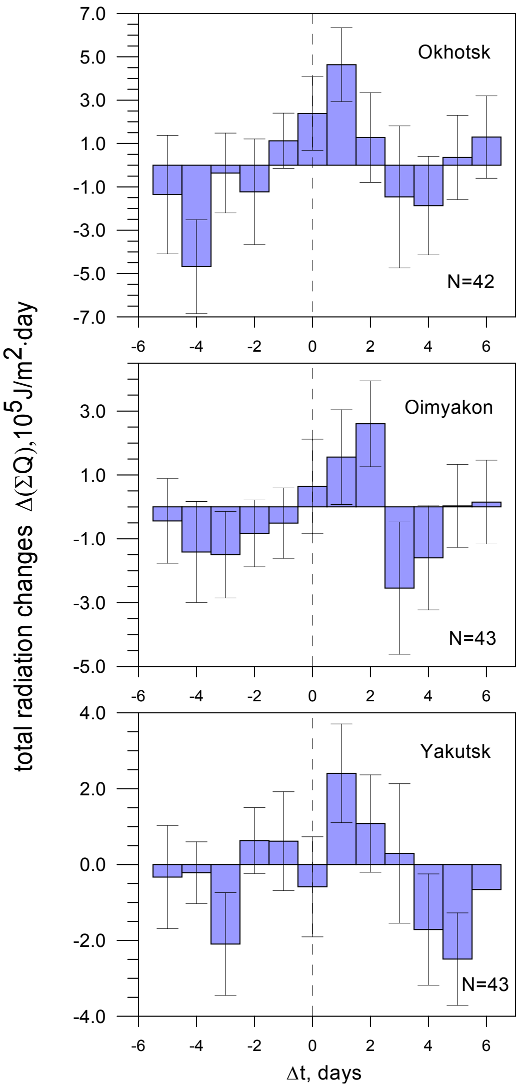

Fig.7. Mean variations of the daily sums of total radiation Δ(ΣQ) at the stations in the latitudinal belt φ = 60-64°N during Forbush-decreases of GCR. Moment Δt=0 corresponds to the day of the Forbush-decreases onset.

However, in using satellite data for estimation of the cloud cover response to solar activity the Russian scientists were also the first. Dmitriev and Govorov [1972] and Dmitriev and Lomakina [1977] used satellite data to consider the cloud cover dynamics after solar flares. Dmitriev and Lomakina [1977] traced the changes in the cloudiness associated with solar flares above four regions of the USA in the latitudinal range 25°-50°N and longitudinal range 65°-130°W and revealed an increase in the cloud cover after solar flares. On the basis of these data, Pudovkin and Raspopov [1992] supposed that the cosmic ray variability could result in the cloud cover variability.

In their first publication Svensmark and Friis-Christensen [1997] cited the paper by Pudovkin and Veretenenko [1995] in Journal of Atmospheric and Terrestrial Physics. However, to our great surprise, on page 70 in a new book by Svensmark and Calder "The Chilling Stars. A New Theory of Climate Change" published in 2007 one can read: "Svensmark thought that the supply of cosmic rays that the Sun admits to the Solar System might help to control the Earth's cloudiness. More cosmic rays, more clouds. **Scientist in Russia had flirted with opposite idea, that cosmic rays might reduce cloudiness"**. This means that distorted information is given to the reader about the results obtained by M.I. Pudovkin and his team. Moreover, on the next page Svensmark and Calder write:"The clouds obeyed the cosmic rays closely. By the norms of climate science the correlation was exceptionally good, and Svensmark and Friis-Christensen were astonished that **no one had noticed such obvious linkage before**. Afraid of being beaten to the announcement of the discovery by other scientists, they rushed to complete a scientific paper. It went off at the end of February 1996 to the journal *Science* in Washigton DC". It is astonishing that the book gives such an incorrect information: the fact that the paper on the relation between cosmic rays and cloudiness was published by Pudovkin and Veretenenko several years earlier than the paper of Svensmark and Friis-Christensen is a convincing proof that the situation is different.

It is interesting to note that the idea to consider links between the cloud cover and cosmic ray variations was prompted to Svensmark by Russian scientists. N. Calder, one of the authors of the book mentioned above, writes in his earlier book "The Magic Sun" published in 1997 and devoted to the scientists of Danish Meteorological Institute K. Lassen, E. Friis-Christensen and H. Svensmark [Calder, 1997]: "A chance remark in May 1995 switched Svensmark on to cosmic rays. A colleague had attended a seminar at the institute arranged by Friis-Christensen in connection with visit by two Russian scientists, and told Svensmark what he had heard. **The Russian had suggested that cosmic rays could alter the transparency of the air** by provoking chemical action, and perhaps **by affecting cloud formation** (page 125)". In other words, at the seminar in Danish Meteorological Institute in 1995 the Russian scientists spoke about a possible relationship between the cloud cover variations and cosmic ray fluxes. This was a meeting in the framework of the joint project supported by the European Commission INTAS-93-3248-ext "Effects on stratospheric ozone and terrestrial climate of varying solar activity", and the Russian scientists participating in the project and at the seminar were Prof. O.M.Raspopov and Dr. O.I. Shumilov. At this seminar they presented a figure (see Fig.8) demonstrating the satellite data on cloud cover variations according to Dmitriev and Lomakina [1977] and also the data on the development of Forbush-decreases of GCR after solar flares and changes in the atmospheric transparency at subauroral latitudes during intense geomagnetic disturbances according to Pudovkin and Veretenenko [1992]. Thus, the problem of the influence of cosmic ray fluxes on the cloud cover was formulated by the Russian scientists at the seminar. The Russian scientists suggested that Danish and Russian colleagues carry out a joint study of this problem. The answer was very specific: in two years Svensmark and Friis-Christensen published a paper on the influence of GCR fluxes on cloudiness [Svensmark and Friis-Christensen, 1997].

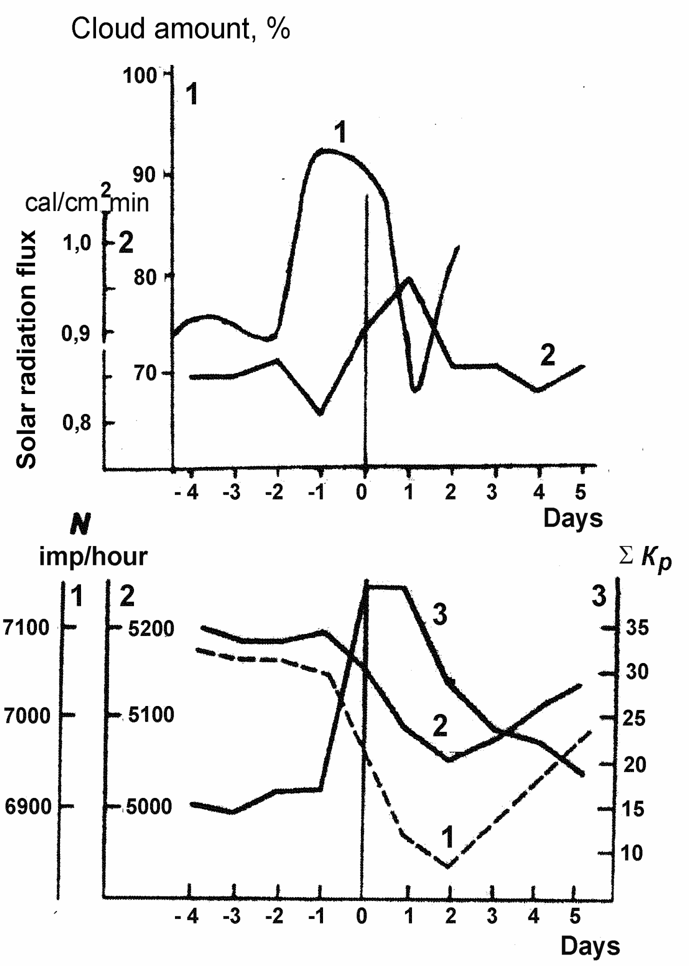

Fig.8. Top: *curve 1* – mean changes of the cloud cover over 4 regions of USA after solar flares according to the satellite data [Dmitriev and Lomakina, 1977]; *curve 2* – variations of the atmospheric transparency in the subauroral zone during the solar flares and the following intense magnetic storms averaged over 27 events [Pudovkin and Veretenenko, 1992]. Moment $\Delta t=0$ corresponds to the day of the magnetic storm onset and $\Delta t=-2$ corresponds to the day of solar flare.
Bottom: *curves 1* and *2* – the cosmic ray variations averaged over the same events in the auroral zone (Apatity) and at middle latitudes (Moscow), respectively; *curve 3* – mean values of geomagnetic ΣK_p-index.

3. Conclusions

To summarize, M.I.Pudovkin and his group made valuable contributions into the solution of a large number of problems concerned with the influence of solar activity and cosmic ray variations on the structure and dynamics of the lower atmosphere and climate parameters. They obtained pioneering results on changes in the cloud cover, atmospheric circulation, and other atmospheric processes under the influence of cosmic ray fluxes.

It is also important to outline here the problems that require close attention in developing the ideas of M.I.Pudovkin and his team. First of all, there is still no quantitative theory explaining the physical mechanism of the influence of cosmic ray fluxes on atmospheric processes. Only first steps in this direction have been made (see, e.g., the review by M.I.Pudovkin [2004]).

Another important direction of research relies on the understanding of the fact that the global influence of cosmic rays (or irradiance variations) on atmospheric processes is realized through the atmosphere-ocean climatic system characterized by internal processes. This means that the response of the system can have a nonlinear character, a regional structure and dynamics. Analysis of the experimental data on the long-term solar activity variations and the results obtained in simulation of the temperature response of the atmosphere-ocean system to solar irradiance variations confirms this statement [Raspopov et al., 2007; 2008; Waple et al., 2002].

The nonlinear character of the atmosphere-ocean system response to external forcing must result in the variability of the atmospheric circulation corresponding to the solar activity variability. In particular, it can manifest itself in the dynamics of cyclonic activity. The results of analysis of specific features of cyclone development in the North-Atlantic region [Veretenenko et al., 2007; Veretenenko and Thejll, 2008] support this idea.

The research efforts of the followers of M.I. Pudovkin are directed to the solution of the problems mentioned above.

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