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# Solar Activity, Space Weather and the Earth's Climate

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## 1. Introduction

The Sun is the ultimate source of energy for the Earth. Energy radiating from our closest star provides the natural power that fuels most of the physical and biological processes important to life. The radius of the Sun is  $6.96 \times 10^{10}$  cm and angular diameter  $\cong 1919''$  (arc seconds). Average distance between the Sun and the Earth is  $1.496 \times 10^{13}$  cm (1 astronomical unit). The mass of the Sun is  $1.99 \times 10^{33}$  g, and luminosity –  $3.84 \times 10^{26}$  W. Solar atmosphere consist of the photosphere and the chromosphere. The **photosphere** is the zone from which the sunlight we see is emitted. It is few hundreds of kilometers thick and has a temperature of  $5500\text{--}6000^\circ\text{C}$ . The **chromosphere** is an irregular stratum above the photosphere where the temperature rises from about  $6000^\circ\text{C}$  to about  $20000^\circ\text{C}$ . The chromosphere is 2000–3000 km thick and the colorful image of this layer can be observed during solar eclipses.

*Solar activity* is a set of non-stationary processes and phenomena in the Sun's atmosphere associated with the changes in solar magnetic fields. Manifestations of solar activity include the emergence and further time evolution of sunspots, faculae, flocculae, protuberances and coronal loops, solar flares and fluxes of solar wind and electromagnetic radiations. *Sunspots* are the most prominent observable signs of solar activity. They are temporary phenomena on the photosphere that appear visibly as dark spots contrasting with surrounding area. They are caused by rather intense magnetic fields, which inhibit convection, forming areas of reduced surface temperature. The diameter of a typical sunspot is 22000–29000 km (30–40"). The corresponding area is 120–160 millionths of the visible hemisphere or Micro Solar Hemisphere (MSH). Very large sunspots can reach diameters of 60000 km or more while the smallest sunspots are roughly 3500 km in diameter (Solanki, 2003). Each sunspot is characterized by a dark core, the umbra, and a less dark halo, the penumbra. Umbra to photosphere brightness is about 0.24, and penumbra to photosphere brightness is about 0.77. The magnetic field strength in the photosphere is approximately 1000–1500 G averaged over a sunspot. The effective temperature of a sunspot is 4200 K (de Jager, 2005). Mean lifetime of a sunspot is of an order of 10 days while some of them can exist up to one half a year. The complex of several sunspots forms a *sunspot group*. The readily observable rise and fall of sunspot number over an approximate 11 year period between minima is the most prominent feature of sunspot activity – the well-known cycle of Schwabe. Modern heliophysics deals with both statistical (synthetic) and physical indices of solar activity.

Statistical indices are determined from data of instrumental observations of the Sun using special mathematical algorithms. They have no direct physical meaning. Physical indices reflect the actual physical solar phenomena and quantify directly measurable manifestations of solar activity (such as radio flux and UV flux). Sunspot number is the most widespread statistical solar index. An astronomer from the Zürich observatory, Rudolf Wolf introduced the relative sunspot number in the middle of the 19<sup>th</sup> century. The sunspot series initiated by him is called the Zürich or Wolf sunspot number  $R_Z$  and it is still widely used as a statistical measure of solar activity. This series starts in AD 1700 (Fig. 1A). Recently Hoyt and Schatten (1998) performed a thorough and widespread archive search and substantially increased the amount of original information. They introduced a new index of solar activity called the group sunspot numbers  $R_G$ . This data set spans the time interval of AD 1610–1995.

*Sunspot area* measurements are available from the Greenwich Observatory for the period 1874–1976. The Greenwich series is based on daily photographic images of the Sun. Recently, this series was substantially expanded by Nagovitsyn et al. (2004) who used additional information obtained by Schwabe, Spörer and de la Rue before 1874 as well as Soviet-Russian astronomers after year 1976. The sunspot area can be considered a physical index, since it is directly linked to the solar magnetic flux emerging at sunspots (Nagovitsyn, 2005).

*Faculae* are long-lived (typical lifetime is 3 times longer than that of sunspots) bright areas, usually situated near sunspots. They occur on the photosphere, but sometimes can extend upwards into the chromosphere. The temperature of faculae is about 300<sup>0</sup> C higher than that of background photosphere, and magnetic field is close to 400 G (Obridko, 2008). Their brightness is usually 1.10–1.45 of the photosphere brightness.

Luminosity or the *total solar irradiance* (TSI – often referred to as the solar constant) is another important index of solar activity. TSI is the wavelength-integrated intensity of solar electromagnetic radiation. Solar constant has been measured since 1978 by satellite radiometers. Two composite TSI records – ACRIM () Fig. 1E) and PMOD series (Fröhlich and Lean, 1998)– were calculated from the original satellite data.

A *solar flare* is a large explosion in the Sun's chromosphere. The energy released during a flare is typically on the order of  $10^{27}$  erg s<sup>-1</sup>. Solar flares can emit up to  $10^{32}$  ergs of energy in various forms including accelerated particles and radiation emitted in spectral ranges from radio waves to X-rays and gamma rays.

The Earth has a mean radius of  $6.37 \times 10^8$  cm and the area of the Earth's surface is  $5.1 \times 10^{18}$  cm<sup>2</sup>. Oceans and seas cover 71% of the Earth's surface, i.e.  $3.62 \times 10^{18}$  cm<sup>2</sup>. Terrestrial atmosphere consists of the troposphere (up to 10–17 km), the stratosphere (10–17 to 50 km), the mesosphere (50 – 80 km) and the thermosphere (above 80 km).

*Magnetosphere* is a spatial region where the motion of charged particles is governed by the Earth's magnetic field. It has a complex structure, determined by interaction between the magnetic field of solar wind, the Earth's magnetic field and the upper atmosphere plasma. Its base lies at the altitude of few hundreds of kilometers while its tail has a diameter of about 40 Earth's radii.

*Geomagnetic activity* is the perturbation of a geomagnetic field caused by changes in magnetosphere-ionosphere current system and closely connected to variations of solar particle flux. Geomagnetic storms, substorms and auroral phenomena are the main manifestations of geomagnetic activity. A strong magnetic storm can change the global field by  $5 \times 10^{-7}$  T or more. Kp index of geomagnetic activity is shown in Fig. 1D.

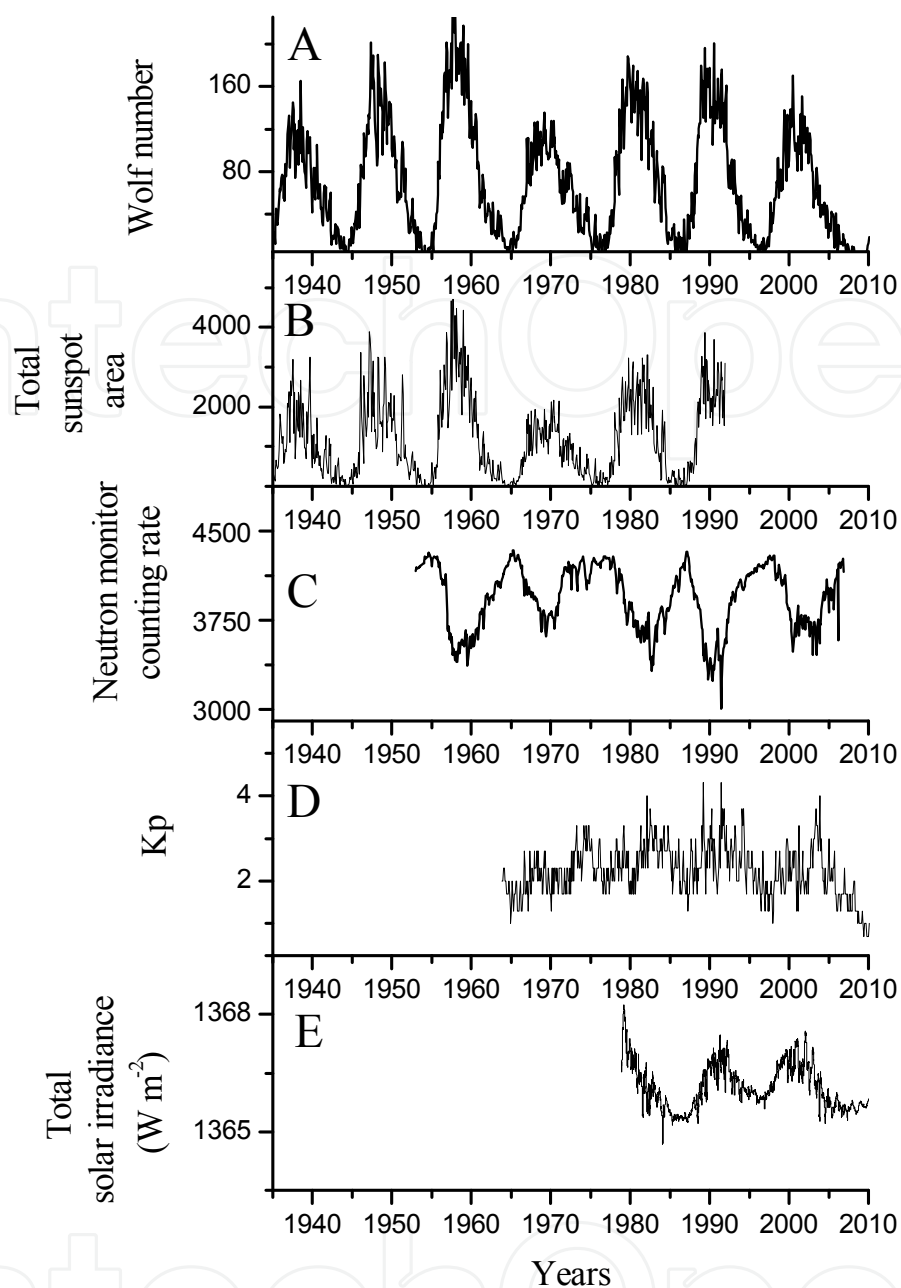


Fig. 1. Some important solar and geomagnetic indices. A – Wolf number, B – total sunspot area, C – counting rate of Climax neutron monitor ( $R_c=3$  GV), D – geomagnetic  $K_p$  index, E – ACRIM record of the total solar irradiance. All plotted records are monthly mean data. They were taken from the sites: [ftp://ftp.ngdc.noaa.gov/STP/SOLAR\\_DATA/](ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/); <http://www.acrim.com/>; <http://www.gao.spb.ru/database/>.

*Solar-terrestrial physics* or *heliogeophysics* comprises a number of scientific disciplines which study various phenomena and processes in the Sun and their manifestations in circumterrestrial space and the Earth's atmosphere and magnetosphere. It is obviously a complex and extensive field, which includes solar physics, astrophysics, cosmic physics, geomagnetism, atmospheric physics, meteorology, climatology and, possibly, some other scientific spheres. Probable influence of solar activity on terrestrial climate is studied by *helioclimatology*. Climate is conveniently defined by means and terms of the weather.

*Atmospheric weather* is a physical state of the atmosphere in a certain place on the Earth at a given time or time interval, which is described by a set of meteorological parameters. Meteorological parameters are the features of the atmosphere's state including temperature, pressure, speed and direction of wind, quality and concentration of thermodynamically active admixtures (water droplets, vapor and aerosols). The changes of weather are the fluctuations of meteorological parameters connected with pure atmospheric processes.

*Climate* is a statistics of weather, which is characterized by meteorological parameters averaged over time intervals generally longer than 30 years.

*Space weather* is a physical state of the circumterrestrial space (upper atmosphere, magnetosphere) at a given moment or time interval, which is described by a set of heliogeophysical parameters. The intensity of solar electromagnetic radiation and fluxes of solar cosmic ray (SCR), rate of ion generation, density and velocity of the solar wind particles, intensity of geomagnetic fluctuations are the main heliogeophysical parameters which form space weather. Space weather parameters averaged over long time intervals determine the *space climate*. Both space weather and space climate are closely connected with solar activity.

One of the enduring puzzles of climatology is how changes in the number of sunspots affect weather and climate on the Earth. A link between darkening of solar disk and rye prices was mentioned in fragments of Cato the Elder (234–149 BC) (Chizhevsky, 1973). B. Balliani was probably the first to assume a link between solar activity and terrestrial climate. In his letter to Galileo, Balliani noted that sunspots can be regarded as coolers of the Sun and, hence, of the Earth. Since this time search for possible solar-climate link has attracted the attention of many researchers. W. Hershel in 1801 revealed appreciable relationship between prices of some farm products, the harvest of which are weather dependent, and sunspot numbers. The work of Hershel was the starting point for a serious Sun-climate research. G. Wild (1882) likely was the first who noted effect of solar flares and geomagnetic disturbances on the surface temperature. In 1959 Ney suggested that intensity of GCR is an agent transferring solar influence on climate (Ney, 1959). Dickinson (1975) reported that fluxes of cosmic ray might influence cloudiness. Recent decades were a period of active investigation of a wide range of solar, solar-terrestrial and solar-heliosphere processes, both theoretical and experimental, performed using both groundbased and space-borne experiments. However, a lot of questions still remain and many problems have to be solved. Some of these questions are: What is the physical mechanism providing a link between solar activity, space weather and climate? Do variations in solar activity and GCR intensity contribute to global warming? What is the role of volcanic activity in long-term climatic change? Do change in geomagnetic dipole field affect terrestrial climate? The answer to these and many other questions require detailed knowledge about the history of climate, solar activity, space weather, volcanic activity and geomagnetic field over as long time scale as possible.

Unfortunately, the modern knowledge about the past of these phenomena is quite poor and has substantial gaps. The direct temperature records usually cover no more than last 100–150 years. The series of measurements of different parameters of solar activity also are short. The longest of them – group sunspot numbers – starts since AD 1610. Accurate observations of solar flares, research of GCR by means of neutron monitors and direct satellite measurements of different space weather parameters cover less than the last 55 years. Thus our current knowledge about many important heliogeophysical processes (the



fluxes of solar and galactic cosmic rays, the solar wind velocity, the strength of interplanetary magnetic field, some geomagnetic indices) cover no more than 3–5 quasi eleven-year solar cycles. It is obvious that targeted observations of the Sun using various instruments cannot supply us this information. The necessary data can only be obtained by means of proxies provided by solar paleoastrophysics and paleoclimatology. Solar paleoastrophysics is the science which makes it possible to reconstruct different parameters of the Sun's activity in pre-instrumental era. Paleoclimatology is a scientific discipline focusing on climate's past. New achievements of paleoastrophysics and paleoclimatology obtained during the last 20–30 years allow us to investigate the evolution of solar activity and climate and examine their possible interrelations over the long time scales otherwise inaccessible to us.

## 2. Solar paleoastrophysics: advances and limitations

Paleoastrophysics is concerned with astrophysical phenomena whose signals reached the Earth before the time of instrumental astronomy. Solar paleoastrophysics uses both the data of historical chronicles (the catalogues of sunspot and aurorae naked eye observation) and indirect indicators of solar activity (the concentration of cosmogenic isotope and nitrate in natural archives).

### 2.1 Paleoastrophysics of cosmogenic isotope

The study of concentrations of cosmogeneous isotopes in natural archives is a one of the basic methods of solar paleoastrophysics. Cosmogenic radiocarbon  $^{14}\text{C}$  and radioberyllium  $^{10}\text{Be}$  originate in the Earth's stratosphere and troposphere due to the effect of energetic *galactic cosmic rays* (GCR). The GCR are charged particles with energies from about 1 MeV up to at least  $10^{20}$  MeV. The source of GCR is outside the solar system but within the galaxy, most likely it is shock acceleration of super-nova remnants. GCR are observed with background neutron monitors (Fig. 1C), which are maximally sensitive to particles with energy of several GeV. The intensity of the GCR particles is given approximately by:

$$\frac{dN}{dE} \approx E^{-\gamma}, \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1} \text{ sr}^{-1}, \quad (1)$$

where  $\gamma \approx 2.6$  ( $E = 10 - 10^6$  GeV).

About 90% of the nuclei are hydrogen (protons), 10% helium ( $\alpha$ -particles), and about 1% heavier elements (C, N, O). Electrons comprise about 1% of GCR (Bazilevskaya et al., 2008). In the inner heliosphere the low energy ( $< 10^3$  GeV) GCR are modulated by solar activity. Thus the intensity of the galactic cosmic radiation is highest during the solar cycle minimum and lowest during solar maximum. Present-day solar modulation of cosmic ray is produced by three major mechanisms (Jokipii, 1991):

- a. The convection of the magnetic field and GCR outward caused by the solar wind flux.
- b. The diffusion of GCR caused by their scattering by the irregularities in the interplanetary magnetic field (IMF). These irregularities are carried away from the Sun by the solar wind. The density of the heliospheric magnetic inhomogeneities depends on the Sun's activity level. When solar activity increases, the density of these heterogeneities rises. The solar wind velocity also shows some positive correlation with solar activity. Therefore the diffusion-convection effects cause the 11-year variation of

GCR intensity. The flux of cosmic ray particles with energy  $E=0.1\text{--}15$  GeV during solar minimum is twice as large as during maximum phase (Stozhkov, 2003).

- c. The drift modulation of GCR is caused mainly by changes of the polarity of the solar magnetic field. Positively charged cosmic rays preferentially enter the heliosphere from the direction of the solar poles during the time when the solar magnetic field in the northern hemisphere has negative polarity i. e. is directed outward (Jokipii, 1991). As a result, cosmic ray time dependence has a peaked form during solar cycles with negative polarity and it has a plateau form during cycles with positive polarity (see Fig. 1C). Since the Sun's magnetic field changes its polarity after every 11-year the cosmic ray intensity curve also appears to follow a 22-year cycle with alternate maxima being flat-topped and peaked. Theoretic calculations performed by Kocharov et al., (1995) has shown that during the global Maunder minimum the amplitude of drift variation can reach 15% for particles with  $E=0.5\text{--}50$  GeV. Solar activity can also influence GCR intensity over a short time scale. Decrease of GCR intensity during several days after the large flares on the Sun and intensive solar coronal mass ejections is called a *Forbush decrease*. The amplitude of Forbush decrease (FD) typically is 2-5% for GCR with  $E=500$  MeV. Powerful solar flares are another source of energetic particles in the Earth's vicinity. Energies of the *solar energetic particles* (SEP) can reach several tens of MeV and sometimes extend into the GeV range. The acceleration of particles by shock waves associated with coronal mass ejection can also play some role in SEP generation. More than 90% of solar energetic particles are protons. They can hit the Earth within 15 minutes to 2 hours after the solar flare. Energy spectrum of SEP can be described with formula:

$$\frac{dN(R)}{dR} \approx \exp(-R / R_0), \quad (2)$$

- where  $N(R)$  is in  $\text{cm}^{-2} \text{s}^{-1} \text{MV}^{-1} \text{sr}^{-1}$ ,  $R=\frac{pc}{Q}$  is magnetic rigidity of particle in MV,  $p$  is the momentum,  $Q$  is the charge, and  $c$  is light velocity.  $R_0$  is a characteristic rigidity, which is different for different flares. Typically  $R_0$  lays in a range 50-100 MV, but for a very powerful flare of 23 February 1956 its value reached 325 MV. *Solar proton event* (SPE) is the enhancement of solar energetic particles in which proton flux with energy  $E_p > 10$  MeV is greater or equal to 10 proton flux units (pfu) or 10 particles  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  (Kurt et al., 2004). SPE last from several hours to some days. Relativistic protons with energies up to 10-20 GeV are called (particularly in Russian scientific literature) *solar cosmic rays* (SCR). Fluxes of these particles can reach appreciable values and be observed with neutron monitors mounted on the ground. As a result *ground level enhancements* (GLE) occur.

Particles with energy more than 1 GeV/nucleon are the main sources of radiocarbon generation. The major part of  $^{14}\text{C}$  is produced by the secondary thermal neutrons in reaction  $^{14}\text{N}(n,p)^{14}\text{C}$ . The rate of atmospheric neutron production depends on the changes in cosmic ray flux. The mean rate of radiocarbon generation in the atmosphere is 2.2-2.5 atoms  $\text{cm}^{-2} \text{s}^{-1}$  or 6.5 kg of  $^{14}\text{C}$  per year. The total mass of radiocarbon in the atmosphere is 45-75 tons. Calculations performed by Kocharov et al. (1990) showed that the contribution of SCR to the radiocarbon generation was only 10-15 % of the GCR contribution during 1956-1972. After origination  $^{14}\text{C}$  is oxidized rapidly to  $^{14}\text{CO}$  and then to  $^{14}\text{CO}_2$ , which, in turn, is homogenized in the atmospheric  $^{12}\text{CO}_2$  pool and involved in a chain of geophysical and geochemical

processes forming the global carbon cycle, and is finally fixed by plants (e.g. tree rings). Radiocarbon decays with a half-life of 5730 years, which is enough in order to study processes which occurred up to 80 000 years ago.

Cosmogenic beryllium is generated in nuclear reactions  $^{14}\text{N}(\text{Ha},\text{X})^{10}\text{Be}$ ,  $^{16}\text{O}(\text{Ha},\text{X})^{10}\text{Be}$ , where Ha are hadrons, X are the other reaction products. The reactions have a threshold character i.e. they take place only if the hadron energy exceeds 40–50 MeV. The mean rate of  $^{10}\text{Be}$  generation in the atmosphere is  $(2.0\text{--}2.7) \times 10^{-2} \text{ at cm}^{-2} \text{ s}^{-1}$ .  $^{10}\text{Be}$  oxidizes rapidly to  $^{10}\text{BeO}$ , then it is captured by aerosols, washed out by precipitation, and preserved in polar ice and sea-bottom deposits.  $^{10}\text{Be}$  decays with a half-life of  $1.5 \times 10^6$  years that is enough to investigate processes with time scales of few millions of years. Approximately two thirds of  $^{10}\text{Be}$  and  $^{14}\text{C}$  are produced in the stratosphere and the residual part is generated in the troposphere. The concentration of  $^{14}\text{C}$  in tree rings is measured by proportional gas counters, liquid scintillation spectrometers and accelerator mass spectrometers. The measurements are expressed as  $\Delta^{14}\text{C}$  which is the difference between the isotopically corrected activity of the sample and NBS standard ( $[\text{C}^{14}]/[\text{C}^{12}] = 1.176 \times 10^{-12}$ ). The dating of tree ring radiocarbon records is made by means of dendrochronology. Thus  $\Delta^{14}\text{C}$  time series usually have 1 year time resolution. The concentration of  $^{10}\text{Be}$  in ice is measured by accelerator mass spectrometry. The dating of beryllium series is made by recognizing layers of impurities attributed to known volcanic eruptions (volcanic markers) and by analysis of simultaneously measured records which have evident seasonal variations ( $\text{H}_2\text{O}_2$ , various ions).

Part of the incoming galactic radiation is deflected by the Earth's geomagnetic field. For this reason the production of cosmogenic isotopes is modulated by the changes in geomagnetic field. The concentration of radiocarbon in the atmosphere is modulated also by changes in global carbon cycle, particularly by variations in the rate of exchange between the atmosphere and mixed as well as deep layers of ocean.  $^{10}\text{Be}$  abundance in polar ice depends on local meteorological conditions. Finally, the concentration of cosmogenic carbon and beryllium in natural archives is found to be dependent on the following factors: (a) GCR flux or spectral shape in the galactic vicinity of the solar system, (b) solar activity, (c) dipole geomagnetic field, (d) global and regional climate. It is important that cosmogenic nuclides  $^{14}\text{C}$  and  $^{10}\text{Be}$  provide a measure of GCR intensity, which is in turn effectively modulated by solar activity. Thus radiocarbon and beryllium records can be used for the reconstruction of solar activity variability over long time scales.

In the USSR, the radiocarbon studies of solar activity in the past began as early ago as 1965–1967 within the scope of the program Astrophysical Phenomena and Radiocarbon formulated by Konstantinov and Kocharov (1965). Eddy (1976) estimated how solar activity had varied during 5000 years using  $\Delta^{14}\text{C}$  data set. He showed that the Sun has gone through both periods of very high solar activity (global maxima) and periods of very low solar activity (global minima). These works together with the efforts of J. Eddy, J. Schove, M. Stuiver, J. Beer and other investigators lay the foundations of solar paleoastrophysics. The longest radiocarbon series was measured in the framework of intercalibration program INTCAL98 (Stuiver et al., 1998) using rings of trees from Germany, Ireland and northwestern USA. The record covers the last 24 000 years and more than the last 10 000 years has decadal time resolution. This data set has been used for the longest sunspot number reconstructions (Fig. 2).



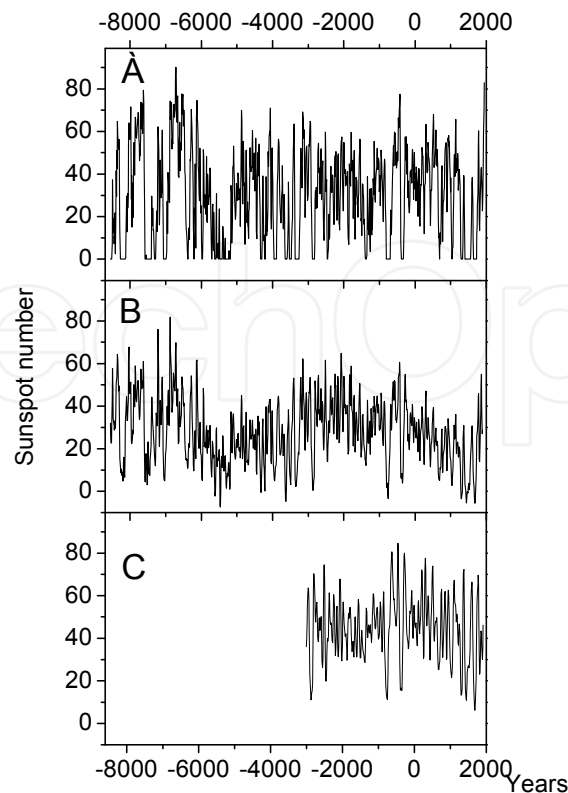


Fig. 2. Radiocarbon sunspot number reconstructions made by: A - Ogurtsov (2005); B - Solanki et al. (2004); C - Nagovitsyn et al. (2003). All the reconstructions were made using  $\Delta^{14}\text{C}$  data of Stuiver et al. (1998).

The radiocarbon solar reconstructions show that the mean level value of sunspot number over the second part of 20<sup>th</sup> century (75–85 Wolf number units) was very high in the context of the last 10 000 years of sunspot history. Solanki et al. (2004) have concluded that the current episode of high solar activity since about the year 1940 is unique within the last 8000 years.

Annual solar reconstructions of different types over the last 1000 years has been produced (Fig. 3): reconstruction of Wolf number of Nagovitsyn (1997) who used the data of Schöve (1983) based on historical accounts of aurorae; radioberyllium reconstructions of Usoskin et al. (2004) and Ogurtsov (2007) who used the long beryllium record from the South Pole (Bard et al., 2000); radiocarbon reconstructions of Nagovitsyn et al. (2003), Ogurtsov (2005), Solanki et al. (2004).

Fig. 3 shows that all the sunspot proxies agree in their major features. Coefficient of annual correlation between different reconstructions is 0.50–0.80. The correlation between reconstructed and instrumentally measured sunspot numbers reaches 0.70–0.80 over the decadal time scale. Thus the main global extremes of solar activity (Oort, Wolf, Spörer, and Maunder minimums and medieval and late medieval maximums) manifest themselves in all the sunspot paleoindicators. Establishing reliably the profound extremes of solar activity throughout the last millennium is an important achievement of solar paleoastrophysics. The analyses of the solar variability on the secular time scale is another field of paleoastrophysical research. The examination of long solar proxies made it possible to unequivocally prove the presence of the century-scale (55–135 yrs) variation of solar activity.

Recently it was shown that this periodicity – the cycle of Gleissberg – consists of two oscillation modes – 55–80 yrs variation and 90–135 yrs variation (Ogurtsov et al., 2002). Bi-centennial (170–260 yrs) solar variation – the cycle of Suess (de Vries) – was also discovered by means of analyzing the proxy data. Research on solar paleoindicators also gave serious evidence for the existence of 500–900-years and ca. 1500-years cycles of solar activity (Bond et al., 2001; Nagovitsyn, 1997; Ogurtsov 2010). Ca. 2300 year solar cycle – the cycle of Hallstatt – has been reported in a few works (see e.g. Vasiliev and Dergachev, 2002).

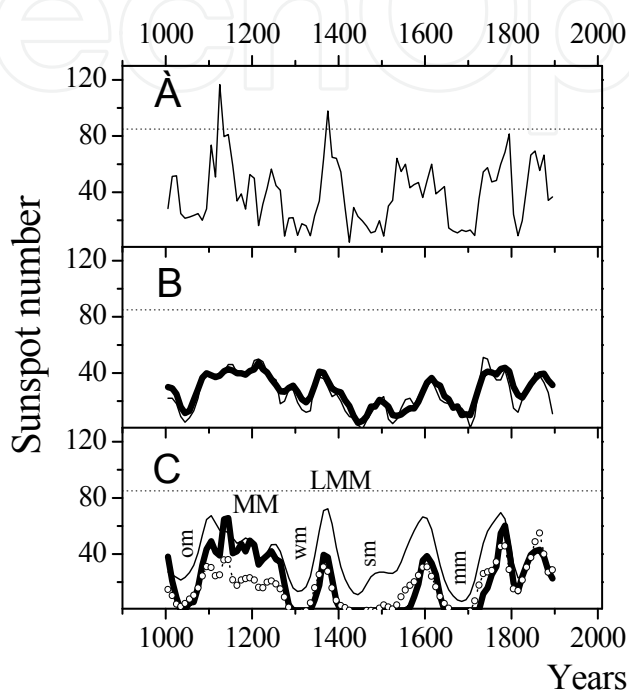


Fig. 3. Sunspot number: A – auroral reconstruction after Nagovitsyn (1997); B – beryllium reconstructions after Ogurtsov (2007, thin line) and Usoskin et al. (2004, thick line); C – radiocarbon reconstructions after Nagovitsyn et al. (2003, thin line), Ogurtsov (2005, thick line), Solanki et al. (2004, circles). MM - Medieval maximum, LMM - Late Medieval maximum, om - Oort minimum, wm - Wolf minimum, sm - Spörer minimum, mm - Maunder minimum.

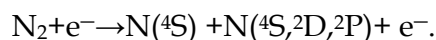
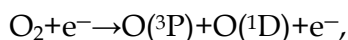
In spite of many valuable results obtained by solar paleoastrophysics a number of problems still remain. Considerable uncertainty in our knowledge about: (a) the millennial-scale variability of geomagnetic dipole field and (b) past climatic changes as well as their influence on cosmogenic isotope abundance, currently challenges the precision of our paleoastrophysical understanding. For example, substantial difference between sunspot number reconstructions after Ogurtsov (2005) and Solanki et al. (2004) (see Fig. 1A,B) is caused mainly by different methods of long-term trend subtraction. Thus, Ogurtsov (2007) has concluded that in its present state sunspot paleoreconstructions most likely contain only qualitative information about the behavior of solar activity in the past but are not very suitable for extracting quantitative information. Nevertheless solar proxies let us elaborate some future scenarios of the evolution of solar activity. In the works of Ogurtsov (2005) and Solanki et al. (2004) it was shown that the average sunspot activity in the first part of 21 century most probably will be weaker than in the second part of 20<sup>th</sup> century.

## 2.2 Paleoastrophysics of nitrate

Nitrate ions ( $\text{NO}_3^-$ ) concentration in polar ice of Antarctica and Greenland has been under investigation for many years (Zeller and Parker, 1981; Herron, 1982; Legrand et al., 1989; Mayewski et al., 1993; Dreschhoff and Zeller, 1994, 1998). The properties of nitrate record in ice are connected with its mechanism of generation. According to Logan (1983); Legrand and Kirschner (1990), Mayewski et al. (1990) nitrate “precursors” – the various  $\text{NO}_x$  (N, NO,  $\text{NO}_2$ ) and  $\text{NO}_y$  (N, NO,  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{HN}_2\text{O}_5$ ,  $\text{N}_2\text{O}_5$ ,  $\text{HO}_2\text{NO}_2$ ,  $\text{ClONO}_2$ ,  $\text{BrONO}_2$ ) molecules – are formed at different altitudes of the atmosphere:

- In the troposphere (due to industrial activity, biomass burning, soil exhalation, lightning and the influence of galactic cosmic rays).
- In the stratosphere and higher altitudes (due to biogenic  $\text{N}_2\text{O}$  oxidation, galactic cosmic rays, solar cosmic rays, solar UV radiation and relativistic electron precipitation).

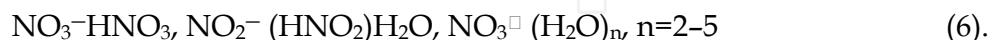
Nitrate sources connected with cosmic radiation are the most important for paleoastrophysics. Energetic SCR and GCR particles as well as relativistic electrons precipitating from the radiation belts produces a lot of secondary free electrons with energies of hundreds of eV, which effectively interact with molecules of atmospheric gases forcing their ionization, dissociation and excitation:



The ions  $\text{O}_2^-$ ,  $\text{N}^+$ ,  $\text{O}^+$ ,  $\text{N}_2^+$ ,  $\text{O}_2^+$ , excited atoms of oxygen and nitrogen,  $\square$  are involved in a complex of photochemical reactions resulting in the generation of nitrogen oxide NO. It is presumed that each pair of ions creates 1.5 NO molecules. NO oxidizes to  $\text{NO}_2$  within few tens of minutes while  $\text{NO}_2$  lives 1-8 days and serves as a source for nitrate:



Reactions (4, 5) take place in the ozone layer in the stratosphere. Thus, a relationship between atmospheric ionization and production of nitrogen oxides appears.  $\text{NO}_3^-$  ions can generate clusters, particularly with water molecules:



These ion clusters have a long lifetime (up to  $10^3$ – $10^4$  s) and thus can be fixed by aerosol particles. After fixation they precipitate on the Earth's surface both by gravitation sedimentation and downward air streams and become finally fixed in polar ice. Nitrate concentration in ice samples usually is measured by spectrophotometer.

Zeller and Parker (1981) as well as Dreschhoff and Zeller (1994, 1998) have reported the existence of an unequivocal link between SPE and short but prominent peaks in  $\text{NO}_3^-$  concentration both in Antarctica and Greenland. 11-year and 22-year cycles were also found by Zeller and Parker (1981), Dreschhoff et al. (1983) and Dreschhoff and Zeller (1998) in

nitrate data. Significant but weak elevation in mean nitrate concentration after SPE was found in an Antarctic nitrate record by Palmer et al. (2001). Thus, analysis of nitrate records measured with ultra-high (few weeks to few months) time resolution can provide us with information about solar flare activity in the past. McCracken et al. (2001A) analyzed nitrate concentration in a 125.6 m long core drilled at Summit, Greenland (72°N, 38°W, altitude 3210 m) and two shorter cores drilled at Windless Bight (78°S, 167°E). The dating of these datasets was based on distinct seasonal variations in nitrate concentration and the data on known volcano eruptions. Because of the large input of sulfides into the atmosphere after each volcano eruption, the electrical conductivity in the ice layer of respective year increases sharply. The conductivity, measured along the ice core simultaneously with the nitrate concentration therefore provided scientists with a number of necessary time markers. McCracken et al. (2001A) identified 70 impulsive nitrate events between 1561 and 1950.

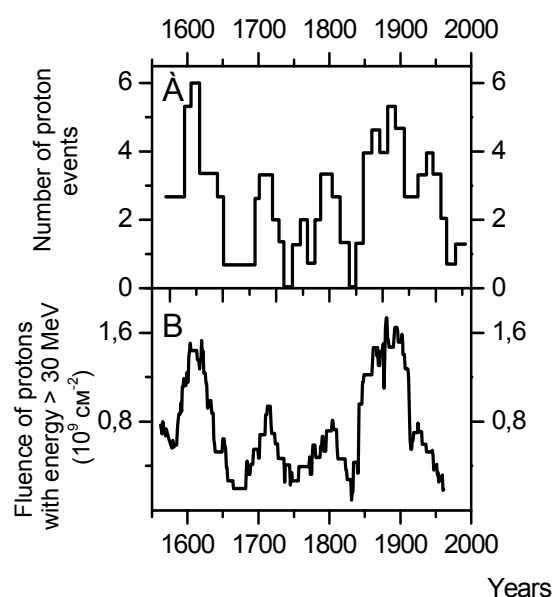


Fig. 4. A – the frequency of solar proton events averaged by a two solar cycle running means (scanned from McCracken et al. (2001B) and digitized); B – the fluence of powerful SPE reconstructed by McCracken et al. (2001A) averaged over 30 yrs.

The omnidirectional proton fluences ( $\text{cm}^{-2}$ ) were also estimated. An analysis of this sequence performed by McCracken et al. (2001B) showed that solar proton events follow the century-scale (Gleissberg) periodicity during 1561–1950 (Fig.4). Interestingly the period of instrumental SCR measurement (after the mid-20<sup>th</sup> century) is a time of rather low frequency of SPE occurrence (see Fig. 4). It should be noted that some powerful SPE in the past were identified using other paleoindicators. Usoskin et al. (2006) discovered 10 SPE (1755, 1763, 1774, 1793, 1813, 1851, 1867, 1895, and 1927) by means of analysis of the data on concentration of  $^{10}\text{Be}$  in Greenland ice. Kostantinov et al. (1992) performed joint analysis of the data on  $^{14}\text{C}$  and  $^{10}\text{Be}$  in natural archives. Substantial increases of SCR flux were established during 1750–1790, 1851–1853, 1868–1869, 1896. These results are in agreement with those of others (McCracken et al., 2001A) who identified SPE with strong ( $> 2 \times 10^9 \text{ cm}^{-2}$ ) fluence of energetic ( $E_p > 30 \text{ MeV}$ ) protons in 1755, 1763, 1774, 1793, 1813, 1851, 1866, 1868, 1895, 1896 and 1928.

Gleissberg periodicity was also revealed in the mean concentration of  $\text{NO}_3^-$  ions in Central Greenland ice (Kocharov et al., 2000). Mayewski et al. (1993) found a 112-year periodicity in their low time resolution nitrate series. Since fluence of solar particles with  $E > 200\text{--}500$  MeV is comparable with that of GCR particles, it is reasonable to assume the century-scale cyclicity in nitrate as the result of the corresponding variation in atmosphere ionization, which, in turn, is caused by the combined effect of the century-type variations in GCR and SCR fluxes. Quasi five-year variability is another important feature of nitrate concentration in Greenland ice (Kocharov et al., 1999). This quasi five-year variation is connected with a tendency of nitrate concentration to increase before and after sunspot maxima – at rise/decline phases of solar cycle (Kocharov et al., 1999; Ogurtsov et al., 2004). Such relationship may be a result of the corresponding tendency for strong SPE.

Despite the results which have confirmed that concentration of  $\text{NO}_3^-$  ions in polar ice actually is an indicator of stratospheric ionization and space weather, interpretations of the nitrate records still are controversial. Some researchers (Herron, 1982; Legrand and Kirchner, 1990) find no solar effects in nitrate data sets. Thus, these authors have rejected the possibility that nitrate concentration can reflect variations of solar activity and have proposed a weak contribution to the polar ice nitrate sequence from the middle atmosphere in comparison to the troposphere. An appreciable ambiguity still presently remains in our knowledge about transport of ions in atmosphere, depositional and post-depositional.

Since paleoastrophysical data have many uncertainties, the analyses of many proxies of different kinds are invaluable tools for the extraction of confident information.

### 3. Paleoclimatology: advances and limitations

Paleoclimatology reconstructs and studies climatic variations before the beginning of the instrumental measurements by means of different proxy indicators. Among the main data used by paleoclimatology are: tree rings (width and density), concentration of stable isotope ( $^{18}\text{O}$ ,  $^{13}\text{C}$ , D) in natural archives (ice, coral and tree rings) and historical documents.

#### 3.1 Dendroclimatology

In 1892 P.N. Shvedov compared data on tree-ring growth with the data on precipitation of few weather stations from southeastern Russia. Shvedov (1892) concluded that droughts over the analyzed region have ca. 9 year cycle and emphasized the value of the tree-ring data for further climatic research (Dergachev, 1994). Later the relationship between radial tree growth and climatic factors was reported by Douglass (1914) as well as other scientists. A.E. Douglass is often considered as the father of dendroclimatology – the discipline, which estimates the past climate conditions from trees (dated tree rings mainly). The basic idea of dendroclimatology is that a discernible reaction occurs in growth increments of trees which grow under severe conditions due to variation of the limiting environmental factors. Trees living in extremely cold condition (northern tree line, upper tree line in mountains) reflect changes of summer temperature. Latewood density usually indicates temperature variation better than tree-ring width. Rings of trees growing in extremely dry conditions could serve as precipitation indicator. Tree rings are one of the most valuable climate proxies because they can be absolutely dated annually by means of dendrochronological cross-dating method. The works of Fritts (1976), Cook and Kairiukstis (1989) has helped dendroclimatology to become popular and over the last decades its methods have become



major tools in reconstruction of past climates in many parts of the world (see e.g. Jones et al., 1998; Briffa, 2000; Briffa and Osborn, 2002; Mann and Hughes, 2002; Helama et al., 2005). Not only ring width responds to climate. Jalkanen and Tuovinen (2001) and Pensa et al. (2006) showed that in Lapland needle production of trees as well as annual tree height increment were strongly related to the mean air temperature of the previous summer. Thus tree-height and needle-trace chronologies provide a novel tool for reconstructing past summer temperatures. Tree-ring data usually are calibrated towards instrumental temperature. Although dendroreconstructions typically have their dating accurate to one year, their ability to encode long-term (centennial and slower) climate variability is often limited by the trend-removal technique applied to remove non-climatic variations in tree-ring time series. The longest temperature dendroreconstructions cover periods up to 7–8 millennia. Coefficient of correlation between instrumental temperature series and tree-ring reconstructions reaches 0.4–0.5 over annual time scale and more than 0.8 over decadal time scale. For latewood density reconstructions these values are 0.5–0.8 and over 0.9 respectively. Coefficient of annual correlation between tree-height increment proxy and measured temperature is 0.61.

### 3.2 Stable isotope climatology

In 1948 H. Urey calculated the temperature dependence of oxygen isotope fractionation between calcium carbonate and water and proposed that the isotopic composition of carbonates could be used as a paleothermometer (Urey, 1948). Later W. Dansgaard proposed the idea of using the isotopic composition of glacier ice as a climatic indicator (Dansgaard, 1954). Since isotopes with different masses have different rates of chemical reactions, natural geophysical and geochemical processes might cause isotope fractionation, which depends on temperature. As a consequence it is reasonable to expect the concentration of stable isotope  $^{18}\text{O}$ ,  $^{13}\text{C}$ , D in natural archives – polar and mountain ice, bottom sediments, corals, tree ring cellulose – to hold information about past temperature. Isotope fractioning of the oxygen isotope has the following chain:  $^{18}\text{O}$  is heavier than  $^{16}\text{O}$  thus water vapor from the tropical ocean tends to have a slightly higher ratio of  $^{16}\text{O}/^{18}\text{O}$  than that of the remaining ocean water. As water vapors traverses toward the poles, they lose the heavier, more easily condensed,  $^{18}\text{O}$  water leading to lower and lower isotopic oxygen ratios. Consequently, the amount of  $^{18}\text{O}$  relative to  $^{16}\text{O}$  in the water vapor becomes less and less as it approaches the poles, preferentially losing  $^{18}\text{O}$  water in the form of rain and snow. The ratio of oxygen isotope is determined by means of gas isotope-ratio mass spectroscopy. The measurements are expressed as  $\delta^{18}\text{O}$  which is per mille (0.1 %) deviation from Vienna SMOW standard ( $[\text{O}^{18}]/[\text{O}^{16}]=2005.2 \times 10^{-6}$ ). Stable isotope records have apparent seasonal cycle which can be used for annual dating accuracy. Deeper into the ice the annual layers become thinner and finally become indistinguishable. Therefore, the dating of the deeper layers depends considerably on the flow model. Discovery of Dansgaard-Oeschger events – rapid climate fluctuations from warm conditions (interstadials) to cold conditions (stadials) – is one of the most important successes of the paleoisotope thermometry. These events that occurred 25 times during the last glacial period (roughly 2–3 ka periodicity) were revealed by means of analysis of  $\delta^{18}\text{O}$  concentration in the ice core retrieved from Greenland (Johnsen et al., 1972). Stable isotope records from Greenland cover time intervals up to 250 000 years and from Antarctica – up to 750 000 years. Correlation between  $\delta^{18}\text{O}$  ice core reconstructions and instrumental series reaches 0.3–0.4 over annual time scale.

The isotopic composition of wood cellulose is another area of paleoisotope temperature reconstructions. Biological and physical processes determine stable isotope  $^{13}\text{C}/^{12}\text{C}$  ratios in organic matter during photosynthetic uptake of  $\text{CO}_2$  from the air (Farquhar et al., 1982) while the ratio  $^{18}\text{O}/^{16}\text{O}$  is determined by isotopic composition of source water to the tree, evaporation effects in tree leaf and biochemical steps during cellulose synthesis (Roden et al., 2000).  $^{13}\text{C}$  abundance in tree-ring cellulose is expressed as  $\delta^{13}\text{C}$  values relative to the Vienna PDB standard ( $[^{13}\text{C}]/[^{12}\text{C}] = 0.0112372$ ). Strong response of  $\delta^{13}\text{C}$  in northern Finland (Kessi) to midsummer temperature was found by Hiltunen et al., (2009). Coefficients of correlation between the  $\delta^{13}\text{C}$  record from Kessi and temperature, measured at the weather stations, is 0.68 at annual time scale and 0.81 at decadal time scale. Thus the stable carbon tree-ring series with annual resolution are valuable for further paleoclimatic research. It should be noted that recent studies have shown that  $\delta^{13}\text{C}$  record is not only a pure temperature proxy but sunshine too (Gagen et al., 2011).

Ocean coral skeletal rings, or bands, also impart paleoclimatological information. Cooler temperatures as well as denser water salinity tend to cause coral to use heavier isotopes in its structure. Deep ocean sediments have been examined to get information about the conditions during the past 1 000 000 years

### 3.3 Other sources of paleoclimatic information

Borehole temperature measurement, paleobotanic data, historical data and melt layer thickness are other proxies used by paleoclimatology. Subsurface terrestrial borehole temperature profiles can be used to obtain an estimate of ground surface temperature changes back in time. An advantage of the borehole data over those from the majority of other climate proxies (tree rings, corals, ice cores, and historical documentary records), is that they do not require calibration against independent surface temperature data. As opposed to tree-rings, borehole temperatures are only sensitive to climate variations at multi-decadal or longer time scales due to the attenuation by the heat diffusion process. Borehole data have been recently used to characterize Northern Hemisphere continental temperature for the past 500 years (Beltrami, 2002; Mann et al., 2003).

Pollen grains which are washed or blown into lakes and peatlands can accumulate in sediments. Plants produce pollen in large quantities and it is extremely resistant to decay. It is possible to identify a plant species from its pollen grain. The identified plant community of the area at the relative time from that sediment layer will provide information about the climatic condition. Pollen-based records are considered sensitive to multi-decadal variability. Pollen analysis has been used to derive quantitative information about the climate of the past 200 000 years.

Contemporary written historical records – diaries, annals – contain information on a variety of natural phenomena: freeze dates, harvest amounts, flowering dates, extreme droughts, hurricanes etc. These data are often highly subjective and unhomogeneous. Thus their analysis is a complicated task. However, promising methodology has been developed to produce centennial time series on past climate extremes (Dobrovolny et al., 2010).

Ice core melt layers store information about summer temperature. The data on melt layer thickness might not reflect the full range of the temperature variability – very cold summers could cause no melt while during very warm summers the whole layer will melt. Thus, coefficient of correlation between melt layer proxies and instrumental temperature often is less than 0.2.

Since different paleoindicators reflect actual temperature changes by different ways the *multiproxies* – the time series, which generalize proxy sets of various types – are often used by paleoclimatology. For example, M. Mann and his colleagues obtained their famous reconstruction using 12 proxy indicators – 7 tree-ring width based, 2 tree-ring density based, 2 based on  $\delta^{18}\text{O}$  in ice core, 1 based on ice accumulation rate (Mann et al., 1999). McCarroll et al. (2003) used multiproxy analysis to several annually-based series from the same trees at treeline. Moberg et al. (2005) combined proxies with low time resolution (pollen, sediments, borehole) data with high-resolution (tree-ring data) using a wavelet technique. Several recent temperature reconstructions provide information about large-scale climate variability over the past 1000 years (Fig. 5). These paleoclimatic proxies include the following temperature records: the multiproxy for the Northern Hemisphere by Mann et al. (1999), the multiproxy for the Northern Hemisphere by Jones et al. (1998), the multiproxy for the Northern Hemisphere by Crowley and Lowery (2000), the extratropical Northern Hemisphere tree-ring proxy by Esper et al. (2002), the tree-ring proxy for the northern part of the Northern Hemisphere by Briffa (2000), the multiproxy for the extratropical Northern Hemisphere produced by Moberg et al. (2005), the multiproxy for the Northern Hemisphere by Loehle (2007) which does not include any dendroclimatological information. Loehle (2007) used the data on pollen, stable  $^{18}\text{O}$  in ice cores and sediments, speleotemperature, Mg/Ca ratio and estimations based on diatoms and planktonic foraminifera. Ogurtsov and Lindholm (2006) showed that millennial climatic records have strong discrepancies in the low frequency domain and, thus, demonstrate different histories of temperature changes during the last 1000 years. They can be divided into three clusters:

- a. The reconstructions of Mann et al. (1999), Jones et al. (1998) and Crowley and Lowery (2000) (Figure 5A,B,C) show an obvious linear decrease of mean temperature until the middle of the 19<sup>th</sup> century and a sharp rise thereafter – the so-called “hockey-stick” form. These records show unambiguously that Earth in the 20<sup>th</sup> century is warmer than at any time during the last millennium.
- b. The reconstructions of Briffa (2000) and Esper et al. (2002) (Figure 5D,E) do not show a similar linear trend. Instead of this, multi-centennial long-term changes dominate, and the recent warming does not seem to be anomalous. To a degree they represent natural climate cycles.
- c. In reconstructions of Moberg et al. (2005) and Loehle (2007) (Figure 5F,G) millennial-scale cycles prevail and the twentieth century is not extremely warm.

In the work of Ogurtsov et al. (2011) it was shown that in spite of discrepancy between different proxies they all testify that in the extratropical part of the Northern Hemisphere the time interval 1988–2008 was likely the warmest two decades throughout the last 1000 years.

A major problem in paleoclimatic studies is short interval of calibration due to limited instrumental data – usually no more than 90–100 years. It is not enough to make confident judgment about the quality of reconstructed long-term climate changes (periods of hundreds of years or more). Further the time of the strongest climate signal, e.g. temperature, during the instrumental period may vary markedly within growing season in the 100-year calibration period (Tuovinen et al., 2009), thus affecting past reconstructions as well. Also divergence, i.e. e.g. temperature-proxy relation becomes opposite by periods (e.g. Seo et al., 2011), increases uncertainty in the reconstructions of the past climate beyond the instrumental period. High-resolution decline in the time series may be interpreted as a short-term dry or cold period although low indices in the series were caused by sudden loss

of needles by pests or pathogens (Ferretti et al., 2002). Therefore the current ability of paleoclimatology to reconstruct precisely the long-term - potentially the most powerful - climate variations is disputable.

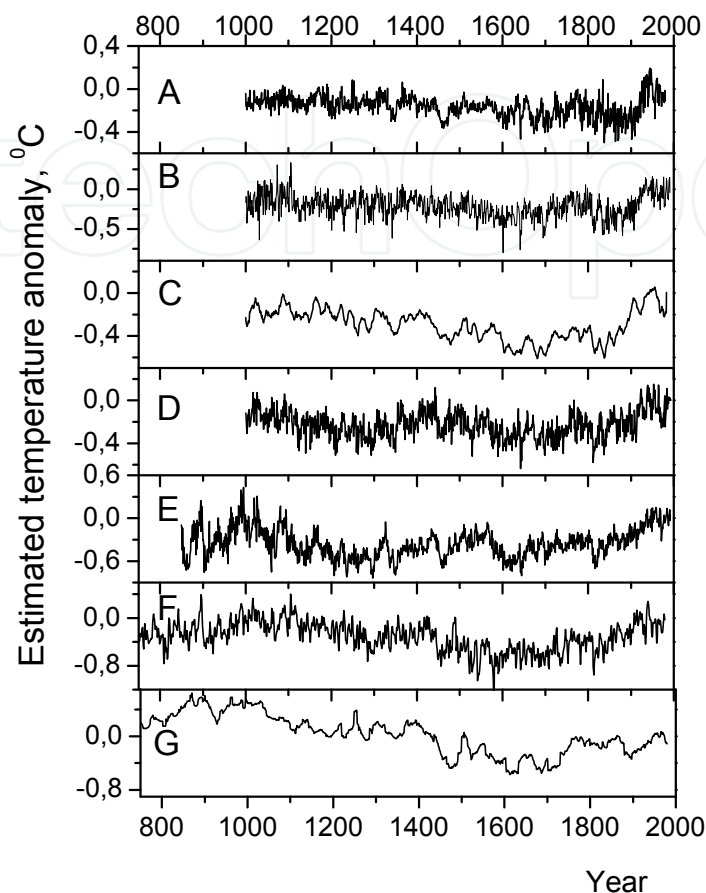


Fig. 5. Millennial-scale temperature proxies, obtained by: A – Mann et al. (1999), B – Jones et al. (1998), C – Crowley and Lowery (2000), D – Briffa (2000), E – Esper et al. (2002), F – Moberg et al. (2005), G – Loehle (2007). All the data sets were adjusted to the mean extratropical instrumental temperature for 1880-1980.

#### 4. Solar irradiance and terrestrial climate

Solar radiation is practically the only source of energy for the terrestrial atmosphere. Therefore the most evident direct effect of solar variability on climate is its influence on the Earth's radiative balance through variations in luminosity. It has been established that TSI follows the general 11-year cycle of solar activity (see Fig. 1E). The amplitude of this variation, however, is small – ca.  $2 \text{ Wm}^{-2}$ . It is not enough to effectively influence climatic processes, particularly if taken into account that short-term oscillations of energy input are substantially attenuated by the thermal inertia of oceans, which has large heat capacity and integrates variations in heat input. The attenuation of long-term (multidecadal and longer) variations is weaker. However it is unknown whether TSI has such slow variability. Direct satellite measurements over 2-3 cycles are not long enough for any decisive conclusion. Nevertheless many prolonged TSI reconstructions have been obtained by different researchers using sunspot numbers and radioisotopes as proxies (Fig. 6).

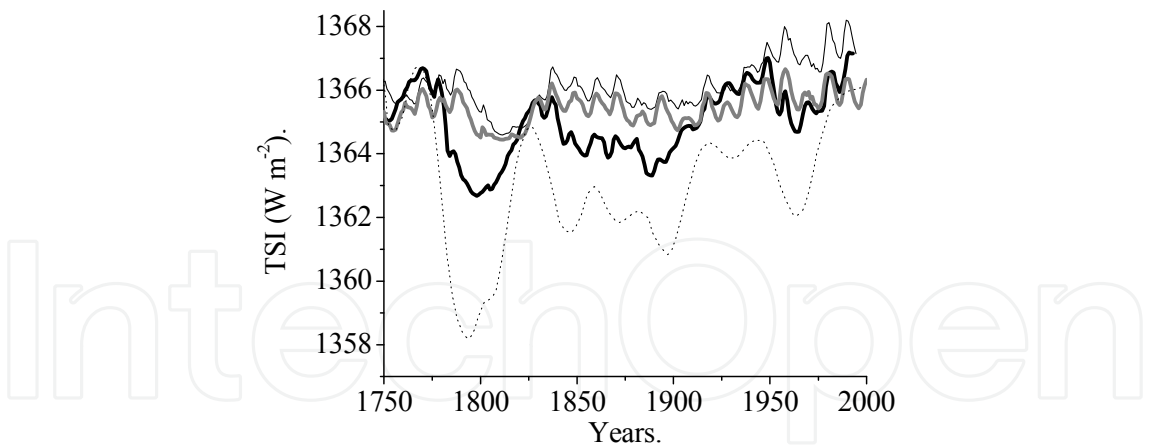


Fig. 6. Reconstructions past variations in the total solar irradiance obtained by: Hoyt and Schatten (1993) - thick black line; Lean et al. (1995) - thin black line; Beer et al. (2000) - dotted line; Mordvinov et al. (2004) - grey line.

During the 20<sup>th</sup> century, the increase in solar irradiance could have been 1-3 W m<sup>-2</sup> or more (Fig.6). That is enough to provide the radiative forcing of 0.18-0.52 W m<sup>-2</sup>. The IPCC estimates a smaller value – according to IPCC (2007) changes in solar irradiance since 1750 is expected to cause a radiative forcing of 0.06–0.30 W m<sup>-2</sup>. Let us evaluate the probable climatic response to this forcing. For a rough quantitative estimation we can multiply radiative forcing by climatic sensitivity  $\lambda_c$ . Estimations obtained using different methods, including analysis of instrumental temperature data, paleodata, the data of the satellite Earth Radiation Budget Experiment (ERBE) etc., are listed in Table 1.

Author	Way of estimation	$\lambda_c$ (°C W <sup>-1</sup> m <sup>2</sup> )
Lindzen and Giannitsis (1998)	Climatic response to volcanic explosions (Krakatau, Katmai, Pinatubo)	0.07
Idso (1998)	8 natural phenomena (equator to pole temperature gradient, faint early Sun paradox, etc.)	0.1
Lindzen and Choi (2009)	1985 to 1996 ERBE data, sea surface temperature	0.14
Lindzen et al. (2001)	Upper-level cloudiness and sea-surface temperature data from the tropical Pacific	0.17–0.43
Schwartz (2008)	Global surface temperature	0.25–0.79
Chylek et al. (2007)	Global surface temperature, CO <sub>2</sub> , aerosol optical depth after 1985	0.29–0.48
Chylek end Lohmann (2008)	Antarctic paleodata (temperature, CO <sub>2</sub> , CH <sub>4</sub> , dust) of LGM to Holocene transition	0.36–0.68
IPCC (2007)	Various ways of estimation	0.53–1.23
Andronova and Schlesinger (2001)	Global mean and hemispheric difference in surface air temperature 1856 - 1997	0.27–2.54
Frame et al. (2005)	Global surface temperature	0.32–3.14
Forster and Gregory (2006)	1985 to 1996 ERBE data 60°N to 60°S, global surface temperature	0.32–3.78

Table 1. Estimations of climate sensitivity.



Available assessments of  $\lambda_c$  differ by more than an order of magnitude (see Table 1). This is caused by the complexity of climatic system which has a lot of feedbacks. Many of these feedbacks are currently not well known. If we consider the estimations of IPCC (2007) we obtain that the increase of solar brightness in the 20<sup>th</sup> century could have resulted from corresponding global warming by 0.10-0.64<sup>o</sup> C. The difference between the lower and upper limits of the solar induced increase in the global temperature reaches a factor six. If we use the sensitivity evaluations not only of IPCC but also of other authors the difference will be even more. Such uncertainty does not allow us to draw any decisive conclusions about the role of the Sun in global warming. It may be significant as well as negligible. This result is in agreement with the IPCC (2007) considering current level of scientific understanding of TSI-climate link as low.

Variation in ultra-violet (UV) solar radiation, which effectively influences ozone layer, is another way to provide a link between solar luminosity and climate. The amplitude of the 11-year variation in UV radiation reaches several percent (ca. 6% at 20 nm). Ozone is the main gas involved in the radiative heating of the stratosphere. Solar-induced changes in ozone can therefore affect the radiative balance of the stratosphere with indirect effects on the troposphere and global circulation pattern. Possible reaction of climatic system to the UV solar variability was analyzed by Haigh (1996), Shindell et al. (1999), Gray et al. (2010).

5. Cosmic ray flux and terrestrial climate

The Sun can influence terrestrial weather and climate not only directly through variations of TSI but indirectly – via modulation of corpuscular radiation entering atmosphere. As we have noted above, the idea that cosmic ray flux could directly influence the weather was proposed by Ney (1959) and developed by Dickinson (1975). However the total energy input of the solar-modulated particles is very small as compared to the energy of atmospheric processes – see Table 2 (the data were taken from Vitinsky et al., 1986; Pudovkin, 1996 and Borisenkov, 1977).

Type of energy	Power (erg/day)
Energy brought in the Earth’s atmosphere by TSI	1.6×10 <sup>29</sup>
Energy brought in the Earth’s magnetosphere by solar wind	up to 3×10 <sup>23</sup>
Energy brought in the Earth’s magnetosphere by the fast solar wind during magnetic storms	up to 4×10 <sup>24</sup>
Energy brought in the Earth’s atmosphere by the flux of GCR with E>0.1 GeV	~10 <sup>22</sup>
Energy brought in the Earth’s atmosphere by the water vapor (latent heat)	4×10 <sup>28</sup>
Energy release by thunder clouds	up to 10 <sup>27</sup>
Power of the cyclone (anticyclone)	up to 10 <sup>25</sup>

Table 2. Characteristic energy of the terrestrial manifestations of solar activity and atmospheric processes.

It is evident from Table 2 that the energy coming into terrestrial magnetosphere and the atmosphere is a few orders of magnitude less than the energy of meteorological processes. Energy input from the very large solar flare of August 1972 is also small – ca. 10<sup>24</sup> erg. For this reason a linear relationship between cosmic rays and the Earth’s climate seems very

unlikely. However, the effect of cosmic radiation on the atmosphere could be very nonlinear. For example, minor changes in the physical and chemical parameters of the atmosphere, which does not require a lot of energy, could appreciably change its optical properties, disturb the energy balance and stimulate powerful atmospheric processes. Indeed, Pudovkin and Veretenenko (1992) have studied changes in the atmospheric transparency following the geomagnetic disturbances, caused by the fluxes of solar and galactic cosmic particles. They showed that corresponding changes in energy balance of the lower atmosphere can reach  $1.5 \times 10^{26}$  erg/day. Starkov and Roldugin (1995) have obtained even a larger value – ca.  $10^{27}$  erg/day. These estimations testify that cosmic radiation in fact can influence terrestrial weather. Since the intensity of cosmic rays is driven by solar activity the proposed mechanism of indirect solar-climate link appears quite plausible. A lot of experimental evidences of the reality of a link between the fluxes of cosmic particles and the physical state of the Earth's atmosphere have been obtained (Table 3).

In Table 3 CR-BR $\uparrow\downarrow$  indicates negative correlation between cosmic ray flux and background radiation i.e. positive correlation between cosmic ray intensity and cloudiness or/and aerosol content. This effect is considered as a manifestation of the *optical* mechanism of the solar-climate link. It is believed that the optical mechanism is caused by the influence of atmospheric ionization on production of new aerosol particles and cloud microphysics. Abbreviation CR-AC indicates a link between cosmic ray flux and atmospheric circulation. Despite the evidence for the reality of a link between cosmic rays and weather and climate the time-period of the experimental studies is rather short – usually no more than 30– 40 years. Even within this short time interval results are equivocal – e.g. some powerful flares were accompanied by increase of aerosol content in the atmosphere while some other flares did not show the effect. Extending data on low cloudiness (International Satellite Cloud Climatology Project – ISCCP) towards 2007 substantially reduces correlation between GCR and low-level clouds (see Fig. 15 in Gray et al., 2010). Moreover Roldugin and Tinsley (2004) reported that during 1978–1989 atmospheric transparency above 45 stations, situated at former USSR territory, decreased (not increased) during Forbush decreases, when sulfate aerosol loading to the stratosphere was high. However, Calgovic et al. (2010) find no response of global cloud cover to Forbush decreases at any altitude and latitude. Because of the lack of experimental data and some controversy in experimental results more information is needed before definite conclusions may be drawn. We can use the paleodata on nitrate concentration  $[\text{NO}_3^-]$  and the conductivity of an ice core extracted by specialists from the University of Kansas in (central Greenland, GISP2 H core, 72°N, 38°W, height 3230 m) for this purpose. Both glaciochemical series cover the time period of 1576–1991 and have extremely high time resolution (approximately 20 samples per year) (Dreschhoff and Zeller, 1994). As we have noted above nitrate concentration in ice could serve as a proxy of atmosphere's ionization. The conductivity of ice is connected with its acidity and, hence, reflects concentration of the sulfate aerosol in the atmosphere. Some  $[\text{NO}_3^-]$  peaks coincide in time with conductivity bursts ( Fig. 7). Ogurtsov (2011) analyzed such events in 1789, 1859, 1895, 1896, and 1908 and showed that the abrupt increase in the concentration of sulfate aerosols in the stratosphere due to additional ionization as a result from precipitation of solar cosmic ray energetic particles is one of the most probable factors that cause simultaneous origination of powerful peaks in the ice conductivity and nitrate concentration. Dreschhoff and Zeller (1994) have related the phenomenon to the direct effect of ionization on the formation of nacreous or polar stratospheric clouds (PSCs), which are largely composed of nitric acid ( $\text{HNO}_3$ ) droplets. Thus, coincidences of peaks in both

Authors	Time inter-val of obser-vation	Type of the data	The revealed effect	Geographic coverage	Time scale of the effect	Type of effect
Pudovkin and Veretenenko (1992)	1961-1984	A	Increase of direct background solar radiation during FDs	USSR, =60°-67° N	days	CR-BR
Roldugin and Vashenyuk (1994)	1972, 1976, 1979	A	Decrease of atmospheric transparency 1-3 days after SCR events	Murmansk, Arkhangelsk, Leningrad	days	CR-BR
Todd and Kniveton, (2004)	1983-2000	S	Reduction of high-level cloudiness after FDs	Antarctica	days	CR-BR
Tinsley and Deen (1991)	1953-1985	M	Link between FDs and winter cyclone intensity	Northern Hemisphere	days	CR-AC
Veretenenko and Pudovkin (1993)	1970-1986	M	Intensification of atmospheric circulation after SCR events and reduction after FDs		days	CR-AC
Shumilov et al. (1996)	Febru-ary 1983	L	Increase of stratospheric aerosol concentration at 15-25 km after GLE event	=45°-65° N Verkhne-tulomsk	days	CR-BR
Marichev et al. (2004)	March 1988, March 1989	L	Increase of stratospheric aerosol concentration at 40-45 km after geomagnetic disturbances	Tomsk	days	CR-BR
Svensmark et al. (2009)	1987-2007	S	Reduction in liquid cloudi-ness and concentration of fine aerosol particles after FDs	Globe	days	CR-BR
Laken et al, (2010)	1986-2006	S	Reduction of a total cloudiness after FDs	=30°-60° N =30°-60° S	days	CR-BR
Kondratyev and Nikolsky (1983)	1962-1970	R	Decrease of atmospheric transparency above 25 km when Wolf number rises from 50-70 to 170	Leningrad	10 years	CR-BR
ISCCP (Marsh and Svensmark, 2000; Palle et al., 2004)	1984-2004	S	Negative correlation between low-level cloudiness and GCR intensity	Globe	10 years	CR-BR
Lu et al. (2007)	1958-2004	M,R	Relationship between solar irradiance and geomagnetic activity and the atmospheric temperature.	Globe	Months-decades	CR-BR
Veretenenko et al. (2007)	~1880-1970	M	Correlation between surface pressure and Wolf number	North Atlantic =20°-40° N =45°-65° S	10-100 years	CR-AC

Table 3. Experimental evidences for a link between solar modulated cosmic radiation and physical state of the Earth’s atmosphere. Abbreviation A means data of actinometrical stations, M – data of meteorological stations, L – data of lidar observations, R- radiosonde data, S – satellite data.

studied glaciochemical series are manifestations of the effect that has been experimentally registered with lidar and satellite equipment for the last 25 years. This proves that the relationship between the aerosol concentration and the ionization rate in the stratosphere is real and makes it possible to extend the interval where this connection exists for more than 200 years. The result provides new evidence of the reality of optical mechanism of the Sun's influence on weather.

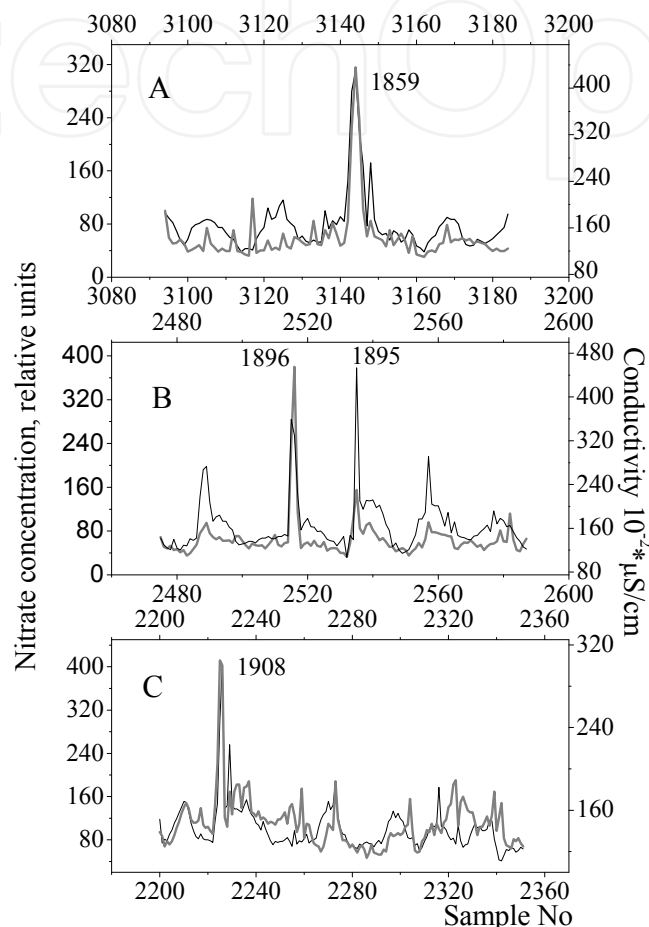


Fig. 7. Concentration of ions (thin black line) and conductivity (thick grey line): (a) in 1859 (the Carrington optical flare), (b) at the end of the 19th century, and (c) in 1908 (the Tunguska event). 100 relative units = 90.3 ng/g  $\text{NO}_3^-$ .

Optical mechanism could also provide solar-climate relationship over longer time scale. The effect of unphysical time lag between long-term variation in global temperature and Wolf number can also be explained in the framework of this mechanism. It has been established that long-term ( $T > 30$  yr) variation in global temperature resemble the variation in sunspot number since the mid-19th century which might be attributed to a solar-climatic connection (see Fig. 8). However, smoothed temperature outstrips solar activity that violates the cause-effect relationship. Friis-Christensen and Lassen (1991) have shown that this phenomenon could be explained by using solar cycle length (SCL) as an indicator of solar activity instead of sunspot numbers - SCL lead sunspot number by 1–3 cycles. However, physical processes responsible for this link have not been established so far, which calls for the search for alternative explanations.

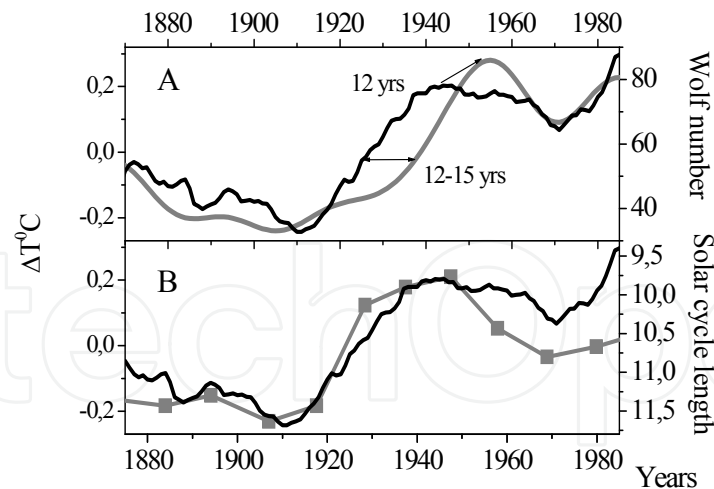


Fig. 8. A – gray curve - Wolf numbers smoothed by the Fourier-filter (frequencies above  $0.04 \text{ years}^{-1}$  are suppressed). Black curve - annual temperature of Northern hemisphere (Jones et al., 2001) smoothed by 15 years. B – gray curve - the length of a solar cycle smoothed on three points. Black curve - the smoothed annual temperature of Northern hemisphere.

Ogurtsov et al. (2004) have revealed a negative correlation between century-type variations in  $\text{NO}_3^-$  concentration in Greenland ice and sunspot number. This study found that the Gleissberg cycle in nitrate leads the corresponding variation in sunspot number by 15–18 years during the last 3 centuries. Since  $[\text{NO}_3^-]$  in polar ice is connected with the stratosphere's ionization it is reasonable to assume that the century-long cycle in stratospheric ionization advances the corresponding cycle in solar activity. Experimental estimation of the aerosol optical depth of the atmosphere, performed by Bryson and Goodman (1980) using data of 42 actinometrical stations situated within  $25^{\circ}$ – $65^{\circ}$  N belt, showed the presence of distinct multidecadal variation (Fig. 9). Long-term changes of atmospheric transparency are generally the result of the corresponding change in the optical depth of the stratosphere. The century-type periodicity in the stratospheric aerosol transparency correlates negatively with the corresponding cycle in sunspots and lead it by 20–25 yrs (Figure 9B). Aerosol in the stratosphere is basically sulfate with a composition of about 75%  $\text{H}_2\text{SO}_4$  and 25%  $\text{H}_2\text{O}$ . Volcanoes are the main source of  $\text{SO}_2$  in stratosphere, from which  $\text{H}_2\text{SO}_4$  is generated. Long-term variation in volcanic activity lags behind aerosol transparency instead of advancing it (Fig. 9C). Volcanic  $\text{SO}_2$  loading into the stratosphere estimated by Kondratyev (1999) does not correlate well with the aerosol optical depth (Fig. 9D). This means that long-term variation of the sulfate aerosol abundance in the stratosphere is influenced not only by volcanic  $\text{SO}_2$  input but also by one additional factor. Ogurtsov (2007) has hypothesized that this factor might be a century-long cycle in stratospheric ionization, which, in turn, is caused by superposition of the century-scale variations in GCR and SCR intensity. I.e. long-term variation of aerosol optical depth of stratosphere is driven by corresponding change in solar-cosmic corpuscular radiation, which produces century-scale cycle in stratospheric ionization advancing the Gleissberg periodicity in sunspot number. The estimation by Ogurtsov (2007) using energy-balance model showed that the observed variation in the atmosphere's transparency during the 20<sup>th</sup> century is enough to provide the global temperature change. Thus, according to Ogurtsov (2007) the positive time lag between long-term variations in surface temperature and Wolf number could not be linked to the change in solar cycle length but to the variation in



stratospheric optical depth. The advancing development of century-long cyclicity in temperature is a result of the following chain of physical processes: solar activity → fluxes of ionizing particles (SCR and GCR) → ionization → number of ultra-fine particles in stratosphere → concentration of stratospheric aerosol → atmospheric transparency → background solar radiation → surface temperature. Thus the effect of positive time shift between century-long variations in temperature and sunspot number could be explained in the framework of optical mechanism of solar-climate link. The most serious problem of the proposed mechanism is the lack of knowledge about the physical processes responsible for a link between ionization and the number of condensation nuclei (CN) and cloud condensation nuclei (CCN). Ion-induced particle formation is a plausible mechanism to provide this link. New aerosols initially appear as small (<2 nm) clusters containing a few molecules. These clusters either may grow by further condensation of nearby gas molecules or evaporate. Above a certain critical size, the cluster is thermodynamically stable and its probability to grow by further condensation is larger than the probability to break up by evaporation. Atmospheric ions enhance the process of clustering of condensable vapor. The presence of a charge stabilizes the embryonic cluster through Coulomb attraction, and reduces the critical size (Yu and Turco, 2000, 2001). The term *ion-induced nucleation* (IIN) describes the formation of new ultra-fine particles from the gas phase, in which ions take a part. The theory of this process was developed in the works of Arnold (1982, 2006), Kazil and Lovejoy (2004) and Yu (2006). It has been shown that although INN is connected directly with ionization, it depends also on the physical parameters of the atmosphere, particularly on the concentration of sulfuric acid vapor [H<sub>2</sub>SO<sub>4</sub>] and temperature. High values of [H<sub>2</sub>SO<sub>4</sub>] (about 10<sup>7</sup> cm<sup>-3</sup> or more) and low (<-50° C) temperature are necessary for effective ion-induced generation of ultra-fine aerosol particles. Therefore solar activity affects the atmosphere in the framework of INN mechanism not directly but its influence is mediated by a few internal terrestrial phenomena – volcanic activity, meteorology etc. Such a complex solar-atmosphere link might be the cause of instability of solar-climatic correlations.

The charge also accelerates the early growth process, due to an enhanced collision probability. As a result the charge appreciably helps the sub-critical embryos to survive and grow to CN and CCN sizes. Thus, despite the IIN mechanism is believed to work mainly under clear sky conditions, it can also communicate solar activity to cloudiness. Experimental evidence for IIN have been obtained by Eichkorn et al. (2002); Lee et al. (2003) and Svensmark et al. (2007). It was shown that changes in the global atmospheric circuit can influence cloud microphysics (Tinsley, 2000). The global circuit causes a vertical current density in fair (non-thunderstorm) weather regions. This ionosphere-surface fair weather current density passes through clouds causing local droplet and aerosol charging at their boundaries, where sharp gradients in air conductivity can occur. Modulation of the global circuit by solar-induced changes in atmospheric ionization (both GCR and SCR effect) provides an alternative plausible route by which solar changes can be transmitted to the lower atmosphere (Tinsley, 2000, 2008). Three potential near-cloud mechanisms of the influence of the conduction current density on clouds have been proposed:

- a. *electroscavenging* is a result of electrically-enhanced efficiency of the collision between charged particles with liquid droplets (e.g. Tinsley et al., 2008).
- b. *Electrofreezing* is connected to the possible influence of electric properties of aerosol on the rate of freezing of thermodynamically unstable super-cooled water droplets (Tinsley and Dean, 1991).

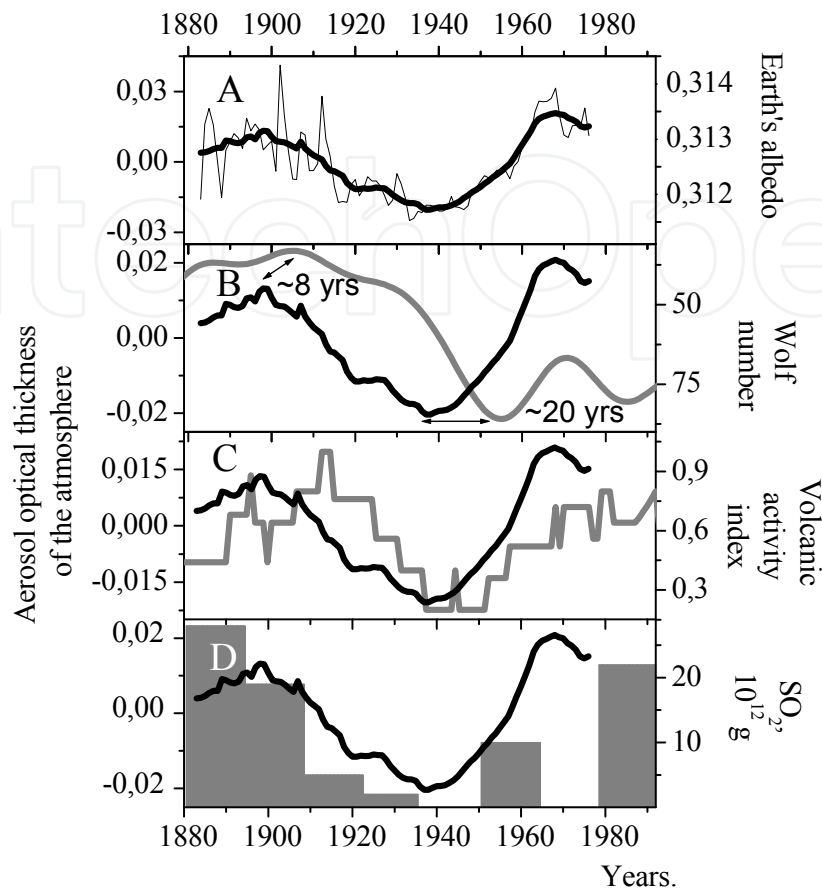


Fig. 9. A – aerosol optical thickness of a middle latitude (25°-45°) stratosphere after Bryson and Goodman (1980) annually interpolated. Thin curve - raw data, thick curve - data smoothed by 11 years; B – gray curve - Wolf number smoothed by the Fourier filter (frequencies above 0.04 years<sup>-1</sup> are suppressed), black curve - aerosol optical thickness of a stratosphere, smoothed by 11 years; C – gray curve - volcanic explosive index after Briffa et al. (1998) smoothed by 25 years. Black curve – smoothed aerosol transparency; D – gray columns – SO<sub>2</sub> loading to stratosphere after Kondratyev (1999).

c. *Electrocoalescence* is connected to the possible increase in coalescence between charged droplets, which could influence droplet size or number (Harrison and Ambaum 2009).

As we have noted above, all the mechanisms work at the boundaries of super-cooled and liquid clouds. Direct experimental evidence for a link between atmospheric electricity and cloud microphysics were obtained by Harrison and Ambaum (2009) as well as Nicoll and Harrison (2009). It should be considered also that the global circuit is dependent on atmospheric column resistance, which, in turn is influenced not only by ionization but also by concentration of sulfate aerosol in the stratosphere, concentration of cosmic dust in upper atmosphere and, probably other factors. The contribution of these factors might obscure solar impact on the vertical current density.

A new mechanism for the connection between solar-modulated corpuscular radiation and physical processes in the lower atmosphere was proposed by Avakyan and Voronin (2010).

They assumed that microwave radiation of the Earth ionosphere during solar flares and geomagnetic storms might influence the condensation processes in the troposphere and thus influence the weather.

Our understanding of possible physical mechanisms of influence of the flux of solar-cosmic corpuscles on the atmosphere of the Earth and influence of solar and geomagnetic activity on weather and climate has considerably improved during the last 2-3 decades.

## 6. Conclusion and prospects for further research

The last few decades were marked by considerable successes in helioclimateology. Both satellite and ground-based observations have brought a lot of new evidence for a link between solar activity and the phenomena of the lower atmosphere. The progress in theory, experiment and modeling has also significantly increased our knowledge of the Sun and solar-terrestrial connections. Nevertheless, the absolutely conclusive proof of the reality of the solar-climate link is still missing. The lack of facts and understanding about the connecting processes at work is the main cause of this shortcoming. Data obtained by experimental observation are quite precise but rather short in time scale. Paleoproxies are much longer but their uncertainty generally increases as a function of time from the present. Thus, in solar-climate research we face a kind of “uncertainty principle”:

$$\frac{\Delta X}{\Delta T} \approx \text{const}, \quad (7)$$

where  $\Delta X$  is the uncertainty of the data, and  $\Delta T$  is the length of the  $X$  time series.

Moreover, it has been shown that the Sun-climate connection, even if it actually exists, may be realized by an indirect and nonlinear way. As a result the search for a link between solar activity and weather and climate has turned out to be a more difficult task than was previously anticipated. Quite possibly further future research in helioclimateology will follow the guidelines envisaged below:

1. Further gathering and accumulation of the information together with its subsequent systematization. This concerns both instrumental monitoring of solar-cosmic and geophysical parameters and work on constructing new paleoreconstructions of solar activity and climate. The development of methods of paleoastrophysics and paleoclimatology is an integral part of this work.
2. The improvement of the methods of statistical analysis, particularly, methods aimed at the search and detection of nonlinear interrelations between the different time series.
3. Further laboratory research of the physical processes which possibly provide a link between solar activity and the low atmosphere.
4. Increasing our understanding about the climatic system and improvements of methods of climatic modeling.

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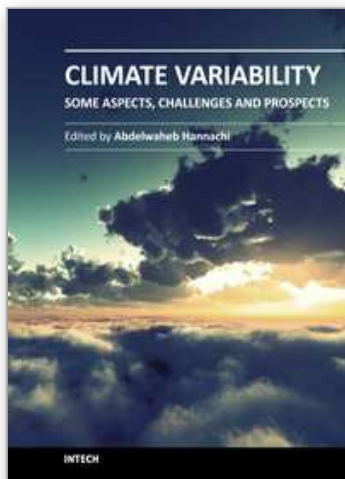


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