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Solar Wind, Cosmic Rays and Space Weather Effects on Global Climate Change

Lev Dorman[1, 2]

[1] Cosmic Ray Department of IZMIRAN, Russian Academy of Science,
[2] Israel Cosmic Ray & Space Weather Center and Emilio Segre' Observatory, affiliated to Tel Aviv University, Technion and Israel Space Agency
lid@physics.technion.ac.il; lid010529@gmail.com

Abstract. The action of space factors on the Earth's climate is realized mostly through cosmic rays and space dust influenced on formation of clouds controlled the total energy input from the Sun into the Earth's atmosphere. From other hand, the propagation and modulation of galactic CR (generated mostly during Supernova explosions and in Supernova remnants in our Galaxy), in the Heliosphere are determined by their interactions with magnetic fields frozen in solar wind and in coronal mass ejections with accompanied interplanetary shock waves. We determine here the link: solar wind – galactic cosmic rays – climate change.

Keywords: solar wind, galactic cosmic rays, clouds, climate change

1 Introduction

It is obviously now that according to data for the past on big variations of planetary surface temperature in scales of many millions and thousands years the Earth's global climate change is determined mostly by space factors: moving of the Solar system around the center of our Galaxy with crossing galactic arms and dust-molecular clouds, nearby supernova and supernova remnants. Important space factor is also the cyclic variations of solar activity and solar wind (mostly in scales of hundreds years and decades). The action of space factors on the Earth's climate is realized mostly through cosmic rays (CR) and space dust influenced on formation of clouds controlled the total energy input from the Sun into the Earth's atmosphere. The propagation and modulation of galactic CR (generated mostly during Supernova explosions and in Supernova remnants in our Galaxy), in the Heliosphere are determined by their interactions with magnetic fields frozen in solar wind and in coronal mass ejections (CME) with accompanied interplanetary shock waves (produced big magnetic storms during their interactions with the Earth's magnetosphere). The most difficult problem of monitoring and forecasting the modulation of galactic CR in the Heliosphere is that the CR intensity in some 4D space-time point is determined not by the level of solar activity at this time of observations and electro-magnetic conditions in this 4D-point but by electromagnetic conditions in total Heliosphere. These conditions in total Heliosphere are determined by development of solar activity during many months before the time-point of observations. It is main cause of so called hysteresis phenomenon in connection galactic CR – solar activity. From other hand, detail investigations of this phenomenon give important possibility to estimate conditions in and dimension of Heliosphere. To solve described above problem of CR modulation in the Heliosphere, we considered as the first step behavior of high energy particles (more than several GeV, for which the diffusion time of propagation in Heliosphere is very small in comparison with characteristic time of modulation) on the basis of neutron monitor data in the frame of convection diffusion theory, and then take into account drift effects. For small energy galactic CR detected on satellites and space probes we need to take into account also additional time lag caused by diffusion in the Heliosphere. Then we consider the problem of CR modulation forecasting for several months and years ahead, what gives possibility to forecast some part of global climate change caused by CR.

2 Solar Activity and Cosmic Ray Variations as Possible Causes of Climate Change

About two hundred years ago the famous astronomer William Herschel (1801) suggested that the price of wheat in England was directly related to the number of sunspots with periodicity about 11 years. He noticed that less rain fell when the number of sunspots was big (Joseph in the Bible, recognised a similar periodicity in food production in Egypt, about 4,000 years ago). The solar activity level is known from direct observations over the past 450 years, and from data of cosmogenic nuclides (through CR intensity variations) for more than 10,000 years (see details in Chapters 10 and 17 in Dorman, M2004). Over this period there is a striking qualitative correlation between cold and warm climate periods and high and low levels of galactic CR intensity, correspondingly (low and high solar activity). As an example, Fig. 1 shows the change in the concentration of radiocarbon ^{14}C during the last millennium (a higher concentration of radiocarbon corresponds to a higher intensity of galactic CR and to lower solar activity).

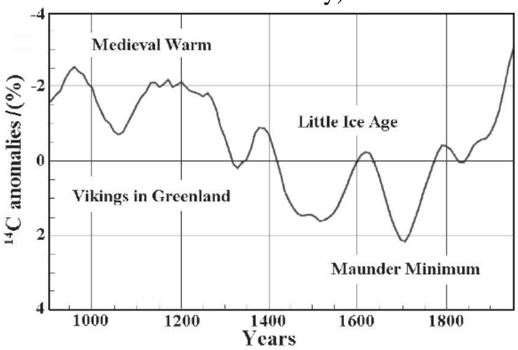

Fig. 1. The change of CR intensity reflected in radiocarbon concentration during the last millennium. According to Swensmark (2000).

It can be seen from Fig. 1 that during 1000-1300 the CR intensity was low and solar activity high, which coincided with the warm medieval period (during this period Vikings settled in Greenland). After 1300 solar activity decreased and CR intensity increased, and a long cold period followed (the so called Little Ice Age, which included the Maunder minimum 1645-1715 and lasted until the middle of 19th century).

3 The Possible Role of Solar Activity and Solar Irradiance in Climate Change

Friis-Christiansen and Lassen (1991), Lassen and Friis-Christiansen (1995) found, from four hundred years of data, that the filtered solar activity cycle length is closely connected to variations of the average surface temperature in the northern hemisphere. Labitzke and Van Loon (1993) showed, from solar cycle data, that the air temperature increases with increasing levels of solar activity. Swensmark (2000) also discussed the problem of the possible influence of solar activity on the Earth's climate through changes in solar irradiance. But the direct satellite measurements of the solar irradiance during the last two solar cycles showed that the variations during a solar cycle was only about 0.1%, corresponding to about 0.3 W/m^2. This value is too small to explain the observed climate changes during solar cycles (Lean et al., 1995). Much bigger changes during a solar cycle occur in UV radiation (about 10%, which is important in the formation of the ozone layer). Haigh (1996), and Shindell et al. (1999) suggested that the heating of the stratosphere by UV radiation can be dynamically transported into the troposphere. This effect might be responsible for small contributions towards 11 and 22 years cycle modulation of climate but not to the 100 years or more of climate changes that were observed in the past and during the last hundred years.

4 Cosmic Rays as an Important Link Between Solar Activity and Climate Change

Many authors have considered the influence of galactic and solar CR on the Earth's climate. Cosmic Radiation is the main source of air ionization below 40-35 km (only near the ground level, lower than 1 km, are radioactive gases from the soil also important in air ionization) – see review in Dorman, M2004). The first who suggest a possible influence of air ionization by CR on the climate was Ney (1959). Swensmark (2000) noted that the variation in air ionization caused by CR could potentially influence the optical transparency of the atmosphere, by either a change in aerosol formation or influence the transition between the different phases of water. Many authors considered these possibilities (Dickinson, 1975; Pudovkin and Raspopov, 1992, Pudovkin and Veretenenko, 1995, 1996; Belov et al., 2005; Dorman, 2005a,b, 2006, 2007). The possible statistical connections between the solar activity cycle and the corresponding long term CR intensity variations with characteristics of climate change were considered in Dorman et al. (1987, 1988a,b). Dorman et al. (1997) reconstructed CR intensity variations over the last four hundred years on the basis of solar activity data, and compared the results with radiocarbon data.

Cosmic rays play a key role in the formation of thunder-storms and lightnings (see extended review in Dorman, M2004, Chapter 11). Many authors (Markson, 1978; Price, 2000; Tinsley, 2000; Schlegel et al., 2001; Dorman and Dorman, 2005; Dorman et al., 2003) have considered atmospheric electric field phenomena as a possible link between solar activity and the Earth's climate. Also important in the relationship between CR and climate, is the influence of long term changes in the geomagnetic field on CR intensity through the changes of cutoff rigidity (see review in Dorman, M2009). It can be consider the general hierarchical relationship: (solar activity cycles + long-term changes in the geomagnetic field) □ (CR long term modulation in the Heliosphere + long term variation of cutoff rigidity) □ (long term variation of clouds covering and aerosols + atmospheric electric field effects) □ climate change.

5 The Connection Between Galactic CR Solar Cycles and the Earth's Cloud Coverage

Recent research has shown that the Earth's cloud coverage (observed by satellites) is strongly influenced by CR intensity (Swensmark, 2000; Marsh and Swensmark, 2000a,b). Clouds influence the irradiative properties of the atmosphere by both cooling through reflection of incoming short wave solar radiation, and heating through trapping of outgoing long wave radiation (the greenhouse effect). The overall result depends largely on the height of the clouds. According to Hartmann (1993), high optically thin clouds tend to heat while low optically thick clouds tend to cool (see Table 1).

Table 1. Global annual mean forcing due to various types of clouds, from the Earth Radiation Budget Experiment (ERBE), according to Hartmann (1993). The positive forcing increases the net radiation budget of the Earth and leads to a warming; negative forcing decreases the net radiation and causes a cooling. (Note that the global fraction implies that 36.7% of the Earth is cloud free.)

Parameter	High clouds		Middle clouds		Low clouds	Total
	Thin	Thick	Thin	Thick	All	
Global fraction /(%)	10.1	8.6	10.7	7.3	26.6	63.3
Forcing (relative to clear sky):						
Albedo (SW radiation)/($W{\cdot}m^{-2}$)	-4.1	-15.6	-3.7	-9.9	-20.2	-53.5
Outgoing LW radiation /($W{\cdot}m^{-2}$)	6.5	8.6	4.8	2.4	3.5	25.8
Net forcing /($W{\cdot}m^{-2}$)	2.4	-7.0	1.1	-7.5	-16.7	-27.7

Connection of CR intensity global variation with the Earth cloud covering is illustrated by Fig. 2, and separately with different types of clouds – by Fig. 3.

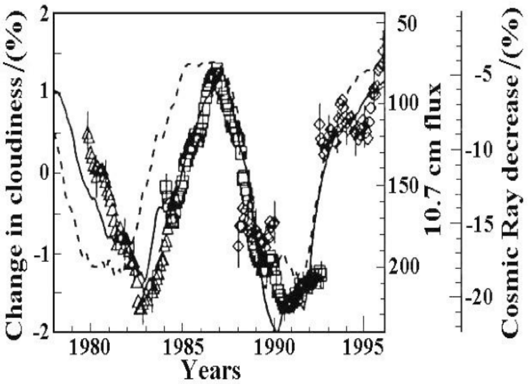

Fig. 2. Changes in the Earth's cloud coverage: triangles - from satellite Nimbus 7); squares - from the International Satellite Cloud Climatology Project); diamonds – from the Defense Meteorological Satellite Program). Solid curve – CR intensity variation according to Climax neutron monitor, normalized to May 1965. Broken curve – solar radio flux at 10.7 cm. All data are smoothed using twelve months running mean. According to Swensmark (2000).

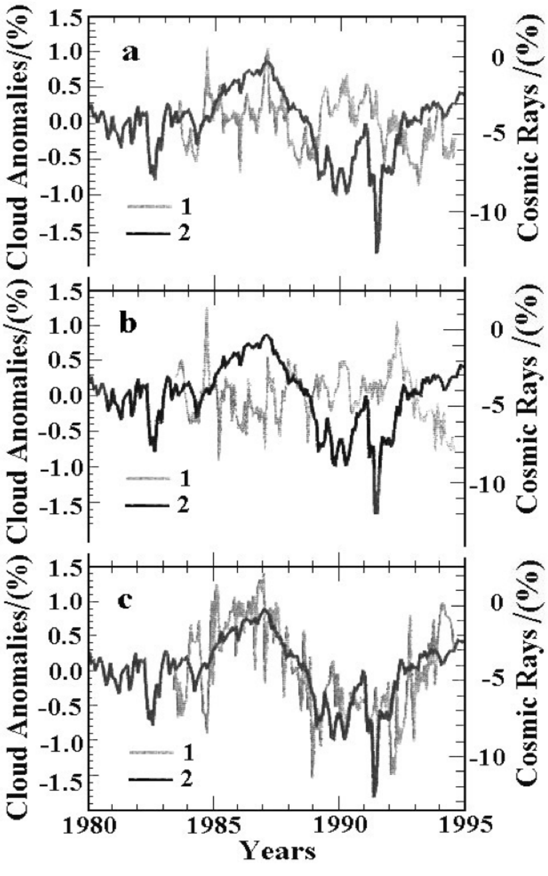

Fig. 3. CR intensity obtained at the Huancayo/Haleakala neutron monitor (normalized to October 1965, curve 2) in comparison with global average monthly cloud coverage anomalies (curves 1) at heights, H, for: **a** – high clouds, H > 6.5 km, **b** – middle clouds, 6.5 km >H > 3.2 km, and **c** – low clouds, H < 3.2 km. According to Marsh and Swensmark (2000).

From Fig. 2 can be seen that variation in cloudiness corresponds very well to variation in CR without any time lag, and the decreasing of CR intensity in Climax neutron monitor on 15% corresponds decreasing in cloudiness on about 3% (positive correlation). From other hand, from Table 1 we can see that the total cloudiness gives input of solar energy – 27.7 w/m^2, so 3% decreasing of cloudiness will give about + 1 w/m^2.

From Fig. 3 can be seen that practically is no connection between CR intensity variations and changes in cloudiness for high and middle altitude clouds (panels **a** and **b**), but is a high positive correlation for low altitude clouds (panel **c**).

6 On Connection of Cosmic Ray Variation with Surface Planetary Temperature During the Last Thousand Years and During 1935-1995

From previous Section 4 follows that with CR intensity decreasing decreases planetary cloudiness what leads to increasing of solar energy input in the low atmosphere and increasing of planetary surface temperature. This can be demonstrate by data of radiocarbon for the last thousand years (see Fig. 1) and by direct CR measurements for about 60 years from 1935 to 1995 (see Fig. 4)

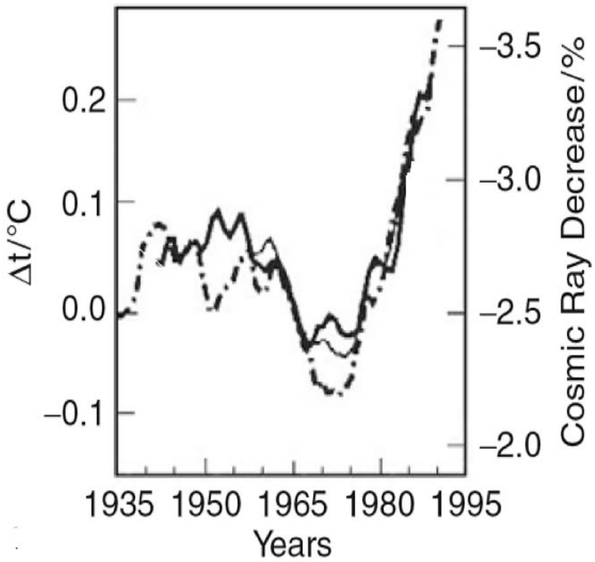

Fig. 4. Eleven year average Northern hemisphere mari-ne and land air temperature variation □t (broken curve), compared with eleven year average CR intensity (thick solid curve – from data of Compton type ion chambers shielded by 10 cm Pb (1937-1994, normalized to 1965), and thin solid curve – from Climax neutron monitor (normalized to ion chambers). According to Swensmark (2000).

7 Solar Irradiance and Cosmic Ray Fluxes during Maunder Minimum: Influence on Climate Change

During Maunder minimum the CR intensity was very high, so the planetary surface temperature is expected to be lower than in years with high level of solar activity. As was shown above (see Fig. 1), exactly this was observed by using ^{14}C data. More detail data on solar irradiation flux, CR intensity (through ^{10}Be), and the air surface temperature are shown in Fig. 5. From Fig. 5 can be clear seen that non solar irradiance, but CR intensity variation is mostly responsible for observed climate change during Maunder minimum.

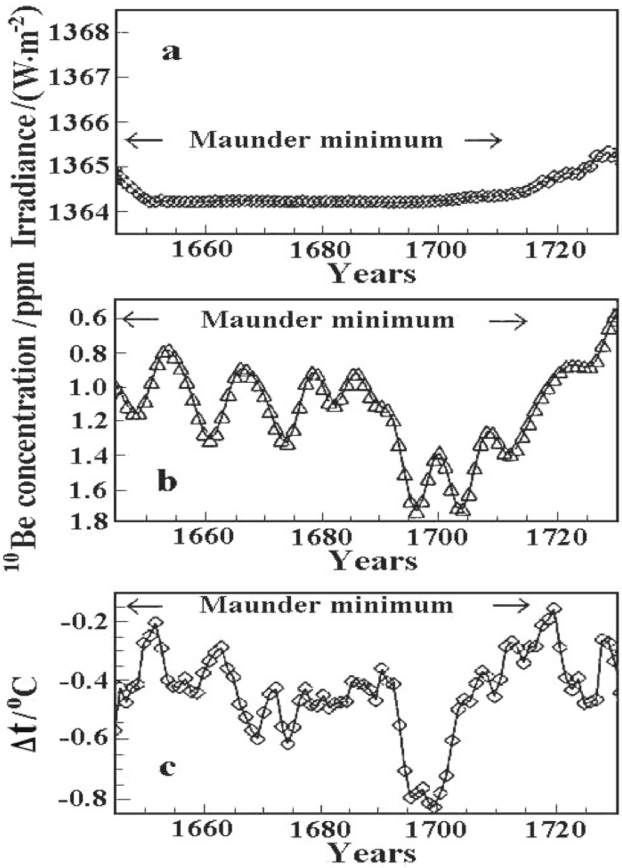

Fig. 5. Situation in the Maunder minimum: **a** – reconstructed solar irradiance (Labitzke and Van Loon, 1993); **b** – CR intensity according to concentration of ^{10}Be (Beer et al., 1991); **c** – reconstructed relative change of air surface temperature, Δt, for the Northern hemisphere (Jones et al., 1998). According to Swensmark (2000).

8 Variations of Cosmic Ray Intensity and Wheat Prices in Medieval England

As it was noted in Section 2, Herschel's observations (1801) were based on the published wheat prices (Smith, M1776), and showed that five prolonged periods of sunspot numbers correlated with costly wheat. This idea was taken up by the English economist William Jevons (1875, 1882). He directed his attention to the wheat prices from 1259 to 1400 and showed that the time intervals between high prices were close to 10-11 years. The coincidence of these intervals with the period of the eleven year cycle of solar activity led him to suggesting that the solar activity cycle was a 'synchronization' factor in the fluctuations of wheat prices. As a next step, he extrapolated his theory to stock markets of the 19th Century in England and was impressed by a close coincidence of five stock exchange panics with five minima in solar spot numbers that preceded these panics. The Rogers (M1887) database on wheat prices in medieval England was used by Pustil'nik, Dorman, and Yom Din (2003) to search for possible influences of solar activity and CR intensity variations on wheat prices. Obtained results are demonstrated in Figs. 6 and 7.

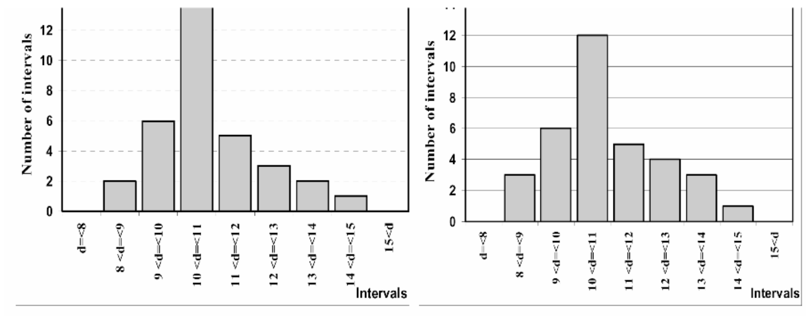

Fig. 6. Distributions of intervals d (in years) between wheat price bursts during 1249-1702 (left), and of intervals between minimums of sunspot numbers during 1700-2000 (right). According to Pustil'nik, Dorman, and Yom Din (2003).

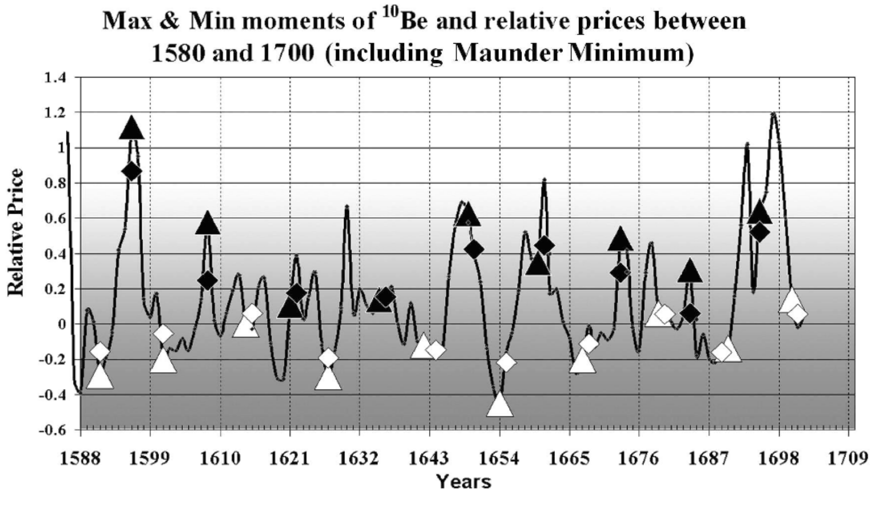

Fig. 7. Relative wheat prices at moments of minimum and maximum CR intensity determined according to ^{10}Be data (Beer et al., 1998). White (black) diamonds show prices averaged for three-year intervals centred at moments of minimum (maximum) CR intensity. White (black) triangles show prices at moments of minimum (maximum) CR intensity. From Pustil'nik et al. (2003).

From Fig. 6 can be seen that the distributions of intervals between wheat price bursts and between minimums of sunspot numbers (or corresponding maximums of CR intensity) are similar, and from Fig. 7 – that with increases of CR intensity are increases also wheat prices (let me remember that for climate in England with a lot of water, for wheat production are important solar days number which decreases with increases CR intensity what leads to decreasing of wheat production and increasing of wheat prices). Let me note that in many other regions of our planet, where is not enough water for agriculture production, the situation expected to be opposite: increasing of CR intensity will lead to increasing of cloudiness, increasing of raining and increasing of wheat and other agriculture production, and to corresponding decreasing of prices.

9 On the Influence of Galactic CR Forbush Decreases and Solar CR Increases on Rainfall

A decrease of atmospheric ionization leads to a decrease in the concentration of charge condensation centres. In these periods, a decrease of total cloudiness and atmosphere turbulence together with an increase in isobaric levels is observed (Veretenenko and Pudovkin, 1994). As a result, a decrease of rainfall is also expected. Stozhkov et al. (1995a,b, 1996), and Stozhkov (2002) analyzed 70 events of Forbush decreases (defined as a rapid decrease in observed galactic CR intensity, and caused by big geomagnetic storms) observed in 1956-1993 and compared these events with rainfall data over the former USSR. It was found that during the main phase of the Forbush decrease, the daily rainfall levels decreases by about 17%. Similarly, Todd and Kniveton (2001, 2004) investigating 32 Forbush decreases over the period 1983-2000, found reduced cloud cover on 12-18%.

During big solar CR events, when CR intensity and ionization in the atmosphere significantly increases, an inverse situation is expected and the increase in cloudiness leads to an increase in rainfall. Studies of Stozhkov et al. (1995a,b, 1996), and Stozhkov (2002) involving 53 events of solar CR enhancements, between 1942-1993, showed a positive increase of about 13% in the total rainfall over the former USSR.

10 Convection-Diffusion and Drift Mechanisms for Long-Term Galactic CR Variation: Possible Forecasting of Some Part of Climate Change Caused by Cosmic Rays

From above consideration follows that CR may be considered as sufficient link determined some part of solar wind as element of space weather influence on the climate change. From this point of view it is important to understand mechanisms of galactic CR long-term variations and on this basis to forecast expected CR intensity in near future. In Dorman (2005a,b, 2006) it was made on basis of monthly sunspot numbers W with taking into account time-lag between processes on the Sun and situation in the interplanetary space as well as the sign of general magnetic field (convection diffusion + drift modulations, see Fig. 8).

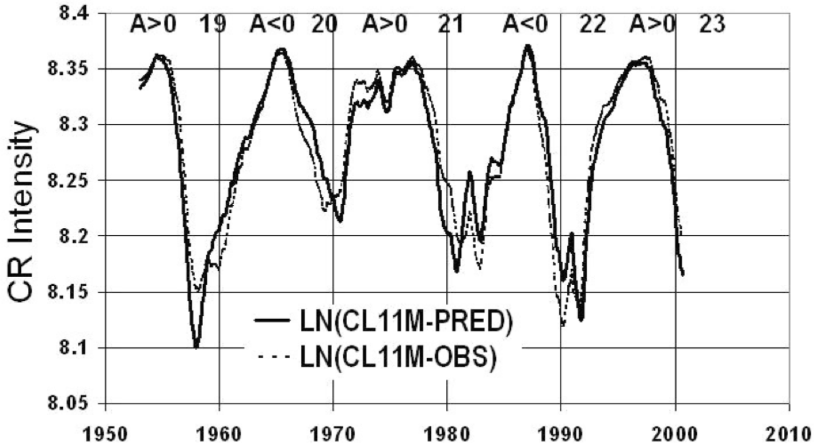

Fig. 8. Comparison of observed galactic CR variations during about 50 years (as 11 month moving averaged at Climax NM) - ln(CL11M-OBS) with predicted in the frame of convection-diffusion and drift modulations ln(CL11M-PRED). According to Dorman (2006).

From obtained results follows that in the frame of convection-diffusion and drift models can be determined with very good accuracy expected galactic CR intensity in the past (when W are known) as well as behaviour of CR intensity in future (if sunspot numbers W can be well forecast).

11 Influence of Main Geomagnetic Field on Global Climate Change through CR Cutoff Rigidity Variation

When we consider galactic CR variations $\square I/I_0$ as a factor influenced on global climate change we need to take into account not only the effects of solar wind and Heliosphere, but also effects of cutoff rigidity R_C changes on the CR intensity variation: $\square I/I_0 = -\square R_C \times W(R_C, R_C)$, where $\square R_C$ is the change of cutoff rigidity and $W(R_C, R_C)$ is the coupling function (see in details in Dorman, M2004, M2009). Results of trajectory calculations of R_C changes are shown in Table 2.

Table 2. Vertical cutoff rigidities R_C (in GV) for epochs 1600, 1700, 1800, 1900, and 2000, as well as change from 1900 to 2000. According to Shea and Smart (2003).

Lat.	Long. (E)	Epoch 2000	Epoch 1900	Epoch 1800	Epoch 1700	Epoch 1600	Change 1900–2000	Region
55	30	2.30	2.84	2.31	1.49	1.31	−0.54	Europe
50	0	3.36	2.94	2.01	1.33	1.81	−0.42	Europe
50	15	3.52	3.83	2.85	1.69	1.76	−0.31	Europe
40	15	7.22	7.62	5.86	3.98	3.97	−0.40	Europe
45	285	1.45	1.20	1.52	2.36	4.1	+0.25	N. Amer.
40	255	2.55	3.18	4.08	4.88	5.89	−0.63	N. Amer.
20	255	8.67	12.02	14.11	15.05	16.85	−3.35	N. Amer.
20	300	10.01	7.36	9.24	12.31	15.41	+2.65	N. Amer.
50	105	4.25	4.65	5.08	5.79	8.60	0.40	Asia
40	120	9.25	9.48	10.24	11.28	13.88	−0.23	Asia
35	135	11.79	11.68	12.40	13.13	14.39	+0.11	Japan
−25	150	8.56	9.75	10.41	11.54	11.35	−1.19	Australia
−35	15	4.40	5.93	8.41	11.29	12.19	1.53	S. Africa
−35	300	8.94	12.07	13.09	10.84	8.10	3.13	S. Amer.

12 Solar System Moving Around the Galactic Centre and Crossing Galaxy's Arms: Influence on the Earth's Climate through Cosmic Rays and Dust

Above we considered space factors acted on the Earth's Climate mainly through CR in frame of scales not bigger than one thousand years. In Fig. 9 are shown data on planetary surface temperature changing during the last 520 million years, caused to the moving of the Solar System around the centre of our Galaxy and crossing galactic arms with bigger probability to interact with molecular-dust clouds and supernova remnants (with bigger intensity of CR and higher density of space dust, which both lead to increasing of cloudiness and decreasing of planetary surface temperature).

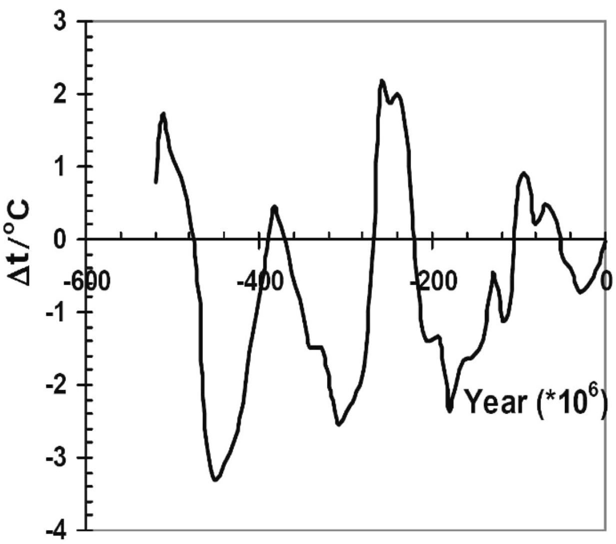

Fig. 9. Changes of planetary air temperature, □t, near the Earth's surface for the last 520 million years according to the paleoenvironmental records. According to Veizer et al. (2000).

From Fig. 9 can be seen that during the past 520 million years, there were four periods with surface temperatures lower than at present time and four periods with higher temperatures.

Conclusions

When considering CR variations as one of the possible causes of long-term global climate change we need to take into account not only CR modulation by solar wind but also the change of geomagnetic cutoff rigidities (see Table 2). It is especially important when we consider climate change on a scale of between 10^3 and 10^6 years: paleomagnetic investigations show that during the last 3.6×10^6 years the magnetic field of the Earth changed the sign nine times, and the Earth's magnetic moment changed - sometimes having a value of only one-fifth of its present value (Cox et al., 1967) - corresponding to decreases of cutoff rigidity, which leads to increases of CR intensity and decreases of the surface temperature. When we consider situation in the frame scales of many thousand and million years, we need to take into account also possible changes of galactic CR intensity out of Heliosphere. It is not excluded that observed in the last hundred years gradual increasing of planetary surface temperature is caused not by anthropogenic factor, but by space factors (mainly by CR intensity variation, see Fig. 4). From my opinion, it is necessary to continue investigations on connection of CR intensity with cloudiness, raining, surface temperature not only by statistical investigations in frames of different time-scales, but also by developing of physical models.

References

Beer et al., 1991: Beer J., G.M. Raisbeck, and F. Yiou "Time variations of ^{10}Be and solar activity", in C.P. Sonett, M.S. Giampapa, and M.S. Matthews (eds.) The Sun in time, University of Arizona Press, 343–359 (1991).

Beer et al., 1998: Beer J., S. Tobias, and N. Weiss "An active Sun throughout the Maunder minimum", *Solar Phys.*, **181**, 237–249 (1998).

Belov et al., 2005: Belov A.V., L.I. Dorman, R.T. Gushchina, V.N. Obridko, B.D. Shelting and V.G. Yanke "Prediction of expected global climate change by forecasting of galactic cosmic ray intensity time variation in near future based on solar magnetic field data", *Adv. Space Res.*, **35**, No. 3 , 491–495 (2005).

Cox et al., 1967: Cox A., G.B. Dalrymple, R.R. Doedl, *Sci. Am.*, **216,** No. 2, 44–54 (1967).

Dickinson R.E. "Solar variability and the lower atmosphere", *Bull. Am. Met. Soc.*, **56**, 1240–1248 (1975).

Dorman L.I., *Cosmic Rays in the Earth's Atmosphere and Underground*, Kluwer Academic Publishers, Dordrecht/Boston/London, M2004.

Dorman L.I. "Prediction of galactic cosmic ray intensity variation for a few (up to 10–12) years ahead on the basis of convection-diffusion and drift model", *Annales Geophysicae*, **23**, No. 9, 3003–3007 (2005a).

Dorman L.I. "Estimation of long-term cosmic ray intensity variation in near future and prediction of their contribution in expected global climate change", *Adv. Space Res.*, **35**, 496–503 (2005b).

Dorman L.I. "Long-term cosmic ray intensity variation and part of global climate change, controlled by solar activity through cosmic rays", *Adv. Space Res.*, **37**, 1621–1628 (2006).

Dorman L.I. "Natural hazards for the Earth's civilization from space, 1. Cosmic ray influence on atmospheric processes", *Proc. of 2-nd Humboldt Symposium*, Lima, 2007.

Dorman L.I., *Cosmic Rays in Magnetospheres of the Earth and other Planets,* Springer, Netherlands, M2009.

Dorman L.I. and I.V. Dorman, "Possible influence of cosmic rays on climate through thunderstorm clouds", *Adv. Space Res.*, **35**, 476–483 (2005).

Dorman et al., 1987: Dorman L.I., I.Ya. Libin, M.M. Mikalayunas, and K.F. Yudakhin "On the connection between cosmophysical and geophysical parameters in 19-20 cycles of solar activity", *Geomagnetism and Aeronomy*, **27**, No. 2, 303–305 (1987).

Dorman et al., 1988a: Dorman L.I., I.Ya. Libin, and M.M. Mikalajunas "About the possibility of the influence of cosmic factors on weather, spectral analysis: cosmic factors and intensity of storms", *The Regional Hidrometeorology (Vilnius)*, **12**, 119–134 (1988a).

Dorman et al., 1988b: Dorman L.I., I.Ya. Libin, and M.M. Mikalajunas "About the possible influence of the cosmic factors on the weather. Solar activity and sea storms: instantaneous power spectra", *The Regional Hidrometeorology (Vilnius)*, **12**, 135–143 (1988b).

Dorman et al., 1997: Dorman L.I., G. Villoresi, I.V. Dorman, N. Iucci, and M. Parisi. "On the expected CR intensity global modulation in the Heliosphere in the last several hundred years". *Proc. 25-th Intern. Cosmic Ray Conference*, Durban (South Africa), **7**, 345–348 (1997).

Dorman et al., 2003: Dorman L.I., I.V. Dorman, N. Iucci, M. Parisi, Y. Ne'eman, L.A. Pustil'nik, F. Signoretti, A. Sternlieb, G. Villoresi, and I.G. Zukerman, "Thunderstorms Atmospheric Electric Field Effect in the Intensity of Cosmic Ray Muons and in Neutron Monitor Data", *J. Geophys. Res.*, **108**, No. A5, 1181, SSH 2_1–8 (2003).

Friis-Christiansen E. and K. Lassen "Length of the solar cycle: an indicator of solar activity closely associated with climate", *Science*, **254**, 698–700 (1991).

Haigh J.D. "The impact of solar variability on climate", *Science*, **272**, 981–984 (1996).

Hartmann D.L. "Radiative effects of clouds on the Earth's climate in aerosol-cloud-climate interactions", in P.V. Hobbs (ed) *Aerosol-Cloud-Climate Interactions*, Academic Press, 151 (1993).

Herschel W. "Observations tending to investigate the Nature of the Sun, in order to find the Causes or Symptoms of its variable Emission of Light and Heat; with Remarks on the Use that may possibly be drawn from Solar Observations", *Philosophical Transactions of the Royal Society*, London, **91**, Part1, 265–318 (1801).

Jevons W.S. "The solar commercial cycle", *Nature*, **26**, 226–228 (1882).

Jevons W.S. "Commercial crises and sun-spots", *Nature*, **19**, 33–37 (1875).

Jones et al., 1998: Jones P.D., K.R. Briffa, T.P. Barnett, and S.F.B. Tett "High resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control run temperatures", The Holocene, 8, 455–471 (1998).

Labitzke K. and H. van Loon "Some recent studies of probable connections between solar and atmospheric variability", *Ann. Geophys.*, **11**, 1084–1094 (1993).

Lassen K. and E. Friis-Christiansen "Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate", *J. Atmos. Solar-Terr. Phys.*, **57**, 835–845 (1995).

Lean J., J. Beer, and R. Breadley "Reconstruction of solar irradiance since 1610: implications for climate change", *Geophys. Res. Lett.*, **22**, 3195–3198 (1995).

Markson R. "Solar modulation of atmospheric electrification and possible implications for the Sun-weather relationship", *Nature*, **273**, 103–109 (1978).

Marsh N.D. and H. Swensmark "Low cloud properties influenced by cosmic rays", *Phys. Rev. Lett.*, **85**, 5004–5007 (2000a).

Marsh N. and H. Swensmark "Cosmic rays, clouds, and climate", *Space Sci. Rev.*, **94**, No. 1-2, 215–230 (2000b).

Ney E.R. "Cosmic radiation and weather", *Nature*, **183**, 451–452 (1959).

Price C. "Evidence for a link between global lightning activity and upper tropospheric water vapour", *Nature*, **406**, 290–293 (2000).

Pudovkin M.I. and O.M. Raspopov "The mechanism of action of solar activity on the state of the lower atmosphere and meteorological parameters (a review)", *Geomagn. and Aeronomy*, **32**, 593–608 (1992).

Pudovkin M. and S. Veretenenko "Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays", *J. Atmos. Solar-Terr. Phys.*, **57**, 1349–1355 (1995).

Pudovkin M. and S. Veretenenko "Variations of the cosmic rays as one of the possible links between the solar activity and the lower atmosphere". *Adv. Space Res.*, **17**, No. 11, 161–164 (1996).

Pustil'nik L., G. Yom Din, and L. Dorman "Manifestations of Influence of Solar Activity and Cosmic Ray Intensity on the Wheat Price in the Medieval England (1259–1703 Years)", *Proc. 28th Intern. Cosmic Ray Conf.*, Tsukuba, **7**, 4131–4134 (2003).

Rogers J.E.T., *Agriculture and Prices in England*, Vol. 1-8, Oxford, Clarendon Press, M1887.

Schlegel et al., 2001: Schlegel K., G. Diendorfer, S. Them, and M. Schmidt "Thunderstorms, lightning and solar activity – Middle Europe", *J. Atmos. Solar-Terr. Phys.*, **63**, 1705–1713 (2001).

Shea M.A. and D.F. Smart "Preliminary Study of the 400-Year Geomagnetic Cutoff Rigidity Changes, Cosmic Rays and Possible Climate Changes", *Proc. 28th Intern. Cosmic Ray Conf.*, Tsukuba, **7**, 4205–4208 (2003).

Shindell et al., 1999: Shindell D., D. Rind, N. Balabhandran, J. Lean, and P. Lonengran "Solar cycle variability, ozone, and climate", *Science*, **284**, 305–308 (1999).

Smith A., *An Inquiry into the Nature and Causes of the Wealth of Nations*, W. Strahan & T. Cadell, London, M1776.

Stozhkov Yu.I. "The role of cosmic rays in atmospheric processes", *J. Phys. G: Nucl. Part. Phys.*, **28**, 1–11 (2002).

Stozhkov et al., 1995a: Stozhkov Yu.I., J. Zullo, I.M. Martin et al. "Rainfalls during great Forbush-decreases", *Nuovo Cimento*, **C18**, 335–341 (1995a).

Stozhkov et al., 1995b: Stozhkov Yu.I., P.E. Pokrevsky, I.M. Martin et al. "Cosmic ray fluxes and precipitations", *Proc. 24th Intern. Cosmic Ray Conf.*, Rome, **4**, 1122–1125 (1995b).

Stozhkov et al., 1996: Stozhkov Yu.I., P.E. Pokrevsky, J. Jr. Zullo et al. "Influence of charged particle fluxes on precipitation", *Geomagn. and Aeronomy*, **36**, 211–216 (1996).

Swensmark H. "Cosmic rays and Earth's climate", *Space Sci. Rev.*, **93**, 175–185, 2000.

Tinsley B.A. "Influence of solar wind on the global electric circuit, and inferred effects on cloud microphysics, temperature, and dynamics in the troposphere", *Space Sci. Rev.*, **94**, No. 1-2, 231–258 (2000).

Todd M.C. and D.R. Kniveton "Changes in cloud cover associated with Forbush decreases of galactic cosmic rays", *J. Geophys. Res.*, **106**, No. D23, 32031–32042 (2001).

Todd M.C. and D.R. Kniveton "Short-term variability in satellite-derived cloud cover and galactic cosmic rays: an update" *J. .Atmosph. and Solar-Terrestrial Physics*, **66**, 1205–1211 (2004).

Veizer et al., 2000: Veizer J., Y. Godderis, and I.M. Francois "Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoiceon," *Nature*, **408**, 698–701 (2000).

Veretenenko S.V. and M.I. Pudovkin "Effects of Forbush-decreases in cloudiness variations", *Geomagnetism and Aeronomy*, **34**, 38–44 (1994).