

The Role of Space Weather and Cosmic Ray Effects in Climate Change

Lev I. Dorman

*Head of Cosmic Ray and Space Weather Center with Emilio Sègre Observatory, affiliated to Tel Aviv University, TECHNION and Israel Space Agency, P.O. Box 2217, Qazrin 12900, Israel
Chief Scientist of Cosmic Ray Department of IZMIRAN Russian Academy of Science, Troitsk 142090, Moscow Region, Russia*

1. **Introduction**
2. **Solar Activity, Cosmic Rays and Climate Change**
 - 2.1. Long-Term Cosmic Ray Intensity Variations and Climate Change
 - 2.2. The Possible Role of Solar Activity and Solar Irradiance in Climate Change
 - 2.3. Cosmic Rays as an Important Link between Solar Activity and Climate Change
 - 2.4. The Connection between Galactic Cosmic Ray Solar Cycles and the Earth's Cloud Coverage
 - 2.5. The Influence of Cosmic Rays on the Earth's Temperature
 - 2.6. Cosmic Ray Influence on Weather during Maunder Minimum
 - 2.7. The Influence of Long-Term Variations of Cosmic Ray Intensity on Wheat Prices (Related to Climate Change) in Medieval England and Modern USA
 - 2.8. The Connection between Ion Generation in the Atmosphere by Cosmic Rays and Total Surface of Clouds
 - 2.9. The Influence of Big Magnetic Storms (Forbush Decreases) and Solar Cosmic Ray Events on Rainfall
 - 2.10. The Influence of Geomagnetic Disturbances and Solar Activity on the Climate through Energetic Particle Precipitation from Inner Radiation Belt

- | | |
|--|---|
| <p>2.11. On the Possible Influence of Galactic Cosmic Rays on Formation of Cirrus Hole and Global Warming</p> <p>2.12. Description of Long-Term Galactic Cosmic Ray Variation by both Convection-Diffusion and Drift Mechanisms with Possibility of Forecasting of Some Part of Climate Change in Near Future Caused by Cosmic Rays</p> <p>2.13. Influence of Long-Term Variation of Main Geomagnetic Field on Global Climate Change through Cosmic Ray Cutoff Rigidity Variation</p> <p>2.14. Atmospheric Ionisation by Cosmic Rays: The Altitude Dependence and Planetary Distribution</p> | <p>2.15. Project 'Cloud' as an Important Step in Understanding the Link between Cosmic Rays and Cloud Formation</p> <p>3. The Influence on the Earth's Climate of the Solar System Moving Around the Galactic Centre and Crossing Galaxy Arms</p> <p>4. The Influence of Molecular-dust Galactic Clouds on the Earth's Climate</p> <p>5. The Influence of Interplanetary Dust Sources on the Earth's Climate</p> <p>6. Space Factors and Global Warming</p> <p>7. The Influence of Asteroids on the Earth's Climate</p> <p>8. The Influence of Nearby Supernova on the Earth's Climate</p> <p>9. Discussion and Conclusions Acknowledgments References</p> |
|--|---|

1. INTRODUCTION

There are a number of space phenomena that influence the Earth's climate and determined its long-term and short-term changes. These include:

- the variability of the Sun's irradiation flux energy;
- the variations of the Earth's orbital characteristics;
- the variable solar activity (with periods of 8–15 a (year), average period of about 11 a), general solar magnetic field (average period of 22 a) together with the related phenomena of variable solar wind, coronal mass ejections and shocks in the Heliosphere and modulated galactic cosmic rays (CR) – see [Section 2](#);
- the solar CR generated during great solar flares – see [Section 2.9](#);
- the precipitation of energetic electrons and protons from the Earth's magnetosphere during magnetic disturbances – see [Section 2.10](#);
- the variable Earth's magnetic field's influence on CR cutoff rigidity and changed galactic and solar cosmic ray intensity in the Earth's atmosphere – see [Section 2.12](#);

- the moving of the solar system around the galactic centre and crossing the Galaxy arms – see [Section 3](#);
- the impacts of the solar system with galactic molecular dust cloud – see [Section 4](#);
- the impacts of the solar system with interplanetary zodiac dust cloud – see [Section 5](#);
- asteroid impacts – see [Section 7](#);
- nearby supernova explosions – see [Section 8](#).

The first phenomenon is the subject of Chapter 2 by Shabtai Cohen, and the second is dealt with by Lucas Lourens in Chapter 5. In this Chapter the other phenomena are discussed and compared to anthropogenic induced changes. Details on CR behaviour in the Earth's atmosphere, magnetosphere and in space are the subject of recent publications by the author [1–3]. The role of these factors in our present climate change will be discussed in the final section of this chapter.

2. SOLAR ACTIVITY, COSMIC RAYS AND CLIMATE CHANGE

2.1. Long-Term Cosmic Ray Intensity Variations and Climate Change

About 200 a ago the famous astronomer William Herschel [4] suggested that the price of wheat in England was directly related to the number of sunspots. He noticed that less rain fell when the number of sunspots was small (Joseph in the Bible, recognised a similar periodicity in food production in Egypt, about 4000 a ago). The solar activity level is known from direct observations over the past 450 a, and from data of cosmogenic nuclides (through CR intensity variations) for more than 10 000 a [1,5]. Over this period there is a striking qualitative correlation between cold and warm climate periods and high and low levels of galactic CR intensity (low and high solar activity). As an example, [Fig. 1](#) shows the change in the concentration of radiocarbon during the last millennium (a higher concentration of ^{14}C corresponds to a higher intensity of galactic CR and to lower solar activity). It can be seen from [Fig. 1](#) that during 1000–1300 AD 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 AD 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 AD and lasted until the middle of nineteenth century).

2.2. The Possible Role of Solar Activity and Solar Irradiance in Climate Change

Friis-Christiansen and Lassen [7,8] found, from 400 a 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 [9]

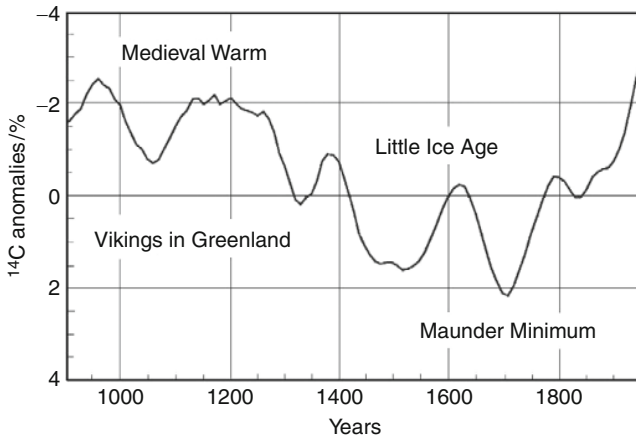


FIGURE 1 The change of CR intensity reflected in radiocarbon concentration during the last millennium. The Maunder minimum refers to the period 1645–1715, when sun spots were rare. From Ref. [6].

showed, from solar cycle data, that the air temperature increases with increasing levels of solar activity. Swensmark [6] 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 $0.3 \text{ W}\cdot\text{m}^{-2}$. This value is too small to explain the present observed climate changes [10]). Much bigger changes during a solar cycle occur in UV radiation (about 10%, which is important in the formation of the ozone layer). High [11] and Shindell et al. [12] 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 a cycle modulation of climate but not to the 100 a of climate change that we are presently experiencing.

2.3. 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 ionisation below 40–35 km (only near the ground level, lower than 1 km, are radioactive gases from the soil also important in air ionisation) [1]. The first to suggest a possible influence of air ionisation by CR on the climate was Ney [13]. Swensmark [6] noted that the variation in air ionisation 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 other authors considered these possibilities [13–22]. 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. [23–25]. Dorman et al. [26] reconstructed CR intensity variations over the last 400 a on the basis of solar activity data and compared the results with radiocarbon and climate change data.

Cosmic radiation plays a key role in the formation of thunderstorms and lightnings [1]. Many authors [27–32] 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 [2]. One can consider the general hierarchical relationship to be: (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 + atmospheric electric field effects) → climate change.

2.4. The Connection between Galactic Cosmic Ray 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 [6,18,20–22]. 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 [33], high optically thin clouds tend to heat while low optically thick clouds tend to cool (see Table 1).

From Table 1 it can be seen that low clouds result in a cooling effect of about $17 \text{ W}\cdot\text{m}^{-2}$, which means that they play an important role in the Earth's radiation budget [34–36]). The important issue is that even small changes in the lower cloud coverage can result in important changes in the radiation budget and hence has a considerable influence on the Earth's climate (let us remember that the solar irradiance changes during solar cycles is only about $0.3 \text{ W}\cdot\text{m}^{-2}$).

Figure 2 shows a comparison of the Earth's total cloud coverage (from satellite observations) with CR intensities (from the Climax neutron monitor (NM)) and solar activity data over 20 a.

From Fig. 2 it can be seen that the correlation of global cloud coverage with CR intensity is much better than with solar activity. Marsh and Swensmark [21] came to conclusion that CR intensity relates well with low global cloud coverage, but not with high and middle clouds (see Fig. 3).

It is important to note that low clouds lead, as rule, to the cooling of the atmosphere. It means that with increasing CR intensity and cloud coverage

TABLE 1 Global annual mean forcing due to various types of clouds, from the Earth Radiation Budget Experiment (ERBE), according to Hartmann [33]

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·m ⁻²)	-4.1	-15.6	-3.7	-9.9	-20.2	-53.5
Outgoing LW radiation /(W·m ⁻²)	6.5	8.6	4.8	2.4	3.5	25.8
Net forcing /(W·m ⁻²)	2.4	-7.0	1.1	-7.5	-16.7	-27.7

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.)

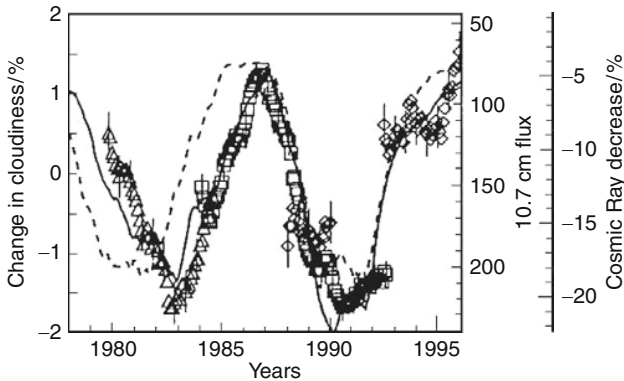


FIGURE 2 Changes in the Earth's cloud coverage: triangles – from satellite Nimbus 7, CMATRIX project [37]; squares – from the International Satellite Cloud Climatology Project, ISCCP [38]; diamonds – from the Defence Meteorological Satellite Program, DMSP [39,40]. Solid curve – CR intensity variation according to Climax NM, normalized to May 1965. Broken curve – solar radio flux at 10.7 cm. All data are smoothed using twelve months running mean. From Ref. [6].

(see Fig. 2), we can expect the surface temperature to decrease. It is in good agreement with the situation shown in Fig. 1 for the last 1000 a, and with direct measurements of the surface temperature over the last four solar cycles (see Section 2.5, below).

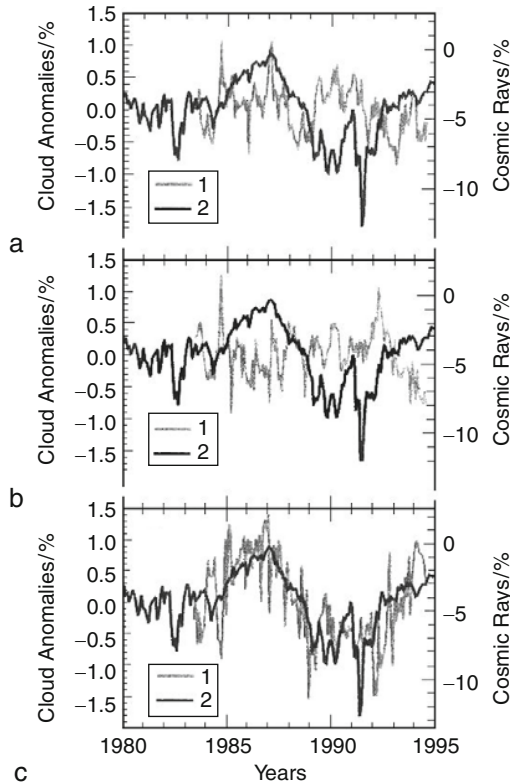


FIGURE 3 CR intensity obtained at the Huancayo/Haleakala NM (normalised to October 1965, curve 2) in comparison with global average monthly cloud coverage anomalies (curves 1) at heights, H , for: a – high clouds, $H > 6.5$ km, b – middle clouds, $6.5 \text{ km} > H > 3.2$ km, and c – low clouds, $H < 3.2$ km. From Ref. [21].

2.5. The Influence of Cosmic Rays on the Earth's Temperature

Figure 4 shows a comparison of 11 year moving average Northern Hemisphere marine and land air temperature anomalies for 1935–1995 with CR intensity (constructed for Cheltenham/Fredericksburg for 1937–1975 and Yakutsk for 1953–1994, [41]) and Climax NM data, as well as with other parameters (unfiltered solar cycle length, sunspot numbers and reconstructed solar irradiance).

From Fig. 4 one can see that the best correlation of global air temperature is with CR intensity, in accordance with the results described in Sections 2.1–2.4 above. According to Swensmark [6], the comparison of Fig. 4 with Fig. 2 shows that the increase of air temperature by $0.3 \text{ }^\circ\text{C}$ corresponds to a decrease of CR intensity of 3.5% and a decrease of global cloudiness of 3%; this is equivalent to an increase of solar irradiance on the Earth's surface of about $1.5 \text{ W}\cdot\text{m}^{-2}$ [42] and is about 5 times bigger than the solar cycle change of solar irradiance, which as we have seen, is only $0.3 \text{ W}\cdot\text{m}^{-2}$.

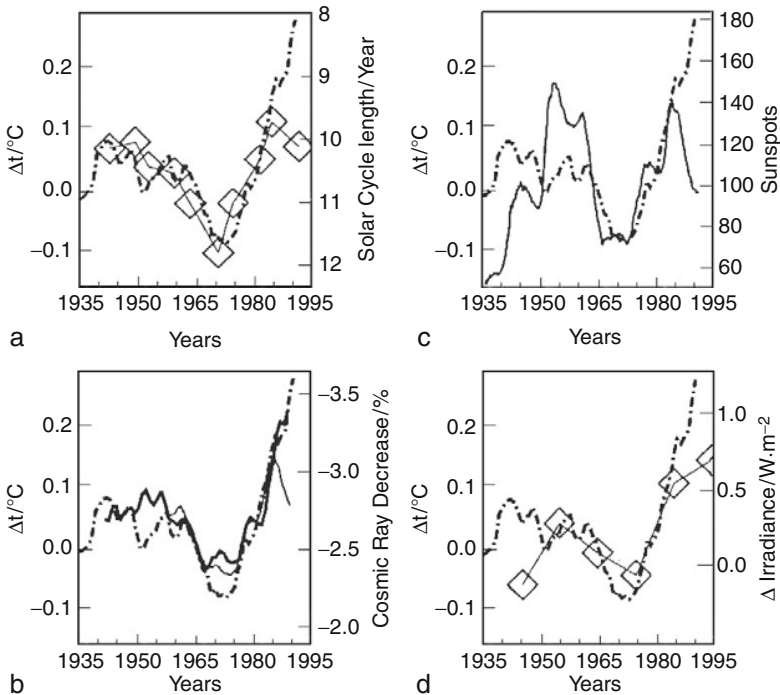


FIGURE 4 Eleven year average Northern hemisphere marine and land air temperature anomalies, Δt , (broken curve) compared with: a, unfiltered solar cycle length; b, Eleven year average CR intensity (thick solid curve – from ion chambers 1937–1994, normalized to 1965, and thin solid curve – from Climax NM, normalized to ion chambers); c, eleven-year average of sunspot numbers; and d, decade variation in reconstructed solar irradiance from Ref. [10] (zero level corresponds to $1367 \text{ W}\cdot\text{m}^{-2}$). From Ref. [6].

2.6. Cosmic Ray Influence on Weather during Maunder Minimum

Figure 5 shows the situation in the Maunder minimum (a time when sunspots were rare) for: solar irradiance [10,43]; concentration of the cosmogenic isotope ^{10}Be [44] – a measure of CR intensity [1]; and reconstructed air surface temperature for the northern hemisphere [45]).

The solar irradiance is almost constant during the Maunder minimum and about 0.24% (or about $0.82 \text{ W}\cdot\text{m}^{-2}$) lower than the present value (see Panel a in Fig. 5), but CR intensity and air surface temperature vary in a similar manner – see above sections; with increasing CR intensity there is a decrease in air surface temperature (see Panels b and c in Fig. 5). The highest level of CR intensity was between 1690–1700, which corresponds to the minimum of air surface temperature [46] and also to the coldest decade (1690–1700).

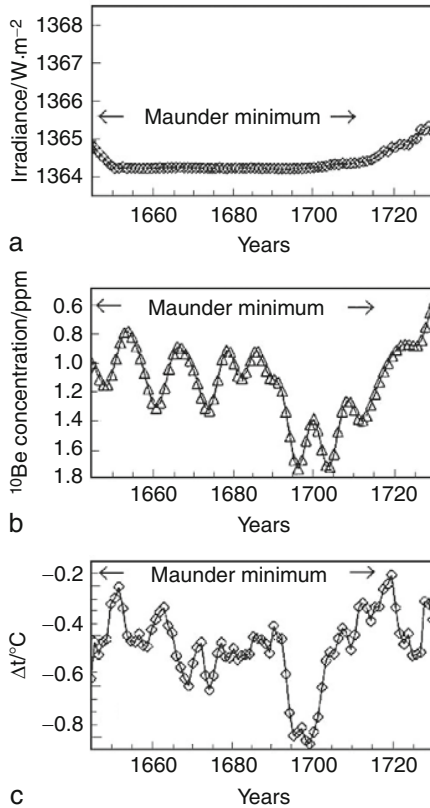


FIGURE 5 Situation in the Maunder minimum: a – reconstructed solar irradiance [9]; b – cosmogenic ^{10}Be concentration [44]; c – reconstructed relative change of air surface temperature, ΔT , for the northern hemisphere [45]. From Swensmark [6].

2.7. The Influence of Long-Term Variations of Cosmic Ray Intensity on Wheat Prices (Related to Climate Change) in Medieval England and Modern USA

Herschel's observations [4] mentioned in Section 2.1, were based on the published wheat prices [47], and showed that five prolonged periods of sunspot numbers correlated with costly wheat. This idea was taken up by the English economist and logician William Stanley Jevons [48]. 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 a. This work was later published by Rogers [49]. The coincidence of these intervals with the period of the recently discovered 11 year cycle of solar activity led him to suggest that the solar activity cycle was a 'synchronisation' factor in the fluctuations of wheat prices (Jevons [50]). As a next step, he extrapolated his theory to stock

markets of the nineteenth 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. He suggested that both solar and economic activities are subjected to a harmonic process with the same constant period of 11 a. However, the subsequent discovery of the non-harmonic behaviour of solar cycles, with periods varying from 8 to 15 a, and the later observation of lack of coincidence between panics predicted by Jevons [48,50] and the actual ones, destroyed his argument.

The Rogers [49] database was used by Pustil'nik et al. [51], Pustil'nik and Yom Din [52] to search for possible influences of solar activity and CR intensity on wheat prices (through climate changes). The graph of wheat prices as a function of time (Fig. 6) contains two specific features:

1. A transition from 'low price' state to 'high price' state during 1530–1630, possibly as a result of access to cheap silver, recently discovered New World.
2. The existence of two populations in the price sample: noise-like variations with low amplitude bursts and several bursts of large amplitude.

Pustil'nik et al. [51], Pustil'nik and Yom Din [52], analysed the data and compared the distribution of intervals of price bursts with the distribution of the intervals between minimums of solar cycles (see Fig. 7).

In their analysis they found that for the sunspot minimum–minimum interval distribution the estimated parameters are: median 10.7 a; mean 11.02 a; standard deviation 1.53 a and for the price burst interval distribution, the estimated parameters are: median 11.0 a; mean 11.14 a; and standard deviation 1.44 a.

The main problem with a comparison between the price and solar activity, is the absence of the time interval, common to sunspot observation data

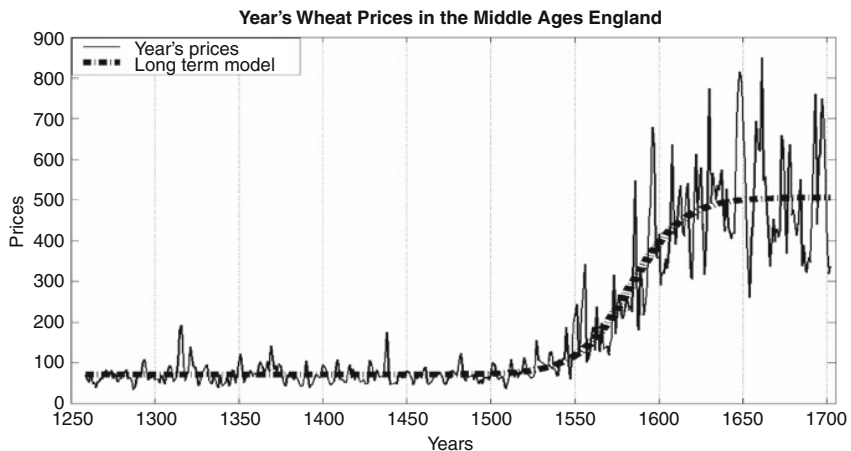


FIGURE 6 Wheat prices in England during 1259–1702 with a price transition at 1530–1630. From Refs. [51,52].

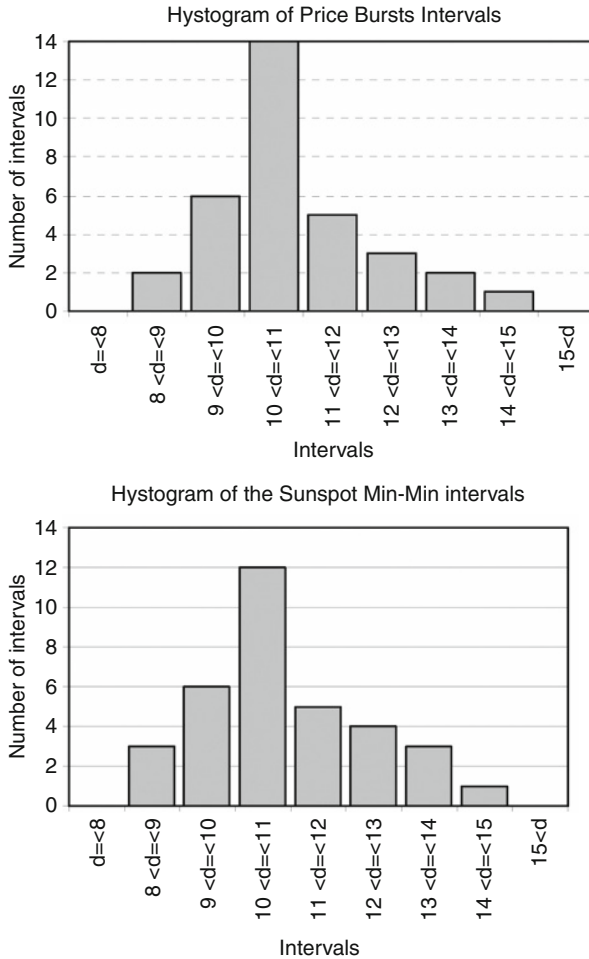


FIGURE 7 Histograms of the interval distribution for price bursts for the period, 1249–1702, and of minimum–minimum intervals of sunspots during 1700–2000. From Refs. [51,52].

(for 1700–2001) and wheat price data (1259–1702). However, the discovery of a strong correlation between the concentration of ^{10}Be isotopes in Greenland ice and CR intensity (according to measurements of CR intensity over the last 60 a [1]) sheds a new light on the problem. In Fig. 8, the wheat prices for 1600–1702 are shown and compared to ^{10}Be data [53]. White marks show prices, averaged for three-year intervals centred on moments of minimum CR intensity. Black marks correspond to average prices in three-year intervals for maximum CR intensities.

As can be seen from Fig. 8, all prices in the neighbourhoods of the seven maxima of CR intensity (correspond approximately to minima of solar activity)

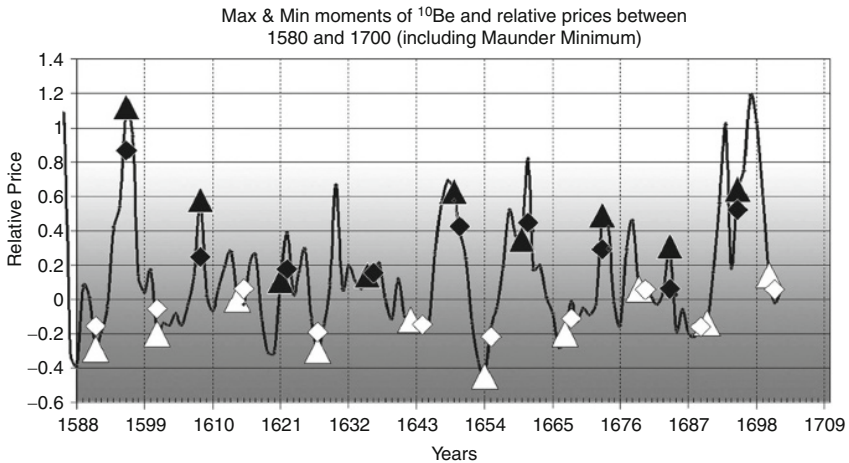


FIGURE 8 Systematic differences in wheat prices at moments of minimum and maximum CR intensity determined according to ^{10}Be data [53]. White diamonds show prices averaged for three-year intervals centred on moments of minimum CR intensity (maximum solar activity); black rectangles show prices averaged over three-year intervals centred on moments of maximum CR intensity (minimum solar activity). White and black triangles show prices at moments of minimum and maximum CR intensity. From Ref. [52].

are systematically higher than those in the neighbourhood of the seven minima of CR intensity (maxima of solar activity) in the long-term variation of CR intensity according to ^{10}Be data [53]. A similar result was obtained by Pustil'nik and Yom Din [54] for wheat prices in USA during twentieth century.

2.8. The Connection between Ion Generation in the Atmosphere by Cosmic Rays and Total Surface of Clouds

The time variation of the integral rate of ion generation, q , (approximately proportional to CR intensity) in the middle latitude atmosphere at an altitude between 2 and 5 km was found by Stozhkov et al. [55] for the period January 1984–August 1990 using regular CR balloon measurements. The relative change in q , $\Delta q/q$, have been compared with the relative changes of the total surface of clouds over the Atlantic Ocean, $\Delta S/S$, and are shown in Fig. 9: the correlation coefficient is 0.91 ± 0.04 . This result is in good agreement with results described above (see Panel b in Fig. 4 and Panel c in Fig. 5) and shows that there is a direct correlation between cloud cover and CR generated ions.

2.9. The Influence of Big Magnetic Storms (Forbush Decreases) and Solar Cosmic Ray Events on Rainfall

A decrease of atmospheric ionisation leads to a decrease in the concentration of charge condensation centres. In these periods, a decrease of total cloudiness

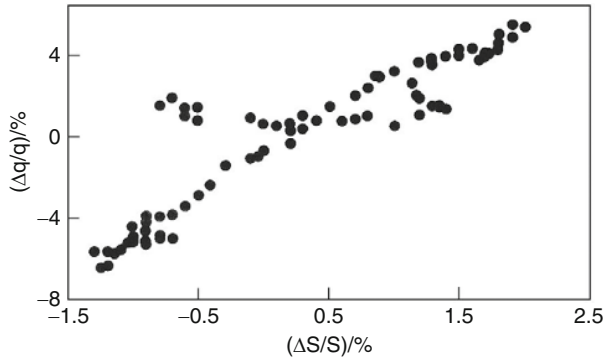


FIGURE 9 The positive relationship between the relative changes of total clouds covering surface over Atlantic Ocean, $\Delta S/S$, in the period January 1984–August 1990 [19] and the relative changes of integral rate of ion generation $\Delta q/q$ in the middle latitude atmosphere in the altitude interval 2–5 km. From Ref. [55].

and atmosphere turbulence together with an increase in isobaric levels is observed [56]). As a result, a decrease of rainfall is also expected. Stozhkov et al. [57–59] and Stozhkov [60] analysed 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 [61,62] investigating 32 Forbush decreases events over the period 1983–2000, found reduced cloud cover of 18% [61] and 12% [62].

During big solar CR events, when CR intensity and ionisation in the atmosphere significantly increases, an inverse situation is expected and the increase in cloudiness leads to an increase in rainfall. A study [57–60] 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.

2.10. The Influence of Geomagnetic Disturbances and Solar Activity on the Climate through Energetic Particle Precipitation from Inner Radiation Belt

The relationship between solar and geomagnetic activity and climate parameters (cloudiness, temperature, rainfall, etc.) was considered above and is the subject of much ongoing research. The clearly pronounced relationship observed at high and middle latitudes, is explained by the decrease of galactic CR intensity (energies in the range of MeV and GeV) with increasing solar and geomagnetic activity, and by the appearance of solar CR fluxes ionising the atmosphere [63]). This mechanism works efficiently at high latitudes, because CR particles with energy up to 1 GeV penetrate this region more easily due to its very low cutoff rigidity. Near the equator, in the Brazilian Magnetic

Anomaly (BMA) region, the main part of galactic and solar CR is shielded by a geomagnetic field. This field is at an altitude of 200–300 km and contains large fluxes of energetic protons and electrons trapped in the inner radiation belt. Significant magnetic disturbances can produce precipitation of these particles and subsequent ionisation of the atmosphere. The influence of solar-terrestrial connections on climate in the BMA region was studied by Pugacheva et al. [64]. Two types of correlations were observed: (1) a significant short and long time scale correlation between the index of geomagnetic activity Kp and rainfall in Sao Paulo State; (2) the correlation-anti-correlation of rainfalls with the 11 and 22 a cycles of solar activity for 1860–1990 in Fortaleza. Figure 10 shows the time relationship between Kp-index and rain in Campinas (23°S, 47°W) and in Ubajara (3°S, 41°W), during 1986. From Fig. 10, it can be seen that, with a delay of 5–11 days, almost every significant (>3.0) increase of the Kp-index is accompanied by an increase in rainfall. The effect is most noticeable at the time of the great geomagnetic storm of 8 February 1986, when the electron fluxes of inner radiation belt reached the atmosphere between 18 and 21 February [65]) and the greatest rainfall of the 1986 was recorded on 19 February. Again, after a series of solar flares, great magnetic disturbances were registered between 19 and 22 March 1991. On 22 March, a Sao Paulo station showed the greatest rainfall of the year.

The relationship between long-term variations of annual rainfall at Campinas, the Kp-index and sunspot numbers are shown in Figs. 11 and 12.

Figures 11 and 12 show the double peak structure of rainfall variation compared to the Kp-index. Only during the 20th solar cycle (1964–1975), weakest of the shown 6 cycles, an anti-correlation between rainfalls and sunspot numbers is observed in most of Brazil. The Kp – rainfall correlation is more pronounced in the regions connected with magnetic lines occupied by trapped particles.

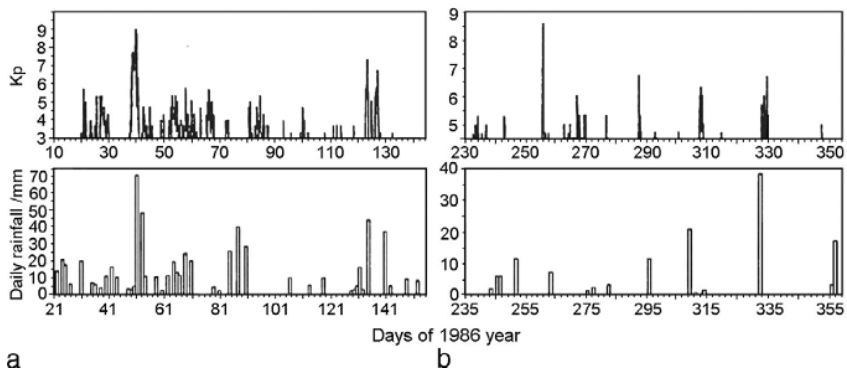


FIGURE 10 The Kp-index of geomagnetic activity (top panels) and rainfall level (bottom panels) in Campinas (left panels a) and in Ubajara (right panels b) in 1986. According to Pugacheva et al. [64].

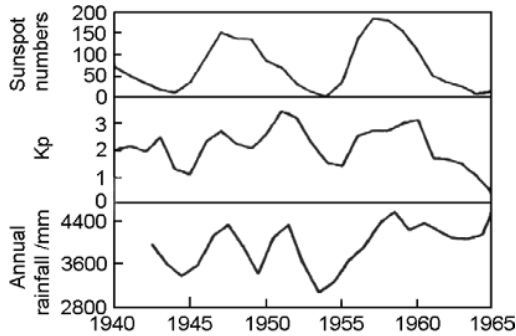


FIGURE 11 Long-term variations of rainfalls (Campinas, the bottom panel) in comparison with variations of solar and geomagnetic activity (the top and middle panels, respectively) for 1940–1965. From Ref. [64].

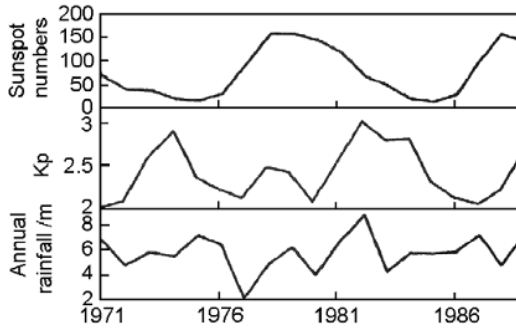


FIGURE 12 The same as in Fig. 11, but for 1971–1990. From Ref. [64].

In Fortaleza (4°S , 39°W), located in an empty magnetic tube ($L = 1.054$), it is the other kind of correlation (see Fig. 13).

From Fig. 13 it can be seen that a correlation exists between sunspot numbers and rainfall between 1860–1900 (11th–13th solar cycles) and 1933–1954 (17th and 18th cycles). The anti-correlation was observed during 1900–1933 (cycles 14th–16th) and during 1954–1990 (cycles 19th–21th). As far as sunspot numbers mainly anti-correlate with the galactic CR flux, an anti-correlation of sunspot numbers with rainfalls could be interpreted as a correlation of rainfalls with the CR. The positive and negative phases of the correlation interchange several times during the long time interval 1860–1990, that was observed earlier in North America (King [66]). Some climate events have a 22 a periodicity similar to the 22 a solar magnetic cycle. Panel b in Fig. 13 demonstrate 22 a periodicity of 11 a running averaged rainfalls in Fortaleza. The phenomenon is observed during 5 periods from 1860 to 1990. During the 11th–16th solar cycles (from 1860 until 1930), the maxima of rainfalls correspond to the maxima of sunspot numbers of odd solar cycles 11th, 13th, 15th and minima of rainfalls correspond to maxima of even solar

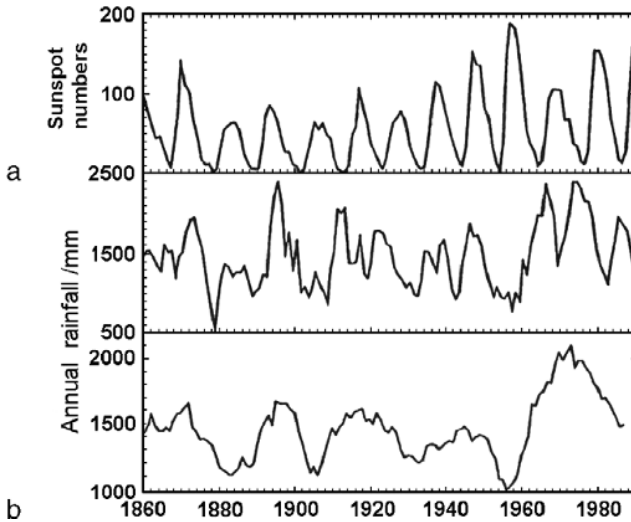


FIGURE 13 The comparison of yearly sunspot numbers long-term variation (the top panel) with 3 and 11 a running averaged rainfalls (Panels a and b, respectively) in Fortaleza (4°S , 39°W) during 1860–1990. From Ref. [64].

cycles 12th, 14th, 16th. During the 17th solar cycle the phase of the 22 a periodicity is changed to the opposite and the sunspot number maxima of odd cycles 19th and 21st correspond to the minima of rainfall. The effect is not pronounced (excluding years 1957–1977) in Sao Paulo.

The difference in results obtained in Refs. [60–62, 64] can be easily understood if we take into account the large value of the cutoff rigidity in the BMA region. This is the reason why the variations in galactic and solar CR intensity in the BMA region, are not reflected in the ionisation of the air and hence do not influenced the climate. However, in the BMA region other mechanism of solar and magnetic activity can influence climatic parameters such as energetic particle precipitation coming from the inner radiation belt.

2.11. On the Possible Influence of Galactic Cosmic Rays on Formation of Cirrus Hole and Global Warming

According to Ely and Huang [67] and Ely et al. [68], there are expected variations of upper tropospheric ionisation caused by long-term variations of galactic CR intensity. These variations have resulted in the formation of the cirrus hole (a strong latitude dependent modulation of cirrus clouds). The upper tropospheric ionisation is caused, largely, by particles with energy smaller than 1 GeV but bigger than about 500 MeV. In Fig. 14 is shown the long-term modulation of the difference between Mt. Washington and Durham for protons with kinetic energy 650–850 MeV.

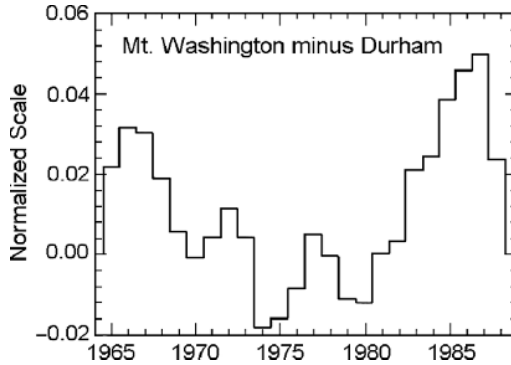


FIGURE 14 The observed 22 a modulation of galactic CR between 1.24 GV and 1.41 GV rigidity (i.e. protons with kinetic energy between 650–850 MeV, ionising heavily in the layer 200–300 g/cm²). From Ely et al. [68].

Figure 14 clearly shows the 22 a modulation of galactic CR intensity in the range 650–850 MeV with an amplitude of more than 3%. Variations of upper tropospheric ionisation do have some influence on the cirrus covering and the ‘cirrus hole’ is expected to correspond to a decrease in CR intensity.

According to Ely et al. [68], the ‘cirrus hole’ was observed in different latitude zones over the whole world between 1962 and 1971, centred at 1966 (see Fig. 15).

Figure 15 gives the cirrus cloud cover data over a 25 a period, for the whole world, the equatorial zone (30°S–30°N) and the northern zone (30°N–90°N), showing fractional decreases in cirrus coverage of 7%, 4% and 17%, respectively.

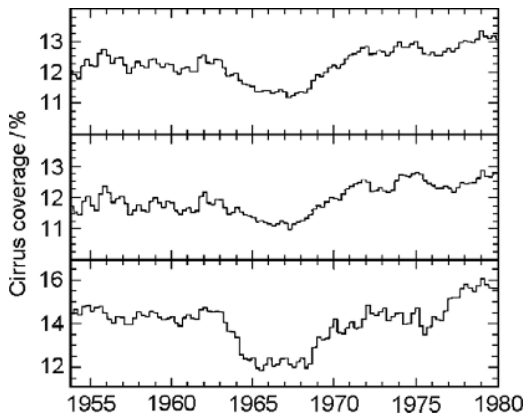


FIGURE 15 The ‘cirrus hole’ of the 1960s for: the whole world (the top panel); the equatorial zone (30°S–30°N; middle panel); the northern zone (bottom panel) From Ely et al. [68].

The decrease of cirrus covering leads to an increase in heat loss to outer space (note, that only a 4% change in total cloud cover is equivalent to twice the present greenhouse effect due to anthropogenic carbon dioxide). The influence of cirrus hole in the northern latitude zone (30°N–90°N), where the cirrus covering was reduced by 17%, is expected to be great (this effect of the cirrus hole is reduced in summer by the increase of lower clouds resulting in enhanced insulation) The low temperatures produced from mid to high latitude significantly increase the pressure of the polar air mass and cause frequent ‘polar break troughs’ at various longitudes in which, for example, cold air from Canada may go all the way to Florida and freeze the grapefruit [68]). However, when the cirrus hole is not present, the heat loss from mid to high latitudes is much less, and the switching of the circulation patterns (Rossby waves) is much less frequent.

2.12. Description of Long-Term Galactic Cosmic Ray Variation by both Convection-Diffusion and Drift Mechanisms with Possibility of Forecasting of Some Part of Climate Change in Near Future Caused by Cosmic Rays

It was shown in previous Sections that CR may be considered as sufficient links determined some part 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 [69–71] it was made on basis of monthly sunspot numbers 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 (see Fig. 16); in Belov et al. [72] – mainly on basis of monthly data of solar general magnetic field (see Fig. 17). From Fig. 16 follows that in the frame of used in [69–71] convection-diffusion and drift models can be determined with very good accuracy expected galactic CR intensity in the past (when monthly sunspot numbers are known) as well as behaviour of CR intensity in future if monthly sunspot numbers can be well forecasted. According to Ref. [72], the same can be made with good accuracy on the basis of monthly data on the solar general magnetic field (see Fig. 17). Let us note that described above results obtained in Refs. [69–72] give possibility to forecast some part of climate change connected with CR.

2.13. Influence of Long-Term Variation of Main Geomagnetic Field on Global Climate Change through Cosmic Ray Cutoff Rigidity Variation

The sufficient change of main geomagnetic field leads to change of planetary distribution of cutoff rigidities R_c and to corresponding change of the i -th component of CR intensity $N_i(R_c, h_o)$ at some level h_o in the Earth’s

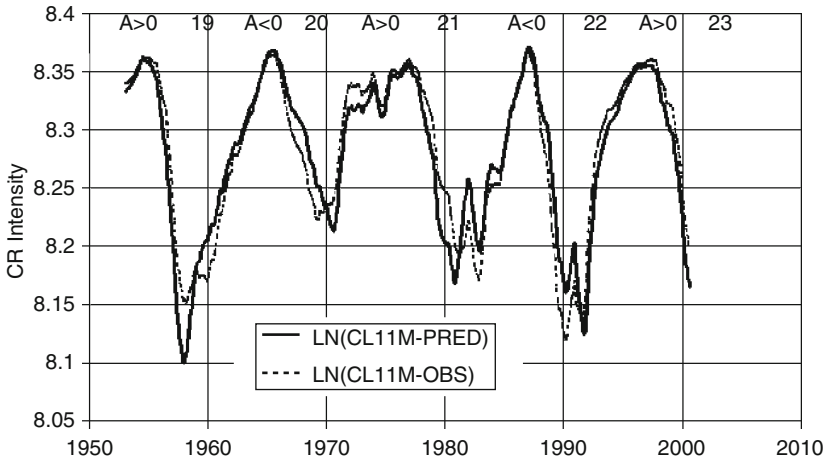


FIGURE 16 Comparison of observed by Climax neutron monitor CR intensity averaging with moving period eleven month LN(CL11M-OBS) with predicted on the basis of monthly sunspot numbers from model of convection-diffusion modulation, corrected on drift effects LN(CL11M-PRED). Correlation coefficient between both curves 0.97. From Dorman [71].

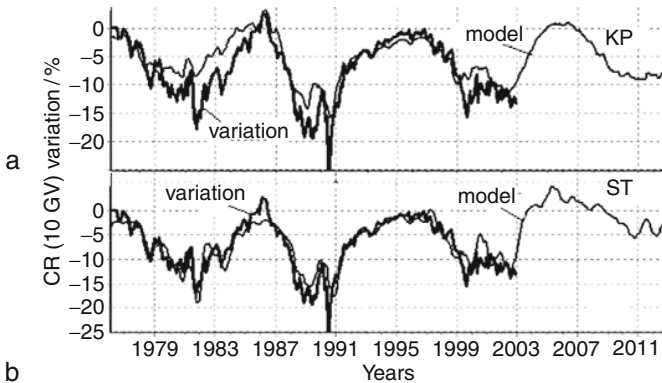


FIGURE 17 The forecast of galactic CR behaviour based on the predicted values of the global characteristics of the solar magnetic field, thick line – data of CR intensity observations (Moscow neutron monitor), thin line – the predicted CR variation up to 2013 based on data of Kitt Peak Observatory (upper panel) and based on data of Stanford Observatory (bottom panel). From Belov et al. [72].

atmosphere $\Delta N_i(R_c, h_o)/N_{i0} = -\Delta R_c W_i(R_c, h_o)$, where $W_i(R_c, h_o)$ is the coupling function (see details in Chapter 3 of Ref. [1]). Variations of CR intensity caused by change of R_c are described in detail in Ref. [2], and here we will demonstrate results of Shea and Smart [73] on R_c changing for the last 300 and 400 a (see Fig. 18 and Table 2, correspondingly).

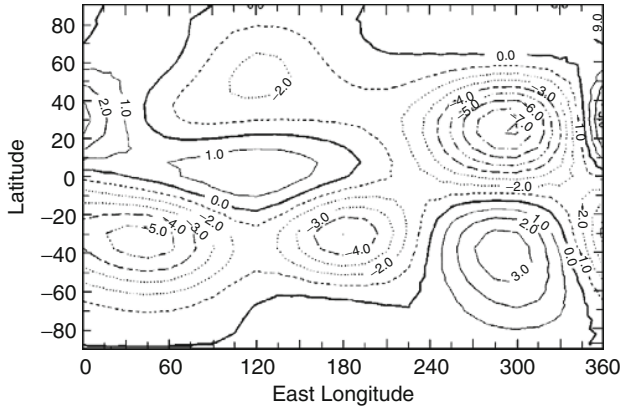


FIGURE 18 Contours of the change in vertical cutoff rigidity values (in GV) between 1600 and 1900. Full lines reflect positive trend (increasing of cutoff rigidity from 1600 to 1900); dotted lines reflect negative trend. According to Shea and Smart [73].

TABLE 2 Vertical cutoff rigidities (in GV) for various epochs 1600, 1700, 1800, 1900 and 2000, as well as change from 1900 to 2000 owed to changes of geomagnetic field. According to Shea and Smart [73]

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	North America
40	255	2.55	3.18	4.08	4.88	5.89	-0.63	North America
20	255	8.67	12.02	14.11	15.05	16.85	-3.35	North America
20	300	10.01	7.36	9.24	12.31	15.41	+2.65	North America
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	South Africa
-35	300	8.94	12.07	13.09	10.84	8.10	-3.13	South America

Table 2 shows that the change of geomagnetic cutoffs, in the period 1600–1900, is not homogeneous: of the 14 selected regions, 5 showed increasing cutoffs with decreasing CR intensity, and 9 regions showed decreasing cutoffs with increasing CR intensity. From Table 2 it can also be seen that at present time (from 1900 to 2000) there are sufficient change in cutoff rigidities: decreasing (with corresponding increasing of CR intensity) in 10 regions, and increasing (with corresponding decreasing of CR intensity) in 3 regions. These changes give trend in CR intensity change what we need to take into account together with CR 11 and 22 a modulation by solar activity, considered in Section 2.12.

2.14. Atmospheric Ionisation by Cosmic Rays: The Altitude Dependence and Planetary Distribution

The main process in the link between CR and cloudiness is the air ionisation which triggers chemical processes in the atmosphere. Figure 19 shows experimental data [74] of the galactic CR generation of secondary particles and absorption at different cutoff rigidities. Figure 20 illustrates the total ionisation of atmosphere by galactic CR (primary and secondary) as a function of altitude.

The planetary distribution of ionisation at the altitude of 3 km [75], is shown in Fig. 21 for the year 2000, and its time variation during 1950–2000 is presented in Fig. 22.

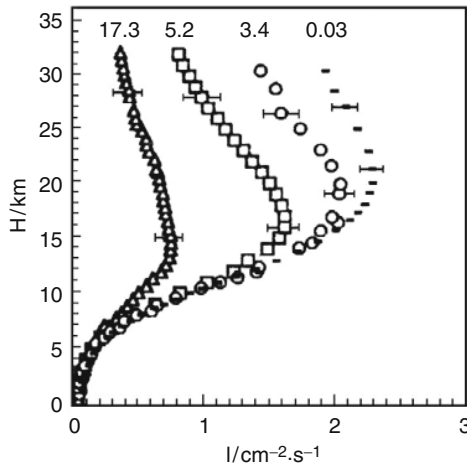


FIGURE 19 The absorption, I , curves of CR in the atmosphere at different cutoff rigidities (numbers at the top in units of GV) as a function of altitude, H . The horizontal bars indicate the standard deviations. From Ermakov et al. [74].

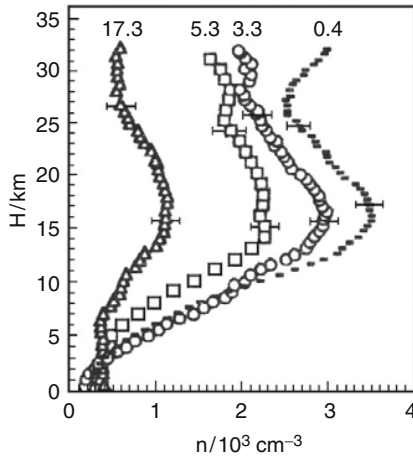


FIGURE 20 The ion concentration, n , profiles as a function of altitude, H , for different geomagnetic cutoff rigidities (numbers at the top are in units of GV). The horizontal bars indicate the standard deviations. From Ermakov et al. [74].

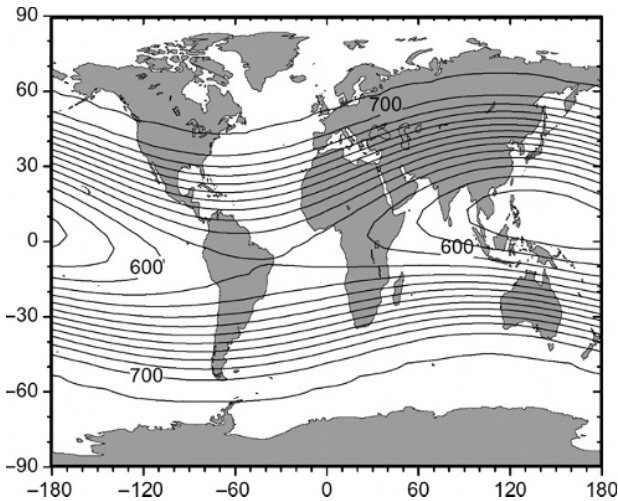


FIGURE 21 Planetary distribution of calculated equilibrium galactic CR induced ionisation at the altitude of 3 km ($h = 725 \text{ g/cm}^2$) for the year 2000. Contour lines are given as the number of ion pairs per cm^3 in steps of 10 cm^{-3} . From Usoskin et al. [75].

2.15. Project 'Cloud' as an Important Step in Understanding the Link between Cosmic Rays and Cloud Formation

The many unanswered questions in understanding the relationship between CR and cloud formation is being investigated by a special collaboration, within the framework of European Organization for Nuclear Research,

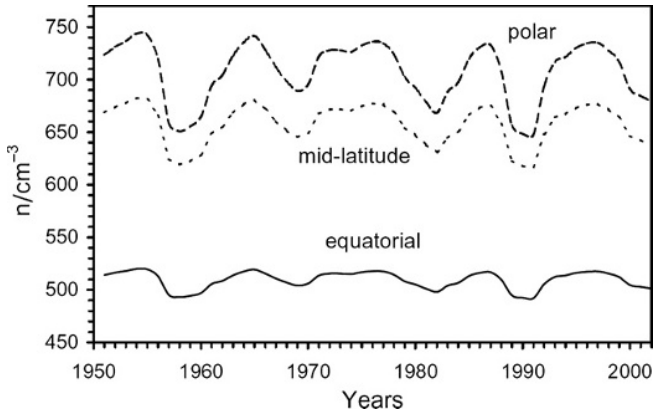


FIGURE 22 Calculated time profiles of the annual ionisation, n , at altitude of 3 km ($h = 725$ g/cm²), induced by galactic CR, for three regions: polar (cutoff rigidity $R_c < 1$ GV), mid-latitudes ($R_c \approx 6$ GV) and equatorial ($R_c \approx 15$ GV) regions. From Ref. [75].

involving 17 Institutes and Universities [76]. The experiment, which is named ‘CLOUD’, is based on a cloud chamber (which is designed to duplicate the conditions prevailing in the atmosphere) and ‘CRs’ from CERN Proton Synchrotron. The Project will consider possible links between CR, variable Sun intensities and the Earth’s climate change (see Fig. 23).

3. THE INFLUENCE ON THE EARTH’S CLIMATE OF THE SOLAR SYSTEM MOVING AROUND THE GALACTIC CENTRE AND CROSSING GALAXY ARMS

The influence of space dust on the Earth’s climate has been reviewed [77]. Figure 24 shows the changes of planetary surface temperature for the last 520 Ma according [78]. These data were obtained from the paleoenvironmental records. During this period the solar system crossed Galaxy arms four times. In doing so, there were four alternating warming and cooling periods with temperature changes of more than 5 °C.

The amount of matter inside the galactic arms is more than on the outside. The gravitation influence of this matter attracts the inflow of comets from Oort’s cloud to solar system [79,80]. It results in an increase in concentration of interplanetary dust in zodiac cloud and a cooling of the Earth’s climate [81].

4. THE INFLUENCE OF MOLECULAR-DUST GALACTIC CLOUDS ON THE EARTH’S CLIMATE

The solar system moves relative to interstellar matter with a velocity about 30 km s⁻¹ and sometimes passes through molecular-dust clouds. During these periods we can expect a decrease in sea level air temperature. According to

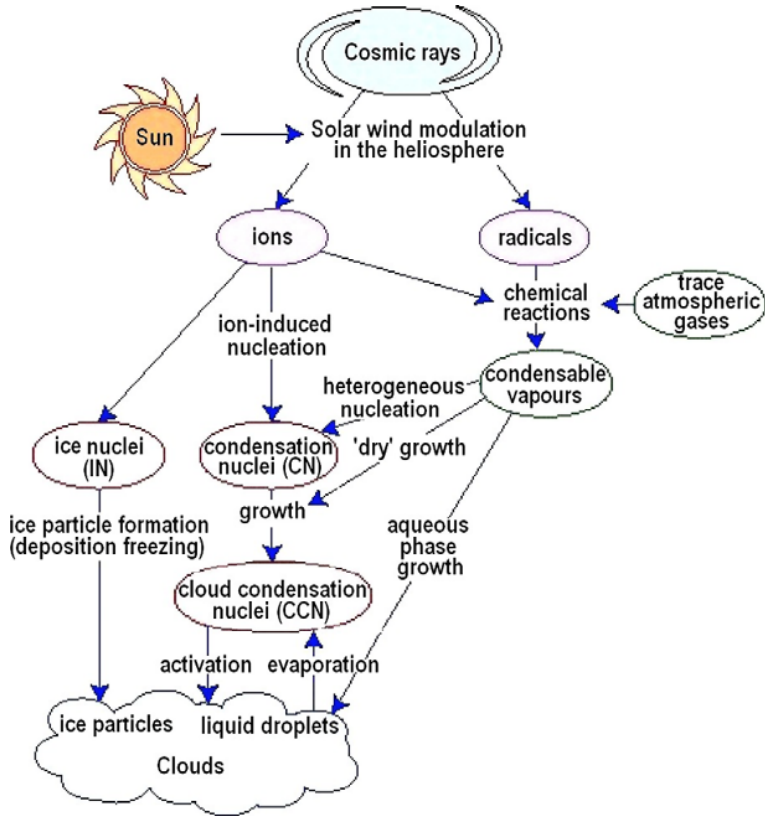


FIGURE 23 Possible paths of solar modulated CR influence on different processes in the atmosphere leading to the formation of clouds and their influence on climate. From Ref. [76].

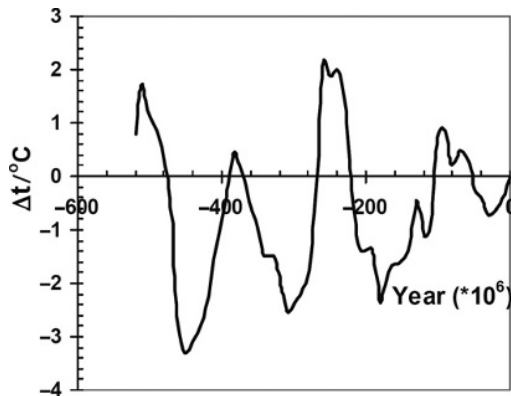


FIGURE 24 Changes of air temperature, Δt , near the Earth's surface for the last 520 Ma according to the paleoenvironmental records [78]. From Ref. [77].

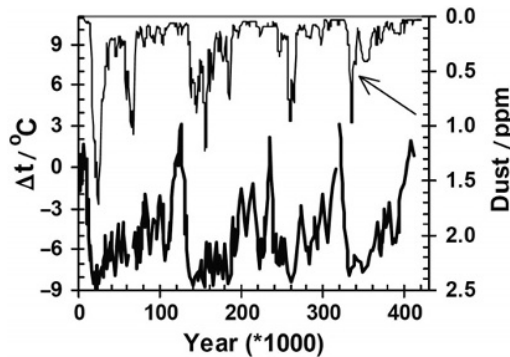


FIGURE 25 Changes of temperature, Δt , relative to modern epoch (bottom thick curve) and dust concentration (upper thin curve) over the last 420 000 a [83]. From Ref. [77].

Dorman [82], the prediction of the interaction of a dust-molecular cloud with the solar system can be performed by measurements of changes in the galactic CR distribution function. From the past we know that the dust between the Sun and the Earth has led to decreases of solar irradiation flux resulting in reduced global planetary temperatures (by $5\text{--}7\text{ }^{\circ}\text{C}$ in comparison with the $0.8\text{ }^{\circ}\text{C}$ increase due to the present greenhouse effect). The plasma in a moving molecular dust cloud contains a frozen-in magnetic field; this moving field can modify the stationary galactic CR distribution outside the Heliosphere. The change in the distribution function can be significant, and it should be possible to identify these changes when the distance between the cloud and the Sun becomes comparable with the dimension of the cloud. The continuous observation of the time variation of CR distribution function for many years should make it possible to determining the direction, geometry and the speed of the dust-molecular cloud relative to the Sun. Therefore, it should, in future, be possible to forecast climatic changes caused by this molecular-dust cloud.

Figure 25 shows the temperature changes at the Antarctic station Vostok (bottom curve), which took place over the last 420 000 a according to Petit et al. [83]. These data were obtained from isotopic analysis of O and H extracted from the ice cores at a depth 3300 m. It is seen from Fig. 25 that during this time the warming and cooling periods changed many times and that the temperature changes amounted up to $9\text{ }^{\circ}\text{C}$. Data obtained from isotope analysis of ice cores in Greenland, which cover the last 100 000 a [79], confirm the existence of large changes in climate.

5. THE INFLUENCE OF INTERPLANETARY DUST SOURCES ON THE EARTH'S CLIMATE

According to Ermakov et al. [77], the dust of zodiac cloud is a major contributory factor to climate changes in the past and at the present time. The proposed mechanism of cosmic dust influence is as follows: dust from

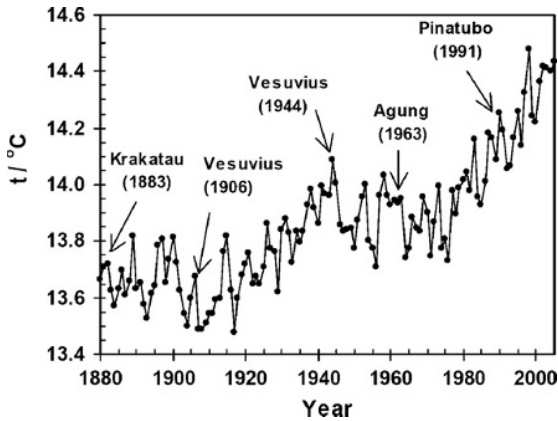


FIGURE 26 Yearly average values of the global air temperature, t , near the Earth's surface for the period from 1880 to 2005 [81]. Arrows show the dates of the volcano eruptions with the dust emission to the stratosphere and short times cooling after eruptions. From Ref. [77].

interplanetary space enters the Earth's atmosphere during the yearly rotation of the Earth around the Sun. The space dust participates in the processes of cloud formation. The clouds reflect some part of solar irradiance back to space. In this way the dust influences climate. The main sources of interplanetary dust are comets, asteroids and meteor fluxes. The rate of dust production is continually changing. The effect of volcanic dust on the Earth's air temperature is illustrated in Fig. 26 [81]. (Note air temperature can be found at ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/global_meanT_C.all)

According to Ermakov et al. [77], the spectral analysis of global surface temperature during 1880–2005 shows the presence of several spectral lines that can be identified with the periods of meteor fluxes, comets and asteroids. The results of analysis have been used [77,84] to predict changes in climate over the next half-century: the interplanetary dust factor of cooling in the next few decades will be more important than the warming from greenhouse effect.

6. SPACE FACTORS AND GLOBAL WARMING

It is now commonly thought of that the current trend of the global warming is causally related to the accelerating consumption of fossil fuels by the industrial nations. However, it has been suggested that this warming is a result of a gradual increase of solar and magnetic activity over the last 100 a. According to Pulkkinen et al. [85], as shown in Figs. 27 and 28, the solar and magnetic activity has been increasing since the year 1900 with decreases in 1970 and post 1980. Figures 27 and 28, show that that the aa index of geomagnetic activity, (a measure of the variability of the interplanetary magnetic field,

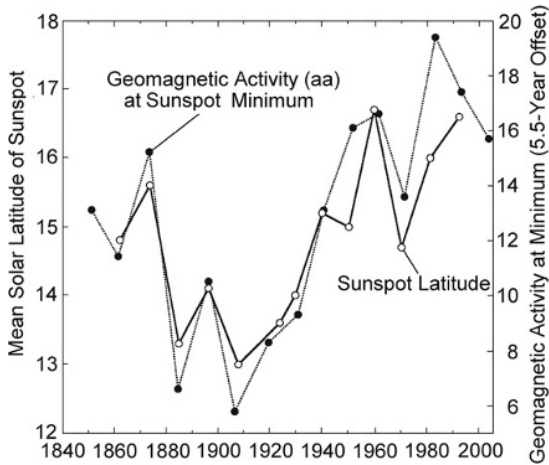


FIGURE 27 The geomagnetic activity (index aa) at the minimum of solar activity and the mean sunspots latitude, from 1840 to 2000. From Ref. [85].

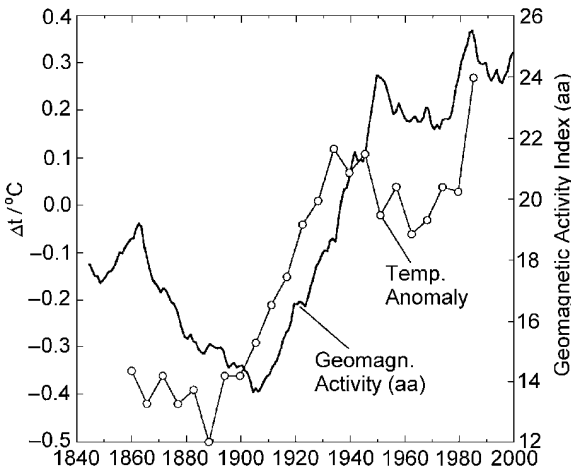


FIGURE 28 The geomagnetic activity (index aa) at the minimum of solar activity variation of the global temperature anomaly, Δt , from 1840 to 2000. From Ref. [85].

IMF), varies, almost in parallel, with the sunspot activity and with the global temperature anomaly.

It has been well established that the brightness of the Sun varies in proportion to solar activity. The brightness changes are very small and cannot explain all of the present global warming. However, the gradual increase of solar activity over the last hundred years has been accompanied by a gradual decrease of CR intensity in interplanetary space [86]. The direct measurements of CR intensity on the ground by the global network of NM as well as

regular CR intensity measurements from balloons in the troposphere and stratosphere over a period of more than 40 a, show that there is a small negative trend of galactic CR intensity [87]) of about 0.08% per year. Extrapolating this trend to a 100 a, gives a CR intensity decrease on 8%. From Fig. 2 it can be seen that the decreasing of CR intensity by 8% will lead to a decrease of cloud coverage of about 2%. According to Dickinson [14], decreasing cloud coverage by 2% corresponds to increasing the solar radiation falling on the Earth by about 0.5%. Using this information, Stozhkov et al. [55] concluded that the observed increase of average planetary ground temperature of 0.4–0.8 °C over the last 100 a, may be a result of this negative trend of CR intensity. Sakurai [88] came to the same conclusion on the basis of analysing data of solar activity and CR intensity.

7. THE INFLUENCE OF ASTEROIDS ON THE EARTH'S CLIMATE

It is well known that asteroids have in the past, struck the Earth with sufficient force to make major climatic changes (the famous dinosaur-killing mass extinction at the end of the Cretaceous, which began the Tertiary era, has been convincingly identified with such an asteroid impact [89], [90]). However, it is unlikely that our present climate change is due in any way to such events. Fortunately today, with modern methods of Astronomy, the trajectory of dangerous asteroids can be determined exactly and together with modern rocket power, could possibly be deflected.

8. THE INFLUENCE OF NEARBY SUPERNOVA ON THE EARTH'S CLIMATE

It is well known that the Sun is a star of the second generation, in that it was born together with solar system from Supernova explosion about 5 Ga ago. From the energetic balance of CR in the Galaxy it follows that the full power for CR production is about 3×10^{33} W. Now it is commonly accepted that the Supernova explosions are the main source of galactic CR. At each explosion the average energy transferred to CR is about 10^{43} – 10^{44} J. From this quantity we can determine the expected frequency of Supernova explosions in our Galaxy and in vicinity of the Sun, and estimate: the probability of Supernova explosions at different distances from the Sun; the expected UV radiation flux (destroyer of our ozone layer and hence a significant player in our Earth's climate), and the expected CR flux. It has been estimated in Dorman et al. [91] and Dorman [82] that if such an event does take place, the levels of CR radiation reaching our Earth could reach levels extremely dangerous to our civilisation and biosphere. Such an event is unlikely to be responsible for our present climate changes.

9. DISCUSSION AND CONCLUSIONS

Many factors from space and from anthropogenic activities can influence the Earth's climate. The initial response is that space factors are unlikely to be responsible for most of our present climate change. However, it is important that all possible space factors be considered, and from an analysis of past climate changes, we can identify our present phase and can predict future climates. During the last several hundred million years the Sun has moved through the galactic arms several times with resultant climate changes. For example, considering the effects due to galactic molecular-dust concentrated in the galactic arms, as given in Fig. 24, we can see that during the past 520×10^6 a, there were four periods with surface temperatures lower than what we are presently experiencing and four periods with higher temperatures. On the other hand, during the past 420 000 a (Fig. 25) there were four decreases of temperature (the last one was about 20 000–40 000 a ago: the so-called big ice period), and five increases of temperature, the last of which happened few thousand years ago. At present the Earth is in a slight cooling phase (of the order of one degree centigrade over several thousand years).

When considering CR variations as one of the possible causes of long-term climate change (see Section 2) we need to take into account not only CR modulation by solar activity 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 a: paleomagnetic investigations show that during the last 3.6×10^6 a the magnetic field of the Earth changed sign nine times, and the Earth's magnetic moment changed – sometimes having a value of only one-fifth of its present value [92] – corresponding to increases of CR intensity and decreases of the surface temperature.

The effects of space factors on our climate can be divided into two types:

- the 'gradual' type, related to changes on time scales ranging from 10^8 a to 11–22 a, producing effects which could be greater than that produced from anthropogenic factors, and
- the 'sudden' type, coming from Supernova explosions and asteroid impacts, for example, and which may indeed be catastrophic to our civilization. Volcanic and anthropogenic factors are also in a sense, 'sudden' factors in their effect on climate change.

It is necessary to investigate all of the possible 'sudden' factors and to develop methods of forecasting and also for protecting the biosphere and the Earth's civilization from big changes in climate and environment. We cannot completely exclude the possibility that a Supernova explosion, for example, took place 20 a ago at a distance of say 30 light years away. In this case its influence on our climate and environment will be felt in 10 a time. According to Ellis and Schramm [93], in this case, UV radiation would destroy the Earth's ozone layer over a period of about 300 a. The recent

observations of Geminga, PSR J0437–4715, and SN 1987A strengthen the case for one or more supernova extinctions having taken place during the Phanerozoic era. In this case a nearby supernova explosion would have depleted the ozone layer, exposing both marine and terrestrial organisms to potentially lethal solar UV radiation. In particular, photosynthesising organisms including phytoplankton and reef communities would most likely have been badly affected.

As Quante [94] noted, clouds play a key role in our climate system. They strongly modulate the energy budget of the Earth and are a vital factor in the global water cycle. Furthermore, clouds significantly affect the vertical transport in the atmosphere and determine, in a major way, the redistribution of trace gases and aerosols through precipitation. In our present-day climate, on average, clouds cool our planet; the net cloud radiative forcing at the top of the atmosphere is about $-20 \text{ W}\cdot\text{m}^{-2}$. Any change in the amount of cloud or a shift in the vertical distribution of clouds, can lead to considerable changes in the global energy budget and thus affect climate [94].

Many of the ‘gradual’ types of space factors are linked to cloud formation. Quante [94] noted that galactic CR [19–22] was an important link between solar activity and low cloud cover (see Figs. 2 and 3). However, new data after 1995 shows that the problem is more complicated and the correlation no longer holds [95]. Kristjánsson et al. [96] pointed out that still many details are missing for a complete analysis, but a cosmic ray modulation of the low cloud cover seems less likely to be the major factor in our present climate change, but its role in future climate changes must not be ruled out.

In this Chapter much emphasis has been given to the formation of clouds and the influence CR plays (through ionisation and influence on chemical processes in atmosphere) in their formation. This does not imply that CR is the only factor in their formation; dust, aerosols, precipitation of energetic particles from radiation belts and greenhouse gases, all play their part. However, the influence of CR is important and has been demonstrated here through:

- a direct correlation during one solar cycle (Figs. 2 and 3) and also for much longer periods,
- the correlation of CR intensity with the planetary surface temperature (Figs. 1, 4 and 5),
- by the direct relationship between CR intensity and wheat prices in medieval England (Fig. 8),
- by the direct relationship between cloud formation and CR air ionisation (Fig. 9),
- by the relationship between geomagnetic activity and rainfall through precipitation of energetic particles from radiation belts (Figs. 10–13) and
- by linking CR intensities with the cirrus holes (Figs. 14 and 15).

The importance of CR cannot be stressed highly enough and it is important to develop methods for determining, with high accuracy, galactic CR intensity variations for the past, the present and for the near future.

In this Chapter several attempts have been made to explain the present climate change (the relatively rapid warming of the Earth discussed in [Section 6](#) for 1937–1994), using space factors:

- through 11 a average CR intensities discussed in [Section 2.5](#),
- by the increasing geomagnetic activity,
- by the decreasing CR intensity (of 8% over the past 100 a) and
- by relating the spectral analysis of Ermakov et al. [[77](#)] to global temperature during 1880–2005.

Their results show the presence of several spectral lines that can be identified with the periods of meteor fluxes, comets and asteroids. On the basis of this work, Ermakov et al. [[77,84](#)] has predicted a cooling of the Earth's climate over the next half-century which they believe will be more important than warming from greenhouse effect.

Finally, it appears that our present climate change (including a rapid warming of about 0.8 °C over the past 100 a, see [Fig. 26](#)) is caused by a collective action of several space factors, volcano activities (with the dust emission rising to the stratosphere, resulting in short term cooling after eruptions), as well as by anthropogenic factors with their own cooling and warming contributions. The relation between these contributions will determine the final outcome. At present the warming effect is stronger than the cooling effect. It is also very possible that the present dominant influence is anthropogenic in origin.

From [Fig. 25](#) can be seen that now we are near the maximum global temperature reached over the past 400 000 a, so an additional rapid increase of even a few degree celsius could lead to an unprecedented and catastrophic situation. It is necessary that urgent and collective action be taken now by the main industrial countries and by the UN, to minimise the anthropogenic influence on our climate before it is too late. On the other hand, in future, if the natural change of climate results in a cooling of the planet (see [Figs. 24 and 25](#)), then special man-made factors, resulting in warming, may have to be used to compensate.

ACKNOWLEDGMENTS

My great gratitude to Abraham Sternlieb, Isaac Ben Israel, and Zvi Kaplan for constancy attention and support of work of Israel Cosmic Ray and Space Weather Center and Emilio Ségre Observatory; to Lev Pustil'nik, Yurii Stozhkov and Igor Zukerman for interesting discussions, and to Trevor Letcher for useful comments.

REFERENCES

1. L.I. Dorman, *Cosmic Rays in the Earth's Atmosphere and Underground*, Kluwer Academic Publishers, Dordrecht/Boston/London, 2004.
2. L.I. Dorman, *Cosmic Rays in Magnetospheres of the Earth and other Planets*, Springer, Netherlands, 2009.
3. L.I. Dorman, *Cosmic Ray Interactions, Propagation, and Acceleration in Space Plasmas*, Springer, Netherlands, 2006.
4. H. Herschel, *Philosophical Transactions of the Royal Society*, London, 91 (1801) 265–318.
5. J.A. Eddy, *Science* 192 (1976) 1189–1202.
6. H. Swensmark, *Space Sci. Rev.* 93 (2000) 175–185.
7. E. Friis-Christiansen, K. Lassen, *Science* 254 (1991) 698–700.
8. K. Lassen, E. Friis-Christiansen, *J. Atmos. Solar-Terr. Phys.* 57 (1995) 835–845.
9. K. Labitzke, H. van Loon, *Ann. Geophys.* 11 (1993) 1084–1094.
10. J. Lean, J. Beer, R. Bradley, *Geophys. Res. Lett.* 22 (1995) 3195–3198.
11. J.D. Haigh, *Science* 272 (1996) 981–984.
12. D. Shindell, D. Rind, N. Balabhandran, J. Lean, P. Lonengran, *Science* 284 (1999) 305–308.
13. E.R. Ney, *Nature* 183 (1959) 451–452.
14. R.E. Dickinson, *Bull. Am. Met. Soc.* 56 (1975) 1240–1248.
15. M.I. Pudovkin, O.M. Raspopov, *Geomagn. Aeronomy* 32 (1992) 593–608.
16. M. Pudovkin, S. Veretenenko, *J. Atmos. Solar-Terr. Phys.* 57 (1995) 1349–1355.
17. M. Pudovkin, S. Veretenenko, *Adv. Space Res.* 17(11) (1996) 161–164.
18. B.A. Tinsley, *J. Geomagn. Geoelectr.* 48 (1996) 165–175.
19. H. Swensmark, E. Friis-Christiansen, *J. Atmos. Solar-Terr. Phys.* 59 (1997) 1225–1232.
20. H. Swensmark, *Phys. Rev. Lett.* 81 (1998) 5027–5030.
21. N.D. Marsh, H. Swensmark, *Phys. Rev. Lett.* 85 (2000) 5004–5007.
22. N. Marsh, H. Swensmark, *Space Sci. Rev.* 94 (2000) 215–230.
23. L.I. Dorman, I.Ya. Libin, M.M. Mikalayunas, K.F. Yudakhin, *Geomagn. Aeronomy* 27 (1987) 303–305.
24. L.I. Dorman, I.Ya. Libin, M.M. Mikalajunas, *Regional Hydrometeorol. (Vilnius)*, 12 (1988) 119–134.
25. L.I. Dorman, I.Ya. Libin, M.M. Mikalajunas, *Regional Hydrometeorol. (Vilnius)*, 12 (1988) 135–143.
26. L.I. Dorman, G. Villorosi, I.V. Dorman, N. Iucci, M. Parisi, *Proc. 25-th Intern. Cosmic Ray Conference, Durban (South Africa)*, 7 (1997) 345–348.
27. R. Markson, *Nature* 273 (1978) 103–109.
28. C. Price, *Nature* 406 (2000) 290–293.
29. B.A. Tinsley, *Space Sci. Rev.* 94 (2000) 231–258.
30. K. Schlegel, G. Diendorfer, S. Them, M. Schmidt, *J. Atmos. Solar-Terr. Phys.* 63 (2001) 1705–1713.
31. L.I. Dorman, I.V. Dorman, N. Iucci, M. Parisi, Y. Ne'eman, L.A. Pustil'nik, F. Signoretti, A. Sternlieb, G. Villorosi, I.G. Zukerman, *J. Geophys. Res.* 108(A5) (2003) 1181, SSH 2_1–8.
32. L.I. Dorman, I.V. Dorman, *Adv. Space Res.* 35 (2005) 476–483.
33. D.L. Hartmann, in: P.V. Hobbs (Ed.), *Aerosol–Cloud–Climate Interactions*, Academic Press (1993) p. 151.
34. G. Ohring, P.F. Clapp, *J. Atmospheric Sci.* 37 (1980) 447–454.
35. V. Ramanathan, R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, D. Hartmann, *Science*, 243(4887) (1989) 57–63.

36. P.E. Ardanuy, L.L. Stowe, A. Gruber, M. Weiss, *J. Geophys. Res.* 96 (1991) 18537–18549.
37. L.L. Stowe, C.G. Wellemayer, T.F. Eck, H.Y.M. Yeh, and the Nimbus-7 Team, *J. Clim.* 1 (1988) 445–470.
38. W.B. Rossow, R. Shiffer, *Bull. Am. Met. Soc.* 72 (1991) 2–20.
39. F. Weng, N.C. Grody, *J. Geophys. Res.* 99 (1994) 25535–25551.
40. R.R. Ferraro, F. Weng, N.C. Grody, A. Basist, *Bull. Am. Met. Soc.* 77 (1996) 891–905.
41. H.S. Ahluwalia, *Proc. 25th Int. Cosmic Ray Conf., Durban*, 2 (1997) 109–112.*
42. W.B. Rossow, B. Cairns, *J. Clim.*, 31 (1995) 305–347.
43. J. Lean, A. Skumanich, O. White, *Geophys. Res. Lett.* 19 (1992) 1591–1594.
44. J. Beer, G.M. Raisbeck, F. Yiou, in: C.P. Sonett, M.S. Giampapa, M.S. Matthews (Eds.), *The Sun in Time*, University of Arizona Press (1991) 343–359.
45. P.D. Jones, K.R. Briffa, T.P. Barnett, S.F.B. Tett, *The Holocene*, 8 (1998) 455–471.
46. M.E. Mann, R.S. Bradley, M.K. Hughes, *Nature* 392 (1998) 779–787.
47. A. Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, W. Strahan & T. Cadell, London, 1776.
48. W.S. Jevons, *Nature* 19 (1875) 33–37.
49. J.E.T. Rogers, *Agriculture and Prices in England*, vols. 1–8, Oxford, Clarendon Press, 1887.
50. W.S. Jevons, *Nature* 26 (1882) 226–228.
51. L. Pustil'nik, G. Yom Din, L. Dorman, *Proc. 28th Intern. Cosmic Ray Conf. Tsukuba*, 7 (2003) 4131–4134.
52. L. Pustil'nik, G. Yom Din, *Solar Phys.* 223 (2004) 335–356.
53. J. Beer, S. Tobias, N. Weiss, *Solar Phys.* 181 (1998) 237–249.
54. L. Pustil'nik, G. Yom Din, *Solar Phys.* 224 (2004) 473–481.
55. Yu.I. Stozhkov, V.I. Ermakov, P.E. Pokrevsky, *Izvestia Russian Academy. Sci. Ser. Phys.*, 65(3) (2001) 406–410.
56. S.V. Veretenenko, M.I. Pudovkin, *Geomagn. Aeronomy*, 34 (1994) 38–44.
57. Yu. I. Stozhkov, P.E. Pokrevsky, I.M. Martin et al., *Proc. 24th Int. Cosmic Ray Conf. Rome*, 4 (1995) 1122–1125.
58. Yu.I. Stozhkov, J. Zullo, I.M. Martin et al., *Nuovo Cimento*, C18 (1995) 335–341.
59. Yu.I. Stozhkov, P.E. Pokrevsky, J. Jr. Zullo et al., *Geomagn. Aeronomy* 36 (1996) 211–216.
60. Yu. I. Stozhkov, *J. Phys. G: Nucl. Part. Phys.* 28 (2002) 1–11.
61. M.C. Todd, D.R. Kniveton, *J. Geophys. Res.* 106(D23) (2001) 32031–32042.
62. M.C. Todd, D.R. Kniveton, *J. Atmos. and Solar-Terr. Phys.* 66 (2004) 1205–1211.
63. B.A. Tinsley, G.W. Deen, *J. Geophys. Res.* 96(D12) (1991) 22283–22296.
64. G.I. Pugacheva, A.A. Gusev, I.M. Martin et al., *Proc. 24th Intern. Cosmic Ray Conf., Rome*, 4 (1995) 1110–1113.
65. I.M. Martin, A.A. Gusev, G.I. Pugacheva, A. Turtelli, Y.V. Mineev, *J. Atmos. and Terr. Phys.* 57(2) (1995) 201–204.
66. J.W. King, *Astronautics and Aeronautics* 13(4) (1975) 10–19.
67. J.T.A. Ely, T.C. Huang, *Geophys. Res. Lett.* 14(1) (1987) 72–75.
68. J.T.A. Ely, J.J. Lord, F.D. Lind, *Proc. 24th Intern. Cosmic Ray Conf., Rome*, 4 (1995) 1137–1140.
69. L.I. Dorman, *Adv. Space Res.* 35 (2005) 496–503.
70. L.I. Dorman, *Annales Geophysicae* 23(9) (2005) 3003–3007.
71. L.I. Dorman, *Adv. Space Res.* 37 (2006) 1621–1628.
72. A.V. Belov, L.I. Dorman, R.T. Guschina, V.N. Obridko, B.D. Shelting, V.G. Yanke, *Adv. Space Res.* 35(3) (2005) 491–495.
73. M.A. Shea, D.F. Smart, *Proc. 28th Intern. Cosmic Ray Conf., Tsukuba*, 7 (2003) 4205–4208.

74. V.I. Ermakov, G.A. Bazilevskaya, P.E. Pokrevsky, Yu. I. Stozhkov, Proc. 25th Intern. Cosmic Ray Conf., Durbin, 7 (1997) 317–320.
75. I.G. Usoskin, O.G. Gladysheva, G.A. Kovaltsov, J. Atmos. Solar-Terr. Phys. 66(18) (2004) 1791–1796.
76. B. Fastrup, E. Pedersen, E. Lillestol et al. (Collaboration CLOUD), Proposal CLOUD, CERN/SPSC (2000) 2000–2021.
77. V. Ermakov, V. Okhlopkov, Yu. Stozhkov, Proc. European Cosmic Ray Symposium, Lesboa (2006) Paper 1–72.
78. J. Veizer, Y. Godderis, I.M. Francois, Nature 408 (2000) 698–701.
79. K. Fuhrer, E.W. Wolff, S.J. Johnsen, J. Geophys. Res. 104(D24) (1999) 31043–31052.
80. O.A. Maseeva, Astronomicheskyy vestnik 38(4) (2004) 372–382.
81. J. Hansen, R. Ruedy, J. Glascoe, and M. Sato, J. Geophys. Res. 104(D24) (1999) 30997–31022.
82. L.I. Dorman, Adv. Geosci. 14 (2008) 281–286.
83. J.R. Petit, J. Jouzel, D. Raunaud, et al., Nature, 399 (1999) 429–436.
84. V.I. Ermakov, V.P. Okhlopkov, Y.I. Stozhkov, Bull. Lebedev Phys. Inst. Russian Acad. Sci. Moscow 3 (2006) 41–51.
85. T.I. Pulkkinen, H. Nevanlinna, P.J. Pulkkinen, M. Lockwood, Space Sci. Rev. 95 (2001) 625–637.
86. M. Lockwood, R. Stamper, M.N. Wild, Nature 399(6735) (1999) 437–439.
87. Yu.I. Stozhkov, P.E. Pokrevsky, V.P. Okhlopkov, J. Geophys. Res. 105(A1) (2000) 9–17.
88. K. Sakurai, Proc. 28th Intern. Cosmic Ray Conf., Tsukuba, 7 (2003) 4209–4212.
89. L. Alvarez, W. Alvarez, F. Asaro, H. Michel, Science 208 (1980) 1095–1108.
90. V. Sharpton, K. Burke, A. Camargo-Zaroguera et al., Science 261 (1993) 1564–1567.
91. L.I. Dorman, N. Iucci, G. Villoresi, Astrophys. Space Sci., 208 (1993) 55–68.
92. A. Cox, G.B. Dalrymple, R.R. Doedl, Sci. Am. 216(2) (1967) 44–54.
93. J. Ellis, D.N. Schramm, Proc. Nat. Acad. Sci. USA Astron. 92 (1995) 235–238.*
94. M. Quante, J. Phys. IV France 121 (2004) 61–86.
95. J.E. Kristjánsson, A. Staple, J. Kristiansen, Geophys. Res. Lett. 23 (2002) 2107–2110.
96. J.E. Kristjánsson, J. Kristiansen, E. Kaas, Adv. Space Res. 34(2) (2004) 407–415.