LINK BETWEEN COSMIC RAYS AND CLOUDS ON DIFFERENT TIME SCALES

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A possible mechanism of solar variability influence upon the Earth's climate is related to a link between the cosmic ray flux and cloudiness. Here we review evidences relating terrestrial climate variability to changes of cosmic ray flux in the Earth's vicinity on different time scales. On daily scales, major Forbush decreases and solar energetic particle events can affect the cyclogenesis in sub-polar regions. At inter-annual scales, a significant correlation between low clouds and cosmic ray induced ionization has been found. Different climate reconstructions depict a correlation with variations of the geomagnetic field intensity throughout the last millennia, providing additional support to a systematic effect of cosmic rays. On very long time scales, a close relation was reported between the global climate and variations of cosmic ray flux expected from local galactic environment changes. Although none of these facts alone is conclusive, in the aggregate they strongly support the link between cosmic rays and climate on Earth. These links are based on phenomenological relations, and theoretical development and experimental investigation of this hypothesis is ongoing.

1. Introduction

The Earth climate is ultimately driven by solar irradiance received by the terrestrial system. However, the detailed process of long-term climatic changes is not yet understood. The most direct mechanism is related to total solar irradiance (TSI) variations caused by variable solar magnetic activity. However, direct measurements of TSI during the last decades show that, while variations of TSI are closely related to the solar activity, their magnitude is too small to explain the climate variations.[1–3] Different solutions to the problem are discussed (see, e.g., a review in Ref. 4) such as a long-term trend in the irradiance,[5–7] a terrestrial amplifier of the irradiance variations,[8,9] or a concurrent mechanism which is also driven by the solar activity. Cosmic rays (CR) are a good candidate for the latter option

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(see, e.g., Refs. 10 and 11). Interaction of CR with the terrestrial atmosphere may affect cloud formation and thus modify the terrestrial energy balance. Even a small change in cloud cover shifts the balance between albedo and transmission of the atmosphere at different wavelengths. This strongly affects the amount of absorbed radiation, and therefore, climate, without notable changes in the solar irradiance. The flux of CR is modulated in the heliosphere thus providing a link to the solar magnetic activity. The CR as a possible climate driver is a topic of high interest nowadays, and quite a number of papers have been published recently discussing different aspects of this relation. Significant progress has been made during the last few years. Here we aim to review numerous results studying the CR–climate link, trying to highlight those which can be directly associated to CR rather than to solar irradiance variations. We highlight the problem from the point of view of a cosmic ray physicist. In Sec. 2, a brief description of possible mechanisms linking CR to cloud formation is presented. In Sec. 3, we review the empirical relations between CR and climate on different time scales. Conclusions are summarized in Sec. 4.

2. Possible Mechanisms

The amount of energy brought by CR into the terrestrial system is negligible compared to solar radiation, but their presence in the atmosphere is important since CR form the main source of ionization in the troposphere and lower stratosphere. Thus CR affect the chemical–physical conditions of the atmosphere and may influence the ability of the terrestrial system to absorb/trap/reflect solar radiation through, e.g., cloud cover. Clouds play an important role in the radiation budget of the atmosphere by both trapping outgoing long wave radiation and reflecting incoming solar radiation. Although these two processes have opposite signs, the net effect of cloudiness is cooling. Therefore, CR act as a trigger so that even a small input variation can produce a strong effect via controlling the atmospheric transparency. However, the details of this seemingly simple scenario are as yet far from being completely understood. Two main mechanisms of CR affecting clouds are discussed in the literature (see, e.g., reviews in Refs. 12 and 13).

One is based on the cosmic ray induced ionization (CRII) of the atmosphere.[14–16] Ions created by CR rapidly interact with molecules in the atmosphere and are converted into complex cluster ions (aerosols), which may grow by ion–ion recombination or ion–aerosol attachment and thus affect the number of aerosols acting as cloud condensation nuclei.

Another mechanism proposed by Tinsley[17,18] employs interaction between the electric field and cloud formation. The CRII controls the atmospheric conductivity, while the same processes which modulate CR (interplanetary magnetic field, solar wind, interplanetary shocks, etc.) affect the state of Earth's magnetosphere. Both mechanisms affect the global electrical circuit, which can modify the precipitation and ice formation in super-cooled water. Also, electroscavenging includes dynamical effects on storm systems.

Also alternative mechanisms may affect clouds without a direct influence of CR. For example, cloud variations can be a result of circulation changes due to stratospheric heating caused by the ozone absorption of solar UV radiation.[8,19] Furthermore, such changes may lead to changes in winter circulation patterns that affect middle latitude storm tracks.[8]

3. Cosmic Rays Versus Climate on Different Time Scales

Variations of CR are caused by different mechanisms on different time scales.[25] In the following subsections we consider them separately.

3.1. *Daily scales*

Regular variations of CR flux depict a diurnal cycle at the level of a few percent due to the local CR anisotropy. We do not consider it here since this diurnal variation cannot be distinguished in the atmospheric data because of the day–night effect. Other CR variations on daily time scale are sporadic. Interplanetary transient phenomena such as, e.g., interplanetary shocks, can suppress the flux of GCR by tens of percent over a few hours, with the subsequent recovery taking several days. This phenomenon is known as a Forbush decrease. On the other hand, strong solar flares or CME-driven shocks can accelerate solar/interplanetary particles leading to a strong increase of cosmic ray flux at the Earth's orbit called a solar energetic particle (SEP) event. Typical profiles of a Forbush decrease and a SEP event are shown in Figs. 1(a) and 1(b), respectively.

Many statistical studies have been performed looking for a relation between sporadic CR variations and atmospheric characteristics. Pudovkin and Veretenenko[26] reported some reduction of the mean cloud cover after Forbush decreases at high latitudes ($> 60^\circ$ N). Roldugin and Tinsley[27]

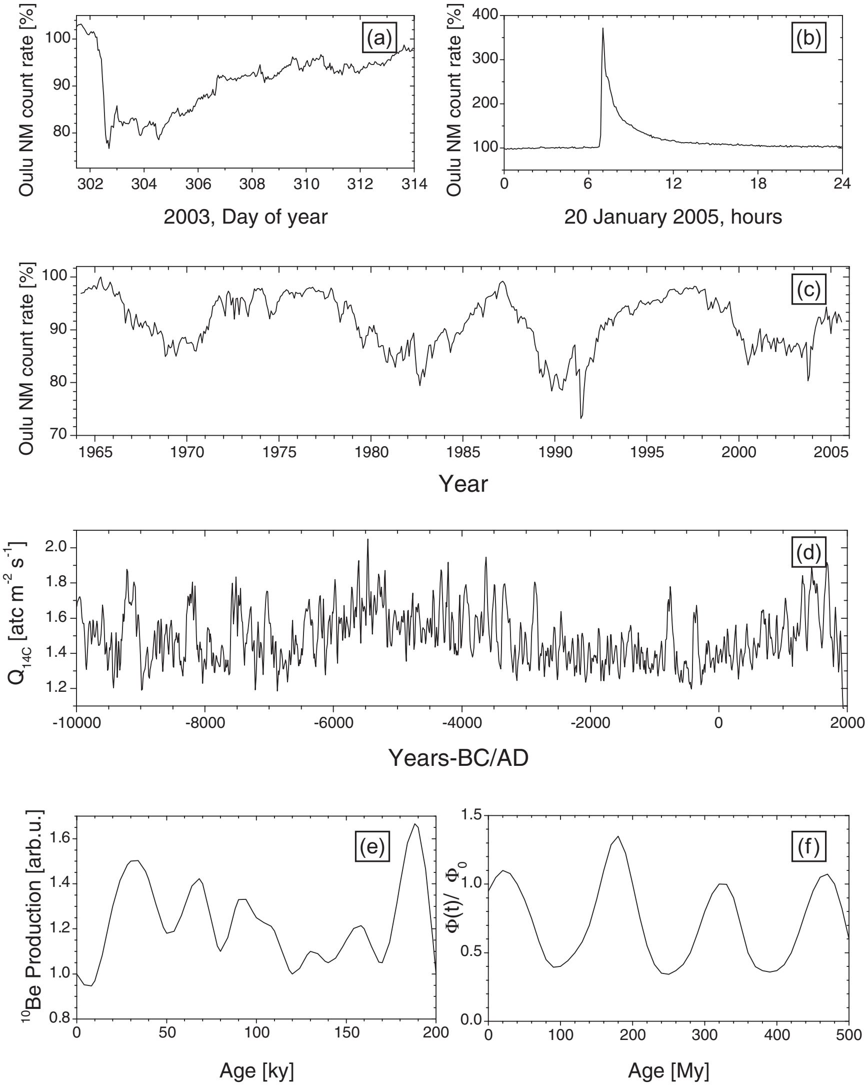

Fig. 1. Cosmic ray variations on different time scales: (a) Forbush decrease recorded by Oulu NM; (b) SEP event recorded by Oulu NM; (c) inter-annual variations recorded by Oulu NM; (d) millennial variations of the ^{14}C production rate (after Refs. 20 and 21); (e) multi-millennial variations of the ^{10}Be production rate (after Refs. 22 and 23); and (f) model simulation of the galactic cosmic ray density variations due to the galactic spiral arm crossings (after Ref. 24).

found changes in the atmospheric transparency associated with Forbush decreases at high latitudes ($> 55°$ N). Kniveton and Tinsley[28,29] and Todd and Kniveton[30] found zonal mean total cloud anomalies associated with Forbush decreases, particularly in polar and equatorial regions. Stozhkov *et al.*[31,32] reported observed changes in precipitation related to Forbush decreases and SEP events.

On the other hand, Tinsley *et al.*[13,33,34] suggested (later confirmed in Ref. 35) that vorticity in polar/subpolar regions can be affected by CR during the cold season — both reduction[33] after Forbush decreases and increase[35] during/after solar particle events were reported (Fig. 2).

In summary, there are hints for an effect of CR on the cloudiness/transparency/cyclogenesis, particularly in high latitude regions during cold seasons, but the results are so far not robust. The primary effect of CR may be related to vorticity/cyclogenesis.

3.2. *Inter-annual/decadal variations*

Temporal variations of CR are dominated by the 11-year cyclicity related to the solar magnetic activity cycle (see Fig. 1(c)). Similar 11-year cycle has been reported in the global low cloud coverage, in association with CR flux, by Svensmark and Friis-Christensen[36,37] and developed by Marsh and Svensmark in a series of papers.[15,38] This result initiated a dispute in the literature with both for[39–42] and contra[43–46] arguments. However, recent studies[47–49] show that not only temporal but also latitudinal distribution of low clouds closely follow CRII variations (Fig. 3). Low cloud

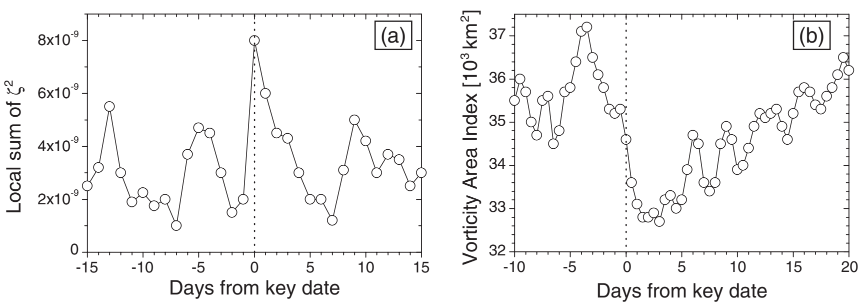

Fig. 2. Superposed epoch changes of the vorticity index. (a) Squared relative vorticity in the North Atlantic region associated with solar particle events (key date) (after Ref. 35) and (b) vorticity area index in the Northern hemisphere associated with Forbush decreases (key date) (after Ref. 33).

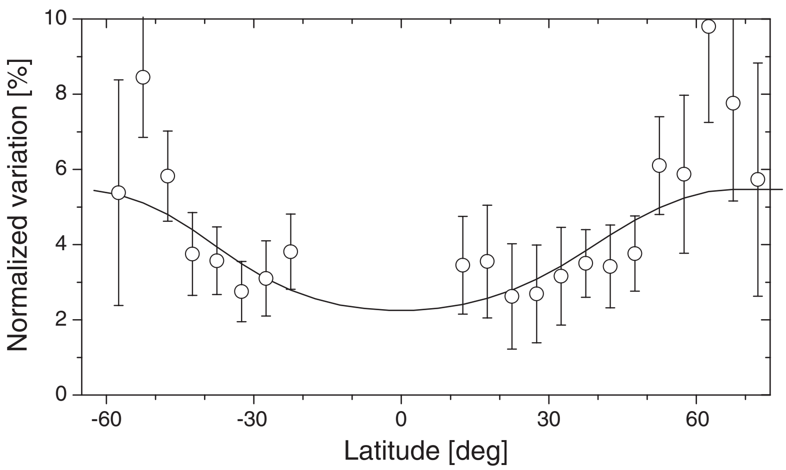

Fig. 3. Latitudinal profiles of the relative variations of the measured low cloud amount (dots) and computed CRII (line) (after Ref. 47).

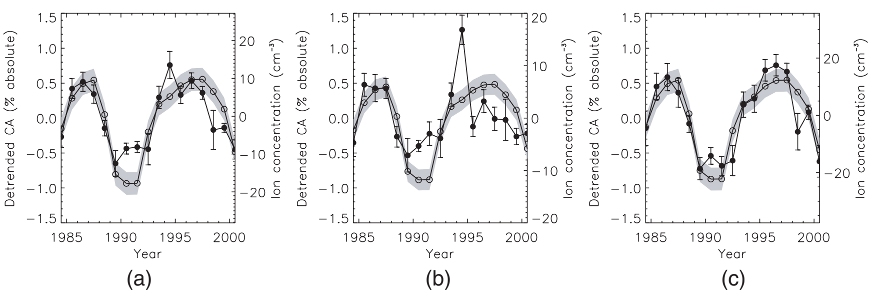

Fig. 4. Time profiles of detrended low cloud amount in percent of the area coverage (solid symbols, left axis) and CRII (open symbols, right axis) for (a) the global average ($60°\mathrm{S} < \lambda < 70°\mathrm{N}$), (b) tropics ($|\lambda| < 25°$), and (c) mid-latitudes ($60°\mathrm{S} < \lambda < 25°\mathrm{S}$ and $25°\mathrm{N} < \lambda < 70°\mathrm{N}$) (after Ref. 47).

amount time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting very significant correlation with CRII over the globe (see Fig. 4). A quantitative regression model has been suggested[47] with a nearly one-to-one relation between the relative variations of cloud amount and CRII. These results support the idea that low cloud amount is modulated by CRII at inter-annual timescales between 1984 and 2000. On the other hand, high clouds show anti-correlation with CRII and middle clouds no apparent correlation, while the total cloud cover shows only marginal correlation.[50] Pallé[50] proposed that low clouds can be partly masked by high clouds in the satellite data set. It seems more likely that other mechanisms, e.g., via the global current system[17] or UV heating[8] which work in anti-phase with CR variations, may dominate at higher altitudes. A careful study including detailed modeling is needed to disentangle different effects at different altitudes.

In summary, the link between *low* clouds and CRII looks quite reliable on the inter-annual time scale after 1983, including also the latitudinal/geographical pattern, however, a more detailed study is needed to understand the relation with other cloud types.

3.3. *Centennial to millennial time scales*

Variations of cosmic ray flux are defined mostly by solar activity changes on the centennial time scale. On longer time scales (Fig. 1(d)), geomagnetic field changes become increasingly important and start dominating CR variations on time scales longer than several millennia (Fig. 1(e)).

A detailed study[51] of a possible link between CR and cloudiness was performed using sunshine observations during the 20th century. Although the data are not easy to interpret and analyze, they concluded that a link between total cloud cover and CR is unlikely but the data are in general agreement with the hypothesis of a link between low clouds and CR.

There are numerous correlations between solar activity and climatic proxies (e.g., δ^{18}O or drift ice debris[52]) during the Holocene, which confirm the link between solar activity and climate. However, such studies cannot distinguish between CR and other solar activity driven effects, e.g., solar irradiance. In order to study explicit CR effects one needs to look for changing CR flux unrelated to solar activity, such as geomagnetic field variations and changes of the local galactic environment. On the multi-millennial time scale it was found that periods of geomagnetic field reversal roughly correspond to cold episodes of the paleoclimatic reconstructions,[53–55] although this correlation is not strong.[56] A detailed study[57] has revealed a weak but persistent correlation between Northern hemisphere temperature and the geomagnetic field intensity during the last millennium, implying that CR play a role in climate variations.

3.4. *Geological time scales*

On the geological time scales (longer than a million years) CR variations are determined by the local galactic environment. It is expected that the density of CR is higher when the Earth is inside dense galactic spiral arms. Shaviv and Veizer[24,58–60] reported a similarity between paleoclimatic reconstructions and variations of CR flux due to the modeled galactic spiral arms crossings, within the uncertainties of the latter (Fig. 5). This result has been both disputed[61] and supported[62] by other researchers. Note that an interpretation of this correlation is not straightforward. In particular, it assumes the constancy of other drivers and the type of climate throughout millions of years. However, e.g., galactic dust, which is abundant in galactic spiral arms, may lead to cooling of the climate during the spiral arm crossing,[63] in synchronization with the CR effect. The rate of geomagnetic field reversals also varies on mega-year scale[64,65] quite synchronously with the climatic variation (see Fig. 5). This itself modulates the CR flux impinging on the Earth also in synchronization with the CR effect due to spiral arm crossing. The corresponding geological processes, leading, e.g., to dust/smoke loading into the atmosphere or changing its physical–chemical characteristics, may also directly affect the climate.

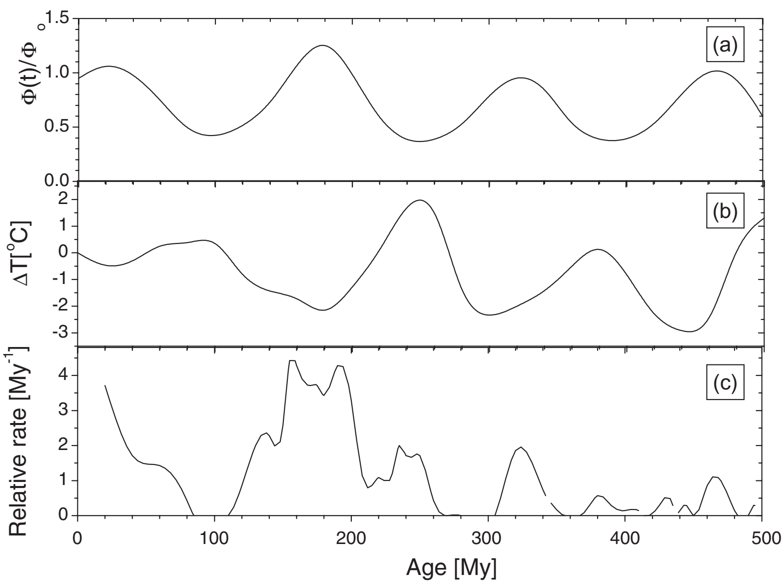

Fig. 5. Very long time variations of: (a) CR flux (after Ref. 24), the same as Fig. 1(f); (b) paleoclimatic reconstruction (after Ref. 24); and (c) the rate of geomagnetic field reversal per million years (after Refs. 64 and 65).

4. Conclusions

We have reviewed recent results and evidence linking cosmic ray flux to terrestrial climate. The results can be summarized as follows:

There are numerous hints of an instantaneous relation between CR and vorticity/cyclogenesis index at high latitudes during cold seasons at the daily time scale.

A significant empirical relation was found between temporal inter-annual and spatial variations of low cloud amount and cosmic ray induced ionization for the period 1983–2000. However, the relation between different types of clouds still needs to be understood.

Although a link between solar activity and climate seems plausible on the millennial time scale, only a marginal correlation with the geomagnetic field variations supports the idea of CR influence upon climate.

Evidence has been presented on a correlation between the mega-year time scale climate proxy series and model variations of CR due to the changes of the galactic surroundings. However, large uncertainties make this result only indicative.

In conclusion, a CR-climate link seems a plausible climate driver, but the present correlations favoring it, while numerous, are not solid. However, in the aggregate, they support the existence of a link between CR and the climate on Earth. The need for a quantitative model able to describe the cosmic ray effect on the atmospheric properties is critical. The next step is to proceed from phenomenological statistical studies to quantitative semi-empirical and physical models.

Acknowledgments

We acknowledge the support from the Academy of Finland, the Finnish Academy of Science and Letters, Vilho, Yrjö and Kalle Väisälä Foundation, and the Russian Academy of Sciences.

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