Cosmic Rays and Climate

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Sir William Herschel was the first to seriously consider the sun as a source of climate variations, already two centuries ago. He noted a correlation between the price of wheat, which he presumed to be a climate proxy, and the sunspot activity:

> "*The result of this review of the foregoing five periods is, that, from the price of wheat, it seems probable that some temporary scarcity or defect of vegetation has generally taken place, when the sun has been without those appearances which we surmise to be symptoms of a copious emission of light and heat.*"
>
> *— Sir William Herschel, Phil. Trans. Roy. Soc. London, 91, 265 (1801)*

Herschel presumed that this link arises from variation in the luminosity of the sun. Today, various solar activity and climate variations are indeed known to have a notable correlation on various time scales. The best example is perhaps the one depicted in fig. 1, on a centennial to millennial time scale between solar activity and the tropical climate of the Indian ocean (Neff et al. 2001). Another example of a beautiful correlation exists on a somewhat longer time scale, between solar activity and the northern atlantic climate (Bond et al. 2001). Nevertheless, the relatively small luminosity variations of the sun are most likely insufficient to explain this or other links. Thus, an amplifier of solar activity is probably required to explain these observed correlations.

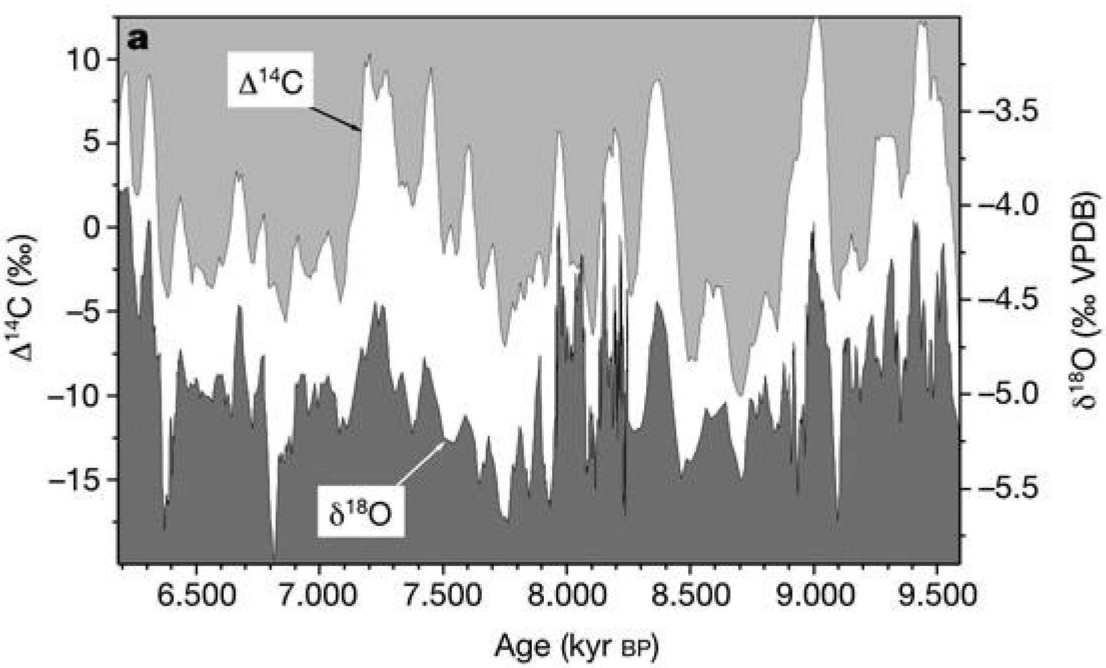

Figure 1: The correlation between solar activity—as mirrored in the ^{14}C flux, and a climate sensitivity

variable, the $^{18}O/^{16}O$ isotope ratio from stalagmites in a cave in Oman, on a centennial to millennial time scale. The ^{14}C is reconstructed from tree rings. It is a proxy of solar activity since a more active sun has a stronger solar wind which reduces the flux of cosmic rays reaching Earth from outside the solar system. A reduced cosmic ray flux, will in turn reduce the spallation of nitrogen and oxygen and with it the formation of ^{14}C. On the other hand, $^{18}O/^{16}O$ reflects the temperature of the Indian ocean—the source of the water that formed the stalagmites. (Graph from Neff et al., 2001, Copywrite by Nature, used with permission)

Several amplifiers were suggested. For example, UV radiation is all absorbed in the stratosphere, such that notable stratospheric changes arise with changes to the non-thermal radiation emitted by the sun. In fact, Joanna Heigh of Imperial College in London, suggested that through dynamic coupling with the troposphere, via the Hadley circulation (in which moist air ascends in the tropic and descends as dry air at a latitude of about 30°) the solar signal at the surface can be amplified. Here we are interested in what appears to be a much more indirect link between solar activity and climate.

In 1959, the late Edward Ney of the U. of Minnesota suggested that any climatic sensitivity to the density of tropospheric ions would immediately link solar activity to climate. This is because the solar wind modulates the flux of high energy particles coming from outside the solar system. These particles, the cosmic rays, are the dominant source of ionization in the troposphere. More specifically, a more active sun accelerates a stronger solar wind, which in turn implies that as cosmic rays diffuse from the outskirts of the solar system to its center, they lose more energy. Consequently, a lower tropospheric ionization rate results. Over the 11-yr solar cycle and the long term variations in solar activity, these variations correspond to typically a 10% change in this ionization rate. It now appears that there is a climatic variable sensitive to the amount of tropospheric ionization—Clouds.

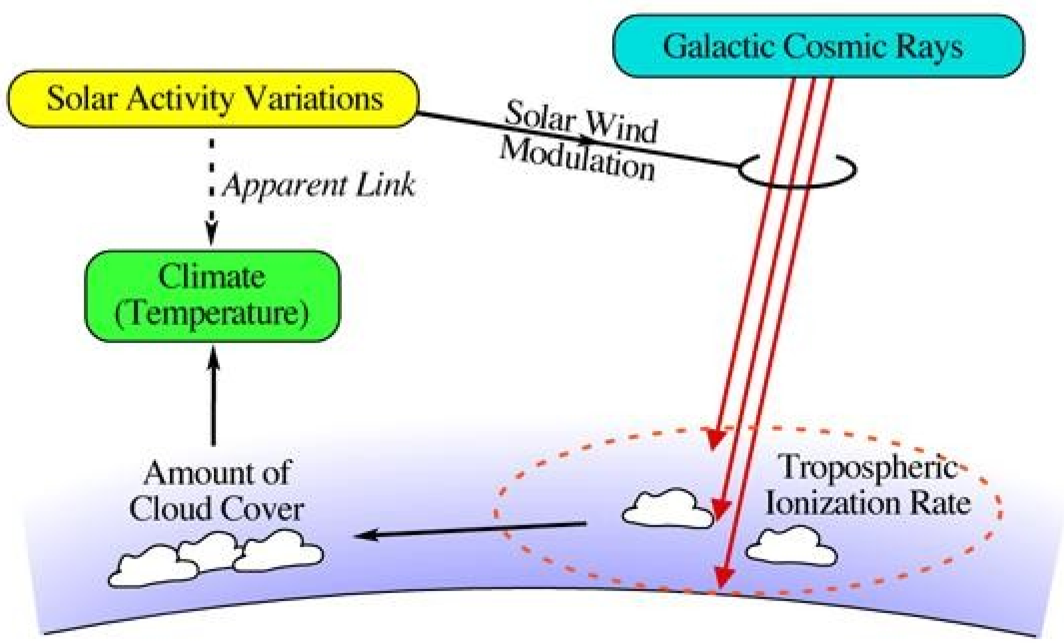

Figure 2: The cosmic ray link between solar activity and the terrestrial climate. The changing solar activity is responsible for a varying solar wind strength. A stronger wind will reduce the flux of cosmic ray reaching Earth, since a larger amount of energy is lost as they propagate up the solar wind. The cosmic rays themselves come from outside the solar system (cosmic rays with energies below the "knee" at 10^{15}eV, are most likely accelerated by supernova remnants). Since cosmic rays dominate the tropospheric ionization, an increased solar activity will translate into a reduced ionization, and empirically (as shown below), also to a reduced low altitude cloud cover. Since low altitude clouds have a net cooling effect (their "whiteness" is more important than their "blanket" effect), increased solar activity implies a warmer climate. Intrinsic cosmic ray flux variations will have a similar effect, one however, which is unrelated to solar activity variations.

Clouds have been observed from space since the beginning of the 1980's. By the mid 1990's, enough cloud data accumulated to provide empirical evidence for a solar/cloud-cover link. Without the satellite data, it hard or probably impossible to get statistically meaningful results because of the large systematic errors plaguing ground based observations. Using the satellite data, Henrik Svensmark of the Danish National Space Center in Copenhagen has shown that cloud cover varies in sync with the variable cosmic ray flux reaching the Earth. Over the relevant time scale, the largest variations arise from the 11-yr solar cycle, and indeed, this cloud cover seemed to follow the cycle and a half of cosmic ray flux modulation. Later, Henrik Svensmark and his colleague Nigel Marsh, have shown that the correlation is primarily with low altitude cloud cover. This can be seen in fig. 3.

Figure 3: The correlation between cosmic ray flux (orange) as measured in Neutron count monitors in low magnetic latitudes, and the low altitude cloud cover (blue) using ISCCP satellite data set, following Marsh & Svensmark, 2003.

The solar-activity – cosmic-ray-flux – cloud-cover correlation is quite apparent. It was in fact sought for by Henrik Svensmrk, based on theoretical considerations. However, by itself it cannot be used to prove the cosmic ray climate connection. The reason is that we cannot exclude the possibility that solar activity modulates the cosmic ray flux and independently climate, without any casual link between the latter two. There is however separate proof that a casual link exists between cosmic rays and climate, and independently that cosmic rays left a fingerprint in the observed cloud cover variations.

To begin with, climate variations appear to arise also from intrinsic cosmic ray flux variations, namely, from variations that have nothing to do with solar activity modulations. This removes any doubt that the observed solar activity cloud cover correlations are coincidental or without an actual causal connection. That is to say, it removes the possibility that solar activity modulates the cosmic ray flux and independently the climate, such that we *think* that the cosmic rays and climate are related, where in fact they are not. Specifically, cosmic ray flux variations also arise from the varying environment around the solar system, as it journeys around the Milky Way. These variations appear to have left a paleoclimatic imprint in the geological records.

Cosmic Rays, at least at energies lower than 10^{15}eV, are accelerated by supernova remnants. In our galaxy, most supernovae are the result of the death of massive stars. In spiral galaxies like our own, most of the star formation takes place in the spiral arms. These are waves which revolve around the galaxy at a speed different than the stars. Each time the wave passes (or is passed through), interstellar gas is shocked and forms new stars. Massive stars that end their lives with a supernova explosion, live a relatively short life of at most 30 million years, thus, they die not far form the spiral arms where they were born. As a consequence, most cosmic rays are accelerated in the vicinity of spiral arms. The solar system, however, has a much longer life span such that it periodically crosses the spiral arms of the Milky Way. Each time it does so, it should witness an elevated level of cosmic rays. In fact, the cosmic ray flux variations arising from our galactic journey are ten times larger than the cosmic ray flux variations due to solar activity modulations, at the energies responsible for the tropospheric ionization (of order 10 GeV). If the latter is responsible for a 1°K effect, spiral arm passages should be responsible for a 10°K effect—more than enough to change the state of earth from a hothouse, with temperate climates extending to the polar regions, to an icehouse, with ice-caps on its poles, as Earth is today. In fact, it is expected to be the most dominant climate driver on the 10^8 to 10^9 yr time scale.

It was shown by the author (Shaviv 2002, 2003), that these intrinsic variation in the cosmic ray flux are clearly evident in the geological paleoclimate data. To within the determinations of the period and phase of the spiral-arm climate connection, the astronomical determinations of the relative velocity agree with the geological sedimentation record for when Earth was in a hothouse or icehouse conditions. Moreover, it was found that the cosmic ray flux can be independently reconstructed using the so called "exposure ages" of Iron meteorites. The signal, was found to agree with the astronomical predictions on one hand, and correlate well with the sedimentation record, all having a ~145 Myr period.

Figure 4: An Iron meteorite. A large sample of these meteorites can be used to reconstruct the past cosmic ray flux variations. The reconstructed signal reveals a 145 Myr periodicity. The one in the picture is part of the Sikhote Alin meteorite that fell over Siberia in the middle of the 20th century. The cosmic-ray exposure age of the meteorite implies that it broke off its parent body about 300 Million years ago.

In a later analysis, with Ján Veizer of the University of Ottawa and the Ruhr University of Bochum, it

was found that the cosmic ray flux reconstruction agrees with a quantitative reconstruction of the tropical temperature (Shaviv & Veizer, 2003). In fact, the correlation is so well, it was shown that cosmic ray flux variations explain about two thirds of the variance in the reconstructed temperature signal. Thus, cosmic rays undoubtedly affect climate, and on geological time scales are the most dominant climate driver.

Figure 5: Correlation between the cosmic ray flux reconstruction (based on the exposure ages of Iron meteorites) and the geochemically reconstructed tropical temperature. The comparison between the two reconstructions reveals the dominant role of cosmic rays and the galactic "geography" as a climate driver over geological time scales. (Shaviv & Vezier 2003)

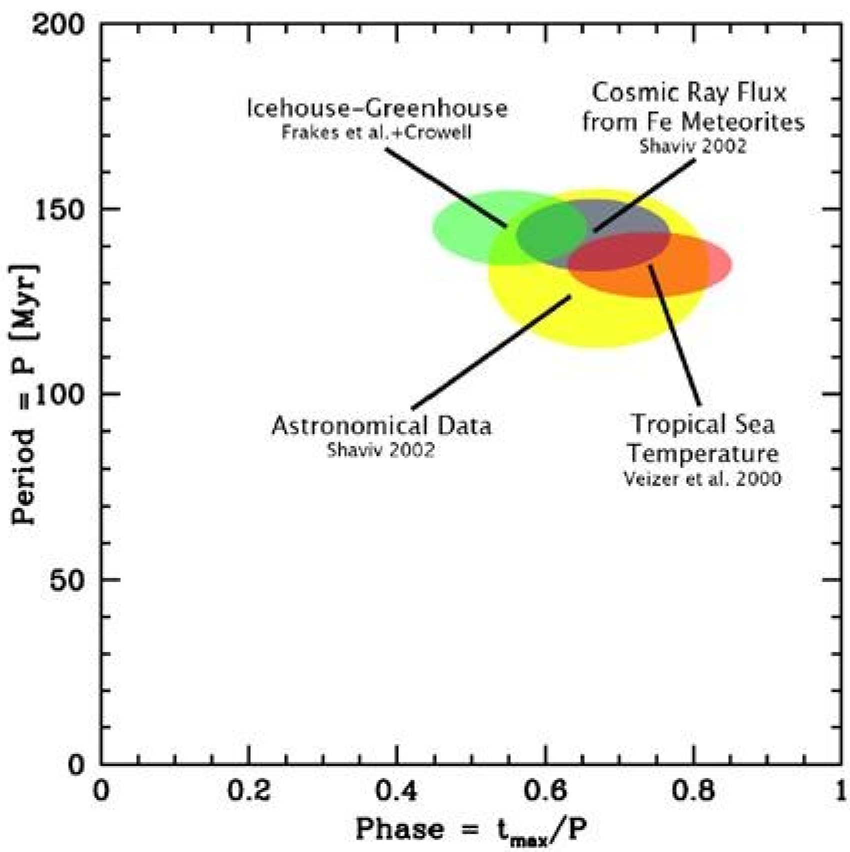

Figure 6: A summary of the 4 different signals revealing the cosmic ray flux climate link over geological time scales. Plotted are the period and phase (of expected peak coldness) of two extraterrestrial signals (astronomical determinations of the spiral arm pattern speed and cosmic ray flux reconstruction using Iron meteorites) and two paleoclimate reconstruction (based on sedimentation and

geochemical records). All four signals are consistent with each other, demonstrating the robustness of the link. If any data set is excluded, a link should still exist.

Recently, it was also shown by Ilya Usoskin of the University of Oulu, Nigel Marsh of the Danish Space Research Center and their colleagues, that the variations in the amount of low altitude cloud cover follow the expectations from a cosmic-ray/cloud cover link (Usoskin et al., 2004). Specifically, it was found that the relative change in the low altitude cloud cover is proportional to the relative change in the solar-cycle induced atmospheric ionization at the given geomagnetic latitudes and at the altitude of low clouds (up to about 3 kms). Namely, at higher latitudes were the the ionization variations are about twice as large as those of low latitudes, the low altitude cloud variations are roughly twice as large as well.

Thus, it now appears that empirical evidence for a cosmic-ray/cloud-cover link is abundant. However, is there a physical mechanism to explain it? The answer is that although there are indications for how the link may arise, no firm scenario, at least one which is based on solid experimental results, is yet present.

Although above 100% saturation, the preferred phase of water is liquid, it will not be able to condense unless it has a surface to do so on. Thus, to form cloud droplets the air must have cloud condensation nuclei—small dust particles or aerosols upon which the water can condense. By changing the number density of these particles, the properties of the clouds can be varied, with more cloud condensation nuclei, the cloud droplets are more numerous but smaller, this tends to make whiter and longer living clouds. This effect was seen down stream of smoke stacks, down stream of cities, and in the oceans in the form of ship tracks in the marine cloud layer.

The suggested hypothesis, is that in regions devoid of dust (e.g., over the large ocean basins), the formation of cloud condensation nuclei takes place from the growth of small aerosol clusters, and that the formation of the latter is governed by the availability of charge, such that charged aerosol clusters are more stable and can grow while neutral clusters can more easily break apart. Several experimental results tend to support this hypothesis, but not yet prove it. For example, the group of Frank Arnold at the university of Heidelberg collected air in airborne missions and found that, as expected, charge clusters play an important role in the formation of small condensation nuclei. It is yet to be seen that the small condensation nuclei grow through accretion and not through scavenging by larger objects. If the former process is dominant, charge and therefore cosmic ray ionization would play an important role in the formation of cloud condensation nuclei.

One of the promising prospects for proving the "missing link", is the *SKY* experiment being conducted in the Danish National Space Center, where a real "cloud chamber" mimics the conditions in the atmosphere. This includes, for example, varying levels of background ionization and aerosols levels (sulpheric acid in particular). Within a few months, the experiment will hopefully shed light on the physical mechanics responsible for the apparent link between cloud cover and therefore climate in general, to cosmic rays, and through the solar wind, also to solar activity. *[Added Note (4 Oct. 2006): The experimental results indeed confirm a link]*

Figure 7: The Danish National Space Center *SKY* reaction chamber experiment. The experiment was built with the goal of pinning down the microphysics behind the cosmic ray/cloud cover link found through various empirical correlations. From left to right: Nigel Marsh, Jan Veizer, Henrik Svensmark. Behind the camera: the author.

The implications of this link are far reaching. Not only does it imply that on various time scales were solar activity variations or changes in the galactic environment prominent, if not the dominent climate drivers, it offers an explanation to at least some of the climate variability witnessed over the past century and millennium. In particular, not all of the 20th century global warming should be attributed to anthropogenic sources, since increased solar activity explains through this link more than half of the warming.

More information can be found at:

1. A general article on the cosmic ray climate link over geological time scales.
2. Henrik Svensmark's web site, including various publications on the cosmic-ray/cloud link.
3. The awaited results of the Danish *SKY* cloud experiment will be reported on their website within several months.

Notes and References:

* On solar activity /climate correlation:

1. For the first suggestion that solar variability may be affecting climate, see: William Herschel, *"Observations tending to investigate the nature of our sun, in order to find causes or symptoms of its variable emission of light and heat"*, Phil. Trans. Roy. Soc. London, 91, 265 (1801). Note that Herschel suspected that it is variations in the total output which may be affecting the climate (and with it the price of wheat).
2. Perhaps the most beautiful correlation between a solar activity and climate proxies can be found in the work of U. Neff et al., *"Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago"*, Nature 411, 290 (2001).
3. Another beautiful correlation between solar activity and climate can be seen in the work of G. Bond et al., *"Persistent Solar Influence on North Atlantic Climate During the Holocene"*, Science, 294, 2130-2136, (2001).

* On cosmic ray and cloud cover correlation:

1. The paper by Henrik Svensmark, reports the correlation between cosmic ray flux variations and cloud cover changes: H. Svensmark, *"Influence of Cosmic Rays on Earth's Climate"*, Physical Review Letters 81, 5027 (1998).
2. The specific correlation with low altitude cloud cover is discussed in N. Marsh and H. Svensmark, *"Low Cloud Properties Influenced by Cosmic Rays"*, Physical Review Letters 85, 5004 (2000).
3. Further analysis including the relative role of CRF variations vs. el-niño can be found in: N. Marsh and H. Svensmark, "Galactic cosmic ray and El Niño-Southern Oscillation trends in International Satellite Cloud Climatology Project D2 low-cloud properties", J. of Geophys. Res., 108(D6), 6 (2003).
4. The analysis showing the geographic signature of the cosmic ray flux variations in the low altitude cloud cover variations can be found it: I. Usoskin et al., *"Latitudinal dependence of low cloud amount on cosmic ray induced ionization"*, Geophysical Research Letters 31, L16109 (2004).

* On cosmic ray climate correlations on Geological time scales:

1. The suggestion that cosmic ray flux variations spiral arm passages could give rise to ice-age epochs is found at: N. Shaviv, *"Cosmic Ray Diffusion from the Galactic Spiral Arms, Iron Meteorites, and a Possible Climatic Connection"*, Physical Review Letters 89, 051102, (2002).
2. A highly detailed analysis, including the cosmic ray reconstruction using iron meteorites is found in: N. Shaviv, *"The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth"*, New Astronomy 8, 39 (2003).
3. The analysis of Shaviv & Veizer demonstrates the primary importance of comic ray flux variations over geological time scales, and with it, place a limit on climate sensitivity: N. Shaviv & J. Veizer, *"A Celestial driver of Phanerozoic Climate?"*, GSA Today 13, No. 7, 4, 2003.

Last Locwood's paper

On July 12th, 2007 Demesure (not verified) says:

Hello Dr Shaviv,
Thanks for your very clear presentation. I have also read your explanation on recent years' correlation and it's rather convincing since the temperature plateau over the last 5 years is rather unprecedented,

whatever it means (I haven't seen any over the last 30 years).
Could you please comment for laymen on the last paper from Lockwood on the "no correlation between CR and temperature after 1985" and widely spread all over the blogosphere (may be in a new post ?).

BTW, you must know that the Lyman's paper on ocean cooling has been corrected last March: no more cooling but no heating either.

Cosmic rays - IPCC report

On August 13th, 2007 Anonymous (not verified) says:

On page 193 in The AR4 IPCC report there is a reference to Kristjansson and Kristiansen,2000 and Sun and Bradley,2002 where they find no correspondance between cosmic rays and clouds after 1991 and low level clouds after 1994. Can you comment on that.

Sure.

On August 19th, 2007 shaviv says:
Here is the response to your question:

- Indeed, Kristjansson and Kristiansen (2000) critically discuss the GCR cloud link. Interestingly, however, they note that a correlation between low clouds and GCR does exist, but discard the correlation as real since no physical mechanism is apparently known. Today, however, more theoretical ideas together with experimental results do exist to indicate that atmospheric ionization, which is controlled by the GCR flux, can affect the formation efficiency of cloud condensation nuclei, and with it the characteristics of cloud cover (e.g., Yu 2002, for a theoretical paper, and Eickorn et al. 2003, Harrison & Aplin 2000 and Svensmark et al. 2007, for experimental results).
- As for Sun and Bradley [2002, JGR], they basically generalize the lack of correlations over small local regions (much less than 10%) to the whole globe. For example they find a lack of correlation between certain cloud constructions over USA and GCR. If one studies the correlation map of Marsh & Svensmark [2003] then there is even a small negative correlation between cloud cover over the USA and GCR. However there are nice correlations if one looks globally. As for the specific comment where they find no correlation between clouds and GCR going back to the 50's, it is necessary to go to the source of their data. Norris [1999] pointed out the possibility of numerous inhomogeneities both temporally and spatially that may be present in the ship-based observations of clouds. In fact, he stated that it "remains uncertain whether the observed increases in global mean ocean total and low cloud cover between 1952 and 1995 are spurious. Corroboration by related meteorological parameters and satellite-based cloud datasets should be required before the trends are accepted as real.".

And for fun, here are my comments on other critiques of the CRF/climate link:

- Kristjánsson et al. [2002, GRL] argue that the correlations with the cloud cover are more likely to be linked to solar irradiance in some form because its correlation with cloud cover is somewhat higher than the correlation with the GCR. This is of course a legitimate claim, however, it cannot rule out the possible GCR/cloud cover link. Nevertheless, independent correlations between GCR flux variations and climate (on the time scale of days—Forbush events, and on geological time scales—due to galactic variations) do appear to exist. Because they cannot be explained with anything other than GCR flux variation, the GCR link should most likely exist by itself or in addition to a direct solar/climate link. Moreover, Kristjánsson et al. [2002] use the data set of VIRGO ver. 19, for the solar irradiance. Even at the time of their work, VIRGO was already up to ver. 25 and vers. 19 was known to have a calibration problem. Using the newer version there is no difference between the solar irradiance correlation and the GCR correlation with cloud cover. So, the most which can be said is that just the correlation between the solar-cycle variations in the GCR and cloud cover is not sufficient to prove that the physical link is necessarily real, but it certainly cannot be used to refute it.

- Kuang et al. (1998) did find a correlation between cloud cover and cosmic rays, but could not conclude if the correlation was coincidental. Namely, they could not conclude whether cloud variations were mainly due to an ENSO effect on clouds or the CRF. In the conclusion they lean towards the CRF or another solar cycle related explanation. Moreover, Marsh and Svensmark (2003) later performed a more elaborate study and showed that there is both an el Niño signal in the clouds and a response correlated with the GCR. This was done by diagonalising the correlation matrix and finding the most dominating eigenmodes. Interestingly the largest eigenvalue is that of the GCR correlation, and the second largest eigenvalue that of the ENSO (and spatially located where one expects to find the el Niño signal). That is, there is a significant GCR-like signal in the cloud cover which cannot be explained away by the ENSO, and the opposite, that an ENSO signal is present, is true as well. These conclusions were also reached by Marsden and Lingenfelter (2003) in a separate analysis and somewhat different methodology.
- Farrar (2000) performs a study on the total cloud cover and concludes that the variations are a result of el Niño, and find little evidence of a role for GCR. A more careful study of this paper reveals however that the author did not actually dismiss the correlation between GCRs and cloud cover ("..., so Figure 2a can also be taken to indicate the cor- relation between local cloud anomaly and cosmic ray flux"). The reason Farrar dismissed the link was mainly because "The resulting patterns are difficult to reconcile with a cos- mic ray effect, which should not have preferences based on ocean basins", however, the fact that most of the correlation is over oceans is expect in the GCR → ionization → CN → CCN → cloud cover scenario, because the effect is expected to be largest where seed aerosols are least abundant—over the oceans. Moreover, the argument that the GCR/cloud cover correlation should be largest over the poles where the GCR flux is highest, which is often used (including in Farrar, 2000), is simply wrong. This is because at energies of ~10GeV, which are required to reach the lower troposphere, the effect of the terrestrial magnetic field is only of order 20% or less. Again, the analyses of Marsh and Svensmark (2003) and Marsden & Lingenfelter (2002) previously mentioned are more comprehensive and demonstrate that both the GCR and the ENSO signals are present in the cloud cover.
- Kernthaler et al. (1999) basicaly use the individual cloud types from the ISCCP C2 data set which at the time were already known to be constructed from an algorithm that was abandoned by the ISCCP group. This was the reason that the ISCCP D2 data set was constructed in the first place. The individual cloud type data from ISCCP C2 were known to be spurious. It is therefore not surprising that Kernthaler et al. (1999) did not find a significant correlation between C2 data and GCR. Using the ISCCP D2 data which superseded, does show a correlation.

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