Solar Influence on Climate: Cosmic Rays

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SOLAR INFLUENCE ON CLIMATE: COSMIC RAYS

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The study of extraterrestrial climatic forcing factors is primarily a study of phenomena related to the Sun. Historically, this field of inquiry began with the work of Milankovitch (1920, 1941), who linked the cyclical glaciations of the past million years to the receipt of solar radiation at the surface of the Earth as modulated by variations in Earth's orbit and rotational characteristics. Subsequent investigations implicated a number of other solar phenomena that operate on both shorter and longer timescales; and this summary reviews the findings of the subset of those studies that involve *galactic cosmic rays* (GCRs).

This field of research begins with the review paper of Svensmark (2007)[1], the Director of the Center for Sun-Climate Research of the Danish National Space Center who describes how he and his colleagues experimentally determined that electrons released to the atmosphere by galactic cosmic rays act as catalysts that significantly accelerate the formation of ultra-small clusters of sulfuric acid and water molecules that constitute the building blocks of cloud condensation nuclei. He then discusses how, during periods of greater solar magnetic activity, greater shielding of the Earth occurs, resulting in less cosmic rays penetrating to the lower atmosphere, resulting in fewer cloud condensation nuclei being produced, resulting in fewer and less reflective low-level clouds occurring, which leads to more solar radiation being absorbed by the surface of the Earth, resulting in increasing near-surface air temperatures and global warming.

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark in his overview of what could rightly be termed the cosmic ray-climate connection.

Svensmark provides support for key elements of this scenario with graphs illustrating the close correspondence between global low-cloud amount and cosmic-ray counts over the period 1984-2004, as well as by the history of changes in the flux of galactic cosmic rays since 1700, which correlates well with Earth's temperature history over the same time period, starting from the latter portion of the Maunder Minimum (1645-1715), when Svensmark says "sunspots were extremely scarce and the solar magnetic field was exceptionally weak," and continuing on through the twentieth century, over which last hundred-year interval, as noted by Svensmark, "the Sun's coronal magnetic field doubled in strength."

Svensmark also cites the work of Bond *et al*. (2001), who in studying ice-rafted debris in the North Atlantic Ocean determined, in Svensmark's words, that "over the past 12,000 years, there were many icy intervals like the Little Ice Age" that "alternated with warm phases, of which the

[1] http://www.co2science.org/articles/V10/N8/EDIT.php.

most recent were the Medieval Warm Period (roughly AD 900-1300) and the Modern Warm Period (since 1900)." And as Bond's 10-member team clearly indicates, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

In expanding the timescale further, while highlighting the work of Shaviv (2002, 2003) and Shaviv and Veizer (2003), Svensmark presents plots of reconstructed sea surface temperature anomalies and relative cosmic ray flux over the last 550 million years, during which time the solar system experienced four passages through the spiral arms of the Milky Way galaxy, with the climatic data showing "rhythmic cooling of the Earth whenever the Sun crossed the galactic midplane, where cosmic rays are locally most intense." In addition, he notes that the "Snowball Earth" period of some 2.3 *billion* years ago "coincided with the highest star-formation rate in the Milky Way since the Earth was formed, in a mini-starburst 2400-2000 million years ago," when, of course, the cosmic ray flux would have been especially intense. In light of these many diverse observations, Svensmark concludes that "stellar winds and magnetism are crucial factors in the origin and viability of life on wet Earth-like planets," as are "ever-changing galactic environments and star-formation rates."

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark in his overview of what could rightly be termed the *cosmic ray-climate connection*. Lockwood *et al*. (1999)[2], for example, examined measurements of the near-Earth interplanetary magnetic field in an effort to determine the total magnetic flux leaving the Sun since 1868. In doing so, they were able to show that the total magnetic flux from the Sun rose by a factor of 1.41 over the period 1964-1996, while surrogate measurements of the interplanetary magnetic field previous to this time indicate that this parameter had risen by a factor of 2.3 since 1901, which observations led the three researchers to state that the variation in the total solar magnetic flux they found "stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field." The results of this study give one pause to wonder just how much of the 0.8°C global temperature rise of the last century might have resulted from the more than two-fold increase in the total magnetic solar flux over that period.

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While ruminating on the work of Lockwood *et al*., Parker (1999)[3] noted additional solar considerations that may also have played an important part in the modern rise of global temperature. Specifically, Parker indicated that the number of sunspots doubled over the prior

2 http://www.co2science.org/articles/V2/N14/C2.php.

3 http://www.co2science.org/articles/V2/N14/C3.php.

100 years, and that one consequence of this phenomenon would have been "a much more vigorous Sun" that was slightly brighter. Parker further pointed out that spacecraft measurements suggest that the brightness (B) of the Sun varies by an amount ΔB/B = 0.15%, in step with the 11-year magnetic cycle. He then indicates that during times of much reduced activity of this sort (such as the Maunder Minimum of 1645-1715) and much increased activity (such as the twelfth century Mediaeval Maximum), brightness variations on the order of ΔB/B = 0.5% typically occur, after which he noted that the mean temperature (T) of the northern portion of the Earth varied by 1 to 2°C in association with these variations in solar activity, stating finally that "we cannot help noting that change in T/T = change in B/B." Furthermore, knowing that sea surface temperatures are influenced by the brightness of the Sun, and that they had risen since 1900, Parker wrote that "one wonders to what extent the solar brightening [of the past century] has contributed to the increase in atmospheric temperature and CO_2" over that period. And in response to his own inquiry it was Parker's "inescapable conclusion" that "we will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate."

Digging deeper into the subject, Feynman and Ruzmaikin (1999)[4] investigated twentieth century changes in the intensity of cosmic rays incident upon the Earth's magnetopause and their transmission through the magnetosphere to the upper troposphere. This work revealed that "the intensity of cosmic rays incident on the magnetopause has decreased markedly during this century" and that "the pattern of cosmic ray precipitation through the magnetosphere to the upper troposphere has also changed."

With respect to the first and more basic of these changes, they noted that "at 300 MeV the difference between the proton flux incident on the magnetosphere at the beginning of the century and that incident now is estimated to be a factor of 5 decrease between solar minima at the beginning of the century and recent solar minima," and that "at 1 GeV the change is a factor of 2.5." With respect to the second phenomenon, they noted that the part of the troposphere open to cosmic rays of all energies increased by a little over 25 percent and shifted equatorward by about 6.5° of latitude. And with the great decrease in the intensity of cosmic rays incident on Earth's magnetosphere over the twentieth century, one would have expected to see a progressive decrease in the presence of low-level clouds and, therefore, an increase in global air temperature, which has indeed been observed.

Stating that "solar magnetic activity exhibits chaotically modulated cycles ... which are responsible for slight variations in solar luminosity and modulation of the solar wind," Tobias and Weiss (2000)[5] confronted the solar-climate forcing topic by means of a model in which the solar dynamo and Earth's climate were represented by low-order systems, each of which in isolation supports chaotic oscillations but which when run together sometimes resonate. By this means they determined that "solutions oscillate about either of two fixed points, representing warm and cold states, flipping sporadically between them." They also discovered that a weak nonlinear input from the solar dynamo "has a significant effect when the 'typical

4 http://www.co2science.org/articles/V2/N18/C5.php.
5 http://www.co2science.org/articles/V3/N34/C1.php.

frequencies' of each system are in resonance." "It is clear," they say, "that the resonance provides a powerful mechanism for amplifying climate forcing by solar activity."

Contemporaneously, Solanki *et al*. (2000)[6] developed a model of the long-term evolution of the Sun's large-scale magnetic field and compared its predictions against two proxy measures of this parameter. The model proved successful in reproducing the observed century-long doubling of the strength of the part of the Sun's magnetic field that reaches out from the Sun's surface into interplanetary space. It also indicated there is a direct connection between the length of the 11-year sunspot cycle and secular variations in solar activity that occur on timescales of centuries, such as the Maunder Minimum of the latter part of the seventeenth century, when sunspots were few in number and Earth was in the midst of the Little Ice Age.

In discussing their findings, the solar scientists say their modeled reconstruction of the solar magnetic field "provides the major parameter needed to reconstruct the secular variation of the cosmic ray flux impinging on the terrestrial atmosphere," because, as they continue, a stronger solar magnetic field "more efficiently shields the Earth from cosmic rays," and "cosmic rays affect the total cloud cover of the Earth and thus drive the terrestrial climate."

One year later, using cosmic ray data recorded by ground-based neutron monitors, global precipitation data from the Climate Predictions Center Merged Analysis of Precipitation project, and estimates of monthly global moisture from the National Centers for Environmental Prediction reanalysis project, Kniveton and Todd (2001)[7] set out to evaluate whether there is empirical evidence to support the hypothesis that solar variability (represented by changes in cosmic ray flux) is linked to climate change (manifested by changes in precipitation and precipitation efficiency) over the period 1979-1999. In doing so, they determined there is "evidence of a statistically strong relationship between cosmic ray flux, precipitation and precipitation efficiency over ocean surfaces at mid to high latitudes," since variations in both precipitation and precipitation efficiency for mid to high latitudes showed a close relationship in both phase and magnitude with variations in cosmic ray flux, varying 7-9 percent during the solar cycle of the 1980s, while other potential forcing factors were ruled out due to poorer statistical relationships.

In the same year, Bond *et al*. (2001)[8] published the results of their study of ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). Based on arduous analyses of deep-sea sediment cores that yielded the variable-with-depth amounts of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern and, with the help of an accelerator mass spectrometer, date a number of recurring alternate periods of relative cold and warmth that wended their way through the entire 12,000-year expanse of the Holocene. The mean duration of the several complete climatic cycles thus delineated was 1,340 years, the cold and warm nodes of the latter of which oscillations, in the words of Bond *et al*., were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period'."

6 http://www.co2science.org/articles/V3/N36/C2.php.
7 http://www.co2science.org/articles/V4/N22/C1.php.
8 http://www.co2science.org/articles/V4/N48/EDIT.php.

The signal accomplishment of the scientists' study was the linking of these millennial-scale climate oscillations -- and their embedded centennial-scale oscillations -- with similar-scale oscillations in cosmogenic nuclide production, which are known to be driven by contemporaneous oscillations in solar activity. In fact, Bond *et al*. were able to report that "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum." In light of this observation they thus concluded that "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting that the cyclical climatic effects of the variable solar inferno are experienced throughout the world.

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At this point in their paper, the international team of scientists cited additional evidence in support of the implications of their work. With respect to the global extent of the climatic impact of the solar radiation variations they detected, they reference studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating thereby that "the footprint of the solar impact on climate we have documented extend[s] from polar to tropical latitudes." They also note that "the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence," further noting that their findings supported previous suggestions that both the Little Ice Age and Medieval Warm Period "may have been partly or entirely linked to changes in solar irradiance."

Another point reiterated by Bond *et al*. is that the oscillations in drift-ice they studied "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system." At two of their coring sites, they identified a series of such cyclical variations that extended throughout all of the previous interglacial and were "strikingly similar to those of the Holocene." Here they could also have cited the work of Oppo *et al*. (1998), who observed similar climatic oscillations in a sediment core that covered the span of time from 340,000 to 500,000 years before present, and that of Raymo *et al*. (1998), who pushed back the time of the cycles' earliest known occurrence to well over one million years ago.

How do the small changes in solar radiation inferred from the cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth's global climate? Bond *et al*. described a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to the Earth's surface, where they envisioned them provoking changes in North Atlantic deep water formation that alter the thermohaline circulation of the global ocean. In light of the plausibility of this particular scenario, they suggested that "the solar signals thus may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint."

Concluding their landmark paper, the researchers wrote that the results of their study "demonstrate that the Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output," noting that their work "supports the presumption that solar variability will continue to influence climate in the future."

The following year, Sharma (2002)[9] presented the case for an even longer oscillation in solar magnetism on the order of 100,000 years that might bear responsibility for the recurring glacial/interglacial periods. This *potential* finding - which has been established for only two of the putative 100,000-year cycles and, hence, could still turn out to be spurious - is based upon the fact that the production of ^{10}Be in the Earth's atmosphere is affected by the intensity of magnetic activity at the surface of the Sun, as well as the Earth's geomagnetic dipole strength. Using preexistent data pertaining to these factors that were obtained from several different sources, Sharma began his analysis by compiling 200,000-year histories of relative geomagnetic field intensity (from natural remanent magnetizations of marine sediments) and normalized atmospheric ^{10}Be production rate (also from marine sediments). Then, with the help of a theoretical construct describing the ^{10}Be production rate as a function of the solar modulation of galactic cosmic rays (which modulation arises from variations in magnetic activity at the surface of the Sun) and Earth's geomagnetic field intensity, he created a 200,000-year history of the solar modulation factor.

This history reveals the existence of significant periods of both enhanced and reduced solar activity; and comparing it with the marine δ^{18}O record (a proxy for global ice volume and, hence, Earth's mean surface air temperature), it was found that the two histories are strongly correlated. As Sharma describes it, "the solar activity has a 100,000-year cycle in phase with the δ^{18}O record of glacial-interglacial cycles," such that "the long-term solar activity and earth's surface temperature appear to be directly related." Throughout the entire 200,000-year period, for example, Sharma notes that "the Earth has experienced a warmer climate whenever the Sun has been magnetically more active," and that "at the height of the last glacial maximum the solar activity was suppressed." It was therefore easy for Sharma to make the final connection; and as he did so, he set forth as a new hypothesis the proposal that "variations in solar activity control the 100,000-year glacial-interglacial cycles," just as they also appear to control essentially all other imbedded and cascading climatic cycles.

9 http://www.co2science.org/articles/V5/N24/EDIT.php.

In a contemporaneous study, Carslaw *et al*. (2002)[10] began an essay on "Cosmic Rays, Clouds, and Climate" by noting that the intensity of cosmic rays varies by about 15 percent over a solar cycle, due to changes in the strength of the solar wind, which carries a weak magnetic field into the heliosphere that partially shields the Earth from low-energy galactic charged particles. When this shielding is at a minimum, allowing more cosmic rays to impinge upon the planet, more low clouds have been observed to cover the Earth, producing a tendency for lower temperatures to occur. When the shielding is maximal, on the other hand, fewer cosmic rays impinge upon the planet and fewer low clouds form, which produces a tendency for the Earth to warm.

The three researchers further noted that the total variation in low cloud amount over a solar cycle is about 1.7 percent, which corresponds to a change in the planet's radiation budget of about one watt per square meter (1 Wm^{-2}). This change, they say, "is highly significant when compared ... with the estimated radiative forcing of 1.4 Wm^{-2} from anthropogenic CO_2 emissions." However, because of the short length of a solar cycle (11 years), the large thermal inertia of the world's oceans dampens the much greater global temperature change that would have occurred as a result of this radiative forcing if it had been spread out over a much longer period of time, so that the actual observed warming is something a little less than 0.1°C.

Much of Carslaw *et al*.'s review focuses on mechanisms by which cosmic rays might induce the synchronous low cloud cover changes that have been observed to accompany their intensity changes. They begin by briefly describing the three principal mechanisms that have been suggested to function as links between solar variability and changes in Earth's weather: (1) changes in total solar irradiance that provide variable heat input to the lower atmosphere, (2) changes in solar ultraviolet radiation and its interaction with ozone in the stratosphere that couple dynamically to the lower atmosphere, and (3) changes in cloud processes having significance for condensation nucleus abundances, thunderstorm electrification and thermodynamics, and ice formation in cyclones.

Focusing on the third of these mechanisms, the researchers note that cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes. Hence, they further refine their focus to concentrate on ways by which cosmic-ray-produced ions may affect cloud droplet number concentrations and ice particles. Here, they concentrate on two specific topics: what they call the ion-aerosol clear-air mechanism and the ion-aerosol near-cloud mechanism. Their review suggests that what we know about these subjects is very much less than what we *could* know about them. Many scientists, as they describe it, believe "it is inconceivable that the lower atmosphere can be globally bombarded by ionizing radiation without producing an effect on the climate system."

Carslaw *et al*. point out that cosmic ray intensity declined by about 15 percent during the last century "owing to an increase in the solar open magnetic flux by more than a factor of 2." They further report that "this 100-year change in intensity is about the same magnitude as the observed change over the last solar cycle." In addition, it should be noted that the cosmic ray intensity was already much lower at the start of the twentieth century than it was just after the

10 http://www.co2science.org/articles/V6/N5/EDIT.php.

start of the nineteenth century, when the Esper *et al*. (2002) record indicates the planet began its nearly two-century-long recovery from the chilly depths of the Little Ice Age.

These observations strongly suggest that solar-mediated variations in the intensity of cosmic rays bombarding the Earth may indeed be responsible for the temperature variations of the past three centuries. They provide a much better fit to the temperature data than do atmospheric CO_2 data; and as Carslaw *et al*. remark, "if the cosmic ray-cloud effect is real, then these long-term changes of cosmic ray intensity could substantially influence climate." It is this possibility, they say, that makes it "all the more important to understand the cause of the cloudiness variations," which is basically the message of their essay; i.e., that we must work hard to deepen our understanding of the cosmic ray-cloud connection, as it may well hold the key to resolving what they call this "fiercely debated geophysical phenomenon."

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One year later, and noting that Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), and Palle Bago and Butler (2000) had derived positive relationships between global cosmic ray intensity and low-cloud amount from infrared cloud data contained in the International Satellite Cloud Climatology Project (ISCCP) database for the years 1983-1993, Marsden and Lingenfelter (2003)[11] used the ISCCP database for the expanded period 1983-1999 to see if a similar relationship could be detected via cloud amount measurements made in the visible spectrum. This work revealed that there was indeed, in their words, "a positive correlation at low altitudes, which is consistent with the positive correlation between global low clouds and cosmic ray rate seen in the infrared."

That same year, Shaviv and Veizer (2003)[12] suggested that from two-thirds to three-fourths of the variance in Earth's temperature (T) over the past 500 million years may be attributable to cosmic ray flux (CRF) variations due to solar system passages through the spiral arms of the Milky Way galaxy. This they did after presenting several half-billion-year histories of T, CRF, and atmospheric CO_2 concentrations derived from various types of proxy data, and after finding that none of the CO_2 curves showed any clear correlation with the T curves, suggesting to them that "CO_2 is not likely to be the principal climate driver." On the other hand, they discovered that the T trends displayed a dominant cyclic component on the order of 135 ± 9 million years, and that "this regular pattern implies that we may be looking at a reflection of celestial phenomena in the climate history of Earth."

[11] http://www.co2science.org/articles/V6/N16/C1.php.
[12] http://www.co2science.org/articles/V6/N39/EDIT.php.

That such is likely the case is borne out by their identification of a similar CRF cycle of 143 ± 10 million years, together with the fact that the large cold intervals in the T records "appear to coincide with times of high CRF," which correspondence is what would be expected from the likely chain of events: high CRF ==> more low-level clouds ==> greater planetary albedo ==> colder climate, as described by Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), Palle Bago and Butler (2000), and Marsden and Lingenfelter (2003).

What do these findings suggest about the role of atmospheric CO_2 variations with respect to global temperature change? Shaviv and Veizer began their analysis of this question by stating that the conservative approach is to assume that the entire residual variance not explained by measurement error is due to CO_2 variations. And when this was done, they found that a doubling of the air's CO_2 concentration could account for only about a 0.5°C increase in T.

This result differs considerably, in their words, "from the predictions of the general circulation models, which typically imply a CO_2 doubling effect of ~1.5-5.5°C," but they say it is "consistent with alternative lower estimates of 0.6-1.6°C (Lindzen, 1997)." It should also be noted in this regard that Shaviv and Veizer's result is even more consistent with the results of the eight empirically based "natural experiments" of Idso (1998), which yield an average warming of about 0.4°C for a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration.

In another important test of a critical portion of the cosmic ray-climate connection theory, Usoskin *et al*. (2004b)[13] compared the spatial distributions of low cloud amount (LCA) and cosmic ray-induced ionization (CRII) over the globe for the period 1984-2000. They used observed LCA data obtained from the ISCCP-D2 database limited to infrared radiances, while they employed CRII values calculated by Usoskin *et al*. (2004a) at 3 km altitude, which corresponds roughly to the limiting altitude below which low clouds form. This work revealed that "the LCA time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting a clear 11-year cycle in phase with CRII." In addition, they found there was "a one-to-one relation between the relative variations of LCA and CRII over the latitude range 20-55°S and 10-70°N," and that "the amplitude of relative variations in LCA was found to increase polewards, in accordance with the amplitude of CRII variations." These findings of the five-member team of Finnish, Danish, and Russian scientists provide substantial evidence for a solar-cosmic ray linkage (the 11-year cycle of CRII) and a cosmic ray-cloud linkage (the in-phase cycles of CRII and CLA), making the full solar activity/cosmic ray/low cloud/climate change hypothesis appear to be rather robust.

In a review of the temporal variability of various solar phenomena conducted the following year, Lean (2005)[14] made the following important but disturbing point about climate models and the Sun-climate connection: "a major enigma is that general circulation climate models predict an immutable climate in response to decadal solar variability, whereas surface temperatures, cloud cover, drought, rainfall, tropical cyclones, and forest fires show a definite correlation with solar activity (Haigh, 2001, Rind, 2002)."

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[13] http://www.co2science.org/articles/V9/N11/C1.php.
[14] http://www.co2science.org/articles/V8/N35/EDIT.php.

Lean begins her review by noting that the beginning of the Little Ice Age "coincided with anomalously low solar activity (the so-called Sporer and Maunder minima)," and that "the latter part coincided with both low solar activity (the Dalton minimum) and volcanic eruptions." Then, after discussing the complexities of this potential relationship, she muses about another alternative: "Or might the Little Ice Age be simply the most recent cool episode of millennial climate-oscillation cycles?" Lean cites evidence that reveals the sensitivity of drought and rainfall to solar variability, stating that climate models are unable to reproduce the plethora (her word) of Sun-climate connections. She notes that simulations with climate models yield decadal and centennial variability even in the absence of external forcing, stating that "arguably, this very sensitivity of the climate system to unforced oscillation and stochastic noise predisposes it to nonlinear responses to small forcings such as by the Sun. "

Lean reports that "various high-resolution paleoclimate records in ice cores, tree rings, lake and ocean sediment cores, and corals suggest that changes in the energy output of the Sun itself may have contributed to Sun-Earth system variability," citing the work of Verschuren *et al*. (2000), Hodell *et al*. (2001), and Bond *et al*. (2001). She notes that "many geographically diverse records of past climate are coherent over time, with periods near 2400, 208 and 90 years that are also present in the ^{14}C and ^{10}Be archives," which isotopes (produced at the end of a complex chain of interactions that are initiated by galactic cosmic rays) contain information about various aspects of solar activity (Bard *et al*., 1997).

Veretenenko *et al*. (2005)[15] examined the potential influence of galactic cosmic rays (GCR) on the long-term variation of North Atlantic sea-level pressure over the period 1874-1995. Their comparisons of long-term variations in cold-season (October-March) sea-level pressure with different solar/geophysical indices revealed that increasing sea-level pressure coincided with a secular rise in solar/geomagnetic activity that was accompanied by a decrease in GCR intensity, whereas long-term decreases in sea-level pressure were observed during periods of decreasing solar activity and rising GCR flux. Spectral analysis further supported a link between sea-level pressure, solar/geomagnetic activity and GCR flux, as similar spectral characteristics (periodicities) were present among all datasets at time scales from approximately 10 to 100 years.

Although scientists still lack a complete understanding of many solar/GCR-induced climatic influences, this study highlights the ever-growing need for such relationships to be explored. As it and others have shown, small changes in solar output can indeed induce significant changes in Earth's climate.

These results support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. Concerning how this relationship works, Veretenenko *et al*. hypothesize that GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation

15 http://www.co2science.org/articles/V8/N52/C1.php.

receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development. Although scientists still lack a complete understanding of many solar/GCR-induced climatic influences, this study highlights the ever-growing need for such relationships to be explored. As it and others have shown, small changes in solar output can indeed induce significant changes in Earth's climate.

Also working in the North Atlantic region, Macklin *et al*. (2005)[16] developed what they call "the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ^{14}C-dated British flood deposits," after which they compared their reconstructed flood history "with high-resolution proxy-climate records from the North Atlantic region, northwest Europe and the British Isles to critically test the link between climate change and flooding." By these means they determined that "the majority of the largest and most widespread recorded floods in Great Britain have occurred during cool, moist periods," and that "comparison of the British Holocene palaeoflood series ... with climate reconstructions from tree-ring patterns of subfossil bog oaks in northwest Europe also suggests that a similar relationship between climate and flooding in Great Britain existed during the Holocene, with floods being more frequent and larger during relatively cold, wet periods." In addition, they say that "an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ^{14}C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods."

In another intriguing study from this time period, Usoskin *et al*. (2005)[17] noted that "the variation of the cosmic ray flux entering Earth's atmosphere is due to a combination of solar modulation and geomagnetic shielding, the latter adding a long-term trend to the varying solar signal," while further noting that "the existence of a geomagnetic signal in the climate data would support a direct effect of cosmic rays on climate." They evaluated this proposition by reproducing 1,000-year reconstructions of two notable solar-heliospheric indices derived from cosmogenic isotope data, i.e., the sunspot number and the cosmic ray flux (Usoskin *et al*., 2003; Solanki *et al*., 2004), and by creating a new 1,000-year air temperature history of the Northern Hemisphere by computing annual means of six different thousand-year surface air temperature series: those of Jones *et al*. (1998), Mann *et al*. (1999), Briffa (2000), Crowley (2000), Esper *et al*. (2002), and Mann and Jones (2003).

In comparing these three series (solar activity, cosmic ray, and air temperature), Usoskin *et al*. found that they "indicate higher temperatures during times of more intense solar activity (higher sunspot number, lower cosmic ray flux)." In addition, they report that three different statistical tests "consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with sunspots," which suggests that something in addition to solar activity must have been influencing the cosmic ray flux, in order to make the cosmic ray flux the better correlate of temperature.

[16] http://www.co2science.org/articles/V9/N48/C3.php.
[17] http://www.co2science.org/articles/V9/N31/EDIT.php.

Noting that Earth's geomagnetic field strength would be a natural candidate for this "something," Usoskin *et al*. compared their solar activity, cosmic ray, and temperature reconstructions with two long-term reconstructions of geomagnetic dipole moment that they obtained from the work of Hongre *et al*. (1998) and Yang *et al*. (2000). This effort revealed that between AD 1000 and 1700, when there was a substantial downward trend in air temperature associated with a less substantial downward trend in solar activity, there was also a general downward trend in geomagnetic field strength. As a result, Usoskin *et al*. suggested that the substantial upward trend of cosmic ray flux that was needed to sustain the substantial rate of observed cooling (which was more than expected in light of the slow decline in solar activity) was likely due to the positive effect on the cosmic ray flux that was produced by the decreasing geomagnetic field strength.

After 1700, the geomagnetic field strength continued to decline, but air temperature did a dramatic turnabout and began to rise. The reason for this "parting of company" between the two parameters, according to Usoskin *et al*., was that "the strong upward trend of solar activity during that time overcompensate[d] [for] the geomagnetic effect," leading to a significant warming. In addition, a minor portion of the warming of the last century or so (15-20 percent) may have been caused by the concomitant increase in the atmosphere's CO_2 content, which would have complemented the warming produced by the upward trending solar activity and further decoupled the upward trending temperature from the declining geomagnetic field strength.

In their totality, these several observations tend to strengthen the hypothesis that cosmic ray variability was the major driver of changes in Earth's surface air temperature over the past millennium, and that this forcing was primarily driven by variations in solar activity, modulated by the more slowly changing geomagnetic field strength of the planet, which sometimes strengthened the solar forcing and sometimes worked against it. Once again, however, the results leave room for only a small impact of anthropogenic CO_2 emissions on twentieth century global warming.

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Once again, however, the results leave room for only a small impact of anthropogenic CO_2 emissions on twentieth century global warming.

Versteegh (2005)[18] reviewed what was known about past climatic responses to solar forcing and their geographical coherence based upon proxy records of temperature and the cosmogenic radionuclides ^{10}Be and ^{14}C, which provide a measure of magnetized plasma emissions from the Sun that impact Earth's exposure to galactic cosmic rays. As a result of this exercise, it was concluded that "proxy records provide ample evidence for climate change during the relatively stable and warm Holocene," and that "all frequency components attributed to solar variability re-occur in proxy records of environmental change," emphasizing in this regard "the ~90 years Gleisberg and ~200 years Suess cycles in the ^{10}Be and ^{14}C records," as well as "the ~1500 years Bond cycle which occurs in several proxy records [and] could originate from the interference between centennial-band solar cycles." As a result, Versteegh concludes that "long-term climate change during the preindustrial [era] seems to have been dominated by solar forcing," and that the long-term response to solar forcing "greatly exceeds unforced variability."

Delving further into the subject, Harrison and Stephenson (2005)[19] introduce their contribution by noting that because the net global effect of clouds is cooling (Hartman, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF)-which had been measured daily at 0900 UT at Whiteknights, Reading (UK) from 1997-2004-with the traditional subjective determination of cloud amount made simultaneously by a human observer, as well as with daily average temperature. They then compared the diffuse fraction measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux. The result, as they describe it, was that "across the UK, on days of high cosmic ray flux (which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by 19% ± 4%, and (ii) the diffuse fraction increases by 2% ± 0.3%." In addition, they found that "during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction."

As for the implications of their findings, the two researchers note that the latter of these observations indicates that diffuse radiation changes are "unambiguously due to cosmic rays." They also report that "at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR." Consequently, they suggest that the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima, and that "this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al.*, 2003) which neglect a cosmic ray effect." In addition, although the effect they detect is small, they say it is "statistically robust," and that the cosmic ray effect on clouds likely "will emerge on long time scales with less variability than the considerable variability of daily cloudiness."

Next, Shaviv (2005)[20] identified six periods of Earth's history (the entire Phanerozoic, the Cretaceous, the Eocene, the Last Glacial Maximum, the twentieth century, and the 11-year

[18] http://www.co2science.org/articles/V9/N46/C2.php.
[19] http://www.co2science.org/articles/V10/N2/C1.php.
[20] http://www.co2science.org/articles/V9/N29/EDIT.php.

solar cycle as manifest over the last three centuries) for which he was able to derive reasonably sound estimates of different time-scale changes in radiative forcing, temperature, and cosmic ray flux. From these sets of data he derived probability distribution functions of whole-Earth temperature sensitivity to radiative forcing for each time period and combined them to obtain a mean planetary temperature sensitivity to radiative forcing of 0.28°C per Wm^{-2}. Then, noting that the IPCC (2001) had suggested that the increase in anthropogenic radiative forcing over the twentieth century was about 0.5 Wm^{-2}, Shaviv calculated that the anthropogenic-induced warming of the globe over this period was approximately 0.14°C (0.5 Wm^{-2} x 0.28°C per Wm^{-2}). This result harmonizes perfectly with the temperature increase (0.10°C) that was calculated by Idso (1998) to be due solely to the twentieth century increase in the air's CO_2 concentration (75 ppm), which would have been essentially indistinguishable from Shaviv's result if the warming contributions of the twentieth century concentration increases of all greenhouse gases had been included in the calculation.

Based on information that indicated a solar activity-induced increase in radiative forcing of 1.3 Wm^{-2} over the twentieth century (by way of cosmic ray flux reduction), plus the work of others (Hoyt and Schatten, 1993; Lean *et al*., 1995; Solanki and Fligge, 1998) that indicated a globally averaged solar luminosity increase of approximately 0.4 Wm^{-2} over the same period, Shaviv calculated an overall and ultimately solar activity-induced warming of 0.47°C (1.7 Wm^{-2} x 0.28°C per Wm^{-2}) over the twentieth century. Added to the 0.14°C of anthropogenic-induced warming, the calculated total warming of the twentieth century thus came to 0.61°C, which was noted by Shaviv to be very close to the 0.57°C temperature increase that was said by the IPCC to have been observed over the past century. Consequently, both Shaviv's and Idso's analyses, which mesh well with real-world data of both the recent and distant past, suggest that only 15-20 percent (0.10°C/0.57°C) of the observed warming of the twentieth century can be attributed to the rise in the air's CO_2 content.

In yet one final study from 2005, de Jager (2005)[21] reviewed what was known at the time about the role of the Sun in orchestrating climate change over the course of the Holocene or current interglacial period, including changes that occurred during the 20th century, focusing on (1) the *direct* effects of *solar irradiance variations* and (2) the *indirect* effects of *magnetized plasma emissions*.

With respect to the first phenomenon, i.e., solar irradiance variations, de Jager writes that "the fraction of the solar irradiance that directly reaches the Earth's troposphere is emitted by the solar photosphere [and] does not significantly vary." The *variable* part of this energy flux, as he continues, is emitted by chromospheric parts of centers of solar activity, and "it only directly influences the higher, stratospheric terrestrial layers," which "can only influence the troposphere by some form of stratosphere-troposphere coupling." With respect to the second phenomenon, de Jager concludes that (1) "the outflow of magnetized plasma from the Sun and its confinement in the heliosphere influences the Earth's environment by modulating the flux of galactic cosmic radiation observed on Earth," (2) "cosmogenic radionuclides are proxies for this influence," and (3) "the variable cosmic ray flux may influence climate via variable cloudiness."

[21] http://www.co2science.org/articles/V9/N45/C1.php.

Of these two phenomena, the author seems to lean toward the latter as being the more significant, noting that the Northern Hemispheric temperature history developed by Moberg *et al*. (2005) "runs reasonably well parallel to" reconstructions of past solar variability derived from cosmogenic radionuclide concentrations, which are proxies for the outflow of magnetized plasma from the Sun. Perhaps most interesting of all, in this regard, is de Jager's observation that "*never* [italics added] during the past ten or eleven millennia has the Sun been as active in ejecting magnetized plasma as during the second half of the twentieth century."

In commenting on his work, de Jager notes that "a topical and much debated question is that of the cause of the strong terrestrial heating in the last few decades of the twentieth century," and that "it is usually ascribed to greenhouse warming." The weight of his review, however, gives credence to the view that *solar activity*, especially that associated with the effects of *ejected magnetized plasma* on the *galactic cosmic ray flux* incident on the Earth's atmosphere, could well be responsible for the bulk of 20th-century global warming, as well as most of the major temperature swings (both up and down) of the entire Holocene.

Solar activity, especially that associated with the effects of ejected magnetized plasma on the galactic cosmic ray flux incident on the Earth's atmosphere, could well be responsible for the bulk of 20th-century global warming, as well as most of the major temperature swings (both up and down) of the entire Holocene.

Writing as background for their work, Usoskin *et al*. (2006)[22] note that many solar scientists believe changes in solar activity have been responsible for significant changes in climate, but that to demonstrate that such is truly the case, a record of past variations in solar activity is required. Accordingly, they write that "long-term solar activity in the past is usually estimated from cosmogenic isotopes, ^{10}Be or ^{14}C, deposited in terrestrial archives such as ice cores and tree rings," because "the production rate of cosmogenic isotopes in the atmosphere is related to the cosmic ray flux impinging on Earth," which "is modulated by the heliospheric magnetic field and is thus a proxy of solar activity." A nagging concern, however, is that the isotope records may suffer from what the five scientists call "uncertainties due to the sensitivity of the data to several *terrestrial* [italics added] processes." Consequently, they devised a plan to attempt to resolve this issue.

Noting that the activity of a cosmogenic isotope in a meteorite represents "the time integrated cosmic ray flux over a period determined by the mean life of the radioisotope," Usoskin *et al*. reasoned that (1) "by measuring abundance of cosmogenic isotopes in meteorites which fell through the ages, one can evaluate the variability of the cosmic ray flux, since the production of cosmogenic isotopes ceases after the fall of the meteorite," and that (2) if they could develop such a meteoritic-based cosmogenic isotope record they could use it "to constrain [other] solar activity reconstructions using cosmogenic ^{44}Ti activity in meteorites *which is not affected by terrestrial processes* [italics added]."

[22] http://www.co2science.org/articles/V10/N8/C2.php.

The researchers' choice of ^{44}Ti for this purpose was driven by the fact that it has a half-life of about 59 years and is thus "relatively insensitive to variations of the cosmic ray flux on decadal or shorter time scales, but is very sensitive to the level of the cosmic ray flux and its variations on a centennial scale." Thus, they compared the results of different long-term ^{10}Be- and ^{14}C-based solar activity reconstruction models with measurements of ^{44}Ti in 19 stony meteorites (chondrites) that fell between 1766 and 2001, as reported by Taricco *et al*. (2006); and in doing so, they ultimately determined that "most recent reconstructions of solar activity, in particular those based on ^{10}Be data in polar ice (Usoskin *et al*., 2003, 2004c; McCracken *et al*., 2004) and on ^{14}C in tree rings (Solanki *et al*., 2004), are consistent with the ^{44}Ti data." Consequently, the results of this study give ever more credence to the findings of the many studies that have reported strong correlations between various climatic changes and ^{10}Be- and ^{14}C-based reconstructions of solar activity.

In yet another paper, Dergachev *et al*. (2006)[23] reviewed "direct and indirect data on variations in cosmic rays, solar activity, geomagnetic dipole moment, and climate from the present to 10-12 thousand years ago, [as] registered in different natural archives (tree rings, ice layers, etc.)." They found that "galactic cosmic ray levels in the Earth's atmosphere are inversely related to the strength of the helio- and geomagnetic fields," and they conclude that "cosmic ray flux variations are apparently the most effective natural factor of climate changes on a large time scale." More specifically, they note that "changes in cloud processes under the action of cosmic rays, which are of importance for abundance of condensation nuclei and for ice formation in cyclones, can act as a connecting link between solar variability and changes in weather and climate," and they cite numerous scientific studies that indicate that "cosmic rays are a substantial factor affecting weather and climate on time scales of hundreds to thousands of years."

Noting that "there is evidence that solar activity variations can affect the cloud cover at Earth," but that "it is still unclear which solar driver plays the most important role in the cloud formation," Voiculescu *et al*. (2006) used "partial correlations to distinguish between the effects of two solar drivers (cosmic rays and the UV irradiance) and the mutual relations between clouds at different altitudes." In doing so they found "a strong solar signal in the cloud cover" and that "low clouds are mostly affected by UV irradiance over oceans and dry continental areas and by cosmic rays over some mid-high latitude oceanic areas and moist lands with high aerosol concentration." Further, they state that "high clouds respond more strongly to cosmic ray variations, especially over oceans and moist continental areas."

Moving one year closer to the present, Gallet and Genevey (2007)[24] documented what they call a "good temporal coincidence" between "periods of geomagnetic field intensity increases and cooling events," as measured in western Europe, where cooling events were "marked by glacier advances on land and increases in ice-rafted debris in [North Atlantic] deep-sea sediments." Their analyses revealed "a succession of three cooling periods in western Europe during the first millennium AD," the ages of which were "remarkably coincident with those of the main discontinuities in the history of Maya civilization," confirming the earlier similar work of Gallet

[23] http://www.co2science.org/articles/V10/N25/C1.php.
[24] http://www.co2science.org/articles/V10/N14/C1.php.

et al. (2005), who had found a "good temporal coincidence in western Europe between cooling events recovered from successive advances of Swiss glaciers over the past 3000 years and periods of rapid increases in geomagnetic field intensity," the latter of which were "nearly coeval with abrupt changes, or hairpin turns, in magnetic field direction."

Gallet and Genevey concluded that "the most plausible mechanism linking geomagnetic field and climate remains a geomagnetic impact on cloud cover," whereby "variations in morphology of the Earth's magnetic field could have modulated the cosmic ray flux interacting with the atmosphere, modifying the nucleation rate of clouds and thus the albedo and Earth surface temperatures (Gallet *et al*., 2005; Courtillot *et al*., 2007)." These observations clearly suggest a global impact on climate, which is further suggested by the close relationship that has been found to exist between "cooling periods in the North Atlantic and aridity episodes in the Middle East," as well as by the similar relationship demonstrated by Gallet and Genevey to have prevailed between periods of aridity over the Yucatan Peninsula and well-documented times of crisis in Mayan civilization.

In another study that took a look at the *really* big picture, painted by rhythmically interbedded limestone and shale or limestone and chert known as *rhythmites*, Elrick and Hinnov (2007)[25] "(1) review the persistent and widespread occurrence of Palaeozoic rhythmites across North America, (2) demonstrate their primary depositional origin at millennial time scales, (3) summarize the range of paleo-environmental conditions that prevailed during rhythmite accumulation, and (4) briefly discuss the implications primary Palaeozoic rhythmites have on understanding the origin of pervasive late Neogene-Quaternary millennial-scale climate variability." They concluded that "millennial-scale climate changes occurred over a very wide spectrum of paleoceanographic, paleogeographic, paleoclimatic, tectonic, and biologic conditions and over time periods from the Cambrian to the Quaternary," and that given this suite of observations, "it is difficult to invoke models of internally driven thermohaline oceanic oscillations or continental ice sheet instabilities to explain their origin." Consequently, they suggest that "millennial-scale paleoclimate variability is a more permanent feature of the Earth's ocean-atmosphere system, which points to an external driver such as solar forcing."

Kirkby (2008)[26] reports that "diverse reconstructions of past climate change have revealed clear associations with cosmic ray variations recorded in cosmogenic isotope archives, providing persuasive evidence for solar or cosmic ray forcing of the climate." He discusses two different classes of microphysical mechanisms that have been proposed to connect cosmic rays with clouds, which interact significantly with fluxes of both solar and thermal radiation and, therefore, climate: "firstly, an influence of cosmic rays on the production of cloud condensation nuclei and, secondly, an influence of cosmic rays on the global electrical circuit in the atmosphere and, in turn, on ice nucleation and other cloud microphysical processes." In doing so, he observes that "considerable progress on understanding ion-aerosol-cloud processes has been made in recent years, and the results are suggestive of a physically plausible link between cosmic rays, clouds and climate," and he says that "with new experiments planned or underway, such as the CLOUD facility at CERN, there are good prospects that we will have some

25 http://www.co2science.org/articles/V10/N20/C2.php.
26 http://www.co2science.org/articles/V11/N21/C2.php.

firm answers to this question within the next few years." Such effort is extremely important, for as Kirkby rightly notes, "the question of whether, and to what extent, the climate is influenced by solar and cosmic ray variability remains central to our understanding of the anthropogenic contribution to present climate change."

In another paper published the same year, Shaviv (2008)[27] begins his intriguing work by noting that "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references in support of this statement. Nevertheless, it has been difficult for the IPCC to accept the logical derivative of this fact, i.e., that solar variations are driving major climate changes, their prime rebuttal being that measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes.

One potential way of resolving this dilemma would be to discover some *amplification mechanism*; but most attempts to identify one have been fraught with difficulty and met with much criticism. In this particular instance, however, Shaviv makes a good case for at least the *existence* of such an amplifier, and he points in the direction of a sensible candidate to fill this role.

More specifically, Shaviv's course of action was to "use the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle" via "the study of three *independent* records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations," each of which can be used "to consistently derive the same oceanic heat flux."

In pursuing this path, Shaviv demonstrated "there are large variations in the oceanic heat content together with the 11-year solar cycle." In addition, he reports that the three independent data sets "consistently show that the oceans absorb and emit *an order of magnitude more heat* [italics added] than could be expected from just the variations in the total solar irradiance," thus "implying," as he describes it, "the necessary existence of an amplification mechanism, although without pointing to which one."

Finding it difficult to *resist* pointing, however, Shaviv acknowledges his affinity for the *solar-wind modulated* cosmic ray flux (CRF) hypothesis, which was suggested by Ney (1959), discussed by Dickenson (1975), and championed by Svensmark (1998). Based on "correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions," this concept, according to Shaviv, "predicts the correct radiation imbalance observed in the cloud cover variations" that are needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle. Thus, Shaviv concludes that the *solar-wind modulated CRF hypothesis* is "a favorable candidate" for *primary instigator* of the many climatic phenomena discussed throughout this chapter.

[27] http://www.co2science.org/articles/V12/N8/EDIT.php.

Seeking additional understanding of the topic was [Knudsen and Riisager (2009)][28] who, while noting that "the *galactic cosmic ray* (GCR) flux is also modulated by Earth's magnetic field," state that "if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between Earth's magnetic field and climate." In a test of this supposition, Knudsen and Riisager set out to "compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen *et al*., 2008) with proxy records for past low-latitude precipitation (Fleitman *et al*., 2003; Wang *et al*., 2005)," the first of which proxy records is derived from a speleothem $\delta^{18}O$ record obtained from stalagmite Q5 from Qunf cave in southern Oman, and the second of which is derived from a similar record obtained from stalagmite DA from Dongge cave in southern China.

In commenting on their findings, the two researchers report that the various correlations they observed over the course of the Holocene "suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment." In particular, they say that the general increase in precipitation observed over the past 1500 years in both speleothem records "cannot be readily explained by changes in summer insolation or solar activity," but that it "correlates very well with the rapid decrease in dipole moment observed during this period," which relationship is explained by the fact that "a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation." As a result, Knudsen and Riisager say that "in addition to supporting the notion that variations in the geomagnetic field may have influenced Earth's climate in the past," their study also provides support for a link "between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system."

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Concurrently, [Ram *et al*. (2009)][29] focused their attention on studies of dust in the Greenland Ice Sheet Project 2, acknowledging that others have shown that the dust concentration in the upper 2.8 km of the ice, spanning approximately 100,000 years, "is strongly modulated at regular periods close to 11, 22, 80 and 200 years, all of which are well-known periods of solar activity" (Ram *et al*., 1998; Ram and Stolz, 1999). But they also concede that "an amplifying mechanism must be at work if solar influence is to be taken seriously." Thus, they go on to describe work that largely satisfies that criterion as it applies to dust variability, indicating that "changes in nucleation processes in clouds associated with the cosmic ray flux (CRF) can provide the necessary amplification," which they describe in abbreviated form as "increased solar activity -> decreased cosmic ray flux ->

28 http://www.co2science.org/articles/V12/N14/C1.php.
29 http://www.co2science.org/articles/V12/N47/EDIT.php.

decreased air-Earth [downward electric] current [density (*Jz*)] -> decreased contact nucleation -> decreased precipitation -> increased dust."

Since this chain of events operates via changes in cloud characteristics, Ram *et al*. conclude that it provides "circumstantial evidence for a Sun/climate connection mediated by the terrestrial CRF," which "may initiate a sufficiently large amplification mechanism that can magnify the influence of the Sun on the Earth's climate beyond the traditional radiative effects." Hence, they encourage additional work to "incorporate the effects of the CRF on *Jz* (and associated nucleation processes), and the subsequent microphysical responses, into macroscopic cloud models that can then be incorporated into global climate models." Until this is done, and done successfully, today's climate models cannot be claimed to include all processes that may be of significance to the accurate simulation of Earth's future climate.

In another contemporaneous study, Henrik Svensmanrk and two coauthors (Svensmark *et al*. 2009[30]), all from the National Space Institute of the Technical University of Denmark in Copenhagen, explored the consequences of Forbush decreases (FDs) in the influx of galactic cosmic rays (GCRs) that are produced by periodic explosive events on the Sun that result in "magnetic plasma clouds from solar coronal mass ejections that pass near the Earth and provide a temporary shield against GCRs." Based on *cloud liquid water content* data obtained over the world's oceans by the Special Sounder Microwave Imager, *liquid water cloud fraction* data obtained by the Moderate Resolution Imaging Spectroradiometer, and data on IR detection of low clouds over the ocean by the International Satellite Cloud Climate Project -- as well as FD data obtained from 130 neutron monitors world-wide and the Nagoya muon detector -- Svensmark *et al*. found what they describe as "substantial declines in liquid-water clouds, apparently tracking the declining cosmic rays and reaching minima some [~7] days after the GCR minima." Concurrently, they also found that "parallel observations by the aerosol robotic network AERONET reveal falls in the relative abundance of fine aerosol particles, which, in normal circumstances, could have evolved into cloud condensation nuclei."

The Danish scientists say their results "show global-scale evidence of conspicuous influences of solar variability on cloudiness and aerosols," and that "the loss of ions from the air during FDs reduces the cloud liquid water content over the oceans." In fact, "so marked was the response to relatively small variations in the total ionization," they concluded that "a large fraction of Earth's clouds could be controlled by ionization." Such observations support Svensmark's theory that solar-activity-induced decreases in GCR bombardment of the Earth lead to decreases in low (<3.2 km) clouds as a result of reduced atmospheric ionization and, therefore, less fine aerosol particles that *under normal circumstances* could have evolved into cloud condensation nuclei that could have resulted in more low-level clouds that *could have cooled the planet* (but, obviously, were not there to do so under conditions of decreased GCR bombardment).

[30] http://www.co2science.org/articles/V12/N31/C1.php.

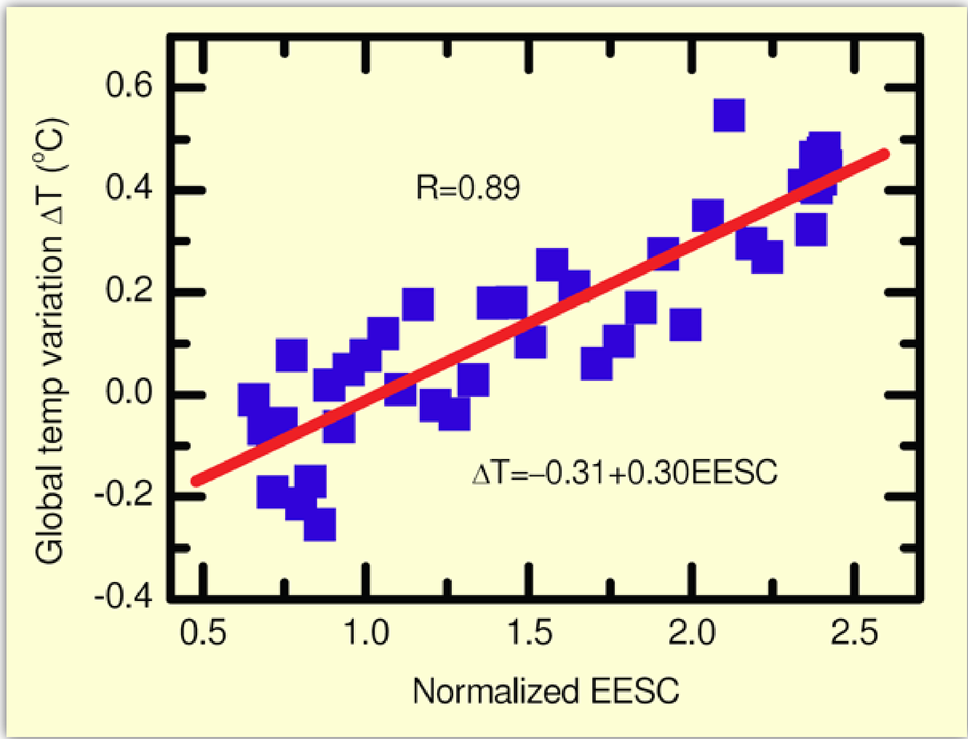
In one final paper, author Qing-Bin Lu (2009)[31] injects a whole new dimension into the contentious debate over what has been the cause of late 20th-century global warming *and* its early 21st-century cessation.

The bulk of Lu's paper is dedicated to describing the new *cosmic-ray-driven electron-induced reaction mechanism* -- or CRE model -- of ozone depletion, which he contrasts with the conventional *photochemical* model of ozone depletion. Near the end of his discussion of this other important subject, however, he makes some original observations about the possible effects of chlorofluorocarbons (CFCs) and cosmic-ray-driven ozone depletion on global climate change, which subsidiary analysis leads one to question the purported role of rising atmospheric CO_2 in 20th century warming.

Lu begins by noting that ozone-depleting CFCs are also greenhouse gases, but that the IPCC has considered them to provide only about 13% of the total radiative forcing produced by *all* of the atmosphere's well-mixed greenhouse gases. He then goes on to challenge the low value of this assessment, stating *emphatically* (as indicated by his use of italics) that "*these conclusions were based on climate model simulations rather than direct observations*." And he thus proceeds to consider some real-world measurements in ways that had not been done before.

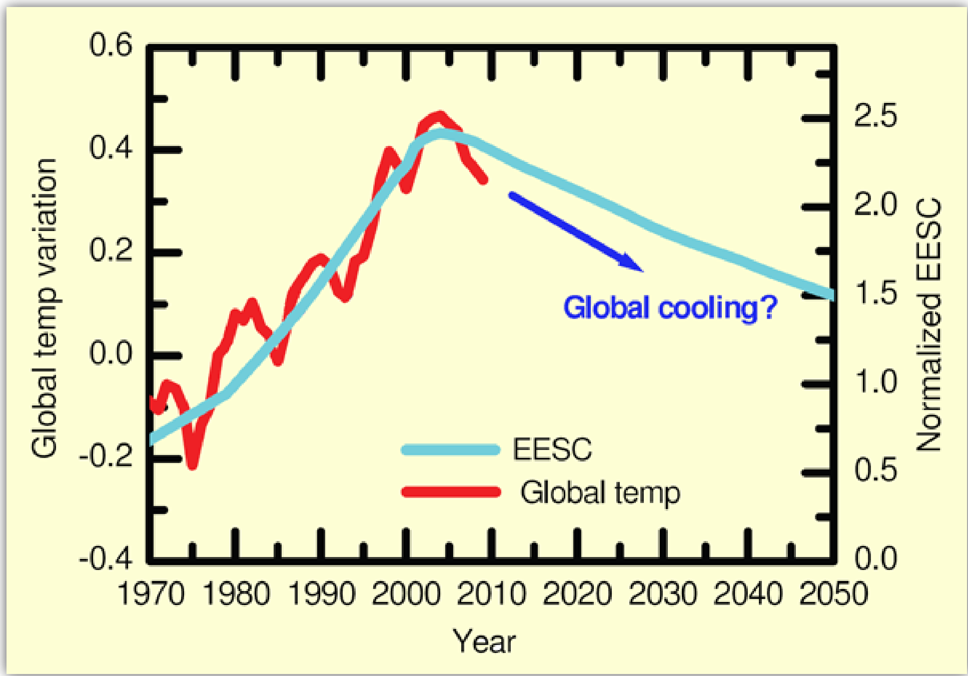
In plotting yearly mean global *temperature* deviations (ΔT, relative to the 1980 mean value) vs. *equivalent effective stratospheric chlorine* concentrations (EESC, normalized to the 1980 value) over the period 1970-2008, for example, Lu found that the former parameter was a well-defined function of the latter, as may be seen in the figure below, where the correlation coefficient (R) of the linear relationship between the two parameters is 0.89 at a probability level (P) of < 0.0001.

[31] http://www.co2science.org/articles/V13/N8/EDIT.php.



Yearly global temperature relative to its 1980 value (ΔT) vs. yearly EESC normalized to its 1980 value. Adapted from Lu (2009).

Of course, *correlation* does not prove *causation*, but Lu makes a point of noting that following the implementation of the Montreal Protocol, the total halogen level in the lower atmosphere was observed to peak in 1994 and the EESC over Antarctica was estimated to peak around the year 2000, after which it actually began to decline, *as did global temperature*, as shown in the figure below. And based on the estimated trend of EESC over the next four decades, Lu's analysis suggests that the Earth may well *continue* to cool -- as it has been gradually doing for the past decade -- until the middle of the current century or more.



Yearly global temperature relative to its 1980 value (ΔT) and yearly EESC normalized to its 1980 value vs. time. Adapted from Lu (2009).

As for what this all means, Lu states in the concluding paragraph of his lengthy treatise that the "observed data point to the possibility that the global warming observed in the late 20th century was dominantly caused by CFCs, modulated by CRE-driven ozone depletion," and that "with the decreasing emission of CFCs into the atmosphere, global cooling may have started since 2002." Nevertheless, Lu does not *contend* that this *must* be the case; he only states that "this is likely a subject deserving close attention."

Clearly, in light of all the evidence presented above, the flux of galactic cosmic rays wields an important influence on Earth's climate, and likely much more so than that exhibited by the modern increase in atmospheric CO_2 , making fluctuations in the Sun the primary candidate for "prime determinant" of Earth's climatic state.

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