THE PRODUCTION OF ATMOSPHERIC NITRIC OXIDE BY COSMIC RAYS & SOLAR ENERGETIC PARTICLES

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Abstract

Galactic Cosmic Rays (GCRs) deposit their energy throughout the atmosphere but peaking in the low Stratosphere and upper Troposphere. GCR ionisation leads to the production of nitric oxide (NO) at significant levels which are also modulated in anti-phase with the solar cycle. This accounts for approximately half the NO at high latitudes with a large $\sim$ 11-year modulation.

Solar Energetic Particles (SEPs) Events occur sporadically but are more frequent around solar maximum. They interact with the atmosphere in the 30-60 km range but occasionally they can penetrate down to below 20 km. Because they show a very dramatic onset with huge increases in energetic protons, SEPs are useful for studying the effects of energetic particles on atmospheric chemistry. Lightning is also a potentially important source of NO and is also possibly correlated with GCRs. Ice core data shows that SEP generated nitrates can reach the ground/low atmosphere in large quantities.

1. INTRODUCTION

This is intended to be a short overview of how cosmic rays do affect atmospheric chemistry and specifically with regard to the various oxides of nitrogen. To illustrate this in a more direct manner, I will focus on "Solar Energetic Particle" (SEP) Events[1]. These are generally rather less energetic than "true" cosmic rays, but they display much greater dynamic variability that allows us to follow some of their effects on the atmosphere. I will also touch on the role of OH and on general ozone effects and conclude with a look back in time by using some recent ice core data, going 400 years into the Sun's active past.

Probably the first person to discuss the possible climatological effects of cosmic rays was Edward Ney [1]. Ney stressed that because the solar modulation of cosmic rays affected low energy particles more than higher energy ones, the atmospheric change in ionisation would show a latitude effect. Having demonstrated that cosmic rays were indeed modulated at all latitudes, he went on to speculate further using a diagram (figure 1). He wondered if there was a connection between ionisation and thunderstorm activity (for example). If so, then a solar cycle modulation might be detectable in the climate data. It should perhaps be stressed here that Ney's paper was written in 1959. Ney commented that his diagram was only a "suggestion" and he was confident that climatologists should be able to come up with many such scenarios and that these could then be tested against the cosmic ray and weather data. Ney concluded by noting that the meteorological variable subject to the largest solar cycle modulation in the denser layers of the atmosphere (*i.e.* greater than 1 mb pressure) is the ionisation produced by cosmic rays and that it should be worthwhile investigating the possible effects of changes in this variable on the climate.

In this paper, I would like to review the role of cosmic rays (and solar energetic particles) in the production of oxides of nitrogen and to then suggest my own "diagrammatic scenario", building on the foundations laid by Edward Ney in 1959. In particular, I would like to stress the role that lightning plays in generating nitric acid in the troposphere and whether this could be influenced by the modulation in atmospheric ionisation and therefore coupled to the solar cycle modulation (via the crucial role played by cosmic rays).

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[1] Solar energetic particles events are also sometimes referred to as Solar Proton Events – SPEs.

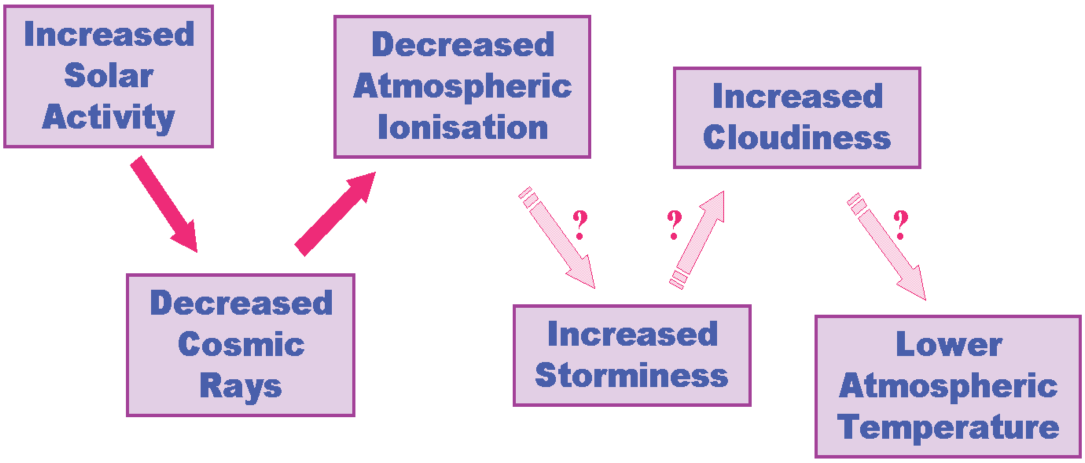

Fig. 1: Ney's diagrammatic scenario illustrating one possible way that solar activity might be coupled to the climate record. The first two links (shown by solid arrows) Ney believed were already firmly established (this was in 1959). However, the last three links were more speculative (as indicated by the shaded arrows and question marks).

2. SOLAR ENERGETIC PARTICLE EVENTS

Solar energetic particle (SEP) events are, in these modern times, inextricably linked with the term "space weather". With the construction of the International Space Station (ISS) and a permanent manned presence in space planned for the near future, it is vital that solar scientists are able to give advanced warning of any solar activity that might be potentially harmful to astronauts and scientists living on the ISS. In some cases (as I will try and show below), the warning given might be very little indeed.

In the past, perhaps the best (and certainly the most beautiful and visual), demonstration that the Sun was "up to something" was the aurora or Northern Lights. These are perfectly harmless events that indicate energetic electrons are streaming into the atmosphere (mostly at the poles but occasionally at more accessible mid-latitudes) and causing the nitrogen and oxygen molecules in the air to fluoresce and emit beautiful ribbons and curtains of flickering coloured light.

In terms of space weather forecasting, the SOHO spacecraft is currently in the front line with its vantage point some 1.5 million km closer to the Sun than Earth (a mere 1% closer). As an example of how dramatic and rapid SEP events can be, lets look at an event from Bastille Day (July 14^{th}). Bastille Day is a national holiday in France and is typically celebrated with parades and parties and firework displays. In the year 2000 (the 210^{th} anniversary), the Sun arranged its own special "fireworks" display.

A large flare was seen to erupt by SOHO to start at 10:12 UT and it peaked at 10:24. It was a 3B flare in the optical classification scheme and an X5 flare in the X-ray band - both of which are fairly impressive events (it is perhaps worth noting that July 2000 was fairly close to the Sun's maximum phase in its 11-year solar sunspot and activity cycle). The flare was from NOAA active region 9077, which was very close to the centreline of the Sun (as viewed from Earth) and just north of the Sun's equator). Solar flares are very often associated with coronal mass ejections (CMEs). CMEs are relatively cool material and once released from the Sun rapidly expand to become "clouds" travelling through interplanetary space (along with the Sun's normal plasma emission - the solar wind - which typically travels at a velocity of about 450 km/s). However, CMEs associated with large flares are very often "fast" events - that is they have velocities in excess of 7-800 km/s. When these CMEs start propagating through the normal solar wind, they start to "sweep up" material and compress/stretch the imbedded solar/interplanetary magnetic field. This leads to shocks forming and the front of the CME becomes a site of in situ particle acceleration. Therefore, such a fast CME produces a large surge of energetic particles (mostly protons) - hence, a solar energetic particle (or solar proton) event.

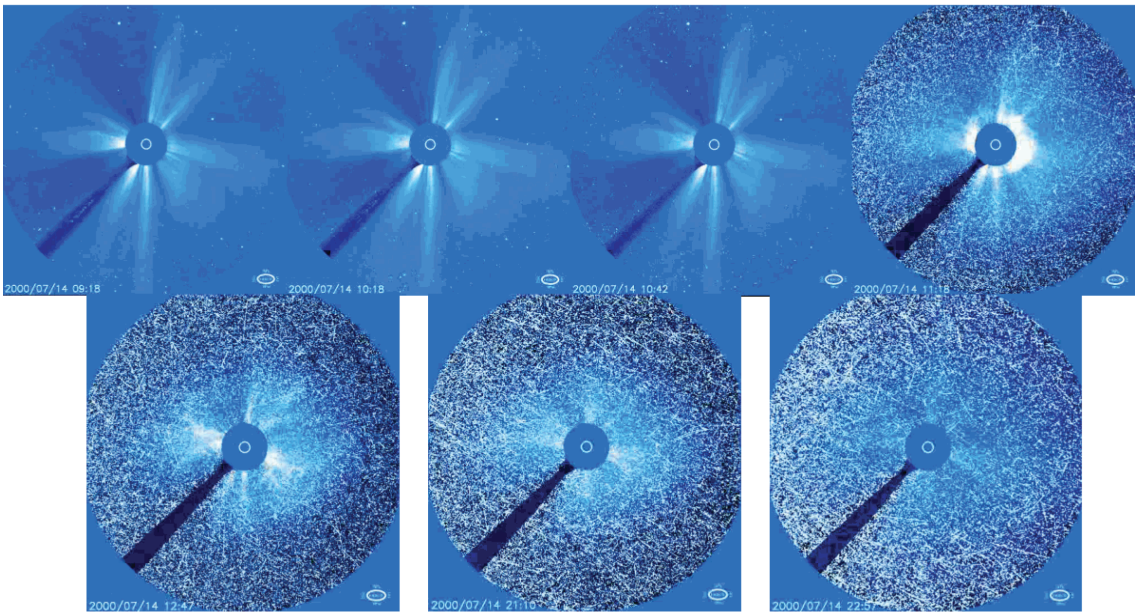

Fig. 2: Images of the SOHO LASCO coronagraph of the halo CME associated with the Bastille Day flare. Notice how the images are very quickly covered with a "snow storm" - i.e. direct impacts on the CCD camera of the energetic particles produced by the CME. The images were taken at (top) 09:18, 10:18, 10:42, 11:18, (bottom) 12:47, 21:10, and 22:57. The bright white ring in the 11:18 image is the CME coming directly towards the Earth that is also visible in the subsequent images. The size of the Sun (obscured) in these images is shown by the small white circle at the centre of each frame.

From the ground, if we want to see the solar corona (i.e. the Sun's hot outer tenuous atmosphere), we normally have to wait for a solar eclipse. However, from space (and indeed high mountains) it is possible to create artificial eclipses by obscuring the Sun's bright visible disk. Such an instrument is called a coronagraph. The coronagraph imager on SOHO is called LASCO and it detected a halo CME from the Bastille Day flare at about 10:54 (figure 2). A halo CME is a CME that the Sun launches essentially directly towards the Earth and hence quickly produces a halo around the Sun (see the top right image of figure 2). However, almost immediately after LASCO detected the CME it was quickly "blinded" by the energetic particles from the event itself - the SEPs (clearly visible as the "snow storm" in the last four images). The SEP event itself is shown in figure 3 along with the CME shock/disturbance in the solar wind that took rather longer to reach the Earth. The SEP particles reached SOHO in around 40 minutes and went on to the reach the Earth in a few minutes later. The steep rise in this event shows an almost instantaneous increase of around ×50,000 in all energy bands and was the biggest SEP event since the previous solar maximum in 1991.

If you were an astronaut on the ISS "outside" doing some work when the flare erupted, you would have had very little warning of the SEP event and the huge dose of radiation coming towards you. Remember, light takes about 8 minutes to get from the Sun to Earth/SOHO — the data then had to be collected and stored on board SOHO before it could be relayed back to Earth, analysed in "realtime" and a possible warning given — all this would have about 30 minutes. This would then give you (the astronaut) just 10 minutes to get back into the habitation module and "hide" behind the protective shielding. This emphasises that flares are not predictable and the size of a flare is similarly not predictable in advance. Having said that, active region 9077 was a large sunspot group, and a big flare was expected from it.

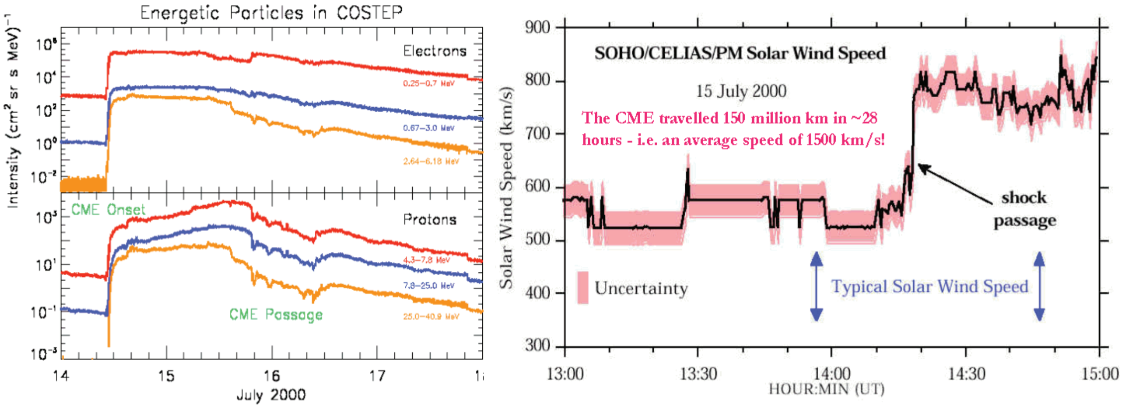

Fig. 3: The left panel shows the almost instantaneous increases in energetic particles and electrons while the right panel detects the arrival of the CME shock at SOHO a mere 28 hours after the flare erupted. It should be noted that the event lasted many days if judged in terms of energetic particles but was measured in hours in terms of X-rays from the flare itself. This emphasises that it is the CME and not the flare that produces the bulk of the energetic particles.

3. COSMIC RAY INTERACTIONS IN THE ATMOSPHERE

Galactic cosmic rays (GCRs) are energetic charged particles that originate throughout the Milky Way galaxy and for the energies that we will be interested in here GCRs are produced in supernova explosions and the subsequent supernova remnant expansion into the surrounding interstellar medium leading to shock acceleration, etc. (In fact, the acceleration mechanism is probably very similar to that at a CME shock front in an SEP event, although on a rather more dramatic scale). GCRs are about 88% protons, 10% helium, around 1% heavier ions and less than about 1% electrons. The energy flux reaching the Earth ($\sim 10^{-9}$ W/cm^2) is almost completely negligible, but GCRs are very definitely important in their contribution to atmospheric ionisation. In particular, GCRs are able to penetrate much deeper into the atmosphere than solar ionising radiation and are the dominant ionisation process below about 60km (with an additional contribution from SEP events as we will see shortly). [NB: This statement is true down to about 3-4 km where surface radioactivity also becomes important]. For GCR energies up to about 20 GeV, the solar wind and solar heliosphere (the region of interstellar space dominated by the Sun, extending out to about 100 AU [1 AU being the average Sun-Earth distance = 150 million km]) does scatter and deflect incoming particles. Since the heliosphere responds to the $\sim$11 year solar sunspot activity cycle, then so does the flux of these lower energy GCRs (the GCR energy spectrum extends to beyond 10^{11} GeV so 20 GeV is "low" for a GCR!). This then opens up the possibility of GCRs coupling to solar activity and producing a measurable climate variation as already noted above by Ney[1]. It is perhaps worth noting that the GCR flux goes *down* at solar maximum and *peaks* at solar minimum - that is, the GCR flux is in anti-phase with the sunspot cycle. The Earth's own magnetic field also provides an addition level of protection from these lower energy GCRs, leading to the already noted latitudinal variation in the cosmic ray data. The largest modulations are seen at high geomagnetic latitudes and the smallest modulations (i.e. sunspot maximum$\longrightarrow$sunspot minimum) are seen around the geomagnetic equator in regions of high "rigidity". This magnetic rigidity means that at the highest level only GCRs with energies around 14 GeV can penetrate to the lower levels of the atmosphere/ground level. However, since this is still less than the 20 GeV energy that is solar modulated, even equatorial regions experience a modulated cosmic ray flux.

3.1 GCR IMPACT ON ATMOSPHERIC CHEMISTRY

When a primary cosmic ray of energy around 1 GeV enters the atmosphere it initiates a huge avalanche of secondary particles (normally referred to as an air shower) with more than a million secondary particles produced. This flux of secondary particles increases as we traverse down through the atmosphere until we reach around 15–25 km (depending on magnetic rigidity and solar cycle phase) below which the flux decreases again. (The ionisation maximum height is more correctly a measure of the total atmospheric column density traversed by the secondaries, which is equivalent to saying the atmospheric pressure). In this paper it is not the ionisation itself that I wish to consider, but the atmospheric chemistry that might result from cosmic rays hitting the atmosphere. Given that the atmosphere is essentially made of nitrogen (N_2), oxygen (O_2) and a trace of water vapour (H_2O), it shouldn't be to surprising that the major chemical species generated by GCRs are oxides of nitrogen and hydrogen — so called NO_x and HO_x. [NO_x — N, NO, NO_2; HO_x — H, OH, HO_2]. There is also a secondary effect on ozone which will be briefly discussed.

Warneck[2] was the first to note that GCRs would be a significant source of NO_x (and particularly NO). (This was around the time that ozone destruction was beginning to be studied and aircraft emissions and other manmade contributions had already been considered as a possible culprit). However, it was Nicolet[3] who first calculated production rates of nitric oxide (NO) by GCRs and also the variation caused by the solar modulation. These calculations showed a large production and modulation effect at high geomagnetic latitude (above 50° latitude) at an altitude of 20 km. Some of the more important reactions are shown below.

$$\mathrm{N_2 \rightarrow N + N^+} \qquad \mathrm{O_2 \rightarrow O + O^+} \qquad \text{(dissociative ionisation)} \tag{1}$$
$$\mathrm{N^+ + O_2 \rightarrow O_2^+ + N} \qquad \mathrm{N^+ + O_2 \rightarrow O + NO^+} \qquad \mathrm{N_2 + O_2^+ \rightarrow NO + NO^+} \tag{2}$$
$$\mathrm{NO + O_3 \rightarrow O_2 + NO_2} \qquad \mathrm{NO_2 + O_3 \rightarrow O_2 + NO_3} \qquad \mathrm{OH + NO_2} + M \rightarrow \mathrm{HNO_3} + M \tag{3}$$
$$\mathrm{OH + O \rightarrow O_2 + H} \qquad \mathrm{H + O_3 \rightarrow OH + O_2} \qquad \mathrm{OH + O_3 \rightarrow H_2O + O_2} \tag{4}$$

As can be seen in (3) and (4) HO_x and NO_x are implicated in ozone destruction. However, it is not just galactic cosmic rays that promote these atmospheric reactions — solar energetic particles can also be important. The only key difference is that SEPs produce their effects in the middle atmosphere while GCRs produce effects, in particular, in the lower stratosphere and upper troposphere. At least nine separate SEP events have been observed to produce ozone depletions in the past three solar cycles, and one of the most dramatic events was the August 1972 SEP. These ozone depletions are believed to be primarily due to the newly created HO_x species, although the role of NO_x cannot be underestimated. There is another difference between GCR and SEPs — SEPs occur most frequently around solar maximum, in particular on the rise just prior to maximum and on the fall a year or two after maximum, while GCRs peak around solar minimum.

Jackman *et al.* [4] looked in detail at the various sources of nitric oxide and where in the atmosphere each process is effective (figure 4). They showed that stratospheric NO is mainly produced from the dissociation of nitrous oxide (N_2O) - which is a by-product of the biological nitrogen cycle. This provides a large and relatively constant background source. However, GCRs and SEPs provide a significant and variable component of NO in the middle atmosphere. In fact, at geomagnetic latitudes greater than 50°, the GCR contribution shows a solar cycle modulation of some 50% and is also responsible for about 50% of the total NO production in the stratosphere and mesosphere. Jackman *et al.* [4] also made detailed calculations for some SEP events. In particular, they showed that the large event in August, 1972 (around three years after solar maximum) produced effects that extended down to 10 km. It also took the atmosphere 1 year to return to pre-event levels.

4. LIGHTNING AS A SOURCE OF NO_x

As can be seen in figure 4, lightning is listed as a major contributor to NO production in the atmosphere. The role of lightning was studied in more detail by Legrand *et al.* [5]. Lightning generates NO by the thermal decomposition of nitrogen and oxygen, and this is likely to be especially important in the Tropics and in the lower regions of the atmosphere (as can be seen in figure 4, where lightning is the only source

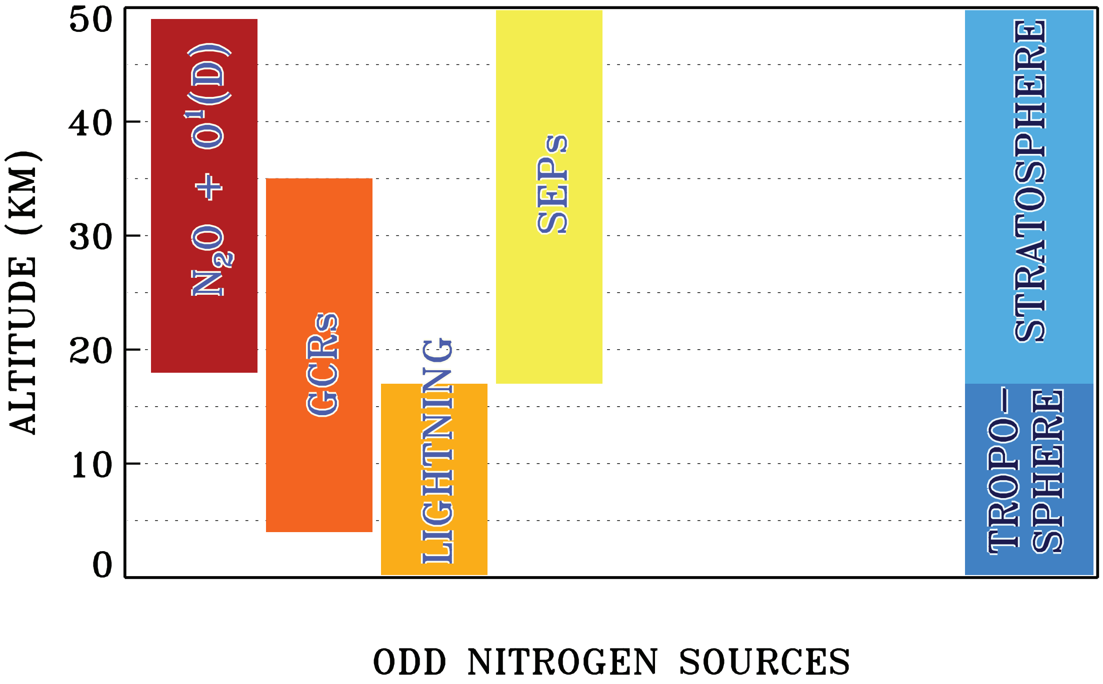

Fig. 4: Atmospheric sources of odd nitrogen (principally NO) (from Jackman *et al.* [4]). Only the 0-50 km altitude range is shown here since the processes that operate at high altitudes are not relevant to the present discussion.

given below 4 km). Legrand *et al.* [5] used a 2-dimensional model to estimate that at the tropopause, lightning contributed 30% of the total NO production at the poles, and this rose to 60% at the equator (compared to GCRs contribution of 10% or less). Charles Jackman [6] in a review talk at the Spring AGU in 2001 suggested that lightning produced NO could contribute up to 1000 kilotons per year to the middle atmosphere (stratosphere + mesosphere). This would make it the single largest source of NO, exceeding the 800 kT/yr from nitrous oxide dissociation. However, there are still significant uncertainties in the exact contribution to NO production made by lightning.

Crucially, galactic cosmic rays do undoubtedly play a role in lightning. As we have already seen, GCRs ionise stratospheric and tropospheric air producing free electrons and light ions. These in turn will determine the electrical conductivity of the air. It is this conductivity that allows a current to flow in the atmosphere in what is generally referred to as the global electric circuit.

4.1 THE EARTH'S GLOBAL ELECTRIC CIRCUIT

The "classical" picture of the Earth's global electric circuit is that the very high conductivity of the ionosphere (maintained by the ionising X-ray and UV radiation from the Sun) is weakly conducted back to the ground through the "fair weather" electric field. Since the ground/oceans are also good conductors, the circuit needs an "up" component to complete it. Since 1916 this upward component/generator as been assumed to be the combined global summation of all the active thunderstorms (Wilson [7]). This situation is shown schematically in figure 5 and an equivalent (simplified) electrical circuit is also shown (Makino & Ogawa [8]). It is the increased conductivity provided by GCRs that allows the circuit to operate and also allows for global redistributions to take place, since GCRs are more influential at the polar regions, this redistribution transfers the effects of GCRs to the middle and low latitudes.

The global electric circuit and its links to GCRs and atmospheric conductivity have been suggested as a mechanism for increasing cloudiness (in a way that is very reminiscent of Ney's (1959) diagrammatic scenario [shown in figure 1]). The idea was proposed by Tinsley [9], and relates to the fair weather

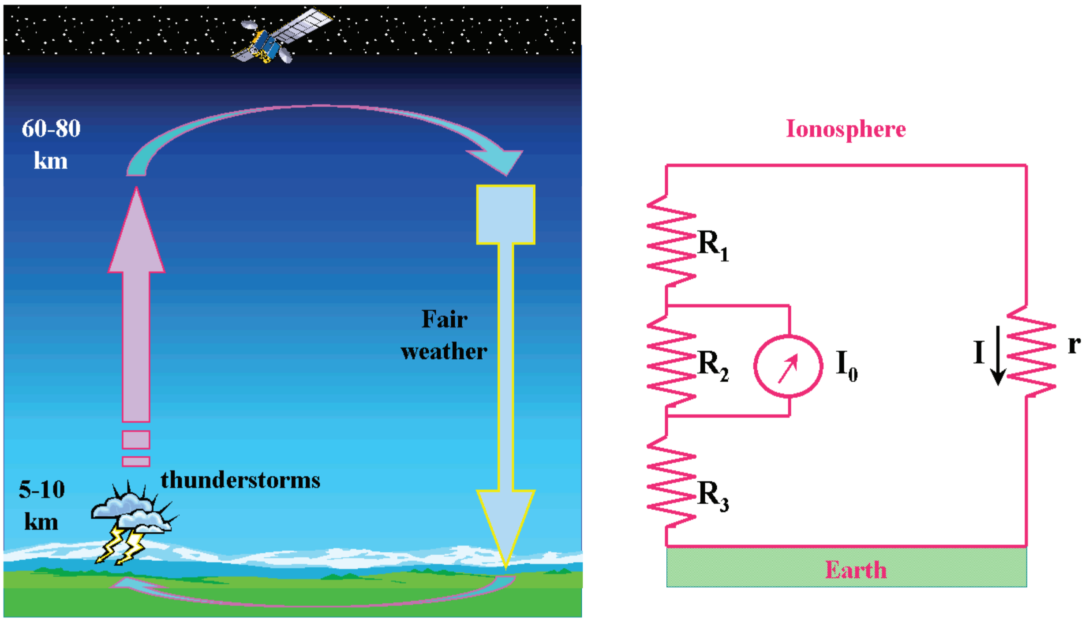

Fig. 5: Schematic of the Earth's electric circuit and the simplified equivalent circuit. The simplified circuit is from Makino & Ogawa [8], where r is the global Earth-Ionosphere resistance, R_1 the resistance between the +ve thundercloud top to the ionosphere, R_2 the resistance across the cloud and R_3 is the cloud to Earth resistance. Thunderstorms can be seen to be the global electric circuit generators.

currents shown in figure 5. These currents flow because of the ∼250 kV potential difference set up between the ionosphere and the ground. This current depends critically on the atmospheric conductivity of the middle and lower atmosphere (and hence on the GCR flux). Tinsley [9] suggested that when this current encounters a cloud, the current flow will see an increased electrical resistance due to the cloud (called R_2 in figure 5), leading to the formation of a positive space charge on the upper surface of the cloud. It is this electrical charging that Tinsley suggests will lead to the scavenging of evaporated aerosol particles and in the freezing of droplets. This electrofreezing process can considerably enhance the overall production of ice nuclei in clouds.

4.2 LIGHTNING MODULATED BY GCRs OR THE SOLAR CYCLE?

As we have already discussed, lightning is a significant source of NO_x in the free troposphere. In the model of Legrand *et al.* [5], lightning was confined to the tropical areas (30°N—30°S) and also to the ground—15 km altitude range (with a relative maximum at 10 km). A global production rate of 2.8 million tonnes/year was assumed (larger than the ∼1000 kT/yr figure given above by Jackman [6], but Jackman was only quoting the amount of NO transported upward into the middle atmosphere). The key question which wasn't addressed by the model is whether the lightning rate (and hence the resultant NO_x) is modulated by solar activity and/or galactic cosmic rays. Above, we certainly suggested that GCRS *should* have an effect on the lightning rate since GCRs will clearly have an effect on the conductivity of the atmosphere. But is there any observational evidence for a link/modulation in the lightning data?

The main "problem" in answering this question is the relative lack of a "global" lightning monitoring network to collect the raw data needed to answer the question. Areas of the world do have some monitoring systems and these lend some support to the idea of a link between cosmic rays/solar activity/solar wind and lightning frequency, but in a somewhat difficult to interpret manor. Lethbridge [10] used data from a lightning network covering much of the continental United States in a superposed epoch analyse. She found that there was a significant increase in thunderstorm activity three–four days after the cosmic ray maximum (taking data on a month-by-month basis from 1956–1976 with seasonal trends removed). A similar correlation was also found with solar-wind magnetic sector boundary crossings and minima in monthly K_p indices. Since the sector boundary crossing also correlated strongly with cosmic ray flux, Lethbridge [10] concludes that the effect was more likely to be due to cosmic rays.

However, strong solar cycle modulations have been found in parameters that relate to the global electric circuit. Measurements of the air-earth current (in fair weather and mostly taken over Lake Superior) in the period 1966–1982 show a clear solar cycle modulation with an amplitude of at least 50% (Olson [11]). The variation was in the sense that the maximum air current density was around solar minimum (1977), while the minimum value was seen in 1969 at the previous solar maximum. Mühleisen [12] also found a variation in the ionospheric potential that was in anti-phase with the solar cycle in 11-years of balloon radiosonde measurements. His results indicated an average ionospheric potential of around 350 kV around solar minimum, falling to $\sim$250 kV close to solar maximum. Both these results would thus appear to be responding to the galactic cosmic ray flux and certainly the air current density result is clearly in agreement with the picture previous presented of atmospheric ionisation and its likely effects on the global electric circuit. The ionospheric potential measurements would also support a link with lightning frequency, since as previously stated lightning/thunderstorms are the generator of the global electric circuit (figure 5). So, it would seem that the answer to our question is probably “yes”, there is a plausible and probable modulation of lightning/thunderstorm activity that responds to changes in galactic cosmic ray flux.

5. SOLAR ENERGETIC PARTICLES AND ICE CORES

As can be seen from the limited set of atmospheric chemical reactions shown in (1)—(4), nitric acid (HNO_3) is one of the stable end points of GCR initiated processes. When nitric acid dissolves in water, it forms nitrate ions (NO_3^-). These nitrate ions can find their way into rain and snow that effectively removes them from the atmosphere. Therefore, places that are permanently frozen can preserve a time record of the rate of atmospheric nitrate production. Zeller *et al.* [13] have analysed nitrate ions in a snow sequence from the Ross Ice Shelf (Antarctica) dating back to 1971. The data had a resolution of 2-3 months and shows a clear annual cycle with sharp peaks in summer and broad minima in winter. The effect is believed to be due to summer heat and low snowfall levels concentrating the non-volatile components of the ice. Zeller *et al.* claimed that two major SEP events are also visible in the snow/ice record, indicated by two sharp peaks in the data. One of these events is the August, 1972 SEP event (again), the other event being from April, 1984. Certainly, the August, 1972 event did produce a major change in the atmospheric NO_x content, and as we have already seen, this effect persisted for around 1 year. Zeller *et al.* suggest that the effects of these events could have been enhanced (in the snow record) by reductions in the snowfall at the time of the deposition of nitrate ions. The data for the 1972/3 southern summer shows a sharp peak in December, some 4 months after the event. This time delay represents the transportation time for the nitrates ions to reach the lower atmosphere and eventually to be removed as snow/rain. Dreschhoff & Zeller [14] later extended this record back to 1927 detecting evidence for further SEP events in July, 1946 and July, 1928. The event in 1946 was already a well-known particle event and the one in 1928 occurred around the time of a white light flare on the Sun. It is interesting to note that the events of 1972, 1946 and 1928 all occurred during the periods of total darkness at the south pole and represent increases of 7, 11, and 4 standard deviations above the series mean. When the 1928 event is corrected for the snow compactness, it increases to 6 standard deviations in significance.

This process of using snow/ice records to study past SEP events can be extended even further back in time. The Greenland ice plateau is another place on Earth that preserves such a frozen record of past events. Dreschhoff & Zeller [15] and Kocharov, Ogurtsov & Dreschhoff [16] have analysed an ultra-high resolution ice core from Greenland. The data comes from a 122 metre long (10cm diameter) ice core drilled into the central East Greenland high ice plateau in summer 1992. The data clearly shows a series of large anomalies in nitrate ion concentration that are almost certainly due to solar particle events. They also measured the conductivity of the ice and this data shows volcanic activity that can be used to "date" the core. For events like Krakatau or Tambora, which are in the southern hemisphere, it is necessary to allow around 1 year for ion transportation to the northern polar regions.

After removing the seasonal background from the nitrate data, it is possible to analyse the longer-term trends in the time series. By smoothing the data with a moving average with a length of about 8 years, several features of the series become apparent. There is a small dip in the early 1800s and a second longer dip from $\sim$1650–1700. These features correspond (in time at least), to the Dalton and Maunder Minima periods (respectively). These are two intervals when solar activity was at a reduced level. Indeed, during the Maunder Minimum, sunspots almost completely disappeared from the Sun's surface and several solar cycles had only one or two spots in total. When directly compared to the sunspot data, the nitrate ion data does not correlate all that well. The lack of quantitative agreement between the two data sets reflects the fact that sunspots are not a good measure of solar flares and solar energetic particle events or the solar wind — which are the two dominant processes that drive nitrate generation (via SEPs and GCRs, respectively).

However, when the data is examined at higher time resolution (i.e. without the smoothing), then some general agreement between the two sets can be found. Two peaks in particular occurred in 1851 and 1849. These could be connected to unusual white light flares seen in Feb., 1851 and Jan., 1849 — 1849 is close to sunspot maximum and 1851 is on the declining phase of the solar cycle. This is quite typical, the largest SEP events generally occur on the rising and declining parts of sunspot cycles - rather than at the peaks of the cycles. When the full data series is analysed for periodicities it is found that a $\sim$5 year period is detectable in the data from 1760—1900. This period is almost exactly half the sunspot cycle and is very compelling evidence for an SEP signature to be present in the data (i.e. the data is likely detecting the rising and falling parts of each $\sim$11 year cycle). This conclusion was tested by taking the sunspot data and frequency doubling it (by multiplying the data by its Hilbert transform). This new sunspot series then showed a period at $\sim$5.3 years, exactly in agreement with the nitrate ion data.

6. CONCLUSIONS

Galactic Cosmic Rays deposit their energy in the low stratosphere and produce NO at ratios depending on the phase of the solar cycle — this accounts for approximately half the NO at high latitudes and with a large $\sim$ 11-year modulation. Solar Energetic Particles Events occur sporadically but are more frequent around solar maximum. They interact with the atmosphere in the 30-60 km range but occasionally reach down below 20 km. However, they are useful for studying the effects of energetic particles on atmospheric chemistry because they have essentially instantaneous rise times with very large proton flux increases. Lightning is also a potentially important source of NO and is also possibly correlated with GCRs. Ice core data shows that SEP generated nitrates can reach the ground/low atmosphere in large quantities.

So, some 40+ years after Ney's original paper [1], what progress (if any?) have we made in investigating the role that cosmic rays (or the resultant atmospheric ionisation) might be having on climate and/or meteorology? Certainly, the correlation reported by Svensmark & Friis-Christensen [17] between global cloud cover and galactic cosmic rays gave renewed vigour to the solar-activity–climate debate. If the link is correct it actually goes in the opposite sense to Ney's original suggestion (figure 1). The exact details of the observational link between cloud cover and cosmic rays was refined when better cloud data became available (Marsh & Svensmark [18]). This showed a very striking correlation between low clouds and cosmic rays and in particular for low cloud top temperature which on the global correlation maps shows a clear and strong positive correlation for clouds in the Tropics. This latter links (i.e. low clouds and Tropics) then suggests a possible link with lightning which was shown above to also have an association with the Tropics and to be the only NO_x process to operate below 5 km. Therefore, I would like to conclude this overview with my own updated "Ney Diagrammatic Scenario" (figure 6). Once again, like Ney [1], I would like to stress that this is only my suggested series of links and more

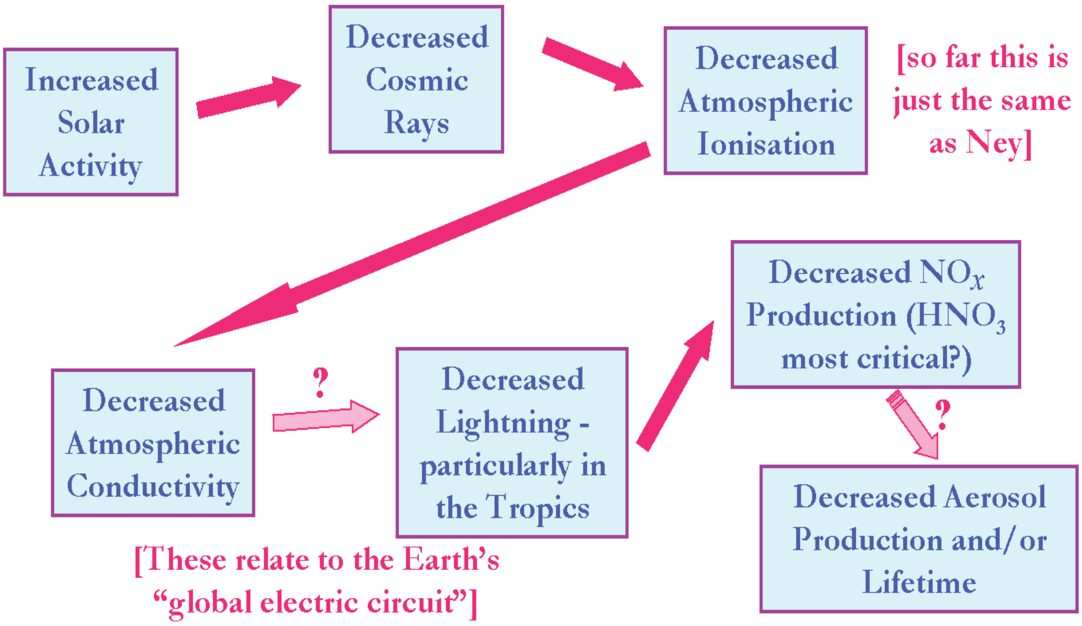

Fig. 6: A revised Ney "diagrammatic scenario" showing a series of possible links between solar activity and cloud microphysics, based on some of the results and suggestions presented in this paper. The link between atmospheric conductivity and lightning needs some further testing and the final link between NO_x species (and HNO_3 in particular) and cloud processes is testable in the proposed CERN/CLOUD experimental facility.

observations and experiments are needed to elucidate the various possible links in the chain of events shown. In particular, the actual demonstration of a total lightning frequency modulation with GCRs is lacking (primarily because of the lack of a good long term monitoring network/system for *global* lightning statistics) and the link between NO_x chemistry (perhaps through the action of nitric acid [HNO_3]?) and cloud microphysics is also speculative. However, this last link is certainly easily testable in the proposed CERN/CLOUD experimental facility.

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