A review of the relevance of the ‘CLOUD’ results and other recent observations to the possible effect of cosmic rays on the terrestrial climate.

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Abstract

The problem of the contribution of cosmic rays to climate change is a continuing one and one of importance. In principle, at least, the recent results from the CLOUD project at CERN provide information about the role of ionizing particles in ‘sensitizing’ atmospheric aerosols which might, later, give rise to cloud droplets. Our analysis shows that, although important in cloud physics the results do not lead to the conclusion that cosmic rays affect atmospheric clouds significantly, at
least if $H_2SO_4$ is the dominant source of aerosols in the atmosphere. An analysis
of the very recent studies of stratospheric aerosol changes following a giant Solar
Energetic Particles event shows a similar negligible effect. Recent measurements
of the cosmic ray intensity show that a former decrease with time has been re-
versed. Thus, even if cosmic rays enhanced cloud production, there would be a
small Global Cooling, not Warming.

1 Introduction

There is, by now, a wealth of literature on the relevance of cosmic rays (CR) to climate
change. Examples favouring a significant effect are: Svensmark and Friis-Christensen
(1997), Palle Bago and Butler (2000) and Svensmark (2007). Those against include
Sloan and Wolfendale (2008) and Erlykin et al. (2009 a,b). The essence of the claim is
that CR ions cause the nucleation of aerosols from trace condensable vapours, leading,
via the growth of the aerosols, to cloud condensation nucleus (CCN) status and thereby
to the water droplet stage. A separate aspect concerns the time variability of the
CR intensity: recent work by 'CLOUD' (Kirkby et al., 2011) relating to laboratory
experiments on the initial stages of cloud condensation nuclei (CCN) have relevance
to the claim and stratospheric nuclei (Mironova et al., 2012) caused by CR in the
stratosphere are potentially important. Both studies will be examined here.

In CLOUD, the nuclei are studied in a large ‘chamber’ and ionizing particles come
from an accelerator under carefully controlled conditions. Sulfuric acid vapour is studied
in detail in that this is considered by Kirkby et al to be ‘the primary vapour responsible
for atmospheric nucleation’.

2 Aerosols

The mechanism by which cloud droplets form is one of some complexity and firstly we examine the process. Following Carslaw et al. (2002) the following stages can be identified.

1. For H₂O and H₂SO₄ vapours there can be condensation (and evaporation) leading to cluster nucleation, (ultra-fine condensation nuclei, UCN), the result being ’subcritical embryos’ of <1-2 nm diameter.

2. Condensation can occur yielding condensation nuclei (CN) - ’critical embryos’ of diameter ∼1-2 nm.

3. Condensation and coagulation can then yield charged condensation nuclei of diameter ∼100 nm.

4. Activation follows and cloud droplets (CD), of diameter 10-20 µm, may then appear. It will be apparent that different experiments will be responsive to different steps in the above: UCN, CN, CCN and CD. It is also clear that many (often the majority) of the UCN will not survive to CD.

In the CLOUD experiment, we assume that we are dealing largely with UCN and CN.

The stratospheric results relate to CCN, aerosols which are recognised by their extinction at wavelengths of 756 nm (satellite studies), and by other wavelengths (eg in some cases at 360 nm).
It is usually assumed (eg Kirkby et al, 2011) that sulfuric acid and ammonia are most relevant in the atmosphere and their effects have been examined in the CLOUD experiment, to be described next.

3 CLOUD.

The main results from CLOUD, of relevance here, are:

(i) ‘Atmospherically relevant ammonia’ mixing ratios of 100 parts per trillion by volume increase the nucleation rate of sulphuric acid particles more than 100-1000-fold. Of main importance to the present work, ions increase the nucleation rate by a factor of between 2 and 10 for ground level Galactic CR intensities.

(ii) The ion-induced nucleation can occur in the mid-troposphere but is negligible in the ‘boundary layer’, i.e. below about 3km altitude. (a fact remarked on by the CLOUD authors).

Specifically, using the temperature dependence of the nucleation rate, CR - will only be relevant for Polar altitudes above about 4 km and Equatorial altitudes above about 8 km, using the universally available temperature, altitude, latitude data. Thus, the boundary layer will be unaffected by CR-induced aerosols, at least for those involved in the CLOUD project, which are thought to be the ones of major importance (an assumption that needs further analysis).

(iii) There is a dramatic increase in nucleation rate with falling temperature (typically a factor $10^4$ in going from 292°K to 248°K), a result due to the change of saturation
4 Discussion of the CLOUD Aerosol Results.

4.1 General Remarks.

Although aerosols are without doubt involved in the generation of CCN, their very uneven distribution across the Globe, for example, NOAA aerosol maps, (NOAA, 2012), in comparison with cloud cover, means that their effect is not straightforward. Their altitude dependence is a matter of importance and this will be examined. Early work by Elterman (1968) showed a slow fall in aerosol density with increasing height: at low altitudes the mean attenuation coefficient was found to be about $3 \cdot 10^{-2} km^{-1}$. More recently Hervig and Deshler (2002) have analysed comprehensive satellite- and balloon-borne data from the standpoint of the altitude variation of aerosols in 4 size ranges, from 386-1020 nm. The data relate to profiles over Laramie, Wyoming for 1984 to 1999. It is found that the density of aerosols is about constant with height from 12 km (their lowest value) to 20 km, after which it falls by a factor of 100 at 30 km. The relevance of this result will become clear later.

Of interest to Cloud Cover is the reported slow increase of atmospheric aerosol density with time (4% - 8% y$^{-1}$ in the mid-latitude lower stratosphere, eg Liu et al., 2012).
4.2 Temperature dependence of nucleation.

In the lower troposphere (the ‘boundary layer’) the temperature is too high for nucleation to have any relevance to the CR, CC problem as already remarked. Since this is the region (LCC: ‘low cloud cover’) where Svensmark and Friis-Christensen (1997) and others (eg Palle Bago and Butler, 2000), found the only evidence for CC,CR correlation then there is clearly no support for the CR, CC hypothesis. In the upper troposphere, where the temperature is lower - typically, at 7.5km, the mean height of the high cloud cover (HCC) band, with $<T> \simeq 235K$, the nucleation rate will be very high (from the CLOUD results) and a big CR, CC correlation would be expected. However, analyses such as our own, Erlykin et al. (2009a) shows no correlation at all for the HCC; this is despite the magnitude of the CR intensity (and its variation) being higher there, as well as the nucleation rate being predicted to be so high.

The dramatic temperature dependance of the nucleation rate would have other detectable effects on the measured CR, CC correlation even if present at altitudes where the temperatures are low enough for the predicted nucleation to be significant. Thus, there would be a strong latitude dependence due to the mean atmospheric temperature being a function of latitude; for example, at an altitude of 6km, $<T> \sim 263^\circ K$ at the Equator, $243^\circ K$ at latitude $45^\circ$ and $220^\circ K$ at latitude $80^\circ$. Taken at face value the CLOUD results would indicate an increase in nucleation rate of about 3 orders of magnitude in going from the Equator to a latitude of $80^\circ$. Even allowing for various reductions due to ‘sinks’ (Kirkby, 2012, private communication) a big change should surely follow.
A search for the latitude dependence of the CR, LCC correlation, or the related dependence on the CR vertical rigidity cut-off (VRCO), gave negative results (Sloan and Wolfendale, 2008) and, indeed, this was one of the first demonstrations of the lack of a genuine CR, (L)CC correlation. A latitude dependence of the correlation was not detected at any altitude, in fact. Thus, the expected big change with latitude for $H_2SO_4$ nucleation anywhere is not observed.

5 Aerosols in the Stratosphere

5.1 Ozone losses

If CR are going to have an atmospheric effect anywhere it is surely in the stratosphere, where the CR intensities are so much higher than at ground level. This is particularly so for Solar Energetic Particles, 'SEP', events, where many of the protons (and heavier nuclei) lose all their energy in the stratosphere.

The influence of SEP on the ozone layer has been a topical subject for some years. Jackman et al. (1999) and others studied the effect of large SEP for the period 1965 to 1995 with positive results. They showed that the very large events of August 1972 and October 1989 caused large increases in long-lived NO$_x$ constituents and that they caused direct ozone losses. Complications included differences between the seasons for impacts on polar ozone.

Relevant work has been reported by Lu (2009). This worker claimed a correlation between CR and the polar ozone loss (hole) over Antarctica for the period 1980 - 2007 and predicted a severe loss in 2008-9. In fact, this loss was not observed.
Our own analysis of yearly sunspot numbers and the area of the Antarctic ozone hole (the data coming from the NOAA, National Weather Service, 2012) shows no correlation between them for the period for which there is accurate data: 1992 - 2011. Specifically, the correlation coefficient is 0.022, with a chance probability of a random association of 0.925. However, the above does not mean that there is no ozone-effect at all; for example, Seppala et al. (2009) claim that large SEP events cause changes in polar surface temperatures. There is, though, the standard problem of distinguishing between CR- and Solar Intensity-induced effects; Lockwood (2012) makes the case for the latter.

5.2 Stratospheric aerosols.

Of greater relevance in the present work is the effects of SEPs on aerosols in the stratosphere. Here, the work of Mironova et al. (2012) is important.

These workers concentrated on the effect on polar stratospheric aerosols of the extreme SEP event of 20 January 2005. They found evidence for the production of a 3-day 'burst' of new particles and for the growth of pre-existing ultra-fine particles in the height range 10-20 km. Presumably these aerosols are in the size region exceeding 100 nm by their diameter. The evidence was only for limited longitude ranges (mainly in the N hemisphere, for the latitude studied, which was 66°-73°N). Our remarks on this interesting result are as follows.

(1) The Polar Stratospheric Clouds (PSC), which may manifest the presence of new aerosols, only occur when the ambient temperature is low enough (less than
about 200°K).

(2) Inspection of other data (e.g., Mironova, 2011) shows that the frequency of temperatures low enough to allow PSC formation (by whatever mechanism) has a dramatic time variation. Specifically, the PSC at Sodankyla, (67°N, 27°E) only occurred in January and February, and occasionally in March. From 1965 to 2005 the January temperature was low enough for PSC for a percentage of the time varying from zero to 64%. The value for January 2005 was 40% and that for February 2005, the highest recorded in the 40-year period in question, was 80%.

The search for an 11-year correlation of PSC is bedevilled by the concentration of PSC in the winter months, but for the 4 solar cycles reported by Mironova (2011) there is no evidence at all of higher rates for higher CR intensities and the equivalent for low CR intensities. PSC therefore require very special thermal condition.

As an upper limit for the generation of (new) clouds in the stratosphere we note that the actual percentages of the fraction of the 40-year period when such clouds can occur are 15% for any cloud at all and 1% for PSC to form with a 50% probability.

(3) The chance probability of an increase in stratospheric extinction (quickly) following a CR event (SEP) cannot yet be evaluated; only one such coincidence has been detected. Even this event was complicated; the apparent SEP-initiated ‘burst’ of aerosols was followed by (it is thought, unassociated) new clouds; there was a burst of PSC some 5 days after the onset of the SEP. This burst of PSC
was associated with a big reduction in temperature ( a fall of 15°C ) which was presumably of 'natural causes' - the influx of very cold air.

(4) Comparison of the mean longitudinal profile of the extinction coefficient for the 2005 event with those available for November 1978 to January 2009 ( McCormick et al., 1982 ) - another period of very low atmospheric temperature - is relevant. Surprisingly, the 2005 event did not show a greater extinction magnitude at the greatest altitudes, such as would have been expected for CR-initiation, the CR intensity increasing with altitude for the SEP event, but the aerosol density being constant ( see §4.1 ).

The implication of the forgoing is that even if the SEP event genuinely initiated a burst of aerosols, and that this burst could cause new clouds, then averaged over time ( see (2) above ) the effect of the stratospheric clouds will be very small and tropospheric implications largely absent. Thus, there is no evidence that SEP have a significant tropospheric climate effect, at least by way of CR ionization in the stratosphere.

6 CR, Climate correlations in the lower atmosphere.

That there might actually be a small, but spatially variable, effect of CR on Climate was shown by Voiculescu et al. (2006) who found evidence for a small CR, CC correlation for limited regions of the Globe from an analysis in which a distinction was made between CC changes initiated by solar UV and by CR. It was found that some 20% - 30% of the Earth’s surface showed a negative correlation for the low cloud cover (LCC) and positive for the middle cloud cover (MCC). There is a complication, however, in that
Erlykin et al. (2009b) claimed that both were due to convective flows of atmospheric air arising from changes in the solar irradiance and not due to CR at all.

It is relevant to point out that case for regional differences in climate change and correlations has been summarised by Lockwood (2012). This work related to solar-induced changes. Marked differences were found across the Globe but the integrated effect was much less than the change due to anthropogenic sources.

Small effects of CR-induced droplet charging on cloud formation have been reported by Harrison and Ambaum (2008).

7 The Cosmic Ray Intensity.

The early claims for a CR, CC correlation and its relevance to Global Warming relied on the CR intensity having fallen since records began: CR cause clouds and reduced clouds cause the warming. However, as we have shown elsewhere (Sloan and Wolfendale, 2011) the rate of CR fall was becoming smaller as the mean Global temperature was increasing rather rapidly. Furthermore, the neutron monitor (NM) data shows that the (smoothed) CR intensity ‘bottomed out’ in the 1980s and has since increased.

We have examined neutron monitor records of the ground level CR intensity from Oulu, Moscow and Jungfraujoch (references given under names). The values of the vertical rigidity cut-off ($VRCO$) are, respectively, 0.8, 2.3 and 4.5 GV. These values, particularly that for the Jungfraujoch can be regarded as representative for the Globe; this follows from the fact that for the region occupied largely by the Low Cloud Cover, $\langle VRCO \rangle \approx 4.5$ GV. Furthermore, for the region (mainly Europe) where Voiculescu et
al. (2006) find evidence for a finite CR,LCC correlation, again $\langle VRCO \rangle \simeq 4.5$ GV.

Figure 1 shows the time-series of the 3 sets of CR intensities. 4-degree polynomial fits have been made to each Solar Cycle, as shown. In order to examine the change of CR intensity with time, in the presence of the 11-year Solar Cycle ( or, more accurately, the rate of rise ) we examine the CR intensities ( NM rates ) at the same point on each Solar Cycle, specifically, the maximum and the minimum. It is apparent that each of the 7 datum years the data are reasonably consistent and no $VRCO$-dependence is apparent.

Further inspection shows that the rates of increase of the maximum NM rates are increasing linearly for the whole period. Those for the minima have fallen slightly before increasing rapidly. Figure 1 (upper panel) shows that the peak NM rates ( CR intensity ) have been increasing since about 1990 and the lower panel gives some evidence that there has been a steady upward change of the rate of increase of the maximum intensity and an irregular, but latterly high rate of increase of the CR intensity minima. Taken overall, from 1970 onwards, the rate of increase has been $2.6 \pm 0.6\%$ per decade ( a correlation coefficient of 0.69 and chance probability 0.087 ).

The interpretation is interesting in its own right but mainly beyond the scope of the present work. Suffice it to say that there is a wealth of evidence pointing to important changes in solar properties in the period 1980 - 1990. Thus, there was a rise before, and rapid fall after in the Solar magnetic moment ( eg Obridko and Shelting, 2009 ). Karam (2003) summarised the somewhat earlier data for solar ion flux, flow speed and ion density ( all at 1AU ) and found the same result: an increase until the 1980s and a fall thereafter.
Finally, in this area, it should be pointed out that the increase in CR ionization in the atmosphere above ground level is higher. Using the data of Bazilevskaya et al. (2008), from the CR peak in 1987 to that in 1997 the increase for Mirny (0.1 GV) is 14±4% for 8.2km altitude and 18±4% for 5 km altitude. For the next cycle, (1997 to 2009) the values are 21±5% for 8.2km and 29±6% for 5km. For Murmansk (cut-off rigidity 0.5 GV) the corresponding values are 2±1% and 11±3% for 8.2km altitude and 5±2% and 13±3% for 5km. The increases for the CR minima, from 1990 to 2002, are 25±5% (8.2km) and 19±4% (5km) for Mirny and 14±3% (8.2km) and 11±3% (5km) for Murmansk.

There is no doubt that the CR intensity has been increasing significantly since the 1980s.

That an increase is not unreasonable can be seen from studies of past sunspot records, the CR intensity being modulated by solar phenomena related strongly to sunspots. Inspection of past sunspot records back to the commencement of telescopic observations in the early 1600s shows slow upward (and downward) movements of the smoothed SSN. Thus, slow changes in the (strongly correlated) CR intensity would occur. Although prediction of the future trend in the CR intensity is hazardous, inspection of the sunspot data shows that after a peak the next higher SSN (ie lower CR intensity) can be 30-100 years away. Thus, it would not be surprising if the present rise in the smoothed CR intensity continued for several decades to come.
Discussion and Conclusions.

It is clear that the new results from CLOUD relating to aerosols indicate that although there could be a CR, Climate correlation by way of nucleation of aerosols, in the lower troposphere it should be very small indeed (a consequence of the ‘high’ temperatures there). All pervading in the aerosol arguments, however, is the uncertain removal mechanisms which interpose themselves between the ultrafine condensation nuclei and embryos, all less than about 2nm in diameter (UCN,CN) and the condensation nuclei of 100nm and beyond (CCN,CD) stages (see §1). In this context, Pierce and Adams (2009) quote loss factor (for CN to CCN) between 10 and 20 in the best case. New CLOUD studies are relating to the effect of aerosols other than those of $H_2SO_4$ and ammonia which may be important in the atmosphere.

The fact that the CR intensity is rising again strongly militates further against a CR/Global Warming connection (in the absence of unphysically long phase lags).

There are other arguments against a CR/Climate correlation, not referred to above. These include a lack of atmospheric changes following nuclear explosions, nuclear accidents and natural radon variations (Erlykin et al., 2009a) and the non-observation of correlations for the type of cloud that should be responsive (if anything is) to CR ionization changes (Erlykin et al., 2009c).

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References

Arnold F (2008) Atmospheric ions and aerosol formation. Space Sci. Rev. 137, 225-239

Bazilevskaya GA, Usoskin IG, Flückiger EO et al. (2008) Cosmic ray induced ion production in the atmosphere. Space Sci. Rev. 137, 149-173

Carslaw KS, Harrison RG, Kirkby J. (2002) Cosmic rays, clouds and climate. Science 298, 1732-1737

Elterman L, 1968, Air Force Cambridge Labs., AFCRL, 68-0153

Erlykin AD, Gyalai G, Kudela K et al. (2009a) Some aspects of ionization and cloud cover, cosmic ray correlation problem. J.Atmos. and Solar-Terr. Phys. 71, 823-829

Erlykin AD, Gyalai G, Kudela K et al. (2009b) On the correlation between cosmic ray intensity and cloud cover. J.Atmos. and Solar-Terr. Phys. 71, 1794-1806

Erlykin AD, Sloan T, Wolfendale AW (2009c) The search for cosmic ray effects on clouds. J.Atmos. and Solar-Terr. Phys. 71, 955-958

Harrison RG, Ambaum MHP (2008), Enhancement of cloud formation by droplet charging. Proc. Roy. Soc. A, 464, 2561-2573

Hervig M, Deshler T (2002) Evaluation of aerosol measurements from SAGE II, HALOE and balloonborne optical particle counters. J. Geophys. Res. 107, 4031-4042

Jackman CH, Fleming EL, Vitt FM, Considine DB (1999) The influence of solar proton events on the ozone layer. Adv. Space Res. 24, 625-630

Jungfraujoch (2012): [http://www.nmdb.eu/nest/search.php](http://www.nmdb.eu/nest/search.php)
Karam PA (2003) *Inconstant Sun: how solar evolution has affected cosmic and ultraviolet radiation exposure over the history of life on Earth.* Health Physics 84, 322-333

Kirkby J, Curtius J, Almeida J et al. (2011) *Role of sulfuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation.* Nature 476, 429-433

Liu Y, Zhao X, Li W, Zhou X (2012) *Background stratospheric aerosol variations deduced from satellite observations.* J. Appl. Meteor. Climatol. 51, 799-812

Lockwood M. (2012) *Solar influence on global and regional climates.* Surveys in Geophys. 33, 503-534

Lu Q-B. (2009) *Correlation between cosmic rays and ozone depletion.* Phys. Rev. Lett. 102, 118501(4pp)

McCormick MP, Steele HM, Hamill P et al. (1982), *Polar stratospheric cloud sightings by SAM II.* J. Atmos. Sci. 39, 1387-1397

Mironova IA (2011), COST Action ES1005

Mironova IA, Usoskin IG, Kovaltsov GA, Petelina SV (2012), *Possible effect of extreme solar energetic particle event of 20 January 2005 on polar stratospheric aerosols: direct observational evidence.* Atmos. Chem. Phys. 12, 769-778

Moscow (2012): [http://helios.izmiran.rssi.ru/cosray/main.htm](http://helios.izmiran.rssi.ru/cosray/main.htm)

NOAA National Weather Service (2012) Climate Prediction Centre - aerosol optical thickness: [http://www.nws.noaa.gov](http://www.nws.noaa.gov)

Obridko VN, Shelting BD (2009) *Anomalies in evolution of global and large-scale solar magnetic fields as the precursor of several upcoming low solar cycles.* Astron. Lett. 35, 247-252

Oulu (2012): [http://cr0.izmiran.rssi.ru/oulu/main.htm](http://cr0.izmiran.rssi.ru/oulu/main.htm)
Palle Bago E, Butler CJ (2000) *The influence of cosmic rays on terrestrial clouds and global warming*. Astron. Geophys. 41, 4.18-4.22

Pierce JR, Adams PJ (2009) *Uncertainty in global CCN concentrations from uncertain aerosol nucleation and primary emission rates*. Atmos. Chem. Phys. 9, 1339-1356

Seppälä A, Randall CE, Clilverd MA et al. (2009) *Geomagnetic activity and polar surface air temperature variability*. J. Geophys. Res. 114, A10312(10pp)

Sloan T, Wolfendale AW (2008) *Testing the proposed causal link between cosmic rays and cloud cover*. Env. Res. Lett. 3, 024001(6pp)

Sloan T, Wolfendale AW (2011) *The contribution of cosmic rays to global warming*. J. Atmos. Solar-Terr. Phys. 73, 2352-2355

Svensmark H, Friis-Christensen E (1997) *Variation of cosmic ray flux and global cloud coverage - a missing link in solar-climate relationship*. J. Atmos. Sol. Terr. Phys. 59, 1225-1232

Svensmark H (2007) *Cosmoclimatology: a new theory emerges*. News and Rev. in Astron. Geophys. 48, 1.18-1.24

Voiculescu M, Usoskin IG, Mursula K (2006) *Different response of clouds to solar input*. Geophys. Res. Lett., 33, L21802(5pp)
Figure 1: The counting rate of Jungfraujoch (Jungfraujoch, 2012), Moscow (Moscow, 2012) and Oulu (Oulu, 2012) Neutron Monitors (upper panel), and the different rates of increase of the NM counts from peak to peak (open symbols) and minimum to minimum (filled symbols) (lower panel). Smooth full lines in the upper panel are 4-degree polynomial fits. The extent to which the smoothed CR intensity has been increasing for the last 20 years can be seen in the lower panel. The increase is marked; that for the higher, important, atmospheric levels, is higher (see text).