Apparent difficulties with a CMAS cosmic ray–weather/climate link

Jake Hebert

In recent years there has been considerable interest in theories that cosmic rays could influence weather and climate. The best-publicized mechanism for such a link is Henrik Svenmsark's theory of 'ion-mediated nucleation' (IMN). A second, less well-known mechanism, called 'charge modulation of aerosol scavenging' (CMAS), involves the downward fair-weather electric current density J_z. Although factors that influence J_z have been shown to be correlated with a number of meteorological variables, there are a number of apparent difficulties with the CMAS mechanism, and these apparent weaknesses are now discussed.

As noted previously,[1] there is a subtle connection between the creation-evolution issue and anxiety over 'global warming' or 'climate change'. Thus a biblical worldview helps to guard against alarmism in this area.

Another reason for taking a judicious approach toward this issue are 'gaps' in our understanding of meteorology: There is a very real possibility that current meteorological and climatological models are not taking into account all the relevant physics. In particular, there is a possibility that cosmic rays could be influencing weather and climate.

Currently, there are two major proposed theoretical mechanisms linking cosmic rays to weather and climate.[2] Both mechanisms involve the fact that increased cosmic ray (mainly proton) fluxes into the atmosphere will increase the number of atmospheric ions. The first mechanism is called *ion-mediated nucleation* (IMN) and has been researched by Danish physicist Henrik Svensmark. The second mechanism, *charge modulation of aerosol scavenging* (CMAS) has been researched by Brian Tinsley of the University of Texas at Dallas. Both theories were discussed in a previous paper, which noted difficulties with the IMN mechanism.[1] This paper now focuses on apparent difficulties with the CMAS mechanism.

Summary of the CMAS mechanism

Before discussing these apparent difficulties, a brief review of the CMAS mechanism is in order. The ionosphere and surface of the earth may be thought of as conducting 'plates' of a spherically symmetric capacitor (figure 1). However, because the thickness of the earth's atmosphere is very small compared to the earth's radius, one may simplify calculations by treating the ionosphere and surface of the earth as plates of a parallel capacitor, between which are 'sandwiched' the troposphere and stratosphere. Because the atmosphere is a weakly conducting medium, the potential difference between the ionosphere and surface of the earth drives a downward fair-weather 'return' current. Ohm's Law gives a relationship between the downward fair-weather ionosphere-to-surface current density, J_z, the global ionospheric potential, V_i, and the columnar resistance, R. V_i is the spatially uniform potential of the ionosphere relative to the earth's surface,[3] typically around 200–300 kV. The columnar resistance, R, is the electrical resistance of a column of air (with a base of 1 square metre) between the earth's surface and the base of the ionosphere. R is composed of two resistors in series, the columnar resistance, T, of the troposphere and the columnar resistance, S, of the stratosphere (figure 2). J_z is very tiny, typically about 1–6 trillionths of an ampere per square metre (pico-amperes per square metre, or pA/m²). Ohm's Law indicates that

$$J_z = \frac{V_i}{R} = \frac{V_i}{T+S} \quad . \tag{1}$$

Generally, the stratospheric columnar resistance, S, is negligible compared to the tropospheric columnar resistance, T (except during times of increased stratospheric aerosol loading, to be discussed later). Hence, eq. 1 usually simplifies to

$$J_z \approx \frac{V_i}{T} \quad . \tag{2}$$

Thus, changes in V_i or T will affect J_z. Eq. 2 provides a possible link between cosmic rays and J_z. *Increasing* cosmic rays into the troposphere will *increase* the numbers of tropospheric ions, resulting in a *decrease* in T (much in the same way that the ions present in salty water cause it to have a lower electrical resistance than deionized water). For a given ionospheric potential V_i, this will result in *higher* values of J_z. Likewise, a decrease in the flux of cosmic rays into the troposphere will result in higher values of T, which, for a given value of V_i, will result in lower values of J_z.

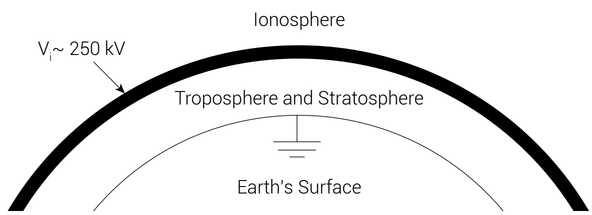

Figure 1. Simplified diagram showing how the ionosphere and surface of the earth may be viewed as conducting plates of a 'leaky' spherically symmetric capacitor.

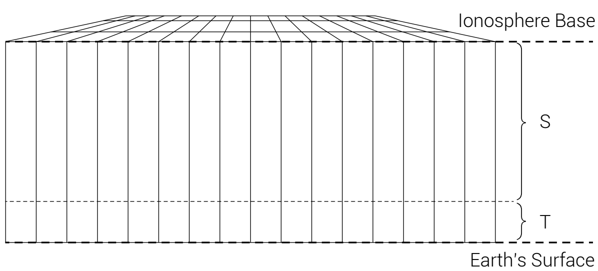

Figure 2. Because the thickness of the atmosphere is negligible compared to the earth's radius, one may simplify calculations by modelling the ionosphere and surface of the earth as conducting plates of a parallel capacitor, between which are 'sandwiched' the troposphere and stratosphere. The lower atmosphere is composed of many columnar resistances in parallel with each other, each of which is composed of a tropospheric columnar resistance in series with a stratospheric columnar resistance. (After figure 1.2 in Hebert[4]).

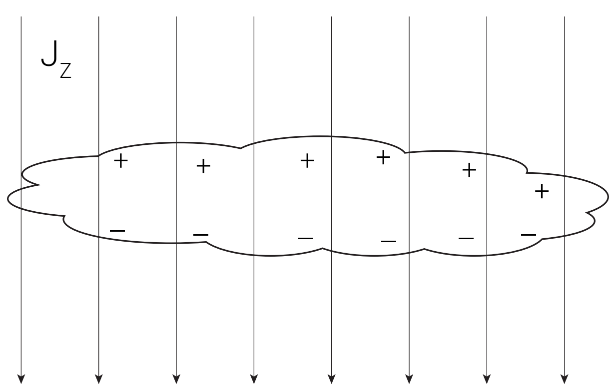

Figure 3. Charge will be present at locations where J_z passes through gradients in conductivity (or resistivity), such as are present at cloud boundaries. This charge will become attached to cloud droplets and aerosols, modulating the rates at which aerosols are scavenged by the droplets. Since some of these aerosols may act as cloud-condensation or ice-forming nuclei, this 'charge modulation of aerosol scavenging' (CMAS) can conceivably affect precipitation and cloud lifetimes.

Because clouds are much less electrically conducting than the surrounding air,[5] conductivity gradients will exist at the tops and bottoms of clouds. One may use Ohm's and Gauss' Laws to show that J_z will result in the presence of electric charge at these cloud boundaries (figure 3):

$$\rho(z) = \left[\frac{\varepsilon_O}{\sigma^2}\frac{\partial\sigma}{\partial z}\right]J_z \quad . \qquad (3)$$

Eq. 3 shows that changes in J_z should alter the amount of charge attached to both water droplets and aerosols within clouds. This charge will be negative at a cloud base and positive at a cloud top. Hence, both water droplets and aerosols at the cloud base will tend to be negatively charged, and water droplets and aerosols at cloud tops will tend to be positively charged. These aerosols include both cloud condensation nuclei (CCNs) and ice-forming nuclei (IFNs).

Computer simulations have shown that, for aerosols and droplets of the same sign, the CMAS effect tends to increase the rates at which large aerosols (radius >~ 0.1 μm) are scavenged by cloud droplets, while simultaneously reducing the rates at which smaller aerosols are scavenged.[6] This tends to favour droplets of smaller average size via Kelvin's 'curvature effect',[7] leading to a reduction in precipitation and increase in cloud lifetime.[8]

Apparently conflicting observations

However, there are a number of apparent difficulties with the CMAS mechanism. Although I am personally convinced that Tinsley's CMAS mechanism is a much more convincing link between cosmic rays and weather/climate than Svensmark's IMN mechanism, candor requires a discussion of such difficulties (full disclosure: Tinsley was my Ph.D. advisor at the University of Texas at Dallas, and it should be noted that he does not share the editorial views of this journal).

First, there are a handful of observations which seem to contradict the theory. One such observation involves what is known as a *heliocentric current sheet crossing* (or *magnetic sector boundary crossing*). A brief digression is necessary in order to present the background information needed to understand this apparent contradiction with the theory.

The *solar wind* plasma consists of a stream of positively and negatively charged particles, with typical speed of between 200 and 800 km/sec. It is a well-known result (first proposed by Hannes Alfvfén) that magnetic field lines within a highly conducting medium, such as a plasma, will be 'frozen' within the plasma.[9] This means that it is nearly impossible for the field lines to move relative to such a highly conducting medium.

The *interplanetary magnetic field* (IMF) is the name given to the solar magnetic field that is carried along by the solar wind into interplanetary space. The fact that the sun's magnetic field lines are 'frozen' within the solar wind plasma helps to provide an explanation for the fact that the IMF has a 'spiral' shape. The sun's rotation and the 'freezing in' of the field lines within the solar wind cause the field lines of the IMF to take on a spiral pattern (figure 4a[10]). Because these curved field lines resemble the pattern assumed by the jet of water from a rotating garden hose, this is often referred to as the 'garden hose effect'.

As one moves away from the sun, the outward field lines in one solar hemisphere become anti-parallel to the inward field lines in the other hemisphere. By the basic rules of electromagnetic theory,[11] this implies the existence of a sheet of current called the *heliocentric current sheet* (HCS), which separates the field lines from the two solar hemispheres. Because the sun's rotation axis does not align exactly with the solar magnetic dipole, the HCS will be tilted relative to the plane of the earth's orbit around the sun. The resulting two-sector structure of the IMF implies that the radial component of the IMF will sometimes be inward and sometimes outward at the location of the earth's orbit. This magnetic sector structure can be more complicated, consisting of more than two (often four) sectors (figure 4b), and this is thought to result from more complicated solar fields resulting possibly from solar plasma ejections. The heliocentric current sheet at such times is thought to be characterized by wavy undulations, not unlike the undulations in a spinning ballerina's skirt (figure 5[12]).[13]

As noted earlier, a time at which the earth passes through the heliocentric current sheet is called a heliospheric current sheet (HCS) or magnetic sector boundary crossing. With this background in mind, we may now discuss this observation that seems to contradict the CMAS theory.

Many charged particles, including energetic electrons, become trapped along the earth's magnetic field lines, bouncing back and forth between two so-called 'mirror points' in opposite magnetic hemispheres on a given field line.[14,15] However, perturbations (such as those resulting from electromagnetic waves) can cause these electrons to 'precipitate' into the earth's atmosphere.[16] Decreases in the number of such electrons precipitating into the stratosphere have been observed during magnetic sector boundary crossings.[17]

Since the stratospheric columnar resistance, S, is generally negligible to the tropospheric columnar resistance, T, in eq. 1, this would not normally have a noticeable effect on J_z. However, S becomes comparable to T after explosive volcanic eruptions due to the resulting large amounts of stratospheric aerosols.[18] At such times, decreases in electrons entering the stratosphere will increase S, resulting in smaller values of J_z via eq. (1).

Analysis of the International Satellite Cloud Climatology Project's (ISCCP's) D1 data series shows that decreases in high-latitude cloud cover occur about 24

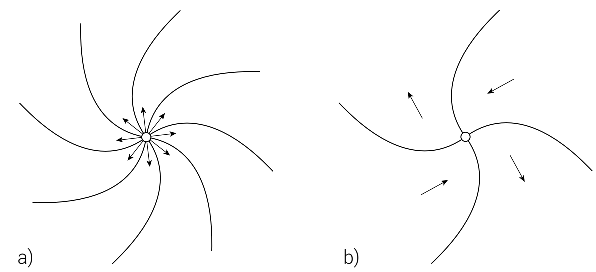

Figure 4. a) The radially outward motion of the solar wind (indicated by arrows), the sun's rotation, and the 'freezing in' of magnetic field lines within the solar wind plasma result in a 'spiral' pattern for the interplanetary magnetic field (IMF) within the solar equatorial plane (after Holzer[10]). **b)** Fairly typical 4-sector structure for the IMF. Arrows indicate regions of inward and outward radial IMF components.

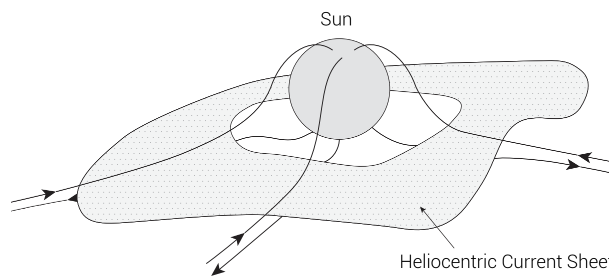

Figure 5. Simplified drawing depicting the 'ballerina' model of the heliocentric current sheet (the 'spiral' pattern of the field lines resulting from the 'garden hose' effect is not evident in this drawing) (after Smith[12]).

hours after magnetic sector boundary crossings (provided the crossings occur during periods of high stratospheric aerosol content).[19] This observation is consistent with the theory, since we generally expect smaller values of J_z to result in *less* cloud cover. Because smaller values of J_z result in less charge on aerosols and cloud droplets, the CMAS effect is reduced in strength, and cloud cover is reduced. Moreover, the fact that this is observed *only* during periods of high stratosphere aerosol loading is also consistent with the CMAS hypothesis: changes in S should affect J_z only when S is comparable to T. A 'problem' however, is that these decreases in total *high-latitude* cloud cover are accompanied by observed *increases* in total *low-latitude* cloud cover.[19] This might appear to be a contradiction with the theory: during periods of high stratospheric aerosol loading, why doesn't cloud cover at *all* latitudes decrease after an HCS crossing?

However, it should be remembered that meteorological variables are affected by *local* values of J_z. Because ionization rates and aerosol content vary with location, columnar resistances vary with location, as well. Since eq. 1 shows that values of J_z depend upon both V_i and R, values of J_z *also* vary with location. A decrease in high-latitude J_z *should* be accompanied by a decrease in *high-latitude* cloud cover, but it is possible for such a decrease to be accompanied by a simultaneous *increase* in *low-latitude* cloud cover. For instance, it is possible that the low-latitude thunderstorm 'generators' act as *constant current sources* in that they provide an essentially constant amount of *total* current to the global electric circuit. In that case, a decrease in current to high latitudes *must* be accompanied by an *increase* in current to the low latitudes, since the total current would remain constant. This increased *low-latitude* J_z would be expected to result in more *low-latitude* cloud cover. Hence, even this apparently anomalous observation is not necessarily inconsistent with the theory.

Another apparent anomaly involves an unexpected decrease in atmospheric transparency measured at Leningrad[20] after so-called *Forbush decreases*, short-term decreases in cosmic rays entering the atmosphere,[21] but Tinsley has offered an explanation for this anomaly.[22]

Also, cloud cover over most of the continental United States has been observed to be strongly anti-correlated with GCR flux, which is opposite what one would expect from the CMAS theory.[23] To the best of my knowledge, this is the only genuinely anomalous observation that has yet to be explained within the context of the CMAS theory.

The problem of energy amplification

Another difficulty involves the relatively small variations in energy fluxes of MeV particles into the atmosphere, which are on the order of 10^{-3} ergs/cm^2/sec, or 10^{-10} J/cm^2/sec = 10^{-10} W/cm^2. However, Tinsley notes that a change in the general atmospheric circulation requires a redistribution of energy on the order of 10^{-3} W/cm^2. Hence variations in these cosmic ray energy fluxes must be 'amplified' by a factor of ~10^7.[24] Because of the apparent difficulty of such amplification, this has long been viewed as a weakness of the theory. In fact, a writer in *Physics Today* dismissed the idea of a cosmic ray–weather/climate connection on this very basis, suggesting that the 'mysterious amplification factors' required for such a link made such a connection untenable.[25]

However, Tinsley addressed this objection over 20 years ago: he argued that nucleation processes, such as those occurring when cloud condensation nuclei or ice-forming nuclei are scavenged by cloud droplets, could initiate and contribute a significant portion of the required amplification,[26] citing multiple experimental results which suggested this possibility.[27] Tinsley has used the example[28] of a small lighted match igniting a large amount of dry brush to illustrate the basic idea: although the energy of the flame itself is not very large, the large amounts of chemical potential energy stored in the brush makes possible the 'amplification' of this small amount of energy. In a similar manner, nucleation processes could 'amplify' the relatively small variations in cosmic ray energy fluxes.

Tinsley also suggested that different instabilities, including *baroclinic* instabilities, could play a secondary role in amplifying energy inputs of charged particles into the atmosphere.[29] 'Baroclinicity' refers to fluid flows characterized by constant density surfaces that are inclined to surfaces of constant pressure,[30] and baroclinic instabilities play an important role in extra-tropical cyclone formation.[31] It was noted in a previous paper that variations in cosmic ray fluxes have already been shown to be correlated with the strengths and areal extents of northern hemisphere cyclonic systems.[1]

In spite of the apparent difficulties, Tinsley and Heelis have noted the following arguments in favour of cosmic ray–weather/climate connection.[32] First, the electrical energy that is modulated by solar activity is deposited directly into the troposphere, as evidenced by the cosmic ray-generated tropospheric ions. Second, the variation in cosmic ray flux is a relatively large percentage of the mean value (about 15% over a solar cycle), as opposed to the very small percentage changes in total solar irradiance (~0.1%) and ultraviolet solar irradiance (~3%).[33,34] Finally, this mechanism provides more energy per particle than do proposed mechanisms involving total solar or ultraviolet irradiance (cosmic ray energies are generally in the MeV range, as opposed to the eV-100 eV range for visible and ultraviolet photons). Thus, if variations in solar activity *are* having an effect on weather and climate, cosmic rays (which are modulated by solar activity[35]) are a more likely candidate than variations in total solar or ultraviolet irradiance.

Conclusion

Although there are some apparent difficulties with Tinsley's CMAS mechanism, a number of meteorological variables have already been shown to respond to a number of inputs which influence the fair-weather ionosphere-to-surface current density J_z. These were discussed in a previous paper[1] and include variations in cloud cover, variations in the strengths and areal extent of northern hemisphere cyclonic systems, and high-latitude pressure responses. These responses occur within hours to days of variations in these inputs, consistent with expected times for droplet distributions within clouds to respond to changes in J_z. Furthermore, the signs of these responses (increases or decreases) are consistent with what one would expect if changes in J_z were the *cause* of the responses.

Although these correlations are consistent with predictions of the CMAS mechanism, they are somewhat circumstantial in nature. One might ask: is there any *direct* evidence that J_z is the link connecting cosmic rays to weather and climate? Have variations in J_z *itself* been shown to be correlated with meteorological responses? Analysis of two independent data sets suggests that the answer to this question is *yes*, and that topic is discussed in another paper.[36]

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