SOLAR ACTIVITY, WEATHER AND CLIMATE: THE ELUSIVE CONNECTION

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Capsule

For two centuries people have wondered if solar activity, in the form of sunspots, magnetic storms and aurorae, affects weather and climate. We are now close to an answer.

Abstract

The search for an explanation of correlations of weather and climate with solar activity has uncovered some subtle effects of the varying solar inputs, which include irradiance, energetic particles, electric fields induced by the solar wind, and the modulation of the galactic cosmic ray flux. Relevant phenomena have been identified in stratospheric chemistry and dynamics and in aerosols, atmospheric electricity, and clouds. The effects are small, and appear intermittently in statistical analyses of observations. Correlations and theory permit responses to several solar inputs effective on the decadal timescales, making it difficult to distinguish them observationally. No mechanism for tropospheric decadal change can be considered to be definitely established, but for the day-to-day timescale there is clear observational evidence for clouds responding to solar wind induced current flow (J_Z) in the global electric circuit, due to changes in ionospheric potential, and independently from Forbush decreases of the cosmic ray flux. The responses to J_Z, also correlate separately with ionospheric potential changes due to changes in day-to-day thunderstorm activity. The identified mechanism is for electric charge effects on in-cloud scavenging, and this implies a decadal response, in view of decadal changes in J_z. However, a complete and quantitative model of the inferred electrically-induced changes in cloud microphysics is not yet available. The failures, successes, and controversies of the search illustrate the somewhat chaotic process of scientific discovery.

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Significance statement

The variable solar input is quasi-cyclic and has apparent effects on atmospheric circulation that need to be better understood, in order to clarify the trends in atmospheric circulation due to greenhouse gas increases. Observations and modelling are reviewed for stratospheric temperature and dynamical responses to solar UV and energetic electron inputs, and for tropospheric responses to cloud opacity changes due to the downward current flow in the global electric circuit passing through clouds. The cloud opacity changes are attributed to electric charge effects on cloud microphysics. They have been shown to affect tropospheric pressure and dynamics on the day-to-day timescale, and there is a need to explore their effects on the decadal and longer timescales.

1. History and Mystery

As a student the author was hearing that eruptions on the sun, which produced auroral displays visible from the campus in Christchurch, New Zealand, and radio blackouts which interfered with the evening news coming from the BBC via shortwave radio, also caused changes in the weather. He learned there was an 11-year cycle of the number of spots, which are concentrations of cooler, highly magnetized material, that can be seen on the surface of the sun. The famous astronomer W. Herschel (1801) had shown correlations of the price of wheat on the London stock market with the 11-year sunspot, and he suggested that in the years when there were more sunspots, the sun was 'sick' and dimmer, and the climate more severe, and thus the wheat yields poorer. However, we now know that the sun is brighter (but by less than 1 part per thousand of the total irradiance on the Earth) in years of maximum sunspots than in years of minimum sunspots, so that explanation is one of many in the history of science generally, and of studies of sun-weather-climate relations in particular, of jumping to an incorrect conclusion.

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There have been many subsequent reports of changes in winter weather in the North Atlantic and Western Europe that correlate with the 11-year sunspot cycle. More than 2000 papers in the 19th and 20th centuries (discussed by Hoyt and Schatten 1997) concern observations, frequently with accompanying postulated mechanisms, that show diverse weather and climate correlations with solar activity in a variety of locations. We now know that both the Sun and the Earth's atmospheres are partly periodic but non-stationary, and partly chaotic systems, with solar energy flowing from the sun's interior to its surface as convecting magnetized plasma, heating the solar corona to millions of degrees Kelvin. The hot magnetized plasma surges out, in a spiral pattern due to the sun's rotation, as from a flame thrower, and its magnetic field is stretched out into sectors of alternating magnetic polarity that make repeated passes over the Earth every 27 days, as the sun rotates (Ness and Wilcox, 1965). The solar wind input is strongly coupled to the outermost Earth's atmosphere and magnetic field, causing energetic particle precipitation; polar aurorae; variations in ionospheric potential at high magnetic latitudes; and magnetic storms (in spite of Lord Kelvin's claim that such a connection was impossible).

2. The NAO and solar activity

In the late 1980s, as we learned more about the upper atmosphere and space environment and the effects of solar activity on them, many more papers and conferences and new books were coming out on possible 'Sun-Earth' connections. Eddy (1976) drew attention to the lack of sunspots and an increase in carbon 14 in tree rings in the late 17th century that coincided with the coldest part of the 'Little Ice Age' in Europe. Kelly (1977) had shown that in the century between 1874 and 1974 surface pressures in winter (December-February) in the North Atlantic had oscillated with an 11-year cycle (the North Atlantic Oscillation or NAO). The oscillation was in phase with sunspot numbers during much of that time, but the relationship was poor or reversed between about 1880 and 1920 (however, during that interval there was weaker solar activity and high concentrations of stratospheric volcanic aerosols, but it is not known if these

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are relevant). The solar cycle in the NAO has been confirmed in pressure data back to 1660 by Gray et al. (2016).

Figure 1 shows a compilation of decadal tropospheric variations in the North Atlantic-eastern USA regions during January-February starting in 1920, and with values from 1952 for the west phase of the quasi-biennial oscillation (QBO) of equatorial stratospheric winds once it became available. The variations are compared to the galactic cosmic ray (GCR) flux and the sunspot number, shown in the upper two panels. The variations were stronger during the QBO west phase (winds from the west), compared to when they were from the east (Labitzke and van Loon, 1989). These decadal variations are consistent with changes in atmospheric circulation, not by a direct input of solar energy, but by a catalytic and/or nudging effect due to one or more of the varying, but energetically much smaller, solar inputs.

On the day-to-day timescale and for extended northern winters (November-March) work by Wilcox et al. (1973) showed that clear correlations of atmospheric pressure with solar wind disturbances had occurred in the 1960s; however, they were not found in the 1970s.

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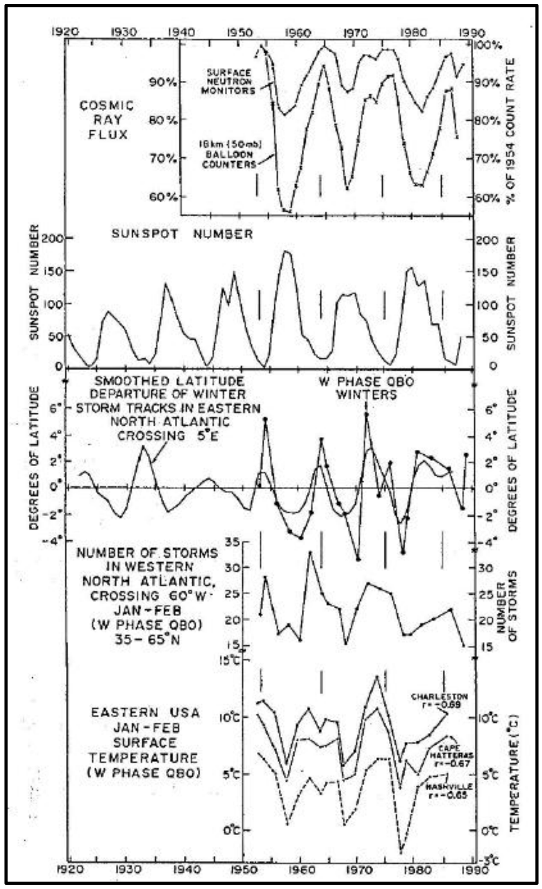

Figure 1. Correlations of cosmic ray flux; sunspot number; winter storm track latitude in the North Atlantic; number of storms in the western North Atlantic; and eastern USA surface temperatures. From Tinsley and Deen (1991).

For global mean temperature, a solar cycle modulation of about 0.1K, together with effects of occasional volcanic eruptions (decreases up to 0.3K for a few years) and ocean-atmosphere interactions such as El Niño-Southern Oscillation (of about 0.2K for a few years), have been demonstrated by Lean (2018). Without taking these natural variations into account, the 'global warming hiatus' of 2001-2011 is difficult to explain. Anthropogenic global warming is about 0.25K per decade. On a regional basis, as in Fig 1, the solar cycle temperature variations can be considerably larger, and of opposite sign in different regions.

3. Mechanisms

3.1. Two categories of mechanisms for circulation changes

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In his insightful BAMS review of possible mechanisms Dickinson (1975) pointed out that "a mean 0.1K decrease in the temperature difference between atmospheric columns in middle latitudes separated by 15^{o} latitude would decrease the zonal mean westerly wind at the tropopause and between these latitudes by of order 2 m/s". This is equivalent to a weakening of the jet stream, with consequences for regional climate. Two classes of processes are able to amplify the relatively small amounts of varying solar energy inputs into changes in atmospheric circulation by creating latitude gradients of temperature. The first class of mechanisms involves ozone changes in the stratosphere, which can be caused by either solar ultraviolet variations or chemical interactions following energetic particle precipitation. By changing the latitude distribution of ozone, latitude gradients of temperature in the stratosphere are set up as the ozone absorbs and emits radiation, as discussed in sections 3.3 and 3.4.

The second class of mechanisms involves solar wind variations, and in one of these its magnetic field (the interplanetary magnetic field or IMF) modulates the latitude distribution of the GCR flux. The modulation of the GCR flux modulates atmospheric conductivity. In another input the changing IMF V_{SW}xB_Y Lorentz electric field induces changes in ionospheric potentials at high latitudes, where V_{SW} is the speed of the Earth relative to the solar wind, and B_Y is the east-to-west component of the IMF, which induces a south-to north potential difference across the Earth. Together with the changes in GCR flux, both modulate the amplitude of the downward flow of current density, J_Z, in the global atmospheric electric circuit. As J_Z flows through tropospheric clouds, it redistributes electric charge and produces changes in cloud microphysics, and small changes in cloud opacity and cloud cover, as will be discussed in sections 3.5 to 3.8. Also, the modulation of the GCR flux can change the rate of ion-mediated nucleation of condensation nuclei in the lower stratosphere. By changing the latitude distribution of tropospheric cloud cover, latitude gradients of temperature are set up by infrared radiative forcing below the clouds and changes in cloud albedo.

Comprehensive reviews of decadal and longer-term sun-climate correlations and mechanisms have been given by given by Lean (1994) and Gray et al. (2010), with a focus on irradiance and ozone mechanisms. However, with decadal observations the attribution to a specific mechanism is very difficult, while day-to-day correlations allow one to separate responses due

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to the solar wind as opposed to solar irradiance. These irradiance mechanisms are included in Table 1, and updates to observations and modelling of irradiance mechanisms since 2010 are discussed briefly in sections 3.3 and 3.4. Solar wind mechanisms are discussed in sections 3.5 to 3.9 and 5. Observations of day-to-day cloud responses will be discussed in section 4, while decadal cloud responses are discussed in Appendix A. The high latitude potential inputs occur during quiet as well as disturbed magnetic conditions. During magnetic storms additional processes occur, as outlined in section 5.

Table 1 compares proposed mechanisms and their theoretically expected effects with attribution of any correlated observations.

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DECADAL SOLAR IRRADIANCE

1. Total Solar Irradiance (TSI) of amplitude 0.06% affects surface temperature.
2. Solar UV change of several percent and observed change of several percent in stratospheric ozone, temperature, and winds, with possible dynamic coupling to the troposphere.
3. Energetic Electron Precipitation. Greater average precipitation in solar maximum years produces NOx, which in polar night is slowly transported to stratospheric levels, reducing polar stratospheric ozone concentration, temperature and winds, with possible dynamic coupling to the troposphere.

ATTRIBUTION: For 1: TSI amplitude is too small to produce observed global temperature change. For 2-3: Although ozone, temperature and dynamical responses to solar UV and energetic particles are clear in the stratosphere, models show the observed decadal variations in the troposphere are inconsistent in amplitude and timing of the stratospheric variations.

DAY-TO-DAY SOLAR WIND INPUTS

1. Under quiet magnetic conditions solar wind Lorentz VxB electric field with sector structure modifies polar-cap potential and J_Z in global electric circuit. Changes in stratiform clouds and below-cloud radiative forcing at high latitudes are correlated with flow of J_Z into clouds.
2. (a) With magnetic activity, Forbush decreases (FDs) of GCR decrease global atmospheric ion concentration and decrease ion-mediated nucleation (IMN) of aerosols, with possible changes in clouds.
   (b) Forbush decreases of GCR modify J_Z at high and mid-latitudes and may modify convective cloud development and latent heat release.
   (c) Solar energetic particles (SEP) often precede magnetic storms, and increase J_Z at high latitudes, correlated with increased cyclone vorticity
   (d) With magnetic storms, minima in relativistic electron precipitation (REP) can decrease middle atmosphere conductivity and decrease J_Z at mid-latitudes, correlated with decreases in cyclone vorticity
   (e) During magnetic storms the disturbance dynamo (DD) from winds in heated thermosphere modifies ionospheric potential at high and mid latitudes, producing J_Z changes.

ATTRIBUTION: For 1: There is clear evidence for high latitude responses of cloud opacity and tropospheric temperature and pressure to the Lorentz electric field in the quiet solar wind sector structure. For 2(a): Modelling indicates that IMN is too small to affect low tropospheric clouds. It is plausible that the J_Z link accounts for the atmospheric dynamical responses (b) through (e) during magnetic storms correlated with the Ap index.

DECADAL SOLAR WIND IPUTS

1. Decadal changes in GCR at high and mid-latitudes correlated with decadal changes in J_z.
2. (a) Decadal changes in mean polar cap ionospheric potential due to solar cycle changes in high latitude ionospheric conductivity, especially in winter, affect J_z.
   (b) Decadal changes in mean polar cap ionospheric potential due to changes in mean V_{SW} and B_Y in the VxB Lorentz electric field input affect J_z.
3. Decadal changes in mean magnetic activity, averaging day-to-day magnetic storm responses, affect J_z.

ATTRIBUTION: 1-3. There are observations of solar cycle changes in J_z at high and middle latitudes as expected from changes in GCR latitude distribution, consistent with modelling (section 5). There are observations of solar cycle changes in clouds globally. The observed correlations of northern Europe winter temperatures and storm track latitudes as part of NAO variations suggest intermittent nudging of the natural decadal NAO oscillation into synchronism with the solar cycle, but there is ambiguity in attributing such nudging to any one mechanism.

Table 1. Mechanisms and their attributions for solar activity connections to weather and climate.

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3.2. Non-stationary correlations

The meteorological community has remained skeptical of the reality of solar activity influences on weather and climate. The amplitudes of the most easily measurable atmospheric responses are small in comparison with the noise in weather and climate, so that a large set of events or number of oscillations have been needed to establish statistical significance in the correlations, but when that was achieved, the correlations were often found to fail to persist in sequential time periods.

Herman and Goldberg (1978) reviewed a great amount of published material and concluded "(there) is considerable evidence suggesting that weather and climate do respond to changes in solar activity on both long and short-term bases." However, they include a section in their book (p. 125-136) on "Correlation Reversals and Failures" of a range of meteorological phenomena with reference to sunspot number that reversed or failed, mostly after about 1920, which remains a major unexplained feature of the otherwise highly suggestive correlations. An analysis of such reversals and failures for the NAO back through the 17^{th} century has been made by Georgieva et al. (2007) who have related them to the north-south asymmetry on the sun of sunspots, and other solar or solar wind parameters.

3.3. Total and UV Solar Irradiance Mechanisms

The decadal oscillations seen in Figure 1 are representative of the NAO, and Thiéblemont et al. (2014) compared two coupled atmosphere-ocean chemistry-climate simulations, one with and one without solar UV variations affecting ozone, and found that in 150-year model runs there was a decadal cycle even without the varying UV input, but that it became stronger and was nudged into partial synchronization with the solar cycle with the UV present, although with smaller amplitude than observed surface pressure and temperature oscillations. Note that this argues against nudging by UV alone, but not by or in combination with some other solar input.

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Similarly, Chiodo et al. (2019) concluded from their state-of-the-art atmospheric modelling that the UV amplitude is too small to account for the reported changes in the NAO on the 11-year solar cycle, and emphasized that the observed changes are non-stationary in comparison with the solar UV variations.

An alternative to the solar irradiance input for the same responses would be that the decadal changes in cloud cover (Voiculescue et al., 2013) are responsible, and are produced by current flow in the global electric circuit affecting cloud cover, as suggested earlier. It seems clear that cloud cover variations have a strong effect on sea surface temperature (as well as land surface temperature) as Boehm and Thompson (2023) have shown by comparing output from two ocean-atmosphere climate simulations, one with coupled clouds and one with clouds prescribed and thus decoupled. The coupled model had a 40-100% increase in the amplitude of monthly to decadal variability over both the North Atlantic and North Pacific oceans.

Millennial timescale climate variations have been inferred from stable isotopes in ice cores by Bond et al. (2001). They used radioactive isotopes in the same cores to infer the presence of simultaneous changes in the cosmic ray flux caused by solar activity. They attributed the climate changes to inferred solar irradiance changes rather than to the directly determined GCR flux changes, but again, as noted above, it is an inappropriate assumption to exclude the primary cause being the GCR variations themselves affecting atmospheric electricity and clouds.

3.4. Energetic Particle Precipitation Mechanism

In addition to the flux from the galaxy of GCR particles of a few GeV energy that are modulated by the solar wind magnetic fields, satellite measurements since 1960 have shown that there are intermittent large fluxes of energetic particles from the Sun and the Earth's magnetosphere penetrating the atmosphere. Particles of tens of keV energy produce visible aurora and changes in chemical constituents, mostly at altitudes above about 80 km, and also changes in atmospheric conductivity, mostly in the lower ionosphere, that can influence the

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current flow in the global atmospheric electric circuit. The GCR particles are always present and ionize air and affect conductivity down to the surface. Precipitating relativistic electrons > 2 MeV energy, (REP), from the Earth's radiation belts intermittently ionize air down to 50 km or so. Short term weather perturbations have been attributed to solar energetic particle events (SEP events) of hundreds of keV energy, and while they occur too infrequently to contribute to climate variations, they have been correlated with increases in winter storm vorticity by Veretenenko and Thejll (2004) and may be due to the associated J_Z increases affecting clouds. Also, reductions in winter storm vorticity following reductions in REP (Kirkland et al., 1996) may be due to J_Z decreases similarly affecting clouds.

New modelling results for energetic particles producing oxides of nitrogen (NOx) and hydroxyl (OH) molecules in the mesosphere and the transport down to stratospheric levels, for comparison with the observed responses there, have been obtained by Seppälä et al. (2009) and Szelag et al. (2022). While the stratospheric ozone and temperature correlations with the solar cycle are well established, it is not clear whether they can induce decadal variations in the troposphere.

3.5. The Global Atmospheric Electric Circuit linking ionosphere and troposphere

In contrast to the weeks required for the NO_X produced at the top of the atmosphere to be transported down in the winter polar vortex to mid-stratospheric levels, current flowing in the global atmospheric electric circuit transfers inputs at the top of the atmosphere to the surface in a few minutes, without attenuation. The voltage difference between the ionosphere and the surface is around 250 kV, maintained by upward current generated by about 1000 thunderstorms and highly electrified convective clouds at any one time, mostly at low latitudes (Hays and Roble, 1979; Roble and Hays, 1979). As Benjamin Franklin demonstrated, a downward electric field in the atmosphere is present far away from thunderstorms. In fact, it is present over the whole globe, because the ionosphere is like a spherical conducting shell, enclosing the weakly conducting atmosphere and the highly conducting surface below, maintaining the current density J_Z of a few pico-amperes per square meter downward

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throughout the global atmosphere. The global nature of the atmospheric electric circuit was established in the 1930s, with the wooden sailing ship ’Carnegie’ travelling the world’s oceans measuring the atmospheric electric field. There are diurnal and seasonal and interannual changes (e. g., due to the El Niño Southern Oscillation) in the global ionospheric potential relative to the surface, due to differing thunderstorm output over the continents and oceans and seasons.

The global circuit can be compared to a global scale semiconducting transistor. Away from thunderstorms the vertical current density J_Z is determined at a given location by the overhead ionospheric potential divided by the column resistance at that location, which is modulated by precipitation of GCR and other energetic particles. The values of J_Z are subject to solar wind modulation by latitude gradients in either the ionizing particle fluxes that determines column resistance, or by the ionospheric potential changes at high latitudes resulting from inputs from the solar wind Lorentz electric field. Tinsley and Heelis (1993) pointed out that satellite measurements showed that the overhead ionospheric potential in regions within about 15^{o} of the magnetic poles varied with the IMF B_Y (east-west) component that reverses as the IMF direction (towards or away from the sun) reverses with the magnetic sector structure (Ness and Wilcox, 1965) of the solar wind.

3.6. Space charge in clouds

Clouds have lower conductivity inside than the air outside, because of the attachment of the air ions to droplets. The air-ions are produced by GCR and other energetic particle influx, and are present throughout the atmosphere, and in all clouds. When the downward current density J_Z flows through clouds, especially stratiform clouds of large horizontal extent, the flow redistributes the air ions to form positive net charge on the top boundary and negative net charge at the lower boundary. This electrical ‘space charge’ is necessary to maintain the current flow through the cloud, and can be observed with instruments on aircraft and balloons (Beard et al., 2004; Nicoll, 2012). The presence of this space charge, i. e., more net charge of one sign

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than the other sign on ions, aerosol particles and droplets, is proportional to J_Z, and was modelled by Zhou and Tinsley (2007, 2012).

3.7. Electro-anti-scavenging.

Throughout the troposphere, including within clouds, GCRs collide with and ionize air molecules. Air ions form in microseconds as polar molecules such as H_2O, H_2SO_4, HNO_3 then attach to the oxygen and nitrogen molecular ions. The air ions then transfer charge in minutes to aerosol particles, and in clouds to the droplets. The electrical effects on collision rates in a population of charged droplets, aerosol particles and air ions then depend on the size distribution of the droplets and particles; the charge distributions on them; and the presence or absence of space charge (Pruppacher and Klett, 1997, Ch. 13). Both Coulomb and image charge forces need to be considered. The Coulomb force between charged droplet-droplet collisions, and charged droplet–aerosol particle collisions, is a repulsive force for two bodies with like charges, and an attractive force for two bodies with unlike charges. Between two bodies small enough so that the image forces are negligible it was shown by Pruppacher and Klett (1997, p 796-7) that for aerosol particles and to the first order the effects on collision rates of the Coulomb attraction and repulsion cancel out for equal number of positively and negatively charged particles. This is not the case when there is appreciable excess charge of one sign (space charge) in a region of a cloud, and when the particles or droplets or ice crystals are small so that their diffusion velocities are greater than their fall speeds. Then the excess of repulsive encounters in the cloud reduces the overall collision (and coagulation) rates, among aerosol particles, droplets and ice crystals. Since the collisions almost always result in sticking, the reduction in collisions results in increases in concentrations determined by the increase in space charge. This is termed *electro-anti-scavenging*, and can occur in aerosol layers as well as in clouds. Within a cloud, the increases in unactivated fine and ultrafine condensation nuclei (CN) together with vapor deposition and mixing, can increase the concentration of cloud condensation nuclei (CCN). Ultimately, with continued cloud processing over several days, there is a reduction in the average size of droplets. For clouds of optical depth < 1 this increases

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the observable opacity of the cloud and/or cloud cover, with consequences for cloud radiative forcing and atmospheric pressure and dynamical changes.

3.8. Electro-scavenging

Whether or not space charge is present, the image charge force (arising from the dipole that a charged body induces on another other, whether the other is charged or neutral) is always attractive and increases the scavenging. The force is short range; approximately inverse as the third or fourth power of the separation between the particle and droplet *surfaces*, as opposed to the inverse square coulomb force between droplet *centers*. This is *electro-scavenging*. The increased fall speed of the larger droplets and the increase in inertia of the larger particles ensures that the ability of the particles to be carried by flow around the droplets is reduced, and the distance between the droplets and particles gets small enough so that the short-range image force ensures capture. The timescale for macroscopic effects on clouds is expected to be shorter for electro-scavenging than for electro-anti-scavenging, since growth times for CN to CCN are not required. Electro-scavenging is modeled by considering charged dielectric spheres. Thus, it can also be calculated for larger droplets collecting small droplets, (Grover and Beard, 1975), but the time constants are very long, unless the charges are considerable larger than in weakly electrified clouds. Charges of at least several hundred elementary charges, such as are found in thunderstorms, are required for appreciable effects on droplet-droplet scavenging (Pruppacher and Klett, 1997, p. 839).

For clouds with larger droplets electro-scavenging of the larger aerosol particles can dominate (Tinsley et al., 2006). Since ionization is present in all clouds, electro-scavenging must be present in all of them. For stratiform clouds, with the downward global current density J_Z flowing through them and creating space charge, electro-anti-scavenging as well as electro-scavenging of aerosol particles can occur. For convective clouds and storms, it was suggested by Tinsley (2012) that both electro-scavenging and electro-anti-scavenging may be work together to narrow the aerosol size distributions, and consequently the droplet size distributions, delay initial precipitation, and allow more water to be carried above the freezing level, to release

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more latent heat of freezing and invigorate the storm (This was suggested for responses of convective storms to varying CCN concentrations by Rosenfeld et al., 2008). The residence time of aerosols in clouds is days to a week or so (Pruppacher and Klett, 1998, p. 248), so electro-anti-scavenging and electro-scavenging processes can occur in days preceding the updraft stage in cyclonic clouds.

Recent parameterizations of rates of one-on-one aerosol-droplet collisions that include those due to electrical interactions have been provided by Zhang and Tinsley (2017, 2018) and Zhang et al. (2018, 2019), built on earlier work in collaboration with K. V. Beard (Tinsley et al., 2000).

Observations of increases in opacity with increasing J_Z (Tinsley et al., 2021; see section 4) favor electro-anti-scavenging as the dominant process for the high latitude cloud responses to J_Z in the presence of space charge. Electro-anti-scavenging would increase the CCN concentration and small droplet concentration and opacity, whereas electro-scavenging would decrease them, depending on droplet size. This is for no change in cloud water content, but it is likely that precipitation would be decreased with electro-anti-scavenging, further increasing the opacity in comparison with the absence of J_Z. Smaller sized droplets or ice crystals of a few microns radius would favor electro-anti-scavenging over electro-scavenging. The preponderance of sulphate ultrafine particles as unactivated condensation nuclei as observed by Humphries et al. (2016), originating in the high latitude free troposphere would favor electro-anti-scavenging.

As noted in Tinsley et al. (2021) an indication of the strength of the repulsive forces involved in electro-anti-scavenging can obtained by comparing on the one hand the electric potential of a charged particle approaching a charged droplet, and on the other hand the thermal kinetic energy of the particle in the line of centers. For typical values of q = 1e (1.6×10^{-19}C) on the particle and Q = 50e on a droplet of R = 3 µm radius, and at a temperature of T = 263 K we have $Qq/(4\pi\varepsilon_0 R) = 3.75 \times 10^{-21}$ J, where ε_0 is the permittivity of free space. This can be compared

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with the average energy of the distribution of the particle velocities in the line of centers; $\frac{1}{2}kT = 1.8 \times 10^{-21}$ J, where k is Boltzmann's constant. So collision is inhibited between these same-sign charged droplets and particles.

There is a lack of data on droplet size distributions in clouds at high latitudes and a lack of charge distributions in clouds generally. Models for monodispersive size and charge distributions for droplets and aerosol particles have been given by Zhou and Tinsley (2007, 2012). Models for charge distributions on polydispersive aerosol size distributions interacting with air ions, but without droplets, have been given by Yair and Levin (1989) but these have not yet been extended to include droplets.

3.9. Problems and solutions

The *Global Circuit-Cloud Microphysics* mechanism, or *Jz-Cloud* mechanism, connecting the solar wind inputs to tropospheric meteorology via J_Z, and amplifying the energy input by a proportionate effect on in-cloud scavenging, cloud cover and cloud radiative forcing, or latent heat release in convective storms, thus overcomes two of the three major problems identified over the years in reviews and discussions of accounting for sun-weather correlations (e. g., Dessler, 1975). These are 1) the problem amplifying the extremely small variations in energy inputs from the sun by many orders of magnitude into the energy of correlated tropospheric changes, overcome by the electrical energy flow modulating a much larger energy flow in cloud radiative forcing and/or latent heat (effectively the global circuit semiconductor-amplifier drives the cloud transducers); and 2) the problem of transmitting the signal observed from the top of the atmosphere down through the shielding provided by many orders of magnitude increasing atmospheric density − especially through the stratosphere with its high stability due to increasing temperature with altitude – overcome by the vertical current density J_Z travelling down without attenuation. The third problem remains − why the intermittent nature of the correlations? This suggests factors not yet taken into account, with candidates being the variations of aerosol at all levels of the atmosphere, in chemistry, size distribution and

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concentration, as relevant to the conductivity throughout the global circuit, and independently relevant to the microphysical responses in clouds. Effects of changes in stratospheric volcanic aerosols (Kirkland et al. 1996) and tropospheric aerosols (Tinsley and Zhou, 2006) have been discussed. Factors determining the effectiveness of nudging processes on internal atmospheric or atmosphere-ocean oscillations include the strength of the winter polar vortex (Veretenenko, 2022); the north-south asymmetry of sunspots on the sun (Georgieva et al. 2007) (which can affect the dominant sign of the IMF near the Earth); and stratosphere-troposphere coupling (Thiéblemont et al. 2015).

4. Cloud responses to J_Z.

4.1. Antarctic clouds and measured J_Z.

Kniveton and Tinsley (2004) and Kniveton et al. (2008) found correlations of cloud cover with changes in J_Z. Figure 2 illustrates the statistically significant correlations of cloud cover over Antarctica 1998-2001 with E_Z, the vertical electric field measured at the Vostok station near the south magnetic pole, that is proportional to J_Z.

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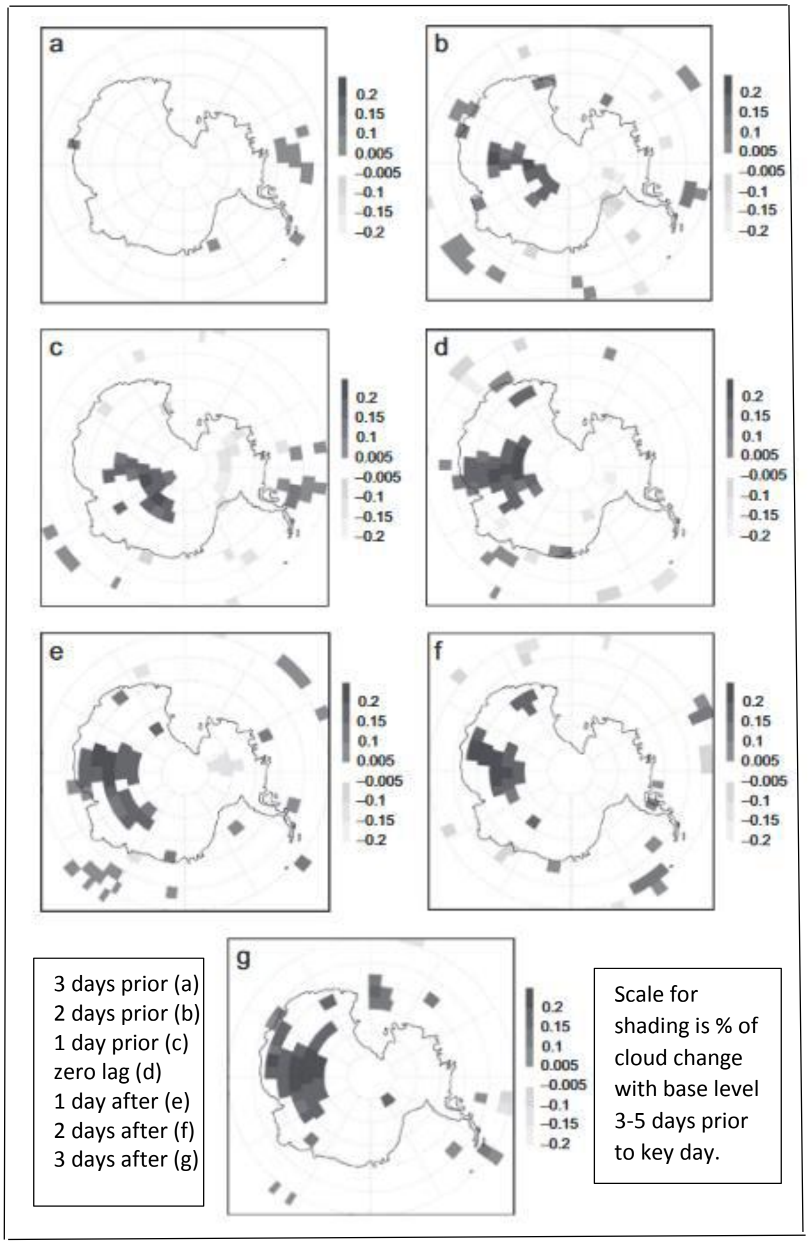

Figure 2. Correlations of satellite-measured cloud cover over Antarctica 1998-2001 with E_Z, the vertical electric field measured at the Vostok station. Vostok is near the south magnetic pole, within the area shaded for statistically significant correlations, and where the ionosphere-earth current density J_Z, is strongly affected by affected by the IMF B_Y changes. From Kniveton et al. (2008).

The day-to-day Vostok E_Z changes (Kniveton et al., 2008) are due to a combination of inputs. Changes related to the overhead ionospheric potential are due to both the IMF B_Y changes and low-latitude thunderstorm-generated global potential. There are changes in column resistance from occasional Forbush decreases (FDs) of GCR. The measured E_Z values, by combining three

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inputs to J_Z from ionospheric potential changes due to IMF B_Y and low-latitude thunderstorms and from FDs - any two of which would constitute noise for analyses using only one of them - can provide a stronger correlation than any one alone, although not providing diagnostic capability by isolating inputs. The location of the statistically significant cloud changes over Antarctica is in the general region of the south magnetic pole and is similar to that obtained by Todd and Kniveton (2001) for correlations of cloud cover over Antarctica with FDs only. The clouds are generally stratiform in nature and with optical thickness less than about unity. The FDs reduce both the air ion production and J_Z.

Surface pressure at Antarctic stations also show correlations with E_Z measured at Vostok and therefore with J_Z (Burns at al., 2007; 2008). The pressure oscillations can be understood as simply due to the day-to-day changes in cloud radiative forcing of the below-cloud atmosphere, associated with the cloud responses shown in Fig. 2. Correlations of surface pressure in both the Arctic and Antarctic were first shown by Mansurov et al. (1974) to be correlated with the IMF direction. The temperature changes due to the radiative forcing of the below-cloud atmosphere correlated with IMF B_Y was shown by Lam et al. (2018) and latitudinal gradients in zonal mean surface pressure by Lam et al. (2013) and Zhou et al. (2018). A similar pattern to that of the cloud responses in Fig 2d (zero lag) was found for regional surface pressure in response to E_Z by Zhou et al. (2018, their Fig 4a) accompanied by pattern of compensating longitudinal wave-like responses over oceanic regions at around 40^o latitude over the Southern Ocean. This wave-like pressure pattern at mid latitudes was also shown for the northern hemisphere by Lam et al. (2013).

4.2. Alert, Canada, clouds and inferred J_Z.

Data from Alert, Canada, of downwelling and upwelling infrared irradiances for 2004-2015 in a superposed epoch analysis with the overhead ionospheric potential and with IMF B_Y, both representing J_Z changes, is shown in Figure 3 from Tinsley (2022). Alert is within the region within about 15^o from the north magnetic pole affected by the IMF B_Y component. The

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overhead potential is represented by *VpN*, the potential at the north magnetic pole derived from the empirical model of Weimer (1995, 1996) which has ionospheric potential differences measured by satellite fitted to spacecraft measurements of the IMF clock angle in interplanetary space. In Fig. 3 the superposed epoch analysis was made separately for +/- jumps in *VpN*, showing a decrease in irradiance 3-5 days later (top left panel), and for -/+ jumps in *VpN*, showing an increase in irradiance 3-5 days later (bottom left panel). On the right the difference between the -/+ and +/- curves is plotted. The use of changes in *VpN* rather than in IMF B_Y provides a better representation of ionospheric potential change since it includes effects of solar wind speed and the IMF B_Z component, and is not dependent on a restricted range of B_Y changes, such as from < -3 nT to > +3 nT. (However, the epochs have not been stratified for the presence or absence of cloudiness, which would be expected to improve the statistics further). The vertical scale units represent W/m^2 for the irradiances, kV for *VpN,* -0.25 nT for B_Y, and standard units (2nT) for Ap. The accompanying Ap increases in the +/- and -/+ cases were small and irregular, and any inputs related to them and to FDs were largely subtracted out in the difference curves. This shows that the overhead ionospheric potential and consequent J_Z variations can modify cloud microphysics independently of any cosmic ray inputs related to Ap.

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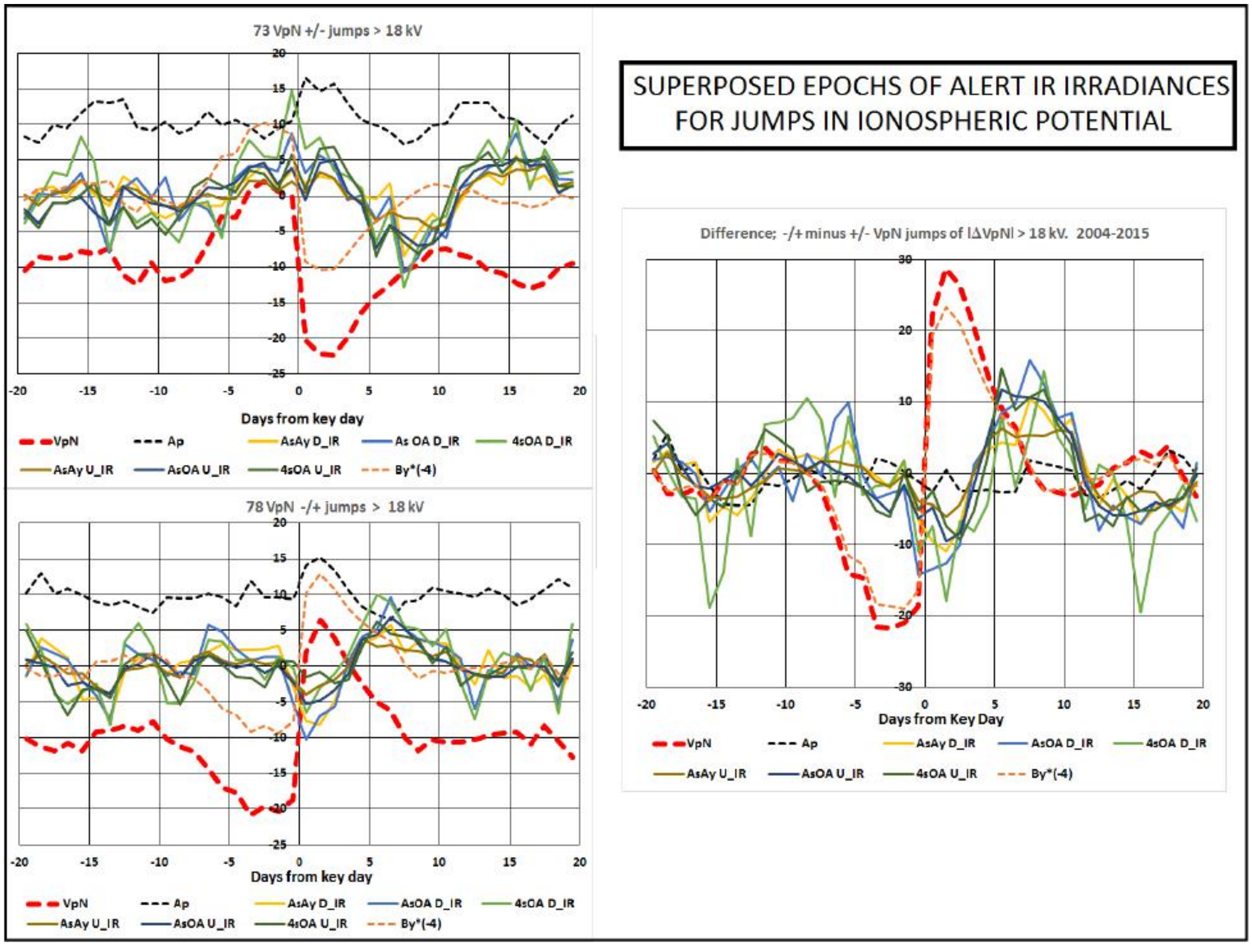

Fig 3. Data from Alert, Canada, of downwelling and upwelling infrared irradiances for 2004-2015 in a superposed epoch analysis with overhead ionospheric potential (heavy dashed red curves) and IMF B_Y (dashed orange curves), together with Ap (black dashed curve) from Figure 3 of Tinsley (2022). For details see text. The curves for irradiances (green, blue, yellow, gold, dark green, dark blue) are for different combinations of seasons and sector structure and upwelling and downwelling. The upper left panel is for a maximum of 73 +/- VpN jumps for all seasons and all sectors, and the lower left panel for 78 -/+ jumps. The difference between the -/+ and +/- curves is shown on the right.

4.3. Equivalence of cloud responses to J_Z from ionospheric potential and GCR fluctuations

There are J_Z changes associated with the set of large FDs that were analyzed by J. Svensmark et al. (2016), H. Svensmark et al. (2021) and Matsumoto et al. (2022), with effects on clouds that were attributed to ion-mediated nucleation. The J_Z changes would also be expected to have an effect on cloud microphysics via the Global Circuit – Cloud Microphysics mechanism. It is possible to estimate the J_Z changes associated with these FDs and to compare them to the J_Z

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changes associated with cloud responses to the polar cap ionospheric potential, to see if the J_Z changes alone could account for the FD effects on clouds. The results shown in Fig 3 correspond to about a 13 W/m^2 change in cloud irradiance for a 45 kV of ionospheric potential change at Alert. The cloud irradiance averages 180 W m^2, and the ionospheric potential averages 250 kV, so this (very approximately) amounts to a 0.4% irradiance change for a 1% J_Z change. Matsumoto et al. (2022, Table 2) gave the IZMIRAN FD magnitudes as averaging 18.5% for the 5 large FDs used by J. Svensmark et al. (2016), who in their Table 3 gave the cloud fraction change as 5.53%. So this (very approximately) amounts to a 0.3% cloud fraction change for a 1% FD and J_Z change. Taking a given percent irradiance change is equivalent to the same percent cloud fraction change, it appears that the J_Z changes by themselves during Forbush decreases may account for the cloud changes for those events, without requiring additional effects of ion-mediated nucleation. We note that J. Svensmark et al. (2016) in their conclusions did not rule out the J_Z mechanism. A caveat is that because the ion production at cloud level also decreases during FDs, the conductivity decreases, but less at low altitudes than at higher altitudes. The conductivity decrease tends to cancel out the electric field and space charge changes due to the J_Z decrease. However, as shown by Zhou and Tinsley (2012), the time constant for reaching equilibrium charge increases, and for low clouds is comparable to mixing times, so this in addition reduces the space charge.

4.4. High and low clouds

The J_Z mechanism favors low clouds rather than high clouds because the amount of space charge generated at cloud boundaries is greatest for low clouds. The space charge depends on the difference in electric field (J_Z divided by conductivity change) between the cloudy and clear air at the cloud altitude (see Pruppacher and Klett, 1997 Chapter 18). The ratio of conductivities of the clear to cloudy air is a strong function of liquid water content (Griffiths et al., 1974) and a weak function of altitude, for clouds when the drift of ions is used to determining ion attachment to droplets. The conductivity at 3 km is about a third of that at 8 km, so that the difference between reciprocal conductivities for low clouds is about 3 times greater than for

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high clouds. Similar results for diffusion of ions determining ion attachment were found by Zhou and Tinsley (2007, 2012). Stratocumulus clouds at 3 km can have up to 10 times the water content of high clouds. So the lower conductivity at the altitude of low clouds, coupled with their higher liquid water content, implies greater space charge for low clouds and favors the J_Z mechanism for stratiform clouds at low altitudes. While the stratiform clouds act as transducers for the conversion of electrical energy to temperature and pressure changes, the conversion is by no means simple. Increases in cloud opacity, for longwave opacity < 1, cause surface warming during polar nights, but the opposite in daytime conditions (Tinsley, 2022) because of increased cloud albedo. This is capable of producing a change in diurnal temperature range without a change in daily mean temperature.

A caveat about space charge accumulation in clouds is that unless they are tens of kilometers in horizontal extent, they do not fully charge with J_Z. The charge is generated at the top and bottom boundaries as J_Z flows through the cloud. However, near the edges the charging is weaker because the current can flow around the edges. So for clouds of smaller horizontal extent such as patchy stratus or summertime cumulus there is only a weak effect on the charging and on the electrically induced microphysical changes, and a weak response for correlations of cloud cover with J_Z. (A similar situation occurs with thunderstorms sending current up to the ionosphere. Mesoscale convective systems are considerably more effective per square kilometer in charging the ionosphere than isolated thunderstorm cells.)

4.5. Microphysics in a GCM climate model

Lubin et al. (1988) used a GCM climate simulation and made a comparison of cloud radiative forcing over the Antarctic continent of ice clouds of particle sizes 10 to 40 µm compared to a control run of water clouds of 10 µm droplets, for perpetual January conditions and unchanged liquid or ice water content. With these conditions there were increases in temperature by 1-2^{o}C in the Antarctic troposphere over the control, and the strength of the westerly winds were reduced by half. The radiative changes were stronger for longwave forcing without shortwave forcing, which suggests that the effects would apply more strongly in the cold season. While

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this work is not a test of the Global Circuit – Cloud Microphysics mechanism, it does show that high latitude cloud microphysical changes can result in significant changes in circulation. The GCM simulation showed significant changes "in the zonal mean circulation and eddies at middle latitudes. In fact, the simulated impacts of the Antarctic cloud radiative alteration are not confined to the Southern Hemisphere. The meridional mean mass flux, zonal wind, and latent heat release exhibit statistically significant changes in the tropics and even extratropics of the Northern Hemisphere." This last point is relevant to the problem of the shifts in phase of the 27-day high latitude pressure response to the IMF B_Y variations (Tinsley, 2022). To the extent that sector-boundary-related changes in GCR cover can occur at times at mid-latitudes, with additional inputs related to magnetic storms, they could produce an opposite change in pressure at the high latitudes.

5. Latitude gradients, regional changes, and the NAO

Both the IMF-induced high latitude ionospheric potential changes and the IMF modulation of the GCR flux modify the latitude gradients in J_Z, as in Fig. 4. The top panel gives estimates of the variation with latitude of the percentage changes in ionospheric potential, and thus in J_Z, due to jumps in ionospheric potential on the day-to-day timescale (orange curve), and those due to the solar cycle change in vertical column resistance due to the GCR flux changes (grey curve), which is also typical of FDs. The high latitude ionospheric potential changes are from the Weimer (1995, 1996) model for jumps in *VpN* averaging about 25 kV, equivalent to the jumps in Fig. 3a and 3b, and are plotted as a function of geomagnetic latitude. The column resistance changes are from the model of Tinsley and Zhou (2006).

There are also changes in polar cap ionospheric potential on the 11-year solar cycle, due to two factors. (a) Decadal changes in the mean potential due to solar cycle changes in high latitude ionospheric conductivity. Especially in winter at solar minimum the solar X-ray and shorter wave UV, and H Lyman α scattered to the nightside, that ionize the air moving across

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the polar cap, are reduced. (b) 11-year changes in mean polar cap ionospheric potential due to changes in mean V_{SW} and B_Y in the VxB Lorentz electric field input. The Weimer (1995, 1996) model has about a 15 kV offset between mid-summer and mid-winter, but because the satellite data covers less than two years, the solar cycle offset was not determined. Observations which show changes in ionospheric convection velocities over a full solar cycle, from which the potential within the northern polar cap can be reconstructed, have been made with the SuperDARN radar arrays and have been parameterized by Lam et al. (2023). An estimate of the solar cycle potential change in winter in VpN due to the conductivity effect that it is 10-15 kV lower at solar minimum (Lam, personal communication, 2023), comparable to the day-to-day amplitude shown in Fig. 4.

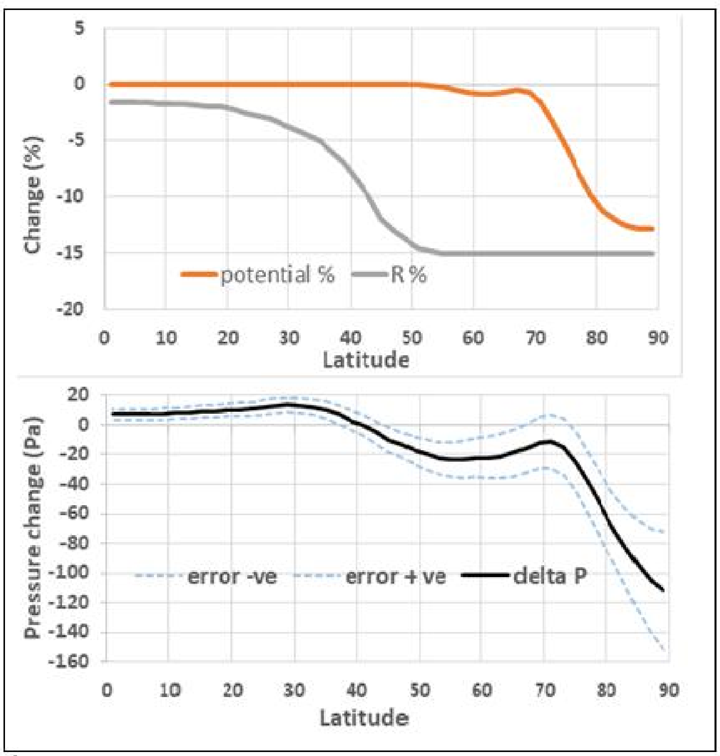

Figure 4: Top panel; Percentage changes with latitude of parameters affecting J_Z. The change in ionospheric potential (orange curve) on the day-to-day timescale is due to alternating solar wind sectors. The potential changes occur inside the polar cap, within about 15^o of the magnetic pole. Also, percentage changes in with latitude of column resistance (grey curve), due to the solar cycle changes in GCR energy distribution, and applicable to FDs. Lower panel; observed surface pressure changes in Pa (black curve) as a function of latitude for the ionospheric potential changes in the upper panel.

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The bottom panel of Fig. 4 shows observed changes in zonal means of surface pressure (black curve) associated with IMF B_Y changes in 1995-2006 greater than 6 nT (equivalent to about 25 kV) from Zhou et al. (2018). Similar patterns were first found in 1999-2002 data by Lam et al. (2013), and in both cases similar patterns are found for the southern hemisphere, with opposite pressure response for a given change in IMF B_Y, consistent with the opposite change in ionospheric potential in the two polar regions. When resolved in longitude the compensating mid-latitude pressure changes show large scale variations similar to Rossby waves (Lam et al. 2013; Zhou et al. 2018).

The comparison in Figure 4 of the latitude variation of the high latitude ionospheric potential changes (top panel, orange curve) with the latitude variation of the day -to-day surface pressure responses (lower panel, black curves) shows the similarity of the latitude of steepest gradient. This supports the inference previously made that the day-to-day cloud and pressure responses are caused by the J_Z and cloud changes. The steepest gradient in the ionospheric potential is in the vicinity of the polar fronts. During magnetic storms the region of maximum gradient shifts equatorward by several degrees, and there are additional ionospheric potential changes at sub-auroral latitudes; sub-auroral ion drifts (SAIDs, Archer and Knudsen, 2018), and at mid and equatorial latitudes; the disturbance dynamo (Huang et al., 2005; Sahai et al., 2005). Additionally, SEPs and REPs have been observed to affect cyclone vorticity, as noted earlier. Increases in gradients of pressure are associated with cyclogenesis and increase vorticity.

The cosmic ray induced J_Z changes would affect the circulation at middle latitudes, which is where Armatova and Veretenenko (2014) found the strongest responses to FDs, in October-March. The maximum effect was observed on the 3rd-5th days in both hemispheres, and it was suggested that this was an effect on cyclone development, resulting from latitudinal gradients in pressure. The longitudes of maximum effect included Western Europe and the North Atlantic, thus being associated with NAO variability.

The latitude variations in column resistance in Fig. 4, are similar to those of GCR in a paper by Ney (1959), who pointed out in his discussion of cosmic radiation and the weather that GCR

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ionization was the input variable “subject to the largest solar cycle modulation in the denser layers of the atmosphere”.

6. Discussion and conclusions.

Of the various proposed mechanisms to explain correlations of weather and climate with solar activity, the *global circuit – cloud microphysics* mechanism or J_Z - *cloud* mechanism is the only one that has no obvious constraints as a general explanation for correlations of changes in tropospheric circulation with solar activity. The observed day-to-day correlations of stratiform clouds with J_Z changes provide a direct explanation, via cloud radiative forcing, for the corresponding, and well documented correlations of tropospheric pressure gradients with high latitude potential changes. In view of these correlations, there is little reason for doubting the J_Z influence. Overall, the results are consistent with the J_Z-cloud microphysics mechanism intermittently nudging the NAO, with its decadal natural frequency of oscillation, into partial synchronization with the 11-year solar cycle.

There is much work to be done to quantitatively test the J_Z connection. Several days appear to be necessary for cumulative effects of electro-anti-scavenging, and this favors clouds with low or negligible updraft speeds, and mixing within the cloud due to the transfer of heat from the warming base to the cooling cloud top. The relative amounts of electro-anti-scavenging and electro-scavenging will depend on the aerosol and droplet size distributions. There is a need for observations of both size and charge distributions of both droplets and particles in weakly electrified clouds, and their evolution with in-cloud processing as the clouds age. Ultimately, it will be necessary to make accurate physical models to test the validity of the J_Z-cloud mechanism.

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The main problem for all mechanisms is to account for the non-stationary nature of the correlations of weather and climate with solar activity. The partly periodic and partly chaotic atmospheres of both the sun and the Earth and weak nudging by the varying solar input is a possible explanation, together with our incomplete knowledge of effects of, for example, the polar vortex, stratosphere-troposphere coupling, the north-south asymmetry of sunspots on the sun, and influences on the global electric circuit, such as changing populations of aerosols of volcanic, surface dust and meteoric origin. It would be premature to assume that no such explanations can be found.

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Availability Statement

No datasets were generated or analyzed during the current study.

Appendix A. Decadal cloud changes

Decadal cloud cover changes correlated with the 11-year solar cycle in GCR are to be expected by analogy to the Forbush decrease-related cloud responses, since the amplitudes of GCR flux changes on the solar cycle are comparable to the amplitudes on the day-to-day timescale. However, the mechanism of ion-mediated nucleation, first proposed by Dickinson (1975) which has been developed by Svensmark and Friis-Christensen (1997), Svensmark (1998), and Yu (2002), has been shown to be not viable. It involves nucleation of aerosol particles on atmospheric ions (ion-mediated nucleation) that may grow by vapor deposition to act as cloud

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condensation nuclei (CCN). As with a reduction in scavenging, the increased production of CCN results in increased cloud opacity. Svensmark and Calder (2007) and Svensmark (2007) argued that the correlations on the decadal timescale of low cloud cover with the GCR flux, taken with the small upward trend of the decadal average flux due to the downward trend of solar activity starting about 1960 (which has now reversed), was an explanation for the global warming trend otherwise due to increasing greenhouse gases. Furthermore, they argued that, not only was ion-mediated nucleation affecting low cloud cover, but it accounted well for climate fluctuations on centennial and millennial timescales, and even 'Snowball Earth' episodes, as the earth passed through spiral arms of the galaxy. Apart from lack of supporting data for their explanation of the 'Snowball Earth' phenomenon, and the discounting of the consequences of greenhouse gas changes, there is another problem with ion-mediated nucleation mechanism itself. While there is now good evidence for nucleation of aerosols on ions from laboratory work by Svensmark et al. (2007) and Kirkby et al. (2011), and evidence for its occurrence in the stratosphere, the model of Pierce and Adams (2009) found that the rate at cloud level (~3 km altitude) is so slow that the ambient aerosol concentration is dominated by production from surface sources such as sulfate or organic particles, and the contribution of ion induced nucleation would be negligible. Another problem for this mechanism is that Wagner et al. (2001) showed from icecap isotope records that there was no discernable climate change during the increase of GCR flux 40 thousand years ago when the geomagnetic field decreased to only 40% of its present value.

In general, decadal cloud cover changes are of limited use as diagnostics on mechanisms, since they can be produced by changes in circulation due to various irradiance as well as solar wind inputs. Veretenenko and Poduvkin (1999) analyzed 6-month averages of surface insolation from the Russian actinometric stations and found that negative correlations with GCR flux and solar flares were observed for high latitudes, above about 57^{o}, while positive correlations were observed at lower latitudes. Marsh and Svensmark (2000) found that only low clouds showed significant correlations. Udelhofen and Cess (2001) looked at cloud cover data for 1900-1987 over the continental USA and found positive correlations with the solar cycle (negative

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correlations with GCR flux) maximizing at latitudes 35-40^{o}. For the whole interval the statistical significance was better than 95%, although poorer in the interval of lower sunspot activity up to 1950. In that respect it is similar to the intermittent correlation of solar activity with the NAO (section 2), and again suggestive of circulation changes.

Boberg and Lundstedt, (2003) found that the NAO had a strong correlation for 1974-2001 in pressure and temperature with annual means of the east-west interplanetary electric field (IEF), defined in this case by the product of the solar wind speed and the north-south, B_Z, component of the IMF. The correlations were only for this IEF positive (B_Z negative), and not for IEF negative (B_Z positive) as is also the case with magnetic activity, and is reflected in Ap. Also, together with the IMF B_Y component, it affects the ionospheric potential at high latitudes (Tinsley 2022 Fig A2), which responds more strongly to positive IEF (negative clock angles in Tinsley et al., 2021, Fig B2) than negative IEF.

Voiculescu et al. (2013) looked for correlations of global cloud cover 1984-2009 with the east-west IEF. The cloud cover correlations were clear at mid-high latitudes with positive IEF values, but not with negative IEF values. These decadal cloud cover variations were strongest for low clouds, and less extensive, predominantly of opposite sign, and in different latitude bands for middle and high clouds. The positive IEF represents the sum of the solar wind inputs to the ionospheric potential and also to the GCR fluctuations that affect high-mid-latitude conductivity, with both affecting J_Z.

Veretenenko and Ogurtsov (2016) pointed to the difficulty in distinguishing between primary responses of low clouds to GCR or J_Z inputs, on a time scale of days, and secondary responses of clouds due to the changes in circulation induced by the primary responses. Changes in the polar vortex were found to influence the responses. The changes in circulation that result in cyclones, troughs and fronts can produce a delayed response, which averages into a decadal response.

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They found that the correlations tended to be opposite at high compared to low latitudes and different over oceans compared to continents, and non-stationary.

Kumar et al. (2023) found correlations of cloud cover with the solar cycle in 42 years of ERA-5 data for mid-latitudes over Eurasia.

Miyahara et al. (2023) found responses of high altitude clouds in 42 years of outgoing longwave radiation, mainly in August over tropical land areas.

Harrison and Lockwood (2020) report on 27-day periodicities in the thickening of low-level clouds, with tropospheric temperature and wind responses, at high Northern Latitudes during solar minimum conditions in 2007-2008, strongest in December 2007 through January 2008. Their model involves co-rotating interaction regions in the solar wind, solar energetic particle precipitation, atmospheric ionization, atmospheric conductivity, J_Z, space charge generation in clouds, and changes in cloud radiative forcing affecting tropospheric temperature and winds. Correlations were shown with the GCR flux of around 2000 MeV energy from the Oulu neutron monitor and in the range 165-200 MeV from the GOES 11 satellite data, but not with solar energetic particle ionization as claimed (see their Fig. 10), since there were no such events recorded in that time span. In December 2007 through January 2008 there was a very stable 2-sector structure in the IMF B_Y and in polar ionospheric potential (Tinsley et al., 2021, see their Fig. 1) which has a stable and uncluttered 27-day periodicity. For several days around the recurring minima in the GCR flux magnetic storms were also occurring. As noted earlier, magnetic storms are associated with ionospheric potential variations and thus J_Z variations at middle and low latitudes. The ionospheric potential variations provide a less ambiguous explanation of the cloud thickness observations.

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