Observations and modeling of Sun-Earth connections

Jonathan J. O'Regan, Jan-Peter Muller, Sarah Matthews

Mullard Space Science Laboratory, University College London,
Holmbury St. Mary, Dorking, Surrey, RH5 6NT, United Kingdom.
jjo2@mssl.ucl.ac.uk

Outline

We present a brief historical overview of work to date assessing the area of Sun-Earth interactions and connections – particularly that of cosmic rays effects on the atmosphere – and a description of the theorized physical mechanisms suspected to amplify the interactions to levels which can greatly affect the Earth's climate and weather systems. The current research direction is then discussed with respect to the current status and outstanding questions of the research area.

Historical Evidence of Sun-Earth Connections

From the beginning of the space age, previously unseen 'striations' of clouds above ocean regions were observed by weather satellites such as TIROS-7. These were subsequently linked to shipping routes, and these 'ship tracks' were discovered to be clouds seeded from the aerosol particles from the exhausts of ships, which provided the necessary medium for condensation and coagulation of liquid water droplets in the pristine ocean air environment. This effect can be clearly seen in MODIS images of the southern Atlantic, Pacific and Indian oceans, where the air is much clearer than in more urbanised areas of the world [clearly visible in *figure-1*].

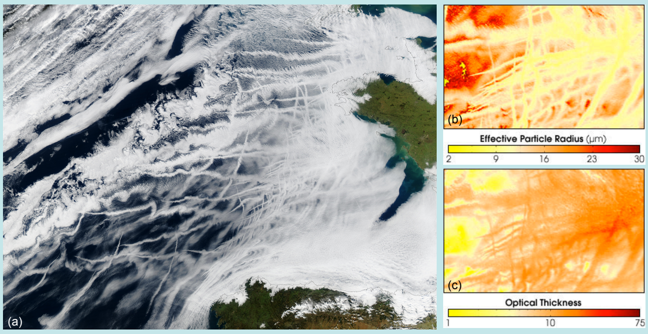

Figure-1: True- and false-colour images from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite from January 27, 2003. The 'ship tracks' are clearly visible on the true-colour image (a), and the false-colour cutaways show two properties of clouds that influence the heat and energy balance of the atmosphere and, as a result, the climate; (b) cloud particle radius, which is the estimated size of the radius of the particles making up the clouds, and (c) cloud optical thickness, which describes how much light is able to pass through a cloud.
[*source: NASA - available from:* http://earthobservatory.nasa.gov/IOTD/view.php?id=3275]

It is the dependence of the condensation process on (charged) particles, such as those aerosols seeded along 'ship tracks', which sparked the further development of the Cloud Condensation Nuclei (CCN) theory – an idea brought to life at the beginning of the last century by the Scottish scientist, C.T.R. Wilson[1]. He posited that vapour condenses on small particles (aerosols), without which vapour itself cannot make the change of phase to liquid or solid. Wilson further developed this idea by showing that the by-products of interactions of the Earth's atmosphere with incident cosmic rays – highly energised particles originating from solar and galactic processes – could potential supply the mechanism by which water vapour in our atmosphere, or clouds, might be able to condense and sublimate.

For centuries, scientists have been conducting studies of the links between observed changes in solar activity with that of climatic changes here on Earth. Traditional sources of evidence on these Sun-Earth connections have focused on areas the likes of northern hemisphere temperature studies [e.g. Friis-Christensen & Lassen (1991)[2]], sea surface temperature studies [e.g. White et al. (1997)[3]], and extensive studies of the infamous 'cold snap' of the Maunder Minimum [e.g. Shindell et al. (2001)[4]] – for more information, see *figure-2*.

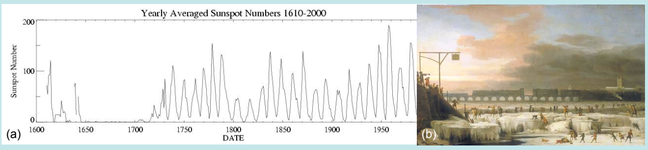

Figure-2: Early records of sunspots, such as depicted in (a) yearly averaged sunspot number, indicate that the Sun went through an unusual period of inactivity in the late 17th century (~1645-1715), where very few sunspots were seen on the Sun. This period of extremely low solar activity also corresponds to a climatic period known as the "Little Ice Age", or Maunder Minimum, when rivers – such as the Thames, pictured in (b) – that are normally ice-free froze and snow fields remained year-round at lower altitudes.
[*sources*: (a) available from: http://www.theresilientearth.com/?q=content/scientists-link-quite-sun-cold-winters
(b) NASA - available from: http://solarscience.msfc.nasa.gov/SunspotCycle.shtml]

Combined with on-going studies of the conductivity of the atmosphere, these and subsequent studies[5-13] propose strong indications that cosmic rays, and as such, solar activity, should play a key role in atmospheric processes here on Earth. While in the past these studies (and those of many other areas of climate forcing such as volcanoes, anthropogenic greenhouse gasses, plate tectonics, orbitally-modulated solar insolation, and variations of solar irradiance) have focused on the effects that should be observable on the Earth's climate over timescales of years, decades and even centuries, very little studies to-date have examined to possible effects of solar activity on modulating and influencing weather events over much shorter time periods, of the order of days to months. Such studies could well be the key to finding if such microphysical processes are indeed occurring, and provide the evidence and support for future solar influenced climatic studies along with better insight into the physical mechanisms themselves which would operate on these shorter timescales. Although studies to-date have been unable to sufficiently establish or rule-out a possible cosmic ray-cloud connection, observations do provide sufficient evidence to suggest that deeper investigation of the effect of cosmic rays on atmospheric processes does offer real possibility of fundamentally new knowledge on the Sun-Earth connection problem[13].

Atmospheric Interactions of Cosmic Rays

There are 2 main theorized mechanisms by which cosmic rays – both those originating from galactic centres (Galactic Cosmic Rays – GCRs) and those created in violent outbursts of solar activity (Solar Energetic Particles – SEPs) – interact with the lower atmosphere of the Earth.

Mechanism #1: Generation of Cloud Condensation Nuclei (CCN)

The first mechanism concerns the influence of cosmic rays on the production of clouds. Ionisation from these cosmic rays enhances the production of new aerosol particles in the atmosphere, as depicted in *figure-3*. Small clusters of these molecules (as few as 2) can then grow by means of condensation of water vapour, and other trace vapour, increasing until a critical size is reached; above this critical threshold, further condensation occurs, but below which, however, evaporation is more likely. This nucleation is ion induced (generated by the pre-existent charge on the aerosols), and stability of the condensing particles is brought about by the forces exerted by coulomb attraction, which at a certain level 'locks' these embryonic clusters into tightly bound nuclei, effectively reducing the critical size needed to sustain the cluster. From this point on, there arises an enhanced probability of collision between clusters and new particles as the growth process becomes accelerated by the charge on the cluster. Droplets are ~100 times more efficient at collecting aerosols when charged rather than neutral. Once the cluster reaches a size of 5 nanometres, the electrostatic effects which previously drove particle collision and coagulation now becomes negligible to the dynamics of particle clusters. As such, low particle mobility in this stage would result in a sharp decrease in coagulation rate[13].

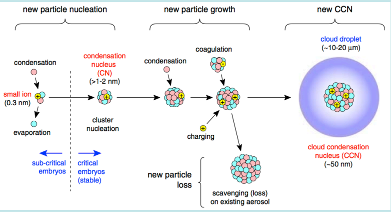

Figure-3: Ion-induced nucleation of new particles from trace condensable vapours and water in the atmosphere leading to production of Cloud Condensation Nuclei (CCN) [source: Kirkby (2007)[13]]

Due to the difficulty for particle clusters to continue to progress beyond this stage of growth, only a small fraction of new particles will ever reach the minimum effective size necessary to become CCN; a size of approximately 50 nanometres. Most particles are subsequently lost due to electroscavenging processes ongoing in the atmosphere. Despite this difficulty, however, these surviving CCN would play a significant role in low altitude cloud formation, and its subsequent effects on atmospheric and climatic processes. Assuming, for example, a solar imprint does exist on low altitude clouds, then the expected modulation of low clouds over the solar cycle is estimated to be ~1% absolute (~3% relative). This represents a net radiative forcing of ~0.5 Wm^{-2} at Earths surface over a solar cycle (~11 years), which is in fact nearly 2.5 times larger than solar irradiance variations itself[13]. Thus, the net cooling effect which results from low clouds could be more strongly affected by the described mechanism of cosmic ray influence than just solar irradiance changes.

Mechanism #2: Modification of the Global Electric Circuit (GEC)

Due to the difference in charge (or potential difference) generated by differing levels of ionisation of the atmosphere, a global electrical current (measuring approximately 1400 A, or ~400 MW of power) continually flows between the two main layers of charge in the Earth environment – the ionosphere and the Earth's surface (*figure-4*). This transfer of charge is sustained by regions of disturbed weather, or thunderstorms – most notably those which are continuously active over tropical land masses[15,16] – which enable the transfer of negative charge from the atmosphere to the ground below. As a result of this movement of negative charge, an equivalent positive current thus flows up from the surface to the ionosphere, in regions of both disturbed and undisturbed weather, carried by the vertical drift of small ions and aerosols. Due to the dominance of cosmic rays over the ionisation levels in the ground-to-mid-mesosphere region of the atmosphere (~3km-65km altitude), cosmic rays are responsible for the generation of all fair-weather atmospheric ionisation within this region; cosmic rays thus fundamentally underpin the GEC[13].

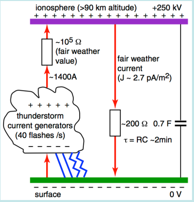

Figure-4: The GEC, showing the current flowing between the ionosphere and Earth's surface.

Observed changes in ionospheric potential and surface potential gradient have already been observed and attributed to changes in cosmic ray flux, which is essentially governed by solar activity, thus highlighting the connections between the Earth and it's star, and demonstrating the impact solar activity has over atmospheric processes[17,18]. These parameters hold knock-on effects for Earth's weather systems, and modification of these parameters will in turn result in a modification of weather systems with respect to cloud formation and evaporation, generation of atmospheric ice crystals, thunderstorm generation, etc. For example, vertical conduction current generates highly charged droplets at upper and lower boundaries of clouds[14], as shown in *figure-5*, which can eventually lead to increased charge separation in a cloud, thus producing thunderstorm clouds and stimulating lightning discharge. Similarly, with respect to droplet freezing, if the charged aerosol is an ice nucleus, then freezing by contact nucleation is induced. This is a particularly efficient mechanism for particle growth, as, due to the large amount of supercooled liquid water (-40^0C to 0^0C) in the tops of clouds, ice crystals will grow rapidly, strongly influencing cloud precipitation, while the release latent heat can influence atmospheric dynamics[13].

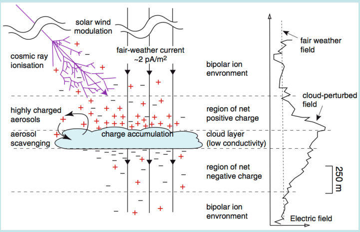

Figure-5: Schematic showing the generation of (unipolar) space charge above and below clouds. This is due to the drift ions – charged particles produced from the interactions of cosmic rays and atmospheric molecules – in the fair-weather electric field.

These charges can become attached to droplets and aerosol particles, as discussed in the CCN mechanism. They are then entrained within the cloud, where they can strongly influence microphysical cloud interactions and processes, such as those discussed above.

Research Direction

The proposed work, herein, follows on from a study conducted in 2008 by Kristjansson et al. (2008)[18], which reassessed the CCN-cosmic ray hypothesis using data from the Moderate resolution Imaging Spectroradiometer (MODIS) on-board NASAs Terra and Aqua satellites, and found no statistically significant correlations between GCRs and cloud parameters. This study focused on deep oceanic and near-land oceanic regions in the Southern Hemisphere region, between the equator and 40^0S for 22 Forbush decrease events, periods of unusually low cosmic ray flux.

Extending this analysis to study polar regions – from 55^0-90^0 North and South, where the magnetic field allows greater penetration of cosmic rays – and using auroral imagery and particle flux data from NASAs IMAGE spacecraft, global lightning data from the World Wide Lightning Location Network (WWLLN) in combination with four MODIS cloud parameters (below), signals of correlation will be investigated, and their statistical significance determined. Given the higher penetration depth of energetic particles near the poles – due to the lower geomagnetic rigidity at higher latitudes – there is an likelihood of interaction of incident energetic cosmic rays with the atmosphere (emphasised by the processes which give rise to aurora). Along with the relatively low abundance of other aerosol sources, the polar regions have thus been chosen as the best ground to identify a solar-driven signal.

Solar cosmic rays, or Solar Energetic Particles (SEPs), rarely penetrate low into the atmosphere below ~55^0 latitude or close to 90^0, as they get constrained within the Earth's magnetic field, which traps the particles leaving them to bounce from pole to pole along magnetic field lines. This is why an auroral *oval* is seen over the poles. Using aurora as an indicator of the area of penetration of the particles into the atmosphere, an overall idea of the configuration of the magnetic field can be established, adding information as to the strength of the storm and the particles generated within, as well as to the extent of which particles are likely to penetrate, providing the geographical area of interest for the analysis.

The 4 main MODIS Cloud parameters used in the analysis are:
– **Cloud droplet effective radius (CER)** as an estimate of the mean size of cloud droplets
– **Cloud liquid water path (LWP)**, the vertically integrated cloud water content, typically of the order of 10-100 gm^{-2} for lower troposphere clouds
– **Cloud optical depth (COD)**, such that: $\mathbf{COD = 3/2 * LWP/(CER * \rho_l)}$ [where; ρ_l = density of liquid water]
– **Cloud Amount (CA)**, the percentage-wise area covered by clouds

It is very difficult to distinguish between the various forcing mechanisms responsible for any observed solar driven phenomena, as all solar indices – total solar irradiance, UV spectral irradiance, or cosmic rays – have very similar variations over the solar cycle. This is increasingly so over longer timeframes. Analysis of the parameters in relation to weather events over the course of several (~3-14) days – depending on the size and duration of the solar storm in question which is generating the cosmic rays – would decrease the difficulty in distinguishing solar indices due to higher temporal resolution of datasets, and reduced averaging, as opposed to previous 'climatic' studies which have averaged the indices in question to extend over several years to decades. This, along with the reduced geographic focus from a global to a regional study, increases the likelihood of detecting a cosmic ray driven signal in the data, as geographic variations in atmospheric dynamics are not averaged out. This allows us to account for the possible influence of local weather patterns on the parameters, and to distinguish actual an solar driven signal from a coincidental signal. Any possible signal which may arise during the cosmic ray influenced event will then be compared to that of the equivalent fair-weather conditions during the same time period of other years, reducing the likelihood of detecting a 'non-cosmic ray' driven phenomenon.

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