Exploring the Cosmic Ray and Cloud Connection through Principal Component Analysis

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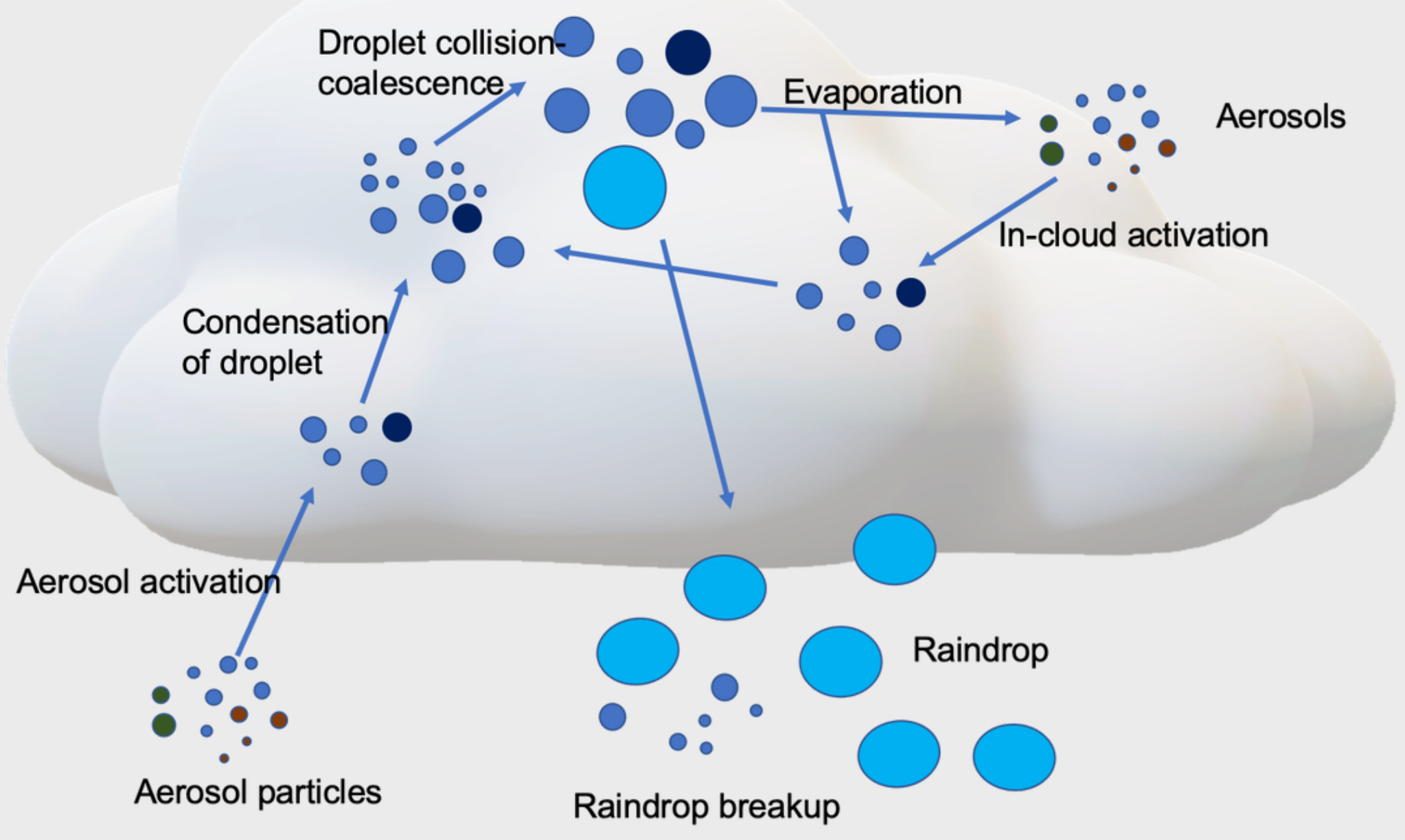
Atmospheric Physics

History of Atmospheric Physics

The formal study of electricity in the atmosphere began in the 18th century, through the experiments of Franklin and D'Alibard (Harrison 2004). As the field progressed, people learned that electricity was still present in the atmosphere even in the absence of thunderstorms because of Lemonnier studying clear air and Canton observing non-thunderstorm clouds (Harrison 2004). It was not until 1997 that Svensmark and Friis-Christensen began to formally investigate how cosmic rays could affect atmospheric electricity.

Introduction to Cloud Physics

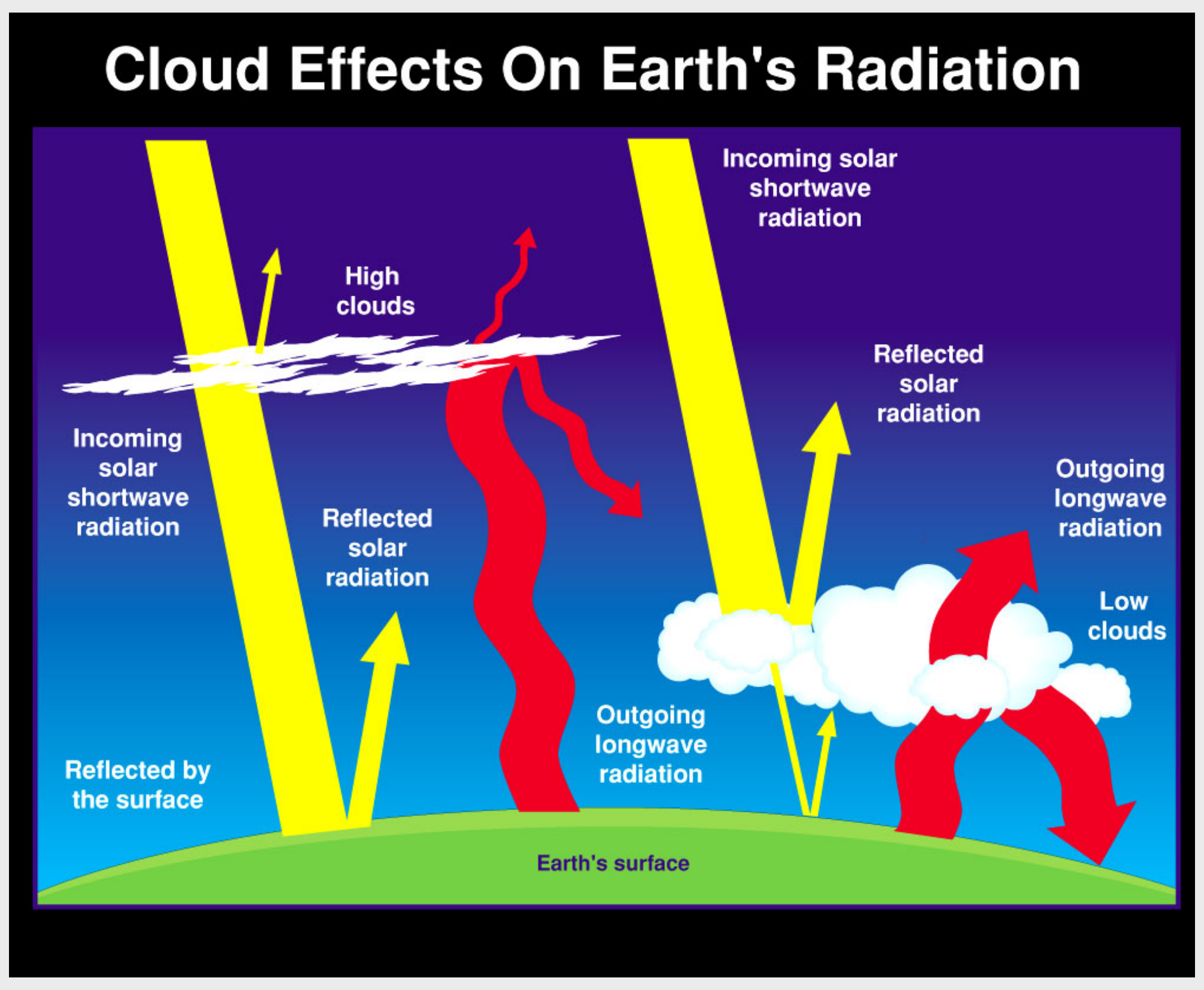
The atmosphere includes aerosols, which are a variety of suspended particles. When enough of these gather, through a process called coagulation, their total diameter exceeds 100 nm and can begin serving as a center for water vapor to collect (Pierce and Adams 2007). Once this happens, they are called Cloud Condensing Nuclei. With enough aerosols and humidity in an area, cloud droplets are formed. Therefore, clouds themselves are just assemblies of these droplets (Rogers 1976).



https://sisichenclouds.weebly.com/research.html

Cloud Properties

What effect clouds have on the weather and climate depends not only on the cloud properties but its altitude. An important feature is the cloud albedo. This is a measure its broadband (including infrared) reflectivity. Multiple factors determine a cloud's albedo, such as thickness, the properties of the individual aerosols and the abundance of ice particles and water content (Han *et al.* 1997). Clouds both reflect radiation from both directions, i.e., space (cooling) and infrared (heating the planet) (Svensmark and Friis-Christensen 1997). The cooling dominates, which leads to a net lower temperature for Earth, implying that cloud cover should be correlated with temperature.



https://visibleearth.nasa.gov/images/54219/cloud-effects-on-earths-radiation

Cosmic Rays

The Earth resides in what we call the Heliosphere, which is defined as the region of space dominated by energetic particles from the sun. These particles shield us from cosmic radiation from outside, to what extent depends on the phase of the solar cycle. Galactic cosmic rays undergo collisions with nuclei in our atmosphere. These result in free protons, neutrons, pions and secondary nuclei. The secondary particles lose energy with every interaction until, eventually, they no longer generate particle cascades. The greatest ionization happens in the lower atmosphere (Marsh and Svensmark 2000). This phenomenon was seen by V.F. Hess with his balloon and airship experiments (Hess 1928).

Of the variety of secondary particles produced, we detect >10 MeV neutrons at the ground level with neutron monitors. Various factors affect how many neutron counts we record. One example is the barometric pressure, which acts as a proxy for the amount of air above the monitor. Correcting for pressure is necessary because the more air secondary particles travel through, the more they become attenuated. Wind speed is potentially another factor, as when the speed gets high enough, the pressure drops significantly. This is problematic because the cosmic rays are still traveling through the same amount of air. Additionally, space weather events, such as Ground Level Enhancements and Forbush Decreases, cause a significant change to the number of cosmic rays that reach Earth. All of this factors can lead to great variability in the count rate, which could possibly affect cloud formation.

Current Understanding of the Connection

Cosmic rays have various correlations with Earth's climate but significant causal relationships have yet to be proven. There have, however, been multiple proposed observations and theories that could lead to a more definitive link. For example, by changing the number of ions in the atmosphere, cosmic rays modify the current flow in the global electric circuit, which can result in an increased number of thunderstorms (Singh and Bhargawa 2020). An even stronger study came out (Harrison *et al.* 2011), which measured how exactly the global atmospheric electrical circuit affected cloud edges and compared this information to neutron monitor data. They found that cloud base heights decreased and low clouds were more numerous when neutron counts were high. Another possibility is that cosmic rays affect the rate of formation of ice particles within clouds (Harrison 2004). So, if we can establish a connection between cosmic rays and clouds, then we can show cosmic rays to have significant, albeit indirect, ramifications on the weather.

A possible process that relates the two is the ion-aerosol clear-air mechanism. This theory states that the charged secondary particles created by cosmic rays not only add to the population of potential condensation nuclei, but also these particles have an easier time attracting aerosols due to their polarity. This could increase the number of particles growing from 1 nm to 5 nm by a factor of 2 (Carslaw *et al.* 2002). This mechanism could help explain why observed nucleation rates are so much higher than theoretical calculations.

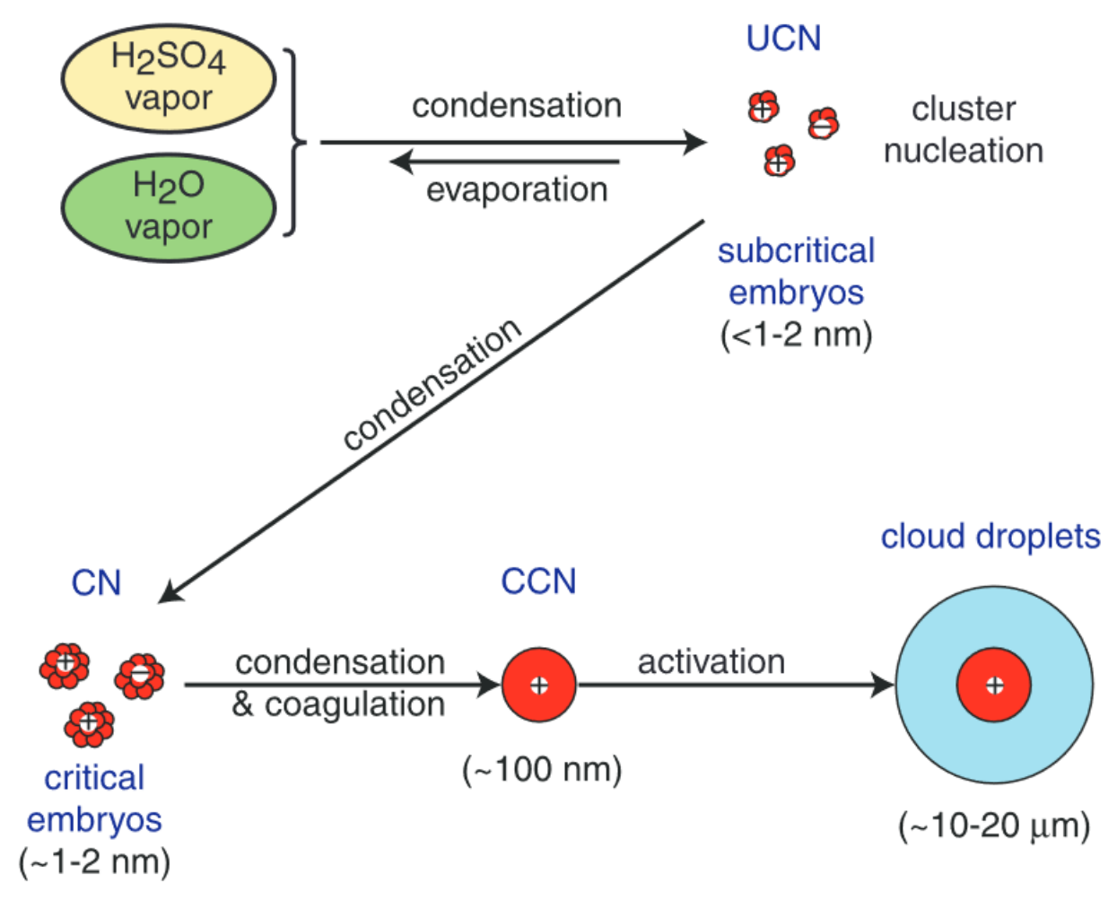


Fig. 3. An "ion-aerosol clear-air" mechanism proposed to link variations in cosmic ray intensity with cloudiness. The diagram shows the ion-catalyzed nucleation of new ultrafine condensation nuclei (UCN) from trace condensable vapors in the atmosphere, which may then grow into new cloud condensation nuclei (CCN).

Carslaw et al. 2002

Although this possibility seems promising, the theory is not bulletproof. Many studies have conflicting results. For instance, in addition to the heliosphere shielding Earth from GCRs, the planet's own magnetic field does this. This effect is weakest at Earth's magnetic poles but evidence has shown the strongest correlation between cosmic rays and clouds at lower latitudes. Near the equator, cosmic rays with less than 10 GeV are almost completely blocked (Lanci *et al.* 2020). This would mean the Cloud Condensing Nuclei must somehow travel between these two regions to produce the correlation in the first place (Pierce and Adams 2009). Additionally, the Cosmics Leaving OUtdoor Droplets (CLOUD) experiment was designed to test this very link through and only found a weak GCR-CCN response. (Pierce 2017).

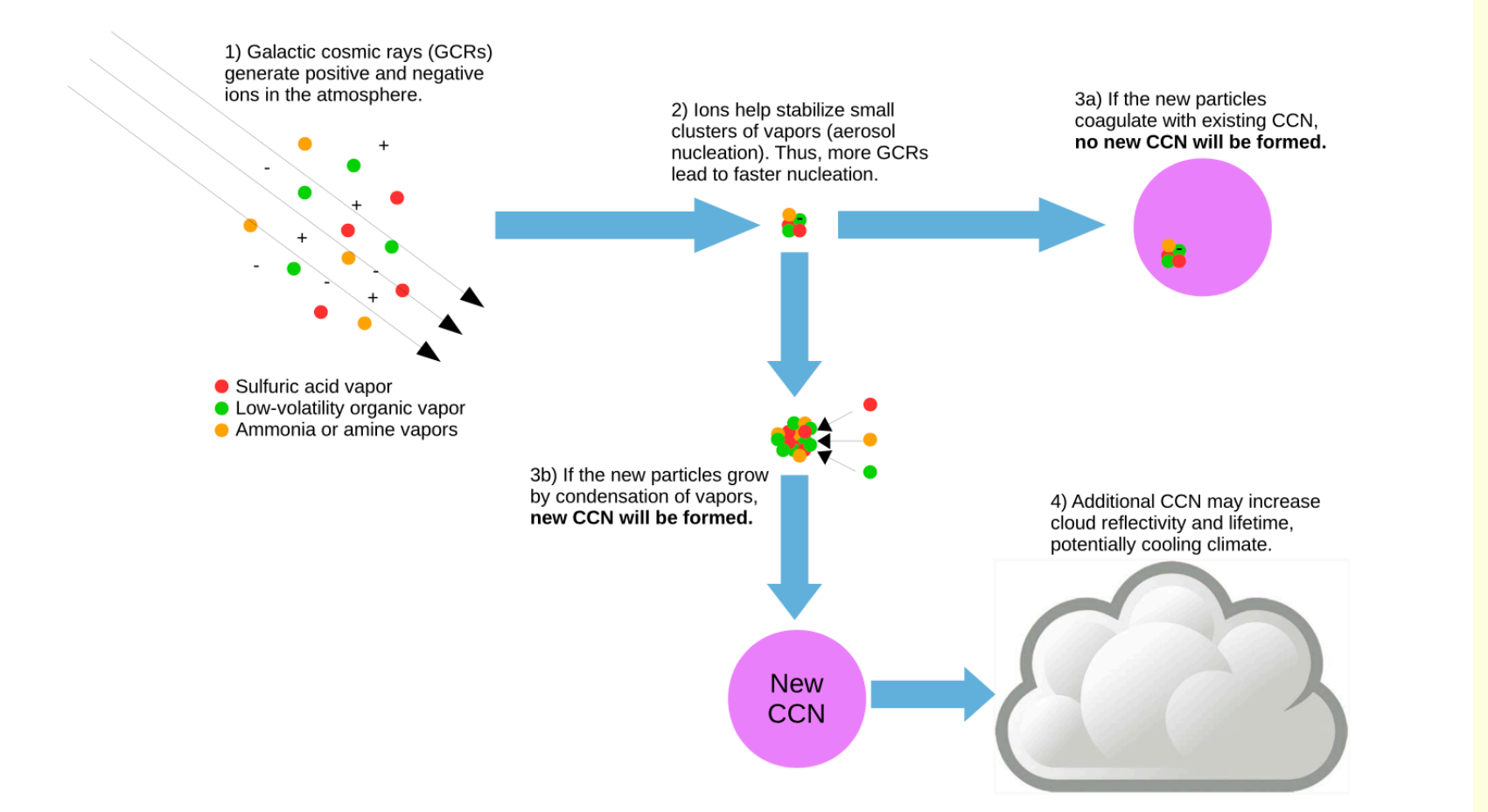


Figure 1. Schematic showing the proposed ion-aerosol clear-sky mechanism of galactic cosmic rays (GCR) affecting cloud condensation nuclei (CCN) and clouds. The degree to which GCR modulate nucleation (steps 1 to 2) and the balance between coagulation losses and growth to CCN (steps 3a and 3b) determine how much GCR can modulate CCN concentrations and potentially cloud properties.

Pierce 2017

However, this point can be countered by the fact the locations with high latitudes, such as Antarctica, do experience different weather conditions that can be attributed to cosmic rays. A 2017 study took measurements of atmospheric electric current density and observed how rates of snowfall changed with cosmic rays. The researchers found that both low and high clouds were correlated with cosmic ray flux, by 23% and 8% respectively (Kumar *et al.* 2017). It could be the case that there is some unknown mechanism that explains the correlation between clouds in low latitude areas and cosmic rays. Even if the ion-aerosol clear-air mechanism itself is insufficient to prove a strong causal link between cosmic rays and clouds, other possibilities exist and should be investigated.

Methods

One problem investigating this connection is that because they are two very different areas of science, the data to study them typically does not come from the same location. For example, the Harrison (2011) study used cloud and GCR data from entirely different countries (the USA and the UK, respectively) and the cloud data are described as "sporadic". Under these conditions, hidden parameters make establishing a causal relationship difficult.

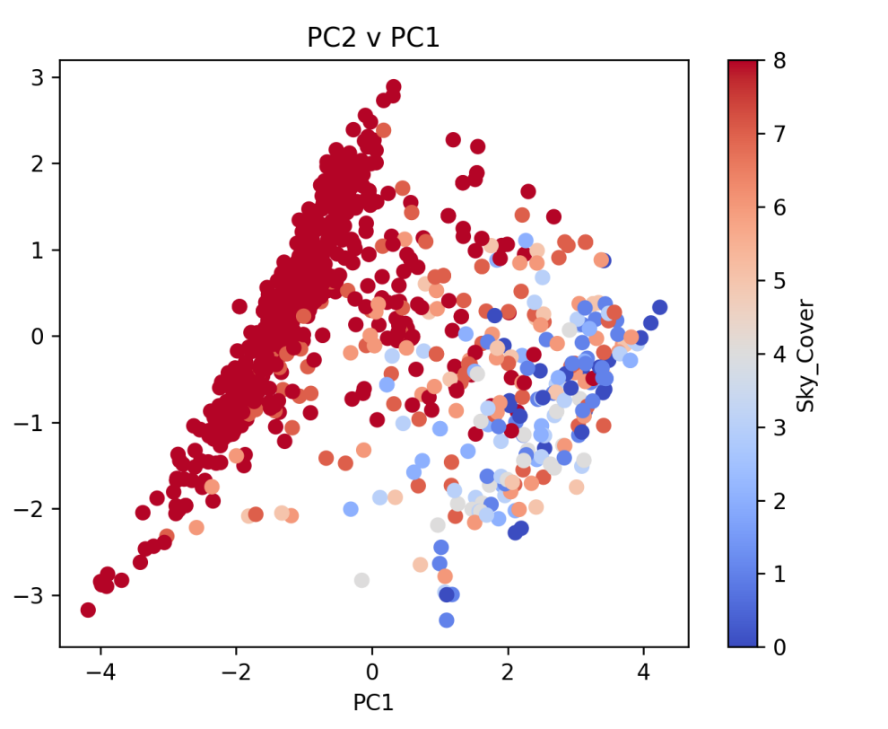
We have the opportunity, because of our relationship with the Mount Washington Observatory, to conduct a controlled field experiment. The Observatory staff records weather data, which we will use in combination with the UNH neutron monitor co-located with the Observatory. The high altitude of the monitor also means we will have greater precision in our measurements. To our knowledge, no study on this topic has been performed using co-located observations.

Initial Result

To investigate this link, we have applied Principal Component Analysis to our combined Neutron Monitor and cloud data. PCA is a dimensionality reduction technique, which can allow you to uncover correlations that would be otherwise hidden. We identify which dimension has the most variance and from there, use vector projections to create orthogonal axes, which are linear combinations of the original data and are known as principal components. Here, the first two principal components account for ~75% of the variance, meaning that PCA is appropriate for this data set. Additionally, the neutron counts contribute significantly to the principal components. The figure below is our initial result, which does show a clear correlation in this space. This is our first attempt to combine cosmic ray and meteorological data. We will be investigating this result further, such as removing the neutron monitor data to see how the other meteorological parameters affect cloud coverage.

Variable	PC1	PC2
Temperature	0.23677887	0.67087
Wind_Speed	-0.36717916	-0.25932
Sunshine	0.44377858	-0.37139
Lowest_Visibility	0.48538352	-0.32295
Clouds_Below_Summit	-0.48043335	0.21118
NM_Total	-0.38178847	-0.44256

PC	Cumilative Variance	
PC1	0.53130484	
PC2	0.74206625	
PC3	0.8458489	
PC4	0.91895899	
PC5	0.97186695	
PC6	1	



Acknowledgments

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References

1. Harrison, R. G. 2004. "The Global Atmospheric Electrical Circuit and Climate." Surveys in Geophysics 25 (5): 441–84.
2. Pierce, J. R., and P. J. Adams. "Efficiency of Cloud Condensation Nuclei Formation from Ultrafine Particles." Atmospheric Chemistry and Physics 7, no. 5 (February 27, 2007): 1367–79.
3. Rogers, R.R. 1976. "A Short Course in Cloud Physics" Pergamon Press
4. Han, Qingyuan, William B. Rossow, Joyce Chou, and Ronald M. Welch. 1998. "Global Survey of the Relationships of Cloud Albedo and Liquid Water Path with Droplet Size Using ISCCP," https://journals.ametsoc.org/view/journals/clim/11/7/1520-0442_1998_011_1516_gsotro_2.0.co_2.xml
5. Svensmark, Henrik, and Eigil Friis-Christensen. 1997. "Variation of Cosmic Ray Flux and Global Cloud Coverage—a Missing Link in Solar-Climate Relationships." Journal of Atmospheric and Solar-Terrestrial Physics 59 (11): 1225–32.
6. Marsh, Nigel, and Henrik Svensmark. 2000. "Cosmic Rays, Clouds, and Climate." Space Science Reviews 94 (1): 215–30.
7. Singh, A. K., and Asheesh Bhargawa. 2020. "Delineation of Possible Influence of Solar Variability and Galactic Cosmic Rays on Terrestrial Climate Parameters." Advances in Space Research 65 (7): 1831–42.
8. Harrison, R. Giles, Maarten H. P. Ambaum, and Michael Lockwood. "Cloud Base Height and Cosmic Rays." Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 467, no. 2134 (October 8, 2011): 2777–91.
9. Carslaw, Kenneth, R Harrison, and J Kirkby. 2002. "Atmospheric Science: Cosmic Rays, Clouds, and Climate." Science (New York, N.Y.) 298 (December):1732–37.
10. Pierce, J. R., and P. J. Adams. 2009. "Can Cosmic Rays Affect Cloud Condensation Nuclei by Altering New Particle Formation Rates?" Geophysical Research Letters 36 (9).
11. Pierce, J. R. 2017. "Cosmic Rays, Aerosols, Clouds, and Climate: Recent Findings from the CLOUD Experiment." Journal of Geophysical Research: Atmospheres 122 (15): 8051–55.
12. Lanci, Luca, Simone Galeotti, Catia Grimani, and Matthew Huber. 2020. "Evidence against a Long-Term Control on Earth Climate by Galactic Cosmic Ray Flux." Global and Planetary Change 185 (January): 103095.
13. Kumar, C P, N. Balan, C. Panneerselvam, Jeni Victor, C. Selvaraj, K.U. Nair, Priya Elango, K. Jeeva, J.C. Akhila, and Subramanian Gurubaran. 2017. "Investigation of the Influence of Galactic Cosmic Rays on Clouds and Climate in Antarctica." Proceedings of the Indian National Science Academy 83 (September): 631–44.