The Relationship between Cosmic Rays and Hurricanes

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[*Abstract*] This paper explores a causal relationship between Galactic Cosmic Ray (GCR) induced ionization and the cloud structure that supports hurricane development. Several observed phenomena can be explained by a relationship between cosmic rays and hurricanes. These are (1) the need for an atmospheric low pressure system, (2) the requirement of strong updraft, (3) and the need for high sustained winds along the ocean's surface for hurricane development; and (4) the disintegration of a hurricane system as it comes onshore and travels over land. An atmospheric low pressure system allows greater penetration of GCRs at the ocean's surface. A strong updraft pulls ocean salt water aerosols high into the atmosphere where they are exposed to very high levels of ionization. High sustained winds at the ocean's surface controls production of ocean salt water aerosols. As hurricanes travel over land, they are starved of marine aerosols which in turn constrain hurricane cloud development & lifetime. This paper presents the hypothesis that ocean salt water aerosols and GCR ionization are primary components of the hurricane formation and intensification process. Surface wind speed drives the production rate of marine aerosols and GCR induced ionization drives the nucleation of marine aerosols and cloud growth.

I. Cosmic Rays

Galactic cosmic rays are high-energy charged particles that originate outside our solar system. About 85% are protons (nuclei of hydrogen atoms), 12% are alpha particles (helium nuclei), and the remainder are electrons and the nuclei of heavier atoms. These cosmic rays typically have energies in the 100 MeV to 10 GeV range. The sun also produces cosmic rays in solar flares or Coronal Mass Ejections (CME). A CME is an explosion in the Sun's corona that spews out solar particles and embedded magnetic fields over the course of several hours. These particles are generally less energetic than GCRs, with energies in the 10 MeV to 100 MeV range.

GCRs strike the Earth's atmosphere, resulting in nuclear collisions that produce a cascade of protons, neutrons & muons, which can penetrate through the stratosphere and troposphere [*Marsh and Svensmark*, 2000]. Ionization in the lower atmosphere (below 35 km) is almost exclusively produced by GCRs, except for the lowest 1 km over land where radioactive gases are the main cause of ionization.

II. Relationship between GCRs and Clouds

Charles T. R. Wilson invented the classic cloud chamber and with it showed that ions behave as cloud condensation nuclei in supersaturated water vapor [*Wilson*, 1927]. GCR flux has been linked to climate variability. *Svensmark and Friis-Christensen* [1997] first reported Earth's cloud cover is strongly correlated with Galactic Cosmic Ray flux modulated by Schwabe solar cycle variations. Refer to Figure 1. They restricted their analysis to data from geostationary satellites over the ocean because cloud cover over the sea behaves markedly different from cloud cover over land. The analysis showed a direct connection between cloudiness and the intensity of cosmic radiation. This analysis has been continued into a second solar cycle uncovering sensitivity towards low clouds and a latitudinal dependence [*Usoskin et al.*, 2004].

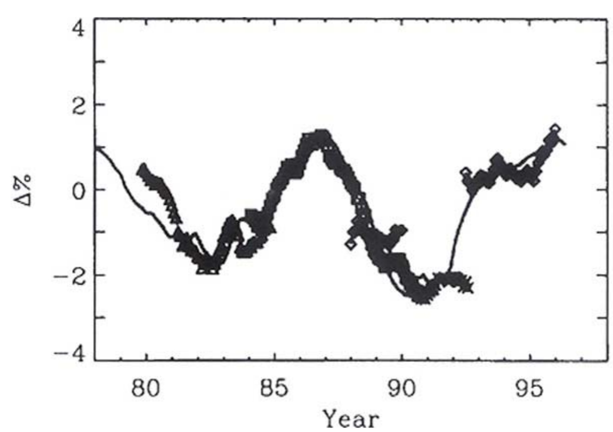

Figure 1. Earth's cloud cover correlates strongly with Galactic Cosmic Ray Flux. Cosmic rays fluxes from Climax (thick curve) plotted against four satellite cloud data sets. Triangles are the Nimbus-7 data, squares are the ISCCP-C2 data, diamonds are the DMSP data, and crosses are the ISCCP-D2 data. [*Svensmark and Friis-Christensen*, 1997]

Ions created by cosmic rays rapidly interact with molecules in the atmosphere and are converted to complex cluster ions [*Hoppel et al.*, 1986; *Gringel et al*., 1986]. These cluster ions may grow by ion-to-ion recombination or ion-aerosol attachment producing cloud condensation nuclei (CCN) at typical atmospheric super saturations of a few percent [*Viggiano and Arnold*, 1995; *Yu and Turco*, 2001]. The droplet distribution of a cloud will then depend on the number of aerosols activated as CCN and the level of super saturation [*Marsh and Svensmark*, 2000]. Experiments with charged raindrops have shown that they are 10-100 times more efficient in capturing aerosols than uncharged drops [*Barlow and Latham*, 1983]. Increases in CCN concentration also inhibit rainfall and contribute to increased cloud lifetime [*Tinsley and Yu*, 2004].

III. Seawater as an Ionizing Agent

As waves break in the ocean, a great number of bubbles are formed underwater. These are referred to as the alpha plume. The bubbles percolate up to the surface forming oceanic white caps and sea foam. One of the properties of ocean seawater is its high surface tension. As air bubbles burst, seawaters high surface tension causes the surrounding water to snap back into the depression left by the bubble. As a result, small droplets of seawater are injected into the atmosphere. The rate ocean salt water aerosols (henceforth referred to as marine aerosols) are generated above the surface of the ocean is controlled by the wind speed [*Monahan et al*. 1983]. Wind speeds greater than 9 m/s, which could be viewed as a minimum threshold, produce great number of spume droplets as the wave crests are torn apart by the wind. *O'Dowd and Smith* [1993] have observed sea salt CCN concentrations up to 100 per cc at wind speeds of 20 m/s. *Monahan and O'Muircheartaigh* [1986] estimated the flux of marine aerosols varies as the cube of wind speed. Hurricanes can generate great surface wind speeds (exceeding 80 m/s) and loft these marine aerosols to very high altitudes in convection updrafts. Marine aerosols can be an important source of cloud condensation nuclei. In addition, the salts in the marine aerosols have the effect of making the water molecules cluster, become more ordered, thus harder to pull apart and evaporate.

Marine aerosols can be raised from the surface of the ocean to great heights by strong updrafts. In September 1997, hurricane Nora traveled up the Baja Peninsula and fell apart leaving behind a cirrus cloud blow off. This gave a team of scientist a unique opportunity to study in fine detail, the unusual cirrus event using the Facility for Atmospheric Remote Sensing (FARS) and the research aircraft and ground based sensors at the Cloud and Radiation Testbed (CART). From the study *Sassen et al*. [2003] concluded the mode of cirrus particle nucleation involved the lofting of sea salt nuclei in strong updrafts into the upper troposphere. This process produced a reservoir of haze particles evolving into halide-salt-contaminated ice crystals.

Seawater is an effective ion transport carrier with a specific electrolytic conductivity of 53 mS/cm at 25 ^{o}C. For example, seawater is used as an electrolyte in magnesium water-activated batteries. This type of reserve battery was developed in the 1940's to meet the emerging military needs for high energy density batteries for applications in electric torpedoes, sonobuoys, weather balloons, air-sea rescue equipment, pyrotechnic devices, marine markers and emergency lighting. Seawater reserve batteries have been built that produce up to 460 kW of power [*Koontz and Lucero*, 2002].

Marine aerosols have natural properties that make them very efficient at capturing nuclear particles within the GCR particle cascade, thus localizing the ionization site. Heavy nuclear particles (protons & neutrons) easily cut deep through the atmosphere dissipating their energy within a very long particle shower where the charge quickly bleeds off and dissipates into the atmosphere. Water is a natural shield to nuclear particle radiation. When high-energy nuclear particles encounter water, they will dissipate the bulk of their ionization energy at a relatively thin penetration depth (referred to as Bragg peak). Refer to Figure 2. At the Bragg peak, the interaction time becomes larger and the value of the energy transfer is at its maximum [*Weber*, 1996]. Fast nuclear particles must be slowed before they are captured. Light nuclei, such as hydrogen (contained in water), are efficient at slowing down these particles through elastic scattering. Other atoms (boron,

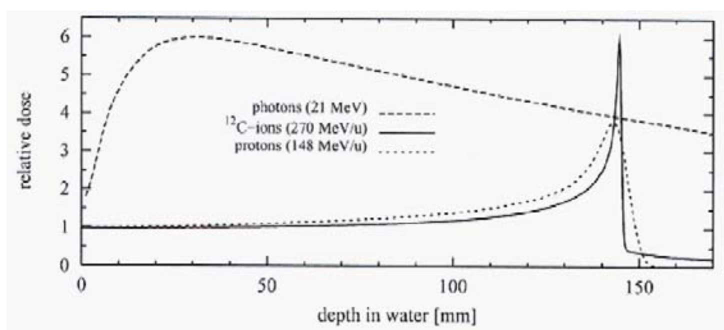

Figure 2 defines *protons* (the main component of GCRs), *heavy ions* (such as carbon ions) and *photons* (such as X-Rays) interact passing through a column of water. The heavy charged particles (protons & ions) are able to cut easily through objects and dissipate significant energy at a penetrated depth (referred to as Bragg peak). [*Weber*, 1996]

cadmium, chlorine, iron, fluorine, lithium and potassium) are very efficient at absorbing nuclear particles once they have been slowed down (thermalized). Seawater, which contains chlorine (~19,400 ppm.) and potassium (~392 ppm.) at 3.5% salinity, provides dramatic improvements to the capture efficiency over pure water (e.g., evaporated ocean moisture). As a result, GCR interactions with lofted seawater droplets localize and concentrate the ionization within the aerosol/cloud structure.

IV. Recent Experimental Studies

It has been suggested that trace amounts of sulfur dioxide in the Earth's atmosphere might be the primary contributor to GCR induced aerosol nucleation which condenses to form clouds. Recently *Svensmark et al*. [2007] conducted experimental studies of aerosol nucleation in air containing trace amounts of ozone, sulfur dioxide and water vapor. The results showed the nucleation process under atmospheric conditions is proportional to the ion density. In other words, cloud cover increases when the intensity of GCR ionization increases and decreases when the intensity declines.

In this paper, I suggest that nucleation of marine aerosols is the primary contributor of hurricane cloud formation. This hypothesis could be tested through a similar experimental study.

V. Low Atmospheric Pressure Systems

The development of a low atmospheric pressure system is one of the observed parameters used by hurricane forecasting experts to predict hurricane development. Hurricane intensity is often measured as a function of barometric pressure. Areas of low pressure are favorable to the rising air that feeds hurricane development. Low Caribbean sea level pressures correspond to more frequent and more intense Atlantic hurricanes and the low pressure systems precede the hurricane activity by several months [*Landsea et al*., 1999].

One phenomenon that can explain hurricane development and rapid growth of cloud structures that support hurricanes relates to increased GCR penetration depth. As air molecules thin out in an atmospheric pressure low, cosmic rays and the shower of secondary particles they spawn are able to penetrate deeper through the atmosphere resulting in a surge of ionization near the Earth's surface.

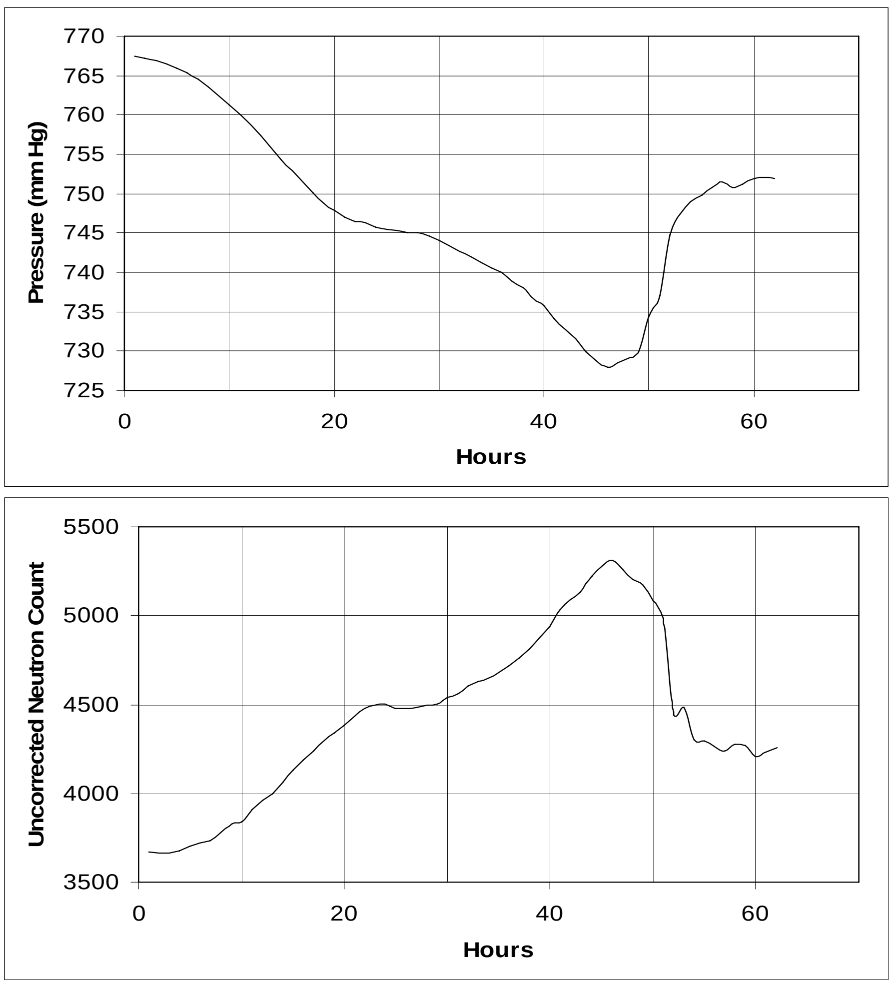

Figure 3. Compares the drop in atmospheric pressure with a surge in GCR penetration during the Thule, Greenland storm. The graph covers the storm period from 1000 UT on 18 February 2005 through 2300 UT on 20 February 2005. [*Bartol Research Institute Dataset*, 2005]

The Bartol Research Institute operates an 18-

tube NM-64 neutron detector array in Thule, Greenland. The monitoring station is located at 76.5 N latitude, 68.7 W longitude and resides at an elevation of 26 meters. A severe storm passed through Thule, Greenland on 18-20 February 2005. During the storm, a pressure drop of 39.5 mm Hg was observed which resulted in a 44.8% increase in detected neutrons. Refer to Figure 3. Neutrons are produced by collisions of cosmic rays with the atmosphere. The neutron counts are indicative of GCR penetration depth.

A causal relationship may exist between the development of low barometric systems and the increased ionization of marine aerosols at the ocean's surface.

VI. Strong Updrafts

The development of strong updrafts is one of the observed parameters used by hurricane forecasting experts to predict hurricane intensification.

Hot towers are tall precipitation towers in the hurricane's eye wall. They produce rain clouds at the top of the troposphere reaching approximately 15 kilometers. Recent research by *Kelley et al.* [2005] showed hurricane intensification was related to the development of hot towers. If the frequency of tall precipitation in the eye wall is at least 33%, there is an 82% chance of wind intensification. Otherwise intensification drops very dramatically.

As a tropical depression transforms into a hurricane, the action is no longer limited to the ocean's surface. Warm moist marine aerosols are uplifted from sea level to heights ~ 15 kilometers. The exposure of the marine aerosols to cosmic rays at these elevations produces exposure rates ~ 2,000 times greater compared to the exposure rates at the ocean's surface. Refer to Figure 4. Since aerosol nucleation is a function of ion density, GCR induced ionization can explain the rapid expansion of the cloud structure that feeds hurricane growth.

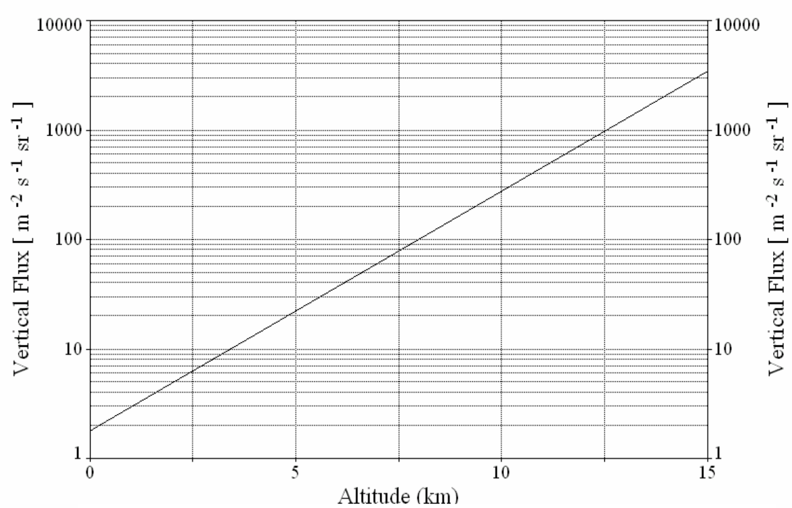

Figure 4. The solid line show vertical flux of cosmic rays (protons, neutrons) in the atmosphere with energy above 1 GeV. [*Yao et al.*, 2006]

A causal relationship may exist between strong updrafts and the growth of the cloud structure that supports hurricane development. This process may also create a feedback loop where great updrafts that pull marine aerosols to extreme heights (e.g., 15 kilometers) increases the hurricanes wind speed which in turn causes a greater release of marine aerosols that feeds the expansion of the hurricane cloud structure.

[As a sidebar, GCR ionization may also explain the effectiveness of cloud seeding programs. Hygroscopic cloud seeding programs infuse salt crystals (calcium chloride) into the cloud base. Strong updrafts pull the crystals up into the clouds where the salt dissolves into the cloud moisture. These salt water aerosols are exposed to GCR induced ionization which enhance aerosol nucleation and cloud growth & lifetime.]

VII. Strong Surface Winds

Wind speed is an observed parameter used by hurricane forecasters to define hurricane intensity. Storms grow from tropical depressions with sustained winds of less than 17 m/s; into tropical storms with sustained wind speeds of 17-32 m/s; into hurricanes with sustained wind speeds greater than 33 m/s.

The increasing ocean surface wind speeds release a strong positive feedback loop. The production rate of marine aerosols is a function of the cube of the wind speed. The increasing surface wind speed release ever increasing marine aerosols that feed storm development. Without the higher surface winds, aerosol production will be limited and unavailable to interact within the GCR ionization process.

A causal relationship may exist between increased ocean level wind speeds and increased marine aerosol production that feeds hurricane cloud production.

VIII. Land Falling Hurricanes

Hurricane strength dissipate rapidly after landfall. The storm leaves behind a weak weather system that generally produces significant levels of rainfall. One parameter that can explain the rapid reduction in hurricane intensity is the loss of continued access to marine aerosols. When a hurricane comes on land, it not only loses access to evaporated ocean moisture but also to marine aerosols. Without access to marine salt water aerosols; aerosol ionization, nucleation and cloud growth will diminish. A causal relationship may exist between land falling hurricanes and reduced aerosol production affecting cloud structure sustainment and lifetime.

IX. Summary

This paper presents the hypothesis that marine seawater aerosols and GCR induced ionization are primary components of the hurricane formation and intensification process.

Galactic cosmic rays are high-energy particles originating outside our solar system. Energetic collisions with Earth's atmosphere produce a cascade of protons, neutrons, muons and other lighter particles. Over the oceans, GCRs are the source of ionization in the lower atmosphere.

Ionization of aerosols by cosmic rays produce cloud condensation nuclei (CCN), the building blocks of clouds. Charged raindrops are 10-100 times more efficient in capturing aerosols then uncharged drops. Increases in CCN concentration inhibits rainfall and contributes to increased cloud lifetime.

Seawater is a good ion transport carrier. The salt in marine aerosols makes water molecules cluster, become more ordered and as a result harder to pull apart and evaporate. Seawater is very efficient at capturing high energy nuclear particles due to its inherent Bragg's Peak properties. Due to these properties, seawater aerosols can become a concentrated ionization site for GCRs. Marine aerosols are injected into the atmosphere at wind speeds greater than 9 meters/second. The production flux rate of marine aerosols from the ocean's surface varies as the cube of the wind speed.

Several observed phenomena can be explained by a relationship between cosmic rays and hurricanes. These are (1) the need for an atmospheric low pressure system, (2) the requirement of strong updraft, (3) and the need for high sustained winds along the ocean's surface for hurricane development; and (4) the disintegration of hurricanes as they come on shore and travel over land.

Air molecules thin out in atmospheric low pressure systems. This allows greater penetration of GCRs and ionization of marine aerosols at the ocean's surface.

The aerosol nucleation process is proportional to the ion density. Strong updrafts pull warm marine aerosols high up from the ocean's surface where exposure rates of GCR ionization are radically greater. At the top of 15 kilometer hot towers above the eye of a hurricane, the GCR exposure rate is 2,000 times greater than at the ocean's surface.

Hurricanes can only form if there is strong sustained wind speed at the ocean's surface. Surface winds provide a strong feedback loop supporting hurricane intensification. Marine aerosol production rates are a function of the cube of wind speed.

As hurricanes come onshore and travel over land, the storm system becomes starved of marine aerosols. Without access to the ocean and the extracted marine seawater aerosols; aerosol ionization, nucleation and the hurricane cloud structure diminishes.

Acknowledgement

Neutron monitors of the Bartol Research Institute are supported by NSF grant ATM-0527878.

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