The Mystery of Cloud Electrification

How precipitation develops, evolves and is moved by airflow at different levels may explain hurricanes' lack of lightning

Robert A. Black and John Hallett

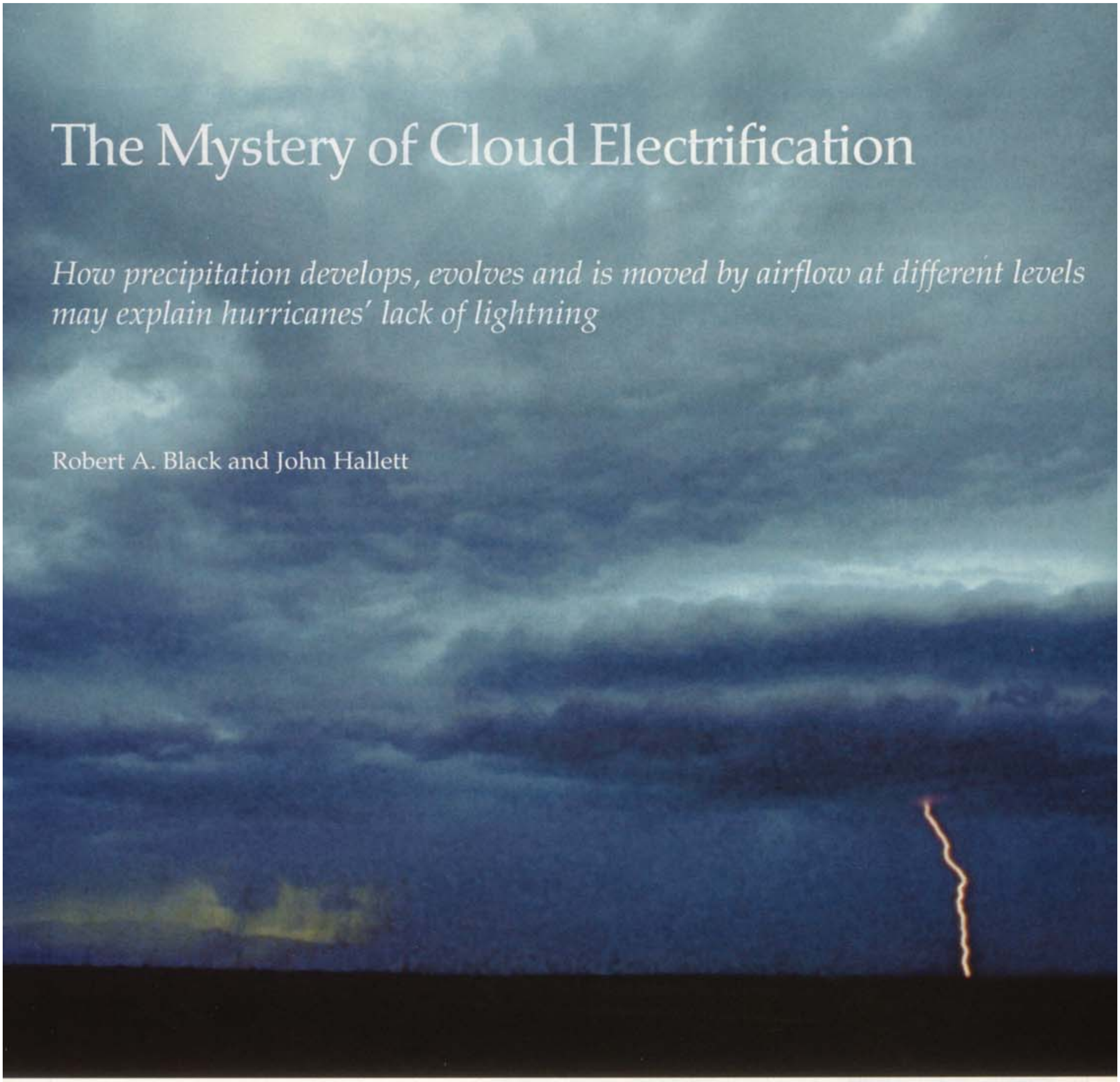

Figure 1. Lightning is known on occasion to transfer charge with current approaching hundreds of thousands of amperes between cloud and ground in a few microseconds, but how does this charge develop? Further, why do some cloud systems, such as this *cumulonimbus* over eastern Colorado, become very lightning productive, whereas other large cloud systems, such as a hurricane, produce very little lightning? The authors find that charge

Poor Captain Nemo met a stroke of bad luck in the Gulf Stream: He and his crew aboard the *Nautilus* encountered a rare type of hurricane—one with abundant electrical activity. A Midwest squall line can generate lightning over an extended period at a rate of more than a stroke per second; a hurricane, on the other hand, rarely produces a stroke more often than every 10 minutes. Why the difference? Part of the answer has been made clear by recent research, including fly-throughs of both types of storms by instrumented aircraft. But storm clouds still hold many mysteries, making the exploration of cloud electrification a rich and fascinating (and often exciting!) field of atmospheric science.

From a functional perspective, lightning is well understood. In the case of a cumulonimbus cloud, the most common thunderstorm cloud, earth and cloud effectively acquire opposite electrical charges, and the air between them serves as an insulator. When the separation of charge aloft is sufficiently large, an ionized path is formed between the cloud and the ground, and a lightning discharge occurs, with the charge transferred from the lower part of the cloud (usually negative) to neutralize the induced positive charge on the earth below. The more fundamental question, however—why is there a lower-level negative charge in the cloud and a positive charge above?—has been more difficult to answer. Further, why do some clouds achieve the charge separation that produces lightning and others not? And why do some produce lots and others little?

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development in cloud systems depends on a proper mix of water and ice particles, which is in turn dependent on powerful convection.

Differences in the lightning productivity of various systems almost certainly lie in their composition and internal motion. In particular, though some have argued that lightning very occasionally may be produced by clouds warmer than 0 degrees Celsius, the presence of ice particles appears to be required for the development of strong electrical fields and lightning. Recent observations suggest further that not just any ice particles will do and that convection in the cloud is fundamental to the formation of the right type.

Understanding how clouds generate lightning is of more than academic interest. Prediction is vitally important for satellite launches, for example, where a single unanticipated stroke can result in the loss of hundreds of millions of dollars, yet unnecessary delays are also costly. Detection of electrical activity may also prove useful in weather forecasting, since it indicates stronger convection and an intensifying system. Finally, because the cirrus clouds produced by strongly convective systems have a profound effect on the earth's radiation balance, an understanding of how they form may prove fundamental to accurate modeling of global warming.

Clouds from the Ground Up

To understand how a cloud becomes electrically charged, it is first necessary to know what clouds are made of and how they form. The answers to these questions can be gained empirically by sampling cloud particles from aircraft, by simulation in the laboratory or by inference from optical and microwave measurements. A simple thermodynamic approach tells us that cloud droplets form as ascending air expands and cools below its dew point *(see Figure 2)*. Because the atmosphere always contains sufficient concentrations of hygroscopic nuclei (sea salt, for example), air need only become supersaturated by a few tenths of a percent relative humidity over 100 percent to form a cloud. In a typical cloud, droplets of 10 to 20 micrometers in diameter (a human hair is about 100 micrometers in diameter) readily form in updrafts of a few meters per second. These particles fall through the air at a speed of 1 to 5 centimeters per second, negligible compared with the speed of updrafts, so they remain suspended as a cloud.

Drizzle and rain range from 0.1 to 4 millimeters in diameter, respectively. In order for such larger drops to form, particles must collide with each other and coalesce, but collisions are unlikely for very small particles. Because droplets in clouds are so small, they have low inertia and follow the airflow around more rapidly falling larger drops—like small insects being swept around a fast-moving car, with only the large ones striking the windshield. The collision process requires drop sizes greater than about 40 micrometers to start, and drops reach this size by nucleation on particles rarely larger than 1 micrometer. Coalescence after collision is most likely in a particular set of conditions: a relatively clean environment, a sufficient supply of water vapor with cloud-base temperatures above 15 to 20 degrees and a collection of nuclei to give the right proportion of smaller and larger drops. An ocean environment such as Hawaii, where the process was first discovered, is ideal.

The fact that clouds are far from symmetrical about a vertical axis makes the simple picture described above somewhat more complicated. Even a cursory observation of the humble cumulus *(cumulus humilus)* shows that most clouds have an upwind and a downwind (or, more technically, an upshear and a downshear) side, plus two sides parallel to the wind shear *(see Figure 4)*. This asymmetry results from the fact that wind speed increases (and sometimes changes direction) with altitude. In extreme cases, the cloud top appears to be almost blown off, which leads to the characteristic anvil shape of deeply convecting thunderstorm clouds. The upshear side is composed of new cloud forming in updraft air that only mixes with surrounding air near the cloud top, where the air becomes negatively buoyant by cooling of the evaporating cloud drops and sinks on the downshear side, a region where larger, precipitation-size drops form and fall out of the cloud.

Supercooling

Water drops can collide and coalesce at temperatures well below freezing: Raindrops can supercool as far as –20 degrees without freezing. This phenomenon, which proves to be fundamental to charge separation within a cloud, can be detected by aircraft mea-

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surements and, indeed, is amply demonstrated by aircraft that ice at these temperatures. Radar can also distinguish liquid water from ice, since raindrops are flattened by air resistance as they fall, changing the radar reflectivity ratio between vertically and horizontally polarized radar beams.

When a mass of air penetrates above the 0-degree-temperature level in a cloud, initiation of the ice phase becomes increasingly likely with decreasing temperature. Freezing is initiated by the relatively rare aerosol particles (fewer than one in 1,000) whose structure bears some similarity to the lattice of an ice crystal. Such particles are of mineral origin (often clay), and are lofted into the atmosphere and sometimes carried thousands of kilometers from their place of origin by prevailing winds. Ice particles appear in significant but highly variable concentrations (a few per liter, on average) at temperatures below about –10 degrees. Their crystalline form depends on temperature. Once they become larger than a few hundred micrometers and fall at speeds greater than 20 meters per second, the crystals capture supercooled cloud drops that freeze as near hemispheres on their surface. As these build up, a porous structure known as soft hail or *graupel* forms *(see Figure 5)*. Graupel has a density about two-tenths that of solid ice.

During experiments done in 1973 in the laboratory at CSIRO in Sydney, Australia, with S. C. Mossop, we discovered that when graupel grows, a very interesting phenomenon takes place. At between –3 and –10 degrees, depending on the number and size of cloud drops present, small ice splinters grow—initially directly from vapor and ultimately by accretion—to produce even more crystals. These secondary crystals result from the accretion and freezing of a special class of cloud droplet that happens to impact on droplets that were collected and frozen earlier in a rather irregular way—a bit like the structure of soot. Such droplets freeze symmetrically from top and bottom as they lose heat to the substrate and the air, giving rise to an increase of pressure in the entrapped water—somewhat like the bursting of freezing water pipes. If the temperature is too cold (below about –10 degrees), the process does not work because the initial ice formed is too defective and deforms under the

Figure 2. Cumulus cloud over the Florida Everglades *(top)* grows when moist air from the Gulf of Mexico and the Atlantic Ocean rises over land heated by the sun. As the water-vapor-laden air expands, it cools and the vapor condenses on minute particles, forming the cloud we see. Because the convecting air rises rapidly (much faster than the cloud particles fall), the droplets are carried with the air motion and rise above the freezing level. The same cloud continues to develop and reaches the *congestus* stage *(middle)*, during which precipitation formation is in its initial stage. A cumulonimbus cloud *(bottom)*, such as this example over Spain, has powerful updrafts capable of carrying water drops well above the freezing altitude, where they become supercooled and eventually form ice particles. (All photographs courtesy of the authors except where noted.)

increasing pressure; if the temperature is too warm (above about –3 degrees), the drop spreads out on impact and fails to form a sufficiently thick ice shell to sustain the pressure. The exact mechanism of ice ejection is still unclear, but crystals collected in flight under these conditions are in the form of ice columns, some 20 micrometers in diameter and 100 micrometers long.

This process leads to an exponential growth in the concentration of ice in a cloud until all the water in the downshear region takes on the ice phase, called *glaciation*. Later experiments suggested that this is a possible origin of charge separation. Simulated graupel moving through a cloud of supercooled drops and ice crystals charges significantly, with the sign and rate of the charge depending on the amount of cloud water and the temperature. Crystals bounce from the growing graupel, leading to a separation of charge by a process that is still far from clear.

The surface of a growing graupel particle is quite a complex terrain, as it is covered in an irregular way by accreted droplets in various stages of freezing—a process that takes some one-hundredth to one-tenth of second, depending on the droplet size. During the freezing process, the droplet maintains a temperature near 0 degrees because of the release of the latent heat of freezing; therefore it has a higher water-vapor pressure. The falling graupel particle itself is heated above ambient temperature and approaches 0 degrees at a sufficiently high accretion rate. Thus the local surface is bathed in vapor in a very complex pattern of local supersaturation, leading to a surface structure of great complexity on a molecular scale—the graupel particle is growing from the vapor in some places and evaporating in others. The impacting crystals bounce under a wide spread of conditions, and it is still a bit of mystery which conditions are best for charge transfer—or, indeed, whether the same charge is always transferred under a given set of environmental circumstances.

In any event, the graupel particles, which have one charge, fall faster than smaller ice crystals with the opposite charge, giving rise to a dipole—a slanted one, if the updraft were formed in a wind shear. (Other types of charge separations, including tripoles and multilayered charge distributions, can develop but are beyond the scope of this article.)

Figure 3. Wind velocity aloft is greater than at the surface, causing this cumulus cloud, viewed perpendicular to the wind direction, to have its upper parts displaced in the downwind direction, called *shear.*

How Much Charge Is Needed?

By measuring the radiation field of a discharge, we can accurately determine a lightning stroke's current and the way it changes with time. Currents can range from several thousand to several hundred thousand amperes delivered in times from microseconds to hundreds of microseconds; the charge transferred per flash is a few to tens of coulombs.

This imposes specific limitations: Since typical thunderstorm charge densities are on the order of 10 coulombs per cubic kilometer, the particle interactions described above must take place over sufficient time and in a large enough volume to generate sufficient charge. Further, the cloud must be deep enough to cover the range of temperatures for charge separation, and the generation process must be able to pro-

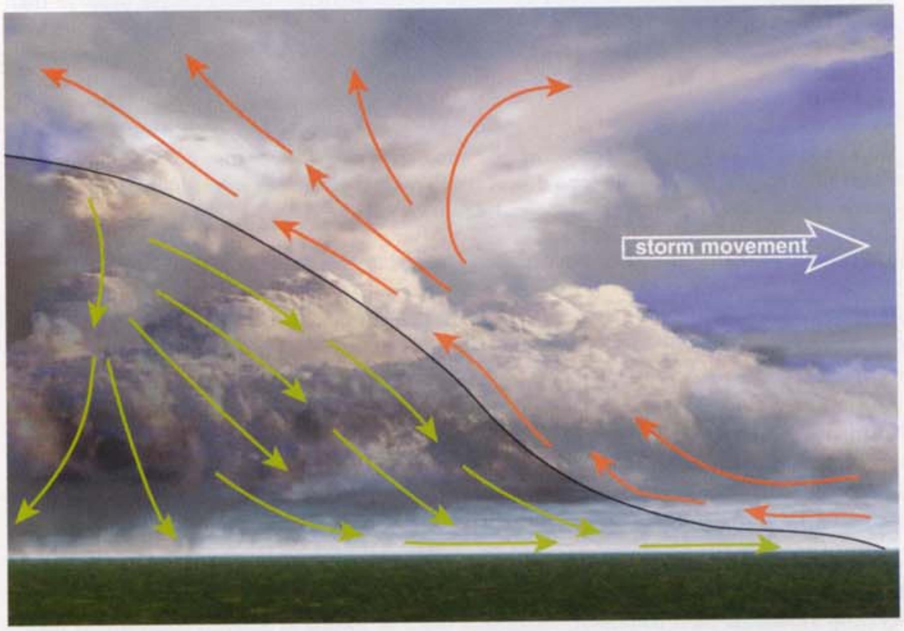

Figure 4. Convection in a cumulonimbus cloud, viewed here perpendicular to wind direction, follows the shear angle. Rising warm air moves upward and to the left, the *upshear* side, while sinking cooler air moves downward and to the right, the *downshear* side. Precipitation falls out on the downshear side. In this example the winds aloft are sufficient to blow the top of the cloud off, forming an "anvil" consisting almost entirely of ice particles.

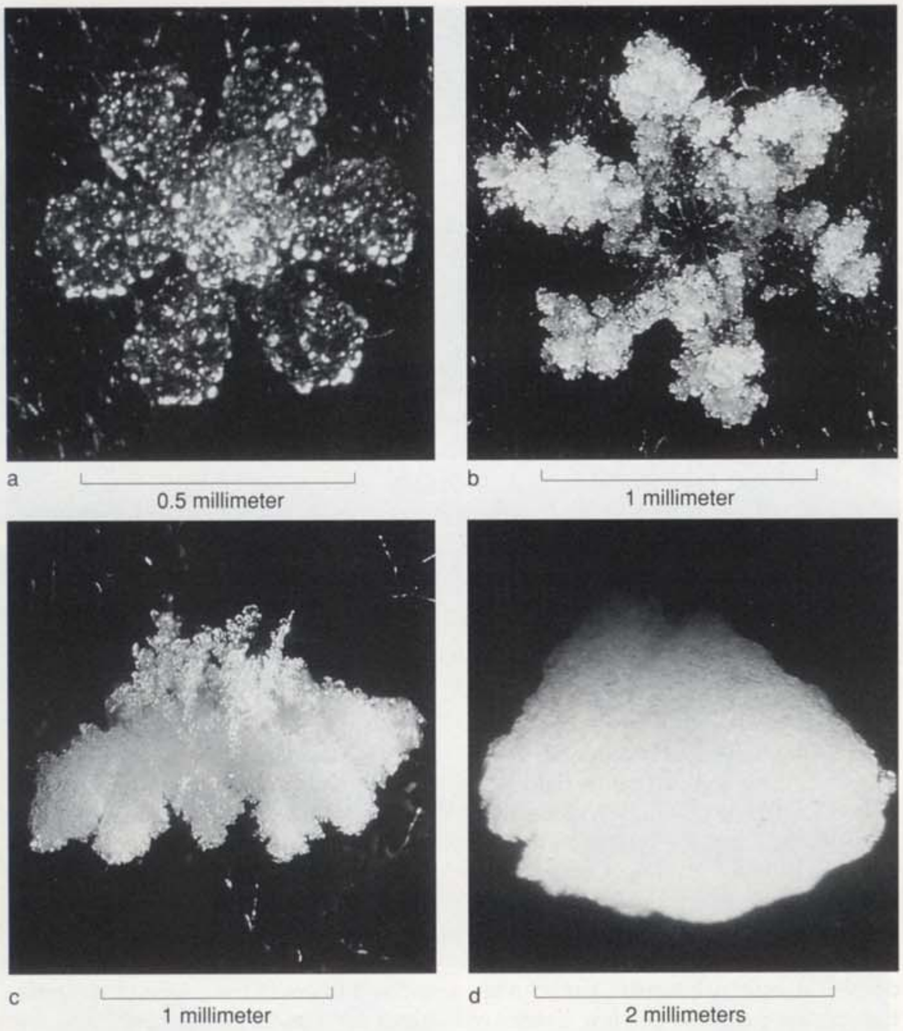

Figure 5. Snow crystals approach the form of soft hail, or *graupel*, as they grow through accretion and freezing of supercooled cloud droplets. Because they are more massive than the droplets, the accreting particles fall more rapidly, colliding with the droplets, which freeze individually. In the first image *(a)*, the original snow-crystal hexagonal shape is still evident. In the second *(b)*, only the basic shape remains. Individual frozen droplets can be seen in all these photographs. As more droplets freeze on the underside of the particle *(c)*, its porous consistency (about two-tenths the density of solid ice) becomes evident. Because the ice accumulates mainly on the downward-facing side, the graupel often grows in a conical shape *(d)*, with the base of the cone down. (With respect to the fall direction of the particles, images *a* and *b* are in plan view, and *c* and *d* are vertical.)

vide a flash rate in excess of 10 per minute, a frequency readily observed in more severe storms. Small clouds of a cubic kilometer or so clearly will not work; 3 to 4 kilometers horizontally and 5 to 8 kilometers vertically are the minimum dimensions.

Shear also plays an important role in the process of charge separation. Recent observations made by research aircraft flying through thunderstorms demonstrate the asymmetry of cloud vertical velocities *(see Figure 7)*. They also show that the supercooled water drops are confined to the upshear, high-updraft region. The downshear region is composed of ice, primarily in the form of vapor-grown ice and aggregates, initiated at the highest, coldest region of the growing cloud. In between lies the most interesting region, with a transition from entirely supercooled water to cloud composed almost entirely of ice crystals, the ice particles consisting of graupel upshear, changing to graupel plus ice crystals, then to ice crystals (columns and needles) and snow downshear *(see Figure 7)*. Charge separation can only take place where the cloud has the optimal mix of particles—a region that may extend only a few hundred meters horizontally. The boundaries of the region, however, are far from stationary. An observational aircraft suffers substantial turbulence during a transect, implying a moderate mixing rate of the ice into other cloud regions. The upshear cloud region is constantly renewed; otherwise the system would quickly cease to exist.

More Complicated Geometries

The airmass thunderstorm frequently forms from convection in moist air overlying a relatively homogeneous land surface that is heated by the sun, with storm activity beginning in the late morning or early afternoon. A similar phenomenon takes place as cold air passes over a warmer ocean, although here the diurnal influence of solar heating is minimal. The cloud that eventually grows into a thunderstorm is but one of many smaller clouds that is especially favored by some surface feature of surface heating or topography overland or a warm spot in the ocean. These systems almost always have vertical shear of the horizontal wind: The charge is usually (but not always) plus above, minus below. The life cycle of the thunderstorm phase is measured in minutes, with the number of lightning flashes ranging from one to a few tens of flashes.

As we consider thunderstorms of longer time scale and larger size, other complications arise. Once a storm has developed, the cold downdraft, enhanced by falling precipitation, descends to the surface and spreads out, initiating other storms, particularly if the cold air (or *gust*) front should pass beneath a neighboring cloud or collide with another gust front from another storm. A sequence of storms may develop, sometimes related to the local topography. If the anvil of a well-developed thunderstorm cloud happens to overlie the newly developing storm, falling ice will rapidly be ingested into the system and may inhibit the orderly development of the electrically charged regions of the single cell, so much that precipitation is produced with little electrical activity *(see Figure 8)*.

Lines of thunderstorms may also develop along cold fronts and sea-breeze fronts. Here the wind direction aloft is often such that the anvil is carried away from newly developing cells, which can evolve as individuals uninfluenced by ice produced by their neighbors. The squall line of the Kansas/Oklahoma/Texas region is a special example. They generally follow a weak, inactive cold front and are fueled by water vapor drawn from the Gulf of Mexico. These systems evolve as a complex flow in three dimensions

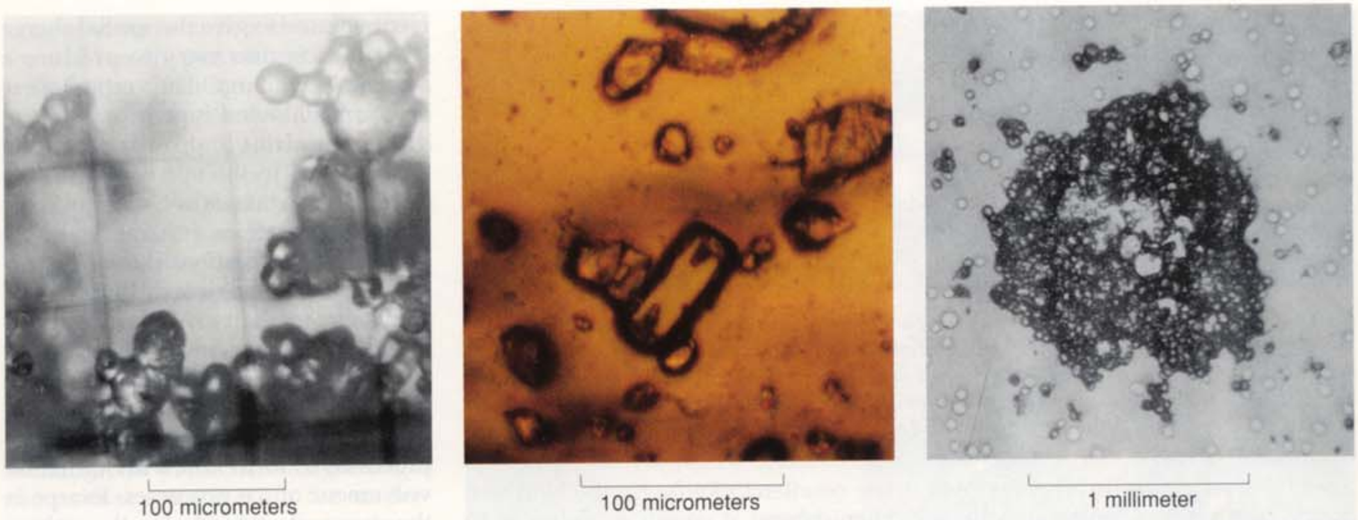

Figure 6. Graupel-particle growth can be simulated in the laboratory, as shown in this photograph of a particle 300 micrometers across *(left)*. The sample was grown in a wind tunnel from supercooled cloud drops 10 to 20 micrometers in diameter, which are visible as frozen individual drops on the particle. Different geometries of accretion and freezing are evident in this example; a few of these cause symmetrical freezing from top and bottom, leading to shattering of the drop. (Photomicrograph by Ya Yi Dong.) Particles can be collected by aircraft penetration of a cloud, in this case *(middle)* at the –8-degree level of a Florida thunderstorm. At the center is a pristine vapor-grown secondary-ice column. A graupel particle *(right)* and the cloud droplets from which it is growing can be seen in this photomicrograph of a sample collected by aircraft penetration of a Montana thunderstorm. (The last two images are of plastic replicas.) Charge separation develops where ice crystals collide with graupel growing by accretion of supercooled cloud droplets and then bounce off.

with ice aloft being rapidly removed in the anvil and the moist air from below feeding upward into an updraft with speeds that are often high enough to grow grapefruit-size hailstones from large amounts of supercooled water. The updrafts need to move at about 50 meters per second to accomplish this feat. Such updrafts carry supercooled rain and cloud drops to considerable heights, with temperatures as cold as –20 degrees.

These storms have intense electrical activity, are essentially steady state (for many hours) and travel sequentially along the moving front. The electrical activity probably evolves from a sheet of mixed particles as in the air-mass thunderstorm, but the squall line has much greater horizontal and vertical extent and is also probably highly convoluted (as suggested by radar echo). The amount of charge separated depends on the relative collision rates of graupel and crystals of different size; the larger hailstones grow with a wet surface and probably do not influence the charge separation all that much, although they may be indicative of extensive regions of smaller graupel of optimum size elsewhere.

Hurricane Dynamics

All of the systems described thus far contrast sharply with a hurricane, which is almost by definition a storm with somewhat circular symmetry.

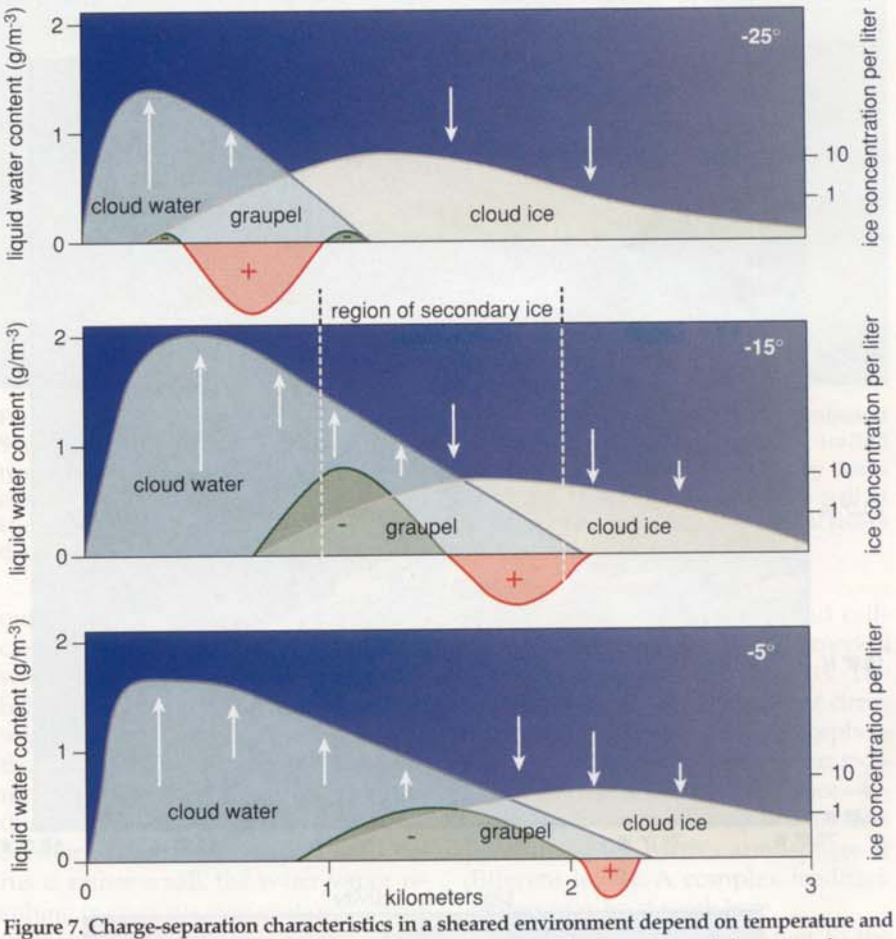

Figure 7. Charge-separation characteristics in a sheared environment depend on temperature and cloud liquid-water content, as shown in these schematics developed from laboratory observations (data from Saunders and Peck 1998). The vertical vectors show up- or downdraft velocity. Graupel grows only in the region where liquid water exists, and charge separation occurs only where graupel and ice are growing. Secondary ice-crystal production takes place under the appropriate conditions in the –5-degree scenario, and the crystals may be carried to higher levels by the updraft. Thus in both the coldest and warmest conditions, little negative charge develops.

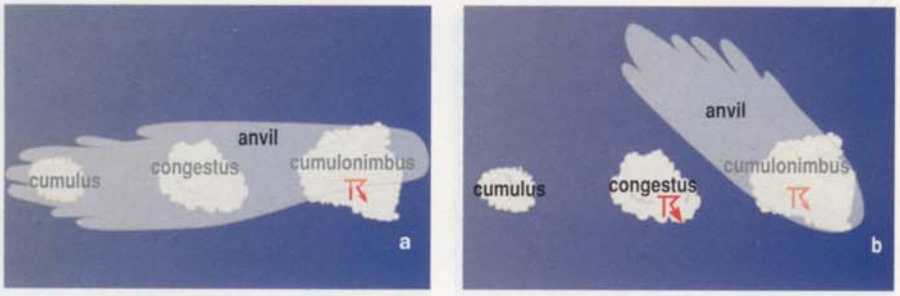

Figure 8. Orientation of a cumulonimbus anvil to other developing convection (seen in plan view) may determine whether new thunderstorms develop. When the anvil overtops newer convection *(a)*, ice particles fall from the anvil and seed newer convection below, preventing water vapor from reaching altitudes where it can become supercooled. But when the anvil blows away from newer convection *(b)*, the system is free to develop and may become electrically active.

Tropical hurricanes form over ocean waters with a surface temperature in excess of 26 degrees. From a satellite, a cloudless eye of some 10 to 30 kilometers in diameter is usually evident, and precipitation in the eye wall, fueled by moist inflow at low altitude, is intense *(see Figure 10)*. Cloud-base temperatures in the eye wall are high—often greater than 22 degrees—and surface winds rotate counterclockwise (in the Northern Hemisphere) at speeds in excess of 50 meters per second. At the top of the storm and well outward from the eye, the cirrus layer outflow is clockwise.

Aircraft flights through hurricanes do show the presence of electrical fields, but the graupel–liquid water–ice turns out to be at the wrong place at the wrong temperature and in insufficient volume to give the spatial charge distribution necessary to produce a lightning discharge. The vertical shear of horizontal wind is present in the region of updraft and outflow all the way around in the eye wall—but the supercooled water is not, so there is not enough separation of charge.

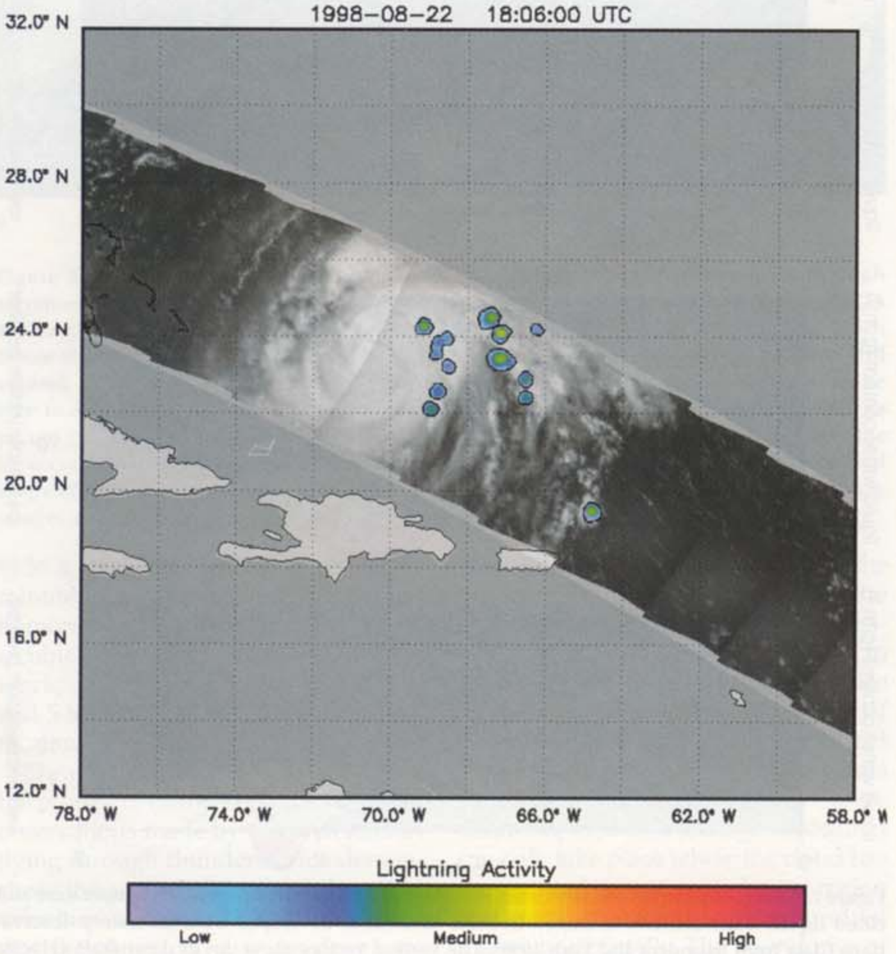

Figure 9. Image of hurricane Bonnie off northeast Cuba on August 22, 1998 from the Lightning Imaging Sensor of the Tropical Rainfall Measuring Mission satellite shows lightning activity only in the outer rain bands, with no activity at all in the vicinity of the eye. (Image courtesy of Steve Goodman, NASA/MSFC.)

Aircraft observations show that hurricanes exhibit a dearth both of updrafts greater than 8 meters per second and of supercooled water at temperatures colder than –5 degrees. Warm cloud-base temperatures provide a great depth of cloud for coalescence processes to form rain without the involvement of ice processes. Except in the strongest updrafts near the melting level, there is usually less than half a gram of supercooled cloud water per cubic meter. Even in the eye wall, the typical hurricane has maximum updrafts that are less than 8 meters per second and maximum supercooled cloud liquid-water content less than 2 grams per cubic meter.

In addition, eye-wall updrafts are far from upright; the wind structure in the eye wall forces the updraft outward and upshear relative to the surface *(see Figure 10)*. This, coupled with the radial outflow, allows precipitation formed by coalescence at lower levels to fall out of the updraft before it reaches the melting level. It also allows ice particles formed at higher levels to "seed" the upstream edge of the updraft, thereby ensuring that little supercooled water survives to reach the –10 degree level. This in turn prevents the proper liquid–ice particle mixture from forming at colder temperatures, which is where most of the charge separation takes place in other systems.

Finally, the orbital period of ice in the anvils resulting from convection in the eye wall is only 30 to 40 minutes, so ice is rapidly distributed around the upper eye and thence outward to the whole outer hurricane. Thus hurricanes lack lightning activity both because the vertical velocity is too low to carry supercooled water up to higher altitude and because of an excess of ice, such that even if water were carried up it would be nucleated prior to forming the graupel necessary for charge separation.

The occasional hurricane that is electrically active has strikingly different dynamics from the typical storm. Such systems are often characterized by highly asymmetrical precipitation—sometimes confined to a "supercell" in just one quadrant—and updrafts greater than 15 meters per second associated with the precipitation. Flights through such a system are far less benign than routine hurricane fly-throughs, with much more turbulence. The supercell usually rotates around the eye, and its electrical activity delineates the eye wall. The weaker vertical updrafts result from a more general symmetrical heating around the hurricane and an overall reduction in the available potential energy for convection.

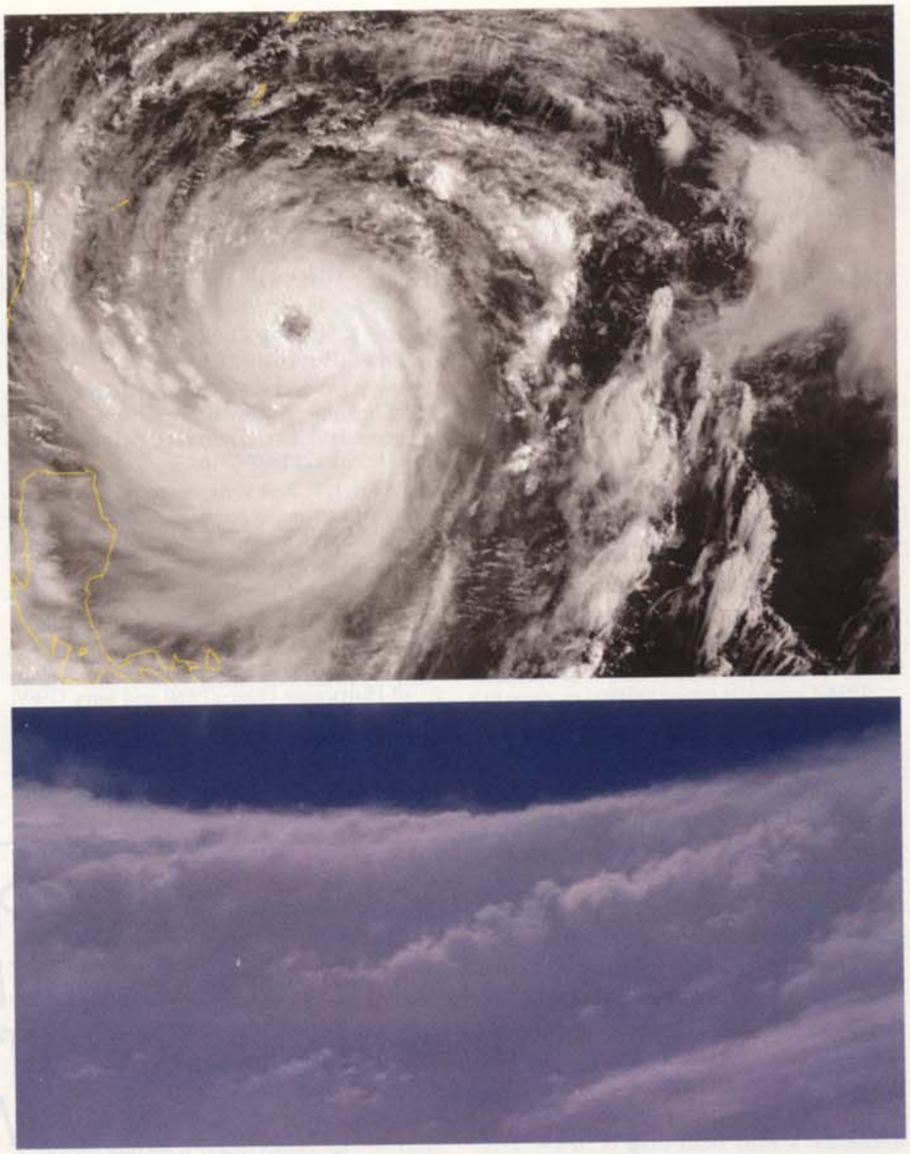

Figure 10. Visible image of 1996 Super Typhoon Herb *(top)* from the Defense Meteorological Satellite Program shows the characteristic spiral band structure of hurricanes (called typhoons in the Pacific). The eye is the cloud-free area at the center, surrounded by dense overcast and tropical cirrus cloud extending far outward. A photograph of the eye wall of Hurricane Olivia taken from a reconnaissance aircraft on September 25, 1994 *(bottom)* shows the diagonal path of ascending air currents marked by striations in the cloud.

Vapor and Global Radiation Balance

Although the prediction of lightning is the primary motivation for understanding cloud electrification, convection and the other mechanisms that produce thunderstorm clouds also may profoundly influence the radiation balance of the earth's atmosphere. Like the better-known greenhouse gas carbon dioxide, water vapor has less impact on incoming radiation from the sun than on outgoing infrared radiation. In the presence of water vapor, the atmosphere is heated at lower levels and cooled aloft. Unlike carbon dioxide, however, water vapor is not evenly distributed in the atmosphere.

Clouds obviously also have a significant influence on the radiation balance, but because of the variable nature of both cloud cover and temperature at various altitudes, the exact influence is very difficult to assess. In particular, the effect of cirrus clouds produced at the tops of the convective systems described in this article depends on the optical depth at various wavelengths, which is in turn influenced by particle size, shape and distribution, cloud spatial distribution, and the amount of moisture and aerosol transported to upper levels. The efficiency of removal of water at lower levels determines the mass flux aloft to form cirrus cloud, and the details of the ice evolution in the critical shear zones determine the size and shape of the particles and their optical properties—processes we cannot yet quantitatively assess on a significant scale. Nonetheless, because it is associated with powerful convective activity, lightning frequency may be related to the input of water vapor into the upper troposphere.

Hurricanes, too, move large amounts of water and water vapor. Much of it may be left as rain along its path, but a hurricane also lofts much water as ice to high levels, detectable as dense cirrus clouds in satellite views of hurricane outflow *(see Figure 10)*. The tops of such clouds reach low temperatures—often well below –50 degrees and occasionally below –80 degrees. This cirrus returns solar radiation to space and influences thermal radiation from lower in the atmosphere. In the overall scheme of things, the area of the earth influenced by immediate hurricane-produced cirrus is rather small; the water vapor resulting from cirrus evaporation, however, may have a somewhat greater effect.

The magnitude of the uncertainties water vapor poses to the earth's radiation budget is probably as great or greater than the contribution of increased carbon dioxide to computations of so-called global warming and calls into question the reliability of numerical models that ignore these effects. The depth and spatial distribution of cirrus clouds near the top of the troposphere influence both the albedo for solar radiation and the radiative flux to space—together with the overall equivalent temperature of the earth's atmosphere at different levels. A complex feedback process may be at work here.

Thus looking for an answer to the simple question of why hurricanes aren't so hot electrically raises questions of a fundamental nature that can lead to techniques and knowledge with much broader application.

Acknowledgments

The authors extend their thanks to all the people at NOAA/AOML and NOAA/AOC who have aided us in our research over the years. Hallett's work has been supported by the the Physical Meteorology Program of the National Science Foundation, Washington, D.C.

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