

Scientific Overview of Cloud Electrification Studies using Aircraft and Radars (CESAR), 2000

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Executive Summary

Observations from lightning–mapping networks, meteorological radars, and storm observers have revealed a correlation between periods of the production of predominantly positive cloud–to–ground (+CG) lightning flashes from convective regions within High Plains thunderstorms and the formation of large hail. While some storms producing large hail do not exhibit such anomalous +CG lightning activity, most storms that do exhibit such activity produce large hail. Much more has been done to address +CG activity in mesoscale convective systems than in severe storms, but in neither case is there yet a good understanding of what causes +CG flashes to occur, or why large hail should be associated with these same processes in severe storms. The basic question to be investigated in CESAR is how localized, mid–latitude convective storms that produce predominantly +CG discharges are different from the much more common situation where CG discharges are predominantly (or entirely) of negative polarity, and how the presence of large hail impacts such polarity. Energetic +CG discharges also occur within trailing stratiform regions of isolated convective systems as well as mesoscale convective systems. With the comprehensive observations proposed for CESAR, we will be able to compare and contrast the nature of these discharges with +CG events in convective regions of severe storms, as well as study and compare the electrical structure of the various +CG–producing systems, all of which have been documented to occur in the proposed CESAR operations area.

A unifying topic in these investigations is the evolution of frozen precipitation, from cloud ice to graupel to large hail, in High Plains thunderstorms. Present charge separation hypotheses rely on the presence of graupel/hail for the generation of strong electrification in these storms. A more complete investigation of hail growth, including the attendant storm dynamics and microphysical processes, is needed to understand both hail generation mechanisms themselves, as well as electrification processes associated with the development of hail. Such investigations are crucial to unraveling the apparent correlation between the production of large hail and the occurrence of +CGs.

A sub–class of +CG flashes are the large peak current positive cloud–to–ground (LPC+CG) flashes. These LPC+CG events occur sometimes within severe, hail–producing storms, but more often within the stratiform regions of (primarily nocturnal) mesoscale convective complexes. Several years of observations confirm that supercell LPC+CGs rarely produce the recently–discovered class of high–altitude discharges named sprites and elves. Yet as these storms undergo upscale evolution into nocturnal MCSs, at some stage sprites and elves suddenly appear. Preliminary data suggest that the key to this transition is the development of an extensive (>50 km horizontal size) dendritic "spider" lightning discharge as a component of the +CG event that is associated with unusually large continuing current,

resulting in substantial charge transfer (≈ 100 C) and energy dissipation. Another objective of CESAR is to obtain more comprehensive data on the relation between LPC+CGs and the occurrence of high-altitude discharges.

Two other areas of investigation lend themselves directly to investigation with the instrumentation proposed for CESAR. These are the role of anvil circulations in thunderstorm electrification and the role of runaway, energetic electron avalanches (as evidenced by bremsstrahlung X-ray observations) on the initiation of lightning. Both of these phenomena are poorly understood.

Deployment of lightning channel mapping systems, instrumented storm-penetrating aircraft, instrumented free balloons, and a triple-Doppler radar network, including two multiparameter radars, is proposed to further investigate the physical linkages between storm dynamics, hail formation, lightning characteristics, storm electrical structure, the production of high-altitude discharges (sprites, elves, blue jets), and processes involved in lightning initiation. We propose to deploy these facilities in the Kansas-Colorado-Nebraska border area from mid-May through mid-August during the summer of 2000 in order to observe the frequent severe convective storms that commonly occur in this area. The result will be improved understanding of the dynamics, microphysics, and electrical character of severe-storm phenomena. This new understanding will form the basis for better utilization of new, state-of-the-art observations of storm structure and lightning activity for public forecast and warning activities.

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1. Program Rationale

1.1 Introduction

In the last 20 years there have been two major field projects that have focused on the complex interaction between thunderstorm dynamics, microphysics, and charging processes that lead to strong electrification and the production of lightning. The Thunderstorm Research International Program (TRIP) concluded several years of field investigations in 1978 and the Convective and Precipitation/Electrification (CaPE) project was conducted in 1991. Both of these projects were conducted in the vicinity of the Cape Canaveral/Kennedy Space Center complex in eastern Florida. The storms that were the focus of these projects were of a warm-based, maritime nature where coalescence initiates the development of precipitation and large hail is a rare phenomenon. Other projects, such as those conducted over the years in Oklahoma, have included studies of storm electricity as ancillary to the primary focus of the projects. Work conducted in the Magdalena Mts. of New Mexico has focused on storm electrification. The storms studied there were a subclass of continental thunderstorms (isolated orographic storms), with severe storms being a rarity.

Studies of the dynamics and microphysics of severe storms producing large hail have included the National Hail Research Experiment (multiple years), the North Dakota Thunderstorm Project (1989), the North Dakota Tracer Experiment (1993), and several projects in Oklahoma. While there has been a small electricity component to some of these projects, storm electrification studies have not been a primary focus and some key observing facilities (lightning mapping, aircraft observations, balloon-borne sensors, or polarimetric radar) have been missing from the data gathering component in each case. In the intervening years since TRIP, several new phenomena have come to light associated with mid-latitude, continental thunderstorms including the occurrence of a high percentage of positive cloud-to-ground (+CGs) flashes associated with certain types of convective activity and hail production, and the

discovery of high-altitude transient optical phenomena, variously labeled as sprites, elves, and blue jets, associated with certain types of +CG lightning. Also, in the intervening years advances in sensing technologies such as lightning mapping systems, the maturation of polarimetric radar technology allowing the determination of precipitation type and possibly concentrations, and improvements in other sensor capability have made more detailed observations of thunderstorm dynamic, microphysical, and electrical characteristics a possibility. This improvement in sensing technology, the lack of previous comprehensive studies of mid-latitude severe thunderstorms, and the discovery of unusual lightning activity associated with some of these storms is the motivation for the proposal of this project entitled Cloud Electrification Studies using Aircraft and Radars (CESAR). While the project title emphasizes the electrification aspects, the project scope includes, on an equal basis, the study of the dynamics and microphysics that attend the development of hail in such storms.

The classic model of thunderstorm charge structure (the positive dipole) developed early in this century is based on lightning-induced electric field changes sensed by instruments on the ground at some distance from mid-latitude thunderstorms. It places a net negative charge layer somewhat above the freezing level, and a more diffuse net positive charge region further above in the upper portion of the storm (e.g. Krehbiel, 1986; Uman, 1987). Since CG lightning is most likely to develop between the lower negative region and the ground, it was not surprising to the early investigators that the predominant CG polarity was observed to be negative. Based on more recent detailed measurements, Williams (1989) established that many thunderstorms exhibit a tripole structure with a weaker positive charge region in the lower portion of the cloud, below the main negative charge center. Williams speculated that this weak lower positive charge center was a factor in strengthening the electric field below the main negative charge layer to the point where negative CG lightning was initiated.

Recent field program activity including balloon-borne soundings of electric fields in storms have led to signs of further complexity in storm electrical structure. For example, Rust and Marshall (1998) showed that the charge structure of storms on the Great Plains often is too complex to be described even grossly as a simple dipole or tripole. Stolzenburg et al. (1994) found that, in the trailing stratiform region of mesoscale convective systems (MCS), the vertical component of electric field and the inferred charge density appear to be relatively uniform over distances of tens of kilometers, but to be stratified into several alternating layers in the vertical. Most recently, Stolzenburg et al. (1998) have synthesized all of their balloon-borne electrical soundings to arrive at a characteristic charge structure that exemplifies MCSs, isolated supercells, and New Mexican air mass storms. Within the updraft core, four charge regions were found: lower positive, main negative, upper positive and upper negative. Outside the updraft, but still within the convective region, they found 6 charge regions with the lower positive region being replaced by a tripolar structure of positive (near cloud base), negative (near 0° C), and positive charge. The remaining three charge regions were as above, but with the charge levels being generally lower in altitude than in the updraft core. They also found that the height of the charge regions within the updraft were dependent on the updraft speed.

The occurrence of +CG lightning has become a topic of considerable interest since the advent of CG detection networks that discriminate positive from negative flashes (MacGorman and Taylor, 1989). While previously thought to be a relatively rare phenomenon, data from these networks have shown that the production of +CGs by thunderstorm systems is common under certain conditions. Several studies have documented examples of storms producing predominantly +CGs, and attempted to generalize to a universal set of conditions responsible for this phenomenon. Among the more recent studies, in which earlier work also is summarized, is MacGorman and Burgess (1994). In this study of 15 storms on four different days, MacGorman and Burgess (1994) noted that (1) the dominant polarity of ground flashes was positive when storms were identified as low-precipitation or classic supercell storms, (2) the dominant polarity changed to negative as the storms changed from low-precipitation to classic supercell storms or from classic to heavy-precipitation supercell storms, (3) large hail usually was produced

during the period in which positive ground flashes dominated, and (4) the majority of severe storms do not produce high densities of positive ground flashes. However there are exceptions to these tendencies. For example, Bluestein and MacGorman (1998) noted one day in which the dominant polarity was negative in a low-precipitation storm and was positive in a classic supercell storm occurring at a different time, but in the same vicinity.

Since popular theories of thunderstorm electrification (Saunders, 1995) involve charge exchange during microphysical interactions between colliding hydrometeors (graupel, snow, cloud ice, supercooled cloud water), it is important that we develop a better understanding of storm dynamics and microphysics to further our understanding of how electrification proceeds. In particular, the CESAR objective of investigating the relationship between the occurrence of large hail and the polarity of CGs in severe storms leads to a number of hypotheses (detailed below) that include (among others) the effects of differential advection, variations in storm dynamics and/or microphysics, in-cloud shear, and larger scale features. In order to sort through the possible competing hypotheses to identify those likely to account for storm electrification (both normal and anomalous) and the polarity of CG lightning, it is imperative to obtain information about the distribution of hydrometeor types and internal storm flow structure related to the development of hail along with detailed observations of electric fields, field changes, and CG locations and polarity.

The past several decades have seen significant advances in understanding the growth of hail in large High Plains convective storms. For a summary of understanding resulting from extensive work in the 1970's, see Knight and Squires (1982). A group of more recent severe storm studies have used precipitation growth models in the context of Doppler-derived, 3D winds to understand overall storm structure and evolution, to identify possible hail embryo source regions and types, and to deduce how hail might be grown. (See, e.g., Miller et al, 1988; 1990.) Other studies have combined this approach with additional, but usually limited, polarimetric radar and aircraft-derived microphysical data to better understand the spatial distribution of precipitation types and their interactions. (See, e.g., Bringi et al, 1996.) Most of these studies of hailstorms lacked concomitant electrical measurements, and in some cases the researchers were forced to rely on Doppler data from rather widely-separated radars, yielding only coarse representations of storm circulations. It is our intent in CESAR to obtain a comprehensive synthesis of dynamic, microphysical, and electrical measurements including high resolution Doppler and polarimetric radar data, aircraft and balloon data, and lightning channel locations to address these relationships.

Many +CG events are characterized by large peak currents, much larger than is normally observed with -CG events. Large-peak-current positive cloud-to-ground (LPC+CG) flashes sometimes occur within the hail-bearing supercells of the High Plains. They are more commonly found within the stratiform regions of (primarily nocturnal) mesoscale convective complexes. Several years of nocturnal observations with image-intensifying cameras confirm that supercell LPC+CGs rarely are associated with sprites or elves, faint discharges extending from tops of storms upward toward the ionosphere. Yet as these storms undergo upscale evolution into nocturnal MCSs, at some stage sprites and elves suddenly commence in association with LPC+CG events (Lyons, 1996). Preliminary work suggests that the key to this transition is the development of an extensive (>50 km horizontal size) dendritic "spider" lightning discharge as a component of the +CG event. There is debate concerning the relative importance of front-to-back and back-to-front circulations, versus *in situ* convective motions, combining with microphysical processes in the stratiform and anvil regions to provide the environment for these +CGs and dendritic lightning structures. A tentative association has been observed between sprites and elves, and LPC+CG events with unusually large continuing currents resulting in substantial (≈ 100 C) charge transfers to ground (Reising et al., 1996; Cummer and Inan, 1977).

There is still currently much debate about the physical process by which lightning initiates in

thunderstorms. Marshall et al. (1995) showed that the magnitude of the vertical component of the electric field observed in storms approaches but rarely exceeds the breakeven threshold for the phenomenon known as runaway electrons. Eack et al. (1996), using a balloon-borne X-ray detector, showed that under some circumstances electric fields in storms are strong enough to produce bremsstrahlung X rays. These observations lend credence to the hypothesis that avalanches of runaway electrons might afford an explanation for the initiation of lightning, since observed electric fields are an order of magnitude too small for the conventional electrical breakdown to begin in air.

It is the view of the CESAR investigators that recent advances in observational technology make it likely that a well-planned field program including comprehensive observations of High Plains thunderstorms, with an emphasis on severe thunderstorms producing predominantly +CG activity and large hail, will yield an observational database suitable for making substantial progress in verifying or rejecting the hypotheses that have been offered to explain the links between hail formation, thunderstorm electrification, lightning initiation, and discharges to the ionosphere. By adding to the slim observational database on the small population of storms that are severe and show anomalous electrical characteristics, and comparing the characteristics of these storms to those of the more common and well-observed storms producing mainly -CG lightning, proposed microphysical and electrification mechanisms can be rigorously tested by applying them to these two quite different classes of storms to see if the same mechanisms can account for the different electrical and microphysical phenomena in these quite distinct environments.

The observations proposed include satellite imagery; radar reflectivity, Doppler winds, and multiparameter signatures; *in situ* measurements of microphysical characteristics, winds, and electric fields from both aircraft and balloons; surface-based measurements of precipitation, CG lightning location and polarity, electric fields, electric field changes, 3D mapping of lightning channels using a newly-built deployable lightning mapping system, and low-light television (LLTV) observations of high altitude discharges. This field program is being proposed for the convective storm season of 2000, in the Nebraska/Colorado/Kansas border region where large severe storms producing predominantly +CG lightning, large hail, sprites, and elves, are climatologically common. We discuss next this storm climatology. A summary of hypotheses constructed to focus our observational efforts then follows.

1.2 Climatological considerations

The proposed CESAR domain lies on the western edge of the extensive zone of high LPC+CG flash density that extends from eastern Colorado northeastward into South Dakota as shown in Figure 1 (from Lyons, Uliasz, and Nelson, 1998). It is situated in the region where late afternoon and early evening supercell hailstorms characteristically begin their upscale evolution into High Plains mesoscale convective systems (often continuing on the remainder of the night while propagating eastward).

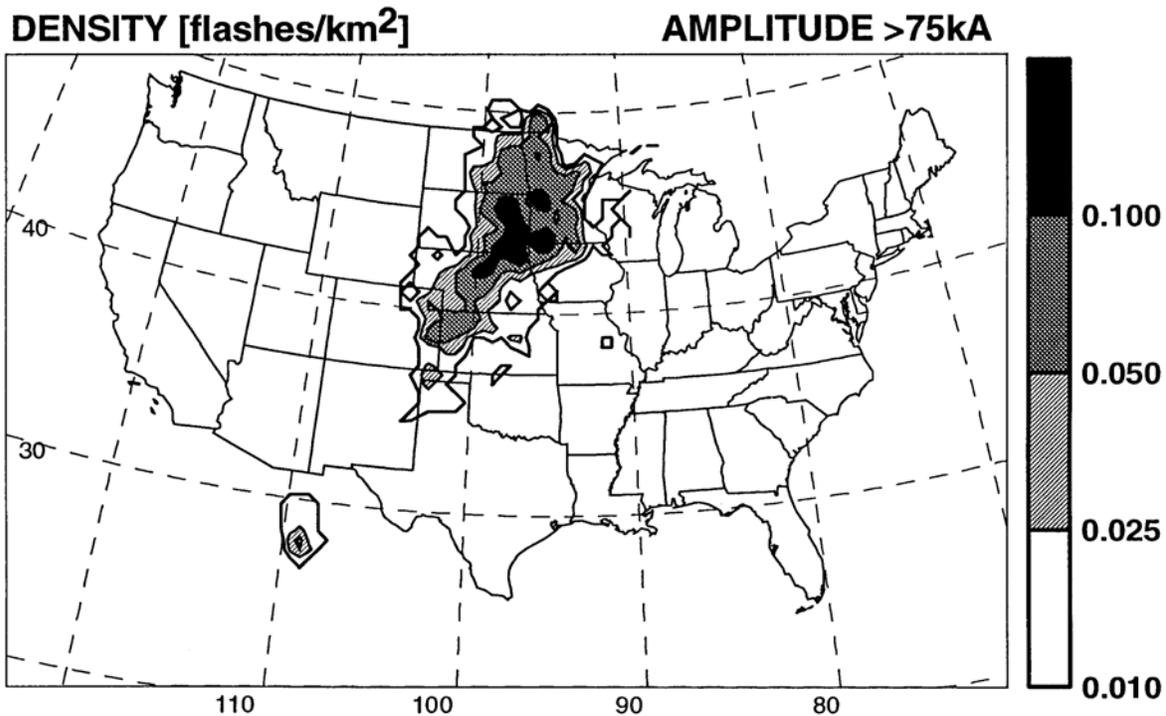


Figure 1: Density of large peak current positive cloud-to-ground flashes is shown, based on a climatology of 14 summer months between 1991 and 1995. Data are derived from the National Lightning Detection Network. Events included in this climatology lowered positive charge to ground and had peak currents exceeding 75kA. (See Lyons et al, 1998.)

A principal region of hail fall is to the lee side of the Rocky Mountains where hail is both frequent and intense, leading to some of the most significant crop and property damage in the US. One maximum hail fall corridor (the average annual number of days with hail ranges from four to nine, Changnon, 1977) extends eastward along the Cheyenne Ridge which is a tongue of elevated terrain that slopes downward as it extends eastward from the Rocky Mountains and just north of the Colorado–Wyoming border. In fact, because of the very high incidence of hailstorms in this area, the National Hail Research Experiment was headquartered just east–northeast of Greeley at Grover, Colorado during the late 60s and early 70s.

Clouds in this region have bases that are usually high (about 3–4 km MSL) and fairly cold (about 5–10° C), leading to precipitation production almost exclusively through ice processes and, apparently in some way, to the production of very large hail (diameters as large as several centimeters). In contrast, storms such as those in Florida have much lower (about 1 km MSL) and warmer (about 25° C) cloud bases, and usually produce heavy rains but with much less and usually smaller hail. Ice processes are certainly involved in deep convective clouds in Florida, but the thicker low–level warm layer probably allows most small hail and graupel to melt before reaching the ground. Updrafts in summertime Florida storms (maximum measured values in the range 20–25 m s⁻¹) are not as vigorous as those in High Plains storms (maximum values exceeding 50 m s⁻¹ have been measured). Roughly speaking, the maximum updraft speeds in storms must be comparable in magnitude to the fall speeds of the largest hailstones

that reach the ground (a 3–4 cm diameter hail falls at about 25–35 m s⁻¹).

This region also has a high density of sprite-producing storms, and includes the area where evolving supercells often begin producing sprites and elves. Figure 2 shows the centroid of sprite-producing storms and the number of events accumulated during a total of 21 weeks of monitoring during the 1995–1998 seasons (within 500 km of Yucca Ridge Field Station [YRFS] in the foothills of the Colorado Front Range outside of Ft. Collins). The estimated frequency of storms producing observable sprites in the proposed CESAR region is 1.5–2.0 per week. The actual number of storms producing sprites probably will be twice that due to the fact that about half the time low clouds obscure the events from ground-based observers.

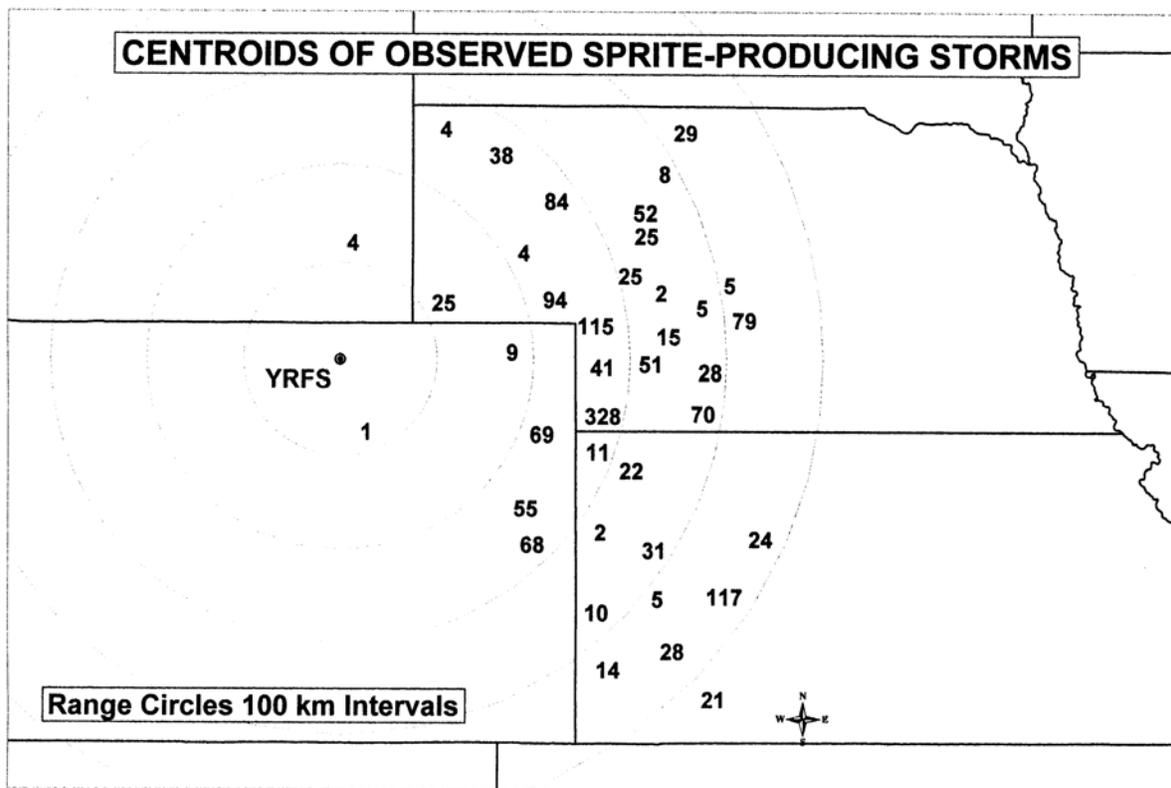


Figure 2: Centroid locations of storms producing sprites are shown, based on 21 weeks of observations from Yucca Ridge Field Station (YRFS) during the convective seasons of 1995-1998. Observations were limited to 500 km range from YRFS.

The range of 150 to 240 km from YRFS is ideal for viewing sprites and their parent cloud systems. Photometers and conventional and low-light video systems at YRFS are able to observe the details of both the CG and IC discharges for much of this range. This relatively close range is also ideal as it allows for LLTV and photometry measurements of blue sprite emissions (indicative of critical ionization processes), which become increasingly difficult due to scattering at ranges >400 km. The proposed

CESAR location is also well suited for stereo observations from mountain observations such as Mt. Evans, CO, and Jelm Mountain, WY, employed during the past several–summer sprite campaigns.

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2.0 Hypotheses

2.1 Hail and +CG Lightning, and Lightning Initiation

The proposed mechanisms for +CG lightning all revolve around the idea that there is something unique about the distribution of electric charge within convective regions of thunderstorms that produce an unusually large percentage of +CG lightning, compared to more typical storms that produce predominantly –CG lightning. The observed correlation between predominantly +CG lightning and hail in the same storms suggests that this unique charge structure is related to unique microphysical processes, or microphysical organization, within the +CG storms. Based on current understanding, the characteristics that distinguish storms that produce an unusually high percentage of +CGs and large hail from other severe and non–severe storms producing mainly –CG activity, may be characterized by one or more of the following:

1) An active region of hail and graupel growth between the 0 and –10°C levels in the storm where either,

(a) inductive charging due to bouncing collisions with water drops or shedding from the liquid layer at the surface, and/or

(b) noninductive charge separation due to ice–ice collisions below the level of charge reversal, or splashing interactions

leads to accumulation of a significant lower positive charge center in the storm consisting mainly of hail (e.g. Williams et al., 1991);

2) a higher (in altitude)-than-usual negative charge accumulation zone (e.g. MacGorman et al., 1989, MacGorman and Nielsen, 1991, and Stolzenburg et al., 1998);

3) an inverted charge distribution, at least in the lower portion of the cloud from which +CGs originate (e.g. Rutledge and MacGorman, 1988);

4) a tilted charge distribution (e.g. Rust *et al.*, 1985, Carey and Rutledge, 1998).

We hypothesize that the great majority of convective storms producing predominantly +CG's from their convective regions also produce large hail.

With regard to the initiation of lightning of all types and polarities, we hypothesize that avalanches of runaway electrons lead to the initiation of lightning discharges.

Despite recent advances, questions remain regarding how and where potential hail embryos are produced, which particle types that could serve as hail embryos are present, which source regions are most likely operating, what are the concentrations of ice particles, how much they deplete the

supercooled liquid water, and what is the relative importance of each in producing hail. Polarimetric radar measurements, in combination with *in situ* airborne microphysical measurements, should help address some of these questions by allowing the identification of particle types and, possibly, quantification of concentrations.

Adequate knowledge of the types and origins of hail embryos, as well as the attendant storm dynamics, is necessary to understand the details of the growth of hail. The following precipitation types have been identified as candidate embryos: ice crystals, drizzle drops, graupel, and raindrops, all of which must be as large as 100 μm to 1 mm in diameter to be effective hail embryos. At least six potential embryo sources have been identified: 1) graupel and perhaps drizzle drops grown in turrets on the flanks of the main updraft, 2) shedding of water drops from melting hail and graupel, 3) shedding from hailstones in wet growth conditions, 4) ice crystals and aggregates grown in relatively stagnant regions of storms where ample time is available for riming into graupel and small hail, 5) cloud and precipitation debris surrounding the main updraft, and 6) growth of drizzle drops from giant aerosol particles (diameters greater than about 50 μm) in the main updraft. Condensational growth upon smaller aerosol particles is typically too slow, and usually produces droplets or ice crystals that are simply transported into the anvil. Observations from CESAR will be used to distinguish between the important embryo sources for the different types of storms studied and detail the flow fields in which these embryos evolve into hail.

2.2 The interrelationship between +CGs, sprites, elves, and blue jets

(1) LPC+CG events which produce sprites are in some way different from the general +CG population, as are the even more powerful LPC+CG's which produce elves.

(2) There is a relationship between intense hail production and blue jets.

(3) Sprites enhance the ELF radiation from a +CG event, allowing it to more effectively ring the earth-ionosphere cavity.

Sprites and elves appear associated almost exclusively with +CG events in MCS's, therefore understanding the mechanisms leading to these +CG events is necessary to understand the production of sprites and elves by storms. Blue jets are not directly related to CG flashes, but a lull in storm CG and intracloud lightning activity occurs for several seconds after each jet. Sprites and elves are associated with LPC+CG events from larger storms (typically $>10,000 \text{ km}^2$ radar echo) while sprites from LPC+CGs in smaller supercells are rare. About 10–25% of the +CGs in the larger MCS's generate sprites or elves. The average peak current in sprite-producing +CGs is about twice that of the rest of the +CG population in the storm, while the elves are associated with the very largest peak currents. Sprites and elves occur preferentially over the stratiform precipitation region of larger MCS's, but are often concentrated in a relatively small portion of that stratiform region (10–30% of area).

What is different about the LPC+CG's that produce sprites? The major mechanism to be tested is that the key to initiation of sprites is an extensive ($>50 \text{ km}$ horizontal size) dendritic "spider" lightning discharge as a component of the +CG event. These flashes are thought to be associated with unusually large continuing currents resulting in substantial charge transfers ($\sim 100 \text{ C}$), and detailed observations are needed to test the validity of this proposed relationship.

There is considerable interest in those LPC+CGs, which are strongly associated with sprites and are very efficient in ringing the earth-ionosphere cavity at extremely low frequencies (ELF) in the Schumann resonance band. Curiously, +CGs occur in (at least) two extreme meteorological situations: when the vertical air motions are very small, as in the stratiform precipitation regions of MCS's, and when the air

motions are extraordinarily large, as in the large hailstorms. These two regimes tend to occur in the nighttime hours and daytime hours, respectively. It is also known that the nighttime ionosphere is higher and also more conducive to dielectric breakdown (sprites) induced by +CGs. There is also some speculation that the sprite itself is modestly enhancing the ELF radiation from the overall +CG/sprite event. In any case, here is a situation where it would be desirable to distinguish between meteorological differences (change in the shape and capacitance of the positive charge reservoir) across the day/night boundary, and changes in the ionosphere (on the ELF cavity and/or on the sprite itself) in explaining the observations. With detailed observations it will be possible to determine why sprites are associated exclusively with +CGs.

2.3 Anvil Circulations

Martner (1995) observed mammatus circulations in a thunderstorm anvil using a vertically-pointing radar, while Stith (1995) reports airborne observations of mammatus in another storm anvil. These circulations can be followed upward almost 1 km into the anvil. It was suggested that a wave instability, gravity waves or Kelvin-Helmholtz waves, might have initiated the wave-like motions in the cloud interior, and that precipitation loading and evaporation might have further shaped the patterns below cloud.

We hypothesize that circulations within the anvil region are initiated by Kelvin-Helmholtz wave instabilities. These wave-like motions are modulated by cloud-base detrainment instability and precipitation loading.

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3. CESAR Operational and Analysis Objectives

Obtain complete sets of observations on a variety of thunderstorms within observing range of a network of 3 Doppler radars, and a lightning channel mapping system. These observations are to include satellite imagery; radar reflectivity, dual-Doppler-derived winds, and multiparameter signatures; *in situ* measurements of microphysical characteristics, winds, and electric fields from aircraft and balloons; surface-based measurements of precipitation, CG lightning location and polarity, VHF emissions from lightning leading to mapping of the discharge channels, lightning charge center locations from multistation electric field-change measurements, characterization of lightning signatures in the ELF and VLF, and low-light observations of high altitude discharges at night.

Compare storm charge structures inferred from electric field profiles inferred within – CG storms versus +CG storms. Are there elevated positive dipoles preferentially in +CG storms? Is the vertical distribution of charge multipolar with a stronger lower positive charge center in +CG storms? Is the inferred dipole of +CG storms of normal polarity, but tilted in the vertical?

Compare lightning channel locations and the distribution of lightning events between intracloud, intercloud, and CG categories in – CG storms versus +CG storms. Where do the +CG events originate and are the lightning paths significantly different between +CG and -CG storms?

Use microphysical observations from penetrating aircraft, vector winds from multiple Doppler radars, and microphysical inferences from multiparameter radar signatures to test the hypothesis that hail growth in the 0 to – 10° C region is more conducive to positive charge separation by noninductive

processes in +CG storms than in storms that produce predominantly –CGs. Observed environmental conditions (e.g. CAPE, surface wet bulb potential temperature, wind shear profile), in-cloud water and rainwater concentrations, and concentrations of small ice particles, along with computed wet/dry growth conditions at the surfaces of growing larger ice particles of a spectrum of sizes, will be compared to results from laboratory experiments in which riming ice targets acquired negative or positive charge, depending on temperature and supercooled liquid water concentrations. Particle charge along the aircraft penetration tracks may be measured directly using modified particle imaging probes (HVPS) with an induction ring device and the distribution of net charge within the storm will be inferred from aircraft and balloon-borne electric field measurements as well as from surface-based lightning channel and charge center observations.

Use a detailed microphysical model, including both dry and wet growth regimes and shedding of water by melting hailstones or those in wet growth, along with Doppler-derived winds to help characterize growth trajectories for precipitation particles. Inferences made from these trajectories will be compared with those from the multiparameter radar measurements to develop a more complete picture of hail growth including embryo type and source regions.

Compute sign and rate of charge separation via inductive collision processes for the observed population of ice particles and water drops, in the observed electric fields. Compare and contrast results between ‘normal’ –CG storms and ‘abnormal’ +CG storms to establish whether inductive charging is possibly more prominent or different in polarity in one type of storm than the other.

Compare magnitudes of computed inductive and noninductive charge separation rates within regions of storms for which microphysical and electric field conditions are measured or can be reliably extrapolated. Look for patterns of differences between +CG and –CG storms that can help to explain their different lightning characteristics.

Compare observed microphysical and environmental conditions in hail-containing regions to the criteria for wet growth and shedding by growing ice particles. Establish regions in storms in which shedding may lead to enhanced drop/hail collisions. From these analyses, find whether such shedding regions are more likely to be found in +CG storms than in –CG storms. If they are found mainly in +CG storms, find whether the sense of the charge separation due to shedding in the ambient field in these regions is such as to lead to a lower positive charge region.

Use multi-dimensional, cloud simulation models that incorporate charge generation and lightning parameterizations similar to those used by Ziegler and MacGorman (1994), MacGorman et al. (1996), Helsdon and Farley (1987), and Helsdon et al. (1992), to simulate the most interesting storms observed during CESAR and diagnose processes that could not be observed directly. Data sets available from CESAR will be much more comprehensive than those available thus far, particularly because they will include simultaneous electric field soundings, precipitation charge measurements, lightning observations, and polarimetric radar observations. Thus, cases observed by CESAR will provide an excellent basis for comparison with model results to examine why some storms produce frequent +CGs.

Characterize in detail, both spatially and temporally, the 3D structure of large peak current +CGs and their associated dendritic horizontal components and the corresponding optical and RF responses of the mesosphere. Desired are coordinated measurements using conventional and LLTV, narrow- and broad-band photometry, and ultra high-speed video of both the lightning channel continuing current and the mesospheric optical emissions. Various ELF, VLF, and VHF measurements can be used to infer many properties of the parent lightning as well as the high-altitude discharges. It is vital in order to evaluate current theoretical models of sprites that we accurately characterize the continuing currents in parent

LPC+CG's as well as document the typical altitudes in which the horizontal dendritic structures occur in the MCS stratiform region.

11) Optically and photometrically characterize lightning-induced luminous emissions above thunderstorms.

12) Use Doppler radar and *in situ* aircraft to map circulations in anvil regions.

13) Acquire *in situ* observations of X-ray emissions from within thunderstorms to test the theory that avalanches of runaway electrons lead to the initiation of lightning discharges.

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4. Experimental Design and Observations

4.1 Facility Utilization

We propose to deploy field observing systems to monitor the environmental wind and thermodynamic-parameter vertical profile, storm windfields, hail development, storm electrification, total lightning activity, and emission of sprites, elves and blue jets from convective storms. A schematic map showing the proposed array of field facilities is shown in Figure 3. With careful analysis of the observations from these facilities, and using, in addition, sophisticated numerical models including detailed microphysical and electrical mechanisms, we can distinguish between the various hypothesized mechanisms relating predominantly +CG lightning production and severe storm structure, to hail production and to high altitude discharges as well. Further, we can develop deeper understandings of hail growth, storm electrification, and discharge characteristics applicable to a spectrum of storm types.

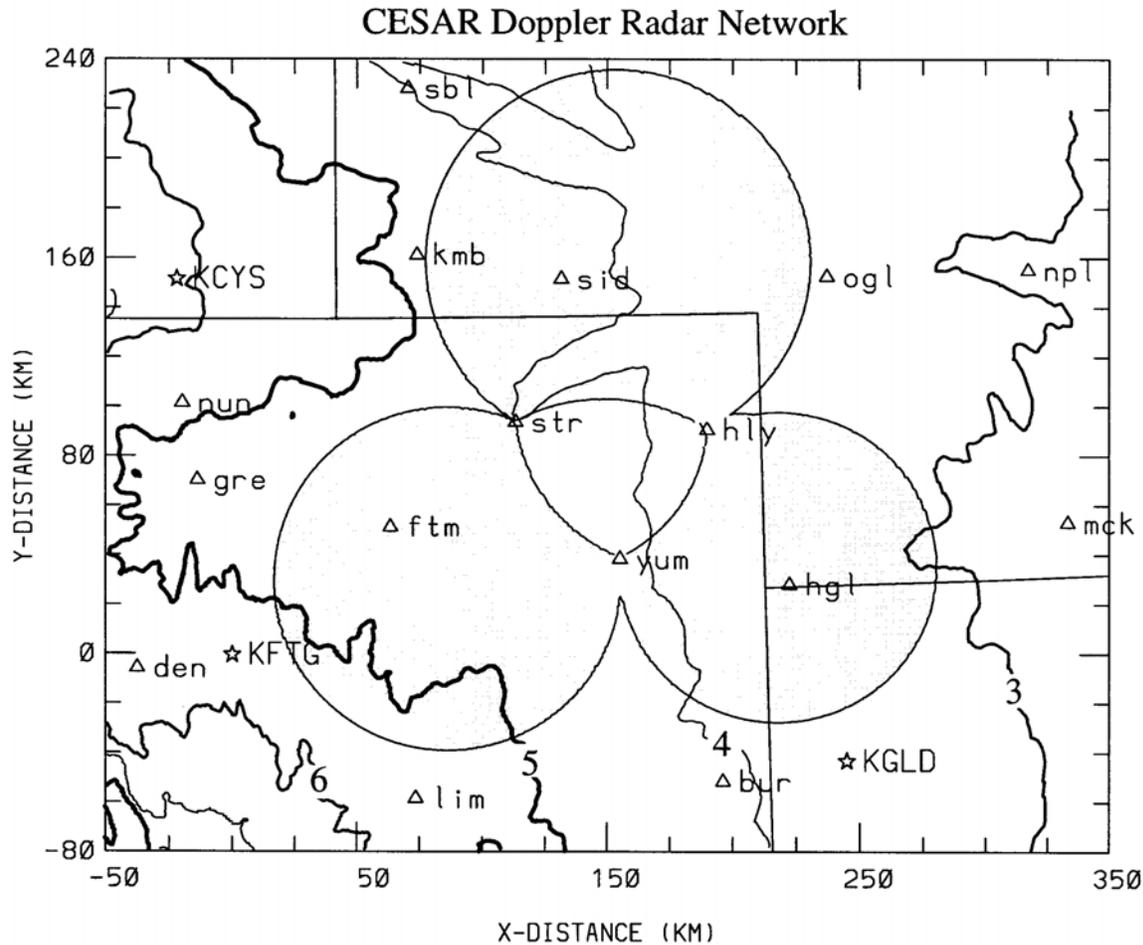


Figure 3: Proposed CESAR Doppler radar network is shown. Radars would be located at STR (Sterling), YUM (Yuma), and HLY (Holyoke), in Colorado. The site at Sterling would be the project operations center, and the site of one of the polarimetric S-band Doppler radars. The LDAR system would be centered within the radar triangle.

Radiosondes

The vertical profile of environmental winds and thermodynamic parameters will be monitored with a dedicated fixed-site CLASS unit. Additional wind observations will be obtained from NCEP operational analyses and from the Doppler radar network.

Radars

In order to obtain radial velocity measurements for determining the evolving 3D winds, the CSU–CHILL and NCAR Spol S–band polarimetric Doppler radars along with a C–band Doppler radar will be deployed in a triple–Doppler configuration at a favorable location near the junction of the Colorado, Kansas, and Nebraska borders (see Fig. 3). The radars will be located at the vertices of a roughly equilateral triangle with 50–60 km sides around the center of the lightning mapping system, which will be of similar extent. In this way the total area of possible dual–Doppler radar coverage will be doubled over that possible with just two Doppler radars, thereby increasing the opportunity to observe a reasonable number of the storms of interest. With this number of radars, three areas suitable for dual–Doppler analysis exist outside the radar triangle, along with one very important triple–Doppler area inside the triangle and coincident with the center of the lightning mapping system. The two S–band polarimetric Doppler radars are available as NSF-supported lower atmospheric observing facilities. The C–band Doppler radar has not been identified specifically as of late-summer, 1998. Candidates are a transportable C–band Doppler radar operated by the Massachusetts Institute of Technology, or a similar one available through Weather Modification, Inc.

Complete volume scans can be completed in about 3 min or less, depending on the size of the storm. It is expected that winds generally will be gridded to 0.5–1.0 km intervals, and when possible, to 0.25 km intervals, thereby resolving scale sizes (for example, width of an updraft) of about 3–5 km or better. In addition to their critical Doppler radial velocity measurements, CSU–CHILL and S–Pol will provide much-needed dual–polarization measurements. Meteorologists with access to a CSU–CHILL or S–Pol display will coordinate operations of the triple–Doppler system, providing scan information about selected storm(s) to both the other radars to ensure that all radars are scanning the same region at the same time. This mode of operation will also ensure that dual–polarimetric data are properly taken in conjunction with the Doppler measurements. Further discussion among CESAR investigators will be needed to refine the strategy for radar scanning, including discussion of the relative merits of PPI vs. RHI sector volume scanning patterns.

Analysis of both environmental winds and storm circulations will be enhanced with additional *in situ* aircraft–measured winds from the SDSM&T T–28 and UND Citation. Mapping of storm circulations is important because the details of the circulation are needed to distinguish between the several competing mechanisms that have been hypothesized to explain how storms become charged, how the charge is distributed, and when charging occurs as well as questions concerning the growth of hail. Therefore, it is essential that the detailed 3D kinematic structure and its evolution be fully resolved. Detailed measurements of a storm by at least two Doppler radars are required since the internal circulation within a severe storm on the High Plains is generally too complex to be resolved by single–Doppler radar methodologies.

Complete polarimetric measurements will also be obtained by both the S–band radars within each of two roughly 80–km radii areas centered on the radars. These polarimetric measurements will be combined with the T–28 and Citation in–cloud measurements of particles ranging in size from cloud droplets to baseball–sized hail to improve polarimetric, radar–based hydrometeor classification schemes. The use of two comparable polarimetric radars offers significant advantages in the resolution of ambiguities that occur when regions of strong reflectivity gradient are viewed with antennas having even modest copolar and crosspolar sidelobes. This is particularly important in large hailstorms because of the broad distribution of hydrometeor types that is expected. The use of dual–polarimetric radars will also help determine if any aspect angle dependencies in scattering from hydrometeors are important in scattering models where such possible dependencies are usually neglected. Lack of fully polarimetric data at S–band in many past studies has severely limited the application of polarimetric techniques to link storm microphysical and electrical evolution. We believe that many of these shortcomings will be overcome with the use of dual–polarimetric radars during CESAR.

Aircraft

Two instrumented aircraft are being proposed for CESAR. The SDSMT armored T-28 will provide *in situ* observations in the lower to middle altitude range within updrafts and hail shafts. The UND Citation will provide *in situ* observations in the upper regions of convective cells and in the anvil regions above and downshear from the active convection.

The SDSMT armored T-28 is equipped to measure the complete spectrum of water and ice particles in clouds, ranging from cloud droplets a few micrometers in diameter to baseball-size hail. It typically spends roughly one hour on-station, and can reach altitudes just over 20 kft MSL. One of its three precipitation particle imaging probes (the HVPS) may have the capability to determine particle charge. In addition, it will be equipped with a well-understood 5-instrument electric field mill system that will be used to map 3D electric fields inside and outside clouds. The T-28 is well suited to the proposed study in that it can penetrate hail-containing regions of clouds to monitor the sizes and growth states (wet/dry) of hailstones and graupel particles and can simultaneously probe the electric field structure of storms.

The UND Citation carries a set of state-of-the-art instrumentation for measurement of wind and turbulence, cloud microphysics, and cloud and state parameters. The aircraft is certified for flight into known icing conditions and will penetrate regions of High Plains storms where reflectivities are less than 45 dBZ. Its ceiling is 13 km with an endurance of 3+ hours with typical IFR reserves. It will be proposed that the Citation be equipped with electric field meters for CESAR. It can then provide important coverage of winds, microphysical characteristics, and electrification in the upper regions of storms, and downshear in the extended anvil region.

The aircraft will provide critical *in situ* microphysical observations that will be used to tune and verify interpretation of the microphysical inferences made using multiparameter radar techniques. In combination with the T-28, the aircraft will provide horizontal profiles of cloud electric field structure at two different altitudes.

4.1.4 Balloons

A group of investigators based at NSSL and OU will be making electric field soundings from a mobile laboratory and balloon launching facility operated by the Joint Mobile Research Facility (JMRF). Vertical soundings are essential for delineating the various charge layers in a particular region of a storm. The JMRF will require frequent communication with an operations center coordinator. In addition, a rental truck will be needed to carry helium, equipment, and an inflated balloon. The total ballooning operations will involve a crew of five to drive and navigate the vehicles, communicate with the operations center, launch and track the balloons, and monitor data telemetry.

It is planned to have at least 20 electric field meters, five electric field-change sensors, and five precipitation charge sensors for mobile balloon launches. Recovered instruments will be refurbished and re-used. Weather guidance will be provided by the operations center, with the final decision on launching a balloon to be made by the principal investigator in the field, because he will be best able to evaluate local safety issues and the likelihood of a successful flight. Since a balloon sounding typically takes at least 40 min to rise through a storm (less time is required in strong updrafts), there probably will be only one sounding per storm during the period when +CGs dominate. However, the crew can launch into successive cells or storms on the same day, if the location and timing of the storms are favorable.

4.1.5 Lightning Mapping Systems

The deployable 3D lightning mapping system being developed by New Mexico Tech was successfully operated in central Oklahoma during June of 1998 as part of the MEaPRS program. The Oklahoma operations have shown that the system provides highly accurate, detailed pictures of the 3D structure and temporal development of lightning discharges within the storm. In turn, such pictures will provide valuable insights into the storm's electrical structure and how lightning itself can affect the electrification. In the Oklahoma operations, a network of 10 stations were deployed over an area 45 by 50 km in extent and provided good quality lightning pictures over a 100 km diameter area, and lesser-quality coverage extending out to several hundred kilometers. For CESAR the system will be deployed over an area comparable to that of the radar system. To improve coverage in the external Doppler lobes, three additional stations would likely be operated at substantially greater distances outside the Doppler array.

Fig. 4 illustrates the type of observations obtained by the system. This shows an extensive (75 km) discharge in a large storm system over the southern end of the network. The discharge was a hybrid intracloud and -CG flash, which in vertical cross-section had 3 layers of channels, whose altitudes and locations are indicative of concentrated charge regions in the storm. In this case the upper two levels correspond to the upper positive and main negative charge regions; the nature of the smaller, lower level is not yet understood, but its existence can be inferred from electric field-change measurements and balloon-borne soundings through similar storm regions. An interesting feature of the upper level channels (i.e. the upper positive charge) is that they decreased in altitude as the discharge progressed horizontally away from the core of the storm. This indicates that the positive charge correspondingly drops in altitude, consistent with inferences from balloon-borne measurements (Stolzenburg et al., 1998).

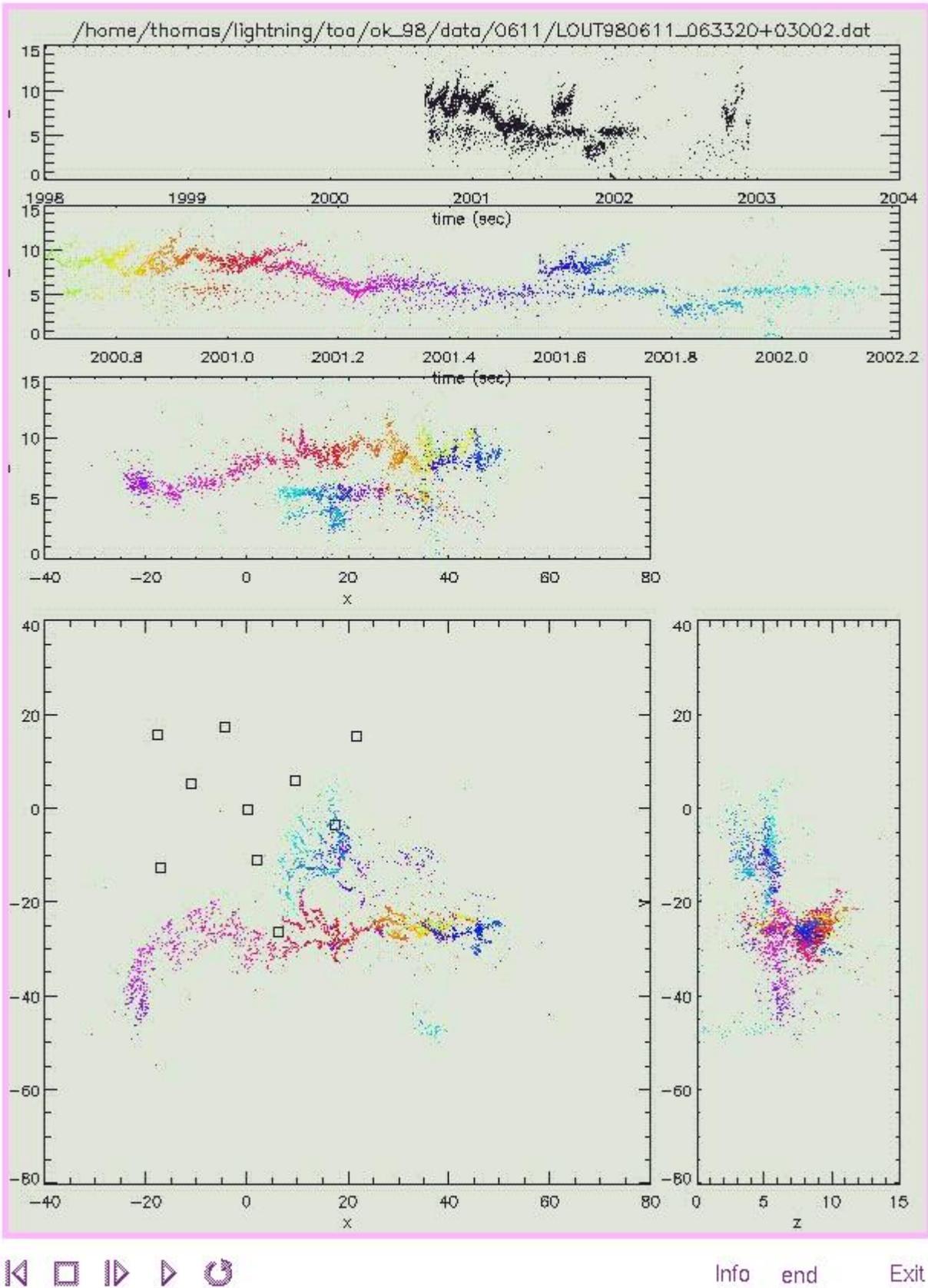


Figure 4: An example of data on a lightning event obtained by the New Mexico Institute of

Mining and Technology LDAR system is shown. The observation was made on 11 June 1998 in central Oklahoma. The top panel shows all emission points for several seconds in a time versus altitude format. Each point represents a discharge associated with breakdown processes occurring during the formation of the lightning channel. Time is in seconds from an arbitrary reference time, and z is in kilometers AGL. The panel just below the top panel shows a subset of the information in the top panel, corresponding to a single lightning event. Color coding is established as a function of time to aid in interpretation of the remaining panels. The bottom 3 panels depict the lightning event in three projections, with the bottom panel showing events projected onto a horizontal plane and the flanking panels showing projections on planes of altitude vs. east-west distance and altitude vs. north-south distance. The color coding depicts evolution in time. Note that the discharge channel shows distinct layers at different elevations, exhibits dendritic structure spanning a horizontal range exceeding 75 km, and that channel formation extends in one direction for some time then switches abruptly to another direction, making these switches several times during the event. The discharge was a hybrid intracloud and -CG flash, which in vertical cross-section had 3 layers of channels, whose altitudes and locations are indicative of concentrated charge regions in the storm. In this case the upper two levels correspond to the upper positive and main negative charge regions; the nature of the smaller, lower level is not yet understood, but its existence can be inferred from electric field-change measurements and balloon-borne soundings through similar storm regions. An interesting feature of the upper level channels (i.e. the upper positive charge) is that they decreased in altitude as the discharge progressed horizontally away from the core of the storm. This indicates that the positive charge correspondingly drops in altitude, consistent with inferences from balloon-borne measurements (Stolzenburg et al., 1998).

Observations of other lightning discharges and of other types of storms are providing an astounding amount of new information and insights into lightning types and the electrical nature of storms. From the relatively small amount of data examined to date, we have identified what appear to be clear-cut examples of inverted polarity discharges (i.e. discharges between an upper negative and main positive charge regions). +CGs have been detected both in normal and inverted-polarity discharges, for example, showing us (not surprisingly) that such discharges can occur in several different modes.

The lightning mapping system is similar to the LDAR (Lightning Detection and Ranging) system developed and operated at Kennedy Space Center in that it measures the time of arrival of radio-frequency lightning radiation at the widely-spaced station locations, but uses GPS technology to measure the arrival times locally at each site rather than by telemetering high-speed data to a central site to obtain time synchronicity. The system is currently being operated around Langmuir Laboratory in central New Mexico. The system will continue to be operated at Langmuir Laboratory during the summer of 1999, as part of a coordinated study of mountain storms using balloon and aircraft measurements similar to those proposed for the CESAR study. For CESAR the measurement capabilities at each site will be expanded to include electric field-change measurements for time-resolved determination of lightning charge centers, as well as electric field mills for studying the overall electrical structure of storms. With the various operations undertaken in 1998 and 1999, the New Mexico Tech group will have substantial experience with the system that will be of great benefit to the CESAR program, and will be able to contrast lightning observations from the storms of that program with the different types of storms in other locations. If the logistics can be worked out, we will attempt

to combine real-time observations from the lightning mapping system with the radar observations to be able to follow the electrification as it develops.

A 2D interferometric lightning channel mapping system (Rhodes *et al*, 1994; Shao *et al*, 1995) may also be used in CESAR, if sufficient funding is available. One such VHF interferometer developed at New Mexico Tech uses dual baselines and is operated at a center frequency of 274 MHz with a bandwidth of 6 MHz. It can determine source directions in azimuth and elevation of VHF emissions from the pulsed initial breakdown process along a developing leader channel with 1 μ s time resolution and an angular resolution of a few degrees. Radio emissions in both initial and subsequent strokes in a flash are recorded. This instrument has been deployed effectively both near Langmuir Laboratory and in Florida near the Kennedy Space Center. Another possible interferometer system is one under development at the Los Alamos National Laboratory (Eack, Rhodes, and Holden) that operates at a higher frequency and can be mounted on top of a van, making it portable to follow storms. Such 2D lightning mapping systems will be included in CESAR if funding is available. The 3D system is a project priority.

4.1.6 National Lightning Detection Network (NLDN)

CG lightning activity will be monitored in real-time using the National Lightning Detection Network (NLDN). This network is a nationwide system for monitoring locations of CG lightning, as well as determining polarity and other characteristics of CG lightning events. The NLDN is capable of detecting CG flashes with an average reliability of 70–90% and a location accuracy of around 1 km, depending on the range from the direction-finder sites used to determine the position. It is understood that the NLDN estimates the location where a CG lightning event attaches to the ground, and that these locations may not be aligned vertically with the location in the cloud where the discharge was initiated.

Arrangements will be made to have a current display of NLDN CG events available at the operations center during CESAR. This display will be critical for evaluating storm characteristics while operations are in progress. Funding will be sought to purchase millisecond NLDN data for the duration of the field project that will be made available to CESAR investigators for post-analysis.

Yucca Ridge Field Station (YRFS)

The YRFS, located 20 km northeast of Ft. Collins, is situated at 1650 m elevation, the highest point within 25 km. It thus has a panoramic view of the entire Front Range and High Plains. Line-of-sight measurements of CG channels to 200 km, IC events to 400 km and sprites to 1000 km have been obtained. The 400 sq ft observation deck can facilitate sensing systems from upwards of a half dozen research teams.

FMA Research will provide 24-hour command and control for the sprite-related aspects of CESAR. FMA can generate forecasts of sprite potential for storm systems, and then, using LLTV monitoring, vector other investigators to sprite-active regions of thunderstorms.

YRFS facilities/services will include:

Real-time optical and RF monitoring of lightning and sprites

Forecasting for sprite-related components of CESAR (perhaps employing the ARPS model to facilitate MCS predictions)

Blue sensitive LLTV for first long-term, ground-based monitoring of blue jets above hail-producing storms

Day and night video monitoring of cloud systems

Near real-time NLDN data displays (via satellite)

Real-time NEXRAD regional radar mosaics (via satellite)

Automated archiving of meteorological data, including GOES and NEXRAD, from the Internet onto CD-ROMs

Continuous archival of most of the products broadcast over NOAAPort onto CD-ROM and/or DVD, including NCEP gridded analyses, METARS, upper air data, profiler, GOES, radar data, etc. (These can be provided to participants on CD-ROM or DVD at cost.)

Sprite-related data summaries will be posted to the sprite web site

4.1.8 Other Field Systems

An operations center will be established at one of the multiparameter radar sites. At this site there will be a display from the site radar with active tracking of aircraft (whose positions will be telemetered to ground for display), and manual tracking of balloon launching and other surface-based activities (with information relayed via cellular phone). The center will have a link to the internet. Near-real-time high resolution geostationary satellite views of the project area will be available through the CIRA world-wide web site based at CSU. Current standard meteorological observations and model forecasts also will be obtained via the internet.

A commercial cellular phone system will be used for communication between the operations center, the radars, the balloon-launching crews, the lightning mapping site, and YRFS. Standard aircraft band VHF radio communications will be used between the project aircraft and between the aircraft and the ground.

Operations

One twelve-week season of field observations is being planned for CESAR in 2000, starting Monday, 15 May and ending on Friday, 4 August. Although storm frequency decreases later in the summer season in this region, those storms that do occur are more likely to be severe later in the summer. Given the expense of deploying the surface-based facilities, it is considered more cost effective to deploy for one long season, rather than two shorter ones focused on the more active earlier part of the convective season.

An outline of planned field operations plan is given here:

Preliminary site selection and logistical arrangements in the eastern area will begin in the fall of 1999. Beginning in April, 2000, efforts will begin to establish the three radar sites and the lightning mapping system sites. One multiparameter radar site will be within convenient distance of a town large enough to

have lodgings for 12–18 field personnel (tentatively Sterling, Colorado), and this site will be the field operations center for CESAR. Crews for several other CESAR facilities, including the lightning mapping system, ballooning team and CLASS unit, also will be based in this town.

The project aircraft, including the armored T–28 and Citation, will deploy to a suitable airport in the region, beginning 15 May. Possibilities include Greeley, CO; North Platte, NE; or Goodland, KS. The ballooning crew also arrives in the field at this time.

Weather forecasting and weather and lightning data archival will be based at YRFS. CLASS radiosondes will be launched as needed from the operations center in order to monitor the evolution of the thermal stratification, humidity profile, and vertical shear of the horizontal wind in the region. Additional upper air information will be obtained from web sites with operational sounding data from NWS sounding sites at DNR, LBF, and DDC.

A rotation will be established among the participating project PI's. Each PI will rotate through the position of daily operations coordinator (OC), and will be assisted by a rotating deputy OC. The OC will be responsible for directing the deployment of the observing facilities to obtain an optimum data set, given the storm activity on a given day. He will have input from YRFS, project radar sites, and the lightning mapping system site via cellular phone. The deputy coordinator will handle operational communications, also via cellular phone.

Aircraft operations will be coordinated from the ground by an aircraft coordinator, under the overall direction of the OC.

On days when storms are developing or are forecast to develop within the region with prime radar and lightning mapping system coverage, a suitable storm or region will be chosen by the OC. The OC will make his selection based on radar observations, weather observations available on-site or at YRFS, and input from other facility operators. Storms likely to become severe will be the highest priority.

If possible, a storm or storm element just pushing through the -10°C level will be targeted for intensive aircraft observations, although if such clouds are not targetable, an older or younger cloud might be chosen. The three radars will begin sector scans in the region containing the target cloud once the cloud has been chosen. The OC will have access to a multiparameter radar display and support from YRFS and on-site meteorological data. He will provide guidance to the aircraft coordinator, and deputy coordinator, who in turn will communicate via radio with the aircraft, and cellular phone or radio relay via aircraft to mobile ground crews.

The Citation will focus on the upper portions of flanking convective turrets, and the anvil region, making penetrations through as much of a cell life cycle as possible. The T–28 will perform reciprocal cloud penetrations along the wind shear vector at fixed altitudes through the main precipitation-containing regions of storms during their active phase, with a trajectory designed to cross both updraft and downdraft regions. The T–28 generally will operate between 15 and 20 kft MSL while the Citation generally will operate above 20 kft. Both aircraft will be capable of detailed microphysical and electric field measurements.

The balloon crew will try to obtain electrical soundings in the same convective cell being studied with the aircraft. If this is not logistically possible, soundings will be attempted in similar cells in the same region displaying desirable radar and lightning characteristics.

Operations, mobile ground crews, and the aircraft will all monitor the same VHF radio frequency.

Communications between ground stations will be by cellular phone. All mobile and fixed ground-based facilities will be able to monitor the ground-to-air radio communications (at least the air portion) and will be equipped with cellular phones for ground-to-ground communications with operations.

Although cloud-penetration aircraft operations will be limited to daylight hours, radar, lightning mapping system, sounding, ballooning, and YRFS operations may begin or be extended into nighttime hours when storms in the region are observed to be, or are forecast to be producing unique CG lightning patterns and/or high altitude discharges. High altitude discharge activity will be monitored from YRFS. Limited Citation aircraft observations may be attempted at night.

Additional Comments on Operations

CESAR is proposed now because of recent, major improvements in our abilities to:

deduce precipitation types and possibly concentrations with polarimetric radar techniques,

map lightning discharges with the new lightning mapping system system,

determine lightning polarities and map lightning locations, and

measure the low concentrations of larger particles and to determine particle charge using the HVPS on the T-28.

More complete temporal and spatial observations in severe storms are needed, including electrical observations with systems such as the ground-based, airborne, and balloon-borne electric field meters and the lightning mapping system proposed for CESAR. These detailed observations along with improved polarimetric radar measurements, and the expectation of defining the 3D wind fields and deducing precipitation growth trajectories can only serve to improve our understanding of hail growth and electrification processes.

A thorough intercomparison of CSU-CHILL and S-Pol data sets will be done to ensure the highest possible quality in the polarimetric measurements. High quality gridded data sets containing storm-relative wind components and the polarimetric radar measurands (Z_{dr} , LDR, ρ_{hv} , K_{dp}) for the priority cases will be generated and provided to CESAR investigators. The planned deployment of the HVPS probe on the T-28 will enable a detailed comparison of hydrometeor image data with radar polarimetric signatures along selected aircraft penetration segments.

The usual experience with the T-28 has been that penetration-altitude changes consume so much time that significant fractions of a cloud's evolution are lost while the aircraft is out of cloud coming to a new altitude. Therefore, we propose to follow the traditional approach developed in past projects using this aircraft. This approach consists of making all penetrations during a flight at the same altitude, but varying the altitude from flight to flight.

The altitudes of interest for T-28 penetrations extend from the freezing level (typically just above the 4-km MSL level in eastern Colorado during the summer) to $\sim -10^{\circ}\text{C}$ (~ 6 km). The aircraft begins to handle sluggishly at altitudes above 6 km. Significant hail growth probably is concentrated in the -5 to -10°C temperature regime, but interesting microphysical interactions related to the so-called "reversal temperature" for noninductive charge separation processes may be found at lower temperatures (higher altitudes).

The Citation will be able to penetrate at altitudes above the -10°C level, but will not penetrate where reflectivities exceed 45dBz in High Plains storms. It can change altitudes more readily than the T-28 and can be expected to remain aloft for 3+ hours, extending storm surveillance into the later stages of evolution.

Continuous monitoring and locating of ELF transients (Q-bursts) believed associated with sprites and elves will be done from a Massachusetts Institute of Technology field site on the East Coast. These observations will supplement the optical and RF observations from YRFS.

There is an on-going Western Kansas Weather Modification Program which currently operates 9 cloud-seeding aircraft in western Kansas and northeastern Colorado during the convective storm season. The goal of the program is to mitigate hail damage with a secondary goal to increase growing season rainfall. Most of the aircraft disperse seeding material at cloud base, while one (as of 1997) higher performance aircraft is used for cloud-top dry ice seeding. WKMWP cloud-top seeding would be more likely than cloud-base seeding to conflict with airspace desired for CESAR operations. CESAR operations will coordinate with the WKMWP operations to assist each other in forecasting and targeting storms, and to avoid airspace conflicts.

It will be possible for CESAR-related operations and analysis to coordinate with on-going experiments in ensemble forecasting at the mesoscale. Dr. Kelvin Droegemeier, at the Center for Analysis and Prediction of Storms at Oklahoma University will be the link between CESAR and these forecasting-related research activities. Droegemeier is part of the Storm and Mesoscale Ensemble Experiment (SAMEX), a mesoscale forecasting experiment involving several research groups. SAMEX is actively conducting forecasting experiments in the High Plains region now, in 1998.

Given the proposed length of the CESAR field season, arrangements will be made to cross-train field personnel to handle multiple tasks, and to arrange for sufficient staffing, for all facilities, so that operations can be conducted on as many days as possible when suitable weather is present in the observational area. All field participants will be able to rotate out of the field at regularly-scheduled intervals for crew rest or to attend to other responsibilities.

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5. Project Management Structure

The project will be structured as a confederation of PI's. Attempts will be made to accommodate all needs, as long as they are related to the overall goal of obtaining complete observational datasets of convective storms, with the top priority being hail-producing electrical storms. Additional investigators whose research goals could be advanced by becoming a part of CESAR will be welcomed into the project subject to the operational priorities already established.

There will be weekly meetings at the operations center involving the PI's in the field, in order to assess the progress of CESAR and make any adjustments to operations management required to improve the field operations.

Individual PI's will be responsible for publishing material related to their ongoing research interests, as well as collaborating with other PI's to produce papers synthesizing various observations into comprehensive case studies or multifaceted analyses. A post-season analysis meeting will be organized

within one year of the end of field work to facilitate collaborative analyses.

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6. Data Management Plan

Project PI's will agree in advance on which data need to be distributed to the project community and in what format. Different PI's, in general, will need different subsets of the overall dataset. "Quick-look" operational summaries, and data listings and/or plots, should be provided by facility PI's to other interested PI's during the course of the project, to the extent possible. At the end of the project, the PI's will prioritize the different project days, with data processing from higher-priority days taking precedence over that from lower-priority days. It is hoped that complete data distribution can be accomplished within 6 to 12 months after the end of the project.

Data from the university-managed facilities will be organized and quality-controlled by the responsible PI's. The S-pol and CLASS data typically can be provided by NCAR within a few months of the end of a field project. L. J. Miller (NCAR) and V. N. Bringi (CSU) will generate gridded radar datasets comprised of 3D wind components and radar measurands for priority days.

A web page will be established for coordinating analysis activities and data distribution. Where possible, data will be available on-line. For larger data sets, sample data will be available on-line, with pointers to more extensive archives and information for obtaining data not available on-line. CSU-CHILL will compile a "quick-look" radar history of each day with significant operations, to be posted at the CESAR web site and distributed to PI's either in the field or shortly after the end of the project, in paper or a common electronic format (e.g. GIF or postscript files).

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As of summer, 1998, the dominant interest in CESAR is from investigators who propose to conduct their work with NSF support. It is hoped that once CESAR has established itself as a field project that will occur, additional interest will be generated among other funding agencies with interest in CESAR–related activities. This document contains a vision for CESAR that is presented in some detail. Nonetheless, our aim is to remain flexible enough to adapt strategies and operations to best take advantage of new insights into storm electrification, hail formation, and storm-related electrical discharge phenomena that may be developed between now and the summer of 2000.

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