THE METEOROLOGY OF TRANSIENT LUMINOUS EVENTS - AN INTRODUCTION AND OVERVIEW

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Abstract This contribution reviews the basics of atmospheric deep convection and electrification as it pertains to the generation of stratospheric and mesospheric transient luminous events (TLEs). Emphasis is placed on sprites and sprite-producing lightning, and the meteorological regimes in which they are found.

2.1 Introduction

This introduction provides a brief overview of key concepts in the atmospheric sciences relevant to investigations of transient luminous events (TLEs), with emphasis on convective clouds and thunderstorms. Our purpose is to familiarize those TLE researchers with little grounding in either the theoretical or operational aspects of meteorology with the terminology that may be encountered in their further explorations and readings of the literature (American Meteorological Society, 2000). Extensive reference resources will allow in depth pursuit of concepts introduced herein.

2.1.1 Scales of Atmospheric Motion

The Earth's atmosphere is a fluid whose energetics is almost entirely derived from the unequal distribution of solar energy upon the planet. The sun's input fluctuates over the time scales of climate change due to variations in the solar output plus eccentricities in the Earth's orbit. Seasonal changes arise from the 23.5° inclination of the axis of rotation to the ecliptic plane, along with a slightly elliptical orbit. The diurnal fluctuations of energy resulting from the planet's rotation are the result of short term imbalances of incoming short wave solar radiation with outgoing long wave radiation. The heterogeneity of solar energy gain at any point on the surface is further modulated by surface characteristics, principally the 75% of the surface covered by water, with its high specific heat, or highly reflective ice packs. Solar heating of land is greatly

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influenced by surface characteristics including land use, soil characteristics, moisture and snow cover.

Unequal temperatures, especially through deeper atmospheric layers, give rise to differences in hydrostatic pressure. Pressure gradient forces, modulated by the Earth's rotation (the Coriolis force), and retarded by friction near the surface, give rise to wind. The Earth's winds transport large amounts of heat and water vapor quasi-horizontally (advection). The patterns of atmospheric motion occur over a series of interlinked and somewhat arbitrarily differentiated scales. Global scale motions (the general circulation) are defined by well defined regions of quasi-steady flow (the polar easterlies, the mid-latitude westerlies, the sub-tropical easterlies and equatorial doldrums). Hemispheric flows, best visualized using polar coordinate charts, reveal the dominant Rossby wave troughs and ridges separating polar air masses from more temperate tropical air. Also found are the major jet streams (polar, mid-latitude, and sub-tropical) just below the tropopause, the demarcation between the 10-20 km deep weather-containing troposphere and the overlying stable, generally quiescent stratosphere. The synoptic, or macro-scale is defined by structures such as the familiar high and low pressure centers and warm and cold fronts of daily weather maps (scale: $\sim$1000 km). But most weather experienced on a day-to-day basis is associated with the mesoscale, systems with scale lengths of tens to hundreds of kilometers (Ray, 1986; Fujita, 1992, pp. 298). Individual thunderstorms are sometimes considered as sub-mesoscale or cloud scale events (Cotton and Anthes, 1989, pp. 883). The microscale refers to intense gradients of temperature and wind found within the planetary boundary layer (PBL) which experiences diurnal changes in depths ranging from tens to several thousands of meters.

Yet it is the molecular scale which in many ways controls key cloud formation processes. The maximum amount of moisture contained by a volume of atmosphere is a strong, non-linear function of temperature (the Clausius-Clapeyron equation). Moisture content can be specified in a variety of ways. Relative humidity is the percentage of moisture compared to its maximum carrying capacity at a given temperature (RH = 100% = saturation). Moisture is also defined by the dewpoint temperature, the temperature at which saturation is reached if air is cooled at constant pressure. The ratio of water vapor to dry air is the mixing ratio. Water is highly unusual in that it exists in all three phases, gaseous, liquid and solid, at common atmospheric temperatures and pressures. Any phase change results in either releasing or absorbing energy (sensible heat). Thus, water vapor is often said to possess latent heat, i.e., $2.501 \cdot 10^6$ J$\cdot$kg^{-1} released upon condensation, plus an additional $3.337 \cdot 10^5$ J$\cdot$kg^{-1} upon freezing. This process is reversible during melting and evaporation. Latent heat is the primary "fuel" of thunderstorms.

Upon reaching saturation, water vapor can not spontaneously condense into liquid without cloud condensation nuclei (CCN), specks of matter ranging greatly in size and origin including crustal materials, sea salt and industrial pollutants. Ice nuclei also play a similar role in allowing direct deposition of ice in the formation of ice crystals. Most cloud particles form in the liquid phase. Cloud droplets may remain supercooled to temperatures as cold as -40°C. The process of converting supercooled droplets to ice crystals is termed glaciation. Many thunderstorm clouds are comprised of liquid droplets near their base, fully glaciated ice crystals at the top, but with a deep mixed phase region between in which electrification processes occur (MacGorman and Rust, 1998, pp. 422).

2.1.2 Basic Concepts of Atmospheric Vertical Stability

The primarily vertical atmospheric transport of heat (sensible and latent) is called convection. Forced convection may result from mechanically driven flows over mountain (orographic) barriers or by horizontally converging air streams. Free (or gravitational or buoyant) convection, the dominant process in thunderstorm growth, arises when a parcel of air is locally less (more) dense than its environment and is thus accelerated upwards (downwards). If the parcel is unsaturated, it will cool (warm) at 1°C per 100 meters of upward (downward) displacement. Due to the effects of latent heat, if the parcel is saturated, it warms or cools at a rate $<$1°C per 100 meters (typically $\sim$0.6°C/100 m in the middle atmosphere). Once initially displaced, the fate of this parcel, however, depends on the environmental lapse rate of temperature, which can be highly variable. If the local environmental lapse rate is greater than that of the displaced parcel, it will continue to accelerate away from its initial position. This is termed an unstable atmosphere, and conditionally unstable if the parcel must be saturated for it to continue to accelerate. If the environmental lapse rate is less than the parcel lapse, then any displacement results in the parcel becoming denser (if moving upward) or lighter (if moving downward) than its environment, with restoring forces returning it to its initial position, often accompanied by oscillatory motions about that point. Atmospheres in which the temperature change with height is constant (isothermal) or increasing (inversion) are always absolutely stable.

The potential for deep convective motions in the atmosphere is often analyzed by applications of parcel theory. Given an observed atmospheric sounding of temperature and moisture, one can easily compute the fate of a parcel (or layer) of air initially displaced from near the surface, or some other arbitrary level in the lower atmosphere. If the parcel is able to continue rising to the point of saturation, it has reached the lifted condensation level (LCL), which marks the cloud's base. Continued ascent may bring it to the level at which it is now more buoyant than its environment, the level of free convection (LFC). From there, upward acceleration continues until reaching a stable layer, most often the tropopause, the abrupt change in environmental lapse rate demarcating the troposphere from the stratosphere above. Most thunderstorm tops flatten out on the tropopause, accounting for the familiar anvil-shaped thunderstorm cloud. The more intense updrafts, however, penetrate into the lower stratosphere for up to several kilometers before becoming negatively buoyant and subsiding. The overshooting domes are often a sign of severe weather.

There are numerous ways to quantify the thermal instability of an air mass. The Lifted Index (LI) is the computed temperature difference between the ascending parcel and its environment at the 500 hPa ($\sim$5500 m) level. Unstable air will have negative LI values, with -10°C being the most extreme buoyancy which may be expected. It is also possible to compute the Convective Available Potential Energy (CAPE, $J{\cdot}kg^{-1}$) which represents the integrated energy in the free convection regime between the LFC and the tropopause penetration. Modestly unstable air may have values in the 500 to 1000 $J{\cdot}kg^{-1}$ range, with the extremes approaching 5000 $J{\cdot}kg^{-1}$ being associated with the most severe thunderstorms. In order for an atmosphere to become unstable enough to support deep convection, various combinations of warming of the lower layers, cooling of the upper layers, or moistening (primarily the lower portion) of the air mass are required.

It should be noted that to induce convection, some form of triggering mechanism is often needed. This is often supplied by a warm air "bubble" near the ground, a product of differential heating. But mechanical lifting induced by flow over terrain, fronts and often the outflows from an adjacent storm, can provide enough initial lift to reach first the LCL and then finally, the LFC. The amount of energy required to reach the LFC, or "breaking the cap" in storm chaser parlance, is the Convective Inhibition (CIN, $J{\cdot}kg^{-1}$). In most cases, CIN $<<$ CAPE, but without this initial energy input the atmosphere's convective potential can not be realized. This, in part, explains why, on warm, humid summer days, convection occurs only in localized regions with discernible patterns often strongly controlled by the triggering mechanisms.

2.1.3 Convective Cloud Nomenclature

With the advent of modern remote sensing systems such as radar during World War II and later, meteorological satellites, convective storm research entered an era of unprecedented activity. Much has been learned through organized field campaigns, the prototype for which is the U.S. Thunderstorm Project held in Florida and Ohio in the late 1940s (Byers and Braham, 1949). Recent programs such as the Severe Thunderstorm Electrification and Precipitation Study (STEPS) (Lang et al., 2004) and the Bow Echo and Mesoscale Convective Vortex Experiment, BAMEX (Davis et al., 2004) illustrate the increasingly specialized nature of such campaigns, not only in the U.S. but, increasingly, worldwide. Such efforts have highlighted the complex and varied structures of convective storm systems, which we can only begin to outline below (Cotton and Anthes, 1989, see for example).

Convective clouds were first formally classified by Luke Howard in 1803. He devised a Latin-based cloud nomenclature system. Howard's "clouds of vertical development" include the modest cumulus cloud, the cumulus congestus (towering cumulus or TCU) and the cumulonimbus (thundercloud or "Cb"). However, convective storms are often organized into systems vastly larger and more multifaceted than any individual cumulonimbus element.

Convective storms are sometimes characterized by their "triggering" or forcing function, such as cold frontal thunderstorms. Mountain, or orographic, thunderstorms commonly occur in the late afternoon during warm seasons over higher terrain. Large stratiform precipitation regions in extratropical cyclones sometimes contain "embedded" convective cells, often poleward of warm fronts. The inventory includes sea and lake breeze storms, urban effect storms, and even forest fire storms. Thunderstorms also occur when winter polar air masses stream over warmer bodies of water such as the Sea of Japan, the Gulf Stream and the "lake effect" storms of the Great Lakes.

Over the past decades it has become common practice to classify atmospheric deep convection according to its structural and morphological features. Among the first to be documented are short-lived (30 to 60 minutes) "air mass" storms, occurring quasi-randomly in air masses, often far from frontal boundaries. Their single cell updrafts quickly transform into downdrafts which then terminate the convective motions. Somewhat longer-lived multicellular clusters also occur. Under conditions of extreme thermodynamic instability (high CAPE) and low level wind shear (high helicity), supercellular storms develop. These storms, which persist for many hours, are prolific producers of large hail and tornadoes. They are accompanied by quasi-steady state, rotating updrafts. They are further sub-classified in low precipitation (LP), classic, and high precipitation (HP) supercells. Squall lines refer to narrow, linear storm systems extending from 100 km to $>$1000 km in length, comprised of nearly continuous or discrete cellular elements. While often associated with cold fronts, they can also propagate far ahead of any frontal zone. Larger clusters of convective storms ($>$2,000 km^2) with lifetimes exceeding several hours are collectively called mesoscale convective systems (MCSs). They typically have intense updrafts and high radar reflectivities in convective cores which, as the MCSs mature, become embedded within much larger stratiform precipitation regions which may trail, surround or lead the intense convection. Some MCSs develop "bow echoes" at their leading edge. These can be associated with intense, sustained straight line winds (derechos). The largest and best organized MCS is the Mesoscale Convective Complex (MCC) appearing in satellite images as a quasi-elliptical cloud mass often well in excess of 100,000 km^2 (Maddox, 1980). Often lasting over 12 hours, they are among the world's most prolific producers of rainfall and lightning. MCCs occur worldwide, but most frequently over mid-latitude land masses during night (Laing and Fritsch, 1997). Nocturnal MCSs and MCCs often evolve upscale from daytime supercellular or squall line convection. Most convective systems produce gust fronts or outflow boundaries which often propagate far from the storm and persist long after its demise but which are critical in triggering new convection, especially when colliding with other outflow boundaries.

Numerical models are increasing our understanding of deep convection processes (Pielke Sr., 2002, pp. 673). Operational weather forecasting models generally do not explicitly realize the form of the convection per se, but rather rely on parameterizations to deduce thunderstorm occurrence. As increasing computer power allows reducing the horizontal computational grids to <10 km and hundreds of meters in the vertical, models will simulate in considerable detail the interplay of dynamics and microphysics of the various classes convection. Experimental modeling runs with horizontal mesh sizes <100 m are beginning to provide meaningful insights into storm scale atmospheric processes. Charge generation, separation, and lightning discharge parameterizations are achieving ever greater sophistication.

2.2 Observations of Convective Phenomema

For the first half of the last century, thunderstorm observations were limited to government weather observing stations. In most nations, a thunderstorm was defined as any period in which thunder could be heard at an observing site, typically an airport weather station. Given that the audible range of thunder is usually limited to 10-25 km, a small fraction of the typical spacing between stations, many thunderstorms went unreported. Visual observations of cumulonimbus clouds were provided at some stations. Most global summaries of convective frequency were cast in terms of "thunder days," days in which one (or more) periods of thunder occurred. Given the scarcity of marine observations, convective climatologies were necessarily biased towards land observations. Given such limitations, it is rather remarkable that Brooks (1925), using estimates based on the global electrical circuit (Bering, 1997), estimated global lightning flash rates to be on the order of 100 s^{-1}. This was remarkably prescient given that today's satellite estimates of global lightning are only less than a factor of two smaller.

2.2.1 Conventional Convective Storm Monitoring

During the wartime development of anti-aircraft radar surveillance systems, anomalous returns were soon recognized as areas of precipitation. The meteorological applications became immediately evident. During the 1940s and much of the 1950s, various military systems were reconfigured to detect atmospheric phenomena, notably precipitation. Many early systems operated at 3 cm wavelengths, ideal for detecting snow and wet clouds, but suffering from attenuation during heavier rain events. A series of hurricanes along the U.S. east coast in the mid-1950s lead to the development of the WSR-57 radar, a minimal attenuation 10 cm radar ideal for probing thunderstorms. Similar systems became commonplace worldwide. Conventional radar returns were described in terms of decibels of reflectivity (dBZ), which are related to precipitation rate. Several hundred Z/R (reflectivity/rainfall) rate algorithms have emerged over the years, so one to one correlations between precipitation rates and reflectivity remain elusive. By the 1980s, computers allowed conversion of radar grey scale CRT displays into colorized images using various dBZ contouring schemes. Typically, very light precipitation is associated with 0-10 dBZ values. Echoes achieving 30 dBZ indicate moderate rain and the possibility of lightning. Intense rain, often accompanied by hail, is indicated for >50-55 dBZ. The most extreme convection peaks around $\sim$ 70 dBZ. Certain reflectivity patterns such as hook echoes, bow echoes and "notches" were qualitatively associated with tornadoes, straight line winds and hail. But means to directly detect potentially damaging surface wind speeds became increasingly urgent. To this end, by the mid-1990s, the U.S. began deploying 10 cm Doppler radars (the NEXRAD WSR-88D) which have since been integrated into a nationwide network. Similar national and regional networks are emerging elsewhere. In addition to reflectivity, a single Doppler radar can measure winds, although only along the beam's radial direction. However, algorithms have been developed which allow detection of supercell storm-scale rotation (mesocyclones), and on occasion, the circulation of very large tornadoes (the TVS, tornado vortex signature). Multiple research Doppler radars can be run in tandem to provide 2-D and 3-D wind fields. Terminal Doppler Weather Radars at airports specialize in the detection of a key aviation hazard, the microburst. New, portable Doppler on Wheels (DoW) are becoming key components of tornado field research programs, providing high resolution views of storm dynamics. Dual-polarization radars can derive 3-D volumetric estimates of major precipitation types within storms, greatly facilitating microphysical investigations.

Based upon brief film records of the Earth's cloud cover obtained using surplus World War II rockets, great hope was placed in the capability of weather satellites to map synoptic scale cloud patterns, such as fronts. With the launch of TIROS I (the television and infrared observation satellite) on 1 April 1960, that hope was realized. Since that date, no tropical storm, typhoon or hurricane has gone unmapped anywhere in the world. But with each successive satellite launch, even more amazing was the degree to which the mesoscale structure of the atmosphere could be deduced. Polar orbiting satellites, which typically provide twice daily views of a given area, were joined in the mid-1960s by geostationary systems. Given hourly or more frequent updates, animations of the cloud patterns revealed structure and organization which greatly aided our understanding of convective processes. Presently, continuous global cloud monitoring is provided by a minimum of five geostationary satellites (two U.S., Europe, India and Japan). High resolution visible imagers provide useful detailed information on daytime convective clouds of all sizes. Somewhat lower resolution infrared scanners provide 24-hour coverage, including estimates of cloud top heights. Middle and upper tropospheric water vapor is another widely used product. Most geostationary satellite data are readily available on line to researchers. Polar orbiting research satellites provide multispectral views of the Earth's surface, clouds and aerosol patterns. NASA's advanced MODIS system provides extremely high resolution snapshots of cloud systems.

Meteorological satellite imagery graphically portrays major convective events such as tropical cyclones (including the convective outer bands), frontal and squall line convection, the intertropical convergence zone (ITCZ), polar lows, and organized MCS and MCC cloud canopies. Smaller scale convective organization along sea breeze fronts and mountains, during cold air advection over warmer waters, and random air mass convection are easily determined. Cumulus clouds demarcating outflow boundaries are routinely visible. Key details of intense convection such as overshooting domes, jet-stream sheared anvil clouds, and V-notch patterns in the top of supercells are among the many clues afforded by higher resolution meteorological satellite images.

Additional remote sensing technologies continue to evolve. Infrasound has shown promise in detecting tornadic circulations as well as signatures for sprites (Bedard Jr. et al., 1999) and Chapter 15. Additional research is required before such techniques become routine.

2.2.2 Lightning Observation Techniques and Terminology

This section will not review the physics of the lightning discharge per se. Such information can be found in a large number of textbooks (Rakov and Uman, 2003; MacGorman and Rust, 1998; Williams, 1988; Uman, 1987; National Research Council, 1986; Volland, 1982; Golde, 1977). Rather, we briefly summarize key terminology used in discussing lightning and provide a brief overview of techniques used to investigate and observe lightning.

The human eye was certainly the first lightning sensing system, and human observations have remained a mainstay of aviation weather observation reporting (though they are gradually being replaced by less descriptive, automated lightning detection systems). Terminology evolved to include cloud-to- ground (CG), cloud-to-cloud (CC), in-cloud (IC) and cloud-to-air (CA) lightning. Today it is more common to distinguish between CG and non-CG (collectively IC) events, which in combination are referred to as total lightning.

The earliest known photographs of lightning were taken by a Philadelphia amateur photographer, William Jennings, between 1883 and 1890. By the following decade, photographs of lightning spectra had been obtained. By the 1920s, the Boys camera was among the early streak photography techniques which began to unmask the complex temporal series of events and spectra comprising the CG flash (Uman, 1987; Salanave, 1980; Golde, 1977, pp. 496). Investigations of lightning striking the Empire State Building in the 1930s by K. B. McEachron, instrumented towers in Switzerland in the 1960s and 1970s (Berger et al., 1975), and rocket triggered lightning (Uman and Krider, 1989), are highlights of earlier studies of lightning. The CG discharge to this day remains a phenomenon of intense research interest. The initial in-cloud breakdown processes may include a stepped leader which, as it approaches Earth, is met by an upward propagating streamer. When the connection is made, a brilliant return stroke transports negative charge (negative polarity CG) or positive charge (+CG) to ground. Much of the current is transferred impulsively within less than a millisecond in peak currents ranging from 10 to $>$100 kA. In many cases, lesser amounts of current flow in a continuing current which can last for tens and, in some cases, hundreds of milliseconds. Negative CGs are usually composed of multiple strokes (3 to 5 being typical, over 40 have been reported) with inter-stroke intervals on the order of tens of milliseconds. These repetitive strokes make the lightning appear to flicker. The entire multi-stroke process is collectively termed a flash. Positive CGs tend to have stroke multiplicities of one, on average have higher peak currents and longer, more intense continuing currents. It is estimated that -CGs outnumber +CGs by nearly an order of magnitude. In multistroke CGs, most strokes are preceded by a dart leader that follows the initial channel to ground. However, recent research suggests that multi-attach point flashes, either branching strokes or strokes following different channels, are quite common (Figure 1). The lightning discharge and storm electrification have been investigated using a wide variety of techniques including networks of automated lightning flash counters, electric field mill networks, acoustic reconstruction of lightning channels, rocket triggered lightning, balloon and aircraft soundings of *in situ* electric fields in clouds and radio frequency (RF) signature analysis of “sferics” (Rakov and Uman, 2003). During the last quarter century, however, major advances have arisen from two primary technologies, terrestrial lightning detection networks and space-borne lightning sensors.

Though the majority of the world's lightning occurs in the tropics, the first practical CG lightning detection network (LDN) evolved in response to forest fire threats in Alaska (Krider et al., 1980). Broadband VLF magnetic direction finding (MDF) systems have been employed in ever growing numbers since the early 1980s for operational detection and location of CG events. Using CG wave form discrimination criteria, the CG return stroke can be distinguished from IC events for a large majority of discharges. The current U.S. National Lightning Detection Network (NLDN) arose from the gradual assembly of regional networks sponsored by various research and utility interests. During the late 1980s, a second technology, time of arrival (TOA) also was developed into a network (Lyons et al., 1989). By the mid-1990s, the benefits of exploiting both MDF and TOA technology resulted in the creation of the hybrid NLDN that exists today (Cummins et al., 1998). The network has subsequently expanded into a North American Lightning Detection Network (Orville et al., 2002), and similar regional networks are emerging worldwide. A typical LDN can provide the following information, either in real time or from archives: return stroke time (millisecond or better), estimated peak current (kA), polarity, location (latitude and longitude), and stroke wave form parameters. Software systems can simulate LDN performance. Estimates of typical locational

Figure 1. A cloud-to-ground lightning flash composed of three separate strokes, each with their own attach points separated by several kilometers. Image courtesy of Tom Nelson.

accuracy (LA) for modern systems are approximately 500 m. Stroke and flash detection efficiency (DE) vary, but typically average 50-70% and 80-90%, respectively (higher for +CGs). Especially for the new hybrid systems, IC rejection is less than perfect. In analyses of LDN data, ICs misidentified as low peak current +CGs ($<$10 kA) are sometimes excised from the data. Currently, LDNs are concentrated on land masses. New experimental networks (Dowden et al., 2002) are providing nearly global coverage of large peak current CG events.

While the peak currents of sprite parent +CGs (SP+CGs) average 25-50% larger than other +CGs in the same storm, peak current is a poor predictor of the TLE potential of any given lightning stroke (Lyons, 1996b). Based upon sprite modeling theory, the charge moment change, a parameter not measured by conventional LDNs, is perhaps the most important lightning metric for sprite researchers (Wilson, 1925, 1956; Huang et al., 1999; Hu et al., 2002). The charge moment change,

$$\Delta \mathrm{Mq}\ (\mathrm{t}) = \mathrm{Z}_q \cdot \mathrm{Q(t)}\ (\text{units, C}\cdot\text{km})$$

is defined as the product of Z_q(km), the mean altitude above ground level (AGL) from which the charge is lowered to ground, and Q(t) (unit, C), the amount of charge lowered. Note this second term is most appropriately considered as a function of time, t.

Numerous investigators have explored the use of ELF transient analysis to detect those SP+CGs capable of initiating sprites. Boccippio et al. (1995), Huang et al. (1999) and Williams (2001) measured essentially the entire ΔMq, including that from continuing currents (tens of ms). Based upon analyses of high speed video (Stanley et al., 1999), it appears that most sprites initiate in the 70-75 km altitude. This allows computation of a ΔMq value on the order of 500-1000 C$\cdot$km required to induce dielectric breakdown in the mesosphere (Williams, 2001). Cummer and Inan (2000) developed a related approach at ELF/VLF which allows routine measurements as a function of time. It is especially effective for determining the impulse charge moment change, iΔMq, covering the first 2 milliseconds of the stroke from almost all CGs over long ranges ($>$1000 km) (Cummer and Lyons, 2004, 2005). In addition, ΔMq for longer periods can also be extracted for the more powerful events (Hu et al., 2002; Lyons et al., 2003a). Though it may vary somewhat from night to night, reflecting changes in ionospheric conditions, it appears that there exists a fairly firm threshold in iΔMq for short delay sprites, those occurring less than $\sim$6 ms after the return stroke (Cummer and Lyons, 2005). This value appears to be in the 100 to 500 C$\cdot$km range. Long delay sprites, in which the continuing current plays a more significant role in imitating breakdown, will require somewhat larger threshold ΔMq values (300-500 kC·km).

Another major development in lightning measurements is VHF 3-D lightning mapping systems. Research applications date to the pioneering work of Proctor in South Africa. The lightning hazard to Space Shuttle launches resulted in the development of an operational Lightning Detection and Ranging System (LDAR) at the Kennedy Space Center in the 1980s. More recently, New Mexico Tech's pioneering Lightning Mapping Array (LMA) (Krehbiel et al., 2000) has been deployed in several major convective storms field programs in the U.S., along with the French 3-D lightning mapping system (SAFIR). Commercial versions of the LDAR II are now gradually coming into use (Demetriades et al., 2003). These systems provide not only the IC flash rates, but the horizontal and vertical extent of electrified clouds as well as the volume from which charge is removed for each discharge. When combined with an LDN, both the CG and IC components can be measured to produce storm total lightning rates.

Satellite lightning measurements are becoming increasingly important. The U.S. military polar orbiting Defense Meteorological Satellite Program (DMSP) pioneered with an optical flash counter in the 1970s. Early analyses revealed a startling order of magnitude land/ocean asymmetry in total lightning counts (Orville and Henderson, 1986). Why lightning is far more prevalent over land masses, remains an area of active research today. DMSP detection of optical "superbolts" (Turman, 1977) also provided early hints that the tail of the statistical lightning distribution may contain extraordinary events far exceeding the "normal" discharge. During the past decade, NASA's Optical Transient Detection (OTD) polar orbiter has mapped global total lightning (Christian et al., 2003). The Tropical Rainfall Measurement Mission (TRMM) has likewise mapped total lightning, though orbital constraints limited the coverage to tropical regions. To date, no civilian geostationary satellite has been equipped with a lightning sensor, a matter of considerable dismay to atmospheric electricians. The U.S. Department of Energy's FORTE satellite (Smith et al., 2002) obtains specialized data on lightning. Spacecraft specifically designed to detect TLEs will be discussed in Chapters 7 and 6 by Blanc and Mende, respectively, notably the ISUAL experiment on the Taiwanese ROCSAT II satellite.

2.3 A Brief History of TLE Observations

For almost 120 years, unexplained luminous phenomena above thunderstorms have been reported in the literature, beginning with MacKenzie and Toynbee (1886), who described what today might be regarded as a giant jet. Davidson (1893), reporting from tropical Queensland, Australia, noted lightning visible on the horizon when suddenly "... a patch of ... rosy light... 5° to

6° in diameter... rose up from above the thunderstorm and mounted upwards; disappearing at an elevation of from 40°-45° ... there were about... twenty-five of the patches in about an hour...." Malan (1937) in South Africa reported "... a long and weak streamer of reddish hue... some 50 km high." Corliss (1977, pp. 542), Vaughan Jr. and Vonnegut (1989) and Vonnegut (1980) are credited with compiling numerous eyewitness accounts from credible observers. Even Nobel laureate Wilson (1956) reported seeing "... diffuse, fan-shaped flashes... extending up into the clear sky...." Yet, without documented evidence, such anecdotal sightings received little attention from the atmospheric electricity community – until the night of 6 July 1989.

Prof. J. R. Winckler and his graduate students were testing a Xybion ISS-255 low-light television (LLTV) for an upcoming research rocket flight. Playback of the video tape revealed a star field, distant "heat lightning" – and two video fields revealing brilliant twin columns of light, extending tens of kilometers into the atmosphere (Franz et al., 1990). These first-ever images of a sprite were presumed to originate over a large MCS in northern Minnesota, several hundred kilometers distant. For the U.S. manned space flight program, the prospect of a new form of "upward lightning" was unsettling, given several unfortunate encounters of spacecraft with lightning (Uman and Rakov, 2003). Similar LLTV cameras were then being flown on the Space Shuttle as part of a mesoscale lightning mapping program. A careful re-inspection of the tapes revealed both a transient airglow enhancement (almost certainly an elve) and more than a dozen "upward lightnings" above thunderstorms (Boeck et al., 1992, 1995; Vaughan Jr. et al., 1992; Lyons and Williams, 1993). By 1993, both ground-based and airborne investigations had been funded by NASA. On the night of 7 July 1993, using Winckler's same Xybion LLTV installed at FMA's Yucca Ridge Field Station (YRFS) near Ft. Collins, CO, almost 250 events were detected during a several hour period above an MCC located 400 km to the east over Kansas (Lyons and Williams, 1993; Lyons, 1994a,b). Within 24 hours, a NASA DC-8 using an LLTV equipped with fish eye lenses detected similar phenomena over an MCC in Iowa (Sentman and Wescott, 1993). Within a year, the FMA and University of Alaska (U of A) teams had noted distinctive VLF audio signatures associated with these events. By this time, at the suggestion of D. D. Sentman, the phenomenon had been named a sprite (after the fleeting spirits in Shakespeare plays) as opposed to "cloud-to-stratosphere lightning," "cloud-to-space lightning" and various other misleading terms that had begun to be used. By 1994, the U of A mounted an airborne campaign which produced the first color images of sprites (Sentman et al., 1995) and the totally unexpected blue jets (Wescott et al., 1995).

During the 1994 and 1995 YRFS sprite campaigns, the correlation between sprites and +CGs became obvious (Lyons, 1996b). An estimated 10,000 optically confirmed sprite observations to date reveal only several confirmed sprites from -CGs (Barrington-Leigh et al., 1999). Also, during the 1994 campaign, YRFS LLTV video data coordinated with ELF Schumann resonance transient (Q-burst) measurements at the Massachusetts Institute of Technology facility in Rhode Island, revealed the vast majority of sprites, or more properly, sprite parent +CGs, had distinctive ELF signatures (Boccippio et al., 1995).

Sprites and blue jets were soon accompanied by other transient luminous events. The predictions of Taraneko et al. (1993) of intense, very brief (<1 ms) glows at the base of the ionosphere associated with lightning EMP (now called elves) were confirmed optically at YRFS in 1995 by Fukunishi et al. (1996). Optical spectra also identified the key $N_2$1P red emissions (Mende et al., 1995; Hampton et al., 1996). Evidence of ionization in some, but not all, sprites was obtained by photometric analyses (Armstrong et al., 1998). Ongoing optical programs at YRFS and New Mexico Tech's Langmuir Lab revealed that what many early observers thought to be elves were, in fact, the halo which precedes some, but not all sprites (Barrington-Leigh et al., 2001; Bering et al., 2004). High Speed Imagers (HSI) operating at 1000 fps at Socorro and YRFS documented the first millisecond-scale structure of sprites (Stanley et al., 1999; Armstrong and Lyons, 2000) and notably, that the initiation point of sprites appears to be in the 70-75 km altitude range. The finer temporal and spatial scale structure of sprites, elves and halos have continued to be explored using a variety of photometric sensors including the fly's eye (Inan et al., 1997), telescopic imagery (Gerken et al., 2000; Gerken and Inan, 2003), high speed, high resolution cameras (Stenbaek-Nielsen et al., 2000; Moudry et al., 2003) high speed telescopic imagery (Marshall and Inan, 2005). U of A flights during the mid-1990s confirmed sprites over South American MCSs. Global sprite watching rapidly expanded with confirmations from Australia (Hardman et al., 2000), above Sea of Japan winter snow squalls (Fukunishi et al., 1999), Europe (Neubert et al., 2001), the Caribbean (Pasko et al., 2002) and East Asia (Su et al., 2002; Hsu et al., 2003) to name but a few. Stratospheric TLE balloon missions (Bering et al., 2004; Holzworth et al., 2005) are being pursued to obtain TLE optical signatures with minimal atmospheric absorption as well as *in situ* electric field transient data directly above the parent lightning discharge. Infrasound measurements have also detected apparent signatures from TLEs of the SP+CG (Bedard Jr. et al., 1999) and Chapter 15.

Sprite observations from space have resumed in recent years, highlighted by the MEIDEX experiment on board STS-107 (Isrealevich et al., 2004; Yair et al., 2004). Nadir observations of sprites have been obtained from the International Space Station (Blanc et al., 2004). As mentioned, the ROCSAT-II ISUAL experiment began observations in mid-2004.

In addition to sprites, elves and halos, a variety of electrical discharges emanating from cloud- tops have been uncovered, further expanding the TLE family. Since 1989, more than 10,000 low-light television (LLTV) images of sprites have been obtained by various research teams (Lyons, 1996b; Sentman et al., 1995; Lyons et al., 2000, 2003a). Many anecdotal reports in the literature (Vonnegut, 1980; Vaughan Jr. and Vonnegut, 1989; Lyons and Williams, 1993; Heavner, 2000; Lyons et al., 2003a) described TLEs which simply can not be categorized as sprites:

"... vertical lightning bolts were extending from the tops of the clouds... to an altitude of approximately 120,000 feet... they were generally straight compared to most lightning bolts..."

"... at least ten bolts of lightning went up a vertical blue shaft of light that would form an instant before the lightning bolt emerged..."

"...a beam, purple in color... then a normal lightning flash extended upwards at this point... after which the discharge assumed a shape similar to roots in a tree in an inverted position..."

"... an ionized glow around an arrow-straight finger core..."

"... an American Airlines captain... near Costa Rica... saw from an anvil of a thunderstorm... several discharges vertically to very high altitudes... the event was white..."

"... the top of the storm was not flat... looked like a dome of a van de Graff generator...clearly saw several bolts of lightning going upwards... dissipating in the clear air above the storm... all in all 5 or 6 occurrences ..."

Upward extending white channels topped by blue, flame-like features were captured on film near Darwin, Australia (Lyons et al., 2003b) and over the Indian Ocean (Wescott et al., 2001). This latter event reached a height of ∼35 km. Welsh geographer Tudor Williams, who in 1968 was residing near Mt. Ida, Queensland, Australia, visually observed a series of lightning-like channels rising at least several kilometers above the top of a large nocturnal thunderstorm. He photographed several of the approximately 15 events (using 50 ASA 35 mm transparency film, long exposures) that occurred at fairly regular intervals over a 45 minute period. Upward-extending electrical discharges from a supercellular thunderstorm over Colorado were observed during the Severe Thunderstorm Electrification and Precipitation Study (STEPS) on 22 July 2000 (Lyons et al., 2003b).

Eyewitness recollections of lightning-like channels emanating from overshooting convective domes of very active storm cells often share common characteristics. They appear bright white to yellow in color, are relatively straight, do not flicker, extend above cloud tops to heights equal to or exceeding the depth of the cloud (10-15 km), are notably long lasting (∼1 second) and can be observed during *daylight*. It is difficult to understand how these might represent the faint blue jet phenomenon reported by Wescott et al. (1995).

On 15 September 2001, a team of scientists familiar with sprites and blue jets were investigating the effects of lightning on the ionosphere at the Arecibo Observatory in Puerto Rico (Pasko et al., 2002). At 0325.00.872 UTC, above a relatively small ($\sim$2500 km^2) storm cell 200 km northwest of Arecibo, the LLTV video captured an amazing upward discharge, blue in color (see the full animation at http://pasko.ee.psu.edu/Nature). Seen as brilliant blue to the human eye, it appeared as a series of upward and outward expanding streamers which rose from the storm top (16 km). The event reached a terminal altitude of 70 km, the estimated lower ledge of the ionosphere. The event lasted almost 800 ms, including several re-brightenings. This case marked the first hard evidence of a direct electrical link between a tropospheric thunderstorm cell and the ionosphere. A series of similar giant upward jets have since been reported emanating from thunderstorm tops over the Pacific near the Philippines (Su et al., 2003). While sprites are believed to occur with a global frequency of several per minute, the frequency of upward jets and lightning- like cloud top discharges remains unknown. It is becoming clear, however, that they are less rare than once believed.

2.4 Characteristics of TLE-Parent Lightning and Storms

Our understanding of TLE characteristics is evolving at a rapid pace. Investigations into the nature of their unusual parent lightning and, in turn, the types of convective storms which give rise to such atypical discharges are likewise an area of accelerating research. We here briefly summarize the current consensus, but readers should note that new details are emerging with each passing month, potentially dating certain aspects of this summary relatively quickly.

2.4.1 The Phenomenology of TLEs

Red Sprites Based upon surface measurements, these are apparently the most frequently observed of the TLEs. Initiation appears to occur most frequently at 70-75 km altitude, with highly structured branching streamers often first propagating downward, followed by upward expansion in luminosity with the top portion of the sprite a more diffuse glow (Pasko et al., 2002). The tendrils sometimes extend below 40 km, and evidence suggests they can reach below 30 km. The lower portion of the sprites often has a distinct blue coloration. It is uncertain if any tendrils might actually make a physical connection with the parent storm top. Like snowflakes, no two sprites are visually identical, but there are several morphological shapes that are repeated. The columnar or c-sprites are very narrow (order 1 km), quasi-continuous, nearly vertical columns, often with downward and upward extending filaments. They can occur in clusters, sometimes of a dozen or more spread out over several tens of km (Wescott et al., 1998). The classic "carrot" sprite has groups of streamers tapering downwards with outward flaring elements above, causing it to resemble its namesake. Larger clusters of sprites often resemble "A-bombs" or "angels." A "typical" storm may produce a sprite every several minutes. In the U.S. High Plains, after initial onset, sprites usually continue for several hours. Several dozen would be a typical number though, on occasion, storms have produced 400 to 750 sprites within 4-5 hours. In certain storms with very frequent sprites, they appear in video as amorphous glows (Gerken and Inan, 2004). The reason for such hyper-active storms is unclear.

The overwhelming majority of sprites are induced by +CG flashes. On occasion, a massive horizontal cloud discharge, called spider lightning (Mazur et al., 1998), can propagate through the cloud for $>$100 km, sometimes with several +CG attach points. These often trigger successive sprites in a "dancer" sequence. Most information on sprite durations has been obtained from video with 16.7 ms resolution. Some sprites, often the brightest, occur within a single video field, but some may persist for ten or more fields, slowly dimming from their peak luminosity early in the event. High speed imagery (1000 fps or better) shows the brightest elements persist for only several milliseconds, although subsequent bright features sometimes emerge from those sprites which evolve structure over time. The delay time between the CG return stroke, which can be determined from HSIs or photometric measurements, is highly variable. Often the brightest events occur approximately 1 ms after the return stroke. However, delays of tens of milliseconds are common. Approximately 10% of sprites can not be associated with +CG from a lightning detection network. Given that the DE for +CGs is $\sim$90%, it is suspected that such sprites did have a parent +CG which remained undetected by the LDN. Some sprites can be seen with the dark-adapted, human eye, though they are sometimes perceived as green, white or yellow due to the vagaries of human vision at such low light levels. The inherent brightness of sprites is usually estimated at around 1.0 MR, but briefly can be several times brighter, with some rare cases thought to reach as high as 10-30 MR.

Peak current is a poor predictor of the sprite potential of a CG. A sprite has been detected with an SP+CG as small as 9 kA. Even in the most "sprite efficient" storm, rarely will more than one in five +CGs initiate a sprite. An ongoing question has been "What is different about those +CGs which initiate sprites?" Cummer (Chapter 9) describes in detail the procedures to extract ΔMq from ELF and VLF signals. During the 2000 STEPS program (Lang et al., 2004; Lyons et al., 2003b), detailed analyses of ΔMq (out to 10 ms after the return stroke) suggested that at 600 C$\cdot$km, there was a 10% of sprite initiation, reaching to 90% by 1000 C$\cdot$km (Hu et al., 2002). Using more impulsive (2 ms) iΔMq estimates, a threshold of 100 to 500 C$\cdot$km for rapid onset sprites (within several ms after a +CG) was found in several storms, with the minimum varying somewhat from night to night (Cummer and Lyons, 2004, 2005).

Experience at YRFS has focused on nocturnal MCS and MCC convection. As illustrated in several papers (Lyons, 1996b; Lyons et al., 2000), SP+CGs tend not to occur until the storm has approached its mature stage and developed a considerable stratiform precipitation region. The SP+CGs tend to cluster in a portion of the stratiform region, sometimes towards the trailing edge where clear cloud electrification processes are very different from those experienced in the high reflectivity convective cores. The MCS stratiform area usually reaches a minimum of 10-20$\cdot10^3$ km^2 before significant sprite activity can be expected. Detailed analyses of 3-D lightning patterns from STEPS storms (Lyons et al., 2003b; Lyons and Cummer, 2004) have revealed several possible signatures. The main centers of VHF emissions, representing IC discharges, remained high in the cloud (8-12 km) during its active growth stage. But as the stratiform precipitation region expanded, a low-level secondary center of VHF activity developed and the +CGs began initiating sprites (Figure 2). As suggested by Williams (1998), this low level positive charge pool is located around 4 km AGL, near the melting layer. Thus, for the cases studied to date, the average Z_q has resided at 3-5 km. This is in marked contrast to the 10 to 20 km many earlier theoretical sprite modeling studies invoked, in part to achieve sufficiently large ΔMq values. However, evidence is accumulating that some SP+CGs can lower 100 to 300 C of charge. Based on the work of Boccippio et al. (1995) and many subsequent papers, it appears that most SP+CGs produce a globally detectable ELF transient signature (Sato et al., 2003; Price et al., 2002b; Füllekrug and Constable, 2000). This allows a crude estimate of global TLE rates of several per minute, assuming most "Q-bursts" represent TLEs. However, it is not known how many ELF transients (Q-bursts) result from non-sprite producing events. The recent puzzling results from MEIDEX, in which optically confirmed sprites could not be matched with ELF signatures (Price et al., 2004) also requires further investigation.

Elves It is likely that the first elve (the singular is *not* elf, to avoid obvious confusion with ELF radio waves) was recorded by the Space Shuttle low light camera. Though theoretically predicted in the early 1990s, the phenomenon was not documented from ground sensors until 1995 (Fukunishi et al., 1996). Elves, though perhaps as bright as a typical sprite ($\sim$1000 kR), are very brief (hundreds of microseconds), and thus invisible to the human eye. They are also difficult to detect using video systems, and is thus better investigated using photometer arrays (Barrington-Leigh et al., 2001). Red in color, an elve is a rapidly expanding toroidal disk, the result of the EMP pulse from a CG discharge. Thus the lag between return stroke and the onset of luminosity is that of the propagating speed of light ($\sim$300 microseconds). In conventional video, an elve will persist only for a single field. The altitude is in the range of 80-100 km and the expanded disk can attain a diameter of 400 km or even larger. While the most accepted theoretical explanations for both sprites and elves are independent of the CG polarity, only elves seem to be associated with a significant percentage of -CG strokes. Typically these have higher peak currents than those for sprites, indicative of the more impulsive nature of the CG source. There has not yet been a systematic survey of rise times for elve parent CGs. Typical ΔMq values approach those for sprites, though more data is required to determine if any threshold may be systematically lower. Using ground cameras, sprites and elves occur intermingled in the same storms, though the ratio varies considerably from storm to storm. It is rare to have just elves or just sprites in a given storm. Given the recent findings from the STS-107 MEIDEX mission (Yair et al., 2004) and preliminary returns from ROCSAT II, elves may be more common than expected from analysis of ground-based video. This

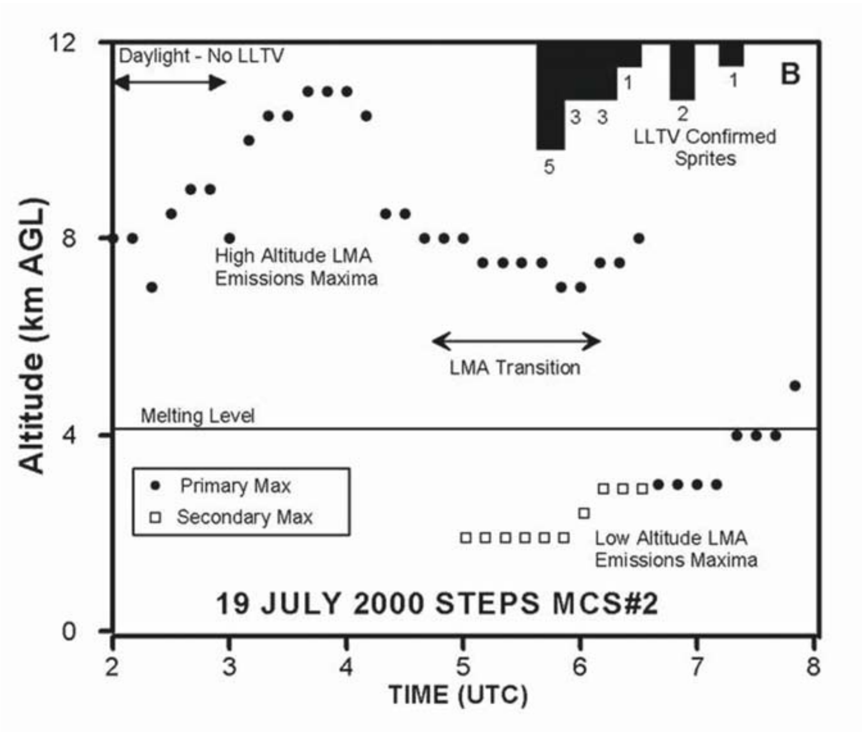

Figure 2. Sequence of events in a sprite-producing MCS When VHF lightning returns from a 3-D lightning mapper remain between 8-11 km AGL, +CGs do not initiate sprites. When a low-level maximum of VHF returns develops as the storm matures, +CGs begin producing sprites. (Lyons et al., 2003a, Courtesy of the American Meteorological Society).

may result from better viewing angles (limb views) but also from more systematic monitoring over the world's oceans. There is growing suspicion that large peak current (and perhaps more impulsive) -CGs are more prevalent over salt water than land (Lyons et al., 1998; Füllekrug et al., 2002).

Halos In the early days of LLTV monitoring, it was common to observe an apparent elve followed by a sprite, sometimes called a "sprelve." While elves do indeed precede some sprites, the "sprelve" in most cases was found to represent a "sprite halo" (Barrington-Leigh et al., 2001; Moudry et al., 2003; Miyasato et al., 2003). High speed video (Armstrong and Lyons, 2000; Stanley et al., 1999; Stenbaek-Nielsen et al., 2000) have shown the halo to be a downward descending, lens shaped amorphous glow that initiates typically one or 2 ms after the return stroke, and persists for 1 to 3 ms. Halos tend to be much smaller (maximum diameter 100 km) and lower (80 to 65 km) than elves. Their brightness is similar to an average sprite (500-1000 kR) and is red in color. Spites often initiate from the underside of the descending halo feature. Unlike sprites, halos have been observed in association with -CGs from the ground. The 1999 balloon campaign (Bering et al., 2004) suggested that numerous halos associated with -CGs were detected by the balloon's optical sensors. While many +CG halos followed by sprites have been noted, no -CG halo is known to have been followed by a sprite. Like elves, halos tend to be centered more or less directly over the parent CG, whereas the sprite centroid can often be offset by up to 50 km (Wescott et al., 2001; Lyons, 1996b).

Blue Jets Perhaps the most distinguishing feature of the blue jet is its rarity. Emerging at speeds of 200 km s^{-1} from thunderstorm anvils, they gradually decelerate as they extend to heights of 30-40 km. Their grainy appearance is distinctive, and their color is almost pure blue (Wescott et al., 2001). The inherent brightness is close to 1000 kR. Thus, they can be seen with the dark-adapted human eye under ideal conditions. First confirmed from the U of A aircraft in 1994 when a hail-producing supercell over Arkansas produced several dozen within an hour, they have been documented only rarely since. In nine years of ground LLTV monitoring at YRFS, none have been recorded. The reasons are several. First, many standard LLTV spectral responses are red biased. But more importantly, most TLEs are usually monitored above storms several hundred kilometers distant, with transmission of the weak blue signal severely attenuated. Evidence to date suggests the blue jet, and their shorter "blue starter" cousins (Wescott et al., 1996), do not appear associated with specific CG or IC discharges, though this later assertion is more difficult to confirm. Blue jets may more likely be associated with intense supercellular storms in which significant amounts of electrical charge are penetrating into the stratosphere by overshooting convective domes. This assertion, too, remains a conjecture to be proven. Space-borne optical sensors may prove more suitable for blue jet detection.

Upward Lightning from Cloud Tops Less is known about this class of TLE than any other. A detailed synopsis of known reports appears in Lyons et al. (2003b). The mere handful of observations does not yet permit their association with specific lightning characteristics. Ranging in vertical extent from upward a few hundred meters to tens of kilometers, it is unknown whether there are a host of distinct classes of upward discharges or merely a broad range of appearances resulting from a basic underlying mechanism. Perhaps the most intriguing is the true "upward lightning" which may be a feature of especially intense deep convection. Visible in daylight, the lightning-like column extends upwards from the cloud top, does not flicker, is yellow to white in color, exhibits little tortuosity, and can persist for 1 to 2 seconds before the entire column fades. Some events may reach above 30 km. Not yet captured on video, only a handful of still photos and eyewitness accounts exist. Their relationship to giant jets (Pasko et al., 2002; Su et al., 2003) remains unknown at this time.

A variety of theoretical papers have detailed TLE mechanisms in great detail. Readers are referred to the following representative papers for in depth discussions of TLE theory (Wilson, 1925, 1956; Taraneko et al., 1993; Rowland, 1998; Rodger, 1999; Huang et al., 1999; Stanley, 2000; Williams, 2001; Pasko et al., 1995, 1996, 1997, 1998, 2000, 2001, 2002; Roussel-Dupré and Gurevich, 1996; Cho and Rycroft, 2001; Bering et al., 2002).

2.4.2 Convective Storm Types and TLEs

TLEs are global phenomena. They have been recorded over all oceans and every continent, save Antarctica. With the gradual assembly of a TLE census using the ROCSAT II satellite, we suspect that the TLE density will bear some resemblance to maps of global lightning (Price, Chapter 4), but there will not be a one to one correspondence. This results from the realization that only few CGs possess the unique characteristics required to initiate sprites (high ΔMq), elves (highly impulse with large ΔMq) and halos (similar to sprites?). Especially in regard to sprites, it is clear that only certain classes of convective storms, and then only during certain parts of their life cycle, generate CGs with the requisite large ΔMq. Much of our understanding of the meteorology of TLE-producing lightning has been gained during field programs in the central U.S., though more recent programs in Europe, East Asia, the Middle East, Japan and Australia have greatly expanded the geographic domain of our understanding. We will summarize our best estimates as to which meteorological regimes will, and will not be, prolific TLE producers, with an emphasis on sprites, the most common and best understood of the phenomena.

Stratiform Cloud Systems : All TLEs appear in some way related to tropospheric lightning. The vast majority of cloud systems, while possibly containing some space charge, do not meet the requirements for lightning. Convective clouds, with vertical motions of at least 5 to 10 ms^{-1} and a substantial depth of mixed phase precipitation (-10°C to -40°C) are required for most lightning. A notable exception is the stratiform precipitation region of MCSs and MCCs, where weaker vertical motions are found, along with unique *in situ* charge generating processes quite dissimilar to those in convective updrafts. Prognosis: No lightning, no TLEs.

Air Mass and Multicellular Thunderstorms: Perhaps the most common of all thunderstorm systems, these cumulonimbi are small ($\sim$10-100 km horizontal dimension) and short lived. While producing ample IC and CG lightning, initial studies suggest they rarely produce large ΔMq strokes. Prognosis: Sprites extremely rare; upward lightning events possible.

Supercells: These severe weather machines, often prolific producers of large peak current +CGs (especially the LP variety), do not typically generate sprites, except during the dying stages when significant stratiform rain areas develop, perhaps reaching a size of 5,000-10,000 km^2. On rare occasions, extremely powerful and impulsive +CGs occurring during the most intense phase of supercell growth have produced sprites due to the extremely large ΔMq they achieved. But these are exceptions that tend to prove the rule (Lyons and Cummer, 2004, 2005, pp. 6). Prognosis: Sprites are rare, except at the end of the storm; may be source of blue jets, giant jets and upward lightning discharges.

Squall Lines: Squall lines can often be relatively continuous zones of convection, or can be composed of discrete supercellular elements. When individual elements are more or less connected at middle and upper levels, it appears sprites and elves can and do occur, as was the case over the U.S. High Plains on 12 October 1997 (Lyons and Nelson, 1998). If contiguous cloudy areas in squall line do attain a size of $\sim$20,000 km^2, sprites may be fairly common. Prognosis: Sprites likely in varying numbers, possibly blue jets, giant jets and upward lightning.

Midlatitude MCSs and MCCs: Multicellular, long-lived clusters of deep convection generally produce large areas of stratiform precipitation which generate TLEs upon reaching 20,000 km^2 area. The more intense the system, such as in the largest MCCs, the higher the sprite and elve rates. Usually reaching their maturity during the night, large MCCs may be the world's most prolific sprite producers. Prognosis: A nocturnal MCC is the best producer of sprites and elves, but not of blue jet or cloud top discharges.

Tropical MCSs and MCCs: Based upon Space Shuttle observations and other limited sampling, it appears that tropical storm clusters should also be notable sprite producers, though whether the frequency would match mid-latitude systems remains unknown. Some evidence suggests that -CGs over salt water may qualitatively differ from their overland counterparts, producing more frequent elves. There have been suggestions that giant jets may be more common above intense maritime convective cores. This remains to be verified. Prognosis: Sprites; possibly giant jets and elves, especially over salt water.

Tropical Cyclones: Mature hurricanes and typhoons do not produce much lightning, and therefore are not likely to be major sources of TLEs. There are several key exceptions, however (Lyons and Keen, 1994). The outer spiral bands of many storms are electrically active. Also, on occasion, explosive supercells will develop within the eye wall circulation. One such event during Hurricane Georges produced a series of blue jets observed by an over-flying ER-2 pilot. Prognosis: Few TLEs, except for the special cases mentioned.

Winter Monsoon Clouds: Cold continental air flowing over adjacent warm waters often results in shallow but intense convection, often with +CGs of extraordinary large peak currents and apparently large ΔMq as well. Sprites and elves have been observed in winter over the Sea of Japan (Fukunishi et al., 1999), have been predicted over the Gulf Stream (Price et al., 2002a) and are likely to occur over the Great Lakes and other open water bodies experiencing extreme cold advection episodes. Embedded convection within intense mid-latitude extratropical cyclones and oceanic polar lows may also be a source of infrequent but large ΔMq flashes and TLEs. Prognosis: While far less frequent than during summer convection, TLEs, especially sprites and elves, can occur during "winter weather" regimes.

2.5 Research Frontiers

Why conduct research on transient luminous events? Little practical justification is required for curiosity-driven research. When John Winckler viewed his very first sprite images, there were no immediately evident "uses" for such knowledge. The initial interest of the scientific community was purely scientific, not pragmatic. Yet, as is so often the case, there are indeed significant implications for this new discipline that was initiated in the night sky over Minnesota on 6 July 1989.

2.5.1 Importance

As discussed, an early driving force for TLE research was the concern for the Space Shuttle's safety during the launch and recovery phase (Lyons, 1996a). A preliminary estimate was that there was on the order of a 1 in 100 chance that a Shuttle recovery trajectory over the central U.S. on a summer night could encounter a sprite. The apparent comparatively low energy density suggested that the potential hazard might be minimal. Yet the ill-informed public speculation that STS-107 was knocked out of the sky by a "sprite" (NASA, 2003, pp. 38) suggests many are not comfortable with our level of understanding of the energetics of TLE phenomena. The recent discovery of giant jets and upward discharges further clouds the issue.

The potential impacts of TLEs on atmospheric chemistry, in particular NO_x production, has been investigated (Lyons and Armstrong, 1997). Initial results suggested that sprites might be locally important in mesospheric chemistry. The role of TLEs in generating terrestrial gamma-rays (Fishman et al., 1994; Inan et al., 1996), and the implications of high energy processes, remains largely unresolved.

TLEs may provide a source of undocumented "optical clutter" for sensors on space-borne military assets (Armstrong and Lyons, 2000). As scientific and defense platforms expand their domain into the stratosphere, it is imperative that the dynamic electrical nature of the region be considered. Sprites, jets and related TLEs are also a potential source of "optical clutter" for space-borne monitoring and missile detection systems. To the extent that their optical signatures are not well characterized, the potential remains for natural phenomena to be misidentified. The potential for intense electrical fields and direct interactions with blue jets, giant jets and upward lightning are an emerging concern for those designing and operating stratospheric station-keeping platforms (unpiloted aerial vehicles [UAVs], high altitude airships [HAAs]) (Lyons and Armstrong, 2004). TLE-related processes appear to be generating infrasound signatures at frequencies similar to those of small nuclear detonations (Bedard Jr. et al., 1999) and Chapter 15. This has potential implications for Comprehensive Test Ban Treaty monitoring activities.

If, as some suggest (Williams, 1992), increasing global temperatures will result in increased global lightning frequency, might not long-term monitoring TLEs be of potential value for global change studies?

And in the broadest sense, do we not need to understand TLEs simply to complete our understanding of the global electrical circuit (Rycroft et al., 2000)? While the optical effects of TLEs may terminate around 100 km, are there significant interactions of TLEs with the radiation belts? Simply stated, TLEs are just one more piece of the giant puzzle of how our world actually works. Today the long term implications of this new knowledge are unknown – but if the history of science is a guide, they may well be important.

2.5.2 Outstanding Research Questions

Every TLE researcher can prepare an expansive listing of unanswered questions. Some of those on the mind of this author would include:

- Are large ΔMq values a necessary AND sufficient cause of sprites?
- Is there a minimum ΔMq sprite threshold, and does it vary over space and time?
- What are the transient electric fields above clouds from SP+CGs?
- What are the meteorological environments which create large ΔMq CGs?
- Do sprites occur during the daytime (Stanley et al., 2000)?
- Why do some 10% of sprites appear to contain significant current flows (Cummer and Stanley, 1999)?
- Do sprite tendrils ever physically connect with cloud tops?
- Do theoretically predicted (Lehtinen et al., 2001) conjugate sprites occur?
- What criteria can be used to discriminate elve-producing CG lightning?
- What accounts for the notable lack of -CG sprites? Is it simply a matter of negative CGs so rarely having large ΔMq values? In U.S. storms examined to date this appears to be the case, yet global ELF monitoring suggests large negative ΔMq are fairly common, especially over the oceans (Füllekrug et al., 2002).
- As indicated by balloon observations, are negative halos are far more common than ground observations suggest (Bering et al., 2004)?
- Why do sprites never follow negative halo events?
- What is the global rate and distribution of TLEs?
- Do all sprites and elves generate ELF Q-bursts? Are all Q-bursts sprites or elves?
- Are giant jets related mostly to maritime storms as has been initially suggested?
- Is there a RF signature to discriminate blue jets and giant jets?

- Do runaway electron processes play any role in TLE mechanisms?
- What meteorological conditions favor blue jets, giant jets and upward lightning? Do these phenomena pose any threat to stratospheric aerospace vehicles?
- Do cosmic rays, gravity waves, meteors and meteoric dust influence TLE imitation and dynamics (Zabotin and Wright, 2001; Suszcynsky et al., 1999; Wescott, 2001)?
- Do TLEs occur in the atmosphere of other planets?

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