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Final Report on NASA Grant NAG-066
Covering the period from October 1987 through October 1994
by
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May 20, 1995

INTRODUCTION

Grant NAG-066 has been in effect since 1987, and appropriate technical reviews have been given, mostly at workshops at NASA/MSFC in Huntsville, AL. These reviews are essentially up-to-date reports of research carried out on the grant, and have been published as NASA Conference Bulletins. We are including copies of those reports through 1993. What follows is a complete summary of research done on this grant since September 1993; this work has not been reported at a NASA workshop.

PARTICIPATION IN THE TOGA-COARE PROGRAM

The LIS Science Conference, convened in conjunction with the 1991 Fall Meeting of the American Geophysical Union in San Francisco, initiated the concept of studying the electrical properties of tropical thunderstorms by coordinating with the TOGA-COARE program, thus achieving important TRMM science at relatively low cost. The presence of a coordinated program the magnitude of TOGA COARE presented a unique opportunity to study simultaneously the dynamics, microphysics, and electrical properties of tropical thunderstorms, an area in which we have primitive understanding at this time.

A primary goal of the investigation was to understand the process or processes which initiate precipitation formation in both strongly convective and weakly convective clouds. Our present concepts suggest that the degree of atmospheric instability that determines updraft velocity differentiates between storms that generate electrical energy and those that do not. In temperate latitudes, storms with strong updrafts are capable of growing and suspending large ice hydrometeors which, together with large ice crystal populations, are believed to play important roles in storm electrification. In the tropics, our knowledge of storm electrical properties and the interactions with updrafts and precipitation is sparse, at best. Indeed, tall columns of ice crystals have been reported reaching to 40,000 feet, yet seemingly producing little or no lightning.

As a result of the LIS Conference, a proposal from Zipser, Orville, Krider (Weidman), Brook, and Christian (Blakeslee, Goodman) received NSF funding to set up three ground stations that detect remote lightning activity in both the TOGA COARE IFA and in surrounding areas including many of the main island groups. The instruments used at these sites were tailored specifically to detect cloud-to-ground lightning out to a distance of 1,000 km. In addition, a waveform recorder was located at one of the stations to record both cloud-to-ground and intracloud lightning in order to provide an estimate of the complete lightning activity. The data from these instruments were to be analyzed in conjunction with the ship and airborne radars, in-cloud microphysics, and electrical measurements from both the ER-2 and DC-8.

(NASA-CR-198577) A STUDY OF LIGHTNING IN WINTER THUNDERSTORMS AND THE ANALYSIS OF THUNDERSTORM OVERFLIGHT DATA Final Report, Oct.   N95-28191

Unclas

The instruments were designed and assembled in record time. Equipment was provided by NASA/MSFC, NMIMT, LLP, and Texas A&M. In August 1992 the instruments were checked and calibrated by Marx Brook and Charles Weidman at the University of Arizona in Tucson. They were shipped to New Guinea and arrived there in early January. The direction finders were installed by Drs. R. E. Orville and Charles Weidman at Kappingamaringi, Rabaul, and Kavieng.The instruments were deployed at the Papua New Guinea Weather Service office, the Rabaul Weather Service office, and at Kappingamaringi near some of the NCAR equipment.

Marx Brook, who built the waveform equipment, was scheduled to go to Kavieng in December but was taken ill. A technician, Mr. Graydon Aulich, studied the waveform equipment and managed to put it into operation when it finally arrived at Kavieng, New Guinea, in January 1993. The waveform recorder was operated through half of January and all of February. It was dismantled in early March and sent back to Socorro as planned. Thus, despite some setbacks, the waveforms of lightning strokes coming from the TOGA COARE IFA were successfully recorded along with the LLP direction finder data. This constitutes a unique data set not only because of the large number of events (about 150,000 strokes), but also because the waveforms include data which can verify the polarity of LLP recorded strokes as well as data from cloud flashes which are not registered by the LLP instrument.

OBJECTIVES

The prime objectives of the subsequent data analysis are as follows:

1. We have begun analysis of the TOGA COARE data set, with a focus on understanding the electrical properties of tropical thunderstorms, and determining if the presence or absence of lightning can be used to infer physical properties such as precipitation formation from ice processes (strong convection) or from warm droplet coalescence (weak convection).

2. On a new NASA grant, we continue the analysis of lightning data from TOGA COARE and from continental U.S. wintertime storms (primarily lake-effect storms). These winter storms, like tropical oceanic storms, tend to be weakly convective and produce low lightning rates. Further, as our research results have demonstrated, the lightning from these storms seems to be significantly different from typical summertime lightning. We are using the information in the lightning data augmented by other available data sets (Weather Service radar and LLP data) to infer aspects of the dynamical and microphysical properties of the storms. Dr. Steve Goodman of MSFC has been working with the radar data from selected winter storms.

3. During the course of our winter storm studies we recorded many lightning atmospherics (sferics) from distances as great as 2,500 km. Many of these waveforms exhibit the well known slow-tail phenomenon produced by dispersion in the Earth-ionosphere waveguide. A few waveforms showing positive and negative slow-tails are shown in Figure 1. The relevance of these phenomena to estimating global precipitation by measuring the strength of the Schumann resonances can be seen when we realize that both the Schumann resonances and the slow-tails propagate in the same cavity. Not all lightning

discharges produce slow-tails: Only those strokes which presumably have a low frequency component (below the cut-off frequency of ~2 kHz) can propagate in the waveguide mode and will therefore couple greater energy into the Earth-ionosphere cavity. Although attenuation curves for the ELF propagation have been calculated, we have been trying to arrive at some sort of ratio or excitation efficiency for lightning strokes which exhibit slow-tails and those which do not. It is also of interest to determine the precise properties of the lightning strokes which produce slow-tails. Although slow-tails were discovered in 1926 and again studied in the 1960s, their source has remained a mystery.

4. In a continuing cooperative effort with the lightning group at MSFC, we have provided improved waveform measuring and recording equipment first used at KSC and then to be set up at Marshall Space Flight Center. This completes a network of three stations (with two others now located at Albany, New York, and Socorro, New Mexico) to complete the study of wintertime storms. The stations will be useful as temporary ground-truth stations for use with the Optical Transient Detector (OTP) satellite which is a lightning imaging sensor (LIS) prototype scheduled for flight in early 1995, and with LIS on the TRMM satellite. (The Marshall instrument will initially be used at KSC during the summer of 1995.) We are budgeting to provide another station to be deployed as a remote ground-truth station in Darwin, Australia.

DATA ANALYSIS

Some preliminary analyses of waveforms from the Kavieng station have already been done. The study of the waveforms is not without problems, for the electrical environment of the Kavieng station was unbelievably noisy. We exhibit three typical records to illustrate the problem. In Figures 2A, 2C, and 2E it is obvious that the 50-Hz background at the site exceeds the amplitude of the waveform signal by a factor of from 2 to 5. We have derived power spectra for a number of flashes which show that the background signal contains 50-Hz harmonics as high as 60 (3,000 Hz) in most cases. In general it looks like we will have to remove from forth to sixty 50-Hz harmonics before we can examine the waveforms. Without going into great detail about the method, we have had success with removing the 50-Hz harmonics by doing a discrete Fourier transform on the data (truncated to provide exactly one cycle of 50 Hz, with a resolution of exactly 50 Hz between points). The waveforms of Figure 2A, 2C, and 2E are shown cleaned up in Figures 2B, 2D, and 2F. Sixty harmonics have been removed. Unfortunately, some of the data in the same frequency range, such as slow-tails, are also removed because they overlap the noise. Thus, the first approach to analyzing the data has been to free the data from the 50-Hz background signals.

A number of results can be achieved without cleaning up the data, at least in many cases. We have been working with Dr. Richard Orville at Texas A&M and with Dr. Richard Blakeslee at NASA/MSFC in checking the LLP direction finder results to determine the type of stroke which was recorded. In a number of cases, the waveforms we recorded were indeed positive ground strokes, as we were able to verify by direct waveform examination. But in a number of cases we have been able to identify positive pulses which are definitely from a cloud flash and which the LLP sensor identified as a positive ground flash. This is not surprising, for the LLP sensors were adjusted to be sensitive to pulses coming from as far away as 900 to 1,000 km. This adjustment involved relaxing some of the acceptance criteria, so that an occasional misidentification is to be expected. Other preliminary polarity identifications of the LLP data show Kavieng with a flash of one polarity while the Kappingamaringi station exhibits a flash of the opposite polarity! This effect is one which we might also expect as we increase the range of acceptable flashes. We found in our winter storm studies that flashes beyond about 700 kilometers are apt to be assigned a reversed polarity because over long distances the original return stroke ground wave is attenuated greatly, while the first ionospheric reflection will arrive with reversed polarity but with very little attenuation.

Some of the important questions we would hope to answer from using the total TOGA COARE data set available to us are as follows: How are updraft velocities and lightning rates related in tropical storms? Is there an updraft velocity threshold below which no lightning is produced, and if there is what is that threshold? Do the same relationships hold for tropical oceanic, wintertime, and continental storms? And most importantly, what are the lightning/rainfall volume relationships for tropical oceanic storms, and do the same relationships hold for temperate zone oceanic and continental thunderstorms?

In our future work, we intend to cooperate closely with the aircraft and radar scientists to find answers to the above questions. Dr. Steve Rutledge, who operated one of the ship radars throughout the TOGA COARE period, is anxious to cooperate in trying to correlate radar precipitation echoes with lightning (or the absence of lightning) activity.

We intend to examine and classify the data from a number of distant storms to find (1) the ratio of slow-tail to non-slow-tail-producing strokes and (2) the ratio of positive to negative slow-tails. We have earlier shown that the polarity of the stroke determines the polarity of the slow-tail, thus establishing that the generation of the slow-tail is specifically a stroke-associated phenomenon. The very low frequencies present in the power spectrum of slow-tails is indeed a distinguishing feature of those strokes.

ACCOMPLISHMENTS ON THE GRANT

In 1987 we initiated our studies of winter storms by setting up equipment at the State University of New York at Albany. These studies were primarily observations of lake-effect storms which occur during late November and through December. Interesting effects on lightning initiation, leader velocities, and electric field magnitudes were discovered which are different from conditions existing in summer storms. By far the most important result of these studies is the realization that electric fields in winter storms appear to be about three times as high as in the active stages of summer storms. This conclusion is consistent with the observation that triggered lightning occurs much more often when aircraft penetrate winter storms than when they penetrate summer storms. We attribute this effect to the dependence of electric field breakdown on the size and nature of the precipitation particles populating the environment. It is well known that the presence of liquid water drops in strong electric fields acts as a voltage regulator: The drops deform in the strong field and break up producing a copious supply of ions which leads to electric breakdown. A series of papers was given and published on this topic, the last one an invited paper at the Fall AGU Meeting in December 1993. A list of publications and papers given at meetings is included under the Publications section.

Studies which we initiated on the U2 aircraft were continued and expanded to include photographic and video images of lightning storms from the space shuttle. These studies showed that a new optical phenomenon reaching high above the atmosphere sometimes appears simultaneously with a lightning discharge. Indeed, we found that in one instance an enhancement of the airglow at about 90-km altitude occurred in coincidence with lightning in a cloud system directly beneath it. There was no luminosity between the flash and the airglow. In most cases, however, the enhanced luminosity is in the form of a diffuse column extending to about 30 km above the clouds but not appearing to be connected to them. The luminosity appears to be very faint but is readily recorded with a sensitive video camera. This is now a very active field of research and includes several groups sponsored by NASA.

As of this writing, we have received new funding to continue our studies under NASA with a new grant entitled "Analysis of TOGA COARE lightning Date."

PUBLICATIONS

Brook, Marx, R. W. Henderson, and Richard B. Pyle. 1989. Positive lightning strokes to ground. *J. Geophys. Res., 87,* 13,295—13,301.

Brook, Marx. 1992. Breakdown electric fields in winter storms. *Letters in Atmos. Electricity, 12,* 47—52.

Brook, Marx. Spherics and Storm Detection (in part). 1992. Two articles in the Seventh Edition of the *Encyclopedia of Science and Technology.* McGraw-Hill, Inc., New York.

Brook, Marx. Breakdown electric fields inside summer and winter storm-clouds: Inferences based on initial lightning leader waveforms. *Proc. 9th Int. Conf. on Atmos. Electricity, Vol. I.,* June 15—19, 1992. St. Petersburg, Russia.

Boeck, W. L., O. H. Vaughan, Jr., R. Blakeslee, B. Vonnegut, and M. Brook. 1992. Lightning induced brightening in the airglow layer. *Geophys. Res. Letters, 19,* 99—102.

Patent: U.S. Patent No. 5,153,508. Method and Apparatus for Determining Return-stroke Polarity of Distant Lightning. NASA Case No. MFS-2610202-CU. October 6, 1992.

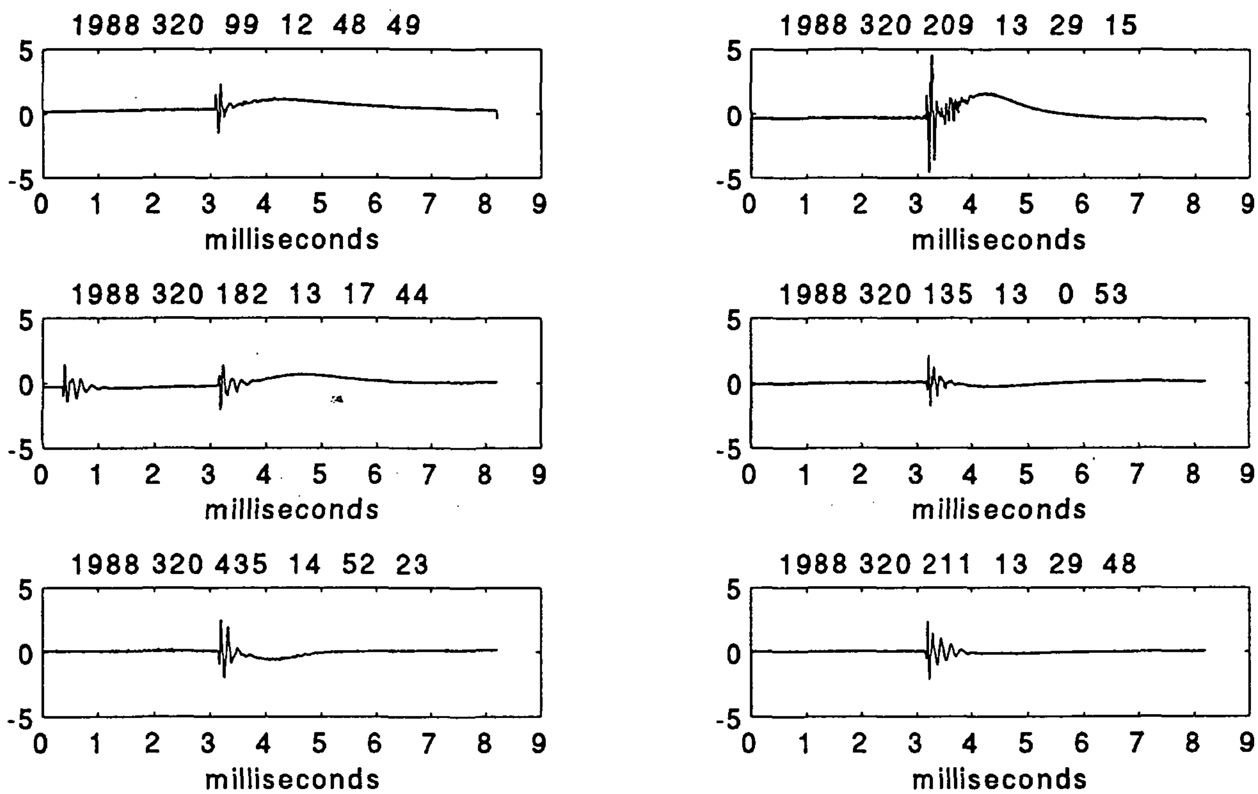

Figure 1. Examples of positive and negative slow tails

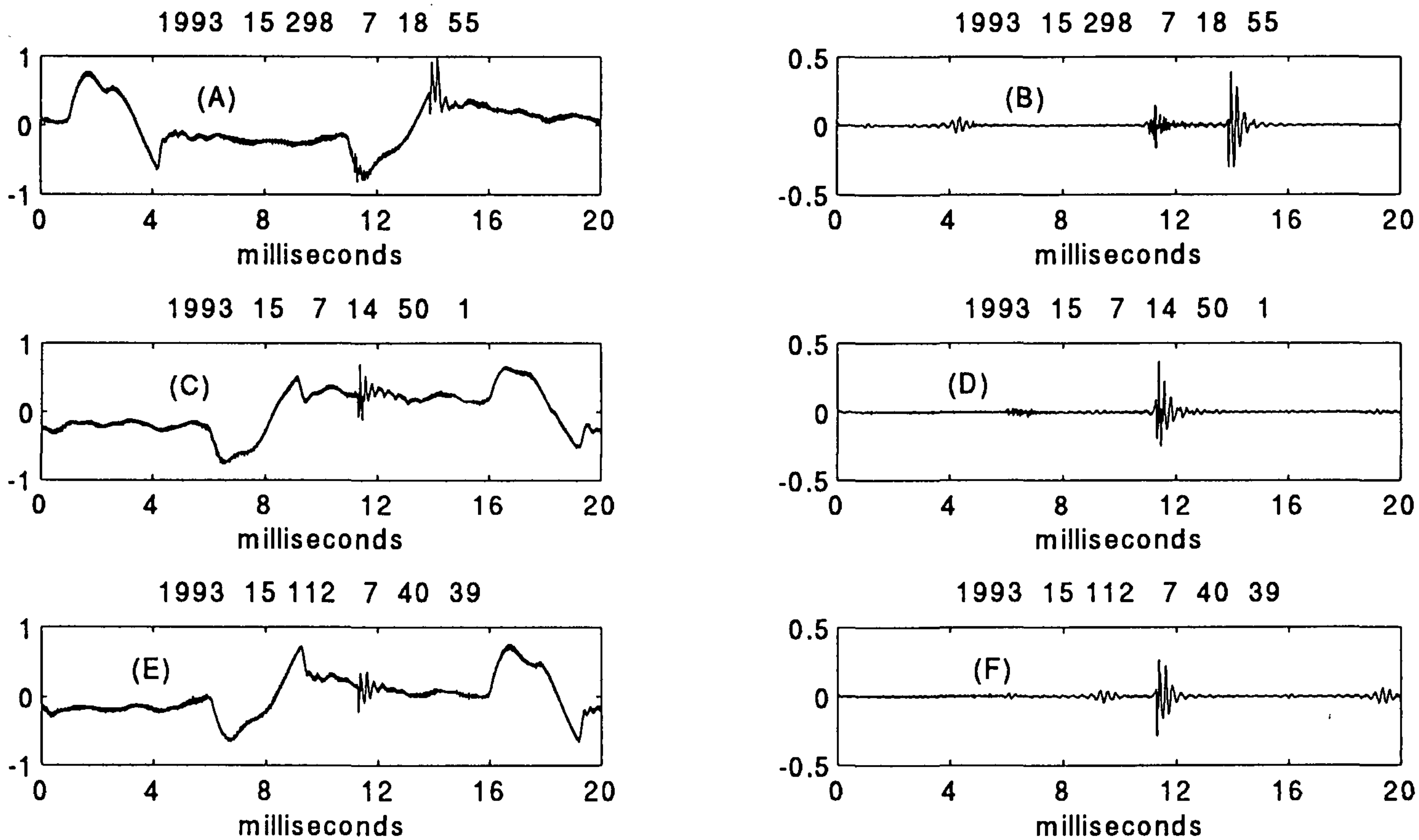

Figure 2. A, C, and E show original signals in 50 Hz noise.
B, D, and F show "cleansed" signals.

Prepared Spring 1992

Title: Electrification in Winter Storms and The Analysis of Thunderstorm Overflight Data

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Background of the Investigation: We have been focusing our study of electrification in winter storms on the lightning initiation process, making inferences about the magnitude of the electric fields from the initial pulses associated with breakdown, i.e., with the formation of the initial streamers.The essence of the most significant findings is as follows: 1) Initial breakdown radiation pulses from stepped leaders prior to the first return stroke are very large, reaching values of 20-30 Volts/meter, comparable to return stroke radiation. 2) The duration of the stepped leader, from the initial detectable radiation pulse to the return stroke onset, is very short--ranging from a minimum 1.5 ms to a maximum of 4.5 ms. These values should be contrasted with the published durations of stepped leaders from summer storms which fall in the range from 6-20 ms. The difference in duration is significant in that the radiosonde soundings for summer and for winter storms show only a 20-30% difference in the height of the -10 degC to -20degC region which is where the lightning charge is found to accumulate. This difference in height cannot account for the difference in duration of the stepped leader (a factor of 2-3) between winter and summer storms. Obviously, the velocity of the leaders in winter storms must be greater by a factor of 2-3 than the leaders in summer storms.

This past summer (June-August) of 1991) we participated in the CAPE program at the Kennedy Space Center in order to acquire data on stepped leaders in summer storms with the same equipment used to get the winter storm data. Our efforts were certainly worth while, because we discovered that the vigorous leaders seen in winter so frequently were present in summer storms, although not as large in amplitude and certainly not as frequent. The analysis of the large amplitude radiation pulses from these summer storms continues at this time, and the conclusions cited earlier with regard to the differences between summer and winter leaders remain unaltered.

It is reasonable to attribute the striking difference in the two types of leaders to the value of the breakdown electric field inside the cloud, i.e., the maximum value of the electric field which can be sustained without the initiation of a discharge. In looking for a different set of in-cloud conditions between summer and winter which might have a major role in influencing the breakdown field we are immediately drawn to the hypothesis that it is the precipitation mix that determines, almost exclusively, the value of the breakdown electric field. Many laboratory studies have been done on the influence of water drops on the breakdown field, and an elegant theoretical and laboratory study was published by G. I. Taylor in 1965. The size of water drops affects the breakdown electric field: larger drops lower the breakdown potential gradient; a factor of 2 increase is acheived in going from 2.4 mm rad drops to 1.2 mm rad. A temperature dependence, though less noticeable, is also present. Surface tension is a function of temperature, and increases with decreasing T.

Ice crystals, also present in the -10 degC to -20 degC region, are not as active in lowering the breakdown potential gradient. Although ice crystals may provide corona, their resistivity is too high to maintain the electric field at the tip after the emission of charge. In general, it has been found that ice crystals initiate breakdown at much higher fields than do water drops. The subject of the influence of ice crystals on the electric breakdown is far from complete and is in need of further study.

A check on the above hypothesis was possible for the Albany winter storm during which time a sounding was taken at the Albany Airport. We were able to determine that in the region of -10 degC to 20 degC the vapor pressure was saturated with respect to ice. Thus there was no liquid water present to lower the breakdown potential gradient; only the ice phase populated the charge accumulation region! This result has important implications related to electric charge separation in clouds, as well as implying that charge storage per unit volume in winter storms can exceed that possible in summer storms.

Significant Accomplishements of the Past Year: We have been able to strengthen our original hypothesis that electric fields in winter storms are higher than they are in summer storms by considering the influence of the precipitation environment in the region of electric charge accumulation. We have been able to propose a reasonable rationale for the observed fact that lightning strokes from winter storms are more destructive and carry larger currents than do the stokes in summer. Stronger fields imply greater charge density, and since the energy stored is proportional to the square of the electric field, we would expect more destructive currents. This result is completely consistent with both aircraft-triggered lightning-damage statistics, and with powerline-damage statistics.

We participated in the analysis of an unusual video photograph (Boeck,et.al.1992) taken from the space shuttle at night which shows an enhancement in the luminosity of the airglow layer directly above a lightning flash which occurred simultaneously within the uncertainty of a video frame. This is the only observed occurence of apparent ionospheric ionization produced by thunderstorm activity 100 km below the airglow layer. If it is not spurious, it demonstrates the existance of an energy coupling mechanism from the troposphere to the ionosphere. We were able to show that the enhancement did not result from return stroke radiation but more likely from one of the horizontally oriented vigorously radiating stepped leaders discussed earlier in this report.

At KSC we also recorded lightning flashes as ground truth for the ER-2 and the Lear jet aircraft doing cloud overflights as part of the CAPE program. As a result of the large amount of good electrical data we obtained it will be possible to get good correlations with the New Mexico Tech Wideband Noise and Coherent Radar and with the NCAR CP-2 Radar. The NMTech interferometer was also operated at the same time, making these data an unusual set for the analysis of electrical-precipitation interactions. All of the 7500 lightning flashes have now been plotted for cursory examination. We are also in the process of looking at the triggered lightning data, correlating that set with the excellent streak camera photographs of Dr. Vincent Idone of the State University of New York at Albany.

Focus of Current Research and Plans for Next Year. If funding is forthcoming, we plan to continue with several activities already in progress.

1) continue the analysis of both winter and summer initial leader data to further clarify the role of precipitation in limiting the maximum value of electric field strength in clouds. We should also like to collaborate with John Latham of the University of Manchester and with Alan Blythe of NMTech in designing laboratory experiments to study the role of ice crystals in in initiating electrical breakdown in clouds.

2). We plan to correlate our lightning measurements with the NMTech Radar and Interferometer data. A particular question of interest to be addressed is: How does a lightning discharge in a volume seen by the radar and the interferometer affect precipitation growth? This is an important question which can now finally be addressed with our dual polarization radar. This radar sees the ionized lightning channels without significant precipitation background clutter in the crosspolar channel, while the copolar channel sees the precipitation echo as normal. We have seen the growth of an echo after lightning, and with circular polarization it has been possible to watch the crystals align with the electric field (induced dipoles) and to see them disalign after lightning. We have not yet put all the data together to see whether electric fields provide enhanced forces for accelerated coalescence of droplets, thus promoting droplet growth. We intend to use these data to study this question.

3). As a result of a workshop discussing the possible role of lightning measurements in the TOGA-COARE program in the South Pacific, we are preparing one of our instrumental systems for use in Kavieng, New Guinea in conjunction with a 3 or 4 station array of LLP direction finders. The direction finders will be modified by LLP to higher sensitivity for use up to distances of 900-1000 km. I have prepared lightning waveforms recorded from those approximate distances to test the modified instruments. We shall be working with Drs. E. Phillip Krider and Charles Weidman to synchronize time between the direction finders and my waveform recorder. Although the instrumentation is NASA funded, a proposal for travel expenses and some analysis has been submitted to NSF by Drs. Ed Zipser and Dick Orville of Texas A&M. I have agreed to donate about three weeks time to setting up the instruments in Kavieng and training a student to operate them.

4). Finally, we want to return to finish the study of the origin of the 'slow tails' to identify the type of lightning flash which produces them. This requires 2 stations, and we hope to operate a pair in either Albany or Socorro with a station in Huntsville. The slow tails may be a unique identifier of continuing current lightning which is estimated to start about 95% of all forest fires.

Publications

1).A paper entitled "Electric Fields in Winter Storms" was given at a US-JAPAN workshop on 'Lightning in Winter Storms' and will be published in "Letters in Atmospheric Electricity, a Japanese journal.

2). A paper entitled "Breakdown Electric Fields in Summer and Winter Storm-Clouds: Inferences Based on Initial Lightning Leader Waveforms" has been submitted for presentation at the St. Petersburg International Conference on Atmospheric Electricity. It will be presented for me by Dr. John Latham. The paper is being expanded to include additional work on the role of precipitation in breakdown and to include better statistics of summer-storm stepped leaders.

3). Boeck,W.L.,O.H.Vaughan,Jr, R. Blakeslee, B. Vonnegut, and M. Brook, Lightning Induced Brightening in the Airglow Layer, Geophys. Res. Lettrs,v19, 99-102,1992.

Electrification in Winter Storms and the Analysis of Thunderstorm Overflight Data. NASA Grant NAG-066.

Principal Investigator: Marx Brook   Prepared 15 May 1991

INTRODUCTION.

Until recently, electrification in winter storms has been observed only casually. Electrical activity is sparse, the lightning flashes are few and far between, and the number of winter thunderstorms is only a small fraction of those that occur in summer. Consequently, most lightning investigators have spent their winters analyzing summer data. The pioneering work of Takeuti et al.(1977) in Japan served to focus the attention of the international community on the existence of anamolous electrical effects associated with winter storms. In particular, the existence of positive return strokes of magnitude as large as 310 Coulombs was a new observation difficult to explain, especially since the Hokuriku winter storm clouds seldom exceeded 4-5 km in height (how do you fit so much charge into such a small volume of cloud ?). Positive lightning strokes were also found to be the dominant polarity of strokes in the Hokuriku winter storms (Brook, et al., 1981).

The emergence of 24 hr operational lightning detection networks has led to the finding that positive lightning strokes, although still much fewer in number than the 'normal' negative strokes, are also present in summer storms. Recent papers such as Goodman, et al.(1988) point up the importance of understanding the meteorological conditions which lead to a dominance of one polarity of stroke over another; in the paper cited the sudden appearance of positive strokes at the end of a storm appeared to presage the end-of-storm downdraft and subsidence leading to downburst activity. It is beginning to appear that positive strokes may be important meteorological indicators.

SIGNIFICANT ACCOMPLISHMENTS OF THE PAST YEAR.

1. DO THE NETWORK BLACK BOXES TELL THE TRUTH? Our initial effort on this grant was a study to verify that the "Black Boxes" used in the lightning networks to detect both negative and positive strokes to ground were telling the truth. After all, for more than 60 years scientists believed that ONLY negative charge was lowered to earth in return strokes.

We made waveform and polarity determinations with our own instrument operating side by side with the SUNYA LLP equipment. We found that, for lightning flashes within about 600 km of the SUNYA equipment the boxes gave the correct identification of stroke polarity. Only very occasionally did we have reason to believe that a pulse from an intracloud discharge was counted as a positive stroke. We were surprised to find, however, that for strokes occurring beyond about 700 km from the equipment, the polarity was generally wrong. Suffice it to say that for large distances over land the ground wave is often severely attenuated; the first ionospheric reflection suffers much less attenuation and arrives at the station with inverted polarity! This and other work related to determining stroke polarity from waveform measurements is discussed in the paper Brook et al., 1989.

2. SLOW TAILS CAN BE USED TO DETERMINE THE POLARITY OF DISTANT LIGHTNING. An outgrowth of this initial work on radiated lightning waveforms was the discovery that it is possible to determine the polarity of distant lightning correctly if the lightning stroke has a low frequency component, such as might be present in the long continuing-current strokes. The cutoff frequency for electromagnetic waves propagating in the earth-ionosphere waveguide is ~2000-3000 Hz depending upon ionospheric height. If the stroke has low frequency components, then the waveform as seen at distances of 500 km or greater from the source shows the attenuated VLF radiation components followed by a 'slow tail' propagating in the earth-ionosphere waveguide. We verified

that, for over one hundred cases, the polarity of the slow tail is the same as the original stroke polarity at the source. This result has important practical application since it is specific as to the frequency content of the stroke. Over 95% of the forest fires started by lightning are due to continuing-current strokes. An application for a patent is in progress (NASA Case MFS-26102-1).

3. LIGHTNING INITIATION IN WINTER vs. SUMMER STORMS. The most important results achieved to date relate to the electric field strength in clouds for winter vs. summer storms. We have been studying the initial breakdown phase of lightning in both strokes to ground and in intracloud discharges. What we find is little or no difference in the initial pulse activity associated with intracloud breakdown, but there is a striking difference between negative stepped leader development in winter vs. summer storms. Specifically, negative leaders in winter storms have a higher propagation velocity, are much shorter in duration, and exhibit E-field amplitudes which are often as large as if not larger than the return strokes which they precede. We interpret these characteristics along with other evidence to indicate that electric fields in winter clouds are considerably greater than they are in summer clouds. Since the electric energy stored in a cloud is proportional to the square of the electric field, we have here a possible explanation for a number of 'anomalous' features of winter storms.

Electric breakdown in clouds is determined not only by atmospheric pressure, but also by the presence of water drops under electric stress. At high values of electric field, water drops distort to ellipsoidal shape, and for high enough field values will go into corona and provide a copious source of ions to initiate a discharge (G.I.Taylor, 1965). Initiation will occur for electric field values well below the normal breakdown potential gradient of air. Thus, for dry air at NTP the breakdown potential gradient is ~30,000 V/cm, but in the presence of liquid water drops it will fall to values as low as 3000 to 10,000 V/cm, depending upon the radius of the drops. The presence of water drops in an electrified cloud can be thought of as providing an upper limit to the value of the local electric field.

Meteorological soundings taken at about the time of our winter storm data indicate that at the 4-6 km level (-10 to -20 deg C environment) the vapor pressure was close to saturation over an ice surface, indicating a dominance of solid rather than liquid form precipitation. We believe that the absence of large numbers of liquid water drops of size significant for lowering the breakdown potential gradient of air is the major factor in allowing the electric field to build up (whatever the mechanism) to values greater than those found in summer storms. The higher energy density achievable in winter storms would increase the probability that aircraft will trigger lightning upon penetration. It was the unusually high lightning related hazard provided by the shallow winter clouds off the sea of Japan which initially motivated the Japanese scientists to investigate the winter storms. A paper on the winter storms is now in an advanced stage of preparation.

4. INSTRUMENT DEVELOPMENT. We continue to upgrade our sensors for the measurement of electric field signals associated with lightning. We completely redesigned the Slow Antenna system to cure two problems: 1) the charge left on the flat plate antenna from blowing snow has been minimized by the use of an inverted 'salad bowl' housing which contains the 18" diameter plate and all the electronics; 2) Reduction of the input bias current to about .5 picoamperes has allowed us to use resistors as large as 10^12 ohms without suffering prohibitive offsets. The 10 second time constant and the high sensivity achieved allowed us to measure electrostatic field changes from as far away as 125 km. The wideband (.1 Hz to 2MHz) Slow Antenna sensor with the 12 bit 2MS/s digitizer is useful in studying simultaneously the radiation as well as the electrostatic fields of lightning.

5. OTHER ANALYSES IN PROGRESS. a) We are analysing lightning flash

records from storms between 40 and 125 km from the sensor. The ratio of electrostatic field, which varies as $\sim 1/R^3$, to the radiation field which varies as $1/R$, for each stroke in a multiple stroke flash is of interest as a possible indicator of the distance R from the receiver. b) An interesting aspect of the initiation process involves the physical processes driving the stepped leader. In particular, the "turn on" and "turn off" aspects of the individual stepped leader pulses do not seem to fit accepted mechanisms. We are sorting through our summer storm lightning data to find several more good leaders from close storms.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR.

Our research objectives remain focused on the electrical aspects of winter storms, how they differ electrically from summer storms, and the association of changes in the cloud physical and dynamical environment with the onset or cessation of positive lightning strokes. We have been working on the hardware components for a second (and possibly a third) measurement station. Plans are to set up three stations, one at Albany, N.Y., one at Huntsville, and another at Socorro or Norman, Ok. We also plan to expand the data acquisition to two channels: 1) The regular E-field channel, and 2) an RF channel at ~250 MHz. The logarithmic receiver channel will provide us with complementary information regarding the lightning stroke initiation process.

Immediate plans for this coming year involve participation in the CAPE program at KSC during July and August. This work would also include cooperative observations with Dr. Vincent Idone on the electrical and optical properties of initial leaders during the ongoing lightning triggered program at KSC. Additional participation is planned with Dr. Richard Blakeslee at Huntsville to provide improved electric field instrumentation for the ER-2. We have also been in touch with the Marshall group regarding the implementation of a lightning monitoring station which would be used in conjunction with radar precipitation estimates for possible algorithm development relating lightning to precipitation as part of the ground truth activities of the TRMM program.

Multiple station measurements of winter storms are planned for this winter (probably late November through early January) with one station at Albany and the other at Huntsville. We are particularly interested in measuring the electrostatic field change involving continuing current strokes close to one station with the second distant station receiving the radiation waveform. This work will hopefully lead to identification of the source of the slow tail waveform. Since many of the large positive strokes in winter storms are accompanied by large continuing currents, we should be able to acquire the necessary data simultaneously at the two stations. We shall also try to arrange for recorded radar records of the winter storms along with the soundings in order to test our hypothesis that the fields within winter storm clouds are stronger than in summer clouds because of the nature of the precipitation mix.

PUBLICATIONS

1.Brook, M., Ron W. Henderson and Richard B. Pyle, Positive Lightning Strokes to Ground, J. Geophys. Res., 94, 13295-13,303 (1989)

In Preparation:Electrification in Winter Storms (Paper presented at Fall AGU meeting, San Francisco,Dec. 1989)

Ratios of Radiation Amplitude to Electrostatic Field Change in Multiple Stroke Lightning Flashes (Paper presented at Fall AGU meeting, San Francisco, Dec. 1990)