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FINAL REPORT

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GRANT TITLE:
Middle Atmospheric Electric Fields over Thunderstorms
(1990 Mod to: Middle Atmospheric and Ionosphere Electrodynamics)

This report includes a summary of accomplishments, a list of publications and an appendix with abstracts of published works.

(NASA-CR-194619) MIDDLE ATMOSPHERIC ELECTRIC FIELDS OVER THUNDERSTORMS Final Report, 1 May 1982 - 30 Jun. 1992 (Washington Univ.) 18 p

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ACCOMPLISHMENTS

This grant has supported a variety of investigations all having to do with the external electrodynamics of thunderstorms. The grant was a continuation of work begun while the PI was at the Aerospace Corporation (under NASA Grant NAS6-3109) and the general line of investigation continues today under NASA Grants NAG5-685 and NAG6-111. This report will briefly identify the subject areas of the research and associated results.

The period actually covered by the grant NAG5-604 included the following analysis and flights:

1. Analysis of five successful balloon flights in 1980 and 1981 (under the predecessor NASA grant) in the stratosphere over thunderstorms,

2. Development and flight of the Hy-wire tethered balloon system for direct measurement of the atmospheric potential to 250kV. This involved multiple tethered balloon flight periods from 1981 through 1986 from several locations including Wallops Island, VA, Poker Flat and Ft. Greely, AK and Holloman AFB, NM.

3. Balloon flights in the stratosphere over thunderstorms to measure vector electric fields and associated parameters in 1986 (2 flights), 1987 (4 flights) and 1988 (2 flights).

4. Rocket-borne optical lightning flash detectors on two rocket flights (1987 and 1988) (the same detector design that was used for the balloon flights listed under #3).

In summary this grant supported 8 stratospheric zero-pressure balloon flights, tethered aerostat flights every year between 1982-1985, instruments on 2 rockets and analysis of data from 6 stratospheric flights in 1980/81 (payloads built under predecessor grant).

Analysis of the data obtained from these flights has resulted in 12 refereed journal papers, one PhD thesis, a NASA Technical Report and numerous contributed and invited papers presented at national and international scientific meetings. The research has included many discoveries and has been filled with exciting new understanding of how the electrodynamic properties and dynamics of thunderstorms affects the middle atmosphere and ionosphere. I think it is fair to say that prior to this research it was thought that thunderstorms and lightning had little direct affect on the ionosphere and magnetosphere (VLF whistler research not withstanding). The discoveries of this combined middle atmosphere - ionosphere (balloon - rocket) research program have demonstrated convincingly that thunderstorms do have a major affect on the ionosphere and middle atmosphere and that at times lightning may be the major energy source to the middle atmosphere and lower ionosphere.

It is important to keep in mind that this "final report" is not "final" in any way except bureaucratically. The only phase of the research that is presently awaiting future plans is that involving the use of tethered balloons in the Hy-wire experiment to detect the global return currents of thunderstorms. The Hy-wire experiment was highly successful by all standards but dramatic new advances using that technology will require multiple, simultaneous flights - a level of financial commitment that has not been approved. On the other hand, the free flight balloons, and the rocket experiments directly over thunderstorms are continuing today under two grants: NAG5-685 (with Croskey at Penn State) for multiple balloons simultaneously flown with mesospheric rockets, and NAG6-111 (with Kelley at Cornell) a rocket experiment for high resolution studies of lightning pulses in the ionosphere.

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Publications Specifically Acknowledging NAG5-604 (see Appendix for abstracts):

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ABSTRACTS of PUBLICATIONS

prepared under NASA Grant NAG5-604

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Abstract

IONOSPHERIC VLF WAVES AND OPTICAL PHENOMENA OVER ACTIVE THUNDERSTORMS

by Ya Qi Li

Chairperson of the Supervisory Committee: Professor Robert H. Holzworth
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In 1987 and 1988, two campaigns, the Wave Induced Particle Precipitation campaign and the Thunderstorm II campaign, were conducted to investigate lightning-generated effects in the upper atmosphere and ionosphere. Two rockets (apogees 420km and 330km) and 6 balloons (float altitudes 30km) were launched near thunderstorms in these campaigns. Optical and electric signals from hundreds of lightning strokes were recorded by both the rockets and balloons.

Using the data obtained in these two campaigns, we have been able to study some problems about lightning-generated VLF waves in the ionosphere which have not been well investigated previously. In this dissertation, we report the following: 1) The downward-looking optical detector on the rocket recorded some anomalous characteristic optical phenomena which had not been reported previously. Our study shows that they occurred above the balloon altitude (30km), and we interpreted the results in terms of discharges at high altitudes. 2) We studied the relation between the amplitude of lightning-generated VLF waves in the ionosphere and the lightning current recorded by the SUNYA lightning network. Our study shows that the amplitude of waves at frequencies below 5 kHz has linear response to the lightning current. Above 5 kHz, there is not a significant linear correlation between the wave amplitude and the lightning current. 3) We have been able to determine the propagation path of the lightning-generated VLF waves from the source to the rocket. The path is consistent with the leaky waveguide hypothesis in which waves travel in the waveguide to the vicinity of the rockets, and then propagate vertically through the ionosphere. 4) We have found that the amplitude of lightning-generated VLF waves have maxima and minima at different altitudes, instead of being attenuated monotonically with altitude as expected. A theoretical model has been proposed which shows that the wave amplitude profiles are the result of interference between waves from an aperture area below the rocket. 5) We numerically calculated the absorption of VLF waves at the bottom of the ionosphere. The electron density gradient of the ionosphere was taken into account. The characteristics of the absorption, such as the frequency dependence, were investigated. Comparing the lightning spectrum received on the ground and by a rocket, we deduced that significant heating of the ionosphere is caused by lightning-generated VLF waves.

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Hy-Wire Measurements of Atmospheric Potential

omit

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A method of directly measuring the electric potential drop across the lowest portion of the atmosphere by using an apparatus called Hy-wire is described. This tethered balloon-borne system has been operated extensively at altitudes near 0.62 km at which voltages over 150 kV were measured with a high impedance device. Also described are measurements of system parameters such as system capacitance (5.6 pF/m), impedance (10^{10} Ω), and response time (tens of seconds). Hy-wire measurements from an around-the-clock experiment at Wallops Island, Va., having a characteristic repetitive diurnal pattern of variability exceeding 40% of the mean, are presented. This diurnal pattern is discussed in terms of both local and global current sources. A demonstration using Hy-wire as a lightning channel model is also presented. These experiments have so far been conducted at mid-latitudes but can also be flown from other locations in an effort to determine whether the lowest atmospheric electric circuit is affected by high altitude and possibly global current systems, and if so how much. The data presented in this paper are not definitive about the source of potential variations. The data are, however, representative of the new Hy-wire technique and demonstrative of the potential usefulness of this technique.

INTRODUCTION

Two centuries ago, electric fields were discovered in the fair weather atmosphere [*Lemonnier*, 1752]. Since that time a large body of literature which documents the global nature of the field and its variability [cf. *Dolezalek and Reiter*, 1977] has been developed. In the past decade, physicists have begun to recognize that a significant interaction occurs between upper and lower atmospheric electric current systems on a global scale. Stratospheric balloon-borne measurements clearly indicate a mixing of electric fields due to ionospheric and weather related sources [cf. *Mozer*, 1971].

To further the understanding of the dynamics of this system of electric fields and currents, a new device, lofted by a tethered balloon and called Hy-wire, has been developed. Hy-wire can continuously monitor, by a direct high impedance voltage measurement, the fair weather atmospheric potential which exists across the lower atmosphere. The Hy-wire experiment concept was developed by *Holzworth et al.* [1981] and a series of test flights from mid-latitudes was begun. In this paper we will briefly describe how the Hy-wire system works and give details of the system impedance, capacitance, noise, and linearity. The Hy-wire data from several days of continuous measurements will be presented to show the diurnal variability in the potential over Wallops Island, Va. We will then discuss various interpretations of the diurnal variability in terms of both global and local sources.

HY-WIRE INSTRUMENTATION

The idea of using tethered balloons or kites to lift payloads to altitudes of several kilometers for studies of the atmospheric electric field is not new [*Peltier*, 1840]. Many difficulties inherent in ground-based, field-mill measurements of electric fields are due to the small-scale size of the fields measured (turbulence scale sizes of 1 m can strongly influence the measurements). Using an antenna which bridges the mixed layer (below 1-2 km usually) can reduce the influence of small-scale electric field variations. *Vonnegut et al.* [1973] showed that it is possible to bridge the lower atmospheric layers with a single long wire and make direct potential measurements. Other flights with a similar system have been conducted by *Willett and Rust* [1981]. Vonnegut's low impedance system involved the generation of a substantial corona current over a large portion of the wire, which could interfere with the potential measurement [*Willett*, 1981]. The Hy-wire system uses a different concept involving an insulated wire and a high impedance measurement at the bottom of the wire.

As described by *Holzworth et al.* [1981], the Hy-wire system consists of a long, high-voltage, insulated conductor connected at the top to a wire-mesh braid and terminated at the bottom inside a large-diameter corona ball, mounted on 1 m Teflon legs (see Figure 1). The tethered balloon is used only to support the insulated wire which hangs slack (vertically) below the balloon. Since the bottom end (corona ball) is insulated to 10^{14} Ω at 100 kV, the capacitance of the long insulated wire can only be charged by currents flowing at the braid (upper) end of the wire. Thus, corona currents will flow until the capacitance of the long wire is charged to a potential below the corona limit for the fine mesh braid (1.3 kV measured in the laboratory in dry air at sea level). At that point the entire Hy-wire system, braid, wire, and corona ball is at the potential of the atmosphere near the upper end within a few kilovolts. A field meter (Monroe electrostatic voltmeter model 144S used throughout these experiments) near the corona ball can then be used to record this potential. This requires a small high-voltage power supply for calibration purposes but results in a totally corona-free, high-impedance system. The type of high-voltage wire and other engineering specifications were given by *Holzworth et al.* [1981].

Two series of Hy-wire flights have given us a better understanding of the system's capabilities. As discussed by *Holzworth et al.* [1981], we can directly measure the system impedance and capacitance by first discharging Hy-wire through a known resistor and then refloating the system. For a resistor $R = 10^9$ Ω, the time constant of the discharge typically is measured to be in the range of 0.5 s per 100 meter altitude, corresponding to a capacitance

$$C = \frac{\tau}{R} \approx 5\,\frac{pf}{m}$$

for a total system capacitance of a few thousand picofarads.

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PREV. ANN. 84A 31540

Reply

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1. INTRODUCTION

A technique for directly measuring vertical atmospheric potential differences called Hy-wire has been reported by *Holzworth et al.* [1981] and *Holzworth* [1984]. These papers describe a measurement process which is a substantial modification of a similar tethered balloon technique first reported by *Vonnegut et al.* [1973]. The major difference between the two tethered balloon techniques is that the Vonnegut et al device operates at low impedance using a high voltage generator, while the Hy-wire technique uses an inherently high impedance ($>10^{13}$ ohms) device. One reason for going to the trouble of solving the high voltage, high impedance problem was to eliminate the corona discharge inherent in the Vonnegut et al. technique [cf. *Willett*, 1981]. To test the Hy-wire technique, several tethered balloon flights from the NASA Wallops Flight Facility (WFF) at Wallops island, Virginia, have been conducted. The site was chosen because of close logistic support and the desire to fly in restricted air space to avoid airplane mishaps. It was recognized at the outset that WFF was in a region where land-sea interactions might substantially affect the electrodynamics. We did not prejudge what we should see because it was clear that if the Hy-wire technique worked we could easily move it to a "clean air" location to do global circuit studies. As it turned out, substantial unexplained atmospheric potentials were seen at WFF which warranted an attempt at an explanation, although not conclusive, in *Holzworth* [1984].

Now *Markson* [this issue] reports that instead of determining that no simple explanation (e.g., neither global not local) can explain the data, I should have concluded that local meteorology was responsible for the potential variations. Furthermore, Markson claims that the Hy-wire technique did not work properly. The first section of this reply will address a fundamental point of disagreement between myself and Markson (i.e., Markson claims that the global circuit has a natural daily UT variability "resembling the Carnegie curve which should be expected on each individual day" [*Markson*, this issue]). The first section will show this to be totally unsubstantiated by the facts.

On the basis of the above premise—that each day should look like the Carnegie curve—Markson attacks the Hy-wire data as not possibly being due to global variations because they do not look like the Carnegie curve. Therefore, in section 3 I address the major individual points of *Markson* [this issue] to show that many of his interpretations of the Hy-wire data are not correct.

2. GLOBAL CIRCUIT VARIABILITY

The global circuit idea stems from a suggestion first made by *Appleton* [1925] that the universal time variation of the fair weather vertical electric field might be the same as that due to worldwide thunderstorms. Since that time, many authors have helped develop the idea of a global circuit in which the action of all thunderstorms working together charges the ionosphere (actually the electrosphere) relative to the earth, and this charge leaks back to the ground through the conducting atmosphere in fair weather regions. One early example of the universal time variation is given by *Mauchly* [1923] from data collected by the Carnegie research vessel. This so-called Carnegie curve is based on a few months of averaged, near-surface electric field measurements over the ocean. It is interesting and significant that since the 1920's several other people (notable in this case is the work of *Markson*, [1977]) have found that when many days or weeks of potential differences or total potential soundings are averaged, one continues to find a UT variability resembling the Carnegie curve. I too agree that there must exist some real forcing function, such as global thunderstorms, which acts to provide a variability in potential which withstands such heavy averaging. The point I want to make is precisely that the Carnegie curve is an average. Individual days could vary significantly from the mean. Markson claims any daily variability is due to local meteorological phenomena. Thus, says Markson, while the global circuit is really functioning like the Carnegie curve, local measurements at Wallops Island just cannot see the UT variation. I do not believe this position is supportable by the evidence. If, as Markson states, the global circuit is driven by global thunderstorms, then why is it so difficult to believe that there can be substantial daily global thunderstorm variations? For instance, the peak of the Carnegie curve at 1900 UT comes when the American continents are in the local afternoon. Thus, American convective thunderstorm activity would be highest (on the average) and this would "pump up" the ionospheric potential. However, it is clear from daily weather maps that occasionally there are days when an entire continent is substantially cloud free. Thus, such a day would be a time when the American continents would not act to charge the ionosphere. The same goes for any specific land mass.

More generally, satellite measurements of lightning frequency distributions [*Orville and Spenser*, 1979; *Turman and Edgar*, 1982] indicate substantial variation on a month to month basis of the location of maximum thunderstorm activity. Recently, the space shuttle astronauts have photographed and witnessed the phenomena of simultaneous lightning covering perhaps 500,000 square miles [*Vonnegut et al.*, 1983]. It appears that an initial lightning stroke will often cause a chain reaction such that within seconds lightning will occur in many adjacent thunderstorms. This might abruptly affect the rate at which these thunderstorms are driving current to the ionosphere.

It would be begging the question to use the measured electrical data to determine what caused the electrical variations in that data set. That is, it is just as incorrect to state that "the data follow the Carnegie curve and therefore must be due to the global circuit" as it is to state "the data do not follow the

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Electrical Measurements in the Atmosphere and the Ionosphere Over an Active Thunderstorm

1. Campaign Overview and Initial Ionospheric Results

M. C. Kelley,[1] C. L. Siefring,[1] R. F. Pfaff,[1] P. M. Kintner,[1] M. Larsen,[1] R. Green,[1] R. H. Holzworth,[2] L. C. Hale,[3] J. D. Mitchell,[3] and D. Le Vine[4]

The first simultaneous electric field observations performed in the ionosphere and atmosphere over an active nighttime thunderstorm are reported here. In the stratosphere, typical storm-related dc electric fields were detected from a horizontal distance of ~100 km, and transient electric fields due to lightning were measured at several different altitudes. In the ionosphere and mesosphere, lightning-induced transient electric fields in the range of tens of millivolts per meter were detected with rise times at least as fast as 0.2 ms and typical duration of 10-20 ms. The transients had significant components parallel to the magnetic field at 150 km altitude. This implies that either considerable Joule heating occurs or a collective instability is present because of the high drift velocities induced by the transient electric fields. Copious numbers of whistlers were genrated by the storm and were detected above but not below the base of the ionosphere. We present here the outline of a new model for direct whistler wave generation over an active thunderstorm based on these observations. The intensity of the observed two-hop whistlers implies that they were amplified along their propagation path and suggests that particles were precipitated in both hemispheres.

Introduction

Lightning, and thunderstorms in general, involve a variety of fascinating physical processes. The experimental program described here was designed to determine the effects of this meteorological phenomenon on the ionosphere and also to investigate electrical effects in the stratosphere and mesosphere. To this end, a thunderstorm electric field campaign was organized and carried out during an active nighttime thunderstorm which moved through the rocket range at the NASA Wallops Flight Center, Wallops Island, Virginia (latitude = 37.8°, longitude = 284.5°).

A 10-cm radar located at Wallops Island was used to monitor the backscatter intensity due to hydrometeors. The radar, along with visual and RF observations, yielded a good indication of thunderstorm activity. A ground-based flat plate antenna also provided valuable diagnostic data.

Two high flying ballistic trajectory payloads were developed to make measurements in the mesosphere and ionosphere over a thunderstorm. One payload had an apogee of 89 km, and the other 154 km. To our knowledge these rockets were the first dedicated to the study of the upward coupling of lightning and thunderstorm from electric fields into the ionosphere. In addition, a zero-pressure balloon was flown at an altitude of near 25 km, and a rocket-borne parachute payload with an apogee of ~75 km carried electric field sensors aloft to characterize the electric field signatures at various altitudes in the atmosphere.

The stratospheric balloon was instrumented with both quasi-static vector electric field detectors and a broadband VLF electric field detector with a maximum frequency of 100 kHz. The electric field detectors consisted of six spherical sensors (1 foot in diameter) mounted on three sets of orthogonal booms (length 3 m) [*Mozer and Serlin*, 1969]. Conductivity measurements using the relaxation time constant method were obtained every 30 min. Similar instrumentation packages have been flown before and are described by *Holzworth* [1981] and *Holzworth and Chiu* [1982]. More details on the ballooon system are given in the companion paper [*Holzworth et al.*, this issue], hereinafter referred to as paper 2.

The Super-Arcus parachute paylod carried a blunt-probe dc electric field sensor (with a maximum frequency of about 100 Hz) and a Gerdien condenser to measure atmospheric conductivities. More detailed information on this measurement configuration can be found in the works by *Hale et al.* [1981] and *Mitchell et al.* [1982] and in paper 2.

Both ballistic payloads were instrumented with dipole electric field detectors employing spherical sensors mounted on the end of extendable booms. The ionospheric rocket, known as Thunder Hi, had two sets of booms of length 5.5 m mounted orthogonally to each other (and to the spin axis of the rocket) with a vertical separation of 1.5 m between boom sets. Thunder Hi also carried a fixed bias Langmuir probe operated in the electron saturation region to measure relative electron densities. The mesospheric rocket (Thunder Lo), which is also described by *Kelley et al.* [1983], had two boom sets of lengths 4.0 m and 5.5 m, oriented perpendicular to the spin axis along with a vertical probe of length 1.3 m along the axis. Both payloads were designed to make dc, low-frequency, and broadband vector electric field measurements. The highest-frequency response for one component of the electric field was 48 kHz. The response time for a full vector measurement was 14 kHz on Thunder Hi and 8 kHz on Thunder Lo.

The storm consisted of four major cells. Figure 1 shows the position of each cell at the launch time of Thunder Lo (August 9, 1981, 0208:00 UT) and 15 s before the launch of Thunder Hi. The locations of Wallops Island and the stratospheric balloon are indicated along with the trajectories of the three rocket payloads. Vertical radar scans of each cell just before launch indicated heavy precipitation reaching up to at least an altitude of 13 km. Radiosonde data indicated that the tropopause temperature minimum was at 16 km, and we estimate

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Electrical Measurements in the Atmosphere and the Ionosphere Over an Active Thunderstorm
2. Direct Current Electric Fields and Conductivity

See also 85N 73231

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On August 9, 1981, a series of three rockets were launched over an air mass thunderstorm off the eastern seaboard of Virginia while simultaneous stratospheric and ground-based electric field measurements were made. The conductivity was substantially lower at most altitudes than the conductivity profiles used by theoretical models. Direct current electric fields over 80 mV/m were measured as far away as 96 km from the storm in the stratosphere at 23 km altitude. No dc electric fields above 75 km altitude could be identified with the thunderstorm, in agreement with theory. However, vertical current densities over 120 pA/m^2 were seen well above the classical "electrosphere" (at 50 or 60 km). Frequent dc shifts in the electric field following lightning transients were seen by both balloon and rocket payloads. These dc shifts are clearly identifiable with either cloud-to-ground (increases) or intercloud (decreases) lightning flashes.

INTRODUCTION

Thunderstorms are known to be the source of the largest atmospheric electric fields at altitudes up to several tens of kilometers [*Mozer*, 1971; *Holzworth*, 1981]. The question of just how far the electrical influence of an isolated thunderstorm extends was the subject of a collaborative rocket, balloon, and ground-based measurement program at Wallops Island, Virginia, in August 1981. (See *Kelley et al.* [this issue] hereinafter referred to as paper 1.) On August 8 at 2215 UT a balloon was launched which reached a ceiling of 30 km about 2 hours prior to the near-simultaneous launch of three rockets. These rockets had trajectories taking them over an air mass thunderstorm with heavy precipitation reaching up to over 13 km (the tropopause was near 16 km). The rocket apogees were 74 km, 88 km, and 154 km altitude, respectively, while the balloon was about 100 km northwest of the storm and drifting down from 30 km to about 20 km over the course of 3 hours. Ground-based electric field measurements were made on Wallops Island within a few kilometers of the rocket launch sites.

An overview of the campaign including the transient and ac electrical phenomena has been addressed in paper 1. The measured dc electric field and conductivity data presented here yield a picture which supports as well as disputes some theories about the extent of thunderstorm dc electrical effects. The long-held philosophy [cf. *Chalmers*, 1967] that the atmospheric electric circuit is confined below an "electrosphere" of 50 km is not supported by these data. Vertical electric currents over 80 pA/m^2 at 70 km were measured. As the conductivity increased, the electric fields became small, and no identifiable storm-related dc electric fields have been found above 74 km (except intense lightning-induced fields as discussed in paper 1). Fields of the order of 100 mV/m were seen both in the mesosphere at 70 km altitude over the storm and in the stratosphere at a horizontal range of 96 km. These measurements will be presented along with a comparison to various theories of electric field mapping in the atmosphere.

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INSTRUMENTATION

A detailed discussion of the complete instrumentation is given in paper 1. Pertinent to the present paper are the following measurements. The vector electric field was measured in the stratosphere on a free-flying balloon using the double Langmuir probe technique [*Mozer and Serlin*, 1969]. These data are accurate to less than 1 mV/m for horizontal electric fields and ±15 mV/m for vertical fields. The balloon payload also measured electrical conductivity by the relaxation time constant method [cf. *Holzworth*, 1981].

The parachute-borne electrodynamics payload, which ejected from the rocket at apogee (75 km), included a Gerdien condenser for measuring both polar components of electrical conductivity [*Mitchell et al.*, 1982] and a sensor for simultaneously measuring the potential difference between a 1-m metallized section of the parachute's lanyard and the payload's outer metallic surface [*Hale and Croskey*, 1979]. (The overall dipole length of this vertical E field probe was 2 m.) Since the flight was at night, there were none of the well-known photoemission problems due to the probe asymmetry; however, a residual work function offset limited the absolute accuracy of these electric field measurements to about 0.1 V/m.

Two high-altitude rockets, Thunder Hi and Thunder Lo, also measured vector electric field, to altitudes of 154 km and 88 km, respectively. As with the balloon, double Langmuir

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Do We Need a Geoelectric Index?

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Introduction

We might put the question slightly differently: What scientific problems require knowledge of the global variability of lower atmospheric electric generators? In this paper, we present our view of the necessity of quantifying global electrical variability and discuss some potential uses of and available methods for producing a geoelectric index.

During this last decade, we have observed an increasing interest in the field of atmospheric electricity. At the 1985 AGU Fall Meeting in San Francisco, Calif., there were seven half-day sessions on various aspects of atmospheric electricity—a great increase over past years (see the abstract listings for the Atmospheric Sciences and SPR: Magnetospheric Physics sessions in *Eos*, November 12, 1985, pp. 815–842 and 1028–1055). This area of interest covers thunderstorm electrification, lightning, and sferics, as well as lightning-induced magnetospheric effects and solar-terrestrial electromagnetic coupling. For many aspects of these studies, it would be advantageous to have a number that is a measure of present global electrical activity, such as thunderstorm occurrence, number of lightning events, or ionospheric electric potential relative to the earth [see also *Markson and Muir*, 1980]. Furthermore, there are many other areas of research that would benefit from a geoelectric index, such as meteorology and atmospheric science.

A geoelectric index should be similar in utility to other solar-terrestrial activity indicators, such as the well-known solar sunspot number or the various geomagnetic indices [see *Rostoker*, 1972]. These numbers are relatively simple to derive from ground-based observations on a routine basis. They are reliable, reproducible from alternative data sets, and historically available for many decades. Although the solar sunspot number is not an optimum index of solar activity (the 10.7-cm solar radio emission or the satellite-based UV observations are better), its simplicity and the length of the available data base outweigh its disadvantages. The same is true for the geomagnetic indices. Geomagnetic observatories exist all over the world. They continuously report data of the variable geomagnetic field, which (when appropriately sampled) gives a fair indication of the ceaselessly varying ionospheric and magnetospheric electric current systems.

The usefulness of these indices is beyond doubt, and the question may therefore be raised whether a geoelectric index might be of comparable value in the near or distant future. Along this line, it is interesting to note that recent research has shown that the large scale return currents of the global circuit are variable by factors of two from the mean daily variation. *Holzworth et al.* [1984] report that simultaneous balloon-borne electric field measurements from widely separated balloons (over 1000 km) in the stratosphere often have the same magnitude and the same temporal variation but nonetheless differ drastically from the "expected" Carnegie Curve (which represents the average universal time variation of the surface electric field: about +20%/−15% variability from the mean; compare *Whipple* [1929]). Thus we now suspect that the global circuit is variable on a time scale of tens of minutes.

Who Are the Potential Users of a Geoelectric Index?

Before we evaluate the different possible methods for deriving a geoelectric index, we will first deal with the question of who might be interested in using such an index and why. We will limit ourselves to three general areas that would greatly benefit from a geoelectric index: atmospheric and space electrodynamics, atmospheric science, and meteorological forecasting. For each of these research areas, we will illustrate basic science problems that might not be solved without a quantitative measure of global electrical activity or the source distribution function. Within atmospheric and space electrodynamics, we will discuss outstanding scientific questions concerning the global circuit, solar-terrestrial coupling, lightning effects on the ionosphere and magnetosphere, and the possible identification of mesospheric electric field generators. Atmospheric science examples will include thunderstorm-generated or -transported molecules, which play an important role in stratospheric chemistry and planetary wave forcing by thunderstorms. Under meteorology, we will discuss the need for better fog forecasting.

Problems in Atmospheric and Space Electrodynamics

The Global Circuit

Wilson's [1920] hypothesis is that thunderstorms are the main generators of the global electric circuit, causing an electric potential between earth and the ionosphere of about ~200–500 kV and electric current density within the fair weather areas of a few picoamperes per square meter. Although it is widely accepted, this hypothesis has not yet been proven beyond doubt [see *Dolezalek*, 1972]. We know that a typical thunderstorm generates an upward dc electric current of the order of 1 A and that extrapolation from meteorological data suggests that ~1000–2000 thunderstorms are active at any time. On the other hand, lightning currents are assumed to close (at least partly) the global circuit between the ground and the storm clouds (Figure 1). The existing data do not

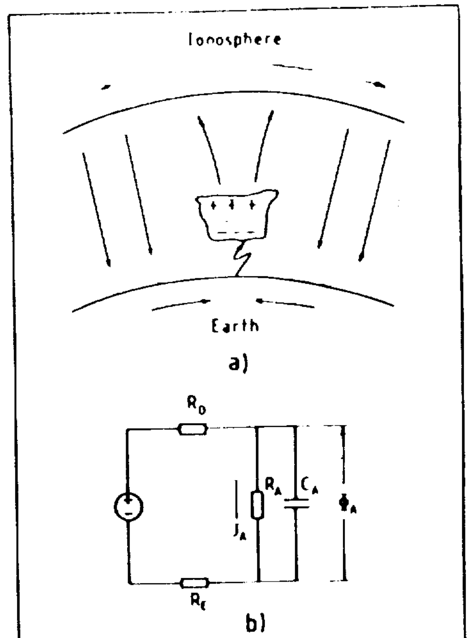

Fig. 1. Electronic circuit equivalent to global electric circuit [from *Volland*, 1984].

allow the determination of a quantitative relationship between the various parts of the global electric circuit. A geoelectric index, along with an extensive short-term measurement program of electrical parameters by airborne, balloon-borne, and satellite-borne detectors, will be necessary to quantitatively understand the global circuit.

Solar-Terrestrial Coupling Processes

It is now widely recognized that the current systems driven by global thunderstorms and by magnetospheric plasma phenomena coexist in the middle atmosphere and above. For instance, recent models of thunderstorm current systems [e.g., *Tzur and Roble*, 1985] show that most of the return current from a thunderstorm generator that penetrates the tropopause flows globally through the ionosphere and along plasmaspheric magnetic field lines. Furthermore, the first experimental evidence of these thunderstorm dc current systems up to at least 70 km altitude (well above the classic "electrosphere": see *Chalmers*, [1967]) has just been reported [*Holzworth et al.*, 1985]. The opposite situation occurs for large-scale electric fields in the magnetosphere, which have long been known to drive current systems down at least to the stratosphere [*Mozer and Serlin*, 1969]. Furthermore, the typical temporal variability of a magnetospheric substorm is of the same order as a large thunderstorm (about 1 hour, say). For these reasons, we suggest that a quantitative estimate of the dynamical variability of the tropospheric source of electric phenomena (such as thunderstorms) is necessary before the importance of upward or downward coupling of electrical phenomena can be clearly addressed. For instance, identifying an effect of a 10% variation in the ionospheric potential caused by solar or magnetospheric phenomena [*Herman and Goldberg*, 1978] would be nearly impossible without knowledge of the natural variations of the ionospheric potential caused by global thunderstorms (or other tropospheric generators).

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Electrical Potential Measurements in the Lower Atmosphere

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Lower-atmospheric potential measurements obtained in 1983 through 1985 using the Hy-wire technique are summarized in this paper. Observed values of the potential were in the range of 50-100 kV in Fairbanks, Alaska, compared with 100-200 kV at Wallops Island, Virginia. While differences are seen in absolute potential for different sites, the daily variations are similar in character. When 1-hour averages are formed from the entire data set the result is a unitary variation very reminiscent of both the Carnegie curve and more recent stratospheric electric field data. A comparison with an aircraft potential measurement in the same vicinity during April 1983 demonstrates that the two techniques yield roughly similar results, except that the Hy-wire measurements were 20-30% lower in absolute value. For the Alaska data, no clear effect on the potential was seen during a 400-nT auroral magnetic perturbation.

1. INTRODUCTION

In this paper we report the results of a series of long-term (several days at a time) continuous measurements of the electrical potential across the lower 1.5 km of the atmosphere. Measurements have been made in North America during local spring and summer at both mid-latitudes and in the auroral zone. The measurement system described in this paper is based on the Hy-wire technique developed with a smaller system by *Holzworth* [1981] and described by *Holzworth et al.* [1981] and *Holzworth* [1984*a*]. Hy-wire is a device capable of making a continuous high-impedance dc potential measurement across the lower 1.5 km of the troposphere. This potential difference measurement is made with a time resolution on the order of 30 s, and the device can be operated continuously for a period of weeks. Continuous data for long periods with this time resolution are not available from the integrated electric field sounding technique [e.g., *Muhleisen,* 1971, 1977; *Markson,* 1977, 1985]. Additionally, this high-impedance Hy-wire method avoids the corona discharge problems inherent in the otherwise similar low-impedance tethered balloon experiments described by *Vonnegut et al.* [1973] and *Willett and Rust* [1981]. Their corona problem is treated theoretically by *Willett* [1981].

The heart of the Hy-wire system is a long insulated high-voltage cable reinforced with a Kevlar core. The insulation is stripped from the upper end of the cable and the internal conductor is connected to a 10-m wire mesh, which is frayed at the ends to form corona points *Holzworth* [1984*a*]. This end is then attached to a 1060-m^3 aerostat with a 15-m piece of ordinary 3/8-inch (0.95-cm) nylon rope and raised to an altitude of 1.5 km agl. (above ground level). The aerostat itself is secured with a separate insulating tether to minimize perturbation of the ambient electrical environment. The detailed specifications of this special, custom-made cable are given in Table 1.

The lower end of the wire is connected, through a cable reel, to a cylindrical aluminum "tank" with hemispherical conducting ends (Figure 1). When the external ground strap is removed, the tank becomes electrically insulated from the ground (on 1-m Teflon legs) with a measured impedance of $\geq 5 \times 10^{13}$ Ω under potential differences of $\lesssim 200$ kV. This is conceptually similar to Ben Franklin's "sentry box" experiment, except that our impedance is higher and we use electronic detectors instead of our fingers!

While the tank is grounded, the wire is first raised to operating altitude. At that time there is a potential difference on the order of 100 kV between the upper end of the grounded cable and the surrounding atmosphere, due to the fair-weather electric field. It is thus in corona and will emit a space charge plume. When the ground is removed, the apparatus (tank, wire, and braid) is electrically floating and is thus charged by the corona current until the potential difference (between the wire and the surrounding air) falls below the corona initiation voltage ($\lesssim 1$ kV). The time constant for this equalization has been measured and is on the order of 30 s. This sets the upper limit of the system's time response for dc potential measurements. Additionally, the system has a fast, capacitively coupled ac response [*Holzworth and LeVine*, 1983]. A few time constants after the removal of the ground strap, the wire and tank are at the potential of the ambient air at 1.5 km, relative to the ground (to within 1% $\approx$ (corona initiation voltage) / (operating voltage); see *Holzworth,* [1984*a*]). The field due to charge stored on the tank at a given potential is measured with an electrostatic voltmeter (Monroe Electronics Incorporated, model 244), previously calibrated with a small high-voltage generator. The apparatus as a whole thus gives us a measurement of ambient potential at 1.5 km relative to the ground, while avoiding any direct connection with the high-voltage tank. Relevant system parameters are given in Table 2.

During the Hy-wire flight at Wallops Island, Virginia, in April 1983, the original Hy-wire system [*Holzworth et al.*, 1981] was operated simultaneously with the new system at another sea level site separated by about 3 km horizontally. Grounding and refloating either system had no discernible effect on the potential measured by the other, even though clearly visible on nearby field mills 10-20 m away. A different comparison was made for the June 1984 flight in Poker Flat, Alaska. Two ground-based field mills built by the University of Minnesota were operated (by a team under the direction of the late Don Olson) during part of the Hy-wire flight. One was placed about 100 m from the Hy-wire site on the ground, and the second field mill was placed about 1000 m away on a hillside, at an altitude of $\approx$150 m (slant range = 1.7 km to top of Hy-wire) relative to the site (see inset, Figure 5). This second field mill did not show any electric field variations related to the groundings and refloatings of the Hy-wire, although a series of careful coincidence experiments were conducted. The first field mill, at the 100-m distance, showed

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Electric Fields in the Middle Atmosphere

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Abstract

All of the solar electromagnetic energy impinging on the earth must pass through the middle atmosphere in some form. This weakly conducting region between the cloud tops and the ionosphere has often been considered to be electrically passive. This paper will review what is known about the large scale electrodynamics of the middle atmosphere and present the results of some recent research which contradicts the historical view of the region. One key to understanding middle atmospheric electrodynamics is a good understanding of the temporally and spatially varying electrical conductivity. With the knowledge of the conductivity, the middle atmospheric effects of external electric generators can often be determined by solving a time dependent boundary value problem often referred to as "mapping" the electric field. This has been a useful technique for study of current generators both below and above the middle atmosphere. Furthermore, contrary to the classical picture, there may be sources of electric fields within the middle atmosphere. Certainly there are sources of variability in the conductivity which actively modify the expected signal from external generators. The many-fold increase in available electric parameter data from within the middle atmosphere has been a great stimulus to recent research. However, this review will conclude that these measurements have tended to raise more questions than answers. That is a clear indication that the field of middle atmospheric electrodynamics is ripe for breakthrough research which will only come as a result of a new and vigorous measurement program.

1. The electrical environment

This is the first of three main sections of the paper in which I will discuss the background electrical environment of the middle atmosphere. The second section will present a review of the main sources for electric fields and currents within the middle atmosphere. This will in turn be followed in the third section with the latest results on variability of these sources along with a discussion of the possibility of a new source within the middle atmosphere.

The electrical environment of the middle atmosphere is characterized by a conductivity which varies by 10 orders of magnitude from about 10^{-12} S/m at the tropopause to about 10^{-2} S/m at the base of the ionosphere. The degree to which electric fields and currents can penetrate into and through the region is a strong function of the local, time-dependent conductivity profile in altitude. In the simplest formulation, appropriate throughout most of the middle atmosphere, the time dependent electrical conductivity (σ_i) for a particular species (i) of charge carrier (e_i) is a function of number density (n_i) and mobility (κ_i): $\sigma_i = e_i n_i \kappa_i$. The conductivity is collision dominated throughout most of the middle atmosphere so that in addition to the species mass (m_i) the mobility is controlled by the ion-neutral collision frequency ν_i. The conductivity is given by the standard Spitzer resistivity [1]: $\sigma_i = n_i e_i^2/m_i \nu_i$ so that $\kappa_i = e_i/m_i \nu_i$. Throughout the middle atmosphere the relation between current density and electric field is given by Ohm's Law $J = \sigma E$ (for isotropic conductivity). For completeness we note that, from the definition of the charge density $J = \Sigma_i n_i e_i V_i$ with V_i being the bulk drift velocity of the ith charge carriers, we can write the mobility of the ith species as $\kappa_i = V_i/E$.

Much effort continues to go into the measurement of conductivity in the middle atmosphere. While it is not the purpose of this paper to critically evaluate the measurements of and techniques for determining conductivity, mobility or charge density, I will discuss the present level of understanding of middle atmospheric conductivity and identify some limitations we should all keep in mind when discussing middle atmospheric electric fields and currents. Figure 1 from Hale [2] is a recent compilation of many measurements of conductivity which serves to emphasize the degree of time dependence of the atmospheric conductivity. This Figure shows that one can reasonably expect a one to two order of magnitude daily variability in conductivity at any altitude and that at some altitudes the range of possibilities is over six orders of magnitude. With this level of variability we must be very careful to understand the source of the conductivity profile used in any theoretical study. In other words, any attempt to relate electrical observations at one altitude to sources in different locations must use the actual conductivity on that day in that location and avoid using a summary profile or other guess such as the average of all the data in Fig. 1. Furthermore, there are only a very limited number of rocket ranges in the world from which data such as those in Fig. 1 can be taken. Thus one should also be careful to understand the basis for global extrapolation of averages from selected sites. Another way to look at Fig. 1 is that the altitudes above balloon heights (say 40 km) and below accurate radar measurements of number density (say 90 km) show the widest variability because of lack of measurements.

Researchers often summarize the conductivity between the ground and the ionosphere with a single exponential profile in altitude (z) with scale height H such as $\sigma = \sigma_0 e^{z/H}$. For instance in the case of Fig. 1 one might lay a ruler along the plot and conclude that a fit giving $\sigma = 10^{-14}$ at the ground and $\sigma = 10^{-2}$ at 100 km would be a good average representation which might be reasonably useful as a global quite average. That would be a scale height of $H = 3.62$ km which is much less than is used in many models [3–5]. The effect of this difference in scale height is dramatically obvious in Ogawa's article [5]. Ogawa derives an estimate of the current to the ionosphere from a thunderstorm (based on a Holzer and Saxon cloud model [6]) to be as much as 17% of the thunderstorm source current (see eq. (5), [5]) using $H = 6$ km. If we set $H = 3.62$ km that number would be only 11% or nearly a factor of two from his rounded up estimate of "as much as 20%" (p. 5952, Ogawa [5]) of the current output from a storm going up to the ionosphere. By extrapolation of this result one might conclude the current to the global circuit was on the average twice as large as can be justified from the average of data in Fig. 1.

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Thunderstorm Related Variations in Stratospheric Conductivity Measurements

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SEE ALSO 90A16414

The vector electric field and polar conductivities were measured by zero-pressure balloon-borne payloads launched from Wallops Island, Virginia during the summers of 1987 and 1988. Data were collected over thunderstorms (or electrified clouds) during 6-hour flights at altitudes near 30 km. The vector electric field measurements were made with the double Langmuir probe high-impedance method, and the direct conductivity measurements were obtained with the relaxation technique. We show evidence for conductivity variations over thunderstorms (or electrified clouds). We find that both positive and negative polar conductivity data do show variations of up to a factor of 2 from ambient values associated with the disturbed periods. Some ideas for possible physical mechanisms which may be responsible for the conductivity variations over thunderstorms are also discussed in this paper.

INTRODUCTION

Following a suggestion of thunderstorm related stratospheric conductivity variations by *Benbrook et al.* [1974], *Bering et al.* [1980] interpreted their conductivity measurements over a thunderstorm as being affected by the presence of the storm itself. However, it was not until recent years that a statistical survey about the conductivity variations over thunderstorms was conducted by *Holzworth et al.* [1986]. They reported 23 cases for which conductivity measurements obtained by balloon-borne instrumentation at 26-km altitude over thunderstorms showed significant variations from the fair-weather values. In several cases these variations exceeded 50% of the mean fair-weather conductivity value. More recently, *Pinto et al.* [1988] also found significant perturbation in the conductivity measurements at 26-km altitude over electrified convective clouds. However, these new results at first seem to be contrary to previous work [cf. *Stergis et al.*, 1957; *Mozer*, 1971; *Holzworth*, 1981; *Barcus et al.*, 1986] in which no significant thunderstorm related conductivity perturbation in the stratosphere was noted. A recent exchange of papers between *Vonnegut and Moore* [1988] and *Holzworth et al.* [1988] has served to focus the issues involved with making these measurements over thunderstorms. One common conclusion of these papers is that further measurements are necessary in order to judge the validity of the reported conductivity variations in the stratosphere. This present paper addresses this suggestion with new data.

It has been known for some time that understanding middle atmospheric conductivity is of primary importance for solving electrodynamic coupling problems between the ground and ionosphere [cf. *Reid*, 1986]. Therefore if these thunderstorm related conductivity variations are indeed real, then our current view of the behavior of the global circuit needs to be reexamined. For example, direct thunderstorm models as well as models about large-scale current systems related to thunderstorms which use a fair-weather conductivity profile may need to be considerably modified.

In this paper, we report our latest results of conductivity measurements over thunderstorms (or electrified clouds) by using zero-pressure balloons launched from Wallops Island, Virginia (latitude = 37.8°, longitude = 284.5°), in July 1987 and July 1988. We will show two cases in which conductivity measurements do present variations while our balloons are over thunderstorm (or electrified cloud) systems. These variations are found to be up to a factor of 2 above fair-weather values. Mechanisms for the conductivity variations over thunderstorms are as yet unknown; however, we will discuss some ideas for possible physical mechanisms which might account for these measurements.

OBSERVATION

The balloons were of zero-pressure type, with float altitudes near 30 km. We note this altitude is nearly a full conductivity scale height above the float altitudes reported in *Holzworth et al.* [1986]. On each balloon, the payload to measure the electric field and conductivity was designed in a manner similar to that described earlier by *Mozer and Serlin* [1969] and *Holzworth* [1977]. Three components of electric field were determined by the potential difference measured on orthogonal pairs of isolated, aquadag-coated, spherical conductors using the double-Langmuir probe technique. The accuracy of the electric field measurements was about ±1 mV/m for horizontal components and ±15 mV/m for the vertical component. Direct conductivity measurements were obtained by the relaxation time constant method. First, the upper and lower vertical conductors were biased to +2.5 V and -2.5 V, respectively, and then allowed to float back to ambient values by collecting ions of different signs. High resolution telemetered data obtained simultaneously from each refloated conductor are separately least squares fit to an exponential equation to get the relaxation time constants ($\tau_\pm$). The polar conductivities are then given by $\sigma_+ = \varepsilon_0 / \tau_+$, and $\sigma_- = \varepsilon_0 / \tau_-$, where ε_0 is the permittivity of free space. The conductivity measurements were made every 10 min.

The lightning flash rate presented in this paper was determined by the number of lightning flashes per minute as seen in the balloon electric field data. The balloons were tracked by radar throughout each flight. Thunderstorm systems were identified by satellite weather observation (i.e., deep convective clouds) and by the State University of New York at Albany (SUNYA) lightning detection network. Therefore the balloon position relative to a thunderstorm system could be determined independently from the payload measurements.

The balloon of July 9, 1988, was released at 2339 UT and attained a float altitude of 30 km at 0114 UT on July 10. It was terminated at 0500 UT after about a 6-hour flight period. Figure 1 shows the areas covered by thunderstorms during this balloon flight given by SUNYA lightning detection network. The little

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INTENSE IONOSPHERIC ELECTRIC AND MAGNETIC FIELD PULSES GENERATED BY LIGHTNING

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Abstract. Electric and magnetic field measurements have been made in the ionosphere over an active thunderstorm and an optical detector onboard the same rocket yielded an excellent time base for the study of waves radiated into space from the discharge. In addition to detection of intense, but generally well understood whistler mode waves, very unusual electric and magnetic field pulses preceded the 1-10 kHz component of the radiated signal. These pulses lasted several ms and had a significant electric field component parallel to the magnetic field. No known propagating wave mode has this polarization nor a signal propagation velocity as high as we have measured. We have investigated and rejected an explanation based on an anomalous skin depth effect. Although only a hypothesis at this time, we are pursuing a more promising explanation involving the generation of the pulse via a nonlinear decay of whistler mode waves in the frequency range 10-80 kHz.

Introduction

In situ data from a number of spacecraft-borne instruments have indicated that transient ionospheric effects accompany lightning discharges [Kelley et al., 1985; Siefring, 1988; Voss et al., 1984]. These are direct electrical transients in the ionosphere over thunderstorms as distinct from the well known packets of whistler mode waves [c.f. Helliwell, 1965], which propagate throughout the magnetosphere and, when amplified by wave-particle processes can result in ionospheric perturbations by precipitated electrons (Trimpi events). It is the direct transient and not the Trimpi event which interests us here. Previous work has described early observations of the electrical transient [Kelley et. al., 1985] as well as associated optical effects [Li et al., 1990]. In this letter we report on a new rocket experiment designed specifically to study this direct transient phenomenon.

The experiment, called Thunderstorm II, was carried out at the Wallops Island Flight Facility in July 1988. It involved the simultaneous launch of two high flying rockets (apogees over 300 km) with electric field and particle detectors. Regional lightning location information was available in real time from the East Coast Lightning Network run by the State University of New York at Albany (SUNYA). The main Thunderstorm II payload was on a magnetically oriented Black Brant IX rocket which was launched over a small thunderstorm cell at roughly midnight true local time. The cell was part of a 500 km long line of thunderstorms which developed over the mountains and slowly died out as the wind patterns caused the line to approach the coast. An example of the local activity in a five minute period including the launch is shown in Figure 1. The calculated lightning rate during this period was 528/hour. The rate had been as high as 6500/hour at the height of the event which occurred four hours earlier.

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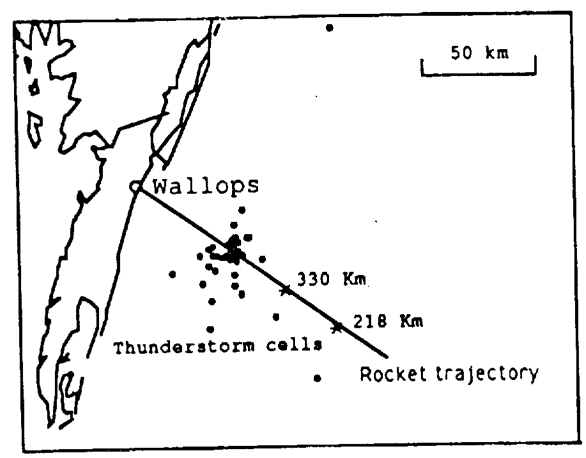

Fig. 1. A map showing the lightning location given by the SUNYA system during a five minute period while the rocket was aloft. A projection of the rocket velocity on the horizontal is also shown.

We concentrate here on the electric and magnetic field data. The former were obtained from double probe detectors using spherical electrodes on the ends of 2 m booms yielding tip to tip separations of 4 m perpendicular to the spin axis. Along the rocket axis the separation was 1 m. An important feature of the telemetry system used was that the data rate was sufficiently high that a major fraction of the electrical energy emitted by a strike was detected with no phase shifts introduced by the electronics. For this experiment we were able to digitize two components of the electric field at a rate of 20,000 samples per second and the other at 10,000 samples per second in real time. Although a major improvement from earlier experiments, we discovered, and show below, that some of the most important frequency bands for the phenomenon of interest here were above this band (in the range 10-80 kHz). The magnetic field detector was a vector search coil instrument mounted in a fiberglass tube which, when the skin was removed, extended four feet from the payload. An optical detector provided crucial and unambiguous timing for the lightning events.

Raw data from the vector electric field detector during one

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Anomalous Optical Events Detected by Rocket-Borne Sensor in the WIPP Campaign

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Paul M. Kintner, [2] Juan V. Rodrigues, [3] Umran S. Inan, [3] and W. C. Armstrong [3,4]

A photodiode sensor has been designed and flown in an experiment to measure the broadband optical power of lightning. Several such sensors were launched on one rocket-borne payload (apogee over 400 km) and four balloon-borne payloads (float altitudes over 30 km) during the Wave Induced Particle Precipitation (WIPP) campaign (Kintner et al., 1987) at Wallops Island during the summer of 1987. Sensors aloft measured the optical power of events occurring below the payloads along with the waveforms of electric field transients. The same transients were recorded simultaneously by a ground-based VLF receiver with a magnetic (loop) antenna. Rocket and balloon sensors detected a great majority of lightning flashes also recorded by the State University of New York at Albany (SUNYA) lightning locating network. Many other signatures which were similar to those of lightning but were not recorded by SUNYA were also detected. Overall during the 10-min flight, more than 500 lightning-related events were detected in the (wide) field of view of the rocket-borne photodiode sensor. Among these is a class of about 23 events all having an anomalous signature, with obvious clustering of optical impulses or continuous emissions, and resulting durations of several hundred milliseconds. Such durations are much longer than typical for the lightning-related events recorded at the rocket, which are more frequent overall. Every anomalous optical event (AOE) was accompanied by broadband VLF signals of a distinctive character, signals which were received on the balloon, the rocket, and the ground. No such AOEs were ever detected by the balloon optical photodiode sensor even when the data suggested that a signal from the AOEs also should have been detectable at the balloon. In fact, no such unusually long-enduring optical events were ever detected by a balloon photodiode sensor on any of six separate flights in 1987 and 1988 under similar experimental conditions. Responses excluded so definitively from detection at the balloons are consistent with events originating primarily at altitudes above the 30 km balloon altitude. In considering possible sources above 30 km we find that the AOEs do not seem to resemble other natural optical phenomena, such as meteors which burn up well above 30 km in the mid-latitude atmosphere.

1. Introduction

During the summer of 1987, as part of the Wave Induced Particle Precipitation (WIPP) Campaign [*Kintner et al.*, 1987], one rocket (apogee over 400 km) and four balloons (float altitudes over 30 km), were launched near thunderstorms from the NASA Wallops Flight Facility (37.8° N, 75.4° W). The rocket was launched at about 0353:49 UT on the night of July 31, 1987, and achieved an altitude of about 412 km 5.5 min later, while a balloon launched about 2 hours earlier floated at an altitude of 31 km. A photodiode sensor for measuring the broadband optical power of lightning and a broadband VLF receiver for measuring electric field were included in both the rocket- and balloon-borne payloads. Two narrow-band photometers and a Reticon imager, provided by George Parks (described by *Massey et al.* [1990]), were also mounted on the rocket. Even though its spatial resolution was relatively low the imager was intended to provide a means for locating (roughly) any important optical events observed.

During the 10-min rocket flight, more than 500 events were detected by the optical sensors on the rocket and balloon together. Many of these events were individually correlated with cloud-ground (C-G) lightning flashes located by the State University of New York at Albany (SUNYA) lightning network. A number of other events not indicated in the SUNYA data can probably be attributed to intracloud (I-C) lightning or to C-G lightning missed by the network. In addition to all these supposed lightning events the rocket detected a third class of optical events which have anomalous signatures. These involve many more optical impulses and longer optical duration (about several hundred milliseconds) than typical of lightning events. These anomalous optical events (AOEs) were always accompanied by characteristic radio signals detected primarily by the ground-based VLF receiver in the form of a strong clustering of VLF impulses embedded in mostly weaker, more continuous noise. At the rocket and balloon the detected amplitude of these characteristic signals was generally less than that of the typical VLF radio impulses or "atmospherics" usually produced by the lightning.

None of the long-duration AOEs were detected by the WIPP balloon photodiode sensor. This is true even though the data from the Reticon imager on the rocket indicated that some of them were from localized sources which should have been visible to the balloon sensor. By this we mean primarily that we have been able to localize some of the AOEs to regions from which the balloon did detect most of the SUNYA-located lightning flashes which were nearly simultaneous with some of the AOEs. In fact, no AOEs of the WIPP or any other type were ever seen by any of the six balloon payloads which were floated in similar situations (four flights in 1987, two flights in 1988; see *Hu et al.* [1989]). This suggests the possibility that the AOEs reported here for the WIPP rocket flight may have occurred above the balloon, that is at some altitude above 30 km.

Lightning discharges in the Earth's atmosphere typically occur below the tropopause at about 15 km altitude maximum. The few reports available indicate that lightning which sometimes goes upward to the clear air above 15 km is uncommon

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Atmospheric Electrodynamics in the US: 1987-1990

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This paper summarizes published atmospheric electrodynamics research of the past few years. It concentrates on the work of US researchers and does not claim to provide a full bibliography. The paper is divided into three general areas: 1. The ionosphere as a source for middle atmospheric electrodynamics; 2. Regional and global scale electrodynamics; and 3. Thunderstorms and lightning.

INTRODUCTION

In the last half of the 1980's we have seen an increase in research spanning the traditionally separated disciplines of tropospheric and ionospheric electrodynamics. We now have strong evidence for the importance of thunderstorm electrodynamics to the mesosphere and ionosphere. Likewise, our understanding of the downward penetration of ionospheric and magnetospheric current systems has grown. We have witnessed an important expansion in our understanding of middle-atmosphere electrodynamics covering a region some have referred to as the ignorosphere. Coordinated thunderstorm campaigns have begun to provide the kind of high resolution parameter measurements with which detailed thunderstorm electrification and lightning models can be tested. Similarly, recent satellite programs have provided us a new diagnostic for large-scale ionospheric electric fields and current systems that are important to atmospheric electrodynamics. Even since the publication of the NRC report [*Krider and Roble*, 1986] there have been developments in our understanding of the global circuit which indicate the inadequacy of simplistic models of global electrification (see *Regional and Global Scale Electrodynamics* section below). It is fair to say that we have no existing models of either global electrodynamics, or indeed of thunderstorm electrification which can accurately predict the occurrence or intensity of either.

Much of the recent growth in understanding of atmospheric electrodynamics has come from new experimental efforts. Recent balloon flights have resulted in the discovery of previously unknown regional scale generators. Airborne and balloon measurements in and through thunderstorms have given us the beginnings of a comprehensive data base for use in modeling thunderstorms. Rocket and satellite flights have given us the first direct evidence for energetic electron precipitation due to lightning as well as the importance of electrodynamics to mesospheric phenomena such as noctilucent clouds.

This paper will provide an overview of United States sponsored research developments in atmospheric electrodynamics during the last few years. In this formidable task I have extensive help from some key, recent reviews within the field. There was no paper in the previous IUGG report on the broad subject of atmospheric electrodynamics (AE) primarily because at the time the National Research Council had just published a book covering much of the subject [*Krider and Roble*, 1986]. Other recent reviews covering various aspects of AE will be mentioned in the topical discussion to follow. In particular, one should take advantage of the recent special issue of JGR which summarized the previous, International Commission of Atmospheric Electricity meeting in 1988 [see *J. Geophysical Res.*, *94*, September 30, 1989].

As is always the case for the IUGG reports, I will be concentrating on investigations by US scientists. Such a review cannot and should not be considered a full field review of a subject in which important contributions are regularly made by scientists in dozens of countries. This review is also complicated by the extreme pressure to keep articles short. I have divided the paper into three more general topic areas and follow with a brief discussion of some key improvements in technique. Working from the top down I will review the recent US work in ionospheric and magnetospheric electromagnetic component to atmospheric electrodynamics, regional and global scale electrodynamics, and electrified clouds and lightning.

IONOSPHERIC AND MAGNETOSPHERIC ELECTRODYNAMICS IMPORTANT TO AE

High Altitude Sources of Middle-Atmosphere Electrodynamics

Since it was demonstrated by *Mozer and Serlin* [1969] that large scale ionospheric electric fields drive important current systems in the stratosphere, there has been a steadily growing body of research on the influence on middle-atmosphere electrodynamics by ionospheric and magnetospheric phenomena. Ionospheric and magnetospheric current generators are responsible for one of the main atmospheric heating effects at high latitudes in the mesosphere and thermosphere: Joule heating. The coupling of these current systems to the neutral atmosphere has been extensively modeled [*Roble et al.*, 1987] and during a solar proton event has been shown to be responsible for a 1° - 3°K/day heating rate, exceeding the daytime ozone heating in the altitude range of 70 to 80 km. Heating rates above 100 km were even higher. *Walker and Bhatnagar* [1989] combine both the energetic particle and joule heating to calculate that in the upper mesosphere the heating rates can exceed 10°K/day. Recent satellite statistical studies [*Heppner*, 1987] and *Lundquist* [1990] provide an updated view of the large scale ionospheric electric field.

One of the more hotly debated subjects is the possible direct influence of magnetopause reconnection, called flux transfer events (FTE's), on ionospheric and atmospheric electric fields and on plasma flows [see *Lanzerotti et al.*, 1987]. The magnetic boundary between open and closed magnetospheric field lines intersects the ionosphere variously between 65 and 75 degrees and the magnetopause near its crossing of the earth-sun line. Thus ionospheric current systems, such as those described in the model of *Crooker* [1990], flow in response to the FTE in the form of closure currents. *Bering et al.* [1989] report balloon-

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A Case Study of Lightning, Whistlers, and Associated Ionospheric Effects During a Substorm Particle Injection Event

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Simultaneous ground-based observations of narrowband and broadband VLF radio waves and of cloud-to-ground lightning were made at widely spaced locations during the 1987 Wave-Induced Particle Precipitation (WIPP) campaign, conducted from Wallops Island, Virginia. Based on these observations, the first case study has been made of the relationships among located cloud-to-ground (CG) lightning flashes, whistlers, and associated ionospheric effects during a substorm particle injection event. This event took place 2 days after the strongest geomagnetic storm of 1987, during a reintensification in geomagnetic activity ($Kp = 5$) that did not affect the high rate of whistlers observed at Faraday Station, Antarctica ($L = 2.46$). At the time of the injection event, several intense nighttime thunderstorms were located over Long Island and the coast of New England, between 400 km northwest and 600 km north of the region geomagnetically conjugate to Faraday. About two thirds of the CG flashes that were detected in these thunderstorms during the hour following the injection event onset were found to be causatively associated with whistlers received at Faraday. During the same period the amplitude of the 24.0-kHz signal from the NAA transmitter in Cutler, Maine, propagating over the thunderstorm centers toward Wallops Island was repeatedly perturbed in a manner characteristic of previously reported VLF signatures of transient and localized ionization enhancements at D region altitudes. Though such enhancements may have been caused by whistler-induced burst electron precipitation from the magnetosphere, the data in this case are insufficient to establish a clear connection between the NAA amplitude perturbations and the Faraday Station whistlers. In view of the proximity of the NAA great circle path to the storm center, heating of the lower ionosphere by intense radiation from lightning may also have played a role in the observed VLF perturbations. The onset of each of the NAA signal perturbation events coincided with an intense cluster of radio atmospherics. Detailed temporal variations in the ELF (0.3-3 kHz) and VLF (3-30 kHz) power of similar "sferic clusters" correlated well with variations in the power of simultaneous "anomalous" optical events (AOEs) observed by a down-looking photodiode detector on a rocket at altitudes between 150 and 412 km.

1. INTRODUCTION

Lightning is a frequent and powerful source of electromagnetic radiation that can couple the neutral atmosphere, the ionosphere, and the magnetosphere. At ELF (0.3-3 kHz) and VLF (3-30 kHz) frequencies, such radiation propagates in the magnetosphere in the whistler mode [*Helliwell*, 1965]. Interactions in the magnetosphere between whistler mode waves and electrons are a form of coupling between atmospheric regions that is well documented but still not completely understood. The whistler mode wave can exchange energy through gyroresonant interactions with trapped energetic electrons at or near the geomagnetic equator, lowering the mirror height of some of the electrons and causing them to precipitate into the atmosphere, either directly in the hemisphere in which the wave originated or in the conjugate hemisphere following mirroring or backscattering from the top of the neutral atmosphere [*Chang and Inan*, 1985]. Bursts of precipitating electrons associated with whistlers have been measured in situ by rockets [*Rycroft*, 1973; *Goldberg et al.*, 1986] and satellites [e.g., *Voss et al.*, 1984]. Precipitation due to whistler-triggered emissions propagating outside the plasmapause has been detected as secondary bremsstrahlung X rays and optical emissions [*Rosenberg et al.*, 1971; *Bering et al.*, 1980; *Helliwell et al.*, 1980; *Doolittle and Carpenter*, 1983].

Secondary ionization due to whistler-induced burst electron precipitation has been causatively associated with characteristic amplitude and phase perturbations of VLF, LF, MF, and HF radio signals propagating in the Earth-ionosphere waveguide [*Baum*, 1963; *Helliwell et al.*, 1973; *Carpenter et al.*, 1984; *Moser et al.*, 1988]. The secondary ionization causes a localized increase in the ionization density at D region altitudes that, analogous to a dent in a metallic waveguide, perturbs the mode structure of the propagating wave. The ensuing constructive or destructive interference between the modes causes a temporary perturbation of the amplitude and/or phase of the signal that is often referred to as a "Trimpi" event [*Wolf and Inan*, 1990]. The delay between the causative radio atmospheric and the "Trimpi" event onset ("onset delay") typically is less than 1 s [*Inan and Carpenter*, 1986], the onset duration typically is less than 2 s, and the recovery lasts about 10-100 s [*Carpenter et al.*, 1984]. (A "radio atmospheric" or "sferic" is the electromagnetic impulse from a discharge in the atmosphere, such as a return stroke in a cloud-to-ground (CG) lightning flash.)

Some VLF amplitude perturbations have been observed with onset delays and/or onset durations of <50 ms, too short to be attributed to whistler-induced burst electron precipitation, although the magnitude and recovery time of the perturbation are consistent with a localized increase in the ionization density at D region altitudes as described above [*Armstrong*, 1983; *Inan et al.*, 1988*a*, *b*]. Such events are thus considered "early" and/or "fast" with respect

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HY-WIRE AND FAST ELECTRIC FIELD CHANGE MEASUREMENTS NEAR AN ISOLATED THUNDERSTORM

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ABSTRACT

Electric field measurements near an isolated thunderstorm at 6.4 km distance are presented from both a tethered balloon experiment called Hy-wire and also from ground based fast and slow electric field change systems. Simultaneous measurements were made of the electric fields during several lightning flashes at the beginning of the storm which the data clearly indicate were cloud-to-ground flashes. In addition to providing a comparison between the Hy-wire technique for measuring electric fields and more traditional methods, these data are interesting because the lightning flashes occurred prior to changes in the dc electric field, although Hy-wire measured changes in the dc field of up to 750 V/m in the direction opposite to the fair weather field a short time later. Also, the dc electric field was observed to decay back to its pre-flash value after each flash. The data suggest that Hy-wire was at the field reversal distance for this storm and suggest that charge realignment was taking place in the cloud with a time constant on the order of 20 seconds.