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A STUDY OF THE CHARACTERISTICS OF THUNDERSTORM CESSATION AT THE NASA KENNEDY SPACE CENTER

A Thesis

by

MICHAEL SHAWN HINSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1997

Major Subject: Meteorology

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Approved as to style and content by:

Richard E. Orville (Chair of Committee)	Michael I. Biggerstaff (Member)
Randall L. Eubank (Member)	Gerald R. North (Head of Department)

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Major Subject: Meteorology

ABSTRACT

A Study of the Characteristics of Thunderstorm Cessation at the NASA Kennedy Space Center.

(August 1997)

Michael Shawn Hinson, B.S., University of Arizona

Chair of Advisory Committee: Dr. Richard E. Orville

A lightning summary was developed for a 100x100 kilometer area centered at the NASA Kennedy Space Center. Spatial and temporal patterns, and first stroke peak currents were analyzed from 1986-1995. Three thunderstorms were chosen due to their proximity to the Kennedy Space Center (KSC) and examined for their end of storm characteristics. Radar echoes at the -10°C and -20°C temperature heights were associated with cloud-to-ground (CG) lightning strike locations from the National Lightning Detection Network. Electric fields were also examined during the same time frame for any correlations.

A pattern was observed for the spatial distribution of CG lightning. An inland maximum in ground flash density was observed during the summer months for both negative and positive flashes. The summer months had the lowest percentage positive flashes (2.5%) while the maximum value occurred during the winter (11.4%). Although thunderstorms can occur at any time during the day, the diurnal distribution of lightning flashes showed that the afternoon

(2000 UTC) was the time of maximum lightning activity.

From a time history of radar echoes, it was found that a 45 dBZ echo, last detected at the -10°C temperature height, may be a good indicator of the end of lightning activity. The observed lag times between this lightning termination signature and the end of all CG lightning flashes was 30 min for all three thunderstorms. Analysis of these storms using the 40 dBZ reflectivity level at the -10°C temperature height, as well as, both reflectivity levels (40-45 dBZ) at the -20°C temperature height did not yield as successful results.

The electric field mill analysis did not provide any conclusive results in identifying the end of CG lightning activity. However, electric fields did remain high even after the termination of all lightning flashes, indicating the high potential for triggered lightning.

DEDICATION

This thesis is dedicated to my beautiful wife Cathy and our two children, Andrea and Christopher. Their love, support, encouragement, and patience throughout this journey over the years have allowed me to reach this goal.

Most of all, I want to thank Cathy for being my wife and sharing her life with me these past years. Although I swore never to return to school, Cathy's love and understanding made it all possible.

ACKNOWLEDGMENTS

I would like to thank the members of my committee, Dr. Richard E. Orville, Dr. Michael I. Biggerstaff, and Dr. Randall L. Eubank for their guidance and support during my research. Special thanks go to Dr. Orville for opening his door to me before I ever arrived at Texas A&M University, his patience with my many questions, his suggestions in focusing my research, and his friendship.

I want also to thank several fellow graduates for their invaluable assistance and friendships. Specifically, I would like to thank Gary Huffines, whose IDL expertise was invaluable, and also Svetla Hristova-Veleva whose undying patience allowed me to partially understand the many facets of the RDSS program. Thanks also to the Orville group and the Biggerstaff group who helped me with my research on numerous occasions and prevented many hours of frustration.

I would like to express my gratitude to the United States Air Force in allowing me the opportunity to pursue my graduate degree and to all of the Air Force Institute of Technology students for their support and friendship.

Most importantly, I want to thank my family--My wife Cathy, my daughter Andrea, and my son Christopher--for their love, patience, and support during the period of my graduate work.

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CHAPTER I

INTRODUCTION

The NASA Kennedy Space Center (KSC) is located on the East Coast of central Florida where thunderstorm frequency is high and lightning poses a serious safety threat to space launches as well as many ground operations. Due to the limited number of space vehicles and their high cost, lightning protection of these assets is a top Air Force and NASA priority. This safety concern begins with the first strike of cloud-to-ground (CG) lightning and continues until the lightning threat has passed.

Most thunderstorms which occur in central Florida during the summer are airmass thunderstorms initiated by local heating and sea breeze convergence (Byers and Rodebush 1948). The synoptic conditions which tend to produce storms over the KSC complex and Merritt Island have been analyzed in detail by Neumann (1968). Most of these storms have similar conditions of moderate west-southwesterly flow up to the 500 mb level and lightning activity which ranges from three hours to less than one hour depending upon the size and organization of the storm.

Although the beginning of lightning activity is

This thesis follows the style and format of *Monthly Weather Review*.

important, knowing when it will end is also of great concern in order to avoid delays in sensitive ground operations. The analysis of CG lightning cessation in any thunderstorm has not received the research needed to understand the associated changes in microphysics or electric fields.

This research focuses on analyzing a 10-year lightning data base for the NASA Kennedy Space Center area and identifying any characteristics that are associated with the cessation of cloud-to-ground lightning. Characteristics of CG lightning to be examined are: ground flash density, percentage positive flashes, first stroke median peak current, and diurnal variations of peak occurrence. Several case studies, representing typical airmass thunderstorms which remain primarily over KSC during their lifecycle, are selected using these data. Each case study involves analyzing the radar reflectivities at two temperature levels, -10°C and -20°C, and at two levels of reflectivity, 40 and 45 dBZ, associated with the end of CG lightning. The changes in electric fields associated with the cessation of lightning in these storms are also examined. Conclusions and possible correlations between radar reflectivities, lightning analysis, and electric fields are presented along with proposals for future research.

CHAPTER II

BACKGROUND

The NASA Kennedy Space Center is located on the east coast of central Florida, midway between Jacksonville and Miami, at 28.61°N, 80.69°W. The complex area totals approximately 57000 hectares with an elevation ranging from sea level to 3 meters. The area analyzed in this study is centered on the three mile long Shuttle Landing Facility (SLF) and extends 50 km (27 nm) out in all directions. Figure 1 is a map of the region with this area of interest superimposed. The 100 km X 100 km box is based upon flight rules established by NASA for lightning criteria extending out to 30 nm used by KSC to provide a safety zone for launch and recovery of space vehicles.

Many studies (Neumann 1968, Jacobson and Krider 1976, Livingston and Krider 1978, Fuquay 1982, Orville et al. 1983, Orville 1994) have been conducted in the past 20 years to observe the characteristics of cloud-to-ground (CG) lightning. These studies have made use of lightning detectors such as magnetic direction finders (DFs) that have been operating in the United States since the early 1980s (Krider et al. 1980; Orville et al. 1983). In 1987, the three lightning networks in operation in the United States: the Bureau of Land Management (BLM) network in the

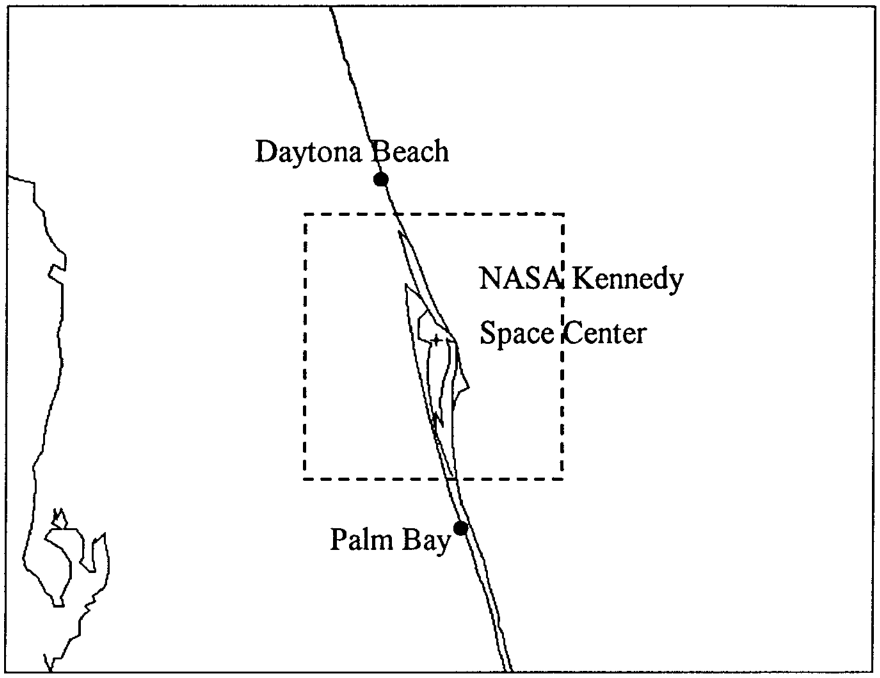

Fig. 1. Map of NASA Kennedy Space Center and surrounding area. Dashed box denotes region of study, where crosshair identifies the location of the Shuttle Landing Facility.

western United States, the National Severe Storms Laboratory (NSSL) network in the central Great Plains, and the State University of New York at Albany (SUNYA) network along the eastern edge of the nation, combined to form the National Lightning Detection Network (NLDN). By 1989, complete coverage extended across the continental United States. Currently the NLDN has a network of approximately 100 sensors with both DFs and time-of-arrival (TOA) capability. Since the use of lightning detection networks are still relatively new, the main purpose of these studies has been to develop data bases and numerical averages of various flash characteristics including; ground flash density, percentage of positive flashes, first stroke mean peak current, and diurnal variations.

Prior research has been conducted relating radar reflectivities to temperature heights for lightning initiation (Buechler and Goodman 1990; Michimoto 1991). However, these studies have concentrated on the initiation of lightning activity and did not analyze end of a thunderstorm. Analysis of the electric fields associated with lightning activity has been conducted in the KSC area, although comparing these with radar echos is relatively new. Section one reviews past studies analyzing lightning characteristics. The second section reviews studies on the relationship between radar reflectivities and temperature heights. The third section reviews studies concerning the electric fields associated with cloud-to-ground lightning activity.

1. Lightning Studies

a. Ground Flash Density

Orville (1991, 1994, also Orville and Silver 1997) determined the annual ground flash densities for the contiguous United States for 1989 and 1989-1991 respectively. They report maximum values for each year are found over central Florida, with values of 10 flashes km^{-2} for 1989, 11 flashes km^{-2} for 1990, and 13 flashes km^{-2} for 1991. As expected, June through August was observed to be the most active for lightning activity in the continental United States.

Silver and Orville (1995) analyzed monthly ground flash densities for the contiguous United States for 1992 and 1993. They observe the highest ground flash densities during the summer of 1992 (August) in Florida and during the summer of 1993 (July) to be in the Midwest. Lowest monthly ground flash densities are observed along the Gulf coast during December with maximum values on the order of 0.045 km^{-2}. Silver (1995) conducted a five year (1989-1994) CG lightning study of the continental United States. He observed highest flash density values in Florida for the majority of the year with maximum values in June (2.23 km^{-2}), July (>2.9 km^{-2}), August (2.76 km^{-2}), and September

(1.45 km^{-2}).

Since these studies are based on the entire United States, the minimum grid resolution utilized (73 km X 68 km) may be too large to resolve smaller scale variations in ground flash densities. For the summer months of Silver's (1995) study, Florida is in a broad flash density contour of 2.9-10 flashes km^{-2}.

b. Percentage Positive Lightning

A ground flash that has a negative electric field change and lowers positive charge to ground is defined as a positive flash. The number of positive flashes divided by the total number of CG flashes (positive and negative) is termed the percentage of positive lightning. Studies have shown that flashes lowering positive charge to ground constitute only a few percent of the total CG flashes. Fuquay (1982) found an average of 3.0% positive CG flashes over three summer seasons (1965-1967) in the mountainous terrain of the northern Rocky Mountains. This is consistent with present findings. Reap and MacGorman (1989) estimated that about 4.0% of all warm-season CG flashes in the entire United States are of positive polarity. Monthly percentage positive values for 1992 and 1993 have been observed for the United States (Silver and Orville 1995). Minimum values are found in the summer with a monthly minimum observed in August of 3.0% (1992) and 3.2% (1993). Maximum values were found in December with a value of 21.5% for 1992 and 24.5% for 1993.

The variation of positive flashes has been observed as a function of the seasons. The increase of positive lightning flashes in winter thunderstorms was first reported by Takeuti et al. (1973) and studied further by Takeuti et al. (1978) and Brook et al. (1982). The low percentage of positive flashes in summer thunderstorms has been summarized by Beasley (1985) and is shown to range from 4.0% to 13.0%.

Positive lightning has been observed to occur in the downshear anvil of a thunderstorm by Rust et al. (1981). This has been termed the tilted dipole structure, where the positive charge (located toward the top of thunderstorms) is displaced downshear of the convective core. Brook et al. (1982) found that a "strong" correlation exists between the fraction of positive ground strokes and vertical wind shear in the cloud layer. Their data suggest that a positive flash should appear at a threshold shear value in the cloud layer of about 1.5 m s^{-1} km^{-1}. Similar results are observed by Rust et al. (1981), Brook et al. (1982), Takagi et al. (1986), Orville et al. (1988), Hill (1988), Engholm et al. (1990), and Stolzenburg (1990).

c. Peak Current

Another characteristic of CG lightning flashes is peak current. Variances and seasonal trends of this characteristic are observed in both positive and negative lightning flashes. Researchers have measured peak current for both positive and negative flashes for over 20 years.

Orville et al. (1987) observed median first-stroke peak currents. They observe that the peak signal strength of positive flashes is 50% higher than that of negative flashes. They also find that monthly values for both positive and negative peak currents in the United States are highest in winter, lowest in summer. Hojo et al. (1989) observe that for positive first-return strokes, the signal strength was larger in the winter. For negative first-return strokes, little difference is observed between median peak currents from summer to winter. Silver and Orville (1995) noticed the highest positive median peak currents in January 1992 (69 kA) and in December and January 1993 (68 kA). Highest negative values are seen in January 1992 and 1993 of 44 kA and 46 kA respectively. These values decrease in the summer months. The lowest positive median peak currents are observed in September 1992 at 32 kA and in July and August 1993 at 33 kA. Negative median peak currents did not decrease as much as the positive flashes with a minimum in May, June, and August 1992, and in May and June 1993 at 29 kA and 28 kA respectively.

d. Diurnal Cycle

Studying the diurnal cycle of lightning is important for determining preferred times of thunderstorm activity in a given geographic region. Many studies have discussed the diurnal variability of lightning at various locations.

Lopez and Holle (1986) analyzed the diurnal variability of lightning in central Florida during the summer of 1983. They report the largest number of flashes occurred between 1900 and 2000 UTC (14%), and the minimum occurred between 1400 and 1500 UTC. This agrees with climatological studies which show that the maximum in lightning activity at KSC occurs from May through September, with a superimposed diurnal maximum from 1700 to 0000 UTC. Maier et al. (1984) analyzed the diurnal variability of lightning at KSC and the Cape Canaveral Air Force Station (CCAFS) during the summers of 1976-78 and 1980. They observed a peak in lightning activity between the hours of 2000 and 2100 UTC. This is in good agreement with Neumann (1968) who observed from 13 years of thunder data (1951, 1952, 1955-67), that the probability of having at least one thunderstorm in progress in the Cape Canaveral area peaks between 2000 and 2200 UTC in the months of June through August.

2. Radar Studies

The relationship between radar reflectivity and CG lightning has been the focus of several studies. Takahashi (1984) carried out a numerical simulation of thunderclouds and pointed out that graupel particles between the -20 and

-10°C temperature levels were responsible for the main charge separation process. Further, the charge separation process around the -10°C temperature level played the most important role in the electrical activity of the clouds.

Buechler and Goodman (1990) looked at 15 storms and concluded that lightning was imminent when radar reflectivity values of 40 dBZ reached the -10°C temperature height and echo tops exceeded 9 km. Michimoto (1991) in analyzing multi-cell thunderstorms in the Hokuriku District of Japan, showed that the first lightning discharge occurred 5 min after 30 dBZ reached the -20°C temperature height, and the peak in lightning activity occurred as strong echoes at the -10°C temperature level descended. He found that in both summer and winter, the peak of lightning activity is observed when several strong echoes of 45 or 50 dBZ are formed at the -10°C temperature level and descend toward the 0°C temperature level.

Hondl and Eilts (1994) analyzed 28 thunderstorms from August 1990 in the central Florida environment using Doppler weather radars. These radar echoes were associated with CG lightning strike locations. By analyzing a time history of these echoes it was found that a 10 dBZ echo, first detected near the freezing level, may be the first definitive echo of a future thunderstorm. The observed lead times between this thunderstorm initiation signature and the first detected CG lightning strike ranged from 5 to 45 min with a median lead time of 15 min.

3. Electric Field Studies

Electric field mills, installed at the NASA Kennedy Space Center, measure the vertical electric field of the atmosphere at ground level. KSC currently operates a large network of electric field mills to detect lightning and electrified clouds. A description of the sensors and maps of their locations have been given previously by Jacobson and Krider (1976), and Maier and Krider (1986).

Livingston and Krider (1978) analyzed electric fields produced by airmass thunderstorms during the summers of 1975 and 1976 in the KSC area. They noticed that Florida thunderstorms produce electric fields at the ground typically between -8 and +6 kV m^{-1} and that these fields are highly variable in both magnitude and polarity. They observed time-averaged and area-averaged fields produced by individual storms are typically -0.8 to -2.1 kV m^{-1} during periods of intense lightning activity and usually 2-4 times larger (-2.3 to -4.3 kV m^{-1}) in the final, less active storm periods. In general, the structures of the electric fields produced by lightning discharges in Florida were found to be similar to those in other geographical areas. Following active lightning periods, large storms usually produce electric fields which undulate rather slowly between large positive and negative values and a low rate of cloud-to-ground lightning discharges. This final slowly varying portion of large storms has been referred to as the end-of-storm oscillation (EOSO) (Moore and Vonnegut 1977).

CHAPTER III

DATA AND METHODS OF ANALYSIS

Cloud-to-ground lightning data for this study were collected by the National Lightning Detection Network (NLDN), operated by GeoMet Data Services, Inc. WSR-88D radar data for the case studies were obtained from the National Climatic Data Center, Asheville, North Carolina. Electric field mill data were compiled and obtained from the 45th Weather Squadron, Patrick Air Force Base, Cocoa Beach, Florida.

1. Lightning Data

The NLDN was originally composed of three distinct networks. The Eastern United States was covered by a network operated by the State University of New York at Albany (SUNYA). In 1989 the three networks were combined into a single network which monitors the contiguous United States. The NASA Kennedy Space Center has had complete, uninterrupted network coverage since 1986. The NLDN system uses a network of over 100 ground based sensors consisting of direction finders (DFs) and time-of-arrival (TOA) sensors. The DFs detect electromagnetic signals produced by lightning discharges as well as having a nominal range of 400 km and a detection efficiency of approximately 70% (Mach et al. 1986; Orville et al. 1988). Location errors of lightning flashes detected by the network until 1994 are 5-10 km (Mach et al. 1986; Orville et al. 1994). The TOA was integrated into the NLDN in 1994. This integration is thought to reduce the location errors to 1 km or less (Cummins et al. 1995). The lightning data from each instrument is transmitted to the Network Control Center in Tucson, Arizona, where it is processed to record time, location, polarity, peak current, and multiplicity of every CG lightning flash it detects. These data are encoded in binary form and disseminated to NLDN subscribers in near real-time.

All CG lightning flashes analyzed in this lightning study were detected by the NLDN within the box, 28.16-29.06°N, 80.18-81.2°W, around KSC for the period 1986-1995 (refer to Figure 1). Over 745 000 total flashes for the ten-year period were broken down by month. Data were grouped into ten-year monthly data sets so as to establish monthly climatologies.

The NLDN archived data were analyzed with the FLASH lightning analysis software. This DOS-based program can be used to produce histograms, scatter plots, time series, and contours of flash counts (ground flash density), peak currents, polarity, multiplicity, and other parameters of detected CG flashes.

The ground flash density (GFD) was determined in an attempt to establish preferred months and locations of lightning flash activity. The GFD is the number of lightning flashes to ground per square kilometer. Grid resolution for the area of study was 1.7 by 2.0 km. Gridded data were scaled by a factor of .14 to account for the assumed 70% detection efficiency of the network and 10-years of data. The data were then mapped for selected time periods and contoured to produce maps of GFD. For average ground flash densities, the scaled total number values of each time period (months) were divided by the number of years in the data set.

Ground flash density maps were made for positive lightning flashes. Because the number of positive flashes was much smaller than the total number of flashes, contour values were much less than those for the total flashes as well. These maps of ground flash density help describe both spatial and monthly variabilities.

Histograms of monthly flash rates, positive CG flashes, mean peak currents, and number of flashes versus day (diurnal changes) are also created for the 10-year study. The monthly flash rates were totaled for the entire period (1986-1995) to indicate the months of highest CG lightning activity. The positive CG flashes were totaled for each month and compared to the total flashes to give percentages of positive lightning. First stroke mean peak current was measured for both positive and negative polarity flashes to analyze monthly variations. The number of flashes versus day (from 0000 UTC to 0000 UTC) was plotted to determine the diurnal nature of the cloud-to-ground lightning over the Kennedy Space Center.

This lightning study was used to analyze some of the basic characteristics of the CG lightning associated with KSC. From these data, several days were selected during months of greatest lightning activity for case studies.

2. Radar Data

The WSR-88D (Weather Surveillance Radar 1988 Doppler) is the new primary network of operational Doppler weather radars that the National Weather Service (NWS) has deployed throughout the contiguous United States. The WSR-88D base data (level II) is continuously collected by the individual sites and archived at the National Climatic Data Center (NCDC). The Doppler radar data used in this study were collected by the Melbourne NWS located in Melbourne, Florida. The Melbourne radar site is approximately 19 km south of the Kennedy Space Center.

In order to use these data, the Sorted Position Radar Interpolation (SPRINT) software (Mohr et al. 1979) was used to interpolate the reflectivity into a common Cartesian grid using a grid spacing of 1 km in the horizontal and 0.5 km in the vertical direction. The next step in the analysis of the data was to use the Cartesian Editing and Display of Radar Data under Interactive Control (CEDRIC) software (Mohr et al. 1986). This program is an interactive program designed for the editing, manipulation, and display of Cartesian-space data fields. CEDRIC was used to analyze the radar reflectivities at each grid point of the scan and prepare the data for GEMPAK conversion. GEMPAK (GEneral Meteorology PAcKage) software (desJardins et al. 1991) is a suite of applications programs for the analysis, display and diagnosis of geo-referenced data. This software was used to convert these data into GEMPAK images to overlay with CG lightning in order to analyze lightning cessation at various radar reflectivities and height levels.

Three case studies were selected based upon the storm cells beginning and ending within the KSC area. The radar and lightning GEMPAK images were analyzed during the lightning cessation at various temperature levels and radar reflectivities. Several studies have analyzed the initiation of lightning activity using radar reflectivities and temperature heights. Buechler and Goodman (1990) found the -10°C height level and a radar reflectivity of 40 dBZ to be an indicator of lightning initiation. Michimoto (1991) analyzed lightning initiation at the -20°C height level and observed a radar reflectivity of 30 dBZ showed the best correlation in detecting the beginning of CG lightning activity. This study analyzed both the -20°C and -10°C height levels using radar reflectivity's of 40 and 45 dBZ.

3. Electric Field Mill Data

The NASA Kennedy Space Center and the Cape Canaveral Air Force Station currently operate a large network of ground-based electric field mills to identify lightning and electrified clouds. These sensors measure the vertical electric field at ground at 34 sites. Figure 2 shows the layout of the field mill network. This field mill data is recorded and archived as a potential gradient value, i.e., a positive charge overhead is recorded as a positive value.

The electric field sensors and the data acquisition system at KSC have been described previously by Jacobson and Krider (1976). Each field mill, has a response time of about 0.1 s. Electric fields between +15 and -15 kV m^{-1} are digitized and recorded at a rate of 50 samples per second with a digitization accuracy of about 30 V m^{-1} (Livingston and Krider 1978). The instruments are calibrated and maintained by KSC personnel, and after allowance is made for a small nonlinearity correction, most field values are estimated to be accurate to within 10%. The data used in this study are one minute averages, every 5 minutes, due to archive problems during the time periods of the case studies.

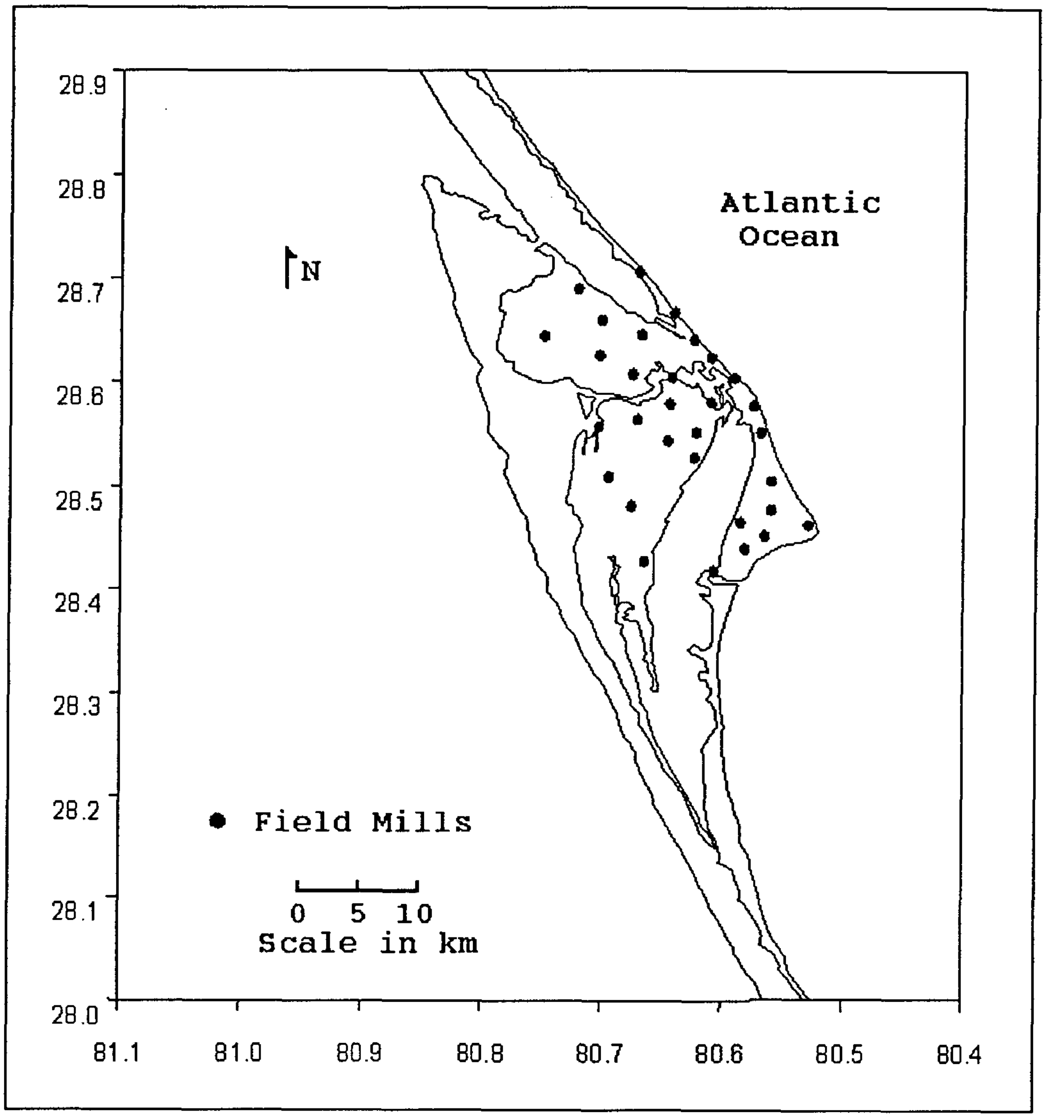

Fig. 2. The locations of the electric field measuring sites at the NASA Kennedy Space Center, Florida.

These data were analyzed using an Interactive Data Language (IDL) program created to contour the values in both surface and 3D images (see appendix). This program ingests the data for every 5 minute span which the user identifies, contours the data and then allows the user to save these images. The contours of the electric fields were then compared to the overlays of radar and lightning images for any correlations, as well as, analyzed for any similarities between storms.

CHAPTER IV

RESULTS

1. Lightning Studies

a. Spatial Distribution and Variability

The number of CG lightning strikes in a given area is referred to as the ground flash density (GFD). Monthly averages of the 1986-1995 data set were created for an "average" year (Figs. 3a,3b,3c). In July (Fig. 3b), highest values (>4.3 km^{-2}) were found in pockets inland and to the west-northwest of KSC. Lower values (>2.5 km^{-2}) extended throughout the remainder of inland areas. A broad maximum existed along the coast and extended inland. There is a distinct offshore minimum that appears in May and is dominant until August (Fig. 3b). Secondary maximas were seen in June and August (Fig. 3b) of >2.5 km^{-2}.

The spatial distribution of ground flash density varied from month to month, with the largest variation between summer and winter months. From May to September (Figs. 3b, 3c), the ground flash densities are respectively higher (>0.54 km^{-2}) than the other months (<0.54 km^{-2}). Lowest CG monthly densities occurred in the winter months of December and January (Figs. 3a, 3c) with maximum values on the order of 0.16 km^{-2}. These lower values were common

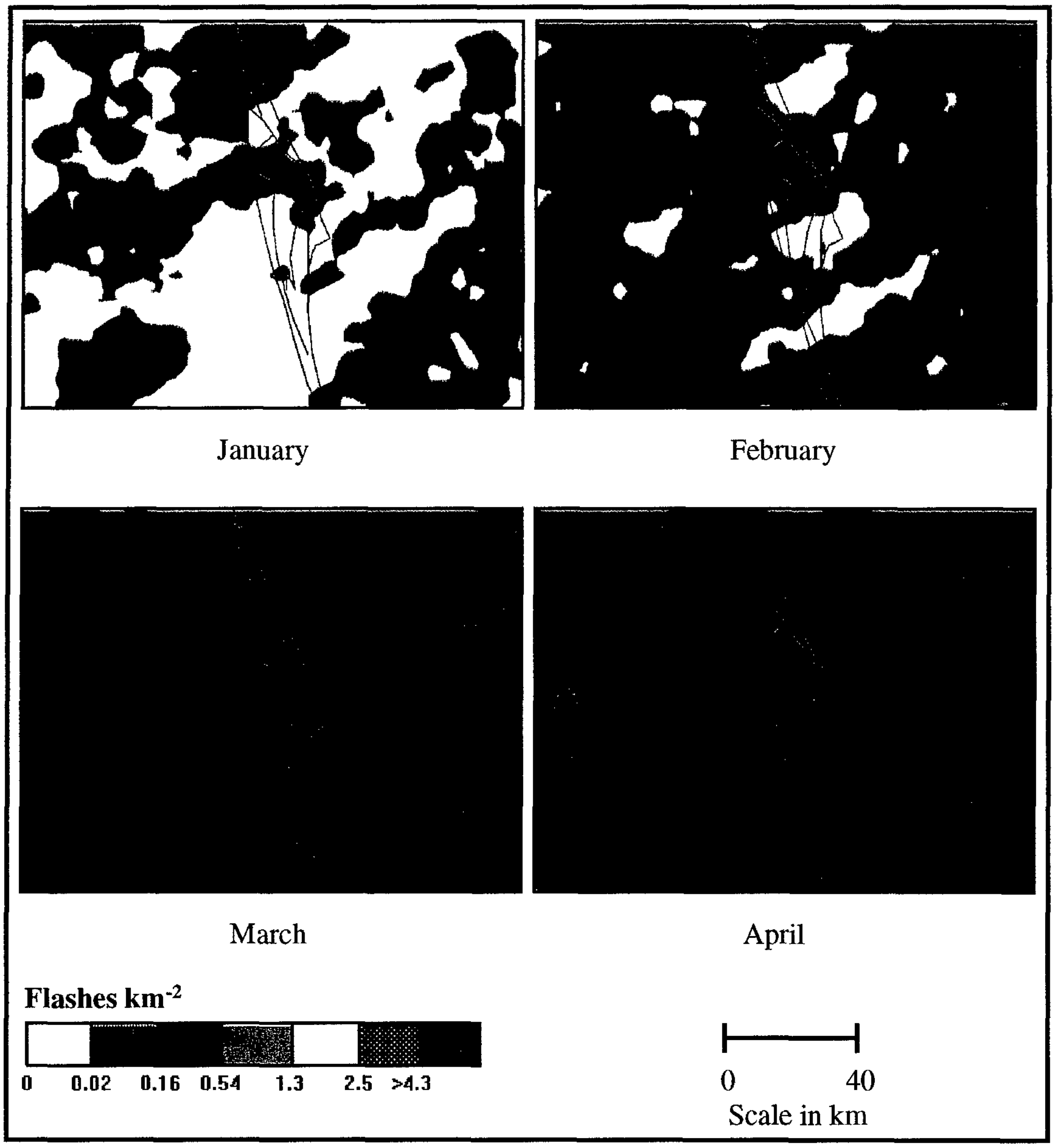

Fig. 3a. Ground flash density contours for the mean 1986-1995 data set. Shown here are January through April.

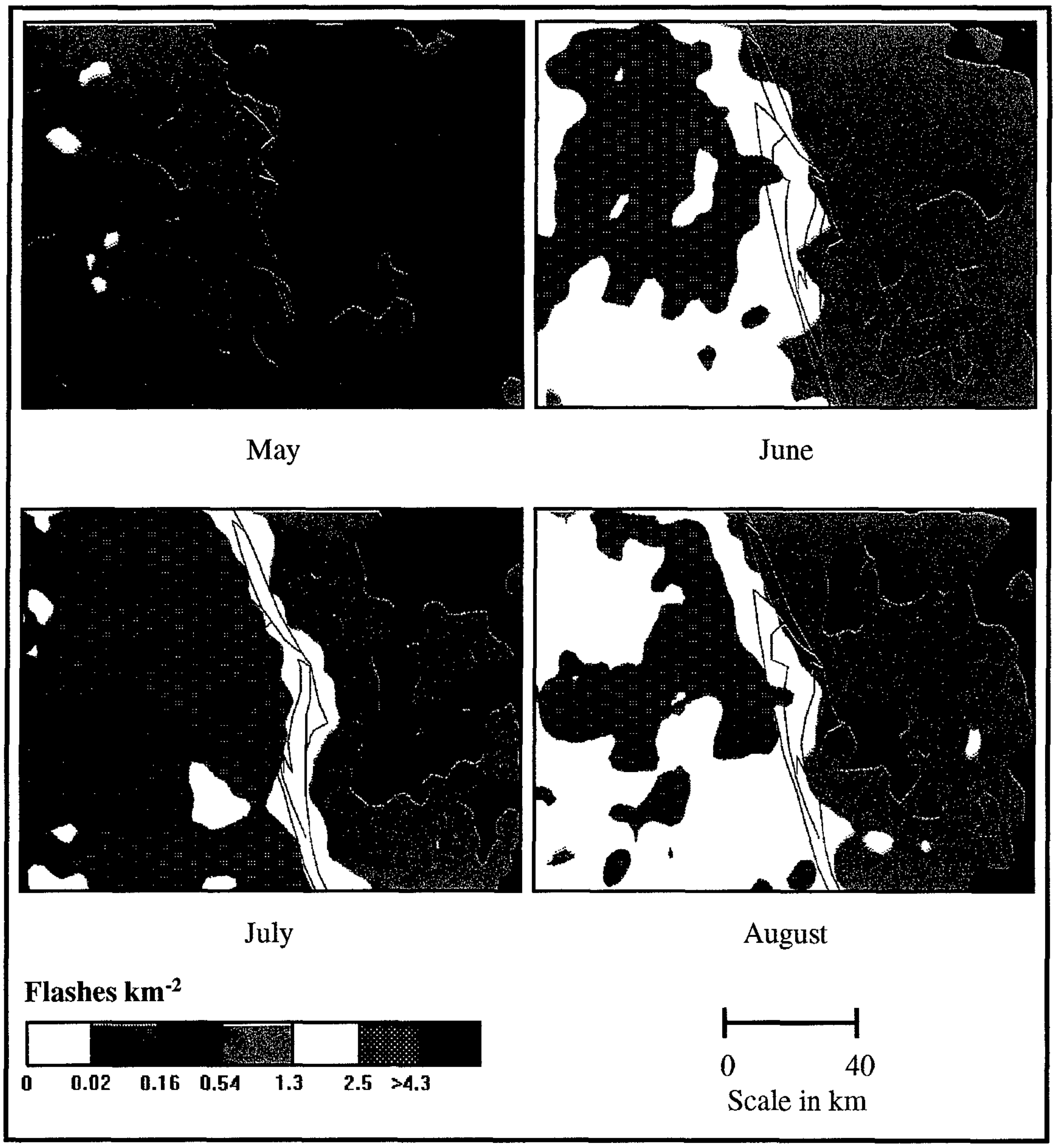

Fig. 3b. Same as Fig. 3a, except for May through August.

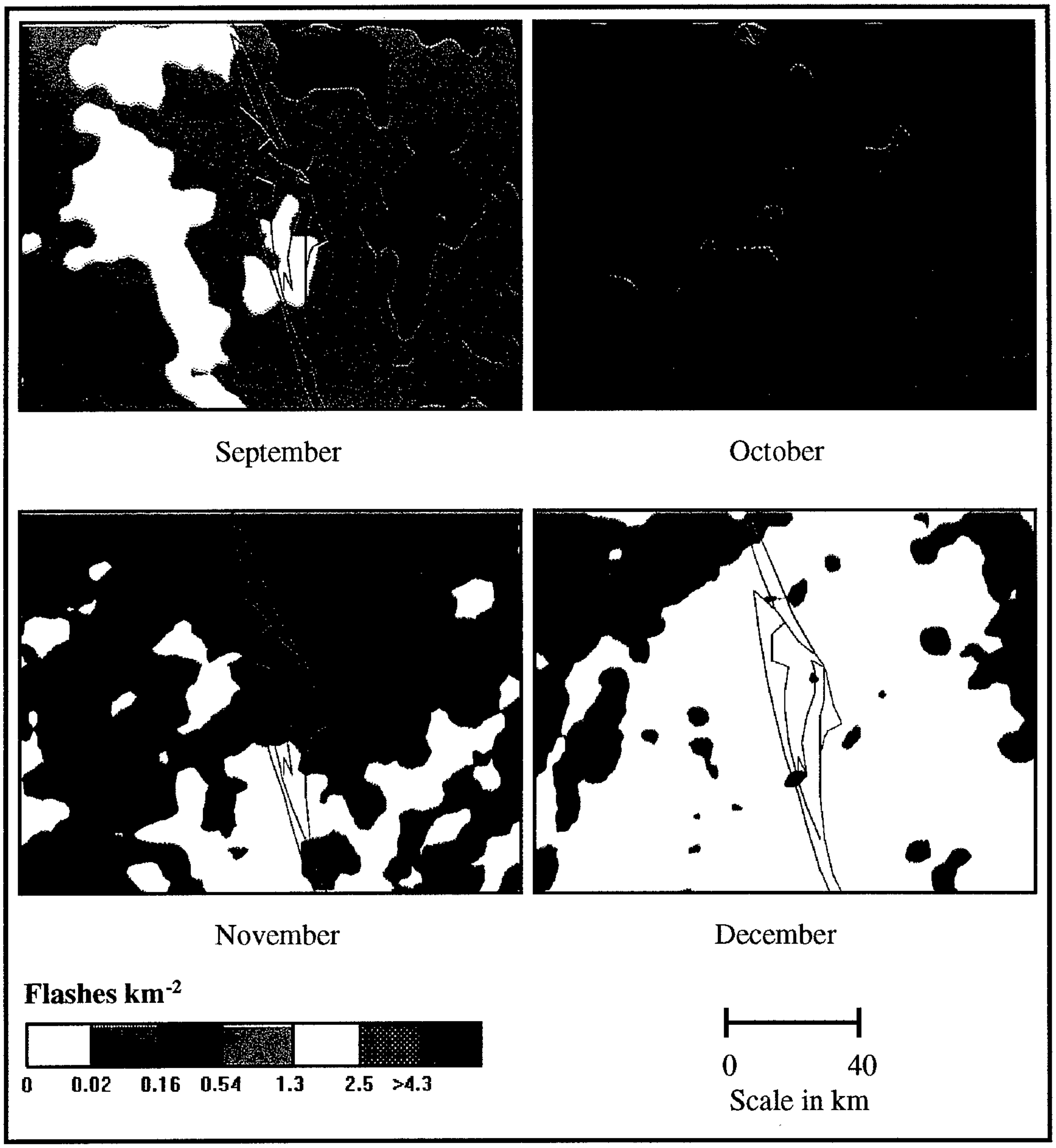

Fig. 3c. Same as Fig. 3a, except for September through December.

throughout the winter months of November through February (Figs. 3a,3c). January and December have the least lightning activity with the average ground flash densities of <0.02 flashes km^{-2}. The transitional months (March, April, and October) have lower maximums (<1.3 km^{-2}) and indicate a slight flash density variation between water and land. The ten year average clearly showed a maximum over land and a minimum over the water for the summer months, while the winter months did not favor either the land or water.

The spatial distributions of the positive ground flash densities were similar to the ground flash density fields Figs. 4a,4b,4c). Minimum flash densities are seen in January and December (Figs. 4a,4c) where the primary values are <0.03 flashes km^{-2}. These predominantly lower values are also observed in February and November. Maximum values of positive flash densities (>1.1 km^{-2}) were seen in June, July, and August (Fig. 4b). These maximums were similar to the ground flash density fields although the areas of maximum density were smaller. These regions of greatest positive flash densities tended to migrate from the northwest to the southwest of KSC from June through August, which did not correspond to the ground flash density fields for the same months. Positive flash densities clearly favored the land over water from April through September which closely followed the ground flash density fields.

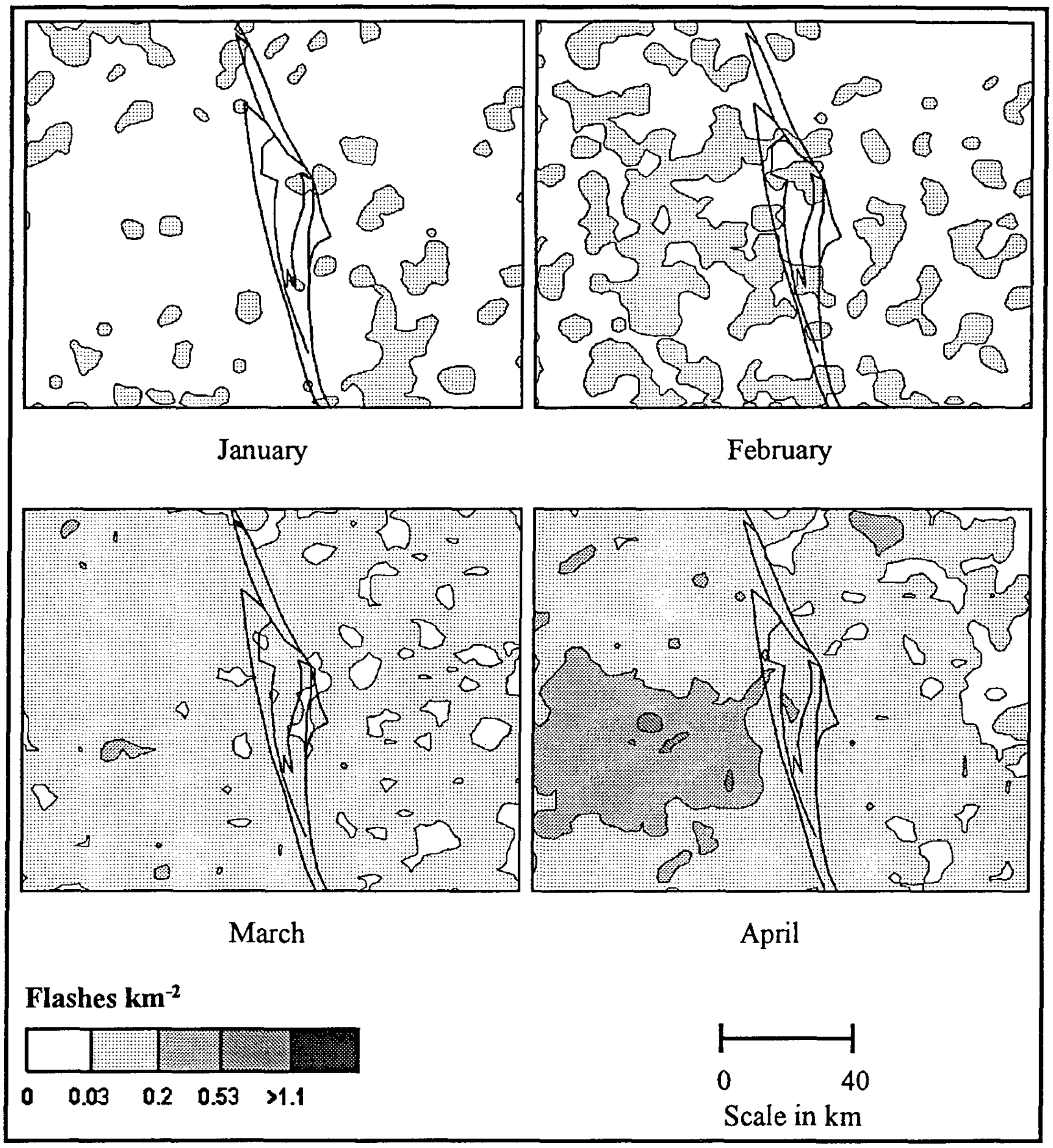

Fig. 4a. Positive ground flash density contours for the mean 1986-1995 data set. Shown here are January through April.

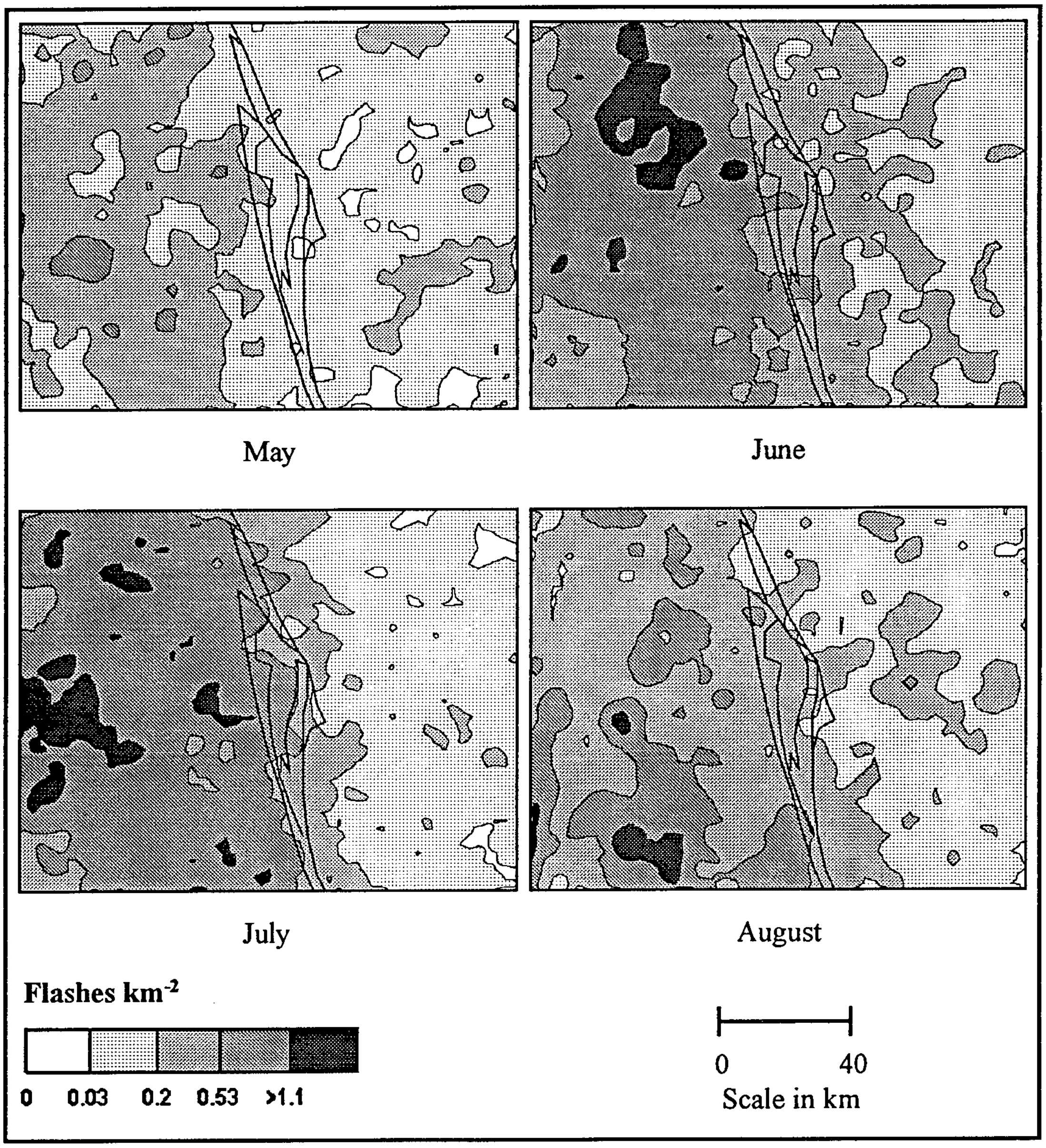

Fig. 4b. Same as Fig. 4a, but for May through August.

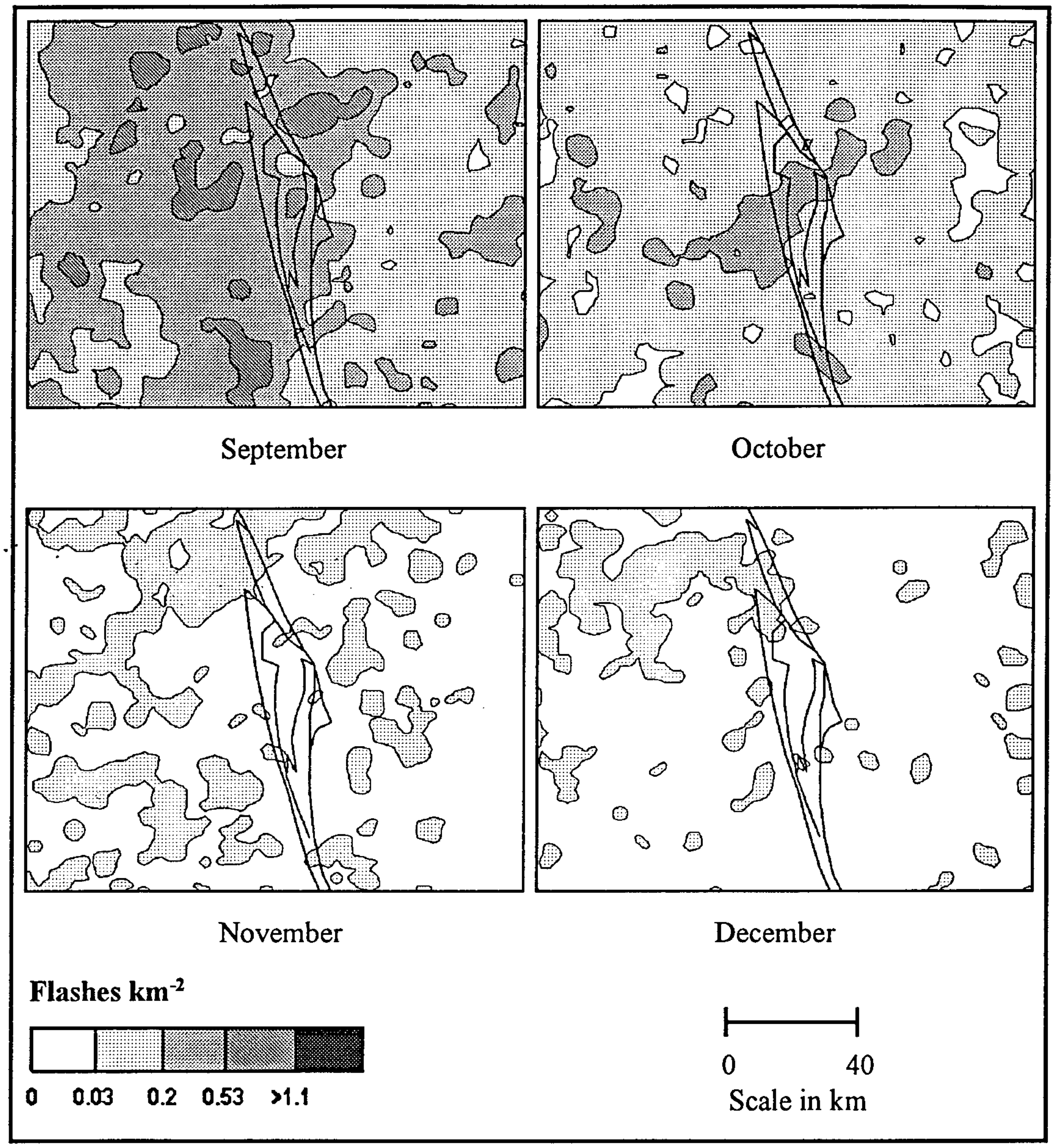

Fig. 4c. Same as Fig. 4a, except for September through December.

Again, the winter months showed no preferred location for maximum positive flash densities.

b. Temporal Distribution and Variability

The distribution and variability of CG lightning flashes can be described on a temporal scale as well as a spatial scale. As has been previously observed (Neumann 1968, Reap and MacGorman 1989, Orville 1994), the vast majority of lightning activity occurs during the summer months, especially July and August. Figure 5 shows the variation of lighting activity over KSC from 1986-1995. The overall frequency of CG flashes slowly increased from January to April, followed by a rapid increase in May through June, to the maximum number of flashes in July. The lightning activity then decreased slightly in August, dropping off rapidly from September until it reached a yearly minimum in December. This pattern generally held true for individual years, although some variability was evident. The months of highest CG activity, June through August, constituted for over 73% of all CG flashes occurring throughout the year.

Although the majority of CG lightning flashes that occur in the United States are of negative polarity, positive lightning flashes are also significant. Positive polarity CG lightning flashes were compared to the overall number of CG lightning flashes to determine the percentage of lightning flashes of positive polarity. Figure 6 shows

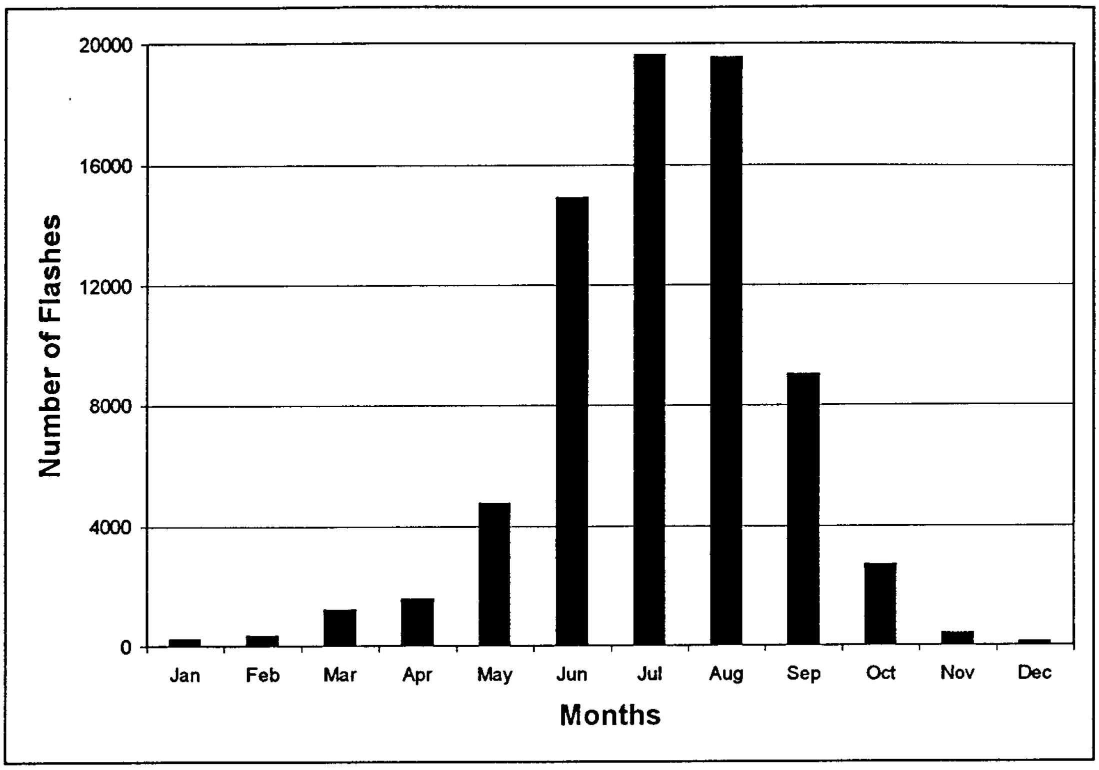

Fig. 5. Total monthly flash rates for KSC, from 1986-1995.

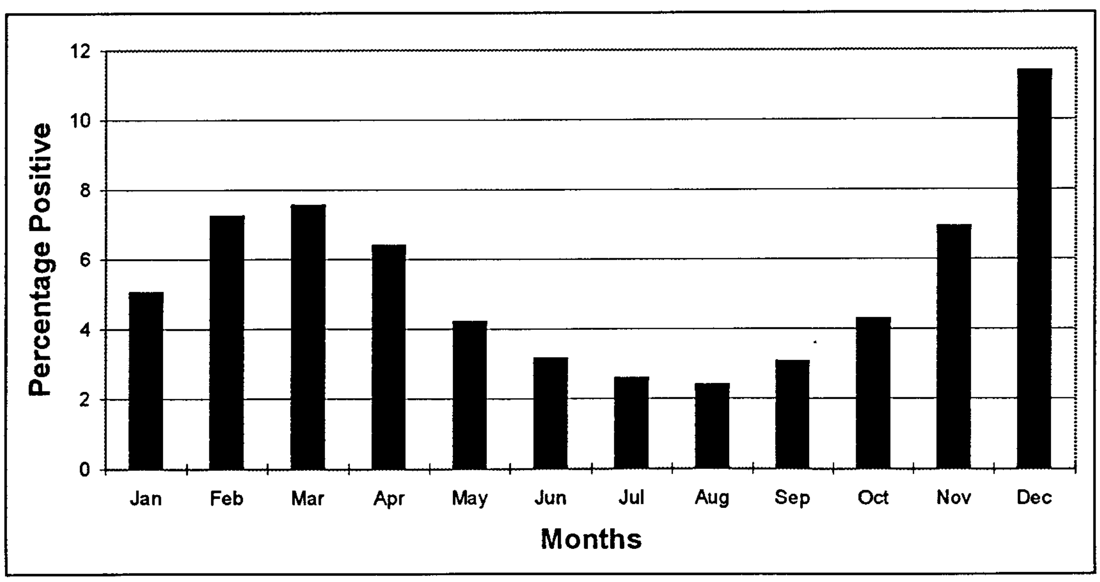

Fig. 6. Average monthly percentage positive cloud-to-ground lightning flashes for the entire period, 1986 through 1995.

the monthly average of percentage positive lightning for the 10-year period. December had the highest percentage of positive lightning, but had the fewest flashes overall. Percentages dropped to around 5% for January and then peaked again in March with values of 7.5%. Although this peak was observed in the spring, the average number of CG flashes were still small compared to the summer months. The lowest values were found in the summer (2.5% in August), coinciding with one of the largest flash rates for any month.

Comparison of the monthly percentage positive values is in good agreement with Silver's (1995) analysis, despite overall lower values for the KSC area. This difference can be attributed to the fact that Silver's study includes the contiguous United States. His wintertime averages were heavily influenced by flashes recorded in the South, especially Florida, where the percentage of positive lightning is low as compared to the rest of the United States (Orville 1994).

Just as the monthly distribution of lightning showed a high degree of variability, the diurnal distribution of cloud-to-ground lightning showed a high degree of predictability. Figure 7 shows the total number of negative lightning flashes versus time of day for the period 1986 through 1995. Although lightning flashes were likely at any time during the day, a distinct minimum of CG

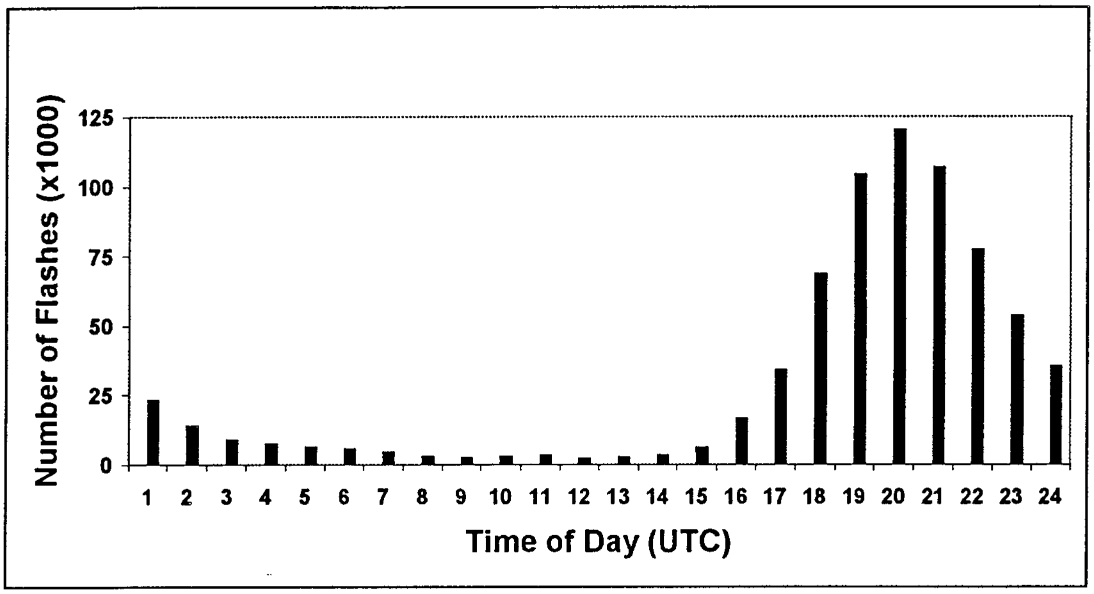

Fig. 7. Number of negative CG lightning flashes versus time of day for the period 1986 through 1995. Subtract 4 hours for Eastern Standard Time. Maximum activity is observed in late afternoon, while minimum activity is seen during the morning hours.

lightning was observed from 0800-1400 UTC. Starting at 1600 UTC there was a sharp rise in the lightning activity culminating in a distinct diurnal maximum at 2000 UTC. Similarly, there was a steep decline in activity from 2100 UTC until 0300 UTC. This timeframe of maximum lightning activity agrees quite well with Neumann (1968) who observed a peak in the KSC area between 2000 and 2200 UTC. This timeframe would correspond to a 1-2 hour lag time from maximum heating over land and development of a sea breeze convergence zone.

Not suprisingly, positive lightning flashes had a similar diurnal pattern (Fig. 8). Although the overall number of flashes were smaller, a peak in the activity was seen at 2000 UTC, the same as the negative lightning flashes. Minimum activity occurred from 0900 UTC through 1100 UTC. No striking differences were observed in diurnal activity when comparing the negative and positive CG lightning flashes.

c. First Stroke Peak Currents

The first stroke peak current was measured by dividing all lightning flashes detected by the NLDN, within the area of interest, into positive and negative polarity flashes. Both sets of flashes were then broken down into an 'average' month for the 10-year data set.

The monthly first stroke mean peak current for

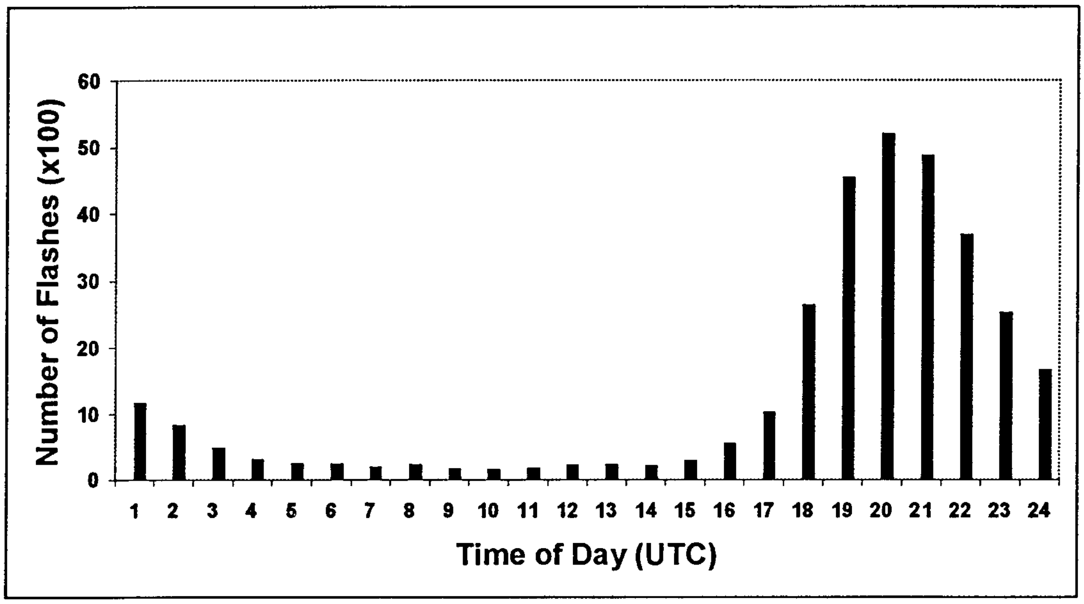

Fig. 8. Same as Fig. 7, except for positive CG lightning flashes.

negative flashes during the period 1986 through 1995 is shown in figure 9. The annual maximum peak was observed in January at 48 kA and a secondary peak in November (45 kA). The spring months of April and May showed the lowest mean peak currents of 34 kA and 33 kA, respectively. Overall, the mean peak current ranged from 33 kA to 48 kA throughout the 'average' year.

Maximum monthly positive peak currents are seen in January at 61 kA (Fig. 10). Mean peak currents slowly decreased through March (54 kA) and then dropped down quite rapidly in May (25 kA). The summer months remained fairly constant, with the annual minimum occurring in July at 24 kA. The peak currents continue to remain constant until October which begins to increase and continues to climb until January when the peak current jumps sharply upward. The range of values for positive mean peak currents (24 to 61 kA) were greater than those for the negative mean peak currents.

Comparisons between negative and positive mean peak currents reveal maximums in winter (January) and minimums in summer months. The positive peak currents have larger values during the winter months, where a few high current positive flashes can have a greater influence on the mean, since the total number of flashes are less. The positive currents also seem to lag the negative values during the spring and summer months, as reflected by minimum peak

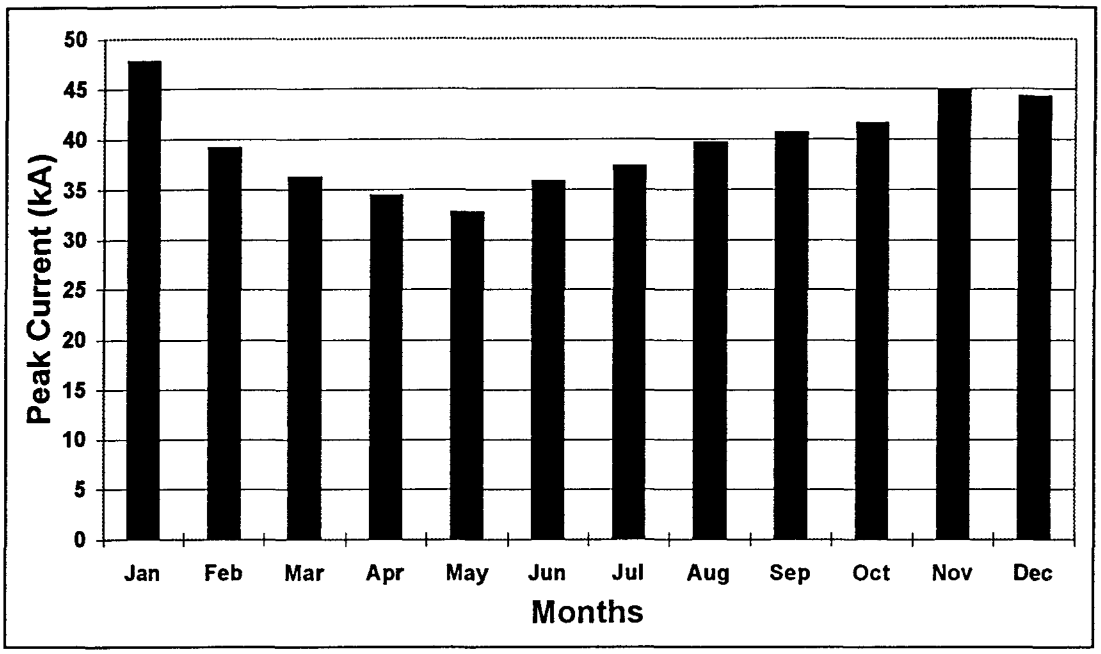

Fig. 9. Monthly first stroke mean peak current (in kA) for negative flashes during the period 1986 through 1995.

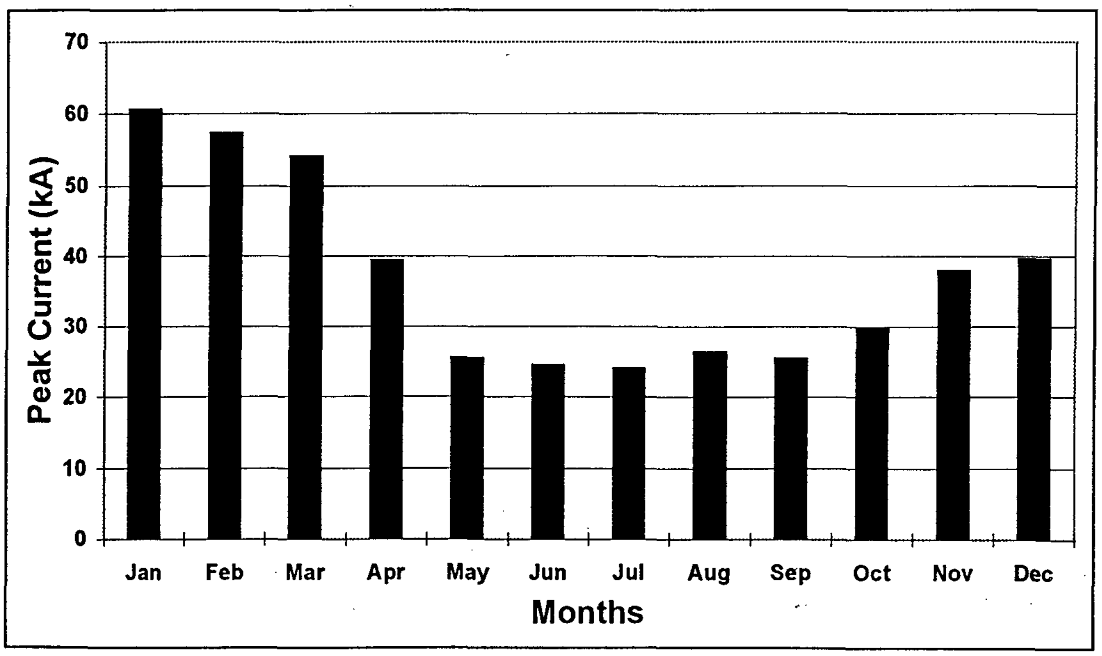

Fig. 10. Same as Fig. 9, but for positive flashes during the period 1986 through 1995.

currents, seen in July and May, respectively. This may be due to the overall number of positive flashes remaining fairly constant until April and May (Fig. 4a), where the numbers increase and result in lower mean peak currents.

2. Radar Analysis

Three cases were selected based upon their developing thunderstorms that were initiated and dissipated within the area of interest for KSC. These storms were analyzed for both the -20°C (7500 m) and -10°C (6000 m) temperature height levels for radar and then overlaid with NLDN lightning flashes. The radar overlays for the particular temperature height are an average value for that height compiled by the CEDRIC program from all 9 elevation angles (.5°-19.5°).

a. Analysis of 26 June 1996

The 26 June 1996 case is a typical example of an air mass thunderstorm, which occurs on a frequent basis within the area of interest for KSC. At the -20°C (7500 m) temperature level, a cutoff of 45 dBZ reflectivity level was used to signify the dissipation of lightning within the storm cell. The last indication of this 45 dBZ reflectivity level was observed at 1951 UTC (Fig. 11a). As this thunderstorm dissipates (Figs. 11,12,13), lightning can be seen until 2030 UTC (Fig. 13i), where lightning had

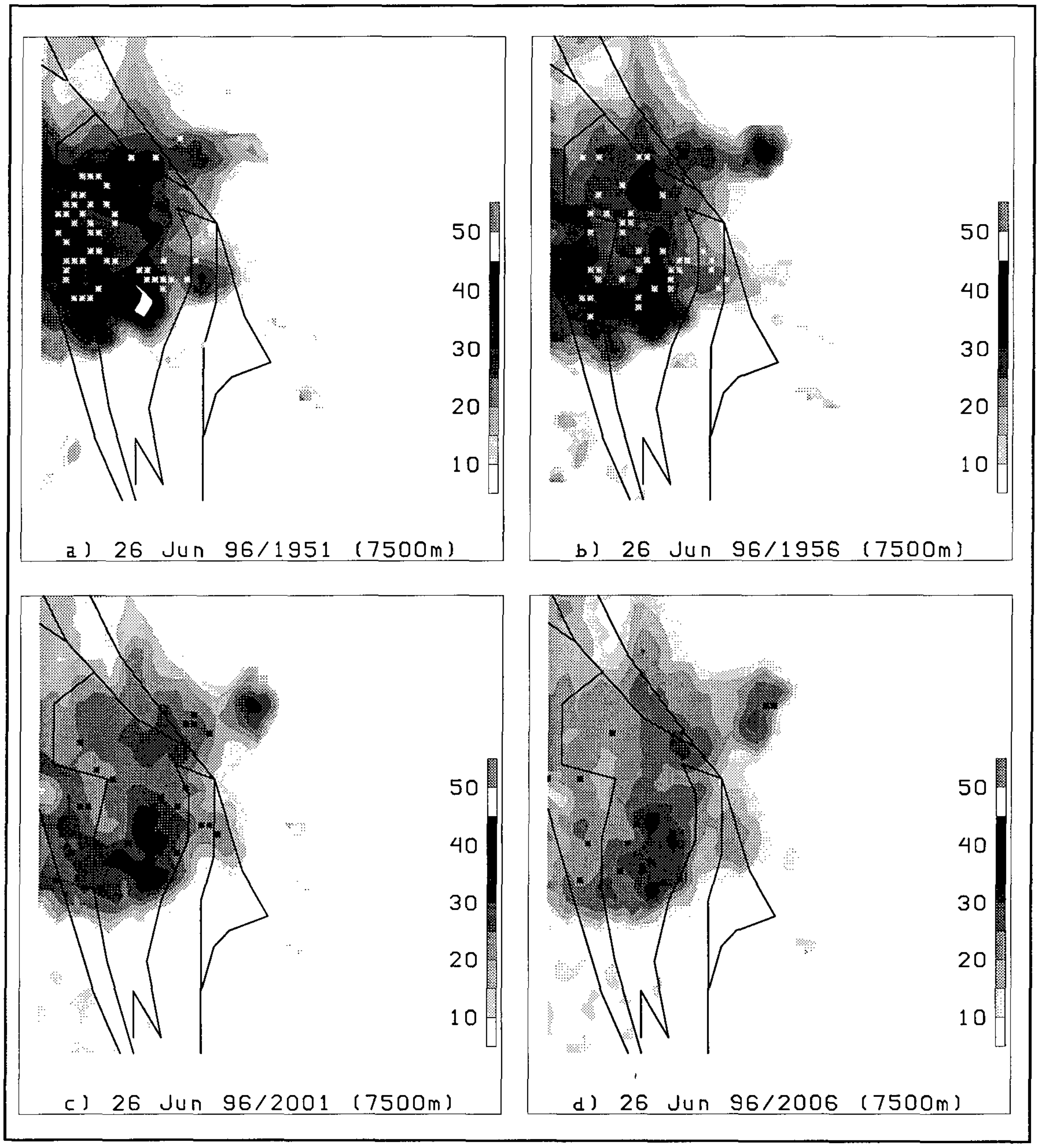

Fig. 11. Series of radar scans at the -20°C temperature height (7500 m) overlaid with NLDN lightning flashes for the 26 June 1996 thunderstorm. Shown here is 1951 UTC through 2006 UTC. The small symbols represent the lightning flashes.

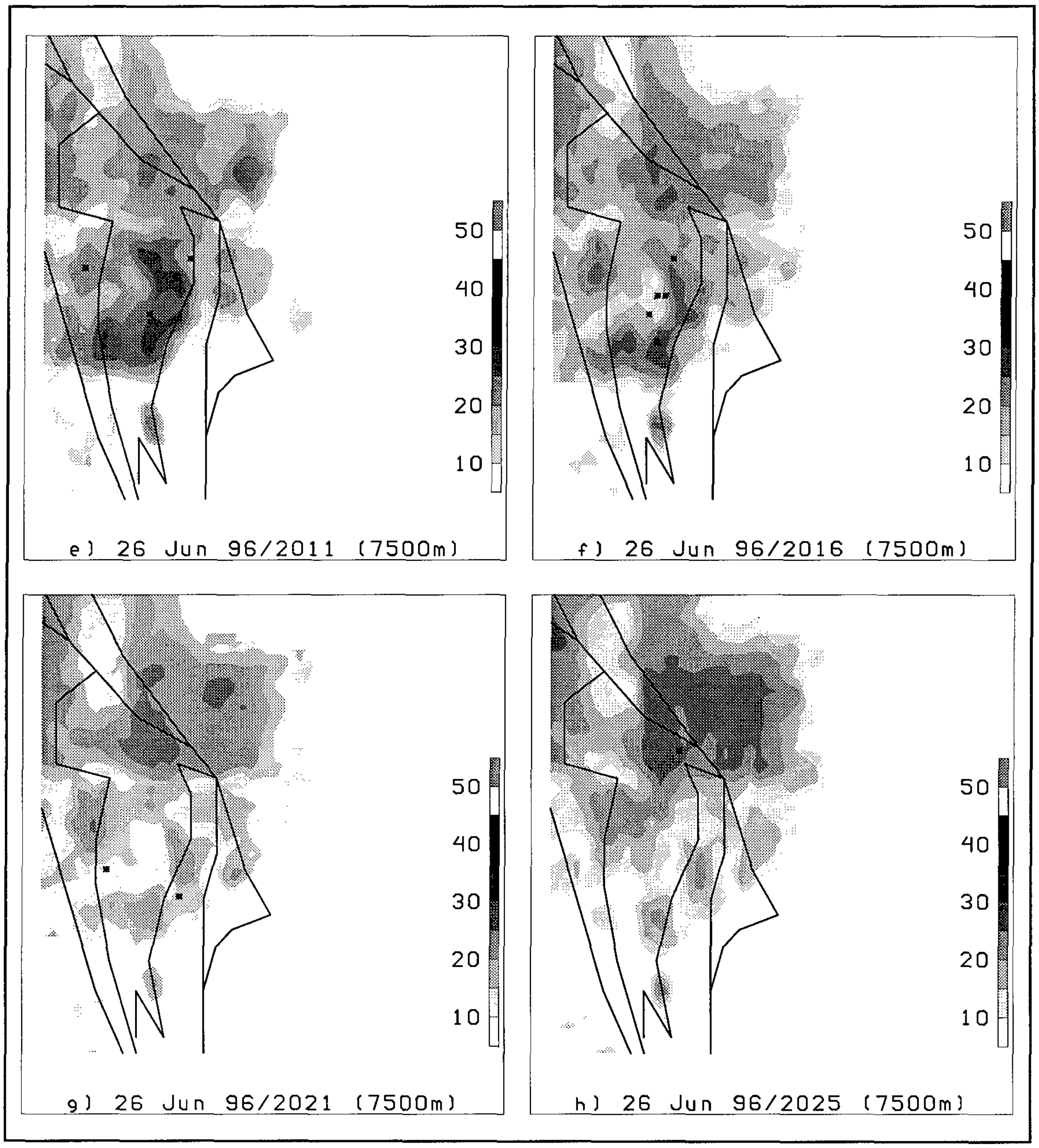

Fig. 12. Same as Fig. 11, except for 2011-2025 UTC.

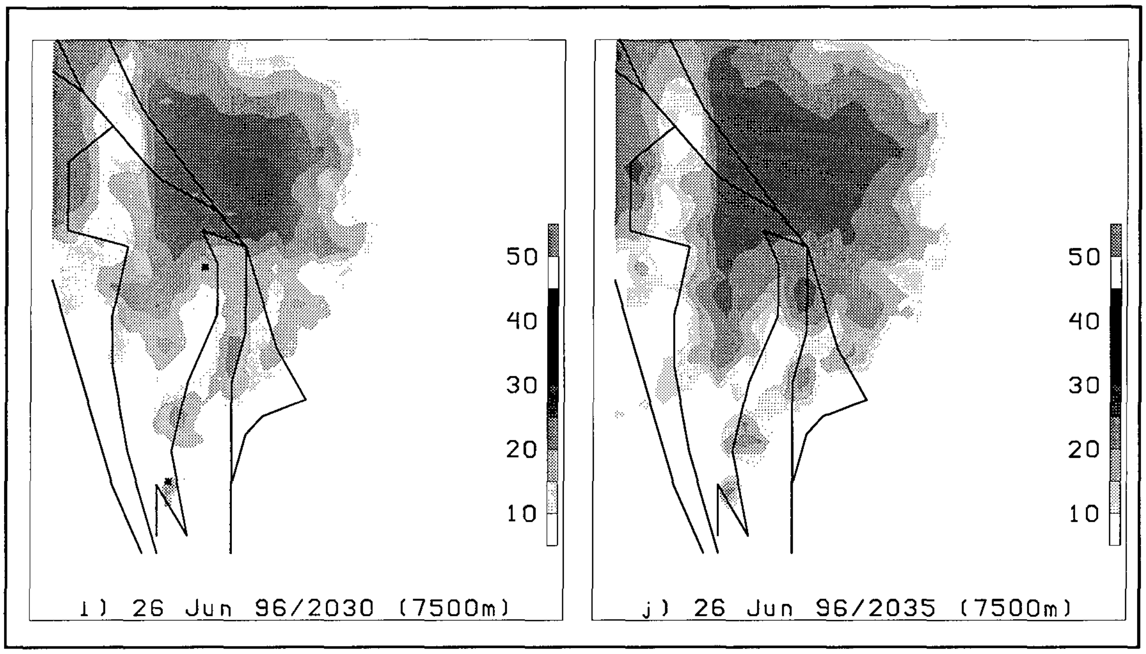

Fig. 13. Same as Fig. 11, except for 2030 UTC. Series (i) shows the last lightning flashes for this storm.

ceased for this thunderstorm. From the time of the 45 dBZ reflectivity cutoff to termination of lightning, 40 minutes had passed. At lightning cessation, reflectivity levels still exceeded 25 dBZ.

The 40 dBZ reflectivity level (at 7500 m) was then analyzed to see how it might signify lightning dissipation. A small pocket of 40 dBZ reflectivity can be seen at 2001 UTC in Fig. 11c. Again, as the lightning dissipates the last lightning is observed at 2030 UTC, resulting in a time lag of 30 minutes until the lightning ceased.

This storm was then analyzed at the -10°C (6000 m) temperature height for the same reflectivity levels (Figs. 14,15). Using the 45 dBZ reflectivity level, the last radar scan indicating this level occurred at 2001 UTC (Fig. 14a). The time that elapsed between this 45 dBZ reflectivity level and the end of lightning (Fig. 15g) was 30 min. Reflectivities remained above 25 dBZ after all lighting activity had ceased. With a reflectivity cutoff of 40 dBZ, the last series indicating this level was seen at 2006 UTC (Fig. 14b). The time lag between using this reflectivity level and termination of lightning was 25 min.

b. Analysis of 13 August 1996

Figure 16a indicates the last 45 dBZ reflectivity level (2051 UTC) appearing at the -20°C temperature height for the 13 August 1996 thunderstorm. As this storm

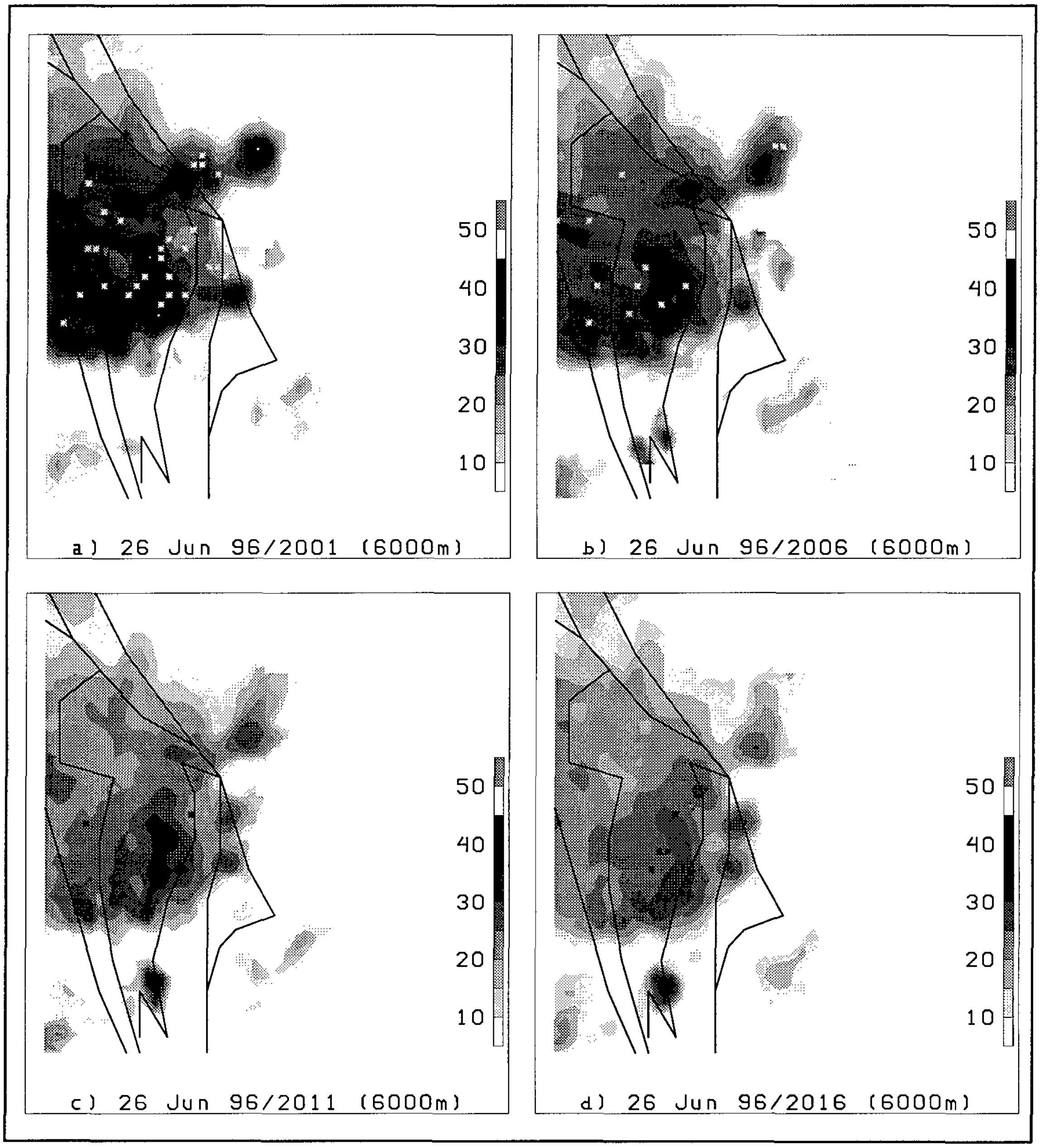

Fig. 14. Series of radar scans at the -10°C temperature height (6000 m) overlaid with NLDN lightning flashes for the 26 June 1996 thunderstorm. Shown here is 2001 UTC through 2016 UTC. The small symbols represent lightning flashes.

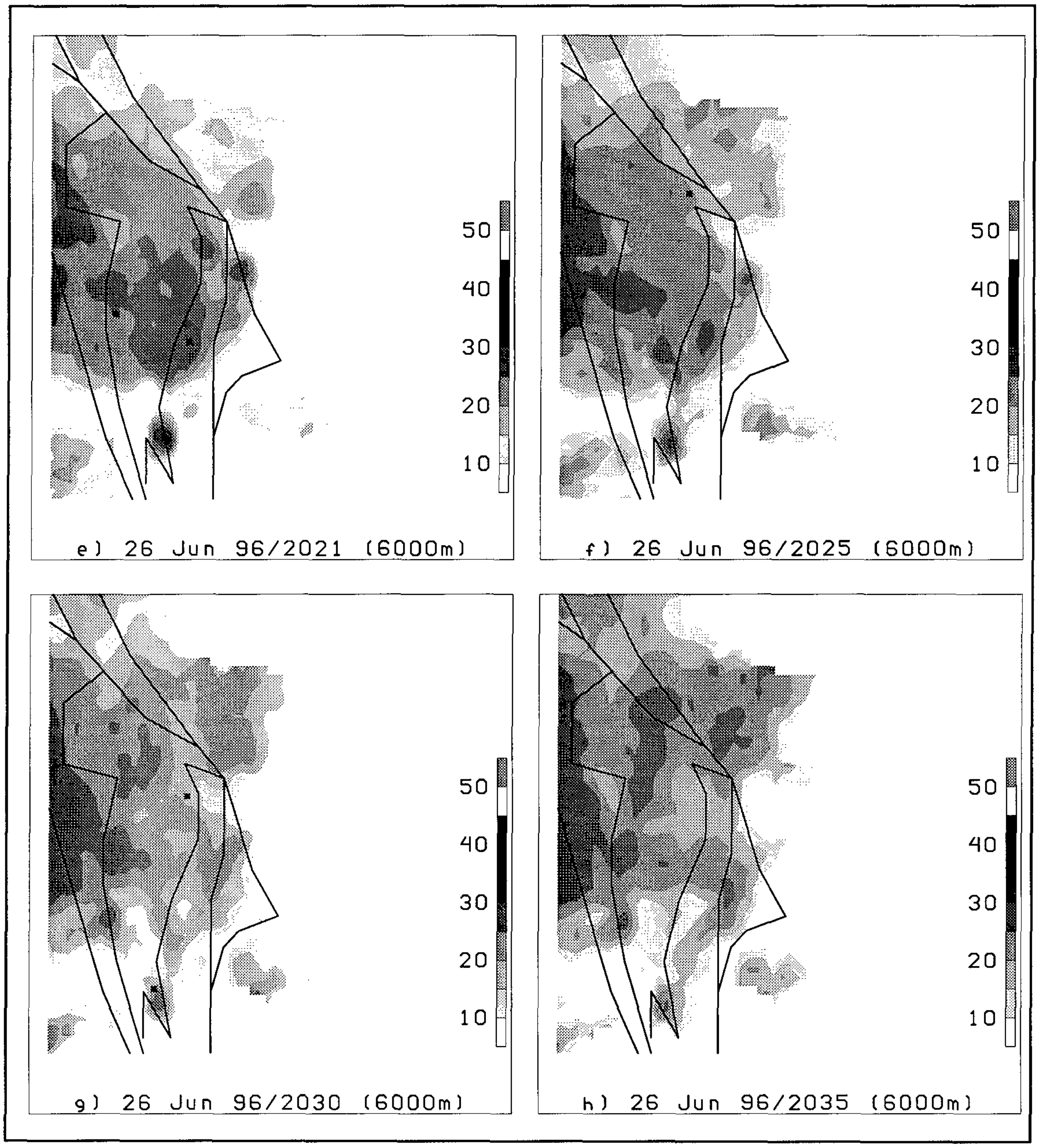

Fig. 15. Same as Fig. 14, except for 2021-2035 UTC. Series (g) indicates the last lightning flashes for this storm.

dissipates (Figs. 16,17,18), lighting activity continues until 2126 UTC (Fig. 17a). From the last 45 dBZ reflectivity level (2051 UTC) until the end of lightning activity (2126 UTC), 35 min passed. Reflectivity levels remained above 25 dBZ after all CG lightning had ceased.

The 40 dBZ reflectivity level (at 7500 m) was then analyzed for lightning dissipation significance. A small area indicating a 40 dBZ reflectivity is seen at 2106 UTC (Fig. 16d). As the storm decreases, the lightning continues until 2126 UTC, resulting in an elapsed time of 20 min.

This storm was then analyzed at the -10°C temperature height (6000 m) for the same reflectivity levels. Using the 45 dBZ reflectivity level, the last radar series indicating this level occurred at 2056 UTC (Fig. 19a). The time lag between this 45 dBZ reflectivity level and the end of lightning activity (2126 UTC) was 30 min. Again, reflectivity's remained above 25 dBZ after termination of all lighting activity.

Using a reflectivity indicator of 40 dBZ to indicate the cessation of lightning, the last radar series reflecting this value was observed at 2111 UTC (Fig. 19d). An elapsed time of 15 minutes was seen between the 40 dBZ reflectivity cutoff level and the end of CG lightning (Fig. 20g).

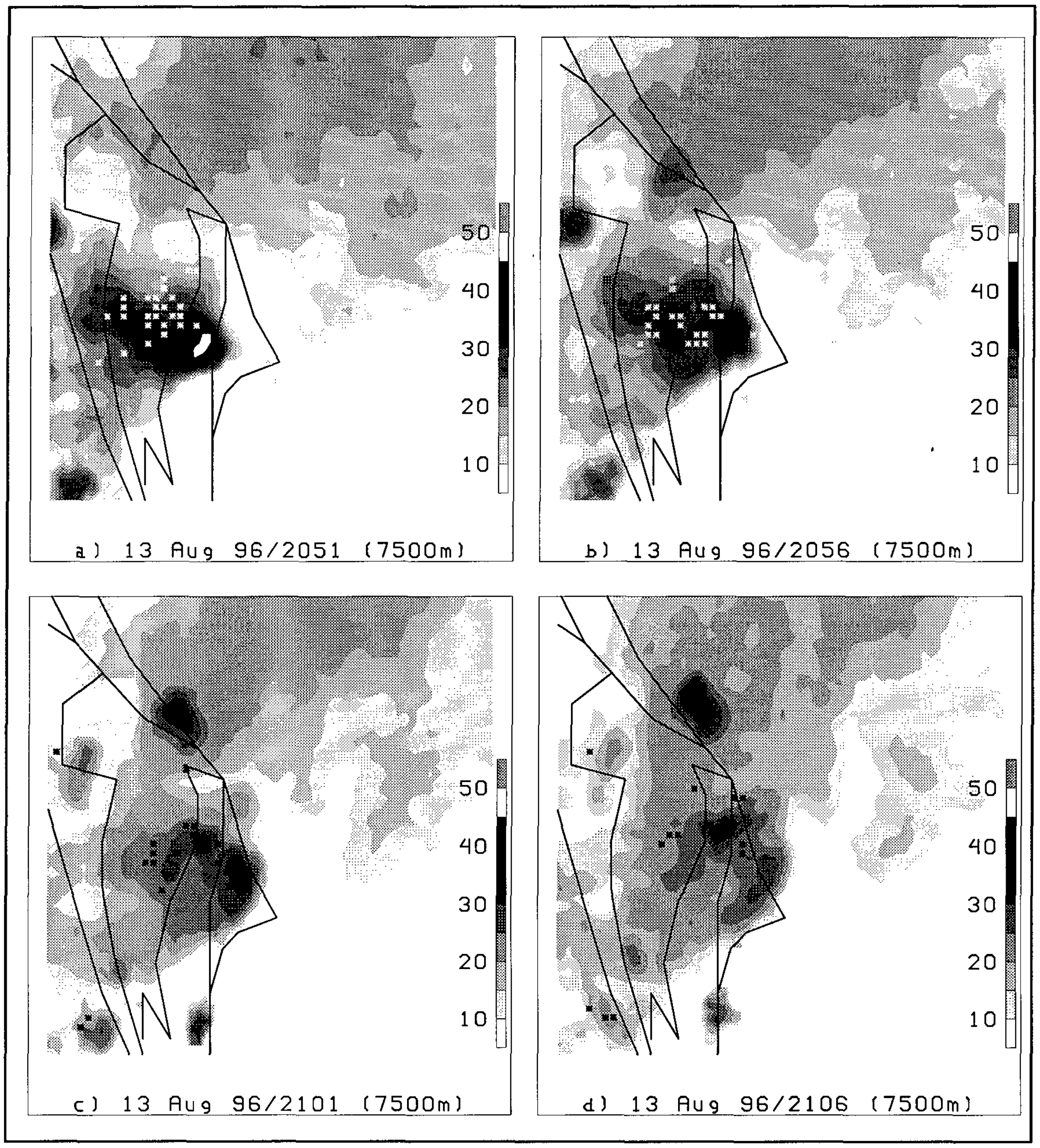

Fig. 16. Series of radar scans at the -20°C temperature height (7500 m) overlaid with NLDN lightning flashes for the 13 August 1996 thunderstorm. Shown here is 2051 UTC through 2106 UTC. The small symbols represent the lightning flashes.

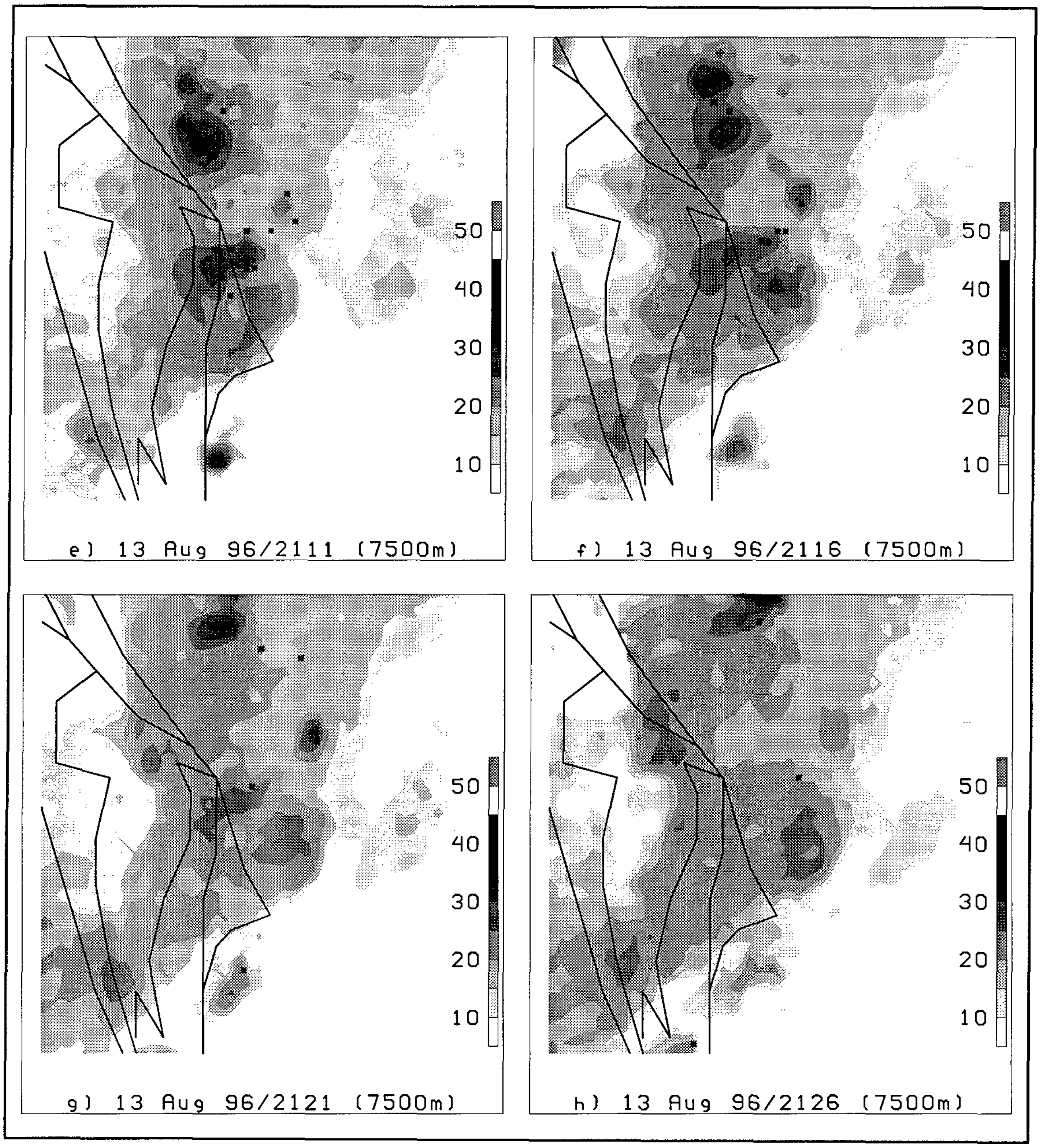

Fig. 17. Same as Fig. 16, except for 2111-2126 UTC.

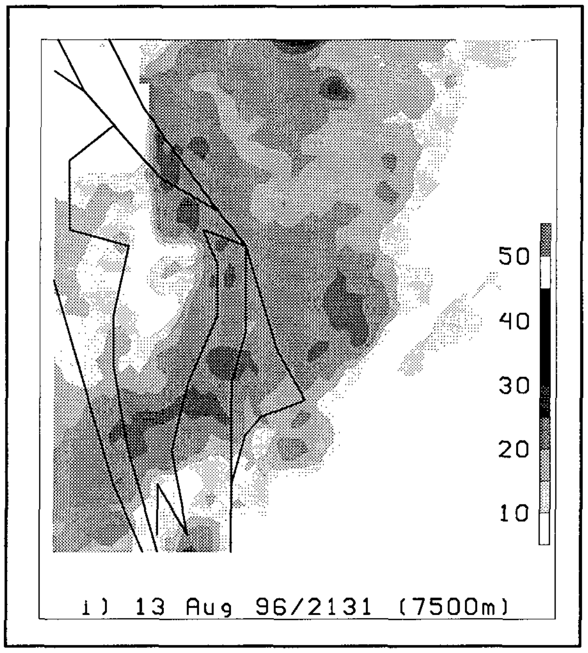

Fig. 18. Same as Fig. 16, except for 2131 UTC.

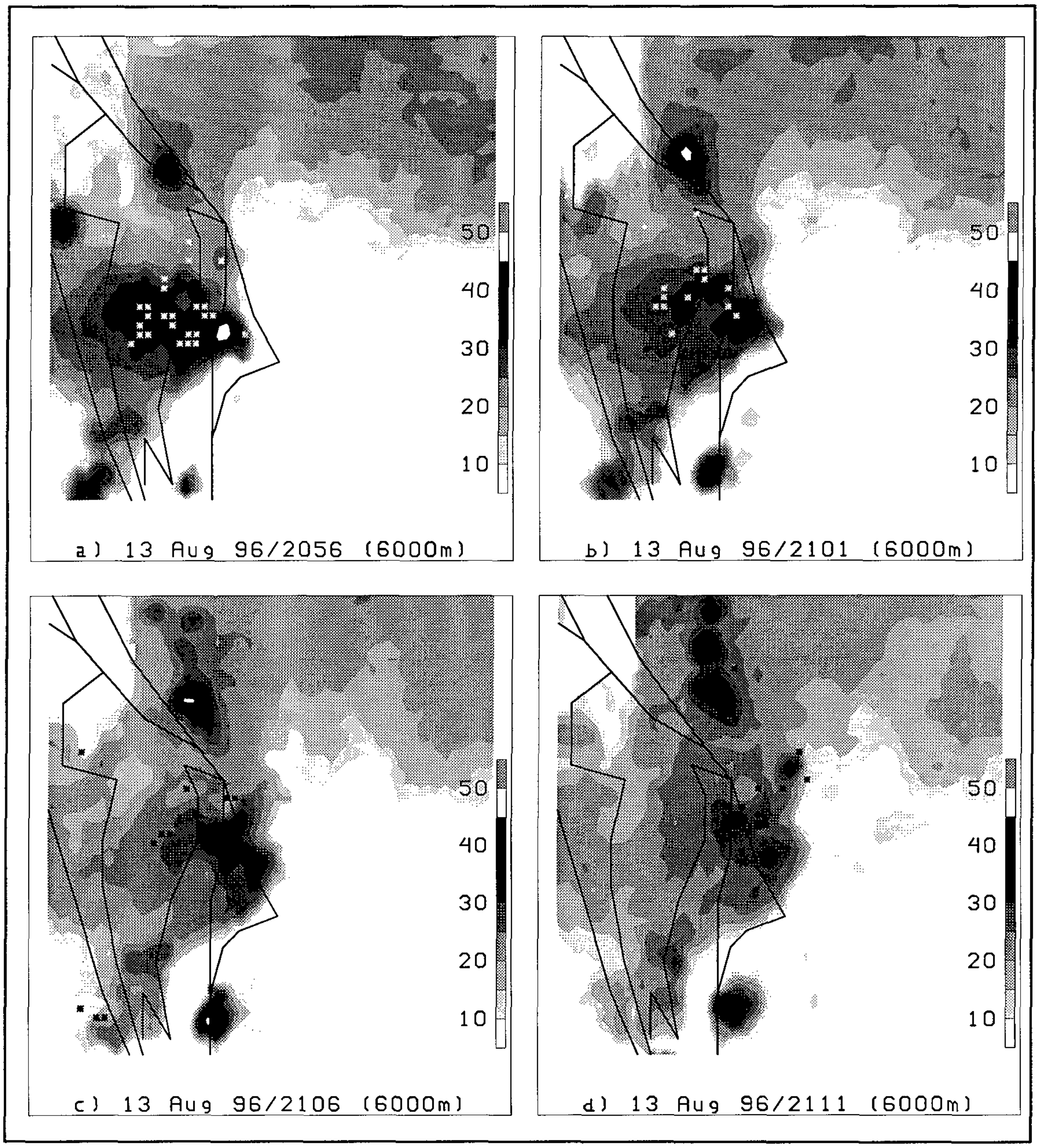

Fig. 19. Series of radar scans at the -10°C temperature height (6000 m) overlaid with NLDN lightning flashes for the 13 August 1996 storm. Shown here is 2056 UTC through 2111 UTC. The small symbols represent lightning flashes. The storm of interest in located at the point of the 45 dBZ reflectivity level in series (a).

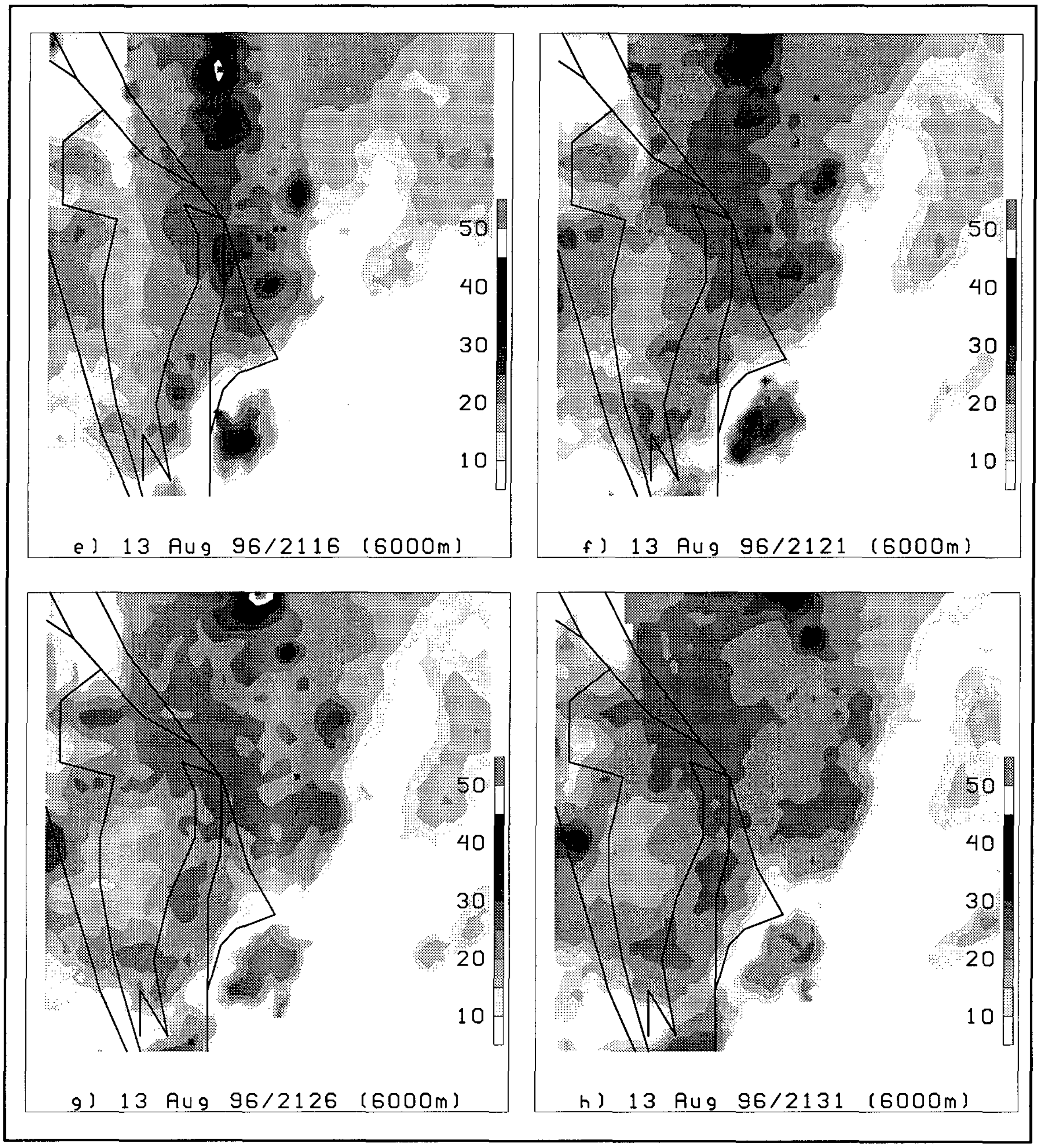

Fig. 20. Same as Fig. 19, except for 2116-2131 UTC.

c. Analysis of 14 August 1996

The 14 August 1996 thunderstorm was analyzed at the -20°C temperature height (7500 m) using the 45 dBZ reflectivity level to signify the cessation of lightning activity. Figure 21a shows the last radar image indicating the 45 dBZ reflectivity level at 2124 UTC. Lightning activity continues throughout this storm (Figs. 21,22,23) until 2204 UTC. From the time of the 45 dBZ reflectivity level to the termination of CG lightning (Fig. 23i), 40 min had passed. At lightning cessation, reflectivity levels were above 25 dBZ, as had been observed in the other two storms.

This storm was then analyzed using the 40 dBZ reflectivity level at the -20°C temperature height. Figure 21d shows the last radar image indicating the 40 dBZ reflectivity level at 2139 UTC. Again, lightning activity continued until 2204 UTC. This resulted in an elapsed time of 25 min, from the 40 dBZ reflectivity indication until end of lightning.

Analysis of this storm at the -10°C temperature height (6000 m) level was accomplished for the two reflectivity levels (Figs. 24,25). Applying the 45 dBZ reflectivity level for an indication of the end of lightning revealed the last radar image at 2134 UTC (Fig. 24a). The observed

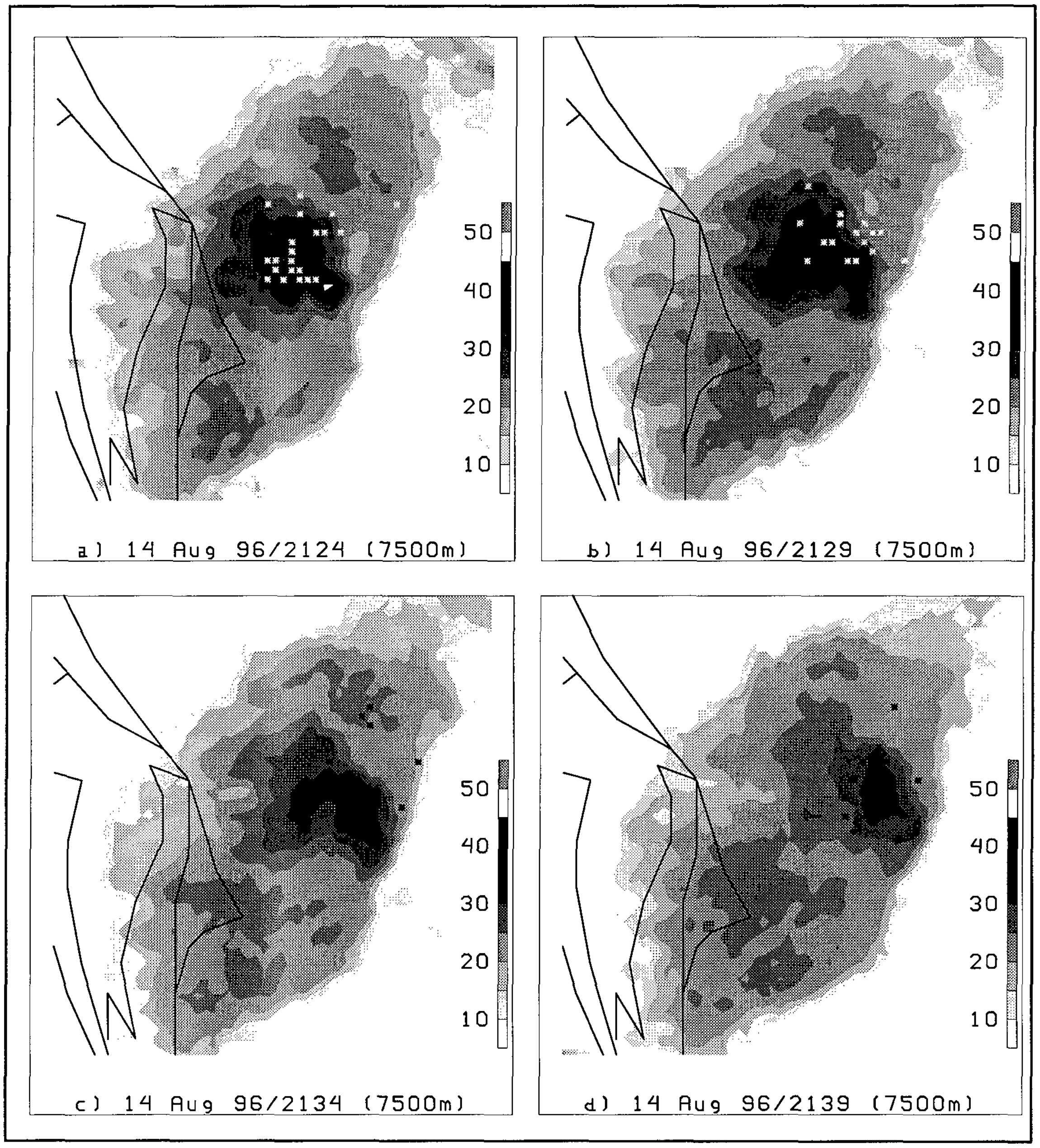

Fig. 21. Series of radar scans at the -20°C temperature height (7500 m) overlaid with NLDN lightning flashes for the 14 August 1996 thunderstorm. Shown here is 2124 UTC through 2139 UTC. The small symbols represent lightning flashes.

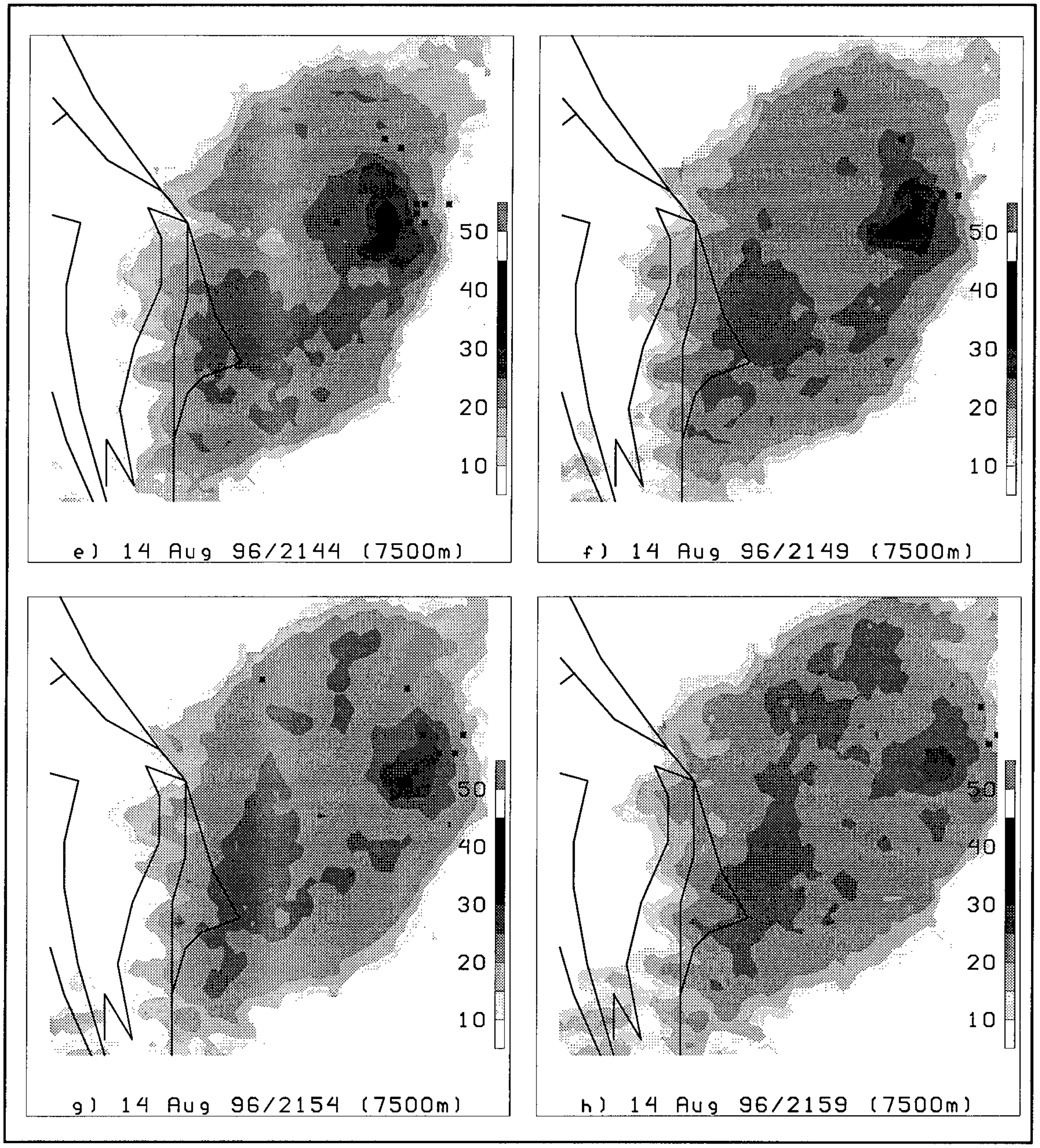

Fig. 22. Same as Fig. 21, but for 2144-2159 UTC.

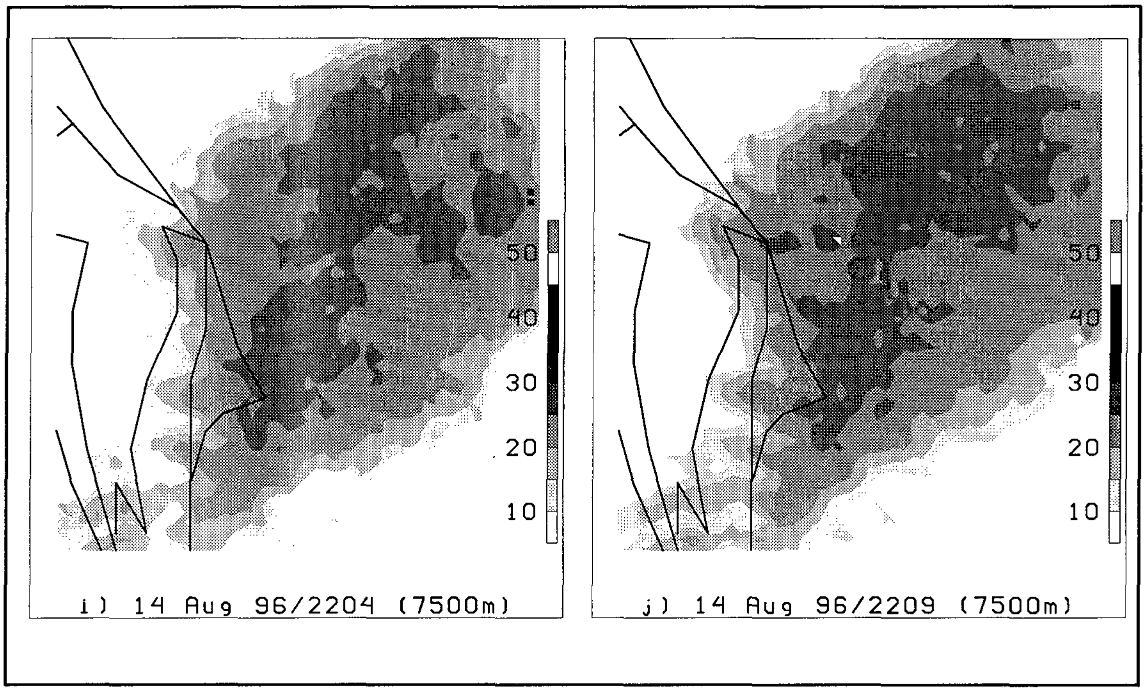

Fig. 23. Same as Fig. 21, but for 2204 UTC.

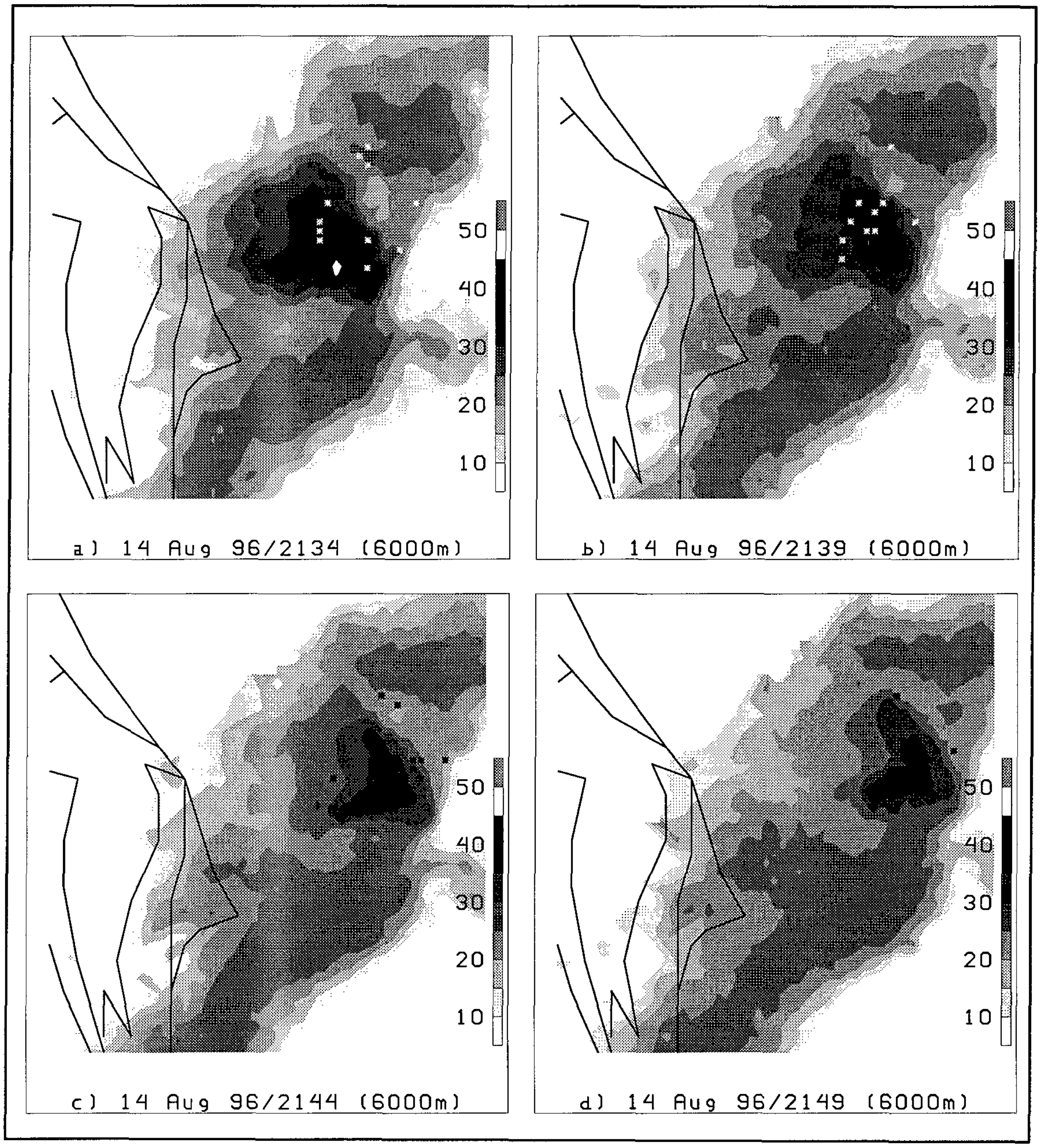

Fig. 24. Series of radar scans at the -10°C temperature height level (6000 m) overlaid with NLDN lightning flashes for the 14 August 1996 thunderstorm. Shown here is 2134 UTC through 2149 UTC. The small symbols represent lightning flashes.

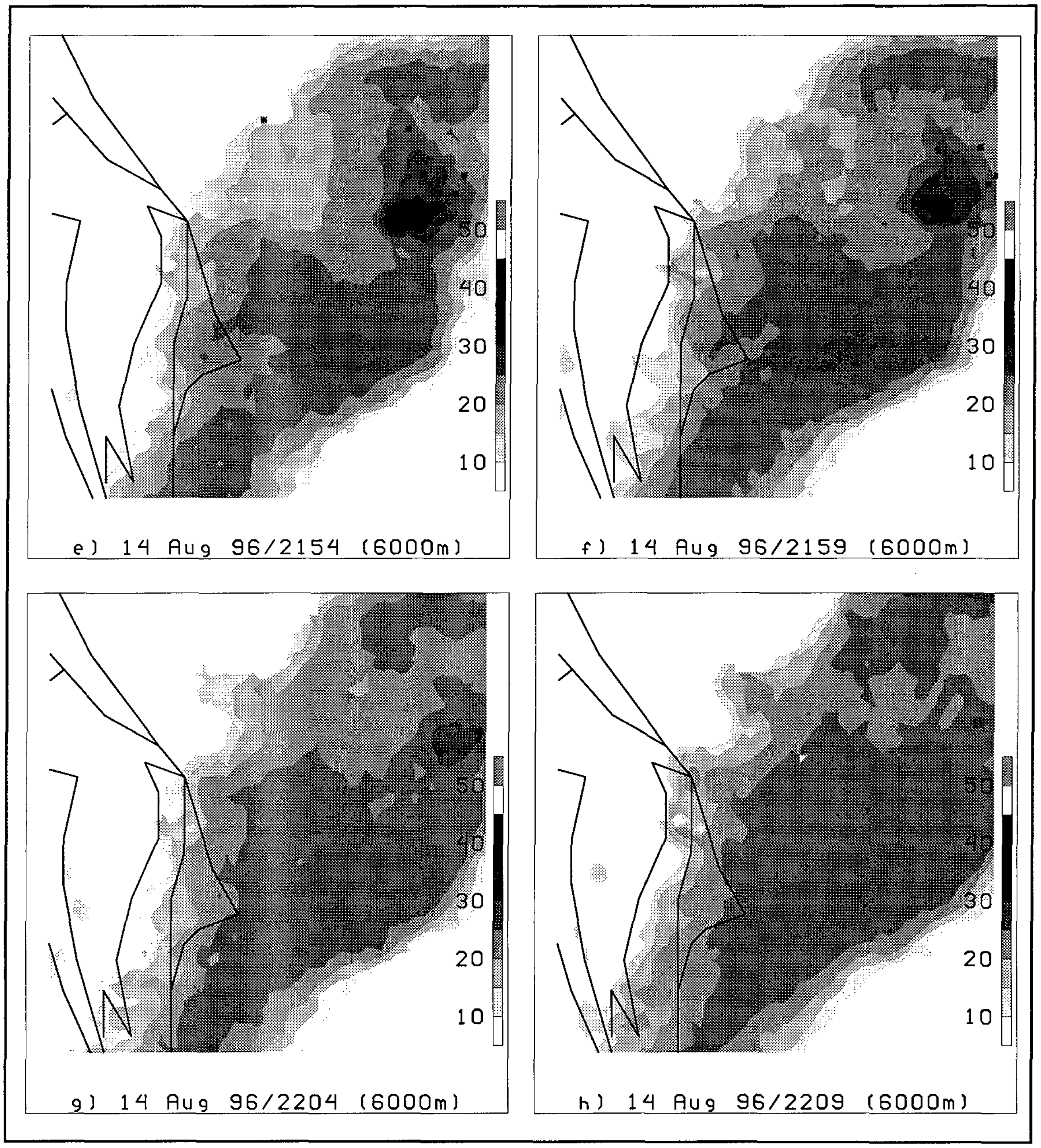

Fig. 25. Same as Fig. 24, but for 2154-2209 UTC. Lightning activity is seen until 2204 UTC (g).

time lag between the 45 dBZ reflectivity level and the termination of CG lightning activity (Fig. 25g) was 30 min. This was the same duration as seen in the other two storms. Reflectivities remained above 30 dBZ after termination of all lightning activity for this storm.

The 40 dBZ reflectivity level (at 6000 m) was then analyzed to observe any significance in lightning cessation. A pocket of 40 dBZ reflectivity is shown in figure 24d at 2149 UTC. The time lag between using this reflectivity level and termination of CG lightning was 15 min.

3. Electric Field Mill Analysis

The electric fields produced by the three air mass thunderstorms were recorded at 34 field mill sites at the KSC location. The field mills measure the electric field. The potential gradient (negative of the electric field) will be assumed to be positive in the sense of a positive charge overhead. This potential gradient will be used for the analysis of these data. Field mills are extremely important in determining whether to launch a space vehicle since launches cannot take place if the electric field is $>|1000 \text{ V m}^{-1}|$. By using an IDL program, both the surface and 3-D contours of the data were created for analysis.

a. Analysis of 26 June 1996

The 26 June 1996 case was analyzed every five minutes

(Figs. 26-29) for changes in it's electric field to observe any possible relationships between the radar and lightning images. Beginning at 1951 UTC (the last radar image with a 45 dBZ reflectivity at the 7500 m level), the electric field shows a large negative peak (<-2500 V m^{-1}) and a smaller positive peak (>1500 V m^{-1}) slightly northeast (Fig. 26). The electric field continues to remain predominantly negative (<-2000 V m^{-1}) until 2010 UTC (Fig. 27) where positive values begin increasing and at 2015 UTC a large positive field occurs (>3000 V m^{-1}). At 2020 UTC (Fig. 28) the positive field decreases and a large negative field returns (<-4000 V m^{-1}). This negative field is then replaced by a large positive field at 2025 UTC (>3000 V m^{-1}) and remains positive (>4000 V m^{-1}) through 2030 UTC (the end of CG lightning). At 2035 UTC (Fig. 29), after termination of CG lightning, the electric field reversed to a very large negative field (<-7000 V m^{-1}) and then appeared to fluctuate between positive and negative values for about 20 min after the end of the lightning activity.

b. Analysis of 13 August 1996

The thunderstorm on 13 August 1996 was also analyzed for changes in its electric fields (Figs. 30-32). Beginning at 2050 UTC (Fig. 30), which corresponds to the last 45 dBZ reflectivity (7500 m), the electric field indicates a large negative field (<-3000 V m^{-1}) and also a positive field slightly west (2000 V m^{-1}). The electric

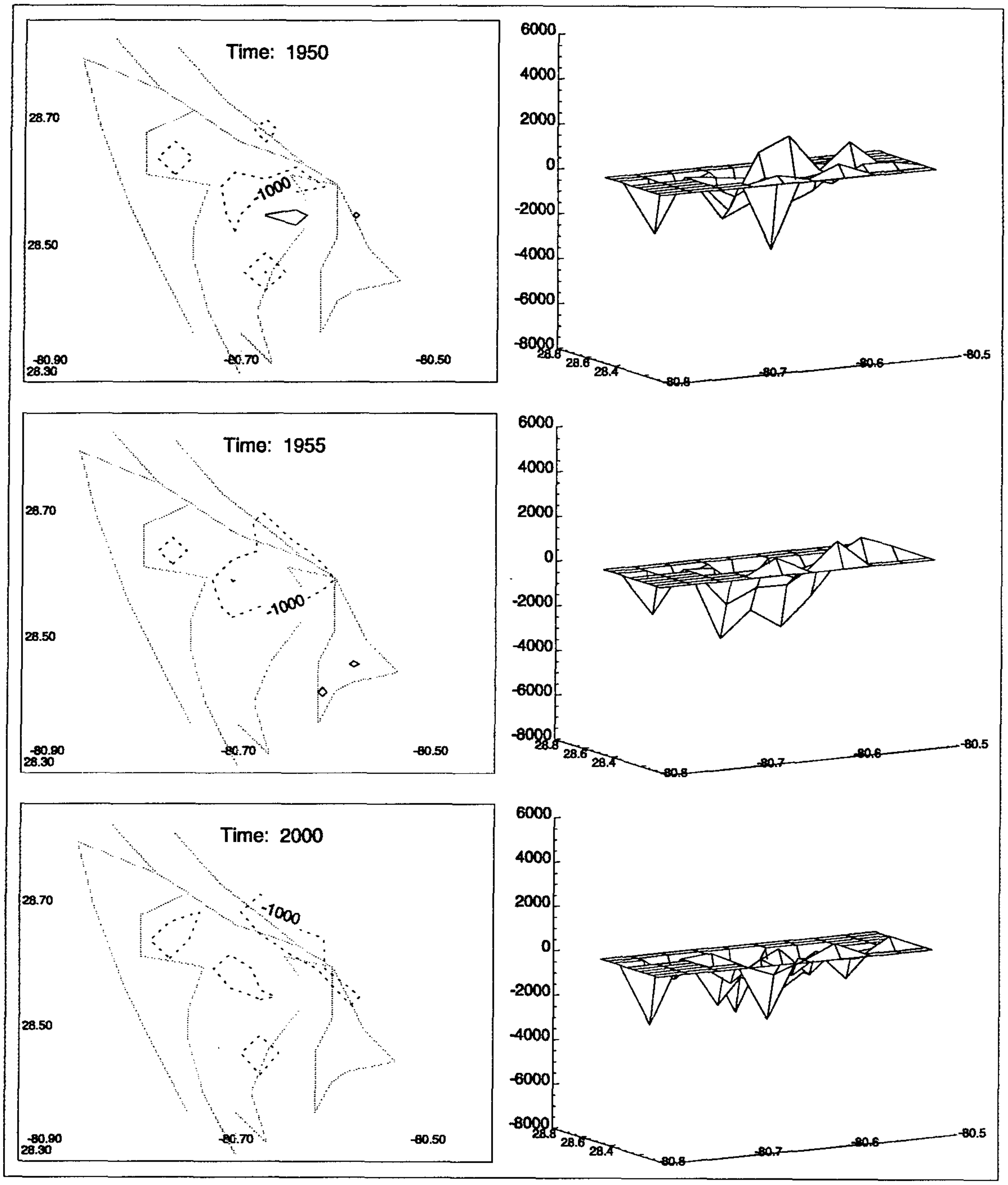

Fig. 26. Electric field mill contours over the KSC area for the 26 June 1996 thunderstorm (1950 UTC through 2000 UTC). Surface contours are located along the left side while their respective 3-D contours are along the right side. The contour lines for the surface contours are denoted by solid lines for positive values and dotted lines for negative values. All values are v m^{-1}.

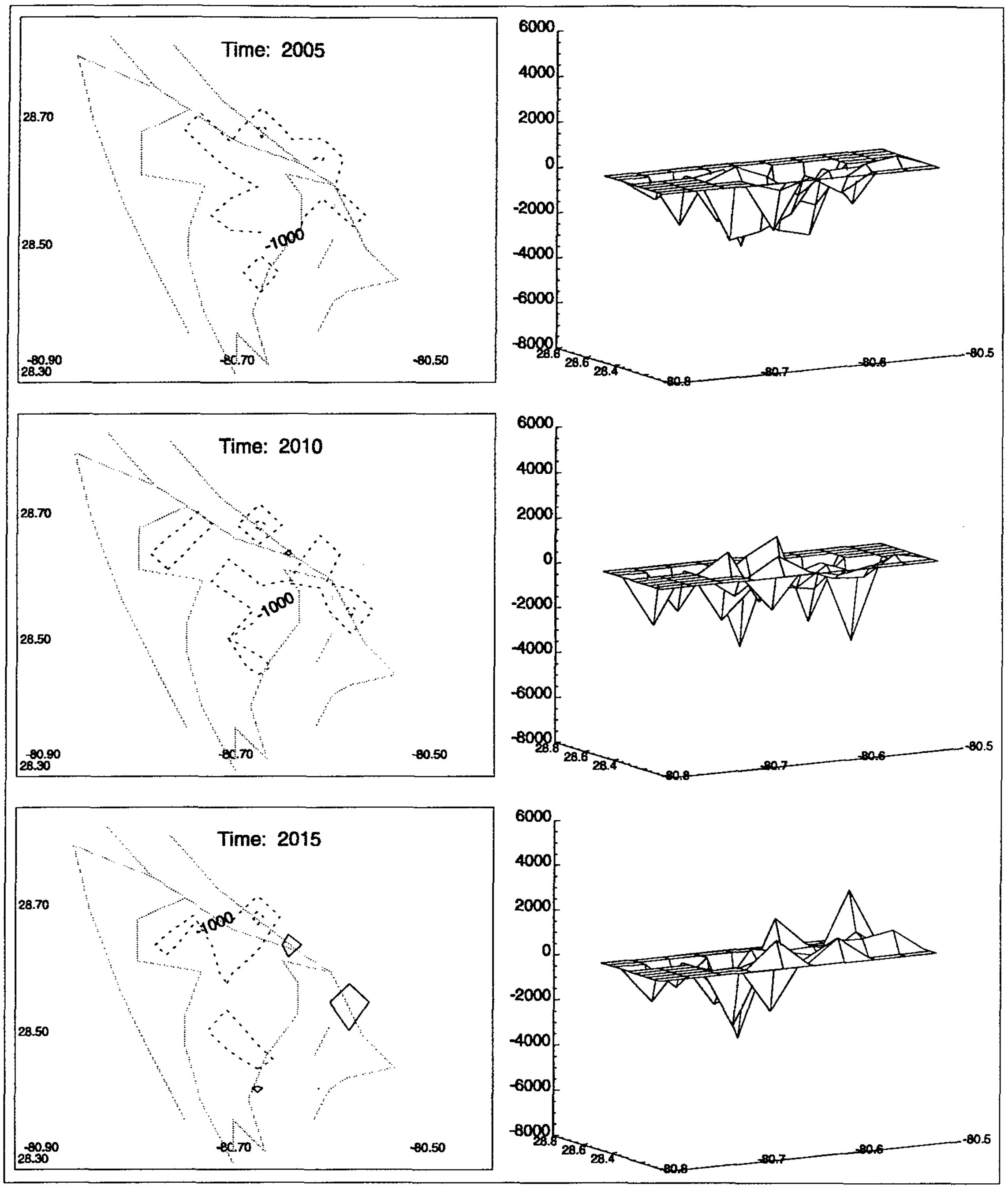

Fig. 27. Same as Fig. 26, except for 2005 UTC through 2015 UTC.

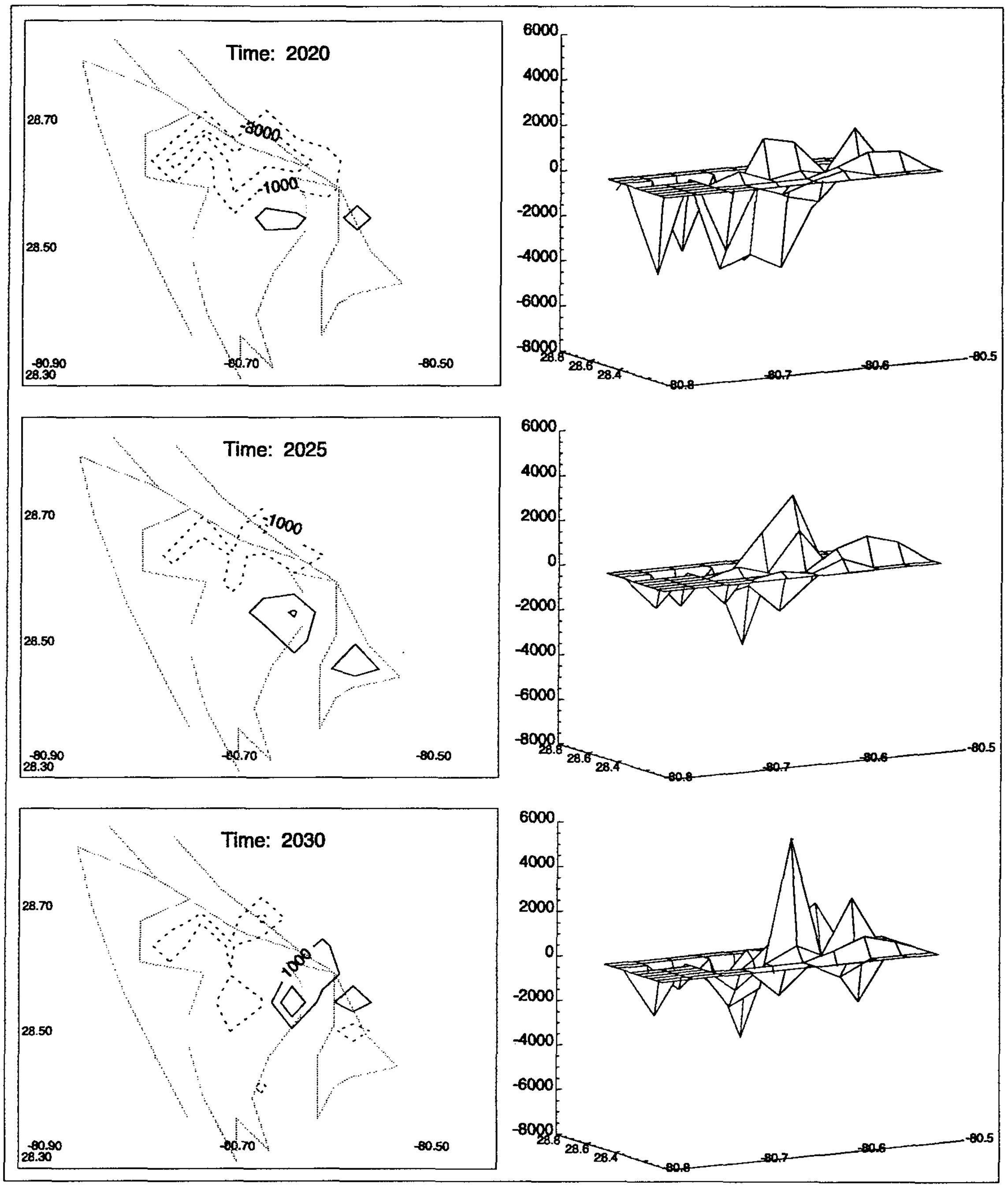

Fig. 28. Same as Fig. 26, except for 2020 UTC through 2030 UTC.

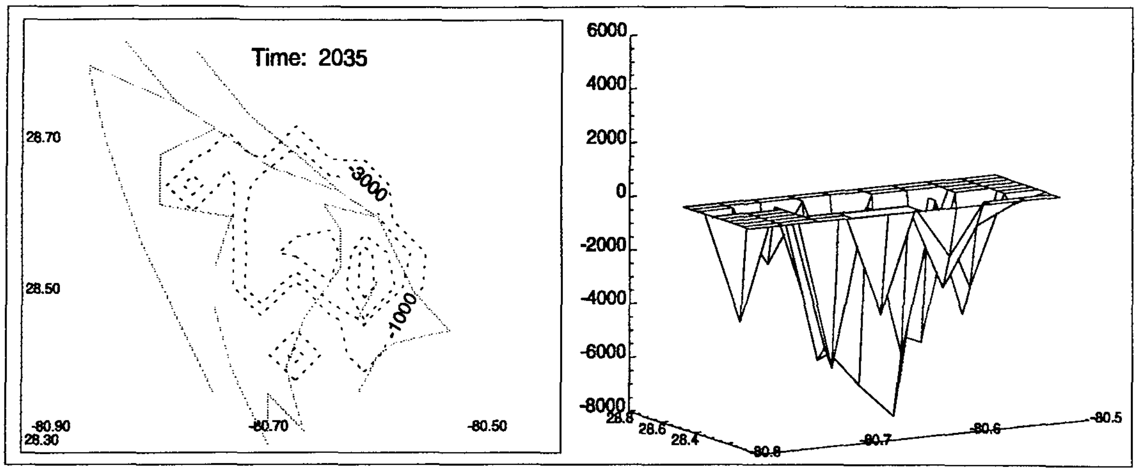

Fig. 29. Same as Fig. 26, except for 2035 UTC.

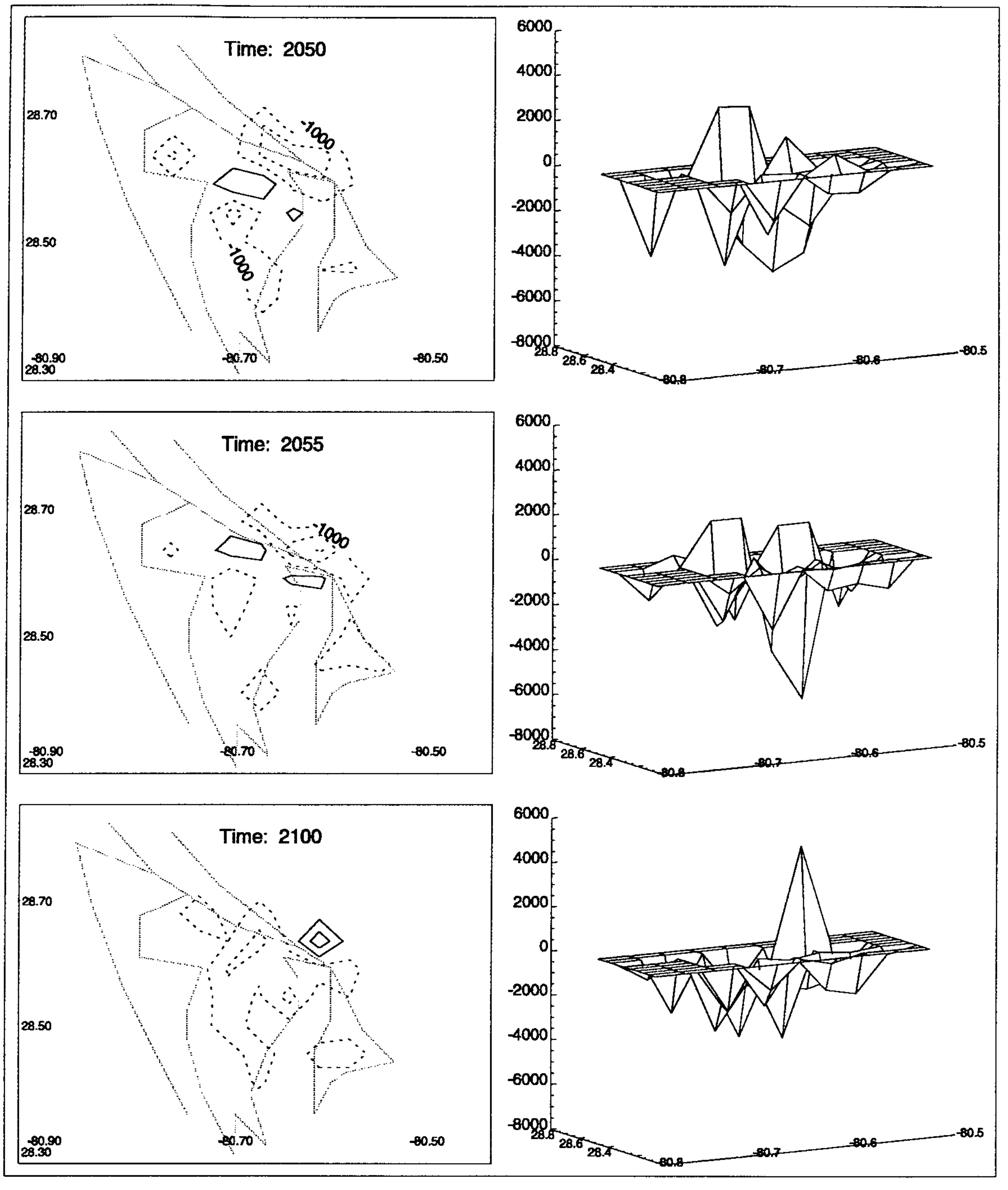

Fig. 30. Electric field mill contours over the KSC area for the 13 August 1996 thunderstorm (2050 UTC through 2100 UTC). Surface contours are located along the left side while their respective 3-D contours are along the right side. The contour lines for the surface contours are denoted by solid lines for positive values and dotted lines for negative values. All values are v m^{-1}.

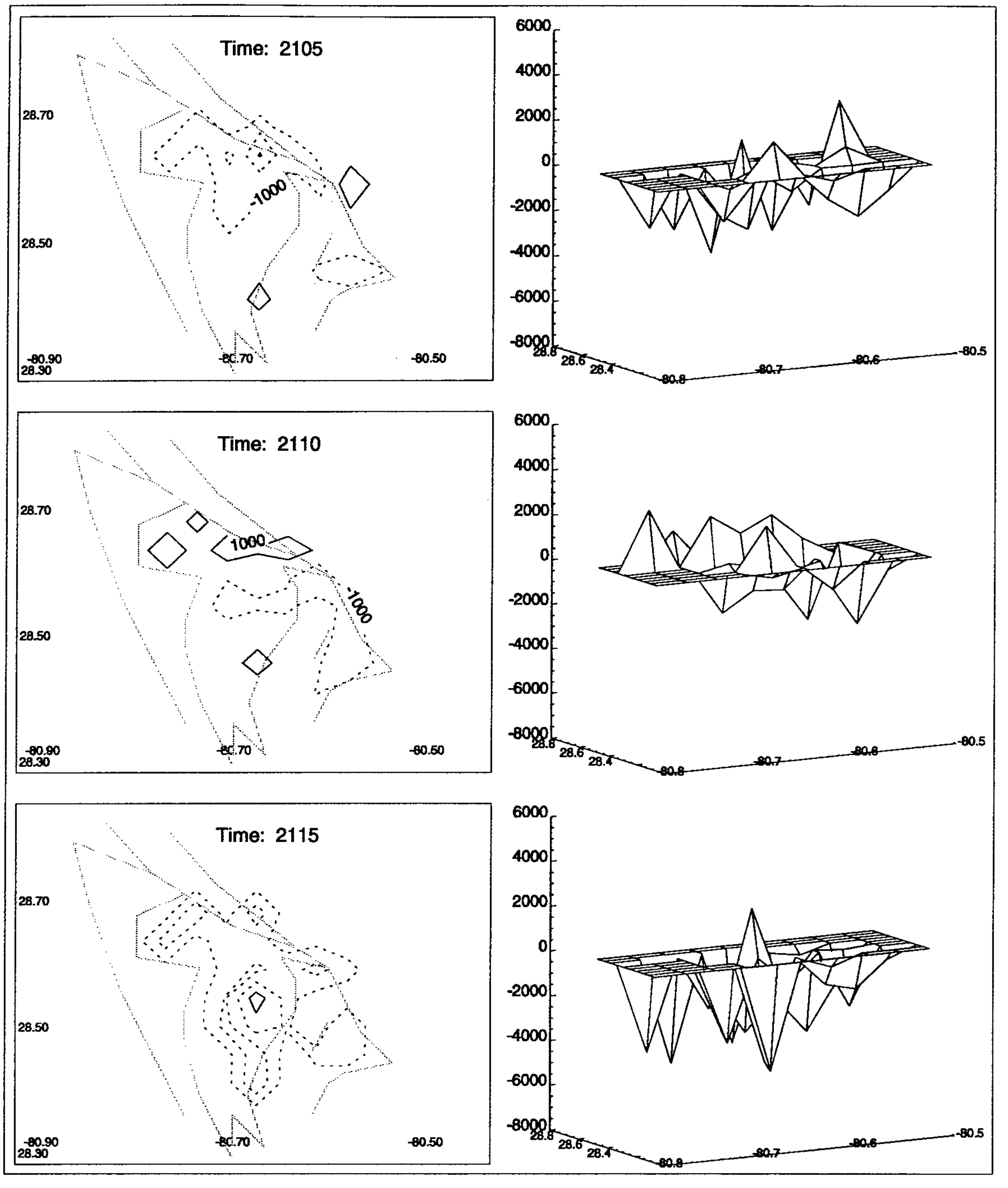

Fig. 31. Same as Fig. 30, except for 2105 UTC through 2115 UTC.

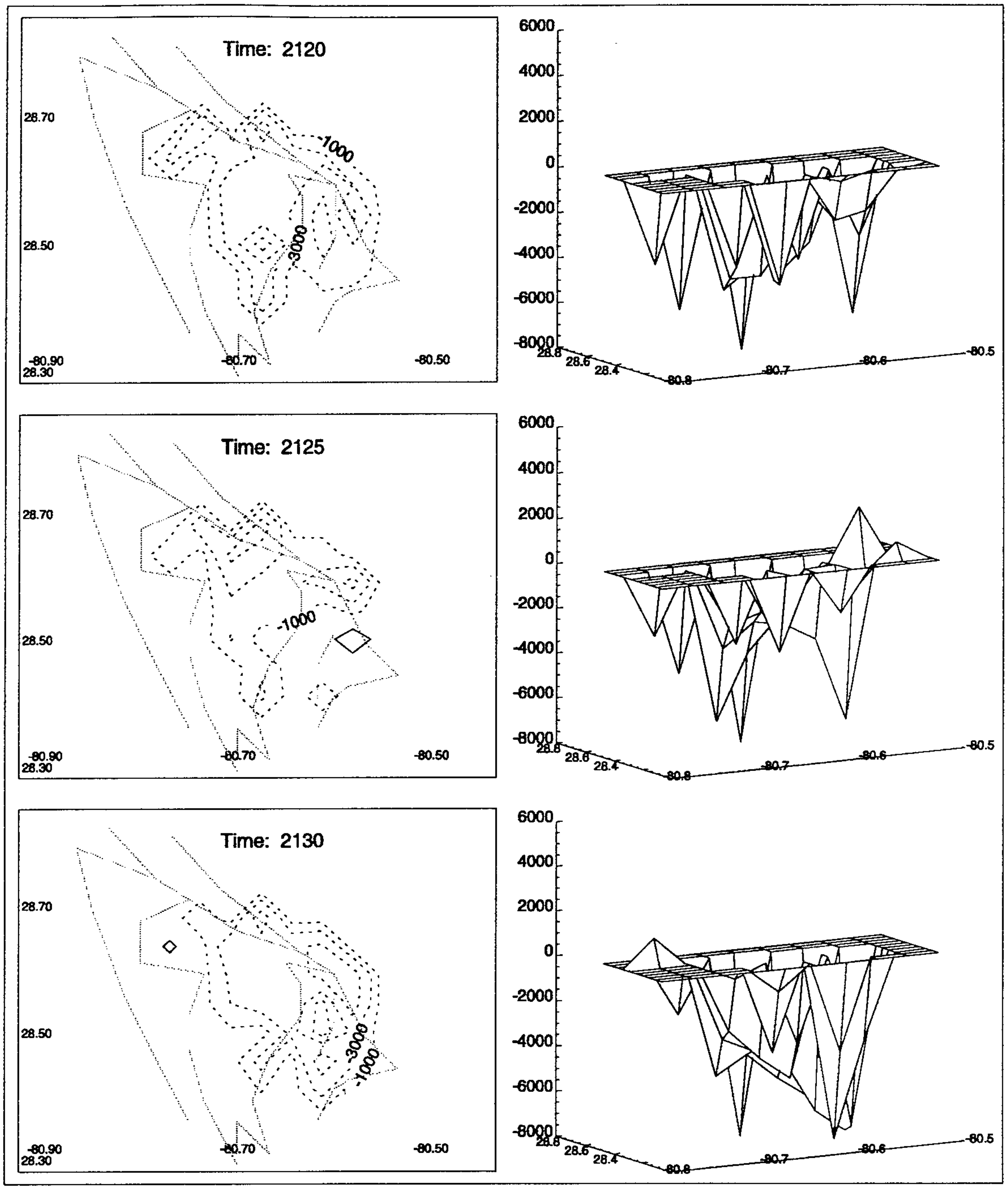

Fig. 32. Same as Fig. 30, except for 2120 UTC through 2130 UTC.

positive field slightly west of 2000 V m^{-1}. The electric field tends to fluctuate from large negative values (<-4000 V m^{-1}) at 2055 UTC to large positive values (>4000 V m^{-1}) at 2100 UTC, until 2115 UTC (Fig. 31) when the electric field remains predominantly negative until the termination of CG lightning. At 2125 UTC the electric field exceeds -6000 V m^{-1} and decreases even more after the end of lightning at 2130 (<-8000 V m^{-1}). After 2130 UTC the positive field begins to increase and the field tends to slightly fluctuate for around 20 min.

c. Analysis of 14 August 1996

An analysis of the 14 August 1996 case was conducted along with the other two storms for changes in the electric fields. Figure 33 shows a very large negative field (<-5000 V m^{-1}) which corresponds to the last radar image indicating a 45 dBZ reflectivity (7500 m level). This negative field remains primarily negative until 2140 UTC (Fig. 34) when a positive electric field begins to appear. This positive field continues to dominate with values reaching >4000 V m^{-1} at 2020 UTC (Fig. 35) and remains positive after the cessation of all CG lightning. A fluctuation of positive and negative fields did not occur with this storm, as was observed in the other two cases. This may have been due to a lower total flash count in this thunderstorm than was observed in the other cases.

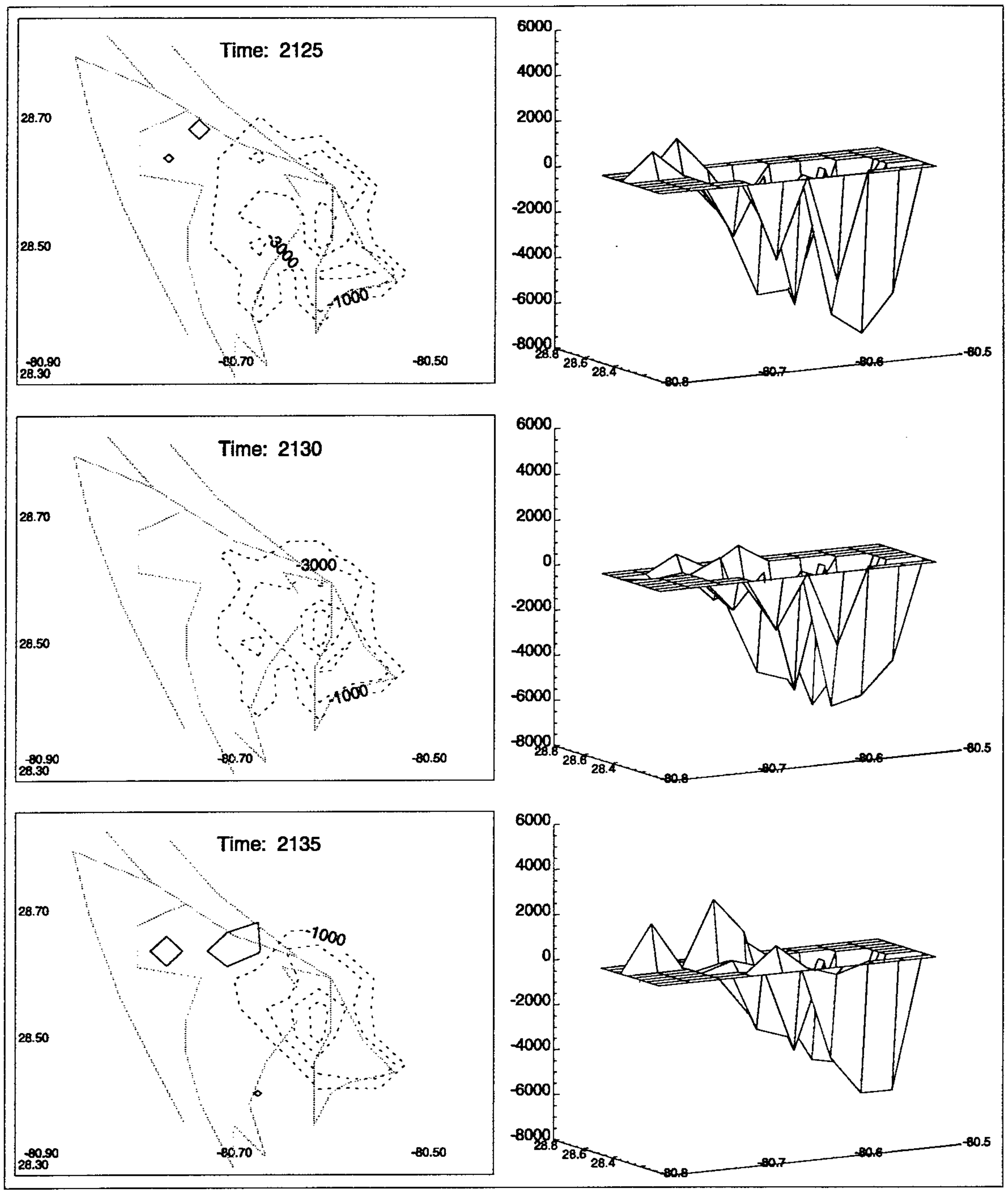

Fig. 33. Electric field mill contours over the KSC area for the 14 August 1996 thunderstorm (2125 UTC through 2135 UTC). Surface contours are located along the left side while their respective 3-D contours are along the right side. The contour lines for the surface contours are denoted by solid lines for positive values and dotted lines for negative values. All values are v m^{-1}.

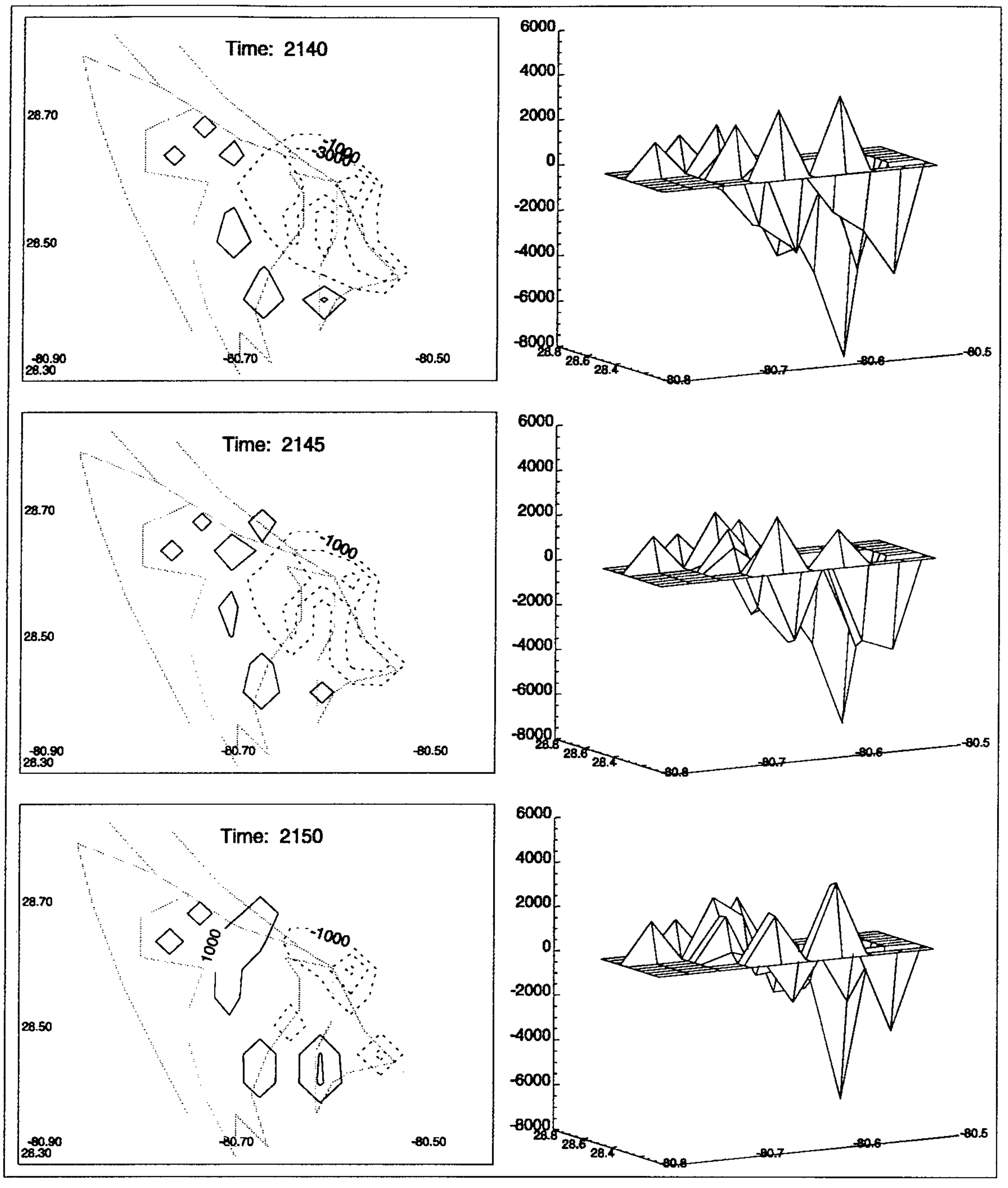

Fig. 34. Same as Fig. 33, except for 2140 UTC through 2150 UTC.

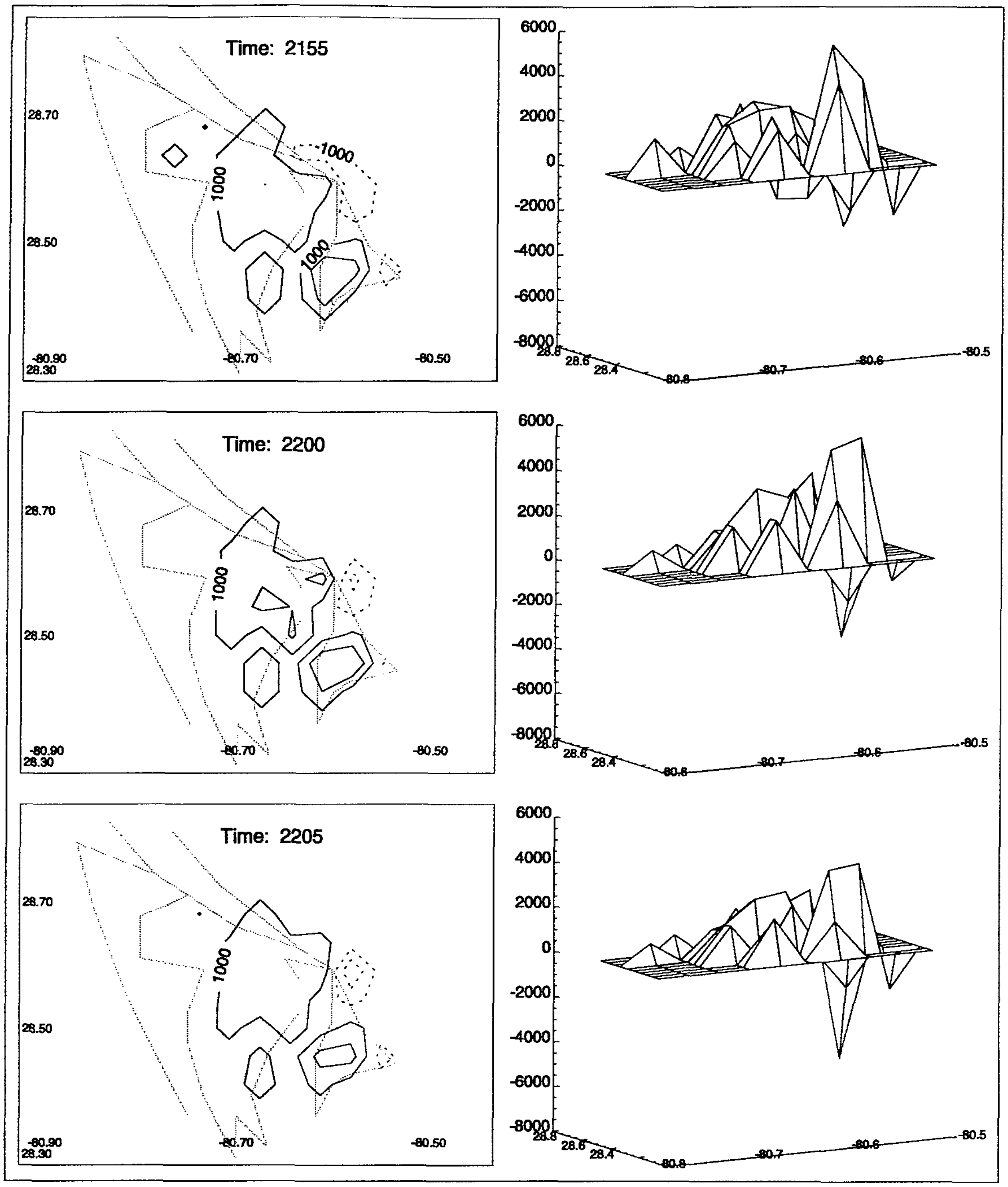

Fig. 35. Same as Fig. 33, except for 2155 UTC through 2205 UTC.

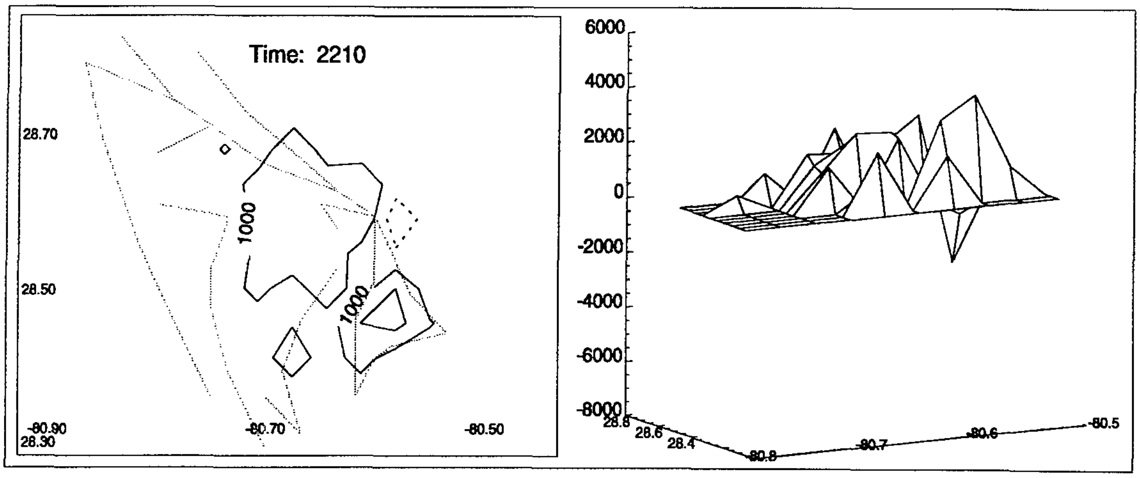

Fig. 36. Same as Fig. 33, except for 2210 UTC.

CHAPTER V

DISCUSSION

1. Lightning Summary

a. Spatial Distributions

From 1986 through 1995, 745 298 cloud-to-ground (CG) lightning flashes were detected in the study area by the National Lightning Detection Network (NLDN). The ground flash densities (GFD) were described on an average monthly basis for all CG lightning flashes and for positive flashes only. The percentage of positive lightning flashes was low, and therefore more easily influenced by individual storms containing high numbers of positive lightning.

The month-to-month GFD patterns showed large variability, especially between summer and winter months. Maximum ground flash densities were observed in July at >4.3 km^{-2} in inland pockets. Secondary maximas were seen during the summer months, from June through August (>2.5 km^{-2}), which agrees with both Silver (1995) and Silver and Orville (1995). A strong sea breeze influence can be seen, beginning in May and continuing through August. The predominant low-level flow is southwesterly, which moves the convergence zone between the Gulf Coast sea breeze and the Atlantic Coast sea breeze over to the Atlantic coastal area. This sea breeze was not only responsible for the onshore lightning maximum, but the consequent lack of diurnal heating over the water also helped contribute to the offshore minimum.

Minimum flash densities were seen in December and January with values on the order of <0.02 km^{-2}. These lower flash counts occur throughout the winter months of November through February, which agrees with Silver (1995). During these winter months, the CG lightning activity did not favor either the land or water. However, the transitional months of March, April, and October begin to show variations in lightning activity between water and land, indicating an increase in temperature variations.

The positive ground flash densities yielded similar results as the ground flash density data. As seen with the ground flash densities, the minimum positive values were observed in December and January (<0.03 km^{-2}), and increased into the summer months, with maximums occurring in June through August (>1.1 km^{-2}). These values were consistent with Silver's (1995) results.

The values of the positive ground flash densities were lower than those seen in the ground flash density contours. Also, pockets of increased positive flash density were observed in July and August, which were not consistent with the maximum values associated with the total ground flash density. Since the overall number of positive flashes is relatively small and could be easily influenced by several storms containing a high number of positive CG lightning, this could explain some of the differences in maximum ground flash density locations.

b. Temporal Distributions

The largest number of CG lightning flashes occur during the summer months, as was also depicted by the ground flash density contours, which was in good agreement with Reap and MacGorman (1989) and Orville (1994). A monthly flash rate was obtained using the 10 years of data. Overall, approximately 73% (54 100) of all CG flashes occurred in the summer months of June, July, and August. Only 1.5% (1117) of the total number of flashes were recorded in the winter months of November through February. The monthly flash rates remained fairly consistent throughout the data set.

The percentage of positive lightning was highest in the winter (December), then declined rapidly in January, increasing through March, and then continuing the decline until August. The summer had the lowest percentage, with a yearly low in August of 2.4%. These values were also observed by Orville (1994), who found overall lower values at the latitude of Florida. The largest percentage positive lightning (December) corresponds to the lowest total number of lightning flashes for the year. This small number of CG flashes probably explains the higher percentage positive being observed during the winter months.

The lightning activity at the KSC displayed a strong diurnal pattern, favoring the afternoon hours (2000 UTC) for CG lightning activity, which agrees with Neumann's (1968) findings. A lightning minimum was observed during the early morning hours from 0300 through 1500 UTC. This can be attributed to the main type of thunderstorm (air mass) occurring over the KSC complex, which develops primarily due to thermally unstable, low shear environments. The positive lightning flashes were very similar in diurnal pattern to the total lightning flashes. As expected, the number of positive flashes was lower, with the peak activity still at 2000 UTC.

c. Peak Currents

First stroke peak currents were measured for both negative and positive lightning flashes. For negative flashes, the winter months all show high mean peak currents with values between 44 kA (December) and 47 kA (January). The remainder of the year is primarily uniform with mean peak currents ranging from 33 kA (May) to 42 kA (October). These values are very close to those found by Silver and Orville (1995) and Silver (1995).

For positive flashes, the overall values of peak currents were higher than the negative flashes. Maximum peak currents were also found in the winter, with a 61 kA average for December. Peak currents declined until late spring, and remained nearly steady through the summer, with a minimum value of 24 kA in July. Peak currents increased again during the fall. Once again, these results are similar to those of Silver and Orville (1995) and Silver (1995).

2. Radar Analysis

By applying concepts for detecting the initiation of lightning utilized by Hondl and Eilts (1994), Michimoto (1991), Buechler and Goodman (1990), and Takahashi (1984), the lightning associated with the end of storm was analyzed. This study analyzed both the 40 and 45 dBZ reflectivity levels at the -10°C and -20°C temperature heights. The temperature heights were chosen due to their location within the mixed phase level and importance in the electrification process.

In analyzing the termination of lightning within the three thunderstorms, the time from last observed radar reflectivity level (40-45 dBZ) and the end of all CG lightning indicated some interesting results. At the -20°C (7500 m) temperature height and using the 45 dBZ reflectivity level, the time lags were; 40 min (26 Jun 1996), 35 min (13 Aug 1996), and 40 min (14 Aug 1996), which were fairly consistent. Using the 40 dBZ reflectivity level at this temperature height did not give as consistent results; 30 min (26 Jun 1996), 20 min (13 Aug 1996), and 25 min (14 Aug 1996). At this temperature height (-20°C), it seems that the 45 dBZ reflectivity level provides a better indicator of the end of lightning within these thunderstorms.

The analysis of the thunderstorms at the -10°C (6000 m) temperature height provided slightly better results. The time from last observed radar echo (45 dBZ) until the termination of all CG lightning was 30 min for all three thunderstorms. By using the last 40 dBZ reflectivity echo at the same temperature height, the time lags until end of lightning were; 25 min (26 Jun 1996), 15 min (13 Aug 1996), and 15 min (14 Aug 1996). At this temperature height (-10°C), the 45 dBZ reflectivity level proved to be a better indicator of CG lightning cessation, by indicating a consistent time lag (30 min) from last radar signature echo (45 dBZ) until the termination of all CG lightning activity.

For these three storms, the best indicator to signal the end of lightning was using the 45 dBZ reflectivity echo at the -10°C temperature height. These results closely parallel the findings of Buechler and Goodman (1990), who observed that when radar values of 40 dBZ reached the -10°C temperature height, the initiation of lightning was imminent. Takahashi (1984) observed from his numerical simulation of thunderclouds that the charge separation process around the -10°C temperature level played the most important role in electrical activity in the clouds. It seems that there is a possible link in both the initiation and termination of lightning within the thunderstorm in analyzing this mixed phase region. A possible explanation why the 45 dBZ level provides a better indicator could be due to the thunderstorm stage (mature) and stronger updrafts than would occur at the beginning of a thunderstorm, allowing the suspension of more and larger graupel particles.

3. Electric Field Mill Analysis

The analysis of the field mill data did not prove useful in comparison to the lightning data. During the peak of lightning activity all three storms indicated a large negative electric field. This was not the case as the lightning terminated. In two of the storms (26 Jun and 13 Aug), the field did oscillate between negative and positive values as seen by Moore and Vonnegut (1977) who referred to this as the end-of-storm oscillation (EOSO). However, the thunderstorm on 14 Aug 1996 was dominated by a large positive field, which did not oscillate.

Although the electric field did not indicate any direct relationships with the end of the CG lightning activity, an important result was observed. In all three thunderstorms, even after the CG lightning had terminated, a large electric field was still present. This indicates that although the CG lightning has ended, the strong possibility of triggered lightning is still a concern for safety.

CHAPTER VI

CONCLUSIONS

A lightning summary of the area around the NASA Kennedy Space Center created from a data set of cloud-to-ground lightning flashes detected from 1986 through 1995 indicated that the majority of all thunderstorms for this area occur over land and during the summer months. Maximum lightning activity occurs during July with secondary maximums in June and August. This increase of lightning activity during the summer months is primarily due to a sea breeze convergence zone along the Atlantic coast during the afternoon under a predominant south-westerly flow.

Positive CG lightning was similar in that maximums occurred during the summer months (June through August), while minimums occurred during the winter months (December and January). The location of the positive lightning activity had essentially the same locations, as did all lightning activity.

The percentage of positive lightning had maximum values during December (11.4%) and minimum values in August (2.5%). Although December had the highest percentage of positive lightning, it also had the least lightning activity of the year.

Diurnal distributions of lightning flashes show that thunderstorms are possible during any time of day. But, the KSC area has a diurnal maximum during the afternoon (2000 UTC) that is seen in both negative and positive CG lightning activity.

Peak currents for both negative and positive lightning flashes revealed maximum values during the winter months (January) and minimums during the spring (negative flashes) and summer (positive flashes). Although the peak currents were slightly larger, on the average, for positive flashes, they were similar to the negative flashes in their variations throughout the year, yet had a greater overall variation in values than the negative currents.

Examination of the radar analysis indicated a distinct relationship when the last observed 45 dBZ reflectivity echo was applied at the -10°C temperature height. This combination provided a consistent time interval (30 min) between last signature echo (45 dBZ) and the end of all CG lightning activity. As with the initiation of lightning, it appears that the estimated time till the cessation of lightning may also be possible. Since this is a small sample size, it cannot be assumed to apply to all storms, but further research may provide more conclusive answers. The use of the 40 dBZ reflectivity level or analyzing the -20°C temperature height did not prove to be as effective within these analyzed storms.

Analysis of the electric fields associated with the lightning did not provide any definite results. However, by observing the electrical fields that were present at the end of all CG lightning activity, it appears that the probability of triggered lightning remains high. Further research with a more comprehensive data set, electrical changes per minute or less, may shed more insight into the cessation of lightning and allow a more thorough ability to estimate the termination of all CG lightning activity within this type of thunderstorm.

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APPENDIX

IDL PROGRAM FOR CONTOURING FIELD MILL DATA

```
;===========================================================
;=----------PROGRAM TO CONTOUR FIELD MILL DATA------------=
;===========================================================
;================= Michael S. Hinson ==================
;===========================================================
;--Creating array for grid--
  n=10.0                            ;Indicates size of grid
  lats=[28.35, 28.8]                ;Limits of lat
  longs=[-80.8, -80.485]            ;Limits of lon
  dellat=(lats(1)-lats(0))/n
  dellon=(longs(1)-longs(0))/n
  bins=fltarr(n,n)
  latvalue=findgen(n)*dellat+lats(0)+(dellat/2.0)  ;placing
  lonvalue=findgen(n)*dellon+longs(0)+(dellon/2.0) ;values
                                                   ;in grid
;--Creating map of KSC--
  loadct, 0                          ;loading color table
  tvlct,r,g,b, /get
  r(0)=255
  g(0)=255
  b(0)=255
  tvlct,r,g,b

;--Identifies and Plots Field Mill Locations--
  FMLATS=[28.7034, 28.6873, 0.0, 28.6641, 28.6579,$
         28.6437, 28.6421, 28.6386, 28.6211, 28.6238,$
         28.6055, 28.6020, 28.6018, 28.5782, 28.5765,$
         28.5750, 28.5618, 28.5549, 28.5492, 28.5414,$
         28.5254, 28.5067, 28.4637, 0.0, 28.4245,$
         28.5491, 28.5028, 28.46, 28.4623, 28.4748, 0.0,$
         28.4366, 28.415, 28.4495]

  FMLONS=[-80.6688, -80.7197, 0.0, -80.6393, -80.6996,$
         -80.6666, -80.7478, -80.6228, -80.6082, -80.7017,$
         -80.6741, -80.6412, -80.5896, -80.6088, -80.6433,$
         -80.5733, -80.6702, -80.7023, -80.6206, -80.6447,$
         -80.6223, -80.6938, -80.6545, -0.0, -80.664,$
         -80.5672, -80.5583,-80.5274, -80.5838, -80.5586,$
         -0.0, -80.5803, -80.606, -80.5637]

;--Labeling Field Mill Locations--
  FM=indgen(34)+1
  FM=string(FM)

;--Creating grid for contouring--
  lonidx=fix((fmlons-longs(0))/dellon)      ;locating fm's
```

```
  latidx=fix((fmlats-lats(0))/dellat)       ;on grid

;--Reads in Field Mill data for contouring--
  !p.multi=[0,2,3,0,0]
  set_plot, 'PS'
  device, filename='14ad.ps',xsize=17,ysize=20
  !P.FONT = 3

; **** Read data for row ****
  filepath='c:\idl\datafiles'
  form='(I7,I7,I5,A5,I7.0)'       ;indicating format of data
  found=(1 EQ 0)
  fmval=0                         ;initializing variables
  dum=0
  ltwin=6
  openr,2, 'c:\idl\datafiles\14aug.txt'
  tm=221000
  cond=''
   while (not(found) and not(eof(2))) do begin
      readf,2,format=form,date,time,fmn,cond,fmval
      found=(time EQ tm)
        if found then begin
          print,'found it',time,fmn
            for i=1,33 do begin
             readf,2,format=form,date,time,fmn,cond,dum
             fmval=[fmval,dum]
             print,'found it',time,fmn
            endfor
        endif
   endwhile
  close,2
  print, fmval
  for i=0,33 do begin
      if (fmval(i) NE 0)then begin
        bins(lonidx(i),latidx(i))=fmval(i)
      endif
  endfor

;--Plots Field Mill Locations and Identifiers--

  !p.multi(0)=6
  MAP_SET, /CYL,/label, LIMIT=[28.3, -80.9, 28.85, -80.4],$
   /USA, con_color=180, color=1, charsize=.5, $
   mlinestyle=0,latlab=-80.90,lonlab=28.318, lonalign=0,$
   latalign=.2,latdel=.1,londel=.1
  no0=where(fmlons ne 0.0)
  PLOTS,FMLONS(no0),FMLATS(no0),PSYM=2,SYMSIZE=0.5,$
   color=1
  dytm='Time: '+strmid(strcompress(tm),0,5)

;--Contours Field Mill Data--
  contour, bins,lonvalue,latvalue, /overplot, $
```

```
  LEVELS = [-6000, -3000,-1000, 1000, 3000, 6000],$
           C_LINESTYLE = [1,1,1,0,0,0],$
           c_labels=[1,1,1,1,1,1],c_charsize=.65
  XYOUTS,-80.7,28.8,dytm,charthick=1,charsize=.8,color=1

;--Plots 3D surface contour--
  !P.FONT = 3
  !p.multi(0)=5
  surface, bins,lonvalue,latvalue, ZRANGE = [-8000, 6000],$
   zstyle=1,xcharsize=1, ycharsize=1,zcharsize=1.3, ax=25,$
   zaxis=3,yticks=4,ytickname=[' ','28.4       ',$
   '28.6       ','28.8       ',' '],$
   xtickname=['-80.8','-80.7','-80.6','      -80.5']
  dytm='Time: '+strcompress(tm)

;*** 2nd row ***
  filepath='c:\idl\datafiles'
  form='(I7,I7,I5,A5,I7.0)'
  found=(1 EQ 0)
  fmval=0
  dum=0
  openr,2, 'c:\idl\datafiles\14aug.txt'
  tm=220000
  cond=''
   while (not(found) and not(eof(2))) do begin
      readf,2,format=form,date,time,fmn,cond,fmval
      found=(time EQ tm)
        if found then begin
          print,'found it',time,fmn
            for i=1,33 do begin
             readf,2,format=form,date,time,fmn,cond,dum
             fmval=[fmval,dum]
             print,'found it',time,fmn
            endfor
        endif
   endwhile
  close,2
  print, fmval
  for i=0,33 do begin
      if (fmval(i) NE 0)then begin
        bins(lonidx(i),latidx(i))=fmval(i)
      endif
  endfor

;--Plots Field Mill Locations and Identifiers--
  !p.multi(0)=4
  MAP_SET, /CYL,/label, LIMIT=[28.3, -80.9, 28.85, -80.4],$
   /USA, con_color=180, color=1, charsize=.5, $
   mlinestyle=0,latlab=-80.90,lonlab=28.318, lonalign=0,$
   latalign=.2,latdel=.1,londel=.1
   no0=where(fmlons ne 0.0)
   PLOTS,FMLONS(no0),FMLATS(no0),PSYM=2,SYMSIZE=0.5,$
```

```
    color=1
  dytm='Time: '+strmid(strcompress(tm),0,5)

;--Contours Field Mill Data--
  contour, bins,lonvalue,latvalue, /overplot, $
  LEVELS = [-6000, -3000, -1000, 1000, 3000, 6000],$
           C_LINESTYLE = [1,1,1,0,0,0],$
           c_labels=[1,1,1,1,1,1], c_charsize=.65
  XYOUTS,-80.7,28.8,dytm,charthick=1,charsize=.8,color=1

;--Plots 3D surface contour--
  !P.FONT = 3
  !p.multi(0)=3
  surface, bins,lonvalue,latvalue, ZRANGE = [-8000, 6000],$
   zstyle=1,xcharsize=1, ycharsize=1,zcharsize=1.3, ax=25,$
   zaxis=3,yticks=4,ytickname=[' ','28.4       ',$
   '28.6       ','28.8       ',' '],$
   xtickname=['-80.8','-80.7','-80.6','      -80.5']
   dytm='Date/Time: '+strcompress(date)+'/'+strcompress(tm)

;**** 3rd row ****
  filepath='c:\idl\datafiles'
  form='(I7,I7,I5,A5,I7.0)'
  found=(1 EQ 0)
  fmval=0
  dum=0
  openr,2, 'c:\idl\datafiles\14aug.txt'
  tm=220500

  cond=''
   while (not(found) and not(eof(2))) do begin
      readf,2,format=form,date,time,fmn,cond,fmval
      found=(time EQ tm)
        if found then begin
          print,'found it',time,fmn
            for i=1,33 do begin
             readf,2,format=form,date,time,fmn,cond,dum
             fmval=[fmval,dum]
             print,'found it',time,fmn
            endfor
        endif
   endwhile
  close,2
  print, fmval
  for i=0,33 do begin
      if (fmval(i) NE 0)then begin
        bins(lonidx(i),latidx(i))=fmval(i)
      endif
  endfor

;--Plots Field Mill Locations and Identifiers--
  !p.multi(0)=2
```

```
  MAP_SET, /CYL,/label, LIMIT=[28.3, -80.9, 28.85, -80.4],$
   /USA, con_color=180, color=1, charsize=.5,$
   mlinestyle=0,latlab=-80.90,lonlab=28.318, lonalign=0,$
   latalign=.2,latdel=.1,londel=.1
   no0=where(fmlons ne 0.0)
   PLOTS,FMLONS(no0),FMLATS(no0),PSYM=2,SYMSIZE=0.5, $
    color=1
  dytm='Time: '+strmid(strcompress(tm),0,5)

;--Contours Field Mill Data--
  contour, bins,lonvalue,latvalue, /overplot, $
  LEVELS = [-6000, -3000, -1000, 1000, 3000, 6000],$
           C_LINESTYLE = [1,1,1,0,0,0],$
           c_labels=[1,1,1,1,1,1],c_charsize=.65
  XYOUTS,-80.7,28.8,dytm,charthick=1,charsize=.8,color=1

;--Plots 3D surface contour--
  !P.FONT = 3
  !p.multi(0)=1
  surface, bins,lonvalue,latvalue, ZRANGE = [-8000, 6000],$
   zstyle=1,xcharsize=1, ycharsize=1,zcharsize=1.3, ax=25,$
   ax=25,zaxis=3,yticks=4,ytickname=[' ','28.4       ',$
   '28.6       ','28.8       ',' '],$
   xtickname=['-80.8','-80.7','-80.6','      -80.5']
  dytm='Date/Time: '+strcompress(date)+'/'+strcompress(tm)

; **** End of row ****
  device,/close
  set_plot='WIN'

end
```

VITA

Michael Shawn Hinson [redacted]. The family moved to Owensville, Missouri in 1963 where they still reside. Michael enlisted in the Air Force in October 1982. He was selected for the Airman Education and Commissioning Program in October 1989 and graduated from the University of Arizona with a Bachelor of Science degree in Atmospheric Science in May 1992. After commissioning he was assigned to Tyndall AFB, Florida, where he remained until June 1995, as the First Air Force Staff Weather Officer and also Southeast Sector Weather Officer.

Michael lives with his wife Cathy, daughter Andrea, and son Christopher. [redacted]