15.7 THUNDERSTORM CHARACTERIZATION DERIVED FROM CLOUD TO GROUND LIGHTNING FLASH DATA BASED ON INTERCOMPARISONS OF HOVMÖLLER DIAGRAMS AND SPATIAL DENSITY DATA

Thomas A. Seliga[1*], David A. Hazen[2] and Cynthia Schauland[3]

1. Volpe National Transportation Systems Center, Cambridge, MA
2. Titan/System Resources Corporation, Billerica, MA
3. Federal Aviation Administration, Washington, DC

1. INTRODUCTION

This paper demonstrates the potential utility of examining lightning flash spatial and temporal density variations as a means of evaluating the effects of thunderstorms on air traffic operations, particularly as they relate to an arbitrarily selected region in the mid-western part of the contiguous United States (CONUS). The region of interest is centered on Kentucky, encompassing a latitude range of 35-41º N and a longitude range of 79-92º W. This region was arbitrarily selected as being representative of an important aviation corridor within the CONUS that is subject to higher delays due to severe weather. The region is centered on Ft. Knox and Louisville, KY and covers, for example, Cleveland and Cincinnati, OH, St. Louis, MO and Memphis, TN; its northern border is just south of Chicago, IL.

The lightning data used here were obtained from archived reports on lightning cloud-to-ground flashes reported by Global Atmospherics, Inc. (GAI) through its National Lightning Detection Network (NLDN). The NLDN detects and reports the occurrence of cloud-to-ground lightning flashes throughout the CONUS (Orville, 1991; Orville and Silver, 1997; Orville and Huffines, 1999; Orville and Huffines, 2001). The lightning data are represented on distance vs time plots or Hovmöller diagrams, similar to those used in previous studies (Seliga et al., 2002a, b). In this paper, the focus in on the latitudes and longitudes that cover the region described above. The Hovmöller plots have a spatial resolution of 0.05º in both latitude and longitude and temporal resolution of 15 minutes. Areal flash density plots within this region over periods of 30 minutes also provide essential information on the location and movement of thunderstorms. Plots of daily, monthly and yearly averages are included to show spatial and temporal flash distributions.

NEXRAD weather radar data are also used to compare areas of lightning activity with precipitation activity during select events. The data were taken from a UCAR web site (Carbone et al., 2001)

2. LIGHTNING AND NEXRAD DATA

The U.S. DOT Volpe Center has utilized and analyzed NLDN data for over 11 years, primarily in support of the FAA's program to automate the detection and reporting of thunderstorms through Automated Weather Observing Systems (AWOS) and Automated Surface Observing Systems (ASOS) (Canniff, 1993; Kraus and Canniff, 1995; Kraus et al., 2000; Seliga et al., 2000). Essentially, NLDN data signify the occurrence of cloud-to-ground lightning flashes and represent the occurrence of thunderstorms throughout the U.S. The data have proven useful for numerous applications (e.g., Changnon, 1988a, b; Holle and Lopez, 1993; Orville, 1997; Orville et al., 1999; Rhoda and Pawlak, 1999; Seliga and Shorter, 2000; Orville and Huffines, 2001; Bates et al., 2001).

The NLDN flash data examined here cover the April-June 1998 time period, which is major period of thunderstorm activity.

NEXRAD data are also used in examining particular events in order to compare precipitation distributions with lightning distributions. The data are in the form of composite radar images of the Central Mississippi River Valley region. The images are typically 30 minutes apart. The NEXRAD data provide ground-truth for the lightning data and to which latitude-longitude flash density plots are compared.

3. HOVMÖLLER DIAGRAMS

The lightning data were examined using time-distance or Hovmöller diagrams, similar to those introduced by Carbone et al. (2002) for analyzing NEXRAD data for warm season storm characterizations over a large portion of the CONUS. Seliga et al. (2002a) demonstrated strong correlations between lightning and NEXRAD data with this technique. The applicable time scales can range from hours to a few days to a few months. Such diagrams have been found useful for climatological studies that examine one or more variables such as rainfall, temperature and winds. Sample latitudinal and longitudinal Hovmöller plots, produced from NLDN data, are shown in Figs. 1 and 2. These plots cover an eleven-day period from May 21-31, 1998. Similar diagrams can be derived for varying time periods, ranging typically from several hours to an entire month. The data may also be averaged over different time periods such as days, weeks, months, seasons and years to yield varying properties of the phenomenon being investigated. In this study, a sequence of days and monthly average Hovmöller

[*] Corresponding Author Address: Thomas A. Seliga, Surveillance and Sensors Division, DTS-53, Volpe National Transportation Systems Center, 55 Broadway, Cambridge, MA 02142-1093; **Email:** seliga@volpe.dot.gov

diagrams are considered first. Then, several plots of selected individual events are finally examined.

A thorough interpretation of the data in Figs. 1 and 2 would require extensive use of other data and is, therefore, outside the scope of this study. Examples of possibly relevant data include images of the spatial distribution of the lightning at different time intervals, satellite and radar data, other meteorological parameters within or affecting the same spatial and temporal domains, topographical features and representations of weather from applicable numerical models. Nevertheless, the data in Figs. 1 and 2 by themselves reveal a number of important features. A changing diurnal pattern is evident in the lightning events, lasting throughout nearly all of the eleven-day period. Distinctive features of the events include: onset and terminal times; duration or persistence of events, as coherent entities and as a function of latitude and longitude; directional movement and speed of different features; location of storm initiation and decay; relative intensity of events; and long-term stability or coherency of events over consecutive days.

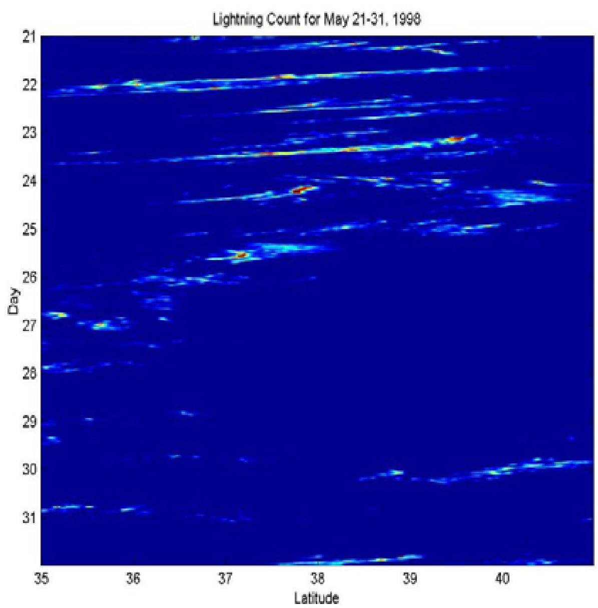

Fig. 1. Eleven-day cloud-to-ground lightning flash Hovmöller latitude diagram of Midwest area

Both figures show that, during this period, mostly N to S and W to E transport, ranging from occasional stationarity to movements at various speeds in both directions, dominated thunderstorm motion. The latitudinal and longitudinal speeds are readily determined from the slopes of the streaks or through 2-D autocorrelations of the diagrams; these speeds vary considerably and often exhibit strong coherency from day to day, from storm cell to storm cell or within a given storm system. For example, Fig. 1 shows a continuing transition of similar, slowly changing events from day-to-day over nearly the entire period, starting with highly coherent, relatively intense, structured events that move rapidly to the S from high latitudes early in the period and ending with less coherent, less intense, nearly stationary events that originate at low latitudes. Fig. 2 shows that these same events retained great similarity in the direction and speed of transport from W-E over the entire time frame (~7-8 days). The day-to-day coherency with latitude is wavelike and strongly suggestive of effects associated with larger scale, synoptic forcing or modulation with a period of around 10-14 days (Orlanski, 1975).

Intensity is also of fundamental interest. The intensity in Figs. 1-2 represents the number of flashes occurring in 0.05^{o} latitudinal and longitudinal swaths over 15 min time intervals. Since lightning activity may be interpreted as a measure of convective strength in warm season events, these intensity values are a measure of thunderstorm severity. In this regard, the first days of Fig. 1 show a strong diurnal variability with storm initiation beginning at high latitudes on the 21st and then proceeding southwards over fairly narrow latitudinal and longitudinal bands over time; to a great extent, this general pattern repeated itself until the 25th.

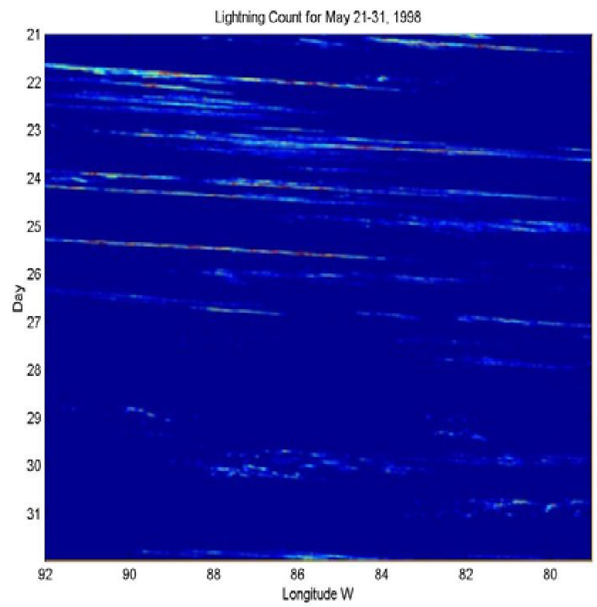

Fig. 2. Eleven-day Hovmöller longitude diagram corresponding to the data in Fig. 1

Although difficult to see in these figures, the intensity of the lightning activity typically fluctuates over time as thunderstorm cells evolve through the process of growth, decay and regeneration during the traverse of the storm systems. Applicable time scales are of the order of tens of minutes to several hours. Individual cells can often be discriminated within these bands as well. Association of these with time samples of the lightning and NEXRAD images over the region of interest helps ensure correct interpretation of the Hovmöller plots.

Fig. 2 shows the corresponding longitudinal Hovmöller diagram for the same time period used to generate Fig. 1. To account for differences between latitude and longitude widths, the lightning flash counts were normalized using a scale factor of 2.07. This plot, similar to Fig. 1, also shows a tendency of sequences of days to repeat a pattern of thunderstorm activity that drifts eastward with the overall set appearing to contain strong periodicity of several days superimposed onto the dominant 10-14 day feature observed in the latitudinal plots. The typical W-E speeds are much greater by around a factor of two than the N-S speeds seen in Fig.1. Other contrasting features in Fig. 2 are the occurrence of both fine and diffuse line widths, corresponding to single cell (or, alternatively, dominantly N-S squall line) and multicell storms, respectively. A striking feature of both the latitudinal (Fig. 1) and longitudinal (Fig. 2) plots is the fact that storm speeds rarely change throughout their lifetime, implying that nowcasting of storm location of periods of several hours can be inferred with a high probability of success. Since intensity variations over the duration of different storms also seem to follow predictable patterns, good nowcasting of storm intensity should also be possible.

In order to illustrate the resolution inherent to the 14-day sequence of Figs. 1-2, Hovmöller diagrams for the 24-hour period on May 20, 1998 are given in Figs. 3 and 4. The latitudinal plot in Fig 3 shows areas of intense flash activity entering the region of interest at 0000 from around 39.5 to 41^o N and moving south. This region dissipated by 0900.

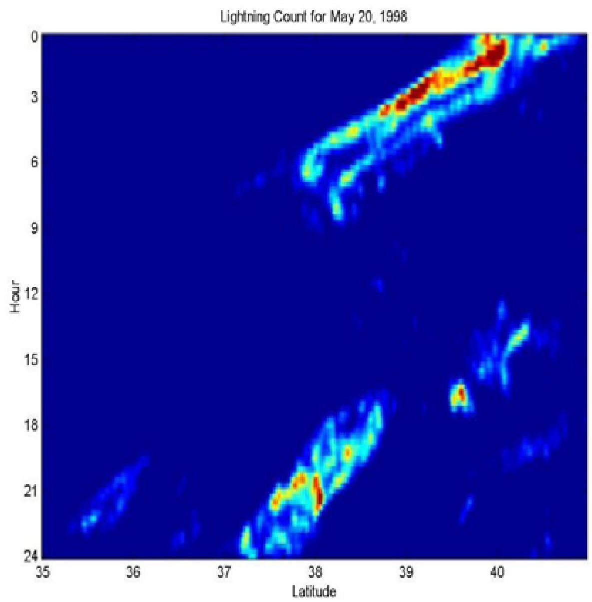

Fig. 3. One-day Hovmöller latitude diagram of Midwest area for May 20, 1998

Another broad line of activity formed just before 1600 just below 39^o N and moved south to 37-38^o N by the end of the day; this system also move south, but at around a factor of two slower speed. Several smaller regions are also present with storms that lasted 4 hours or less. Fig 4 shows that the activity that was evident at 0000 between 39.5 - 41^o N extended mostly over longitudes from 86 - 90^o W, and that this storm complex moved W-E at a speed of around 38 knots. The combinations of diffuse longitudinal and latitudinal Hovmöller plots are evidence of a multicell storm system; the presence of high intensity regions in the plots corresponds to individual thunderstorm cells.

During the latter half of the day, another feature arises that represents a narrow squall line that began around 1700 at ~ 88.2^o W and eventually extended over ~ 1^o in latitude, lasting into the next day. Similar to the previous storm earlier in the day, this line moved from W-E at about 38 knots, although its transport N-S, as noted previously, was significantly faster by a factor of around two. The presence of multiple cells within the squall line is evident in the latitudinal plot (Fig. 4), but not readily seen in the longitudinal plot (Fig. 3). There was also a slightly broader line of activity moving eastward that entered after 1200; this activity narrowed somewhat with longitude over time, ending with a burst of intensity at around 1700 that was centered on ~ 39.5^o latitude. Less intense storms, having very different longitudinal features, are also present in the late afternoon record. East of the main storm system, two storms were stationary in longitude, while west of this system the secondary storm moved eastward similar to the main storm system. From Fig. 3, it is seen that the former two storms were north of the main storm, while the latter was south of the main storm.

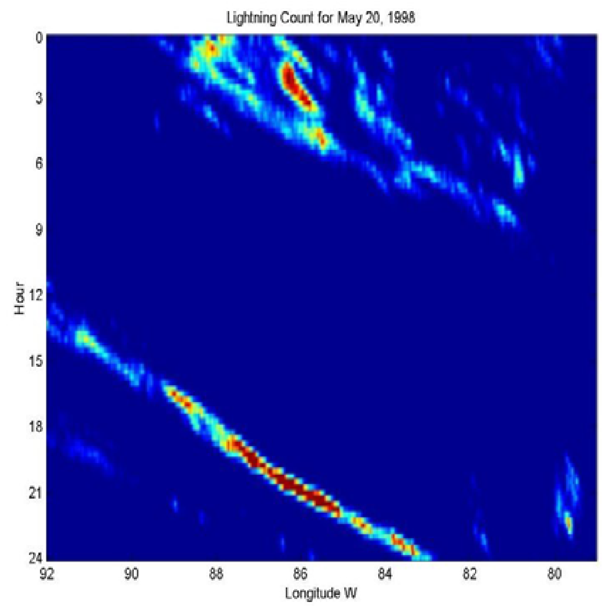

Fig. 4. One-day Hovmöller latitude diagram of Midwest area for May 20, 1998

3.1 Average Hovmöller Diagrams

Hovmöller diagrams of averaged data are also useful for determining features of storms in the region of interest. Figs. 5 and 6 are average Hovmöller plots of lightning flash data for the month of May 1998. Similarly, Figs. 7-8 and 9-10 are plots for the spring (April – June) and annual lightning flash events for this same year. A number of characteristics of storms in this region can be readily gleaned from these representations.

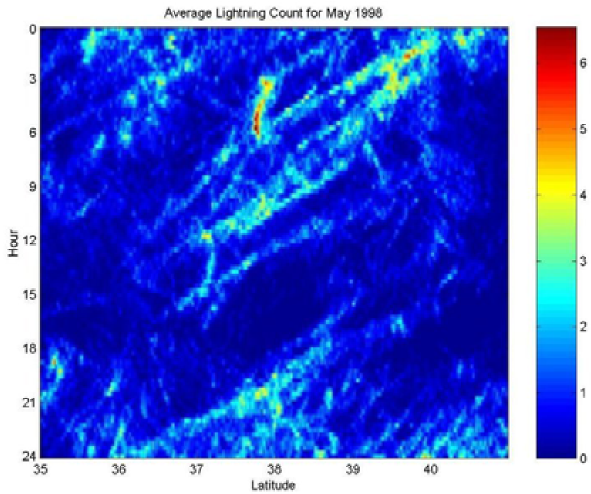

Fig. 5. Hovmöller latitude diagram of May 1998 average flashes

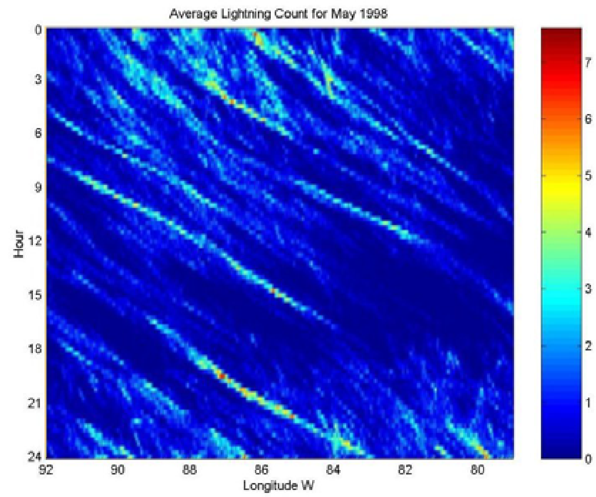

Fig. 6. Hovmöller longitude diagram of May 1998 average flashes

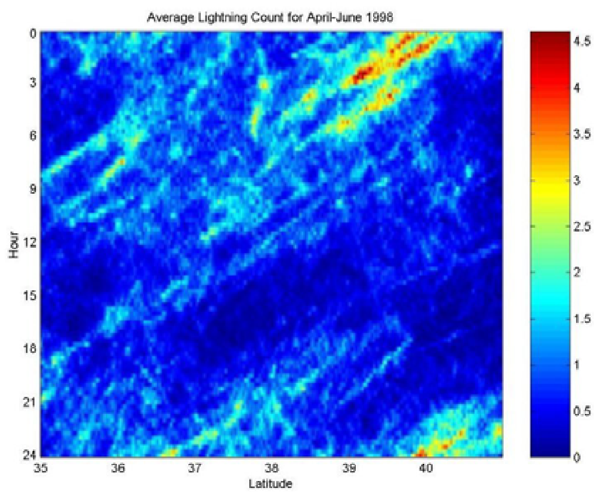

Fig. 7. Hovmöller latitude diagram of Spring 1998 average flashes

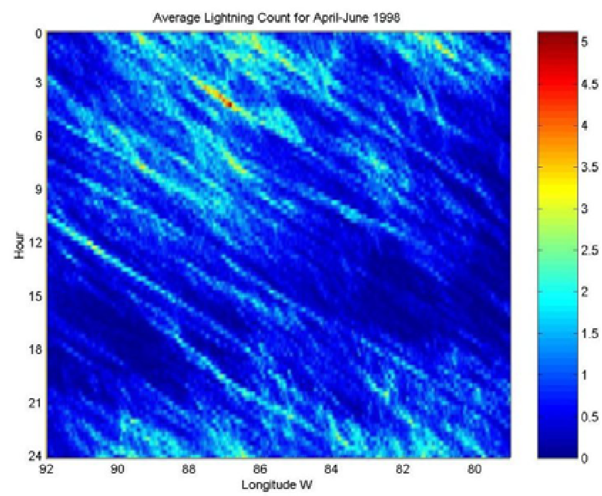

Fig. 8. Hovmöller longitude diagram of May 1998 average flashes

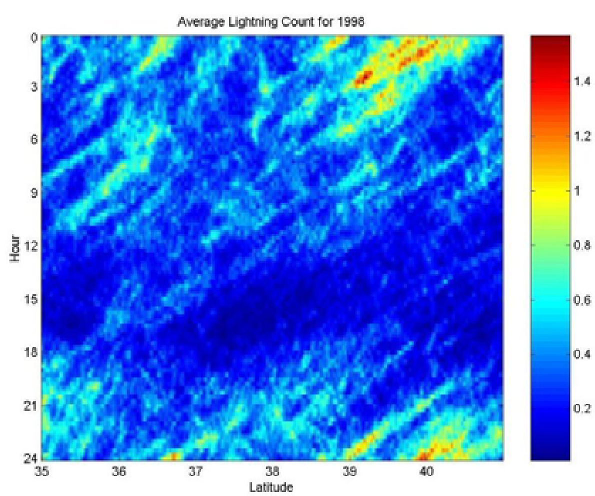

Fig. 9. Hovmöller latitude diagram of 1998 average flashes

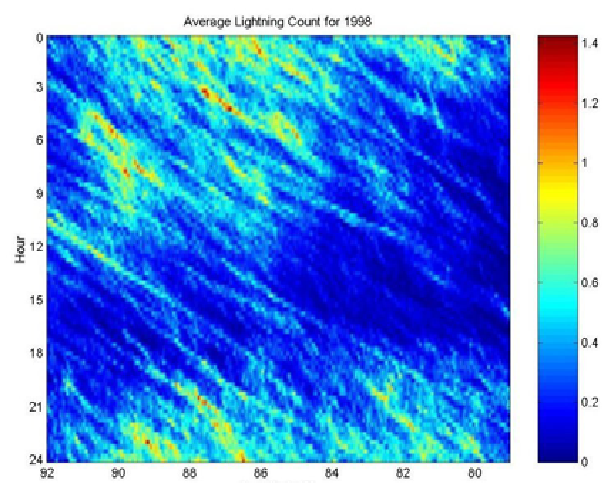

Fig. 10. Hovmöller longitude diagram of 1998 average flashes

Storm Motion The progression of storm systems is dominantly from W-E and N-S, consistent with the common pattern of midlatitude convective activity (Houze, 1993). Speeds W-E are typically around twice as fast as the N-S speeds.

Diurnal Pattern All the plots show the expected strong diurnal pattern associated with convection responding to solar heating. For example, thunderstorm initiation typically begins after noon local time (~ 1800 GMT), peaks in the late afternoon and ends around 5 AM, producing a morning lull. Occasionally, storm tracks are seen to extend on through this lull. Also, the general trend of onset and ending times of the dominant storm period tracks westward in accordance with the change of local time with longitude. The termination time of severe thunderstorm activity is particularly variable between the eastern and western sectors as seen in Figs. 6, 8 and 10.

Latitude Bands Both the intensity and number of storms appear dominant in the northern sector of the region, with this pattern happening consistently throughout the month of May, during the spring and annually.

Longitude Bands The occurrence and intensity of storms over the longitudinal range of interest are more uniform than their occurrence with latitude, although the band from ~ 84-90^{o} exhibits more proclivity towards thunderstorm activity.

Commonality The monthly (May), spring (April-June) and yearly latitudinal and longitudinal diagrams are highly similar. This means that thunderstorm behavior in the region is not only dominated by the spring season but also similar throughout the year.

Geographic Distribution The banding of lightning activity seen in the Hovmöller diagrams suggests the possibility of a strong dependence of thunderstorms with geography. This was tested by producing an average lightning flash density image over the region of interest as seen in Fig. 11. The location of several key cities is noted on this image. The image shows a number of large areas with high lightning activity as well as a number of areas with considerably less activity by as much as a factor of five or more (e.g., the regions north of Memphis and the very large region bordered on the west by St. Louis, on the south by Louisville, on the east by Cincinnati and on the north by Indianapolis and beyond compared to the region on the east between ~ 79-84^{o} W and 35-39^{o} N).

4. LATITUDE-LONGITUDE AND NEXRAD PLOTS

Latitude-longitude images of 30-minute flash counts were examined during events selected from the spring 1998 period to locate and examine storms in more detail. The plots were then animated in time to explore the behavior of these events. Major cities within the region are also identified. These images could then be compared with images of NEXRAD precipitation data (Carbone et al., 2001) obtained during the same time period. They also provide important insights into the identity of the storms that are represented on the Hovmöller diagrams. A sample storm is discussed to illustrate how insights into storm behavior can be gleaned from the lightning data presented in the ways indicated. The discussion is limited, since the purpose is to illustrate potential rather than perform in-depth analyses. The latter are outside the scope of the current effort.

Images of average flash distributions covering a day, a month, the spring season and the 1998-year were also produced as shown in Figs. 11-14. The images of average lightning activity can also be compared with the region's topography to help ascertain its possible influence on storm development.

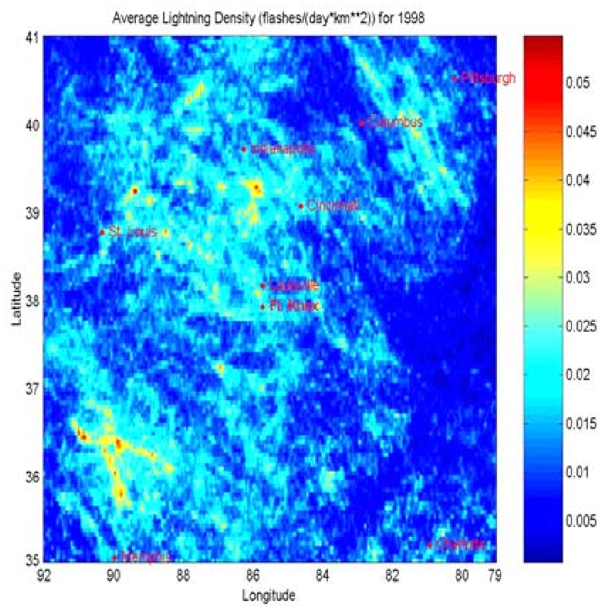

Fig. 11. Latitude-longitude image of average flash distribution for 1998

4.1 Average Flash Distributions

Fig 11 shows the average flash distribution for all of 1998. A few days in July and December are missing from the data set. Note the areas of elevated average activity north of Memphis, TN; between St. Louis, MO and Cincinnati, OH and the area east of Columbus, OH. The activity north of Memphis is mostly over the Mississippi River Valley just east of the Ozark Plateau. Another area of increased activity is north of the Ohio River valley. The area east of Columbus encompasses the Appalachian Plateau, consisting of rolling hills and valleys northeast of Columbus, gradually changing into steep hills and valleys in the southeast. Slightly east of Columbus and extending westward are the Till Plains, consisting of gently rolling plains and occasional hills. Interestingly, the NNW to SSE alignment of lightning activity follows the general topographic contours of the region, suggesting an orographic influence on convective storm activity as weather systems migrate west to east.

Average activity was also somewhat elevated in the Louisville-Ft. Knox, KY area that is a short distance south of the Ohio River. There is an extended region west and north that corresponds generally to a portion of the greater lowlands, Gulf Plains Region that starts at the Gulf of Mexico and extends north to Illinois as well as into the Southern Lowlands of Indiana. The region of decreased activity that is east of 82^o W and between about 36-39^o N corresponds to the Appalachian Plateau (Cumberland Plateau south of the Ohio River in Kentucky). Note that data in this region of low lightning activity may be suspect; the northern and southern borders appear to have distinctive edges as well as form. The boundaries appear ellipsoidal, suggesting that they might possibly be due to an instrumental/detection defect or other fault/limitation in an NLDN receiver. This possibility has not been investigated.

Fig 12 shows the average lightning activity for the spring April-June 1998 time period. The areas of increased activity are very similar to those in Fig. 11. Modest exceptions include the additional area of increased activity south of the Louisville-Ft. Knox area (note the different intensity scales). The great similarity between the annual and seasonal images indicates that thunderstorm activity in this region is dominated by spring storms as derived previously from the Hovmöller plots.

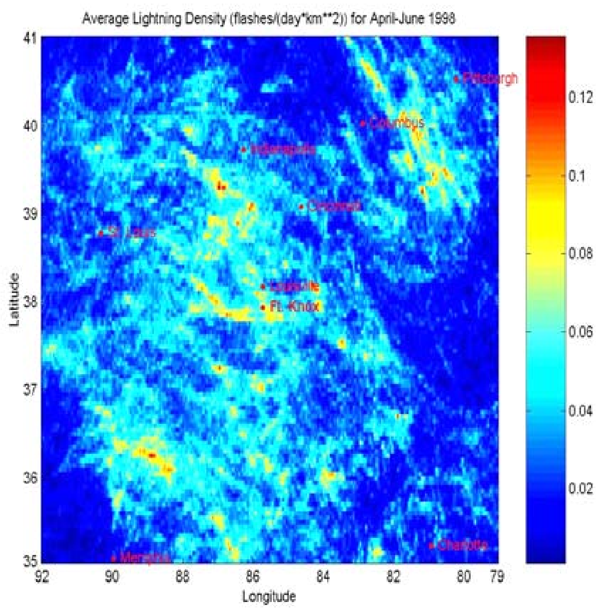

Fig. 12. Latitude-longitude image of average flash distribution for April-June 1998

Fig. 13 shows the averages for May 1998. Unlike Figs. 11-12, the areas of highest activity are in the Louisville-Ft. Knox area with major tracks intersecting this region from W to E as well as on a line from the NNW. Note that the areas that showed increased activity in Figs. 11-12, namely north of Memphis and east of Columbus, were obviously from a different time period in the spring of 1998.

Images of daily events also are useful for evaluating the intensity and tracks of thunderstorms that occur throughout a region of interest, for assessing the accuracy of forecasts and nowcasts of thunderstorms and for determining regions of convective precipitation.

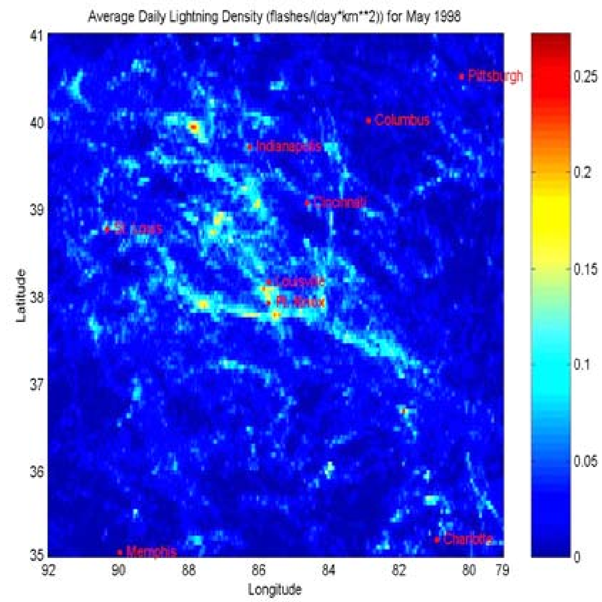

Fig. 13. Latitude-longitude image of average flash distribution for May 1998

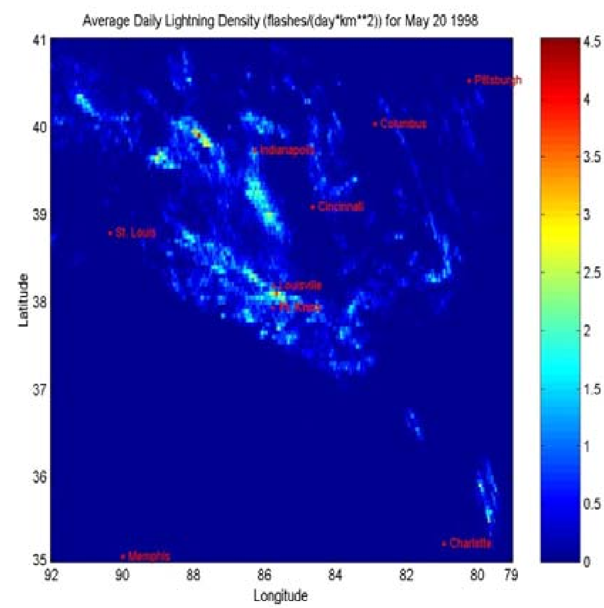

Fig. 14. Latitude-longitude image of average flash distribution for May 20, 1998

4.2 NEXRAD-NLDN Sample Event Day

The event day examined is May 20, 1998, which was the first of several consecutive days in which lightning flash activity was recorded in the Louisville-Ft. Knox, KY area. The Hovmöller plots for this day are given in Figs. 3 and 4; although specific referral to them is not included in the forthcoming discourse, features and properties of the storms can be found in these figures. NEXRAD data were also available, but with some data gaps.

On this day, the first major city affected was Indianapolis, which experienced a rather intense area of flash activity from about 0100-0130 GMT. The cell moved in from the NW as part of the extended storm system described in Section 2 under this day's activity. Next to that cell was a somewhat larger cell to the east. The two cells merged by 0200 after the former just moved south of Indianapolis. No NEXRAD data were available.

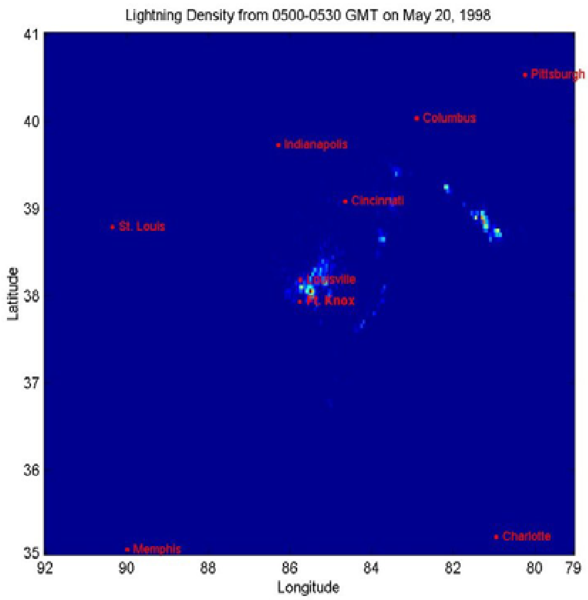

Fig. 15. Sample Latitude-Longitude plot, 30 min counts

At 0330-0430, another cell within the system passed just west of Cincinnati. Meanwhile, the cells that passed through and west of Indianapolis merged and approached the Louisville area. This region experienced lightning flash activity from about 0430 to almost 0600. An image of the activity between 0500-0530 is shown in Fig. 15. The storm dissipated as it passed through Ft. Knox and, by 0930, all activity had almost completely dissipated. The 0400 NEXRAD plot indicated an area of moderate to heavy rain in southern Indiana and northern Kentucky with Ft. Knox on the edge of the moderate rain. The NEXRAD frames from 0430-0530 showed the area of moderate to heavy rain moving southeast with south central and southeastern Indiana, western Ohio and northern Kentucky affected, including Louisville. The 0530 NEXRAD frame is shown in Fig. 16.

Louisville experienced another storm from about 2030-2200. This system entered the area of interest from the northwest around 1230 and was small in extent. The NEXRAD image for 1230 shows a small area of heavy rain in north central Illinois and a much larger area of moderate to heavy rain in northeast Missouri and central Iowa. The rain cell in Illinois dissipated considerably and was mostly confined to northwest central Illinois. The other component expanded and intensified somewhat by 1400 with a weaker and smaller second cell to the southwest. The NEXRAD plots for 1330 and 1400 show that this system re-intensified and became more compact as it moved through Illinois. Meanwhile, the larger area of rain had moved into western Illinois and eastern Missouri with areas of heavy rain near the Missouri-Illinois border by 1400. The 1430 NEXRAD image showed the small cell dissipating into a very small cell of moderate to heavy rain in east central Illinois, and the larger rain area moving further into western Illinois. The two cells dissipated and, by 1500, merged into a single cell located about 80 statute miles north of St. Louis, MO. The NEXRAD image taken at 1500 also shows this, with only the larger area of rain surviving and moving into central Illinois. The cell then dissipated somewhat by 1700; in the meantime, new cells formed east of St. Louis.

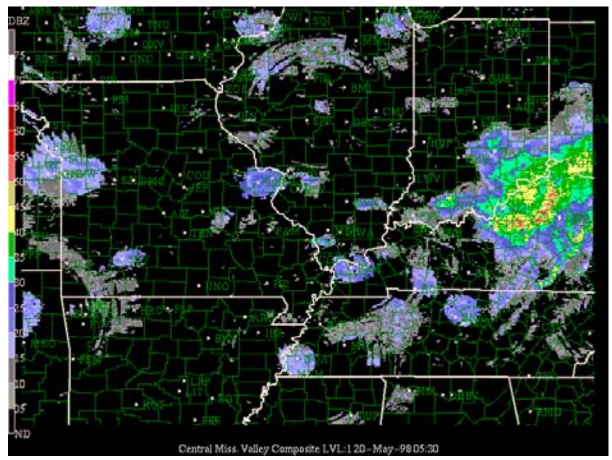

Fig. 16. Sample NEXRAD image of the storm of May 20, 1998 at 0530 GMT (Carbone et al., 2001)

There are no NEXRAD data available from 1700; however, at 1630, the storm system had moved almost entirely out of Missouri and covered much of central and southern Illinois. The cells then narrowed by 1730, shrunk into two small but moderately intense cells about halfway between St. Louis and Louisville by 1800. The 1730 NEXRAD image showed the rain area becoming somewhat tighter with two areas of heavy rain as it moved into east central Illinois. The areas of heavy rain were located at the northern and southern limits of the rain area in Illinois. There was an area of very light rain between the southern heavy rain cell and the principal area of moderate to heavy rain. The two cells merged completely by 1900 and continued to approach the Louisville-Ft. Knox area. The cell dissipated somewhat by 1930 and re-intensified slightly by 2000 as it continued to approach Louisville and Ft. Knox. The corresponding rain event had spread out as it went through southern Indiana and approached Ft. Knox. As the cell entered the Louisville-Ft. Knox area by 2100, it had spread out somewhat in east-west extent. The 2030 NEXRAD image showed heavy rain on the south central

Indiana-Kentucky border surrounded by an area of light to moderate rain. The northern limit of the flash activity was Louisville, and the center of the storm passed through Ft. Knox between 2030-2130. The storm remained intact after it passed through Ft. Knox through the end of the day as it continued its ESE motion. NEXRAD data were not available after 2030.

5. SUMMARY

This study examined lightning activity within the Midwestern part of the CONUS in order to demonstrate how time-distance or Hovmöller plots with latitude and longitude can be used with other representations of lightning data such as latitude-longitude plots to help elucidate the spatial and temporal behavior of thunderstorm activity. Such representations of lightning data appear relevant to improving the nowcasting of thunderstorms out to several hours; this is based on both the general features of storm behavior evident in the plots and cursory examination of sample storm events.

Hovmöller plots with time resolution of 15 minutes and spatial resolution of 0.05^{o} in latitude and longitude appear adequate to show the onset, decay and temporal evolution of thunderstorms over periods of hours, days, months and seasons. As demonstrated previously (Seliga et al., 2002a) through comparisons of Hovmöller plots of lightning and NEXRAD-based rainfall, the radar and NLDN data are highly correlated in space and time, although exceptions to this were seen previously in hurricane events that were dominated by the formation of warm stratiform precipitation. The speeds and intensity of individual thunderstorm cells and storm systems are readily deduced from the Hovmöller plots. This representation, particularly when combined with geographical images of lightning activity and radar-derived precipitation, suggests a number of empirical means of deducing short-term forecast properties of thunderstorms, including intensity, stage of development, direction of travel and speed, cellular structure, duration, etc. Directed research on these topics is necessary in order to develop suitable algorithms for this purpose and to effect useful means of integrating these with data from other sensors and inferences from numerical forecasting products. The inclusion of such representations and associated inferences in the analysis of thunderstorm-producing weather systems should prove useful for improving forecasting and nowcasting of severe weather for use by the general public as well as for specific applications such as in aviation operations and studies of climatology and hydrology.

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