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A CLIMATOLOGY OF THE ORIGIN, MOVEMENT, DURATION, AND TERMINATION OF CONVECTIVE SYSTEMS IN THE NORTH-CENTRAL UNITED STATES

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Major Professor's Signature

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A CLIMATOLOGY OF THE ORIGIN, MOVEMENT, DURATION, AND TERMINATION OF CONVECTIVE SYSTEMS IN THE NORTH-CENTRAL UNITED STATES

By

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ABSTRACT

A CLIMATOLOGY OF THE ORIGIN, MOVEMENT, DURATION, AND TERMINATION OF CONVECTIVE SYSTEMS IN THE NORTH-CENTRAL UNITED STATES

By

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Lighting observations from the summer season of 2004 were used to develop a climatology of the origin, movement, duration, and termination of convective systems in the north-central United States. Previously-proposed mechanisms of nocturnal convection were assessed based on the characteristics of the convective systems. Most nocturnal systems that occurred in the central plains and Great Lakes region formed upstream and propagated into these regions. Nearly 60% of non-local nocturnal systems in the central and eastern plains (99.9°W-90°W) formed near the Rocky Mountains, typically during the afternoon hours. These results support earlier work suggesting that the nocturnal precipitation maximum in the central United States is largely due to propagating systems from the lee of the Rocky Mountains. Additionally, the findings suggest that propagating systems that form farther eastward in the central plains contribute to nocturnal convection in the Great Lakes region. Locally-formed nocturnal convection was also observed. The majority of local nocturnal systems formed during the nighttime or morning hours when the low-level jet is climatologically most frequent. Convection that formed over the Great Lakes at all times of the day was often short-lived, and propagating systems typically terminated within 2 hours after moving over the Great Lakes. These observations suggest that the lake surfaces, which are typically cooler than the surrounding land surfaces especially during the daytime hours, inhibit convection.

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Chapter 1 Introduction and Objectives

1.1 Introduction

Atmospheric convection is defined as the mass motions within the atmosphere that result in the transport and mixing of the properties of the atmosphere (American Meteorological Society 2000). Convection within the atmosphere is often associated with the rising motion of moist air that results in the development of cumulonimbus clouds, and thus, precipitation, although convection may also be dry (i.e., producing no precipitation at the ground) (American Meteorological Society 2000). Furthermore, strong convective updrafts are essential to thunderstorm development (American Meteorological Society 2000).

Convective weather systems, including thunderstorms and systems that produce heavy precipitation, are common throughout the continental United States. A fascinating aspect of convection is the variation in the time of day convection is most likely to occur. Thermodynamically, thunderstorms are expected to occur in the late afternoon hours when intense daytime heating destabilizes the atmosphere (Pitchford and London 1962, Balling 1985, Walters and Winkler 1999). Despite this, a well documented nocturnal precipitation maximum exists during the summer (June, July, and August) within the northern and central portions of the United States (Kincer 1916, Wallace 1975, Easterling and Robinson 1985, Winkler *et al.* 1988, Winkler 1992). A number of mechanisms have been suggested for the nocturnal maximum; however, no detailed theory regarding organized nocturnal convection exists today (Trier *et al.* 2006).

Summertime nocturnal convection also occurs in portions of the Great Lakes region (Wallace 1975, Easterling and Robinson 1985, Winkler *et al.* 1988, Winkler 1992). The Great Lakes introduce more complexity to the diurnal cycle of convection within the region, due to possible impacts of the lakes on convective systems. Most research has focused on the influence of the Great Lakes on wintertime precipitation (e.g., Changnon 2006, Schroeder *et al.* 2006). Summertime effects of the lakes on convection are not well documented and are therefore poorly understood.

This study develops a climatology of the origin, movement, duration, and termination of convective systems (i.e., thunderstorms) in the north-central United States (from central Montana and Wyoming to western New York) that will be used to assess the relative importance of proposed forcing mechanisms for nocturnal convection and the influence of the Great Lakes on convection.

1.1(a) Nocturnal Convection

Diurnal variations in convective activity have been investigated throughout the United States. The well known study of diurnal precipitation patterns by Kincer (1916) was the first to document the nocturnal precipitation maximum in the Great Plains. Since then, multiple studies have concluded that areas experiencing a nocturnal precipitation and thunderstorm maximum vary both geographically and seasonally (Wallace 1975, Astling *et al.* 1985, Easterling and Robinson 1985, Riley *et al.* 1987, Winkler *et al.* 1988, Winkler 1992, Walters and Winkler 1999).

The diurnal cycle is more pronounced for convective systems that produce heavy rainfall and/or thunderstorms compared to stratiform (i.e., non-convective) systems or systems that produce only light precipitation. Also, the diurnal cycle is strongest in summer compared to other times of the year (Wallace 1975, Easterling and Robinson 1985, Winkler *et al.* 1988). A number of studies have identified heavy precipitation by a rainfall rate of at least 2.5 mm h^{-1} (Wallace 1975, Winkler *et al.* 1988, Winkler 1992) while others have used hourly frequencies of thunder observations to examine thunderstorm activity across the north-central United States (Wallace 1975, Easterling and Robinson 1985). During the summertime the general cycle of thunderstorms and heavy precipitation exhibits an afternoon maximum in the southern and eastern regions of the United States (Easterling and Robinson 1985, Wallace 1975, Winkler *et al.* 1988). In the central portions of the country a west to east shift in the phasing of heavy summertime precipitation is evident with an afternoon maximum in precipitation over the Rocky Mountains and western Great Plains that transitions to a nocturnal maximum over the eastern plains (Wallace 1975, Balling 1985, Riley *et al.* 1987, Higgins *et al.* 1997, Dai *et al.* 1999). Interestingly, Winkler *et al.* (1988) and Winkler (1992) showed that the area experiencing a nocturnal maximum of heavy precipitation in the central United States decreases in size in summer compared to other times of year. The decrease corresponds with an expansion of the area exhibiting an afternoon maximum of heavy precipitation in the southern and eastern portions of the country, possibly due to the effect of stronger boundary-layer heating in summer. The generalized boundary of the region with most frequent nocturnal heavy precipitation is shown in Figure 1-1 (Winkler 1992). In terms of summertime thunderstorm frequency, Wallace (1975) identified a nocturnal maximum in Oklahoma, Kansas, Iowa, and Nebraska, and this maximum peaks earlier in the night (near midnight) than that of the precipitation maximum (near sunrise). Although much attention has been focused on the nocturnal maximum in the central plains states, a number of studies cited above (Kincer 1916, Wallace 1975, Easterling and Robinson 1985, Winkler 1992) showed that the region of nocturnal convection extends as far eastward as eastern Michigan and southward to northern Texas (Figure 1-1).

The weakest diurnal signal of heavy precipitation is observed during the winter (Wallace 1975, Winkler *et al.* 1988). Despite this, Wallace (1975) found a nocturnal wintertime maximum in heavy precipitation across the northern and eastern portions of the United States. Winkler (1992) illustrated that the area of heavy nocturnal precipitation extends to the eastern and southeastern regions of the country during the winter, while Riley *et al.* (1987) noted a broad nocturnal heavy precipitation maximum within the states of Nebraska, Wyoming, South Dakota, and Colorado. The transitional seasons of spring and autumn have received less attention in the literature concerning nocturnal precipitation; however, Winkler (1992) observed that the region of nocturnal heavy precipitation expanded from winter to spring extending into much of the New England states. Riley *et al.* (1987) also observed an increase in the area of the nocturnal heavy precipitation maximum within the central plains during the spring that extended into most of Kansas. Winkler (1992) found the autumn region of nocturnal heavy precipitation to be similar to that of summer, therefore generally smaller relative to other seasons and confined to the central portions of the United States.

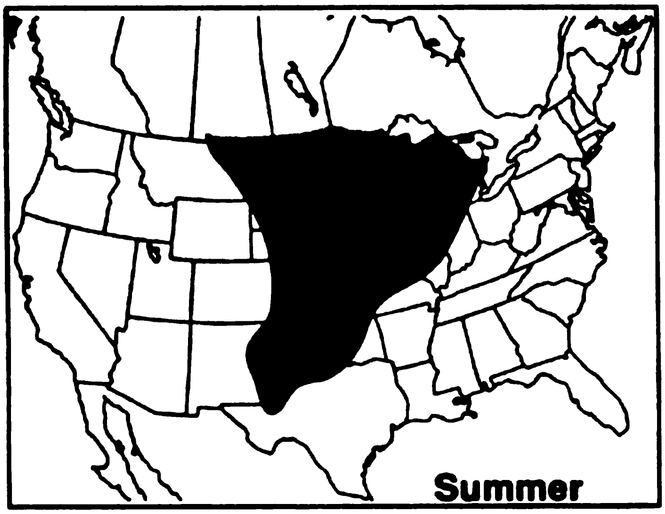


Figure 1-1. Region of summertime heavy nocturnal precipitation (Winkler 1992).

As mentioned above, the area experiencing nocturnal convection in summer extends into the western Great Lakes region. Easterling and Robinson (1985) noted a summertime maximum in thunderstorm activity around midnight in the western portion of the Great Lakes. Wallace (1975) also observed a near midnight summertime maximum in thunderstorm frequency in the vicinity of Lake Michigan, southern Wisconsin, and the northern portions of Illinois and Indiana. In addition, heavy precipitation has a nocturnal preference in most of the western Great Lakes region including Minnesota, Wisconsin, most of Illinois, northern Indiana, and a majority of the Upper and Lower Peninsulas of Michigan (Winkler 1992; Figure 1-1). Also, Kincer (1916) observed that approximately 50% of warm season (April – September) precipitation in western Michigan, northern Indiana, and the entire states of Illinois, Wisconsin, and Minnesota occurred during the nighttime hours. Although multiple studies have illustrated the existence of frequent nocturnal convection within the Great

Lakes region, the mechanisms associated with this phenomenon are not well documented.

1.1(b) Proposed Mechanisms of Nocturnal Convection

Nocturnal convection has interested many researchers as it is an unexpected phenomenon under the premise that convection is most likely to occur during the afternoon hours when intense boundary-layer heating causes low-level instability that favors convection. Various studies have proposed a handful of theories to explain the occurrence of nocturnal convection. The most frequently suggested mechanisms are: 1) the nocturnal low-level jet (Means 1954, Hering and Borden 1962, Pitchford and London 1962, Bonner 1968, Nicolini *et al.* 1993, Higgins *et al.* 1997, Walters and Winkler 2001, Walters *et al.* 2008), 2) eastward propagating systems that originate in the lee of the Rocky Mountains (Riley *et al.* 1987, Dai *et al.* 1999, Carbone *et al.* 2002, Jiang *et al.* 2006, Tuttle and Davis 2006), 3) mesoscale convective complexes (MCCs) (Maddox 1980, Maddox *et al.* 1982, Augustine and Howard 1991), 4) radiative cooling of cloud tops (Kraus 1963, Gray and Jacobson 1977), and 5) diurnal cycles of low-level convergence (Wallace 1975, Dai *et al.* 1999).

Nocturnally Enhanced Low-Level Jet

The low-level jet (LLJ) is a phenomenon that has been widely studied over the last sixty years. The LLJ is a lower-tropospheric wind maximum, usually found within the lowest 1 or 2 km of the troposphere (Blackadar 1957, Nicolini *et al.* 1993, Higgins *et al.* 1997). All areas of United States can experience LLJs (Walters *et al.* 2008), but they are most common in the central region of the country (Pitchford and London 1962, Bonner 1968), as LLJs often occur to the east of high topography (Nicolini *et al.* 1993). Although LLJs in the United States can have any direction and occur throughout all seasons of the year (Walters *et al.* 2008), the well documented central plains LLJ is often southerly in origin and most frequent during the summer (Blackadar 1957, Pitchford and London 1962, Bonner 1968, Walters *et al.* 2008). The climatological summertime maximum of the southerly LLJ is located in a region extending from southern Texas northward to southeastern South Dakota (Walters *et al.* 2008). Studies that used twice daily rawinsonde observations (i.e., 00 and 12 UTC) to identify LLJs observed the highest frequency during the morning at 12Z (Bonner 1968, Walters *et al.* 2008). Those studies that used more frequent observations, such as profiler observations, for smaller geographical regions found that the LLJ is most frequent during the nighttime hours of 06 – 09 UTC (Mitchell *et al.* 1995, Arritt *et al.* 1997). The nocturnal preference and geographic location of the LLJ are the primary reasons this phenomenon is linked to the occurrence of nocturnal convection.

Perhaps the most significant contribution of the southerly LLJ to convection is the advection of warm, moist air which acts to destabilize the pre-convective environment (Means 1954, Blackadar 1957, Pitchford and London 1962, Bonner 1968). In addition, regions of convergence and rising motion associated with the LLJ have been closely linked to areas of convection (Pitchford and London 1962, Nicolini *et al.* 1993, Walters and Winkler 2001). The most common convergence region associated with the LLJ is the decelerating leading edge of the jet (Nicolini *et al.* 1993, Tuttle and Davis 2006);

however, the region to the west (left) of the jet axis has also been noted as a region of convergence (Walters and Winkler 2001).

Eastward Propagating Convective Systems

Another proposed mechanism for the existence of nocturnal convective activity is eastward propagating convective systems. A number of studies have suggested that convective systems that initiate west of the nocturnal precipitation region tend to propagate eastward and contribute to the nighttime precipitation maximum (Riley *et al.* 1987, Dai *et al.* 1999, Carbone *et al.* 2002, Jiang *et al.* 2006, Trier *et al.* 2006, Tuttle and Davis 2006). Many of these systems originate during the afternoon hours over the eastern slopes of the Rocky Mountains and travel eastward where they reach the central portions of the country during the nighttime hours (Riley *et al.* 1987, Dai *et al.* 1999, Carbone *et al.* 2002, Jiang *et al.* 2006). Jiang *et al.* (2006) observed that approximately half of the mean summer rainfall over the Great Plains (e.g., from western Wyoming, Montana, and Colorado to eastern Minnesota, Iowa, and Missouri) can be attributed to eastward propagating systems from the Rocky Mountains. Furthermore, they found that many eastward propagating convective systems reach their maximum rainfall intensities during the nighttime hours as they travel across the Great Plains. Based on these findings, Jiang *et al.* (2006) suggested that these eastward propagating systems may be the primary source for nocturnal precipitation in the Great Plains. Conversely, Riley *et al.* (1987) suggested that systems that propagate from the lee of the Rocky Mountains cannot solely account for the nighttime precipitation maximum in the central United States and that much of this rainfall is locally generated. These conflicting observations demonstrate the lack of understanding surrounding the mechanisms responsible for nocturnal convection in the central United States.

A subset of the eastward propagating systems mentioned above are mesoscale convective systems (MCS). A MCS is an organized convective system (Augustine and Howard 1991) that can develop into hundreds of kilometers in size (Houze *et al.* 1989), and produces a contiguous precipitation area of at least 100 kilometers in the horizontal scale (American Meteorological Society 2000). Some MCSs may develop into larger systems called mesoscale convective complexes (MCCs). The criteria defining a MCC are derived from satellite imagery and include a minimum cloud shield of 100,000 (50,000) km^2 at a temperature of -32°C (-52°C) or less for at least 6 hours (Maddox 1980, Maddox *et al.* 1982, American Meteorological Society 2000). The maximum extent of a MCC is calculated at the time when the contiguous cold cloud shield with temperatures less than -33°C is largest (American Meteorological Society 2000). MCCs often reach their maximum extent during the night (Maddox 1980, Augustine and Howard 1991). In order to be classified as an MCC, the spatial eccentricity of the system must be at least 0.7 (i.e., quasi-circular) during maximum extent (Maddox 1980, Maddox *et al.* 1982, Augustine and Howard 1991, American Meteorological Society 2000). The scale of MCCs is substantially larger than that of individual thunderstorms; Maddox (1980) indicates that the size of a MCC is more than two orders of magnitude larger than an individual thunderstorm. MCCs can produce substantial rainfall and various types of severe weather including flash floods (Maddox *et al.* 1979, Maddox 1983), tornadoes, hail, winds, and intense electrical storms and usually have lifetimes of at least 12 hours (Maddox 1980). These massive systems are frequently found in the central United States (Maddox 1980, Maddox 1983, Augustine and Howard 1991, Augustine and Carcena 1994, Anderson and Arritt 1998) and have often been observed in the Great Lakes region (Maddox 1983, Augustine and Howard 1991). MCCs are most frequent during the warm season (March – September). Short-wave troughs have been suggested as playing a role in MCC development (Maddox 1983) although low-level thermal forcing and conditional instability have been observed as the primary factors in MCC formation (Augustine and Howard 1991). Because of their nocturnal preference and frequent production of intense rainfall, MCCs are suggested to play in important role in the nocturnal precipitation maximum located in the central United States (Maddox 1980, Augustine and Howard 1991, Anderson and Arritt 1998).

Radiative Cooling of Cloud Tops

Another prospective mechanism for nocturnal convective activity is radiative cooling of cloud tops (Kraus 1963, Gray and Jacobson 1977). During nighttime hours, cloud tops tend to cool more rapidly than cloud bases as the tops of clouds are radiating into the free atmosphere, while the radiation from the cloud base is absorbed by the water vapor within the surrounding cloud. Instability is generated from the temperature gradient within the cloud which causes vertical overturning (i.e., rising motion) that continues through the nighttime hours (Kraus 1963, Gray and Jacobson 1977). The vertical overturning raises the height of the cloud base resulting in deeper convection and increased nighttime rainfall (Kraus 1963, Gray and Jacobson 1977).

Diurnal Cycles of Low-Level Convergence

Dai *et al.* (1999) proposed that diurnal cycles of low-level convergence are primarily responsible for the afternoon precipitation maximum in the western United States including the Rocky Mountains and the nocturnal precipitation maximum found east of the Rocky Mountains. They speculated that solar heating of the atmosphere and the surface causes diurnal variations of large scale pressure gradients and atmospheric circulations. Surface pressure gradients during the summer result in maximum convergence over the Rocky Mountains in the afternoon and near midnight in the adjacent plains (Kansas and Nebraska). They suggested that a combination of this convergence cycle with favorable atmospheric static stability would likely result in convection in the late afternoon and early evening over the Rocky Mountains and near midnight in the central plains. Wallace (1975) also speculated that nocturnal convection over the central United States may be caused by low-level convergence; however, he noted that convergence was likely due to diurnal heating over sloped terrain (Holton 1967, Lettau 1967) and diurnal variations in frictional drag of the planetary boundary layer.

Previous Convective Climatology of the North-Central United States

In an attempt to speculate on the possible mechanisms responsible for nocturnal convection, Patterson *et al.* (1995) investigated the spatio-temporal characteristics of convective activity, including system generation, movement, and duration within the north-central United States during the summer of 1991. Radar observations were used to subjectively identify convective systems within the study area. Only radar echoes that were labeled as thunderstorm cells (i.e., TRW on the radar images) were used in the analysis. Thunderstorm cells that were located within three degrees of latitude or longitude were considered to be part of the same system. The study area included most of the north-central plains and extended eastward into the Great Lakes (from Montana and Wyoming to eastern New York) and was divided into six west-to-east regions. The origins of systems that existed within each region were determined and system movement was assessed by finding the relative frequency of locally generated systems (i.e., systems that generated within a particular region) versus those that originated upstream. The number of hours that elapsed from the time of system formation until the system reached a particular region was determined to evaluate the persistence of systems that existed within each region.

Patterson *et al.* (1995) observed that convective systems were most likely to form on the lee side of the Rocky Mountains and over the western Great Plains (eastern Montana, Wyoming, and the western Dakotas and northwest Nebraska). Regardless of location, systems developed more frequently in the afternoon hours (18 – 23 UTC) than any other time of day. A particularly interesting result was that the origin locations of many systems were clustered in space. Clusters of system formation were found in Nebraska, Wyoming, Montana, Iowa, and the southern Great Lakes region. The authors suggested that orographic lifting, the nocturnal LLJ, and the Great Lakes may be mechanisms for initiation of convective clusters. A substantial number of systems existed during the nighttime hours over portions of the central plains (eastern Dakotas, northeastern Nebraska, western Minnesota and Iowa) and the Great Lakes region.

Across the study area most systems were local in nature. However, non-local systems frequently occurred in Iowa, Minnesota, Wisconsin, Illinois and the eastern Great Lakes during the night (06 UTC – 11 UTC), and the western Great Lakes during the evening (00 UTC – 05 UTC). Their study also observed that systems that formed in the far western portions of the study area were likely to persist longer than those that initiated in the central portion of the study region. The authors suggested that the long persistence of systems that formed in the lee of the Rocky Mountains and over the western Great Plains could indicate the existence of MCCs.

A major limitation of the Patterson *et al.* (1995) study was the short study period of only one summer season. The use of radar observations to identify convective systems was another limitation as convective precipitation can be difficult to distinguish from stratiform (i.e., non-convective) precipitation on radar images. Another drawback is that certain convective system behavior was not considered in detail. For example, multiple convective systems may merge into one system (Maddox 1980) or conversely individual systems may divide into two or more systems. Patterson *et al.* (1995) did not identify merging systems and in the cases of splitting systems, only the longer system path was retained for analysis. Finally, the study did not examine the termination locations of convective systems which provided an incomplete picture of convective system behavior.

A more complete climatology of convective systems that includes the origin, movement, total duration, and termination of convective systems is needed to better speculate on possible mechanisms of nocturnal convection. The development of such a detailed climatology is the primary objective of the present research. This study expands on Patterson *et al.*'s (1995) analysis in a number of ways. First, although both the current study and that of Patterson *et al.* (1995) are confined to a single summer season, the use of two different seasons (2004 for this study and 1991 for the earlier study) provides an the opportunity to assess the interannual variability of the characteristics of convection in the north-central United States. Second, lightning observations were used in this research and are advantageous for studying convective systems compared to radar data as lightning data are convective by definition, whereas radar observations are not. Third, to gain a better understanding of convective system behavior, splitting and merging systems were considered in great detail in the present study. Fourth, including the Great Lakes in a detailed convective system climatology provided a unique opportunity to investigate the possible influences of the Great Lakes on warm season convection.

1.1(c) Influences of the Great Lakes on Convection

The Great Lakes can significantly affect weather systems within the region; however, their influence on cool season precipitation events has received the most attention. The frequency and intensity of wintertime precipitation can be substantially increased by the Great Lakes. This enhancement is known as "lake effect." Surprisingly, little is known about the warm season influence of the Great Lakes on convective activity within the region.

Basic thermodynamic principles would suggest a diurnal effect of the Great Lakes on warm season convective activity. During the intense afternoon heating in the summer months lake temperatures are cooler relative to land surfaces. One might expect convection to be suppressed as cooler temperatures over the lakes relative to land surfaces would act to stabilize the air at or near the surface. Conversely, during the nighttime hours of the summer months, lake temperatures are often warmer compared to the land surfaces and could provide an environment favorable for convection. This theory is supported by Patterson *et al.* (1995) who observed convective systems to originate more frequently over Lake Erie during the nighttime hours compared to other times of day. However, the remaining Great Lakes did not exhibit a similar diurnal variation in system generation suggesting that additional factors may influence convection in the Great Lakes region. Bosart and Galarneau (2005) conducted two case studies of summertime convective systems over the Great Lakes and observed varying influences of the different lakes on convection. A mesoscale convective system that originated during the evening in New Mexico almost three days prior to reaching the eastern Great Lakes intensified as it interacted with Lake Erie during the afternoon hours. Warm southerly flow that occurred ahead of the system encountered the cooler waters of Lake Erie, which was thought to enhance frontogenesis and intensify convection as the system approached the lake. The authors also examined a system that developed as a squall line in Iowa during the night, and found that this system intensified as it traveled over Lake Michigan during the morning hours, possibly due to enhanced surface convergence at the leading edge of the squall line based on southerly flow over lower Lake Michigan. The system traveled across southern Michigan and dissipated over Lake Erie during the afternoon. The case studies suggest that the Great Lakes may have an influence on warm season convection. However, as no convective climatology currently exists for the Great Lakes region, it is not known how frequently systems initiate or dissipate over the Great Lakes, therefore, the effect of the Great Lakes on convective systems is not currently well understood.

1.1(d) Previous Studies of Convective Systems

The previous discussion illustrated the usefulness of a convective climatology to better document where convective systems form, move, and dissipate, along with their durations. Relatively few studies have attempted to identify and track individual systems for use in a climatological analysis; however those that have identified and tracked convective systems employed both subjective and objective methods. These methods involved the use of different data sets including lightning observations, radar observations, and satellite imagery to investigate convective systems at varying scales of analysis (Maddox *et al.* 1982, Maddox 1983, Augustine and Howard 1991, Hagen and Finke 1999, Steinacker *et al.* 2000, Tuomi and Larjavaara 2005). As described above, Patterson *et al.* (1995) subjectively identified and tracked convective systems from radar observations. Subjective classification of systems has also been applied to lightning observations. For example, Hagen and Finke (1999) used lightning observations to identify and classify thunderstorms across southern Germany. Daily maps (00 – 24 UTC) of cloud-to-ground (CG) lightning flashes from1992 to 1996 were created to identify thunderstorm days from May through September. Convection on days with ≥100 lightning flashes in at least twenty minutes was classified as stationary thunderstorms, moving thunderstorms, or thunderstorm lines. The classification scheme was entirely based on the visual inspection of the phenomenological characteristics of size and shape, with no a priori consideration given to the synoptic environment.

Murphy and Konrad (2005) examined the spatial and temporal patterns of thunderstorms in the southeastern portion of the United States. Thunderstorm events from the summer seasons of 1995 to 1999 were identified and classified from CG lightning observations. Maps of hourly CG lightning flashes were created and the maps that had at least one flash were used for thunderstorm identification. A thunderstorm event began at the time of the first lightning flash and terminated when at least one hour passed with no lightning. The frequency of lightning flashes was determined for each hour of a thunderstorm event and the lightning pattern at the hour with the highest frequency of lightning observations was classified by size and shape (i.e., eccentricity) into local, multilocal, regional, elliptical, linear, widespread, and undefined thunderstorm types. Precipitation patterns were analyzed by examining hourly radar mosaics for a subset of thunderstorm events. The radar patterns were subjectively classified based on a scheme developed by Zajac and Rutledge (2001) as isolated cells, cluster of cells, noncontiguous line, contiguous line, linear MCS, and cluster MCS.

Other studies of convective systems have specifically investigated MCCs in the United States (Maddox 1980, Maddox *et al.* 1982, Augustine and Howard 1991, Anderson and Arritt 1998). MCCs are defined based on criteria from satellite imagery (see 1.1(b)). Some studies identified MCCs from satellite imagery using a software package developed by Augustine (1985) that automatically computes the areas and centroids of cloud-tops that have temperatures of -52°C or less and estimates cloud-top eccentricity (Augustine and Howard 1991, Anderson and Arritt 1998), while other studies did not explicitly describe their MCC identification technique (Maddox 1980, Maddox *et al.* 1982). Trajectories of MCCs have been analyzed by plotting the location of the first storms that evolve into each MCC along with the locations of MCC initiation, maximum extent, and termination (Maddox *et al.* 1982, Maddox 1983, Augustine and Howard 1991). MCC initiation is defined as the time when the minimum size requirement is first attained and termination occurs when the minimum size requirement is no longer satisfied (Maddox *et al.* 1982, Maddox 1983, Augustine and Howard 1991, American Meteorological Society 2000). Plotting MCC trajectories has shown the regions where these systems are most likely to form and travel and that these systems often follow an anticyclonic path (Maddox 1980, Augustine and Howard 1991).

Methodological studies have developed automated procedures for the identification (Steinacker *et al.* 2000, Tuomi and Larjavaara 2005) and tracking (Steinacker *et al.* 2000) of convective cells. Convective systems are generally comprised of cells that form and dissipate throughout the lifetime of a convective system. Therefore, the scale of a convective cell is generally much smaller than that of a convective system. Tuomi and Larjavaara (2005) created a cell search algorithm that identifies clusters of CG lightning flashes. The algorithm was developed on lightning observations over Finland and designed to be used on a time sequence of lightning flashes. The objective of their study was to develop an automated method to identify individual convective cells; therefore the algorithm employed relatively short time and distance criteria. Lightning flashes that occur within 15 minutes and 15 km of each other are grouped into the same cell, however, the rules may be user specified to group lightning flashes within larger time intervals and distances. The authors argued that the algorithm produced realistic size and temporal characteristics of individual convective cells.

Steinacker *et al.* (2000) developed an automated procedure to track convective cells and cell complexes from lightning and radar observations. Two case studies of convective systems that occurred in July of 1996 in the Alpine region of Austria were used in the study. Lightning density was plotted on a 4 x 4 km^2 grid at a twenty minute resolution. The radar data were also converted into a 4 x 4 km^2 grid to compare lightning density and rain rates. A weighted filter was applied to both grids to identify grid point maxima. In order to be identified as a maximum, the grid point value had to exceed a threshold value (which can be variable) and be larger than the surrounding grid point values. Each grid point maxima was referred to as a convective "cell". Displacement vectors for consecutive plots were used to track convective cells, and movement was restricted so that in certain cases splitting and merging were not allowed. One distinct advantage of their method is that the scale of analysis can be adjusting by modifying the weighted filter; therefore the method can be used to track individual convective cells or cell complexes (i.e., systems). A disadvantage is that it is designed to limit the behavior of a cell by prohibiting splitting or merging (or both).

Based on the previous studies described above, no particular method has been accepted as a standard for identifying and tracking convective systems. Automated procedures are advantageous for long time series and convective cell identification at small scales, as both may be too tedious to explore manually. However, subjective procedures can be useful when examining larger scale systems and detailed behavior of convective systems (e.g., splitting and merging systems) for shorter time series where a visual inspection is possible. The present study was interested in identification of convective systems, not cells, and used a time period that was suitable for manual system identification. This study also chose to closely monitor splitting and merging systems to more accurately track convection within the study region. Therefore, a subjective method was chosen for the analysis.

1.2 Objectives

The primary goal of this research is to develop a climatology of convective system origin, movement, duration, and termination that expands on the study by Patterson *et al.* (1995). The climatology will be used to address four different research objectives.

The first objective is to simply describe the characteristics of convection in the north-central United States including the following questions:

- Where in the north-central United States are convective systems most likely to form?
- At what time of day does convection most often form and does the time of day vary geographically?
- How often do systems propagate eastward from their origin location compared to the number of systems that dissipate close to their origin location?
- How far do systems typically propagate eastward and does the distance vary by the time of day that the system forms?

- Where are convective systems most likely to terminate in the north-central United States?
- What time of day does convection typically dissipate and does the time of day vary across the study region?
- What is the typical duration of convective systems and does duration vary by time of day or origin of the system?
- Do durations vary for systems that terminate in different regions or at different times of the day?

The second objective is to use the convective climatology to assess the relative contribution of LLJs and the eastward propagation of convection to the occurrence of nocturnal convection in the north-central United States. The LLJ has a distinct spatial and temporal preference, and locally forming nighttime and morning convective systems where LLJs are frequent would be highly suggestive of the LLJ as an important mechanism for these systems. On the other hand, frequent eastward propagating systems should also exhibit a distinct spatial and temporal "fingerprint" in the convective climatology, particularly in the system duration statistics and in the distance traveled from origin. Other mechanisms that have been proposed for the formation of nocturnal precipitation, such as radiative cooling of cloud tops, enhance nocturnal convection throughout the study area, and consequently the influence of these mechanisms is not easily detectable from the convective climatology and not considered here. The types of questions addressed in this part of the analysis include:

- Do most nocturnal systems that exist within the core of the nocturnal convection region form locally or propagate into the region?
- Does the geographic location of nocturnal convection align with the climatologically frequent location of the LLJ?
- Does the timing of nocturnal convection correspond to the time when the LLJ is climatologically most frequent?
- How often can a system occurring during the night and morning be traced to the western plains or eastern slopes of the Rocky Mountains?
- Do nocturnal systems that form non-locally display MCC characteristics (e.g., long durations)?
- Where do systems that exist in the Great Lakes during the night and morning hours form?
- Are evening systems typically "remnants" of afternoon convection?

The third objective is to use the convective climatology to provide an initial assessment of the potential influences of the Great Lakes on summertime convective systems. Questions considered for this objective include:

- How often do convective systems form over the Great Lakes and does this vary by time of day?
- How frequently do convective systems terminate over the Great Lakes and are diurnal variations in storm dissipation evident?

- Do systems that move over the Great Lakes in the afternoon dissipate soon after interacting with the cooler lake waters? If not, how long do systems typically last after interacting with the lakes?
- Do systems that move over the Great Lakes during the night persist for longer periods of time than those that move over the Great Lakes during other times of day?
- What is the typical duration of convective systems that form over the Great Lakes?
- Where do systems that interact with the Great Lakes generally form?
- How long do systems typically interact with the Great Lakes?
- How long do most systems persist after interacting with the Great Lakes?
- What are the surface synoptic features associated with convective systems as they move over the lakes?

Finally, this research will be used to evaluate how the use of different data sets, the methods employed, and the study period affect the robustness of convective climatologies. The primary question addressed is:

- How does the climatology produced here compare with the climatology presented by Patterson *et al.* (1995)?

Chapter 2 Data and Methods

This chapter describes the methods used to develop the climatology of convective systems for the north-central United States and the Great Lakes region. The data set and study area are first described. Next, the criteria used to identify convective systems and to follow their movement are explained. The following sections describe the analyses performed to assess the spatial and temporal variations in system origin, movement, duration, and termination. The chapter concludes with a discussion of the methods used to analyze the spatial and temporal variations of convective systems that form over or traverse the Great Lakes.

2.1 Data and Study Area

Lightning observations for the summer season (June, July, and August) of 2004 were selected for this study. Lightning observations were chosen over other observations such as precipitation or radar reflectivity, as lightning, by definition, is associated with convective storms, whereas it is difficult to distinguish between stratiform and convective systems from precipitation observations or radar reflectivity measurements. The 2004 summer season was chosen for analysis because precipitation was above average across most of the study area, and thus there were likely more storm systems compared to a summer with below normal precipitation. Although multiple years would have been preferred for the analysis, the study period was limited to one summer season due to the large cost of the lightning observations.

The study area is defined from 109°W to 74°W and 40°N to the northern border of the United States (Figure 2-1). This area, which extends from the High Plains to the eastern Great Lakes, was chosen because nocturnal precipitation is common in this region (Wallace 1975, Astling *et al.* 1985, Balling 1985, Easterling and Robinson 1985, Winkler *et al.* 1988, Winkler 1992). The study region also corresponds with the area used in the earlier work by Patterson *et al.* (1995), facilitating comparisons between the two studies. Including the Great Lakes region was of particular interest as it allows for an investigation of the potential diurnal influences of the lakes on convective systems.

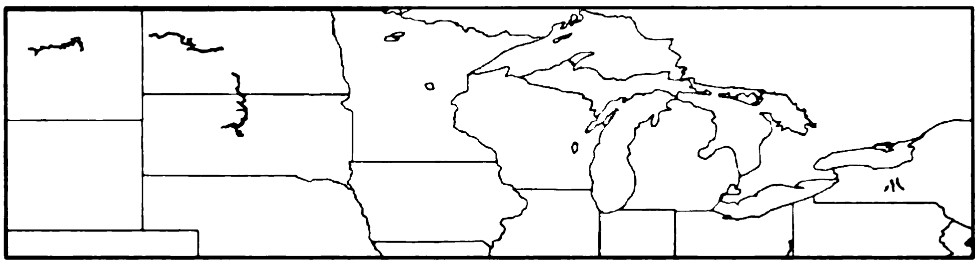


Figure 2-1. The study area extending from 109°W to 74°W and 40°N to the northern border of the United States.

Lightning observations were obtained from Vaisala Inc., which now operates the National Lightning Detection Network (NLDN). The NLDN is comprised of 113 lightning sensors in the continental United States and underwent an extensive system-wide upgrade in 2003 (Grogan 2004). The upgrade involved replacing old lightning sensors with Vaisala IMPACT ESP (Enhanced Sensitivity and Performance) lightning sensors, which resulted in both updated sensing equipment and technology (Grogan 2004). The IMPACT ESP sensors detect cloud-to-ground lightning discharges using both Magnetic Direction Finding (MDF) and Time of Arrival (TOA) technologies (Vaisala Inc. 2008), compared to the earlier sensors that only employed TOA technology (Grogan 2004). Approximately 20 sensors are located within the current study area. Two sensors are needed to determine accurate discharge locations (Vaisala

Inc. 2008). A lightning flash may consist of up to 20 return strokes and for each lightning flash the time in Greenwich Mean Time (GMT), location in latitude and longitude, polarity, first-stroke amplitude, and multiplicity (number of return strokes) are recorded (Grogan 2004). Preliminary results of the upgrade showed a minimum 90% flash detection efficiency and a 60-80% stroke detection efficiency (Grogan 2004). The median stroke location accuracy is 500 meters (Grogan 2004). The NLDN can also detect some cloud lightning activity, which is also referred to as cloud-to-cloud or intracloud lightning (American Meteorological Society 2000). However, the detection efficiency is substantially lower (10-30%) compared to CG lightning activity (Grogan 2004).

This study only used CG lightning observations, intracloud (IC) lightning was not included due to poor detection efficiency as mentioned above. The contribution of IC and CG lightning to total lightning activity in thunderstorms over the continental United States varies geographically (Boccippio *et al.* 2001). Although some estimates attribute over 50% of total lightning activity to IC flashes (American Meteorological Society 2000), the IC to CG ratio has been observed to range from around 1.0 to 3.0 in the vicinity of the Rocky Mountains and over the Great Lakes region and increase to approximately 4.0 to 7.0 in the central and northern plains (Boccippio *et al.* 2001). However, the exclusion of IC lightning activity likely had only a small impact on detecting convection in this study area. For this study convection was defined by the existence of two or more CG lightning flashes. It is highly unlikely that an occurrence of convection would be missed as more than one CG lightning flash would be expected.

2.2 Convective System Identification

To develop the climatology of convective systems for the north-central United States, each system that existed within the study area during the summer of 2004 was identified and tracked using a multi-step process described below. Previous studies that investigated convective systems using lightning data have adopted both subjective (Hagen and Finke 1999, Murphy and Konrad 2005) and objective approaches (Steinacker *et al.* 2000, Tuomi and Larjavaara 2005) to identify and follow systems. The review of previous methodologies in Chapter 1 demonstrated that a standard, well-accepted approach for identifying and tracking convective systems currently does not exist. For this research, a subjective approach was used as the splitting and merging nature of systems, which is difficult to describe objectively, was considered in detail and the length of the study period was amenable to visual inspection of the data. A flow chart outlining the major steps for identifying and following systems is shown in Figure 2-2.

SYSTEM IDENTIFICATION FLOWCHART

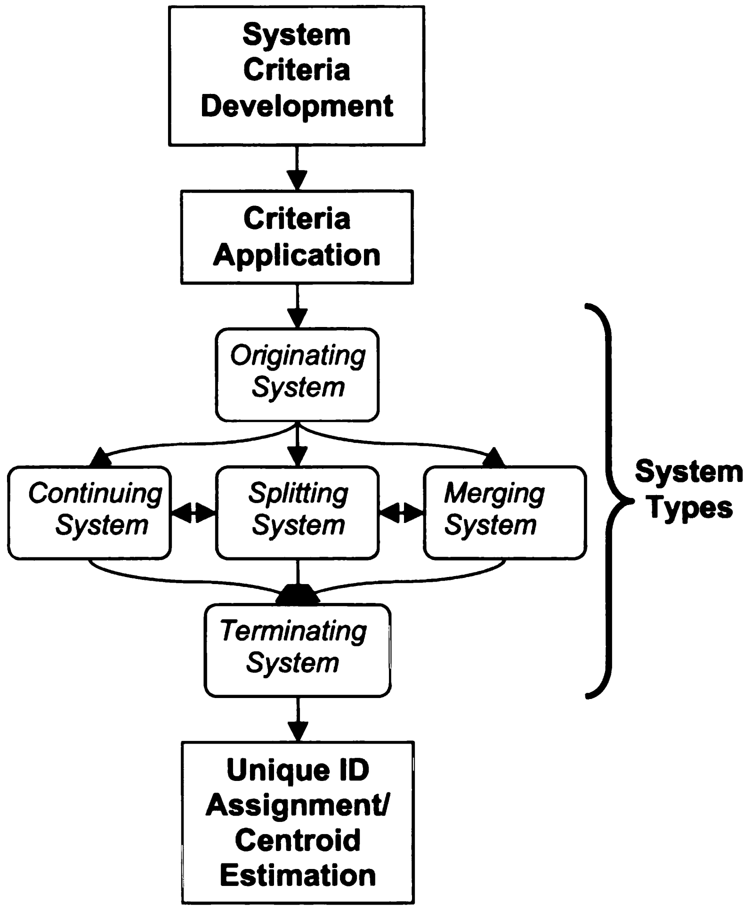


Figure 2-2. The major steps in identifying and tracking convective systems.

2.2(a) Development of Criteria to Identify and Track Convective Systems

The first step of identifying convective systems was to develop a set of criteria for system initiation, movement, behavior (e.g., splitting systems), and termination. The criteria were designed to identify convective systems rather than convective cells.

Convective cells are organized units of convection (American Meteorological Society 2000) that initiate and dissipate throughout the lifetime of a convective system. Convective cells generally only exist for 30 minutes or less compared to typical convective systems which may last on the order of 1 to 2 hours, or highly organized convective systems (i.e., MCCs) that often have durations exceeding 6 hours (American Meteorological Society 2000). A fixed size definition for a convective cell does not exist; however, previous studies have identified convective cells at sizes ranging from 4 km to 15 km (Steinacker *et al.* 2000, Tuomi and Larjavaara 2005). The purpose of this study was to analyze convective systems (not cells), including MCSs, which by definition are 100 km or larger in at least one direction (American Meteorological Society 2000). Therefore, a larger scale of analysis was chosen for system identification (i.e., > 100 km).

The criteria for identifying systems were developed using a subset of 5 days (~120 maps) from the study period. Maps were plotted of the lightning observations that occurred within a 20-minute period centered on each hour, or in other words, the lightning flashes that occurred within the last ten minutes of one hour and the first ten minutes of the following hour. The maps were labeled with the hour at which the twenty-minute interval was centered; for example, a map of lightning flashes from 01:50 – 02:10 Coordinated Universal Time (UTC) was labeled as 02 UTC. These maps are referred to below as "hourly" maps since they are labeled by hour, even though only the flashes for a 20-minute period are plotted. Plotting the lightning flashes for 20-minute interval at the top of each hour is similar to producing a "snapshot" of each system. The breaks between the "snapshots" made it easier to identify systems and their movement with time, compared to plotting all of the lightning flashes for an entire hour. A latitudinal and longitudinal grid was overlaid on the lightning flash maps and the number of grid cells between clusters of lightning flashes was used to distinguish separate clusters of flashes (i.e., convective systems). Different grid cell sizes were evaluated. For each grid cell size, an informal visual check was performed by comparing the lightning flash maps from 00 and 12 UTC to national radar mosaics from the Unisys Weather website (www.weather.unisys.com). Convective systems were inferred on the radar images from systems with an echo intensity of at least 45 Dbz, which are, by definition, moderate thunderstorms (Unisys Weather 2007). The convective systems identified on the radar mosaics were then compared to those identified on the lightning maps, where two or more lightning flashes were identified as a system. The reasons for comparing systems as detected from the lightning and radar observations were to: 1) evaluate potential impact of not including systems with only IC lightning in the climatology and 2) provide some guidance for choosing the size of the grid mesh. Most convective systems identified on the radar images were also observed on the lightning flash maps suggesting that almost all convective systems had at least two CG lightning flashes. Using a grid cell size of 0.5° latitude by 0.5° longitude to distinguish convective systems showed the greatest agreement between the radar composites and lightning flash maps in terms of the number and size of convective systems identified. After considerable experimentation, the following criteria were defined for identifying and tracking systems.

Originating Systems: Convective systems originated if the lightning flashes for the current hour were not located within two adjacent (in any direction, including diagonals) grid cells of any lightning flashes from the previous hour. Lightning flashes separated by more than two adjacent grid cells were considered different systems, and flashes that occurred within two adjacent grid cells were considered to be part of the same system.

Continuing Systems: If a system that existed in the current hour was located within two adjacent grid cells of a system identified for the previous hour, the system was considered to be a "continuing" system.

Splitting Systems: A system was considered to have "split" if two or more separate systems are found within two adjacent grid cells of a single system from the previous hour. The resulting systems must be separated in space by more than two grid cells (Figure 2-3).

Merged Systems: Systems merged if a single system in the current hour was located within two adjacent grid cells of multiple systems from the previous hour (Figure 2-4).

Terminating System: If in the current hour no lightning flashes occurred within two adjacent grid cells of the location of a system from the previous hour, the system was considered to have terminated. There are two types of terminating systems:

- *Exiting Systems:* These are terminating systems that were located within one degree latitude or longitude of the study area boundaries during the last hour of recorded lightning activity.

- *Decaying Systems:* Terminating systems located more than one degree latitude or longitude from the study area boundaries during the last hour of recorded lightning activity were considered to be decaying systems.

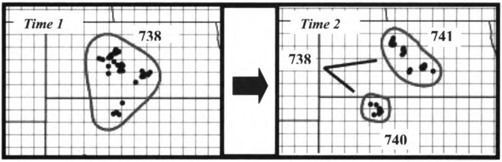


Figure 2-3. An example of a splitting system. Each black circle represents a lightning flash. At time 1, the system had an identification number of 738 and all lightning flashes were within two adjacent grid cells of another flash (see system criteria) and were considered to be part of one system. In time 2, the system split into two separate systems, both of which were within two adjacent grid cells of the original system at time 1. Thus, system #738 was considered a splitting system that produced systems #740 and #741.

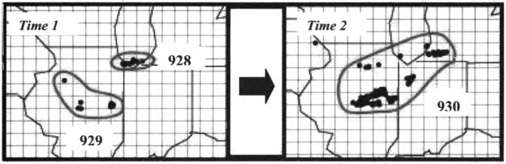


Figure 2-4. An example of a merging system. Each black circle represents a lightning flash. At time 1, two systems existed with the identification numbers of 928 and 929. The systems were separate because the two clusters of lightning flashes were more than two adjacent grid cells apart from each other. At time 2, one system existed with an identification number of 930. The system was within two adjacent grid cells of system #928 and #929 from the previous time period and was therefore considered a merged system.

2.2(b) Unique ID Assignment and Centroid Estimation

Once the criteria described above were established, "hourly" lightning maps were created for each hour of the study period. Originating systems, continuing systems, splitting systems, merged systems, and dissipating systems were identified on the maps. Once all systems that existed during the study period were identified, a unique identification number was assigned to each system (Figures 2-3 and 2-4). Splitting or merged systems were given a new identification number at the time the split or merge occurred. The identification numbers were used to track the systems. In addition, the centroid (in latitude and longitude coordinates) of the system was estimated visually. A rough estimate of the centroid was sufficient for this study, as the system locations were intended to be analyzed for relatively broad regions within the study area allowing for some subjectivity in the estimate of the system location. Also, finding an "exact" centroid location is not possible because the physical boundaries of a convective system cannot be distinguished using lightning observations alone. The cloud shield may extend beyond the locations of the lightning flashes. Also, areas within the system with only cloud-to-cloud lightning activity were not detected.

2.3 Database Development

A database was created that included the system identification number, the date and time at which the system was first identified, type of origin (e.g., originating system, splitting system, or merged system), the centroid location for each hour the system existed, the date and time of termination, and a code indicating the type of termination (i.e., exiting or decaying). Table 2-1 displays sample entries from the database. The system identification number is listed in column 3 as the "StormID". If a system was the result of a two systems that merged, the identification numbers of the original systems are listed in columns 1 and 2 under "Merge1" and "Merge2". The type of system termination is listed as the "End Code" in the last few columns of the database and has four possible values: "55" for systems that split, "66" for those that merged, "88" for those that exited the study region, and "99" for those that decayed within the study region. If a system split, the identification numbers of the resulting systems are listed in the columns after the end code. The "9999" entry is simply used as a place holder when no system identification number belonged in that column. The remaining columns list the starting and ending dates of each system, the hours of the day a system existed, and the centroid locations. An entry (i.e., row) in the database may represent the entire lifetime of a system if no splitting or merging occurred. Otherwise, a row represents a segment of a system's lifetime.

Table 2-1. Example entries from the database of convective systems.

Merge1	Merge2	StormID	Start Month	Start Day	Hr1	Lat	Lon	...
106	107	108	6	8	0	41.3	-100.7	...
9999	9999	109	6	8	0	46.5	-93.8	...
105	109	110	6	8	3	47.3	-92.3	...
9999	9999	111	6	8	3	43.4	-107.4	...

...	End Month	End Day	End Hr	EndCode	Split1	Split2	Split3
...	6	8	12	55	121	122	123
...	6	8	3	66	9999	9999	9999
...	6	8	9	88	9999	9999	9999
...	6	8	5	99	9999	9999	9999

System Path Formation

System paths (or tracks) were needed in order to follow the movement of the convective systems and were constructed by working backwards from the location of system termination. Each path was constructed by piecing together previous system segments until the origin of the system was found. The paths for those systems that started as new systems and terminated with no splitting or merging in their lifetime were straightforward to identify as they are represented by a single row in the database. Systems that began from a split or merger and terminated by dissipating or by exiting the study region were considered to be the terminating segment in a system path. If the terminating segment was the result of a splitting system, the earlier system was added to the beginning of the system path (Figure 2-5). If the terminating segment formed from the merger of two or more earlier systems, the merging system that originated farthest west was added to system path. A path was completed when a system segment was added that had originated as a new system and was not the result of a split or merger. The result is a path from the origin location to termination location for each system within the study region. Due to the splitting nature of systems, there are a larger number of terminating locations compared to origin locations, and many systems share the same origin and path segment up to the point where a split occurred.

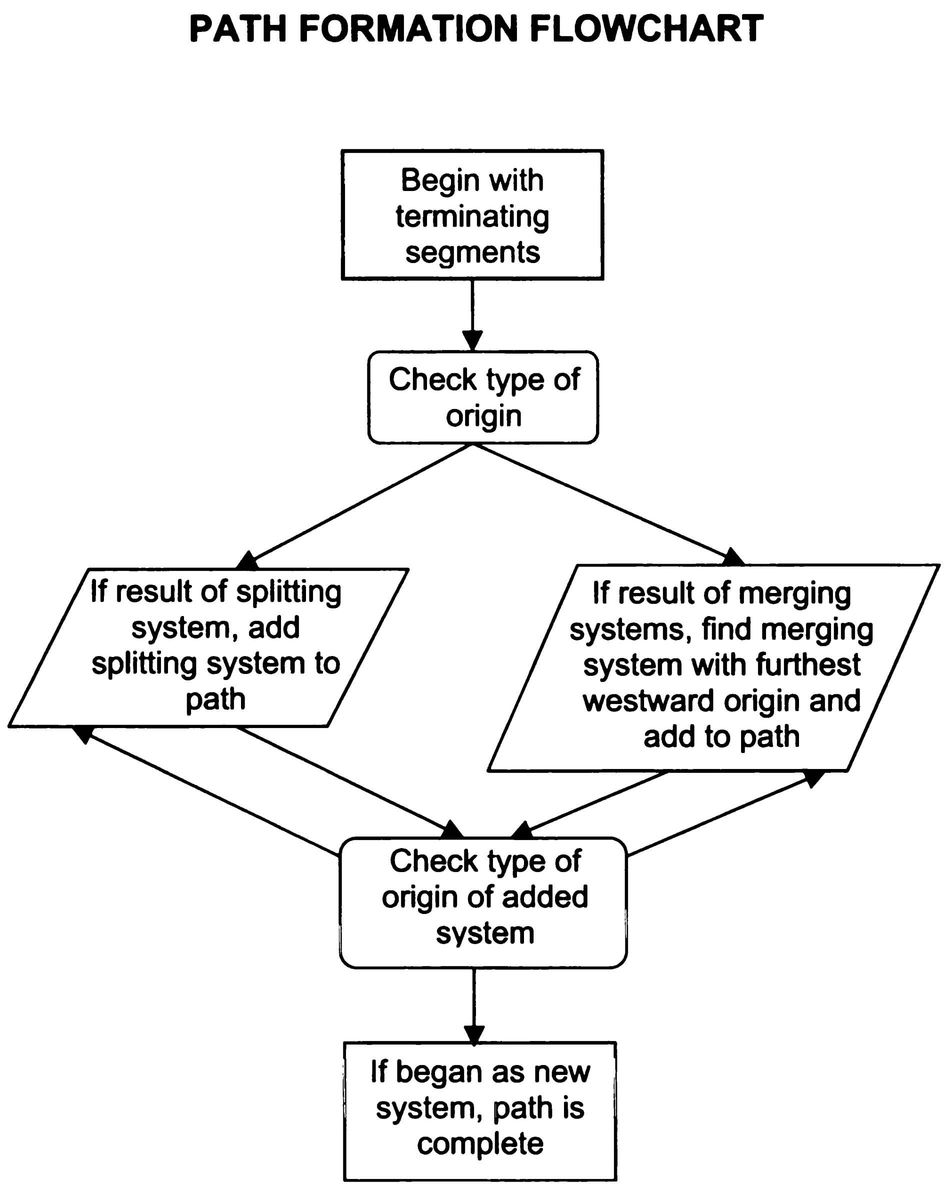


Figure 2-5. Flowchart of system path formation for splitting and merging systems.

2.4 Regional Analysis

The study area was divided into six west-to-east regions (Figure 2-6), similar to the regions used by Patterson *et al.* (1995), to help identify and summarize spatial differences in the characteristics of the convective systems. The regional divisions were: 109°W - 100°W (Region 1), 99.9°W - 95°W (Region 2), 94.9°W - 90°W (Region 3), 89.9°W - 85°W (Region 4), 84.9°W - 80°W (Region 5), and 79.9°W - 74°W (Region 6). The regions are generally equal in size, with the exception of Region 1 which is considerably larger. For each region, and for the study area as a whole, the temporal characteristics of the convective systems were summarized by six-hour time steps: 00-05 UTC (evening), 06-11 UTC (night), 12-17 UTC (morning), and 18-23 UTC (afternoon). The time periods were also chosen based on the earlier work of Patterson *et al.* (1995).

Because of the complications introduced by systems splitting and merging, three types of analyses were employed to investigate the temporal and spatial characteristics of the systems. These analyses are referred to as 1) analysis by system origin, 2) analysis by system termination, and 3) analysis by region of existence and are discussed in detail below.

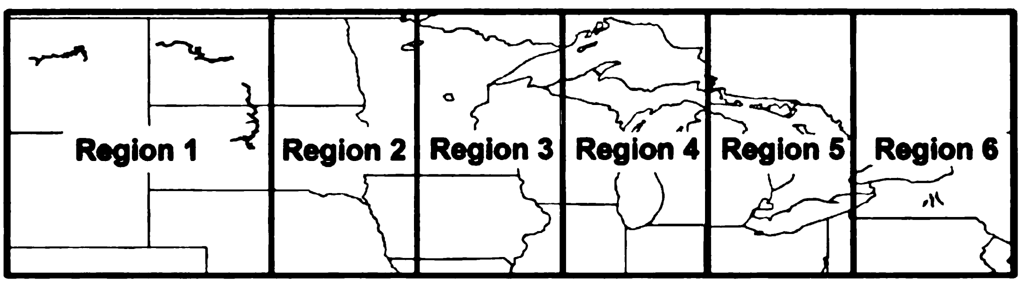


Figure 2-6. Study area with regional divisions.

2.4(a) Analysis by System Origin

The focus of this analysis is where and when systems originated and the durations and paths of systems that originated in different regions of the study area. The frequency of system origins across all times of day was summarized for the entire study area and for each region separately and displayed graphically using pie charts in order to identify possible regional variations in the timing of system formation. The advantage of this analysis is that systems with multiple termination locations were only counted once in the analysis, bearing in mind that a system may split one or more times during its lifetime. To assess the movement of the systems originating at different times of the day and in different regions, a system was traced, using the paths created previously, from the region of origin to the region of termination. The paths were used to calculate the percentage of systems that terminated "locally" (i.e., within the same region where they formed) and those that terminated outside the region where they formed. The percentage of systems that terminated locally or within each of the downstream regions was calculated using the number of termination locations in the denominator. For clarification, the number of system origins and the number of termination locations are included in the pie charts for each region and time of day.

Additionally, the frequency of termination locations within one degree latitude and longitude of the study area boundaries was determined by region, as these locations may reflect convective systems that exited the study area rather than decayed within the study area. The study area boundary along which the "exiting" termination location was found was also examined. As mentioned earlier in this chapter, the southern boundary of the study area is defined by 40°N across the entire west-east extent, however, the northern boundary is defined by the northern border of the United States, therefore the latitudinal bounds change from west-to-east. Because of this, termination locations with a latitudinal coordinate that fell on 42°N or south of this latitude were considered to represent systems that exited the study area to the south. Conversely, termination locations with a latitudinal coordinate to the north of 42°N represented systems that exited to the north. These criteria were modified for systems that exited to the west or east. In order to exit to the west, the longitudinal coordinate of the termination location fell on or west of 107°W. To exit to the east, the longitudinal coordinate of the termination location occurred at or east of 76°W. In the cases where the latitudinal and longitudinal coordinates fell into multiple directional categories, the direction in which the system exited was based on the longitudinal criteria.

The duration of each of system was also determined to investigate possible differences in the persistence of systems that originated in different regions and/or at different times of the day. System duration is simply defined as the number of hours that lightning activity was recorded for a system. System durations were grouped into six categories of unequal time length (1-2 hours, 3-4 hours, 5-9 hours, 10-17 hours, 18 to 29 hours, ≥ 30 hours). The categories were chosen by visual identification of "breakpoints" on a histogram of the durations for all systems. The categories are similar to those used in the earlier study by Patterson *et al.* (1995). The percentage of systems that fell within each duration category was summarized according to the region and time period the systems formed and displayed using bar graphs. Each system path from origin to termination was treated separately for the duration calculations; therefore, the number of termination locations per region and time period was used to calculate percentages.

2.4(b) Analysis by System Termination

The systems were also analyzed starting with the location and time when systems terminated and then extracting the origin, movement, and duration for each "terminating system". The advantage of this analysis is that it explicitly considers the multiple termination points that result from systems splitting during their lifetime. The frequency of termination locations for each region within study area was determined by time period. Termination frequencies by region and time period are displayed using pie charts. To determine the source regions of the convective systems that terminated within each region, each system was traced backward in time from its termination location to its origin. The percentage of terminating systems that originated locally versus non-locally was also calculated for each region and time period and displayed on pie charts. The frequency and direction of exiting systems were then examined by region of termination. A system was considered to have exited from a particular region if the longitudinal coordinate of the centroid at termination fell within the longitudinal bounds of that region. The same directional criteria described for exiting systems in 2.4(a) was used for this analysis as well. In addition, the duration of each system was determined in order to investigate the persistence of systems that dissipated within each region by time of day. The durations were displayed as bar graphs using the same categories described above for the analysis by system origin.

2.4(c) Analysis by Region of Existence

Systems were also analyzed by the regions and time periods in which they existed. The motivation for this analysis was to be able to compare the results of this study with those of the earlier study by Patterson *et al.* (1995) which identified convective systems that occurred within each region and time period and then determined the source regions of these systems. Based on the source region, the systems were classified as local (i.e., systems that formed within the region) and non-local systems. The percent of local versus non-local systems was calculated for each region and time period using the total number of systems located within each region at a particular time period as the denominator. Systems were also analyzed based on their age (i.e., number of hours of recorded lightning activity) at the time they moved into each region. System ages were grouped by the same categories previously used by Patterson *et al.* (1995): 1 hour, 2 – 10 hours, 11 – 19 hours, and ≥ 20 hours and the percentages for each category were displayed using bar graphs.

2.5 Lake System Analysis

The final objective of this research is to investigate the potential influences of the Great Lakes on convection within the region. A convective system was said to have "interacted" with the Great Lakes if at least one lightning flash on the hourly plots of the 20-minute lightning flashes centered on the hour occurred over any of the Great Lakes during the system's lifetime. For simplicity, these systems are referred to below as "lake systems". Origin, termination, and persistence were analyzed for all lake systems. Also, each hour of lake interaction was recorded for all lake systems. For cases where lake systems split after lake interaction, only the system that persisted the longest after splitting was retained for analysis.

Lake systems were classified into three exclusive categories: 1) lake origination, 2) lake termination, and 3) lake interaction. A "lake originating" system was defined as a system that interacted with one or more of the Great Lakes during the hour that the system was first observed on the lightning plots. "Lake terminating" systems were defined as systems that dissipated within two hours of a lake interaction. The remaining lake systems fell into the "lake interaction" category which meant they had not formed over, nor terminated over the Great Lakes, but rather interacted with them at some point during the system's lifetime.

Surface synoptic features (e.g., frontal boundaries) were identified for each lake system at the time of lake interaction to determine the features that are most often associated with convection occurring over the Great Lakes at different times of day. Surface weather maps archived by Unisys Weather (www.unisys.weather.com) at 00 and 12 UTC were used for this analysis. Many lake interactions occurred between the archived map times, therefore surface features in these cases had to be inferred to the time of lake interaction. The surface maps for each lake system were examined multiple times by more than one analyst to provide consistency of feature identification and to minimize the degree of subjectivity involved in this process.

The surface features most frequently identified were frontal boundaries and surface troughs. Frontal boundaries included cold fronts, warm fronts, stationary fronts, and occluded fronts. A front was noted as the surface feature if convection over the lakes occurred along the frontal boundary. Although frontal features were also present for the "prefrontal convection", "behind a cold front", and convection "within the warm sector" categories, the convection in these cases did not exist at the frontal boundary. Prefrontal convection was recorded as the surface feature if the convection over a lake was substantially ahead (e.g., to the east of an eastward moving front) of a frontal boundary. When lake convection occurred to the west of a cold front or warm front, the surface feature was noted as "behind a cold front" or "within a warm" sector, respectively. Convection over the lakes on the upstream side of an organized low pressure system was considered to be "behind a low pressure system". A trough was noted when lake convection either occurred to the east of a trough axis that was drawn on the map or, when a trough axis was not included on the map, near a region of wind convergence. There were a few cases where a high pressure system was considered to be the prominent surface feature associated with area of lake convection. An unclassified category was reserved for instances where no surface feature was apparent near the area of lake convection. The surface synoptic features were analyzed by each lake system type.

2.5(a) Lake Originating Systems

An interesting question regarding lake originating systems is whether or not system generation varies by individual lake. To address this question, the origin locations of lake originating systems were displayed on a map of the study region. In addition, the termination locations of lake originating systems were mapped to identify possible spatial patterns in system decay. The frequency of lake originating systems by time of day was also analyzed along with temporal variations in the surface synoptic features associated with these systems. In addition, system duration (defined as the total number of hours of recorded lightning activity over the entire lifetime of the system) and lake duration (defined as the number of hours when lightning activity was recorded over any of the Great Lakes) were recorded for each lake originating system and displayed using histograms. System duration was also analyzed by the time of day systems formed to assess possible temporal variations in the persistence of lake originating systems.

2.5(b) Lake Terminating Systems

One question concerning lake terminating systems is whether or not the frequency of system termination differs for each lake. To address this, the termination locations were mapped and compared to the locations where the systems initially formed. The temporal variability of terminating systems was addressed by identifying the hour that each system terminated, and surface synoptic features were examined to better understand the synoptic environment of systems that terminated over the lakes. System age at first lake interaction and lake duration were also analyzed for the lake terminating systems.

2.5(c) Lake Interacting Systems

Lake interacting systems are particularly interesting as, by definition, they persisted after lake interaction, unlike lake terminating systems. Insights on these systems can be gained by comparing their characteristics to those of lake terminating systems. The spatial variability in the formation and dissipation of lake interacting systems was analyzed by mapping the origin and termination locations. To assess the temporal variability of these systems, the time of day of the initial interaction with a lake was displayed using a histogram. In addition, the typical surface synoptic features associated with lake interacting systems were studied. Also, the system age at first lake interaction was determined for each lake interacting system as well as the length of time that the system was located over a lake. Histograms were used to display both measures of persistence. In addition, the persistence of systems from the time they first moved over the lakes until dissipation was analyzed by the time of day of initial lake interaction.

2.6 Summary

This chapter summarized the methods used to create a climatology of convective system origin, movement, duration, and termination for the north-central United States. Furthermore, methods for analyzing the characteristics of convective systems that originated, dissipated, or moved over the Great Lakes were described. The methods were selected to better understand the characteristics of convective systems in the study area and to evaluate possible forcing mechanisms for nocturnal convection, based on the correspondence of the climatological characteristics with expected patterns given previously-proposed theories for the formation of nocturnal precipitation.

Chapter 3 Characteristics of Convective Systems in the North-Central United States

This chapter describes the characteristics of the convective systems that occurred in the north-central United States during the summer of 2004 in terms of the time and location of origin and termination, system duration, and movement. As discussed in Chapter 2, the analysis was approached three ways, focusing on what is referred to as "originating systems", "terminating systems", and "existing systems" in order to obtain multiple perspectives on the spatial and temporal characteristics of convection within the region and to take into account splitting and merging systems.

3.1 Lightning Activity during the Summer of 2004

In order to place the climatological analysis in the context of the frequency of lightning activity, regional and hourly lightning flash frequencies, as well as "hourly" sequences of accumulated lightning flashes are displayed and discussed below. As noted in Chapter 2, only the lightning flashes that occurred in the 20-minute interval that straddled each hour were included in the convective system analysis, however, the overall total flash frequency, in addition to the total flash frequency of the 20-minute intervals, were summarized by region and time of day (Table 3-1 and Table 3-2). Lightning flash frequency generally decreased from west-to-east across the study area (Table 3-1) with an exception found in Region 2, where flash frequency was lower compared to both Region 3 and Region 4. Interestingly, a considerable decrease in flash frequency was observed between Region 4 and Region 5. The frequency of lightning flashes also displayed a distinct diurnal pattern (Table 3-2) as flash frequency was typically highest during the late afternoon and evening hours (20 UTC – 04 UTC), with a minimum evident during the later morning hours (14 UTC – 16 UTC). The regional and hourly frequencies provide a general indication of the spatial and temporal distribution of lightning observations within the study area. To gain further insights into the geographic and diurnal variability of lightning activity, "hourly" lightning accumulations (using the 20-minute interval of lightning flashes) over the entire study period are displayed on maps below.

Table 3-1. Overall total regional frequency of lightning flashes and the total frequency of the 20-minute intervals of lightning flashes used in the convective system analysis for the summer of 2004. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W).

Region	Total Flashes	20-Minute Totals
Region 1	1,048,458	348,750
Region 2	717,246	239,013
Region 3	929,013	309,101
Region 4	753,363	249,703
Region 5	420,358	139,953
Region 6	308,276	101,755
Total	4,176,714	1,388,275

Table 3-2. Overall total hourly frequency of lightning flashes and the total frequency of the 20-minute intervals of lightning flashes used in the convective system analysis for the summer of 2004.

Hour (UTC)	Total Flashes	20-Minute Totals
0	322,931	106,280
1	314,729	108,214
2	289,743	103,364
3	248,583	88,957
4	224,464	78,063
5	198,789	69,634
6	178,392	61,902
7	161,661	56,301
8	139,739	50,832
9	121,064	42,528
10	109,295	38,501
11	100,904	33,421
12	88,009	32,731
13	62,706	24,988
14	46,389	16,727
15	51,106	15,508
16	53,805	17,306
17	81,793	20,381
18	125,508	34,566
19	161,554	46,764
20	214,505	60,872
21	269,867	82,890
22	296,313	95,970
23	314,865	101,575
Total	4,176,714	1,388,275

In the early morning hours (12 – 13 UTC) of the 2004 summer season, cloud-to-ground lightning was most frequent over most of Iowa, southern Minnesota, and southwestern Wisconsin (Figure 3-1). Lightning also was relatively frequent in the eastern Great Lakes region, including portions of northern Pennsylvania and western New York. During the mid-morning hours (14 – 15 UTC) lightning density generally decreased across the study region; however, frequent lightning activity was observed over Iowa and much of Wisconsin, and northern Illinois. Lightning activity was infrequent in the western portion of the study period (Montana, Wyoming, western North and South Dakota, western Nebraska) and the eastern Great Lakes region. During the late morning hours (16 –17 UTC), lightning activity was relatively infrequent throughout most of the study region, although distinct clusters of higher flash densities were seen over South Dakota, Iowa, and northern Illinois. Also, compared to the mid-morning hours, lightning activity increased somewhat over the Great Lakes, particularly the Lower Peninsula of Michigan and Pennsylvania.

Flash density increased in the early afternoon hours (18 – 19 UTC) from southern Minnesota and Iowa eastward to New York (Figure 3-2). During the mid-afternoon (20 – 21 UTC), lightning activity remained high over the eastern two-thirds of the study region and increased compared to earlier time periods over the Rocky Mountain region and High Plains (Wyoming, northern Colorado, western Nebraska and western South Dakota). Lightning activity in the late afternoon hours (22 – 23 UTC) was similar to the activity observed during the mid-afternoon over much of the eastern portion of the study region, whereas flash densities increased over the High Plains.

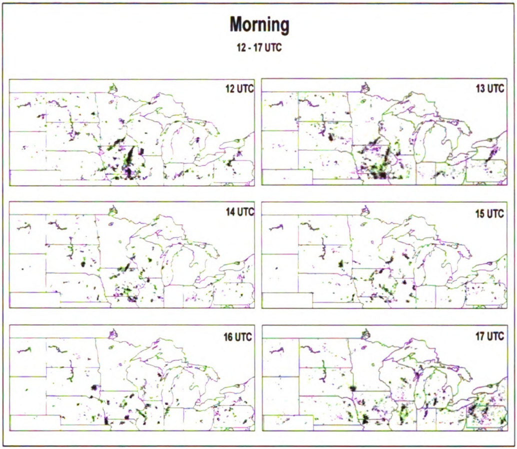


Figure 3-1. Lightning flash density over the entire study period for the hours of 12 - 17 UTC (morning). Each "hour" displays the lightning flashes that occurred during the 20-minutes at the top of that hour.

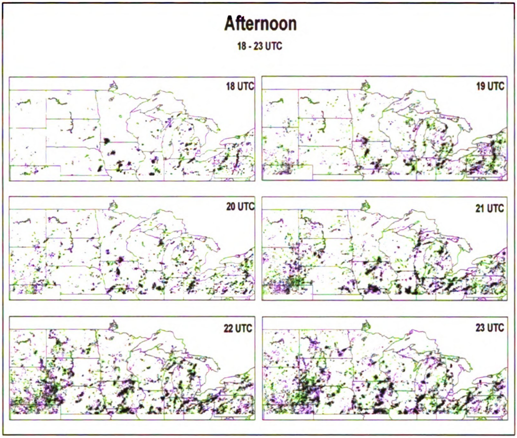


Figure 3-2. As in Figure 3-1 except for 18 - 23 UTC (afternoon).

Frequent lightning activity was observed over the much of the study region during the early evening hours (00 – 01 UTC), especially over western Nebraska and western South Dakota, and also from Iowa to northern Indiana (Figure 3-3). Flash density decreased slightly during the mid-evening hours (02 – 03 UTC), particularly in the extreme eastern portion of the study region, while three distinct regions of lightning activity were evident over Nebraska and South Dakota, Iowa, and northern Illinois and northern Indiana. During the late-evening, lightning frequency continued to decrease over much of the study region, with almost no lightning activity recorded over

Pennsylvania and New York. However, areas of high flash density were still evident over southern Nebraska, southern Iowa, and northern Illinois.

The highest flash densities during the early nighttime hours (06 – 07 UTC) were observed over much of the central plains (South Dakota, Nebraska, southwestern Minnesota, and Iowa) and the Great Lakes region (Wisconsin, northern Illinois, and Lake Michigan). The far eastern portion of the study region (Pennsylvania and New York) had very few lightning flashes during this time period (Figure 3-4). Lightning activity remained fairly high over the central plains during the mid-nighttime hours (08 – 09 UTC), while flash density decreased in the Great Lakes region. The extreme western (Montana and Wyoming) and eastern portions of the study region were virtually devoid of lightning activity in the mid-nighttime period. During the late night period (10 – 11 UTC), flash density was highest over southern Minnesota and Iowa and continued to decrease over the remaining portions of the study region.

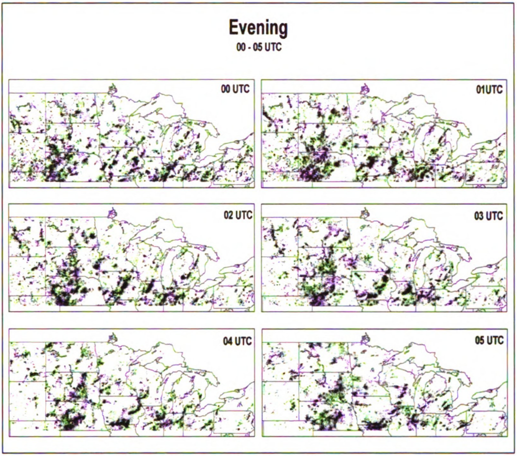


Figure 3-3. As in Figure 3-1 except for 00 - 05 UTC (evening).

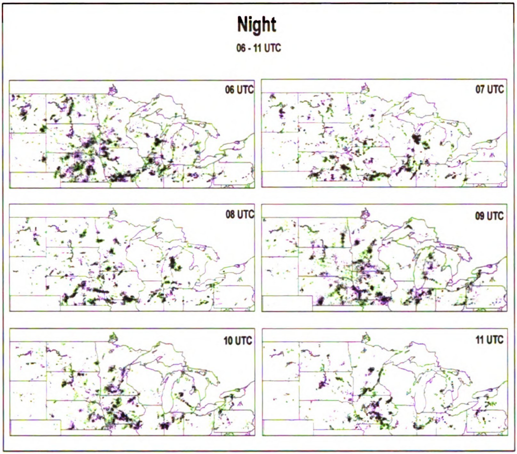


Figure 3-4. As in Figure 3-1 except for 06 - 11 UTC (night).

From the maps above, spatial and diurnal variations in the lightning activity are evident. However, it is difficult to infer convective system characteristics such as origin, movement, duration and termination from the flash densities alone and these aspects of convective systems are needed in order to evaluate the different theories that have been proposed for the occurrence of nocturnal precipitation. For example, it is not possible, using only the lightning accumulation maps, to assess the contribution of eastward propagating systems rather than locally generated systems to the frequency of nocturnal precipitation. An additional complicating factor is that the frequency of cloud-to-ground lightning flashes can vary greatly for different systems making maps of flash density difficult to interpret. Consequently, a necessary step to understanding the characteristics of convection is to identify individual convective systems from the lightning observations and trace the movement of these systems in time.

3.2 Analysis by System Origin

3.2(a) Frequency of System Origination by Time of Day and Region

During the summer season of 2004, a total of 837 convective systems originated within the study area. Of these systems, roughly 50% originated in Region 1 (Figure 3-5a). The large number of systems that originated in Region 1 is partially due to the larger size of the region compared to the other regions, but, in addition, the number of systems that originated in Region 1 reflects a greater frequency in system generation over the western portion of the study region. System formation decreased considerably in the regions to the east with 14% of systems originating in Region 2 and 9% originating in Region 3. Regions 4, 5, and 6 displayed a similar frequency of system formation as Region 3.

Convective systems were more likely to form in the afternoon hours (18 – 23 UTC) with 44% of systems forming during this time period (Figure 3-5b). The development of convective systems generally decreased during the remaining time periods as 22% of systems formed during the evening (00 – 05 UTC) period and 17% formed during the night (06 – 11 UTC) and morning (12 – 17 UTC) periods.

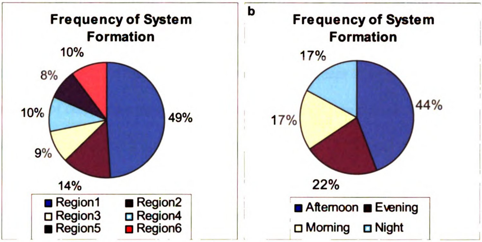


Figure 3-5. The frequency of system origin by a) region and b) time period. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W). The time periods are: Afternoon (18 – 23 UTC), Evening (00 – 05 UTC), Night (06 – 11 UTC), and Morning (12 – 17 UTC).

Temporal variations existed between regions in the relative frequency of system formation (Figure 3-6), although, regardless of region, more convection formed during the afternoon. Because the number of convective systems varied by region the discussion below is presented in terms of relative percentages by region. However, the number of convective systems per region is provided in Figure 3-6 to help interpret the percentages. Over 48% of the systems that originated in Region 1 formed in the afternoon (18-23 UTC), compared to 24% during the evening (00-05 UTC), 15% at night (06-11 UTC), and 13% during the morning (12-17 UTC). Afternoon systems were somewhat less frequent, and night and morning systems more frequent in Region 2 with 37% of systems originating in the afternoon, 25% during the evening, 19% at night, and 18% in the morning. Afternoon systems also were frequent in Region 3, as 42% of the convective systems that initiated in this region did so between 18-23 UTC. Convection was somewhat less likely to initiate in the evening hours in Region 3 compared to the two upstream regions with only 15% of systems forming during this time period. The relative frequencies were 23% and 20% for the night and morning periods, respectively. Afternoon systems were also frequent in Region 4 and Region 5, where 41% of convective systems generated during this time period. For Region 4, the frequency of convection that formed during the evening (21%) was slightly larger than that for Region 3, but smaller than in Region 1 and Region 2. For Region 5, convective systems were less likely to initiate during the evening hours compared to all of the upstream regions, with only 12% of the convective systems that formed in this region occurring during the evening period. The frequency of system generation during the night and morning periods was 20% and 18%, respectively, for Region 4 and 26% and 21% for Region 5. In Region 6, the frequency of convection forming in the afternoon was similar to that of upstream Region 4 and Region 5; evening and morning systems were somewhat more frequent in Region 6 compared to the two upstream regions; and nighttime convection was less frequent compared to Region 5 but similar to that for Region 4. The relative frequencies of system formation in Region 6 were 40%, 20%, 13%, and 28% for the afternoon, evening, night, and morning periods, respectively.

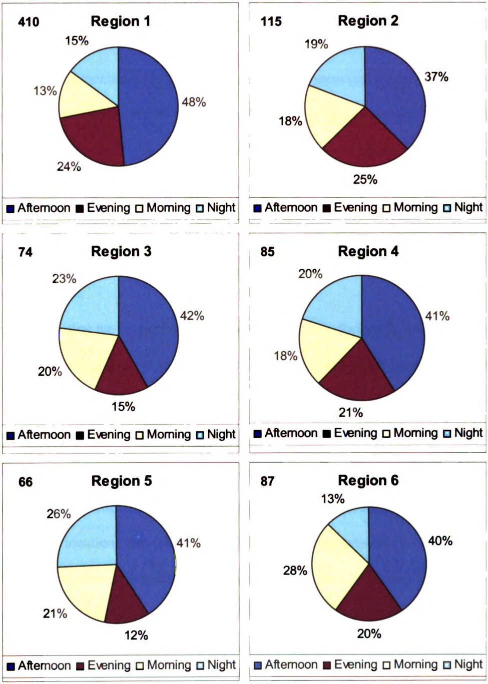


Figure 3-6. The frequency of system origin by time period for each region. The number of systems that originated in each region is shown in the upper left corner.

3.2(b) Movement Beyond the Study Area

Obviously some of the convective systems terminated outside of the study area. As previously mentioned in Chapter 2, an exiting system was one where the system was located within one degree latitude or longitude of the study area boundary during the last hour of recorded lightning activity. The impact of exiting systems was addressed two ways. First, the proportion of systems originating from a region that had one or more termination locations near the borders of the study area was estimated. Second, the proportion of termination locations within a region that represent exiting systems was calculated.

Estimating the proportion of systems that initially formed in a region and later exited the study area is complicated by the multiple termination locations for many system origins. Therefore, for the first method of analyzing exiting systems, the proportion of exiting systems was calculated in terms of the number of termination locations, rather than the number of system origins. The analyses indicate that a substantial proportion of the systems that originated within each region had one or more termination locations that fell close to the study area boundaries (Table 3-3). Keep in mind that a system with a termination location classified as "exiting" could also have had another termination location classified as "decaying" given that multiple termination locations per system was common. For systems that originated in Region 1, Region 2, and Region 4, approximately 40% of their termination locations were classified as exiting. Nearly half of the termination locations for the systems that initiated in Region 3 exited the study area. Not surprisingly, given their proximity to the eastern border of the study area, more than 60% of the termination locations for systems originating in Region 5, and 70% for those originating in Region 6, were located close the study boundaries.

Table 3-3. Frequency of termination locations for convective systems that formed in each region that were located within one degree latitude or longitude of the study area boundaries. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W).

Region 1	42%
Region 2	42%
Region 3	48%
Region 4	41%
Region 5	62%
Region 6	72%

The frequency of termination locations near each of the study area boundaries was calculated to estimate the relative movement (zonal versus meridional) of convective systems exiting the study area. Aside from Region 1 and Region 6, most "exiting" termination locations were observed along the southern border of the study area, particularly for systems that originated in Region 3 and Region 4 (Table 3-4). The large number of systems originating in Region 1 with one or more termination locations along the western border partly reflects small, short duration convective systems that formed and dissipated along the western boundary of the study area and does not necessarily represent systems that translated from east to west. Not surprisingly, most systems that formed in Region 6 had one or more termination locations close to the eastern boundary of the study area.

Table 3-4. The percentage of termination locations classified as "exiting" that were located along the northern, southern, eastern, and western boundaries of the study area for convective systems that originated in each region.

	Exit North	Exit South	Exit East	Exit West
Region 1	19%	43%	1%	38%
Region 2	40%	54%	6%	0%
Region 3	26%	70%	4%	0%
Region 4	26%	67%	7%	0%
Region 5	27%	57%	16%	0%
Region 6	19%	24%	56%	0%

The second method of addressing the potential impact of exiting systems on the study results is to consider the percentage of termination locations in a region that represent exiting rather than decaying systems. Almost half of all termination locations in Region 1 by definition represent exiting systems, although as pointed out above the frequency of exiting systems is likely overestimated in Region 1 because of short term convection along the western boundary of the study area (Table 3-5). The proportion of termination locations that likely represent exiting systems decreased in Region 2, Region 3, and Region 4 compared to Region 1, with the percentages ranging from 34-40%. The eastern regions show a considerably higher frequency of "exiting" termination location as more than 60% of the termination locations in Region 5, and nearly 70% of those in Region 6 likely reflect exiting systems.

Table 3-5. Percent of termination locations by region that were within one degree latitude and longitude of the study area boundaries and likely represent exiting systems. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W).

Region 1	45%
Region 2	34%
Region 3	35%
Region 4	40%
Region 5	61%
Region 6	69%

The position of the termination locations with respect to the study area boundaries supports the interpretation above of the movement of exiting systems (Table 3-6). Most (47%) of the "exiting" termination locations in Region 1 were found along the western border, whereas for Region 2, Region 3, Region 4, and Region 5 the majority were along the southern border. Not surprisingly, most termination locations (57%) for likely exiting systems found in Region 6 were along the eastern border.

Table 3-6. The percentage of termination locations classified as "exiting" that were located along the northern, southern, eastern, and western boundaries of the study area by region.

	Exit North	Exit South	Exit East	Exit West
Region 1	17%	36%	0%	47%
Region 2	35%	65%	0%	0%
Region 3	36%	64%	0%	0%
Region 4	26%	74%	0%	0%
Region 5	32%	68%	0%	0%
Region 6	18%	25%	57%	0%

These statistics on the proportion of "exiting" termination locations, viewed either from the perspective of originating systems or by the proportion of the total number of termination locations within a region, need to be kept in mind when interpreting the analyses of system movement, duration, and the time and location of termination that are presented below. The analysis of termination locations in 3.2(c) is limited to only the last location of a system within the study area. In many instances, the system may have terminated at a considerable distance outside of the study area. Because of this, duration may be underestimated as the portion of a system's lifetime outside of the study area is not included in the duration statistics. Additionally, a system may have been incorrectly identified as a local rather than a propagating system if the termination location fell along the boundary of the region that is shared with larger study area. For example, termination locations for systems that formed in Region 6 that fall along the eastern boundary are considered local systems rather than propagating systems even though they may have propagated outside of the study area.

3.2(c) Movement of Originating Systems

The following analysis examines the movement of convective systems from their origin location. The purpose of the analysis is to determine the degree to which systems that originate within each region remain local or propagate eastward. It is important to remember that a system originating in a particular region may have multiple termination locations if the system split into multiple systems during its lifetime. Also, as pointed out above, this analysis does not consider termination locations outside of the study area. Because of the multiple termination locations per system, the analyses below area presented as percentages of termination locations rather than system origins. To assist in interpreting the percentages the absolute numbers of termination locations by region and time period are shown in Table 3-7. In addition, the number of system origins and the number of termination locations by region and time period are included in Figures 3-7 through 3-12 for reference.

Table 3-7. Absolute frequencies of termination locations for systems that formed in Regions 1-6 during each time period. Note that all systems are assumed to terminate within the study area. The regional divisions are: Region 1 (109°W-100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W). The time periods are: Afternoon (18 – 23 UTC), Evening (00 – 05 UTC), Night (06 – 11 UTC), and Morning (12 – 17 UTC). These frequencies were used to calculate the percentages of local versus non-local system termination in Figures 3-7 through 3-12.

Region and Time Period of Formation	Termination Region						
	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Total
Region 1 Afternoon	245	49	36	13	12	3	358
Region 1 Evening	98	11	3	1	4	2	119
Region 1 Night	59	10	6	0	2	0	77
Region 1 Morning	75	17	5	1	0	0	98
Region 1 total = 652							
Region 2 Afternoon	0	31	20	3	3	0	57
Region 2 Evening	0	19	8	4	5	7	43
Region 2 Night	3	17	3	0	0	0	23
Region 2 Morning	0	14	14	8	5	1	42
Region 2 total = 165							
Region 3 Afternoon	0	0	26	10	5	4	45
Region 3 Evening	0	0	8	3	1	0	12
Region 3 Night	0	0	15	2	1	2	20
Region 3 Morning	0	0	15	4	2	0	21
Region 3 total = 98							
Region 4 Afternoon	0	0	2	32	13	3	50
Region 4 Evening	0	0	0	17	4	0	21
Region 4 Night	0	0	0	14	5	5	24
Region 4 Morning	0	0	0	16	0	0	16
Region 4 total = 111							
Region 5 Afternoon	0	0	0	2	22	8	32
Region 5 Evening	0	0	0	0	7	1	8
Region 5 Night	0	0	0	0	12	7	19
Region 5 Morning	0	0	0	1	8	11	20
Region 5 total = 79							
Region 6 Afternoon	0	0	0	0	1	44	45
Region 6 Evening	0	0	0	0	0	17	17
Region 6 Night	0	0	0	0	0	12	12
Region 6 Morning	0	0	0	0	1	33	34
Region 6 total = 108							

The majority of systems that originated in Region 1 terminated locally (i.e., within Region 1) regardless of time of day (Figure 3-7), keeping in mind that systems exiting the region across the study area boundaries are considered to have terminated locally. Evening systems were most likely to remain local (82%) while the afternoon had the lowest frequency of locally terminating systems (68%). Of the systems that terminated outside of Region 1, most terminated within Region 2. However, those that originated during the evening and afternoon hours propagated farther eastward than systems that originated during the morning and nighttime hours. Some systems that formed in Region 1 during the afternoon and evening periods terminated as far eastward as Region 6, while very few systems that originated during the night and morning periods traveled farther than Region 3.

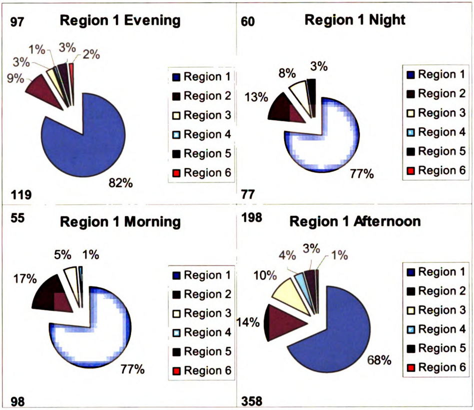


Figure 3-7. Systems that originated in Region 1 (109°W - 100°W) were traced forward in time to their termination location. Each pie chart section represents the percentage of termination locations that fell within a particular region. The number of termination locations per region is shown in the bottom left corner and the number of system origins per region in the upper left corner. Systems that exited the study area were considered to have terminated in the region they were last detected.

Region 2 displayed greater temporal variation in the percentage of systems that terminated locally (Figure 3-8). Only 33% of systems that originated during the morning period terminated locally, whereas 74% of the systems that formed during the nighttime hours terminated locally. The percentage of systems terminating locally was 54% and 44% for the afternoon and evening periods, respectively. Of the evening systems that originated in Region 2, 12% traveled to Region 5 and 16% to Region 6. On the other hand, only 5% of the systems that formed in the afternoon hours propagated to Region 5 and none to Region 6. Also, no systems that formed during the nighttime hours traveled beyond Region 3. Some systems during the 06 - 11 UTC period (night) propagated "upstream" with 13% of systems that originated during the night terminating in Region 1. This movement is partially a result of the subjective methods employed to estimate the system centroid locations. In some cases during a system split or merger, new centroids were located to the west of the previous centroid, which resulted in an apparent westward movement of the system.

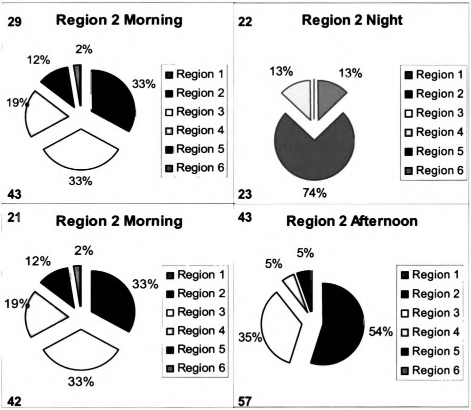


Figure 3-8. As in Figure 3-7 except for Region 2 (99.9°W – 95°W).

Convective systems that originated in Region 3 were most likely to terminate locally, regardless of time of day, although some diurnal variability was evident (Figure 3-9). The highest frequency of locally terminating systems was observed during the night at 75% of systems compared to a minimum of 58% in the afternoon period. For systems that terminated outside of Region 3, 9% of systems that initiated in the afternoon and 10% of systems that formed at night traveled as far east as Region 6, whereas none of the systems that formed in the morning and evening periods propagated as far eastward.

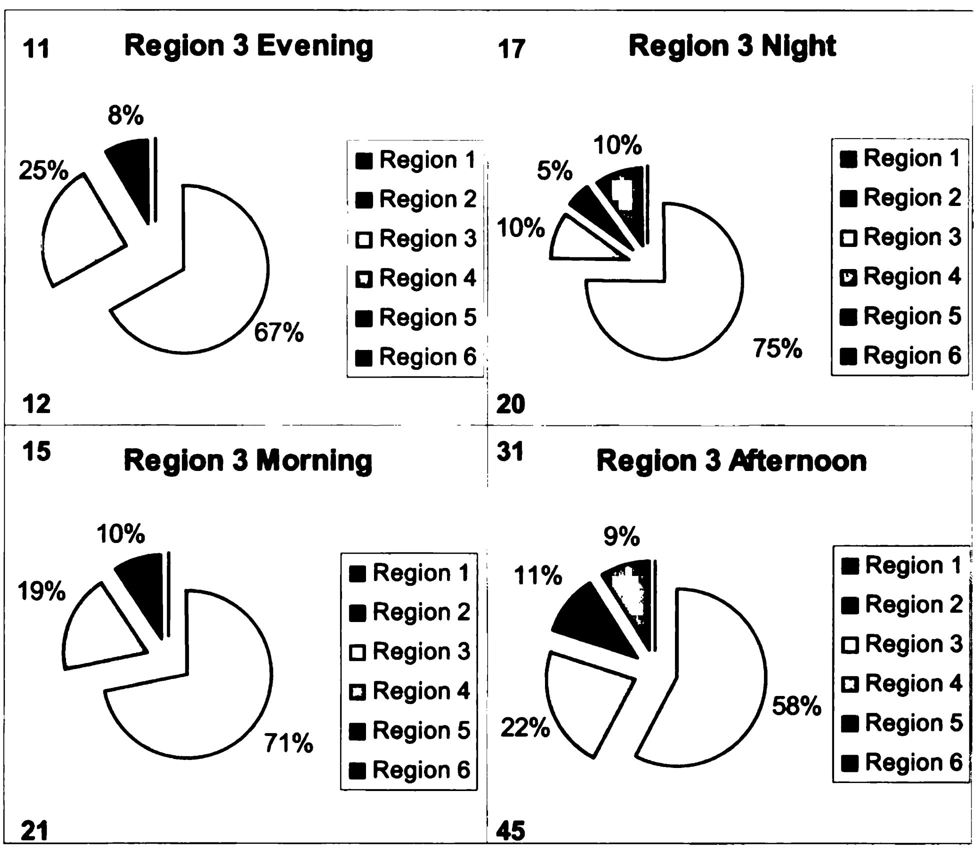


Figure 3-9. As in Figure 3-7 except for Region 3 (94.9°W - 90°W).

Greater temporal variation in the percentage of systems that terminated locally was apparent for systems that originated in Region 4 (Figure 3-10), although regardless of time of day systems were more likely to terminate within Region 4. All systems that originated during the morning period terminated within the region, which was not found for any other time period or region. A substantial proportion (81%) of systems that formed during the evening terminated locally as well, and those systems that did propagate outside the region terminated in neighboring Region 5. Convective systems that initiated during the night and afternoon periods were less likely to terminate within Region 4, with afternoon systems more likely to terminate in Region 5 and nighttime systems equally likely to terminate in Region 5 and Region 6.

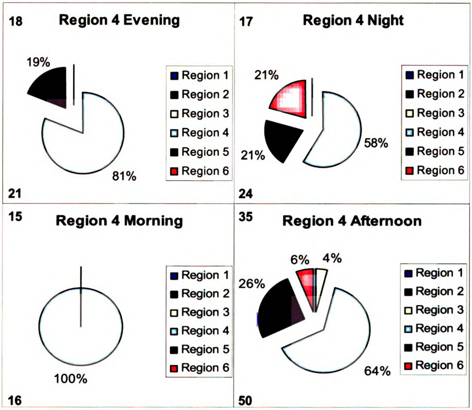


Figure 3-10. As in Figure 3-7 except for Region 4 (89.9°W - 85°W).

Of the systems that originated in Region 5, most were found to have terminated locally with the exception of those systems that formed during the morning period (Figure 3-11). The percentage of systems terminating locally was 69%, 88%, and 63% for the afternoon, evening, and night periods, respectively. Conversely, convection that developed in the morning hours was more likely to terminate outside of Region 5, as 55% of systems that originated during this time period terminated in Region 6. As expected given the eastward extent of the study region, almost 100% of the systems that originated in Region 6 terminated locally (Figure 3-12) regardless of time period.

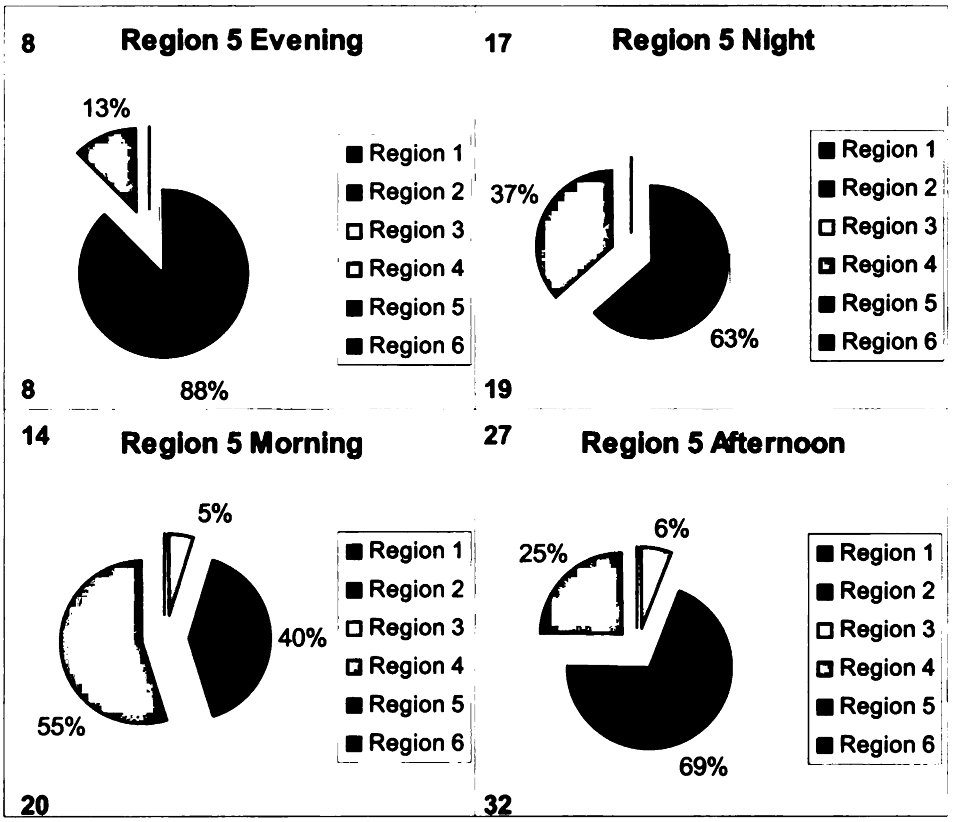


Figure 3-11. As in Figure 3-7 except for Region 5 (84.9°W - 80°W).

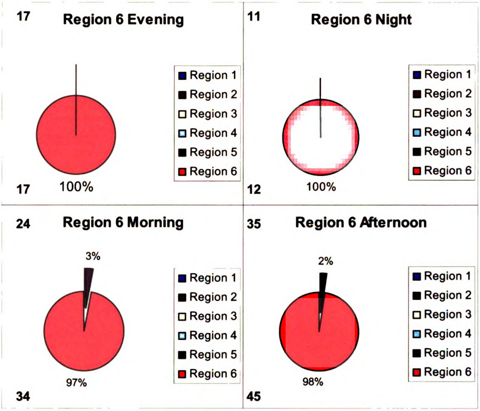


Figure 3-12. As in Figure 3-7 except for Region 6 (79.9°W - 74°W).

3.2(d) System Duration

System duration is defined as the number of hours of recorded lightning activity for a system while it was located within the study area boundaries. Systems that exited the study area had longer durations than reported here. Durations were grouped into six categories of unequal size (1 to 2 hours, 3 to 4 hours, 5 to 9 hours, 10 to 17 hours, 18 to 29 hours, ≥ 30 hours) to compare across the study region. The categories were chosen based on visually identified "breakpoints" on a histogram of the durations of all convective systems that formed within the study period (Figure 3-13). The breakpoints appeared to delineate natural groupings of all system durations and were therefore chosen for the duration categories. The categories are not identical to those used in the earlier study by Patterson *et al.* (1995), although they are very similar. The number of termination locations per region was once again used to calculate percentages for this analysis.

The durations of the convective systems identified in the summer of 2004 ranged from 1 to 50 hours (Figure 3-13). Approximately 25% of all systems dissipated within 2 hours of formation. However, a considerable number (40%) of systems existed from 3 to 9 hours and nearly one third had durations of more than 10 hours.

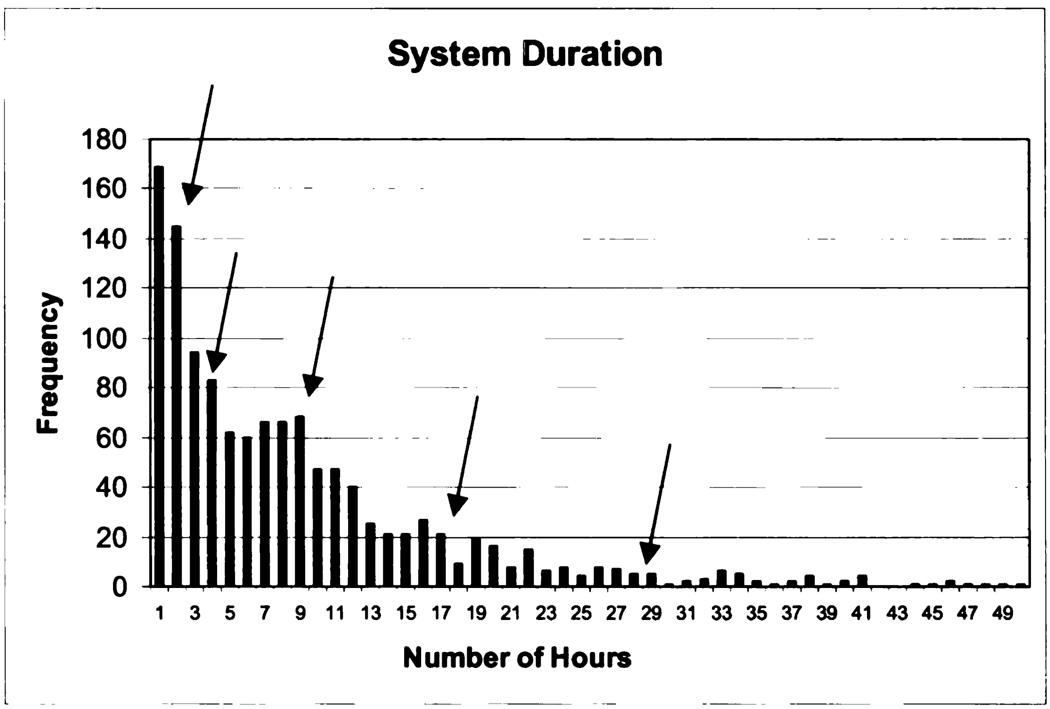


Figure 3-13. Duration of all originating systems. Arrows indicate breakpoints used to create duration categories.

The duration of convective systems that formed in Region 1 varied by time of day (Figure 3-14). Systems that originated during the evening and night periods tended to have shorter durations than those that generated during the morning and afternoon hours. Of the systems that originated during the evening and night periods, 38% and 43% persisted for 2 hours or less, respectively. Conversely, the durations for more than 50% of systems that initiated during the afternoon fell in the 5 to 9 hours or 10 to 17 hours categories, and only 13% of the afternoon systems persisted for 2 hours or less. Systems that formed within Region 1 during the morning hours displayed a bi-modal distribution of system duration, as 23% of the systems had durations of 1 to 2 hours and 28% persisted for 10 to 17 hours. The few systems that formed within Region 1 and persisted for 30 hours or more were more likely to have originated during the afternoon hours.

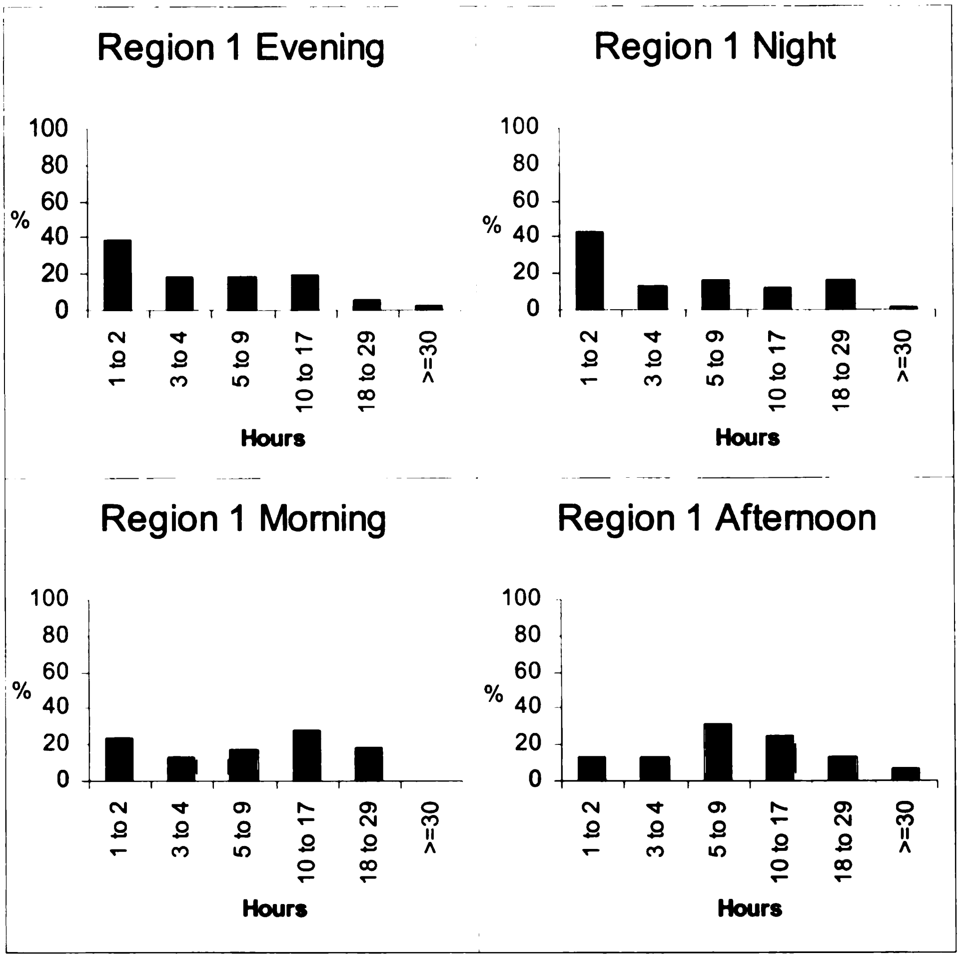


Figure 3-14. Durations of systems that originated in Region 1 (109°W - 100°W).

Greater temporal variation in system duration was evident for systems that originated in Region 2 (Figure 3-15). Systems that formed at night generally had shorter durations. All nighttime systems had durations of 9 hours or less, and 52% of the systems persisted only 1 to 2 hours. In contrast, 69% of the systems that formed during the morning persisted for 10 hours or longer, and 19% persisted at least 30 hours. A bi-modal distribution is evident for systems that originated during the afternoon with 28% of systems falling in the 1 to 2 hours category and 35% falling in the 5 to 9 hours category. Evening systems were more likely to have shorter durations, as 65% of systems generated during this time period existed for 9 hours or less, although 16% of systems persisted for 30 hours or longer.

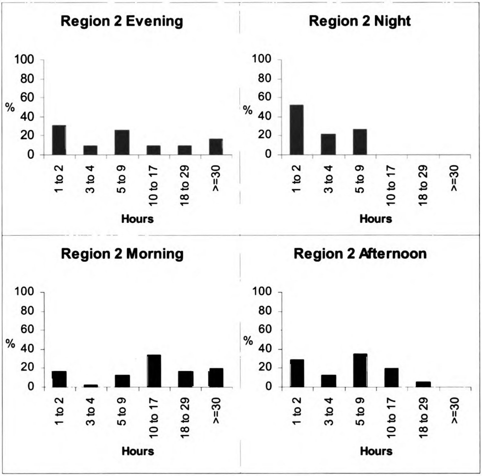


Figure 3-15. Durations of systems that originated in Region 2 (99.9°W - 95°W).

Most of the systems that originated in Region 3 persisted for 9 hours or less within the study area (Figure 3-16). A substantial number (67%) of evening systems had durations of only 1 to 2 hours and no evening systems persisted more than 9 hours. Of the systems that originated during the afternoon and morning hours, over 65% existed for 9 hours or less, with 24% falling into the 10 to 17 hours category for both time periods. Convection that formed during the nighttime period was more likely to have longer durations, with 20% of systems persisting for 18 to 29 hours.

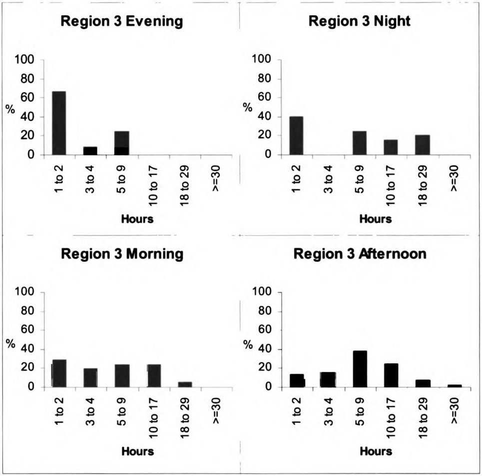


Figure 3-16. Durations of systems that originated in Region 3 (94.9°W - 90°W).

Convection that initiated within Region 4 was less likely to persist for long periods of time compared to convection that formed in the upstream regions (Figure 3-17). This was likely an artifact of the proximity of this region to the eastern border of the study area, as some systems exited the study region before termination. Systems that originated during the evening and morning periods generally existed for 4 hours or less before terminating or moving out of the study region and no systems from these times that had durations of more than 17 hours within the study area. On the other hand, systems that formed during the afternoon and nighttime periods were more likely to persist within the study area for 5 hours or longer. Systems that persisted for more than 18 hours were most frequent during the nighttime period.

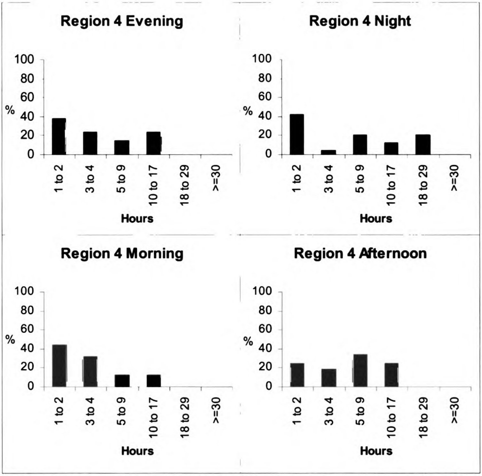


Figure 3-17. Durations of systems that originated in Region 4 (89.9°W - 85°W).

The distance from the eastern border of the study area also affected the system durations for the Region 5. Nonetheless, some diurnal variations in storm duration were observed (Figure 3-18). Convection that formed in the evening and nighttime periods had short durations as 76% of evening systems and 64% of night systems persisted for 4 hours less. In contrast, 70% of systems that originated during morning period, and 56% of storms that formed in the afternoon, persisted for at least 5 hours, with some afternoon events having durations of 30 hours or more.

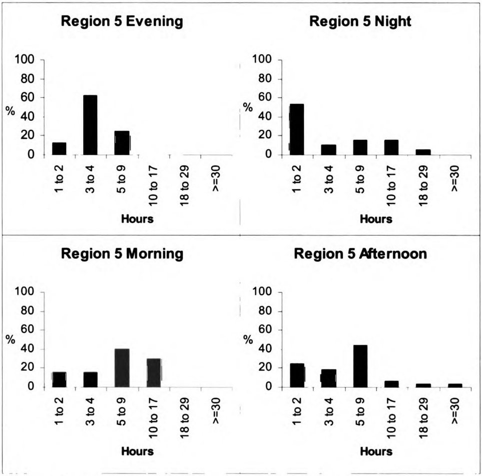


Figure 3-18. Durations of systems that originated in Region 5 (84.9°W- 80°W).

The duration of convection that formed in Region 6 varied substantially, in spite of Region 6's location at the eastern edge of the study area. Similar to Region 5, the majority of convective systems that formed in Region 6 persisted 9 hours or less

(Figure 3-19). When viewed by time of day, over 75% of systems that formed during the evening and night persisted for no more than 4 hours. Longer duration systems were more likely to have formed in the morning and afternoon hours. Over 70% of morning systems and 56% of evening systems persisted for at least 5 hours. In addition, 41% of morning systems persisted for 10 to 17 hours.

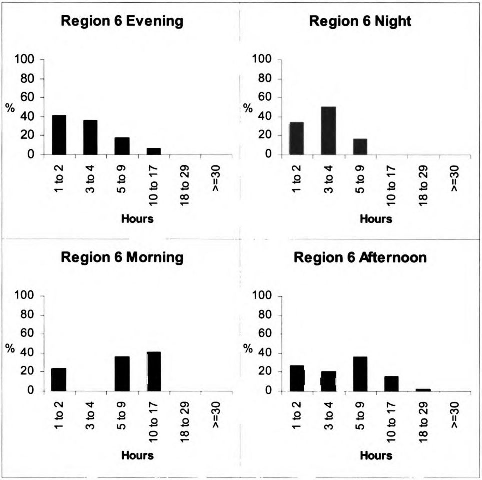


Figure 3-19. Durations of systems that originated in Region 6 (79.9°W - 74°W).

3.3 Analysis by System Termination

The spatio-temporal characteristics of convection were also examined from the perspective of the region in which convective systems terminated. In order to speculate on the mechanisms of convection within the study area, temporal characteristics of system termination are needed, as certain mechanisms are dependant on time of day (i.e., a nocturnal low-level jet). Therefore, the spatial and temporal patterns of both the origin and termination of convection are helpful to evaluate the possible mechanisms responsible for these systems. The following analysis examines the temporal variation of system termination by region, keeping in mind that some systems terminated outside of the study area. Terminating systems are also traced backward in time to identify the first occurrence of lighting activity within the study area and the length of time they persisted (i.e., duration) within the study area. The additional findings gained from these analyses compliment the analyses in the preceding sections and are discussed below.

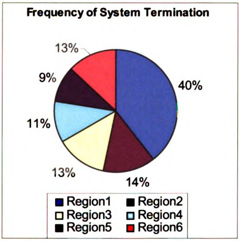
Similar to the analyses for system origin, the temporal and spatial variations of system termination are shown in terms of percentages. To assist in interpreting these percentages, the absolute number of system terminations by region and time of day are provided in Table 3-8.

Table 3-8. The number of termination locations by region and time of day and the region of origin within the study area. The regional divisions are: Region 1 (109°W-100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W). The time periods are: Afternoon (18 – 23 UTC), Evening (00 – 05 UTC), Night (06 – 11 UTC), and Morning (12 – 17 UTC). These frequencies were used to calculate the percentages of local versus non-local system termination in Figures 3-22 through 3-27.

Region and Time Period of Termination	Region Of Origin						
	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Total
Region 1 Afternoon	89	0	0	0	0	0	89
Region 1 Evening	223	0	0	0	0	0	223
Region 1 Night	100	2	0	0	0	0	102
Region 1 Morning	65	1	0	0	0	0	66
Region 1 total = 480							
Region 2 Afternoon	12	17	0	0	0	0	29
Region 2 Evening	21	33	0	0	0	0	54
Region 2 Night	27	16	0	0	0	0	43
Region 2 Morning	27	15	0	0	0	0	42
Region 2 total = 168							
Region 3 Afternoon	8	4	17	0	0	0	29
Region 3 Evening	10	24	21	2	0	0	57
Region 3 Night	13	12	12	0	0	0	37
Region 3 Morning	19	5	14	0	0	0	38
Region 3 total = 161							
Region 4 Afternoon	3	1	3	19	1	0	27
Region 4 Evening	3	1	9	24	2	0	39
Region 4 Night	3	10	7	19	0	0	39
Region 4 Morning	6	3	0	17	0	0	26
Region 4 total = 131							
Region 5 Afternoon	3	1	0	2	12	0	18
Region 5 Evening	7	3	3	5	17	1	36
Region 5 Night	5	4	3	11	12	1	36
Region 5 Morning	3	5	3	4	8	0	23
Region 5 total = 113							
Region 6 Afternoon	0	5	1	0	6	31	43
Region 6 Evening	3	3	2	5	14	46	73
Region 6 Night	2	0	2	3	3	14	24
Region 6 Morning	0	0	1	0	4	15	20
Region 6 total = 160							

3.3(a) Frequency of System Termination by Time of Day and Region

Of the termination locations that were identified in the summer of 2004, 40% fell within in Region 1 (Figure 3-20a). The termination locations include the last position of systems that decayed within the study area and also of those systems that exited the study area during the next hour. Approximately 9% to 14% of systems terminated within each of the other regions, a much lower frequency compared to Region 1. When examining systems across the entire study area (Figure 3-20b), systems were more likely to have terminated during the evening period (40%). Systems were approximately equally likely to have terminated during the other time periods.



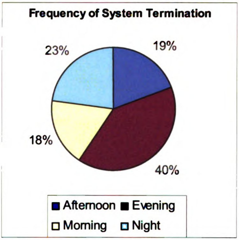


Figure 3-20. The frequency of system termination by a) region and b) time period. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), Region 5 (84.9°W – 80°W), and Region 6 (79.9°W – 74°W). The time periods are: Afternoon (18 – 23 UTC), Evening (00 – 05 UTC), Night (06 – 11 UTC), and Morning (12 – 17 UTC).

Forty-six percent of systems that terminated in Region 1 did so during the evening (Figure 3-21). System termination within this region was least frequent during the morning (14%). The percentage of systems that terminated during the morning increased to 25% in Region 2, while systems terminated somewhat less frequently (32%) in the evening period compared to Region 1. The distribution of the frequency of system termination by time of day for Region 3 was similar to that of Region 2. In Region 4, systems were equally as likely to terminate during the evening and night periods, with 30% of systems terminating in each time of these two time periods. A similar distribution was observed in Region 5, with only a slight decrease in the afternoon compared to Region 4. Region 6 showed a substantial increase in the percentage of systems that terminated during the evening (46%) and afternoon (27%) compared to Region 4 and Region 5, and therefore a decrease in the percentages of systems terminating during the morning and night periods.

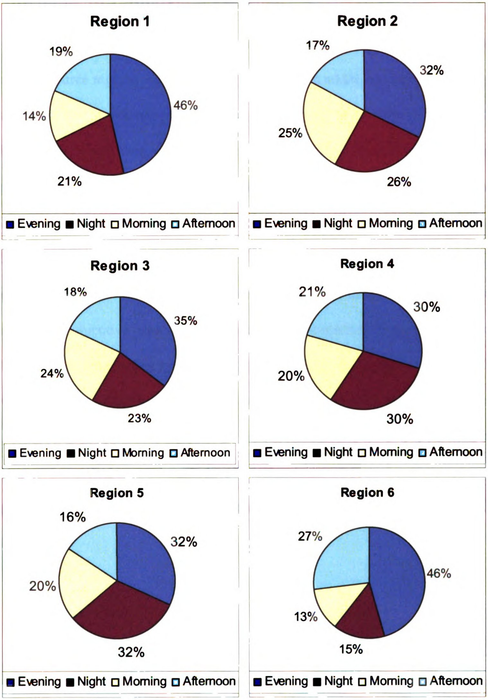


Figure 3-21. The frequency of system termination by time period for each region.

3.3(b) Paths of Terminating Systems

Convective systems were traced backward in time from their termination location to their source regions within the study area to gain additional information regarding the origin and movement of convection. Percentages of convective systems that formed locally versus upstream were determined using the frequency of termination locations per region and time period shown in Table 3-8. As expected given the location of Region 1 at the western edge of the study area, almost all systems that terminated in Region 1 originated locally (i.e., within Region 1) regardless of time of day. The only exceptions were a small number of systems that appear to have originated downstream due to the subjective nature of identifying system centroids (Figure 3-22). The relative frequency of terminating systems that formed locally versus those that formed upstream varied by time of day in Region 2. As shown in Figure 3-23, systems that terminated during the night and morning periods were more likely to have originated upstream in Region 1 (> 60%) as opposed to locally. This contrasts with the afternoon and evening periods where approximately 60% of the terminating systems originated within Region 2.

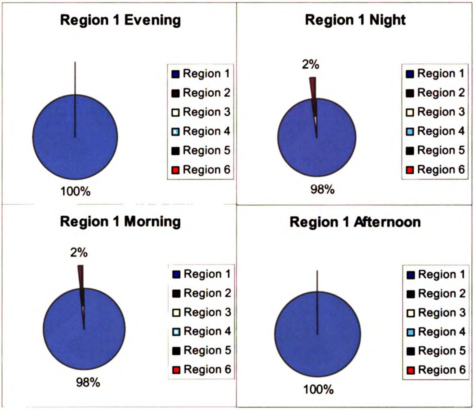


Figure 3-22. Systems that terminated within Region 1 (109°W - 100°W) were traced backward in time to their region of origin. Each pie chart segment represents the percentage of systems that originated in a particular region.

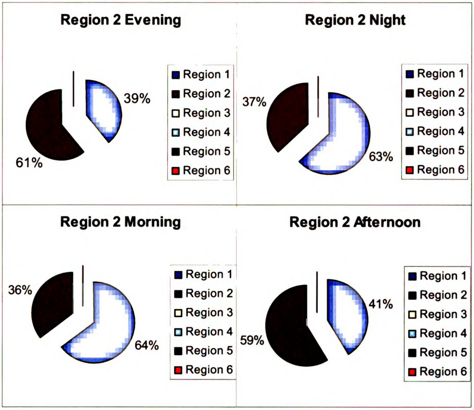


Figure 3-23. As in Figure 3-22 except for Region 2 (99.9°W - 95°W).

For Region 3, the afternoon period was the only time of day when the majority (approximately 60%) of systems that terminated within the region also formed within the region (Figure 3-24). In contrast, roughly one-third of systems that terminated during the evening, night, and morning periods had originated in Region 3. For the nighttime period, systems that originated upstream were equally as likely to have initiated in Region 1 and Region 2. The systems that formed outside of Region 3 that terminated during the morning, however, were more likely to have originated in Region 1, as 50% of systems were traced back to this region. Most non-local systems that terminated during the evening originated in Region 2.

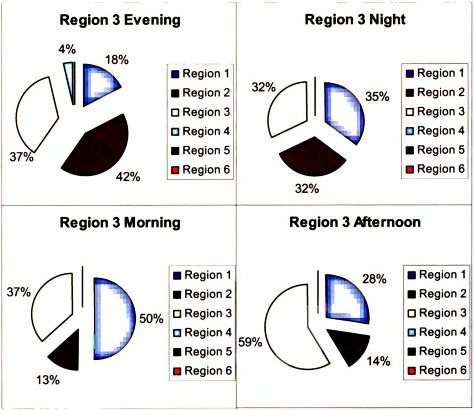


Figure 3-24. As in Figure 3-22 except for Region 3 (94.9°W - 90°W).

Most convective systems that terminated within Region 4 were generated locally (Figure 3-25) with the exception of those that terminated during the nighttime period. More than 60% of systems that terminated during the afternoon, evening, and morning periods generated within Region 4. During the evening and afternoon periods, non-local systems could be traced back to each upstream region; however, none of the non-local systems that terminated during the morning hours originated in neighboring Region 3. Approximately half of the systems that terminated during the night originated upstream, mostly in Region 2.

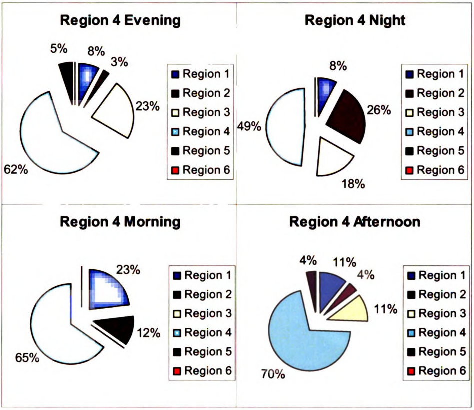


Figure 3-25. As in Figure 3-22 except for Region 4 (89.9°W - 85°W).

In contrast to Region 4, systems that terminated in Region 5 were more likely to have originated upstream (Figure 3-26). The only exception to this is the afternoon period, where 67% of systems that terminated within Region 5 were generated within the region. The frequency of locally generated systems is larger for systems that terminated during the evening period (47%) compared to the nighttime (33%) and morning (35%) hours, but still over half of the systems that terminated in the evening hours originated upstream. Non-locally generated systems that terminated during the morning hours were approximately equally as likely to have originated in any of the upstream regions, whereas for the nighttime period systems were most likely (31%) to have originated immediately upstream in Region 4.

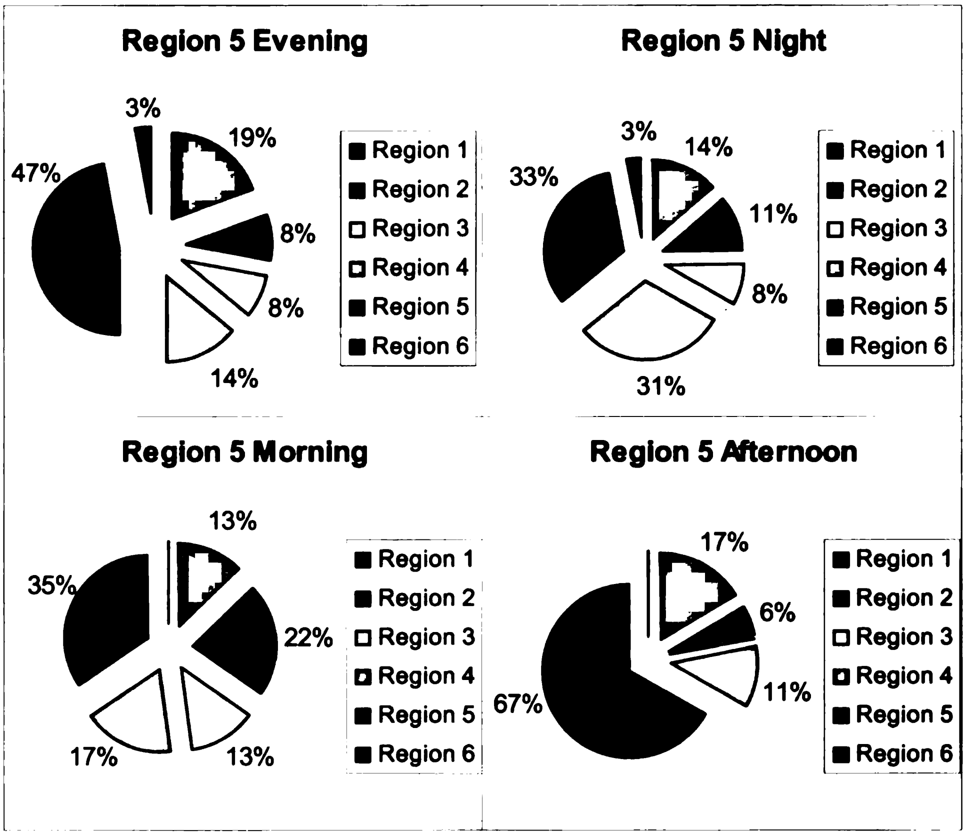


Figure 3-26. As in Figure 3-22 except for Region 5 (84.9°W - 80°W).

Of the systems that terminated in Region 6, most had formed within the region, regardless of time of day (Figure 3-27). The frequency of non-locally generated systems was highest during the evening and nighttime hours when approximately 40% formed upstream. In contrast, systems that terminated during the morning and afternoon hours were much more likely to have formed locally as nearly 75% of systems during both time periods originated within Region 6.

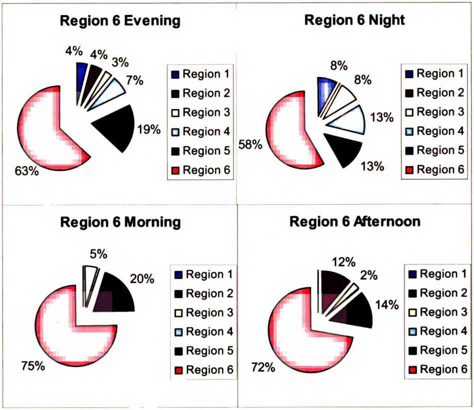


Figure 3-27. As in Figure 3-22 except for Region 6 (79.9°W - 74°W).

3.3(c) System Duration at Termination

The duration of terminating systems, or in other words, the length of time a system existed within the study area before either decaying or exiting, varied both spatially and temporally. In Region 1, of the systems that terminated during the afternoon period, almost all had existed for 9 hours or less before they dissipated (Figure 3-28), with more than 80% with durations of only 1 to 4 hours. Conversely, most systems (62%) that dissipated during the evening period had formed at least 5 hours prior to termination. Nighttime systems displayed a bi-modal distribution, as most systems that terminated during this period had a lifespan of either 1 to 2 hours (33%) or 10 to 17 hours (32%). System duration was more evenly distributed among the duration categories for systems that terminated during the morning period.

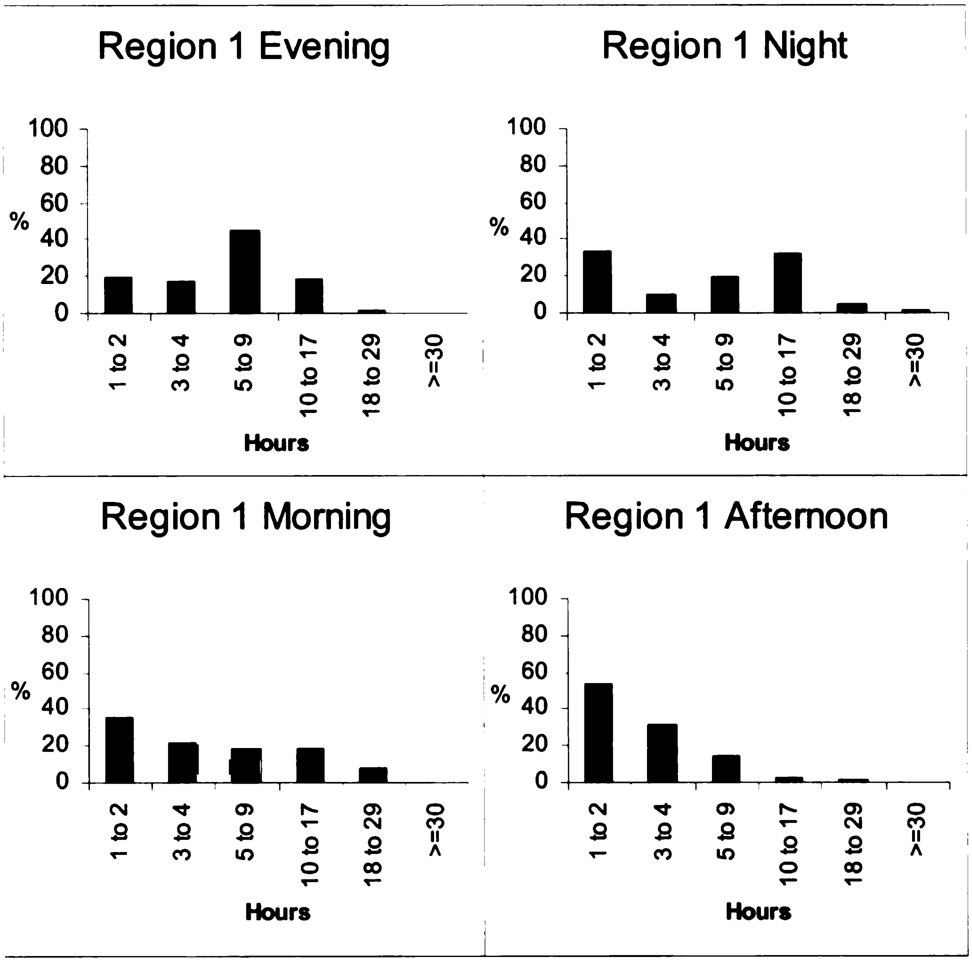


Figure 3-28. Duration of systems that terminated in Region 1(109°W - 100°W).

Compared to Region 1, systems that terminated within Region 2 were more likely to have existed for a longer time period before dissipating (Figure 3-29). Approximately 33% of systems that terminated during the morning formed more than 18 hours earlier, and the lifespan of 65% of systems terminating at night was greater than 10 hours. In contrast, most systems that terminated in Region 2 in the afternoon had only existed for 9 hours before dissipation. The distribution of system duration was more variable for systems terminating during the evening hours with 33%, 30%, and 19% of systems having persisted 1 to 2 hours, 5 to 9 hours, and 10 to 17 hours, respectively, at the time of termination.

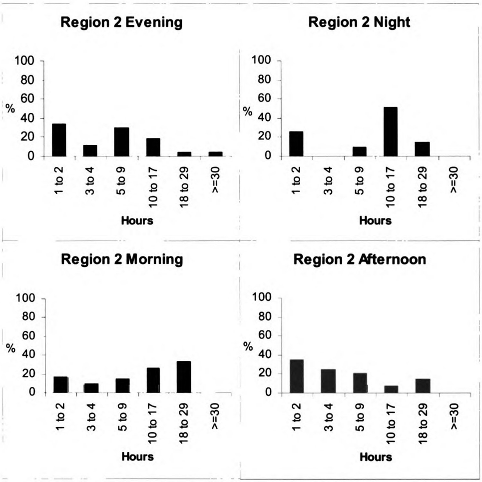


Figure 3-29. Duration of systems that terminated in Region 2 (99.9°W - 95°W).

Frequency of system duration varied by time of day for systems that dissipated in Region 3. For both the afternoon and evening periods, more than 60% of systems that terminated at these times had existed for 9 hours or less (Figure 3-30). On the other hand, systems that terminated during the morning and night periods were more likely to have formed at least 10 hours prior to termination. Unlike the other time periods, almost 10% of nighttime systems had existed for more than 30 hours before dissipating.

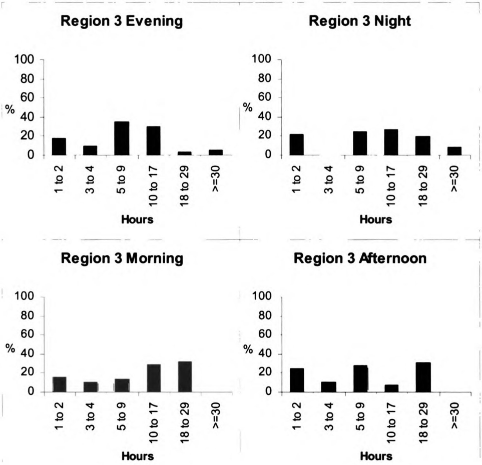


Figure 3-30. Duration of systems that terminated in Region 3 (94.9°W - 90°W).

Most systems that terminated in Region 4 formed 9 hours or less prior to dissipation regardless of time of day (Figure 3-31). In particular, 41% of systems formed no more than 2 hours before terminating during the afternoon period. Although a majority of systems that terminated during the nighttime period had durations of 9 hours or less, a substantial number (46%) of systems formed at least 10 hours prior to termination. A similar distribution was observed during the morning period. Approximately 41% of system durations fell into the 5 to 9 hours category for systems that terminated during the evening, with a roughly equal number with durations of 4 hours or less.

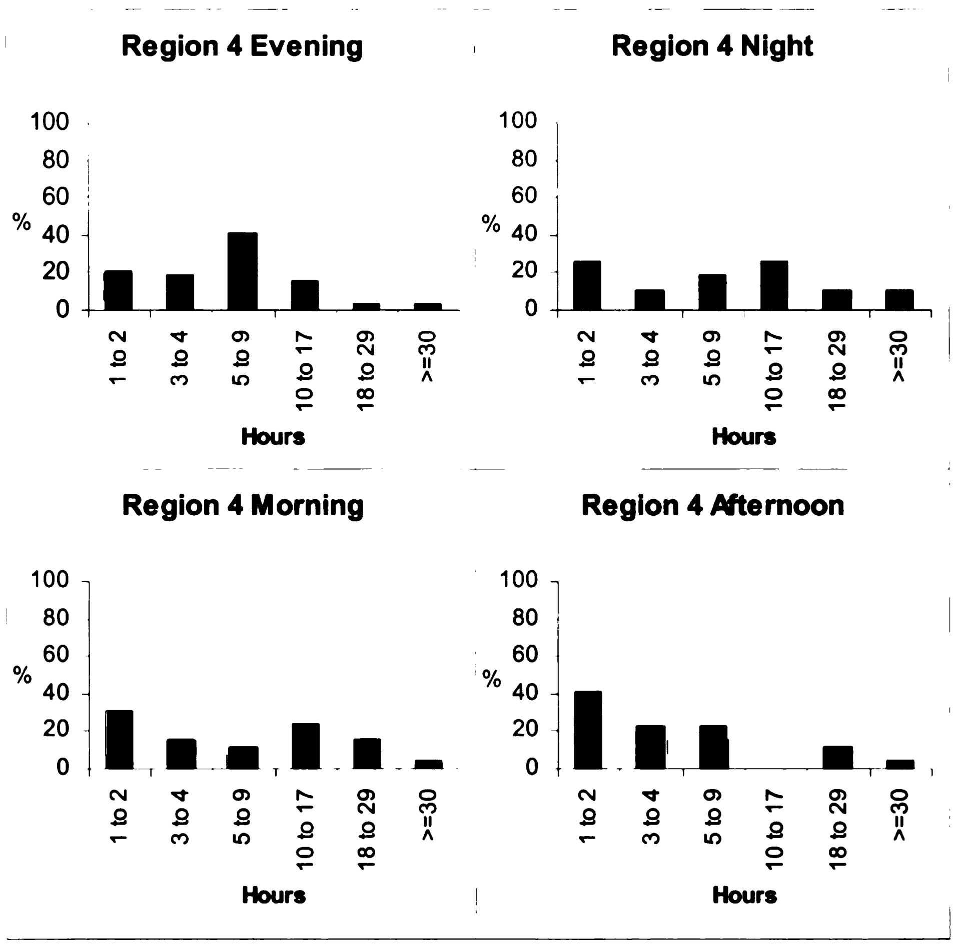


Figure 3-31. Duration of systems that terminated in Region 4 (89.9°W - 85°W).

Longer durations tended to be more frequent for systems that terminated within Region 5 compared to many of the upstream regions (Figure 3-32). Approximately 31% of systems that terminated in the evening hours formed at least 18 hours prior to dissipation with only around 20% having existed for 4 hours or less before termination. In contrast, over 60% of systems that terminated during the afternoon period had formed no more than 4 hours before dissipating in Region 5. Systems that terminated in the morning frequently had long durations, with 56% of the systems having persisted at least 10 hours before dissipating. The lifespan of systems was much more variable for systems that terminated during the nighttime period, with 25%, 23%, and 17% of systems having persisted 1 to 2 hours, 10 to 17 hours, and >30 hours, respectively.

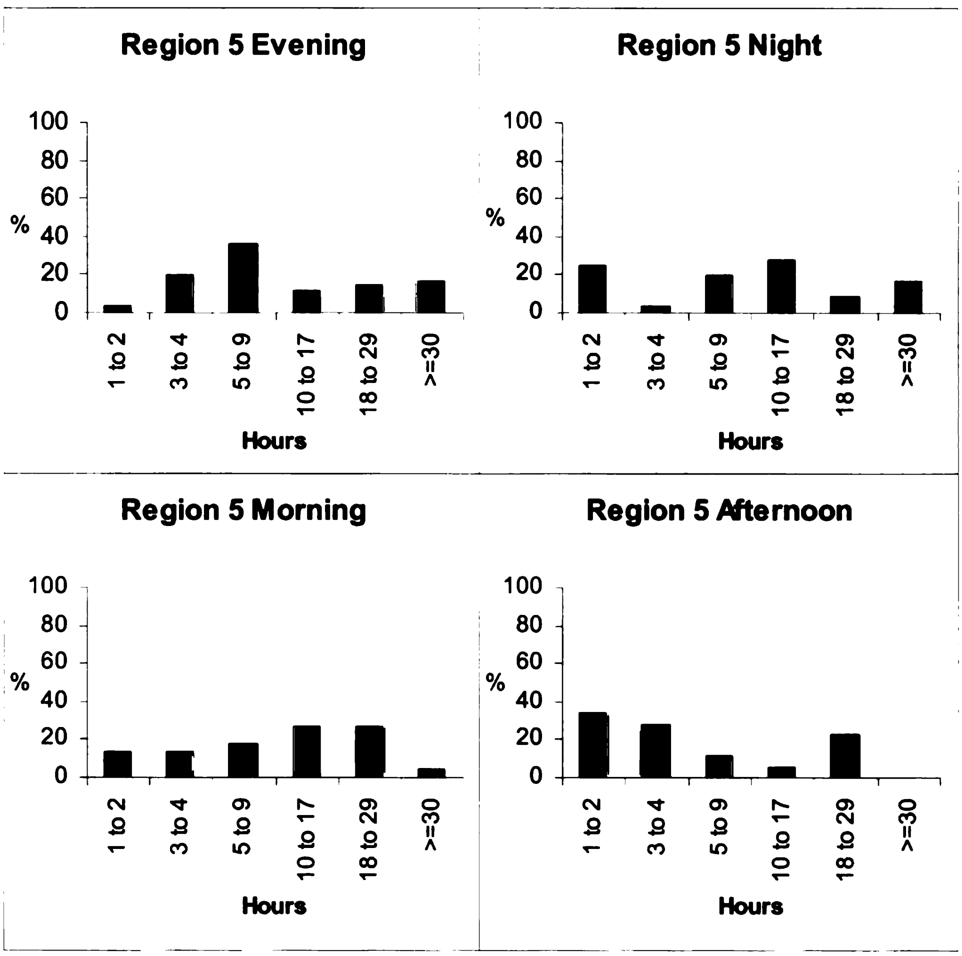


Figure 3-32. Duration of systems that terminated in Region 5 (84.9°W - 80°W).

Systems that terminated in Region 6 most likely formed no more than 9 hours before dissipating, although the distribution of system duration varied by time of day (Figure 3-33). Approximately 66% of systems that terminated during the evening period had existed from 5 to 17 hours. Conversely, 65% of systems that dissipated during the morning hours formed less than 5 hours prior to termination. System duration was much more evenly distributed among the duration categories for the nighttime period, although a majority of systems had existed for 9 hours or less before termination. The afternoon period displayed a bi-modal distribution as the duration of 35% the convective systems terminating at this time of day fell in the 1 to 2 hours category and 33% fell within the 5 to 9 hours range.

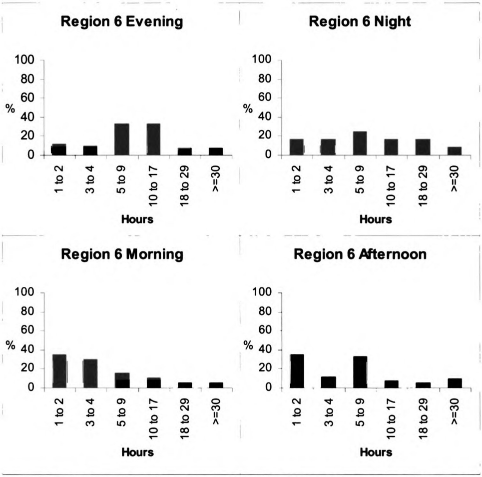


Figure 3-33. Duration of systems that terminated in Region 6 (79.9°W - 74°W).

3.4 Analysis by Region of Existence

In the following analysis by "region of existence" the characteristics of convective systems in a particular region by time of day are investigated. The systems did not need to have originated or terminated in the region. This analysis was performed to compare the convective characteristics of systems that were identified in summer of 2004 using lightning data to those systems from 1991 that were identified using radar imagery. This comparison allows the impact of data choice on system identification and the interannual variability of convection within the study area to be assessed. In the discussion below, the results of this study are compared to the earlier findings of Patterson *et al.* (1995). In addition, the results from the analysis by region of existence are used in Chapter 4 to evaluate the relative importance of the LLJ and eastward propagating systems to the nocturnal maximum in convection.

3.4(a) Frequency of Convection by Time of Day and Region

In the discussion below, the frequency of existing convection is presented as percentages to facilitate comparison across regions and time periods with differences in the absolute number of systems (Table 3-9). To calculate these percentages, "existing systems" within each region were counted in each of the time periods they occurred, recognizing that some systems may be counted for more than one time period, depending on system duration. Similar to the previous analyses, the origin of existing systems is limited to the first occurrence of CG lightning flashes within the study area and the termination location is considered to be the last appearance of the system within the study area. System age refers to the period that the existing system was observed within the study area.

Table 3-9. Absolute frequencies of systems that existed in Regions 1-6 during each time period that formed in each region. The regional divisions are: Region 1 (109°W - 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W - 90°W), Region 4 (89.9°W - 85°W), Region 5 (84.9°W - 80°W), and Region 6 (79.9°W - 74°W). The time periods are: Afternoon (18 - 23 UTC), Evening (00 - 05 UTC), Night (06 - 11 UTC), and Morning (12 - 17 UTC). The frequencies were used to calculate the percentages of local versus non-local system origination for Figures 3-35 through 3-39.

Region and Time Period of Existence	Region of Origin						
	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Total
Region 1 Afternoon	260	1	0	0	0	0	261
Region 1 Evening	340	0	0	0	0	0	340
Region 1 Night	166	3	0	0	0	0	169
Region 1 Morning	100	2	0	0	0	0	102
Region 1 total = 872							
Region 2 Afternoon	29	54	1	0	0	0	84
Region 2 Evening	75	56	1	0	0	0	132
Region 2 Night	79	34	1	0	0	0	114
Region 2 Morning	50	30	0	0	0	0	80
Region 2 total = 410							
Region 3 Afternoon	16	17	41	1	0	0	75
Region 3 Evening	21	45	28	2	0	0	96
Region 3 Night	34	25	21	0	0	0	80
Region 3 Morning	36	12	24	0	0	0	72
Region 3 total = 323							
Region 4 Afternoon	12	6	13	41	3	0	75
Region 4 Evening	12	11	20	42	2	0	87
Region 4 Night	12	18	11	31	0	0	72
Region 4 Morning	15	9	3	21	0	0	48
Region 4 total = 282							
Region 5 Afternoon	7	3	1	8	35	4	58
Region 5 Evening	8	7	8	14	23	3	63
Region 5 Night	7	8	7	15	21	1	59
Region 5 Morning	4	6	4	6	18	1	39
Region 5 total = 219							
Region 6 Afternoon	1	8	3	4	16	60	92
Region 6 Evening	4	3	2	7	18	58	92
Region 6 Night	2	2	3	3	7	22	39
Region 6 Morning	0	2	2	0	10	33	47
Region 6 total = 270							

For all regions, more convective systems existed during the evening hours compared to other times of the day (Figure 3-34). This general observation appears to contradict the results of the analysis by system origination, which suggested that systems were generally less likely to form during the evening. The analysis by termination, however, showed that convective systems frequently terminated during the evening period. The larger number of systems that existed in the evening hours suggests that system frequency was a summation of systems originating during this time period, the persistence of systems that formed earlier, the movement of systems that had formed earlier in other regions, and the splitting of systems prior to or during the evening period. Of the systems that existed in Region 1, almost 40% occurred during the evening, while only 12% were observed during the morning (Figure 3-34). Although convective systems were also most frequent during the evening period within Region 2, the frequency of systems existing during the morning (20%) and night (28%) was greater than that for Region 1 and the frequency during the afternoon (20%) and evening (32%) was less. Region 3, Region 4, and Region 5 display similar distributions to Region 2. Systems that existed in Region 6, however, were equally as likely to have occurred during the afternoon and evening period with much lower frequencies during the morning and night.

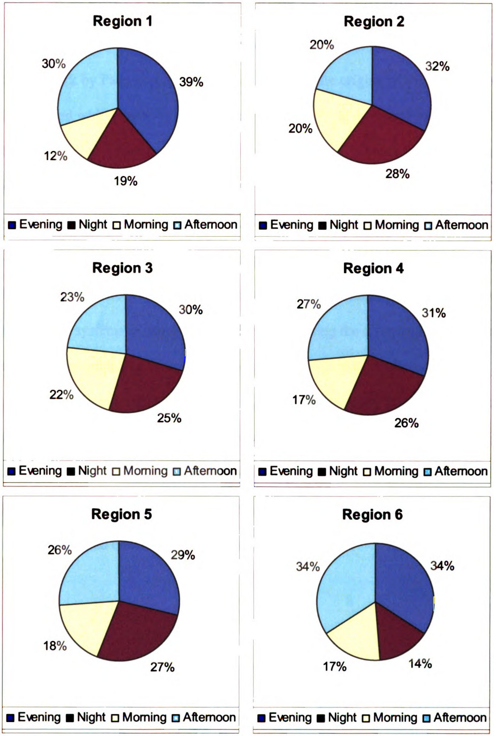


Figure 3-34. The frequency existing systems by time period for each region.

3.4(b) Local versus Non-local Sources of Convection

Some differences are revealed between the results of this study and those of the earlier work by Patterson *et al.* (1995) concerning the origins of convective systems that existed within each region. The analysis of lightning observations for 2004 show that for Region 2, the majority of convective systems that existed during all time periods, aside from the afternoon hours, had originated upstream in Region 1 (Figure 3-35). Conversely, the analysis of radar observations for 1991 suggests that most systems that existed within Region 2, regardless of time period, were locally generated. More agreement between the two studies is evident for Region 3, as both found the majority of systems existing within this region during the afternoon formed locally and those occurring during the nighttime originated upstream. Of the systems that existed during the evening and morning periods, however, this study found that most had formed upstream (Figure 3-36), while the earlier study found that most had originated locally. This discrepancy is largest for the morning period, where the analysis of the lightning observations suggests that about 50% of the systems that existed at this time of day originated considerably upstream in Region 1.

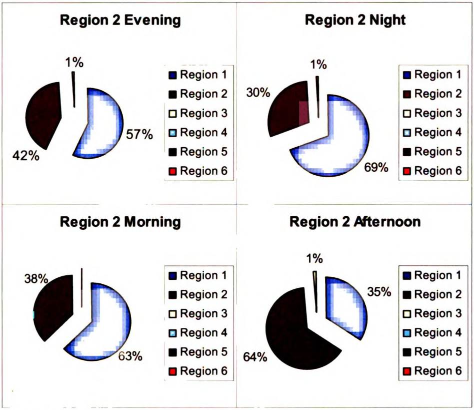


Figure 3-35. Systems that existed within Region 2 (99.9°W-95°W) were traced back in time to their region of origin. Each pie chart segment represents the percentage of systems that originated in a particular region.

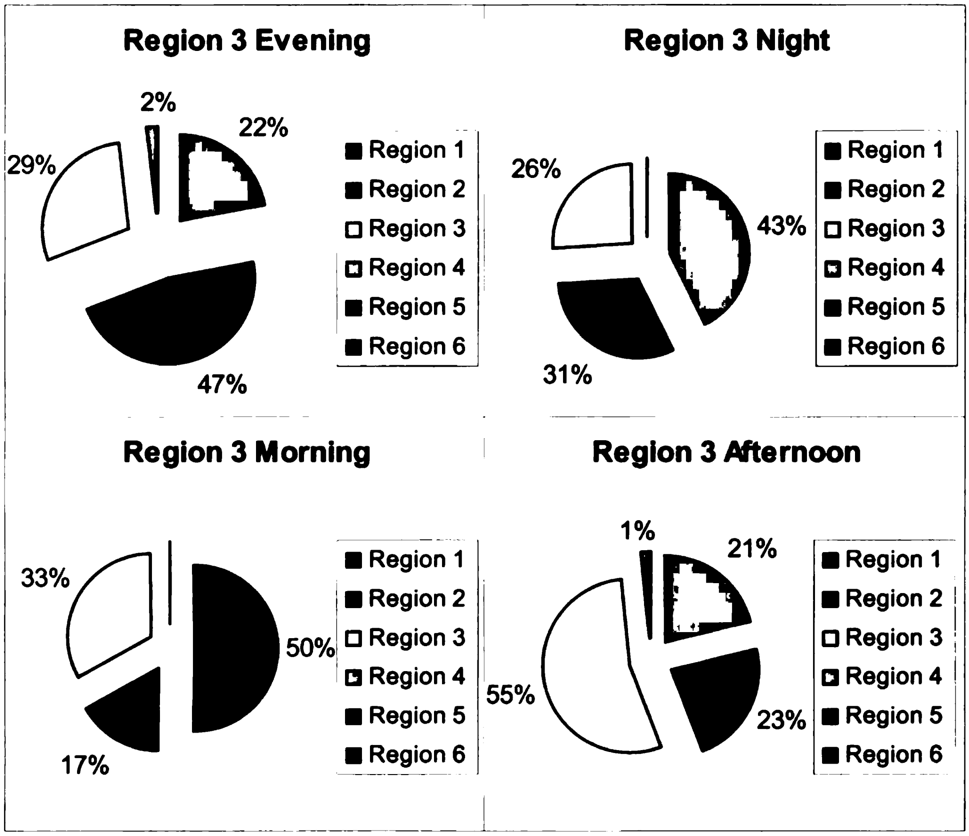


Figure 3-36. As in Figure 3-35 except for Region 3 (94.9°W - 90°W).

For systems that existed in Region 4, the two studies are in general agreement regarding the frequency of locally versus non-locally generated systems for all time periods excluding the afternoon. The results of Patterson *et al.* (1995) suggested that approximately half of the systems that existed within the evening, night, and morning periods formed locally and the results of this study found that a little less than half of these systems formed locally (Figure 3-37). Less agreement is observed between the two studies during the afternoon where Patterson *et al.* (1995) found that systems were much more likely (80%) to have originated in Region 4 than the results of this study indicate. For Region 5, both studies suggest that the systems that existed during the evening period were more likely to have originated upstream. Both studies are also in agreement for the afternoon period where they found that most systems formed in Region 5. The results observed during the night and morning periods do not agree as well. This study suggests that a majority of convective systems that occurred during the night and morning periods within Region 5 formed non-locally (Figure 3-38), whereas Patterson *et al.* (1995) found that most systems during these time periods formed within Region 5. In Region 6, this study suggests that regardless of time of day, systems were most likely to have originated locally (Figure 3-39). Similar results were observed in the study by Patterson *et al.* (1995) for only the afternoon and morning periods. Their analyses suggested that systems existing within Region 6 during the night and evening periods were slightly more likely to have formed outside the region.

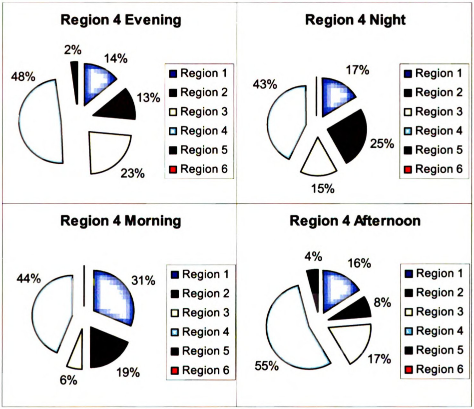


Figure 3-37. As in Figure 3-35 except for Region 4 (89.9°W - 85°W).

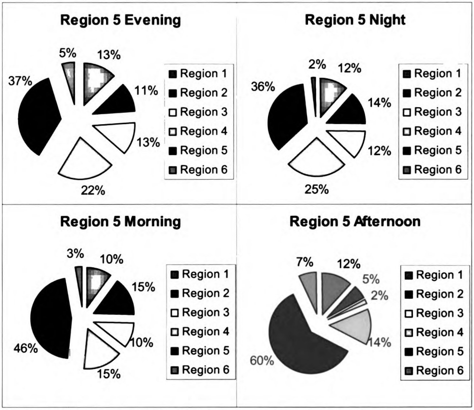


Figure 3-38. As in Figure 3-35 except for Region 5 (84.9°W - 80°W).

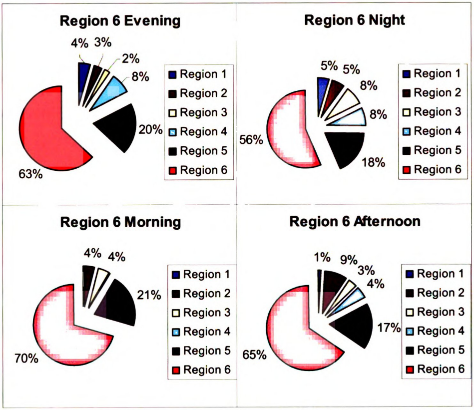


Figure 3-39. As in Figure 3-35 except for Region 6 (79.9°W - 74°W).

3.4(c) System Age Within Each Region

The system age within each region is defined as the amount of time a system had been in existence within the study area as it entered a particular region. The system age was determined only at the first appearance within a region; therefore the system age for Region 1 was predominately 1 hour, as this region encompasses the westernmost portion of the study area. A few system ages of 2 hours were detected in Region 1 in both this study and the work by Patterson *et al.* (1995) resulting from the apparent upstream movement of a small number of systems. The results of both studies were in good agreement regarding the ages of most systems that existed within Region 2. The agreement was highest during the afternoon period when both studies suggested that systems tend to be "younger" during this time period than at other times of day as over 60% of systems had formed one hour prior to entering Region 2. Much agreement was also observed during the evening period when almost 90% of systems in both studies had ages of 10 hours or less (Figure 3-40). The results of both studies suggested that over 70% of systems that existed during the night and morning periods were "younger" than 10 hours. However, systems that had been in existence for a considerable length of time ($\geq$11 hours) were observed more frequently during the night and morning periods in this study than in the earlier work.

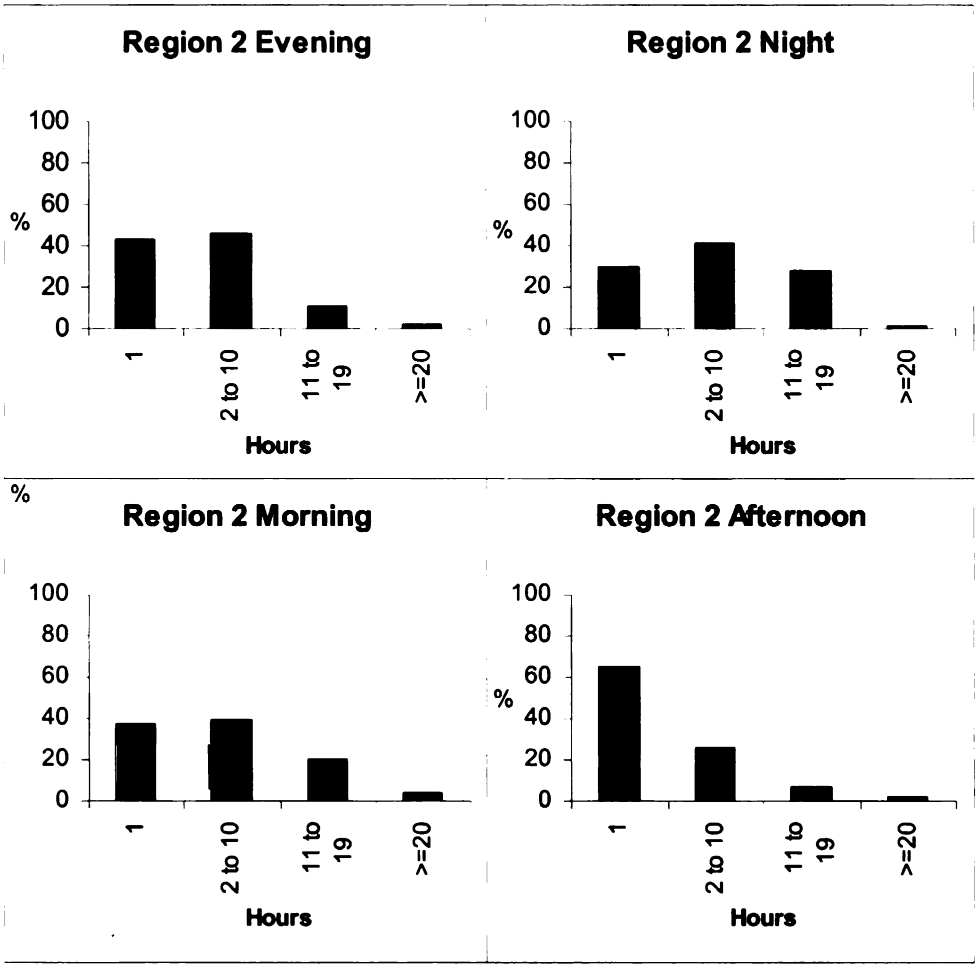


Figure 3-40. Age of systems within Region 2 (99.9°W - 95°W).

Differences in system age were greater for Region 3. Patterson *et al.* (1995) found the systems that existed during the morning hours most likely initiated in the preceding hour, while this study observed that most systems existing at this time of day in Region 3 formed 11 to 19 hours earlier (Figure 3-41). During the evening hours, Patterson *et al.*'s (1995) study suggested that systems most likely formed within the past hour whereas this study found only 29% of systems formed within the last hour and 49% had been in existence for 2 to 10 hours. The nighttime hours showed more agreement between studies in that roughly 60% of systems that existed during this time period had ages of 10 hours or less, although "older" systems of 20 hours or more were much more frequent for the earlier study (20%). Both studies agreed that over 50% of afternoon systems had formed in the past hour.

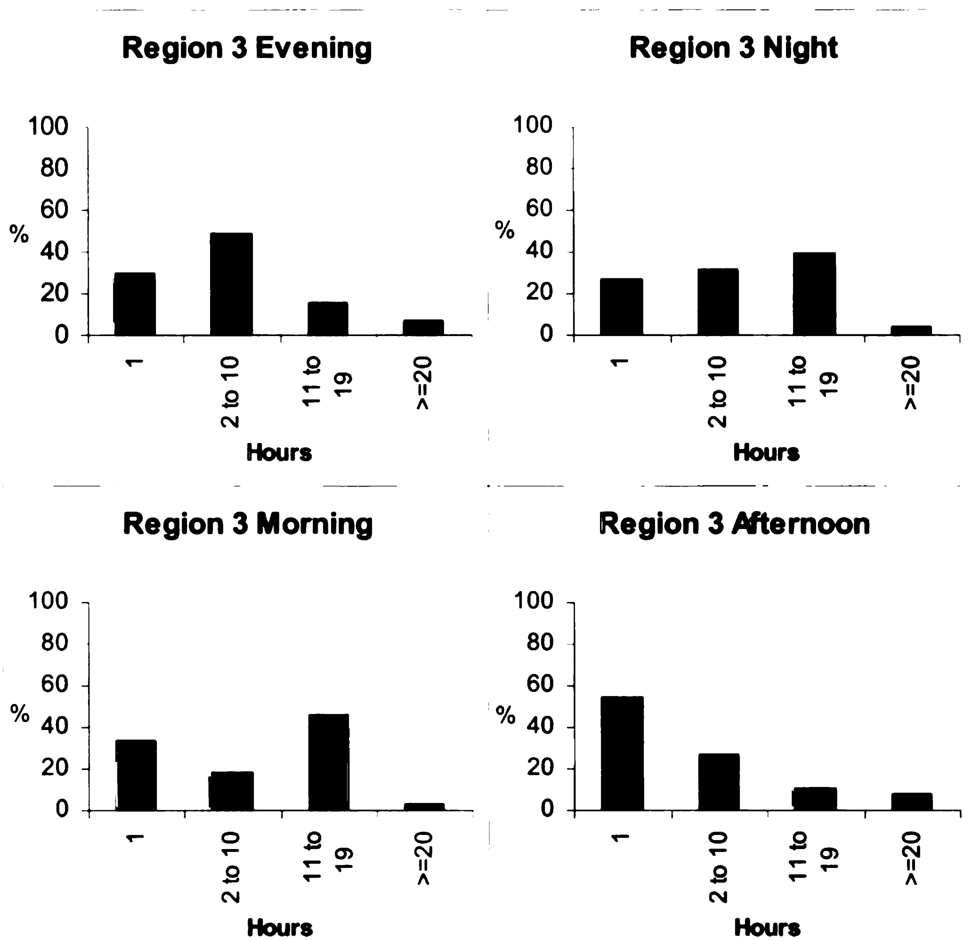


Figure 3-41. Age of systems within Region 3 (94.9°W - 90°W).

For Region 4, the results of Patterson *et al.* (1995) and this study were in general agreement that systems that occurred in this region during all time periods most likely formed 1 hour prior to entering the region. The earlier study, however, found the percentage of "young" systems to be much higher (80%) during the afternoon period. Results of this study also suggested that "older" systems of at least 20 hours were more frequent within Region 4 compared to the upstream regions (Figure 3-42), which differed from Patterson *et al.'s* (1995) results.

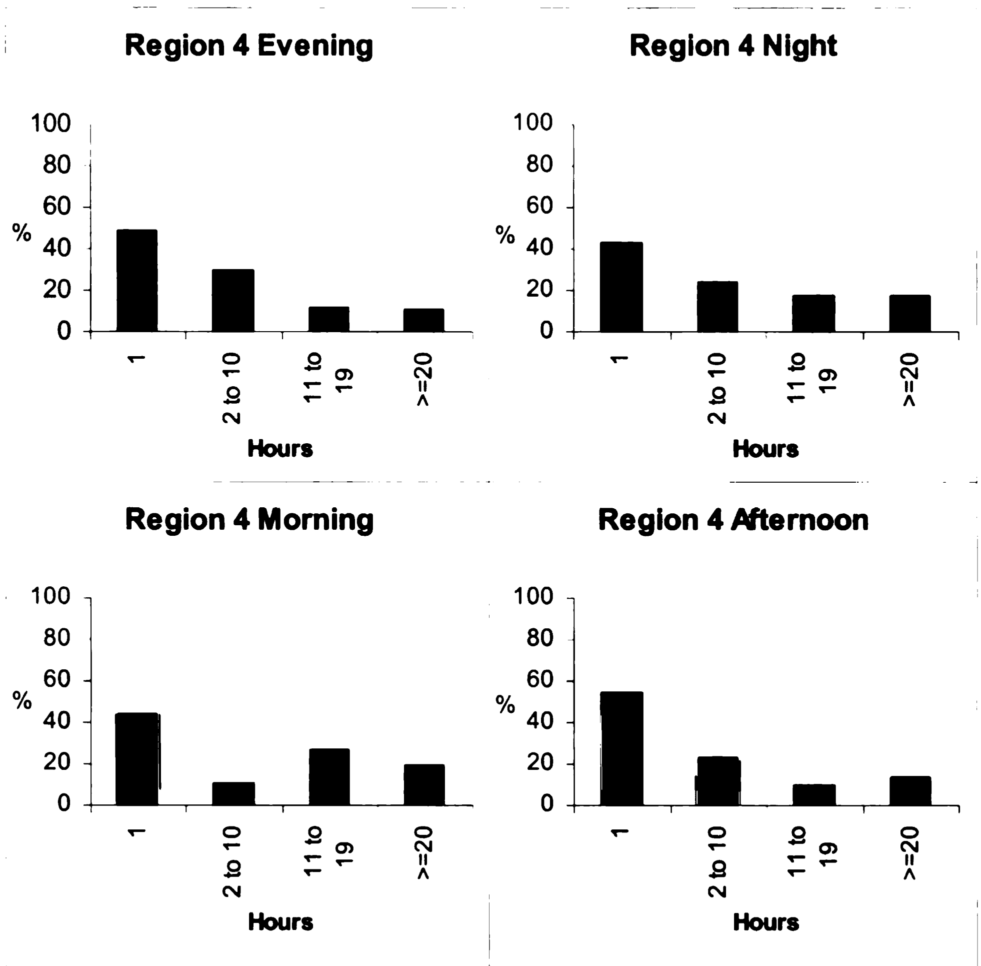


Figure 3-42. Age of systems within Region 4 (89.9°W - 85°W).

More disagreement was observed between the two studies concerning system age for Region 5, where this study found that almost 50% of systems formed at least 11 hours prior to entering the region during the morning period (Figure 3-43). In contrast, Patterson *et al.* (1995) suggested that the majority (almost 70%) of systems that occurred during the morning had formed in the past hour. A similar discrepancy was observed during the night period as Patterson *et al.'s* (1995) study showed that almost

80% of systems that existed during this time period had initiated in the past hour, whereas this study suggested that systems were more likely to have existed for at least 2 hours before entering the region. More agreement regarding system age was observed during the afternoon and evening time periods when both studies showed that approximately 60% of systems that occurred during the afternoon formed only 1 hour prior to entering Region 5 and that at least 70% of systems that existed during the evening formed no more than 10 hours earlier.

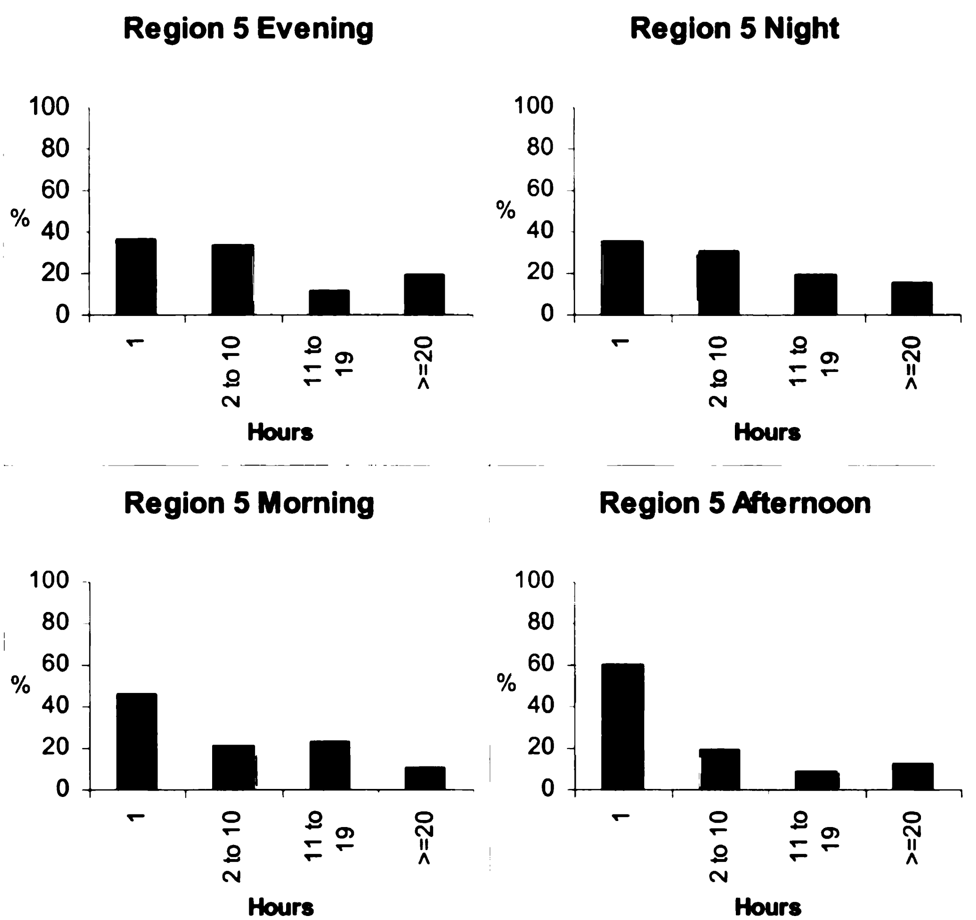


Figure 3-43. Age of systems within Region 5 (84.9°W - 80°W).

Finally, the agreement between the two studies concerning system age within Region 6 varied by time period. Both studies suggested that systems were much more likely (> 60%) to have formed only 1 hour prior to entering Region 6 during the morning and afternoon period and that nearly 80% of systems during the evening had existed for 10 hours or less. The nighttime period displayed less agreement as this study showed that a majority (60%) of systems formed during the previous hour, while Patterson *et al.* (1995) observed that nearly half of nighttime systems had been in existence from 2 to 19 hours. Generally, this study found systems that were at least 20 hours "old" to be more frequent (Figure 3-44) in Region 6 than Patterson *et al.*'s (1995) study suggested.

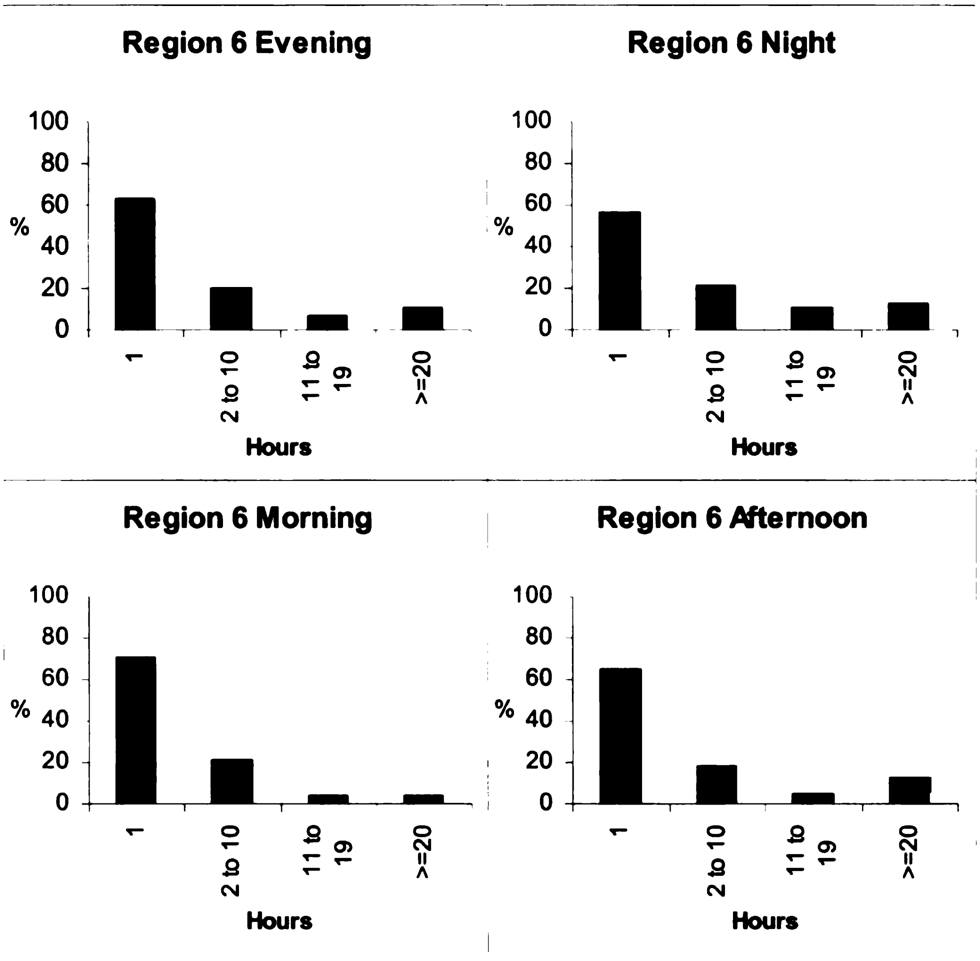


Figure 3-44. Age of systems within Region 6 (79.9°W - 74°W).

3.5 Summary of Results

The following sections highlight the key findings regarding the characteristics of convective systems described in this chapter. The analysis by system origin, system termination, and region of existence are summarized to identify important spatial and temporal variations of convection across the north-central United States. Convective characteristics are first discussed by region and then time period. These characteristics were developed for the period when the system was found within the study area. Some systems either originated or dissipated outside of the study area. Consequently, system duration and age are likely underestimated as well as the proportion of propagating versus local systems.

3.5(a) Regional Characteristics of Convective Systems

Region 1

- Most systems that originated in Region 1 formed during the afternoon hours. Systems were least likely to originate in Region 1 in the morning hours.
- The majority of systems that formed in this region terminated locally, regardless of time of day, although some systems that formed in Region 1 dissipated in all of the downstream regions.
- Of the systems that formed in Region 1 and moved out of the region, the majority terminated in Region 2 (the neighboring downstream region).
- The average duration of systems that originated in Region 1 is 10 hours, ranging from 7 hours for systems that formed during the evening to 11 hours for those that formed during the afternoon.
- The evening hours were the most likely time for systems to terminate within Region 1.
- Most systems that terminated within Region 1 had formed locally.
- The average duration of systems that dissipated within this region was 6 hours.

Region 2

- Systems existing within Region 2 were more likely to have formed in Region 1, with the exception of the afternoon hours when most convective systems had formed locally.
- Similar to Region 1, systems that formed in Region 2 were more likely to do so in the afternoon hours. Systems were least likely to originate in the morning.
- The majority of systems that formed in Region 2 during the afternoon and nighttime hours terminated locally, whereas systems that formed during the evening and morning hours were more likely to terminate downstream.
- Most of the systems that formed in Region 2 and did not terminate locally dissipated in Region 3, although some systems that formed in the evening and morning could be traced eastward to Region 5 and Region 6 before dissipating or exiting the study area.
- As for Region 1, the average duration of systems that formed in Region 2 was 10 hours. Average durations differed considerably by time of day, from 3 hours for systems that formed at night to 16 hours for those that formed in the morning.
- Systems were most likely to terminate in Region 2 during the evening and nighttime hours.
- The systems that terminated in Region 2, regardless of time of day, were generally equally likely to have formed locally or upstream of the region,

although systems that terminated in Region 2 during the night and morning periods were more likely to have formed in Region 1.

- Systems that terminated within Region 2 had an average duration of 10 hours, which is notably longer than those that terminated in Region 1, likely resulting from systems that propagated from Region 1 into this region.

Region 3

- Similar to Region 2, most systems that existed within Region 3 had formed upstream, aside from those that occurred during the afternoon hours, which were primarily generated locally.
- Most non-local systems existing in Region 3 during the night and morning periods had formed in Region 1.
- Convection was more likely to form in Region 3 during the afternoon and least likely to form during the evening.
- More than half of the systems that formed in Region 3, regardless of time of day, terminated locally.
- A majority of the non-locally terminating systems dissipated in Region 4, the neighboring downstream region.
- Systems that formed during the nighttime and afternoon periods and terminated downstream propagated to Regions 4, 5, and 6, whereas no systems that formed during the morning and evening hours traveled as far eastward as Region 6.

- The average duration of systems that originated in Region 3 was 8 hours, which is less than the average value for systems that formed in both upstream regions. The average durations ranged from 3 hours for evening systems to 9 hours for nighttime systems.
- Convection was most likely to dissipate during the evening hours.
- The majority of systems that terminated in Region 3 during the evening, nighttime, and morning hours had formed upstream.
- Systems that terminated within Region 3 had an average duration of 11 hours, slightly larger than those that terminated in Region 2.

Region 4

- Systems that existed in Region 4 were equally likely to have formed locally or propagated downstream from westward regions.
- Depending on time period, approximately 25-50% of the convective systems that existed in Region 4 had originated in Region 1 or Region 2, indicating relatively long system durations and tracks.
- Systems that formed in Region 4 were more likely to do so during the afternoon and least likely to originate during the morning.
- Approximately 60% of systems that formed in Region 4 also terminated within the region.
- The average duration of systems that formed in Region 4 is 6 hours, which is less than the average durations of all upstream regions. Durations

ranged from 4 hours for systems that originated during the morning to 9 hours for those that originated at night in Region 4.

- Convection was most likely to dissipate during the evening and nighttime hours.
- Of the systems that terminated within Region 4, a majority had formed within the region as well, although more than 30% had formed in Region 1 and Region 2.
- Systems that terminated in this region had an average duration of 9 hours, which is less than the average durations for both Region 2 and Region 3.

Region 5

- Systems that existed in Region 5 during all times of day excluding the afternoon, were likely to have formed in any of the upstream regions, while afternoon systems were mostly locally formed.
- Similar to Region 3, the afternoon hours were the most likely time for systems to form while convection was least likely to originate during the evening.
- With the exception of the morning hours, most systems that formed in Region 5 terminated locally.
- The average duration of systems that formed in Region 5 was 6 hours, the same as for Region 4. Durations ranged from 4 hours for systems that formed during the evening to 7 hours for afternoon and morning systems.

- Similar to Region 4, convection was most likely to terminate during the evening and nighttime hours.
- Aside from the afternoon hours, systems that terminated in Region 5 were more likely to have formed upstream, with generally equal frequencies of systems that formed in each upstream region.
- The average duration of systems that terminated within Region 5 was 13 hours, which is the longest for systems terminating in any region, indicating frequent propagating systems with relatively long tracks.

Region 6

- Most systems that existed in Region 6 formed locally. The majority of non-local systems had formed in the neighboring upstream region.
- As in all other upstream regions, the most likely time for convection to form was the afternoon. Unlike other regions, systems were least likely to form during the nighttime hours.
- The average duration of systems that formed in Region 6 was 6 hours, the same as for Region 4 and Region 5. [The average durations generally decreased from west to east across the study region, which may reflect the proximity of the eastern regions to the boundary of the study region.] Average durations of systems ranged from 4 hours for evening and nighttime forming systems to 8 hours for systems that initiated during the morning.

- Almost half of all systems that terminated in Region 6 did so during the evening hours.
- Terminating systems were more likely to have formed locally rather than upstream. Of the systems that formed upstream, most formed in Region 5 (the neighboring upstream region).
- The average duration of systems that terminated in Region 6 was 10 hours, roughly equal to that of Region 2, Region 3, and Region 4 but less than the average duration for Region 5.

3.5(b) Temporal Characteristics of Convective Systems

Afternoon (18 – 23 UTC):

- More than 50% of systems that formed during the afternoon terminated locally.
- Over half of the convection present in the afternoon in any region formed locally.
- Convection that formed at this time of day had an average duration of 9 hours. Average durations for afternoon convection ranged from 6 hours for systems that formed in Region 4 and Region 6 to 11 hours for those that formed in Region 1.
- 60-70% of the convection that terminated in the afternoon hours formed locally.

Evening (00 – 05 UTC):

- With the exception of Region 2, most convection that formed in the evening hours terminated locally.
- Convection that terminated during the evening was more likely to have formed locally for Region 1, Region 4, and Region 6 and less likely to have formed locally for Region 2, Region 3, and Region 5.
- The average duration of systems that formed during the evening period was 7 hours, which is less than the average duration of systems that formed during the afternoon. The average durations ranged from 3 hours for Region 3 to 14 hours for Region 2.
- Except for Region 1 and Region 6, the majority of convective systems existing in the evening formed in an upstream region.
- For all regions, the majority of non-local systems existing during the evening had formed in the neighboring upstream region, indicating relatively short tracks and durations for these systems.
- Approximately 40 – 60% (depending on region) of "local" systems existing during the evening initially formed during the afternoon hours and at least 50% of all non-local systems formed during the afternoon hours, suggesting that afternoon boundary layer heating likely plays a considerable role in the formation of systems existing in the evening.

Night (06 – 11 UTC):

- Systems that formed at night for the most part terminated locally.

- The average duration of systems that formed at night was 7 hours, which is the same as for evening systems, but less than the average duration of systems that originated in the afternoon. The average durations of systems that formed during the evening ranged from 3 hours for Region 2 to 9 hours for Region 3 and Region 4.
- For Region 1 and Region 6, the majority of systems existing at night formed locally, but for the other regions the majority of systems formed upstream and moved into the region.
- The majority of non-local systems existing in Region 2 and Region 3 at night formed in Region 1, but this was not the case for Region 4, Region 5, and Region 6. Non-local systems existing at night in Region 4 mostly formed in Region 2 and most systems existing in Region 5 and Region 6 originated in the neighboring upstream region.
- The source regions of nighttime convection indicate fairly long durations and tracks for nighttime systems in Region 3 and Region 4 and relatively short durations and tracks for Region 2, Region 5, and Region 6.
- Only 10 – 25% (depending on region) of local systems existing during the nighttime hours originated during the afternoon and 0 – 30% formed during the evening hours. The relatively few local systems that formed during the afternoon hours suggests that boundary layer heating has only a minor influence on nighttime local convection and that another mechanism, perhaps the LLJ, is responsible for the formation of convection.

- Approximately 40 – 65% of "non-local" systems existing at night originated during the afternoon hours, while only 10 – 20% formed during the evening. The relatively high frequency of non-local systems that formed upstream during the afternoon indicates that eastward propagating systems contribute to the occurrence of nighttime convection (discussed in more detail in Chapter 4).

Morning (12 – 17 UTC):

- Convective systems that formed Region 1, Region 3, and Region 4 in the morning hours dissipated locally. On the other hand, the majority of systems that formed in Region 2 and Region 5 dissipated in downstream regions.
- The average duration of systems that formed in the morning hours was 10 hours, which is greater than the average durations of all other time periods. Average duration varied considerably by region and ranged from 4 hours in Region 4 to 16 hours in Region 2.
- The majority of convective systems existing during the morning hours formed upstream, with the exception of morning convection in Region 1 and Region 6, which formed locally.
- For Region 2, Region 3, and Region 4, the majority of non-local systems present during the morning hours formed in Region 1, although systems that formed in other regions were also present. Some morning systems in Regions 5 also originated in Region 1, but were equally likely to have

originated in the other upstream regions. For Region 6, the majority of non-local convective systems formed in neighboring Region 5.

- Local convective systems existing in morning hours were much more likely to have formed during the nighttime period compared to the afternoon and evening hours. This finding suggests that the LLJ may be a factor in their formation.
- Non-local systems existing in the morning hours were more likely to have originated during the afternoon hours compared to other times of day, suggesting that boundary layer heating was a factor in their formation.

The findings of the origin, movement, duration, and termination of convective systems presented here provide insights into the spatial and temporal variations of convection across the study area which will be discussed in more detail in Chapter 4 with respect to possible forcing mechanisms of nocturnal convection.

Chapter 4 Evaluation of Proposed Forcing Mechanisms for Nocturnal Convection in the North-Central United States

Numerous studies have examined nocturnal convection in the central United States and have proposed a number of mechanisms that may contribute to this phenomenon. Despite this, no comprehensive theory of nocturnal convection presently exists (Trier *et al.* 2006). The spatial and temporal characteristics of convective systems described in the previous chapter will be used to evaluate the possible forcing mechanisms responsible for nocturnal convection and their relative importance within different regions of the study area.

The core of the nocturnal convection regime discussed in Chapter 1 extends from eastern North and South Dakota, and eastern Nebraska through the Lower Peninsula of Michigan, which includes Region 2, Region 3, Region 4, and Region 5 of the current study area (Figure 2-6). This research focuses on two proposed mechanisms for nocturnal convection which are: 1) the nocturnal LLJ (Pitchford and London 1962, Bonner 1968, Walters *et al.* 2008), and 2) the occurrence of eastward propagating systems that form over the eastern slopes of the Rocky Mountains and the higher elevations of the western Great Plains (Riley *et al.* 1987, Dai *et al.* 1999, Jiang *et al.* 2006). Each of these proposed mechanisms should produce a unique "fingerprint" in the spatial and temporal characteristics of convective systems across the study region. LLJs are climatologically more frequent in the northern and central plains (Figure 4-1) and occur most often during the nighttime and morning hours (Mitchell *et al.* 1995, Arritt *et al.* 1997, Walters *et al.* 2008). Nocturnal systems that originate locally during the night and morning periods in the regions where the LLJ frequently occurs would suggest the presence of LLJs during the formation of nocturnal convection. The occurrence of eastward propagating systems would be indicated by frequent non-locally generated nocturnal systems that can be traced back to the eastern slopes of the Rocky Mountains and western Great Plains. Using primarily the results from the "Analysis by Region of Existence" discussed in 3.4, the following sections examine the spatial and temporal patterns of convective systems across the north-central United States. These patterns are analyzed in the context of the expected "fingerprints" of convection associated with LLJs or eastward propagating systems to assess the relative importance of these two phenomena to the formation and occurrence of nocturnal convection within the study area.

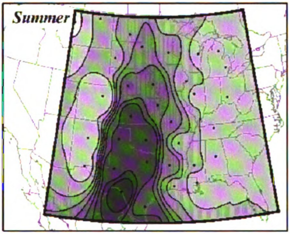


Figure 4-1. The region that LLJs are climatologically most frequent. Darker shades represent higher relative frequencies (Walters *et al.* 2008).

4.1 What is the frequency of local versus non-local nocturnal systems?

The first step in assessing the potential mechanisms of nocturnal convection is to determine the relative frequency of locally versus non-locally generated systems. A large number of locally generated systems should be evident where LLJs frequently occur (i.e., the north-central plains) during the night and morning periods to support the contention that the nocturnal LLJ is a likely mechanism for nocturnal convective systems. The portion of the north-central plains that most frequently experiences LLJs during the summer includes much of Nebraska, North and South Dakota, Minnesota, and parts of western Wisconsin (Walters *et al.* 2008), which corresponds to Region 2 and Region 3 of the study area. Interestingly, the frequency of locally-generated nocturnal convection was relatively low in both regions as 30% or less of the convective systems that existed during the nighttime hours, and less than 40% of systems that existed during the morning hours, formed locally (Table 4-1).

Table 4-1. Frequency of systems that existed within Regions 2 - 5 during the night and morning periods that originated locally versus non-locally. The regional divisions are: Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

	NIGHT (06 – 11 UTC)		MORNING (12 – 17 UTC)	
	Local	Non-Local	Local	Non-Local
Region 2	30%	70%	38%	62%
Region 3	26%	74%	33%	67%
Region 4	43%	57%	44%	56%
Region 5	36%	64%	46%	54%

Local generation of systems that existed during the night and morning hours is not necessarily an indication that that the LLJ was a factor associated with system formation. The initial timing of system formation also needs to be considered. Nocturnal convection may be the result of afternoon-generated systems that linger through the evening until the nighttime hours within a particular region. Although systems that formed during the afternoon may have been generated locally, these systems would have likely been associated with boundary-layer heating as opposed to the LLJ. Over 90% of locally-generated systems that existed during the morning period in Region 2 and Region 3 formed during the nighttime or morning hours (Table 4-2). In addition, a majority (>55%) of locally-generated systems existing during the nighttime period had originated during the morning or nighttime, although morning-generated convection was extremely infrequent (<6%), as these systems would have formed more than 12 hours prior. These findings suggest that locally-generated systems existing during the nocturnal hours within Regions 2 and 3 were likely coincident with an LLJ, as their geographic location and time of formation is consistent with what would be expected for this mechanism. This conclusion is supported by the work of Tuttle and Davis (2006) who found for their study area, which roughly corresponds to Region 2, that convection often formed near the northern terminus of the LLJ and that the intensity of precipitation was positively correlated with the strength of the LLJ.

Table 4-2. The percentages of locally-generated nocturnal systems that formed nocturnally. The number of locally-formed systems within each region and time period (listed in the left column) that originated during the night (06 – 11 UTC) and morning (12 – 17 UTC) periods was determined. Percentages were calculated using the total number of local systems for that region and time period as the denominator. The regional divisions are: Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

Region and Time Period	Percent of Locally-Generated Nocturnal Systems that Formed During the Night and Morning
Region 2 (Night)	71%
Region 2 (Morning)	96%
Region 3 (Night)	76%
Region 3 (Morning)	96%
Region 4 (Night)	55%
Region 4 (Morning)	90%
Region 5 (Night)	81%
Region 5 (Morning)	95%

An intriguing observation is that the relative frequency of locally-generated systems existing during the night and morning periods increased eastward in the vicinity of the Great Lakes (Region 4 and Region 5). However, the apparent increase in local convection in Region 4 and Region 5 relative to Region 2 and Region 3 is misleading. The actual number of systems present in Region 2 and Region 3 during the nighttime and morning periods was considerably larger than the number of systems observed in Region 4 and Region 5 (Table 4-3). The absolute frequencies of locally-formed nocturnal systems suggest that locally generated convection in the central U.S. (Region 2 and Region 3) and the Great Lakes region (Region 4 and Region 5) was fairly similar in the summer of 2004, but greatest in Region 2. Although LLJs are most frequent in the central United States, they have often been observed in the Great Lakes region as well (Walters *et al.* 2008). Based on the time of day that the local nocturnal systems within Region 4 and Region 5 formed (Table 4-2), the LLJ may have been a contributing factor to nocturnal convection within these regions as well.

Table 4-3. Absolute frequencies of total nocturnal systems and locally-formed nocturnal systems in Regions 2 -5 (values represent number of systems and not percentages). The time periods are: Night (06 – 11 UTC) and Morning (12 – 17 UTC). The regional divisions are: Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

	Total		Local	
	Night	Morning	Night	Morning
Region 2	114	80	34	30
Region 3	80	72	21	24
Region 4	72	48	31	21
Region 5	59	39	21	18

Although the spatial and temporal characteristics of locally-generated nocturnal convection suggest that the LLJ was likely associated with the formation of nocturnal convection, the overall relative frequencies of local versus non-local convection indicate that non-local systems provided a substantially larger contribution to nocturnal convection than local systems (Table 4-1). Almost three-fourths of nighttime systems, and two-thirds of morning systems that existed in Region 2 and Region 3 had originated upstream. Furthermore, more than half of the nocturnal systems that occurred in Regions 4 and 5 formed upstream.

Comparison of the results of this study to those of Patterson *et al.* (1995) provides an indication of the robustness of the inferences made above. In general, the Patterson *et al.* (1995) study suggested a higher frequency of locally-generated nocturnal systems for the summer of 1991 compared to what was found here for the summer of 2004. For Region 2, their analyses indicated that more than half of nocturnal systems existing during the night and morning hours were locally-generated, whereas in the summer of 2004 the majority of systems formed upstream. For Region 3, there was greater agreement for the nighttime hours with both studies suggesting that systems occurring at this time of day formed upstream, although the studies were in conflict regarding the relative frequency of local versus non-locally generated systems during the morning hours. For Region 4, both studies found that approximately 50% of the systems occurring in the night and morning were locally-generated, but for Region 5 the results of Patterson *et al.* (1995) suggested that a much larger portion of nocturnal systems formed locally.

4.2 How many nocturnal convective systems can be traced to an origin near the Rocky Mountains?

The theory that eastward propagating systems from the eastern slopes of the Rocky Mountains contribute to the nocturnal convective maximum in the north-central United States suggests that many nocturnal systems should have formed during the afternoon hours in the region of high topography in the western portion of the study area. To evaluate this theory, the relative frequency of system generation in Region 1 is examined below.

A considerable number of nocturnal systems observed within the study area formed in Region 1. Nearly two-thirds of all nocturnal systems that occurred in Region 2 and over 40% of all nocturnal systems that existed in Region 3 were traced back to Region 1. When taking into account only non-local systems that occurred nocturnally in Region 3, approximately 60% or more formed in Region 1 (Figure 4-2). Of the nocturnal systems observed in Region 2 and Region 3 that originally formed in Region 1, approximately 60 – 90% (not shown) formed during the afternoon hours, the period when convection is most frequent near the Rocky Mountains and over the western Great Plains. In contrast, less than 30% of non-local systems that existed in Region 4 at night and about 55% of non-local systems that existed in the morning hours originated in Region 1. The longer distance to Region 4 compared to the upstream regions may explain why there were somewhat more systems originating from Region 1 that were observed during the morning versus nighttime hours. Less than 20% of non-local systems that occurred in Region 5 during the night and morning hours originally formed in Region 1. These analyses indicate that the contribution of eastward propagating systems originating in Region 1 to nocturnal convection decreased, as one might expect, from west to east. Eastward propagating systems were particularly important contributors to nocturnal convection during the summer of 2004 in the eastern Dakotas, northeastern Nebraska, Minnesota, and Iowa. The large number of eastward propagating systems from the Rocky Mountains observed for Region 3, and the modest number observed for Region 4, is particularly fascinating as these regions include much of the western Great Lakes, which is not known to frequently experience these systems.

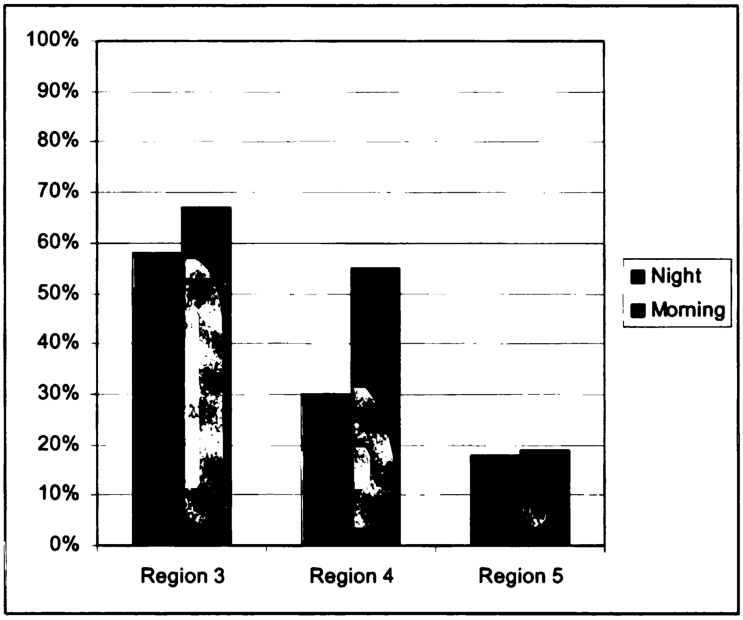


Figure 4-2. Percentages of non-local systems that existed within Regions 2-5 during the night (06 – 11 UTC) and morning (12 – 17 UTC) periods that formed in Region 1. The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

As noted earlier, MCCs have received much attention in the literature due to their impact on the climatology of the central plains and have been suggested to contribute to nocturnal convection in the north-central United States. The criteria that define MCCs are fairly specific (see 1.1(b)) and they cannot be explicitly identified from the present convective climatology. However, the presence of MCCs can be inferred based on their general spatial and temporal characteristics. MCCs often form near the Rocky Mountains and propagate eastward, reaching the central plains (e.g., the Dakotas, Nebraska, Iowa, Minnesota) during the nighttime and morning hours and often have durations exceeding 12 hours (Maddox 1980, Maddox *et al.* 1982, Augustine and Howard 1991). The results of this study show that many systems across the region displayed similar characteristics. The ages of nocturnal systems generally increased eastward across the study area with system ages ranging from 2 – 10 hours in Region 2 to greater than 11 hours in Region 3 and Region 4. Nocturnal systems with particularly long (i.e., $\geq$ 20 hours) durations also suggest the possibility of regenerating convective systems (Carbone *et al.* 2002), as propagating systems in the United States with durations that exceed the lifetime of typical MCCs (i.e., > 12 hours) have often been observed to be part of a succession of convective systems that dissipate and regenerate along the same path. The spatial and temporal characteristics of eastward propagating systems observed during the nighttime and morning hours across the study area suggest that MCCs may have played an important role in nocturnal convection during the summer of 2004, particularly in Region 2 and Region 3. In addition, regeneration of convective systems possibly contributed to particularly long-lived systems that occurred in the vicinity of the Great Lakes.

4.3 Where do non-local nocturnal convective systems that exist in the Great Lakes region form and at what time of day?

The Great Lakes displayed a high frequency of non-local systems; however, a substantial proportion did not form over the eastern slopes of the Rocky Mountains and western Great Plains (Table 4-4). Non-local systems that occurred during the nighttime in Region 4 were more likely to form in Region 2 (44%). Over 50% of these systems that originated in Region 2 did so during the morning hours of the previous day (not shown). The initiation time of the systems that formed in the morning hours in Region 2 coincides with the time of occurrence of LLJs, which are frequent in this region, suggesting that the LLJ was a possible forcing mechanism. This is an interesting possibility as the LLJ is usually thought to induce local convection or maintain convection that has traveled into the LLJ region (Tuttle and Davis 2006), rather than initiate convection that propagates eastward after formation. The location and time of initiation of non-local nocturnal systems existing in Region 4 suggests that the LLJ may contribute to non-local nocturnal convection as well as locally-generated convection. This further implies that nocturnally-generated convection in one region can contribute to nocturnal convection in downstream regions. Another insight to the source of nocturnal convection in the Great Lakes region is that a substantial (30%) portion of the nighttime systems observed in Region 4 that originated in Region 2 formed in the afternoon. This is an indication that the lee slopes of the Rockies are not the only source of eastward propagating systems but that these systems can also form during the afternoon in the central plains (eastern North and South Dakota, northeastern Nebraska, western Iowa, western Minnesota).

Table 4-4. Percentages of non-locally formed nocturnal systems that existed within Regions 4 and 5 that originated in each upstream region. The time periods are: Night (06 – 11 UTC) and Morning (12 – 17 UTC). The regional divisions are: Region 1 (109°W- 100°W), Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

	Region1	Region 2	Region 3	Region 4
Region 4 Night	30%	44%	26%	
Region 4 Morning	55%	34%	11%	
Region 5 Night	18%	22%	18%	39%
Region 5 Morning	19%	28%	19%	28%

Systems that existed within Region 5 during the nighttime hours could be traced to all upstream regions; however, non-local systems were more likely to form in Region 4 compared to the regions farther west (Table 4-4). Half of these systems that originated in Region 4 did so during the afternoon hours, which suggests that boundary layer heating played a role in the initiation of convection that propagated into the eastern Great Lakes during the night and morning. The remaining systems that propagated eastward from Region 4 formed in the evening and nighttime hours, possibly when LLJs were present. None of these systems formed over the Great Lakes, and only slightly over 10% of afternoon-generated systems that occurred in Region 5 during the night formed over the Great Lakes, suggesting that the lakes did not contribute to the formation of nocturnal convection.

Non-locally generated convective systems existing in Region 5 in the morning hours formed in all upstream regions, with slightly more systems forming in Region 2 and Region 4 and slightly less in Region 1 and Region 3. Any speculation on associated mechanisms needs to be undertaken cautiously due to the relatively small number of systems (39 total) that occurred within Region 5 during the morning hours.

Approximately half of the systems that originated in Region 1 through Region 3 and eventually reached Region 5 during the morning formed during the afternoon period. Thus, afternoon instability over the western and central plains likely contributed somewhat to morning convection in Region 5. Systems that formed during the nighttime hours also contributed to morning convection in Region 5, as about 50% of the systems that had originated in Region 4 formed during the night.

4.4 Are most evening systems remnants of afternoon convection?

Although nighttime and morning systems are especially fascinating due to the generally unfavorable conditions for convection during these time periods, evening systems are also interesting. The diurnal heating cycle provides an ideal environment for convective systems to develop during the late afternoon and early evening as the intense heating during this time of day often results in the destabilization of the lower atmosphere. As the evening progresses, the instability weakens and the atmosphere begins to stabilize after sunset. Consequently, most evening systems are expected to be remnants of convection that formed during the afternoon hours, and this was generally observed across the study region. At least half of the evening systems that occurred within Region 2 through Region 5 originated during the afternoon hours (Figure 4-3). The contention that most evening systems are lingering or dissipating afternoon convective systems is further supported by the generally short durations of evening systems. Over 70% of convective systems that existed during the evening hours had formed less than 10 hours earlier.

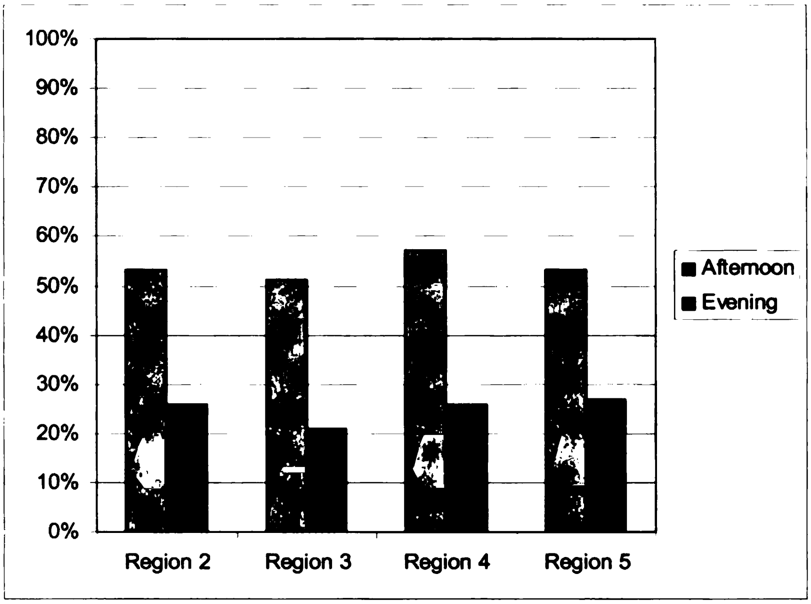


Figure 4-3. Percentage of systems existing during the evening hours in Region 2 – Region 5 that formed during the afternoon and evening hours. The time periods are: Afternoon (18 – 23 UTC) and Evening (00 – 05 UTC). The regional divisions are: Region 2 (99.9°W - 95°W), Region 3 (94.9°W – 90°W), Region 4 (89.9°W – 85°W), and Region 5 (84.9°W – 80°W).

4.5 Summary of Key Findings

A number of interesting findings regarding nocturnal convection were revealed through the analysis of the spatial and temporal characteristics of the convective systems presented in this study. An important observation is that eastward propagating systems contributed more to the occurrence of nocturnal convection within the study region compared to locally-generated convection. This result is in agreement with that of a number of previous authors (Carbone *et al.* 2002, Jiang *et al.* 2006, Tuttle and Davis 2006) who found that a substantial proportion of nocturnal convective systems that occur within the eastern plains (eastern North and South Dakota, northeastern

Nebraska, Minnesota, Iowa) had formed over the higher terrain of the eastern slopes of the Rocky Mountains and western Great Plains (Montana, Wyoming, northern Colorado, western North and South Dakota, northwestern Nebraska). A unique finding of this study is that eastward propagating systems also contributed to the occurrence of nocturnal convection in the vicinity of the Great Lakes including Wisconsin, northern Illinois, northern Indiana, and the Upper and Lower Peninsulas of Michigan. However, except for the morning hours in Region 4, only a small portion of these systems initially formed along the lee slopes of the Rocky Mountains or in the western Great Plains. Rather, the systems formed farther eastward in the central plains (i.e., Region 2). Furthermore, a substantial proportion of nocturnal systems in the Great Lakes region that originated in the central plains formed during the evening, night and morning hours, implying that convection that forms nocturnally can propagate eastward and contribute to the occurrence of nocturnal convection in downstream regions.

The spatial and temporal distributions of locally-generated nocturnal convection were somewhat surprising. The frequency of locally-formed nighttime and morning systems in Region 2 and Region 3, in spite of their location where LLJs are climatologically more frequent, was very similar to that observed in Region 4 and Region 5, where LLJs are not as frequent. Most nocturnal systems that were locally-generated initially formed during the nighttime or morning hours, an indication that the LLJ was likely an important factor for their formation.

Some differences in the spatial and temporal distributions of nocturnal convection were observed for the 1991 and 2004 summer seasons. In general, Patterson *et al.* (1995) suggested a higher frequency of locally-generated nocturnal systems, especially for Region 2. Both studies were in agreement that a substantial proportion of nocturnal systems that occurred in the vicinity of the Great Lakes were locally generated.

Chapter 5 Origin, Duration, and Termination of Convective Systems over the Great Lakes

In Chapters 3 and 4, the spatial and temporal characteristics of convection during the summer season (June, July, and August) of 2004 were investigated by examining the origin, movement, duration, and termination of systems within the study area. Another motivation of this study was to analyze the potential impacts of the Great Lakes on summertime convection.

Convective systems that interacted with Great Lakes were considered "lake systems." A lake interaction occurred when a system had at least one lightning observation over any of the Great Lakes. Lake systems were classified into three exclusive categories: 1) lake origination, 2) lake termination, and 3) lake interaction. To be classified as a "lake originating" system, at least one lightning flash from a system must have occurred over the Great Lakes at the time the system formed. "Lake terminating" systems either dissipated over the Great Lakes, or within two hours after interacting with the lakes, and had not formed over them. The remaining lake systems fell into the "lake interaction" category, which meant they had formed upstream of the Great Lakes, then moved over the lakes and persisted for more than two hours after the last lake interaction.

The spatial and temporal characteristics of system formation and termination were analyzed for each lake system category. As in the previous chapters, system characteristics were evaluated only for the time period the system was located within the study area. In the discussion below, "termination" refers the last hour a system was observed within the study area. Terminating systems include both systems that decayed within the study area and those that exited the study area. Surface synoptic features were also identified for the time a system originated or first moved over a lake to evaluate the possible surface forcing mechanisms (e.g., a cold frontal boundary) associated with systems that interacted with the Great Lakes. The duration of systems that originated over the lakes was examined by time of day the systems formed. In addition, system "age" at the time of first lake contact was evaluated by the time of day of first lake interaction for terminating and interacting lake systems. The number of hours that a system was located over a lake was analyzed for all lake system categories.

In some instances, systems split prior to or while over a lake into two or more new systems, resulting in a larger number of lake systems than locations of system formation (i.e., lake system origins). A total of 158 lake systems and 136 lake system origins were identified within the study region during the summer season of 2004 (Table 5-1). The total number of lake systems, rather than system origins, was used when calculating the percentages below.

Systems were more likely to terminate over the lakes than form over or move across them, as 52% of lake systems dissipated within 2 hours of their last lake interaction, 28% originated over the lakes, and 20% interacted with the lakes at some point during their lifetime. Terminating systems were more likely to split prior to or over the lakes compared to originating or interacting lake systems as the number of terminating systems is considerably higher than the number of system origins.

Table 5-1. Frequency of lake system origins and total number of lake systems.

	Originate	Terminate	Interact	Total
Total Number of Origins	40	65	31	136
Total Number of Systems	44	83	31	158
Percent of Total Systems	28%	52%	20%	

5.1 Analysis of Lake Originating Systems

Convective systems formed over each of the Great Lakes (Figure 5-1). Although somewhat more systems formed over Lake Superior, this may simply be an artifact of Lake Superior's relatively large size. Fewer systems formed over Lake Huron compared to the other Great Lakes, while an approximately equal number of systems originated over Lakes Michigan, Erie, and Ontario. A substantial number of the systems that formed over the Great Lakes terminated over the lakes as well (Figure 5-2). Over 80% of lake originating systems dissipated over the lakes, and the four lake originating systems during summer 2004 that split after their formation had at least one termination location over the lakes. As anticipated based on the larger number of systems that formed over Lake Superior, more systems terminated over Lake Superior. Fewer systems terminated over Lake Erie compared to the other lakes. The origin and termination locations of systems that formed over the Great Lakes suggest that most of these systems remained fairly local as they evidently traveled only short distances before dissipating.

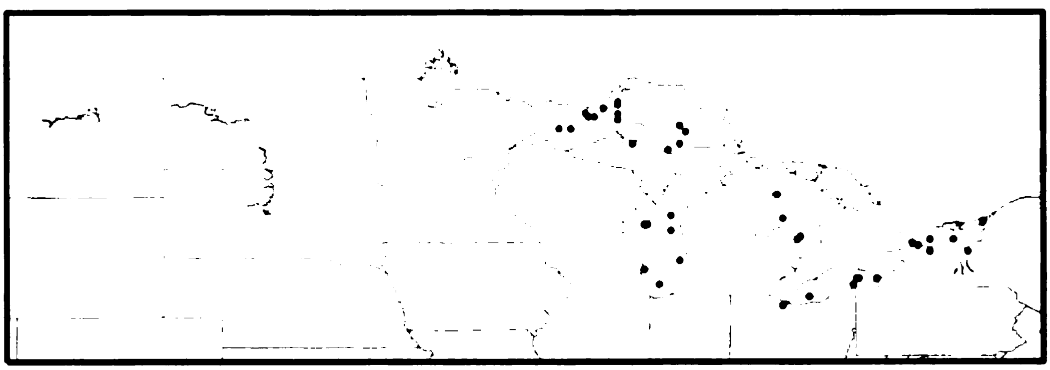


Figure 5-1. Centroid locations of lake originating systems at the time of system formation. At least one lightning observation from each system occurred over the lakes at this time.

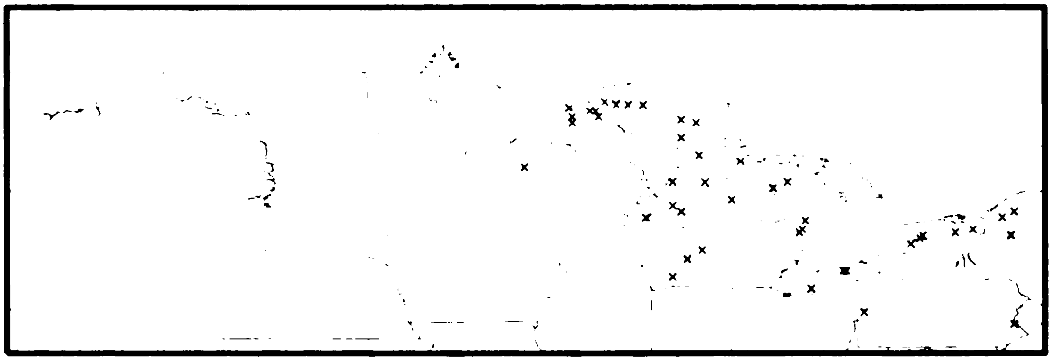


Figure 5-2. Centroid locations at the time of dissipation of lake originating systems.

System generation was approximately evenly distributed throughout the day (Figure 5-3). Systems were slightly more likely to form during the early afternoon hours (18 – 20 UTC) and a slight minimum in system initiation occurred during the early evening hours (00 – 02 UTC). The number of systems that formed over the Great Lakes was fairly uniform for the remainder of the day.

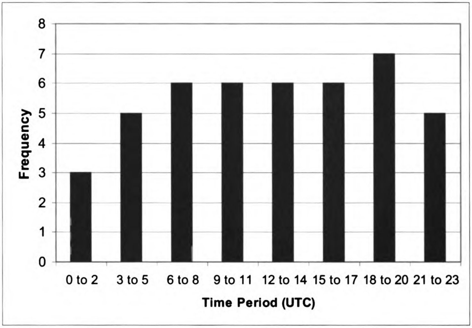


Figure 5-3. Frequency of lake system origination by time period (UTC).

Surface Synoptic Features

Surface synoptic features present during the hours of lake interaction were identified for each lake system. Forty-one percent of systems that originated over the Great Lakes in the summer of 2004 were associated with a cold frontal boundary (Table 5-2). Warm fronts were the second most frequent surface feature with 16% of systems forming along a warm frontal boundary. Systems that originated over the lakes were equally likely to form along stationary fronts (9%), ahead of a frontal boundary (11%), or near a surface trough (11%). Only a small percentage (5% or less) of lake originating systems formed upstream of a low pressure system, along an occluded front, or were unclassified.

Table 5-2. Frequency of surface features by lake system category.

	Originate	Terminate	Interact
Cold Front	41%	43%	23%
Warm Front	16%	11%	10%
Stationary Front	9%	8%	29%
Occluded Front	2%	0%	0%
Trough	11%	22%	16%
Pre-frontal Convection	11%	5%	6%
Behind Cold Front	0%	1%	0%
Behind Low Pressure System	5%	4%	3%
Warm Sector	0%	1%	3%
High Pressure System	0%	2%	0%
Unclassified	5%	2%	10%

During almost all time periods, systems that formed over the lakes were more likely to be associated with a frontal surface feature versus a non-frontal surface feature (Table 5-3). The "frontal" category includes only systems that occurred along a cold, warm, occluded, or stationary frontal boundary. The systems that were associated with the remaining surface features were considered "non-frontal". Non-frontal features were observed most often with systems that formed over the lakes during the early night (06 – 08 UTC) and late afternoon hours (21 – 23 UTC). Cold fronts were the most frequent frontal feature for all times of day excluding the late evening (03 – 05 UTC) and late morning hours (15 – 17 UTC) when warm fronts were the dominant surface feature (Table 5-4).

Table 5-3. Percentages of frontal versus non-frontal surface synoptic features associated with lake originating systems by time period (UTC). The synoptic features were identified during the time that a system occurred over the lakes and the time periods refer to the time of system formation.

Lake Originating	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Frontal	100%	80%	50%	67%	67%	67%	71%	60%
Non-Frontal		20%	50%	33%	33%	33%	29%	40%

Table 5-4. Frequency of surface synoptic features associated with lake originating systems by time period (UTC).

	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Cold Front	2	1	2	3	2	1	5	2
Warm Front		3			1	2		1
Stationary Front	1		1	1	1			
Occluded Front						1		
Trough		1	1	1			1	1
Pre-frontal Convection			1		1	1	1	1
Behind Cold Front								
Behind Low Pressure System				1	1			
Warm Sector								
High Pressure System								
Unclassified			1			1		

Persistence Measures

The total duration, or persistence, of lake originating systems is presented in Figure 5-4. Total duration is defined as the number of hours a system existed from the time of origin until termination. Over half of all lake originating systems persisted for 2 hours or less. Of a total of 44 systems that formed over the lake, 27% persisted for only one hour and another 27% persisted for only 2 hours before dissipating. For those systems that persisted for more than 2 hours, a majority, or 27% of lake originating systems, had durations in the range of 3 to 7 hours. Approximately 18% of all lake originating systems persisted for at least 10 hours before termination.

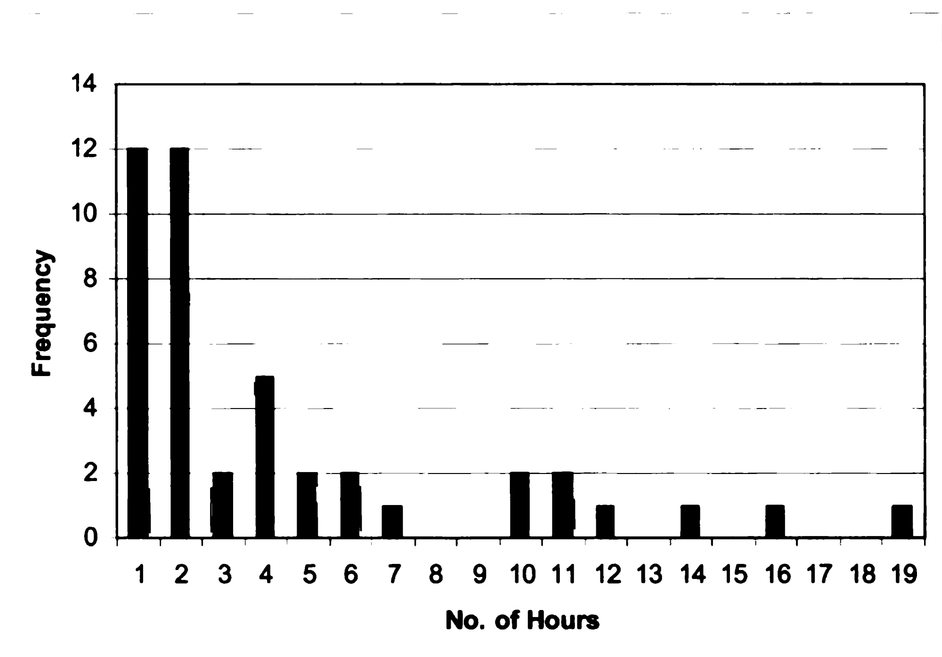


Figure 5-4. Total duration of lake originating systems.

To determine temporal differences in the persistence of systems that formed over the Great Lakes, durations were examined by time of day (Figure 5-5). Of all the systems that formed over the Great Lakes, the system with the longest duration (19 hours) originated in the early nighttime hours (06 – 08 UTC), while the remaining systems that formed during this time period persisted for only 4 hours or less. Systems that originated during the early afternoon hours (18 – 20 UTC) typically had longer durations compared to those that originated during other time periods. Relatively long durations of at least 6 hours were also observed for systems that originated in the late evening (03 – 05 UTC) and late morning (15 – 17 UTC) hours. Most systems that formed during the remaining time periods had durations of no more than 4 hours.

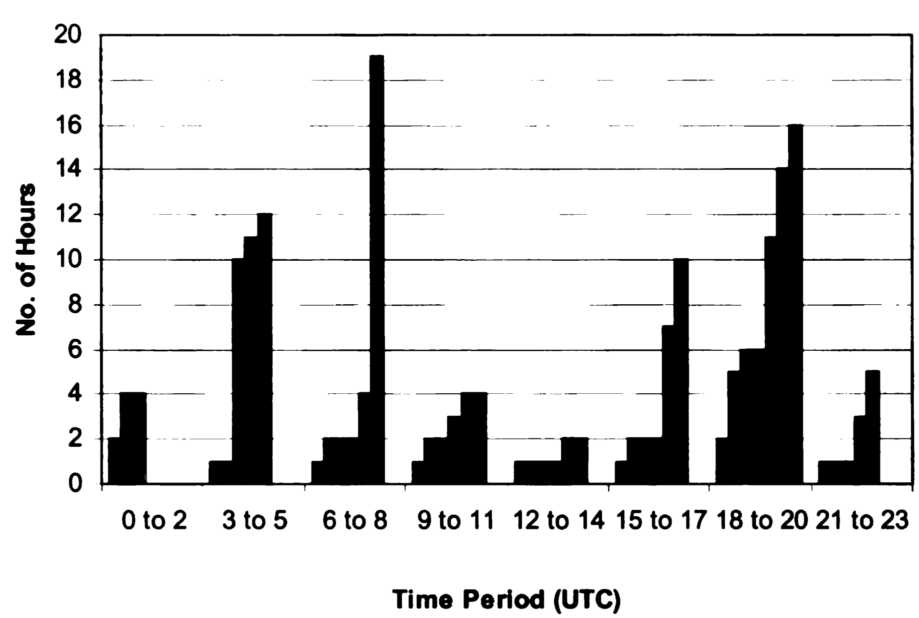


Figure 5-5. Duration of lake originating systems by time period (UTC). Each bar represents the duration of a system that formed in that particular time period shown on the horizontal axis.

The number of hours each system remained over the lakes was also determined and is referred to as the "lake duration." Most lake originating systems remained over the lakes for only 1 to 2 hours (Figure 5-6), which was anticipated based on the short overall durations of 2 hours or less. Approximately 20% of systems that formed over the lakes had lake durations of 4 or 5 hours, while another 11% had lake durations of 8 to 10 hours. Only one lake originating system persisted over the lakes for more than 10 hours.

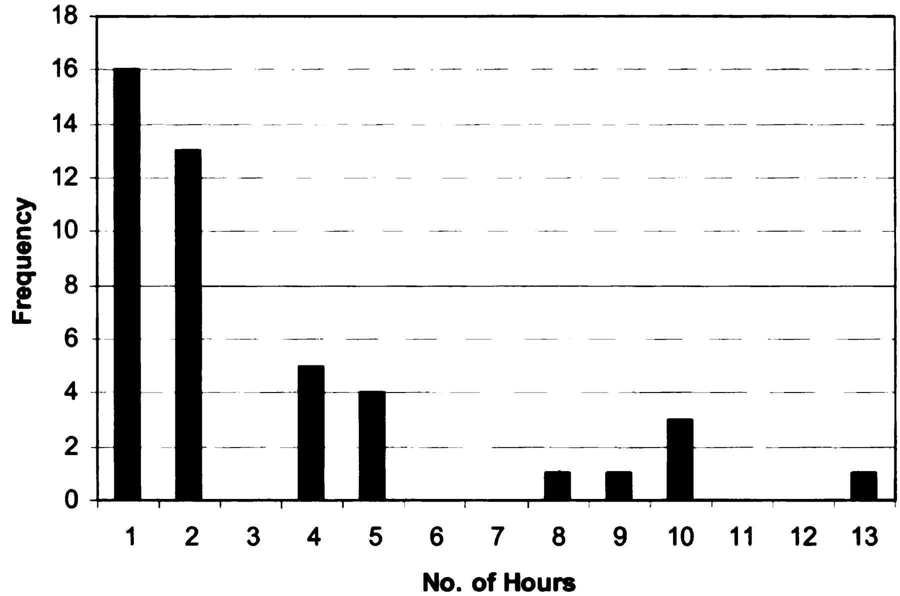


Figure 5-6. Number of hours that lake originating systems occurred over the Great Lakes before dissipating.

5.2 Analysis of Lake Terminating Systems

Convective systems that terminated over the Great Lakes during the summer of 2004 formed in all parts of the north-central United States (Figure 5-7). A west-east gradient in system generation is evident, however, as more lake terminating systems formed in the eastern portion of the study area. Because of the subjectivity in estimating centroid locations, some systems appear to have traveled upstream before terminating over the lakes. System termination was most frequent over the eastern Great Lakes (Figure 5-8), particularly over Lake Huron, and many also terminated over Lake Erie and Lake Ontario or immediately downstream. System termination was less frequent over Lake Superior and Lake Michigan. Based on the distribution of origin and termination locations for the lake terminating systems, it is evident that a large portion of these systems propagated from the western portion of the study before terminating over the lakes. The frequency of system termination was variable throughout the day with more systems dissipating shortly after midnight (06 – 08 UTC) (Figure 5-9), and few systems dissipating in the late morning (15 – 17 UTC) and early afternoon (18 – 20 UTC) hours.

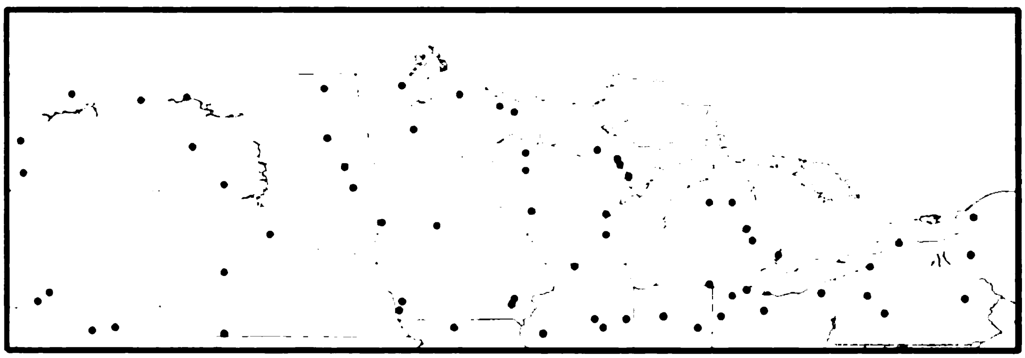


Figure 5-7. Centroid locations of lake terminating systems at the time of system formation.

Figure 5-8. Centroid locations at the time of dissipation of lake terminating systems.

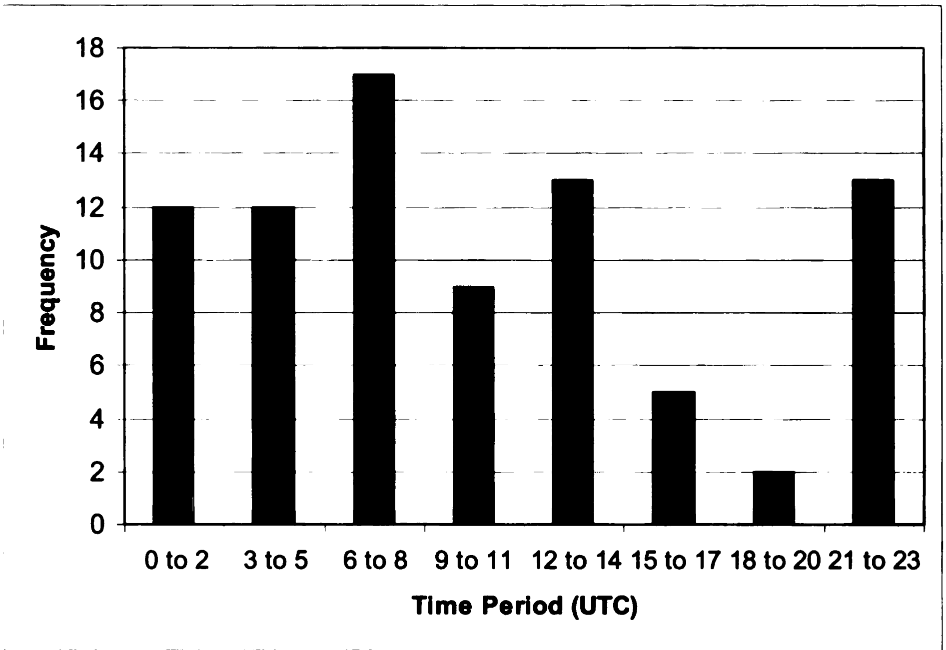


Figure 5-9. Frequency of lake termination by time period (UTC).

Surface Synoptic Features

Similar to lake originating systems, convective systems that dissipated over the lakes were often (42%) associated with cold frontal boundaries (Table 5-2). In contrast, lake terminating systems infrequently occurred ahead of a frontal boundary (pre-frontal convection) or along a warm front compared to systems that formed over the lakes. The most pronounced difference between the two lake system types, however, is that the relative frequency of convection associated with surface troughs was twice as large for lake terminating systems (22%) as for lake originating systems (11%). Systems that dissipated over the lakes were equally as likely to occur along a stationary front as systems that formed over the lakes.

Compared to systems that formed over the lakes during the early and late evening hours (00 – 02 UTC and 03 – 05 UTC, respectively) and the early and late afternoon periods (18 – 20 UTC and 21 – 23 UTC, respectively), the relative frequency of non-frontal surface features increased for systems that terminated over the lakes during these time periods (Table 5-5). However, frontal features were more frequently associated with systems that dissipated during most time periods, similar to originating systems. Cold fronts were the most common frontal feature for each time period with the exception of the late morning hours (15 – 17 UTC), as systems that terminated over the lakes during this time period were more likely to occur along a warm frontal boundary (Table 5-6). A relatively high frequency of systems that terminated during the early evening (00 – 02 UTC) and early night periods (06 – 08 UTC) occurred near a surface trough.

Table 5-5. Percentages of frontal versus non-frontal surface synoptic features associated with lake terminating systems by time period (UTC). Synoptic features were identified during the time that a system occurred over the lakes and the time periods refer to the time of termination.

Lake Terminating	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Frontal	50%	67%	65%	67%	69%	80%	50%	54%
Non-Frontal	50%	33%	35%	33%	31%	20%	50%	46%

Table 5-6. Surface synoptic features of lake terminating systems by time period (UTC).

	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Cold Front	6	7	7	3	6	1	1	5
Warm Front			3	1	1	3		1
Stationary Front		1	1	2	2			1
Occluded Front								
Trough	4	2	4	3	2		1	2
Pre-frontal Convection	1		1		1			1
Behind Cold Front		1						
Behind Low Pressure System		1						2
Warm Sector								1
High Pressure System	1					1		
Unclassified			1		1			

Persistence Measures

The number of hours a lake terminating system had existed at the time of first lake interaction, or system age, was examined (Figure 5-10). Although most lake terminating systems formed 8 hours or less before reaching the lakes, almost 20% formed 10 to 19 hours earlier, and another 15% formed more than 23 hours prior to lake interaction.

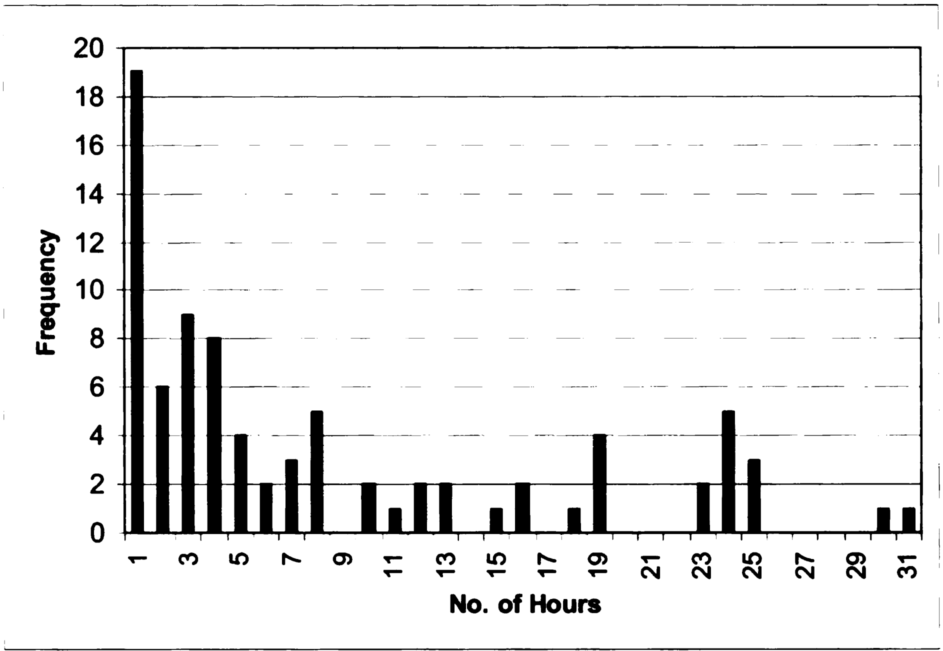


Figure 5-10. Age of lake terminating systems at the time of first lake interaction.

Lake duration, or in other words, the number of hours that lake terminating systems existed over the lakes before dissipating was also determined (Figure 5-11). Systems that terminated over the lakes had much longer lake durations than systems that formed over them. Few originating systems persisted over the lakes for more than 2 hours (Figure 5-6), while well over half of lake terminating systems were located over the lakes for at least 4 hours. The longest lake duration was 41 hours for systems that terminated over the lakes compared to only 13 hours for lake originating systems.

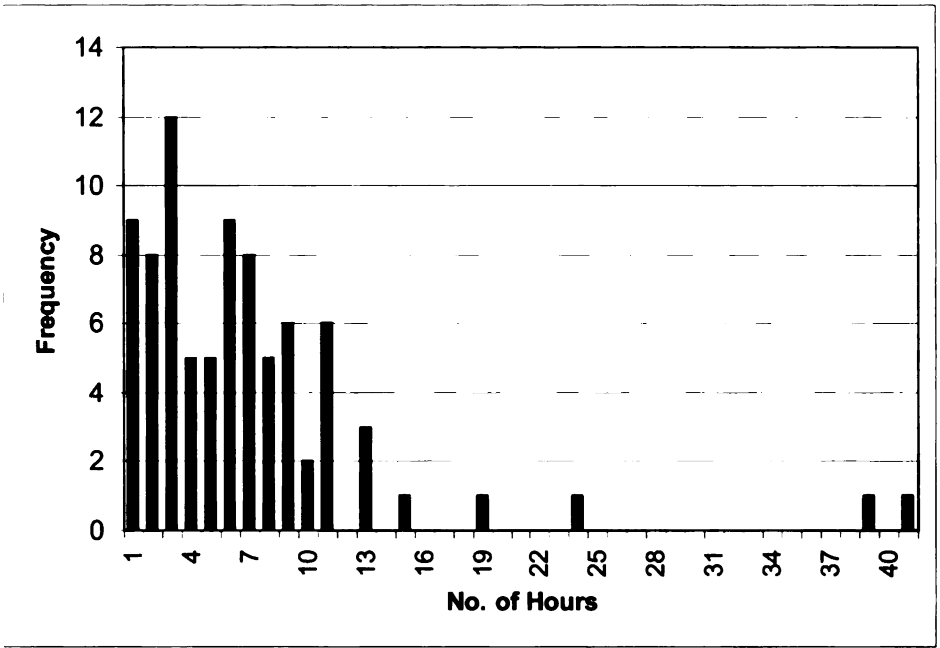


Figure 5-11. The number of hours that lake terminating systems occurred over the Great Lakes before dissipating.

5.3 Analysis of Lake Interacting Systems

To gain insights as to why some systems persist after lake interaction, the spatial and temporal characteristics, as well as surface synoptic features, of lake interacting systems were compared to those of lake terminating systems. The origin locations for lake interacting systems were generally confined to the southeastern portion of the study region (Figure 5-12). Most lake interacting systems originated in the northern portions of Illinois and Ohio, and western Pennsylvania and frequently dissipated in Pennsylvania (Figure 5-13). System termination was frequent in the Lower Peninsula of Michigan, northern Ohio, and eastern New York.

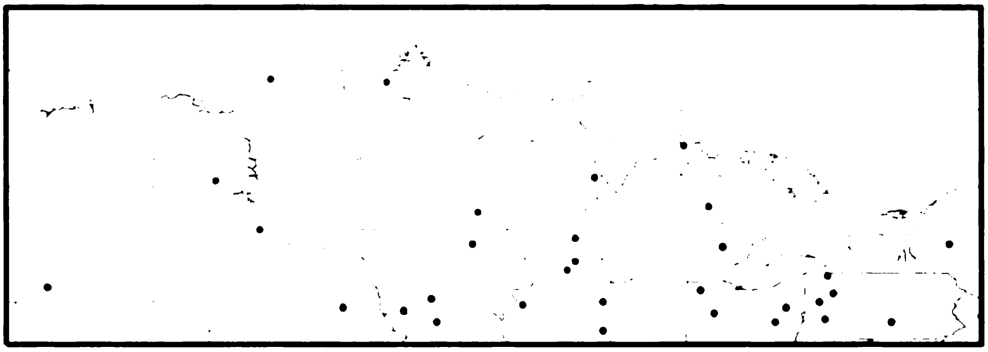


Figure 5-12. Centroid locations of lake interacting systems at the time of system formation.

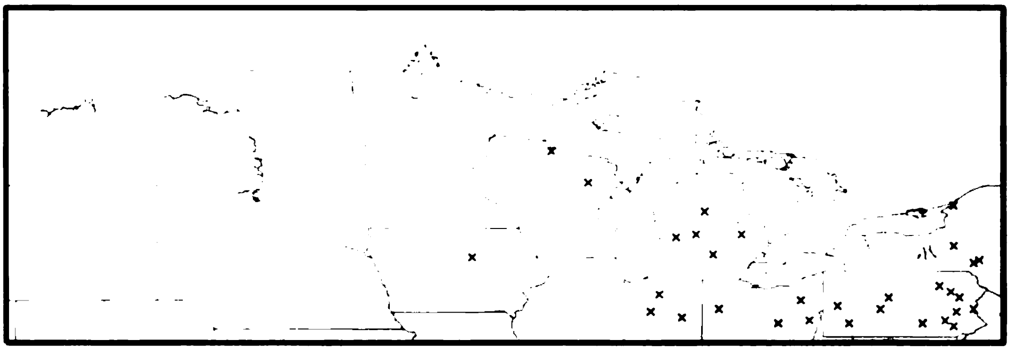


Figure 5-13. Centroid locations at the time of dissipation of lake interacting systems.

The time of day each system first moved over the Great Lakes was determined, and a slight maximum was observed during the afternoon hours (18 – 20 UTC) (Figure 5-14). Systems were equally as likely to move over the lakes during the late morning hours (15 - 17 UTC), early evening (00 – 02 UTC), and late evening (03 – 05 UTC) periods. A very small number of systems first interacted with lakes during the early night and early morning periods, and none did so during the late night hours.

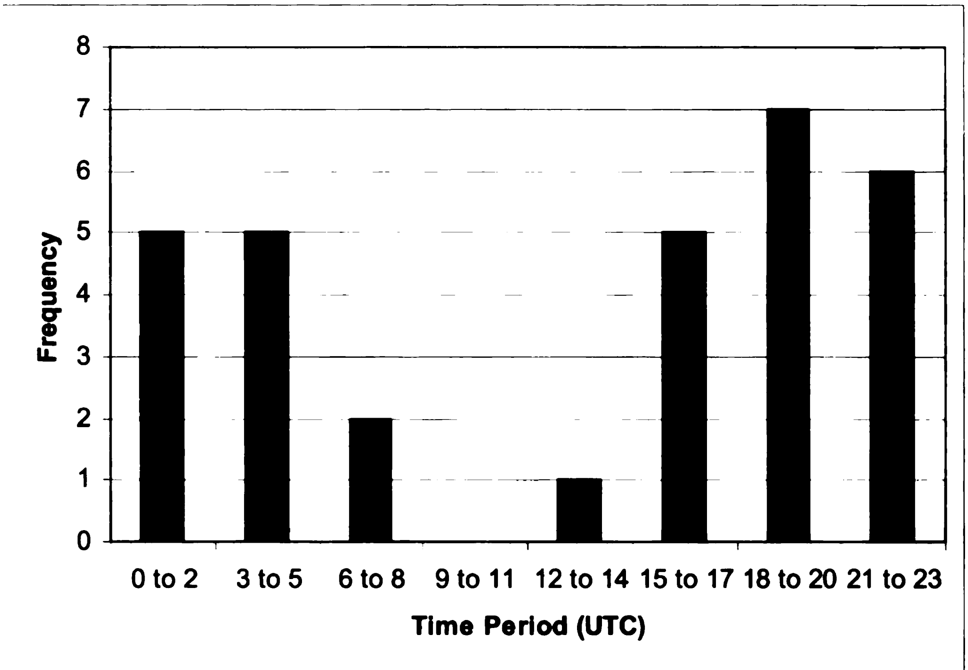


Figure 5-14. The time period that lake interacting systems first moved over the lakes.

Surface Synoptic Features

The surface synoptic features that were frequently associated with lake interacting systems differ compared to those associated with lake originating and terminating systems. Lake interacting systems were more likely to have occurred along a stationary front (29%), whereas systems that formed or dissipated over the lakes were associated with cold frontal boundaries. The frequency of convection along a cold frontal boundary was only 23% for lake interacting systems compared to 43% for lake terminating systems (Table 5-2). Lake interacting systems were equally as likely to occur along warm fronts or ahead of frontal boundaries as lake terminating systems. Lake interacting systems associated with surface troughs (16%) were more frequent compared to systems that formed over the lakes (11%), but less frequent compared to lake terminating systems (22%). A larger portion (10%) of surface features were unidentifiable and considered unclassified for lake interacting systems than the other lake systems.

The majority (>60%) of systems that initially interacted with the lakes during the evening, night, and morning periods were associated with frontal features (Table 5-7). Non-frontal features were much more frequent (>66%) for systems that first interacted with the lakes during the early and later afternoon hours, whereas stationary frontal boundaries were more frequent for the early nighttime and late morning hours (Table 5-8). Systems that interacted with the lakes during the afternoon were most often associated with surface troughs.

Table 5-7. Percentages of frontal versus non-frontal surface synoptic features associated with lake interacting systems by time period (UTC). Synoptic features were identified during the time that a system occurred over the lakes. Time periods refer to the time that a system first moved over the lakes.

Lake Interacting	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Frontal	80%	100%	100%		100%	60%	29%	33%
Non-Frontal	20%					40%	71%	67%

Table 5-8. Surface synoptic features of lake interacting systems by time period (UTC).

	0 to 2	3 to 5	6 to 8	9 to 11	12 to 14	15 to 17	18 to 20	21 to 23
Cold Front	2	2			1		1	1
Warm Front	2	1						
Stationary Front		2	2			3	1	1
Occluded Front								
Trough						1	2	2
Pre-frontal Convection	1							1
Behind Cold Front								
Behind Low Pressure System						1		
Warm Sector							1	
High Pressure System							1	
Unclassified							1	1

Persistence Measures

Lake interacting systems were generally "younger" at the time of first lake interaction compared to systems that terminated over the lakes (Figure 5-15). Almost 78% of lake interacting systems formed 5 hours or less before moving over the lakes, compared to 55% of lake terminating systems (Figure 5-10). Approximately 10% of lake interacting systems existed for 16 hours or more before reaching the lakes, while almost 23% of terminating systems persisted for at least that amount of time before lake interaction.

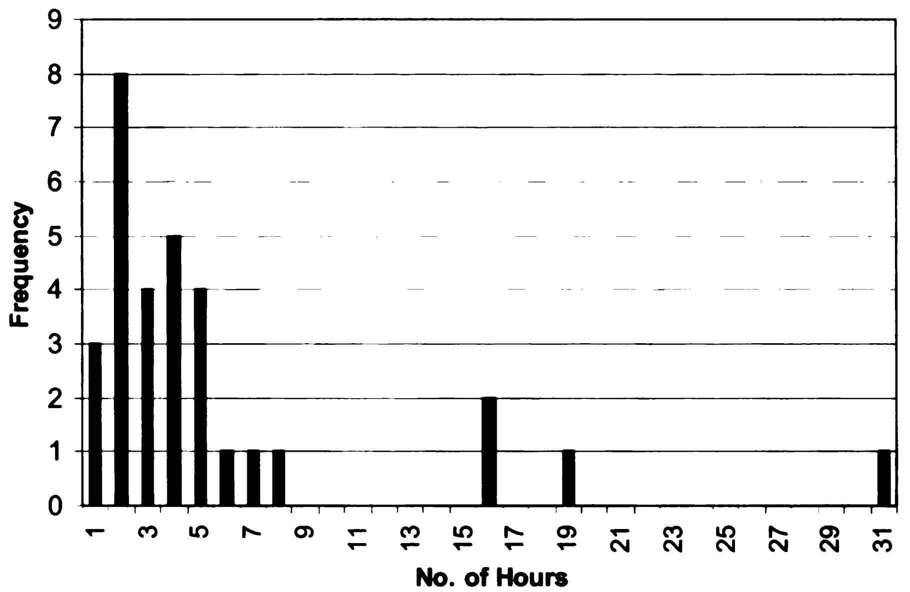


Figure 5-15. Age of lake interacting systems at first lake interaction.

The number of hours each system persisted from the time they initially moved over the Great Lakes until dissipation was determined and examined by the time of day of first lake interaction (Figure 5-16). Systems that first moved over the lakes during the early evening (00 – 02 UTC) and later evening (03 – 05 UTC) generally persisted longer than those that moved over the lakes during other time periods. The shortest durations were observed for systems that first interacted with the lakes during the early afternoon (18 – 20 UTC) and late afternoon hours (21 – 23 UTC).

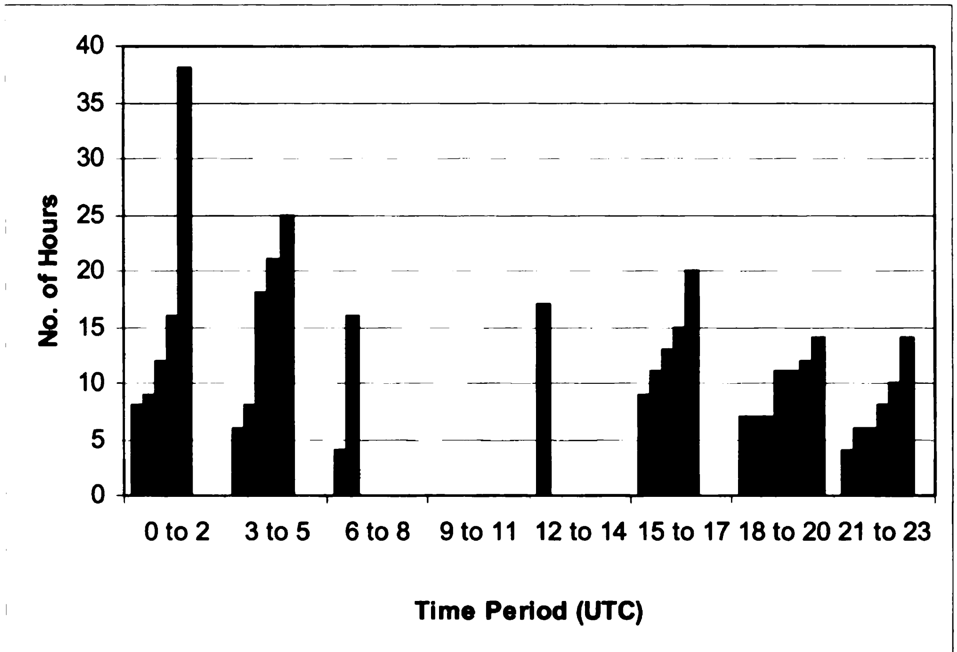


Figure 5-16. Duration of lake interacting systems after first lake interaction. Each bar represents the duration (after first lake interaction) of a system that initially interacted with the lakes at the time period shown on the horizontal axis.

The time spent over the lakes was typically shorter for lake interacting systems than for terminating systems. Almost 60% of lake interacting systems existed over the lakes for 4 hours or less (Figure 5-17) compared to 41% for systems that terminated over the lakes. Longer lake durations of at least 5 hours were more frequent for lake terminating systems as 42% persisted from 5 to 10 hours over the lakes while only approximately 25% of lake interacting systems had lake durations of this length.

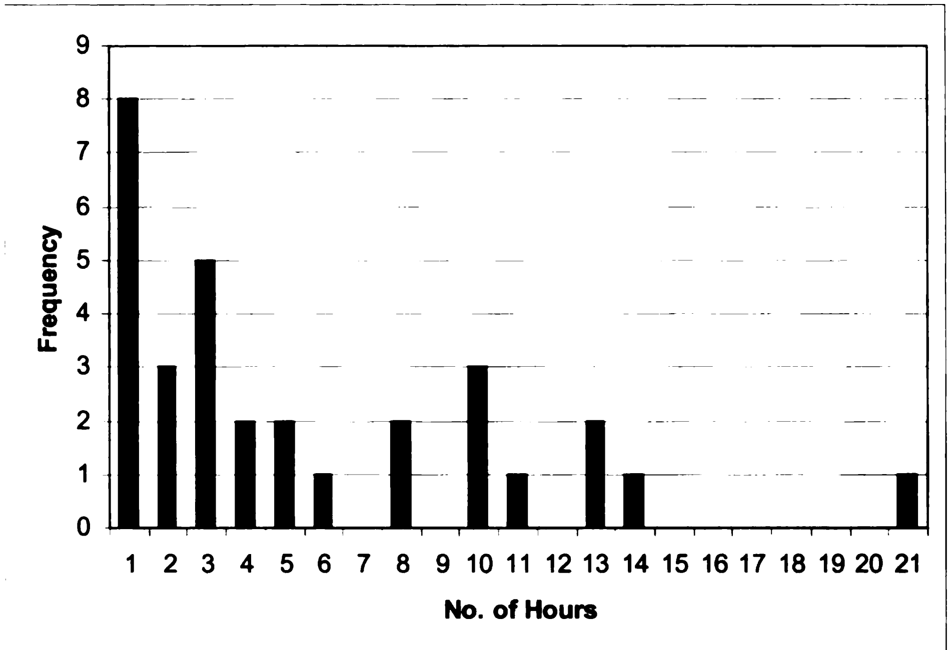


Figure 5-17. The number of hours that lake interacting systems occurred over the Great Lakes before dissipating.

5.4 Summary of Results

The spatial and temporal characteristics of convective systems that interacted with the Great Lakes were analyzed to assess potential influences of the Great Lakes on convection. Specifically, diurnal variations of system origination, termination, and persistence were examined along with the surface synoptic features that were present while convection occurred over the lakes. Based on the findings of this analysis, no definitive conclusions can be drawn, as the results suggest that the Great Lakes have varying impacts on convection within the region. Nonetheless, valuable insights are gained into the nature of summer season convection over the Great Lakes and are summarized below.

Of the lake systems that were identified for the summer of 2004, systems were considerably more likely to terminate over Great Lakes than form over or interact with them. This initially may suggest that the lakes have a suppressing effect on convection, however, the small number of systems examined in this analysis does not allow for such a broad generalization. Most of the systems that originated over the lakes were short-lived, with total durations of 2 hours or less. Surprisingly, convection was slightly more likely to form over the Great Lakes during the early afternoon (18 – 20 UTC) when cooler water temperatures relative to ambient air temperatures may create an environment unfavorable for convection. In addition, systems that formed over the lakes during the afternoon hours often persisted longer than systems that originated during most other time periods. Lake originating systems most often formed along a cold frontal boundary suggesting that these systems had strong surface lifting but did not persist due to the cold water temperatures.

Convective systems that formed upstream and terminated over the Great Lakes often dissipated over Lake Huron and in the vicinity of Lakes Erie and Ontario, which may reflect their proximity to the eastern boundary of the study area. A rather surprising result is that systems were more likely to dissipate over the lakes during the early nighttime hours (06 – 08 UTC), when the relatively warm lake surface could provide favorable convective conditions, and were least likely to dissipate during the early afternoon. Lake terminating systems generally persisted over the lakes longer than most systems that formed over them, which could be an indication that the Great Lakes may, in some instances, provide conditions that are suitable for the maintenance of convection rather than initiation. Similar to lake originating systems, convection that terminated over the Great Lakes was frequently associated with a cold frontal boundary.

In general, lake interacting systems persisted over the lakes for a shorter time period than systems that terminated over the lakes. Systems that initially moved over the lakes during the early evening persisted longer than systems that moved over the lakes during most other time periods. Unlike lake terminating systems, lake interacting systems were more likely associated with overrunning precipitation as stationary fronts were more frequent than cold fronts for these systems.

Chapter 6 Discussion and Conclusions

This study developed a climatology of the origin, movement, duration, and termination of convective systems across the north-central United States for the summer season of 2004. In particular, the goals of this study were to: 1) describe the spatial and temporal characteristics of convection throughout the study area, 2) evaluate the relative contribution of the LLJ and eastward propagating convection to the occurrence of nocturnal convection in the study area, 3) evaluate the correspondence of the current climatology to that presented earlier by Patterson *et al.* (1995), and 4) provide an initial assessment of the potential influences of the Great Lakes on summertime convection. The major findings are discussed in the following sections.

6.1 Spatial and Temporal Characteristics of Convective Systems in the North-Central United States

Several questions regarding the spatial and temporal characteristics of convection across the north-central United States were proposed (see 1.2) and to address these questions, convective systems were analyzed by system origin, termination, and region of existence. Each type of analysis provided insights into the spatial and temporal variability of convection across the study region. To facilitate temporal comparisons of convection across the study area, systems were aggregated into four time periods (afternoon, evening, night and morning) and six west-to-east regions. The analysis was limited to the time period a system was present within the study area even though some systems formed outside of the study area and others terminated after exiting the study area. System origination and termination refer to the first and last hours, respectively, that a system was observed within the study area, and duration is the lifetime of a system within the study area.

The analyses of convective systems suggest the following generalizations regarding the spatial and temporal variations of convection in the north-central United States during the summer season (June, July, and August) of 2004. Convective systems were considerably more likely to form in Region 1 (eastern Montana and Wyoming and western North Dakota, South Dakota and Nebraska) compared other parts of the study area. Across all regions, but particularly for Region 1, convective systems formed most often during the afternoon hours (18 – 23 UTC). Convection that formed across the study area typically remained “local” (i.e., terminating in the region in which it formed). Exceptions were the convective systems that originated in Region 2 (eastern North Dakota, South Dakota, Nebraska and western Minnesota and Iowa) during the evening (00 – 05 UTC) and morning hours (12 – 17 UTC), and those that initiated in Region 5 (eastern Michigan and northern Ohio) during the morning, which typically propagated downstream of the region of origin. Despite the local nature of most convection, propagating systems formed in all regions during all times of day. The distance traveled by propagating systems varied by region and time of day, although some propagating systems from each region traveled as far east as Region 6 (western New York and Pennsylvania). The average duration of convective systems generally decreased from west to east across the study area, although this was partly an artifact of the distance to the study area boundary. Surprisingly, systems that formed in the morning hours, when conditions are generally unfavorable for convection, had longer durations compared to systems that formed at other times of the day.

Although the general tendency was for convection that formed in a particular region to remain local until termination, the analysis by system termination suggests that a considerable number of systems formed upstream of the region in which they terminated (excluding Region 1 as it is the westernmost region). In general, systems that terminated in the afternoon were more likely to have formed locally. Systems that terminated during the nighttime and morning hours were typically of "non-local" origin in most regions, except in Region 6 where at all times of day most terminating systems had formed locally. Overall, convection was most likely to terminate in Region 1, and systems generally dissipated more often during the evening hours, although convection terminated equally as frequently during the night in Region 4 (eastern Wisconsin and Illinois, western Michigan, and northwestern Indiana) and Region 5. Across all regions, systems that terminated during the nighttime and morning periods had longer durations compared to those that terminated in the afternoon and evening periods. Also, systems that terminated in the eastern portion of the study area persisted longer before dissipating compared to those that terminated in the western portion of the study area.

When viewed from the perspective of all convection systems occurring in a particular time period or region, and not just those that initiated or terminated in that period or region, most convective systems observed in the extreme western (Region 1) and eastern (Region 6) portions of the study area were local in nature, regardless of time of day. In the other regions, the majority of convective systems existing during the afternoon were locally-generated systems, while most evening, night, and morning systems formed upstream of the region.

6.2 Evaluation of the Relative Importance of the LLJ and Eastward Propagating Convection to the Occurrence of Nocturnal Convection

The convective characteristics described above were used to evaluate the relative contribution of LLJs and eastward propagating systems to the occurrence of nocturnal convection within the north-central United States during the summer of 2004. As defined by previous studies, the "core" of the nocturnal precipitation regime corresponds to Region 2 through Region 5 of the current study area. Most nocturnal convection (i.e., convection existing during the nighttime and morning periods or from 06-17 UTC) was not generated locally but rather propagated eastward from a region to the west. Region 1 was an important source of nocturnal convection in Region 2 and Region 3, and to a lesser extent for Region 4 and Region 5. Most systems that initially formed in Region 1 originated during the afternoon hours, consistent with eastward propagating systems from lee slopes of the Rocky Mountains and the High Plains. Not all nocturnal systems originated in Region 1, however. A substantial number of nocturnal systems in Region 4 originated in Region 2, often much earlier in the day during the morning hours and perhaps in conjunction with a LLJ. Nocturnal systems in Region 5 most likely originated immediately upstream in Region 4, frequently during the afternoon hours at the time of greatest boundary layer heating.

Although the overall frequency of locally-generated nocturnal convection was substantially less than that of non-local convection, most locally-generated nocturnal convection formed during the nighttime and morning hours, supporting the LLJ as a likely mechanism for these systems. Surprisingly, local convection was nearly as frequent in the vicinity of Great Lakes compared to the central plains where the LLJ is climatologically most frequent.

These findings strongly support the theory that eastward propagating systems from the elevated terrain contribute substantially to nocturnal convection across the north-central United States. A particularly interesting observation is the existence of nighttime convection in Region 4 that had originally formed in Region 2 during the morning. The LLJ has mostly been associated with local nocturnal convection; however, these results suggest that the LLJ may also contribute to nocturnal convection in regions downstream.

Relation to Previous Studies

The results of this study strongly support the findings of a number of recent studies that have examined the LLJ and eastward propagating systems in relation to the nocturnal precipitation maximum in the central United States. Although this study found the relative frequency of locally formed nocturnal convection to be considerably less than convection that formed upstream, local convection was still an important contributor to the occurrence of nocturnal convection in the north-central United States. In particular, the large number of locally formed nocturnal systems observed in Region 2 and the speculation on the role of the LLJ in the formation of these systems is in agreement with the study by Tuttle and Davis (2006). In their study, Tuttle and Davis (2006) examined precipitation during the warm seasons of 1998-2002 within the region of the central United States extending from 100°W – 95°W, which corresponds to Region 2 of the current study area. Within this region, they observed a nocturnal precipitation maximum that resulted from both eastward propagating systems from the elevated terrain of the western plains, and from locally generated precipitation. Comparison of composite radar observations and Rapid Update Cycle (RUC) modeled wind fields revealed that precipitation within central United States was closely linked with the occurrence of the nocturnal LLJ. In addition, they found that on days with strong LLJs, locally formed convection increased nearly 25% compared to a 5-year climatology developed from radar observations. Clearly, the work of Tuttle and Davis (2006) had a distinct advantage over the current study as they were able to identify the occurrence of LLJs as opposed to infer their existence. Nonetheless, their results make the speculation on the role of the LLJ to the occurrence of local nocturnal convection in Region 2 increasingly valid.

The large number of nocturnal systems that formed during the afternoon hours in the lee of the Rocky Mountains (Region 1) and propagated into the eastern Dakotas and Nebraska (Region 2), Minnesota, Iowa, and western Wisconsin (Region 3) is in agreement with the work of Carbone *et al.* (2002) and Jiang *et al.* (2006). Carbone *et al.* (2002) examined precipitation episodes over a large portion of the continental United States from 1997 – 2000. They observed frequent precipitation events originating near 105°W (i.e., near the Rocky Mountains) during the afternoon hours, which is largely consistent with the results of the current study. In addition, Carbone *et al.* (2002) found, using radar observations, a precipitation maximum that propagated eastward from the Rocky Mountains and was responsible for a nighttime and early morning diurnal rainfall signal in the Great Plains to approximately 96°W (which includes most of Region 2). The results of the current study are in agreement with those of Carbone *et al.* (2002) as most nocturnal convection that occurred as far east as 95°W (the eastern boundary of Region 2) had formed near the lee slopes of the Rocky Mountains or in the High Plains. On the other hand, Carbone *et al.* (2002) also indicated that nighttime rainfall eastward of 96°W (Region 3, Region 4 and Region 5) was often non-propagating, whereas this study showed that nighttime precipitation in this area was more often associated with propagating systems. However, their overall results suggest the importance of propagating precipitation to nocturnal rainfall in the central United States.

Similarly, Jiang *et al.* (2006) found eastward propagating systems from the Rocky Mountains could be the key factor in the nocturnal maximum in rainfall over the central plains (100°W – 90°W), which corresponds to Region 2 and Region 3 of the current study area. Using North American Regional Reanalysis Data from 1970 – 2003, they employed extended empirical orthogonal functions (EEOF) analysis for May - August precipitation. Based on this analysis, they observed that precipitation often formed over the ridge of the Rocky Mountains during the afternoon then traveled eastward and often intensified as it reached the central plains during the night. Furthermore, they showed that the precipitation events in the central plains with strong eastward propagating signals displayed a prominent rainfall peak during the night, suggesting that the contribution of rainfall from these events results in the nocturnal precipitation maximum in the central United States. The strong eastward propagating signal in rainfall observed by Jiang *et al.* (2006) is largely consistent with the results of this study that found systems existing in Region 2 and Region 3 were most likely to have formed in Region 1 (i.e., the lee of the Rocky Mountains). The current study, however, is advantageous to the work of Jiang *et al.* (2006) by explicitly examining individual convective systems, whereas systems were not identified in the earlier study.

The findings of the study performed by Dai *et al.* (1999) disagreed with the current results, as they suggested that propagating systems play a secondary role in the occurrence of nocturnal convection in the central United States compared to other mechanisms. They examined gridded observational precipitation data from 1963 – 1993 and observed the well documented late afternoon maximum in precipitation over the Rocky Mountains, and a nighttime to early morning precipitation maximum east of the Rocky Mountains into the central plains. Using surface pressure observations, computed divergence values, and derived convective available potential energy (CAPE) values from NCEP/NCAR reanalysis data, they deduced that low-level cycles of convergence are largely associated with the diurnal cycle of precipitation in the central United States. They suggested that the combination of atmospheric static instability and low-level convergence results in afternoon convection over the Rocky Mountains, while high nighttime CAPE values combined with nighttime low-level convergence induced by surface pressure cycles induces nocturnal convection east of the Rocky Mountains and into the central plains. Furthermore, they indicated, based only on the phase transition in the timing of precipitation near the Rocky Mountains, that some systems that form in this region propagate eastward, but typically dissipate at around 97°W. This clearly disagrees with the current results that found a substantial number of systems from the lee of the Rocky Mountains that propagated eastward of 95°W. Dai *et al.*'s (1999) use of gridded, and therefore averaged, precipitation values over their study period could possibly have resulted in their findings of infrequent propagation of convection, as individual systems were not examined.

The results of this study are also valuable in the context of understanding the deficiencies of GCMs in resolving the diurnal cycle of precipitation over the central United States. Jiang *et al.* (2006) discussed the inability of current GCMs to produce the nocturnal precipitation maximum over the central United States and that instead GCMs show a daytime maximum in precipitation over the Great Plains. A number of large-scale processes that have been suggested to contribute to the nocturnal precipitation maximum in the central United States such as the LLJ and low-level convergence cycles should be captured by GCMs, however, eastward propagating precipitation is poorly simulated by GCMs (Jiang *et al.* 2006). Interestingly, regional climate model (RCM) simulations that can produce the eastward propagation of convective systems can accurately simulate the nocturnal precipitation maximum over the central United States (Liang *et al.* 2004). The frequency of eastward propagating systems observed in this study, combined with the similar results of recent studies (e.g., Carbone *et al.* 2002, Jiang *et al.* 2006) illustrates the importance of understanding these phenomena. The established association of these systems to nocturnal convection, along with the knowledge that GCMs poorly simulate these systems, and the success of recent RCM simulations in producing nocturnal convection is highly suggestive that improving the eastward propagating signal could lead to improvement in the ability of GCMs to resolve the diurnal cycle of precipitation (Jiang *et al.* 2006).

6.3 Comparison of Convection during the Summers of 1991 and 2004

The findings of this study differ somewhat from those of the earlier study by Patterson *et al.* (1995). They observed that convection during the summer of 1991 was primarily locally-generated across the north-central United States, although non-locally generated systems were relatively more frequent in the nighttime hours compared to other times of day. In contrast, evening, nighttime, and morning convection was "non-local" for most regions (except Region 1 and Region 6) during the summer of 2004. In general, eastward propagating systems appeared to play a much larger role in the occurrence of nocturnal convection during the summer of 2004, and based on the frequency of "local" convection, the LLJ was likely more important during the summer of 1991. These differences are supported by Jiang *et al.* (2006) who observed large interannual variability in the occurrence of eastward propagating systems, with 1991 showing a relative minimum in eastward propagating precipitation, although 2004 was not included in their study. The differences between the two studies may reflect the degree of interannual variability of convection in the north-central United States. On the other hand, the dissimilarities could be a result of the different methods used by the two studies, including the use of radar versus lightning observations and the different criteria employed to identify systems and their behavior.

To investigate the potential interannual variability between the summer of 1991 and the summer of 2004, average synoptic patterns were examined for both seasons. Monthly averages of 500 mb geopotential height, surface temperature, and precipitation were obtained from the Climate Diagnostics Bulletin (CDB) available through the National Oceanic and Atmospheric Administration (NOAA) (NOAA 1991, NOAA

2004). Overall, some differences between the two seasons were evident that may provide insights into the variation of the frequency of locally versus non-locally generated convection. In general, the summer of 1991 was characterized by above average 500 mb geopotential heights, and therefore warmer temperatures, and also above normal amounts of precipitation. In particular, June of 1991 showed anomalously high 500 mb heights over the north-central United States including the Great Lakes region. Well above normal temperatures were observed over the central United States during the months of June and August, with above average amounts of precipitation during June. In addition, precipitation in the upper Midwest was shown to be above average during the month of July, although the remaining portions of the United States had normal amounts of precipitation.

In contrast, the summer of 2004 was characterized by below average 500 mb heights, cooler temperatures, and above average precipitation. July and August in particular showed anomalously low 500 mb heights over the north-central United States with an amplified trough over the Great Lakes. Below average temperatures were observed for June, July, and August which was likely associated with anomalous northwesterly flow that was located upstream of the upper-level trough. July and August showed above average amounts of precipitation in the central United States.

Although both summer seasons had generally above average amounts of precipitation, the upper-level ridge pattern and higher temperatures of 1991 compared to the upper-level trough pattern and cooler temperatures of 2004 may have had a direct influence on the characteristics of convection observed during these seasons. Summertime LLJs are often associated with upper-level ridges over the central United

States (Walters *et al.* 2008), which may contribute to the high frequency of local convection found in the summer of 1991. In addition, the 2004 CDB indicated that the above average amounts of precipitation observed in July and August of 2004 were related to a series of cold frontal passages during these months. Convection occurring along these cold frontal boundaries may explain the larger frequency of propagating convection during this season compared to 1991.

6.4 Characteristics of Systems that Occur over the Great Lakes

Convective systems that formed over or traversed the Great Lakes were grouped into three exclusive categories of lake originating, lake terminating, and lake interacting systems. Based on these analyses, convective systems were more likely to terminate over the Great Lakes than form over, or only interact with the lakes, although this could simply have been an artifact of the proximity of Lakes Huron, Erie, and Ontario to study area boundary. Convective systems were more likely to form over the Great Lakes during the early afternoon hours and originated more often over Lake Superior compared to the other lakes. Most systems that formed over the Great Lakes persisted two hours or less, although systems that formed in the early afternoon hours tended to persist somewhat longer.

Lake terminating systems more often dissipated over the Great Lakes in the early nighttime hours (06 – 08 UTC) and rarely terminated over the lakes during the early afternoon. Terminating systems were located over the Great Lakes for an average of 7 hours before dissipating compared to only slightly more than 3 hours for systems that formed over the lakes. In general, terminating systems were equally as likely to form across the entire study area. On the other hand, lake interacting systems usually formed in the southeastern portion of the study area. These systems were slightly more likely to move over the lakes during the early afternoon (18 – 20 UTC) compared to other times of the day. They remained over the Great Lakes for an average of 6 hours and, on average, dissipated 12 hours after initially moving over the lakes. Systems that initially interacted with lakes during the early evening (00 – 02 UTC) hours usually persisted longer than systems that interact with lakes during other times of day.

Most systems that originated or terminated over the lakes were associated with cold frontal boundaries, regardless of the time of day they were observed over the lakes. This observation suggests that strong frontal forcing often initiated convection over the lakes. The short lifetime of lake originating systems and the frequent termination of systems over the lakes and soon after the time of last lake interaction suggests that the lakes had a negative influence on convection, possibly because of the relatively cool lake temperatures during summer. On the other hand, lake interacting systems were usually associated with stationary fronts and consequently overrunning precipitation. The cooler lake waters may have helped strengthen the frontal boundary and therefore intensified these systems, which may have contributed to the longer persistence of these systems after interacting with the lakes. This idea is supported by Bosart and Galarneau (2005), who suggested that temperature differences of land and lake surfaces in the Great Lakes region can result in a quasi-stationary frontal boundary, which can in turn intensify convection along the thermal boundary.

These findings suggest that the influence of the Great Lakes on convective systems is highly complex. Of particular note is that no consistent diurnal pattern was evident for systems that originated or terminated over, or interacted with, the Great Lakes. Conflicting findings were evident for systems that formed over the lakes compared to those that moved over the lakes. The fairly short time period and consequently small number of systems included in this study suggest that further research is needed.

6.5 Limitations and Recommendations for Further Research

As for most research, this study has shortcomings that need to be addressed. The short study period of only one summer season is perhaps the most significant limitation, as results of only one season cannot be generalized with confidence to longer time periods. Expanding on the earlier work of Patterson *et al.* (1995) was an attempt to accommodate this deficiency by comparing the characteristics of convection for two different summer seasons. However, this comparison was complicated by the use of different data sets (e.g., lightning versus radar observations) and by employing different criteria in the identification of systems. Future convective climatologies would strongly benefit from the use of multiple seasons for analysis, particularly for examining the Great Lakes region, as the interannual variability would be better evaluated with an extended study period. Another limitation of this research is that CG lightning observations may underestimate the area of convection, although to what extent is unknown, as some systems or portions of systems may experience only IC lightning activity. Currently, IC lightning flashes are poorly detected by lightning sensors, and until lightning sensing technology substantially improves, IC flashes are unlikely to be used in climatological analyses such as this study. A third disadvantage is the subjectivity in the process used to identify convective systems. The lack of an accepted objective method, the larger size of the systems of interest, the limited study period, and the detailed monitoring of system behavior were the reasons a subjective method was chosen. However, biases can be introduced through subjective analysis that can affect the results. An automated method is highly recommended for future convective system analysis, not only to avoid subjective biases, but also because the visual identification and tracking of systems for even one summer season proved to be time consuming. Automated procedures would also allow for the analysis of extended study periods to be more easily undertaken.

The aggregation levels of the study design may have masked important and interesting finer scale patterns. The regional and temporal divisions used in the convective system analyses were chosen primarily to facilitate comparisons between this study and the earlier work of Patterson *et al.* (1995). By choosing relatively coarse spatial and temporal resolutions important information was possibly overlooked. Using two- or three-hour time periods would have provided both interesting and valuable insights into the origin and termination of convection as very different convective mechanisms can potentially occur within the six-hourly time periods. In addition, latitudinal (north-south) divisions would have provided the opportunity to investigate the meridional movement of convection within the study area, which was considerable based on the large number of systems that exited across the northern and southern study boundaries. Objective techniques, such as statistical cluster analysis, to group systems by time and location of system formation and termination would have also provided valuable insights into the finer-scale spatial and diurnal variation of these convective characteristics. In addition, this study did not directly investigate the mechanisms responsible for nocturnal convection but rather inferred them from the climatological characteristics of the convective systems. Supplemental climatological information such as surface and upper-level synoptic conditions would allow for the identification of LLJs and other synoptic-scale forcing mechanisms for nocturnal convection. RCM simulations for particular regions within the study area could also be used to identify the existence of LLJs and better understand the physical processes leading to the formation of convection. The limitations of the data and research design imposed a number of constraints on the interpretation of the analyses; however, valuable insights were gained into the characteristics of convection within the north-central United States. In addition, the findings of this study point to the importance of further research on the mechanisms of nocturnal convection within this region as well as the influence of the Great Lakes on summertime convection.

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