Occurrence of Summertime Convective Precipitation and Mesoscale Convective Systems in Finland during 2000-2001

ARI-JUHANI PUNKKA

Finnish Meteorological Institute

Helsinki, Finland

MARJA BISTER

Division of Atmospheric Sciences, Department of Physical Sciences,

University of Helsinki, Finland

8 July 2004

Corresponding author:

Ari-Juhani Punkka

Finnish Meteorological Institute

P.O. Box 503

00101 Helsinki – Finland

[redacted]

Abstract

There are few if any studies of statistics of deep convection occurring in high latitude regions. In this study, the basic characteristics of convective precipitation and mesoscale convective systems (MCSs) in Finland and nearby regions have been investigated by using composite reflectivity data from seven operational C-band weather radars. The period of study covered summers 2000 and 2001 from the beginning of April to the end of September. During the study period, the fraction of days with convective precipitation (with reflectivity exceeding 40 dBZ) occurring anywhere in the study region was 88% and the fraction of days with heavy convective precipitation (with reflectivity exceeding 50 dBZ) was 61%.

MCS was defined by means of radar reflectivity as follows: a continuous area of stratiform precipitation (18-40 dBZ), with long axis of 100 km or more in at least one direction, must exist for at least 4h, and during the lifetime of the system the maximum reflectivity must exceed 40 dBZ during at least two consecutive hours. All precipitation features that met these criteria were considered MCSs whether they occurred in extratropical cyclones or not. MCS was qualified as intense if the maximum reflectivity exceeded 50 dBZ during at least two consecutive hours. The total amount of MCSs observed in the study region was 341 out of which 32% were intense. Over 50% of all intense MCSs occurred in July when the majority of systems travelled along south-north or southeast-northwest oriented paths. For instance, in July 2001 34 intense MCSs developed in the study region. The majority of intense systems arrived in the region of study from a channel outlined by the Sarema and the Karelian Isthmus.

The average duration of all MCSs was 11.1h with a monthly minimum of 9h occurring in July. Generally, the intense and midsummer MCSs were clearly modulated by

the diurnal heating/cooling cycle whereas the non-intense and springtime systems were less dependent on the time of the day.

1. Introduction

Research of weather phenomena at high latitudes has mainly focused on the synoptic scale disturbances which undoubtedly play the most important role in wintertime weather. However, summertime mesoscale convective phenomena in Finland have been observed to cause significant damage.

Little is known about the statistics, formation mechanisms and characteristics of MCSs in Scandinavia. In Western Europe the most typical synoptic situation causing severe thunderstorms is the so called Spanish plume (Browning and Hill 1984, McCallum and Waters 1993, Young 1995, Gray and Marshall 1998, van Delden 1998). A tongue of warm and moist boundary layer air flows northward from Spain and the Mediterranean Sea in front of an approaching upper level trough. Usually, the boundary layer air is capped by an elevated inversion creating “the loaded gun” situation. In this situation a strong MCS (or two) may develop over France and the United Kingdom. In Finland, forecasting experience has shown that a situation conducive to MCS development occurs when a warm moist air mass flows into the region from the south or southeast under the influence of an upper level trough. These conditions have some similarities to the Spanish plume.

The goal of this study is to gather statistics of MCSs over Finland and its surroundings. Mesoscale convective systems have typically been identified by using satellite or radar imagery. Many of the satellite imagery studies (Maddox 1980, Augustine and Howard 1991, Laing and Fritsch 1997, Anderson and Arritt 1998, Laing and Fritsch 2000) have focused on the most extensive MCSs which are classified as mesoscale convective complexes (MCCs, Maddox 1980). The cold anvil cloud of an MCC may be as large as hundreds of thousands of square kilometers and the convective complex may survive for over 24h (Maddox 1980). It is obvious that the use of satellite imagery to examine the details and intensities of precipitation structures within MCSs can be very challenging. On the other hand, due to the long lifetimes and paths of MCSs, the use of imagery from a single radar can lead to under sampling. To overcome these problems, we have chosen to use time lapse composite radar reflectivity in this study.

Even though there are a large number of case studies of MCSs using radar data (Ogura and Liou 1980, Knupp and Cotton 1987, Smull and Houze 1985, Smull and Houze 1987, Johnson and Hamilton 1988, Grady and Verlinde 1997, Knupp et al. 1998a-b), there are few statistical studies on the frequencies of occurrence of MCSs (including non-severe cases) using such data. The only study the authors are aware of is the work of Geerts (1998) where he reviewed MCS activity over the southeastern U.S. Bluestein and Jain (1985) studied an 11-year period of radar data but their study focused on springtime severe squall lines out of the whole MCS population. Hilgendorf and Johnson (1998) studied only those MCSs exhibiting a classical leading line – trailing stratiform region structure. Houze et al. (1990) studied *major* rain events during springtimes 1977-1982 with the aid of reflectivity and precipitation data.

We have chosen to adopt the methods (to be discussed in section 2) used by Geerts (1998) to ease the comparison between MCS statistics over geographically diverse regions. However, it is important to note the following differences between this study and the review of southeastern U.S. MCSs conducted by Geerts (1998). First, the area of our study region was between 73% and 88% of the area used in the Geerts study. The first ratio of the areas applies for year 2000 and the second for year 2001 as our study region was larger for 2001. Therefore, more MCSs could be expected to occur in the larger study region of Geerts. Second, Geerts examined MCSs occurring during the course of one year whereas our study covered two six month periods in two different years. Finally, and perhaps most significantly, the Geerts study area was located between 30ºN and 40ºN, whereas our study reviewed MCS activity in the area bounded by 60ºN and 70ºN.

The definition of an MCS depends on the data source. Houze (1993) defined an MCS to be a cloud system with thunderstorms and a contiguous precipitation area and a horizontal extent of at least 100 km in any direction. If composite reflectivity data are used, this definition must be modified as thunderstorms cannot be directly detected with radar. In this study we accepted a slightly modified version of the MCS definition used by Geerts (1998). This definition is based on radar reflectivities and will be discussed in section 2.

Geerts (1998) found that the average duration of the 398 MCSs studied in the southeastern U.S. was 9h. In this study the total number and average duration of MCSs were 341 and 11.1h, respectively. In the southeastern U.S. during summertime, MCSs tended to be rather short-lived and small in extent whereas in the wintertime, longer-lasting and large systems were more common. Summertime MCSs were clearly modulated by the diurnal cycle but wintertime cases were driven by synoptic forcing and hence, were not strongly dependent on the time of day. As will be discussed in section 4, our results of MCSs over Finland were qualitatively similar regarding differences between summertime and non-summertime MCSs.

In the following section, data and terminology are presented. The frequency of convective precipitation in Finland is discussed in section 3 and in section 4, the statistics of MCSs during April to September in 2000 and 2001 are presented. It must be emphasized that the results merely represent a two-year sample. Thus, any climatic conclusions are very preliminary.

2. Data and definitions

This study covered the two periods from the beginning of April to the end of September in 2000 and 2001. The study region, shown in Fig. 1, consisted of a network of seven operational C-band weather radars, of which six were Gematronik Meteor 360AC radars and one was a Meteor 500AC radar. The systems were provided with signal processors (RVP6 or RVP7) and radar software (IRIS) from Sigmet Inc. Ground clutter was eliminated efficiently by applying Doppler filtering in signal processing. In summer 2000, the northernmost radar (Luosto) was not yet in operation and therefore, the northern boundary of the study region reached only southern Lapland (solid arc in Fig. 1). Thus, the total area of the study region was about 548 000 km^2 in summer 2000 and 663 000 km^2 in 2001.

Convection was studied using pseudo-CAPPI (constant altitude plan position indicator) composite reflectivity data of the radar network at the height of 500 m above the sea-level. The spatial resolution of the composite images was 1 x 1 km and the temporal resolution was 30 minutes. Since this survey did not focus on the evolution of single convective cells, the resolution of 30 minutes can be considered adequate. In the study of MCSs by Geerts (1998) the corresponding values were 2 x 2 km and 15 minutes.

The radar data covered 366 days and consisted of 17 568 radar images. There were a few missing images during year 2000 mainly due to telecommunication problems. Some of the missing images were recovered and the total fraction of missing data was 5.3%. Since missing images were not consecutive, they probably did not significantly affect MCS detection.

The reflectivity range was divided into 8 bins but the two lowest bins (those with values of reflectivity less than 17 dBZ) were neglected. Precipitation was labelled as *stratiform* if the reflectivity was between 18 and 40 dBZ and as *convective* if the reflectivity was over 40 dBZ. This definition is close to the ones used by Houze et al. (1990), Geerts (1998), Hilgendorf and Johnson (1998), and Parker and Johnson (2000). Furthermore, echoes exceeding 50 dBZ were labelled as *heavy convective precipitation*.

However, above-mentioned definitions may lead to problems when examining polar air mass convection which sometimes consists of well-defined cellular echoes that do not exceed 40 dBZ (J. Koistinen 2002, personal communication).

Bright banding in the melting layer may also cause problems. During summertime in Finland, the bright band is usually located 2-3 km AGL and the radar beam meets the bright band at the distance of 150-200 km from the radar. At these distances the radar beam is so wide (beam half width of about 3 km) that the bright band can only partially fill it and erroneously high dBZ values are somewhat compensated by dry snow above the bright band (J. Koistinen 2004, personal communication). Moreover, at the distances of 175-250 km from radar the beam volume is completely above the melting layer, within snow which results in reflectivity underestimation.

During the spring and fall months when the freezing level is located lower, the bright banding problem is worse; especially within widespread nimbostratus precipitation where the maximum reflectivity is well below 40 dBZ (J. Koistinen 2004, personal communication). At small distances radar beam volume can entirely be filled by the bright band and result in reflectivity overestimation of up to 5-7 dBZ (J. Koistinen 2004, personal communication). Since the bright banding is mainly limited for reflectivity values of under 40 dBZ, it has probably only minor influence on the amount of convective precipitation and MCSs. This is also suggested by the results of Geerts (1998) which will be discussed shortly (the lowering of minimum dBZ threshold). The bright band can extend the MCS duration by couple of hours especially during spring and fall months if the precipitation area is located at the suitable distance from the radar. The total effect of the reflectivity overestimation due to bright banding and the above-mentioned underestimation due to radar measurement in the snow on the results remains unknown.

The definition of MCS was adopted from Geerts (1998) to make comparison of results easier. With a slight modification to his definition, an MCS is an area of precipitation which satisfies two criteria. *First, a continuous area of stratiform precipitation (18-40 dBZ), with long axis of 100 km or more in at least one direction, must exist for at least 4h. Second, during the lifetime of the system the maximum reflectivity must exceed 40 dBZ during at least two consecutive hours. Moreover, an MCS was qualified as intense if the maximum reflectivity exceeded 50 dBZ during at least two consecutive hours.* Note that according to this definition also systems within extratropical cyclones were considered as MCSs if they met these criteria.

The only change we made to the definition of Geerts' (1998) was the lowering of the threshold of stratiform precipitation from 20 dBZ to 18 dBZ. This was due to the original format of the composite reflectivity data (thresholds 18, 40 and 50 dBZ). Geerts (1998) studied the effect of lowering the threshold on the results. He found out that a decrease of the thresholds from 20 dBZ to 10 dBZ resulted in only 11 more MCSs to the total amount of 398 cases. Thus, the effect of a 2 dBZ decrease is probably minor.

It should be recalled that our MCS definition allows some rather weak precipitation areas to be labelled as MCSs. An example of this might be a cold front accompanied by a rain band, which looks non-cellular in the radar images and in which the maximum reflectivity barely exceeds 40 dBZ during two consecutive hours. Such cases were more common in spring and autumn than in midsummer. However, our MCS definition is almost the same as that used by Geerts (1998) and Houze (1993).

Since the study was carried out over a limited area, some MCSs were not completely tracked. An MCS might form beyond the radar range or it might propagate outside the range before decaying. Owing to the tracking problem, the *duration* of MCS was defined as follows: time that an MCS spends inside the study region. This means that either the total lifetime equals the duration or it is longer than the duration. The completely tracked systems were also examined separately to find out the effect of this problem on the statistics.

Moreover, the 100 km condition for stratiform precipitation dictated the *time of initiation and decay* so that MCSs initiated at the moment when the condition was met for the first time. Correspondingly, MCSs decayed at the moment when the region of stratiform precipitation failed to meet the condition. The *time of maximum intensity* of MCS was defined to be the moment when the area of convective precipitation in MCS was largest. This was done subjectively by using reflectivity loops.

During the manual tracking process, information of each MCS was collected. This information included the time of initiation and decay, duration, time of maximum intensity, direction of propagation, and geographic location. Each MCS was also described qualitatively and significant echo features were subjectively determined (e.g. leading line/ trailing stratiform structure). Finally, the track of each MCS was drawn on a map. MCS tracks were subjectively identified according to the movement of the estimated midpoint of each system. MCS tracks might be prone to greater error in those cases where the MCS was not completely contained within the study region. Therefore, tracks near or on the edge of the study domain should be examined with caution.

An example of manual MCS tracking process is shown in Fig. 2. The case starts with scattered thunderstorms over Estonia (Fig. 2a) 60 minutes before the MCS initiation. During the following hour, convective cells form a southwest-northeast oriented line (Fig. 2b). At the same time, the long axis of the continuous area of stratiform precipitation exceeds 100 km and an MCS is initiated. The time of the maximum intensity is reached after 2.5h from the initiation and the maximum reflectivity has exceeded 40 dBZ (and 50 dBZ) for over 2h at this time (Fig. 2c). Four hours after the initiation, the long-axis of stratiform precipitation region still exceeds 100 km and the precipitation area is now qualified as an (intense) MCS (Fig. 2d). Shortly after, the system gradually weakens (Fig. 2e) and decays after 6h from the initiation (Fig. 2f).

3. Convective precipitation in Finland

The days during which the maximum reflectivity exceeded 40 or 50 dBZ were recorded. Even a single cell with the peak reflectivity exceeding 40 or 50 dBZ in the study region was sufficient to meet the convective precipitation definition. This method is unquestionably somewhat arbitrary. By extending the study region, the frequency of convective precipitation days will gradually converge to 100%. Nevertheless, the percentages are useful information for the weather forecasters in Finland and regions nearby.

During the study period, 322 out of 366 days (88%) were qualified as convective precipitation days. In 2000, the fraction was 83% and in 2001 it rose up to 93% which is in accordance with the larger study region in 2001 (Fig. 1). In April, May and September the monthly fraction ranged from 60% to 96%. From June to August, the monthly fraction of convective precipitation days turned out be 85-100% (not shown). The percentages clearly show that summertime convective precipitation is almost a daily phenomenon over the Finnish radar network.

The fraction of days with heavy convective precipitation was 58% in 2000 and 65% in 2001. The monthly fractions are presented in Fig. 3. In April, May, and September heavy convective precipitation occurred on about 35% to 50% of all days. From June to August the fraction exceeded 70% each month with the maximum of 92% in July. Although the exact nature and the extent of heavy convective precipitation were not considered, it is generally known that reflectivities of over 50 dBZ are associated with an increased threat of hail, downbursts, lightning, and even flash floods.

4. MCS statistics

a. Frequencies

During the two six-month periods, 341 mesoscale convective systems were observed. Out of these 151 systems occurred in April to September of 2000 and 190 systems in April to September of 2001. Again, the increase of the number is in accordance with the larger study region in 2001 but may also be due to more convective activity during 2001. Of all MCSs, 34% met the condition of intense system in 2000 and 32% in 2001.

The monthly distribution of MCSs is shown in Fig. 4. MCSs were most common in July. In April, May and September the number of MCSs was much lower. Figure 5 shows that the fraction of intense systems in Finland was highest in July (58%) and lowest in spring. In spite of a relatively small amount of MCSs in September, about 25% of the systems were intense. In April and May, snow cover and ground frost may still exist in many places and surface temperatures of the Baltic Sea are fairly low. Therefore, boundary layer temperatures and low-level moisture content are typically much lower in spring than in midsummer and early fall. Consequently the likelihood for heavy convective precipitation is smaller in spring than in midsummer and even fall. This probably explains the low fraction of intense MCSs in spring.

In comparison to the results of Geerts (1998), the monthly amounts of MCSs were typically larger in the southeastern U.S. than in Finland from April to June (not shown). This difference, however, became smaller in late summer. Part of the difference is explained by the different size of the study regions. Fig. 5 shows that there was also a large difference in the percentages of intense systems between Finland and the southeastern U.S. in early summer. This difference became smaller in July-September. It must be remembered that the study region of this study and the study region of Geerts (1998) have different climates. For example, in Finland there is not a moisture source nearby which would be comparable to the Gulf of Mexico.

As has been mentioned above, two six-month periods is not enough for drawing climatic conclusions. With the aid of lightning statistics, however, information of convective activity in relation to the long-term averages can be obtained. According to Tuomi (2000), the total lightning amounts in Finland in June and July 2000 were fairly close to the long-term average. The same was actually true for the whole year 2000. In July 2001, the long-term average was slightly exceeded but the overall lightning activity of year 2001 was only 71% of the average (Tuomi 2001). Assuming that the lightning amount and MCS activity correlate positively, the MCS activity during these two summers may not be very far from a long-term average.

b. Lifetimes and durations

According to the definition of an MCS applied in this study, the duration of the system should be at least 4h. The mean duration of all MCSs was 11.1h which is almost two hours longer than in the southeastern U.S. (Geerts 1998). It must be recalled that Geerts (1998) compiled statistics from a one-year period while in this study the two summer-halves of the year were surveyed. The 20% difference in the extent of the study regions may affect the duration in case of partially tracked systems. Longer mean duration over a smaller study region may be the result of long-lived, baroclinically fuelled systems during spring and fall months in Finland. As discussed earlier, also the bright banding effect within cool air masses in Finland can erroneously extend the MCS duration in some cases.

Fig. 6 presents a monthly distribution of MCS durations. In April, May and September the mean duration was over 12h in Finland. The relatively long duration in spring and fall was probably at least partly due to strong baroclinic activity. Many of the early summer and fall MCSs were presumably sustained by migratory synoptic disturbances.

In comparison to early summer, MCSs in July tended to be quite short-lived in Finland (Fig. 6). The mean duration of MCSs in July was only about 9h which might be explained by less baroclinic activity than in early summer. A clear distinction prevails between the southeastern U.S. and Finland when examining early summer durations. According to Fig. 6, the mean difference was 4-8h but decreased in mid- and late summer. Interestingly the shortest-lived MCSs seemed to occur a few months earlier in the southeastern U.S. than in Finland.

The frequency distribution of MCS durations is shown in Fig. 7. Most of the MCSs in Finland had durations of about 6h. This compares to about 5h for the southeastern U.S. MCSs studied by Geerts (1998). Longer MCS durations (over 10h) were more common in April-May-September than in June-July-August (Fig. 7). It is also noteworthy that durations over 20h were nearly absent in the southeastern United States during June-July-August (Geerts 1998) but in Finland a small percentage of systems survived over 20h.

The duration of an MCS appeared to be modulated more by season than intensity. The mean duration of intense MCSs was 10.7h, while non-intense MCSs lasted 11.4h on the average (not shown). The difference between durations of all MCSs in April-May-September and June-July-August was 2.5h, being longer in April-May-September.

c. Times of initiation, dissipation and maximum intensity

Owing to the limited study area, some MCSs initiated and/or decayed outside the study region. If an MCS formed outside the study region, the time of initiation was determined to be the time when the system arrived in the study region. Correspondingly, the time when a system left the study region, was considered as the dissipation time. In order to study the effect of this problem on the results, the fully tracked MCSs were also examined separately.

When considering all MCSs, the times of initiation were distributed rather evenly (Fig. 8). Minor peaks were observed at 7-10 and 19-24 UTC (the Finnish local time in summer can be calculated by adding three hours to the Coordinated Universal Time (UTC)). Investigation of fully tracked systems changed this result only in that the above-mentioned peaks were slightly stronger. The times of dissipation were also distributed smoothly with a minor peak at 16-18 UTC. In a distribution of fully tracked systems the corresponding peak was somewhat wider (16-20 UTC). In the southeastern U.S., a pronounced peak of MCS formation occurred just after midday with MCS dissipation most likely between 13-17 UTC. The diurnal variation in the southeastern U.S. was clearly stronger than in Finland. The lower dependence on the diurnal cycle in Finland than in the southeastern United States might be another effect of the presumed more important role of baroclinic disturbances in Finland than in the U.S. during the warm half of the year. The formation peak interestingly occurred a few hours earlier and the dissipation peak a few hours later in Finland than in the southeastern U.S. It is possible the earlier sunrise and later sunset in Finland could explain some of this difference.

If the intense MCSs are examined separately, the initiation peak becomes significantly stronger. Fig. 9 shows that the initiation peak is now from 11 to 15 UTC. The dissipation peak is centered on 17 UTC. As a summary, strong MCSs are more often initiated in the late afternoon than at other times of the day. Non-intense MCSs depend much less on the time of day.

The dependence of the duration on the time of the formation is presented in Fig. 10 for midsummer (June-July-August). It seems that the time of the initiation is a poor predictor of the MCS duration.

The time of maximum intensity was mostly reached 9-11, 13-17 or 3-6 UTC (not shown). It must be emphasized that none of these intervals dominated and the distribution was fairly even. Interesting information can be gained if the intense and non-intense MCSs are examined separately (Fig. 11). Relatively many of the intense systems achieved their maximum intensity in the afternoon or early evening (10-17 UTC). Two minor peaks occurred just after the midnight and in the morning. It is possible that they are associated with nocturnal cloud top cooling and destabilized lapse rates (Laing and Fritsch 1997). It is interesting that the afternoon peak correlates well with the peak time of lightning activity in Finland (T. Tuomi 2003, personal communication). For the non-intense MCSs, the distribution was more even with the afternoon peak being nearly absent but the morning maximum still existing. Results for the fully-tracked intense systems were similar to those for all intense systems.

It is known that convective activity often reaches its maximum intensity very soon after initiation. This feature can also be seen in Fig. 12. The majority of systems gained their maximum intensity within 6h from the formation. The time interval rarely exceeded 9h (about 10 cases) and the most common value was between one and four hours. However, there seemed to be a slight variation depending on the time of day. The systems that formed during afternoon (10-13 UTC) reached their maximum intensity within one to four hours. The MCSs that formed in the late evening or at night reached their maximum intensity often after six hours from the formation.

d. Paths

During the tracking process all MCSs were individually labelled. For each month a map was drawn with paths of all MCSs. It must be remembered that the determination of a path was solely dependent on the portion of the MCS which was inside the study region. Therefore, paths near the boundaries of the study region should be examined with caution. Only the main characteristics of each month are described in the following. Path maps of intense MCSs are shown and discussed in the end of this section.

In April, May and September, MCSs mostly traveled along southwest-northeast oriented paths. In midsummer, the main direction of arrival shifted to south and southeast. Especially in April and May many MCSs formed near the Finnish coastline. This may be an indication of contrast between cold SSTs and a partly snow-free ground. Moreover, coastal convergence may play a minor role. During mid- and late summer MCSs tended to travel farther and even initiate over relatively warm sea areas.

The examination of intense MCSs gives further valuable information. The paths of intense MCSs are presented in Fig. 13. No intense systems arrived from a sector between north-northwest and east. Usually intense systems traveled along southwest-northeast, south-north and southeast-northwest oriented paths and seemed to “avoid” the sea areas during spring and early summer. Furthermore, the season clearly affected the paths of intense MCSs. According to Fig. 13a, in April, May, August and September, intense systems traveled mainly over southern and central Finland. In the midsummer (Fig. 13b), the MCSs also reached northern Finland but even then they tended to avoid traveling over the widest sea areas (the Northern Baltic and the Gulf of Bothnia). The narrow Gulf of Finland did not seem to act as a hindrance for the intense MCSs. Maddox (1980), Fritsch et al. (1986), Augustine and Howard (1991) and Anderson and Arritt (1998) reported similar northward movement for mesoscale convective complexes in the United States during midsummer.

The locations of formation and decay of intense MCSs are presented in Fig. 14. Many of the intense MCSs came over Finland from a region between Sarema and the Karelian Isthmus. Inside the borders of Finland, the most typical area of formation of intense MCS extended from the southwestern Finland to the Northern Karelia.

5. Conclusions

The occurrence of convective precipitation and mesoscale convective systems (MCSs) in Finland was studied by analyzing composite radar images. All precipitation systems that met the radar reflectivity based criteria (section 2) were considered MCSs whether they occurred within extratropical cyclones or not. The data only covered two six-month periods (April to September) in 2000 and 2001. Therefore, the following climatic conclusions do not have a strong basis. The most essential results were:

- Convective precipitation, with radar reflectivities exceeding 40 dBZ, was a frequent phenomenon over the study region. The fraction of convective precipitation days was 88% and the fraction of heavy convective precipitation days with radar reflectivities exceeding 50 dBZ was 61% with the peak frequency of the latter occurring in July (92%).
- The total amount of MCSs observed in the study region was 341 out of which 133 MCSs were qualified as intense. MCSs were most frequent from June to July. Fifty-one percent of all MCSs observed during the two six-month periods occurred in June or July.
- In April, May, and September, anywhere from 5 to 30 MCSs were observed monthly but in June, July and August these numbers rose to between 20 and 60. When compared to the findings of Geerts (1998), MCS occurrence in Finland was nearly equal to that of the

southeastern U.S. from July to September. In spring, the amounts of MCSs were much larger in the southeastern U.S. than in Finland.

- The fraction of intense MCSs was only 0 to 10 percent in April and May. Percentages rose to between 25 and 60 percent in the June-to-September period. In July, over 50% of the systems were qualified as intense. Only in July, were these percentages close to those observed in the southeastern U.S. In other months, they were significantly smaller in Finland than in the southeastern U.S.
- The average duration of MCSs was 11.1h. In July, the mean duration was shortest (9h) and in April it was longest (13h). MCSs tended to live longer in Finland than in the southeastern U.S. This was the case especially in spring and may partially be the result of rather low freezing level height and the bright banding effect. In July the durations were nearly equal.
- Intense MCSs appeared to be modulated by the diurnal heating/cooling cycle with the most typical times of formation being from 9 to 15 UTC, with dissipation around 17 UTC. The non-intense MCSs showed weak diurnal modulation.
- In April, May, and September, MCSs traveled mostly along southwest-northeast directed paths. In midsummer, the main direction of arrival shifted to south and southeast.
- Intense MCSs reached northern Finland mainly during midsummer. The most common arrival channel of intense MCSs was outlined by Sarema and the Karelian Isthmus.
- Many of the results of this study suggested that MCSs associated with baroclinic disturbances may be common in Finland. This was especially true for the months of April, May, and September.

These results show that convective phenomena play an important role in the summertime weather in Finland. The comparisons to the findings of Geerts (1998) about MCSs in the southeastern U.S. showed that despite of the different climates, there were some similarities in the MCS characteristics. The amount of MCSs, the fraction of intense MCSs and mean duration were nearly equal in midsummer, especially in July.

It should be emphasized that the definition of an MCS applied in this study allowed some fairly weak precipitation areas to be qualified as MCSs. On the other hand, the aim of this work was not to study severe cases only but to *objectively* gather general information on mesoscale convective precipitation areas in Finland.

These preliminary results should be verified by further surveying composite reflectivity data over a larger number of years. This would allow a more reliable comparison of high and mid-latitude convection statistics.

Acknowledgments. The authors wish to thank Jarmo Koistinen for giving some helpful comments, Harri Hohti for helping in the recovering of missing radar data and Tapio Tuomi for providing lightning statistics.

References

Anderson, C. J., R. W. Arritt, 1998: Mesoscale convective complexes and persistent elongated convective systems over the United States during 1992 and 1993. *Mon. Wea. Rev.*, **126**, 578-599.

Augustine, J. A., K. W. Howard, 1991: Mesoscale convective complexes over the United States during 1986 and 1987. *Mon. Wea. Rev.*, **119**, 1575-1589.

Bluestein, H. B., M. H. Jain, 1985: Formation of mesoscale lines of precipitation: severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.*, **42**, 1711-1732.

Browning, K. A., F. F. Hill, 1984: Structure and evolution of a mesoscale convective system near the British Isles. *Quart. J. Roy. Meteor. Soc.*, **110**, 897-913.

van Delden, A., 1998: The synoptic setting of a thundery low and associated prefrontal squall line in western Europe. *Meteorol. Atmos. Phys.*, **65**, 113-131.

Fritsch J. M., R. J. Kane, C. R. Chelius, 1986: The contribution of mesoscale weather systems to the warm-season precipitation in the United States. *J. Climate Appl. Meteor*., **25**, 1333-1345.

Geerts, B., 1998: Mesoscale convective systems in the southeast United States during 1994-95: A survey. *Wea. Forecasting*, **13**, 860-869.

Grady, R. L., J. Verlinde, 1997: Triple-doppler analysis of a discretely propagating, long-lived, high plains squall line. *J. Atmos. Sci.*, **54**, 2729-2748.

Gray, M. E. B., C. Marshall, 1998: Mesoscale convective systems over the UK, 1981-97. *Weather*, **53**, 388-396.

Hilgendorf, E. R., R. H. Johnson, 1998: A study of the evolution of mesoscale convective systems using WSR-88D data. *Wea. Forecasting*, **13**, 437-452.

Houze, R. A., B. F. Smull, P. Dodge, 1990: Mesoscale organization of springtime rainstorms in Oklahoma. *Mon. Wea. Rev.*, **118**, 613-654.

Houze, R. A., 1993: *Cloud dynamics*. International geophysics series, volume 63, Academic Press, 557 pp.

Johnson, R. H., P. J. Hamilton, 1988: The relationship of surface pressure features to the precipitation and airflow structure of an intense midlatitude squall line. *Mon. Wea. Rev.*, **116**, 1444-1472.

Laing, A. G., J. M. Fritsch, 1997: The global population of mesoscale convective complexes. *Quart. J. Roy. Meteor. Soc.*, **123**, 389-405.

Laing, A. G., J. M. Fritsch, 2000: The large-scale environment of the global population of mesoscale convective complexes. *Mon. Wea. Rev..*, **128**, 2756-2776.

Knupp, K. R., W. R. Cotton, 1987: Internal structure of a small convective system. *Mon. Wea. Rev.*, **115**, 629-645.

Knupp, K. R., B. Geerts, S. J. Goodman, 1998a: Analysis of a small, vigorous mesoscale convective system in a low-shear environment. Part I: Formation, radar echo structure, and lightning behaviour. *Mon. Wea. Rev.*, **126**, 1812-1836.

Knupp, K. R., B. Geerts, S. J. Goodman, 1998b: Analysis of a small, vigorous mesoscale convective system in a low-shear environment. Part II: Evolution of the stratiform precipitation and mesoscale flows. *Mon. Wea. Rev.*, **126**, 1837-1858.

Maddox, R. A., 1980: Mesoscale convective complex. *Bull. Amer. Meteor. Soc.*, **61**, 1374-1387.

McCallum, E., A. J. Waters, 1993: Severe thunderstorms over south-east England, 20/21 July 1992: Satellite and radar perspective of a mesoscale convective system. *Weather*, **48**, 198-208.

Ogura, Y., M. T. Liou, 1980: The structure of a midlatitude squall line: a case study. *J. Atmos. Sci.*, **37**, 553-567.

Parker, M. D., R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.*, **128**, 3413-3436.

Smull, B. F., R. A. Houze Jr., 1985: A midlatitude squall line with a trailing region of stratiform rain: Radar and satellite observations. *Mon. Wea. Rev.*, **113**, 117-133.

Smull, B. F., R. A. Houze Jr., 1987: Dual-doppler radar analysis of a midlatitude squall line with a trailing region of stratiform rain. *J. Atmos. Sci.,* **44**, 2128-2148.

Tuomi, T. J., 2000: Lightning observations 2000. *Geofysikaalisia julkaisuja 51,* Finnish Meteorological Institute, Helsinki, 44 pp.

Tuomi, T. J., 2001: Lightning observations 2001. *Geofysikaalisia julkaisuja 55,* Finnish Meteorological Institute, Helsinki, 41 pp.

Young, M. V., 1995: Severe thunderstorms over south-east England on 24 June 1994: A forecasting perspective. *Weather*, **50**, 250-256.

Figure captions

FIG. 1. The area of study (light shading) and operational weather radars (white and black boxes). The Arctic Circle marked by a dashed line and the northern boundary of study region in 2000 by a solid arc. Geographic locations: GB = Gulf of Bothnia, GF = Gulf of Finland, KI = Karelian Isthmus, NB = Northern Baltic, NK = Northern Karelia and S = The Sarema.

FIG. 2. An example of radar picture analysis. (a) Scattered thunderstorms over Estonia 60 min before the MCS initiation. (b) MCS initiation. The long axis of stratiform precipitation region exceeds 100 km. (c) Time of maximum intensity. The maximum reflectivity has exceeded 40 dBZ (and 50 dBZ) for over 2h (condition 2).(d) Stratiform precipitation region has lasted for 4h (condition 1). (e) MCS weakens and (f) after 6h, the long axis of continuous area of stratiform precipitation does not anymore exceed 100 km (time of decay).

FIG. 3. Fraction of heavy convective precipitation days in Finland in 2000-2001.

FIG. 4. Summarized MCS frequencies in Finland in 2000-2001.

FIG. 5. Fraction of intense MCSs in Finland in 2000-2001 and in the southeastern United States (Geerts 1998).

FIG. 6. Mean duration of MCSs in Finland in 2000-2001 and in the southeastern United States (Geerts 1998).

FIG. 7. Distribution of MCS durations in Finland in 2000-2001.

FIG. 8. Time of initiation and dissipation of all MCSs in Finland in 2000-2001.

FIG. 9. Time of initiation and dissipation of intense MCSs in Finland in 2000-2001.

FIG. 10. Dependence of MCS duration on the time of initiation in Finland in June-July-August 2000-2001. Each box represents one MCS.

FIG. 11. Time of maximum intensity for the intense and non-intense MCSs in Finland in 2000-2001.

FIG. 12. Dependence of maximum intensity on the time of initiation in Finland in 2000-2001. Each black box represents one MCS.

FIG. 13. The paths of intense MCSs in Finland in 2000-2001 (a) for April, May, August and September (b) for July. Asterisk (double arrowhead) denotes that a system has formed (decayed) beyond the radar range. Correspondingly, black dot (plain arrowhead) denotes that a system has formed (decayed) within the radar range. Month of occurrence is marked by a number close to the arrowhead (4 = April, 5 = May etc.).

FIG. 14. Start and end points of paths of intense MCSs in Finland in 2000-2001. Asterisks, dots and arrowheads are marked as in Fig. 13.

FIG. 1. The area of study (light shading) and operational weather radars (white and black boxes). The Arctic Circle marked by a dashed line and the northern boundary of study region in 2000 by a solid arc. Geographic locations: GB = Gulf of Bothnia, GF = Gulf of Finland, KI = Karelian Isthmus, NB = Northern Baltic, NK = Northern Karelia and S = The Sarema.

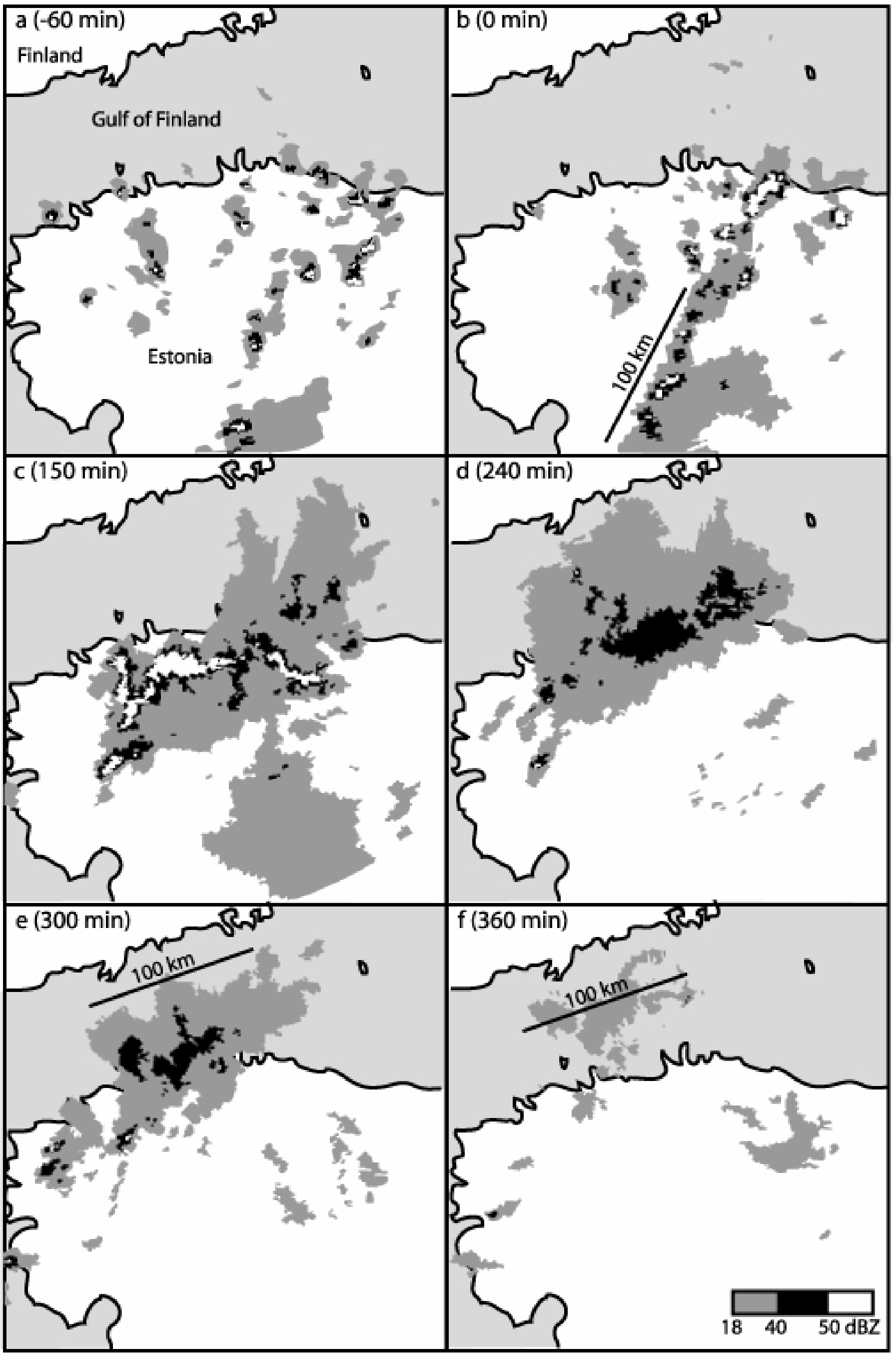

FIG. 2. An example of radar picture analysis. (a) Scattered thunderstorms over Estonia 60 min before the MCS initiation. (b) MCS initiation. The long axis of stratiform precipitation region exceeds 100 km. (c) Time of maximum intensity. The maximum reflectivity has exceeded 40 dBZ (and 50 dBZ) for over 2h (condition 2).(d) Stratiform precipitation region has lasted for 4h (condition 1). (e) MCS weakens and (f) after 6h, the long axis of continuous area of stratiform precipitation does not anymore exceed 100 km (time of decay).

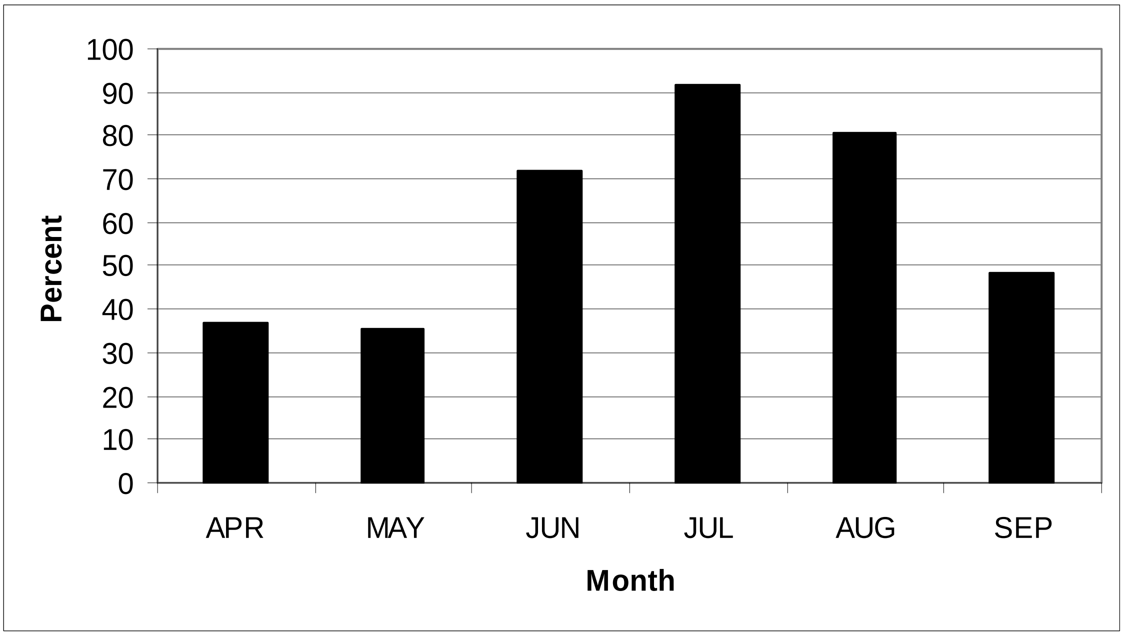

FIG. 3. Fraction of heavy convective precipitation days in Finland in 2000-2001.

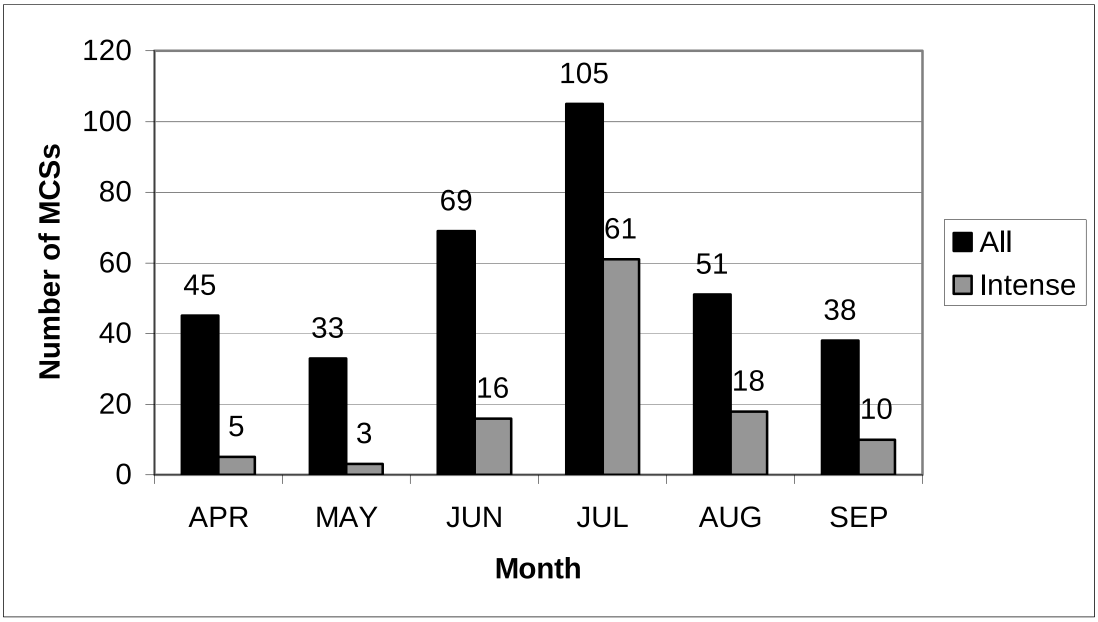

FIG. 4. Summarized MCS frequencies in Finland in 2000-2001.

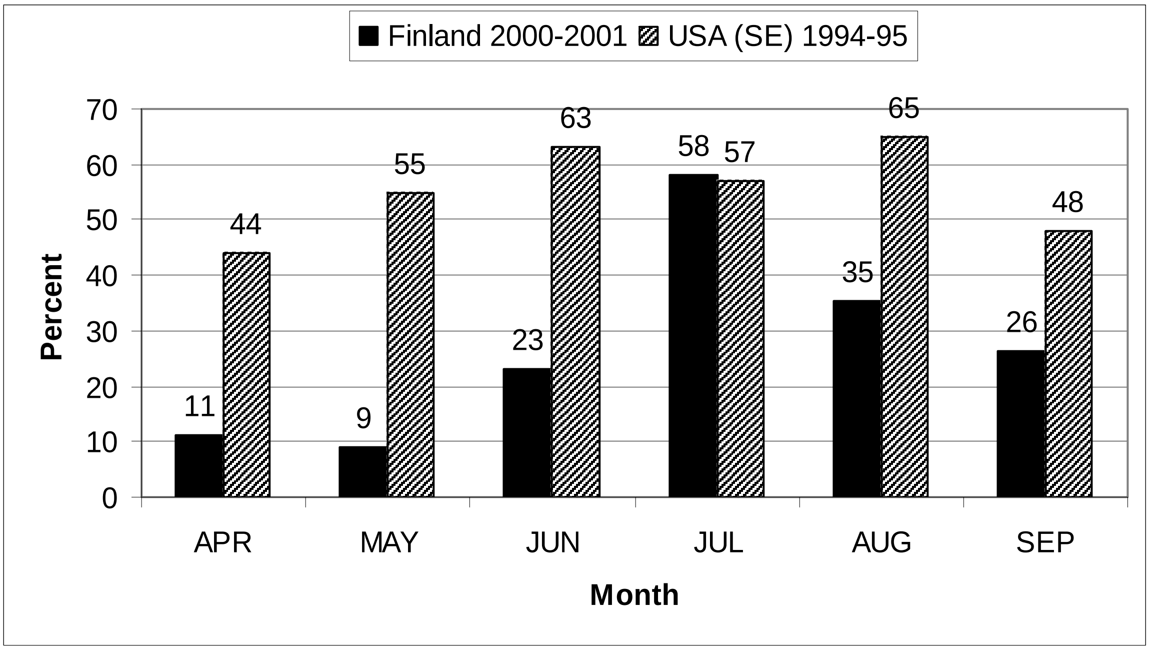

FIG. 5. Fraction of intense MCSs in Finland in 2000-2001 and in the southeastern United States (Geerts 1998).

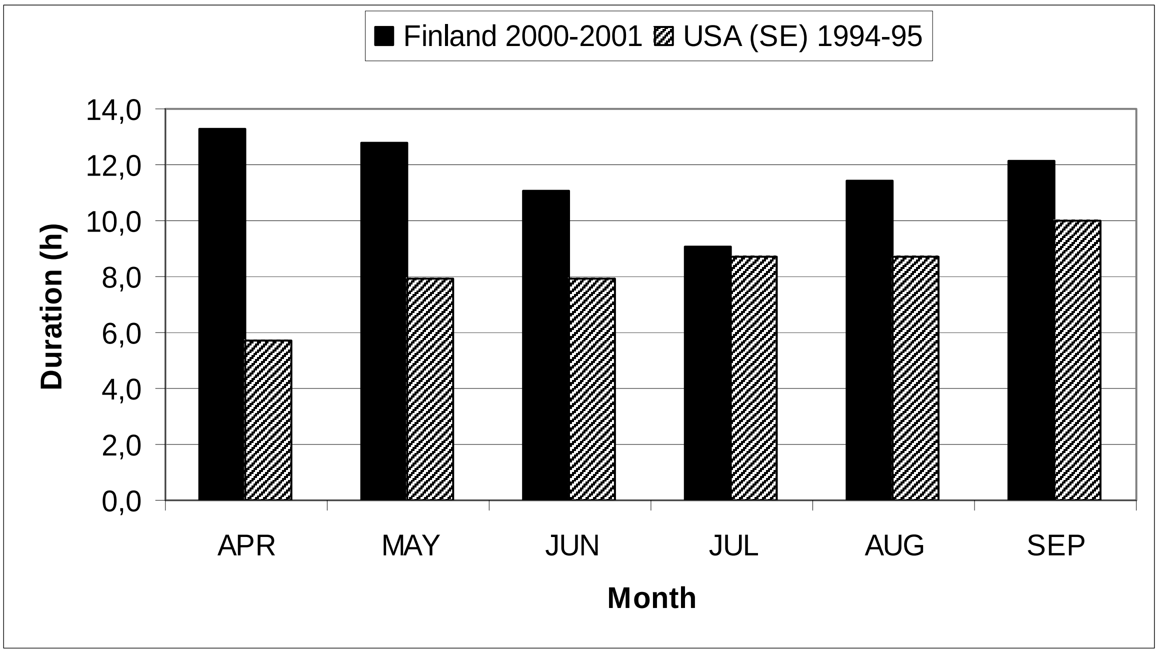

FIG. 6. Mean duration of MCSs in Finland in 2000-2001 and in the southeastern United States (Geerts 1998).

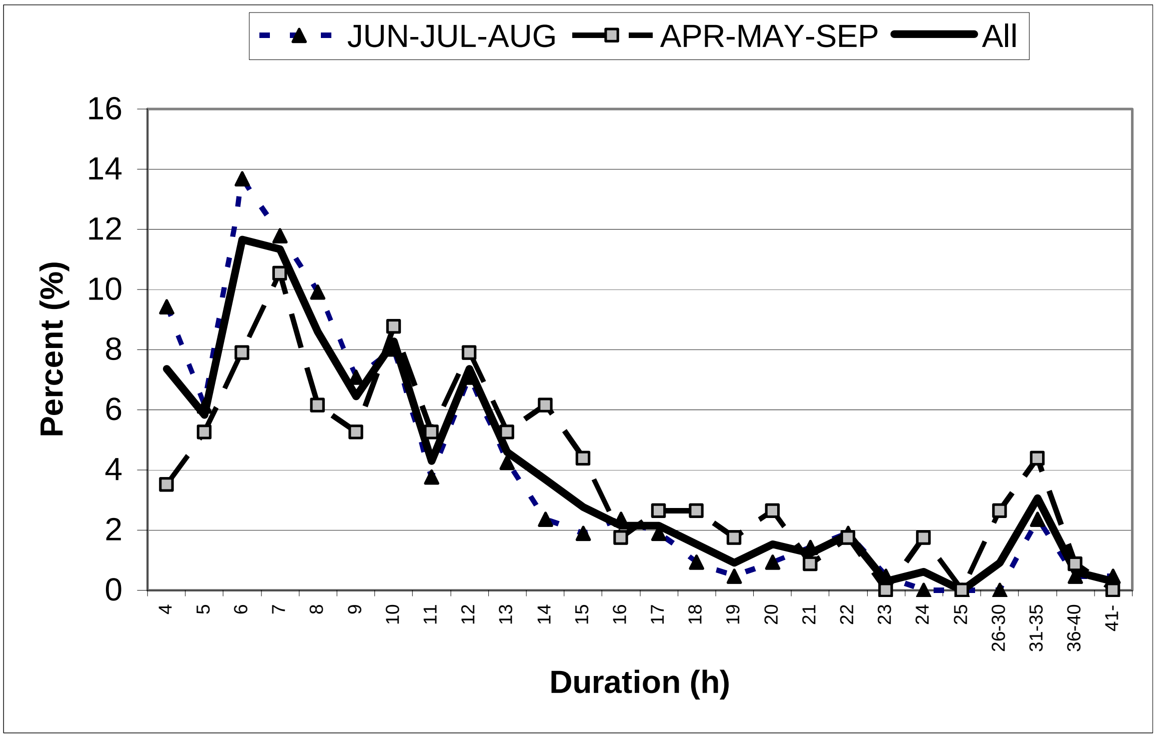

FIG. 7. Distribution of MCS durations in Finland in 2000-2001.

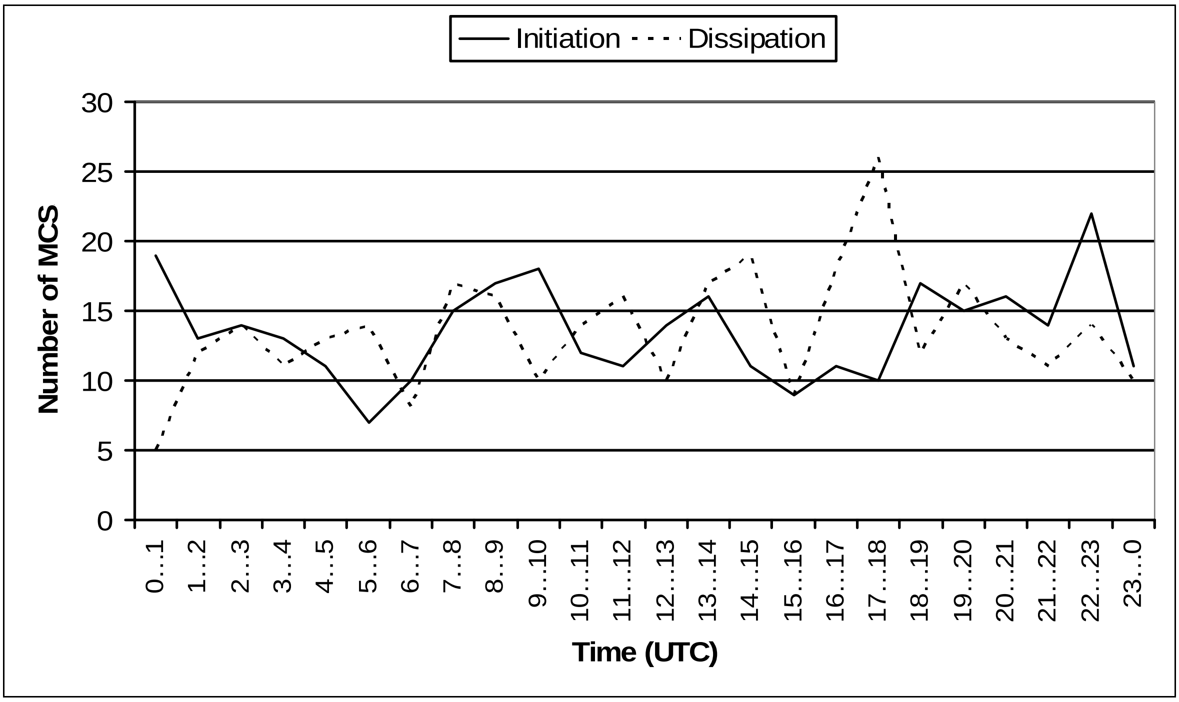

FIG. 8. Time of initiation and dissipation of all MCSs in Finland in 2000-2001.

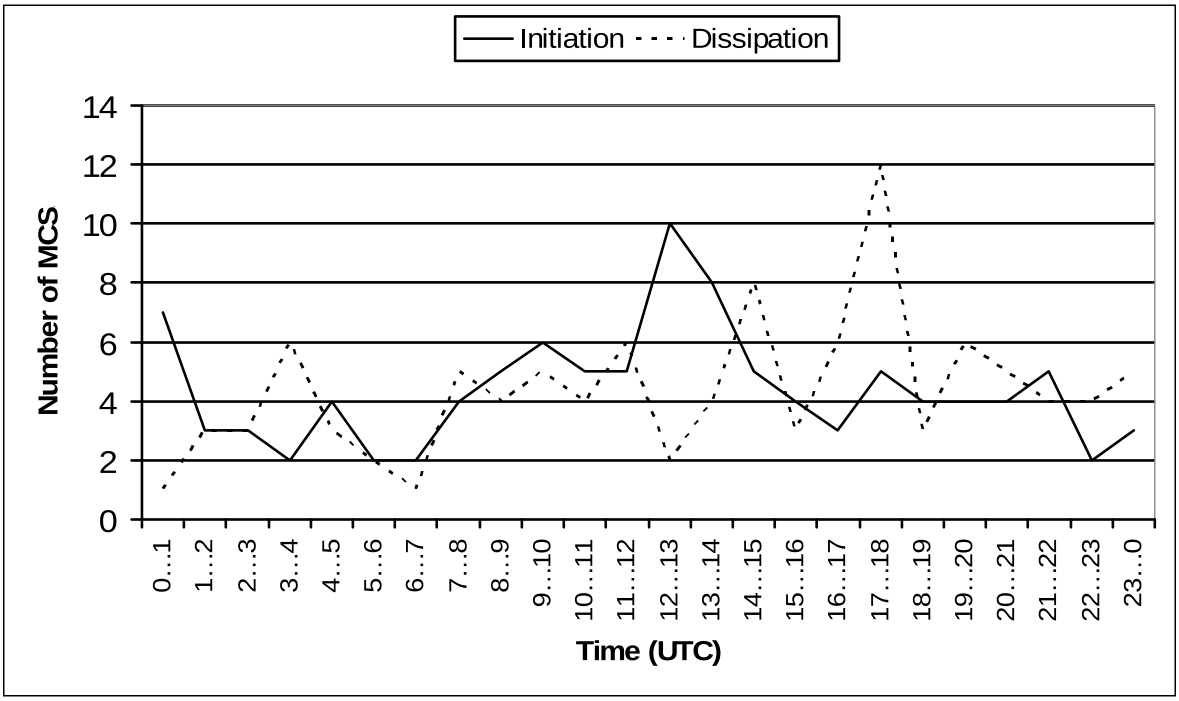

FIG. 9. Time of initiation and dissipation of intense MCSs in Finland in 2000-2001.

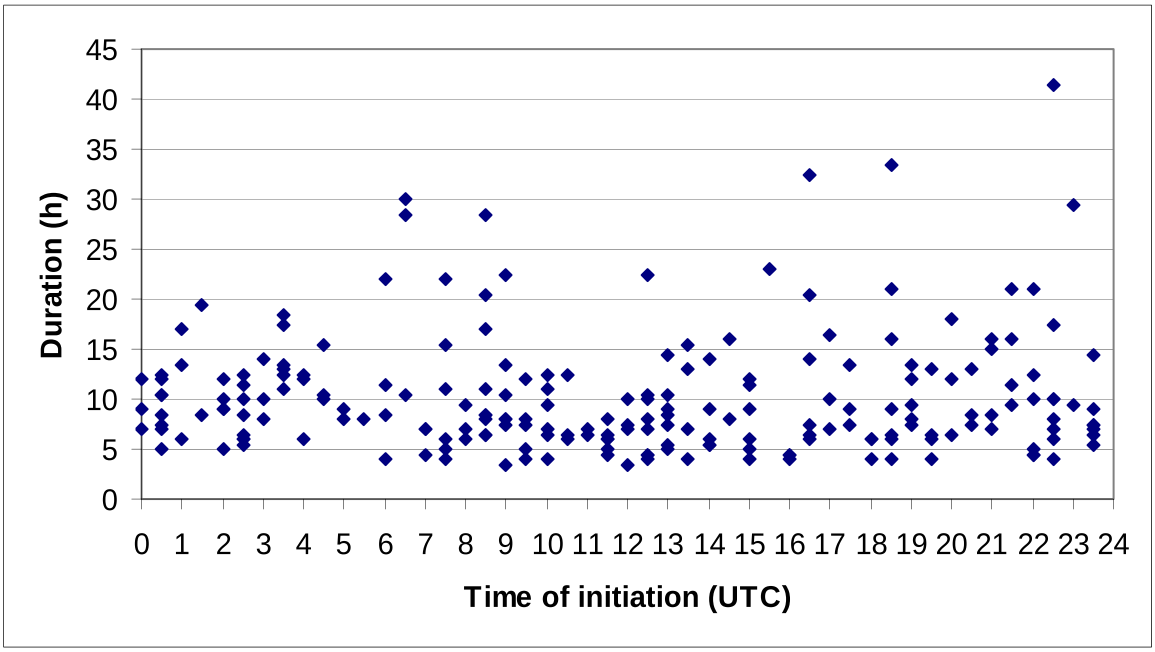

FIG. 10. Dependence of MCS duration on the time of initiation in Finland in June-July-August 2000-2001. Each box represents one MCS.

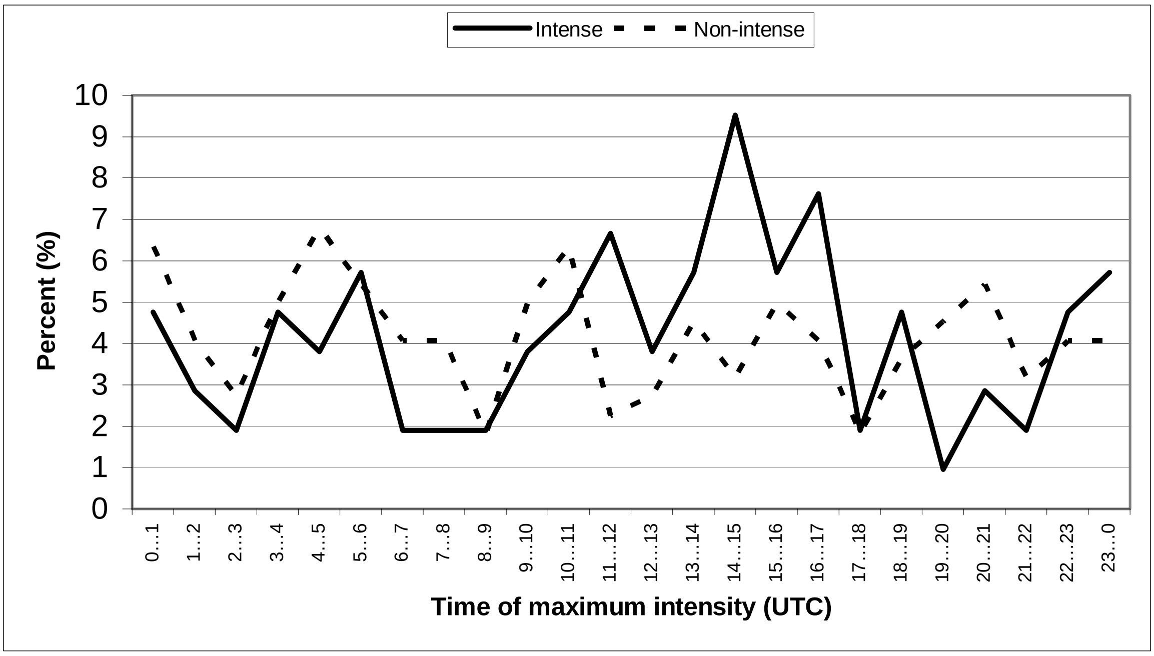

FIG. 11. Time of maximum intensity for the intense and non-intense MCSs in Finland in 2000-2001.

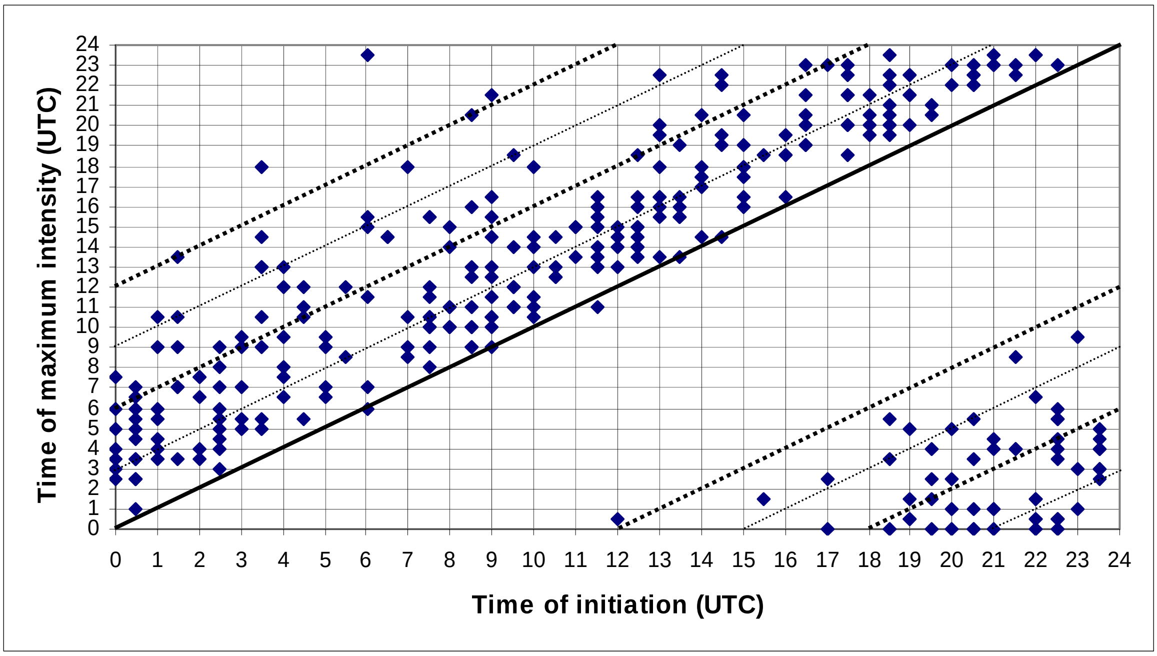

FIG. 12. Dependence of maximum intensity on the time of initiation in Finland in 2000-2001. Each black box represents one MCS.

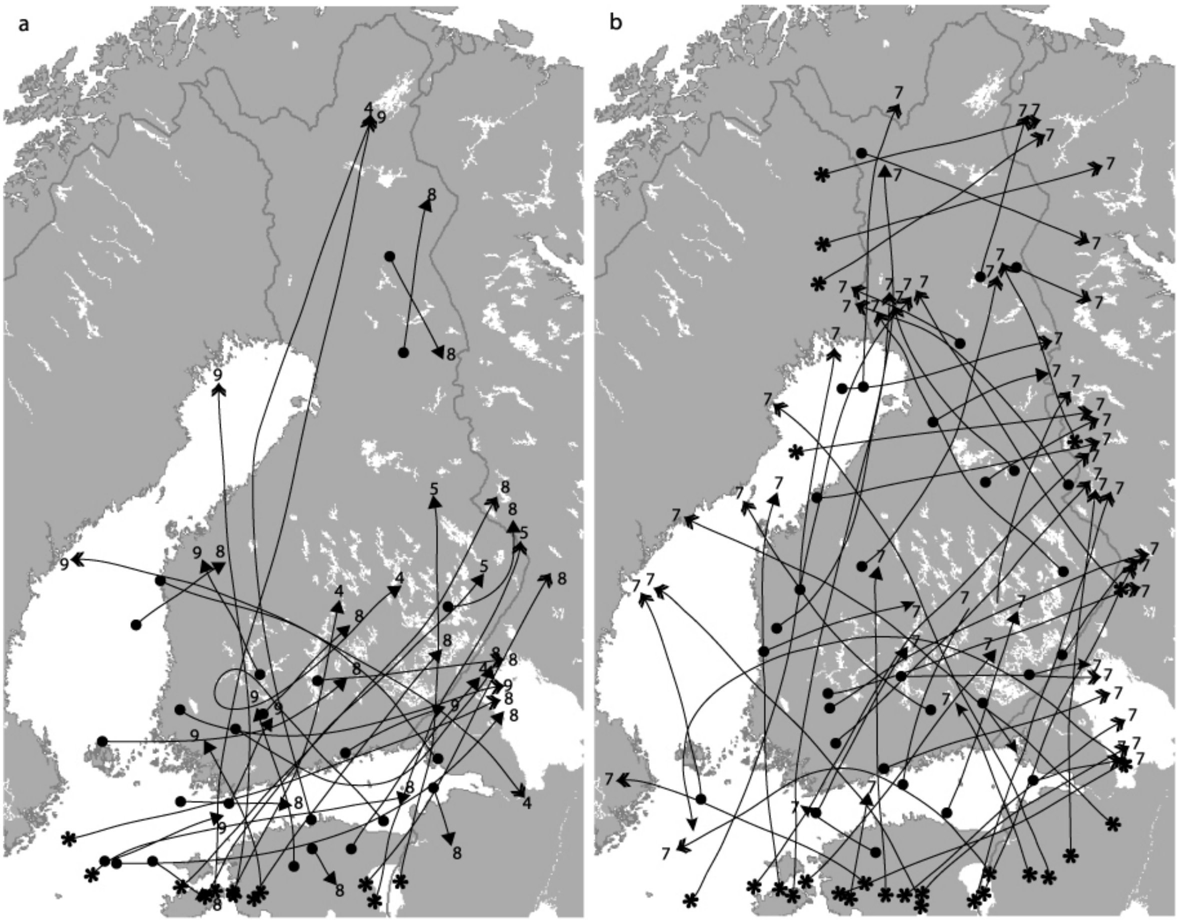

FIG. 13. The paths of intense MCSs in Finland in 2000-2001 (a) for April, May, August and September (b) for July. Asterisk (double arrowhead) denotes that a system has formed (decayed) beyond the radar range. Correspondingly, black dot (plain arrowhead) denotes that a system has formed (decayed) within the radar range. Month of occurrence is marked by a number close to the arrowhead (4 = April, 5 = May etc.).

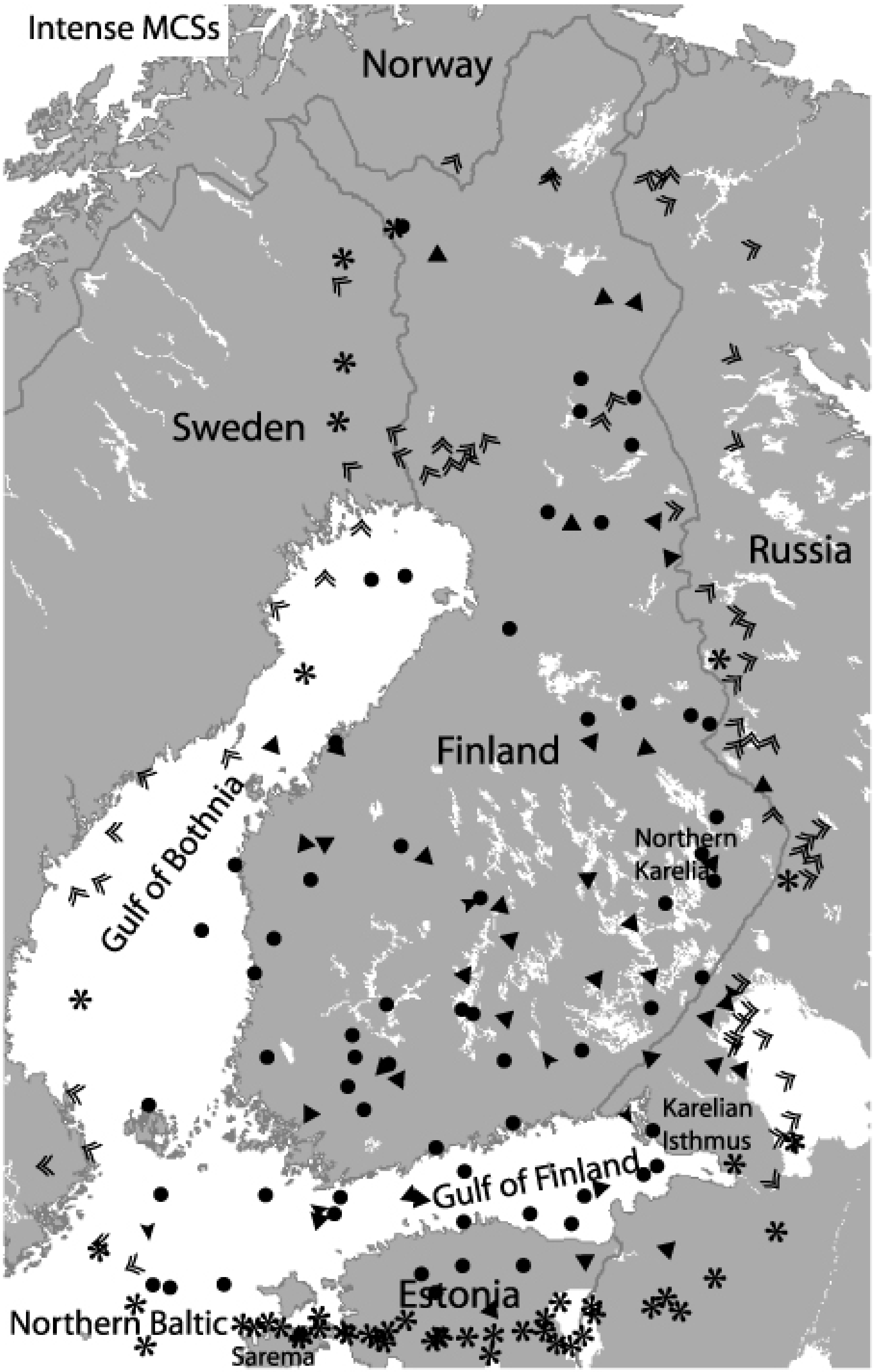

FIG. 14. Start and end points of paths of intense MCSs in Finland in 2000-2001. Asterisks, dots and arrowheads are marked as in Fig. 13.