Mesoscale Convective Systems and Their Synoptic-Scale Environment in Finland

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ABSTRACT

The environments within which high-latitude intense and nonintense mesoscale convective systems (iMCSs and niMCSs) and smaller thunderstorm clusters (sub-MCSs) develop were studied using proximity soundings. MCS statistics covering 8 years were created by analyzing composite radar imagery. One-third of all systems were intense in Finland and the frequency of MCSs was highest in July. On average, MCSs had a duration of 10.8 h and traveled toward the northeast. Many of the linear MCSs had a southwest–northeast line orientation. Interestingly, a few MCSs were observed to travel toward the west, which is a geographically specific feature of the MCS characteristics. The midlevel lapse rate failed to distinguish the environments of the different event types from each other. However, in MCSs, CAPE and the low-level mixing ratio were higher, the deep-layer-mean wind was stronger, and the lifting condensation level (LCL) was lower than in sub-MCSs. CAPE, low-level mixing ratio, and LCL height were the best discriminators between iMCSs and niMCSs. The mean wind over deep layers distinguished the severe wind–producing events from the nonsevere events better than did the vertical equivalent potential temperature difference or the wind shear in shallow layers. No evidence was found to support the hypothesis that dry air at low- and midlevels would increase the likelihood of severe convective winds. Instead, abundant low- and midlevel moisture was present during both iMCS cases and significant wind events. These results emphasize the pronounced role of low- and midlevel moisture on the longevity and intensity of deep moist convection in low-CAPE environments.

1. Introduction

Numerous recent investigations on European mesoscale convective systems (MCSs) have shown that organized deep moist convection is a frequent phenomenon over the whole continent (e.g., Morel and Senesi 2002; García-Herrera et al. 2005; Lewis and Gray 2010). Occasionally, severe and devastating forms of MCSs, such as derechos, occur in Europe (Gatzen 2004; Punkka et al. 2006; Gatzen et al. 2011; Hamid 2012; Törmä et al. 2013). In Finland, the total volume of fallen trees during the 2002 derecho was $1 \times 10^6$ m$^3$ (Punkka et al. 2006). In late July and early August 2010, 8 years later, an unusual series of severe MCSs, including two confirmed derechos hit Finland. About $8 \times 10^6$ m$^3$ of trees were fallen and 35 000 km of power lines were damaged (Safety Investigation Authority 2010). From a weather forecaster’s point of view, severe MCSs are a significant challenge due to their infrequent occurrence in Finland. Severe MCSs are not a part of the daily forecasting routine for duty forecasters. Thus, forecasters need to learn from previous events and, based on this knowledge, attempt to issue correct forecasts when a real situation takes place.

MCS studies conducted in the United States offer irreplaceable information for researchers and weather forecasters in Europe. In addition, the ingredients for deep moist convection (Doswell et al. 1996) remain the same regardless of geographic location. However, earlier studies have shown that every geographic area has its own special characteristics that can only be identified by conducting area-specific studies. First, Brooks (2009) showed that the probability of severe weather occurring is different for the United States and Europe when similar values of convective available potential energy
(CAPE) and deep-layer wind shear are present. Second, the synoptic-scale patterns that are conducive for the formation of MCSs vary from area to area. This can lead to differences in the average direction of MCS movement (Punkka and Bister 2005; Lewis and Gray 2010; Parker and Johnson 2000; Coniglio and Stensrud 2004). Third, most MCS studies have been conducted in environments with high average CAPE values. James and Markowski (2010) showed that dry air above the cloud base may decrease the downdraft and cold pool intensity in a low-CAPE environment. These results encourage conducting area-specific MCS studies in Finland and other areas.

While most MCS studies are based on satellite data (e.g., Maddox 1980), the precipitation structures below cold cirrus clouds can only be studied with the aid of radar reflectivity data. Therefore, the scarcity of European radar data–based MCS studies is surprising. Most studies only have data from one or two Doppler radars (e.g., Schiesser et al. 1995; Hagen et al. 2000; Rigo and Llasat 2007; Davini et al. 2011; Goudenhoofdt and Delobbe 2012), which ultimately hinders the tracking of convective systems and increases the number of partly tracked MCSs. The only studies that utilize data from more than two radars and that the authors are aware of are Punkka and Bister (2005) and Walther and Bennartz (2006). Punkka and Bister (2005) studied the occurrence of MCSs in Finland and nearby regions by utilizing data from seven radars. Walther and Bennartz (2006) used data from the Advanced Weather Radar Network for the Baltic Sea Region (BALTRAD; Michelson et al. 2010), which includes numerous individual radars. However, as the main focus of their study was the occurrence of stratiform and convective precipitation over the Baltic Sea region, they did not consider MCSs. One potential reason for the scarcity of radar-based European MCS studies might be the difficulties encountered in cross-border radar data exchange.

In the United States, MCS research has advanced from climatological (e.g., Maddox 1980; Bluestein and Jain 1985; Bluestein et al. 1987; Geerts 1998) and structural investigations (e.g., Smull and Houze 1985, 1987; Houze et al. 1990; Parker and Johnson 2000) toward studies concentrating on forecasting issues, such as MCS initiation, sustenance, longevity, and severity (e.g., Gale et al. 2002; Jirak et al. 2003; Coniglio et al. 2004, 2007, 2010; Kuchera and Parker 2006; Cohen et al. 2007; Jirak and Cotton 2007; Lombardo and Colle 2012). For the time being, corresponding studies are unfortunately exceedingly rare in Europe.

In addition to compiling the statistics of MCS occurrence (section 3), this study aims to provide weather forecasters with new methods to assist in forecasting organized deep moist convection and convective straight-line winds. This will be done by creating three populations of cases: days with intense MCSs, days with nonintense MCSs, and days with sub-MCS-scale clusters of thunderstorms (explained in section 2 in detail). For each population, composite weather maps, proximity soundings, and corresponding box-and-whiskers plots are analyzed (section 4). The best discriminators between the three groups of days will be identified with the aid of sounding analysis. Finally, the corresponding sounding analysis will be done for the days with significant and insignificant amounts of wind-related emergency callouts.

2. Data and methods

The study period covered eight warm seasons from April to September 2000–07. In addition, four cold seasons from October to March were examined in order to create a general overview of the wintertime MCS frequency. Two main data sources were used in this study: composite radar reflectivity imagery for MCS detection and proximity soundings for describing the MCS environment. Moreover, to determine the synoptic-scale weather pattern within which the different types of events occur, the composite maps of mean sea level pressure, 300-hPa geopotential height, and 700-hPa specific humidity were produced based on reanalysis data.

a. MCS detection and radar data

The extent of the study area was dictated by the Finnish radar network coverage (Fig. 1), which is roughly confined between the latitudes of 60° and 70°N. During the study period, the network experienced two updates. In 2000, the network consisted of six C-band radars but a year later, a seventh C-band radar was deployed in northern Finland (Fig. 1). In 2005, another C-band radar was added to the network in western Finland.

The spatial and temporal resolutions of the pseudo–constant altitude plan position indicator (CAPPI) composite images were 1 km × 1 km and 30 min, correspondingly. Reflectivity values between 18 and 40 dBZ were classified as stratiform precipitation and values exceeding 40 dBZ were labeled as convective precipitation. This definition is the same as used by Punkka and Bister (2005) and is very similar to the definitions used in other radar data–based studies by Houze et al. (1990), Schiesser et al. (1995), Geerts (1998), Hilgendorf and Johnson (1998), Hagen et al. (2000), Parker and Johnson (2000), and Goudenhoofdt and Delobbe (2012).

The generic and widely used MCS definition originally proposed by Houze (1993) can be applied to radar data as follows:
a continuous area of stratiform precipitation (18–40 dBZ), with a long axis of more than 100 km in an arbitrary direction exists for at least four consecutive hours; 

- during the lifetime of the system, convective precipitation (over 40 dBZ) is present during at least two consecutive hours; and 

- an MCS is classified as intense if the maximum reflectivity exceeds 50 dBZ for at least two consecutive hours.

This definition allows fairly modest mesoscale precipitation areas to be included in the MCS dataset. The study approach differs from that often taken in studies based on satellite data (e.g., Maddox 1980; Anderson and Arritt 1998; Morel and Senesi 2002). Very few, if any, of the MCSs analyzed in this study could be classified as mesoscale convective complexes (MCCs), which are frequently the focus of satellite data–based studies.

By using composite reflectivity loops, the MCSs were manually identified. Several figures were collected during the tracking process, including the time of initiation, time of decay, time of maximum intensity, and the direction of MCS motion. The initiation of an MCS was declared when the 100-km condition was met for the first time. The time of decay was defined to be the time when the system no longer fulfilled the condition. The time when the area of the most intense echoes was largest was called the time of maximum intensity.

In this study, MCS duration means the elapsed time between the time of the first and last MCS detections. About 10% of the MCSs initiated and decayed beyond the radar range. The inclusion of partially sampled MCSs mainly affects the statistics of MCS duration, which is discussed in section 3b in more detail. Hence, in the following sections no distinction is made between completely and partially tracked MCSs.

b. Proximity soundings and wind-related emergency callouts

Three types of days were of particular interest during the study period:
1) days with at least one intense MCS (iMCS hereafter), 
2) days with at least one nonintense MCS but no intense MCSs (niMCS hereafter), and
3) days with no MCSs but sub-MCS-scale thunderstorms and thunderstorm clusters with at least 100 detected cloud-to-ground lightning strikes over the study domain (sub-MCS hereafter).

Lightning data were retrieved from the Nordic Lightning Detection System (Mäkelä 2011). During the study period, 382 iMCS days, 569 niMCS days, and 245 sub-MCS days were recorded.

The differences in the environment between the above-mentioned classes were studied with the aid of rawinsonde observations from seven sounding stations (Fig. 1). The definition for proximity soundings (Brooks et al. 1994) was as follows:

• the sounding should be launched within 3 h of the time of the maximum intensity,
• the sounding should be located within 200 km of the nearest 40- or 50-dBZ echo, and
• the most unstable parcel in the sounding should have at least a modest amount (>50 J kg\(^{-1}\)) of convective available potential energy and should not show signs of contamination from earlier convective activity.

The raw sounding data were analyzed with the General Meteorological Package/National Skew-T Hodograph Analysis and Research Program (GEMPAK/NSHARP) (DesJardins and Petersen 1985). In total, 131 proximity soundings for iMCSs, 53 for niMCSs, and 105 sub-MCSs were found. Box-and-whiskers plots of various thermodynamic and kinematic parameters were created in order to illustrate the differences between the three classes.

In addition, daily information of the locations and times of wind-related emergency callouts for the years 2001–07 were retrieved from a Ministry of Interior database (PRONTO; available online at https://prontonet.fi). Most of these callouts were due to fallen trees on main and side roads. Only days with at least 10 callouts were regarded as significant (SIG hereafter) wind damage days. The remaining days were classified as nonsignificant (NONSIG hereafter). The dataset of the SIG cases consisted of 8 (38) niMCS, 13 (70) sub-MCS, and 47 (68) iMCS soundings.

3. MCS occurrence

During the 8-yr study period, 1782 warm-season mesoscale convective systems were detected, out of which 649 (36%) were classified as intense. To quantify the frequency of cold-season (October–March) MCSs, the composite reflectivity data from four winter periods were also examined. Including four cold seasons added 218 MCSs to the dataset. Only seven cold-season MCSs were classified as intense, which demonstrates that excluding cold-season cases (Punkka and Bister 2005) results in only 2% of intense MCSs being neglected.

a. Annual and monthly distribution

The occurrence of MCSs varies considerably from year to year (not shown). For example, in 2000, only 146 warm-season MCSs were detected but 4 yr later there were 356 MCSs. The numbers of iMCSs in 2000 and 2004 were 51 and 146, respectively. The peak season for the occurrence of MCSs is midsummer: July and August (Fig. 2). On average, almost 60 MCSs per month are observed in July. Also, iMCSs reach their maximum frequency in July and August, when about 50% of all MCSs qualify as being intense. There are no substantial differences compared to the results presented by Punkka and Bister (2005) for the years 2000–01.

Figure 2 shows that the changes in the monthly mean MCS occurrence are large during early summer and fall. This is particularly true for iMCSs, as these types of systems are virtually absent from December to March. These abrupt changes are probably related to the rapid changes in insolation during the intermediate seasons. These results are consistent with many MCS and convective storm studies conducted in central and western Europe. In the United Kingdom (Gray and Marshall 1998; Lewis and Gray 2010) and in Belgium (Goudenhoofdt and Delobbe 2012), convective precipitation is maximized during midsummer. In contrast, in the continental United States, the peak in MCS occurrence has been observed to occur earlier, during April–July (Houze et al. 1990; Geerts 1998; Bentley and Sparks 2003).

b. Duration

In this study, the average duration of an MCS was 10.8 h. The average duration for the intense MCSs
(10.1 h) was 1 h shorter than for the nonintense MCSs (11.1 h). The shortest MCS durations during the warm season were recorded during July and August.

The frequency distribution of MCS durations is slightly skewed toward short durations; the mode and the median of the MCS duration are 4 and 8.5 h, correspondingly. The skewed distribution is also illustrated in Fig. 3. The cumulative frequency distribution shows that approximately 70% of the iMCSs have a duration of less than 10 h. Moreover, iMCSs with a duration of less than 10 h are more common than the corresponding niMCSs. As a result of the limited areal extent of the radar coverage, 10% of the MCSs analyzed in this study were initiated and decayed beyond the radar range. The durations of the partly and fully tracked systems were 12 and 9 h, respectively. The dataset also includes some MCSs with exceptionally long durations. In most instances, these cases are related to slow-moving, or even stationary, low pressure systems. The related mesoscale precipitation areas have convective precipitation for only a few hours but the stratiform precipitation remains over the study domain for significantly longer. The proximity sounding data are only analyzed from the times and locations when the MCSs have (intense) convective precipitation (40 or 50 dBZ) associated with them. Thus, the results based on these data are not affected by the extended length of the stratiform precipitation in some cases.

The results for MCS duration are in rough agreement with previous European studies. Schiesser et al. (1995) found that MCSs in Switzerland have an average duration of 8 h. Rigo and Llasat (2007) reported that MCSs in Catalonia usually remained within the radar measurement range for less than 10 h. Parker and Johnson (2000) showed that the average lifetimes of quasi-linear convective systems varied from 6 to 12 h in the central United States. In the southeastern United States (Geerts 1998), the duration minimum did not take place in midsummer but in March–June.

c. Time of initiation, decay, and maximum intensity

Many iMCSs initiate during the afternoon and early evening (Fig. 4), between 1000 and 1700 UTC (local time in summer is UTC + 3 h). Because of their strong dependency on the diurnal cycle, they tend to decay in the evening or in the very early hours of the morning, between 1600 and 2200 UTC. For niMCSs, a clear initiation peak is observed during nighttime and morning hours and a less pronounced decay peak is visible around midday and in the afternoon. The reasons for these peaks are unknown. In the 2000–01 data (Punkka and Bister 2005), these peaks for the niMCSs were not particularly strong.

There is also a pronounced afternoon and evening peak in the distribution of the time of maximum iMCS intensity.
intensity (Fig. 5). The peak is located between 1100 and 1700 UTC and is consistent with the known daily cycle of deep moist convection. The maximum intensity distribution for niMCSs does not have a pronounced diurnal cycle but a narrow morning maximum is evident between 0300 and 0700 UTC. This is probably associated with niMCSs that initiated during the preceding night.

The time of initiation only has a minor effect on MCS durations (Fig. 6). The noon and afternoon iMCSs have, however, durations that are a few hours shorter than the intense systems that initiate during other times of the day. Moreover, the afternoon iMCSs reach their maximum intensity within 3–4 h after initiation whereas nocturnal iMCSs require 5–6 h to reach their maximum intensity (Fig. 7). The time of day may also help predict whether the MCS will become intense or not. About 50% of the MCSs that initiate during the afternoon will be classified as intense (Fig. 8). For nocturnal MCSs, the corresponding fraction is only 20%–30%.

d. MCS line orientation and direction of MCS motion

Roughly 80% of the MCSs in this study moved toward the sector between northwest and east (Fig. 9). The most common direction of motion is northeast and there are slightly more iMCSs than niMCSs that move toward the north. The iMCSs that have a component of motion toward the west is a geographic-specific feature (Punkka et al. 2006; Järvi et al. 2007). These situations are related to a highly meridionally elongated upper-level flow structure, which is discussed further in section 5. The synoptic-scale pattern also affects the orientation of linear MCSs. The most common convective line orientations in this study are southwest–northeast, south–north, and southeast–northwest (Fig. 10).

4. MCS environment

a. Synoptic-scale environment

A common perception of Finnish weather forecasters is that episodes of widespread deep moist convection occur most frequently during warm and moist southerly or southeasterly airflow from the Baltic countries and...
Russia. This particular weather pattern takes place when an area of low pressure is located south, southwest, or west of Finland. Recently, this perception has been supported by results of several case studies of significant convective weather events in Finland (e.g., Punkka et al. 2006; Järvi et al. 2007; Rauhala and Punkka 2008; Törmä et al. 2013).

To identify synoptic situations that are associated with the development of MCSs, National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) were used to create composite maps (http://www.esrl.noaa.gov/psd/data/composites/nssl/day/) for the July and August iMCS, niMCS, and sub-MCS days. This geographic-relative compositing technique has severe limitations due to its smoothing effect on the resulting fields. Thus, this technique does not allow the MCS environment or the different stages of the MCS life cycle to be closely examined. The synoptic-scale weather patterns of individual cases may deviate substantially from the composite. Individual events feature more pronounced anomalies (of, e.g., moisture and temperature) and the orientation of the mean flow over the study region may differ as well (e.g., southeasterly flow instead of southwesterly).

The composite 300-hPa geopotential height field suggests that in the MCS cases an upper-level trough is located to the west of the study area (Fig. 11). In the iMCS, the mean sea level pressure field shows that a low pressure is located west of Finland, which would lead to southerly surface-level flow. In the niMCS cases, a low pressure area is located partly over Finland. The sub-MCS fields greatly deviate from the MCS cases, having an upper-level ridge west of Finland and a surface ridge of high pressure stretching from western Europe to Scandinavia. This pattern would lead to westerly surface-level flow.

Distinctions between the iMCS and sub-MCS days are also observed in other composite maps. For example, maps for the 850- and 925-hPa levels suggest that cooling (warming) and drying (moistening) of the lower troposphere would occur prior to the sub-MCS (iMCS) events (not shown). Differences in moisture also appear at the 700-hPa level where the iMCS environment is most humid and the sub-MCS environment driest (Fig. 11). The role of humidity above cloud base will be discussed in more detail in the following sections.

b. Proximity soundings: Thermodynamic parameters

The SIG class proximity soundings are those that were launched during the sub-MCS or MCS days that had at least 10 wind damage reports. The soundings in the NONSIG class were from the sub-MCS or MCS days with fewer than 10 wind damage reports (see section 2 for details). A Student’s t test was performed to determine if the datasets were statistically different from each other. We recognize that many of the parameters discussed in this study are not free to vary independently. For example, dry low-level air affects the values of CAPE and the lifting condensation level (LCL) height.

The iMCS and SIG classes have the highest median values of most unstable CAPE, about 800 J kg$^{-1}$ (Fig. 12a).
The niMCS class has the lowest value of around 500 J kg\(^{-1}\). Since the MCS intensity is directly determined from, and thus is directly related to, the radar reflectivity in this study, it is not surprising that intense systems occur in situations with higher CAPE. According to parcel theory, more energy leads to more intense updrafts, which enhance hydrometeor production or even hail formation inside the updraft regions, and, eventually, leads to higher radar reflectivities.

The above-mentioned CAPE values are considerably lower than in studies concerning the central United States (e.g., Bluestein and Jain 1985; Bluestein et al. 1987; Parker and Johnson 2000). Brooks (2009) studied environments of severe convective weather in Europe and the United States and also observed much lower CAPE values in Europe. Moreover, Jirak and Cotton (2007) showed that the amount of CAPE could distinguish rather well between MCS and sub-MCS cases in the central United States.

The low-level mixing ratio (defined as being within the lowest 100 hPa of the atmosphere) distributions (Fig. 12b) have many similarities with the CAPE distribution (Fig. 12a). The iMCS and SIG classes possess the highest median values of around 9 g kg\(^{-1}\) whereas the sub-MCS and the NONSIG soundings are noticeably drier. The low-level moisture differences between the iMCS and niMCS, the iMCS and sub-MCS, as well as the SIG and NONSIG classes are significant at the 99% confidence level. The 850–500-hPa lapse rate is not able to discriminate any classes from each other and the median values are around 6.5 K km\(^{-1}\) in every class (Fig. 12c). This is also confirmed by statistical tests that show that lapse-rate distributions are not significantly different.

The distributions of maximum vertical equivalent potential temperature differences \(\Delta \theta_e\) (Fig. 12d) largely resemble the CAPE distributions (Fig. 12a). The absolute \(\Delta \theta_e\) values are, however, noteworthy. For the SIG
FIG. 12. Box-and-whiskers plots for proximity soundings for different event classes. (a) Most unstable CAPE (J kg\(^{-1}\)), (b) mixing ratio (g kg\(^{-1}\)) of the lowest 100 hPa, (c) 850–500-hPa lapse rate (K km\(^{-1}\)), (d) max vertical equivalent potential temperature difference (K), (e) LCL height (m) for the layer-mean (lowest 100 hPa) air parcel, (f) 500-hPa relative humidity (%), and (g) 700-hPa relative humidity (%). The extreme values are located at the tips of the whiskers. The center bar contains 50% of the cases and the horizontal line inside the bar shows the parameter median value.
In this study, the 0–3-km bulk wind shear (Fig. 13a) is a better discriminator than the 0–6-km bulk wind shear; it is able to discriminate the iMCS cases from the sub-MCS cases at the 99.9% confidence level and even the iMCSs from the niMCSs at the 95% level. The bulk wind shear from the surface to 6 km (not shown) is able to discriminate the iMCS class from the sub-MCS class at the 99% confidence level, which is not the case between the other classes. The median value in the SIG class is 10 m s\(^{-1}\), which is almost equal to the typical values for nonsupercell thunderstorms in the United States (Thompson et al. 2003). According to Evans and Doswell (2001), typical 0–6-km wind shear values in derecho cases are between 12 and 20 m s\(^{-1}\) but during nonderecho MCS situations they range from 5 to 13 m s\(^{-1}\).

The mean wind speeds for three different layers were calculated: 0–6 km, 850–200 hPa, and lifting condensation level–equilibrium level (LFC–EL). The layer-mean wind parameters show particularly good ability in separating the iMCS from the sub-MCS class as well as the SIG from the NONSIG class. The layer-mean wind distributions are statistically different at the 99.9% level. For example, the mean wind for the cloud-bearing layer (LFC–EL) has a median value of 13 m s\(^{-1}\) in the SIG class (Fig. 13b), whereas the corresponding value in the NONSIG class is only 9 m s\(^{-1}\).

Many recent MCS studies in the central and eastern United States have shown that the deep-layer-mean winds distinguish between different MCS populations. The mean wind and bulk wind shear layers up to 10 km discriminate mature MCSs from decaying MCSs (Coniglio et al. 2007) and weak MCSs from severe wind–producing MCSs (Cohen et al. 2007) over the United States. Moreover, Coniglio et al. (2006) showed in their model simulations that the intensification of wind shear over a very deep layer led to deeper updrafts.
5. Discussion and summary

The occurrence of mesoscale convective systems in Finland and nearby regions over an 8-yr period was studied. In addition to the radar data–based MCS statistics, the MCS environment was investigated with the aid of proximity soundings. Three subsets of events were studied; intense mesoscale convective systems (iMCSs), nonintense mesoscale convective systems (niMCSs), and smaller clusters of thunderstorms (sub-MCS). Moreover, soundings from days with significant (SIG) and negligible (NONSIG) amounts of wind damage were examined separately. Box-and-whiskers plots were compiled from the proximity sounding data for each class of events. Composite maps based on NCEP–NCAR reanalysis data were created in order to determine the accuracy of the perception commonly held by Finnish weather forecasters of synoptic situations that favor the development of MCSs in Finland.

a. MCS features

The manual investigation of the radar reflectivity composite imagery revealed the following MCS properties:

- MCSs were most common in July and August, and iMCSs were very rare in winter. Of the systems, one-third became intense (maximum reflectivity exceeding 50 dBZ for at least two consecutive hours).
- The average MCS duration was 10.8 h but short-lived systems were most common.
- The iMCS events showed a strong diurnal cycle, having a preference to initiate in the afternoon and dissipate in the evening.
- Afternoon systems reached their maximum intensity quicker than MCSs during other times of day and they were more likely to reach the iMCS status than other systems.
- The majority of the MCSs moved toward the sector between the northwest and east. Some MCSs possessed a motion component toward the west.
- The most typical convective line orientations were southwest–northeast, south–north, and southeast–northwest.

b. Large-scale weather patterns

The evolution of the synoptic-scale (and mesoscale) weather patterns a couple of days, or even hours, before the onset of deep moist convection critically affects the intensity, areal extent, and convective mode of an event. Several studies in Europe (e.g., Hernández et al. 1998; Lewis and Gray 2010) and in the continental United States (Maddox 1983; Hilgendorf and Johnson 1998; Laing and Fritsch 2000; Parker and Johnson 2000) have shown that upstream upper-level troughs are a commonly observed feature in conjunction with MCSs of varying extents and intensities. These troughs modify the large-scale environment to be more conducive to organized deep moist convection by, for example, affecting moisture transport and the deep-layer wind shear. Upstream upper-level troughs have been observed in Finland during various MCS situations (e.g., Punkka et al. 2006; Järvi et al. 2007; Rauhala and Punkka 2008; Törnä et al. 2013). They were also observed in this study in composite reanalysis maps in the MCS cases (Fig. 11). During the sub-MCS events, the upper-level composite field was dominated by a ridge of high pressure. However, the reliability of these composite maps is questionable as a result of the smoothing effect of the compositing method on the resulting fields.

In this study, the majority of the MCSs moved toward the northeast yet a small fraction of the systems traveled toward the west. Throughout most of Europe, the prevailing direction for MCS motion is east or northeast (Schiesser et al. 1995; Hagen et al. 1999; Morel and Senesi 2002; García-Herrera et al. 2005; Rigo and Llasat 2007; Davini et al. 2011; Goudenhoofdt and Delobbe 2012). According to Lewis and Gray (2010), some MCSs in the United Kingdom move toward the north or northwest. These MCSs with a northeasterly component to their motion occur when a synoptic pattern called a European easterly plume is present. During this synoptic pattern, a strong high pressure area is located over Scandinavia and a plume of warm air streams westward toward the United Kingdom. Kolios and Feidas (2010) showed that in southeastern Europe the average MCS motion direction is toward the north. A vast majority of the MCSs in the continental United States move toward the east or southeast (Maddox 1980; Bentley and Sparks 2003) and systems having a motion component toward the west are rare.

Differences within the synoptic framework (e.g., location and orientation of upper-level troughs) are also reflected in the orientation of linear MCSs. In this study southwest–northeast, south–north, and southeast–northwest orientations were most common, which partially deviates from the typical line orientation observed in the continental United States. According to Geerts (1998), Parker and Johnson (2000), and Schumacher and Johnson (2005), southwest–northeast and west–east line orientations are most frequent in the continental United States.

From time to time, a meridionally elongated upper-level trough and low pressure area are located west or southwest of Finland enabling southerly or south-easterly flow from the Baltic countries and Russia into...
Finland (e.g., Punkka et al. 2006; Järvi et al. 2007; Rauhala and Punkka 2008; Törmä et al. 2013). During these situations, the southerly flow brings moisture-rich air to Finland. This weather pattern is occasionally associated with a cold front approaching from the southwest or even south. The frontal and vertical wind profile together might lead to the formation of a linear MCS that, by North American standards, has a rare line orientation and motion direction. The line orientation (e.g., southeast–northwest) originates from the orientation of the frontal boundary and the peculiar direction that the MCSs travel in (such as toward the northwest or west) is due to southerly to easterly steering flow.

The above-mentioned weather pattern also affects the midlevel lapse rates. However, the proximity soundings showed that midlevel lapse rate is a poor discriminator between the event classes. The lapse-rate values found in this study are between 6 and 6.5 K km$^{-1}$ and therefore are very low compared to the typical values for MCSs in the central United States (Jirak and Cotton 2007; Cohen et al. 2007; Coniglio et al. 2007).

c. Role of moisture

The role of low-level moisture was clearly observed in this study in the iMCS class. According to the proximity sounding analysis, the low-level mixing ratio discriminated between the iMCS and niMCS classes and between the iMCS and sub-MCS classes, as did the CAPE values. In addition, the LCL height was lowest in the iMCS cases and notably higher in the sub-MCS class. The above-mentioned results suggest that low-level moisture has an effect on the type of deep moist convection.

Unlike low-level moisture, the role of dry air above the cloud base has received limited attention in previous studies. James and Markowski (2010) recently performed a numerical study on the effect of dry air on deep moist convection. One of their main findings was that dry air above the cloud base did not reinforce the downdrafts and cold pool if CAPE was low. Moreover, the updraft mass flux was observed to decrease when dry air was present. In Finland, CAPE values are typically modest and therefore high humidity above cloud base might be beneficial for the development and sustenance of deep moist convection.

The 850-, 700-, and 500-hPa pressure levels are mainly located above the convective cloud base in Finland. An examination of composite specific humidity maps for these levels (700 hPa shown in Fig. 11) reveals that the most substantial differences are situated in the southern half of the study domain. In this area the iMCS cases have the highest moisture values, followed by the niMCS cases. The sub-MCS cases are notably drier than the MCS classes. In the relative humidity plots for the same pressure levels (not shown), differences between the MCS classes are minor over the southern part of the study area. However, in the northern part the niMCS cases have the highest relative humidity values. Again, the sub-MCS cases are notably drier than the MCS cases over the whole study area. As previously noted, the reliability of the composite maps is rather limited but similar moisture features are also visible in the proximity soundings. The sub-MCS cases occur in considerably drier environments than do the MCS cases.

Despite the fact that no definitive conclusions can be drawn based on this brief analysis, the results suggest that moisture above cloud base could be important for the upscale growth and intensity of deep moist convection in Finland and nearby regions. Analogously with the findings of James and Markowski (2010), dry midlevel air appears to favor sub-MCS-scale weak convection as opposed to MCS-scale convection in our study.

Our results did not show any evidence that would indicate that dry low- or midlevel environments are more prone to produce severe wind events than moist environments. According to Kuchera and Parker (2006), the midlevel relative humidity only differed slightly between the environments of severe convective wind–producing thunderstorms and ordinary thunderstorms.

Moreover, our results could not verify the validity of the 20-K equivalent potential temperature rule (Atkins and Wakimoto 1991), which is widely used for the prediction of downbursts in the United States. The median value for the SIG class was only slightly over 10 K. Instead of moisture-dependent variables, deep-layer-mean winds (0–6 km, 850–200 hPa, and LFC–EL) were able to distinguish between the SIG and NONSIG classes at a very high level of confidence.

d. Implications for forecasting

Based on the results and discussion in the earlier sections, the following remarks about the dynamic and thermodynamic environment of Finnish MCSs can be made:

- The sub-MCS-scale deep moist convection takes place in notably drier low- and midlevel environments than MCSs. The intense MCSs occur in the most humid low-level environments. Whenever modest CAPE is available, weather forecasters should pay special attention to areas with high moisture values in the low- to midtroposphere.
- The presence of dry low- and midlevel air does not seem to increase the likelihood of severe convective wind events in areas with modest CAPE values.
- Midlevel lapse rates are very similar in MCSs and sub-MCSs. The lapse rate fails to discriminate between the
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