**Significant-Hail-Producing Storms in Finland: Convective-Storm Environment and Mode**

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**ABSTRACT**

The environmental characteristics and convective mode of significant hailstorms (those storms producing reported hail 5 cm or larger in diameter) in Finland during 1972–2011 were analyzed. Altogether, 23 significant-hail-day environments were analyzed by modifying radiosonde data from proximity soundings in the observed data archives of the Finnish Meteorological Institute. Convective parameters derived from the environmental soundings were compared between a set of significant-hail soundings and a null set of nonsevere-thunderstorm soundings. A subset of 13 significant-hail days was examined using data from a network of Doppler radars during 1999–2011. Convective-storm mode and storm characteristics (e.g., hook echo, bounded weak-echo region) were determined for the 18 significant-hail-producing storms during these days. Most (78%) of these storms producing significant hail in Finland occurred with supercells. Of the significant-hail days, 39% (9 out of 23) did not have the minimum of 15 m s$^{-1}$ of deep-layer (0–6 km) shear commonly expected for supercells. Convective parameters of significant-hail and thunderstorm-day environments were substantially different from each other. Specifically, significant-hail environments had a mean most-unstable convective available potential energy (MUCAPE) of 1464 J kg$^{-1}$ and deep-layer shear of 17.5 m s$^{-1}$, whereas thunderstorm days had a MUCAPE of 593 J kg$^{-1}$ and deep-layer shear of 10.2 m s$^{-1}$. Larger hail was associated with higher values of MUCAPE. The lifetimes and track lengths of significant-hail-producing storms were related to the convective mode and storm environment. Specifically, larger deep-layer shear seemed to support longer lifetimes and track lengths. Nonsupercells had shorter lifetimes, shorter stormtrack lengths, and lower speeds than supercells. The value of deep-layer shear was smaller for nonsupercells than for supercells. Discrete supercells had higher speeds, longer lifetimes, and longer track lengths than cluster supercells.

**1. Introduction**

Recent studies have shown the frequency of hail occurrence in Finland (Tuovinen et al. 2009; Tuovinen and Schultz 2010; Saltikoff et al. 2010). The hail season in Finland lasts from May to September, but severe hail (diameter of 2 cm or larger) tends to occur mostly between late June and early August (Tuovinen et al. 2009). Since 2008, the number of severe-hail observations has tripled because a select group of people (10–20 storm spotters and meteorologists) monitor a radar-based hail algorithm during the summer months and contact eyewitnesses for reports across Finland wherever certain hail algorithm criteria are exceeded (Tuovinen and Schultz 2010). These efforts over the period 2008–12 have resulted in an annual mean of 43 hail days, 17 of which produce a mean of 57 severe-hail events. However, the interannual variability of severe-hail observations can be considerable. There have been as few as 11 observations on 6 severe-hail days in 2012, but as many as 90 observations on 22 severe-hail days in 2010.

Although significant hail [diameter of 5 cm (~2 in.) or larger; Hales (1988)] accounts for only 19% of all severe-hail observations [e.g., Fig. 6 in Tuovinen et al. (2009)], it is more likely to cause damage such as broken windows, broken plastic or glass windshields, and dented cars (Tuovinen and Rauhala 2010). Although a few case
studies of significant hail in Finland have been performed (Tuovinen 2007; Rauhala 2011), studies on the severe-hail environment and convective mode of storms generally do not exist. The only related studies are by Roine (2001), who studied stability indices in thunderstorm environments in southern Finland during May–August for two years (1998 and 2000) and by Punkka and Bister (2015), who studied the synoptic and thermodynamic environment of MCSs in Finland covering eight warm seasons (April–September for 2000–07). In contrast to Finland, many more studies have been performed on severe- or significant-hail environments in the United States (e.g., Brooks and Craven 2002; Craven and Brooks 2004; Brooks 2009; Cintineo et al. 2012; Johnson and Sudgen 2014; Allen et al. 2015). Other climatological studies of hail have been performed in Europe (e.g., Van Delden and Groenemeijer 2007; Kunz and Puskeiler 2010; Pučik et al. 2013), Australia (Allen et al. 2011), and Turkey (A. Kahraman 2014, personal communication).

Hail can be produced by various convective modes. The morphologies of convective storms causing significant hail have been studied in the United States by Gallus et al. (2008) and Smith et al. (2012). Significant-hail events in the United States are produced overwhelmingly by supercell thunderstorms (e.g., Rasmussen and Blanchard 1998; Thompson et al. 2003; Smith et al. 2012). Blair et al. (2011) studied over 500 giant-hail (10.2 cm or 4.0 in.) reports in the United States and found that 99% were produced by supercells. Therefore, forecasting the convective mode (specifically, supercells) does help forecasters in the United States to anticipate the occurrence of significant hail.

We wish to determine if the significant-hail-producing storms in Finland are supercell storms and if they exhibit common characteristics that can aid in their identification. We also want to emphasize that high-latitude significant-hail environments have not been studied before, raising the question of how the convective-storm environments of Finland differ from other places around the world. Finally, understanding the modes of hail-producing storms and studying their environments would improve forecasting. Thus, the purpose of this paper is to create a climatology of significant-hail events in Finland, leading to an improved understanding of the convective-storm environments and storm modes. Section 2 introduces the methods and data used in this study. The results are shown in section 3, and section 4 concludes this paper.

2. Data sources and methods

All the cases used in this study have been selected from a database of severe hail in Finland that is based on previously published climatologies (Tuovinen 2007; Tuovinen et al. 2009) and reports from recent years. For 1972–2011, 35 significant-hail reports have been documented by the Finnish Meteorological Institute (FMI). The significant-hail database is likely incomplete, especially before 2006, when a systematic routine of collecting eyewitness reports of hail was unavailable. Since 2007, severe-hail reports have also been collected with the help of a radar-based hail algorithm (Tuovinen and Schultz 2010), which has increased the number of reports. The incomplete data reduce the sample size and might have an influence on event frequency, for example, on the diurnal distribution (i.e., if some reports are missing, the current distribution would likely show fewer events during the nighttime compared to the real distribution) and on the geographical distribution. Only one or a few significant-hail reports were associated with each individual storm. Thus, a detailed geographical distribution of each hail swath is unable to be presented, which may bias the data toward underreporting the true size of the swaths.

Observations depend on people to make the reports, and this may lead to a population bias of reports around where people live and travel. For example, Allen et al. (2015) showed a bias of reports along roads. Such bias is a problem in Finland, especially in Lapland in northern Finland, which is extremely sparsely populated (Tuovinen et al. 2009). However, severe hail does occur and is reported even in Lapland [Fig. 7 in Tuovinen et al. (2009)]. Severe-hail observations, such as hail size and time of occurrence may contain errors. Hail size has been confirmed by a photograph taken of the largest observed hailstone along with an object for comparison in 33 cases; hail size has been estimated by eyewitnesses in 2 cases. Thus, we believe that the documented hail size of the events in this dataset is highly reliable. It is possible that hail-size reports were not received from the part of the swath with the largest hail or there were other errors in the size estimates. In addition, we classified hail sizes in bins every 0.5 cm, so errors in the exact hail size were not expected to be a big problem for our intended purposes.

For the time of occurrence, the dataset shows that the best eyewitness time was reported within a range of 5 min [e.g., 1445–1450 local time (LT); LT = UTC + 2 h] and, in the worst case, 60 min (e.g., 1700–1800 LT). However, for cases in 1999–2011, we were able to estimate the onset of significant hail at each observation report location within 5 min based on the highest radar reflectivity factor at the lowest elevation angle. Before the availability of radar data in 1999, significant-hail observations may contain larger uncertainties in location and timing.

a. Sounding analysis

Observed soundings from significant-hail days were selected to study the environmental conditions. Soundings were selected to be in the inflow to the storm by
looking at the synoptic situation. For example, a sounding from one of the events occurred on the cold side of an airmass boundary and was therefore removed from the sounding dataset (this event was used in the convective mode studies, though). The following proximity-sounding criteria were chosen: the nominal sounding time must have been within 5 h before and 2 h after the first significant-hail report and within 400 km of that hail report. These criteria are similar to the ones used by Rasmussen and Blanchard (1998). This method resulted in 23 significant-hail-day soundings in Finland during 1972–2011. A majority of the 23 cases were well within the chosen sounding criteria: 20 events (83%) were closer than 200 km from the sounding site and 17 events (71%) were within 2 h of the sounding.

Soundings are made at three locations in Finland (Fig. 1): Jokioinen (southern Finland; at 0000 and 1200 UTC), Jyväskylä (central Finland; at 0000 and 1200 UTC before summer 1998, and at 0600 and 1800 UTC afterward), and Sodankylä (northern Finland; at 0000 and 1200 UTC). Afternoon soundings (1200 UTC) were mostly used (20 soundings at 1200 UTC, 1 at 1800 UTC, and 2 at 0000 UTC), as they were closest to the occurrence times of our cases.

Only one sounding was selected for each significant-hail day for this study. If a significant-hail day had several storms producing significant hail, the storm producing the largest hail size was selected for further analysis. For each case, we selected the closest sounding in space and time, and archived sounding data were input into the FMI meteorological workstation. Soundings were modified (temperature, dewpoint, and wind speed and direction) at the lowest level based on the nearby surface observation. Above the surface, only the temperature profile was modified to yield a dry-adiabatic lapse rate to the lifting condensation level. In each case, the observation was taken from the closest available observation station 30–60 min prior to the significant-hail observation. The mean distance between the closest station and the hail observation was 31 km. To calculate the deep-layer shear (0–6 km AGL), we chose the closest data point from the sounding that was below 6 km in every case. This level was no more than 250 m from the actual 6-km height.

Using deep-layer shear has some commonly known problems. It neglects the directional structure of the wind field, which can result in appreciable helicity, and does not necessarily capture the effective depth over which shear is important to a storm (Bunkers et al. 2006b; Thompson et al. 2007). Nevertheless, we have used deep-layer shear to compare our results to the previous literature.

To be able to compare the significant-hail environment to an average nonsevere environment, we also constructed a dataset of thunderstorm days. We chose Jokioinen 1200 UTC soundings over the period 2007–13 and examined all the cases that had at least one lightning observation during 1100–1300 UTC within 100 km of the sounding site. Soundings that had zero convective available potential energy, occurred during a day with significant hail in Finland, or had a 2.0–4.99-cm hail observation within 150 km or 3 h from the sounding site were excluded. This method resulted in 93 thunderstorm soundings, which serve as a null set to our hail cases. The criteria used for thunderstorm days are more stringent because soundings were not modified as multiple lightning observations can occur over a period of time. Therefore, we assume that the 1200 UTC (=1500 LT) sounding is representative of the environment. Thunderstorm days were chosen as the null set rather than 2–4.99-cm hail days.
Because of the uncertainty of knowing for sure that significant hail did not fall on a day with 2–4.99-cm hail.

b. Parent-storm classification

The convective mode of the storms was classified based on radar imagery. Radar data were available from all eight 5-cm wavelength radars operated by FMI since 1999. Most of the storm tracks were closer than 120 km to the nearest radar because, at this range, storms are reasonably well sampled, even at lower elevation angles. Only five storms moved farther than 120 km from the radar during their lifetimes, and three of those five moved out of the radar coverage in eastern Finland later in their lifetimes. The closest radar data were used for the analysis during the storm evolution, and simultaneous data from multiple radars were used if needed. Radar data were available for 12 elevation angles: every 5 min for the lowest four elevation angles and every 15 min at higher elevation angles. Reflectivity was viewed on a plan position indicator (PPI) because it was available for all of the cases. Good quality radar velocity data were not available, so supercell determinations were based solely on reflectivity data.

The radar analysis showed that the 25 significant-hail reports in Finland during 1999–2011 were caused by 18 separate storms. Thus, our study comprises a whole dataset from 1972 to 2011 with 35 individual reports and 23 significant-hail days. This dataset breaks into two smaller datasets of 1972–98 (no radar data, but soundings), with 10 reports and 10 significant-hail days, and 1999–2011 (radar and sounding data), with 25 reports, 18 storms, and 13 significant-hail days.

Parent-storm types were identified and divided into different convective modes (Fig. 2), similar to Trapp et al. (2005), Gallus et al. (2008), and Smith et al. (2012). In this study, all storms were cellular and no linear storm structures were observed. Storms were classified in four categories: discrete supercell, cluster supercell, cluster cell, and discrete cell. Supercells were divided into right movers (RMs) and left movers (LMs).

For each storm, the storm type was defined based on the mode just prior to the first significant-hail report. As velocity data from radars were not available, a storm was classified as a supercell if it had a persistent hook echo (visible in at least three consequent radar pictures). A storm was defined as discrete if it was isolated (i.e., not connected by weaker echoes) and as a cluster if it was connected by weaker echoes. In discrete and cluster cells, supercell features [e.g., hook echo, bounded weak-echo region (BWER); Lemon and Doswell (1979)] were generally not apparent prior to the first significant-hail report. However, some of these storms may have experienced supercell characteristics during some other period of their lifetime. One of the storms defined as a discrete cell was identified as a right-moving cluster supercell at a later stage of its lifetime. One of the cluster-cell storms was so
far away from the radar that the beam height of the lowest elevation angle was too high (3 km), and another cluster-cell storm had an orientation to the radar such that the heavy precipitation in the storm core may have prevented detection of a possible hook echo. Furthermore, there are types of supercell storms (high-precipitation supercell, low-precipitation supercell) that lack hook echoes in some cases. Thus, some of the storms in this study may have been supercells without hook echoes. Also, with no velocity data available to identify the defining supercell characteristic (i.e., the midlevel mesocyclone), a few storms may be misclassified.

The storm track was determined for each storm as the linear distance between the location of the first and last 20-dBZ echoes at any elevation angle. If the storm decayed as it became embedded within stratiform precipitation, the storm was tracked until the individual cell could no longer be identified. If storm splitting occurred after the first significant-hail report, the right mover was tracked to obtain storm track, track length, and lifetime (Fig. 1).

3. Results

Of significant hail, 64% was observed during the late afternoon and early evening (1600–2000 LT; Fig. 3) and seemed to occur later than severe hail [Fig. 5 in Tuovinen et al. (2009)]. There are no known events during 0200–1200 LT. In Australia, 80% of severe-thunderstorm reports occurred between 1500 and 2000 LT and less than 5% occurred between midnight and midday (Allen et al. 2011).

a. Convective available potential energy

Throughout the paper we used most-unstable convective available potential energy (MUCAPE) because it is more commonly employed by operational forecasters in Finland and it is more suitable for different convective environments compared to mean-layer convective available potential energy (MLCAPE).

The environments of the 23 significant-hail days are characterized by high MUCAPE values for Finland. Out of 23 of the significant-hail days, 22 had MUCAPE values above 850 J kg\(^{-1}\) (Fig. 4). Significant-hail soundings had larger values of MUCAPE than soundings during thunderstorm days (mean of 1464 vs 593 J kg\(^{-1}\)) (Fig. 5a). It was found that 75% of significant-hail soundings had MUCAPE larger than 922 J kg\(^{-1}\), whereas 75% of thunderstorms had MUCAPE less than 826 J kg\(^{-1}\). Larger hail tends to occur during larger MUCAPE values on average (Fig. 4). For example, 7.0–7.99-cm hail cases had a mean MUCAPE of 2055 J kg\(^{-1}\), which was larger than the other categories (5.0–5.99 cm for 1140 J kg\(^{-1}\) and 6.0–6.99 cm for 1540 J kg\(^{-1}\)).

Punkka and Bister (2015) showed that intense, damaging MCSs in Finland had median MUCAPE values of about 800 J kg\(^{-1}\), whereas nonintense MCSs had only about 500 J kg\(^{-1}\) [Fig. 12a in Punkka and Bister (2015)]. These MUCAPE values are evidently lower than in our study. In comparison to studies elsewhere, Kunz and Puskeiler (2010) found that the mean surface-based convective available potential energy (SBCAPE) in their study of severe-hail events in southwestern Germany was 1250 J kg\(^{-1}\), and Van Delden and Groenemeijer (2007) found that the mean MUCAPE for hail larger than 3 cm in the Netherlands was close to 1100 J kg\(^{-1}\) and increased with increasing hail size. Pucik et al. (2013) studied severe-weather proximity soundings (2008–11) from central Europe. They found that significant-hail events favor environments with sufficient overlap of instability and deep-layer shear with approximate mean values of 2000 J kg\(^{-1}\) MUCAPE and 20 m s\(^{-1}\) of shear. Allen et al. (2011) found that MUCAPE values in Australia are the
highest in significant severe events (mean category of 1600–2000 J kg\(^{-1}\)), although MUCAPE values of 3000–4000 J kg\(^{-1}\) are observed in most extreme cases. In the United States, the storm environment for severe convection in general seems to have larger CAPE values than elsewhere in central Europe or Australia because of steeper midtropospheric lapse rates and ample low-level moisture (Brooks 2009). This is also evident in Johnson and Sudgen (2014), where the mean value of MUCAPE of 2.0–3.25-in. (5–9 cm) hail events in the United States was 2671 J kg\(^{-1}\).

b. Deep-layer shear

Of the significant-hail days, 39% (9 out of 23) had deep-layer shear values lower than 15 m s\(^{-1}\) (Fig. 4), a threshold above which is considered necessary to support supercells (Thompson et al. 2003). When comparing storm environments with different hail sizes, larger hail sizes tended to occur in higher-shear environments (Fig. 4). Similar relationships between hail size and deep-layer shear have been documented in the United States by Johnson and Sudgen (2014), although the magnitude of the wind shear in their study was distinctly higher. In our study, there was a clear difference in deep-layer shear values of the significant-hail days (mean 17.5 m s\(^{-1}\)) and thunderstorm days (mean 10.2 m s\(^{-1}\)). Whereas 75% of the significant-hail days had shear above 12 m s\(^{-1}\), 75% of thunderstorm days had shear below 13.5 m s\(^{-1}\) (Fig. 5b). We also determined 1–8-km shear values and found smaller differences between the two datasets (for significant-hail days 15.4 m s\(^{-1}\) and for thunderstorm days 13.4 m s\(^{-1}\)). In comparison, of the 539 U.S. supercells studied by Bunkers (2002), 95% had more deep-layer shear than 13 m s\(^{-1}\), but he concluded that supercells were possible with values higher than 10–15 m s\(^{-1}\).

Similar results to our study have been obtained in the Netherlands, where the majority of hail events (larger than 3 cm) formed in environments with less than 15 m s\(^{-1}\) (12.3 m s\(^{-1}\)) deep-layer shear (Van Delden and Groenemeijer 2007). Van Delden and Groenemeijer (2007) suggested that some of the severe-hail events were produced by multicell storms rather than supercells. Allen et al. (2011) found that the mean value of deep-layer shear was 15 m s\(^{-1}\) for severe-thunderstorm cases and between 20 and 25 m s\(^{-1}\) for significant severe-thunderstorm cases. They also concluded that the majority of environments supported supercells. Thus, the above comparison suggests that the amount of deep-layer shear in significant-hail events is common in convective surroundings from around the world (Brooks 2009; Allen et al. 2011).

c. MUCAPE versus deep-layer shear diurnal and annual cycles, and the product of MUCAPE and deep-layer shear

When comparing occurrence times of significant-hail events, the significant hail that forms during 1600–2159 LT has the largest MUCAPE values (mean 1550 J kg\(^{-1}\)). The largest significant-hail sizes tend to occur later in the evening; the maximum diameter on average occurs during 1800–2159 LT (mean 6.8 cm), consistent with the fact that larger hail tends to occur with the larger MUCAPE environments. The events that occur during 1600–1959 LT have the largest deep-layer shear (mean 20.3 m s\(^{-1}\)) in comparison to events that occur during 2000–2159 LT somewhat less often (15.8 m s\(^{-1}\)). At other times, the shear values are smaller, with a mean of 13.0 m s\(^{-1}\).

All significant-hail days in this dataset occurred between 30 May and 18 August, with 74% of the days (17 out of 23) occurring in July or August. The average storm

![Figure 4](image-url)
environment does not differ much from month to month in this small sample (Fig. 6). Specifically, if the monthly mean of MUCAPE for significant hail is examined for June–August, the values in the minimum and maximum months are only 1.5% different from each other (June mean MUCAPE is 1536 J kg\(^{-1}\); July and August values are both 1514 J kg\(^{-1}\)). Instead, significant-hail days in July have large deep-layer shear values (mean 20.9 m s\(^{-1}\)), whereas the wind shear in Finland during July is not normally that high. According to A.-J. Punkka’s blog of severe convective storms in Finland (http://tinyurl.com/p3a7hwp), the mean value of deep-layer shear during the summer season June–August of 1961–2010 in Finland was 11.5 m s\(^{-1}\), lower than in other months of the year. Similar findings arise in the United States [e.g., Fig. 11 in Craven and Brooks (2004)] where significant hail occurs in the weaker deep-layer shear environments during July–August compared to April–May. During all summer months, significant-hail days in our study had a higher mean deep-layer shear value (17.5 m s\(^{-1}\)) compared to the long-term seasonal mean (11.5 m s\(^{-1}\)).

When looking at the whole dataset of soundings (both null and significant-hail cases combined), the probability of significant hail increases as certain values of the product of MUCAPE and deep-layer shear are exceeded (Fig. 7). The small sample sizes at high-end probabilities make the product of MUCAPE and deep-layer shear curvature more erratic. This is in analogy with the data from the United States and Europe [Fig. 7 in Brooks (2009)]. The probability that soundings are associated with significant hail in Finland resembles that for Europe [Fig. 7 in Brooks (2009)], but the significant-hail probabilities in Finland are even higher at a smaller value of the product of MUCAPE and deep-layer shear.
d. Storm convective mode

In Finland, most of the significant-hail-producing storms (78%, or 14 out of 18 storms during 1999–2011) were supercell storms. Observed parent-storm modes were right-moving cluster supercells (eight cases), right-moving discrete supercells (five cases), a left-moving discrete supercell (one case), cluster cells (two cases), and discrete cells (two cases). All significant hail was produced by cellular convection. This distribution is very different from the results of Gallus et al. (2008) in the United States, where the largest number of significant-hail reports per case were associated with linear systems. Their result is likely influenced by the fact that linear systems are much larger scale and therefore likely produce more storm reports. Also, they did not include supercells as a separate category, even though embedded supercells are frequent in linear systems in the United States. Smith et al. (2012) found results more similar to our study, as almost all of their significant-hail events were produced by supercells. In our study, there were no clear differences in the mean maximum hail sizes between different parent-storm
modes because all 18 cases had produced maximum hail at least 5 cm in diameter.

Most of the storms (78%, or 14 out of 18 storms) had a lifetime of more than 3 h; 30% had a lifetime of 5 h or more. Discrete significant-hail-producing supercells had longer lifetimes than cluster supercells. The longer lifetime of discrete supercells was discovered earlier by Bunkers et al. (2006a). One explanation for the longer lifetime could be that the isolated storms are less influenced by the outflow of nearby storms. Also, sustained updrafts are more likely to suspend large hailstones for an increased period of time, allowing greater growth rates. Bunkers et al. (2006a) noticed that short-lived supercells typically deteriorate because of storm mergers or changes in convective mode. They also noticed that 74% of long-lived supercells (lifetime at least 4 h) in their study had significant hail associated with them.

The mean storm-track length in the whole dataset was 188 km, but there was variability; five storms had storm tracks shorter than 100 km and eight storms had a track longer than 200 km. Generally, the nonsupercells had shorter storm-track lengths (a mean of 87 km), cluster supercells were substantially longer (186 km), and discrete supercells the longest (257 km) (Table 1). The maximum measured storm track was 394 km.

The majority (67%) of significant-hail-producing storms moved toward the northeastern quadrant (0°–90°), and all but one occurred in the southern and central parts of Finland (Fig. 1). The northernmost case occurred on 1 July 2010 near Kemijärvi (66.5°N). During the most recent hail season of 2014 (not included in this study), significant hail was observed even farther north, as up to 6-cm hail damaged the small community of Kaarensuvanto (68.3°N) near the Swedish border (http://ilmatieteenlaitos.fi/tiedote/25584868).

When comparing storm direction of movement between storm modes, there seemed to be a difference between discrete and cluster supercells and ordinary cells (Table 1). The direction of movement of right-moving discrete supercells was mainly from the west and southwest. The speed of motion of the storm was on average higher in discrete supercells compared to the cluster supercells, and even lower in ordinary cells (Table 1). The weaker deep-layer shear is likely related to the slower storm motions.

All significant-hail-producing supercells experienced one or more changes in the direction of movement during their lifetime. Storm splitting occurred in most (six out of eight) of the cluster supercells, but in only a

<table>
<thead>
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<th>Parameter</th>
<th>Unit</th>
<th>No. of cases</th>
<th>Cluster supercell</th>
<th>Discrete supercell</th>
<th>Ordinary cells</th>
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<td>1080</td>
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<td>186</td>
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<tr>
<td>5-cm hail onset time</td>
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<tr>
<td>Direction of motion</td>
<td>°</td>
<td>18</td>
<td>214</td>
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</tbody>
</table>

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When comparing storm direction of movement between storm modes, there seemed to be a difference between discrete and cluster supercells and ordinary cells (Table 1). The direction of movement of right-moving discrete supercells was mainly from the west and southwest, whereas the direction of motion of cluster supercells was from the south and southwest (Fig. 8). The speed of motion of the storm was on average higher in discrete supercells compared to the cluster supercells, and even lower in ordinary cells (Table 1). The weaker deep-layer shear is likely related to the slower storm motions.

All significant-hail-producing supercells experienced one or more changes in the direction of movement during their lifetime. Storm splitting occurred in most (six out of eight) of the cluster supercells, but in only a
few of the discrete supercells (two out of six). The time from storm onset to the first significant-hail report varied between the two supercell types (Table 1). In discrete supercells, the significant hail was observed later in the storm’s lifetime, whereas in all cluster supercells significant-hail fall was observed within 2 h of the storm onset (Fig. 9). In two cases, the significant hail was observed within the first hour after storm formation. In ordinary cells, the storm lifetime was shorter, and also the onset time of significant hail occurred on average earlier than in supercell storms.

To look for radar signatures that precede significant hail, we consider the structure and evolution of the storms. By definition, all 14 significant-hail-producing supercells had a persistent hook echo. Eleven out of 14 had a bounded weak-echo region observed before the first significant-hail occurrence. However, in six cases, the storm lost both of these features close to the onset of the significant-hail fall. We speculate that the hail fall might have affected the radar-observable storm shape in these cases. Another possible explanation is that the hail fall occurred in response to the weakening of the updraft and consequential loss of capability to suspend the significant hail. Otherwise, no common features in the occurrence of the hook echo and bounded weak-echo region along the storm’s lifetime were observed. Also, no common storm-development structure was present before the significant hail began falling; each storm had a different evolution. All supercells, however, began as ordinary cells or as multicells before they developed into supercells. Similar onset morphologies were observed with supercell hailstorms in Oklahoma (Nelson and Young 1979).

Although supercell storms are observed in Finland by forecasters several times during a summer, only a few supercell cases have been documented and confirmed before this study. These cases have been mainly tornadic supercells (Teittinen et al. 2006; Outinen and Teittinen 2008; Teittinen and Mäkelä 2008) and significant-hail events (Tuovinen and Rauhala 2010; Rauhala 2011). This present study adds 14 identified supercell storms to the number of known supercell cases in Finland.

e. Storm convective mode in different environments

The time from storm onset (i.e., first 20-dBZ echo) to the first significant-hail report in a storm is only weakly related to the MUCAPE in the storm environment (Fig. 9). For times greater than 150 min, MUCAPE tends to be smaller, although this is a result of only two cases. Cluster supercells that produce significant hail have higher environmental MUCAPE than discrete supercells (Table 1). Significant-hail-producing discrete supercells form in somewhat higher deep-layer shear environments than cluster supercells (Table 1), and very high MUCAPE values are uncommon in discrete supercell cases (Fig. 8). Generally with all storm modes, the storm lifetime (i.e., time from the first 20-dBZ echo to the last 20-dBZ echo) increased with higher deep-layer shear (Fig. 10). Similar results have been shown by Bunkers et al. (2006a,b), who observed the short-lived (≤2 h) supercells to have lower deep-layer shear (0–8 km AGL) compared to the supercells with longer lifetimes. High deep-layer shear is also related to high values for storm motion and hail size (Table 1). The ordinary significant-hail-producing cells have on average the shortest lifetime, low shear, and very high MUCAPE for Finland (Table 1).

f. Significant-hail swaths

Significant-hail swath lengths were estimated if multiple significant-hail observation reports were obtained along an individual storm track. For the five storms with
multiple reports, the observed significant-hail swath lengths were 20, 21, 23, 32, and 35 km long. These hail swaths were long compared to the hail swaths (any size hail) observed in Oklahoma: 18.1 km for supercells and 8.1 km for ordinary cells (Nelson and Young 1979). Basara et al. (2007) produced a climatology of hail swaths over Oklahoma, but did not calculate swath lengths. The only difference between the five storms in our study compared to the Oklahoma cases was that they moved faster (mean of 13.8 m s$^{-1}$) than the Oklahoma storms (mean of 9.8 m s$^{-1}$). However, because of the limited number of ground-truth observations, hail reports were likely from only a small fraction of the entire hail swath. More recently, Barrett and Dixon (2012) studied a devastating hailstorm of 5 May 1995 in rural northern Texas by comparing radar and normalized difference vegetation index (NDVI) satellite data. They found three distinct hail swath (numerous reports of 5–10-cm hail) lengths of 8, 10, and 30 km. Gallo et al. (2012) studied hail damage over Iowa on 9 August 2009 by combining surface reports, radar data, and satellite imagery, showing significant-hail swaths over 50 km in length. In southwestern Germany, hailstorm tracks were found to be more than 70 km long in most cases from storms producing hail sizes 2 cm or larger (Kunz and Puskeiler 2010). In Switzerland (Schmid et al. 1997), three studied supercell cases produced hail swaths (any hail size) that varied between 70 and 170 km. Thus, the hail swaths in Finland tend to be smaller than hail swaths farther south in Europe.

g. Forecasting implications

Only 4 of the 18 studied significant-hail-producing storms in this study were classified as nonsupercells. By our definition, the supercells must have hook echoes. However, since supercells are possible even without hook echoes, our four nonsupercell cases may have actually been supercells. Therefore, forecasting convective mode and supercells would help significant-hail forecasting in Finland. For multicells (cluster cells and discrete cells) to produce significant hail, very large MUCAPE values for Finland seem to be needed (>1500 J kg$^{-1}$), although this is based on only three cases. To identify significant-hail-producing storms with radar, hook echoes and BWERs are often used. In our study, hook echoes were present in all 14 supercell cases by definition and BWERs were observed in 11 of the 14 cases. Forecasters need to know that these features may not be visible in radar imagery during the hail fall.

4. Conclusions

Although 78% of the significant-hail-producing storms in this study were supercells, not all of them have the amount of deep-layer shear generally suggested to be required to produce supercells. Of the significant-hail days, 39% have less than 15 m s$^{-1}$ deep-layer shear, the generally used criterion for supercells. As short-lived supercells tend to have weaker deep-layer shear than supercells with longer lifetimes (Bunkers et al. 2006a), our lower deep-layer shear suggests shorter supercells lifetimes than generally recognized, although the lack of Doppler radar velocities may limit our ability for a precise time of supercell onset. Larger hail tended to occur in storms that formed in higher environmental wind shear, a result that can be partly explained by the longer lifetimes of these storms at higher-shear values. There was a vast difference in deep-layer shear for thunderstorm and significant-hail environments. Although thunderstorm days had a mean of 10.2 m s$^{-1}$ deep-layer shear, for significant-hail events it was 17.5 m s$^{-1}$.
Significant hail formed in Finland in environments where MUCAPE was large (mean 1464 J kg\(^{-1}\)). Hail size tended to increase with higher MUCAPE values. During days with thunderstorms but no severe hail, the mean MUCAPE was lower (593 J kg\(^{-1}\)). Also, nonintense and damage-causing MCSs in Finland (Punkka and Bister 2015) had lower MUCAPE values than significant-hail-producing storms. For ordinary storms to produce significant hail, very high MUCAPE values seemed to have been needed (mean 2150 J kg\(^{-1}\)) along with low deep-layer shear (9.3 m s\(^{-1}\)). In contrast, the MUCAPE in discrete supercells was distinctly lower (mean 1080 J kg\(^{-1}\)), but seemed to be compensated by higher wind shear (23 m s\(^{-1}\)). Examination of different storm modes also showed that discrete supercells had on average longer lifetimes and longer storm tracks than cluster supercells. Discrete supercells also formed in higher deep-layer shear environments and had higher speeds of motion. In cluster supercells, the MUCAPE was on average larger than in discrete supercells and the significant hail was observed earlier in the storm’s life cycle. Significant-hail cases in Finland tended to occur in somewhat lower MUCAPE environments than in the United States, Australia, and central Europe, but the deep-layer shear was comparable to other locations.

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