A Climatological Comparison of Radar and Ground Observations of Hail in Finland

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ABSTRACT

Two approaches to producing a hail climatology for Finland are compared. The first approach is based on 70 yr of hail reports from different sources (newspapers, storm spotters, and other volunteers). The second is derived primarily from radar data. It is shown that a selection of newspaper articles of hail damage covering a period of 70 yr provides a good overview of the typical monthly and diurnal distribution of hail occurrence over the country. Radar data covering five summers (2001–05) provide another data source, but with different potential sources of errors. The two distinct methods compared in this paper give roughly the same results in describing the hail climatology of Finland, which gives additional confidence in each of the methods. On the basis of both methods, most hailstones are observed in the afternoon, 1400–1600 local time. The hail “season” extends from May to early September with maximum occurrences in June, July, and August. This means that hail is most frequently observed when the convective energy available for storm growth is at its diurnal or seasonal peak. The length of the hail season is the same according to both radar and newspaper data. The main difference emerges in relation to July and August events: 37% of news about hail events is published in newspapers in late July but only 8% in early August, whereas for radar data the numbers are more evenly distributed, 33% and 18%, respectively. This can be partially explained by sociological factors—July is the main holiday month in Finland, when outdoor activities in more remote areas are more popular.

1. Introduction

Hail climatologies describing the temporal and spatial distribution of significant hail have mainly been published in countries where damage caused by hail is common. In Australia, for instance, hailstorms are by far the most heavily insured natural hazard (Schuster et al. 2006), and in Canada they pose a serious threat to property and crops (Etkin and Brun 1999). These climatologies are often related to hail suppression by cloud seeding, agricultural and property losses, as well as to the aviation risks caused by hailstorms. Vinet (2001) mentions that in France the location of hailpads is concentrated in areas with hail-sensitive crops such as grapes. Webb et al. (2001) base their classification of hailstorms on their occasioned damages, but note that differences in building materials and types may affect the extent of damage in different countries.

Observations of hail and thunder have been collected for statistics and published in the early twentieth century in Finland and its neighboring country Sweden. For Finland, the Societas Scientiarum Fennica collected and published observations for the period 1887–1906. The editor of the 1903 thunder observations report complained that it was difficult to find observers in such a sparsely populated country and compared the situation with that in “civilized countries in Central-Europe” such as the Kingdoms of Prussia, Bavaria, and France. He noted that the density of weather stations in, for example, Saxony, was more than 10-fold that in Finland (Karsten 1907). The Swedish statistics for 1865–1917 show an average of 2–4 hail days annually in the latitude band corresponding to Finland and up to 6 hail days in the southernmost parts of Sweden (Hamberg 1917).

The climate of Finland is similar to that of the northern half of Sweden, and hailstorms are relatively rare. Nevertheless, even for such unlikely conditions, it is important for forecasters to clearly assess the risks associated with any given weather hazard that they may encounter while on duty. Climatology can help a forecaster to understand when a given event is most likely and to quickly realize the significance of a rare event when it occurs.

Another use of hail data is for the quality control of radar-based estimates of accumulated precipitation. Since
the relationship between radar reflectivity and precipitation amounts is different for hail than for rain, the occurrence of hail causes an overestimation of precipitation. To correct this overestimation, we must know the occurrence of hail at the same temporal and spatial resolution as that of the original radar data (Koistinen et al. 2008).

Data fusion methods combining radar reflectivity with temperature have been developed around the world to detect hailstorms, since single polarization weather radars do not provide all the necessary data to distinguish hail from heavy rain. For instance, Soviet scientists compared various radar parameters to the height of the 0°C isotherm (Waldvogel et al. 1979), whereas Auer (1994) used the cloud-top temperature. However, it is difficult to know how well these methods are suited to the Finnish climate because the verifying surface observations are usually not available. This paper therefore suggests a climatological approach for this validation. Radar data from seven radars during five summers, combined with temperature data from the archives of the European Centre for Medium-Range Weather Forecasts (ECMWF), have been used to create a high-resolution climate dataset for the assessment of hail occurrence and other phenomena related to convection and precipitation.

According to the Glossary of Meteorology of the American Meteorological Society (Glickman 2000), hail is defined as “precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds, nearly always cumulonimbus.” The quote from the glossary continues, “By convention, hail has a diameter of 5 mm or more, while smaller particles of similar origin, formerly called small hail, may be classed as either ice pellets or snow pellets.” Graupel is defined as “heavily rimed snow particles, often called snow pellets; often indistinguishable from very small soft hail except for the size convention that hail must have a diameter greater than 5 mm” (Glickman 2000). Operational applications concentrate more on forecasting and observing hail rather than graupel because graupel, also known as soft hail, often breaks or flattens out when hitting an object, without causing immediate damage (Schaefer and Day 1998, p. 244). From a weather radar perspective, hailstorms are more commonly detected than those containing graupel, since the convective clouds that produce hail have a large vertical extent and are thus well picked up by radars, even at long ranges. Radar-based hail-identification algorithms are known to miss graupel showers originating from low clouds, which are common in cold weather (Waldvogel et al. 1979).

Most climatological statistics are based on weather station reports. For Finland, however, there is no climatology of hail based on weather station reports. Tuovinen et al. (2009) created a climatology of severe hail (larger than 2 cm in diameter) based on non-standard data sources such as 70 yr of newspaper reports. The other climatological study made in Finland using a large dataset of convective phenomena is the thunderstorm climate of Finland during 1998–2007 by Tuomi and Mäkelä (2008). These two are used as references in this paper.

The main advantages of radar data are its consistency and good spatial and temporal resolution, whereas the dataset used by Tuovinen has a longer historical perspective. Radars can also detect hail of any size, while Tuovinen limited his studies to hailstones larger than 2 cm in diameter. This paper assesses the differences between the datasets from an annual, seasonal, and regional perspective. The data from the lightning locator system are used as an independent proxy for severe convection in Finland.

The scope of this paper is to compare a new hail climatology based on radar data with that deduced from the surface-based data of Tuovinen et al. If the climatologies found by the two disparate methods are similar, it adds confidence to the radar-based method, which can then in turn be used as a reference for other radar-based applications.

2. Data and processing methods

a. Radar data

1) EXTENT AND COVERAGE OF THE DATA

In this study a dataset of seven radars for 5 yr (2001–05) covering 5 summer months (May–September) of each year is examined. Volume sets for four elevations were archived every 15 min during the first 2 yr and every 5 min since June 2003, generating almost three summers of high-time resolution data. The elevations used were 0.5°, 1.5°, 2.5°, and 4°. These elevation angles and the typical vertical resolution in the case of radars spaced 140 km from each other are shown in Fig. 1.

During the 2001–05 period, the Finnish Meteorological Institute (FMI) operated seven C-band Doppler radars. The foundation year and coordinates of the radars are listed in Table 1 (Koistinen 2005). In southern Finland, the distance between radars is 140–200 km and measurements are made in bins that are 500 m long and 1° wide, up to 250 km in range. Thus, data from two or three radars are available over most of the study area. The location of the radars and their coverage are shown superimposed on a topographical map of Finland in Fig. 2. As Finland has no high mountains, the horizon of all the radars is near 0° elevation with no major beam blockage, and in general, the radar coverage is excellent up to a latitude of 68°N.
2) PROCESSING OF RADAR DATA

The data underwent several stages of processing. During the measurement, all the usual methods of Doppler filtering and thresholding were applied. The residual clutter and phenomena such as second trip echoes and the solar signal were removed using image processing methods described in Peura (2002).

The data from the seven radars are combined in a 3D Cartesian mosaic similar in principle to that described by Langston et al. (2007). There are several challenges associated with creating a 3D radar mosaic due to the nature of radar data and the spherical coordinates of radar observations. Even though only the four lowest elevations were used in this study, the number of data points in the vertical at any given location exceeds this, since at most locations the areas covered by different radars overlap.

The data were analyzed on a 1-km grid. At the outer edge of the radar measurement range of 250 km, a 1° bin is almost 5 km wide, and each measurement bin would cover several analysis grid boxes, which we will refer to as pixels. We decided to allot each measurement bin to one pixel only, leaving gaps in the analysis, instead of filling these gaps artificially with the data of neighboring pixels. This may cause apparent differences in data at the edges of the network compared to the areas covered by several radars. However, as the geometry stays the same, the observed seasonal and temporal behavior should not be affected. The areas selected for our study of regional differences also took this factor into account.

Hail is identified in the radar data using the method developed by Waldvogel et al. (1979). They compared several criteria for hail based on radar parameters and temperature to criteria for hail pad observations in Switzerland, to develop a method to attempt to distinguish hail cells from heavy rain cells. The criterion they selected was based on comparing the height of radar echoes stronger than 45 dBZ and the height of the 0°C isotherm. If the radar detects echoes stronger than 45 dBZ higher than 1.4 km above the freezing level, the Waldvogel method marks those echoes as hail.

Operational weather services in Finland, the Netherlands, and Belgium use a hail detection method based on the Waldvogel method (Delobbe et al. 2005), which also forms the basis of the method used in the Next Generation Weather Radar (NEXRAD) network in the United States for detecting hail of any size (Witt et al. 1998).

To use the Waldvogel method for this archived dataset, the 0°C isotherm heights were retrieved from the ECMWF Meteorological Archival and Retrieval System (MARS) database, which is the main repository of meteorological data at the ECMWF (Raoult 2001). For the period of this study, the ECMWF model had a resolution of TS11, corresponding at these latitudes to roughly 39 km. The data were interpolated onto a 0.225° latitude–longitude grid. For details about the ECMWF forecast model, we refer the reader to Simmons and Hollingsworth (2002; and references therein).

Delobbe and Holleman (2006) studied the uncertainties in radar echo heights used as input for this kind of
methodology. By comparing cross sections from two radars, they found that because of the broadening of the radar beam, the uncertainty in the determination of the convective core increases with range. Another error source is that of the beam overshooting the strongest echoes.

The Waldvogel method is better suited to indicating the formation of hail. However, it is possible that hailstones are correctly observed aloft, but that they melt before they reach the ground. They also travel significant horizontal distances. If a 1-cm hailstone falls vertically from a height of 5 km without being caught up in air currents, the fall takes 10 min, in which time the storm can move 10 km. However, the inherent advection of falling hail is not the only disturbing factor: in convective situations, shear and secondary circulations are usually present. Thus, hailstones cannot be expected to reach the ground at the time and place they are observed with the Waldvogel method. In this study, this is nevertheless not a major problem, as the exact location of the observation is not required.

The processing of the radar data used in this work is different from that of those used in the operational weather process in Finland. Operationally, it is more important to find every probable hailstorm. Here we wanted to decrease the number of false alarms, even at the cost of decreasing the probability of real detection of hail. The cases where we still may have false alarms are related to the melting of hail, but there are no methods available to verify such events.

3) POSSIBLE ERROR SOURCES IN THE RADAR DATA

The list of error sources for radar measurements of precipitation is long. They can be roughly divided into four categories: missing data, echoes not related to weather, overestimation of intensity, and underestimation of intensity. Not all these error sources are relevant for hail climatology. On the other hand, some rare error sources are more serious for hail than for other kinds of precipitation measurements.

Hailstones are typically observed in connection with strong convection, often accompanied by thunder and heavy rain, sometimes with downbursts and flash flooding. In Finland, the availability of radar data is usually excellent, 98%–99.9%. The missing data situations are often related to breaks in electricity supply or data connections. Such situations are more likely to happen during severe weather, especially for radars where electricity and telecommunication lines stretch long distances in forested areas, where storms can cause trees to fall and break power or telephone lines.

In this study, the monthly hail maps were inspected visually and compared with the monthly lightning maps, to ensure that the possible outages in electric power and data communications did not completely remove data relating to the strongest convective events.
The attenuation of C-band radar is not usually a problem in the temperate climate of Finland. However, in heavy rain showers, attenuation causes underestimation of the radar echo reflectivity, especially if the showers occur above the radar and cause radome attenuation. Heavy rain showers often occur in the same weather situations as hailstorms.

When favorable conditions (temperature and moisture) prevail in the atmosphere, microwaves can propagate in an abnormal way and be reflected from the ground or the sea surface. These disturbances are called “ground and sea clutter caused by anomalous propagation.” Hailstorms occur in weather situations having in general a near-neutral atmospheric temperature profile, which yields normal propagation conditions for microwaves, and thus the anomalous propagation mode is unlikely to occur. In daily forecasting work, a meteorologist is usually aware of the conditions causing a risk of anomalous propagation, and does not confuse these echoes for hail. However, in a climatological dataset, clutter echoes in such conditions are not automatically excluded, and could be potentially classified as hail cases. In Finland, an effective Doppler filtering removes most ground clutter, but residual echoes from the sea and ships still remain in anomalous propagation cases. In this work, the sea areas were excluded.

4) CLIMATOLOGICAL REPRESENTATIVITY OF THE RADAR DATASET

The same radar dataset has been used by Koistinen et al. (2008) in their work to study extreme precipitation events. To estimate the climatological representativity of the precipitation of these summers, they compared the distributions of gauge observations from these 5 yr with the reference periods 1961–90 and 1971–2000. Based on investigating conditions at five stations, they conclude that the precipitation climate of the summers in 2001–05 represents relatively well the climate of the reference periods, and can thus be used to describe the Finnish climate.

b. Lightning locator data

In this study, the lightning locator–based thunderstorm climatology is used as an independent reference describing severe convection in Finland. Since 1998, the current lightning detection network of the Finnish Meteorological Institute has been based on the detection of ground flashes via low-frequency (LF) electromagnetic radiation. These data are also exchanged within an international network including Finland, Norway, Sweden, and Estonia. During this 10-yr period, the network has been improved and the detection efficiency increased. The technical details of the system are described in the thunderstorm climatology study of Tuomi and Mäkelä (2008), in which thunderstorm statistics have been adjusted to account for the changes in the detection efficiency.

c. Surface observations

1) NEWSPAPER ITEMS

Hail damage in Finland is such a rare event that it is often reported in local newspapers. Tuovinen et al. (2008) collected a comprehensive hail dataset by carefully browsing microfilms of national major newspapers at the National Library for the years between 1930 and 1993, and for each year during the period from May to early September. In addition, newspaper articles of severe weather events between 1994 and 2005 were found with the aid of the main newspapers’ internet databases.

Tuovinen et al. found 155 cases documented in the newspapers, which constitutes 65% of the surface dataset cases used in this work; the remaining 35% came from volunteers during two campaigns organized by the FMI.

2) VOLUNTEERS’ OBSERVATIONS

In May 2006, a brief request for recent and historical large hail observations was placed on the front page of the FMI’s Web site for some weeks. This proved to be an efficient way to collect hail cases, because most of the observations sent via e-mail included a photo of either the damage or the hail itself. Up to 46 cases (19% of all cases) were gathered in this way. Nevertheless, every case was checked against weather radar data to assess whether high-reflectivity values had occurred that fit the observed location and time. Some problems were detected with a few eyewitness reports, in which there was a mismatch of the time, date, or even year of observation. In these cases, a request to check the observation was sent to the observer and, if clarification was not possible, the observation was rejected. In the diurnal distribution, 45 such cases (of the total 240 cases) were rejected because of an uncertain observation time.

In addition to the Web site campaign, a more organized collection of hail reports was organized with a small network of voluntary storm observers. A group of about 50 storm observers has been cooperating with the FMI on a hail observation program since 2004. They contributed 35 severe hail reports—15% of the 240 hail reports based on surface observations. These reports were used to examine diurnal and seasonal distributions of hail. These observers are organized as a section of the Ursa Astronomical Association, and are scattered around southern and central Finland, mainly south of 63°N. They have access to radar-based fields of probability of hail produced by the FMI every 5 min, and in return.
they report hail and other strong convective phenomena. As amateur astronomers, these people are keen observers and very well aware of the significance of time accuracy in their reporting. However, the difference between hail, graupel, and ice pellets was perhaps not always so clear to them, especially as in Finnish the general term “rae” (granule) is often used for both hail and graupel. During summer 2008, they added an extra field in their report describing the material of the observed hail, adding one of the following attributes: “white,” “whitish,” “transparent,” “clear-ish,” “snowy,” “white and fluffy,” and “white, soft and porous.”

d. Other possible data sources

Other types of data can and have been used in other similar studies (e.g., Schuster et al. 2005; Hohl et al. 2002; and Holleman 2001). These methods, and the reasons why they were not used, are briefly described in the appendix.

3. Results and discussion

a. Number of hail days

From our dataset covering 77 yr of newspaper data, each summer there was an average of 5 days with severe hail reports, but with a large variability from year to year (Fig. 3). For radar data, there is no unambiguous number. Punkka and Bister (2005) studied a two-summer period (2000-01) looking for days when the radar reflectivity in 500 m CAPPI images exceeded 40 or 50 dBZ. They concluded that summertime convective precipitation is almost a daily phenomenon over the Finnish radar network, and heavy convective precipitation occurred on 35%–50% of all days. Although they did not study the exact nature of the convective systems, it is generally known that reflectivities over 50 dBZ are associated with increased risk of hail. Our results with a larger dataset confirm their conclusions: the Waldvogel criterion for hail (reflectivity >45 dBZ at height higher than 1.4 km above the freezing level) is fulfilled every summer day at least one point in the Finnish radar network. On some days, there are just a few hail pixels in the radar data, but days with more than 35,000 hail pixels do also occur. Considering that 288 measurements are performed every day, this means on average over 120 hail pixels in every 5-min map.

We also tested the possible influence of the threshold value (45 versus 50 dBZ) on the results by recalculating hail occurrence from radar data for the year 2004 using the 50-dBZ threshold. Then we compared it to the lightning data, as used in Fig. 4. As expected, the number of daily pixels decreased and the number of no-hail days increased. Additionally, the number of days with hail but no lightning (“false alarms”) decreased but, on the other hand, the number of opposite mismatches (lightning but no hail) increased. Furthermore, the correlation with lightning data decreased (however, a Pearson correlation of nonnormally distributed variables is not very relevant here). Consequently, we assume that our results based on the classical 45-dBZ threshold are representative.
The daily variance of the number of hail pixels for summer 2004 is shown in Fig. 4. During this whole summer, there were no reports of hail from any of the synoptic stations, but newspapers and volunteers reported hail on 9 days. As a qualitative indicator of convective activity, the number of located cloud-to-ground (CG) lightning strokes (from Tuomi 2004) is also shown in Fig. 4. The picture shows that on all hail days noted by human observers, radar data also showed at least some hailstones. Conversely, between 11 May and 22 June, there were no newspaper or volunteer hail reports, only a small number of hail observations from radars and few lightning strokes. On the other hand, from 16 July to 11 August and again from 20 August to 2 September, there were no newspaper reports of hail, even though both radars and the lightning locator system indicated large amounts of convective activity.

It is not surprising that the radar-based estimate of the number of hail days is higher than that observed in ground reports. Many hailstones can fall undetected by human eyes. Moreover, ground reports concentrated on severe hail cases, while the radar data can show hailstones of any size. Additionally, the radar “sees” even hail that melts before it reaches the ground.

Even though lightning can occur without hail and hail can occur without lightning, lightning data act as a rough measure of convective storm occurrence. Days having the largest number of radar observations classified as hail also have a significant amount of lightning, and the days of heaviest lightning activity have a significant number of hail observations in the radar data.

b. Diurnal variation

The diurnal variation (Fig. 5) in the different datasets was studied by sorting each dataset into bins of 2-h duration, and calculating the percentage of observations in each period.

The surface observation reports show a clear maximum in the afternoon with a maximum for 2–4-cm hailstones at 1400–1600 LT, and at 1600–1800 time for very large hailstones (>4 cm). Practically no hail is reported during the night. Such a maximum occurrence in the afternoon and early evening is typical for hail fall observations in other parts of the world as well, for example, in France (Dessens 1986), Italy (Giaiotti et al. 2003), Canada (Paul 1980) and New South Wales, Australia (Schuster et al. 2005). Webb et al. (2008) found a strong preference for hailstorm occurrence just after the mean time of peak daily temperatures, but also some events independent of surface heating. In New Zealand, Steiner (1989) compared spontaneous reports from the press to hourly standard reports from the weather stations, and noticed a maximum afternoon occurrence in data from the press in a majority of the studied areas. In Alberta, Canada, Brimelow et al. (2004) used a radar-based “severe pixel count” and noticed severe convection usually starting after 1200 LT, and reaching its peak 1600–1800 LT.

The radar parameter used is total number of grid cells classified as hail using the Waldvogel criterion, accumulated from the eight measurements made during the 2-h period. The diurnal distribution has a smoother distribution with a maximum occurring at 1400–1600 LT, and a minimum at nighttime (0200–0600 LT). Afternoon maximum and nighttime minimum are also seen in the other Finnish convection-related study: Tuomi and Mäkelä (2008) report that the lightning locator data have a maximum slightly later (1500–1700 LT), with the nighttime minimum lasting from 0400 to 0900 LT.

The diurnal distribution is quite similar to that observed in Sweden for the period 1865–1917. There the maximum of hail was observed at 1300–1400 LT, and for lightning at 1600–1700 LT, while the maximum for graupel was already observed earlier, at 1100 LT (Hamberg 1917).

The general shape of all the distributions of convective phenomena mentioned above is rather similar. The
differences can be explained by both a physical and a sociological factor. Surface reports are related to the largest hail, while there is no size limit in the radar dataset. A major part of the severe convection in Finland is not forced solely by frontal or other synoptic weather systems but is driven or enhanced by solar heating. Thus the statistical maximum of occurrence of large hail and thunder occurs during the late afternoon hours. Second, reported observations are manmade, and less people are outside to make observations at night. The lightning and radar data suggest that nocturnal events of strong convection do occur, but they are much less common compared to daytime events.

c. Seasonal variation

The seasonal variability was studied by segregating our data into periods of 2 weeks (Fig. 6). In all datasets, the maximum (34%–38% of all observations) is observed during the second half of July, while May and September occurrences were few in number. As was true for the diurnal distribution, the shape of the seasonal radar observations’ distribution is rather...
similar to that of the distribution of the other observations. The largest difference is the sudden decrease of reports of smaller hailstones from the end of July to the beginning of August.

The straightforward physical explanation of this seasonal distribution is that hail is most frequent during the climatologically warmest month, July (Drebs et al. 2002), when also the largest hailstones are generated because of the enhanced convective energy available for their growth. Correspondingly, the diurnal distribution displays its maximum near the warmest time of the day.

In addition to the seasonal cycle of convective activity, part of the explanation can relate to human behavior: July is the main holiday season in Finland, when more people spend time outdoors, especially in remote areas, where normally there is no one around. An additional reason might be that summer holidays also take priority over politics and other socioeconomical matters, so that newspapers welcome stories about hail events. In support of this latter explanation, it may be mentioned that Finland has an exceptionally dense coverage of local–regional newspapers, which encourage laymen to submit their stories and photographs (even cellphone camera quality is accepted). In August, society returns to its normal course (e.g., school starts), so there is less space left for hail news.

The hail statistics can be compared to another source of information of convective activity: the lightning locator statistics. Ten-year statistics of lightning observations (1998–2007) show that the thunderstorm season starts in approximately late May, with the maximum occurrence of lightning (negative and positive cloud-to-ground lightning) being observed in mid-July (Tuomi and Mäkelä 2007). Afterward, the amount of CG lightning decreases steadily until the end of August. As observed by the FMI ground lightning location system of eight sensors, there are on average somewhere over 100 000 CG strikes within Finnish territory every summer (Tuomi and Mäkelä 2007).

The same radar data as above, but grouped into 5-day periods, are compared with the lightning observations in Fig. 7. The use of 5-day periods shows more detail, but cannot be applied to surface observations because of their small number. In addition, the average daily maximum temperature in Helsinki, Finland (Kaisaniemi observation station), for the same 10 yr as the lightning dataset is depicted to indicate the warmest time of the year.

d. Regional differences

The population of Finland is strongly concentrated in the coastal areas (southern and western parts of the country). Elsewhere, the country is characterized by a very sparse population, vast forested areas, thousands of lakes in central Finland, and hilly landscapes in the north. The average population density is 17.4 individuals km$^{-2}$. The lowest density is found in Savukoski, northern Finland, 0.22 km$^{-2}$. Of the 20 counties, 7 have a population density of over 30 km$^{-2}$, while the northernmost ones have less than 5 (Lapland 2.0 and Kainuu 3.9) (Finland in Figures 2007).

As weather observations are typically performed near population centers, none of the observation networks are spatially homogeneous throughout the country. Geostationary satellites have a coarser resolution at high latitudes, and the overpass times of polar-orbiting satellites are not suitable for studies of convection. Radar images for near-surface precipitation cover the country in a satisfactory manner up to 68.5°N, but for hail detection additional measurements from the mid- and upper troposphere are required, and these measurements are not homogeneously distributed.

The best regional coverage for convection-related weather phenomena is achieved by the lightning locator network. However, although it has a homogeneous dataset, this only covers 10 yr, a short period over which the effect of random or low-frequency weather variations can affect the representativeness of the results. The 10-yr flash density map of Tuomi and Mäkelä (2007) (Fig. 8) displays a northwest–southeast maximum zone with over 40 lightning strokes per year in 10 km $\times$ 10 km squares, which extends from the west coast (63°–65°N) to the eastern border (61°–62°N). The areas to the southwest and south of this band, in principle warmer, are characterized by a density of less than 30 lightning strokes per year per grid square. This is probably due to the proximity of a cold sea (average sea surface temperatures of Finnish sea areas in July are 13°–17°C; Leppäranta and Myrberg 2009) inhibiting convection, as the prevailing winds are southwestlies. North of 65°N, lightning densities expectedly decrease again to below 30, and even to below 20, flashes per year per grid square.

Based on this lightning density map, we selected three areas having different representative climatological characteristics (see Fig. 8). Each area was selected to be 10 000 km$^2$ in size, and at roughly similar distances from the nearest radars, and within regions where lightning locator data do not need to compensate for the changes in detection efficiency. From these areas we selected all hail pixels in the 5-yr dataset and all lightning in the 10-yr dataset.

In this comparison of hail versus flash counts, the three selected areas (in southern, eastern, and northern Finland) seem to display similar spatial distributions (Fig. 9). The eastern area has on average more hail than the two other areas. However, the year-to-year variability (illustrated
with error bars in Fig. 9) is large. The standard deviations of the radar data are smaller than those of the flash data. We suggest that this is due to the shorter time series of the radar data.

4. Connections between these findings and the operational weather service

a. Operational applications in Finland

The Waldvogel method used in this work was designed to give a single deterministic criterion. In the operational weather service, forecasters have preferred to use an index that measures the uncertainty embedded in this criterion. At the Royal Netherlands Meteorological Institute, Holleman et al. (2000) developed a method to estimate the probability of hail (POH) based on Waldvogel’s work. The Holleman method has been used at the FMI since 2003 and in the operational weather service of several other European countries (e.g., Belgium and the Netherlands).

Holleman developed the equation for the probability of hail:

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\frac{\text{Flash } (\%)}{\text{Temp } (\circ C)}
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Fig. 7. The relative number (%) of radar observations classified as hail 2001–05 (positive bars) and lightning observations 1998–2007 (negative bars). Both datasets are scaled so that the sum is 100%. The dashed line represents the 5-day average of the 10-yr average (1998–2007) daily maximum temperature (°C) in Helsinki (Kaisaniemi).
POH = 0.319 + 0.133(H45 − FZL),

where H45 is the maximum height of the 45-dBZ echo and FZL is the freezing level (i.e., the height of the 0°C isotherm; both in kilometers).

Tests of the method in the Netherlands (Holleman 2001) and Belgium (Delobbe et al. 2005) show a high detection rate. In Belgium, 94% of the verification cases had a probability of hail of 50% or higher. All events with a hail size of at least 2 cm were detected, with a probability of hail of at least 80%. The methods used in the Belgian study did not allow the determination of the false alarm rate (FAR). Holleman achieved poor results in several May cases, which he attributed as being connected to “winter hail” falling from shallow clouds in large-scale weather phenomena, because shallow events cannot be seen with a radar at long distances. After limiting the dataset to summer hail only by selecting cases with a freezing layer of 2 km or higher, he got critical success indices of 0.48 and 0.56 for the different datasets. Unlike Delobbe et al., Holleman was able to calculate false alarm rates because of his more extensive reference dataset; he found that the choice of the warning threshold was very sensitive in obtaining a satisfactory balance between FAR and missed cases.

In the Holleman method for POH calculations, 0°C isotherm heights are combined with radar observations of the maximum height of the 45-dBZ echo. In the FMI procedure, the occasional “beam undershooting” (i.e., the situation in which the highest radar beam does not “see” an echo above it) is compensated for by extrapolating upward when necessary. Extrapolation is needed when the reflectivity at the highest measurement point is over 45 dBZ. In these cases the reflectivity is assumed to decrease by 5 dBZ km⁻¹ above that level, thus allowing the height of 45 dBZ to be estimated. Even though this method can overestimate the exact value, it at least gives an indication of the probable presence of hail. Each
POH value is flagged according to whether it is based on actual radar measurement or extrapolation. On average, 8% of the values come from extrapolated height estimates. The extrapolation is needed most often in the vicinity of the most northern radar, Luosto, because there no data from neighboring radars are available to correct for beam undershooting near the radar.

This study encourages the use of radar-based hail detection in the operational weather service. The climatological studies give confidence in the use of the Waldvogel method, and the Holleman method adds more usability to the same physical principle. For weather forecasters, the near–real timeliness and the temporal and spatial resolution make radar a valuable tool. In addition to that, flagging of the inferred hail data can be used to remove overestimation caused by hail in the radar-based precipitation estimates.

b. **Foreseeable changes in the observations**

Manual synoptic observation practices have quickly disappeared during the last decade or so, and most synoptic stations are now automatic. Most automatic stations are equipped with sensors that can detect some form of solid, hard precipitation, but they cannot distinguish hail from graupel. Thus, estimates of the shape and type of hydrometeors will increasingly rely on remote sensing techniques.

In Finland, the FMI radar network is evolving constantly. In 2007, for instance, the scanning schedules and selection of elevation angles were changed to better respond to the new requirements for Doppler wind data. Thus, datasets will no longer be directly comparable with those of previous years. Current radars will be gradually replaced by dual-polarization radars. These will provide several new parameters that can be used for hydrometeor classification (Ryzhkov et al. 2005).

On the other hand, these changes will mean a disruption in the data time series, as the scan schedules will again be changed; the radar sensitivity will also be different.

Thus, the present study has been able to make full use of all available homogenous data, so that this climatology will be useful as a reference set for future studies utilizing the new data sources.

5. **Conclusions**

According to this study, hail detected by radar seems to have meteorologically reasonable distributions in time, place, and probability. Occurrence maxima occur in (late) afternoon and during the warmest months of the year. There are no clear regional differences, but such patterns would not be very clear anyway in areas with generally less hail and convective activities.

We have shown here that newspaper articles provide a novel source of reports of extreme weather (though the definition of “extreme” depends, naturally, on the local climate). They can be used as an independent source for ground references, but the results must be interpreted carefully, as the observations are not made with scientific purposes in mind. Distributions based on this dataset of newspaper reports agree well with the independent radar datasets.

Using remote sensing techniques (radar) enables better spatial and temporal resolution than any surface observations. Spontaneous observations, such as those made by voluntary storm observers or newspaper reporters, are especially influenced by people’s current everyday activities. Remote sensing observations do not have such a bias, although they do have other weak sides.

Here we have used the Waldvogel method, which studies convective cores in the upper parts of clouds. This means that a hailstone correctly identified thereby can still melt before hitting the ground. Other radar-based methods typically collect data from the height range of 500–1500 m. Therefore, a perfect agreement between these methods was not expected, nor was it found.

Using Waldvogel-type algorithms for radar-based hail detection puts demands on the scanning strategy. Reasonably high elevations must be scanned fairly frequently. An operational scan strategy is always a compromise, since adding spatial resolution means decreasing temporal resolution. Convective weather systems develop so rapidly that frequent updates of the low-elevation scans are needed. However, our good results with hail detection suggest that some of the valuable measurement time should also be devoted to higher elevations.

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**APPENDIX**

**Other Possible Sources of Reference Data**

a. **Surface data**

Many researchers (e.g., Schuster et al. 2005; Hohl et al. 2002; Holleman 2001) have used insurance claims...
as reference data for hail observations. In Finland, three major insurance companies (If, A-Vakuutus, and Pohjola) and the Federation of Finnish Insurance Companies were approached for records of hail damage to vehicles or other property. Unfortunately, such information was not available because hail damage to vehicles in Finland is classified in the same category as collision accidents.

In research projects, hailpads have been used as a reference instrument (Waldvogel et al. 1978; Sanchez et al. 1996). They are simple, reliable, and cheap, but their use needs a lot of manpower, so they are not very suitable for studying the climatology of large areas.

Another traditional reference for radar studies is observations from weather stations. The FMI database contains 3-hourly observations from approximately 50 synoptic stations for the period 1960–2007. Hail is reported as defined by the World Meteorological Organization (WMO) code 4677 (Table A1) using weather codes 89 and 90 (hail, no thunder), as well as 93, 94, 96, or 99 (thunder with hail, small hail, graupel, or severe thunderstorm with hail).

Altogether, there were 474 such reports (i.e., roughly one observation in 5 yr at each station). These observations were sorted by temperature for additional quality control. Unfortunately, 75% of these observations were made at temperatures lower than or equal to 10°C. Thus, we suspect that the major part of these events is graupel or ice pellets, and therefore different from classical summer hail.

Etkin and Brun (1999) met a similar problem when investigating Canada’s hail climatology. Because of the fact that in Canada ice pellets have often been recorded as hail, they restricted their analysis to the warm months of May–September. In New Zealand, Steiner (1989) analyzed hourly standard reports from weather stations, and noticed a difference from the hail damage reports in the press. He also concluded that it is likely that much of the hail reported by the climatological stations is indeed really ice pellets or small hail.

Hail climatologies in other countries are usually based on surface observations [e.g., Zhang et al. (2008) in China, Schuster et al. (2005) in New South Wales, and Etkin et Brun (1999) in Canada]. For Finland, the remaining dataset after the removal of suspicious reports is far too small for any statistical analysis. Thus, synoptic observations were not used in this work.

b. Alternative radar-based methods

A conventional (i.e., single polarization) weather radar cannot directly detect hail. Instead, statistical methods related to typical meteorological properties of hailstorms are used. Radar reflectivity is related to the sixth power of the diameter of the target. Hailstones, which are typically larger than raindrops, thus generate large reflectivities.

The simplest approach is to use radar data from a height relatively close to the ground and mark all pixels with a reflectivity over a threshold (typically 50 or 55 dBZ) as hail pixels. This method is used operationally, for example, in Slovenia (Strajnar and Zagar 2007). Schuster et al. (2005) used in their hail study a threshold of 55 dBZ at CAPPI levels of 1500 m. Since the reflectivity Z measured by radar depends on the size and number of hailstones, an estimate of hail kinetic energy can be derived from the reflectivity (Waldvogel et al. 1978). This kinetic energy has been used as the descriptive parameter by, for example, Schuster et al. (2006) and Hohl et al. (2002).

The weak point of using constant altitude radar data is the bias due to the distance from the radar, since in areas farther away from the radar, even the lowest radar beam often overshoots the strongest echoes. It is also difficult to distinguish hail from clutter, and in climatological applications this may cause a bias in either direction, depending on how thoroughly the clutter has been eliminated. The advantage of such a method compared to the Waldvogel method is that it minimizes the error caused by the time the hailstones take to fall to the ground after being observed by radar aloft and by storm advection. It also has the same main advantages as other radar methods: consistency and good spatial resolution.

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