FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS

NO. 88

ON THE USE OF WEATHER RADAR FOR MESOSCALE APPLICATIONS IN NORTHERN CONDITIONS

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ACADEMIC DISSERTATION in meteorology

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in Auditorium of Finnish Meteorological Institute (Erik Palmenin aukio 1) on May 20th, 2011, at 12 o'clock noon.

Finnish Meteorological Institute
Helsinki, 2011

ISBN 978-951-697-741-9 (paperback)
ISSN 0782-6117
Unigrafia
Helsinki, 2011

ISBN 978-951-697-742-6 (PDF)
http://ethesis.helsinki.fi
Helsinki, 2011

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PREFACE

The work presented in this thesis has been carried out at the Meteorological Research Unit of the Finnish Meteorological Institute (FMI) during the period 2008–2010.

This thesis is finished almost 20 years after my master s thesis. That time, I was not even considering graduate studies, I was eager to go forecasting. The forecasting offices, especially those in Kuopio and Tampere, have been the places where I have acquired much of the knowledge and motivation for the meteorological parts of this work. Hence, I would like to thank colleagues and co-workers for the tuition.

In 1996, I joined the FMI radar team. This was the second intensive learning phase. Not only did I learn about LNA, VIL and RCP (and other TLAs) but also about relativeness of everything: how one man s rubbish is another man s gem, and how ”useless academic snobbery” becomes ”a million dollar question” within a decade. Hence, I d like to thank the past and present members of the extended radar team for providing multiple vantage points to all matters measurable and priceless.

The articles which form this thesis would not have appeared at this pace without the encouragement of my immediate supervisors Asko Huuskonen and Sylvain Joffre, who were always available for in-house reviews, advice and opinions. I am also grateful to my responsible supervisor, Hannu Savijärvi, for his patience during the long years of my graduate studies.

The encouraging comments of two pre-reviewers of this thesis, Professor Chris Collier and David Hudak, have helped me to strengthen my knowledge at the areas where is was weakest, which makes me calmer waiting for the day of defence. I also wish to express my most sincere appreciation to the anonymous reviewers of all the papers. For a student of a small niche in a small country, the reviewers are important teachers.

I wish to express my gratitude to all of my co-authors: Asko, Jarmo, Harri, Heikki, Ljuba, Jari, Janne, Timo, Otto, Ilkka, Marjo and Dmitri - the path to an accepted paper has not always been so smooth, but supporting each other we have almost always arrived there.

Almost finally, I wish to apologise to my family and friends whom I have sorely neglected even more than usual over the last three years, and thank everyone for the shelter they gave me from the storms of the real world allowing me to enjoy the sunny uplands of a carefree graduate student.

Finally, words can t express my gratitude to Ari.

Helsinki, April 2011

Elena Saltikoff

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

I Saltikoff, E, Huuskonen, A, Hohti, H, Koistinen, J and Järvinen, H, 2010: Quality Assurance in the FMI Doppler Weather Radar Network. *Boreal Env. Res.* 15: 579–594.

II Saltikoff, E and Nevvonen, L, 2011 : First experiences of operational use of a dual-polarisation weather radar in Finland. *Meteorol. Z.* 20 (in press), doi: 10.1127/0941-2948/2011/0197

III Saltikoff, E, Tuovinen, J-P, Kotro, J, Kuitunen, T, and Hohti, H, 2010: A climatological comparison of radar and ground observations of hail in Finland. *J. Appl. Meteor. Climatol.*, 49: 101–114. doi: 10.1175/2009JAMC2116.1

IV Hyvärinen, O and Saltikoff, E, 2010: Social media as a source of meteorological observations. *Mon. Wea. Rev.* 138: 3175-3184. doi: 10.1175/2010MWR3270.1

V Juga, I, Hippi, M, Moisseev D and Saltikoff, E, 2010: Analysis of weather factors responsible for the traffic ”Black Day” in Helsinki, Finland, on 17 March 2005. *Met. Appl.* 17 (in press) doi: 10.1002/met.238

BRIEF DESCRIPTION OF THE CONTENT OF PAPERS 1-5 AND AUTHOR S CONTRIBUTION

I Saltikoff, E, Huuskonen, A, Hohti, H, Koistinen, J and Järvinen, H 2010: Quality Assurance in the FMI Doppler Weather Radar Network. *Boreal Env. Res.* 15: 579–594.

PAPER I describes the first national Doppler radar network in Finland, how it was designed and is used, and most importantly, what were the main meteorological, technical and geographical incentives and constraints, while setting up the network. The author compiled the paper based on several conference papers by the FMI radar team during the two previous decades, in many of which she was also one of the authors. The author was also responsible for the major part of the writing, apart from the section on "Sun calibration".

II Saltikoff, E and Nevvonen, L 2011 : First experiences of operational use of a dual-polarisation weather radar in Finland. *Meteorol. Z.* 20 (in press), doi: 10.1127/0941-2948/2011/0197

PAPER II describes the major upgrade to dual-polarisation radars, the needs and limitations guiding the new measurements, and shows with examples what the new radars can measure. The author is responsible for the end-user interviews and analysis of the weather cases as well as writing the text and constructing the images.

III Saltikoff, E, Tuovinen, J-P, Kotro, J, Kuitunen, T, and Hohti, H 2010: A climatological comparison of radar and ground observations of hail in Finland. *J. Appl. Meteor. Climatol.*, 49, 101-114. doi: 10.1175/2009JAMC2116.1

PAPER III discusses hail detection as an application for a conventional radar network. The method has been used operationally for years, but not verified. This paper suggests an indirect verification method by comparing the statistical properties of the results with those of an independent data set. The author was responsible for the radar-related parts of the paper: calculations from grid level to climatological values as well as writing major parts of the text.

IV Hyvärinen, O and Saltikoff, E 2010: Social media as a source of meteorological observations. *Mon. Wea. Rev.* 138, 3175-3184. doi: 10.1175/2010MWR3270.1

PAPER IV introduces the use of a novel data source as a surface reference for remote sensing applications, namely, photos published in web-based non-meteorological services such as Facebook and Flickr. The author was in charge of the two case studies with radar detecting hail, and also contributed to the writing of the text.

V Juga, I, Hippi, M, Moisseev D and Saltikoff, E 2010: Analysis of weather factors responsible for the traffic ”Black Day” in Helsinki, Finland, on 17 March 2005. Met. Appl. 17 (in press) doi: 10.1002/met.238

PAPER V concentrates on an analysis of a high-impact winter weather case. Radar data are used for a fine analysis of the changes in intensity and form of the precipitation leading to severe traffic accidents. The author performed the comparisons of radar data to the other instruments, and also contributed to the writing of the text.

These five papers address with different emphases, on the one hand, the properties and use of weather radars and, on the other hand, the analyses of meteorological phenomena observed with these radars. In the following, the technological aspects are discussed in Chapter 2, while Chapter 3 concentrates on the meteorological phenomena. In both chapters, the first section is a background review as to the relevant issues, while the second section summarises the scientific results. Finally, Chapter 4 presents an outlook for the future with respect to technical developments, scientific challenges and applications for end users.

1 INTRODUCTION

Before weather radars were used, even high-impact weather systems could remain undetected by standard weather observation networks. In 1971, for instance, a storm suddenly occurred during a sailing competition at Emäsalo, witnessed by dozens of participants, but only one wind measurement exists as an official record of the storm, because it was too small and short-lived to be ”caught” by the observation network with the then-existing mean spatial resolution of 50 km and time resolution of 3 h. On 14 December 1981, a lake-effect snowstorm, developed over the Gulf of Finland and halted traffic on the motorways west of Helsinki due to 5-10 cm of accumulated snow. Again, there was no forewarning, and nobody knew about it before the snow was on the road.

Weather radars have the capacity to observe small-scale weather phenomena connected with storms, including heavy rain, snow or hail. These observations also provide valuable information on near-future development of such phenomena. Therefore, in order to adequately observe and forecast hazardous weather situations from the point of view of the safety and efficient functioning of society and the economy, the Finnish Meteorological Institute (FMI) has over a period of years endeavoured to acquire a suite of weather radars. However, the mere acquisition of such instruments is not the end of the story. To satisfy the needs of the weather service, a complex chain of factors is involved, of which weather radars are only a part, as illustrated in Fig. 1.1. This thesis addresses one of the feedback mechanisms in that diagram: how, , based on our understanding of the atmosphere, the measurement scheme can be planned better and, vica versa, how analysis of these observations adds to our understanding of the atmosphere.

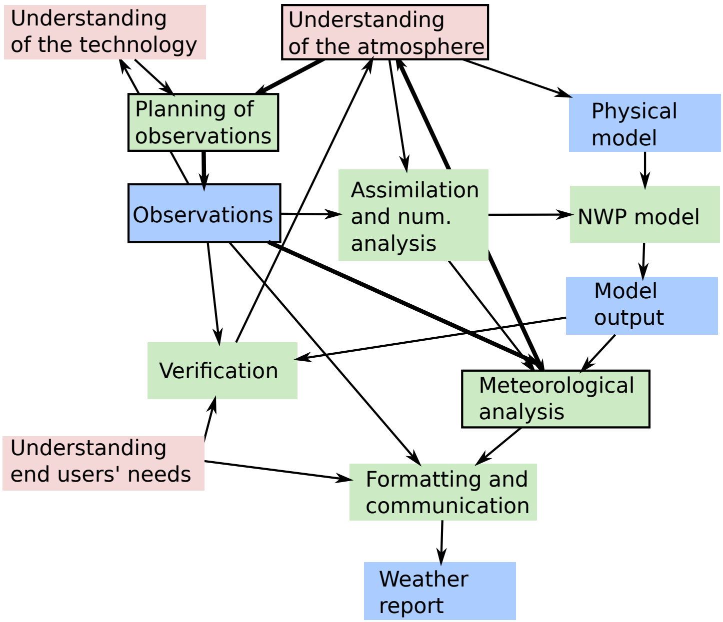

FIGURE 1.1. Sketch of the chain of operations and phases for generating a weather report based on an understanding of the atmosphere, and technology, as well as of the needs and behaviour of end users. Pink boxes denote understanding, green boxes activities and blue boxes resulting products. The components discussed in this thesis are the boxes framed in black.

2 WEATHER RADARS

Weather radars operate by radiating pulses of electromagnetic energy and detecting the echo returned from scattering objects. The location of the target is determined by the timing between the transmission and reception (Skolnik, 1990). From this backscattered radiation we can deduce a considerable amount of information on the surrounding atmosphere: where it is raining or snowing and how heavily, and how the targets are moving with the wind. More advanced methods can give estimates of turbulence (e.g. Lee, 1977), wind shear and even the shapes of the scattering particles (e.g. Bringi and Chandrasekar, 2001; Ryzhkov et al., 2005) .

2.1 EVOLUTION OF WEATHER RADARS

Radars have been used to detect precipitation since the 1940s and 1950s - the research in the early years had strong military connections, and hence all the details are not openly documented (Doviak and Zrnić, 1993). During the first decades, at least until 1970, radar meteorology relied on real-time displays and photographs or other methods of saving a live image (Whiton et al., 1998). The development of signal processors in the 1970s enabled a huge step from radar images to radar data. Using these processors to save data to computer media, it was possible to combine measurements from different altitudes and different moments of time, and so to create all the products which are nowadays considered standard output of a radar system, such as constant altitude images (CAPPI = Constant altitude plain position indicator), vertically-integrated liquid water (VIL) and accumulated precipitation products, as described e.g. in Cluckie and Collier (1990).

Since those days, the weather radar has been used for quantitative precipitation estimates (QPE), even so much so that in some places it has been called ”rainfall radar”. Three types of uncertainties complicate the use of radar for QPE: natural variability of particle-size distributions, vertical reflectivity profile and instrumental considerations. The vertical profile of reflectivity (VPR) in stratiform liquid precipitation has a typical shape with a maximum in the melting layer and a decreasing gradient above that. It results from growth of the hydrometeors in the snow aggregation regime, different dielectric constants and fallspeeds of raindrops and snowflakes. Deducing the rainfall rates on ground from radar measurements aloft requires taking into account the vertical profile of reflectivity. Joss and Lee (1995) have described a sophisticated method, while Koistinen (1986) showed that even crude estimates of VPR can improve QPE. Particle size distributions add a fundamental source of uncertainty, because radar reflectivity Z is proportional to the 6th power of hydrometeors diameter, while the rainfall rate R is roughly proportional to the 4th power of particle diameter, but all R(Z) relationships are extrapolations of empirical values, achieved with limited data sets (Joss and Waldvogel, 1990).

Zawadzki (1984) summarized the factors affecting the precision of radar measurements of rain. These included technical and geometrical limitations as well as the fundamental properties of precipitation processes, details for which our understanding is incomplete. Since then, corrections for many of the factors he listed have been developed and brought into operational use (e.g. Saltikoff et al., 2010). However, there are fundamental differences between the measurement principles of radars and raingauges, and all attempts to replace one with the other will lead to compromises and a loss of information.

Radars are expensive and long-lasting instruments. Perhaps this is at least one reason for the large delay in transferring innovation in weather radar technology from the research community to the operational community. Simple and useful Doppler applications were already introduced in 1960 s (e.g., the velocity azimuth display VAD; Lhermitte and Atlas (1961); Browning and Wexler (1968), yet some large weather services only started to acquire Doppler radars 40 to 50 years later (e.g. Tabary et al., 2006; Rennie et al., 2010). It is not always easy to forecast which innovations will become operationally acceptable. At the seminar of the European project COST 73 in 1989, Randeu (1991) gave a keynote presentation on new weather radar techniques supposed to be ready for operational use at that time. He clearly saw the emergence of Doppler and dual-polarisation capabilities. He was right about dual frequency being restricted to special research applications, but the frequencies and applications discussed that time were slightly different from those of cloud radars used today (e.g. Matrosov et al., 2005; Huang et al., 2009). However, the electronically-steered (phased array) antennas, which were then expected to be in use by the end of the next decade, have not yet been introduced into operational weather services.

In the world of operational weather radars, the latest major change is the introduction of dual polarisation. Dual-polarisation weather radars have been used in research and in tests for more than 30 years (e.g. Seliga and Bringi, 1976; Bringi and Chandrasekar, 2001), and the idea of using polarised microwaves to analyze clouds and precipitation has existed since at least the early 1950 s (e.g. Browne and Robinson, 1952). European national meteorological services (NMS) are currently acquiring their first dual-polarisation radars. In 2010, there were approximately 30 of them out of a total of 180 weather radars, and dual-polarisation is becoming the new standard requirement for operational weather radars (Tabary et al., 2009; Holleman, 2009). In the United States, the WSR-88D (NEXRAD) Doppler weather radar network will start to be upgraded with a dual-polarisation capability in late 2010 (Istok et al., 2009; Smalley et al., 2009).

Arguably, the era of pure radar meteorology is approaching its end. What is coming instead is an era of fusion of data and methods. Instead of trying to solve all the relevant weather parameters, including for instance the prevailing wind and temperature profile, from radar measurements alone, information is used from the source where it is best and most easily available, e.g., from radiosoundings or numerical weather prediction systems. We are able to observe the atmosphere with several instruments, and

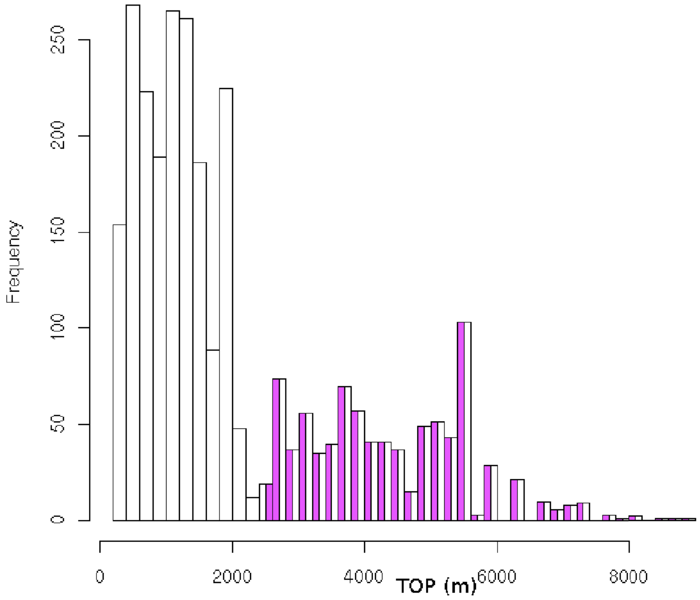

FIGURE 2.1. Echo tops measured with the Vantaa radar in May 2007. White bars: all echoes, red bars: echoes classified as ice-top clouds.

we even have some theoretical knowledge of the processes occurring out there. This fusion does not have to be complicated or fully automatic. Simply superimposing images of data from different sources can improve their interpretation. Operational NMSs took the first steps in this direction before the research community, by designing meteorological workstations from the 1980s onwards. However, experience has shown that it is not straightforward to combine data from disparate data sources. Again, just as in the simple case of one type of observations described in Fig 1.1, analysing products of data fusion will broaden our understanding of the atmosphere, and this eventually will enhance the data fusion methodology further.

2.2 OPTIMIZING THE MEASUREMENTS OF THE FMI RADAR NETWORK

The quality and availability of FMI radar data is on a high level; since 1999 data availability has been over 98 %. One of the reasons for this success is that the measurements have been designed for specific applications and the local environment using interdisciplinary knowledge of the atmosphere, technology, data users and geography. This design process is reported in PAPER I.

The main compromise in planning the scanning schedule for radar observations is between spatial and temporal resolution: a scanning radar is always pointing in one direction only, so that collecting data from all the necessary directions takes time, and the more resolution in azimuth and elevation one wants, the longer the data collection takes. On the other hand, to follow rapid developments of convective systems, the user would like to take frequent measurements in those specific appropriate directions.

The compromise chosen at FMI was to build a volume scan of 9-11 elevation angles, and repeat those in different combinations every 5 to 15 minutes. The best selection for those 11 elevation angles depends on the applications and local climate. The main applications using data from above 1 km are wind profiles, cloud tops and the applications studying height and intensity of convective cores. Hence, the highest vertical resolution is needed near and below the height of typical cloud tops. The median and 25% quartiles of the heights of precipitating clouds are indicated in Fig. 3 of paper I, as background to the selection of elevation angles.

Typical cloud top heights were calculated from echo tops measured with the eight FMI operational radars during one year (2007). Measurements were grouped by month and radar - as an example Fig. 2.1 shows the histogram of echo tops for May in Anjalankoski (southeastern Finland). In the majority of measurements, echo tops are found below 2 kilometres. These echoes are mainly related to clear air echoes, and occasionally also to non-precipitating cumulus clouds, which can be detected above or in the immediate vicinity of the radar, even though they give a very weak signal. To separate these echoes from actual tops of precipitating clouds, a simple method was needed. Precipitation can be generated through the Bergeron-Findeisen mechanism only if the cloud tops are cold enough. The typical climate for each month and each radar was represented by the average surface temperature of the nearest weather station. Hence we derived a simple method based on this temperature as the starting value, from which we calculate a moist-adiabatic lapse rate to estimate the level of the 0-degree isotherm, to which one kilometre is added, to estimate the tops of first mixed-phase clouds. This simple procedure was accurate enough to separate the two echo top populations, as seen in Fig. 2.1. (A more sophisticated method for classifying vertical reflectivity profiles using temperatures from numerical weather prediction models is presented by Koistinen et al. (2003b); at the time of writing of Paper I, climatological values based on that method were not available.)

In 2004, Northern European NMSs listed the 15 worst problems in radar measurements (Saltikoff et al., 2004). By 2010, the Finnish Meteorological Institute had improved its performance in 13 of these challenges, as described in Table 1 and also in Paper I. Dual polarization is expected to help in four of these fifteen challenges, and thus further improve the output data quality and relevance.

The three oldest radars in the FMI network reached 15 years of age and were replaced by dual polarisation radars in 2009-2010, after the writing of paper I. The main triggers for the replacement process were visible signs of mechanical wear, and some spare parts being in short supply. The upgrade also enabled the use of new technologies and methods, such as more advanced processing and dual-polarisation applications. The upgrade process and first experiences of using the new data are reported in PAPER II.

Table 2.1 Challenges for Northern European weather radars as listed by the BALTRAD in 2003, and the FMI actions and plans. (Table taken from from Paper I)

Challenge	Action	Status 2010
Radar siting	Design and experience	Not a problem
Beam blocking	Siting	Not a problem
Scan strategy	Compromises	Continuing work
Ground clutter	Doppler	Operational
Anaprop clutter	Doppler	Operational
Vertical reflectivity profile	Correction	Operational
Assimilation	Task change	Operational
Nowcasting and detection of phenomena	Tasks, algorithms, dual polarization	Operational
Total beam overshooting	More radars	Operational
Gauge adjustment	Kriging	Partially operational
Attenuation by precipitation	Dual polarization	To be implemented
Water phase	Dual polarization	To be implemented
Overhanging precipitation	Data fusion, compositing algorithms	Ongoing research
Sea clutter	Dual polarization	Ongoing research

For a long time, dual-polarisation radars remained purely a research instrument, until applications reached operational maturity. FMI was among the first to integrate dual-polarisation radars into an existing radar network. The configuration procedures for bringing dual-polarisation radar measurements into the production process differ from those for conventional radars. Since the new radars have to be part of the existing weather service infrastructure, the new measurements have to be specifically designed so that all existing services can continue at the same operational level as before.

After the measuring procedures have been designed, the schedule has to be allowed to run for a while so that its behaviour in different weather situations can be analyzed. In Paper II, the first analysis was made through three case studies. These cases showed that dual polarisation reveals properties of a precipitation event not seen from conventional radar data. However, much of the expected value of dual polarization is in potential improvements in data quality in already-existing applications such as precipitation measurements.

Data quality is not an universal parameter. It is possible to define a quality index for a specific use of the data, such as for hydrological models (e.g. Szturc et al., 2010) but the priorities between different kinds of errors are user dependent. This is illustrated by two examples in Paper I: the forest-fire risk and nowcasting by extrapolation. Forest-fire risk indexes are an example of long-term use, because they need data of accumulated precipitation throughout the season. Hence, positive and negative random errors tend to average out, but the effect of even a small systematic bias (such as miscalibration) can accumulate destructively. Nowcasting is an example of an opposite priority in error types: it is mainly used for rain/no rain warnings, so that even large systematic errors are not so important; instead, transient random errors, such as ship clutter, can lead to unacceptable results.

3 MESOSCALE WEATHER

Mesoscale (”meso” in Greek means intermediate) is a name for weather phenomena typically 1-50 km in size, 1-12 h in lifetime. The exact limits of how large and how small are the phenomena that fall into this scale-range is not clear-cut, but in general, ”intermediate” means the size class between local phenomena and synoptic-scale phenomena (such as low pressure systems). According to Markowski and Richardson (2010), M.G.H. Ligda was the first to use the word mesoscale in 1951 in a review of radar storm observations (Ligda, 1951).

According to Orlanski (1975), our understanding of these intermediate scales grew slowly, because in earlier days it was difficult to obtain useful observational data of these phenomena. Famously, they were described as phenomena too small to be observed in a network of traditional weather stations, yet too big to be understood from single-site data alone. Two factors changed the trend in the 1970s. On the one hand, there was a surge of interest in the urban environment and severe weather conditions. On the other hand, relevant operational data finally became available, when the digital processing of radar and satellite data facilitated the implementation of algorithms developed in earlier years (Doviak and Zrnić, 1993).

Orlanski (1975) and Fujita (1986) divided the mesoscale into three sub-classes (Table 2).

The most well-known mesoscale phenomena are perhaps tornadoes and hurricanes, even though one may argue that tornadoes are too small, while hurricanes too big (excluding ”midget typhoons” named by Fujita, 1986), to be truly mesoscale. This thesis does not discuss these, as it concentrates on phenomena, that can are frequently seen in Finland and in regions with a similar cool climate.

3.1 MESOSCALE WEATHER PHENOMENA AFFECTING DAILY WEATHER IN FINLAND

According to the classic Köppen classification, the climate of the southern coast of Finland belongs to class Dfb, and the rest of the country to Dfc, i.e., a cool and moist continental / subarctic climate of cold and snowy winters and precipitation throughout the year. The summer is warm, not hot, and in the north it is also short (Jylhä et al., 2010). There are no mountains above 1350 m, but the gulfs of the Baltic Sea embrace Finland from two sides. Hence, typical mesoscale phenomena include those related to the differential heating and cooling of land and sea: sea and lake breezes in summer and the land breeze and lake effect snow in winter. In addition to those coastal phenomena, the phases of precipitation and phenomena related to deep moist convection are also discussed, due to their importance in daily weather.

Table 3.1 Examples of phenomena in different sub-classes of the mesoscale.

Name	Spatial scale	Temporal scale	Example
alpha	200 - 2000 km	6 h - 2 days	weak anticyclones
beta	20 - 200 km	30 min - 6 h	mesoscale convective systems
gamma	2 - 20 km	3 - 30 min	most thunderstorms

3.1.1 Water phases

One of the major cold season mesoscale weather phenomena that strongly affects everyday life in Southern Finland is the change in the various phases of water in precipitation. Such phenomenon can typically happen on the mesoscale both spatially and temporally: snowfall in the morning turns to rain in the afternoon, or while snow falls at Helsinki airport 20 km inland, Helsinki cathedral virtually on the coastline can be soaked in rain. Not surprisingly, the Finnish language has special words for melting snow: it is ”räntä” when it falls, and ”loska” when it lays on the ground.

Korhonen (1918) found that 39 % of the yearly precipitation in central Helsinki (Kaisaniemi, 60° 15 N, 25° 03 E) falls as a mixture of snow and rain, either simultaneously or in sequence, but in any case within the same measurement period of 24 hours. On average, snowfall is observed on 107 days a year in Helsinki, but on 182 days at Sodankylä (67° 22 N, 26° 38 E), in Northern Finland (Ilmatieteen laitos, 1991). The snow cover lasts on average 135 days in Helsinki, and 212 days in Sodankylä (Heino and Hellsten, 1983).

These numbers indicate the necessity of spatial and temporal analysis of the various phases of water in precipitation: there are 77 days a year when the borderline between snow and rain is crossing Finland somewhere. Such analyses require interpolation, and thus cannot be based on discontinuous observations of precipitation types. In order to study the connection between temperature, humidity and the water phase, I took observations from 1980 to 1989 from the 18 weather stations used to determine the representative statistics of Finland s climate (Ilmatieteen laitos, 1991) and sorted them by the most common water phase for each humidity-temperature combination (shown in Fig. 3.1). As expected, snow was most common whenever temperature was below freezing. Freezing rain and drizzle are such rare phenomena that they do not show up in the diagram. Wet snow (”räntä” in Finnish, WMO ww-codes 68 and 69) occurred only at near-zero temperatures when humidity is high. Note worthily, snow can also occur at temperatures above freezing, when humidity is low. This is probably related to evaporational cooling of the snowflakes falling through dry air.

For radar applications, we need a continuous equation. A curve describing probability of precipitation falling as rain as function of temperature and humidity was fit to the same dataset was the one used to create Fig. 3.1. The resulting equation is presented in paper I, and Fig. 3.2 displays the use of that equation together with a radar image.

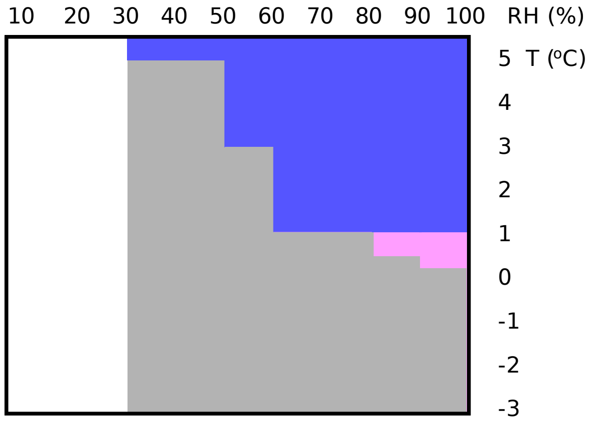

FIGURE 3.1. Most common type of precipitation as function of relative humidity (RH) and temperature (T). Blue indicates rain, grey snow, pink snow and rain. When humidity is smaller than 30 %, precipitation in these temperatures is very rare.

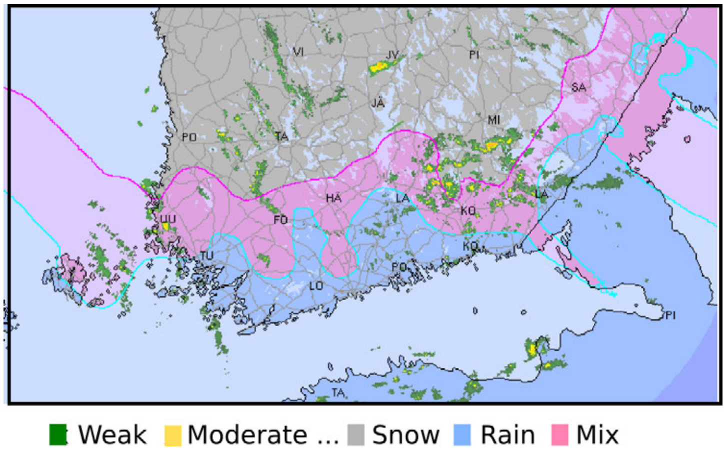

FIGURE 3.2. A radar composite for 16 November 2010 superimposed on background coloured according to the most probable phase of water precipitation: blue areas indicate rain, gray areas snow and the pink areas, both snow and rain are likely. The method is described in Paper I.

In Finland, the melting snowflake is an important but short-lived episode in the life of almost every hydrometeor reaching the ground as a raindrop (excluding drizzle drops). From typical temperature profiles and fallspeeds, one can count, that an ice crystal initially spends one to a few hours growing to a snow crystal and eventually into a snowflake, but only 2-10 minutes as a melting snowflake, before finally, in summer this melts completely to a raindrop, accelerates its fallspeed and hastens down to the Earth s surface. In spite of its relative ephemeral nature, melting snow has attracted a lot of attention from radar meteorologists. For laymen, it can be described as a form of precipitation that feels like rain but looks like snow. From the perspective of radar measurements, we can say the flakes have the size and fallspeed of snowflakes, but the dielectric properties of water surfaces. Hence the radar reflectivity peaks in the melting layer, also known as the bright band. In the hands of an inexperienced user of radar data, this could lead to an overestimation of precipitation intensity. In a modern weather radar service, the overestimation is corrected using knowledge of the vertical profile of reflectivity (Koistinen et al., 2003a). Recently, Giangrande et al. (2005) and Boodoo et al. (2010) have shown that the parameters of dual-polarization radars can be used effectively to follow the temporal and spatial variation of the melting layer height and thickness. This is especially important in cold and temperate climates, where much of precipitation is associated with fronts, because in frontal situations the temperature gradients are sharp.

For end-users, another problem remains: what is the water phase of the falling precipitation reaching the ground? Dual-polarisation technology enables one to distinguish the types of the hydrometeors measured (Straka et al., 2000). After the snowflakes have fallen below the radar measurement volume, they can still melt (or even evaporate). Figure 3.3 illustrates this challenge, with the radar characterising the return signal as snow at both edges of the image. However, it is likely that all the snowflakes there had also melted before reaching the ground (this case is discussed in more detail in paper II). This phenomenon has caused disappointments for those who were eagerly waiting for the dual-polarisation radars to solve the challenge of analysing the phases of water, and it is the reason why hydrometeor classification images are not distributed to the general public. On the other hand, in the hands of expert users, the hydrometeor classification can be a welcome reminder that some radar measurements are always made in snow, at least at longer distances where the radar beam is above the melting layer.

3.1.2 Snow types

Within the precipitation class of ”snow”, several sub-types can be classified by their growth mechanisms. Ice particles can grow by three main mechanisms: vapour deposition (sublimation), riming and aggregation.

When invisible water vapour turns into directly solid ice, the process is called vapour deposition or sublimation. The resulting crystals are clear and delicate, like ferns and lace. If this takes place on a surface, it is called hoar frost. Sublimation occurs most actively at temperatures near -12 °C, because there the saturation points for ice and liquid water are furthest away from each other, so any water drops can evaporate while the ice crystals keep growing (Pruppacher and Klett, 1996).

Many clouds include minuscule supercooled liquid water droplets with a typical

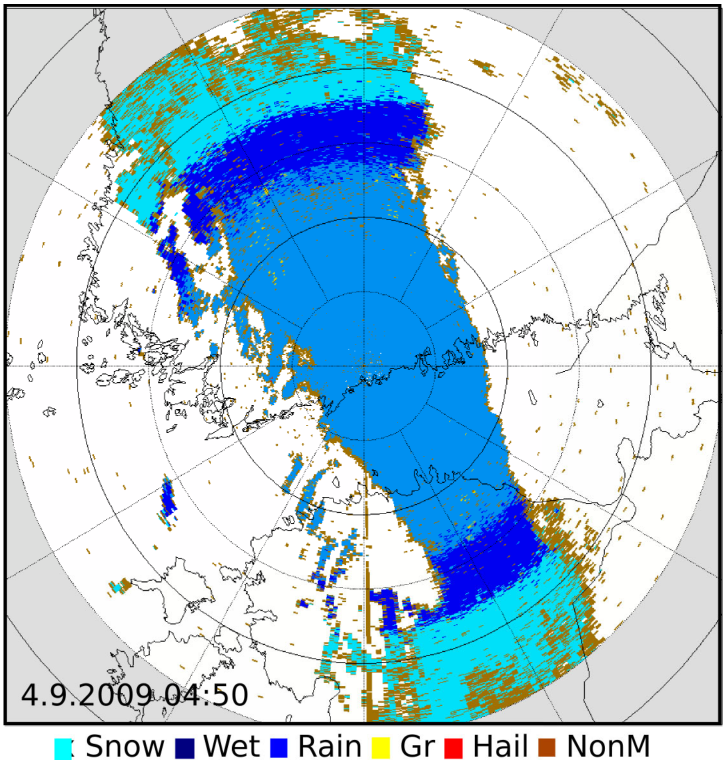

FIGURE 3.3. Hydrometeor classification on display of Vantaa dual-polarization radar. In the cyan areas the radar has measured snow, wet snow in the dark blue areas and rain in the light blue areas.

radius of the order of 10 to 100 micrometers. When these droplets attach themselves to a surface, this is called riming. Rimed ice crystal particles are plump and whitish. An extreme case of a rimed hydrometeor is graupel (Pruppacher and Klett, 1996).

When existing snow crystals attach to each other, they form aggregates. Aggregation affects the fall speed and the scattering properties of the snowfall (Fabry and Zawadzki, 1995).

Knowing the dominant growth mechanism gives indirect information for several applications. Areas of significant riming present a serious risk to aviation. The shape of the falling particles is one of the factors affecting the density of the snowpack on the ground (defined as the ratio of liquid water content to the thickness of snow) and this in turn is an important factor in snow clearance operations. The type of fallen snow is of significance to road maintenance operations, since snow drifting caused by the wind occurs for low-adhesion snow, which is then blown to roads from surrounding fields, while stickier snow would have more tendency to pack and polish into a very slippery snow-ice cake at the surface. In forest canopies, the snow load on the tree crowns grows both by riming and by the attachment of moist snow; this may cause great damage to trees and to power lines directly and by the falling of rimed trees (Hoppula, 2005).

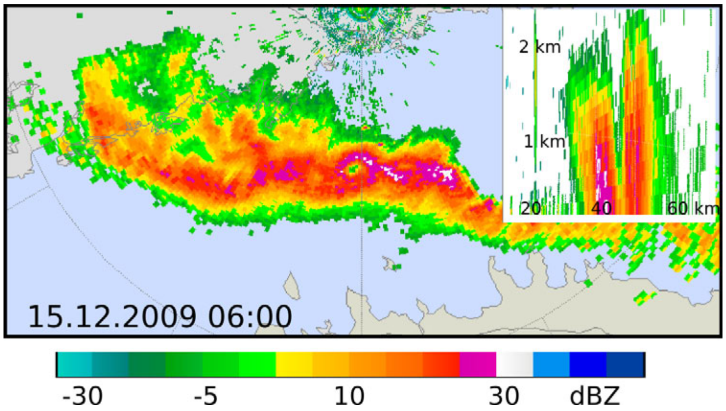

FIGURE 3.4. Vortices in band of lake-effect snow on 15 December 2009 at 6 UTC over the Gulf of Finland. Reflectivity CAPPI at the height of 500 m and RHI southwards from the Vantaa radar. The precipitating system was less than 2 km deep.

3.1.3 Lake-effect snowfall

In Finland, ”the country of a thousand lakes”, the occurrence of so-called lake effect snow is important, but not so much actually around the lakes. The name originated from weather phenomena around the Great Lakes of North America, but compared to them, Finnish lakes are not great (or large) enough. Lake-effect snowstorms get their energy from the temperature difference between the open water and very cold, continental air blowing over the water. These provide the most spectacular outbreaks of boundary layer convection in winter (Markowski and Richardson, 2010). In the case of Finnish lakes, the mass of water is so small that it cools rapidly and freezes early. However, the Gulf of Finland and the Bay of Bothnia, to which Finland is adjacent, are favourable locations for the occurrence of lake effect snow.

Markowski and Richardson (2010) mention that the convective clouds associated with lake-effect precipitation can be several kilometres deep. However, even shallower lake-effect clouds can produce significant amounts of snowfall (see Fig 3.4), and these shallow yet intense clouds present challenges to the design of a radar network in coastal areas in a cold climate.

The organization of convection in a lake-effect snowstorm depends on the ratio of the wind speed to the maximum fetch distance. When the wind is strong, offshore convection is rapidly organized into horizontal convective rolls. When the wind is weaker, it is more likely that bands parallel to the shoreline (and perpendicular to the mean wind) are formed in the land-breeze convergence zone. With very weak winds, convection can be organized into vortices that stay over the sea and have the structure of a miniature hurricane (Laird et al., 2003). These vortices provide another example of mesoscale weather systems that can only be observed with remote sensing instruments. An example of such vortices is shown in Fig 3.4.

3.1.4 Sea breeze

A notable summer-time mesoscale phenomenon on the coasts of Finland is the sea-breeze circulation, which is powered by the differential heating between the rapidly warming land surface and the cool sea surface. This is felt as cool but sunny summer days in the parks of central Helsinki, sudden wind changes at Malmi (8 km from the coastline) and afternoon showers at Nurmijärvi (40 km from the coastline). A sea-breeze circulation is observed on the south coast of Finland on an average of fifty days each summer (Karttunen et al., 2008). For radar meteorologists, the sea breeze front is a classic because it can be observed by radars even before the first cumuli are seen by naked eye (e.g. Atlas, 1960). In Finland, the sea breeze circulation has been studied, e.g., by Gahmberg et al. (2010), using radars and numerical models. In this thesis, no direct study of the sea breeze is presented, but its accumulating effect on precipitation can be seen in the detailed precipitation maps used for forest-fire forecasting as discussed in Paper I.

An example of a sea-breeze front is shown in Fig 3.5. On the inland side of the sea-breeze front, one observes further bands of weak radar echoes - these are related to roll vortices. A comparison with simultaneous satellite images (not shown) indicated that all of the radar echoes were clear-air echoes.

When the forecaster knows the conceptual model of the sea breeze, these kinds of radar images can help him/her in analysing and nowcasting wind fields and temperatures in coastal areas.

3.1.5 Convective systems

Orlanski (1975) identified the surge of interest in severe storm weather conditions as one of the main reasons for the development of mesoscale meteorology. Severe storms are associated with deep convection. Convective storms exist under a wide variety of conditions and evolve in an equally wide variety of ways (Weisman and Klemp, 1986).

According to Doswell (2001), hazardous weather events (large hail, damaging wind gusts, tornadoes and heavy rainfall) are generally the result of the energy released by the phase changes of water, which contribute to buoyancy. For updrafts, condensation releases energy, for downdrafts, melting hail and evaporating raindrops create extra negative buoyancy.

Taxonomies of convective systems are largely based on the basic unit of convective systems, a thunderstorm cell, as depicted by Byers (1949). These cells seldom occur alone; it is more common for them to form in organized or unorganized groups. In unorganized multicell groups, downdrafts from older cells accelerate the development of younger cells. Organized multicell groups occur in situations with moderate wind shear in the lower troposphere. New cells are systematically formed at the forward edge of the cluster, and while they mature, they have an apparent movement through the cluster. These clusters live longer than unorganized groups, because they have a

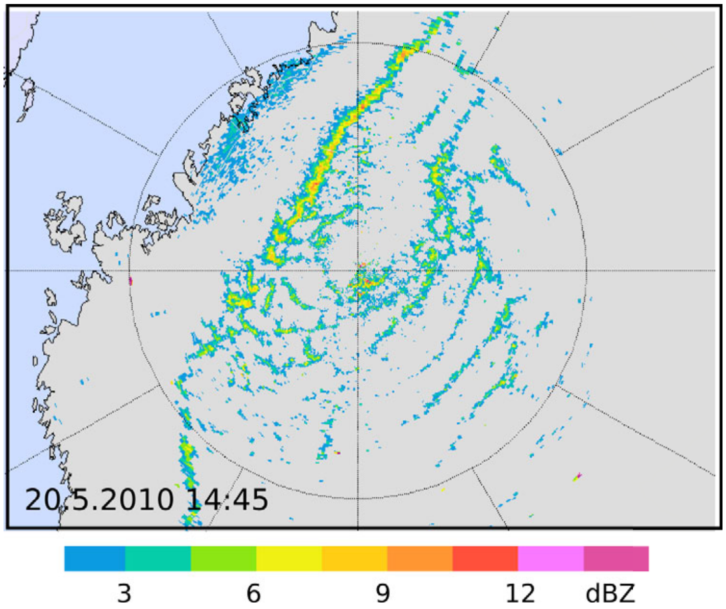

FIGURE 3.5. A pronounced sea-breeze front seen as a yellow line of reflectivity, most probably caused by the convergence of insects. Vimpeli radar, 20 May 2010. The surface wind between the coastline and the band is perpendicular to the coastline (northwesterly sea breeze), while on the other side the prevailing wind is from the southwest.

constant supply of ambient warm and moist air.

Markowski and Richardson (2010) note that a disproportionately large number of severe weather events, such as large hail and tornadoes, are related to a relatively rare storm type called a supercell. Supercells were originally so-named due to their longevity; they can persist for 1-4h (even up to 8 h), but at present, the widely-accepted practice is to identify them by a dynamical criterion: the presence of a persistent, deep mesocyclone within the updraft. Such mesocyclones can be identified in the velocity fields of Doppler radars, and as a typical pattern of weaker radar reflectivity in the updraft. Just like organised multicell systems, supercells are also associated with vertical wind shear, but this shear layer is deeper and often stronger for supercells.

Doswell (2001) explained that the considerable arbitrariness in defining thresholds for the characterization of severe weather phenomena is related to the mismatch between the events and the reports of these events. For instance, a hailfall case produces typically a several kilometers wide and long swath of hail, and even if we have one point observation from that swath, we can not be sure whether the largest hailstones in the swath were actually measured or yielded damage to be reported.

This randomness connected to single-point observations affects the classification of the phenomena and the comparisons between different datasets and events, such as forecast verification, the validation of remote sensing systems and investigations related to climate change. It may be argued that apparent trends in severe weather occurrence are just the result of changes in the density of observational capabilities. Hence, Bellon and Zawadzki (2003) claim that, in contrast, a climatology based on properly calibrated radar data would have the advantage of being more consistent over the region of interest and during the entire period of observation. They also note that because of its continuous space coverage, radar is the only instrument, that will not miss any severe weather event within its domain of observation, while other observing means are more concentrated in densely-populated areas. In PAPER III, hail climatology based on radar and other observations is discussed.

Punkka et al. (2006) studied a high-latitude derecho - a severe thunderstorm outbreak, which destroyed 1 million cubic metres of trees along a 450 km long, 100 km wide swath in less than 6 hours in Eastern Finland. The progression of the cold pool ranged mainly between 50 and 70 km/h but reached up to 90 km/h. Frequently-updated remote sensing data are needed for the analysis and warning of such intensive, relatively small and rapidly-moving systems.

Some statistical studies of deep convection occurring in high-latitude regions have been published during the first decade of this century. None of these could rely on weather station data alone. Punkka and Bister (2005) studied the basic characteristics of convective precipitation and mesoscale convective systems in Finland using radar data. Tuovinen et al. (2009) published a climatology of severe hail in Finland (1930-2006) based on observations made by volunteers and published in newspapers. Tuomi and Mäkelä (2008) compiled a thunderstorm climate of Finland (1998-2007) using the well-calibrated Finnish network of lightning locators. Brimelow et al. (2004) created a climatology of severe thunderstorms in central Alberta using radar-based methodology.

3.2 RADAR OBSERVATIONS OF MESOSCALE WEATHER PHENOMENA

3.2.1 Wintertime phenomena

The first case study of Paper II illustrates the challenge of precipitation type classification: even though all surface observations show liquid rain, most of the radar measurements are made in snow, due to the measurement geometry and the curvature of the Earth s surface. However, when a radar measures liquid raindrops, in Finland they normally stay liquid until reaching ground level, and thus the classification can be used to warn about the extremely dangerous case of rain falling on cold surfaces and freezing. According to the end-users responsible for snow clearance (interviewed in paper II), the phase of the precipitation when it reaches ground level is the key factor for their activities. For them, it is not enough to see radar echoes indicating precipitation, since decisions regarding snowploughing, gritting and salting depend on the precipitation type. A radar image allows them to make these decisions early, before in situ observations are available, but the phase of the precipitation must be known. For this purpose, a simple statistical equation was developed as described in paper I. Using temperature and humidity measured at surface weather stations and analyzed onto a grid of 10 x 10 km, this equation computes the probability for precipitation to fall in liquid form in that environment. It is visualized by changing the background colour of the radar images. The user interviewed found this product useful in principle, but needed still more information: in his profession, being able to differentiate between different types of snow would allow more specific planning of road maintenance. This remains a challenge for dual-polarisation radars.

A water phase map allows separating further data processing for snow and rain. For physical reasons, different reflectivity to precipitation rate equations are used. In addition, the visualization scheme for snowfall and rainfall is different. If snow is expected, the lightest blue shade corresponds to -6 to 0 dBZ, and everything stronger than +30 dBZ gets the strong red shade indicating heavy snowfall. If rain is expected, no signals weaker than +6 dBZ are shown, and the light blue is reserved for the range +6 dBZ to +10 dBZ. The other end of the scale,there are steps for +40 dBZ and +50 dBZ to find the areas of hail and torrential rain. This change of visualization scheme allows the display of light snow in winter but hiding much of the occasionally misleading insect echoes in summertime, even though the reflectivity values are the same. Since the scheme is chosen for each location for each image independently, it is possible to adapt to situations when it is still snowing in northern Finland while the summer has already arrived to the southern parts of the country.

The density of the falling snow is related to the growth mechanism and thus also to the fall speed of the particles. Fall speeds can be measured with a vertically-pointing Doppler radar (Zawadzki et al., 2001). This is a rare measuring configuration and gives detailed data from only one location. For the purpose of a weather service, it would be more suitable to implement a method that would cover larger areas. For instance, attempts have been made to combine different polarimetric parameters in each pixel to solve for the type of snow crystals (e.g. Ryzhkov et al. (2005). Another approach is to study the vertical structure of these parameters and to map the entire life and development of typical snow particles (Moisseev et al., 2009).

A third approach is explored in PAPER V, by relating the snow type to visibility. There are empirical algorithms relating radar reflectivity (essentially scattering of microwaves) to the reduction of visibility due to snowfall (essentially by scattering of visible light). Existing algorithms need a ”calibration parameter” (Rasmussen et al., 1998). We show in Paper V that the relationship between visibility and reflectivity is connected to snow particle type (Figure 3.6). In that paper, the snow type is taken from detailed surface observations. If in the future the snow particle types can be classified with dual-polarization radars, the visibility can be estimated from radar data alone also in the areas where no surface observations are available, such as sea areas. This would increase significantly the usability of reflectivity-visibility algorithms in daily forecasting.

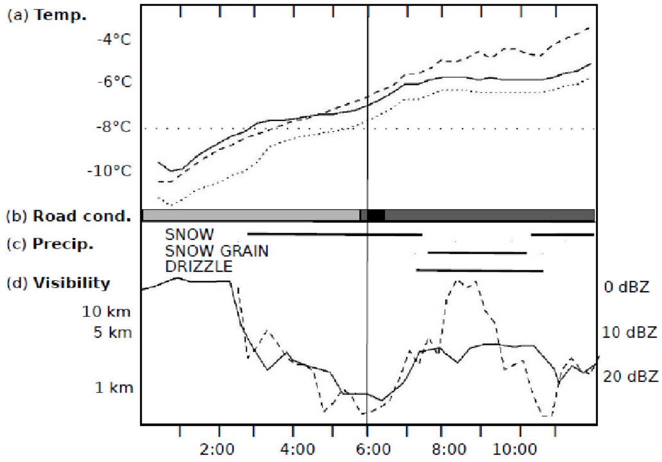

FIGURE 3.6. Temperature (upper panel), visibility (lower panel, solid line) and radar reflectivity (lower panel, dashed line) in snowfall (17 March 2005). Image from paper V.

3.2.2 Summertime phenomena

Weather radar measurements can give more information than other observation methods of two phenomena related to deep moist convection: small-scale variations in precipitation, and hail.

Traditionally, radar-based quantitative precipitation estimates (QPE) are compared to gauge estimates, even though, as is well known, is fraught with a multitude of problems. The radar measures the instant population of hydrometeors within an atmospheric volume of size of a few kilometres, typically at altitudes between 500 and 5000 metres. The gauge, on the other hand, catches a subset of them much later, if ever, after the drops may have experienced wind drift, melting, evaporation or orographic growth. In the gauge, eventually, they typically mingle with other hydrometeors arriving there somewhat earlier or later.

A typical summertime weather service product, which depends on radar data is maps of the forest-fire indexes. Forest fires are principally forecasted by comparing potential evaporation and rainfall, with rainfall taken from radar data. Before radar data were available, weather station data were used. Weather stations are often located at the coast, within the sea-breeze zone, and measure less rainfall and more sunshine than that experienced inland. The current FMI operational forest fire index is produced on a 10 x 10 km grid, and forecasters are also using a new test product with a 1 x 1 km grid. Because evaporation is taken as the potential evaporation (without distinguishing between different land use), the accumulating dryness map actually reflects the mesoscale climatology of precipitation in Finland. Nevertheless, the swaths of strong convective systems or the systematic organization of sea breezes can sometimes be seen in these maps. On the other hand, as discussed in Paper I, the maps show us mercilessly even small systematic errors of the radar system.

Hail can be observed with many different systems: even amateurs can do it without any special training or equipment. However, radar is the only instrument able to collect evidence of the absence of hail. Both - positive and negative - observations are relevant, e.g., for accident-related investigations and in the aviation weather service. These applications are critical ones, due to the possibility of legal consequences,with weather data used as evidence.

In Finland, the interest of hail for radar meteorology is traditionally related to the possible overestimation of QPE. As a high-impact phenomenon, hail is also a parameter of public interest. Newspapers publish stories of hail damage, and there are even organized storm spotters. However, standardized observations of hail are rare, since a hailstorm seldom hits a weather station during the short duration of a regular observation; in addition, the WMO guide to manual observations does not emphasize hail, but pays more attention to the characteristics of the thunderstorm, which is however often connected with the occurrence of hail. Hence, there is not much material to validate radar-based hail observations. Papers III and IV describe attempts to find evidence among new sources of weather information.

In PAPER III, statistics of five years of radar-based hail estimates are compared to hail climatology collected from newspaper articles and voluntary observations. According to this study, hail detected by radar seems to have meteorologically-reasonable distributions in time, place and probability. Occurrence maxima are found in (late) afternoon and during the warmest months of the year.

The use of 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.

In PAPER III, we use the Waldvogel method (Waldvogel et al., 1979) to study convective cores in the upper parts of clouds. Using Waldvogel-type algorithms for radar-based hail detection sets a constraint on the scanning strategy, as 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. Nevertheless, our good results with hail detection suggest that some of the valuable measurement time should also be devoted to higher elevations.

In the second case study of Paper II, hail is detected using dual polarisation. The measurements used there are made at a lower height than in the Waldvogel method, typically 500-1500 m. Just as snowflakes, also hailstones too can still melt when they fall through warmer air below the radar measurement volume. Therefore, a perfect agreement between radar methods and surface observations cannot be found. However, even those hailstones that melt before hitting the ground pose a danger to aviation, and they can also be seen as an indicator or even precursor of other convection-related severe weather phenomena such as downbursts (e.g. Fu and Guo, 2007).

In Paper III, we show that newspaper articles provide a novel source of reports of extreme weather, though the definition of ”extreme” depends naturally on the local climate. Distributions based on this dataset of newspaper reports agree well with the independent radar datasets.

In PAPER IV, the radar-based hail observations are compared to another novel reference dataset found in social media. Several researchers have invited volunteers to mail in their observations (as also for Paper III), but in Paper V, we also spied unsuspecting people. These have posted their photos on the web to tell, e.g., how hailstorms spoiled their picnic or golf round. Public places like golf courses are easy to find on a map, but there is also an increasing number of cell phones with GPS. Photographs taken with this latter function are automatically tagged with position coordinates, and these we made use of.

According to Papers III and IV, both newspaper articles and social media posts can be used as an independent source for ground truth, but the results must be interpreted carefully, as the observations are not made with scientific purposes in mind. They do not provide proof that a certain phenomena did not occur, hence they can not be used for classical statistical verification based on hits and misses, as there is no data giving the misses.

4 FUTURE DIRECTIONS

Doswell (2001) noted that "..its line-of-sight geometry makes a radar marginal as a source for mesoscale information and, like satellites, it does not collect quantitative information about common meteorological variables (temperature, pressure, humidity)". While there are already quite a number of methods to estimate temperature, pressure and humidity, a task perhaps more suitable for future radar meteorology is to try to use radar to collect information about less common meteorological variables such as visibility and hydrometeor types (including the plethora of different forms of snow). In Fig. 3.6, a time series of radar reflectivity is plotted together with visibility, temperature and observed precipitation type. This example illustrates that there is potential for new insight to improve our understanding of wintertime mesoscale weather phenomena using weather radars.

In the period of fifty to twenty years ago, when Doppler radars became operational, the velocity data were first used in a limited number of applications, such as for vertical wind profiles and clutter cancellation. Efforts were made to imitate more established data sources, e.g., radio soundings of wind in the form of a velocity azimuth display (VAD; Lhermitte and Atlas, 1961; Browning and Wexler, 1968) and using volume velocity processing (VVP; Waldteufel and Corbin, 1979). Attempts were made to assimilate these data in the same way as pilot soundings are used. The assimilation of VAD wind profiles has eventually made very little impact; for instance the German Weather Service has recently decided not to assimilate VAD-data operationally (Stephan et al., 2010). However, the use of data has grown gradually, and the users have started to benefit from radar velocity data through innovations such as super-observations and direct 4DVAR assimilation (Järvinen et al., 2009).

It is quite likely that a similar development will also take place with dual polarisation. The first applications are already here, but only after years of routine measurements and active use of existing tools, new methods, targets and needs arise. At the moment there are not many applications, if any, that directly answer the requirements of end-users. Nevertheless, even these existing applications, in the hands of a well-trained forecaster, will improve the quality of weather services; hopefully the accumulating experience of the possibilities of the new tools, together with knowledge of the user s needs, will lead to further innovations.

In these papers, I have described how radars can be used to observe mesoscale phenomena. Through the radar, detected backscattered radiation becomes data, and by a complicated knowledge-based processing, data turn into information. This information has increased our knowledge about atmospheric phenomena. But even this knowledge has little, if any, value, if it does not aid the actions of those people who are responsible for other people s safety. On the modern information highway, the last decametres from the processing computer to the display, and the final decimetres from the brain to report-writing hand may be the most challenging.

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