BALTEX
Baltic Sea Experiment

World Climate Research Programme / Global Energy and Water Cycle Experiment
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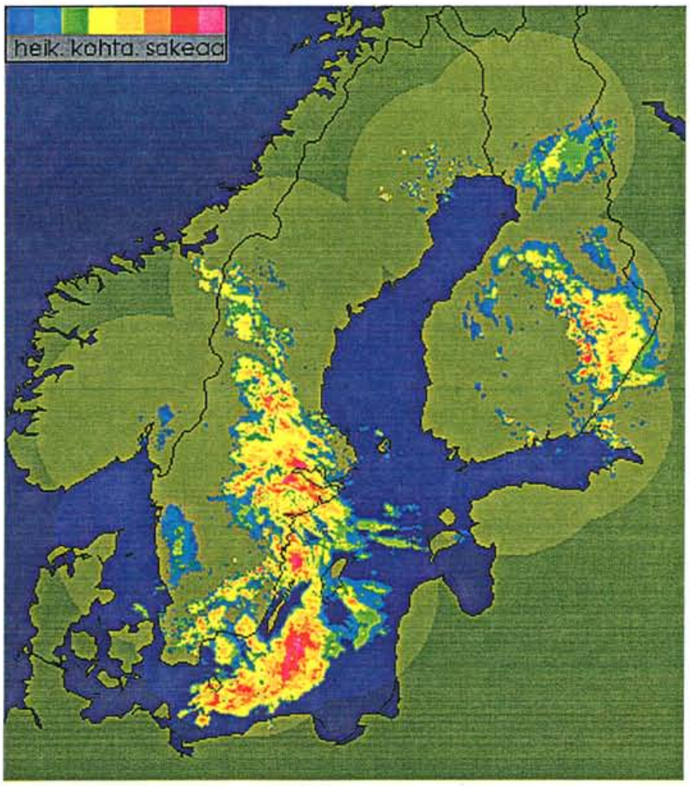
BALTEX Radar Research

- A Plan for Future Action -



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Cover Page Figure : NORDRAD radar reflectivity composite at 14 UTC on May 29, 1996. As it is a customer product, the scale explanation is in Finnish. The scale starts from -6 dBZ and one colour step is 6 dBZ.

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Contents

ABSTRACT

Radar has been proven to considerably enhance the information on precipitation at the surface, in particular over areas with sparse or completely missing precipitation measurements. A BALTEX radar workshop, held from May 20 to 21, 1996, at the GKSS-Research Centre, Geesthacht, reviewed the present radar coverage in the BALTEX region as well as the current use of radar products in both operational and research applications.

This report is a summary of the most important results and recommendations. It should be considered as an extension of Section 5.4 of the BALTEX Initial Implementation Plan.

The Baltic Sea, with practically no direct precipitation measurements at its surface, covers more than 20 per cent of the BALTEX region; hence a complete radar coverage of this large inland water body is of high importance for BALTEX. The workshop identified large gaps within the existing network, especially along the eastern portion of the Baltic Sea, and recommended to close these gaps with at least two additional radar stations in Poland (in the Gdansk region) and in the Baltic States (preferably near Riga), respectively. The presently available satellite data cannot close these gaps since precipitation estimates based upon such data are insufficiently accurate to meet the BALTEX requirements.

It is further recommended to combine all radars into a BALTRAD (BALTEX Radar) network over much of the BALTEX region with the objective of delivering homogeneous radar products for the entire area to the BALTEX research community. Some suggestions for the organisation and infrastructure of BALTRAD which should be built on experience with the existing NORDRAD network are given to archive these BALTRAD products for research purposes in BALTEX.

A number of BALTEX research projects are suggested whose goals are to produce optimum rainfall fields from radar. The need is stressed to develop methods of data assimilation of the BALTRAD products in order to improve numerical weather prediction models.

1 INTRODUCTION

BALTEX, the Baltic Sea Experiment, had been established over the past few years to

- investigate the energy and water budgets within the Baltic Sea water catchment area and their dependencies on external forcing by the global atmospheric circulation,

- develop coupled comprehensive models including the atmosphere, the land surface with vertical and horizontal hydrological processes, the Baltic Sea and the ice for the Baltic catchment,

- develop methodologies for such studies over other larger river drainage basins.

The Initial Implementation Plan (International BALTEX Secretariat, 1995) should be consulted for details of the BALTEX programme.

The BALTEX strategy makes intensive use of available ground- and satellite-based information and of modelling capabilities which have been developed in several of the participating countries.

Precipitation plays a major role in water and energy cycles; however, it cannot be measured directly over the entire Baltic Sea, the Kattegat and the North Sea. Precipitation is urgently needed

- to validate modelled results,
- to enable budget studies for the different basins of the Baltic Sea,
- for many practical applications.

Over land the density of precipitation gauge stations in much of the BALTEX region is too low for many research and operational applications.

A relatively dense weather radar network, NORDRAD, has been established in Sweden, Norway and Finland, whose data are merged into operationally available products, examples of which are given in Figures 1.1 and 1.2. Additional radars cover Denmark, Northern Germany and the southern portion of the Baltic Sea, and central areas of Poland. But no radar information is available over the eastern portion of the Baltic Sea and the territories of the Baltic States, Russia, Belarus and southern Poland.

A BALTEX radar workshop, held from May 20 to 21, 1996, at the GKSS Research Centre in Geesthacht, Germany, identified

- the need for and use of weather radar data in general,
- the potential value of the present weather radar network (NORDRAD),
- recommendations
    - on improvements to the existing network, and
    - on the data processing and handling procedures and policies to make this data fully available for the purposes of BALTEX research.

Nine scientists (see Appendix A) from five countries attended this meeting. A preliminary version of the group's report has been presented to the BALTEX SSG during its fourth meeting in Sopot, Poland.

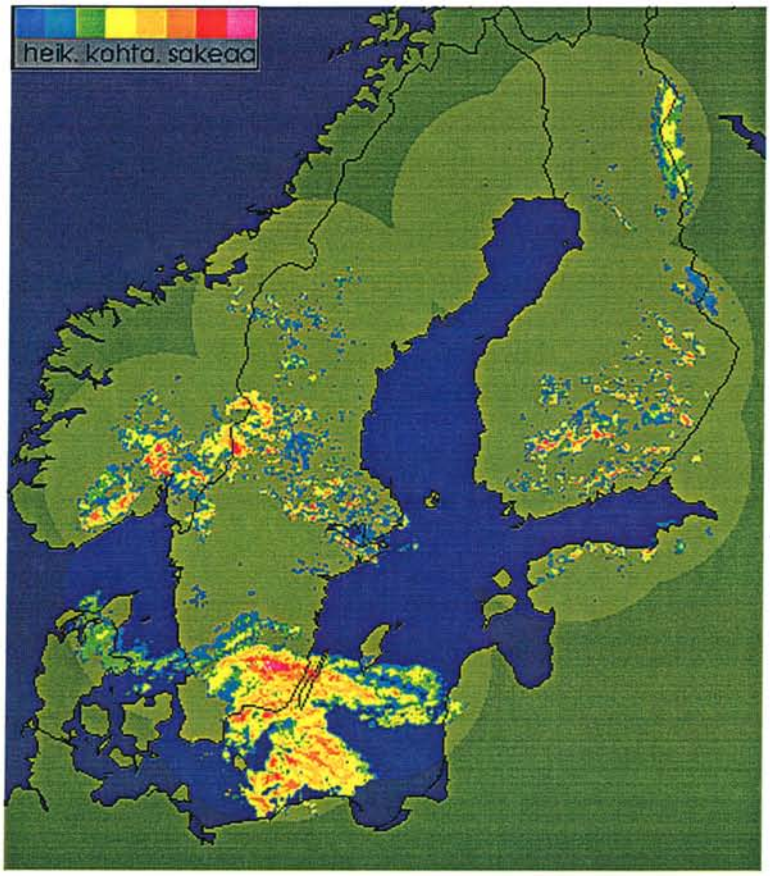

Figure 1.1 : NORDRAD reflectivity composite at 14 UTC on May 27, 1996. As it is a customer product, the scale explanation is in Finnish . The exact scale starts from -6 dBZ and one colour step is 6 dBZ.

2 THE NEED FOR PRECIPITATION AND SOIL MOISTURE DATA

2.1 Human activity and precipitation

The impact of human activity on the environment in which we live may be both beneficial and detrimental to our continued existence. Precipitation influences the way in which we are able to produce food, our drinking water, our transport, the management of waste and may even endanger our lives through river flooding and drought. Measurements of precipitation are essential in all these areas to improve scientific understanding, and to develop forecasting systems to both warn of hazards and enable the optimisation of management procedures. Modern radar offers both precipitation and wind measurements, and therefore is a primary observing system for BALTEX.

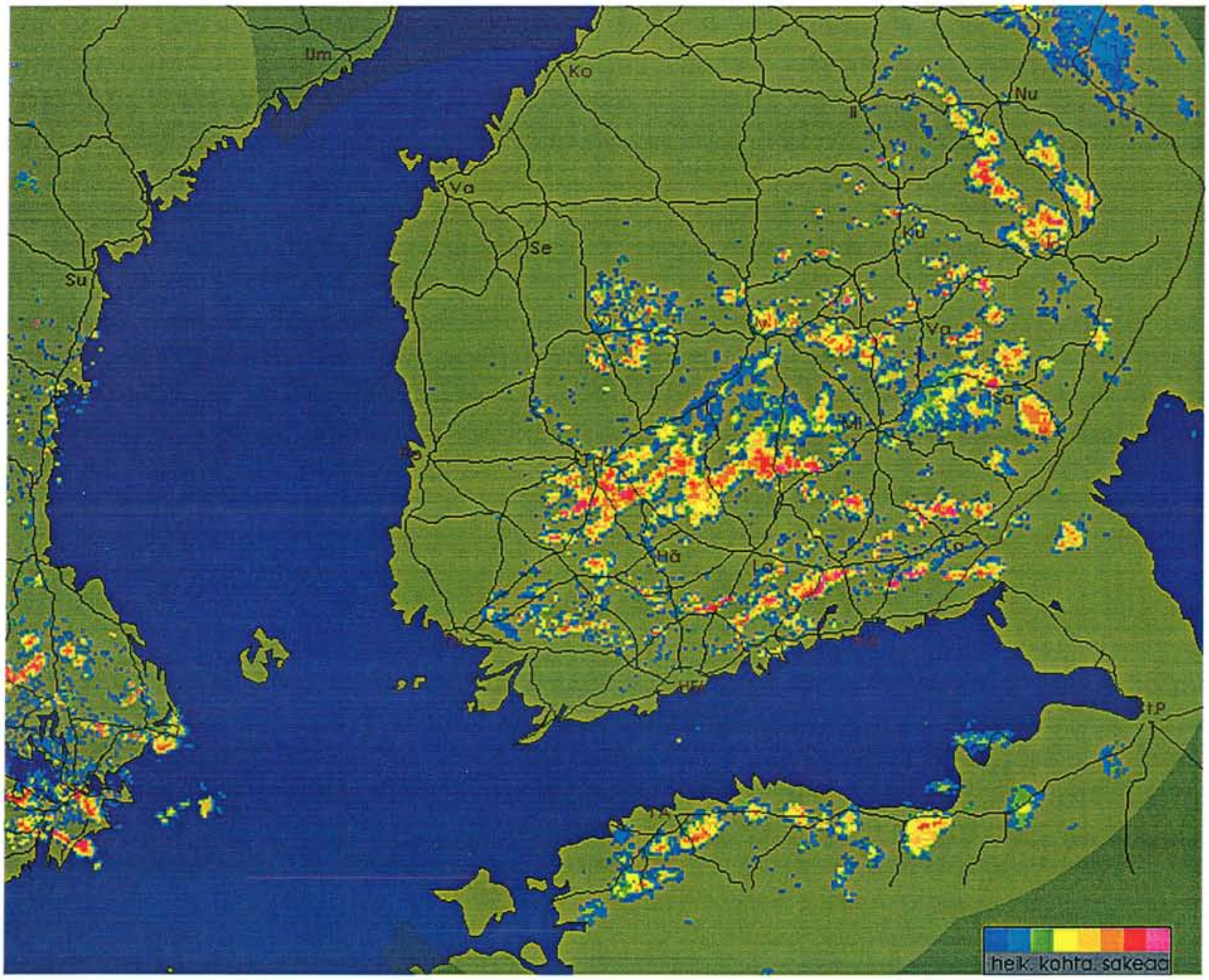

Figure 1.2 : High resolution part of the NORDRAD composite at 14 UTC on May 27, 1996. The reflectivity scale is equal to that in Figure 1.1.

In this section we discuss specific requirements for precipitation and soil moisture data. Detailed specifications of resolution and accuracy will depend upon the particular application being considered. However, within the BALTEX area it is clear that the need for such measurements extends over the whole region focusing upon precipitation measurements over the Baltic Sea itself.

2.2 Scientific basis of weather forecasting

The role of precipitating clouds in climate is seen as fundamental in studies of climate change globally, regionally and on the local scale. Rain is a key component of the hydrological cycle yet is poorly observed in many areas, particularly over the oceans and large sea areas such as the Baltic (Browning, 1990).

Meso-scale weather systems, which result in most of the weather which effects human existence, are forced either by the large scale flow, or by the lower boundary, and it is clearly necessary that this forcing should be correctly specified if a good weather forecast is to be obtained. The primary response of the atmosphere to forcing occurs through condensation of water, and the consequent release of latent heat. Hence a detailed specification of the three-dimensional moisture distribution is required for the accurate prediction of the meso-scale response to forcing. In particular, the three-dimensional specification of rainfall enables latent heating to be input to numerical models so providing a modification of the initial state variables. The result may have a significant impact upon future forecasts, and therefore must be understood in some detail. Precipitation data, at much increased spatial and temporal resolution, are therefore needed as an essential element of model initialisation procedures, and to verify numerical model studies of meteorological systems and climatic dynamics.

On a smaller scale the interaction of the atmosphere with both the land and sea surfaces requires knowledge of the precipitation reaching the surface. Sensible and latent heat fluxes impact boundary layer development and may be significantly changed by the occurrence of precipitation and evaporation. In addition, land surface heteorogeneities in soil moisture have a large impact upon evapotranspiration leading to local circulations and changes in local weather (Browning, 1980). Detailed measurements of soil moisture and precipitation on scales ranging from a few metres to many hundred of kilometres are required over time periods from minutes to months. Such data are necessary to improve model parametrization of physical processes as well as for model verifications.

Unfortunately small errors in the observations used to make weather forecasts can cause large errors in the forecasts themselves (Strensrud and Fritsch, 1994). Sometimes quite complex feedback mechanisms between precipitation, soil moisture and surface fluxes lead to unexpected outcomes. The water budget of the Baltic Sea remains uncertain. Indeed, it is not clear whether net precipitation (precipitation minus evaporation) is positive or negative over the sea area. Detailed spatial and temporal measurements of precipitation and other meteorological parameters are needed to clarify these uncertainties.

2.3 Hydrological forecasting

Modelling river flow is essential for reliable prediction of river flooding and water resources management. Flooding endangers lives and property, and the management of water resources is central to safeguarding the availability of drinking water and hydro-electric power generation. Both too much and too little water must be avoided. Too much water, as well as directly threatening humankind, may also result in degradation of water quality through wash off of agricultural chemicals and storm sewage overflows. Too little water must be insured against by harnessing what precipitation has occurred in the optimal way (Rodda, 1995).

Precipitation is the primary input to hydrological forecasting procedures. A wide range of numerical models has been developed to relate continuous measurements of net precipitation to river flow. Some models make use of river catchment integrated precipitation, whereas others require such information over small areas within individual river subcatchments (Collier, 1996).

Whilst the accuracy with which precipitation measurements are needed is very important, it needs to be specified with a knowledge of the hydrological characteristics of the river catchment being modelled. Reproducibility in space, time and quantitative accuracy is very important since consistent error characteristics are the basis of sound model calibration. Without wide area measurements of precipitation, river flow cannot be predicted with any certainty. Clearly over lakes and the Baltic Sea precipitation estimates are essential if the whole Baltic basin is to be modelled successfully.

In addition to precipitation, an essential element in hydrological modelling is knowledge of soil moisture conditions. Whilst soil moisture depends upon antecedent precipitation, it also depends upon soil type, slope and vegetation. Hence, spatial variations of soil moisture may be significant, and must be measured continuously. The spatial distribution of soil moisture can also be modelled at the regional scale, using hydrological models (Lindström *et al.*, 1996), used for operational monitoring applications.

2.4 Operational uses of precipitation measurements and forecasts

Measurements of precipitation and numerical model forecasts of precipitation underpin many operational activities within the Baltic area. Precipitation measurements are used in real-time for agriculture, forestry, fishing and building and construction to guide work schedules. Spraying, harvesting, pouring concrete and outdoor maintenance to name a few, are all activities specifically influenced by precipitation. Forecasts of precipitation amount and timing are essential, and are linked to weather systems moving from all directions over the area. Measurements are therefore essential from all parts of the Baltic region. To leave any area devoid of measurements, or even with limited coverage, hampers operations not just in these immediate areas, but also in other areas a considerable distance away. Uncertainties introduced by poor temporal or spatial coverage are very detrimental (Browning and Collier, 1989).

All transport systems may be affected by the weather. Whilst the affects of precipitation are just one aspect of this, precipitating systems are associated with significant winds (which can be measured directly by Doppler radar) and conditions of sea and ground state which may generate adverse conditions for ferries and for aircraft landing and taking off. Heavy rain, freezing rain, and particularly, snowfall may bring land transport to a halt.

Increasingly in the region there is an awareness that industrial activity may produce air pollution. This takes the form of the emissions of heat, aerosol or chemicals into the lower atmosphere, or, in extreme cases as for the Chernobyl accident, the emissions of radioactive material. Heat and inert aerosol may lead to convective rainfall downstream of industrial areas. Chemical pollution, be it from industry or the motor car, may be detrimental to human health and damage crops and vegetation.

Radioactive emissions, likewise, may produce significant damage, a problem of some concern in the Baltic region given the proximity of many nuclear power stations. Whilst these forms of pollution are carried by the winds and deposited over wide areas, the occurrence of rainfall may locally wash out large amounts of material in specific locations (e.g. Puhakka *et al.*, 1990). Both measurements of precipitation and forecasts are essential both to warn of areas of likely contamination and where further contamination may occur in the immediate future. Precipitation data with high spatial resolution must be available continuously to provide the foundations for such warning systems (Collier, 1996).

3 WEATHER RADAR AND ITS APPLICATIONS

3.1 Basic principles of weather radar

Weather radars are ground-based, active remote sensing systems. They transmit short pulses of electromagnetic radiation and then record the strength of the returned radiation after it has interacted with various targets. The range of the measurement is estimated from the time of receipt of the returned pulses. The frequency of the transmitted radiation is selected to be optimal for detecting precipitation while minimising attenuation effects from atmospheric gases and precipitation itself.

Weather radar systems scan the atmosphere at predetermined antenna elevation angles and generate three-dimensional volumes of data by layering scans from several such antenna elevations.

Many radars have Doppler capability. This ability provides information on the radial velocity of precipitation using the Doppler frequency shift between transmitted and received pulses. The knowledge of the wind direction can be derived from this information, as can information on the fall velocities of hydrometeors.

The ranges of weather radar systems vary from around 100 km for Doppler modes to around 250 km. Only shorter ranges are used in some systems for Doppler wind measurements (so called Doppler mode) and longer ranges only for precipitation intensity measurements (so called intensity mode). Some operational radar systems measure simultaneously Doppler and intensity data up to 250 km. Radar data is generated with typical spatial resolutions of approximately 1-2 km and temporal resolutions of usually 5-20 min.

3.2 Weather radar types and operators in the BALTEX region

Modern weather radars are digital systems, delivering binary data which can be used directly in computerised environments both for display and for automated analysis. Research radars are often highly configurable, allowing the user to program exactly how the radar should collect data. Such radars require constant interaction by an operator and are used on an event basis. In Europe most operational radars are completely automatic systems; they collect data according to a pre-defined schedule and deliver products (Table 3.2) according to a prespecified list. They require minimal operator intervention but are not as flexible as research radars.

All the radars specified in the BALTEX region (Figure 3.1 and Table 3.1) are digital, operational systems. Those organisations operating weather radars in the countries within the BALTEX region are usually either national civilian or armed forces' weather services. The presentation given in this chapter (Figure 3.1, Tables 3.1 and 3.2) is largely based on the present use of such operational radar systems.

3.3 State of the art of weather radar research and development

Weather radar research is highly varied and contains a multitude of fields of specialisation, ranging from observations of individual phenomena with highly specialised equipment to operational activities using conventional real-time networks. Comprehensive presentations and discussions of current research activities can be found in Atlas (1990) for the United States and Collier (1996) for Europe. The work being done within the COST-75 European action (see Collier (ed.), 1994) contains numerous examples of current research activities. This section's content is largely taken from a recent review by Joe (1996).

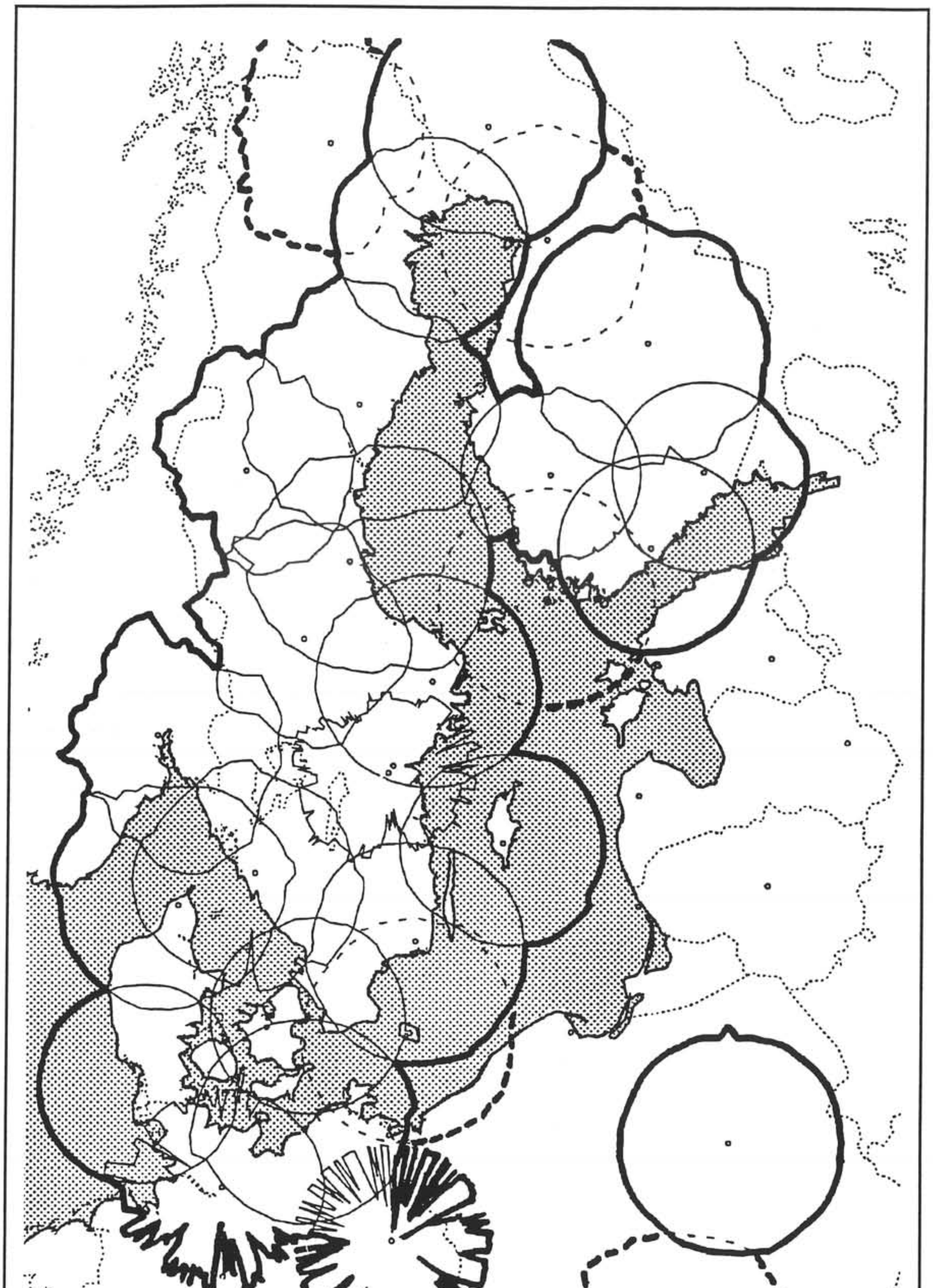

Figure 3.1: Map showing radar coverage at 1500 m above mean sea level. An estimate of the radar-covered area is given by connecting the outer boundaries of individual station radii around each station. Planned stations are indicated by dashed lines. Local obstacles near the station may lead to deformations of the ideal circular form of the radar range. The map is created by using a software package created by KNMI (Newsome, 1992).

Table 3.1: Radar inventory for the BALTEX region.

St. No. = Station number.
stat. = status (1 = operational, 0 = planned).
Lat., Lon. = Geographical position (degrees).
H = Elevation above mean sea level (m).
B = Main lobe width (degrees).
R = Maximum operational range (km).
Y = Year of installation.
T = Type (* = Doppler, letter = band if not C-band).
O = Operator (C = civilian, M = military).

St. No.	stat.	Lat.	Lon.	H	B	R	Y	T	O	Location
NO41	1	59.855	10.386	458	0.9	240	87	*	C	Oslo
SN41	1	58.583	16.152	57	0.9	240	83	*	C	Norrköping
SN42	1	59.656	17.949	74	0.9	240	86	*	C	Stockholm
SN43	1	57.723	12.172	164	0.9	240	88	*	C	Göteborg
SN44	1	57.238	18.384	58	0.9	240	90	*	C	Gotland
SN45	1	56.296	15.613	123	0.9	240	90	*	M	Karlskrona
SN46	1	63.644	18.402	522	0.9	240	92	*	M	Örnsköldsvik
SN47	1	65.544	22.114	35	0.9	240	93	*	M	Luleå
SN48	1	61.579	16.716	389	0.9	240	93	*	M	Hudiksvall
SN49	1	60.723	14.880	458	0.9	240	94	*	C	Leksand
SN50	1	63.176	14.456	475	0.9	240	95	*	M	Östersund
SN51	0	67.265	20.374	649	0.9	240	96	*	M	Kiruna
FI40	1	60.575	22.114	83	0.5	300	86	X	C	Masku
FI41	1	66.609	25.844	209	0.5	300	88	X	C	Rovaniemi
FI42	1	60.271	24.873	83	0.9	250	93	*	C	Vantaa
FI43	1	61.767	23.080	154	0.9	250	93	*	C	Ikaalinen
FI44	1	60.904	27.111	139	0.9	250	93	*	C	Anjalankoski
FI45	1	62.862	27.385	268	0.9	250	95	*	C	Kuopio
FI46	0	59.6	22.1		0.9	250	97	*	C	Korpo
FI47	0	64.8	26.0		0.9	250	97	*	C	Muhos
DN41	1	55.600	12.620	5	0.9	240	86		C	Kastrup
DN42	1	55.173	8.552	10	0.9	240	92	*	C	Rømø
DN43	1	57.489	10.136	93	0.9	240	94	*	C	Sindal
DN44	1	55.300	9.117	35	1.8	200	91	S*	C	Karup
DN??	0	54.9	15.4			240	98	*	C	Bornholm
DN??	0	55.6	12.0			240	98	*	C	Brorfelde
DL42	1	53.623	9.998	46	1.1	230	90		C	Hamburg Fuhlsbüttel
DL43	1	54.174	12.059	35	1.0	230	94	*	C	Rostock-Warnemünde
DL45	1	52.479	13.389	80	1.1	230	91		C	Berlin-Tempelhof
PL41	1	52.400	20.967	125	0.5	250	91	XS	C	Legionowo
PL42	1	50.142	18.726	357	1.0	250	95	*	C	Ramza

Table 3.2: Availability of operational radar products in the BALTEX region.
(* = available, A = archive)

Country	Norway	Sweden	Finland	Denmark	Germany	Poland
NORDRAD member	*	*	*			
SINGLE RADAR PRODUCTS:						
volume scans	*	*	A	A	*	A
CAPPI layers	*	*	*	*		*
precipitation intensity, mm/h		*	*	*		*
reflectivity, dBZ	*	*	*	*	A	*
radial wind, m/s	*	*	*			
echo top, m	*	*	*			*
wind soundings, m/s		*	*			
accumulated precipitation., mm			*			*
Liquid water content, g/m3			*			
Vertically integrated liquid water (VIL), mm			*			
Horizontal wind vectors as CAPPI layers		*	*			
COMPOSITE PRODUCTS:						
precipitation intensity, mm/h		*				
reflectivity, dBZ		*	*	*	*	
echo top, m						
windspeed, m/s, winddirection						

3.3.1 Precipitation estimation

There is a long history of using the power of the radar return to estimate the amount and distribution of precipitation. Most work has concentrated on estimating rainrate; operational experience in measuring solid phase precipitation is little by comparison. Reviews by Joss and Waldvogel (1990) and Smith (1990) provide comprehensive discussions on the state of the art, and many related aspects, of estimating precipitation with weather radar. This section will briefly summarise some of the techniques being used today to measure precipitation.

The ***drop size distribution*** (DSD) and ***terminal velocity*** of hydrometeors are two major factors controlling the ability to estimate precipitation intensities. Radar reflectivity (Z) is usually assumed to be equal to the sum of the diameter of drops to the sixth power per unit volume($Z = \Sigma D^6$). Thus, the DSD will fundamentally influence Z. Marshall and Palmer (1948) observed that rain DSDs are exponentially distributed and formulated the most widely used empirical relationship to date:

$$N(D) = N_0 \exp(-\Lambda D)$$
$$\Lambda = 4.1R^{-0.21}(mm^{-1})$$
$$N_0 = 8 \times 10^3 (m^{-3} mm^{-1})$$

where $N(D)$ indicates the number of drops with diameter D and R is the rainrate.

Exponential distributions have also been observed for hail and snow, although uncertainties remain in the measurement of the dimension, mass and type of snow crystals and aggregates; even larger uncertainties remain in the equivalent precipitation rate. The terminal velocity measurement is required to convert DSDs to rainrates. Standard formulations for rain, snow and hail all exist, yet those for snow and hail remain uncertain due to the inherent difficulties in studying them.

By definition **Z-R** ***relationships*** relate radar reflectivity (Z) directly with the rainrate (R) and have been the subject of numerous studies over the last four decades. R is a product of the mass content (M) and the fall velocity (w_t) in a radar volume. Since R is roughly proportional to the 4th power of the particle diameters, and Z is proportional to the 6th power of the particle diameters, the natural variability in DSD gives an important source of uncertainty when estimating precipitation with radar. Various approaches in deriving Z-R relationships include measuring DSDs and comparing radar Z with measured R at the ground. Whereas the latter is specific for the given radar system, it has the advantage of being able to account for errors in the radar calibration. Numerous Z-R relationships have been derived (Figure 3.2), the most classic and widely accepted of which is $Z = 200R^{1.6}$ from Marshall and Palmer (1948). Attempts at classifying precipitation event types as a means of explaining part of the variability of the Z-R relationship have not resulted in much improvement and may be difficult to implement on an operational basis.

For snow and hail, Z-R relationships are more uncertain. Typical relationships are

$$|K|^2 \times Z = 540R^2$$

for dry snow and

$$|K|^2 \times Z = 2000R^2$$

for wet snow (Andersson *et al.*, 1985), where $|K|^2$ is the dielectric constant of the snow type. Thresholding high reflectivities is the most common means of identifying hail. While much effort has been devoted to studying the variation in the Z-R relationship, far greater errors in precipitation estimation result if the differences between reflectivity aloft (combined with increasing range from the radar) and precipitation reaching the ground are ignored (Joss and Lee, 1995).

Area-time integration of total amounts of rainfall for complete storms gives results which are independent of the rain intensity distribution within them. Good agreement between radar accumulated rainfall and rain gauges has been found when using this approach with the Marshall-Palmer Z-R relationship at short ranges from the radar and when the radar beam does not contain melting snow. Its value is however inherently limited to climatological applications.

Raingauge-radar methods attempt to adjust the radar-derived rainrate to surface measurements by gauges, given that the latter are the accepted standard for point measurements. The value of this approach is that it allows the comparison of two mutually independent data types to derive a potentially more accurate precipitation measurement. The fundamental limitations of both radar and gauge must naturally be taken into account. Radars can suffer from calibration errors and the use of poor *Z-R* relationships. These factors can be compensated for by adjusting with gauge data. The density of a gauge network and the variability of rainfall pattern decides how accurate gauges can estimate precipitation. Also, since rainfall patterns are not homogenous, there is no reference to determine the gauge network accuracy. Intercomparisons between radar and gauges should be routinely made as a means of checking both methods' performance.

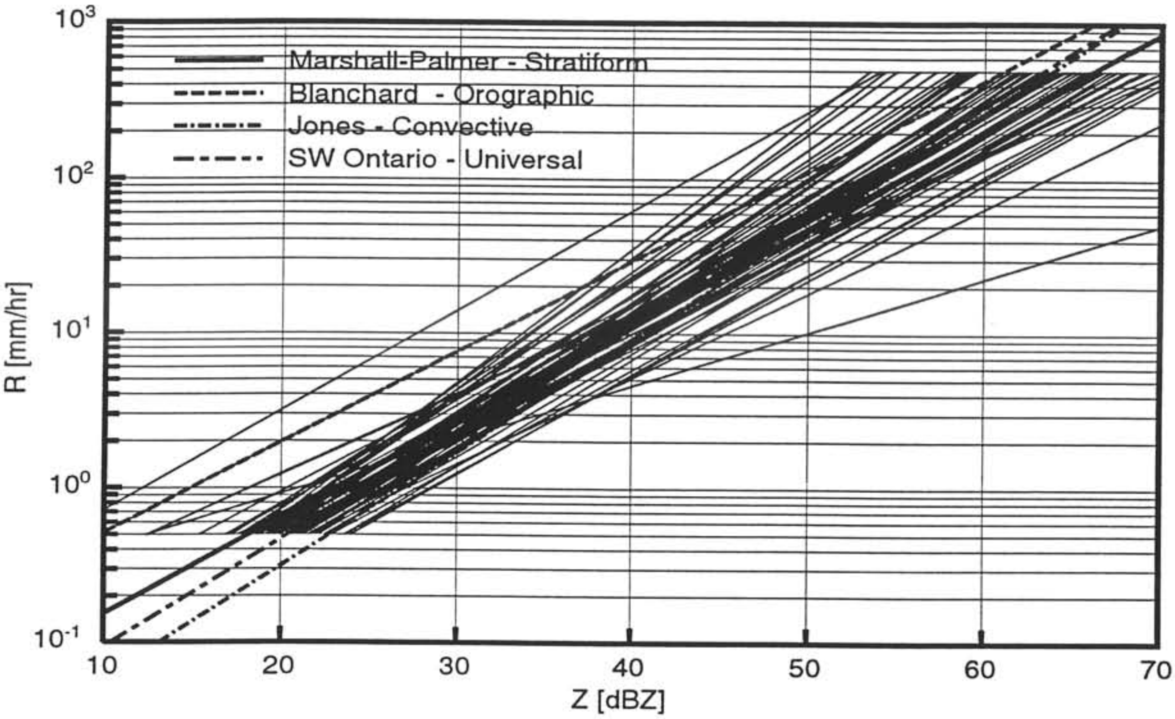

Figure 3.2: Battan's (1981) classic compilation of over 69 *Z-R* relationships, four of which are emphasized.

If a clear radar bias can be determined, adjustment with gauge data can result in significant improvement. The general guideline is, however, to first test whether the bias between gauge and radar is larger than the standard deviation of the random scatter of the gauge versus radar. Should this be the case, then adjusting the radar data with gauge data will lead to consistent improvement. There is presently no common approach in adjusting radar with gauge data. Techniques based upon area time integration of radar and raingauge data (Rosenfield et al., 1994) offer possible improvements, althoug it is not yet clear whether such techniques are better than simple regression (Seed et al., 1996).

The integration of ***hydrological discharge measurements*** with radar is an interesting recent development, in that it compares the radar data with the integrated net result of a precipitation event. Its main benefit is that it eliminates the uncertainties involved with the representativeness of point measurements from single rain gauges. It does, however, introduce a number of new uncertainties, the most important of which is the knowledge of the hydrological characteristics of the given catchment area. If a representative model of a catchment area is not available, the integration time required to compare radar with discharge measurements will be increased, limiting real-time applications. The application of models, which can use past experience of various hydrological events and conditions, may improve the ability to use this approach in real-time (Joss and Lee, 1995). Greater imminent improvements are however foreseen resulting from better radar correction algorithms (Joss *et al.*, 1995).

Precipitation attenuates the intensity of radar signals and it is necessary to be aware of attenuation effects when estimating heavy rainfall at wavelengths less than 10 cm. ***Estimating attenuation*** can, however, be used to estimate rainrates. In operational environments, this approach turns out to have a number of practical limitations. Either a known target at a known range must exist for use with conventional systems, or bistatic systems (one transmitter with >1 receivers at different locations) must be used. Multipath reflections from mainlobe edges and side lobes, from quasi-horizontal systems, lead to poor results. This approach is currently not widespread.

Dual wavelength techniques require an attenuating and non-attenuating wavelengths to derive DSD parameters. Accurately calibrated systems and matched beams are required in order for this approach to work. Also, severe or complete attenuation of the shorter wavelength (not uncommon in cases of intense precipitation) limits the range at which this method can be reliably used. Due to the lack of reliable operational dual wavelength systems, this approach is not common for real-time applications.

Differential phase, dual polarisation and ***precipitation typing*** are all methods which analyse the polarisation diversity characteristics of the received radar signal. Polarisation techniques are formulated on the basis that drop shape changes with drop size (Figure 3.3) and that consequent relationships can be measured.

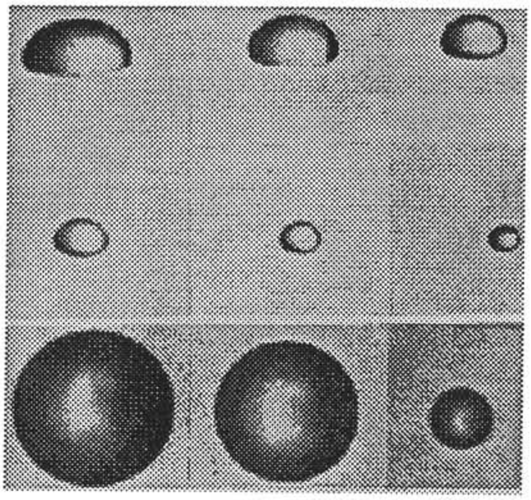

Figure 3.3: Drop shape as a function of drop size: the basis for the use of polarisation techniques. Drop diameters are, from left to right:
first row: 4.00, 3.68, and 2.90 mm, second row: 2.65, 1.75 and 1.35 mm,
third row: 393, 354, and 155 μm (note the difference in scale),
(original plates from Pruppacher and Beard, 1970).

Differential phase requires alternately or simultaneously transmitted vertical and horizontal waves. The specific differential phase (K_{DP}) is a measure of the difference between the phase shifts in reflectivity from the two polarisation's. Since large drops are oblate with a minor vertical axis, the phase shift from horizontally polarised waves will be greater than that from vertically polarised waves. Benefits in using the K_{DP} are that it can be used to identify hail, it is independent of system calibration, rain attenuation, beam blockage and beam filling, since differential phase shifts are unaffected by these.

Dual polarisation methods attempt to analyse the relationship between the return powers from two different polarisation's. As the name reveals, the radar system must have dual linear polarisation. A common parameter used as an indicator of mean oblateness of precipitation particles is the Z_{DR}, which is the ratio of horizontal to vertical polarised return powers. Dual parameter approaches often use combinations of Z_{DR} and Z_H, or Z_H and Z_V to derive rainrates.

Precipitation typing is a closely related approach which uses polarisation information to classify precipitation qualitatively. For example, large hail are oblate and fall with a minor horizontal axis. As mentioned previously, large rain drops are also oblate and fall with a minor vertical axis. So, Z_{DR}, should be negative for hail and positive for rain. A number of formulations utilise the K_{DP} as this measure is also sensitive to particle shape.

Benefits of polarisation diversity techniques may be found at close ranges, where valuable information may be derived on precipitation particle distributions and other parameters related to cloud physics. For operational activities, such as those performed by weather services, the usefulness of polarisation diversity is in question as such techniques require highly accurate calibration of the radar system and non-interfering radomes. The number of radars with polarisation diversity capability are relatively few and often used for research purposes.

Vertical profiling can be used to estimate rainrates, given a Doppler radar which can point its antenna vertically. The DSD is determined through measuring the velocity spectrum. Given air with zero horizontal velocity, each component of the Doppler velocity spectrum is the same as the terminal velocity and thus the drop size. Each frequency component's amplitude is related to the number of drops of that drop size. A complication is the presence of up- or downdrafts which must be accounted for above the lowest elevations. Common to most methods is the extreme sensitivity in drop number concentrations to errors in vertical velocity.

Vertical profile corrections attempt to account for radar underestimating surface rain at greater range. This effect is a result of the radar beam becoming wider and higher in elevation with increasing range, which gives decreasing reflectance with height. The difference between precipitation measured by radar and measured at the ground increases with range as a result. This effect can be especially pronounced in stratiform rain and snow. Highly variable vertical reflectivity profiles, both within storms and for different storms, add to the difficulty in developing a universal method. Examples of vertical profiles of particle velocity and reflectivity can be seen in Figure 3.7. Joss and Lee (1995) recommend using observed vertical profile climatologies as a means of compensating for radar's inherent disadvantage. They also set out requirements for operational profile corrections and discuss limitations of their approach. Addressing this vertical profile issue is fundamentally important for quantitative applications of radar data. Advances in operational algorithms are expected in the relatively near future.

Nowcasting models of precipitation probability and amount using radar have been developed (Browning and Collier, 1989, Andersson and Ivarsson, 1991) and are an example of practical uses of precipitation information derived from radar. Such models are being used to provide information in urban hydrology and agriculture, to name but two applications. A recent thesis on point process models for use with radar imagery (Larsen, 1995) exemplifies an interest in applying more sophisticated algorithms in attempting to improve the accuracy of short term forecasts.

3.3.2 Wind measurements

As previously mentioned, Doppler weather radar systems can be used to measure wind parameters. Using the Velocity Azimuth Display (VAD) technique (Lhermitte and Atlas, 1961), radars can be used as vertical profilers, providing profiles of wind direction and wind speed with high temporal resolution; the vertical resolution of such profiles is dependent on the presence and characteristics of precipitation targets but is generally considerable higher than those provided by radiosondes. Although the latter commonly rise to higher altitudes, radars have the additional advantage of not being prone to sensor drift. Typical vertical resolution of VAD profiles is around 100 m, where the maximum altitude of a profile can range from 5 to 10 km or higher, depending on weather conditions. Using many radars, VAD profile networks have been developed which provide information operationally and which can be used as a forecast analysis tool and for use in numerical weather prediction models (Svensson, 1995). An example of VAD profiles compared with radiosonde profiles is seen in Figure 3.5.

In both theory and through a case study in Finland (Prof. J.Rinne, pers.comm., to be published) it has been found that the accuracy of a horizontal wind vector derived from the radial Doppler component of a single elevation angle (PPI) is of the order of ± 10 cm/s provided that the actual wind field is horizontally linear and the radial wind data is available from all azimuth angles. This accuracy will be even better when data from all elevation angles is used.

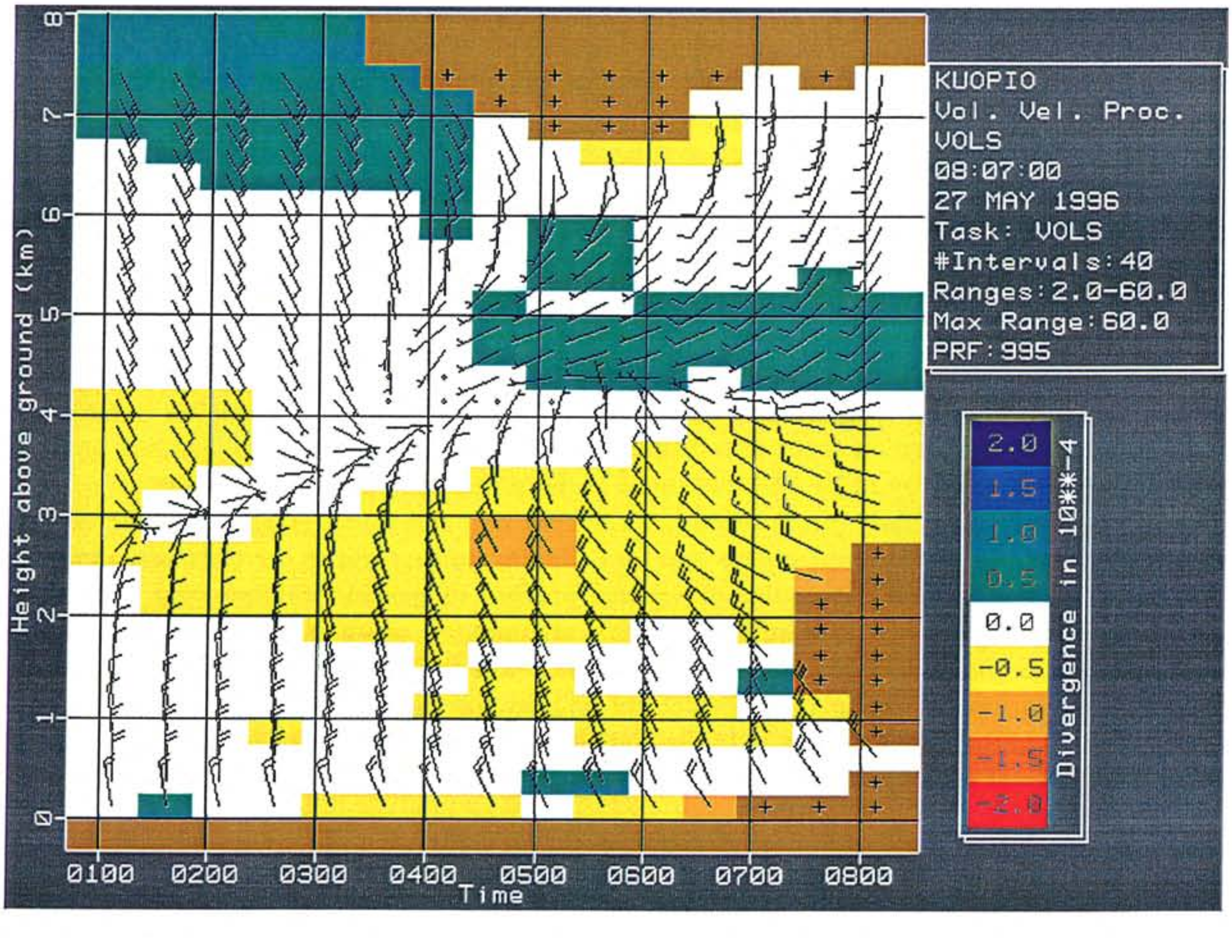

Figure 3.4: Time-height cross section of VVP wind soundings derived at the Kuopio Doppler radar on 27 May, 1996, 01 UTC - 08 UTC. The colour background exhibits the radar derived distribution of divergence ($10^{-4}s^{-1}$).

An algorithm called VVP (Velocity Volume Processing) is similar to the VAD technique except that it is an improved analytical approach (Waldteufel and Corbin, 1979). VAD or VVP wind profiles are produced routinely in Sweden and Finland and work is underway in several countries to implement similar routines. Figure 3.4 exhibits an example of VVP wind soundings and divergence from the Kuopio radar in Finland. The case shown is related to a passage of a developing frontal wave by cold air advection. Bistatic Doppler radar networks have been developed and are able to derive three-dimensional vector windfields in real time (Wurman, 1995), yet very few operational systems exist today.

The benefits of using radar techniques to measure profiles of wind speed and direction are at this point well defined. Present activities aim at enhancing these capabilities by developing better ways of generating operational profiles from clear-air echoes, which are also seen in Figure 3.5. In some countries work is ongoing to use fields of divergence estimated from Dopple radar data to enhance precipitation measurements.

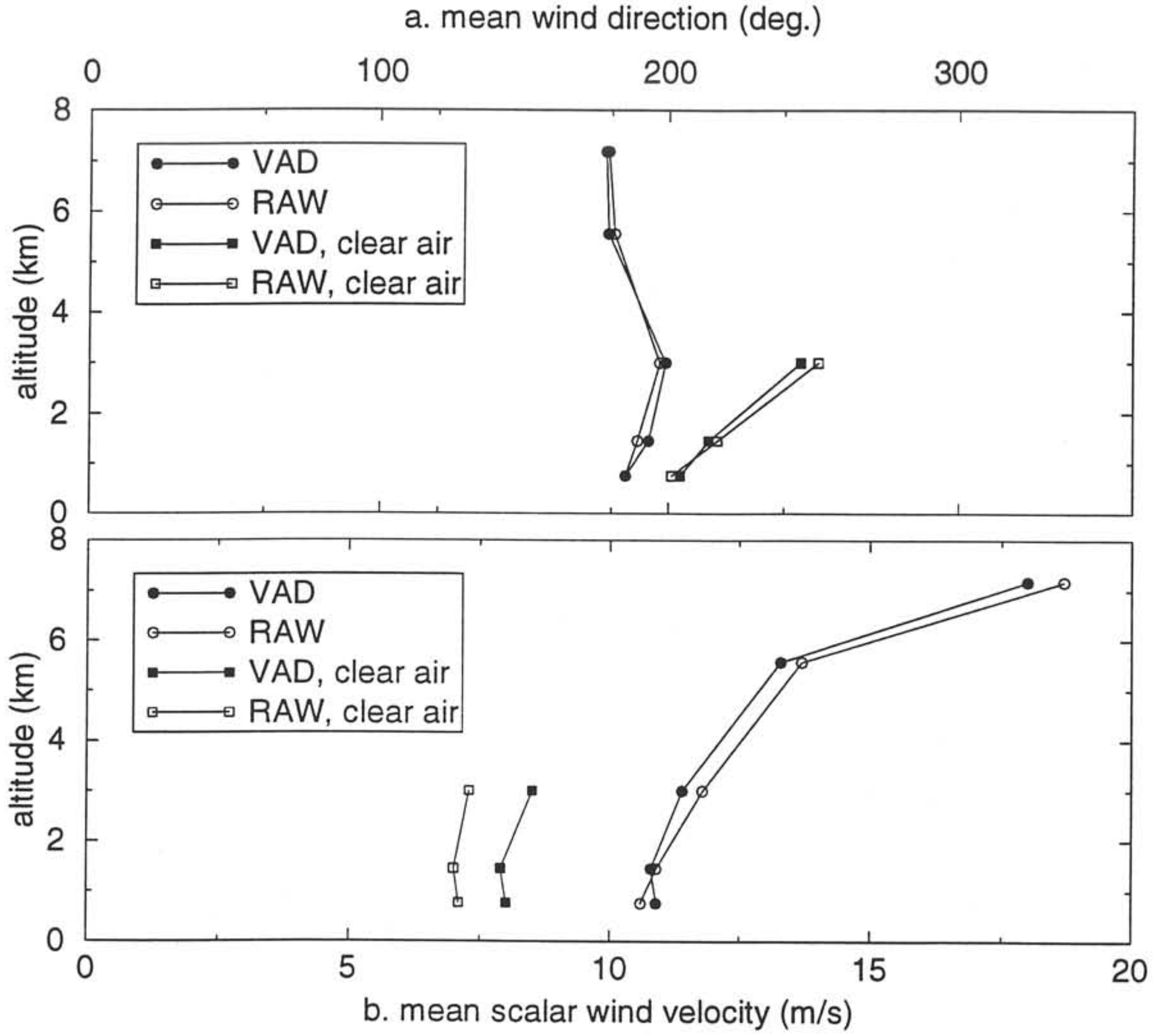

Figure 3.5: Comparison of radar-derived vs. radiosonde-derived profiles of a) wind direction and b) wind speed for the radar at Göteborg, Sweden. The values are integrated over the period 28 June - 30 September, 1995.

3.3.3 Improved algorithms for quality control

For the purposes of this report, the discussion will be limited to the current status of prioritised operationally-oriented research.

The characteristics of weather radars and their data are well-known empirically and intuitively. A wealth of information exists on the various sources of error to which radars are prone. Of these errors, some of the trickiest to deal with are those resulting from ***anomalous propagation*** (ANAPROP) of the radar beam. In this context, anomalous propagation is synonymous with super-refraction of the radar beam caused by a rapid decrease with height in the atmosphere's refraction index. Typical such situations occur with:

- advection of warm, dry air over a cold sea, common for the Baltic Sea during spring and early summer,
- radiation inversion, during night or during winter over snow-covered areas,
- cold air domes, following rain produced by heavy showers or hail.

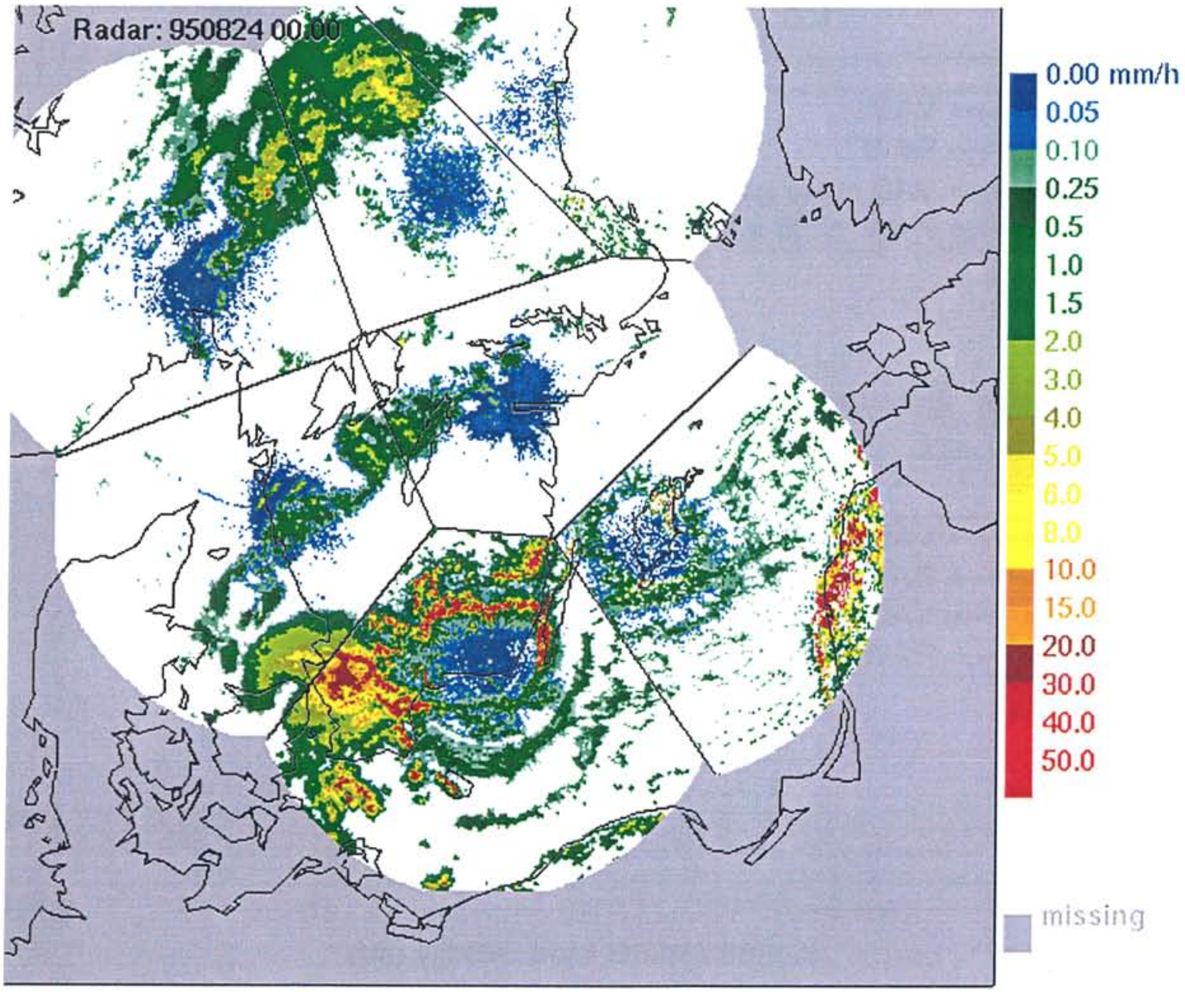

Figure 3.6: An example of anomalous propagation echoes together with strong precipitation echoes over southern Scandinavia. A meso-scale cyclone is located over south-western Sweden. Immediately to the east is strong ANAPROP from land along with sea clutter seen as concentric rings around the Karlskrona and Gotland radars. ANAPROP can also be clearly discerned from the Polish and Baltic State coasts.

ANAPROP gives echoes from the earth and/or sea surfaces which are highly variable in time and space (Figure 3.6). Unless treated, these false echoes will be considered to be precipitation echoes in automatic applications and result in inaccurate precipitation products. Although ANAPROP as a phenomenon has long been observed, the ability to automatically analyse and treat it in real-time applications has been limited until recently due to limitations in computer performance. A great amount of present research activity is being carried out on identifying and correcting (or removing) echoes resulting from ANAPROP (e.g. Joss and Lee, 1995). While a number of standard algorithms available with Doppler systems are effective in removing ANAPROP from land (compare Figures 4.2 and 4.3), identifying and treating ANAPROP from sea is a more difficult task, even in Doppler mode since such echoes depend upon surface characteristics in a non-linear way. However, in general, improvements are foreseen in the near future in ANAPROP treatment algorithms which will result in higher quality radar data and radar-derived products.

Another area of current quality control research deals with developing algorithms for automatic detection and correction of effects caused by the ***melting layer*** or "bright band". This is closely related to the ***vertical profile correction*** discussion in section 3.3.2 which is also an area of current activity. Improved algorithms in both these areas are vital for improvements in quantitative precipitation applications. Figure 3.7 illustrates the bright band through vertical profiles of particle velocity and reflectivity.

Improvements are also foreseen in the ability to adjust radar data with independent systems such as raingauge networks.

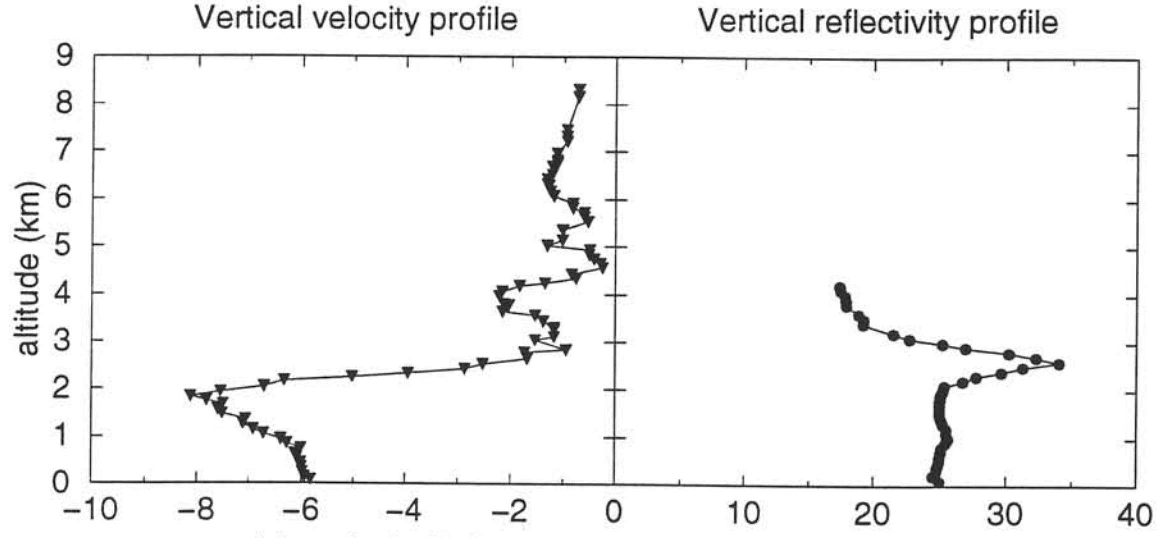

Figure 3.7: Vertical profiles of particle velocity and reflectivity as measured by the radar at Norrköping, Sweden, on Sept. 15, 1995, 00 UTC. The bright band can be identified through the peak in reflectivity combined with the sharp increase in particle fall velocities.

3.3.4 Monitoring of severe weather

Due to rapid changes in space and time of severe weather, radar is the only realistic means to monitor it over large areas. Severe weather can be identified using radar echo intensities, areas and patterns. Doppler capability can provide information on the intensity of winds associated with gust fronts, downbursts and tornadoes.

High reflectance intensity (50 dBZ or greater) and its height developement are commonly used to detect potentially severe thunderstorms. Forecasters are also advised to look for typical echo shapes, such as hook echoes, overhangs, spiral bands and eyewall structures, as a means of detecting severe weather.

Using Doppler radars, tornado warnings use the meso-cyclone signature (or velocity couplet) which is observable in mid-levels of a storm and which descends to cloud base. Tornado warning lead-times have been around 20 min for situations in Oklahoma (JDOP, 1979). The Tornado Vortex Signature (TVS) is the location of a very tight circulation in a small region of a meso-cyclone; these have been detected aloft around 30 min before a tornado has touched down (Brown and Lemon, 1976). Terminal Doppler Weather Radar systems (TDWR) are used at airports to help protect aircraft during takeoff and landing. TDWRs are routinely used to monitor downbursts and microbursts of air which are common near areas of convective activity.

Common for almost all types of present severe weather warning systems is the requirement of a trained operator, although considerable efforts exist to generate automatic methods. For example, the Finnish radar software includes automatic detection and warning algorithms for shear lines. However, statistical verification of the validity of such algorithms is still lacking.

3.3.5 Monitoring of synoptic and meso-scale weather systems

Weather radar can monitor synoptic and meso-scale weather at high spatial and temporal resolutions, for areas around 125 000 km^2. Since earth curvature causes the radar beam to increase in height with increasing range from the antenna, the maximum range at which a radar can confidently monitor weather is approximately 200 km. Networks of radars, such as the international NORDRAD co-operation (e.g. Carlsson, 1994), provide the means of extending monitoring coverage in an effective manner.

Over the past 20 years, advances in computer hardware and software have led to increased interactivity in radar user systems for monitoring purposes. Examples of such systems are FRONTIERS/NIMROD and GANDOLF in the UK (Collier, 1996), a system developed for research and monitoring in Italy (Nativi *et al.*, 1995) and VRIS in Denmark (Overgaard, 1994). Such systems allow the user to interact with radar imagery to visualise the data in a multitude of ways, both alone and together with additional types of information. A new generation of analysis and visualisation tools are currently being developed which provide visualisation of three-dimensional volume data (Doick and Holt, 1995, Bolin and Michelson, 1996). These show promise in both interactive and automated monitoring applications.

Flood forecasting and control systems are an example of an application of recent improvements to the above mentioned computer advances combined with improvements in radar data processing algorithms. Such an operational system (Cluckie and Owens, 1989) uses radar together with numerical models.

3.4 Additional data sources

3.4.1 Satellite data

Satellite estimates of precipitation are derived from the radiative characteristics of clouds in a wide range of frequency bands (see e.g. Simmer, 1996, and references therein for a recent review on retrieval of precipitation from satellites). A large body of research exists in which the SSM/I sensor on the DMSP series of orbiting satellites has been utilised. These are passive microwave sensors ranging from 19 to 85 GHz. Data from these sensors can provide information on the presence of precipitation over sea. Land and coastal areas contaminate the precipitation signal; research is currently underway to attempt make this data more useful in coastal areas. A number of forthcoming sensors, both on American and European platforms makes the analysis of precipitation from satellite more promising in the future.

Weather radar measurements are more direct in that radars actively sense the characteristics of the hydrometeors. Whilst radar offers higher accuracy in general than satellite techniques over small areas and time periods, the two approaches are complementary. Satellite precipitation estimates have been used to provide information where there are weaknesses in radar coverage, particularly over sea areas where there are almost no surface-based observations. It should be borne in mind that satellite techniques suffer to a greater or lesser degree from errors arising from sampling even for geostationary satellites. Radar information is available every few minutes, and, except in extreme cases of convective rainfall, sampling is not a problem. Within BALTEX it is envisaged that effort will be put into using techniques to blend radar and satellite imagery in ways to improve the database in data sparse areas.

Passive microwave sensors are not able to provide reliable information over land. Rain gauges are almost unavailable over sea. Weather radars are the only sensors that are able to provide information, with high spatial and temporal resolution, simultaneously over both land and sea.

3.4.2 Observations at land stations

Precipitation is operationally measured at conventional rain gauge land stations. Most of these stations give integrated precipitation depths for 12-hours intervals. A minor fraction includes even 6-hourly or only daily precipitation values.

In terms of accessibility land station data may be divided into data from

- synoptic stations
- special precipitation stations.

While measurements from synoptic stations are disseminated via GTS and, hence, are easily accessible for research purposes, data from special precipitation stations are stored at a variety of national or regional centres. This includes data from climate stations which are normally operated by national weather services and data from automatic stations operated by different other national agencies in some countries. It is important to note that the number of special precipitation stations is much larger (by a factor of up to 10 in some countries, see Table 3.3) compared to the synoptic stations. Efforts have been undertaken in the frame of BALTEX to extract data from all available precipitation stations from national and regional archives into the BALTEX Meteorological Data Centre. For the BALTEX - PIDCAP period (August to

November 1995) precipitation data from more than 3500 stations will be made available for BALTEX research purposes (Table 3.3). Presumably, it is the most dense station network which has been made available for the entire Baltic Sea catchment region so far. It is, however, not dense enough to have at least one observation on average within each 18 km × 18 km gridpoint of the regional BALTEX model REMO. In some areas in the north and east of the BALTEX region only about half of the REMO model gridpoints have at least one station with in situ observations of precipitation available.

Country	**GTS precipitation stations**	**GTS and non-GTS precipitation stations**
Belarus	8	60
Denmark	30	620
Estonia	23	60
Finland	45	530
Germany	29	299
Latvia	23	95
Lithuania	18	72
Poland	59	1237
Russia	9	160
Sweden	220	762
Total	**464**	**3886**

Table 3.3: Number of stations with available precipitation data (GTS versus GTS plus non-GTS) during the BALTEX - PIDCAP period (August to November 1995) in the BALTEX region.

It is of crucial importance for BALTEX that the existing precipitation station density (as has been achieved for example during the PIDCAP period) will not be reduced during the future main BALTEX observational phase. The national weather services and other organisations holding precipitation data should be requested to offer all available station data free of charge for research purposes within BALTEX.

3.4.3 Marine observations

At present, in situ measurements of precipitation over the Baltic Sea, and generally over global ocean areas, based on operational instruments or networks are almost unavailable. As part of the BALTEX research programme specific ship rain gauges (Hasse *et al.*, 1994) have been recently installed on four ferry boats and at an automatic weather station north of the island of Darss. The ferry boats run regularly on a route from Travemünde, Germany to Helsinki, Finland. These ship gauges are especially designed to compensate for the instruments flow distortion bias under high wind speed conditions, which is of utmost importance when measuring precipitation on the open sea on a running ship.

These data are expected to be of great importance for verification of model output and adjustment of remotely sensed precipitation, both from radar and satellite.

The ship rain gauge data are expected to form the only ground truth from the open Baltic Sea. It is planned to run these gauges regularly during the coming years thus covering the major observational period of BALTEX, and providing for climatological estimates at least along the track of the ferry boats.

It is urgently recommended that additional ship rain gauges be installed on ferry boats running on additional ferry routes across different parts of the Baltic Sea.

4 FUTURE RESEARCH REQUIREMENTS FOR BALTEX

4.1 Networking

Our ability to exchange data over international borders is being continuously improved as a result of enhanced computer and network performance. The NORDRAD network is such an example, where data from radars in Norway, Sweden and Finland are merged to form composite images which are then used in various applications. Two different countries or radar operators seldom operate the same make of radar system. This gives rise to differences in radar-derived products which can be attributed to differences in radar system calibration. Even if different operators run the same type of system, they may not be calibrated in the same way. An illustration of this phenomenon can be found in Figure 4.1. Therefore, there exists a clearly defined requirement for research in developing methods for analysing and adjusting reflectivity values to create a homogenous composite product containing data from two or more radars.

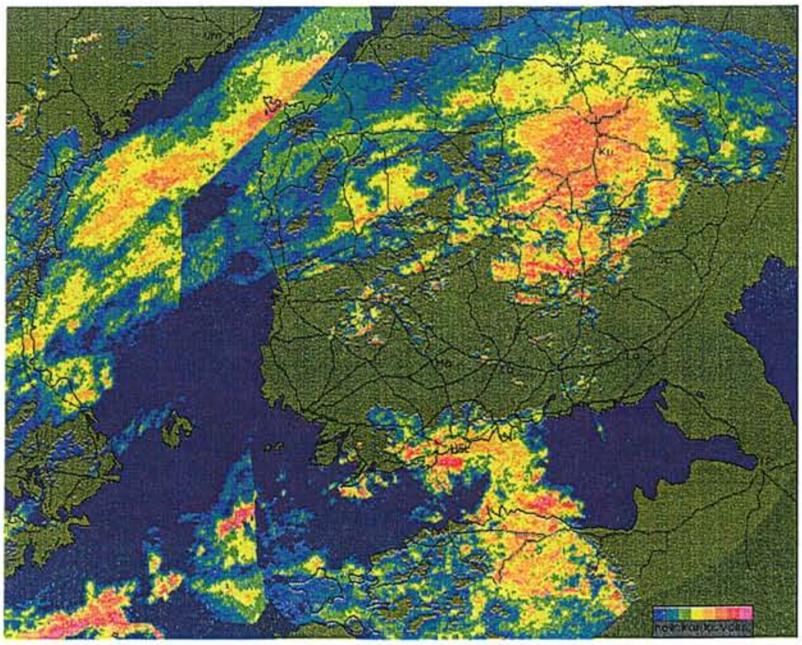

Figure 4.1 : Differences in radar system calibration between Swedish (Ericsson) and Finnish (Gematronik) radars cause heterogeneous composite images. This example is at 17 UTC on July 11, 1996 (thunderstorms over southern Finland) and the reflectivity scale is equal to that in Figure 1.1.

The collaboration required within BALTEX makes this type of research activity highly suitable. The geographical area to be monitored with radar, the number of radars, and the differences among radars all contribute to the complexity of the task of generating homogenous radar-derived products. More specific issues are discussed in section 4.3.1.

4.2 Increasing radar network coverage

There is a strong need to establish a complete radar coverage of the Baltic Sea - and at a later stage over the entire water catchment area of the Baltic Sea. In what follows the acronym BALTRAD is used as a working title for a weather radar structure suitable for covering the entire Baltic Sea catchment basin. Existing and planned radars are listed in Table 3.1.

In order to completely cover the Baltic Sea there is a need for two more radars (assuming that each has a range of at least 200 km). Suitable locations could be

- **near Gdansk Poland,**
- **in the area between Ventspils and Riga Latvia.**

It should be noted that the optimum location for a weather radar in a network may not be optimal in terms of local requirements. The local infrastructure (e. g. availability of roads, electricity, telecommunication, towers) is very important when selecting a radar site. For building up a weather radar network the locations should be selected with future extensions in mind. One future goal may be to cover the main roads around the Baltic Sea, including the planned *Via Baltica*. With this in mind one more radar each is needed in Estonia and Lithuania and also additional stations in Poland. Such an extended weather radar network will be of great benefit for the transportation system (air traffic, sea traffic, roads, railroads) around and over the Baltic Sea.

It is assumed that there is one focal point in each country (in NORDRAD it is called a national node) which will collect radar data from the national territory and will send it to a central BALTRAD node. It is suggested that radar products be sent in real-time or near real-time. One of the existing NORDRAD national nodes (e.g. SMHI or FMI) are possible candidates as the main BALTRAD node. SMHI is presently judged the most suitable because of the existing lines to Denmark and Latvia and because of the recently made upgrades to the computer systems at SMHI. FMI is also an alternative. An important product from each radar will be a pseudo-CAPPI reflectivity product. BALTEX will have to agree on and use a common radar format. In doing so, BALTEX shall rely on the work which is going on within the Liaison Group on Operational European Weather Radar Networking (LGOEWRN). Specific details will be worked out by the BALTEX Working Group on Radar.

Some resources are needed to establish or extend the communication lines between the national nodes and SMHI. The present situation is as follows:

- Finland - the present line (64000 bit/s) has acceptable capacity, even when the planned radars are included,
- Denmark - the present line (9600 bit/s) may need extended capacity when the radar at Bornholm is included,
- Germany - no distribution of radar data between Germany and Sweden at present - a permanent line or eventually a GTS-line may be used,
- Poland - the same as for Germany,

- Latvia - there exists a permanent line (12000 bit/s) between Norrköping and Riga with further connections Riga-Tallinn and Riga-Vilnius each with a capacity of 4800 bits/s.

The central BALTRAD node would create a high resolution (2 km horizontal resolution) BALTRAD-composite. This radar composite would be distributed to the additional BALTRAD national nodes using the same distribution channels as were listed above. The BALTRAD-composites would also be archived by the central BALTRAD node.

The use of the BALTRAD-composite will have to follow the general BALTEX data exchange policy and hence be restricted to research within the BALTEX-project. However, extensions might be possible according to further radar data exchange agreements to be developed in the future.

4.3 Requirements for radar data

A major key to improvements in the use of radar lies in the ability to apply improved quality control algorithms on the radar data itself. As previously mentioned, recent enhancements to computer technology now provide the ability to deal with such issues in a comprehensive manner. While a great deal of research is currently underway in this area, the following quality control topics are of particular relevance to radar research within BALTEX:

- ANAPROP (both ground and sea clutter)
- attenuation
- vertical reflectivity profile
- snowfall measurements.

Regarding the analysis of winds, future requirements relevant both for BALTEX and in general include research to develop improved conventional methods and the application of variational approaches. Of interest to operational forecasters is the possibility of developing algorithms for improved use of spectral width to provide information on the variability ("turbulence") within sample volumes.

The following subsections detail important research requirements for radar data for BALTEX.

4.3.1 Quantitative accuracy of radar precipitation data

In order to provide quantitatively acceptable precipitation data from radar, the BALTRAD products should represent a homogenous precipitation field over the whole coverage area, showing no inhomogeneities due to differences between the various countries' radar systems . This can be achieved by creating and applying operationally agreed-upon algorithms and procedures which remove or reduce the most severe errors from the national reflectivity fields:

- Differences in the electrical calibration of each individual radar and between the different radar systems in each BALTEX country should be reduced. For example, a systematic bias of the order of approximately 10 dB has been discovered in the operational NORDRAD composites between the Ericsson and Gematronik radars. Work to remove such biases has already been started between the Nordic countries as a NORDRAD continuation project. First results are given by Dahlberg (1996).

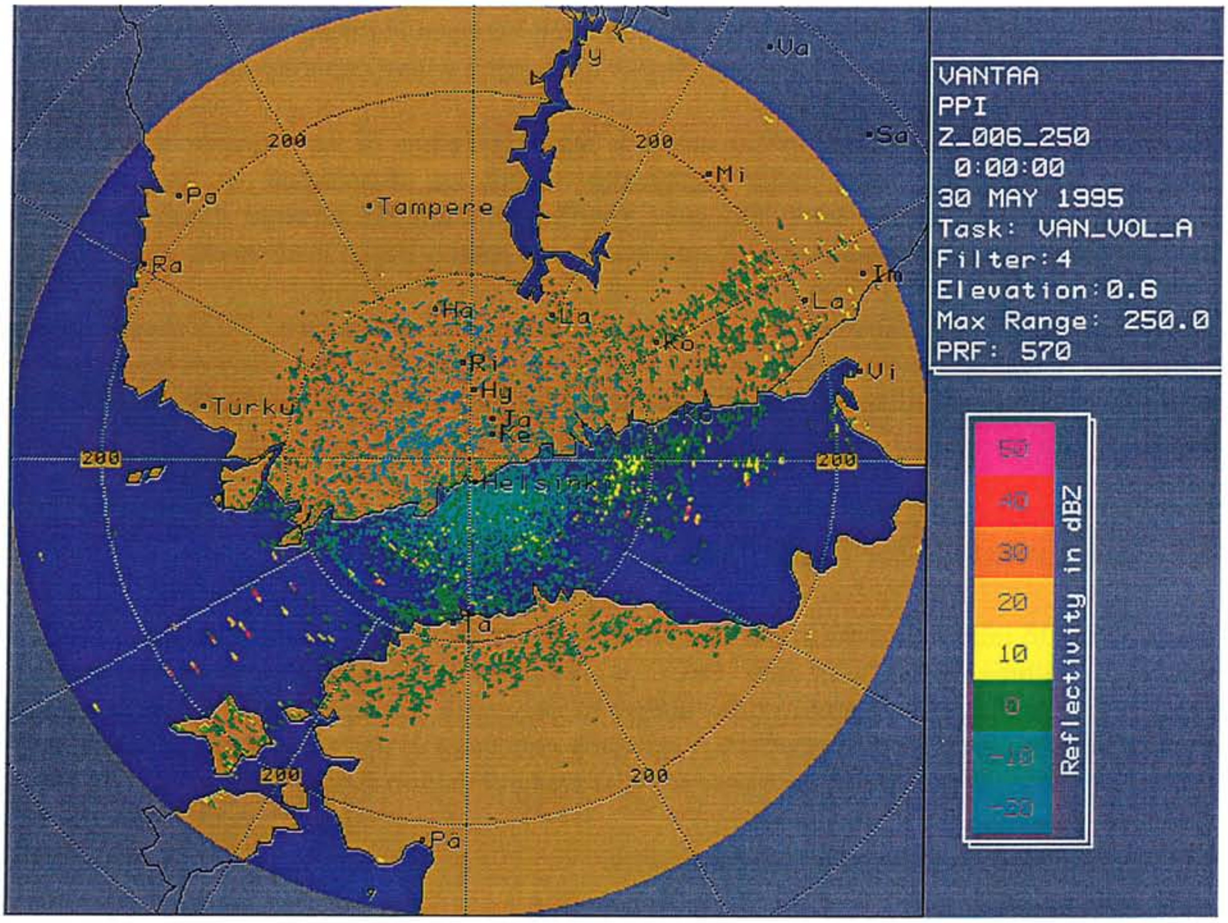

Figure 4.2: Operational lowest elevation radar reflectivity field at the Vantaa radar on 30 May 1995, 00 UTC, showing weak ground and sea clutter patterns.

- In cases of anomalous propagation (ANAPROP) which is common over the Baltic Sea, especially in spring and in summer, echoes from ground targets may erroneously simulate precipitation patterns. By using different correction methods (e.g. Doppler-filtering, echo structure analysis or radar-satellite comparisons) ground clutter can be rejected quite efficiently (see e.g. Lee *et al.*, 1995). Figures 4.2 and 4.3 exhibit a concrete operational example on the effect of a Doppler filter on severe ANAPROP. However, not all BALTEX countries have good operational tools for ground clutter cancellation. Sea clutter is often much weaker than ground clutter but, on the other hand, algorithms and operational methods to eliminate it are lacking in the BALTEX countries. A clear need exists to develop and implement ground and sea clutter rejecting methods in the countries where such tools are not yet well-established.

- Variations in the vertical reflectivity profile can introduce large sampling differences between the radar measurement aloft and the precipitation at ground level. The average tendency of radar reflectivity to decrease as a function of height, and the propagation effects of the radar beam introduce a systematically increasing underestimation with range (often 5-20 dB at ranges of 100-200 km from a radar) of radar estimated precipitation at ground level. In cases with a clear bright band, strong overestimation (up to 5 dB) occurs at ranges where the radar beam intercepts the bright band. In cold and temperate climates both of these factors are usually far more important to correct than the much discussed effects of the variations in hydrometeor size distributions (Joss and Waldvogel, 1990). The correction can be based on the observed vertical reflectivity profiles near the radar (Andrieu et al 1995, Koistinen 1994) or could be based on application of the 3-dimensional water content distribution from NWP model output.

- The correction due to the vertical reflectivity profile "shifts" the radar measured reflectivity from the detection height to ground level. In order to create correct precipitation values in units of mm from these reflectivities, the actual dielectric properties of the hydrometeors at ground level, i.e. the phase of hydrometeors (liquid, solid, mixed), must be known. Sources of information are automatic weather stations and high resolution NWP models together with the known high-resolution topography of the ground. This factor has received less attention in radar meteorology as much of the work has been restricted to warm season rainfall. However, over the Baltic drainage area all phases of precipitation occur daily during most of the year at ground level.

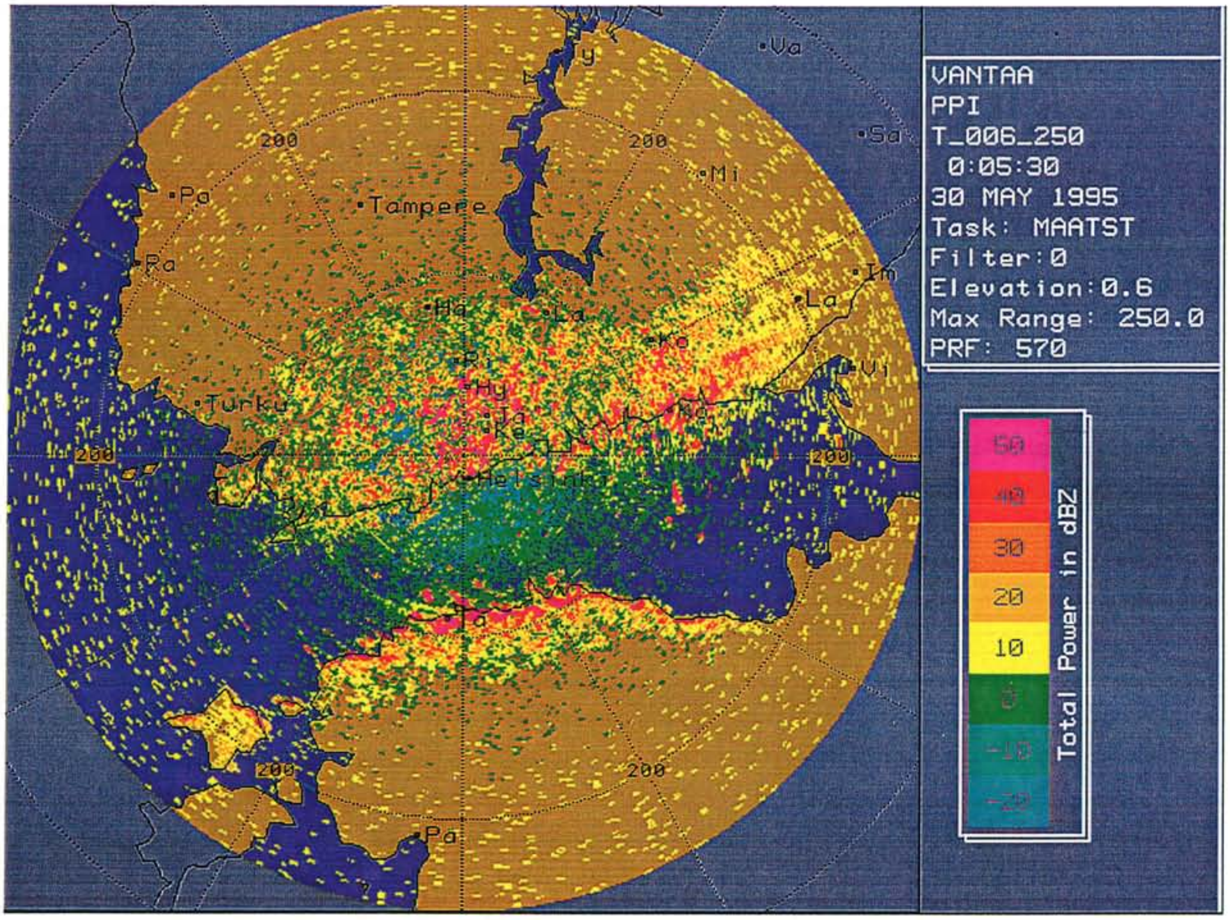

Figure 4.3: As in Figure 4.2, but without operational IIR Doppler filtering during the signal processing. Ground clutter due to ANAPROP is extremely strong. The noise level threshold is also higher than in Figure 4.2.

The above mentioned correction steps should be based on existing algorithms, if available, or based on algorithms developed as part of the BALTEX project, and they should be applied preferably in real time. The resulting composite product will be the BALTRAD reflectivity field, which should have small *relative* errors between different parts of the area of radar coverage. The time interval between BALTRAD reflectivity fields should preferably be between

5 and not more than 15 minutes when these products (instantaneous precipitation intensities) are integrated into accumulated precipitation.

In order to generate hourly accumulated precipitation at ground level (mm) with an acceptable error level in absolute terms, a post-detection gauge adjustment is required for BALTRAD precipitation and reflectivity fields (e.g. Barbosa, 1991). This adjustment should be based mostly on 12-hour or 24-hour accumulated gauge observations. In cases of large gauge errors, i.e. snowfall and considerable wind, the gauge error should be corrected prior to the adjustment. Figure 4.4 is an example of the observed average gauge-radar difference during a 3-month period at the Rovaniemi radar in Finland. Although the radar bias is approximately 5-15 dB depending on the range, the gauge adjustment shown in Figure 4.4 creates accurate hourly point precipitation amounts, see Figure 4.5. By integrating the adjusted point values into areal 24-hour values over areas larger than e.g. 400 km^2, an error in area precipitation of less than ±4 mm with a probability of 99% is obtained if compared to the actual gauge-measured area values (see Figure 4.6).

The BALTRAD hourly precipitation product will probably be the first international, quantitatively uniform radar precipitation product.

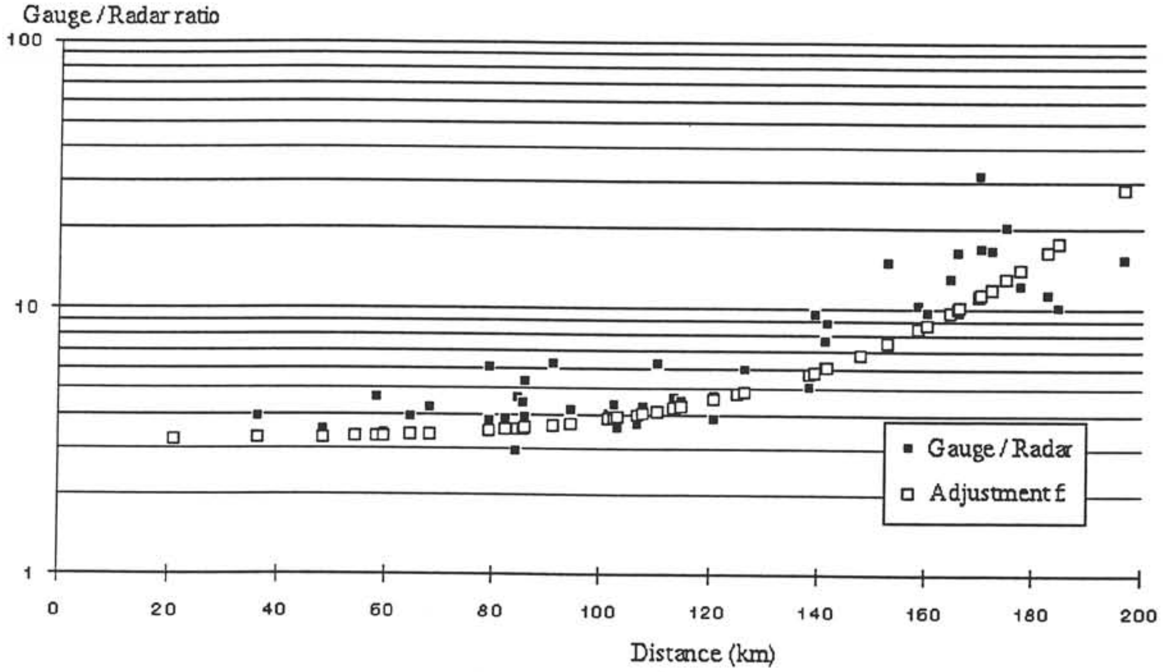

Figure 4.4 :. Average non-corrected gauge/radar ratio of daily rainfall as a function of range from the Rovaniemi radar (black squares). Each square represents the mean of 33 selected rain days in June-October 1992 at a rain gauge location. Open squares denote a gauge adjustment curve fitted to the observed values and applied *a posteriori* to all radar measurements.

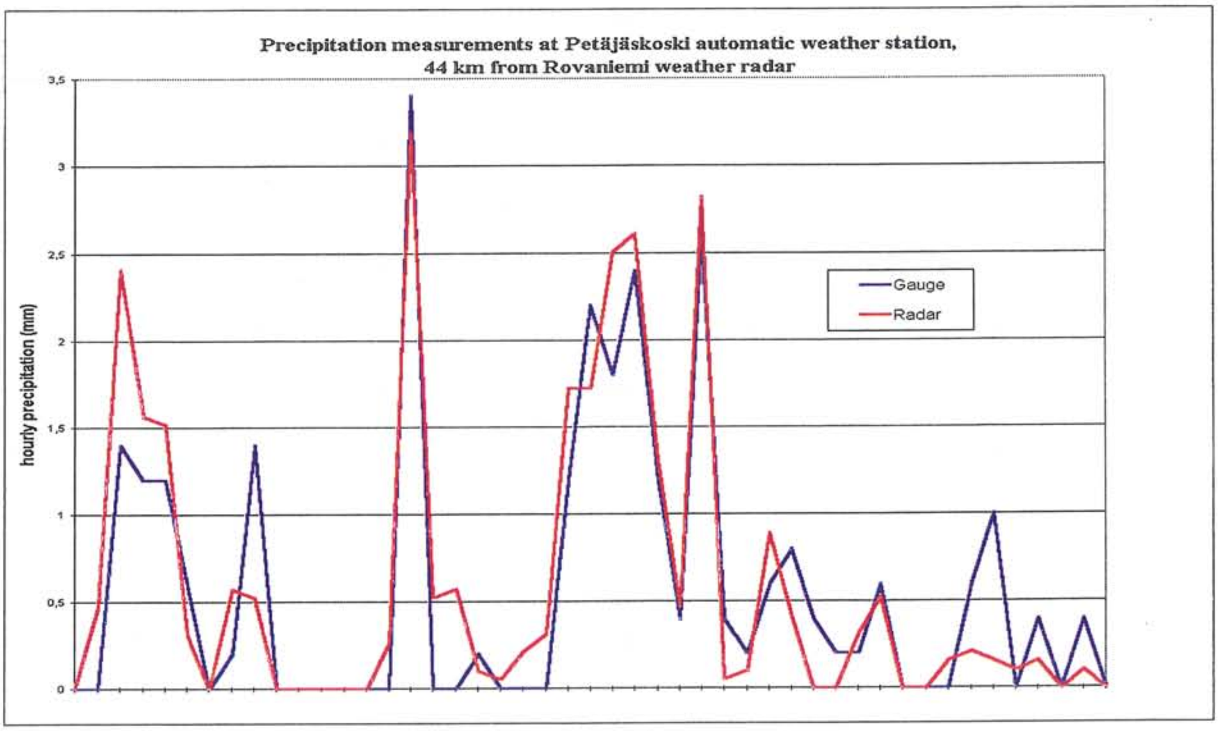

Figure 4.5 : An example of hourly rainfall amount measured at an automatic weather station (blue curve) and derived from a weather radar (red curve) between 14 August, 13 UTC, and 16 August, 11 UTC, 1992. The radar values have been adjusted by using the curve in Figure 4.4.

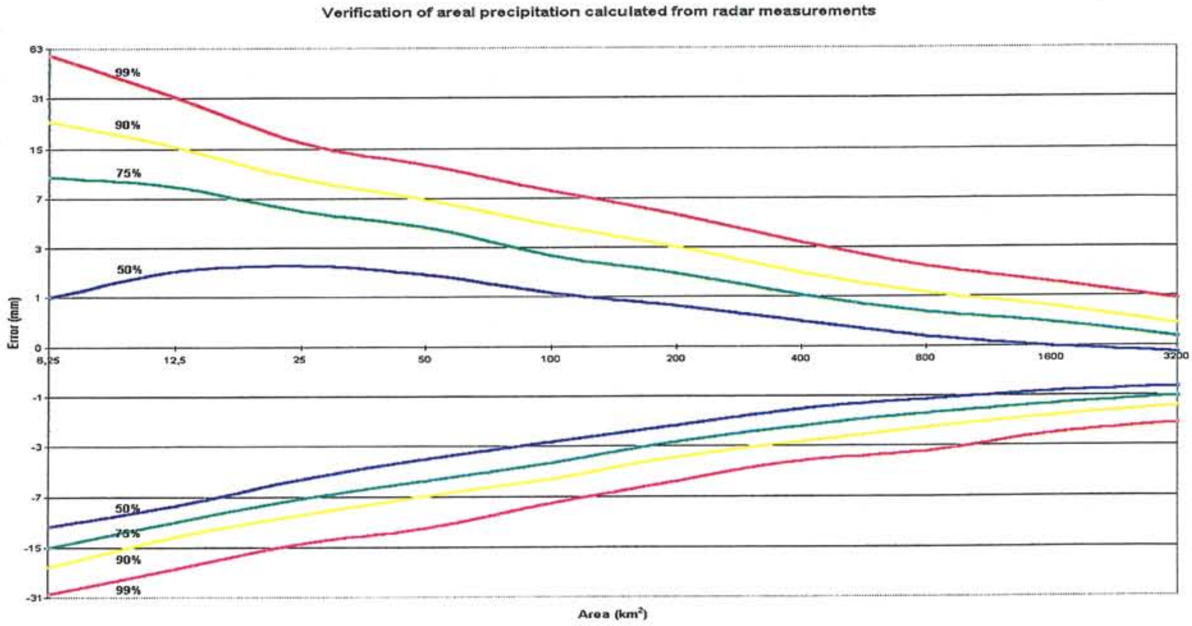

Figure 4.6: Probability distribution of the error (mm) in daily radar-measured area precipitation as a function of area size. The radar measurements are from the Rovaniemi or Masku weather radars and have been adjusted by gauges using the curve in Figure 4.4 for Rovaniemi and a respective curve for the Masku radar. Only cases with gauge-measured area precipitation exceeding 10 mm are included.

4.3.2 Doppler wind products

VAD and VVP wind soundings (section 3.3.2) should be archived hourly, at a minimum, for the purposes of numerical model verifications. The countries which have operational Doppler radars in use but do not provide VVP or VAD wind soundings should implement appropriate software to gain the full benefits of the radars. In addition to horizontal winds this includes the derivation of vertical velocity (including the terminal velocity of hydrometeors), divergence, deformation and axis of dilatation, which are important quantities in atmospheric processes. Figure 3.4 exhibits an example of VVP wind soundings and divergence from the Kuopio radar in Finland. The case shown is related to a passage of a developing frontal wave followed by cold air advection.

4.3.3 Volume scans

For the purposes of research in atmospheric dynamics and microphysics and for three-dimensional model verifications especially in case studies, original volume scans of both reflectivity and radial Doppler wind are needed. The requirement of volume data should be carefully considered case by case as the amounts of such data easily create practical problems. For example, an uncompressed volume scan in the Finnish Doppler radars contains 2 MB of data.

4.3.4 Data archive

The BALTEX project needs a central radar data archive where all relevant data will be stored. Reflectivity, precipitation and Doppler wind products should be stored for a time period covering the intensive observational periods of BALTEX. This archive should be freely available to all BALTEX research groups at institutes in the countries actively contributing to BALTEX. Uses of BALTEX radar data and products derived from it must be in accordance with the general BALTEX data exchange policy, and are thus restricted to research and development activities within BALTEX. The use of radar data from the BALTRAD network for uses other than these will have to be decided on a case by case basis.

BALTEX volume data will be available for all BALTEX member states for research purposes. It will be decided *a posteriori* and case by case which radars and which periods of time will be archived. The general format for radar products in the archive shall follow the international standards, which at present means BUFR. BALTEX shall rely on the work started by COST73 (Newsome, 1994) and continued by the Liason Group On European Weather Radar networking (LGOEWERN).

4.4 Integration with other data types

As mentioned in section 3.3.2, there is currently no common approach in integrating rain-gauge data with radar. The ability to access automatic gauge networks in real-time or with a time-step of around one hour is a relatively recent enhancement which should enable improvements in analysing radar with gauge data. For BALTEX purposes, a logistical framework for exchange of gauge data between countries is underway which should make this approach feasible and highly valuable.

Due to the lack of surface measurements at sea, the increased ability to collect data from ship gauges should lead to increased understanding of surface precipitation characteristics at sea. Integrating ship measurements, such as those mentioned in section 3.4.3 would be highly valuable in future research activities, provided they can be made available in real- or near-real time.

As a means of better understanding radar data, it is desirable to integrate information on land surface characteristics. Digital Terrain Models (DTMs, synonymous with "physiographic databases") are digital representations of such phenomena. A common example of a DTM is the Digital Elevation Model (DEM). By integrating a DEM with radar data, important information can be derived on the origins of ANAPROP echoes which can then be treated accordingly. An example of this can be found in Doick and Holt (1995). DTMs on soil and vegetation types can be valuable in developing new methods for soil moisture modelling using radar-based precipitation measurements. This type of approach is certainly relevant within BALTEX and has previously been touched upon in section 4.3.1.

Remotely sensed information from satellites can provide complementary information on the state of clouds and precipitation. With the increasing availability of passive microwave data from the DMSP series of polar orbitors, the ability to use such data together with radar in real-time or near-real time applications should be evaluated. This is especially interesting for the BALTEX region since a major study object is the Baltic Sea itself, where conventional observations are relatively sparse. The forthcoming NOAA-K platform will contain the AVHRR/3 instrument with the new channel 3A, centred at 1.6 μm and to be used during daytime. This channel may provide important information which can be used to separate clouds from snow-covered surfaces during daytime, which is a great step forward for use in cold climates. The AMSU instrument, also starting on NOAA-K will provide the advantage of passive microwave data concurrently with AVHRR data, which will hopefully provide information on the spatial distribution of precipitating clouds along with the ability to derive profiles of precipitation intensities. There are numerous additional new sensors, which show potential for combination with weather radar data, and which are due to be borne on future platforms such as the NOAA and METOP series. For a comprehensive discussion of the outlook for new space-borne remote sensing systems, consult ESA (1995).

Despite the coarse resolution found in many Numerical Weather Prediction (NWP) model fields, the output from such models is often the only data available which approximates the general state of the atmosphere. Higher resolution meso-scale NWP models offer typical resolutions of 20 × 20 km or better and 20 or more vertical levels. Information derived from such 3-D data, such as the refractivity of the lowest atmospheric layers, can be used together with radar data to help analyse the potential for and behaviour of ANAPROP. Temperature profiles could help in analysing the presence of the melting layer and thus aid in correcting for effects caused by it. In general, a more comprehensive integration of NWP data together with radar should be evaluated as a means of producing more accurate precipitation and wind products.

Meso-scale analysis schemes (Häggmark *et al.*, 1996) integrate data from surface instruments, radars, NWP fields and DTMs in an attempt to produce overall best estimate products of precipitation, among others. This is a new high level approach which uses rigorous quality control and optimal interpolation procedures to integrate data from different sources. Output consists of gridded precipitation fields with a resolution of 0.1°. Potential precipitation applications include operational storm and flood warning, urban and landscape catchment hydrology, and agricultural task planning. Weather radar is the data source which provides the highest resolution data, both in time and in space. An evaluation of the methods used in meso-scale analyses may lead to improved approaches in applications more closely related to radar.

4.5 Applications to Numerical Modelling - Validation, Verification and Assimilation

Weather radar data can be exploited in several ways to improve Numerical Weather Prediction (NWP) models. The identification of systematic errors in a model's precipitation climatology, both in terms of spatial distribution and amounts, can help focus work on necessary improvements to data assimilation schemes or physical parametrisations. An archive of *BALTRAD composites* would be valuable for such studies, especially if it were processed to impose a *gauge adjustment* to the precipitation rates over the whole Baltic Sea catchment domain. Inclusion of other data sources, as in the MESAN precipitation analysis at SMHI may also be beneficial. On a case study basis, volume scan information can assist with the validation of, for example, cloud microphysics parametrizations (Ballard and Hutchinson, 1995).

Radars already offer possibilities for data assimilation. Within observing system experiments, verification against radar data provides a method of discovering which components of the observing network are most beneficial to NWP precipitation forecasts (Graham *et al.*, 1996).

Wind data from Doppler radars (either radial wind components or VAD/VVP profiles) are potentially valuable to NWP models, and will be relatively easy to incorporate into current data assimilation systems. The impact of such data should be assessed.

Precipitation rate estimates from radar are more difficult to assimilate directly, but assimilation techniques already exist which can improve precipitation patterns in meso-scale NWP models, with benefit mostly in the first 6-12 hours of forecasts in frontal situations (Jones and Macpherson, 1996). These techniques are based on so called *latent heat nudging*, a method originally applied to tropical or sub-tropical systems with proxy rainfall derived from satellite data (Manobianco *et al.*, 1994).

It is worth noting that advanced methods of *variational data assimilation* are currently under development within the HIRLAM project and at several NWP centres worldwide. By the end of the decade, there is likely to be considerable activity in assimilating precipitation data into high resolution, operational NWP models, in such a way that the model's dynamics and physics adjust over a period of time to generate the observed precipitation. Pilot experiments in the USA already indicate the encouraging prospects for such methods to deliver better short-period precipitation forecasts (Zupanski and Mesinger, 1995).

Radar precipitation estimates can also be used to improve the initialization of soil moisture in NWP models. Currently, there is interest within the wider NWP community in land-surface data assimilation schemes which are uncoupled from the atmospheric NWP model, and which are therefore not subject to biases in its precipitation or radiation forcing (Mitchell, 1994 and Macpherson, 1996). A good precipitation analysis is required to drive such land-surface models, and a gauge-adjusted BALTRAD product could meet this need.

5 PROPOSALS FOR FUTURE ACTIONS

In previous chapters we have identified by implication a number of proposals for improving the availability of both radar data and the precipitation and wind data derived from it. In addition some suggestions for future management of research tasks are made. These are summarised in what follows:

a) Increasing the number of radars

Whilst the present coverage of radars in the BALTEX area is extensive there are significant weaknesses over the eastern part of the area. Funding for at least two additional radars, one in Poland and one in Latvia is necessary. Immediate action is needed to ensure availability during the main BALTEX observing period. In addition, negotiations should be concluded to ensure that data from Danish radars are available, emphasising particularly data from a new installation on Bornholm.

b) Development of a BALTRAD product

Several countries are generating and recording raw reflectivity which could be referred to as the equivalent of a WMO level 1 product. In order to provide a basic product to satisfy many of the needs of BALTEX for precipitation, it is proposed that a BALTRAD precipitation product, equivalent to WMO level 1 1/2, be generated and archived routinely. Such a product would be processed only to a level commensurate with the application of electronic calibration and basic (standard) conversion from reflectivity to rainrate. Extensive adjustment algorithms (e.g. range-, bright band-, raingauge adjustments etc.) would not be applied to these data. More sophisticated processing to create level 2 or 3 products would be undertaken as required by individual research groups off-line. One of the participating agencies in BALTEX are urged to take responsibility for the creation and archiving of the BALTRAD product, under the super-vision of the BALTEX Radar Working Group..

(c) Research project to produce ‘optimum’ rainfall fields

In order to study water balance, and for the modelling studies, it will be necessary to expend research effort on preparing ‘optimum’ precipitation data sets. A number of individual small research projects would contribute to this process, namely

i) Adjustments and corrections required to create an internationally uniform BALTRAD precipitation product:

- The basic requirement for quantitative use of radar network composites for precipitation and liquid water content verification over the BALTEX area is that all significant electrical differences, which at present may exceed 10 dB, must be eliminated between the individual radar systems. This can be achieved by agreeing on common calibration methods and studying the exact way how the radar constant (including all losses) is calculated and how the raw signal is processed to dBZ values in each system. This technical optimisation will typically not explain the remaining differences of the order of 2-5 dB. Adjustment algorithms are needed, based on the measured echo statistics, which will find and correct systematic differences between adjacent pairs of radars and systematic changes in the time series of each individual radar. In spite of many operational radar networks, this kind of work is quite new in the weather radar community.

- Echoes from ground and sea often obscure the true distribution of precipitation. In common cases of anomalous propagation (ANAPROP) the resulting strong and wide areas of ground clutter, especially along the coasts of the Baltic Sea, will lead to totally wrong meteorological conclusions if the echoes are interpreted as precipitation. Not all BALTEX countries have efficient operational methods to reject ground clutter from radar composites and none of the systems is provided with sea clutter cancellation algorithms. Therefore research is needed to develop the most suitable clutter rejection tools (Doppler filtering, echo structure analysis, radar-satellite comparison) for all radar systems so that the optimal BALTRAD composite is free from non-meteorological echoes.

- The sampling difference between the measured dBZ value aloft and the actual value at ground level can be often in the range from -15 dB up to + 5 dB due to partial beam overshooting of shallow precipitation, beam intersecting the melting layer, low level evaporation or low level orographic growth of precipitating particles. Much of this difference can be removed by determing the actual vertical dBZ profile by the radar itself or by a simple statistical model taking the required parameters e.g. from NWP products. Research is proposed to test and implement algorithms which estimate the vertical reflectivity profile and correct the sampling differences which the profile introduces into products which are believed to reflect the ground truth.

- Even when we have corrected the measured dBZ values aloft to ground level values, the conversion of dBZ values to accurate precipitation intensity values(mm/h) requires knowledge of the actual ground level phase (rain, sleet, snow, hail) of precipitation at each map pixel. A research is suggested to integrate temperature, humidity and precipitation observations from (automatic) weather stations with high resolution terrain information and create a BALTRAD product of the distribution of precipitation phase at ground level.

- In spite of the implementation of all above mentioned electrical and meteorological corrections, the resulting precipitation product may locally deviate too much from the gauge observed ground values. Therefore we need to agree, test and implement some of the many available gauge-radar integration methods to be used as a final stage to create the optimal precipitation sets. The resulting BALTRAD precipitation field will be absolutely accurate compared to gauge values and still preserve the high resolution time-space variations, which can be measured only with the radar network.

It should be emphasised that, in addition to the post detection use in the BALTEX project, the optimal precipitation products (instantaneous precipitation intensity, accumulated precipitation and precipitation phase distribution in a grid of 2 km x 2 km) would be very useful real time implementations in operational national weather services.

ii) Combination of radar with satellite data.

iii) The use of numerical model output to improve precipitation analysis.

d) Development of numerical model data assimilation procedures

In order to effectively use the precipitation and wind information, recorded during BALTEX for model validation and as input to models, it is necessary to devote research effort on developing methods of data assimilation. Several approaches need to be explored. Modelling groups should be encouraged to examine whether techniques for assimilation of precipitation data already in use at some NWP centres could be applied to help meet their needs. Further research on new techniques for variational assimilation of precipitation estimates should also be pursued.

An archive of gauge adjusted BALTRAD composites should be seen as an important tool for those developing NWP models for BALTEX applications. As first step, the models' precipitation climatologies should be compared with BALTRAD estimates. This could guide deductions concerning the weaknesses of data assimilation schemes and model parametrizations. Secondly, modelling groups should examine whether current techniques for assimilation of precipitation data could be implemented to improve their model's short-period forecast performance. Modellers should also pursue new work on variational assimilation of precipitation data. There is a need to demonstrate the impact of assimilating Doppler wind data on a high resolution NWP model. Groups interested in soil moisture estimation should consider whether BALTRAD precipitation estimates could supply driving data for land-surface models.

(e) Soil moisture and evaporation data

Estimates of soil moisture and evaporation from surface-based meteorological observations, ERS-1 Satellite Synthetic Aperture Radar and direct measurements need to be collated, quality controlled, blended together and analysed to produce a dataset for the whole BALTEX area over the whole observational period.

(f) Research funding

Some of the studies articulated above are suitable candidates for funding under the CEC Framework IV Programme, the final call for which is anticipated in September 1996. It is recommended that a lead organisation be identified to prepare bids to this programme in at least areas (c), (d) and perhaps (e) above. International participation in such project proposals is essential, and proposals should be angled in terms of potential benefits to parts of Europe other than the BALTEX area, particularly the Mediterranean.

g) Research management

The BALTEX Radar Working Group should continue to meet regularly, perhaps every six months. Its terms of reference should be extended to include research project and BALTRAD products monitoring. The group should be responsible for reporting on progress and should draw together research results and experience made available outside BALTEX. The terms of reference and the membership of this group should reflect these responsibilities. There is a need to generate a catalogue of precipitation and soil moisture data. This task should be undertaken by the Steering Group, who would ensure its publication and wide circulation.

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List of Acronyms and Abbreviations

AMS	American Meteorological Society
AMSU	Advanced Microwave Sounding Unit
ANAPROP	Anomalous Propagation
AVHRR	Advanced Very High Resolution Radiometer
BALTEX	Baltic Sea Experiment
BALTRAD	BALTEX Radar Network
BUFR	Binary Universal Form for the Representation of Meteorological Data
CAPPI	Constant Altitude Plan Position Indicator
COST	European Co-operation In Science and Technology
DEM	Digital Elevation Model
DMSP	Defense Meteorological Satellite Programme
DSD	Drop Size Distribution
DTM	Digital Terrain Model
FMI	Finnish Meteorological Institute
GTS	Global Telecommunication System
HIRLAM	High Resolution Limited Area Model
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherland Met. Institute)
LGOEWRN	Liason Group On European Weather Radar Networking
MESAN	Mesoscale Analysis Project
METOP	Meteorological Operational Platform
NOAA	National Oceanic and Atmospheric Administration
NORDRAD	Nordic Weather Radar Network
NWP	Numerical Weather Predciction
PIDCAP	Pilot Study for Intensive Data Collection and Analysis of Precipitation
REMO	Regional Model
SMHI	Swedish Meteorological and Hydrological Institute, Norrköping
SSG	Science Steering Group
SSM/I	Special Sensor Microwave / Imager
VAD	Velocity Azimuth Display
VRIS	Vejrradar informationssystem
VVP	Velocity Volume Processes

APPENDIX A

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No. 2 : Baltic Sea Experiment BALTEX - Initial Implementation Plan.
March 1995, 84 pages.

No. 3 : First Study Conference on BALTEX, Visby, Sweden, August 28 - September 1, 1995.
Conference Proceedings. Editor: A.Omstedt, SMHI Norrköping, Sweden.
August 1995, 190 pages.

No. 4 : Minutes of Second Meeting of the BALTEX Science Steering Group
at Finnish Institute of Marine Research in Helsinki, Finland, January 25-27, 1995.
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No. 5 : Minutes of Third Meeting of the BALTEX Science Steering Group
at Strand Hotel in Visby, Sweden, September 2, 1995.
March 1996.

No. 6 : BALTEX Radar Research - A Plan for Future Action.
October 1996, 46 pages.

Copies are available upon request at the International BALTEX Secretariat.