Proceedings of ERAD (2002): 357–362

ERAD 2002

BALTEX radar achievements at the end of the main experiment

D. B. Michelson[1], **J. Koistinen**[2], **R. Bennartz**[3], **C. Fortelius**[2], **and A. Thoss**[1]

[1]Swedish Meteorological and Hydrological Institute, Norrkping, Sweden
[2]Finnish Meteorological Institute, Helsinki, Finland
[3]Department of Atmospheric and Oceanic Sciences, University of Wisconsin at Madison, USA

Abstract. The Baltic Sea Experiment's (BALTEX) Main Experiment commenced on 1 October 1999 and, since then, the BALTEX Radar Data Centre (BRDC) has been providing homogeneous datasets from the BALTRAD network to a multitude of applications. These datasets are briefly presented. New quality control procedures have been incorporated into the generation of these datasets and new results on the performance of a multisource method for identifying and removing non-precipitation echoes are presented. The performance of the gauge adjustment technique used at the BRDC is also summarized. One application of BRDC datasets is in the validation of precipitation produced by a numerical weather prediction model, and an example of such activities is given. Another application is presented where BRDC datasets have been used in the development of an algorithm for retrieval of precipitation information from different satellite sensors. BALTEX radar activities are being continued as part of the global GEWEX Coordinated Enhanced Observing Period, and ongoing research activities designed to further improve the quality of radar-based datasets are briefly outlined.

1 Introduction

Accurate precipitation measurements are essential to improve scientific understanding of energy and water cycles, and to develop forecasting systems to both warn of hazards and enable the optimisation of management procedures. Satellite remote sensing techniques alone cannot yet provide reliable precipitation estimates, especially at high latitudes, despite their global coverage. Rain gauges with sufficient spatial and temporal resolution are almost unavailable over the sea. Weather radars are the only sensors which are able to provide precipitation observations, with high spatial and temporal resolutions, simultaneously over both land and sea. The activities of the BALTEX Working Group on Radar (Brandt et al., 1996) have lead to the establishment and operation of the BALTEX Radar Data Centre (BRDC), designed to collect data from those radars in and proximate to the Baltic Sea and it's drainage basin, to process these data into series of homogeneous products, to dissiminate these products to BALTEX data users, and to archive all data and products (Michelson et al., 2000). These activitites are a major contribution to the BALTEX Main Experiment, starting on 1 October 1999, which merges into the Global Energy and Water Cycle Experiment (GEWEX) Coordinated Enhanced Observing Period (CEOP), ending on 30 September 2004 (Raschke et al., 2001).

The BALTEX Radar Network (BALTRAD) consists of around 30 C-band, almost all Doppler, weather radars in Norway, Sweden, Finland, Denmark, Germany, and Poland. This network provides BALTEX with composite images of radar reflectivity factor every 15 minutes with 2 km horizontal resolution. Three and 12 hour radar-based accumulated precipitation products are also produced at the same horizontal resolution using an adjustment technique employing gauge observations. A third product is wind profiles, generated using Velocity Azimuth Display (VAD) and Volume Velocity Processing (VVP) techniques, which are being assimilated into numerical weather prediction (NWP) models in the Nordic region (Lindskog et al., 2002) and in the CWINDE Project (Dibbern et al., 2001) in the United Kingdom. BALTRAD products are available to BALTEX data users on CD-ROM.

This paper summarizes many of the gains achieved through BALTEX radar research in recent years. The quality control methods built into the product generation algorithms are highlighted with some new results on their evaluation. An example is given of how BRDC datasets are being used to validate precipitation produced by an NWP model. Another example of the use of the datasets is through efforts to retrieve precipitation information by combining data from different satellite sensors. Finally, ongoing radar research activities designed to further improve the quality of BALTRAD data are briefly presented.

2 BALTRAD precipitation products and their accuracies

2.1 Radar reflectivity

BALTRAD composites are based on single-site reflectivity products from six national radar networks. The configura-

Correspondence to: D. B. Michelson
(Daniel.Michelson@smhi.se)

Table 1. Percent Correct (PC), False Alarm Rate (FAR), and Hanssen-Kuipers Skill (HKS) scores for five echo classes based on 243 uncorrected (UC) and corrected (C) composite images from July, 2000, using the ΔT mask

Echo class	Mean sample	FAR		PC		HKS	
		UC	C	UC	C	UC	C
weak	455980	0.53	0.41	93.5	95.9	0.93	0.91
strong	426410	0.05	0.03	99.8	99.8	0.998	0.98
land	333830	0.38	0.27	93.1	95.5	0.92	0.92
sea	147560	0.43	0.31	94.9	97.0	0.95	0.91
all	481390	0.39	0.27	93.6	96.0	0.93	0.93

tion of radars in any two given networks is different, as are the characteristics of their data. The most effective means of reducing clutter in reflectivity products is found in those radars where Doppler capability is available and used out to full operational range. For other radars, such as the Ericsson systems used in Sweden, Doppler data is available out to a range of 120 km. This allows the generation of so-called hybrid pseudo-CAPPI products where Doppler data is merged with non-Doppler data. This leads to cleaner products at only relatively short ranges with data from such radars.

However, the BALTRAD network consists of many radars located near the sea, and clutter generated from moving waves on the sea surface during super-refraction (ducting) conditions cannot be removed using Doppler methods. Insects, birds and ships are examples of other moving targets which generate echoes which are difficult to remove using Doppler processing. A pragmatic method employing operationally available Meteosat-b IR data and analyzed 2-m temperature from SMHI's MESAN system (Häggmark et al., 2000) has been developed and applied with the goal to identify and remove spurious radar echoes. The method defines potentially precipitating clouds in areas where the temperature difference is greater than or equal to 20°, the result being a so-called ΔT mask under which all radar echoes are retained and all others rejected as being spurious. Due to our cold climate and the oblique viewing angle of the Meteosat platform, it is necessary to compliment this definition with two "failsafe" thresholds: -5°C for the 2-m temperature and 0°C for the satellite temperature, under which all areas are defined as containing potentially precipitating clouds (Michelson et al., 2000).

The method was evaluated using data from July, 2000. A set of 243 BALTRAD composites was analyzed by an operator and spurious echoes were identified and masked manually. These masked composites were then compared with composites which were filtered using the ΔT mask and unfiltered composites. Qualitative statistics were derived using standard contingency tables (Wilson, 2001) for five classes of echoes: weak ($\leq$10 dBZ), strong ($>$10 dBZ), land, sea, and all.

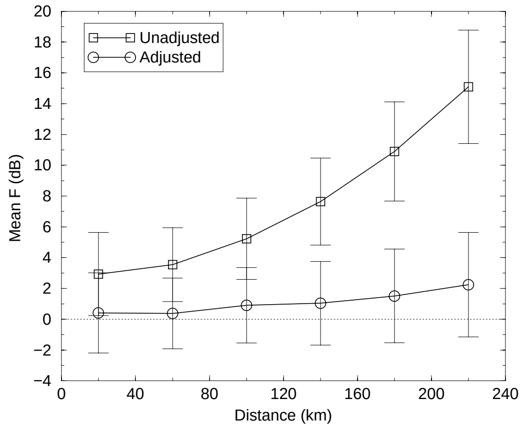
The results, summarized in Table 1, show that FAR decreases with the use of the ΔT mask and PC increases for all but one class. The HKS is calculated by subtracting the probability of false detection (POFD) from the probability of detection (POD). The slightly lower values of HKS result from the POD being lower with the filtered data, while lower values of POFD resulting from the filtering are not lowered an equivalent amount or more. This means that the use of the ΔT mask successfully removes a significant amount of non-precipitation at the expense of a small amount of true precipitation. The use of ΔT is successful at identifying and removing sea clutter but with a higher penalty to true precipitation compared to its use over land. Higher quality radar signal processing combined with enhancements to this simple multisource method will hopefully lead to higher quality products in the future.

2.2 Gauge-adjusted radar data

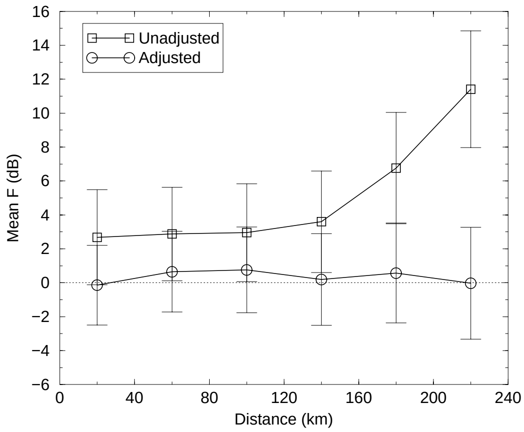
Precipitation gauges are commonly viewed as providing accurate point measurements. Weather radar is commonly perceived as being able to capture precipitation's spatial distribution well in relative terms. Numerous studies over the past few decades have sought to integrate radar data with gauge observations to arrive at quantitatively accurate and spatially continuous radar-based precipitation measurements. Gauge adjustment techniques may be classified into those based on the gauge-to-radar (G/R) ratio and "sophisticated" techniques which can involve probability matching of radar reflectivity and rain rate, statistical interpolation methods, or Kalman filters (Barbosa, 1994).

G/R-based techniques are generally well suited for operational real-time use since they are robust and generate results which are more quantitatively useful than unadjusted radar data. We have applied such a gauge adjustment technique for the purposes of generating precipitation datasets for BALTEX. The method and its lineage are presented in Michelson et al. (2000) and Michelson and Koistinen (2000). In short, the technique involves the derivation and application of the logged gauge-to-radar ratio $log_{10}(G/R)$. This variable is used to derive a uniform distance-dependent relation between radar and gauge data, and a spatially analyzed F field. The final adjustment factor applied to a given radar-based value is a weighted combination of the uniform and spatial adjustment factors, based on observation density. The use of long temporal integrations of radar data and gauge data allows the use of a technique based on the uniform distance-dependent relation for normalizing data from a heteogeneous radar network to a common level prior to gauge adjustment (Michelson, 2001a).

The gauge adjustment technique was evaluated using two three-month periods: a winter period (December, 1999-February, 2000) and a summer period (June-August, 2000), and independent climate station data from around 1600 gauges. G/R point pairs were binned into 40 km strata averages, standard deviations, and histograms of $F = 10\ log_{10}(G/R)$ for each stratum were derived. The results are summarized in Koistinen and Michelson (2002) and in Fig. 1.



(a) December 1999 – February 2000



(b) June – August 2000

Fig. 1. Bias as a function of distance with daily accumulations before and after gauge adjustment. Error bars denote one standard deviation. Note the difference in Y-axis scales.

The mean biases are minimized, while the variabilities in all but the most proximate 40 km stratum are also reduced. In all but the most distant couple of strata for the winter evaluation, the mean bias is minimized to within one dB which is around a 25% loss. Only in the most distant winter stratum does the bias exceed 2 dB, which is roughly a 60% loss, where the corresponding unadjusted bias exceeds 3000%! Standard deviations are lower for adjusted data in all but a couple of strata. This means that significant improvements to the accuracy of radar-derived accumulated precipitation are gained out to full operational range resulting from the use of this gauge adjustment procedure. Results from previous similar work in the UK (Collier, 1986) report roughly similar performance but do not go beyond ranges of 75 km. Results from northern Australia using the Window Probability Matching Method (Rosenfeld et al., 1995) are also roughly compatible but only extend to ranges of 130 km.

These results show the value of gauge adjustment in improving the quantitative value of radar-based accumulated precipitation estimates by addressing the issue of bias against

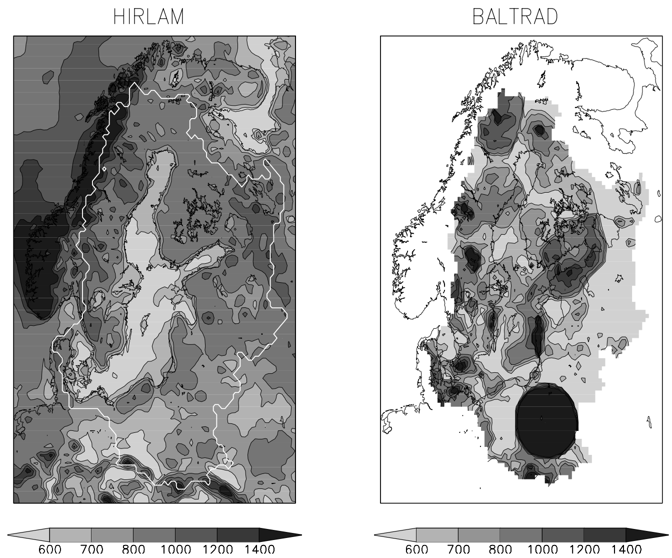


Fig. 2. Total precipitation, in units of mm, for the 12-monthly period of October 1999 through September 2000 as given by HIRLAM and by BALTRAD. The HIRLAM-data is accumulated over hours six to twelve from four forecast cycles every day. The high-resolution BALTRAD-data have been transformed to the grid of the HIRLAM system by box-averaging.

gauge observations. Further improvements, particularly in reducing the variability about the mean bias, may be gained by addressing those issues raised in Sect. 5.

3 HIRLAM validation

The BALTEX regional reassimilation project (Fortelius et al., 2002) uses the numerical weather prediction system HIRLAM for quantifying climatic energy and water cycles over the catchment basin of the Baltic Sea. The products include precipitation amounts on the model grid, having a horizontal resolution of approximately 22 km and covering northern and central Europe and the north Atlantic.

Figure 2 shows the total precipitation during the 12-monthly period of October 1999 through September 2000 as given by HIRLAM and as computed from 12-hourly gauge-adjusted BALTRAD precipitation totals. The HIRLAM-data is accumulated over hours six to twelve from four forecast cycles every day. The modelless results show a rather flat distribution, and the variability is related to the topography in a rather obvious manner. Thus orographically-induced maxima are present on the western slope of the Scandinavian mountain range, as well as on the foothills of the Carpatian mountains. The Baltic Sea itself induces a minimum in the precipitation. This, at least in the model, arises mainly from the summertime heating contrast between land and sea, favouring convection over land.

The pattern given by BALTRAD is rather more variable, and even contains some obviously spurious features. The circular maximum centered on the radar site in Legionowo

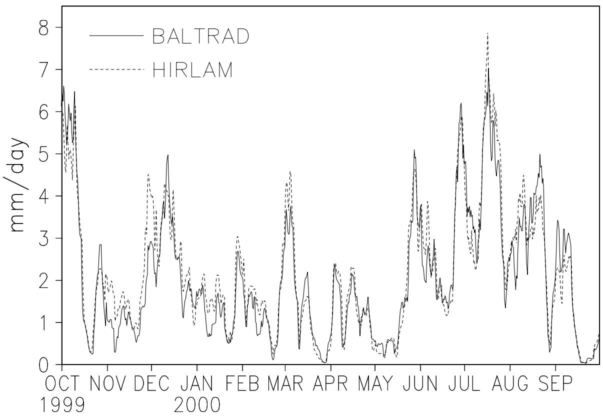


Fig. 3. Areal precipitation amounts for a validation region covering southern Finland. The dashed lines show 5-day running averages as given by HIRLAM, while the solid lines are based on BALTRAD data. The HIRLAM-data is accumulated over hours six to twelve from four forecast cycles every day.

in Poland is a striking example. Other suspicions features include the strong maxima along the eastern and western coasts of Baltic proper. Anomalous propagation echoes registered by the radar at Hemse on the island of Gotland under ducting conditions probably cause this pattern. Spatially variable systematic errors of this kind seem to make the BALTRAD data less suited for determining accurate long term mean values over large areas. The greatest value of these data probably resides in their ability to capture synoptic-scale, day-to-day variability.

This ability is amply demonstrated in Fig. 3, showing precipitation amounts for a rectangular validation region covering southern Finland. Shown are 5-day running averages as given by HIRLAM (dashed lines), and BALTRAD (solid lines). The correspondence between the two completely independent estimates is very good in all seasons.

4 Satellite-based precipitation retrieval

BRDC datasets have been extensively used to develop, validate, and continuously monitor precipitation retrievals based on satellite data. While satellite data are the only means to derive global estimates of precipitation, their accuracy is typically hampered by low spatial resolution and sampling problems associated with the fixed overpass times of polar orbiting satellites. In the following subsections we will give an overview of the current activities on the validation of satellite data and discuss possible future application in the framework of forthcoming internationally coordinated approaches to globally observe precipitation. We divide this discussion roughly into nowcasting/short range forecasting products and climatological products.

4.1 Nowcasting/short range forecasting products

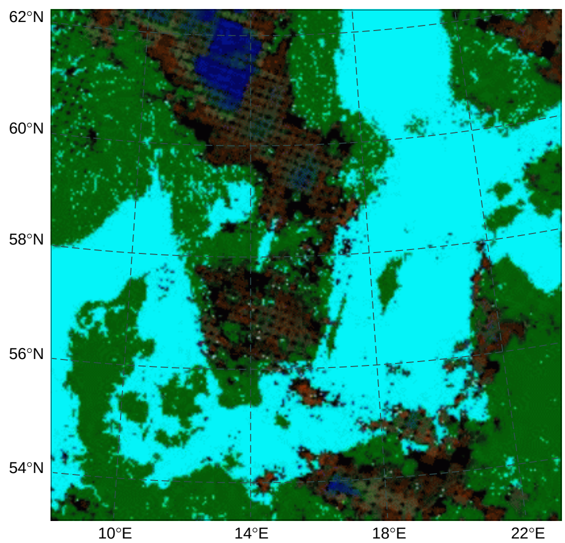
Intensity and spatial distribution of precipitation are key parameters in nowcasting/forecasting applications. Satellite data help forecast precipitation in areas where ground-based radar data are not available, such as the North Atlantic ship tracks. Within the framework of EUMETSAT's Satellite Application Facility on Nowcasting and Short Range Forecasting (SAF-NWC) a tool has been developed to estimate precipitation intensity from instruments onboard the operational NOAA weather satellites NOAA-15, NOAA-16, and other forthcoming satellites. The precipitating clouds product is a product that combines passive microwave observations taken by the Advanced Microwave Sounding Units A and B (AMSU-A/B) and observations in the visible and infrared spectral range taken by the Advanced Very High Resolution Radiometer (AVHRR). The main information about precipitation is derived from AMSU-A/B while AVHRR is mainly used for quality control, such as to suppress spurious precipitation from AMSU in areas were no clouds likely to precipitate can be found. The microwave part of the algorithm has been described in detail by Bennartz et al. (1999) and Bennartz et al. (2002). An approach was chosen to provide likelihood estimates of precipitation in different intensity intervals. The precipitation likelihood for different predictors has been be inferred from co-located gauge-adjusted BALTRAD composites. An example of this product is found in Fig. 4.

4.2 Climatological products

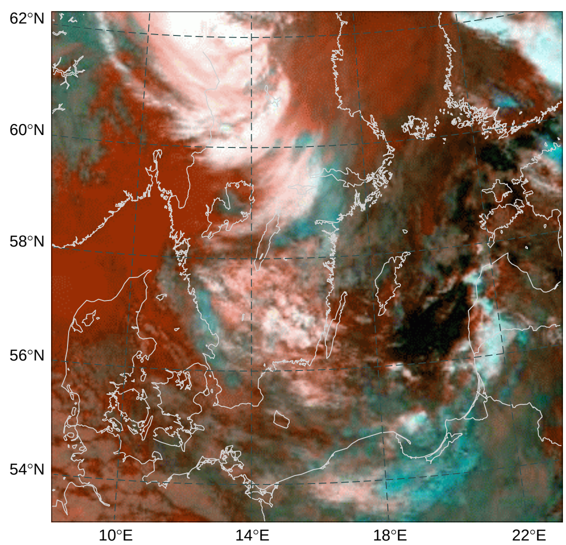
From a climatological point of view the the absolute accuracy of precipitation measurements is of crucial importance. Since the launch of the Tropical Rainfall Measuring Mission (TRMM) in November 1997, considerable progress has been made in understanding tropical rainfall. However, from the satellite point of view, several issues associated with precipitation retrieval in extratropical areas have not been fully understood. While for tropical rainfall the use of the low-frequency emission signal provides direct information on rainfall at altitudes close to the surface, the use of the emitted signal for remote sensing of precipitation at high latitudes, especially in winter, is hampered by two factors:

First, in winter the typical freezing level height of high-latitude cyclone varies between 0 and 1.5 to 2 km above the surface. Thus, the layer of liquid precipitation is extremely shallow. Analyzing a set of different precipitation events in the Baltic area, using co-located weather radar and Special Sensor Microwave/Imager (SSM/I) satellite data, Bennartz and Michelson (2002) show that the emission signal obtained at the satellite is weak and only moderately correlated with precipitation intensity. Bennartz and Petty (2001) use radar data obtained in the Baltic area to establish a physical relation between rain rate and volume scattering by ice particles in the upper part of precipitating clouds.

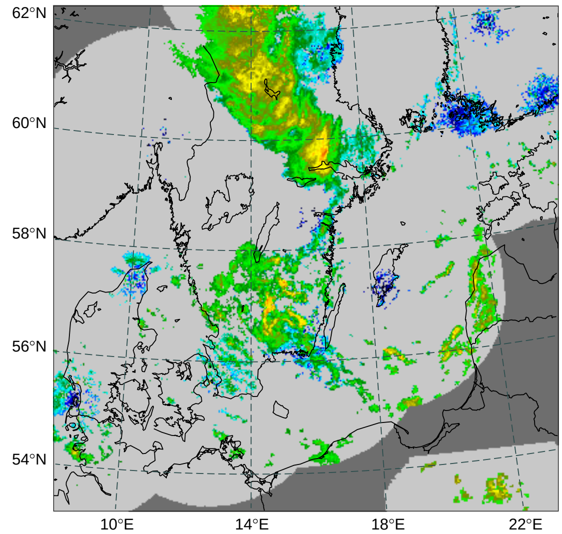
Secondly, the availability of moisture is limited and thus the precipitation intensity of frontal precipitation events is



(a) PC product displayed as a false colour image of likelihood in different intensity classes. Red is assigned to very light precipitation, green to light to moderate, and blue to intense precipitation.



(b) False colour image of AVHRR channels 3 (red), 4 (green) and 5 (blue), respectively.



(c) BALTRAD composite subimage. Cold (blue-green) colors signify light to moderate precipitation and warm (yellow-orange) colors give moderate to heavy precipitation.

Fig. 4. AVHRR/AMSU precipitating cloud (PC) product over the southern Nordic region taken from a NOAA-15 overpass on 27 June 2000, 07:37 UTC, along with corresponding AVHRR false colour image and BALTRAD composite from 07:30 UTC.

usually small compared to tropical precipitation systems. Convective precipitation events, for example caused by cold air outbreaks, usually exhibit somewhat higher precipitation intensities. However, the typical horizontal scale of a single convective precipitation cell is very small (a few kilometers) so that the field-of-view averaged precipitation intensity of a coarse-resolution low-frequency spaceborne radiometer is poor.

BRDC datasets are a key tool to verify algorithms for the retrieval of precipitation information from satellite sensors. Currently, the quality of data from the Advanced Microwave Scanning Radiometer (AMSR-E) onboard NASA's AQUA mission is being assessed, partly in the Baltic region with datasets from the BRDC. The Baltic area is also a valuable validation site for forthcoming satellite missions, most importantly, the European Earthcare mission and the Global Precipitation Mission (GPM).

5 Ongoing BALTEX radar research

The results of the evaluation of the gauge adjustment technique (Sect. 2.2) show how such methods succeed in lowering radar's mean bias against gauge observations, but they are not as successful at reducing the variability. This can be explained to a certain extent by the sampling errors incurred when comparing radar data with gauge observations (Kitchen and Blackall, 1992; Seed et al., 1996), but there is still room for improvement. Where gauge adjustment should be applied towards the end of the production chain as a means of minimizing any residual bias, methods applied beforehand should address one minor and one major issue both related to the local measurement environment.

The minor issue addresses the precipitation phase, either at the height of the radar measurement or at the surface. In northern Europe, the melting layer can exist even in midwinter which causes bright bands (BB) in radar data. A given radar image, or even a given pulse, may contain solid, liquid and mixed precipitation phases during any season in this region. This limits the use of static $Z-R$ or Z_e-S relations for quantitative measurements of precipitation rates. Saltikoff et al. (2000) performed a spatial water phase analysis based on synoptical observations and linearly interpolated $Z-R$ relation coefficients for snow and rain in areas of mixed phase. Michelson (2001b) used atmospheric state variables from an NWP model to derive phase information aloft and apply appropriate $Z-R$ relations there. Common to both strategies is the difficulty in evaluating the accuracy of the results, and no improvements have been proven thus far.

The major issue addresses that of the vertical profile of reflectivity (VPR), its variability in both time and space, and hence the ability to correct a precipitation estimate aloft to an equivalent surface measurement. Koistinen and Michelson (2002) show how radar can underestimate surface rainfall by 15-20 dB at ranges beyond 150 km, and this effect clearly overshadows any benefit gained through the application of correct $Z-R$ relations. Current work is underway to develop and apply VPR correction methods for the Baltic region, and we are encouraged by recent successes elsewhere (Vignal et al., 2000; Germann and Joss, 2002).

Acknowledgements. We are grateful to the European Commission for supporting much BALTRAD/BRDC related work. Within Framework IV, this has been done in the project "PEP in BALTEX" under contract ENV4-CT97-0484, and within Framework V it is being continued in the "CLIWA-NET" project under contract EVK2CT-1999-00007. The work being performed as part of the AQUA mission is done under NASA grant NRA-00-OES-03 to Ralf Bennartz. We would also like to contribute this paper to the work being conducted in COST Action 717.

References

Barbosa, S., Brief review of radar-raingauge adjustment techniques, in Advances in radar hydrology, (Eds) M. E. Almeida-Teixeira, R. Fantechi, R. Moore, and V. M. Silva, pp. 148–169, European Commission, Brussels, EUR 14334 EN, 1994.

Bennartz, R. and Michelson, D. B., Correlation of precipitation estimates from spaceborne passive microwave sensors and weather radar imagery for BALTEX PIDCAP, Int. J. Remote Sensing, (accepted for publication), 2002.

Bennartz, R. and Petty, G. W., The sensitivity of microwave remote sensing observations of precipitation to ice particle size distributions, J. Appl. Meteor., 40, 345–364, 2001.

Bennartz, R., Thoss, A., Dybbroe, A., and Michelson, D. B., Precipitation analysis from AMSU. Visiting scientist report in the EUMETSAT Nowcasting SAF, SMHI Reports Meteorology Nr. 93, SMHI, SE-601 76, Norrköping, Sweden. 36 pp., 1999.

Bennartz, R., Thoss, A., Dybbroe, A., and Michelson, D. B., Precipitation analysis using the advanced microwave sounding unit in suppport of nowcasting applications, Meteorol. Appl., 9, 177–189, 2002.

Brandt, R., Collier, C., Isemer, H.-I., Koistinen, J., Macpherson, B., et al., BALTEX radar research - a plan for future action, Publication No. 6, International BALTEX Secretariat, GKSS Research Center, Geesthacht, Germany, 1996.

Collier, C. G., Accuracy of rainfall estimates by radar, part I: Calibration by telemetering raingauges, J. Hydrology, 83, 207–223, 1986.

Dibbern, J., Monna, W., Nash, J., and Peters, G., eds., COST Action 76 - Final report - Development of VHF/UHF Profilers and Vertical Sounders for use in European Observing Systems, European Commission, 433 pp., 2001.

Fortelius, C., Andr, U., and Forsblom, M., The BALTEX regional reanalysis project, Boreal Env. Res., 7, 193–201, 2002.

Germann, U. and Joss, J., Mesobeta profiles to extrapolate radar precipitation measurements above the alps to the ground level, J. Appl. Meteor., 41, 542–556, 2002.

Häggmark, L., Gollvik, S., Ivarsson, K.-I., and Olofsson, P.-O., Mesan, an operational mesoscale analysis system, Tellus, 52A, 2–20, 2000.

Kitchen, M. and Blackall, R. B., Representiveness errors in comparisons between radar and gauge measurements of rainfall, J. Hydrology, 134, 13–33, 1992.

Koistinen, J. and Michelson, D. B., BALTEX weather radar-based precipitation products and their accuracies, Boreal Env. Res., 7, 253–263, 2002.

Lindskog, M., Järvinen, H., and Michelson, D. B., Development of Doppler radar wind data assimilation for the HIRLAM 3D-VAR, HIRLAM Technical Report 52, HIRLAM-5 Project, 2002.

Michelson, D. B., Normalizing a heterogeneous radar network for BALTEX, AMS Radar Calibration Workshop: RADCAL 2001 Presentations CD-ROM, AMS, Boston. version 1.0, 2001a.

Michelson, D. B., Diagnosing Z-R relations using NWP, in Preprints 30th AMS Int. Conf. on Radar Met., pp. 179–181, AMS, 2001b.

Michelson, D. B. and Koistinen, J., Gauge-radar network adjustment for the Baltic Sea Experiment, Phys. Chem. Earth (B), 25, 915–920, 2000.

Michelson, D. B., Andersson, T., Koistinen, J., Collier, C. G., et al., BALTEX Radar Data Centre Products and their Methodologies, RMK 90, SMHI, SE-601 76 Norrköping, Sweden, 76 pp, 2000.

Raschke, E., Meywerk, J., Warrach, K., Andræ, U., Bergström, S., et al., The Baltic Sea Experiment (BALTEX): A European contribution to the investigation of the energy and water cycle over a large drainage basin, Bull. Amer. Meteor. Soc., 82, 2389–2413, 2001.

Rosenfeld, D., Amitai, E., and Wolf, D. B., Improved accuracy of radar WPMM estimated rainfall upon application of objective classification criteria, J. Appl. Meteor., 34, 212–223, 1995.

Saltikoff, E., Koistinen, J., and Hohti, H., Experience of real time spatial adjustment of the Z-R relation according to water phase of hydrometeors, Phys. Chem. Earth (B), 25, 1017–1020, 2000.

Seed, A. W., Nicol, J., Austin, G. L., Stow, C. D., and Bradley, S. G., The impact of radar and raingauge sampling errors when calibrating a weather radar, Meteorol. Appl., 3, 43–52, 1996.

Vignal, B., Galli, G., Joss, J., and Germann, U., Three methods to determine profiles of reflectivity from volumetric radar data to correct precipitation estimates, J. Appl. Meteor., 39, 1715–1726, 2000.

Wilson, C., Review of current methods and tools for verification of numerical forecasts of precipitation, COST 717 Working Document WDF_02_200109_1, 14 pp., 2001.