BALTEX weather radar-based precipitation products and their accuracies

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This paper briefly reviews the measurement of precipitation by radar, discusses factors affecting the accuracy of such measurements, and outlines how such factors may be dealt with to improve the quality of precipitation measurements by radar for the purposes of the Baltic Sea Experiment (BALTEX). Precipitation products from the BALTEX Radar Network (BALTRAD) are then briefly presented, along with descriptions of how their qualities are improved, as are some new results on their accuracies. Intelligent compositing of data from a heterogeneous network, combined with innovative quality control, is shown to give high quality high resolution information for monitoring relative precipitation variability simultaneously over land and sea in both time and space. Gauge adjustment of radar-derived accumulated precipitation is shown to efficiently minimize the radar data's bias with increasing distance, thus yielding quantitatively useful datasets for application by the BALTEX community.

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 provide reliable precipitation observations, especially at high latitudes. 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 led 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 GEWEX Coordinated Enhanced Observing Period, ending

on 30 September 2004 (Raschke *et al.* 2001).

The BALTEX Radar Network (BALTRAD) consists of around 30 C-band, mostly 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. 3 and 12-hour radar-based accumulated precipitation products are also produced at the same horizontal resolution using an adjustment technique employing gauge observations. BALTRAD products are available to BALTEX data users on CD-ROM.

This paper first briefly reviews the measurement of precipitation by radar, discusses factors affecting the accuracy of such measurements, and outlines how such factors may be dealt with to improve the quality of precipitation measurements by radar for the purposes of BALTEX. The BALTRAD precipitation products are then briefly presented, along with descriptions of how their qualities are improved, as are some new results on their accuracies.

Weather radar measurements and factors affecting their accuracies

Reflectivity measurements

There are typically 120–1000 measurement bins along each radar beam from the radar site to the maximum measurement range of 240–250 km. The number of azimuthal measurement bins in a circular antenna scan with a fixed elevation angle (called PPI scan) is usually 360. Thus an average horizontal density of radar measurements may be one measurement per square km. In Finland such a density is 600 times higher than that of the operational gauge network. PPI scans are repeated applying e.g. 10 elevation angles between 0.5° and 45°. The resulting 3-D scan is called a polar volume.

The measured quantity is the effective radar reflectivity factor Z_e (often called reflectivity):

$$Z_e = \frac{\overline{P}_r r^2}{LC|K|^2} \qquad (1)$$

where r is the measurement range, $\overline{P}_r$ average received microwave power, L two-way attenua-

tion in the propagation path antenna-scatterers-antenna, C so called radar constant including the influencing parameters of the radar hardware (transmitted power, pulse length, antenna gain, system losses) and $|K|^2$ the dielectric factor, which depends on the relative fractions of ice and water in the hydrometeors (Probert-Jones 1962). As the power variations in weather radar receivers span a range of factor 10^{11}, the dBZ unit is used representing reflectivity measured in decibels with respect to the unit of Z, 1 mm^6 m^{-3}, such that

$$dBZ = 10 \log_{10} \frac{Z_e \left[mm^6\, m^{-3} \right]}{1 \left[mm^6\, m^{-3} \right]} \qquad (2)$$

Inaccuracies in precipitation reflectivity measurements originate from the factors in Eq. 1. In most existing radar systems the stability of the technology which influences calibration (C, r and $\overline{P}_r$) is excellent, typically ±0.2 dB (3% in rain rate) during repeated calibration tests in time intervals of several months (Joss *et al.* 1996). Unfortunately the absolute accuracy of the calibration of a radar system is not as good. It is quite difficult to individually diagnose and measure all possible factors during the transmission-receiving-digital processing chain (Koistinen *et al.* 1999, Manz *et al.* 2000).

The main losses outside the antenna (L) which can introduce major errors to reflectivity measurements are partial beam blocking, attenuation due to precipitation (Battan 1973) and attenuation due to a wet radome (Germann 1999). Where the antenna is located at a site surrounded by obstacles (buildings, trees, hills, mountains), the obstacles can cut the propagating beam partially or totally at some distance from the radar. The amount of beam blocking varies among radars in BALTRAD and has not yet been corrected although methods to estimate it exist (Stagliano 2000). In two cases, at Radars Luleå and Norrköping, blocking is so severe in the majority of azimuth angles that the data from these radars has been rejected from BAL-TRAD accumulated precipitation products. Any community applying BALTRAD precipitation products as a quantitative reference at a given point or small area (under 1000 km^2) should first ensure that the site is not located in a sector of severe beam blocking. The other two attenua-

tion mechanisms are usually small in northern Europe, as high rainfall intensities producing severe attenuation occur mainly during the period June–August. So far attenuation due to precipitation and due to a wet radome is not uniformly corrected in BALTRAD products.

Precipitation measurements

If the size and water phase distribution of hydrometeors is known, the precpitation intensity can be calculated:

$$R = 10^{\frac{(dBZ - 10\log_{10} A)}{10\,b}} \qquad (3)$$

where A and b are factors depending on the water phase and size distribution of the hydrometeors (Marshall and Palmer 1948). It should be noted that the unit of R is mm h^{-1} but the measured value is instantaneous, representing the 0.1 second long period when each bin was measured. In BALTRAD precipitation products $A = 400$ and $b = 2$, assuming all precipitation is solid in winter (October–March). During the rest of the year $A = 200$ and $b = 1.5$ (rain).

When accumulated precipitation is derived, it is assumed that the measured intensity field (R_i) remains constant during the time period (Δt_i) until the next reflectivity field is available (in BALTRAD products $\Delta t_i = 15$ minutes). Therefore the accumulated precipitation R (mm) at a radar measurement bin is

$$R = \sum R_i \Delta t_i \qquad (4)$$

where summing is performed over the time period selected. In BALTRAD three hour and 12 hour accumulations are produced.
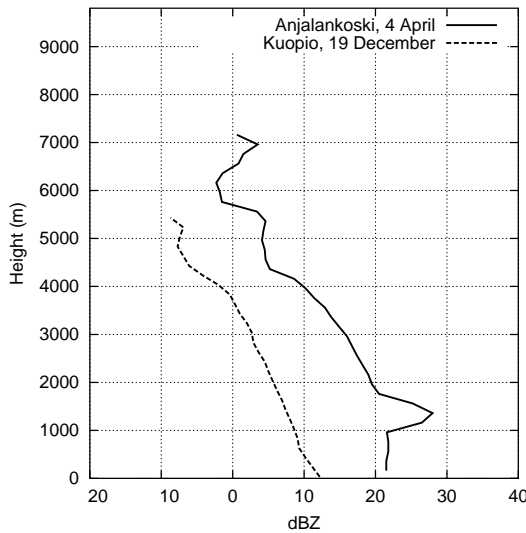
When reflectivity measurements are transformed into precipitation estimates two additional sources of inaccuracy will be added to those related to reflectivity only. The effective radar reflectivity (Z_e) is accurately measured but the scatterers may not be precipitating hydrometeors. Assumptions and selected constants in Eq. 3 may not be valid everywhere. Reflectivities originating from sea and land surfaces are called sea and ground clutter. Several methods (based either on real time signal processing or

on post-detection algorithms) are available for clutter suppression (Lee *et al.* 1995) and are applied to BALTRAD data. As a result BALTRAD products have been mostly cleaned from clutter (although a statistical evaluation is not available).

The natural variability of hydrometeor distribution is wide and rapid in time and space. As a consequence, any "optimal" *Z-R* relationship, measured directly e.g. with a disdrometer, will not implicate statistically significant improvement in radar precipitation measurements unless the integration period is very long (Joss and Germann 2000). Hence, it is reasonable to use a fixed *Z-R* relation, based on very large hydrometeor samples, separately for rain and snow and possibly for convective and stratiform rain (Smith and Joss 1997). Saltikoff *et al.* (2000) applied a real-time selection of *Z-R* factors based on the analysis of ground level hydrometeor phase (rain, sleet, snow) and, as a reference, a fixed *Z-R* for rain. The resulting 12 hour accumulated precipitation (R) was compared to gauge measurements (G) at the same locations. Table 1 demonstrates the effect of optimal, phase-dependent relation. As the selection between the two choices introduces only minor changes to gauge-radar comparisons, while the difference itself remains large, it can be concluded that improvements gained through optimal *Z-R* relation between radar reflectivity factor and precipitation intensity are masked behind other, much larger sources of bias. Thus the selection of the *Z-R* relationship in the

Table 1. Average logarithmic ratio (F) of gauge-measured 12 hour precipitation to unadjusted radar measurements (in dB units) above the gauge location as a function of range from the radar. Constant refers to continuous use of a fixed *Z-R* (for rain), whereas Variable refers to optimally varying *Z-R* according to the water phase at the ground. The period is from January to April 2000 and 2939 gauge-radar pairs. Reproduced from Saltikoff *et al.* (2000).

Z-R function	Range from radar (km)			
	0–50	50–100	100–150	150–250
Constant	0.1	1.4	2.5	4.7
Variable	0.4	1.5	2.4	4.3

Fig. 1. Two vertical profiles of reflectivity averaged from single polar volumes at ranges of 5-40 km from the radar. Solid line represents rain and dashed line snowfall at ground level.

BALTRAD production is not critical from the point of areal and long term average accuracy. The most outstanding violation will appear in cases of wet hail, which will introduce very high reflectivities (55–70 dBZ). In such cases Eq. 3. will lead to overestimation of rain by a factor of 3–10. The time-space fraction of hail occurance is very small, usually covering an area of the order of 10 km^2 and time period of 30 minutes. Still the practical consequence is that without a hail detection algorithm we can't use radar reliably for a local, urban-scale flood warning. For larger areas (1000 km^2 or more) the radar-based flood warnings are much more reliable without hail detection. In unusually heavy, widespread precipitation events, all attenuation effects should be corrected, or the radar measurement can underestimate precipitation easily by 50%.

Vertical sampling geometry

Radar measurements are made at increasing height and with an increasing measurement volume with increasing range, making them decreasingly representative for surface conditions. A radar measurement (Z_e), and possibly even (R) from Eq. 3, can be accurate aloft, at the

height of radar measurement, but it is not necessarily valid at the surface. This inaccuracy is not a measurement error but a sampling difference. The vertical profile of reflectivity (VPR) above each surface location can be denoted as $Z_e(h)$, here h is height above the surface. The shape of the VPR determines the magnitude of the sampling difference.

Figure 1 shows an example of two measured VPRs. As we know the shape of the radar beam pattern (f^2) and the height of the beam center (h) at each range r, it is easy to calculate from a VPR what the radar would measure at each range, $Z_e(h,r)$:

$$Z_e(h,r) = \int f^2(y)Z_e(y)dy \qquad (5)$$

where the integration is performed vertically (y) from the lower to the upper edge height of the beam (Koistinen 1991). The vertical sampling difference S (in decibels) is then

$$S = 10\log_{10}\frac{Z_e(0)}{Z_e(h,r)} \qquad (6)$$

where $Z_e(0)$ is the reflectivity at the surface in the VPR. Hence, by adding the sampling difference (S) to the measured reflectivity aloft (dBZ) we get the reflectivity at the surface, dBZ(0):

$$dBZ(0) = dBZ + S \qquad (7)$$

When we apply Eq. 6 to the reflectivity profiles presented in Fig. 1, the resulting sampling difference can be seen in Fig. 2. In snowfall the difference increases monotonously as a function of range, indicating significant underestimation of surface precipitation already at close ranges. In rainfall the radar measurement is relatively accurate up to the range 130–140 km. It should be noted that the overestimation introduced to the ground level precipitation estimate due to the bright band in Fig. 1 is very small in Fig. 2 (in the ranges 50–110 km). By comparing the two curves in Fig. 2 we can conclude the following: when the height of the bright band is more than approximately 1 km above the antenna, the overestimation due to the bright band will compensate the underestimation effect of snow in the beam. As a result a radar measurement is more accurate to longer ranges than it would
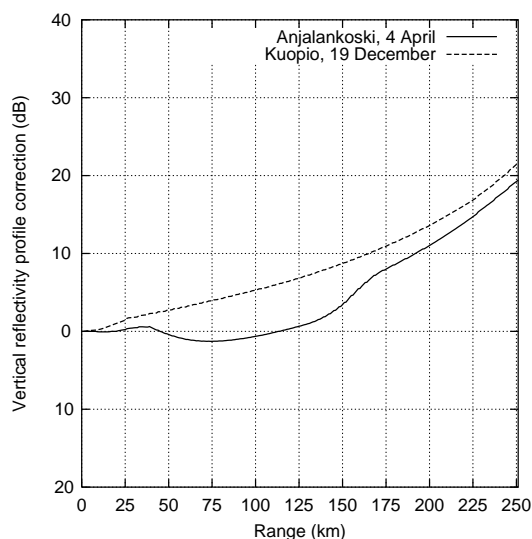
be without a bright band. If the bright band is located at a low altitude (0–500 m), the resulting overestimation of surface precipitation will be much larger (typically 2–8 dB) but restricted to a short range interval close to the radar. At ranges of 150 km and beyond the radar will underestimate surface rainfall by 4–19 dB as the beam will measure at heights of 2–4 km, where light snowfall occurs. Such biases are definitely larger than systematic errors due to any other source in a well-calibrated radar system. In both cases the gauge-radar sampling difference can be approximated e.g. by a range-dependent, second order (parabolic) function.

Any surface precipitation measurement aimed to adjust (correct) or validate radar measurements is typically applicable only in a very short range interval (Fig. 2). Therefore, an adjustment based on gauge measurements to improve radar measurements, should contain statistically representative numbers of gauge-radar observation pairs at all ranges (Kitchen and Blackall 1992). Otherwise the resulting precipitation estimate can be worse than uncorrected radar data (Joss *et al.* 1995). In BALTRAD precipitation products, gauge adjustment has been applied successfully to minimize calibration errors and vertical sampling differences from the data set.

BALTRAD precipitation products and their accuracies

Reflectivity composites

BALTRAD composites are produced with a horizontal resolution of 2 km, a temporal resolution of 15 minutes, and a depth of around 0.4 dBZ (Michelson *et al.* 2000) using data from all available BALTRAD radars. Data from individual BALTRAD radars are received at the BRDC. These data may be in the form of 3-D polar volumes (Sweden) from which so-called Pseudo-CAPPI products are generated, pregenerated Pseudo-CAPPIs (Norway, Finland and Denmark), or other horizontal 2-D product (Germany, Poland). Before composites may be generated from them, they must first be geometrically transformed to a common projection and matched to a common reflectivity factor interval.
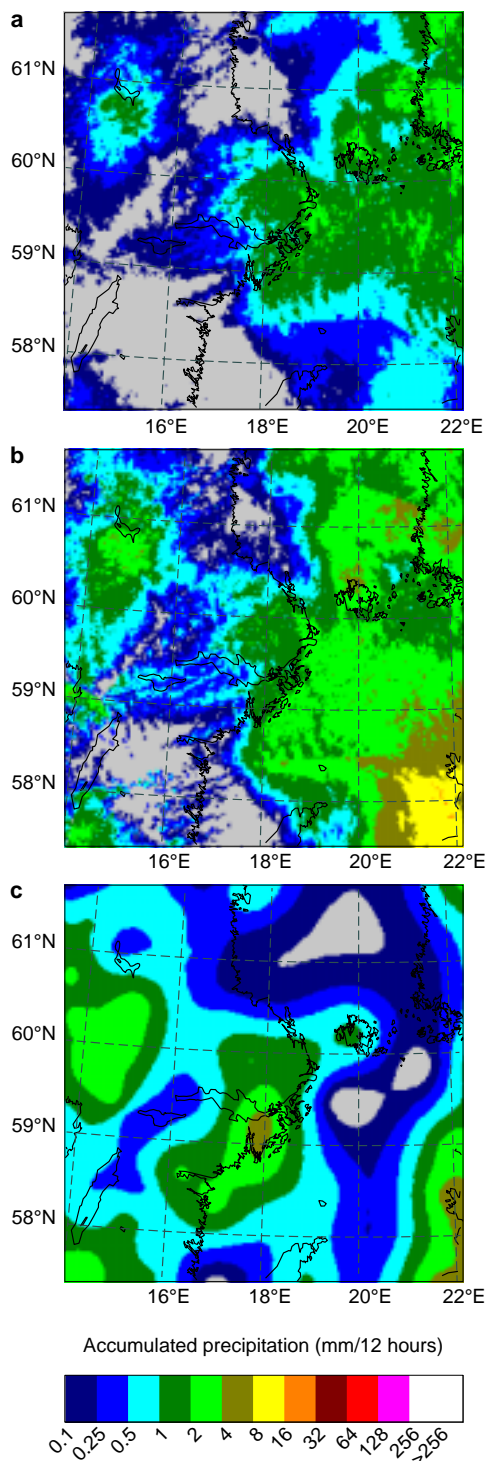

Fig. 2. Sampling difference (dB) between the measured reflectivity and actual reflectivity at ground level as a function of range. The graphs represent the vertical profiles of reflectivity in Fig. 1. Elevation angle is 0.4° and one-way beamwidth is 0.95°.

BALTRAD composites are generated using an algorithm where each ouput value is taken from that radar where the distance from the input pixel to the earth's surface is the shortest and is referred to as the "minimum distance to earth" (MDE) algorithm (Michelson *et al.* 2000).

Many BALTRAD radars have Doppler capability out to full range, and these data will often be of the highest quality. With many radars, Doppler information is only available out to 120 km and one simple way of raising the quality of Pseudo-CAPPI products at the BRDC is to merge Doppler with non-Doppler data. A novel multisource approach to quality control has been adopted at the BRDC for identifying and removing remaining non-precipitation echoes. It involves combining temperature information from the Meteosat-b IR channel with 2-m analyzed temperature fields from SMHI's operational Mesoscale Analysis system (MESAN) (Häggmark *et al.* 2000) as a means of seperating areas with and without potentially precipitating clouds. Radar echoes are retained in areas where the difference between satellite brightness and analyzed temperatures are greater than or equal to 20 °C, the analyzed temperature is below –5 °C, or the satellite brightness temperature is

Accumulated precipitation (mm/12 hours)

Fig. 3. Comparison of 12-hour accumulated precipitation using different methods. 7 February 2000, 18 UTC for Radar Arlanda's coverage area. — **a**: Unadjusted radar. — **b**: Gauge adjusted radar. — **c**: Optimal interpolation of corrected gauge sums.

below 0 °C. Otherwise the corresponding radar echoes are rejected. Simple visual inspection of the results using this method show that it succeeds in removing non-precipitation echoes while retaining true precipitation during the warmer seasons when problems with anomalous propagation are most frequent (Michelson *et al.* 2000).

Gauge-radar adjustment technique

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. As has been done by Barbosa (1994), one may classify gauge adjustment techniques 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.

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. The gauge adjustment technique applied at the BRDC is a *G/R*-based technique which is a further development of that presented by Koistinen and Puhakka (1981). Their technique, in turn, is based on improvements to that presented by Brandes (1975) and an application of the analysis technique presented by Barnes (1973). The details of the BALTRAD gauge adjustment technique are presented in Michelson *et al.* (2000) and in Michelson and Koistinen (2000).

Gauge adjusted radar products are produced with accumulation periods of three and 12 hours. Enough gauge observations from SYNOP are available every 12 hours at 6 and 18 UTC, so the 12-hour products are produced for these times. The three-hour products are simpler in that they are only based on the distance-dependent adjustment factor determined at the previous 12 hour term. Since no gauges are used for the three-hour

products, these products contain no merged interpolated gauge observations and so the results are available only in areas with radar coverage.

The gauge observations used for gauge adjustment are subjected to a systematic correction procedure based on an application of the Dynamic Correction Model originally presented by Førland *et al.* (1996). This statistical correction procedure accounts mainly for the flow distortion error (wind loss) but also takes into account characteristics of those gauge types used in the BALTEX region. Input to the gauge correction procedure is hourly gridded meteorological variables provided by SMHI's MESAN system (Häggmark *et al.* 2000), which allows a disaggregation of 12-hourly precipitation observations into hourly components. The implementation used at the BRDC is presented in Michelson *et al.* (2000).

An example of a BRDC 12-hour, gauge-adjusted radar-based precipitation accumulation is given in Fig. 3b, alongside unadjusted radar and interpolated gauge observations. The coverage area includes parts of eastern Sweden, portions of the Baltic Sea, the Åland islands, and the southwestern corner of Finland. The gauge adjustment technique suceeds in raising the level of the radar accumulations to match that given by gauges. But a comparison of results over land and sea reveals that the interpolated SYNOP gauge measurements are unable to reflect even the gross precipitation distribution over the sea, whereas the correspondence over land is much better.
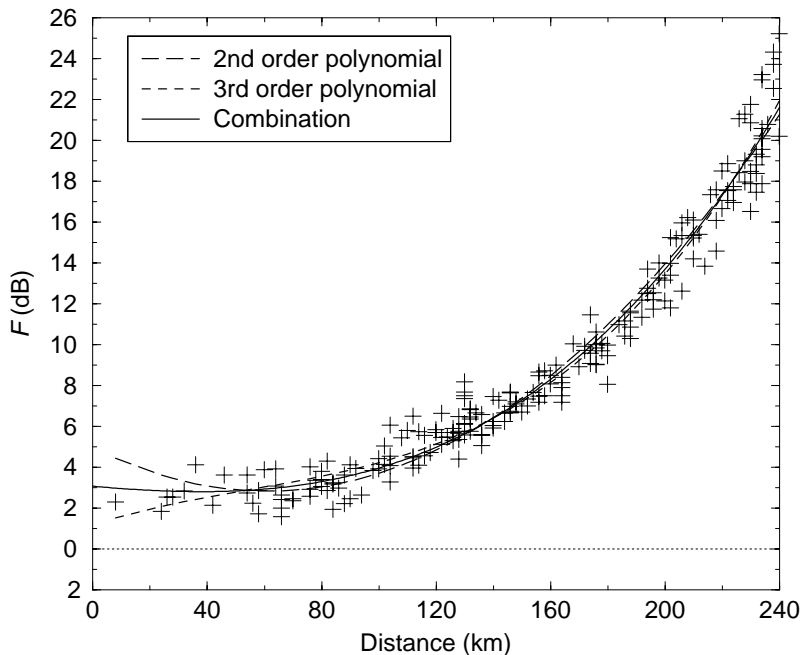
Accuracy of precipitation products

One of the main problems of conducting a gauge adjustment of composited radar sums is that differences in the accumulations between any two overlapping radars may be caused by systematic differences in the radars' electrical calibration levels. Given a comparison of several (2–3) months of accumulated precipitation from gauges and from individual radars, the relation between G/R and distance will be generally valid. In other words, such a long integration period will yield uniformly distributed precipitation amounts throughout a given radar's coverage area. Hereafter, instead of G/R, we will apply the logarithmic gauge-radar ratio F:

$$F(\text{dB}) = 10\log_{10}(G/R) \qquad (8)$$

In BALTRAD production only those observation pairs where $G > 0.5$ mm and $R > 0.1$ mm have been used. The radar's "generic" precipitation pattern will be roughly isotropic if the radar is unobstructed. Radar-based precipitation totals will decrease with increasing distance from the radar (*see* Fig. 2) while gauge totals will remain at the same level throughout the radar's coverage area. If a comparison is made for each radar in a network using the same integration period, then the y-axis offset in F's relation with distance will reflect the system bias between gauge sums and radar sums at each radar site. Ideally, this system bias is not coupled to meteorological or climatological phenomena; it is only a measure of the radar's calibration level in relation to an external source which consists of the gauge totals. The y-axis offset determined for each radar can then be used to normalize the sums from each radar before generating composite sums. The ensuing spatial adjustment will be largely devoted to minimizing the range dependency on the radar sums. Alternatively, the complete relation comprising the system bias and the dependency on distance can be used for each radar as a means of normalizing data to a common level. The final adjustment which follows in this case will be almost entirely spatial.

This strategy was applied using two three-month integration periods: December 1999 to February 2000 and June to August 2000 (Michelson 2001). The objective was to study the relations derived during fully developed winter and summer conditions. Data from around 1600 offline gauges from the Norwegian, Swedish and Finnish climate station networks were used for these purposes. Third order polynomials were used to derive the F relations as a function of distance. This was conducted such that the observations were used together with second and third order polynomials to produce two seperate datasets of equal length. The final third order polynomials were used with these two datasets to arrive at the final relations. This procedure is illustrated in Fig. 4 where the system bias (*y*-axis

Fig. 4. Relation between the gauge-to-radar ratio (*F*) with distance from the radar for Radar Kuopio and the three-month winter integration period.

intercept) for Radar Kuopio in winter conditions reveals a 3 dB underestimation by the radar, and this underestimation increases with increasing distance after around 60 km.
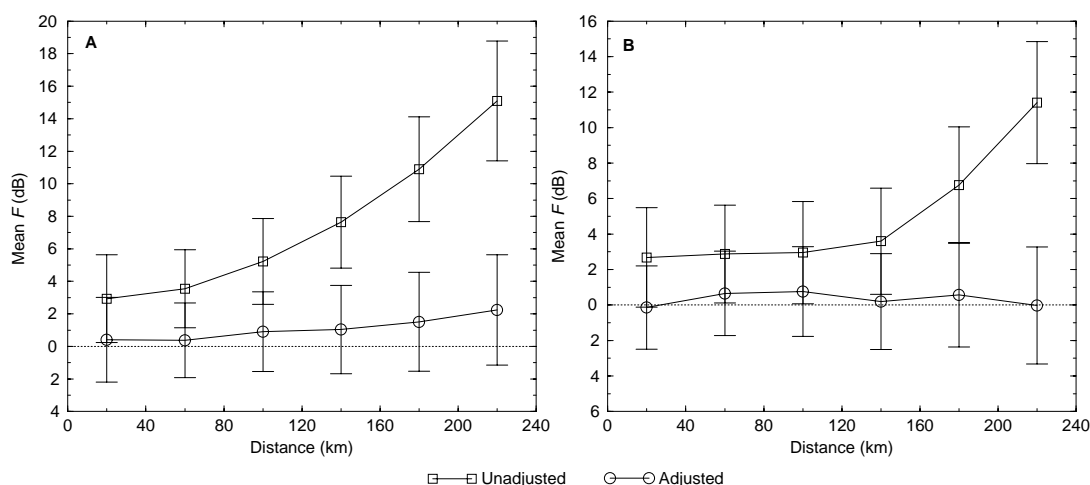
Coefficients for data from Norwegian, Swedish and Finnish radars, along with Danish Radar Copenhagen, were derived both for winter and summer periods. In some cases, data from poorly sited radars gave rise to noisy relations which were physically unrealistic and therefore unusable. In such cases, average coefficients from the same type of radar were used instead.

Two methods were employed in order to evaluate this strategy: the gauge adjustment technique was rerun using data from both seasons to generate 12-hour accumulated precipitation products using the SYNOP gauge observations only. Three sets of data were compared: (1) completely unadjusted radar data, (2) bias corrected radar data, using provisionally determined coefficients presented in Michelson *et al.* (2000), before being adjusted, and (3) fully normalized radar data, using the third order polynomials, before being adjusted.

Each dataset was evaluated against the climate station networks' gauge observations, in 40 km wide strata. The results are summarized in Fig. 5a for the winter period and Fig. 5b for the summer period. The bias in unadjusted winter data is larger than that during summer due to the generally shallower precipitation and, thus, higher risk of it being overshot by the radar beam. However, in both seasons, the gauge adjustment technique used with full normalization has clearly succeeded in minimizing the distance bias. Only in the more distant winter strata (160–240 km) does the bias exceed 1 dB, which is around a 25% loss. The results may be further illustrated using histograms of the variable *F*(dB) for each distance strata (Fig. 6). In each case the effect of gauge adjustment is shown to reduce the bias and the variability of *F*. The effect of system bias correction, using the previously determined coefficients in Michelson *et al.* (2000) is shown to leave a slight negative bias at shorter distances. Full normalization improves upon this by reducing both the bias and the variability at most distances. Significant improvements are gained out to full operational range. Results from similar work (e.g. Collier 1986) report similar performance but do not go beyond relatively short ranges.

Fig. 5. Bias as a function of distance with daily accumulations before and after gauge adjustment. Error bars denote one standard deviation. — **a**: December 1999–February 2000. — **b**: June–August 2000
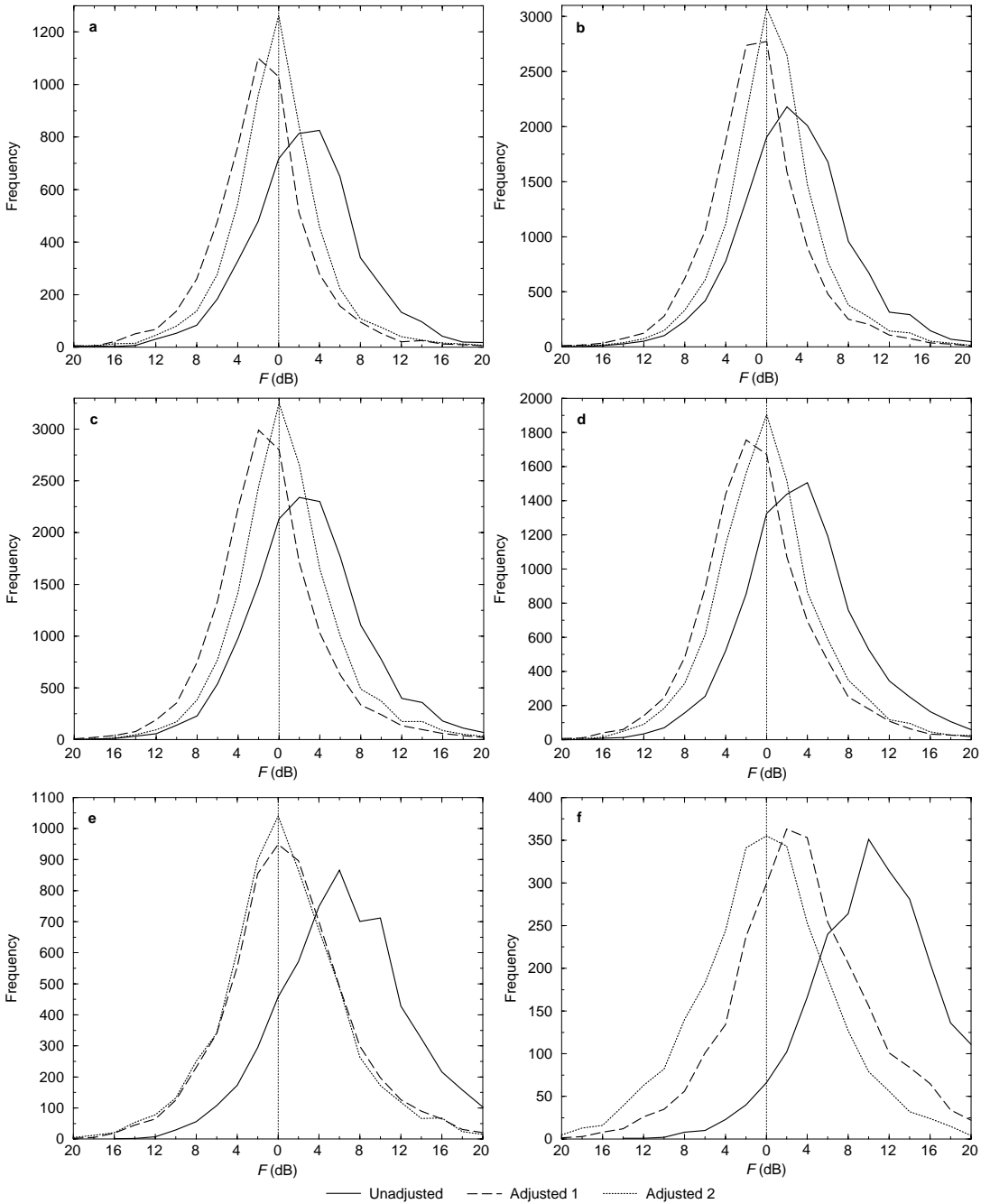
These results show the value of gauge adjustment in improving the quantitative value of radar-based accumulated precipitation. Further improvements may be gained, in the form of reduced scatter in the comparison with gauges, if precipitation phase type-dependent *Z-R* relations and VPR corrections are applied as outlined above. For example, the present adjustment can correct only the average effects of the bright band during each gauge-radar comparison period, as the altitude of the bright band can vary rapidly during that time. Even if the height remains fairly constant, a perfect bright band adjustment would require higher order polynomial fitting as the effect of a low level bright band would appear as a sudden and deep local minimum in the gauge-radar pairs e.g. at close ranges of 40–60 km in Fig. 4. This is the subject of ongoing radar research within BALTEX and elsewhere.

Conclusions

The measurement of precipitation by weather radar has been briefly reviewed in this paper, and factors affecting the accuracy of such measurements have been discussed. An outline of how such factors may be dealt with to improve the quality of precipitation measurements by radar, with emphasis on BALTEX objectives, has also been presented.

The measurement resolution of the BALTRAD reflectivity composite is superior compared to any gauge network for monitoring relative precipitation variability simultaneously over land and sea in both time and space. The gauge adjustment technique, developed for BALTRAD accumulation products, is effective in minimizing the bias which is mostly caused by the sampling difference between radar and gauge measurements. The average bias in the BALTRAD 12 hour accumulation products is less than 1 dB (25%) at all ranges (0–240 km) in summer and in winter up to 160 km. At ranges of 160–240 km in winter the product tends to underestimate surface precipitation by 1–2 dB (25%–60%). The adjustment technique also suppresses random errors. The remaining random errors are efficiently reduced by integrating either in time or in space. For example in Finland areal integration shows that in cases when the areal rainfall exceeds 10 mm (potential risk for flooding), the radar measurement error is less than 1 mm with probability of 50%, where the area exceeds 200 km² (Brandt *et al.* 1996). In an area around 200 000 km² (Fortelius 2002), excellent agreement has been shown between BALTRAD precipitation estimates and estimates from the numerical weather prediction model HIRLAM.

Fig. 6. *F*(dB) histograms for the period June–August 2000 for 40 km wide distance strata. Adjusted 1 uses the system bias correction prior to gauge adjustment. Adjusted 2 uses full normalization prior to gauge adjustment. — **a**: 0–40 km. — **b**: 40–80 km. — **c**: 80–120 km. — **d**: 120–160 km. — **e**: 160–200 km. — **f**: 200–240 km

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