6B.5 POSSIBLE EXTREME MARINE SNOWFALL AS SEEN BY BALTRAD

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1. INTRODUCTION

Accurate quantitative precipitation estimates (QPE) are essential for improving our understanding of energy and water cycles in the long term, but also in improving our ability to provide reliable forecasts and warnings for facilitating transport and optimizing communications, benefiting various sectors of the economy, and ultimately to help save lives and property. Weather radar provides our only observation system capable of monitoring precipitation with high resolution in both time and space.

The Baltic Sea Experiment (BALTEX) is the European continental-scale energy and water-cycle experiment conducted under the auspices of the Coordinated Energy and Water-Cycle Observations Project (CEOP), which sorts under the Global Energy and Water Cycle Exeriment (GEWEX), the World Climate Research Programme (WCRP), and ultimately the WMO. Within the framework of BALTEX, the BALTRAD network and BALTEX Radar Data Centre (BRDC) at SMHI have provided harmonized datasets since the start of the so-called BRIDGE campaign in 1999. One of the products generated at the BRDC is 12-hour accumulated precipitation (RR) valid at the Earth's surface at 6 and 18 UTC.

During the evaluation of an operational implementation of the RR product at SMHI, extreme snowfall was observed over the Norwegian Sea during the period 2-6 March 2006, primarily from met.no's northernmost radar at Røst (Fig. 1). This has led us to formulate this case study, with the objectives to determine whether the extreme snowfall amounts found in the RR product are achievable in reality, and to highlight the capabilities and limitations of weather radar-based QPE using the chosen methodology.

The radar at Røst is a Gematronik C-band Doppler weather radar installed in 2003-2004. The island of Røst is located above the artic circle as an extension of the Lofoten islands, and it is both small and flat. The height of the base of the concrete radar tower is five m a s l. The radar's coverage area is permanently blocked in a few sectors by nearby islands, as illustrated by Fig. 1.

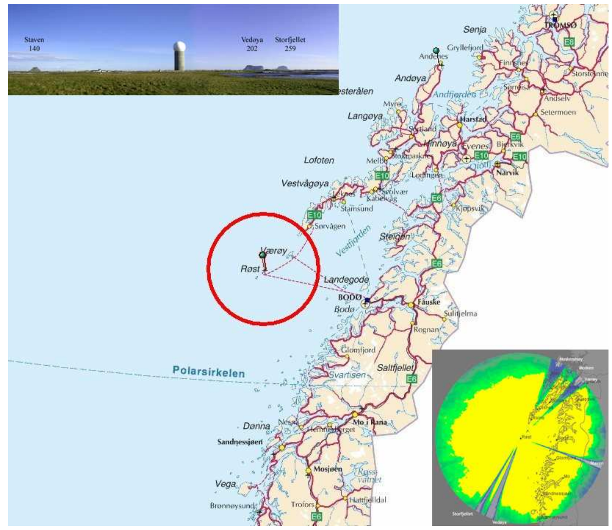

FIG. 1: Radar Røst, its location, and it's permanent blockages.

2. THE WEATHER 2-6 MARCH 2006

In the area covered by the Røst radar, all precipitation during this period is snow. Air and land-surface temperatures are below zero. ECMWF NWP model fields exhibit a rather uniform fresh polar or even arctic airmass in which typical 850 hPa temperatures were -14 – -12°C. Model fields and the nearest soundings indicate no inversions, jet streaks, or warm layers aloft at the time of the appearance of snowbands in the satellite and radar images on 2 March. Thus it can be concluded that no synoptic scale tropospheric fronts existed in the region which could have triggered the initial development of line convection. Later, when the snow band was already well developed, the ECMWF model fields for 3-4 March show a 500 hPa short-wave trough coming in from the north, associated with an arctic front near the surface. At the time the band exists (3 March 1500 UTC), this front is located rather far out in the Norwegian sea and it remains unclear how significant forcing on the existing band it introduced. Anyway, at the location of the snow bands, the ECMWF model fields just indicate a col or a broad surface trough at all levels from the surface up to 300 hPa. The band is thus associated with a stationary surface trough or col which forms a SW-NE oriented deformation axis (Fig. 2). North of this line, northerly flow prevailed, whereas south of it the flow was from southerly directions. From the time series of radar images, convergence of convective cells towards this deformation line can be seen resulting in the formation of one dominant precipitation band. The band of marine convection remained stationary for sev-

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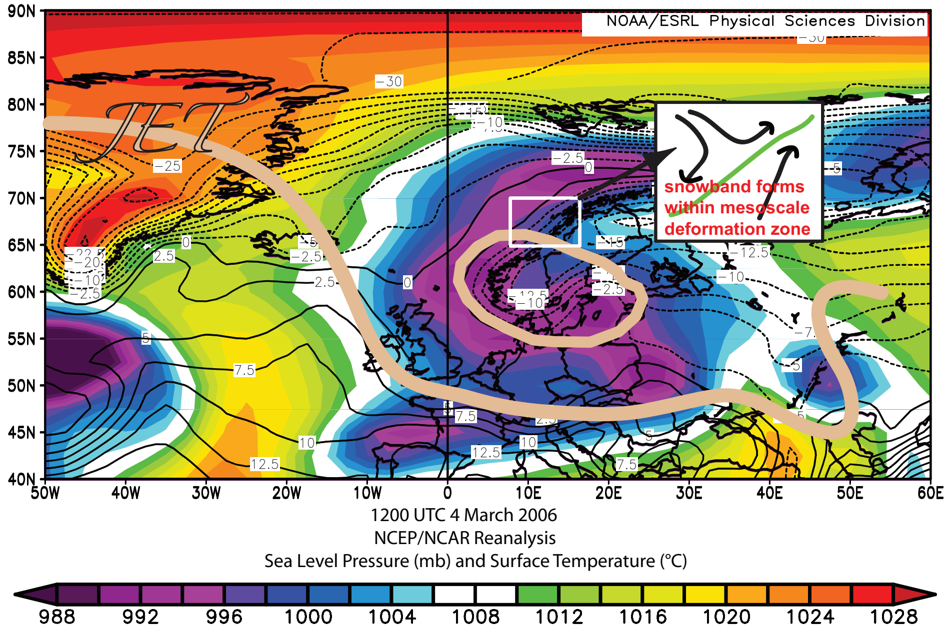


FIG. 2: Temperature and pressure conditions associated with this case study. Courtesy NOAA Earth System Research Laboratory, Boulder, Colorado.

eral days. Echo structures in radar data suggest a strong gradient in convective inhibition from one side of the band to the other or a strong gradient in CAPE. One guess is that the arctic front is able to release the instability that is otherwise capped, which is why the convective cells are more intense (and deeper, we think) on the northern side of the band. Other evidence to support this interpretation are the occasional apparent boundary-layer rolls south of the band, which indicate shallow convection, likely capped by an inversion. A simple explanation for intense and deep convection north of the line is a long cyclonic fetch of very cold airmass above a relatively warm sea with surface temperatures around +6° (Fig. 3). Deep convection could be definitely triggered by the large air-sea temperature contrast. It can be concluded that the band was associated with a mesoscale convergence line with no signs of frontal temperature contrasts and weak synoptic forcing. Snapshots of satellite and radar data illustrating the situation are found in Fig. 4.

3. DATA AND METHODS

Today BALTRAD comprises the operational C-band weather radar networks in Norway, Sweden, Finland, Estonia, Denmark, and Poland, with a renewed data feed expected soon from Germany. The characteristics of the contributing radars can be found online at the Eumetnet OPERA website[1]. Composite products containing radar reflectivity factor are generated every 15 minutes at two-km horizontal resolution. These composites are quality-controlled using cloud-type products from the Meteosat

[1] http://www.knmi.nl/opera/

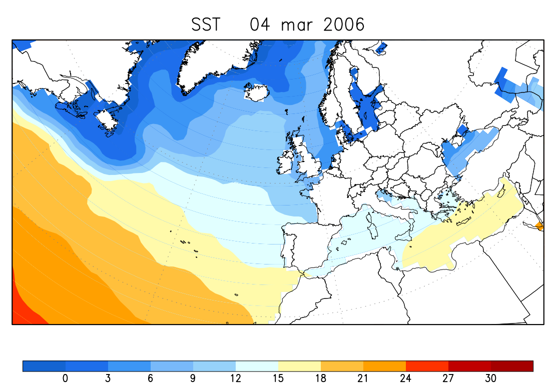
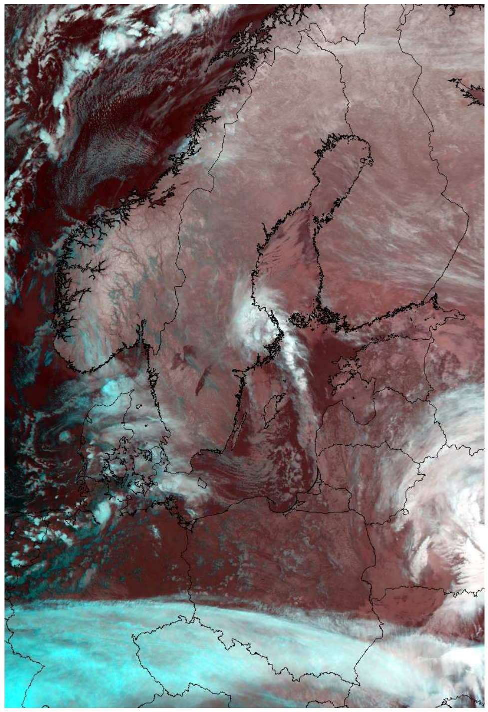
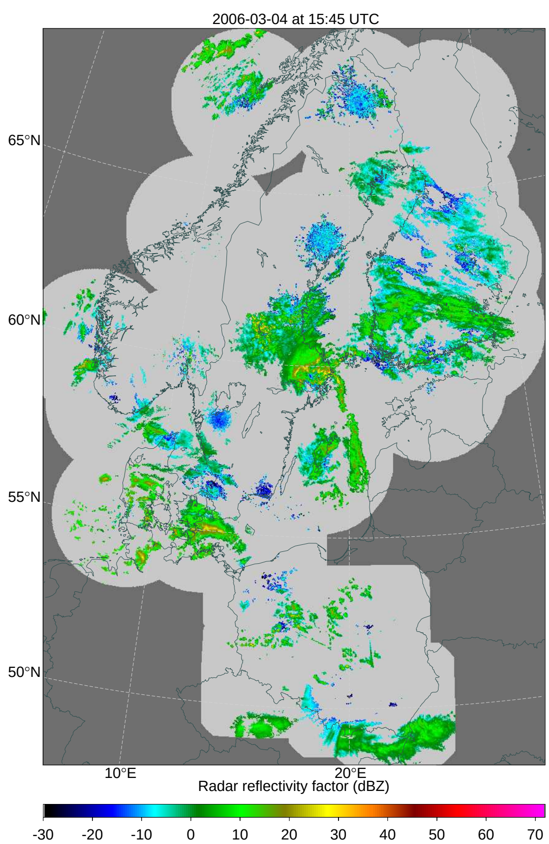


FIG. 3: Weekly mean sea-surface temperatures for 4 March 2006, according to the NOAA, available from the NCEP NOMADS Meteorological Data Server.



(a) NOAA 15 AVHRR channels 3,4, and 5 at 15:50 UTC.



(b) BALTRAD composite at 15:45 UTC.

FIG. 4: Satellite and radar data from 4 March 2006.

Second Generation (MSG) platform and NWC SAF classification algorithms (Michelson, 2006). These composites provide the basis for subsequent QPE.

Gauge adjustment of precipitation amounts given by radar has proven to provide an effective family of methods for improving the accuracy of radar-based QPE (Gjertsen et al., 2004). The basis for the BALTRAD gauge-adjustment technique is the gauge-to-radar ratio (*G/R*), where gauge and radar precipitation accumulations are twelve-hourly at 6 and 18 UTC using observations available through the GTS from the synoptic network. The gauge observations are systematically corrected, mostly for the underestimate due to wind, according to Michelson (2004), which is especially important in snow. The original implementation of this gauge-adjustment technique is described in more detail in Michelson and Koistinen (2000), and the technique's performance is presented in Koistinen and Michelson (2002). The original implementation involves the analysis of a fully-spatial adjustment factor which is weighted against a first guess consisting of an adjustment factor as a function of surface distance from the radar. In practise, it has been found that the density of real-time SYNOP observations is so low that the spatial analysis has almost no impact on the final result. So, the new real-time implementation uses only the first guess. In the plots presented here, correction factor $F = 10\log(G/R)$.

It should be noted that there were no supporting observations available for this case. Satellite data at these latitudes cannot be used to quantify precipitation, the nearest soundings were launched from the mainland, no precipitation gauges were found at sea, and there was no anecdotal evidence of severe snowfall, e.g. from crews on fishing or other vessels. Unfortunately also, no vertical profiles of radar reflectivity (VPR) are available at present from Norwegian radars, and volumes containing only three low sweeps (0.5, 1.5, and 2.5°) are archived.

4. EXTREME SNOWFALL?

We have not found any indication of the presence of atmospheric ducting which could have impacted on radar beam propagation during this period. Such conditions lead to super-refraction of part of the radar beam, leading to the systematic underestimation being less than normal with increasing range. This means that the derived adjustment factors would be too severe in such cases.

The temperatures are too cold for a melting layer to exist, so there is no need to consider the presence of a bright band.

It was hoped that a closer look at the gauge-radar relations for this case would provide insight into the validity of the operationally-adjusted radar-based accumulations for this case. The operationally-derived relations are illustrated in Fig. 5. Each curve (except "All dates") has been derived using all gauge-radar point pairs covered by BALTRAD in a ten-day moving time window in order to ensure enough data to give a reliable result.

The gauge-radar relations are often noisy, and the

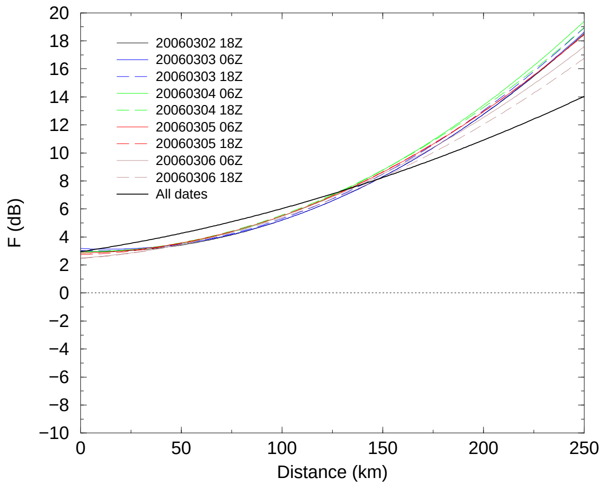


FIG. 5: All operational automatically-derived gauge-radar relations as a function of distance from the radar. The thick black curve is derived from all observations during 2-6 March.

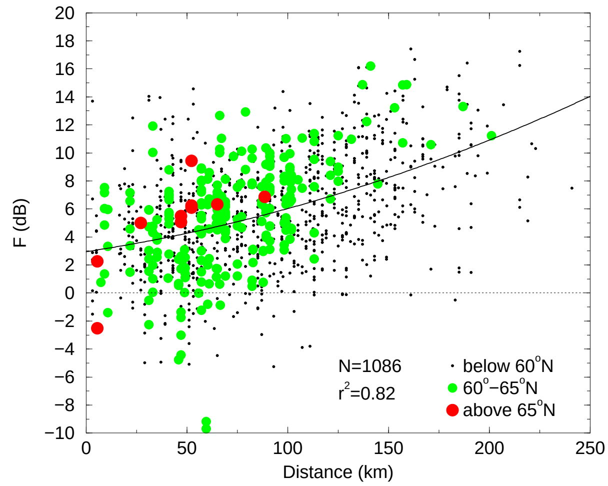


FIG. 6: All gauge-radar point pairs.

large variability is due to several error sources. One of these errors is caused by partial shielding of the radar beam due to terrain, forest, buildings, and other obstructions. Another effect is that of inhomogeneous beam filling which, in cold conditions, is often caused by partial beam overshooting at relatively proximate ranges. Either effect results in a "system" bias forming, ie. a correction which is independent of range, and such a bias is pronounced (around 3 dB) in this case. Yet, even if this system bias were removed, the correction at distant ranges would still be extreme, and so would be the resulting snowfall in the RR product. With the system bias, our correction factors at maximum range exceed 16 dB, and this is truly extreme yet not unreasonable in a cold climate.

It should also be noted that the choice of Z–R relation will impact on the system bias. Most, if not all, radars' factory settings use a Z–R relation valid for rain, and the radar is hopefully calibrated so as to give no bias when comparing against gauge data. If a Z–R relation for rain is used in snow, a system bias like the one we have will form. This is not a bad thing, however, since gauge-radar-ratio-based adjustment techniques like ours make the choice of Z–R coefficients redundant, provided the same coefficients are consistently used; the technique will normalize the radar data to the amounts given by the gauges anyway. Neverthless, the use of constant Z–R coefficients in snow and rain in the same dataset will cause greater scatter in the gauge-radar relations than if phase-dependent coefficients were used.

We extracted the gauge-radar point pairs for 2-6 March and stratified them by latitude (Fig. 6). We also derived their relation with distance ("All dates" in Fig. 5 which is the same as in Fig. 6). The results are noisy, as expected, but we notice that point pairs above 60°N indicate the need to higher correction factors than the overall relation in the curve. We also added precipitation accumulations from Norwegian climate station data (collected offline) in the hopes of seeing a similar tendency, but these data unfortunately only added noise. Nevertheless, the stratification by latitude indicates that colder conditions further north required higher correction factors than those derived operationally.

However, the lack of observations at distant ranges indicates that snowfall was generally too shallow to capture at such ranges due to beam overshooting, and that this characteristic leads to so few data as to make the derived relations unreliable beyond around 175 km. The green and red points in Fig. 6 are blue in Fig. 7, and the green relation in Fig. 7 is based on them. While this relation appears reasonable at short to intermediate ranges, it is clearly exaggerated at distant ranges.

The analysis of gauge-radar relations in Figs. 5-7 led us to formulate a speculative relation designed to remove the system bias, correct more at intermediate ranges, and be rather conservative at distant ranges. The result is the red curve in Fig. 7 which caps the correction factor at 12 dB. This formulation was not chosen to be physically meaningful, as it does not correspond with an assumed VPR of convective snowfall; the curve does, however, attempt to fit the observed data.

Uncorrected radar accumulations for a four-day period, ending at 6 UTC on 6 March, are illustrated in Fig. 8. These data clearly show the effects of the system bias and the underestimation it gives. The data also display a clear range bias. Nevertheless, the snowfall band which dominated the period can be discerned. The corresponding accumulation generated using the operationally-derived correction factors is found in Fig. 9. The system bias is gone, the band is seen more clearly, and the range bias is minimized judging by the homogeneity of the snowband. The snowfall amounts are extreme, 5180 km^2 with at least 100 mm and 36 km^2 with

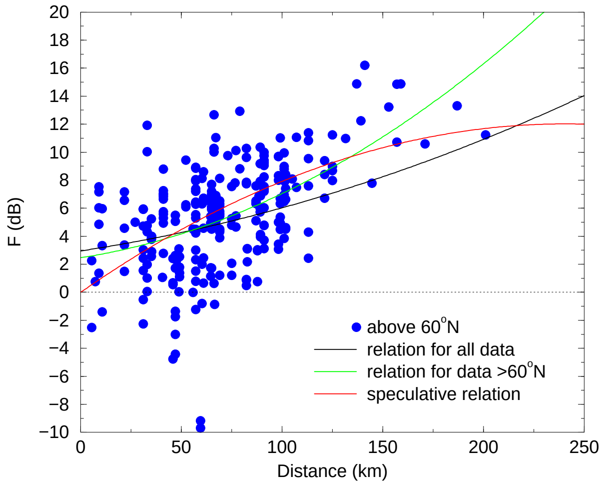


FIG. 7: All gauge-radar point pairs.

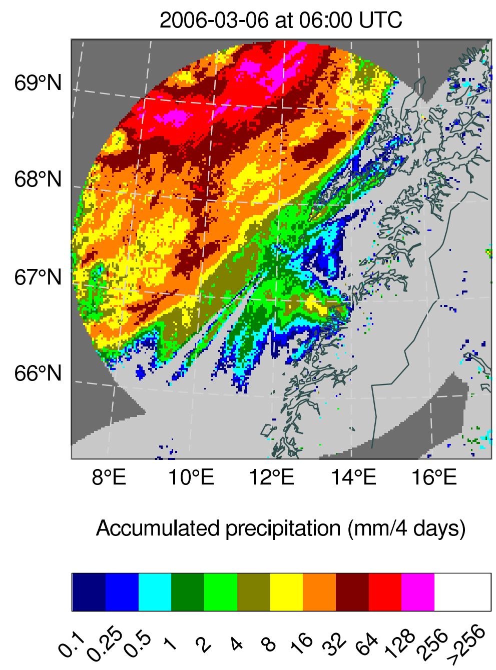


FIG. 9: Operationally adjusted radar.

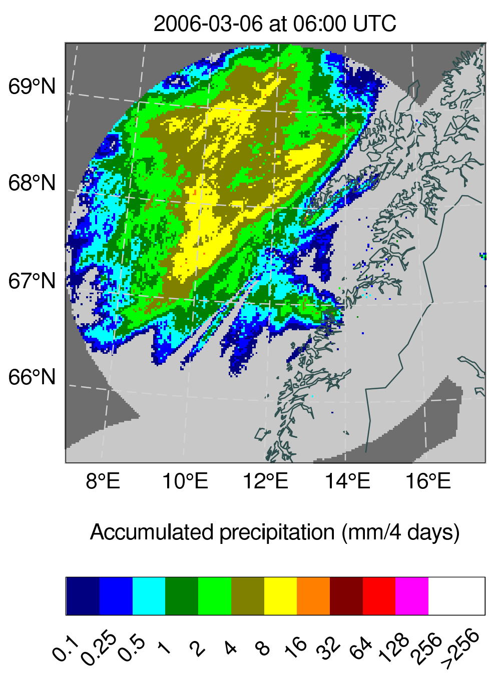


FIG. 8: Unadjusted radar.

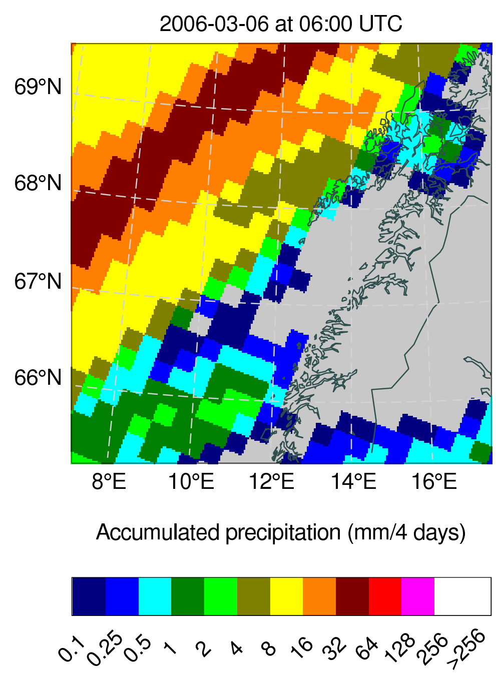


FIG. 10: Operational analysis from SMHI's MESAN system.

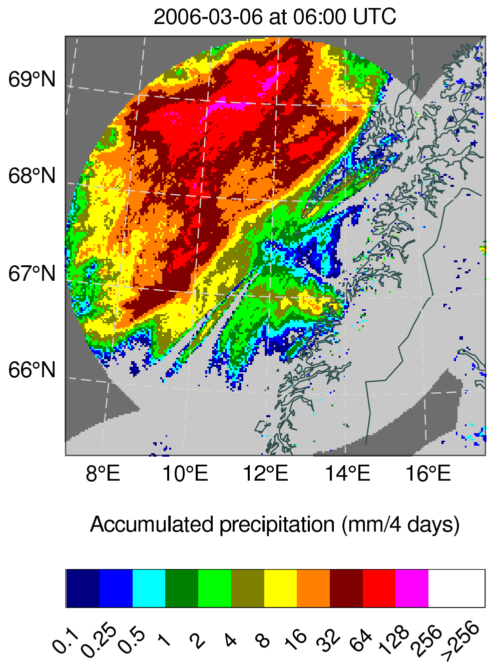


FIG. 11: Adjusted radar using speculative relation in Fig. 7.

at least 200 mm, and these amounts are what raised our original suspicions.

By comparison, Fig. 10 shows an accumulation of the operational analyses derived by SMHI's Mesoscale Analysis (MESAN) system (Häggmark et al., 2000). The MESAN precipitation analysis uses the HIRLAM numerical weather prediction (NWP) model output as a first guess which is then modified by other data sources, including gauges and (at the time) unadjusted radar, using data assimilation techniques. It is clear from the MESAN output that it has succeeded in capturing the snowband, but that snowfall amounts appear to be low. What is not captured in this four-day accumulation is timing errors and extrapolation artifacts which are apparant at shorter integration periods.

If we apply the speculative adjustment relation found in Fig. 7, we get the accumulation found in Fig. 11. This result adds more precipitation closer to the radar and reduces amounts at distant ranges. The result still appears to contain a range bias at distant ranges, which indicates that the speculative relation may be too conservative there. Here we have 3096 km^2 with at least 100 mm and 28 km^2 with at least 200 mm over the four days.

A speculation on the differences between the gauge-adjusted results and those found in MESAN lies in the systematic correction of gauge observations conducted prior to gauge adjustment. Without taking into account differences in spatial distribution, the differences in maxima between gauge-adjusted results and those from MESAN are over 100% in places, and this is despite the fact that MESAN includes it own systematic correction of its precipitation field using its other gridded variables. Systematic correction of snow observations can easily add over 50% more snow to that measured, and this is assuming that most gauges are equipped with wind shields (Michelson, 2004). Despite this, most reference datasets for validating precipitation, both liquid and solid, are not systematically corrected. This may lead to models and analysis systems being tuned to give lower snowfall amounts than often encountered in reality. This implies that the significantly larger amounts observed in gauge-adjusted radar data may be realistic anyway.

5. CONCLUSIONS AND OUTLOOK

Based on the available information received and analyzed thus far, the gauge-adjusted precipitation accumulations generated during 2-6 March 2006 appear to be reasonable. There are limits to the accuracy of radar-based QPE, in this case achieved through gauge adjustment, at distant ranges, and so an uncertainty remains about the validity of the results achieved there. Perhaps the real amounts lie somewhere in between those found in Figs. 9 and 11. Nevertheless, these radar-based results indicate that the convective snowfall generated in the stationary mesoscale deformation zone off the northern Norwegian coast were indeed extreme by any measure, and that the extreme nature of this case was not captured by any other observational, model, or analysis source.

Had it been possible to perform a VPR correction, the VPRs upon which the correction had been based may not have been representative for the stationary snowband located offshore due to the differences between the Artic airmass north of the convergence zone and that at the radar site. When the convergence zone weakened during 6 March and snowfall made landfall, the intensity of the convection had weakened considerably and the reflectivities found in radar data were weaker and more widespread. Had VPRs been available, they may have not been representative for the extreme conditions found offshore earlier.

This extended abstract represents work in progress. We have not yet performed any detailed analysis of NWP model profiles in an attempt to gain a better understanding of the processes which the model was capable of resolving. There are, however indirect implications for NWP; as the modelling consortia are moving towards establising high-resolution non-hydrostatic model configurations, these new configurations will inevitably be faced with the challenge of resolving processes like the ones highlighted here. Perhaps this is where variational assimilation of radar reflectivities can make a valuable contribution.

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