J5B.8 PHYSICALLY-BASED "DOWN-TO-EARTH" MODELLING OF SURFACE PRECIPITATION USING SYNERGETIC RADAR AND MULTISOURCE INFORMATION

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1. INTRODUCTION

Radar measurements are made at increasing height and with an increasing measurement volume with increasing range, making them decreasingly representative for surface conditions (Fabry et al. 1992; Kitchen and Jackson 1993; Koistinen et al. 2003). Commonly, users of radar data are interested in considering a radar image as containing surface information, an example being the use of radar-derived precipitation information as input to a hydrological rainfall-runoff model. This necessitates the systematic correction of radar reflectivities aloft to be valid at the surface prior to such quantitative application.

The vertical profile of reflectivity (VPR) has been identified as being a suitable basis for such a correction. Several implemented VPR correction schemes have shown that significant effort must be devoted to collecting, analysing and understanding the characteristics of VPRs (Gray et al. 2002; Pohjola and Koistinen 2002) prior to the formulation of the correction method itself. Then, the VPR used in the correction procedure must be derived in a way which is spatially and temporally consistent, the meso-beta technique presented by Germann and Joss (2002) being an example used in complex Alpine conditions. Finally, if the method is being applied to data from a radar network, VPRs must be further rendered spatially representative for any given point which is covered by two or more radars (Koistinen et al. 2003).

There are a number of inherent limitations of using the VPR as the basis for correction.

- The used VPR may have been derived out to e.g. 40 km range, but is assumed to be representative for the radar's full coverage area.
- Unless there is a specific treatment of overhanging precipitation, all vertical reflectivity gradients will give positive corrections, which is not necessarily correct.
- For areas covered by more than one radar, two or more VPRs must be interpolated in space in order to minimize the risk that edge effects in composite products are amplified. If none of the VPRs used in the interpolation process are derived using data at the given range, then this introduces uncertainties associated with data representativity. It also implies that artificial gradients in the horizontal reflectivity distribution risk being introduced into the correction process.
- The phase of the hydrometeors, and hence the importance of identifying and treating the bright band, must be taken into account to reduce the uncertainty in the value of the derived surface reflectivity.

The first three of these points are inherent to the use of VPRs in the correction process. However, Numerical Weather Prediction (NWP) model output has been identified as providing a potential means of improving the quality of radar observations (Hardaker et al. 1999; Mittermaier and Illingworth 2003).

Based on recent developments in VPR correction techniques, and more detailed knowledge achieved regarding their strengths and weaknesses, the issue of formulating an alternative VPR-like correction technique which is based on NWP model physics, and which employs information from an NWP model, has been addressed. This abstract summarizes a new method whereby radar measurements aloft are combined with modelled and analysed meteorological variables with the objective to estimate the precipitation intensity at the surface. Central to this method is the exploitation of cloud physics, as formulated for use in NWP, in an attempt to account for physical processes impacting on precipitation during its decent from echo height to surface.

2. METHODS

The method formulation is designed to use three dimensional NWP model output and 2-D analysis fields, but only to use this information to arrive at a surface precipitation estimate. There is no propagation forward in time, and there is no requirement on preserving the model's dynamic balance. The guiding principle is that the method be relatively simple and computationally inexpensive in order for it to be usable in real time.

The method is referred to as "Down-to-Earth" (DTE), and it employs forecast fields from the High Resolution Limited Area Model (HIRLAM) NWP model (Undén et al. 2002) along with analysis fields from SMHI's Mesoscale Analysis (MESAN) system (Häggmark et al. 2000). Quality controlled radar data from the BALTRAD network (Koistinen and Michelson 2002) have been used.

MESAN is an analysis system used operationally to generate hourly gridded meteorological variables for nowcasting purposes. DTE makes use of four MESAN analysed fields: the cloud base height, near-surface temper-

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ature, surface pressure, and near-surface relative humidity, the details of which are all found in Häggmark et al. (2000).

2.1 Parameterization of cloud water profiles

Modern NWP models make use of wet cloud physics based on formulations given by Kessler (1969). Kessler-type schemes rely on, and are subsequently very sensitive to, cloud water parameterizations being accurate and/or in balance with the rest of the model. Usually, an NWP model generates the cloud water during each model iteration (time step), and then depletes it in the process of generating precipitation. Unless the model state is saved to file during the time step calculations, the cloud water will be depleted and therefore unavailable for external use. This presents a practical constraint when using model cloud water from operational model states. Another constraint is the horizontal resolution of the model. Grids are becoming finer, yet at present a typical operational horizontal resolution for HIRLAM is around 20 km, which is still 100 times the area of a 2 km radar pixel. In the future, some operational models will have grid resolutions approaching that of the radar data. Use of model cloud water directly for the purposes of generating precipitation in DTE is therefore unrealistic and an alternative strategy must be formulated.

The used parameterization is simple and robust, and based on the modification of a wet adiabatic ascent. The MESAN cloud base height defines the starting point for the generation of a wet adiabatic cloud water profile according to Curry and Webster (1999). Temperature, pressure and humidity profiles from HIRLAM are used to constrain the calculations, the result being a wet adiabatic ascent which corresponds as well as possible with the given model state at the given location.

The profile will contain the upper limit of cloud water achievable. Due to the reduction of cloud water resulting from entrainment of unsaturated air, precipitation, and freezing, Karstens et al. (1994) modified the cloud water profile to be representative for non-precipitaing clouds, and a variation on this method has been applied which takes into account the general shape of unimodal cloud water profiles in precipitation modelled with HIRLAM.

2.2 Physical model

The cloud microphysics module, recently introduced into HIRLAM-5, was extracted and adapted for use in DTE. The following description of the cloud physics is based on that found in the reference version documentation (Undén et al. 2002).

The stratiform scheme is based on the work of Sundqvist (1988) and was originally developed by Rasch and Kristjánsson (1998) (hereafter RK) for the NCAR CCM3 model. The treatment of condensation and evaporation processes follows the Sundqvist scheme quite closely, although using specific humidity instead of relative humidity in the computations. The microphysics (conversion of cloud condensate into precipitation) is different from Sundqvist, following formulations used in Cloud Resolving Models (CRM). The formation of precipitation is clearly separated into five process that make the diagnosis and improvement of the parameterization easier. Although, only one predicted variable is used for cloud condensate, four different species are represented. A diagnostic approach is used to compute cloud fraction following Slingo (1987).

In RK, four types of condensate are represented: suspended liquid and ice, and falling liquid and ice. Currently, only the total suspended condensate (q_c) is a prognostic variable, as in Sundqvist. At the beginning of the computations, and for each model layer in DTE, q_c is decomposed into liquid and ice assuming that ice phase increases linearly from 0°C to -20°C. Precipitation is assumed to be snow at temperatures below freezing.

Five processes are considered to convert condensate into precipitation: autoconversion, coalescence, local production of ice and ice collecting rain and snow. The conversion rates are parameterized following bulk microphysics formulations used in smaller scale CRM. Autoconversion is parameterized following Chen and Cotton (1987). Coalescence is parameterized in accordance with Tripoli and Cotton (1980). Ice autoconversion is modelled following Lin et al. (1983), in a form proposed for liquid processes by Kessler (1969), but with a temperature dependence similar to the one proposed by Sundqvist (1988). Accretion and the collection of liquid by snow follow Lin et al. (1983). All snow is assumed to melt in layers where the temperature exceeds 0°C. Further details are found in Rasch and Kristjánsson (1998).

The initial precipitation rate is given by the converted radar reflectivity to precipitation rate at the echo's height, optionally using the method for diagnosis and application of dynamic Z-R relations (DZRs) following Michelson (2001). From the echo height to the cloud base, this precipitation rate is subject to the RK scheme at each model layer using the forecast variables from HIRLAM, depleting the parameterized cloud water. In DTE, the total precipitation production is not allowed to exceed the equivalent of 30 dB.

From the cloud base to the surface, evaporation acts upon the generated precipitation at each model layer. At present, the evaporation scheme is that proposed by Gregory (1995) for rain, although it is possible to partition rain and snow and treat each phase separately. This evaporation method uses the modelled temperature, pressure and relative humidity in each model layer, and a check is included to ensure that the amount of evaporated rain does not exceed that which would bring a given model layer to saturation. Total evaporation through the profile is not allowed to exceed the equivalent of -30 dB.

HIRLAM makes use of the convection scheme described in Kain and Fritsch (1993), but convection has not been specifically included in the DTE model yet.

3. EVALUATION AND DISCUSSION

DTE has been tested and evaluated using data from the wet summer of 2000, specifically from June 24 to August

31. Hourly HIRLAM and MESAN data, and radar data every 15 minutes, were used.

A comparison of daily precipitation totals was conducted which employed observations from around 1600 climate station gauges in Norway, Sweden and Finland. The integration period for daily precipitation is 6 to 6 UTC. Corresponding radar totals were generated with the maximum tolerated data loss being nine of 96 images. For each daily radar-based total, the average distance to the radar contributing to the output pixel was also computed.

The statistical measure upon which the evaluation was based is the gauge-to-radar ratio on the decibel scale: $F(dB) = 10\log(G/R)$. This is a convenient measure since the mean value of F is the bias expressed in a way which is directly applicable to radar measurements. Likewise, standard deviations of F also express variability in dB which is a natural radar scale. An additional advantage is that F is typically normally distributed (Cain and Smith 1976; Collier 1986; Koistinen and Puhakka 1986; Koistinen and Michelson 2002). Using F helps give a better intuitive understanding of the agreement between gauge and radar measurements.

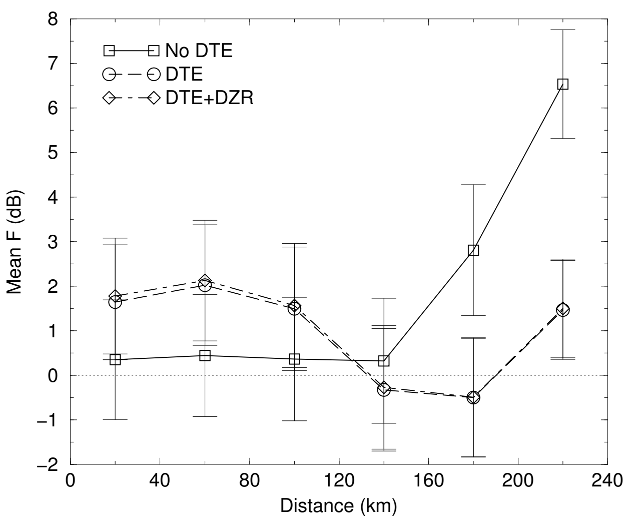

Figure 1: Bias as a function of distance for daily accumulations with radar only (No DTE), DTE, and DTE combined with DZR (DTE+DZR). Error bars denote one standard deviation.

Mean values of F, along with their standard deviations, were derived in 40 km wide distance strata for three comparisons (Fig. 1):

- gauges vs. uncorrected radar accumulations,
- gauges vs. radar accumulations derived following the application of DTE,
- gauges vs. radar accumulations derived following the application of dynamic Z-R relations (Michelson 2001) and then DTE.

Histograms illustrating the distributions of F for each stratum were also generated, an example of which is given in Fig. 2.

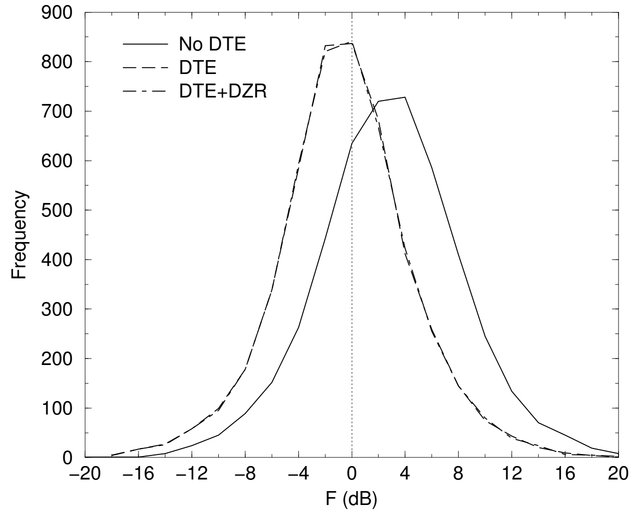

Figure 2: F(dB) histograms for the period June 24 to August 31, 2000 for the distance interval 160-200 km.

Evaporation from or below the cloud base to the surface at short to intermediate distances increases the bias against gauge measurements, since evaporation is the dominating term at these distances where the input radar data were more-or-less unbiased. An uncertainty in this context is the influence of the defined product height and how this varies among data from radars in a network. Another uncertainty is the Gregory (1995) evaporation scheme itself which is documented as being more efficient compared to others. Between 120-200 km, the bias is minimized to be within 1 dB, yet beyond around 200 km bias again exceeds 1 dB.

The introduction of DZRs into the DTE procedure does not lead to more accurate results. In fact, at shorter distances, both F biases and standard deviations increase marginally with the use of DZRs. A partial explanation for this may be that the impact of the bright band during summer conditions is found at relatively distant ranges where the beam is broad and therefore influenced to a lesser extent than at shorter ranges during colder seasons. Perhaps, the bright band cannot be accurately resolved using the DZR method.

DTE is very sensitive to the MESAN cloud base height, since this is where the cloud water profile, and thus the available precipitable water, is initiated and also the height at which evaporation starts. Improvements to the cloud base analysis technique should lead to more reliable DTE results.

Further uncertainties impacting on the variability of the bias against gauges lie in error sources which are untreated in the input radar data, such as site-specific quality issues.

In summary, the robustness of the DTE procedure and the synergetic use of multisource data provides a framework wherein improvements to input radar data and to NWP model physics and forecast skill are likely to lead to higher accuracy of DTE results. For the time being, however, DTE is an interesting experimental alternative to conventional VPR correction techniques.

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4. References

Cain, D. E. and Smith, P. L., 1976. Operational adjustment of radar estimated rainfall with rain gage data: a statistical evaluation. In *Preprints: 17th Conf. on Radar Met.*, pp. 533–538. AMS.

Chen, C. and Cotton, W. R., 1987. The physics of the marine stratocumulus-capped mixed layer. *J. Atm. Sci. 44*, 2951–2977.

Collier, C. G., 1986. Accuracy of Rainfall Estimates by Radar, Part I: Calibration by Telemetering Raingauges. *J. Hydrology 83*, 207–223.

Curry, J. A. and Webster, P. J., 1999. *Thermodynamics of Atmospheres and Oceans*. Academic Press. 471 pp.

Fabry, F., Austin, G. L., and Tees, D., 1992. The accuracy of rainfall estimates by radar as a function of range. *Quart. J. Roy. Meteor. Soc. 118*, 435–453.

Germann, U. and Joss, J., 2002. Mesobeta Profiles to Extrapolate Radar Precipitation Measurements above the Alps to the Ground Level. *J. Appl. Meteor. 41*(5), 542–556.

Gray, W. R., Uddstrom, M. J., and Larsen, H. R., 2002. Radar surface rainfall estimates using a typical shape function approach to correct for the variations in the vertical profile of reflectivity. *Int. J. Remote Sensing 23*(12), 2489–2504.

Gregory, D., 1995. A Consistent Treatment of the Evaporation of Rain and Snow for Use in Large-Scale Models. *Mon. Wea. Rev. 123*, 2716–2732.

Häggmark, L., Gollvik, S., Ivarsson, K.-I., and Olofsson, P.-O., 2000. Mesan, an operational mesoscale analysis system. *Tellus 52A*(1), 2–20.

Hardaker, P. J., Macpherson, B., and Brown, P. R. A., 1999. Weather radar and Numerical Weather Prediction models. In *COST 75 Advanced weather radar systems. International seminar*, pp. 451–459. European Commission. EUR 18567 EN.

Kain, J. S. and Fritsch, J. M., 1993. Convective Parameterisation for Mesoscale Models: The Kain-Fritsch Scheme. In: The representation of cumulus convection in numerical models. Eds: K. A. Emanuel and D. J. Raymond. *AMS Monograph 46*, 246p.

Karstens, U., Simmer, C., and Ruprecht, E., 1994. Remote sensing of cloud liquid water. *Meteorology and Atmospheric Physics 54*, 157–171.

Kessler, E., 1969. On the Distribution and Continuity of Water Substance in Atmospheric Circulations. *Meteor. Monogr. 10*(32), 84.

Kitchen, M. and Jackson, P. M., 1993. Weather Radar Performance at Long Range - Simulated and Observed. *J. Appl. Meteor. 32*, 975–985.

Koistinen, J. and Michelson, D. B., 2002. BALTEX Weather Radar-based Precipitation Products and their Accuracies. *Boreal Env. Res. 7*(3), 253–263.

Koistinen, J., Michelson, D. B., Hohti, H., and Peura, M., 2003. Operational measurement of precipitation in cold climates. In Meischner, P. (Ed.), *Advanced Applications of Weather Radar*, Chapter 3. Springer. (in press).

Koistinen, J. and Puhakka, T., 1986. Can we calibrate radar with raingauges? *Geophysica (Helsinki) 22*, 119–129.

Lin, B., Farley, R. R., and Orville, H. D., 1983. Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor. 22*, 1065–1092.

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

Mittermaier, M. P. and Illingworth, A. J., 2003. Comparison of model-derived and radar-observed freezing-level heights: Implications for vertical reflectivity profile-correction schemes. *Quart. J. Roy. Meteor. Soc. 129*(587), 83–96.

Pohjola, H. and Koistinen, J., 2002. Diagnostics of reflectivity profiles at the radar sites. In *Proc. ERAD (2002)*, pp. 233–237. EMS: Copernicus GmbH.

Rasch, P. J. and Kristjánsson, J. E., 1998. A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *J. Climatol. 11*, 1587–1614.

Slingo, J. M., 1987. The development and verification of a cloud prediction scheme for the ECMWF model. *Quart. J. Roy. Meteor. Soc. 113*, 899–927.

Sundqvist, H., 1988. Parameterization of condensation and associated clouds in models for weather prediction and general circulation simulation. Physically Based Modelling and Simulation of Climate and Climatic Change, M E Schlesinger, Ed. *Kluwer Academic 1*, 433–461.

Tripoli, G. J. and Cotton, W. R., 1980. A numerical investigation of several factors contributing to the observed variable intensity of deep convection over south Florida. *J. Appl. Meteor. 19*, 1037–1063.

Undén, P., Rontu, L., Järvinen, H., Lynch, P., Calvo, J., Cats, G., Cuxart, J., Eerola, K., Fortelius, C., Garcia-Moya, J. A., Jones, C., Lenderlink, G., McDonald, A., McGrath, R., Navascues, B., Nielsen, N. W., Ødegaard, V., Rodriguez, E., Rummukainen, M., Rõõm, R., Sattler, K., Sass, B. H., Savijärvi, H., Schreur, B. W., Sigg, R., The, H., and Tijm, A., 2002. HIRLAM-5 Scientific Documentation. Technical report, HIRLAM-5 Project, SMHI, SE-601 76, Norrköping, Sweden. 144 pp.