Proceedings of ERAD (2004): 469–473 © Copernicus GmbH 2004

ERAD 2004

The fit of Doppler radar radial winds with the NWP model counterpart

K. Salonen and H. Järvinen

Finnish Meteorological Institute, Meteorological Research, P.O. Box 503, 00101 Helsinki, Finland

Abstract. An observation operator for Doppler radar radial winds has been developed. It transforms the numerical weather prediction (NWP) model wind vector from the model space to the observation space corresponding to the observed quantity. Resolution of the Doppler radar radial raw wind observations is typically higher than the resolution of NWP models and some preprocessing is necessary for data assimilation. One possible preprocessing method is to generate spatial averages, superobservations (SOs), from the raw radial wind data. In this article, the fit of SOs generated with varying spatial averaging with the NWP model counterpart is studied. Model experiments indicate that SOs generated with 10–15 km resolution fit the best the model counterpart when the model resolution is 22 km.

1 Introduction

Limited area numerical weather prediction (NWP) models focus more and more on very high resolution (kilometric scale) and on forecasting of extreme weather events, like heavy precipitation and strong winds. Thus, high resolution observations are needed to determine the initial state of the model. Radar wind observations are extremely useful in forecasting rapidly developing mesoscale phenomena. In these scales the geostrophical adjustment is weak and wind observations are the most important source of information when determining the state of the atmosphere. The European Doppler radar network has been rapidly expanding during recent years. In many countries, like Finland and Sweden, the radar network has an excellent geographical coverage and Doppler radars provide wind observations with good temporal and spatial resolution. A 10-day assimilation and forecast experiment (Lindskog et al., 2004) indicates that the use of radar wind data has positive impact on wind and temperature forecasts in the low and middle troposphere.

Correspondence to: K. Salonen
(Kirsti.Salonen@fmi.fi)

Remote sensing observations are usually not directly related to the NWP model variables and some processing methods must be used before presenting the data to the NWP model. With the Velocity Azimuth Display (VAD) technique (Browning and Wexler, 1968) vertical profile of horizontal winds can be obtained from the raw radar wind data. Assimilation of the VAD wind profiles is straightforward with various data assimilation methods, for example with optimal interpolation or variational data assimilation. Another possible processing method is to generate radial wind superobservations (SOs) with spatial averaging from the raw data. SOs are smoother than the raw data and represent a prescribed spatial scale. Direct data assimilation of SOs is possible with variational data assimilation where a model counterpart for the observation is calculated with the so called observation operator. Observation operator transforms the model wind vector from the model space to the observation space corresponding to the observed quantity, that is, from model u and v components to radial wind, in our case.

The aim of the work presented in this article is to define the optimal resolution for the SOs from the NWP model point of view. The hyphothesis is that SOs should not represent too much small scales which are not resolved by the forecast model. On the other hand, there is no sense to smooth away all the non-linear information that simple processing to wind profiles does. Section 2 of this article describes the characteristics of Doppler radar radial wind SOs. Formulation and evaluation of the observation operator is given in Sect. 3 and defining the optimal resolution for the SOs is discussed in Sect. 4. The article is concluded by a brief summary in Sect. 5.

2 Superobservations

The horizontal resolution of the Doppler radar radial wind raw data is around one kilometer whereas the typical resolution of a mesoscale NWP model is still of the order of ten kilometers. Doppler radar wind observations thus represent

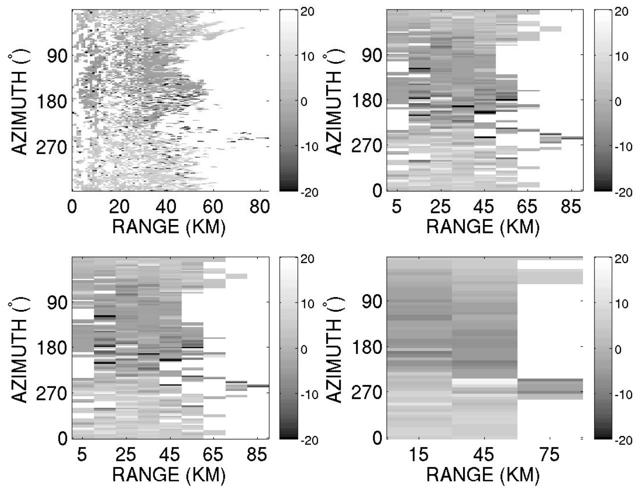

Fig. 1. An example of the Doppler radar radial wind raw data (a) and superobservations generated through horizontal averaging with 10 km resolution (b), 20 km resolution (c) and 30 km resolution (d).

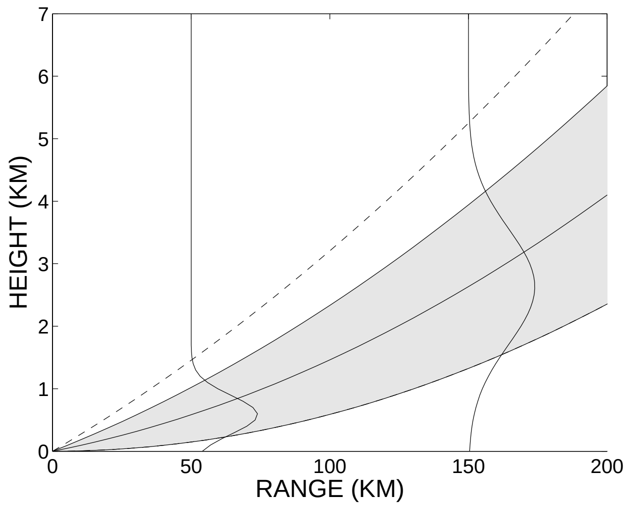

Fig. 2. An illustration of the radar beam broadening with 1° beamwidth (shaded area), upper limit for the Gaussian averaging kernel (dashed line) and shapes of the weight function with measurement ranges of 50 km and 150 km. The radar beam elevation angle is 0.5°.

partly phenomena which are not resolved by the NWP model. Calculating spatial averages from the raw data decreases this representativeness error. The processing software for superobservation generation has been developed as an extension to the Radar Analysis and Visualization Environment RAVE (Michelson, 1999).

The SO generation is based on horizontal averaging. The desired resolution for the SO can be defined with two parameters, range bin spacing and the angle between the output azimuth gates. For example SOs generated with parameters 10 km and 3° represent approximately 10 km resolution. Near the radar the raw polar data used in the averaging is selected from the area limited by the arc distance of the two adjacent output azimuth gates. After the arc distance exceeds the value of range bin spacing, range bin spacing defines the data selection area. With this approach fewer polar bins influence on SO near the radar than with longer measurement ranges and averaging of radial winds with significantly different directions is avoided. More details about the SO generation can be found in Lindskog et al. (2004).

Figure 1 shows raw polar data and SOs with 10 km, 20 km and 30 km resolutions. Between the azimuth angles 70° and 240° the radar radial wind is mainly negative, i.e. towards the radar, while elsewhere the radial wind is mainly positive. Some local discontinuities can be seen in the raw polar data. These outlying data are likely due to radar echoes from non-meteorological targets, such as birds or ships, or aliased wind observations. After horizontal averaging the wind field is smoother and the local discontinuities have vanished. With 30 km resolution most of the variability of the real wind field is also smoothed, which is of course not desirable.

3 Observation operator for Doppler radar radial winds

3.1 Observation operator formulation

The analysis method used in High Resolution Limited Area Model (HIRLAM) reference system (Unden et al., 2002) is 3-dimensional variational assimilation (3D-Var) (Gustafsson et al., 2001; Linskog et al., 2001). 3D-var is based on minimizing the cost function

$$J = J_b + J_o = \frac{1}{2}(\mathbf{x}-\mathbf{x^b})^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x^b}) + \frac{1}{2}(\mathbf{y}-H\mathbf{x})^T\mathbf{R}^{-1}(\mathbf{y}-H\mathbf{x}). \tag{1}$$

J_b measures the distance of the model state $\mathbf{x}$ to the model background state $\mathbf{x^b}$ and J_o to the observations $\mathbf{y}$ respectively. Each source of information is weighted according to its error covariance matrix, $\mathbf{B}$ for the model background state and $\mathbf{R}$ for the observations. Observation operator H produces the model counterpart of the observed quantity.

The formulation of the observation operator for the Doppler radar radial winds (Salonen et al., 2003) involves

1. Horizontal and vertical interpolation of the NWP model wind components u and v to the observation location.

2. Projection of the interpolated NWP model horizontal wind towards the radar, and finally on the slanted direction of the radar beam.

The broadening of the radar beam is modelled by using Gaussian averaging kernel in the vertical interpolation instead of linear interpolation. Figure 2 displays the beam broadening and examples of the vertical averaging kernel at ranges of 50 km and 150 km. The obscuring effect of the

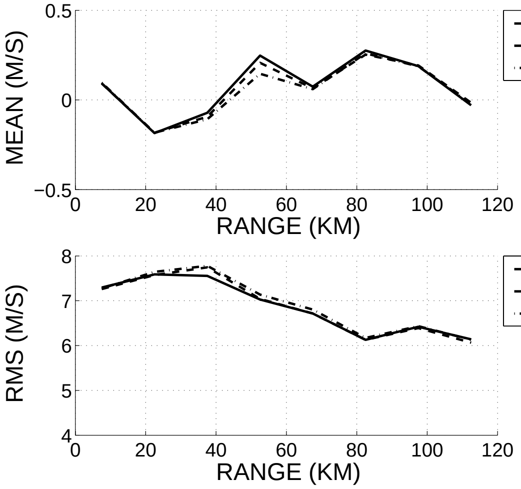

Fig. 3. Mean (upper panel) and rms (lower panel) difference between 15 km resolution SOs and the model counterpart as a function of range. The observation operator with linear interpolation in vertical, with Gaussian averaging kernel, and with Gaussian averaging kernel and the the Snell's law are denoted by solid line, dashed line and dash-dotted line respectively.

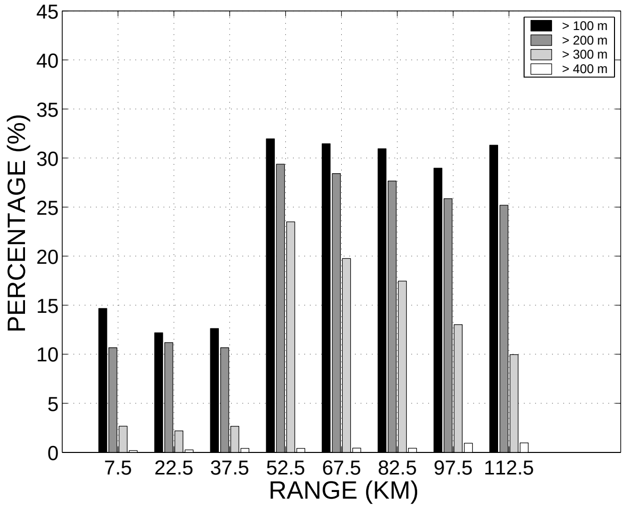

Fig. 4. Percentage of observations for which the difference of observation height calculated as $\frac{4}{3}r$-law and as calculated with the Snell's law is more than 100 m (black), 200 m (dark gray), 300 m (light gray) and 400 m (white) at different measurement ranges.

radar horizon is taken into account by assuming a radar horizon of 0° elevation angle, below which the model information is not used. This lower limit of the averaging kernel is denoted by the lower limit of the shaded region in Fig. 2. An empirical upper integration limit is set to 1.5 times the beamwidth (Koistinen, 2003). This is based on the fact that the radar reflectivity usually decreases rapidly above that height. The upper limit for the averaging kernel is denoted by a dashed line in Fig. 2.

Radar beam bending is taken into account by applying the Snell's law. The local refraction index is calculated from the NWP model temperature and humidity profiles for model levels assuming horizontal homogeneity between the measurement and the radar location. The calculated effective elevation angle is used in the projection of the horizontal wind on the slanted direction of the radar beam. This approach modifies also the observation height from the value obtained by applying the $\frac{4}{3}r$-law (Doviak and Zrnic, 1993).

3.2 Observation operator evaluation

A two-week experiment (1 to 14 June 1999) has been performed to evaluate the accuracy of the observation operator. Radar wind observations are from the Swedish radar network where the unambiguous velocity interval is ±48 m/s. SOs generated with 15 km resolution have been used in the experiment. The observation operator assumes that the projection of the vertical velocity on the radar beam is negligible. This implies that the observation operator is applicable for assimilation of radar data only with low elevation angles. In the following results elevation angles 0.5°, 1.3° and 2.4° are considered. The model counterpart is calculated from the HIRLAM model background state which is a 6-hour forecast. The model resolution is 22 km on 40 vertical levels.

The mean and root-mean-square (rms) difference between the SOs and the model counterpart are shown in Fig. 3 as a function of range. The mean difference is negative up to measurement range of 40 km, but with longer measurement ranges the observed wind is stronger than the model counterpart. In terms of mean difference, observation operators taking into account the broadening (gauss), or the broadening and the bending (snell) of the radar beam perform slightly better. The rms difference is the smallest for the observation operator using linear interpolation in vertical.

Accounting for the beam bending in the observation operator has an impact on the elevation angle used in the projection of the model wind vector and on the observation height. Figure 4 shows the percentage of the observations where the difference between the observation height as calculated by $\frac{4}{3}r$-law (provided by the RAVE software) and as calculated by the Snell's law is more than 100 m, 200 m, 300 m and 400 m, respectively.

With measurement ranges 52.5–112.5 km 25–30% of the observations exceed the value 200 m. It is more common that the observation height given by the $\frac{4}{3}r$-law is higher than the observation height calculated with the Snell's law, i.e. the bending of the radar beam is stronger than in the normal conditions (ICAO standard atmosphere). Only in 0.1–0.4% of the cases the height calculated with the Snell's law is over 200 m higher than the height provided by RAVE. The difference between the observation heights is over 400 m for approximately 1% of the observations with measurement ranges longer than 97.5 km.

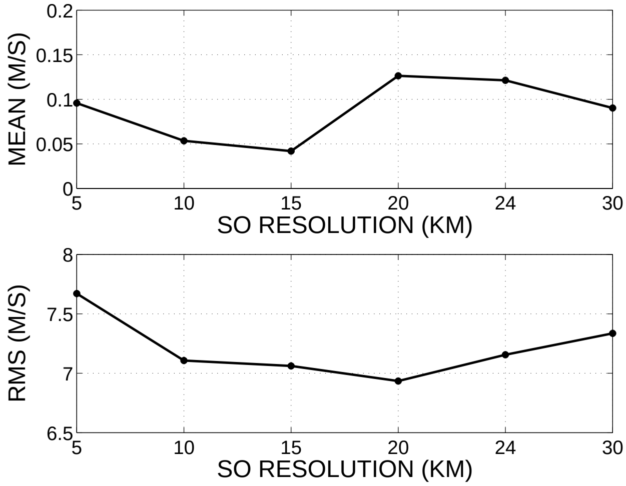

Fig. 5. Mean (upper panel) and rms (lower panel) difference between the Sos and the model counterpart as a function of SO resolution.

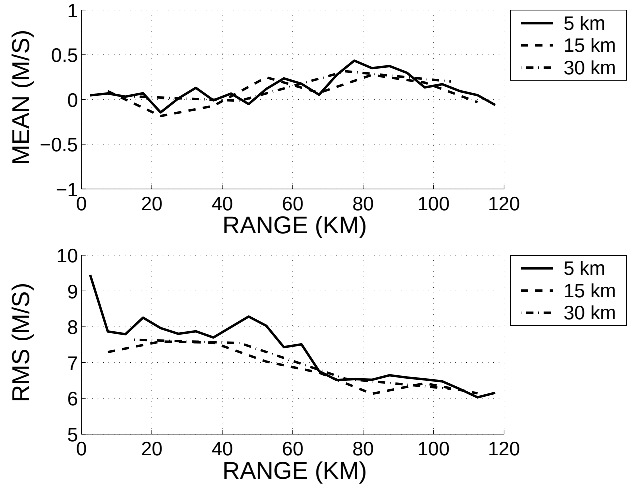

Fig. 6. Mean (upper panel) and rms (lower panel) difference between the SOs generated with 5 km (solid line), 15 km (dashed line) and 30 km (dash-dotted line) and the model counterpart as a function of measurement range.

4 Optimal SO resolution

A set of two week experiments has been performed to study the fit of the SOs generated with different resolutions to the model counterpart. SOs are generated with 5 km, 10 km, 15 km, 20 km, 24 km and 30 km resolutions. The model counterpart is calculated using the observation operator accounting for the broadening and the bending of the radar beam. The model resolution is again 22 km on 40 vertical levels.

Figure 5 shows the mean and the rms difference between the SOs and the model counterpart as a function of SO resolution. In general, the mean difference is always positive, i.e. the observed wind is stronger than the model wind. The mean difference is smallest for the SO resolution of 15 km. The variation in rms difference is quite small for SOs generated with 10–24 km resolutions and the minimum is attained with 20 km resolution. SOs generated with 5 km resolution have the largest rms difference and also the mean difference is nearly twice as large as the mean difference for 10 km or 15 km resolution SOs.

Figure 6 displays the mean and the rms difference as a function of measurement range for SO resolutions 5 km, 15 km and 30 km. The mean difference is generally small for all resolutions, and tend to be the largest around 80 km measurement range. In terms of rms difference, SOs generated with 15 km resolution perform the best and SOs generated with 5 km resolution the worst. One reason for this behaviour is that the 5 km SO contains fewer raw data and the random errors in raw data do not average out as effectively as for example in the 15 km SO. Furthermore, if the raw data includes information of non-meteorological targets, the 5 km SO generation does not smooth that information away with short measurement ranges as effectively as SO generation with coarser resolution. Another possible source of mean and rms difference is that the 5 km resolution SO includes wind field variations which are not represented in the 22 km resolution model.

5 Summary

An observation operator for the Doppler radar radial winds has been developed and tested for the HIRLAM 3D-Var. Model experiments reveal that in terms of mean difference between the SO and model counterpart, observation operator using Gaussian averaging kernel and the Snell's law performs the best. It is typical that the observation height calculated with the Snell's law is lower than the observation height given by the $\frac{4}{3}r$-law.

Model experiments with 22 km resolution HIRLAM model indicate that among a range of SO resolutions the SOs generated with 10–15 km resolution have the best fit with the model background. With 5 km resolution, especially with measurement ranges less than 60 km, the rms difference between SOs and the model counterpart is significantly larger than for SOs with coarser resolution. Possible reasons for this are that 5 km resolution SOs represent partly phenomena which are not resolved by the forecast model, and with short measurement ranges the local discontinuities are not smoothed away from the 5 km resolution SOs.

Acknowledgement. This research has been funded by the Academy of Finland project "Doppler radar wind data assimilation".

References

Browning, K. A. and Wexler, R.: The determination of kinematic properties of a wind field using Doppler radar, J. Appl. Meteor., 7, 103–113, 1968.

Doviak, R. J. and Zrnic, D. S.: Doppler radar and weather observations, Second edition, San Diego Academic Press, Inc., 562, 1993.

Gustafsson, N. and Co-authors: Three-dimensional variational data assimilation for a limited area model, Part I: General formulation and the background error constraint, Tellus, 53A, 425–446, 2001.

Koistinen, J.: FMI Personal communication, 2003.

Lindskog, M. and Co-authors: Three dimensional variational data assimilation for a limited area model, Part II: Observation handling and assimilation experiments, Tellus, 53A, 447–468, 2001.

Lindskog, M., Salonen, K., Järvinen, H., and Michelson, D. B.: Doppler radar wind data assimilation with HIRLAM 3D-Var, Mon. Wea. Rev., 132, 1081–1092, 2004.

Michelson, D. B.: RAVE User's Guide, Available from SMHI, SE-601 76, Norrköping, Sweden, 51, 1999.

Salonen, K., Järvinen, H., and Lindskog, M.: Model for Doppler radar radial winds, 31st American Meteorological Society Conference on Radar Meteorology Volume I, 142–145, 2003.

Unden, P. and Co-authors: HIRLAM-5 Scientific documentation, Available from SMHI, SE-601 76, Norrköping, Sweden, 144, 2002.