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Processing of Doppler radar radial winds for data assimilation

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1 Introduction

Atmospheric wind field is 3-dimensional and variable over time and space. Doppler radar measures one component of the wind vector, ie. the radar radial component. For complete description of the wind field simultaneous measurements should be made with three Doppler radars. Usually only one radar is available and the availability of the other two radars is compencated by simplifying assumptions about the structure of the wind field. Widely used methods to retrieve vertical profiles of horizontal wind are VAD (Lhermitte and Atlas, 1961) and VVP (Browning and Wexler, 1968) methods. Both are based on linear wind field assumption.

An alternative retrieval approach is to use a numerical model of the atmospheric dynamics as a constraint for resolving the full 3-dimensional wind field from the radial wind measurements of a single Doppler radar. Variational data assimilation technique provides the framework for appropriately relating the model variables to the observed variables, like radar radial winds. The benefit of direct use of radial winds is that observations include non-linear information of the wind field unlike wind profiles generated with VAD or VVP algorithms where the non-linear features are smoothed away. The drawback is that in the NWP (numerical weather prediction) models the implied background error covariance structures filter out small scale observational information.

The amount of Doppler radial wind measurements is very large and some preprocessing prior to data assimilation must be made. One possibility, as discussed in this paper, is to generate spatial averages of the raw data.

This article is organized as follows. Section 2 describes the principle of radar wind measurements and how the raw data can be preprocessed before introducing to an NWP model. Section 3 discusses the azimuthal behaviour of bias in radar radial wind observations and introduces a new method to estimate bias in wind speed and wind direction. Section 4 considers the best resolution for averaging raw data from the NWP model point of view and section 5 concludes the paper.

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2 Processing of radar radial wind observations

Doppler radar emits electromagnetic waves to investigate atmospheric properties (Doviak and Zrnic, 1993). Radial velocity of scattering particles is determined from the observed phase difference between successive radar pulses. With constant elevation angle and range the radial wind component v_r has a form of cosine as a function of azimuth angle ϕ

$$v_r = w \sin\theta_e + v_h \cos\theta_e \cos(\delta - \phi), \tag{1}$$

if the linear wind field assumption is valid. w is the vertical wind component, θ_e is the elevation angle, v_h is the horizontal wind component and ($\delta + \pi$) is the wind direction.

Typical resolution for radar observations is 0.5 – 1 km in space and 5 – 15 minutes in time while the horizontal resolution of present-day mesoscale NWP models is 5 – 10 km with 1 – 6 h assimilation cycle. Some preprocessing is thus needed to decrease the amount of observations before using the data in the NWP models. Commonly used solution to decrease the amount of data and process radial wind observations is to calculate spatial averages, so called superobservations (SOs), from the raw data. SOs are smoother than the raw observations and better represent the model resolution. Figure 1 displays an example of raw radial wind data and corresponding SOs. Spatial averaging smoothens the wind field and fills in the data gaps. Another, but not as good, possibility is to use data thinning, i.e. to use a subset of raw observations with sparse resolution. In the thinned data, random errors in individual observations can be quite large.

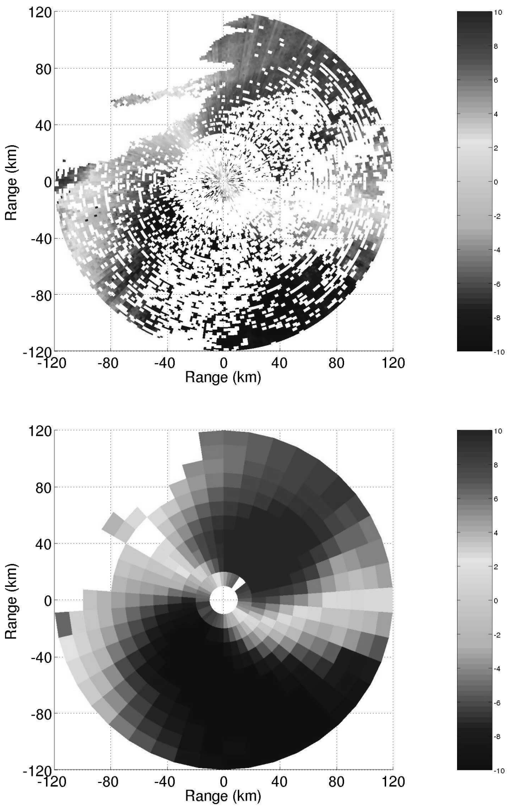

Fig. 1. An example of the Doppler radar radial wind data (upper panel) and SOs generated with spatial averaging (lower panel).

3 Notes on verification methods

The quality of all observation types is closely monitored against model predictions before introduction to the NWP model data assimilation system. Monitoring reveals possible problems in the observing system, like systematic biases in the data. Typical verification statistics for conventional wind observations are bias, standard deviation and rms error of the wind speed and direction. Verification of Doppler radar radial wind observations requires special attention because of the characteristic of the measurement. Mixing different azimuth directions in the bias calculation easily results in near zero bias. Still, there might be systematic differences between observed and modelled wind direction and/or wind speed. Studying the bias as a function of azimuth angle can reveal those differences.

3.1 A theoretical example

An important quality aspect of the radar radial wind observations is the azimuth dependence of bias. This is illustrated with a thought experiment where there is a difference between the observed and the true wind speed. Let the observed wind speed be 17 m/s from the South and the true wind speed be 15 m/s from the South. In this case the radial wind has a form of cosine with amplitudes of 17 m/s and 15 m/s, respectively as shown in figure 2. The difference between the observed and true radial wind (hereafter bias) has also a form of cosine with an amplitude of 2 m/s. If the bias statistic is calculated by summing up biases over all azimuth directions, the opposite bias values will cancel out and the resulting bias statistic is zero, even though there is a systematic 2 m/s difference in the observed and true wind speed. The bias statistic behaves similarly also in the case where there is a systematic difference in wind direction, or both. A non-zero bias statistic is obtained if:

- the linear wind field assumption is not valid
- there are no backscatterers in all azimuth directions
- the radar is unable to measure all azimuth directions due to obstacles
- the radar measurement is contaminated by non-meteorological echoes like birds, ground clutter etc. in some azimuth directions

In order to obtain a realistic estimate of the systematic errors in the data, a method which accounts for the azimuth dependence of the bias must be used. Next subsection introduces a method to estimate bias in wind speed and direction from the radar radial winds.

3.2 Behaviour of real data

In order to be able to calculate the radial wind bias as a function of radar azimuth angle in a consistent way, a reference

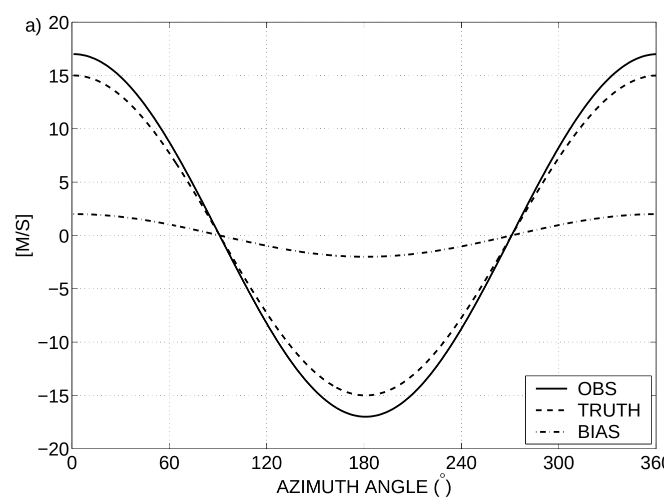

Fig. 2. An example of the azimuthal behaviour of radar radial wind bias. Observed wind is 17 m/s from the South (solid line) and true wind is 15 m/s from the South (dashed line). Bias is shown with the dash-dotted line.

wind direction must be chosen. All wind observations are rotated towards this reference direction. The procedure is as follows. Each radar radial wind observation has a model counterpart, and the corresponding model wind components u and v are known. The wind direction at the observation location can be defined from the model u and v components. The observation azimuth angle is rotated towards the reference wind direction by the difference between the reference wind direction and the model wind direction. With this method the nominal wind direction is the same for all observations in one scan. The procedure is repeated for all scans at different times.

This subsection presents verification of a one month data set which consists of 533 000 radar radial wind SOs and their model counterparts. The model counterparts are calculated from HIRLAM (High Resolution Limited Area Model) (Undén et al, 2002) 6h forecasts with 9 km horizontal resolution. HIRLAM variational assimilation system (Gustafsson et al, 2001) (Lindskog et al., 2001) includes an observation operator for radar radial winds (Salonen et al., 2003). In this study the reference wind direction is South.

Figure 3 shows the mean observed radial wind speed (solid line), mean background radial wind speed (dashed line) and their difference (bias) (dash-dotted line) as a function of azimuth angle. Subjectively, the mean observed and the mean background radial wind speed follow very well the linear wind field assumption, ie. the radial wind has a form of a cosine as a function of the azimuth angle. The amplitudes of the observed and background radial winds are nearly the same but there is a small phase difference that indicates systematic difference in wind direction.

Elevation angles 0.5°, 1.1°, 2.3° and 3.2° are considered, for which the vertical velocity component is negligible and the first term of (1) can be left out. Thus, by fitting $v_r = v_h \cos(\delta - \phi)$ to the data it is possible to estimate the mean horizontal wind speed and direction. In this case the mean observed wind speed is 11.91 m/s from 184° and the mean background wind speed is 11.88 m/s from 180°. There is thus a small 0.03 m/s bias in wind speed and 4° bias in the wind direction.

4 Optimal SO resolution

As discussed in section 2, raw radial wind data need preprocessing before assimilation into an NWP model. This section considers what is the best spatial resolution for SOs from the NWP model viewpoint. A set of one month (January 2002) experiments have been performed with the HIRLAM model to study the fit of the SOs generated with different horizontal resolutions to the model counterparts. The raw radar radial wind observations used in the experiments are from the Swedish radar network where the maximum measurement range is 120 km and the unambiguous velocity interval is

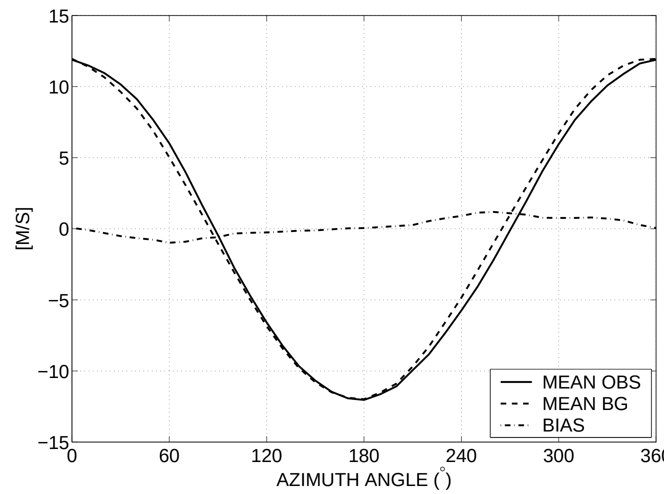

Fig. 3. The mean observed radial wind speed (solid line), the mean background radial wind speed (dashed line) and their difference (bias) (dash-dotted line) as a function of azimuth angle.

±48 m/s. The resolution of raw data is 1 km in range and 0.9° in azimuth (420 azimuth gates per 360° scan).

Details of the SO generation method used in these experiments can be found in Lindskog et al. (2004). The SO generation is based on horizontal averaging. Desired resolution for the SO is defined with two parameters, the range bin spacing (hereafter ΔR) and the angle between the output azimuth gates (hereafter $\Delta\phi$). 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 $\Delta\phi$. After the arc distance exceeds the value of ΔR, ΔR 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.

Characteristics of the SOs used in the experiments are summarized in Table 1. SOs have been generated with ΔR = 10 km and with varying azimuthal resolutions. The number of SOs varies from 1 025 400 for SOs with 0.9° resolution in azimuth to 196 800 for SOs with 8.6° resolution in azimuth. Since the scanning strategy is to measure only up to 120 km in range, $\Delta\phi$ is the more influential parameter to the size of the averaging area in the SO generation. Fig. 4 displays the averaging lengths as a function of measurement range. Only SOs with azimuthal resolution 6.0° and 8.6° reach the full 10 km resolution inside the 120 km measurement range.

Figure 5 displays the bias for wind speed and wind direction as a function of resolution in azimuth. The bias is estimated as described in section 3. Minimum bias for both wind speed and direction is obtained with 1.7° resolution in azimuth. The resolution of these SOs is about one third of the model resolution. With other SO resolutions the model background wind speed is on average stronger than the observed

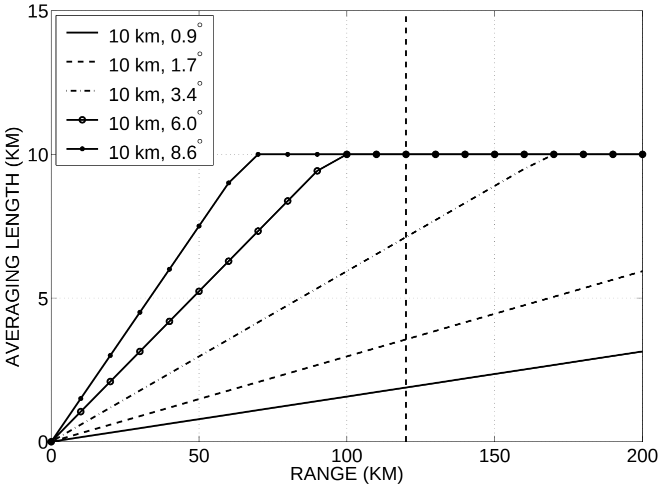

Fig. 4. Schematic illustration about the averaging lengths applied in the SO generation at different measurement ranges.

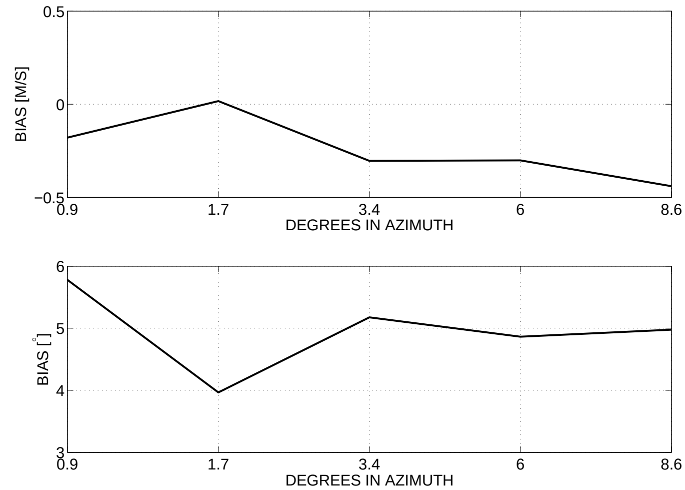

Fig. 5. Bias for wind speed (upper panel) and for wind direction (lower panel) shown as a function of SO resolution in azimuth.

wind speed. 70% of 0.9° resolution SOs have been generated from only one or two raw observations. These SOs are influenced most if the raw data contains systematic ground clutter or backscatter from non-meteorological targets such as birds or ships. The SO generation can average out random errors effectively but, on the other hand, averaging of radial winds with significantly different directions should be avoided.

5 Conclusions

The resolution of mesoscale NWP models is increasing and observations are needed with high spatial and temporal resolution. Variational data assimilation enables use of observations which are not directly linked with model variables, like radar radial winds. Raw radar radial wind observations must be preprocessed before assimilation into NWP models. SO generation is a good option because it averages out random errors effectively. Experiments with 9 km resolution HIRLAM model show that the best fit between the SOs and model background is gained with 1.7° resolution in azimuth.

The nature of radar radial wind as a function of azimuth angle sets challenges to the verification of these observations.

	Resolution in azimuth (°)	**Approximate number of observations**
SOs	0.9	1025400
	1.7	532600
	3.4	414300
	6.0	262400
	8.6	196800

Table 1. Summary of SO resolutions and number of SOs used in the experiments.

Bias calculation over all azimuth angles can result near zero values even in presence of differences in observed and true wind speed or/and wind direction. The bias in wind speed and direction can be estimated from the data by fitting the cosine function of v_r to the data.

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