Application of Radar Wind Observations for Low-Level NWP Wind Forecast Validation

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ABSTRACT

The Finnish Meteorological Institute has produced a new numerical weather prediction model–based wind atlas of Finland. The wind atlas provides information on local wind conditions in terms of annual and monthly wind speed and direction averages. In the context of the wind atlas project, low-level Applications of Research to Operations at Mesoscale (AROME) model wind forecasts have been validated against radar radial wind observations and, as a comparison, against conventional radiosonde observations to confirm the realism of the wind forecasts. The results indicate that the systematic and random errors in the AROME wind forecasts are relatively small and are of the same order of magnitude independent of the validating observation type. The validation benefits from the high spatial and temporal resolution of the radar observations. There are over 4000 times as many radar observations as radiosonde observations available for the considered validation period of July 2008–May 2009.

1. Introduction

Many countries focus on developing strategies to replace and complement traditional energy sources, such as fossil fuels and nuclear energy, with renewable non-polluting energy sources. Wind power is one alternative and its use is growing rapidly. Knowledge about local wind conditions is essential for building wind power plants in appropriate locations.

To meet the requirements of the wind power industry, the Finnish Ministry of Employment and Economy requested a new wind atlas, containing detailed information on average wind conditions in Finland, at several heights between 50 and 400 m above the ground, and with horizontal resolution in the kilometer range for the entire country, and less than 1 km for regions of special interest. The Finnish Meteorological Institute (FMI) secured the contract by a plan based on massive use of numerical weather prediction methods, relying on the Applications of Research to Operations at Mesoscale (AROME; Seity et al. 2011) NWP model and the Wind Atlas Analysis and Application Program (WAsP; Mortensen et al. 1993) statistical model. The resulting atlas was made public in 2009 and is available and described online (see http://www.windatlas.fi/en/index.html.)

To confirm the realism of the NWP model–based wind forecasts, they need to be validated against reliable observations (e.g., Costa et al. 2006; Delaunay et al. 2009). Traditionally, the quality of wind forecasts is studied by comparing the forecasts to 10-m synoptic wind observations near the ground, to mast wind observations below 400-m height, and to radiosonde wind observations in the upper atmosphere. However, the spatial and temporal resolution of these conventional wind observations is relatively poor.

Doppler weather radars provide a complementary source of wind information. Observations are available with high spatial (0.5–1 km) and temporal (5–15 min) resolution, and their applicability to NWP model validation has been successfully demonstrated (e.g., Salonen et al. 2008). For example, a Doppler radar scanning with 2° elevation angle up to 150-km range with a 1-km resolution in range can provide wind information up to 6.5-km height with a nominal resolution of ~35 m in height along the radar beam.

In the context of the wind atlas project, low-level AROME 6- and 12-h wind forecasts have been validated against radar radial wind observations and, as a comparison, against conventional radiosonde observations. The aim is to confirm the realism of the AROME wind
forecasts. Radar observations from the FMI radar network have been utilized. The FMI radar network consists of eight Doppler weather radars, which are able to cover most of the country. The comparison has been done according to seasons.

The article is organized as follows. Section 2 briefly discusses the Finnish Wind Atlas and how it has been produced. Section 3 describes the model data and observations used in the wind atlas validation, and section 4 shows the validation results. A short summary is given in section 5.

2. The Finnish Wind Atlas

The new wind atlas of Finland provides information about the wind conditions in terms of monthly and annual averages. The simulation consists of 72 months of data from the period 1989–2007. Forty-eight months of the simulation cover the average wind conditions in Finland, and the remaining 24 months constitute 2 years constructed from the months with the strongest and the weakest mean winds, respectively (see http://www.windatlas.fi/en/index.html).

The simulations are based on the joint use of the AROME NWP model and the WAsP statistical model, which is widely used in wind atlas applications. The nonhydrostatic AROME model describes the atmospheric physics as accurately as possible for weather forecasting purposes. The variables predicted by AROME are three-dimensional wind vector, pressure, temperature, specific humidity, turbulent kinetic energy, cloud fraction, five condensed water species (rain, snow, graupel, cloud liquid water, cloud ice), soil temperature and humidity, snow cover, and the exchange of heat, moisture, and momentum between the surface and the atmosphere (Bouttier 2009). For the wind atlas, the AROME model has been run with 2.5-km horizontal resolution and 40 levels in the vertical. The grid interval in the vertical increases with height. The lowest 1 km includes eight levels and the vertical grid varies between 70 and 200 m. The lowest model level is at about 30 m. The model domain covers Finland and nearby areas, and the model setup is similar to the setup used for the operational daily forecast runs at FMI. The wind atlas is based on 6-h AROME forecasts.

The statistical WAsP model has been applied at coastal and other windy regions to provide wind information with 250-m horizontal resolution for five altitudes: 10, 25, 50, 100, and 200 m. WAsP model modifies the wind time series produced by AROME to generate a climatological description of wind conditions by taking into account the effects of local roughness and topography (Mortensen et al. 1993).

In the final products, wind information is given for seven altitudes: 50, 75, 100, 125, 150, 200, and 400 m. Figure 1 shows the average wind speed at 200-m height with 2.5-km horizontal resolution for January, as an example of the results.

3. Datasets used in the validation

To confirm the realism of the wind forecasts used in the wind atlas production, operational AROME 6- and 12-h forecasts have been validated for the period of July 2008–May 2009. The period is divided into four sub-periods according to seasons. Validation has been done against radar radial wind observations, as well as against
conventional radiosonde observations, as a comparison. The validation period has been chosen based on the availability of suitable radar observations. The applied model version and the domain are exactly the same for the wind atlas period and for the validation period. Thus, although these periods are not the same, the validation results obtained reflect the general model performance. Table 1 summarizes the number of observations available from each data source for each subperiod. The following subsections give more details on the datasets used in the validation.

### a. Radar observations

The FMI weather radar network consists of eight radars (marked with circles in Fig. 1). A measurement task designed especially for high-quality wind measurements is operated at the FMI radars every 15 min (Saltikoff et al. 2010). The measurement task consists of three low elevation scans, $2^\circ$, $4^\circ$, and $6^\circ$. The dual-pulse repetition frequency (PRF) technique (Dazhang et al. 1984) is applied to alleviate ambiguity problems. The resulting unambiguous velocity interval in the measurement task is approximately $35.9 \text{ m s}^{-1}$, and the unambiguous range is $150 \text{ km}$. The range resolution of the observations is $1 \text{ km}$, and the azimuthal resolution is $1^\circ$. In total, the dataset for the considered validation period of July 2008–May 2009 consists of over $26,000,000$ observations from the eight radars.

Figure 2 sketches the resolution of the radial wind observations. The left panel of Fig. 2 shows the observation heights as a function of measurement range for elevation angles of $2^\circ$, $4^\circ$, and $6^\circ$. The right panel of Fig. 2 provides a view of the vertical resolution. The nominal vertical resolutions for elevation angles $2^\circ$, $4^\circ$, and $6^\circ$ are $35, 70$, and $105 \text{ m}$, respectively. However, in reality the radar wind measurement is a weighted average from the radar measurement volume, which becomes larger the longer the measurement range (e.g., Doviak and Zrnić 1993). Thus, the actual vertical resolution is somewhat degraded.

The quality of the FMI radar wind observations has been studied in detail in Salonen et al. (2011). Radar observations go through various preprocessing steps, including ground clutter filtering (Saltikoff et al. 2010), before they can be used for NWP model validation or data assimilation purposes. In general the quality of the radar wind observations is good but in occasional cases the unambiguous velocity interval is exceeded, and observations include remaining ground clutter (erroneous zero velocity observations) or other nonmeteorological observations, despite the performed preprocessing. These erroneous observations can be effectively detected and removed with the so-called background quality control procedure. Each observation $y_i$ is tested against its model counterpart $H[x_{b,i}]$ and if it fulfills the inequality

$$\frac{(H[x_{b,i}] - y_i)^2}{\sigma_{b,i}^2 + \sigma_{o,i}^2} \leq L,$$

it is accepted. In Eq. (1) $\sigma_{b,i}$ and $\sigma_{o,i}$ are the background and observation error standard deviations, respectively. Here, values of $3.6 \text{ m s}^{-1}$ for $\sigma_{b,i}$ and $6 \text{ m s}^{-1}$ for $\sigma_{o,i}$ have been used, and the subjective rejection limit $L$ is set to $6$ (Lindskog et al. 2004). Thus, the quality control allows observation minus model counterpart departures in the $\pm 17 \text{ m s}^{-1}$ range.

In the following sections, validation results are shown for radar wind observations from an elevation angle of $2^\circ$ only, and measurements are considered up to the $80$-km measurement range. This corresponds approximately to a $3.2$-km height. This elevation angle and maximum range are chosen because they give the most detailed high-quality observations for the altitudes interesting from the wind atlas point of view. Measurements from the first $10 \text{ km}$ from the radar are excluded to further minimize the impact of observations contaminated by ground clutter.

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Table 1. Number of observations from each data source for each period.

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<td>570</td>
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<td>271 100</td>
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<td>865 800</td>
<td>1 123 400</td>
<td>935 600</td>
</tr>
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</table>
b. Radiosonde observations

There are three radiosonde stations in Finland providing observations on a daily basis (marked with boxes in Fig. 1). Observing times for Jokioinen and Sodankylä stations are 0000 and 1200 UTC, and for Jyväskylä station 0600 and 1800 UTC. In this study, 0600 and 1200 UTC observations are utilized, as the initial time for the operational AROME runs is 0000 UTC. The radiosonde dataset consists of \( \sim 6000 \) observations in total.

c. Model data

The Finnish Wind Atlas is based on 6-h AROME forecasts. In this validation 12-h forecasts have also been considered in addition to the 6-h forecasts because there are more radiosonde observations available at 1200 UTC.

Model counterparts for the wind observations are produced with the so-called observation operators from the forecast fields. In case of the radiosonde wind observations, the observation operator simply interpolates the horizontal model wind components \( u \) and \( v \) to the observation location in the horizontal and vertical. Bilinear interpolation is used in the horizontal interpolation, and linear interpolation (linear in \( \ln p \); i.e., linear in mass) is used in the vertical interpolation.

The observation operator for radar radial wind observations also interpolates the model wind field to the observation location (Salonen et al. 2003; Järvinen et al. 2009).

Bilinear interpolation is used in the horizontal interpolation, and a Gaussian averaging kernel is used in the vertical interpolation. The Gaussian averaging kernel takes into account the broadening of the radar pulse volume as a function of measurement range. The interpolated wind components are then projected on the horizontal plane toward the radar and on the vertical plane to the slanted direction toward the radar. The applied observation operator also takes into account the pulse path bending.

4. Validation results

In the following, the validation results are considered in terms of observation minus model counterpart wind speed and direction bias, and standard deviation. Bias gives information about the systematic modeling and/or observation errors, while standard deviation describes the magnitude of random errors. Details about the special aspects of radar radial wind bias estimation can be found from Salonen et al. (2007). Standard deviation of the radar radial wind component is studied directly.

a. Comparison to radar observations

Figure 3 shows the wind speed bias as a function of height for 6-h AROME forecasts calculated against wind observations from the Vimpeli radar for all four considered seasons. The wind speed bias varies mainly between \( \pm 0.5 \text{ m s}^{-1} \). Thus, the bias is relatively small.
Scatterplots (not shown) reveal that occasionally the dual-PRF technique systematically fails to resolve the correct radial wind speed. This is due to the fact that the short and long PRFs are used in adjacent azimuth angles and the azimuthal resolution may not always be sufficient to resolve the correct wind speed. This can happen if there is a strong gradient in the radial wind speed (e.g., due to a mesocyclone) or close zero velocity when there is a naturally strong gradient in the radial wind speed (E. Saltikoff 2010, personal communication).

This feature of the dual-PRF technique evidently affects the wind speed bias statistics as not all affected observations can be detected and removed by the quality control procedures.

Figure 4 is similar to Fig. 3 but for the wind direction bias. The bias varies between ±5°. For autumn and spring seasons the bias is actually very close to zero above 1-km height. It can be concluded that in terms of the wind direction bias the quality of both the AROME wind forecasts and the radar wind observations is very good.
Figure 5 shows the standard deviation for the radial wind component as a function of height. It varies between 2 and 3.5 m s$^{-1}$. The occasional failure of the dual-PRF technique, discussed in the context of bias, contributes also to the magnitude of the random error. Other sources of random observation errors include exceedance of the unambiguous velocity interval and remaining nonmeteorological echoes, such as ground clutter, which are not detected and removed by the general radar data preprocessing or by the background quality control applied.

Validation of AROME 6-h forecasts against wind observations from the other radars from the FMI network gives very similar results, excluding the radar at Luosto. This will be discussed more in section 4c. Validation of the 12-h forecasts gives also consistent results.

b. Comparison to radiosonde observations

Radiosonde wind observations are considered to be of very high quality. The drawback is that their spatial and temporal resolution is rather low. In this study, AROME wind forecasts have been compared to radiosonde observations to determine whether the quality of radar wind observations is comparable to the quality of radiosonde observations and thus sufficient for this kind of model validation purposes.
The bias and standard deviation statistics against radiosonde observations are produced with the verification package applied in the operational AROME suite. The verification package provides wind speed and direction bias and standard deviation statistics for constant pressure levels of 925, 850, 700, 500, 300, 200, and 100 hPa. Radar observations from a 2° elevation angle are available to ~3-km height, which corresponds to ~700-hPa height.

Figure 6 shows the wind speed bias (upper-left panel), wind direction bias (upper-right panel), and the wind speed standard deviation (lower panel) for AROME 6-h wind forecasts calculated against radiosonde observations from Jyväskylä for the period September–November 2008. The dashed lines in the figures indicate the approximate height up to which radar observations are available. The wind speed bias varies between −0.5 and 0.2 m s⁻¹ and the wind direction bias between −5° and −1°; the standard deviation is 2–3.8 m s⁻¹. Thus, the magnitude of the biases and the standard deviation are of the same order as when calculated against radar wind observations. Results are similar for other considered periods as well.

Comparison of the wind speed bias calculated against Jyväskylä radiosonde observations (upper left panel of Fig. 6) and against Vimpeli radar wind observations (upper right panel of Fig. 3) for the September–November

![Figure 5](image-url)
2008 period reveals that near the ground the biases have opposite signs. The bias is positive when calculated against radar observations (i.e., observed wind speed is on average stronger than the model wind speed) and is negative when calculated against radiosonde observations.

Vimpeli is approximately 160 km to the northwest of Jyväskylä. Wind speed bias calculated against observations from the Ikaalinen radar, located approximately 160 km to southwest from Jyväskylä, is negative at low levels (not shown). Scatterplots show that wind observations from the Vimpeli radar have somewhat suffered from the failure of the dual-PRF technique. Thus, the difference in the sign of the bias is mainly caused by observation bias, and no conclusions about the meteorological significance of the difference can be drawn.

Validation results against radiosonde observations for the 12-h AROME wind forecasts (not shown) are again very similar than the results for 6-h forecasts, and they support the conclusion that radar observations are extremely valuable supplement to the observations used for this kind of model validation purposes. However, careful attention needs to be paid to the observation quality to avoid misleading conclusions.

c. Mutual benefits

Monitoring the quality of model forecasts against observations gives important information about the observation quality as well. A good example of this mutual benefit is for the Luosto radar, which was included in the validation study.
The validation results against wind observations from Luosto are rather similar to other results during July–August 2008 (not shown). However, in the autumn period the wind direction bias increases substantially and receives values as high as 150° (left panel of Fig. 7). Typically the radial wind measurements are interpreted such that negative values are toward the radar and positive values are away from the radar. This is defined in the radar software. Because of a human error, the positive and negative values were interpreted conversely for some time, and this caused the large wind direction biases in the validation. The error was fixed and the validation results returned back to the same level as for the other radars (right panel of Fig. 7).

This example demonstrates clearly how comparison against model data can reveal flaws in the observations, which in the worst case could remain unnoticed for a very long time.

5. Summary

The Finnish Meteorological Institute has produced a new NWP model-based wind atlas of Finland. The wind information represents the mean monthly and annual wind conditions over the last 50 years. The information is given with 2.5-km horizontal resolution over all of Finland, and with 250-m resolution for coastal and other windy regions. The wind atlas is based on AROME NWP model 6-h forecasts. The WAsP statistical model has been used for providing the 250-m resolution information.

To confirm the realism of the wind forecasts used in the wind atlas production, operational AROME 6- and 12-h wind forecasts have been validated against radar radial wind observations and radiosonde wind observations for the period July 2008–May 2009, according to seasons. The FMI weather radar network consists of eight radars, which are able to cover most of the country. A wind measurement task applying dual-PRF technique is operated at the radars every 15 min. Radar wind observations have a nominal vertical resolution as high as ~35 m. The radiosonde observations used for the validation are from Jyväskylä station (0600 UTC) and from Jokioinen and Sodankylä stations (1200 UTC).

The validation results indicate that the systematic and random errors are relatively small and of the same order of magnitude independent of the validating observation type. The validation clearly benefits from the large number of radar observations. Radar observations have significantly higher resolution both in space and in time than the radiosonde observations. There are over 4000 times more radar observations available for the considered period. However, special attention needs to be paid to the radar data quality when interpreting the results. At the FMI radars the observation quality is occasionally degraded by the failure of the dual-PRF technique.

![Fig. 7. Wind direction bias as a function of height calculated against wind observations from the Luosto radar. Considered periods are (left) September–November 2008 and (right) March–May 2009.](image-url)
Long-term validation of a NWP model against observations gives information about the systematic model errors, but it can also reveal hidden flaws in the observation quality. A good example of this is for the radar at Luosto where the positive and negative radial wind values were interpreted conversely for some time. Thus, this kind of model validation benefits both the NWP model development and the observation quality.

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REFERENCES


