Quality Control and Verification of Weather Radar Wind Profiles

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ABSTRACT

Weather radar wind profiles (WRWPs) have been retrieved from Doppler volume scans using different implementations of the velocity–azimuth display (VAD) and volume velocity processing (VVP) methods. An extensive quality control of the radial velocity data and the retrieved wind vectors has been applied. The quality and availability of the obtained wind profiles have been assessed by comparisons with collocated radiosonde observations and numerical weather prediction (NWP) data over a 9-month period. The comparisons reveal that the VVP methods perform better than the VAD methods, and that the simplest implementation of the VVP (VVP1) method performs the best of all. The availability fraction of VVP1 wind vectors is about 0.39 at ground level and drops below 0.16 at a 6-km altitude. The observation minus background statistics of the VVP1 wind profiles against the High Resolution Limited Area Model (HIRLAM) NWP model are at least as good as those of the radiosonde profiles. This result clearly demonstrates the high quality of (quality controlled) weather radar wind profiles.

1. Introduction

Doppler weather radars are capable of providing upper-air wind observations using dedicated methods for retrieval of wind profiles. In the early 1960s, Lhermitte and Atlas (1961) and Browning and Wexler (1968) introduced the velocity–azimuth display (VAD) technique for the extraction of upper-air wind data from Doppler radar observations. When using the VAD technique, it is not possible to separate the contributions of the vertical velocity, which is a sum of the vertical wind velocity and the hydrometeor fall velocity, and the divergence of the horizontal wind field to the offset of the VAD. Improved versions of the VAD technique, which are mainly designed to separate these two contributions, were developed in the late 1980s and early 1990s and have been dubbed the extended-VAD (EVAD) technique (Srivastava et al. 1986; Matejka and Srivastava 1991) and the concurrent extended-VAD (CEVAD) technique (Matejka 1993). Instead of processing a single VAD or a series of VADs, one can also process all available volume scan data within a certain height layer at once using a multidimensional linear regression. This so-called volume velocity processing (VVP) technique has been introduced by Waldteufel and Corbin (1979). Nowadays, both the VAD technique and the VVP technique are widely used to retrieve wind profiles from Doppler radar observations.

Despite the widespread use of the VAD and VVP retrieval techniques, only a few verification or case studies with the retrieved wind profiles have been reported so far and no intercomparison study between VAD and VVP retrieved horizontal wind data has been published up to now. Andersson (1998) has published verification results of VAD wind profiles against those from radiosonde and the High Resolution Limited Area Model (HIRLAM) numerical weather prediction (NWP) model. Both the availability and the accuracy of the VAD wind vectors of the Swedish weather radars were investigated. The EVAD technique has been used to study the trailing anvil region associated with a squall line (Srivastava et al. 1986). Profiles of wind speed and direction, hydrometeor fall speed, and divergence have been obtained. Details of the kinematic structure of the midlatitude squall line are revealed by this Doppler radar study. Xin and Reuter (1998) have investigated how the number of VVP parameters affects the accuracy of the retrieved parameters and have applied the optimized VVP technique to an Alberta, Canada, storm. It is concluded that the initiation and enhancement of precipitating cells were associated with the

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VVP low-level convergence. An interesting intercomparison of divergence and vertical velocity obtained by (C)EVAD and VVP techniques is presented by Cifelli et al. (1996). The performances of the techniques were quite similar, although the VVP profiles often extended to greater heights. Unfortunately, no intercomparison of the retrieved wind speeds and directions was made. Boccippio (1995) has performed a diagnostic analysis of the VVP retrieval technique and he has developed an algorithm for preparation and analysis of a robust VVP retrieval.

In this article we present an intercomparison of different implementations of the VAD and VVP retrieval techniques and an extensive verification of Doppler radar VVP wind profiles against radiosonde and HIRLAM NWP model profiles. Nine months of wind profile data have been used for the intercomparison and verification. Different implementations of modules to retrieve wind profiles from Doppler volume scan data using the VAD and VVP techniques have been considered as well. It is concluded that the VVP retrieval technique provides wind profiles with better availability and/or quality than the VAD technique. In addition, it is found that the simplest implementation of the VVP technique, that is, with the fewest wind field parameters, provides the best horizontal wind data. Verification results indicate that the biases of the VAD and VVP wind profiles satisfy the accuracy requirements for upper-air wind measurements as provided by the World Meteorological Organization (WMO 1996). Finally, observation minus background statistics of the VVP1 wind profiles against the HIRLAM model will be presented that demonstrate the high quality of weather radar wind profiles.

2. Retrieval of wind profiles

a. Radial velocity from a local wind model

For wind profiling by single-Doppler radar a linear wind model is usually taken to approximate the wind field in the vicinity of the radar. This linear wind model is centered horizontally at the location of the radar and vertically at the height of interest z_0. The components of the local wind field in the x, y, and z directions are $U(\mathbf{r})$, $V(\mathbf{r})$, and $W(\mathbf{r})$, respectively, and in the linear wind model they are approximated by

$$U(\mathbf{r}) = u_0 + x\frac{\partial u}{\partial x} + y\frac{\partial u}{\partial y} + (z - z_0)\frac{\partial u}{\partial z}, \qquad (1)$$

$$V(\mathbf{r}) = \upsilon_0 + x\frac{\partial \upsilon}{\partial x} + y\frac{\partial \upsilon}{\partial y} + (z - z_0)\frac{\partial \upsilon}{\partial z}, \qquad (2)$$

$$W(\mathbf{r}) = w_0 + (z - z_0)\frac{\partial w}{\partial z}, \qquad (3)$$

where u_0, υ_0, and w_0 are the components of the wind field at the center and $\partial u/\partial x$ (and similar terms) are partial derivatives of the wind field at the center. Waldteufel and Corbin (1979) have shown that the partial derivatives of $W(\mathbf{r})$ in the x and y directions enter the equation for the radial velocity only in combination with the partial derivatives of $U(\mathbf{r})$ and $V(\mathbf{r})$ in the z direction. In locally stratiform situations, where the linear wind model is most likely to apply, the horizontal derivatives of the vertical velocity are much smaller than the vertical derivatives of the horizontal velocities and they can, therefore, be neglected (Waldteufel and Corbin 1979).

The modeled radial velocity at a certain position can be calculated from the linear wind model and the terminal fall velocity W_f of the hydrometeors. The radial velocity at (x, y, z) in the local wind field is the component of the field along the line of sight of the radar, that is, the line connecting the origin and the point of interest. The radial velocity V_r is the sum of the terminal fall velocity and the scalar product of the wind field vector and line-of-sight vector

$$V_r(\mathbf{r}) = \frac{x}{R}\cdot U(\mathbf{r}) + \frac{y}{R}\cdot V(\mathbf{r}) + \frac{z}{R}\cdot (W(\mathbf{r}) + W_f), \qquad (4)$$

where $R \equiv |\mathbf{r}|$ is the range from the radar. Using Eqs. (1)–(3) for the linear wind model, the elementary equation for the radial velocity $V_r^{(3)}$ is obtained:

$$V_r^{(1)}(\mathbf{r}) = (w_0 + W_f)\sin\theta + u_0\cos\theta\sin\phi + \upsilon_0\cos\theta\cos\phi, \qquad (5)$$

$$V_r^{(2)}(\mathbf{r}) = V_r^{(1)}(\mathbf{r}) + \frac{\hat{D}}{2}R\cos^2\theta + \frac{\hat{H}}{2}R\cos^2\theta\sin2\phi + \frac{\hat{T}}{2}R\cos^2\theta\cos2\phi, \qquad (6)$$

$$V_r^{(3)}(\mathbf{r}) = V_r^{(2)}(\mathbf{r}) + \frac{\partial w}{\partial z}\Delta z\sin\theta + \frac{\partial u}{\partial z}\Delta z\sin\theta\sin\phi + \frac{\partial \upsilon}{\partial z}\Delta z\sin\theta\cos\phi, \qquad (7)$$

where ϕ, θ, and Δz are the beam azimuth, the beam elevation, and the deviation from the height of interest z_0, respectively. The divergence $\hat{D}$, the stretching deformation $\hat{T}$, and shearing deformation $\hat{H}$ of the local wind field are defined according to Browning and Wexler (1968). Equations (5) and (6) are obtained when all derivatives and the vertical derivatives, respectively, are neglected in Eqs. (1)–(3). The preceding three equations describe the radial velocity as deduced from a local wind model with an increasing level of complexity and they are fundamental to the wind profile retrieval techniques.

b. Velocity–azimuth display and volume velocity processing

When the mean radial velocity at constant range and elevation is displayed as a function of azimuth, the resulting curve can be approximated by a sine [see Eq. (5)]. The wind speed and direction can be determined from the amplitude and the phase of this sine, respectively (Lhermitte and Atlas 1961; Browning and Wexler 1968). The quantitative analysis of an observed VAD is usually done via a Fourier series decomposition. The radial velocity as a function of the azimuth is modeled by a truncated Fourier series,

$$V_r(\phi) = \frac{a_0}{2} + \sum_{n=1}^{N} a_n \cos n\phi + \sum_{n=1}^{N} b_n \sin n\phi. \quad (8)$$

The Fourier coefficients a_n and b_n are determined by a fit of this series to the observed VAD. The obtained coefficients can only be interpreted using a local wind model. Using Eq. (6) for the radial velocity from the local wind model, the first five Fourier coefficients can be written as

$$a_0 = 2\sin\theta\,(w_0 + W_f) + R\cos^2\theta\,\hat{D}, \quad (9)$$

$$a_1 = \cos\theta\, v_0; \quad b_1 = \cos\theta\, u_0, \quad (10)$$

$$a_2 = R\cos^2\theta\,\hat{T}/2; \quad b_2 = R\cos^2\theta\,\hat{H}/2. \quad (11)$$

In this article two different VAD algorithms, dubbed VAD1 and VAD2, using either only three or all five Fourier coefficients are evaluated. One disadvantage of the VAD retrieval method is that the conversion of a Doppler volume scan to a wind profile is not straightforward. For each height layer, several VADs are usually available, which all have to be quality controlled and fitted to obtain the horizontal wind field parameters (u_0, v_0). The sets of wind field parameters have to be combined to a final set that is representative for the height layer of interest, which is usually done by a weighted average (Matejka and Srivastava 1991).

Instead of processing a series of VADs, one can process all available Doppler volume data within a height layer at once. Waldteufel and Corbin (1979) have introduced the so-called volume velocity processing retrieval method. The VVP method extracts the parameters of the local wind field by a multidimensional linear fit of the radial velocity equation to the observed Doppler volume data. Equations (5)–(7) for the radial velocity suggest three different VVP algorithms with an increasing level of complexity, dubbed VVP1 (three parameters), VVP2 (six parameters), and VVP3 (nine parameters). In their original article Waldteufel and Corbin (1979) proposed the most comprehensive implementation of the VVP method because knowledge of the vertical derivatives allows, in principle, for a quality control of the extracted parameters by comparison of successive height layers. Boccippio (1995) argues that the vertical derivatives should be discarded to avoid problems with linear dependencies between different basis functions and he favors the use of the VVP2 retrieval technique.

It has been suggested that the VAD retrieval method is more robust than the VVP method because the basis functions used in the VAD analysis are orthogonal and independent of the local wind model (Srivastava et al. 1986). The orthogonality of the basis functions is reduced, however, by the presence of gaps in the collected data (Matejka and Srivastava 1991). In addition, Boccippio (1995) has found that a relatively simple subset (VVP2) of the original model of Waldteufel and Corbin (1979) can be used to obtain a robust and stable fit.

c. Quality control in wind profile retrieval

In this section, several sources of error that affect the quality of the wind profiles and ways to control them in a retrieval algorithm will be highlighted.

The retrieval methods for wind profiles approximate the local wind field by a uniform or a linear wind model. Inevitably deviations of the local wind field from the wind model will cause errors in the retrieved wind parameters. Caya and Zawadzki (1992) have investigated the effect of nonlinearity of the local wind field on the quality of the VAD retrieval. It is concluded that the parameters of the VAD analysis have no clear physical meaning when the wind field is nonlinear, but intuitively it is expected that for weak nonlinearities the associated errors should be small. Errors due to nonlinearities of the wind field are controlled by application of a maximum range (e.g., 25 km) on the analyzed volume data.

Side lobe clutter and other ground clutter in the received Doppler signal is suppressed using a digital time domain filter before the mean radial velocity is calculated. Strong clutter is not suppressed completely, however, and it will cause a bias of the mean radial velocity toward zero. The application of a minimum range (e.g., 5 km) on the analyzed volume data and rejection of data from low elevations ($<1°$) reduces the impact of clutter on the quality of the wind profiles. In addition, the error can effectively be controlled by rejection of all radial velocities close to zero (<2 m s^{-1}) before the wind profile retrieval method is applied. For significant wind speeds this will hardly have an effect, but apparent wind speeds close to zero, true or false, will not be retrieved.

The absence of hydrometeors or other scatterers leads to gaps in the radial velocity data. Wind profile retrieval algorithms have problems with large gaps because the basis functions loose orthogonality and the linear fit becomes unstable. To avoid gross errors, no wind field retrieval should be performed on volume data with large gaps. In the processing the azimuthal circle is divided into eight sectors and for each sector the number of available data points is counted. When the number of points is below a certain threshold (default of five) for two neighboring sectors, the height layer will not be processed any further.

The most straightforward way to obtain a solution for a general linear least squares problem is based on normal equations. The solution using normal equations is, however, susceptible to round-off errors. In addition, the normal equations are often almost singular, and then no solution is found at all. The cure for these problems is a solution by singular value decomposition (SVD), which gives the best approximation in a least squares sense (Press et al. 1992). For the VVP retrieval methods, the wind field parameters are determined from a single SVD solution for all available data within the height layer of interest. The VAD wind field parameters are obtained from a number-of-points-weighted average of all SVD solutions for the individual VADs within the height layer of interest.

The unambiguous interval of the radial velocity data is extended by a factor of 3 using the dual-pulse-repetition-frequency (PRF) technique (Sirmans et al. 1976). Analysis of dual-PRF velocity data has revealed that a small fraction of the range bins will be dealiased incorrectly (Holleman and Beekhuis 2003). These velocity outliers constitute typically 1% of the range bins, and the velocity error will be twice the low or high unambiguous velocity of the primary observations (20 or 26 m s^{-1} in our case). The velocity outliers can efficiently be flagged by a comparison with the modeled radial velocity obtained from a first fit. After removal of the outliers, using a deviation threshold of, for example, 10 m s^{-1}, the final wind field parameters are again determined by a second wind model fit.

Migrating birds and actively flying insects are a major source of error for wind profile retrieval methods (Koistinen 2000; Collins 2001). Bird migration can easily be recognized by inconsistency of the wind vectors or by deviation of the Doppler wind profiles from reference profiles. Koistinen (2000) has noted that the standard deviation of the radial velocity determined from the wind profile retrieval is larger in bird migration than in rain. The standard deviation of the radial velocity σ is calculated from the SVD solution using the chi-squared merit function (Press et al. 1992):

$$\sigma^2 = \sum_{i=1}^{N} [V_{r,i} - V_r(\mathbf{r}_i)]^2/(N - M), \qquad (12)$$

where $V_{r,i}$ are the observed radial velocities, N is the number of radial velocity data, and M is the number of parameters in the radial velocity model. The retrieved wind vectors are quality controlled by rejection of the vectors with a standard deviation greater than a certain threshold. The quality and availability of wind vectors are coupled, and the optimum setting of standard deviation threshold depends on the application of the profiles (see section 4a).

The quality control thresholds and the relevant parameters of the Doppler volume scan and the wind profile processing are summarized in Table 1.

3. Available data

The Royal Netherlands Meteorological Institute (KNMI) operates two C-band Doppler weather radars from Gematronik (Meteor AC360). In this study only data from the radar in De Bilt, Netherlands (52.10°N, 5.18°E, and 44 m MSL), are used. The radars have an antenna with a 4.2-m diameter and a beamwidth of about 1°. The peak power and width of the transmitted pulses are 250 kW and 0.8 μs. A dedicated Doppler volume scan has been defined that is repeated every 15 minutes. The unambiguous velocity is extended using the dual-PRF technique (Sirmans et al. 1976; Holleman and Beekhuis 2003). The low and high PRF have been set to 750 and 1000 Hz, respectively, in order to extend

TABLE 1. Summary of the quality control thresholds and the most important parameters of the Doppler volume scan and the wind profile processing.

Parameter	Value
Low/high PRF	750/1000 Hz
Number of pulses per ray	30/40
Elevations	0.5, 2, 3.5, 5, 7, 9, 12, 15, 20, 25 (°)
Layer thickness	0.20 km
Min/max range	5/25 km
Min radial velocity	2.0 m s^{-1}
Number of points per sector	5
Velocity deviation threshold	10.0 m s^{-1}
Standard deviation threshold	2.0 m s^{-1}

the unambiguous velocity interval by a factor of 3, that is, up to 40 m s^{-1}. The 10 elevations of the volume scan have been optimized for profiling up to an altitude of about 6 km. The RVP6 Doppler signal processor (Sigmet, Inc.) offers two sets of infinite impulse response (IIR) filters for clutter suppression by digital time domain filtering (Sigmet 1998). IIR filter 3, which offers a 40-dB suppression of clutter, has been selected. Radar products are generated using Gematronik software (Gematronik 2003). More details on the KNMI radars and the settings can be found in Holleman (2003).

During a 9-month period volume data from the Doppler radar profiles from the radiosonde launches in De Bilt and data from the HIRLAM NWP model (Unden et al. 2002) have been gathered. The setup of the radars for Doppler scanning was finalized by 1 October 2001 (starting date). The ending date is determined by the temporary termination of the radiosonde launches at De Bilt on 1 July 2002. During this verification period, Vaisala RS90-AL radiosondes were launched four times a day and data from 22 610 radar scans were collected. The radiosonde profiles are binned into 200-m-thick height layers in order to facilitate comparison with the Doppler radar wind profiles.

HIRLAM, which is being developed by a consortium of eight European countries (Unden et al. 2002), is run operationally at KNMI. The model analyzes the state of the atmosphere eight times a day, and it makes 48-h forecasts four times a day. During the verification period the hydrostatic HIRLAM model used 31 vertical levels and it had a horizontal resolution of 55 km (22 km from 5 March 2002). Profiles have been extracted from the model's initialized analyses at the grid point nearest to De Bilt (distance 11 km) and they were interpolated to 200-m-thick height layers.

4. Results

a. Comparison of retrieval algorithms

The Doppler radar wind profiles at De Bilt have been verified against the profiles from the collocated radiosonde station. In the upper frame of Fig. 1 the rms vector differences are plotted as a function of the availability fraction for three wind profile retrieval methods (VAD1, VVP1, and VVP3). The availability fraction of the retrieved wind vectors is varied by changing the standard deviation threshold (lower frame of the figure). Increasing this threshold from 0 to 6 m s^{-1}, the availability fractions and rms vector differences increase from 0 to 0.29 and from 1.5 to 4.5 m s^{-1}. The availability fractions are averaged over all altitudes, that is, between 0 and 6 km. Andersson (1998) has performed a verification of VAD wind profiles from C-band Ericsson Doppler radars against radiosonde profiles from a station at a 10-km distance and he found rms vector differences between 3.5 and 4.0 m s^{-1}.

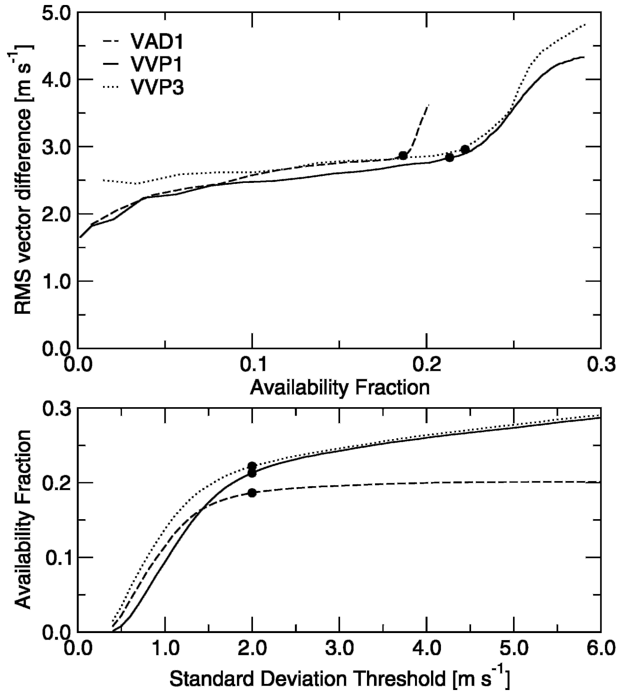

FIG. 1. Rms vector differences between radar and radiosonde wind vectors as a function of the availability fraction of the radar wind vectors are shown in the upper frame. The lower frame shows the availability fraction as a function of the applied standard deviation threshold. Curves for two implemented volume velocity processing (VVP1 and VVP3) methods and one implemented velocity–azimuth display (VAD1) method are shown. The filled circles mark the points corresponding to a standard deviation threshold of 2.0 m s^{-1}.

Figure 1 shows two important aspects of the wind profile retrieval methods: quality and availability. Retrieval methods that combine high quality (low rms vector differences) with high availability are preferred. It is evident from the figure that the VVP1 retrieval method performs better than the VAD1 and VVP3 methods. The VVP1 retrieval method also performs better than the VAD2 and VVP2 retrieval methods (not shown). The difference between VAD1 and VVP1 is mainly due to the higher availability of the VVP wind data for standard deviation thresholds above 1.5 m s^{-1} (see the lower frame of Fig. 1). During a VAD retrieval all azimuthal circles are quality controlled individually, while during a VVP retrieval all velocity data within a height layer are quality controlled collectively. Therefore, a sector gap and thus a rejection from further processing is more likely during a VAD retrieval. For standard deviation thresholds below 1.5 m s^{-1}, the availability is higher for VAD1 than for VVP1, which is caused by the larger number of fit parameters, that is, three parameters for each individual VAD circle. The verification results also show that the VVP retrieval based on the most simple wind model provides the best horizontal wind data. This result may seem counterintuitive, but it is most likely due to the nonorthogonality of the VVP basis functions. The addition of the higher-order basis functions with (small) linear dependencies can degenerate the robustness of the regression method and cause fluctuations of the retrieved wind field parameters (Boccippio 1995).

The actual choice for the standard deviation threshold has to balance the quality of the wind vectors with their availability and it depends on the application. The shape of the rms vector differences versus the availability fraction curves naturally suggest a threshold just before the bending point, where for VVP1 the rms vector differences is 2.8 m s^{-1}, the availability fraction is 0.21, and the applied standard deviation threshold is 2.0 m s^{-1}. This threshold has been used for all retrieval methods in the remainder of this article, but, in fact, the optimum threshold depends on the application, for example, nowcasting or assimilation into a NWP model. The standard deviation information should, therefore, be provided with the retrieved wind profiles allowing the user to choose the threshold. The filled circles in Fig. 1 mark the points corresponding to a standard deviation threshold of 2.0 m s^{-1} for all methods.

b. Availability of wind profiles

Using a standard deviation threshold of 2.0 m s^{-1} histograms of the wind speeds observed by Doppler radar using the VVP1 retrieval method have been constructed. The constructed histograms for the 0–2-, 2–4-, and 4–6-km height ranges are shown in Fig. 2. The vertical axis represents the wind vector count per 1 m s^{-1} wide bin using all available radar wind profiles between 1 October 2001 and 30 June 2002. It is evident that the total number of available wind vectors and the mean wind speed decrease and increase, respectively, with increasing height. The vertical dashed line marks the maximum unambiguous velocity of the Doppler scans. It is remarkable that for the upper height range a significant number of wind vectors with speeds above the unambiguous velocity are observed. This is also observed for the VAD1 retrieval method (not shown). For these high wind speeds the observed VAD curves will be distorted: radial velocities greater than the unambiguous velocity will be aliased and shifted by 80 m s^{-1}. Apparently the wind profile retrieval methods are capable of dealing with these outliers.

In Fig. 3 the availability fraction wind vectors is plotted as a function of height for the VAD1 and VVP1 retrieval methods. All available wind profiles (9 months of data) and a standard deviation threshold of 2.0 m s^{-1} have been used to calculate these fractions. It is evident that the availability of wind data using the VVP1 retrieval method is higher for all altitudes. The VVP1 availability fraction decreases from 0.39 for the lowest bin to 0.16 for the highest bin. In the boundary layer the

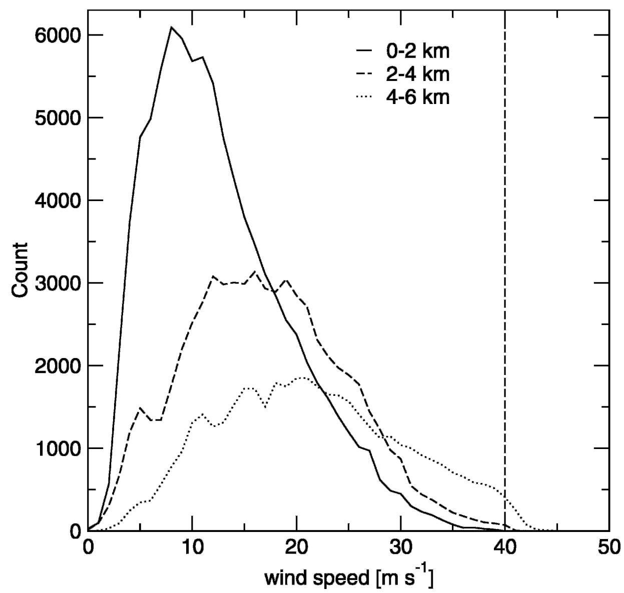

FIG. 2. Histograms of the observed VVP1 wind speeds for three different height layers using a standard deviation threshold of 2.0 m s^{-1}. The vertical dashed line marks the maximum unambiguous velocity.

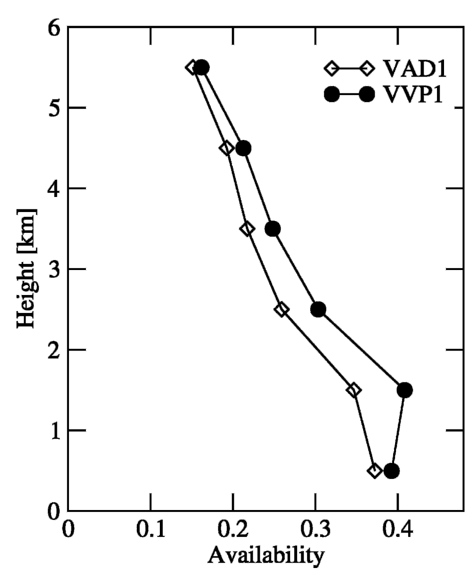

FIG. 3. Availability fraction of wind vector data as a function of height for the VAD1 and VVP1 methods, compiled using 9 months of data and a standard deviation threshold of 2.0 m s^{-1}.

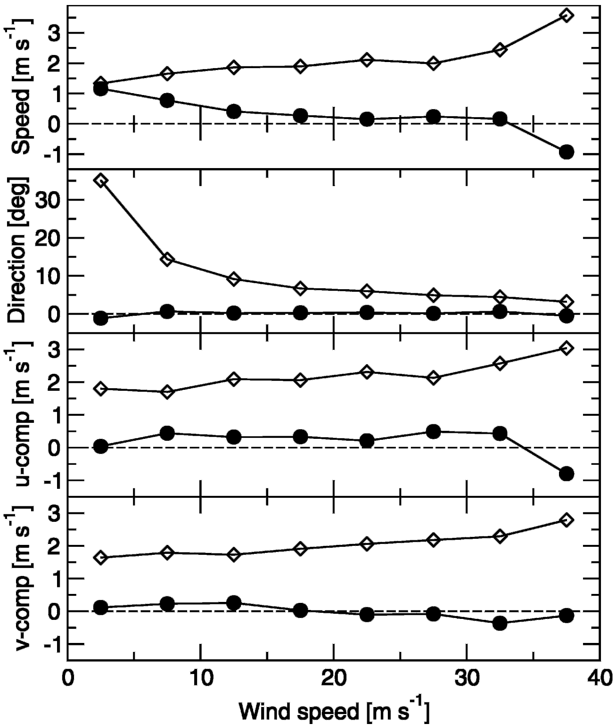

FIG. 4. Bias (●) and standard deviations (◇) of the wind speed, wind direction, u component, and v component as a function of wind speed. These data have been obtained from the verification of VVP1 profiles between 0- and 6-km altitude against those from the radiosonde.

radar radiation is scattered by precipitation, refractive-index gradients, insects, and birds (Wilson et al. 1994), and above the boundary layer the radiation will be scattered primarily by precipitation. The observed availability at low altitudes (0–2 km) is considerably lower than the 0.83 and 0.64 at 925 and 850 hPa, respectively, as reported by Andersson (1998). His rms vector differences are also considerably higher, suggesting that a different balance between availability and quality was chosen.

c. Verification as a function of speed

The results of an analysis of the VVP1 wind profile data as a function of wind speed are presented in Fig. 4. All retrieved wind vectors between 0- and 6-km altitude have been used to construct this figure. The two upper frames display the bias and standard deviation of the wind speed and direction with respect to the radiosonde data. The wind speed bias is generally smaller than 0.5 m s^{-1} and is positive, that is, the VVP1 wind speeds are slightly higher than those of the radiosonde. The relatively large positive bias for wind speeds lower than 10 m s^{-1} is due to the rejection of radial velocities close to zero (see section 2c). For wind speeds higher than 35 m s^{-1}, the observed negative bias is probably caused by the maximum unambiguous velocity of 40 m s^{-1}. The bias of the wind direction is less than 1° and thus is negligible. For the standard deviation of the wind direction a strong dependence on the wind speed is observed. This standard deviation drops from a rather high value of about 35° at low wind speeds to a value of only 3° at high wind speeds. The wind direction is determined from the ratio of the horizontal wind field components, and this ratio naturally has a large standard deviation for low wind speeds.

The bias and standard deviation of the Cartesian u and v components of the retrieved wind vectors with respect to the radiosonde data are shown in the two lower frames of Fig. 4. The observed biases of the Cartesian components are generally close to zero (<0.5 m s^{-1}), and only the u component is systematically underestimated for wind speeds close to the maximum unambiguous velocity. The preferred westerly flow in the Netherlands is the cause for the observed underestimation of the u component at high wind speeds. The standard deviation of the Cartesian components gradually increases from 1.5 m s^{-1} at low wind speeds to 3 m s^{-1} at high wind speeds.

According to the WMO (1996) *Guide to Meteorological Instruments and Methods of Observation*, the required accuracy of upper-air wind speed measurements is 1 m s^{-1} and that of upper-air wind direction measurements is 5° and 2.5° for wind speeds below and above 1.5 m s^{-1}, respectively. This confirms that the observed biases of the VVP1 and VAD1 (not shown) wind speed and direction against radiosonde data are within acceptable limits; that is, they satisfy the WMO accuracy requirements. The observed standard deviation of the wind speed and direction do not meet the WMO accuracy requirements but, apart from the (in) accuracy of the radar observations, errors of the radiosonde measurements and sampling differences also contribute to the observed standard deviation.

d. Verification as a function of height

Figure 5 shows the bias and standard deviation of the wind speed and direction for the VAD1 (upper frames) and VVP1 (lower frames) retrieval methods as a function of height. These quality measures have been obtained from verification against the radiosonde profiles. Because the mean wind speed increases with height, these verification results are correlated to those in Fig. 4 and similar features can, indeed, be seen. For both retrieval methods, the wind speed bias is slightly positive (<0.5 m s^{-1}) at all heights. The standard deviation of the wind speed slowly increases from 1.5 m s^{-1} at low

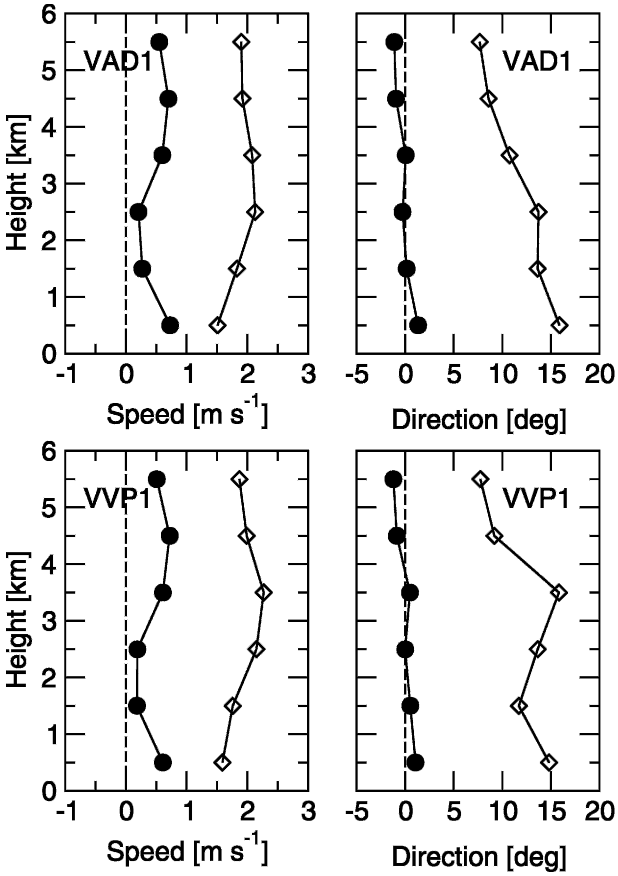

FIG. 5. Profiles of the bias (●) and standard deviation (◇) of the wind speed and direction from the verification of the (top) VAD1 and (bottom) VVP1 wind data against radiosonde.

altitude to about 2.0 m s^{-1} at the highest altitude. The wind direction bias for both retrieval methods is small (<1.3°) at all heights, but a remarkable sign change is seen between 3- and 4-km altitude. This sign change is not observed in the wind direction bias as a function of wind speed, and it therefore must originate from a height effect. The decrease of the standard deviation of the wind direction with increasing height is similar to that with increasing wind speed.

The resemblance of the wind speed verification results as a function of height for the VAD1 and VVP1 retrieval methods (Fig. 5) is striking. This indicates that the quality of the wind speed data from both retrieval methods is similar. At low and high altitudes the verification results for the wind direction are also very similar, but around 3-km altitude a clear increase in the standard deviation of the wind direction is seen for the VVP1 method only. A further investigation of the wind vector data from both profile retrieval methods did, unfortunately, not result in a clear understanding of the cause of this difference.

The observation minus background statistics for the VVP1 (upper frames) and radiosonde (lower frames) wind profiles against the HIRLAM NWP model (Unden et al. 2002) are shown in Fig. 6. The figure shows the bias and standard deviation of the Cartesian u and v components of the wind vectors calculated for the 9-month verification period. In this comparison the radiosonde has a clear advantage over the weather radar because the radiosonde profiles are assimilated by HIRLAM. It is therefore not a surprise that the observed biases of the wind vector components from the radiosonde are only a few tenths of a meter per second and thus negligible. The standard deviation of the radiosonde wind vector components against the HIRLAM background is between 1.5 and 2.0 m s^{-1} at ground level and gradually increases to almost 3.0 m s^{-1} aloft. This increase is probably due to the increase of the wind speeds with height and to the drifting of the radiosonde. For the VVP1 wind data, a small positive bias (maximum 0.5 m s^{-1}) for both Cartesian components is found again, which already has been dis-

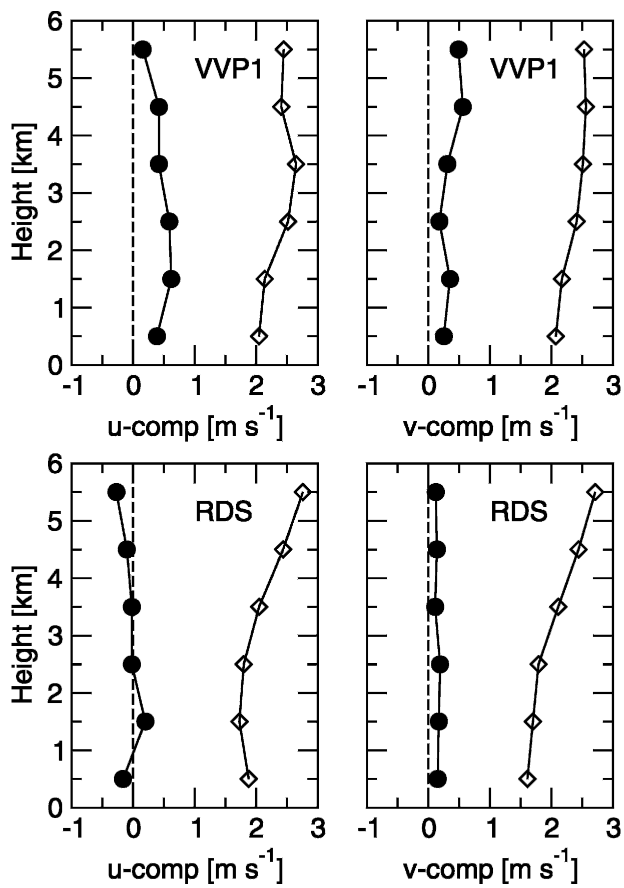

FIG. 6. Profiles of the bias (●) and standard deviation (◇) of the Cartesian u and v components from the verification of the (top) VVP1 and (bottom) radiosonde wind data against HIRLAM.

cussed in section 4c. The standard deviation of the VVP1 wind vector components against the HIRLAM background is around 2.0 m s^{-1} at ground level and about 2.5 m s^{-1} aloft. Figure 6 shows that observation minus background statistics of the VVP1 wind profiles are at least as good as those of the radiosonde profiles. Taking into account the advantage of the radiosonde data because of the assimilation, this result evidently demonstrates the high quality of the weather radar wind profiles.

e. Removal of elevations

For the development of operational scanning strategies it is important to know whether data from all 10 elevations are really needed to obtain wind profiles of sufficient quality. The weather radar wind profiles at De Bilt have been recalculated from the volume scan data using the VAD1 and VVP1 retrieval methods, but data from selected elevations have been removed. The availability fractions and rms vector differences with respect to radiosonde profiles are shown as a function of height in Fig. 7 for three scenarios labeled "10 elev," "9 elev," and "5 elev." The first scenario, 10 elev, with all elevations is plotted for reference purposes only. In the second scenario data from the lowest elevation (0.5°) have not been used, and in the third scenario data from all odd-numbered elevations (0.5°, 3.5°, . . .) have not been used.

Figure 7 shows that the removal of the lowest elevation from the scan data improves the quality of the VAD1 and VVP1 wind vectors below 2- and 4-km altitude, respectively, and that it slightly reduces the availability below 1 km. This finding supports the idea that the quality of radial velocity data from low elevations is of poor quality at short ranges due to, for example, contamination with sidelobe clutter. In the third scenario the number of elevations, and thus the scanning time, has been reduced by a factor of 2. It is evident from the figure that the drastic reduction of the scanning time has only a minor impact on the quality of the VAD1 wind vectors and the availability of the VVP1 wind vectors. These results show that the radar wind profiles could be provided more frequently without a significant loss of performance.

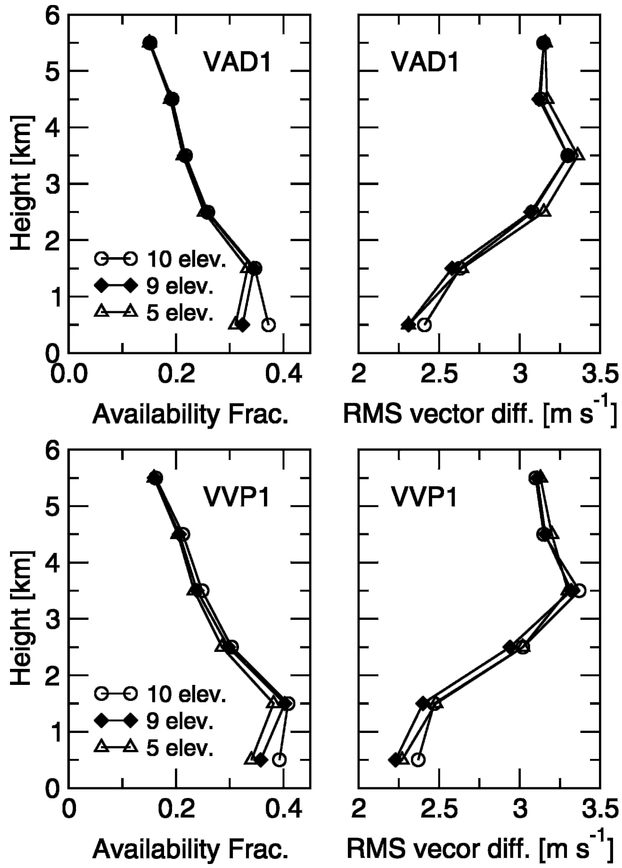

FIG. 7. The effect of a reduction of the number of elevations on the (left) availability and (right) quality of the (top) VAD1 and (bottom) VVP1 wind profiles. The wind profiles have been verified against the radiosonde profiles.

5. Conclusions

The intercomparison of different implementations of the VAD and VVP wind profile retrieval methods, using radiosonde profiles as a reference, revealed that the VVP methods perform better than the VAD methods. In contrast to a VVP retrieval, where all available scan data within range is quality controlled at once, all velocity–azimuth circles are quality controlled individually during a VAD retrieval, and this results in a higher rejection rate. Furthermore, it was found that the simplest implementation of the VVP retrieval method provides the best horizontal wind data. Owing to the nonorthogonality of the basis functions, addition of higher-order functions with (small) linear dependencies may cause fluctuations of the retrieved parameters.

An availability fraction of VVP1 wind vectors of about 0.39 is found in the lowest 1 km of the troposphere, and this availability drops below 0.16 at 6-km altitude. Verification as a function of wind speed of the VAD1 and VVP1 wind vectors against radiosonde data indicated that the biases of the retrieved wind speeds satisfy the WMO accuracy requirements for upper-air wind measurements. Experiments with selective removal of elevations from volume scan data revealed that a drastic reduction of the scanning time has hardly any impact on the performance of the retrieved VAD and VVP wind vectors.

A comparison of the observation minus background statistics for the VVP1 and radiosonde wind profiles against the HIRLAM NWP model has been performed. The observed biases of the wind vector components are negligible for the radiosonde data and are slightly positive (<0.5 m s^{-1}) for the VVP1 data. The observed standard deviation of the radiosonde and VVP1 wind vector components is comparable at ground level and it is slightly lower for the VVP1 data at higher altitudes. Thus, the observation minus background statistics of the VVP1 wind profiles are at least as good as those of the radiosonde profiles. This result demonstrates the high quality of (quality controlled) weather radar wind profiles.

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