Impact of Observation Operators on Low-Level Wind Speed Retrieved by Variational Multiple-Doppler Analysis

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Abstract

This study investigated the impact of observation operators on low-level wind speed analysis. An evaluation of wind speeds retrieved by variational multiple-Doppler analyses using radial velocities (Vr) based on the formats of both a Plan Position Indicator (PPI) (hereafter, PPI-V AR) and a Constant Altitude Plan Position Indicator (CAPPI) (hereafter, CAPPI-V AR) was performed for comparison with wind speeds observed by a wind profiler during the warm season of three consecutive years. The statistical analysis showed that PPI-V AR was more accurate than CAPPI-V AR at 500 m above ground level (AGL). The error of CAPPI-V AR at 500 m AGL was caused by a representative error of CAPPI-formatted Vr, derived from a certain radar whose beam height was far from the analysis level, and this error became more obvious the greater the vertical difference in wind speed across the analysis level. CAPPI-V AR uses CAPPI-formatted Vr from each radar equally; thus, the representative error might cause performance degradation of CAPPI-V AR at 500 m AGL. Conversely, PPI-V AR uses PPI-formatted Vr from each radar with appropriate weighting based on the beam height distance from the analysis level. PPI-V AR showed better results at 500 m AGL because the observation grid points were dense around 500 m AGL. Therefore, PPI-V AR can provide a wind field that has spatial continuity, which might provide a better solution. The spatial continuity of CAPPI-V AR is also suitable for traditional multiple-Doppler wind analysis that explicitly integrates the continuity equation vertically and therefore, traditional multiple-Doppler wind analyses commonly use CAPPI-V AR (e.g., Ray et al. 1980; Sun and Crook 1997, 1998). However, the process of derivation of CAPPI-V AR includes a spatial interpolation procedure, and errors associated with this procedure could affect CAPPI-V AR accuracy. This study focused on the region near the atmospheric boundary layer where the observation grid points of PPI-V AR are rather dense and thus, PPI-V AR should be capable of retrieving accurate low-level wind speeds. Therefore, it is important to comprehend the quantitative difference between PPI-V AR and CAPPI-V AR in the lower-level atmosphere.

The purpose of this work is to investigate the quantitative analysis error of low-level wind speeds retrieved by PPI-V AR and CAPPI-V AR (hereafter, WSPPI-V AR and WCAPPI-V AR, respectively). PPI-V AR is obtained from three Doppler radars was used for the low-level wind speed analyses. For the evaluation of error, horizontal wind speed observations were obtained from a wind profiler (hereafter, WPR) located close to the three radars. In order to conduct a robust evaluation, the statistical analysis was based on data from the warm seasons of three consecutive years.

2. Data and methods

WSPPI-V AR and WCAPPI-V AR were analyzed for precipitation systems that passed over WPR (see Fig. 1 for its location) at Nagoya in Japan during the warm seasons (April–September) of three consecutive years (2011–2013). WPR was installed by the Japan Meteorological Agency. There were three X-band multi-parameter (MP) radars operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) located around the WPR and their respective locations (Anjo, Bisai, and Suzuka) and observational ranges are presented in Fig. 1. The data resolution of MLIT X-band MP radar was 150 m for range and 1.2° for azimuth, and the observational range was 80 km (Maesaka et al. 2011). The number of elevation angles for a single volume scan was 12 (1.0, 1.6, 2.7, 3.8, 5.1, 6.5, 8.1, 10.0, 12.0, 14.3, 17.0, and 20.0°), and it took 5 min to make one volume scan. The time interval of WPR observation was 10 min (details of WPR observations are described below) and thus, CAPPI-V AR can provide a wind field that has spatial continuity, which might provide a better solution. Therefore, PPI-V AR can avoid errors due to interpolation from the radar coordinate grid point to the analysis coordinate grid point, which should be larger than when interpolation is done in reverse (Gao et al. 1995). Variational multiple-Doppler wind analysis using radial velocity based on the PPI format (hereafter, PPI-V AR) has been used by Shimizu et al. (2008) and Potvin et al. (2012a, b, c). Gao et al. (1999) mentioned that one advantage of PPI-V AR is that it is a single-step method that combines interpolation and analysis. The analysis is performed directly in a Cartesian coordinate system; only interpolation from the Cartesian (analysis) coordinate grid point to the polar (radar) coordinate grid point is needed. Therefore, PPI-V AR can avoid errors due to interpolation from the radar coordinate grid point to the analysis coordinate grid point, which should be larger than when interpolation is done in reverse (Gao et al. 1995). Variational multiple-Doppler wind analysis using radial velocity based on the CAPPI format (hereafter, CAPPI-V AR) has been used by Shimizu et al. (2008) and Kim et al. (2012). One of the advantages of CAPPI-V AR is the spatial continuity of the analysis. The CAPPI-formatted radial velocity (CAPPI-V) is produced by a Cressman-type interpolation (Cressman 1959) of PPI-formatted radial velocity (PPI-V). Therefore, CAPPI-V AR can provide a wind field that has spatial continuity, which might provide a better solution. The spatial continuity of CAPPI-V AR is also suitable for traditional multiple-Doppler wind analysis that explicitly integrates the continuity equation vertically and therefore, traditional multiple-Doppler wind analyses commonly use CAPPI-V AR (e.g., Ray et al. 1980; Sun and Crook 1997, 1998). However, the process of derivation of CAPPI-V AR includes a spatial interpolation procedure, and errors associated with this procedure could affect CAPPI-V AR accuracy. This study focused on the region near the atmospheric boundary layer where the observation grid points of PPI-V AR are rather dense and thus, PPI-V AR should be capable of retrieving accurate low-level wind speeds. Therefore, it is important to comprehend the quantitative difference between PPI-V AR and CAPPI-V AR in the lower-level atmosphere.

The purpose of this work is to investigate the quantitative analysis error of low-level wind speeds retrieved by PPI-V AR and CAPPI-V AR (hereafter, WSPPI-V AR and WCAPPI-V AR, respectively). PPI-V AR is obtained from three Doppler radars was used for the low-level wind speed analyses. For the evaluation of error, horizontal wind speed observations were obtained from a wind profiler (hereafter, WPR) located close to the three radars. In order to conduct a robust evaluation, the statistical analysis was based on data from the warm seasons of three consecutive years.
grid point values (for CAPPI-V AR, the observation grid point value corresponded to the analysis grid point value).

The analysis grid spacing for PPI-V AR and CAPPI-V AR was 1 km in the horizontal and 500 m in the vertical and the analysis time interval was 5 min; both identical to CAPPI-V. The same volume scan was used for both PPI-V AR and CAPPI-V AR. Because of the limitation of analysis accuracy, the region where the intersection angle between each radar was < 20° was not used for the analysis. It is noted that PPI-V AR at 500 m above ground level (AGL) only used PPI-V, between 500 and 1000 m AGL because of the limitation of the bilinear interpolation operator.

The horizontal wind speed observed by WPR (hereafter, WS_{WPR}) was used for the evaluation. A detailed description of WPR can be found in Kato et al. (2003). The observation time interval was 10 min and the vertical observation spacing was about 300 m (the lowest observation level is 450 m AGL). Because the horizontal coverage of WPR was increased in the vertical direction (about 1 km at 3000 m AGL), the evaluation was performed for heights below 3000 m AGL. WS_{WPR} was interpolated linearly at 500-m intervals after ensuring its accuracy. WS_{WPR} was averaged over 10 min; thus, WS_{PPI-V AR} and WS_{CAPPI-V AR} were also averaged over the same period. To evaluate the wind speed error quantitatively, the root mean square error (RMSE), relative RMSE (RRMSE; RMSE as a percentage of root mean square WS_{WPR}), mean bias error (MBE), and relative MBE (RMBE; MBE as a percentage of mean WS_{WPR}) were calculated between the analysis and observed wind speed. These values were averaged at each level for the three warm seasons.

3. Results and discussions

Vertical profiles of the RMSE and RRMSE of WS_{PPI-V AR} and WS_{CAPPI-V AR} from the warm seasons of three years (2011−2013) are presented in Fig. 2. Vertical profiles of the MBE and RMBE of WS_{PPI-V AR} and WS_{CAPPI-V AR} for the same period are shown in Fig. 3. The vertical profile of the mean WS_{WPR} is also shown in Figs. 2 and 3. A sample size of at least 4400 (about 30 days) was used for calculating the averaged error value; the sample size was varied according to the altitude and method used. Figure 2 shows that at 500 m AGL, the RMSE and RRMSE of WS_{PPI-V AR} (1.6 m s$^{-1}$ and 24%, respectively) are smaller than those of WS_{CAPPI-V AR} (2.0 m s$^{-1}$ and 29%, respectively). The mean WS_{WPR} at 500 m AGL was smaller than that above 500 m AGL (see Figs. 2 and 3) and therefore, the RMSE of wind speed at 500 m AGL was relatively larger than that above 500 m AGL. Figure 3 shows that the MBE and RMBE of WS_{PPI-V AR} and WS_{CAPPI-V AR} at 500 m AGL are both
positive values, and that WS\textsubscript{CAPPI-VAR} is overestimated considerably with respect to WS\textsubscript{WPR}. At 1000 m AGL, the RMSE and RRMSE of WS\textsubscript{PPI-VAR} were comparable with those of WS\textsubscript{CAPPI-VAR}, whereas above 1000 m AGL, the RMSE and RRMSE of WS\textsubscript{PPI-VAR} were larger than the RMSE and RRMSE of WS\textsubscript{CAPPI-VAR}. At 3000 m AGL, however, the RMSE and RRMSE of WS\textsubscript{PPI-VAR} were once again seen to be comparable with those of WS\textsubscript{CAPPI-VAR}. The MBEs of WS\textsubscript{PPI-VAR} were relatively small above 1000 m AGL, while the MBEs of WS\textsubscript{CAPPI-VAR} were considerably positive and negative at 2000 and 2500 m AGL, respectively.

Because surface wind damage is frequently caused by microbursts and tornadoes, whose wind speeds attain maximum values at around 200 m AGL and decrease with altitude (Wilson et al. 1984; Wurman and Kosiba 2013), it is important to monitor the wind field at altitudes that are as low as possible. Therefore, the error factors of WS\textsubscript{PPI-VAR} and WS\textsubscript{CAPPI-VAR} at the lowest level (500 m AGL) are discussed in detail. To understand which observation grid points had the greatest effect on the analysis accuracy at 500 m AGL, the distribution of observation grid points around WPR was investigated. Figure 4a shows the observation grid points of PPI-V\textsubscript{r} from each radar around a 2 \times 2 km horizontal square centered on WPR, projected to a west–east cross section. Figure 4b shows the relative vertical distance from an analysis grid point to the centroid of the observation grid points inside the influence ellipsoid of CAPPI-V\textsubscript{r} for each radar (hereafter, RVD). The lowest observation grid point of Anjo, Bisai, and Suzuka was located at around 500, 500, and 800 m AGL, respectively (Fig. 4a); thus, at 500 m AGL, RVD of Anjo and Bisai was small (0.11 and 0.17 km, respectively), while that of Suzuka was relatively large (0.34 km). Figure 4c shows the mean vertical distance between an analysis grid point and observation grid points inside the analysis grid of PPI-V\textsubscript{VAR} from all radars (hereafter, MVD). MVD was small (0.19 km) at 500 m AGL and the observation grid points were dense in the vicinity of 500 m AGL (Fig. 4a).

The relationship between the error factor of WS\textsubscript{CAPPI-VAR} and the distribution of observation grid points at 500 m AGL mentioned above is discussed. CAPPI-V\textsubscript{r} was produced by a Cressman-type interpolation of PPI-V\textsubscript{r}. In general, the centroid of observation grid points inside the influence ellipsoid represents CAPPI-V\textsubscript{r} at the analysis grid point. The error of CAPPI-V, tends

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**Fig. 4.** (a) Observation grid points of PPI-V\textsubscript{r} from each radar around a 2 \times 2 km horizontal square centered on the wind profiler (WPR), projected to a west–east cross section. Red squares, green circles, and blue triangles denote the observation grid points from Anjo, Bisai, and Suzuka, respectively. Black asterisks and gray rhombuses indicate the observation grid points of WPR and the analysis grid points of PPI-V\textsubscript{VAR} and CAPPI-V\textsubscript{VAR}, respectively. (b) Mean relative vertical distance from an analysis grid point to centroid of observation grid points inside the influence ellipsoid of CAPPI-V\textsubscript{r} for each radar (red squares: Anjo, green circles: Bisai, blue triangles: Suzuka). (c) Mean vertical distance between an analysis grid point and observation grid points inside the analysis grid of PPI-V\textsubscript{VAR} from all radars.
to be larger when RVD becomes large, i.e., when the observation grid points are distributed unevenly and are far from the analysis grid point inside the influence ellipsoid. This error is the so-called representative error and it is likely to appear when PPI-V, inside the influence ellipsoid is not uniform. Actually, when RVD of Suzuki at 500 m AGL was large and there was a difference in the mean WS in two VAs (2.7 m s\(^{-1}\), the error of WS\(_{\text{CAPPI-V AR}}\) at 500 m AGL was large. This result suggested that the representative error of CAPPI-V, from Suzuki at 500 m AGL was probably large. CAPPI-V AR used CAPPI-V, from each of the three radars equally; thus, CAPPI-V, from Suzuki might have caused the performance degradation of CAPPI-V AR at 500 m AGL.

The relationship between the error factor of WS\(_{\text{PPI-V AR}}\) and the distribution of observation grid points at 500 m AGL is discussed. Unlike CAPPI-V AR, PPI-V AR used PPI-V inside the analysis grid from all radars, simultaneously. The small MVD at 500 m AGL, as shown in Fig. 4c, indicates that observation grid points were dense in the vicinity of 500 m AGL. Specifically, the numbers of observation grid points from Anjo and Bisai in the vicinity of 500 m AGL were larger than from Suzuki and Bisai around 800 m AGL (Fig. 4a). Therefore, PPI-V AR was much affected from PPI-V in the vicinity of 500 m AGL rather than around 800 m AGL. For PPI-V AR, the contamination of the representative error caused by PPI-V around 800 m AGL could be reduced; therefore, the accuracy of WS\(_{\text{PPI-V AR}}\) was better than that of WS\(_{\text{CAPPI-V AR}}\).

To verify the above discussions can be identified in actuality, two cases were investigated in detail (the detailed results are described in the supplementary materials). One case involved a large difference in wind speed at 500–1000 m AGL (hereafter, LD case) and the other involved a small difference in wind speed at 500–1000 m AGL (hereafter, SD case). In the LD case, the error of WS\(_{\text{CAPPI-V AR}}\) at 500 m AGL was larger than that of the warm season of three years. In the SD case, the errors of WS\(_{\text{PPI-V AR}}\) and WS\(_{\text{CAPPI-V AR}}\) at 500 m AGL were small and similar to the error of WS\(_{\text{PPI-V AR}}\) at 500 m AGL of the warm seasons of the three years. These results suggested that the error of WS\(_{\text{CAPPI-V AR}}\) at 500 m AGL became larger for greater differences in wind speed at 500–1000 m AGL.

From the above discussions considering wind retrieval at 500 m AGL, PPI-V AR should be more accurate than CAPPI-V AR when the representative error of CAPPI-V, from a certain radar is large. This error becomes large when values of PPI-V, from a certain radar inside the influence ellipsoid are distributed unevenly and are far from the analysis level, and when greater vertical differences in wind speed exist across the analysis level. The error factor above 1000 m AGL could be explained by the similar error factor at 500 m AGL; hence, this subject will be discussed in future work.

4. Summary

To investigate the impact of observation operators on the analysis of low-level wind speed, an evaluation of wind speeds retrieved by variational multiple-Doppler analyses using radial velocities based on the formats of both a Plan Position Indicator (PPI-V AR) and a Constant Altitude Plan Position Indicator (CAPPI-V AR) was performed with wind speeds observed by a wind profiler during the warm seasons of three consecutive years. The statistical analysis showed that PPI-V AR was more accurate than CAPPI-V AR at 500 m AGL, where the observation grid points were dense, and the RMSE of WS\(_{\text{PPI-V AR}}\) and WS\(_{\text{CAPPI-V AR}}\) at this level were 1.6 and 2.0 m s\(^{-1}\), respectively.

One of the error factors of WS\(_{\text{CAPPI-V AR}}\) at 500 m AGL was the representative error of CAPPI-V. Although the analysis grid point at 500 m AGL, for the evaluation in this study, was not far from each radar, the centroid of the observation grid points inside the influence ellipsoid of CAPPI-V, for one radar was far from the analysis grid point. Therefore, CAPPI-V, at 500 m AGL from one radar could have been affected by the representative error through the interpolation procedure. This error became more obvious the greater the vertical difference in wind speed across the analysis level. CAPPI-V AR used CAPPI-V, from each of the three radars equally; hence, CAPPI-V, from one radar might have caused the performance degradation of CAPPI-V AR at 500 m AGL. Conversely, PPI-V AR used PPI-V inside the analysis grid from all VAs, simultaneously. Observation grid points were dense in the vicinity of 500 m AGL; thus, PPI-V AR was much affected by PPI-V, in the vicinity of 500 m AGL rather than from the analysis grid point. In PPI-V AR, the contamination of the representative error caused by PPI-V, far from 500 m AGL might be reduced; therefore, the accuracy of WS\(_{\text{PPI-V AR}}\) was better than that of WS\(_{\text{CAPPI-V AR}}\). To reduce the analysis error caused by the representative error, radar volume scans with a large number of elevation angles from at least two radars is required. In the near future, if radar volume scans with suitably large numbers of elevation angles could be achieved using phased-array Doppler radar, it is expected that wind speeds could be obtained more accurately at any level.

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