1. Introduction

Wind shear in a localized region usually causes serious damage on transport systems. Real-time observation of wind field with dual polarimetric Doppler weather radars gives us the most effective solution for preventing the damage caused by wind. Fig 1 shows weather map on Japan on April 7, 2016. Low pressure came from west and severe weather hit Osaka-Bay area. Three Doppler radars have been deployed and observed rain distribution at 10:00 a.m. is shown in Fig 2. Three radars are installed at KOB (Kobe University), KIU (Kobe International University), and INT (FURUNO INT center). A case study for estimation of 3D wind field using the triple-Doppler analysis is presented here.

2. Triple-Doppler Analysis

By deploying the three radars within 10 km range, 3D wind field is directly estimated by the triple-Doppler analysis as shown in Fig 3. And Fig 4 shows the VAD analysis using each radar. VAD analysis is useful to get reference wind field to compare with triple-Doppler analysis. Fig 5 shows estimation of horizontal wind field. The wind field around the Osaka Bay is observed in real time using the Multi-Radar System. Radar strategy is presented in Table 1.

3. Comparison of wind field

Fig 6 shows a comparison of wind velocity between triple-Doppler analysis and VAD analysis. This result shows that VAD analysis and triple-Doppler analysis are precise and reliable among three radars. RMSE is 1.2 m/s and correlation coefficient is 0.96. Although VAD method can only analyze average wind field with liner approximation, triple-Doppler method can directly analyze 3D distribution of wind field.

Fig 7 shows a comparison of horizontal wind direction. A typical wind shear is observed in the altitude between 2500 m and 3000 m. RMSE is 1.2 deg and correlation coefficient is 0.99.

Fig 8 shows a comparison of vertical raindrop speed. In the altitude lower than 3000 m the vertical speed is fast due to liquid particle. On the other hand, in the altitude higher than 4000 m the vertical speed is slow due to ice particle. The altitude between 3000 m and 4000 m is the melting layer and the speed is changing drastically. This result shows that melting layer is observed with triple-Doppler classification.

4. Variational Method

The variational method in this paper is based on Shimizu and Maesaka (2006). The variational analysis is a procedure that minimizes a cost function \( f \) defined here to be the sum of squared errors due to misfit between observations and analyses subject to constraints. As shown in Equation (1), \( f \) is expressed as the sum of equations (2) to (3). Here \( J_{1,0} \) is the difference between the analyzed three dimensional velocity \((u, v, w)\) and the observed radial velocity \( V_{r_m} \). The cost function \( J_{1,0} \) imposes mass conservation constraint on the analyzed wind field. The cost function \( J_{2,0} \) is a function of \((u, v, w)\) at all calculation points, and the three-dimensional wind velocity field is estimated by finding the combination of \((u, v, w)\) that minimizes the cost function \( J \). A steepest descent method was used for the minimization.

\[
J = J_{1,0} + J_{2,0} \tag{1}
\]

\[
J_{1,0} = \sum_{i} \sum_{j} \lambda_{i,0} (V_{r_m} - u \cos \alpha + v \cos \beta + w \cos \gamma)^2 \tag{2}
\]

\[
J_{2,0} = \sum_{i} \sum_{j} \lambda_{i,0} b_{i,j} D^2 \tag{3}
\]

\[
D = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \tag{4}
\]

\[
V_{r_m} : \text{the observed radial velocity}
\]

\[
\alpha, \beta, \gamma : \text{Direction cosine from radar position}
\]

\[
\rho : \text{the mean air density}
\]

\[
\lambda_{i,0}, \lambda_{0,0} : \text{Commonly referred to as penalty constants}
\]

5. Idealized Data

We used idealized data on the wind velocity field \((u=10[m/s], v=10[m/s], w=0[m/s])\) satisfying the continuous equation with vorticity \((0.1[s])\) at the center of each layer. The horizontal grid spacing is 200m and vertical grid spacing is 100m.

The observation noise is given by Eq.(5).

\[
V''_{r_m} = V_{r_m} (1 + \varepsilon) \quad \varepsilon : \text{noise} \tag{5}
\]

We investigated the relationship between the number of the radars and percentage of noise in observation value.

The number of observation points is 75000 (50000) when using three (two) radars.

We focus on vertical vorticity defined by Eq.(6).

\[
\text{Vertical vorticity} = \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \tag{6}
\]
6. Result and Discussion

**Fig 9** shows estimation accuracy based on the number of radars and observation noise (Left), and estimation accuracy when the noise is 1 m/s and observation velocity (Right). The RMSE with three radars is lower than that with two radars when the noise is less than 100% of the observation wind velocity. On the other hand, when the noise exceeds 100%, the RMSE with two radars is lower than that with three radars.

Since the actual observation noise is assumed to be around 1 m/s (Ishihara 2001), it is found that estimating accuracy improves by using three radars when the wind velocity is larger than about 2 m/s.

7. Conclusions

In a case study of 7 April 2016, when wide area rain was observed by three polarimetric weather radars, the result of Triple-Doppler analysis and VAD analysis are compared. The analysis using a compact dual polarimetric X-band Doppler weather radar indicates the possibility for understanding the horizontal wind field and vertical drop velocity.

The vorticity estimated by using three radars is more accurate than using two radars unless the noise exceeds 100% of the observation. Hence, when the actual observation noise is assumed around 1 m/s, the vorticity estimated by using two radars would be effective in the weak wind field (less than 2 m/s). This study demonstrates to estimate the vorticity by using three-dimensional variational method. When the wind field satisfies a continuity equation, the vorticity is estimated without damping. Therefore, the estimation of 3D wind field and vorticity contributes to safe operations in urban transportation systems, and supports safe takeoffs and landings at airports during strong wind weather and severe storm.