Estimation of 3D Wind Field and Vorticity with Higher Spatial Resolution Using Multi Compact X-Band Weather Radars

Masahiro Minowa[1], Toshiaki Takaki[1], Kosuke Okawa[2], Satoru Oishi[2], Eiichi Nakakita[3] 1 FURUNO ELECTRIC CO., LTD., Japan, 2 Kobe University, 3 Kyoto University

FURUNO

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 of 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 KOBE (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.

※Local time

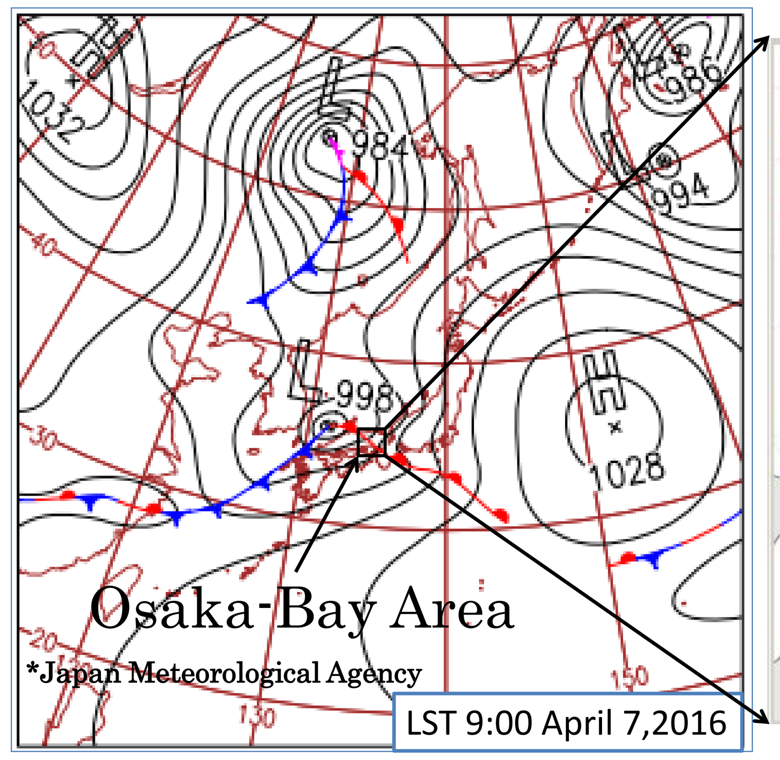

Fig 1：Weather Map

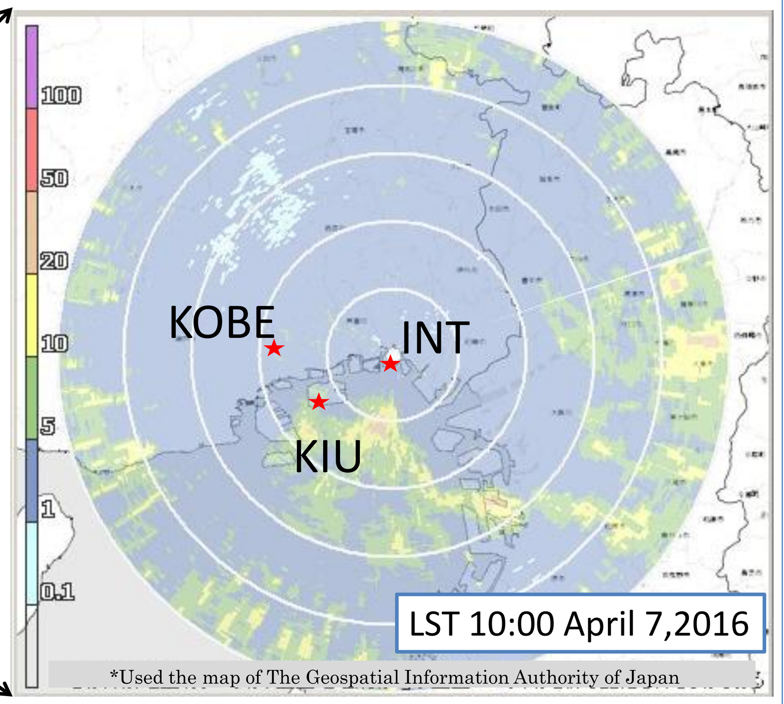

Fig 2 ：Rain Distribution

2.Triple-Doppler Analysis

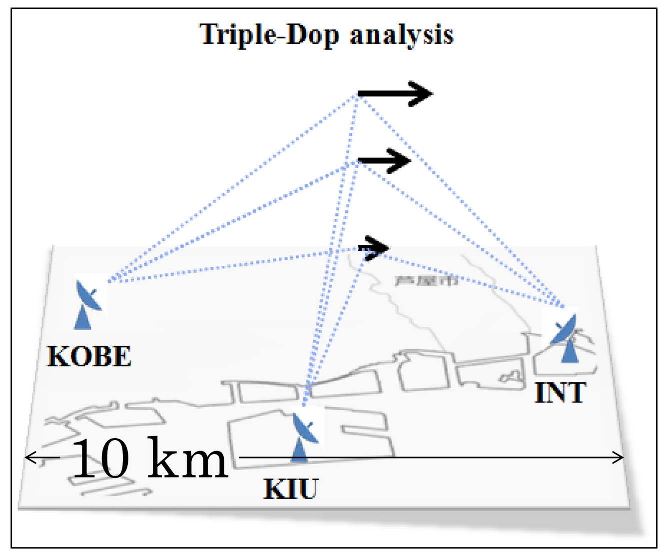

Fig 3: Triple-Doppler analysis

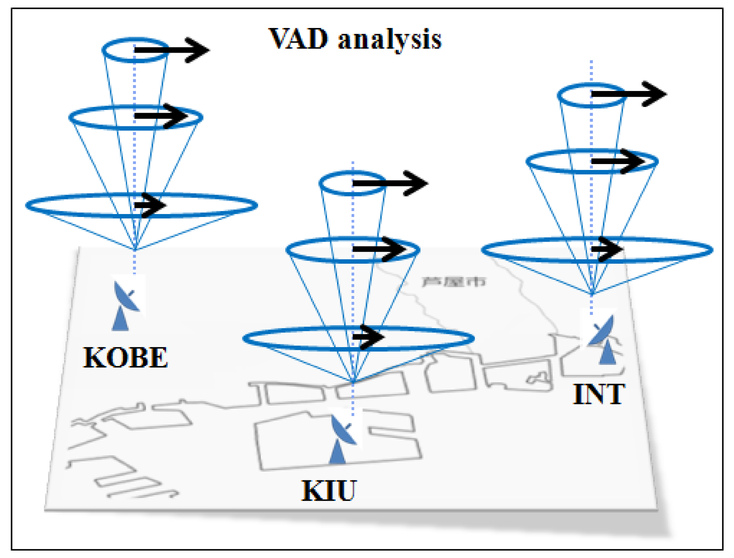

Fig 4: VAD analysis

Observation Time	
April 7, 2016 10:00-11:00 every 2 min	
Data Grid Size	
100 m	
Scanning elevation	
7,14,22,29,37,44 51,58,64,69,75,90 deg	
Antenna rotation	
7 rpm	
Pulse	
Short pulse 1µsec Long pulse 50µsec	

Table 1: Radar strategy

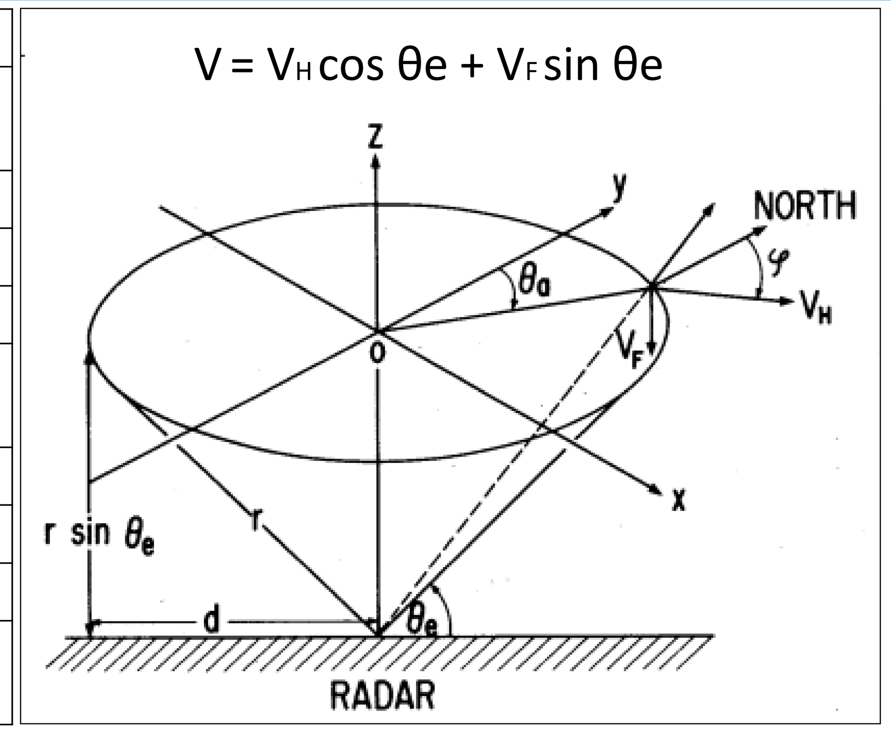

Fig 5: Estimation with VAD

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 3000m and 4000m is the melting layer and the speed is changing drastically. This result shows that melting layer is observed with triple-Doppler method, and it helps improve the accuracy of hydrometeor classification.

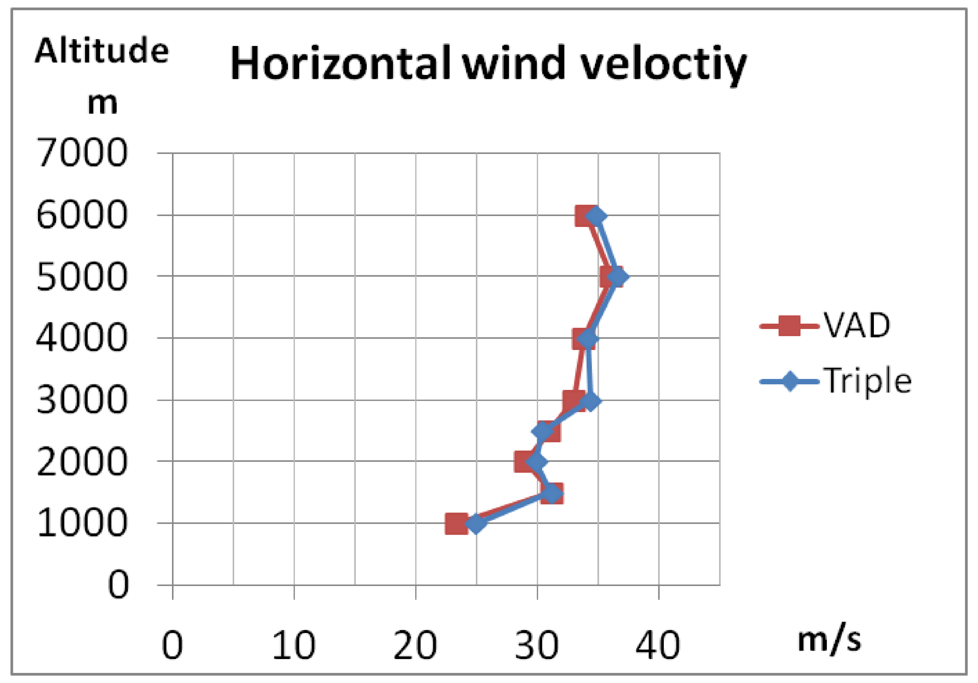

Fig 6: Comparison of wind velocity

RMSE: 1.2 m/s Triple vs. VAD in 10 min average
Correlation coefficient: $R^2 = 0.96$

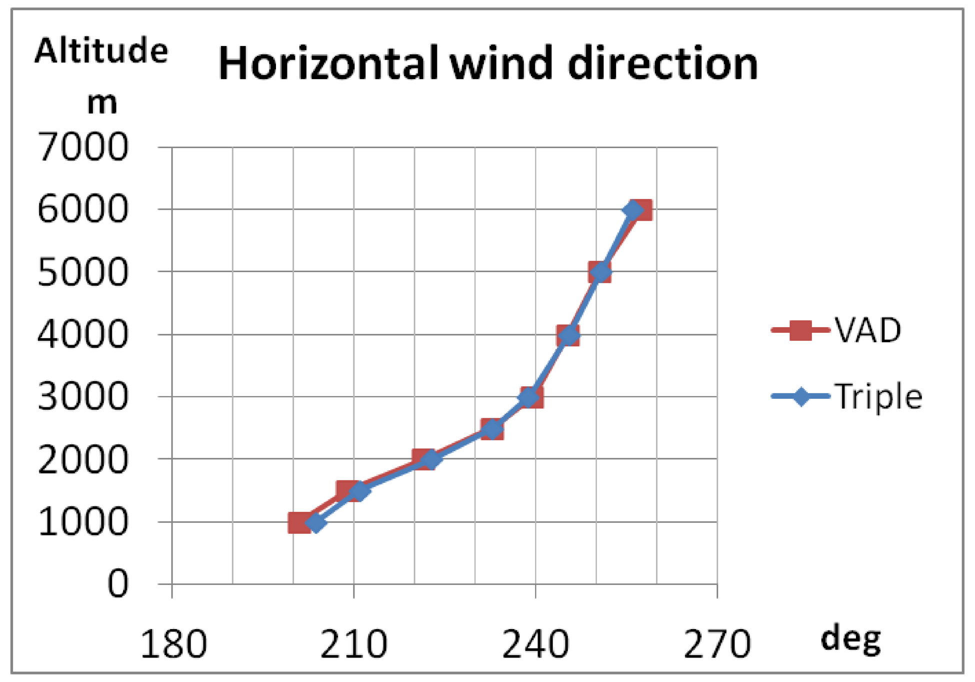

Fig 7: Comparison of wind direction

RMSE: 1.2 deg Triple vs. VAD in 10 min average
Correlation coefficient: $R^2 = 0.99$

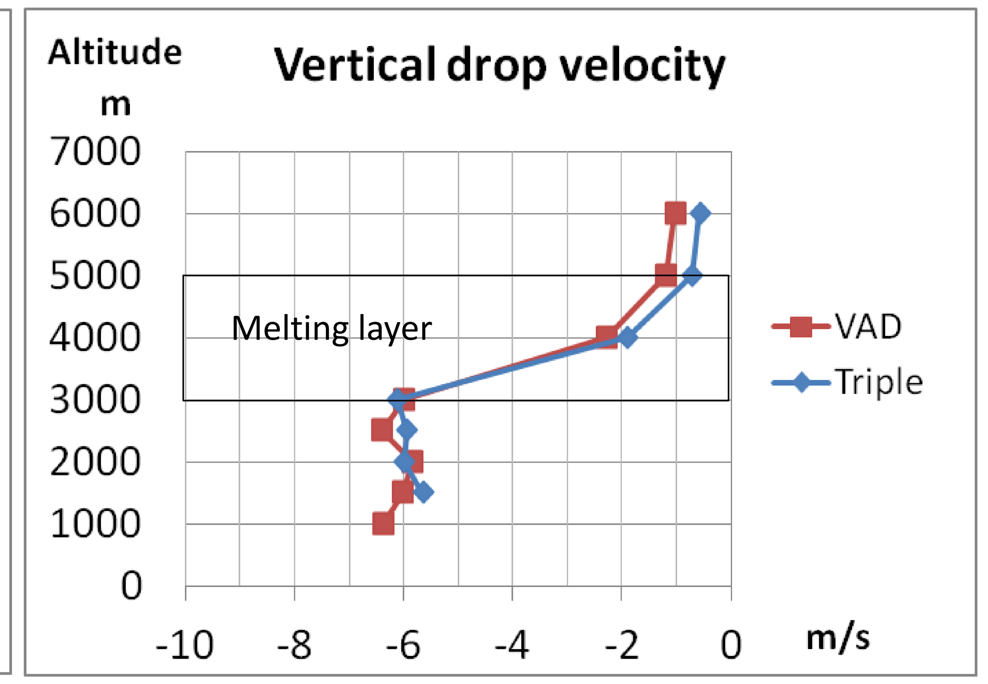

Fig 8: Comparison of vertical drop velocity

RMSE: 0.6 m/s Triple vs. VAD in 10 min average
Correlation coefficient: $R^2 = 0.96$

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 J defined here to be the sum of squared errors due to misfit between observations and analyses subject to constraints. As shown in Equation (1), J is expressed as the sum of equations (2) to (3). Here J_0 is the difference between the analyzed three dimensional velocity (u, v, w) and the observed radial velocity V_{rm}. The cost function , J_d , imposes mass conservation constraint on the analyzed wind field. The cost function J 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.(Gao *et al.* 1999)

$$J = J_0 + J_d \quad (1)$$

$$J_0 = \frac{1}{2}\sum_{i,j,k} \lambda_0 (V_{rm} - u\mathrm{cosA} + v\mathrm{cosB} + (w + w_t)\mathrm{cosC})^2 \quad (2)$$

$$J_d = \frac{1}{2}\sum_{i,j,k} \lambda_d D^2 \quad (3)$$

$$D = \frac{\partial \bar{\rho} u}{\partial x} + \frac{\partial \bar{\rho} v}{\partial y} + \frac{\partial \bar{\rho} w}{\partial z} \quad (4)$$

V_{rm} : the observed radial velocity
cosA,B,C : Direction cosine from radar position
ρ : the mean air density
λ_o , λ_d : 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).

$$V'_{rm} = V_{rm}(1 + \varepsilon) \qquad \varepsilon : \text{noise} \quad (5)$$

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).

$$\text{Vertical vorticity} = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \quad (6)$$

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 1m/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 of 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].

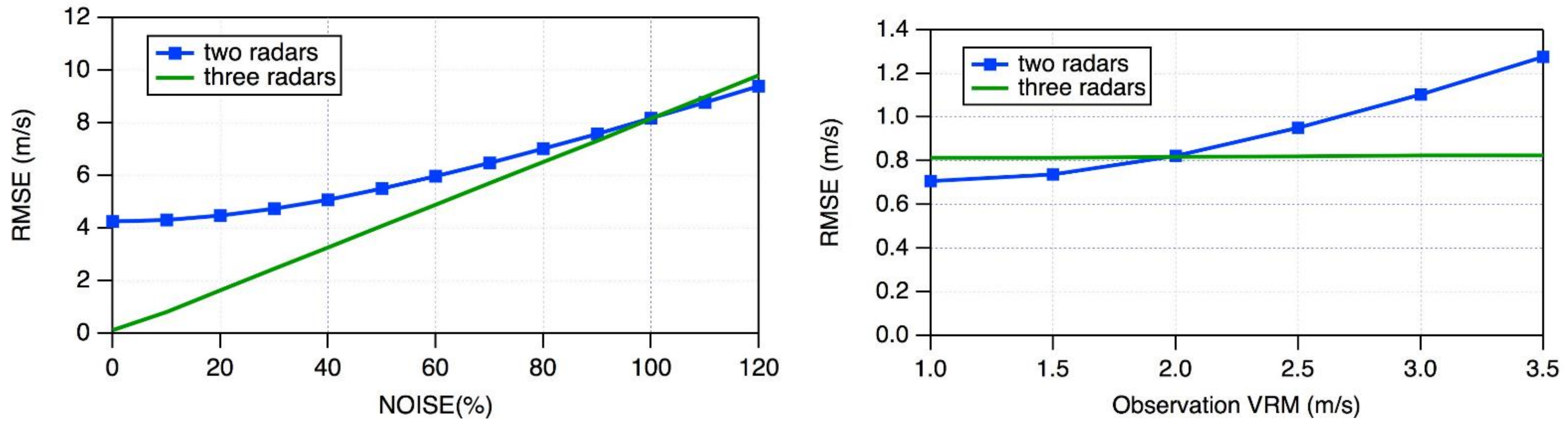

Fig 9: RMSE and observation noise(Left) , RMSE when the noise is 1m/s and observation velocity(Right).

Fig 10 shows a vorticity obtained from the horizontal wind velocity field reproduced by using three radar and vertical vorticity. The calculation result using three radars was reproduced well at RMSE = 0.1[m/s]. It shows that artificial vorticity 0.1[/ s] was reproduced without weakening. Vorticity satisfying the continuous equation should not be recognized as an error in the variational method. Therefore, it is possible to estimate the vorticity using the variational method.

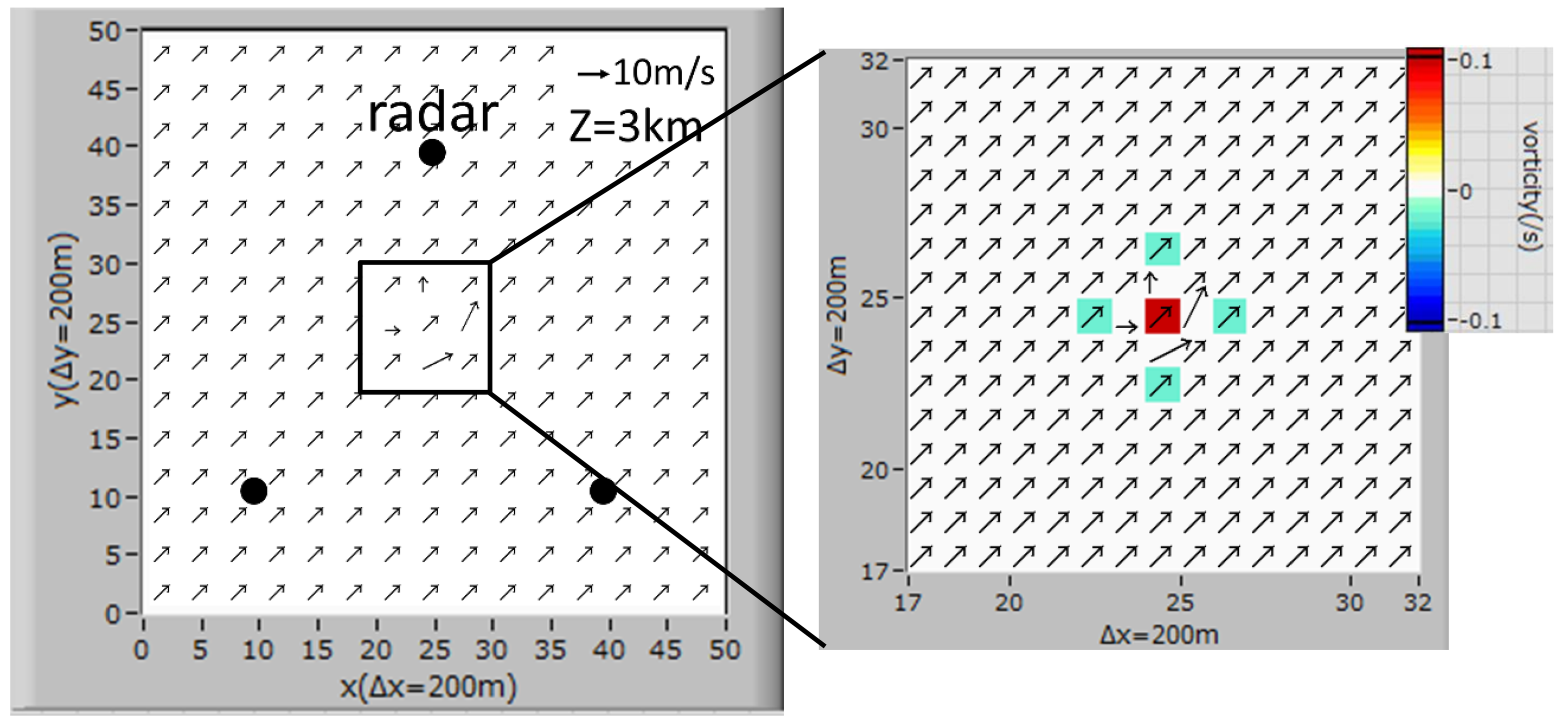

Fig 10: Horizontal wind velocity field and vertical vorticity（RMSE=0.1m/s）

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 filed (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.