P11A.5 DOPPLER WEATHER RADAR NETWORK OVER THE KOREAN PENINSULA

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1. INTRODUCTION

Many countries operate a radar network consisting of weather radars to monitor and predict meteorological phenomena. The United States installed the Next Generation Radar (NEXRAD) network covering all the areas of the U. S. (Klazura and Imy 1993) and the Japan Meteorological Agency (JMA) has been operating the radar network of total 19 radars (Makihara 1996). The European Union countries have performed efforts to combine national networks of each member country and hence utilized radar information over Europe, as known the series of the Cooperation in Science and Technology (COST) actions (Collier 1992; Meischner and Hagen 2000) and the Operational Programme for the Exchange of Weather Radar Information (OPERA, Köck et al. 2000). The precipitation and wind information obtained from these radar networks have been utilized in the studies on understanding of the dynamics and precipitation production of hazardous mesoscale convective systems, hydrology of water resource management through quantitative precipitation measurement, weather forecasting through data assimilation into numerical weather prediction (NWP) models, and nowcasting.

In recent, the Korea Meteorological Administration (KMA) established an operational radar network consisting of total 11 Doppler radars. In addition, the Republic of Korea Air Force (KAF) has operated 5 Doppler radars and the U.S. Air Force (USAF) has operated two Weather Surveillance Radar-1988 Doppler (WSR-88D) radars. These radars are apart by about 120 km in average and their observable ranges are longer than 100 km. Thus this operational radar network consisting of 18 radars covers the whole of the southern Korean Peninsula. One notable thing is that the all radars have the Doppler capability, hence it is possible to retrieve wind fields in high resolution over the southern Korean Peninsula through a multiple-Doppler wind retrieval technique using 3 or more radars. In this paper, the operational Doppler radar network in Korea is introduced. An algorithm for retrieving wind fields from radar data produced by the network is developed, and preliminary results are presented.

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2. RADAR NETWORK OVER KOREA

Figure 1 shows the locations of the radars operated by KMA, KAF, and USAF. The RKSG and RKJK radars which are the WSR-88D radar are operated by USAF. The KAF radars are RKWJ, RSCN, RTAG, RYCN, and RWNJ, which are operated at C-band frequencies. The others, total of 12 radars, are operated by KMA and at C- or S-band. KMA plans to upgrade C-band radars to S-band radars to mainly mitigate attenuation effect due to precipitation. The RKSN radar was upgraded to S-band during 2006 to 2007 and an upgrading of the RDNH radar will be followed. The C-band radar at RCJU of KMA was retired in summer, 2006 in accordance with the start of observations of two new S-band radars of RGSN and RSSP.

As shown in Figure 1, the 18 radars are impartially distributed over the area of about 100,000 km^2 of South Korea. Comparing the number of radars with respect to the area, it is found that the operational radar network over Korea is 3.5 and 11 times denser than that of JMA (Makihara 1996) and NEXRAD over the contiguous US (Klazura and Imy 1993), respectively. Another notable thing on the network over Korea is that all operational radars have Doppler capability measuring radar reflectivity, radial velocity, and spectrum width. For the velocity measurements, the radars have a maximum observable range from 100 km to 250 km, with a range resolution from 0.125 km to 1.0 km and an azimuth resolution of about 1°. The USAF radars are mostly operated as the schedule of the volume coverage pattern (VCP) 21. Namely, a volume scan is framed by 360° full scans at 9 elevation angles from 0.5° to 19.5°. This volume scan repeats every 6 minutes. The KAF radars frame a volume with scans at 6 to 9 elevation angles from 0.5° to 35.0°.

One volume scan of the KAF radars needs about 4 minutes repeating every 10 minutes. The KMA radars, except for RBRI, RCJU, RDNH, and RKSN, carry out one volume scan at 10 to 15 elevation angles from 0° to 45° every 10 minutes.

The four radars at C-band (RBRI, RCJU, RDNH, and RKSN) of KMA scan at relatively low elevation angles below 7.0°. A purpose of these radars is to measure radar reflectivity at long distance for watching precipitation rather than velocity measurements. Therefore, these four radars are operated at relatively low pulse repetition frequencies (PRFs) from 250 to 499 Hz and consequently their observable ranges are relatively long from 240 to 256 km, compared to velocity measurements of general C-band Doppler radars. Further, the low PRFs result in low Nyquist (or maximum observable) velocities. Those four radars have Nyquist velocities from 3.5 to 6.7 m/s, while the other radars do higher velocities than 16 m/s. In particular, the Nyquist velocities of the S-band radars of KMA (e.g., RGDK, RKWK, RSSP, etc) are higher than 30 ms^{-1} due to the extension by using a dual-PRF capability of 400 and 600 Hz.

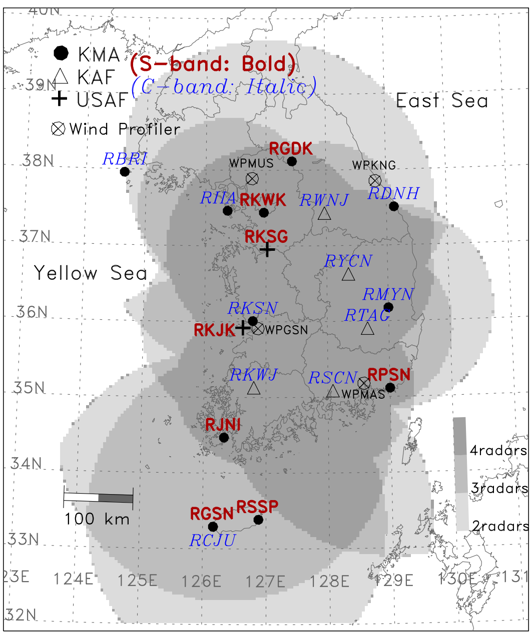

Fig. 1. Locations of the operational radars over Korea. The gray shaded areas denote the overlapped areas by two, three, and four or more radars. The locations of four wind profilers are also shown with the ⊗ marks

In Figure 1, the gray scaled areas mean how many radar observations are overlapped at each grid points, under the condition of the volume scan strategy of the radars. In the figure, most areas of the southern Korean Peninsula are covered by three and more radars. Consequently, it is possible to retrieve wind fields in high resolution almost over the southern Korean Peninsula, through multiple-Doppler wind retrieval scheme using three or more radars. It is worthwhile to note that the wind-retrievable area shown in Fig. 1 is subjective to the conditions of the effects of occultation by topography and the earth curvature. These factors can slightly decrease the wind retrievable area. In addition, observations by the four C-band radars (RBRI, RCJU, RKSN, and RDNH) are not included in the present study, because their Nyquist velocities are too low to resolve aliasing effect of radial velocity. The upgrade of the RKSN, RDNH, and RBRI radars as mentioned above contributes to wider retrievable area, in particular over the north-western and north-eastern seas of Korea. In Figure 1, four sites of wind profilers of KMA (WPMUS, WPKNG, WPGSN, and WPMAS) are also plotted. The wind profilers are operated at the frequency of 1290 MHz with 5 beams: one vertical and four oblique directions slanted by 17° from the vertical toward north, east, south, and west. These profilers are used for the comparison with wind fields from the radar network to evaluate the radar wind retrievals.

3. WIND RETRIEVAL FROM RADAR NETWORK

One benefit using a radar network is that the continuous watch of precipitation systems is possible by overcoming regions where a single radar can not scan, caused by conical scan of antenna and the earth curvature. In particular, this benefit is considerable over complex orography areas. Additional important advantage is apparent in retrievals of the 3-dimensional winds (u, v, w) through multiple-Doppler analysis using more than 3 radars. Ray et al. (1978, 1980) showed that as the number of radars increases, the 3-dimensinal winds are increasingly better derived over a larger area. They also showed that the derived fields (e.g., divergence and vorticity) from the horizontal wind became better with increasing the number of radars used. The multiple-Doppler analysis has additional advantage that it is free from the requirement of a relation between radar reflectivity and terminal velocity, which must be assumed *a priori* in

Dual-Doppler analysis for deriving the vertical air velocity (*w*). In this study, therefore, the wind fields over the southern Korean Peninsula are retrieved from the multiple-Doppler wind retrieval scheme using the radars operating by KAF, USAF and KMA.

3.1 PROCESSING OF RADAR MEASUREMENTS

Before retrieving winds, the radial velocity measurements were processed in terms of the effect of aliasing and elimination of noises. The aliasing effect was first corrected using an algorithm with a constraint that radial velocities should be continuous from gate to gate, along radial direction and also azimuth direction. In circumstances with strong wind such as typhoon, however, since the radial velocities at gates adjacent radar are already aliased, the aliased velocities at further gates are not corrected properly. To overcome this circumstance, the wind measurements at the surface observatories around the radar were used for correcting radial velocities adjacent the radar. A 10-minute mean wind of the surface observatories within a radius of 30 km from the radar was used in this study.

Next, the velocity measurements of S-band radars of KMA contain noises that appear randomly as like sparks at one or two consecutive gates, which is most likely due to the small number of pulses of about 35 to 45 related to low PRF (400 and 600 Hz) and consequently weak sensitivity of the radar system. These noises were eliminated by comparing a radial velocity at a given gate with a mean value within an area surrounded by 15 gates in radial direction and 7 rays in azimuth centered at the given gate. That is, when the difference from the mean value was larger than 10 ms^{-1}, the radial velocity at the given gate was considered as a noise and eliminated. Finally, the radial velocities processed by the procedure above was filtered and smoothed by a median filtering over consecutive 7 gates in order to negate high frequency random fluctuations from gate to gate.

3.2 WIND RETRIEVAL

Once the measurements from each radar were processed by the procedures above, the wind fields were then retrieved using the Sorted Position Radar INTerpolation (SPRINT) and the Custom Editing and Display of Reduced Information in Cartesian space (CEDRIC) packages of National Center for Atmospheric Research (NCAR) (Mohr et al. 1986).

In the interpolation to the Cartesian coordinate by SPRINT, the site of the RKSG radar was set as the center of the analysis region shown in Fig. 1, which corresponded to an area from -300 to 300 in east-west and from -500 to 300 km in north-south direction. The CEDRIC codes were slightly modified so as to be synthesized up to 20 radars, in order to include all radars over Korea. The *u* and *v* components were retrieved from the 3-equation solutions using three or more radars. The w component was derived from integration of the anelastic continuity equation, using a variational scheme with a boundary condition of *w*=0 at the surface and echo top (assumed 17 km height). The horizontal wind components were variationally adjusted to minimize the mean difference between horizontal and vertical divergences. Finally, the winds retrieved were displayed and saved in regions only where the geometric errors related to the looking direction of each radar (or standard deviation normalized by radar measurements) of *u* and *v* were less than 2 ms^{-1}.

4. RESULTS

To evaluate the wind retrieval algorithm using the radar network, two rain events were applied: one is the typhoon Ewiniar (TY0603) accompanying with strong wind over the southern Korean Peninsula, and another is a thunderstorm accompanying with mesocyclone of a diameter of about 30 km.

4.1 Case I: Typhoon Ewiniar

During 1800 UTC 9 July to 1100 UTC 10 July 2006 when the typhoon had passed over the Korean Peninsula, the wind fields were retrieved from the radar network, with resolution of 5$\times$5 km in horizontal and 0.5 km in vertical. The winds retrieved from the radar network were compared with those measured by the wind profiler shown in Fig. 1, in order to evaluate the radar wind retrievals. In the comparisons (Fig. 2), the wind profiler winds were averaged for 10 minutes for consistency with the volume observations of the radars. The radar winds ware also averaged over five grids around the closest grid point to the wind profiler site. In Fig. 2, the radar winds are in good agreement with the profiler winds. The variations of wind speeds and directions with time and heights are comparable, although the wind directions from radars are slightly smaller than those from profiler over the WPKNG profiler.

Figure 3 is scatter plots of wind speed and direction between radars and profilers. The wind speeds show good agreements with each other. The

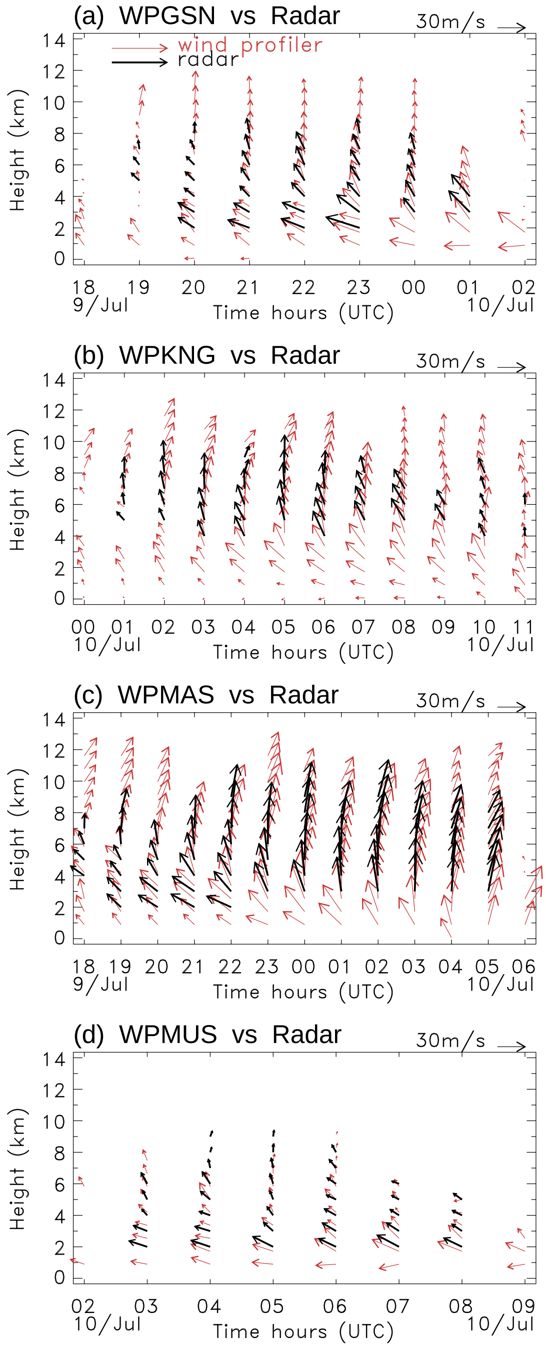

Fig. 2. Comparisons of the horizontal wind vectors retrieved from the radars and measured by the wind profilers during 18 UTC 9 July to 11 UTC 10 July 2006 with an interval of 1 hour.

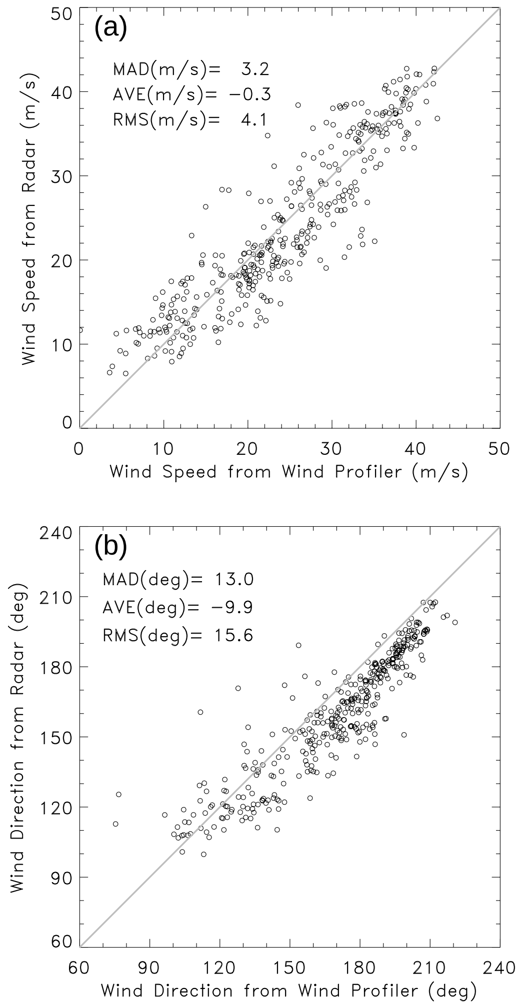

Fig. 3. Scatter plots of (a) wind speed and (b) wind direction between the radar retrievals and the wind profiler measurements.

radar winds deviate by only -0.3 ms^{-1} in average from the profiler winds. The mean absolute deviation is 3.2 ms^{-1}. The wind directions from radar also agree with the profiler measurements, but they are smaller by -9.9° in average than those from profilers. The radar wind directions have a mean absolute deviation of 13°. The wind profiler was originally designed for observing clear air where homogeneity of wind field, in particular vertical velocity, can be assumed, and hence it has an error in wind measurements of about 4 ms^{-1} under the condition of precipitations where homogeneity is not acceptable (Wuertz et al. 1988). Considering this measuring error of wind profiler and further differences in sampling between radar and profiler, it can be concluded that the radar wind obtained in this study are reliable. When it is assumed that the wind profiler winds are true without error, the root mean square error of the wind speed and direction from radars are 4.1 ms^{-1} and 15.6°, respectively.

4.2 Case II: Thunderstorm

A reliability of the wind retrieval algorithm using the radar network was further examined with a well-developed thunderstorm in meso-β scale, with a mesocyclone of a diameter of about 30 km. Figure 4 shows the synthesized radar reflectivity and the horizontal wind vectors at heights of 2 km and 5 km, at 1440 UTC 30 June 2005 when a severe storm accompanying strong wind, lightning, and hail passed around Chuncheon, Kangwon Province. The wind fields were retrieved from the RKSG, RKWK, RGDK, RIIA, and RWNJ radars with a horizontal resolution of 1×1 km. At the height of 2 km, a hook echo was well recognized around 127.65°E and 37.75°N, where a weak echo region (WER) occurred distinctly. The surrounding of the WER is characterized by a cyclonically rotating vortex (mesocyclone). At the height of 5 km, WER did not occur while radar reflectivity was very high over 60 dBZ, implying the presence of hail. The WER was recognized up to about 3.5 km height. A WER is an indicator implying the existence of strong updraft, hail aloft, and hence severity of storm.

Figure 5 presents a vertical structure of the storm along the A-B line in Fig. 4, which is parallel to the direction of the storm movement (290° and 15 m/s in the same sense as a wind is defined). The reflectivity pattern presented a maximum value of 64 dBZ at 6 km height and WER at low heights. And the reflectivity pattern was tilted toward ahead of storm and an overshooting of echo occurs at 12 km height over the storm core. The wind vectors along the cross section showed convergence at low heights and upward motion at the storm core. The pattern of the vertical air velocity had a maximum of 13 ms^{-1} at the core. The horizontal divergence and vertical vorticity fields had a coupled pattern that the convergence at low heights was linked to the divergence at echo top. The positive area of vorticity was also tilted as same as in that of the reflectivity pattern. The patterns of reflectivity and wind fields described above represented well a typical structure within a well-developed supercell thunderstorm (Houze, 1993).

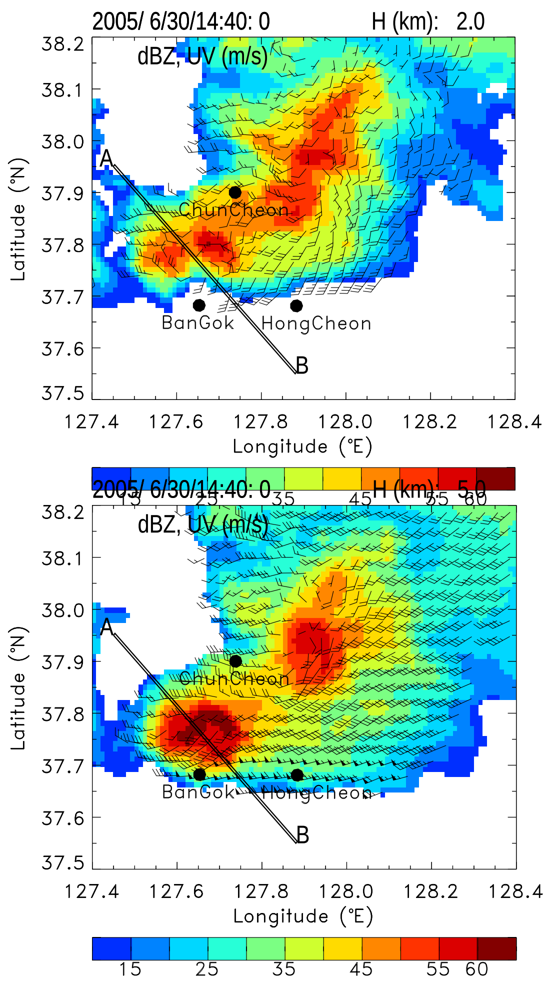

Fig. 4. Composite images of radar reflectivity and horizontal wind vectors at heights of 2 km and 5 km at 1440 UTC 30 June 2005.

5. CONCLUSIONS

According to the results above obtained from the typhoon and a meso-β scale thunderstorm, it is concluded that the retrieved wind fields from the operational Doppler radar network over Korea are reliable. Using the wind retrieval algorithm in this study, we are now studying on kinematic and dynamic structures within severe convective storms over the

Korean Peninsula, and further on improvement of forecast through data assimilation of the retrieved wind fields into NWP models.

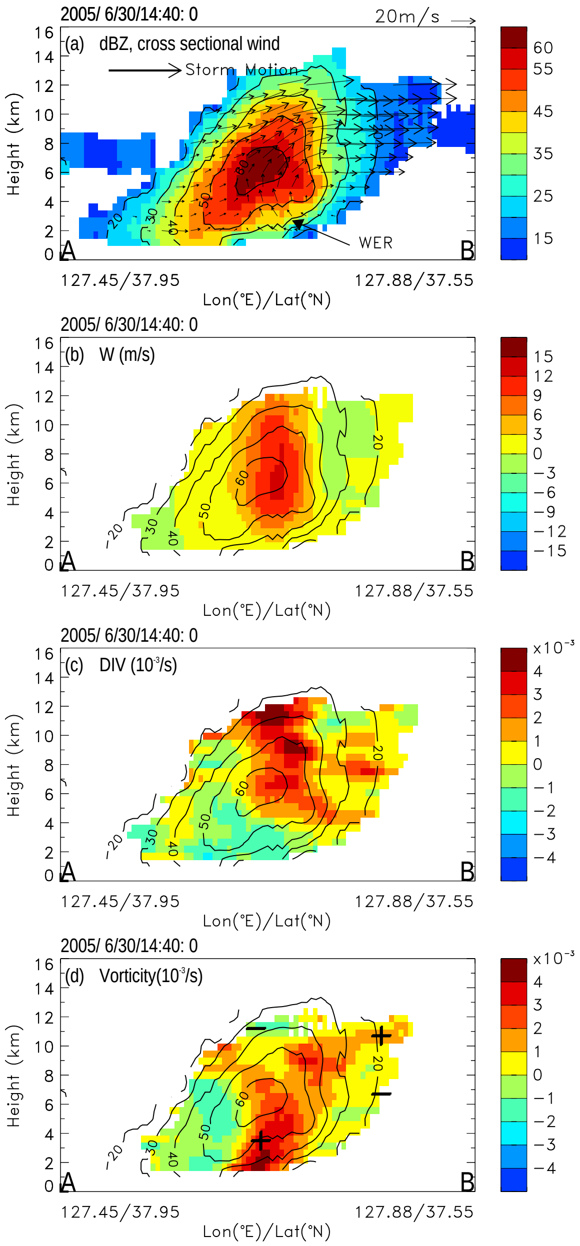

Fig. 5. Vertical cross sections of (a) radar reflectivity and wind vector, (b) vertical air velocity, (c) divergence, and (d) vorticity along the A-B line shown in Fig. 4. The contours denote the radar reflectivity.

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