NOTES AND CORRESPONDENCE

Characteristics and Performance of the Operational Wind Profiler Network of the Japan Meteorological Agency

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Abstract

The Japan Meteorological Agency (JMA) started the operation of a wind profiler network, the Wind profiler Network and Data Acquisition System (WINDAS), in April 2001. The WINDAS is a network consisting of thirty-one 1.3 GHz-band wind profilers, with dense spatial resolution of 130 km on the average over the main islands of Japan. Operated with high data accuracy, under strict data quality control and high data availability, from reliable system operation. Height coverages of wind measurement are 6–7 km in summer, 3–4 km in winter and 5.3 km on the average through a year. The main purpose of the operation of WINDAS is to provide upper-air wind data to the numerical weather prediction (NWP) of the JMA, particularly to the hydrostatic (till 2004) and non-hydrostatic (from 2004) mesoscale numerical model (MSM). The WINDAS data are assimilated into the MSM using a full forecast-analysis system, with 4-dimensional variational method. From statistical analyses and some case studies, it was confirmed that the WINDAS data has contributed to improve accuracy of the MSM for mesoscale weather systems, particularly for heavy rainfall events. Being put on GTS, the wind data are distributed to the world in real-time. Although a problem of data contamination from migrating birds had occurred in the first year of the operation of the WINDAS, it was practically solved by developing a removal algorithm.

1. Introduction

Atmospheric radars were originally developed in 1970s for research of the mesosphere and stratosphere (Woodman and Guillen 1974), and were widely applied to research of winds in the troposphere, referred to as wind profilers during the 1980s. Usefulness of a wind profiler network in meteorological services was firstly demonstrated in the U.S. in early 1990s as the NOAA Profiler Network (NPN) (Weber et al. 1990; van de Kamp 1993; NOAA 1994). The NPN has been operated using thirty-five 400 MHz-band wind profilers located mainly in the central U.S., and the data has contributed to the NWP and operational forecasts (Stanley et al. 2004). The European wind profiler network has also been operated using 50 MHz-band atmospheric radars, 400 MHz-band wind profilers and 1 GHz-band wind profilers, since the mid-1990s as the WINDE project in COST-74 (Action 74 in the European co-operation in the field of scientific and technical research) and as EUPROF in the COST-76 project (Nash et al. 2000; Oakley et al. 2000; Dibbern et al. 2001).

In Japan, extremely severe rainstorms frequently occur associated with typhoons, the Baiu-front and midlatitude cyclones, causing serious damages to human activities due to flash floods or landslips. Actually during 2004,
the number of records of one-hour rainfall amount more than 50 mm (80 mm) amounted to be 453 (29) in the mesoscale surface network of the JMA, which consists of 1,300 automated weather stations (AMeDAS). One of the most important missions of the JMA for weather disaster prevention is to increase ability of monitoring and forecasting severe rainstorms. The improvement of forecasting severe rainstorms primarily depends on enhancement of the NWP. The JMA thus developed the mesoscale numerical model (MSM), with horizontal grid size of 10 km, and started its experimental operation in 1998, in order to predict mesoscale severe rainfall systems being organized on horizontal scale from several 10 km to several 100 km (meso-β scale). The existing upper-air observation stations using radiosondes in Japan are located at intervals of 300 to 350 km, and are insufficient for monitoring a mesoscale weather systems. In order to operate the MSM effectively, a newly developed upper-air observation network, with horizontal space being comparable to the horizontal scale of targeting weather systems, was required for providing initial values to the MSM.

The JMA made observation system experiments (OSEs) using the MSM with data from wind profilers, Doppler radars and commercial aircraft, and then verified that wind profilers should be introduced to the operation of the NWP with the highest priority in order to increase forecast accuracy of MSM for severe rainstorms (the JMA Numerical Prediction Division, 2000). On the basis of the assessment from the OSE, and the experience of wind profiler operation since 1889 at the Meteorological Research Institute of the JMA (Kobayashi et al. 1999), the JMA decided to establish an operational wind profiler network in order to increase capability of upper-wind observations over Japan (Ishihara and Goda 2000). Twenty-five wind profilers had firstly started to be in operation in April 2001, and six more wind profilers were added to the network during March to June 2003. The network is referred to as the Wind profiler Network and Data acquisition System (WINDAS). In this paper, we present characteristics and performance of WINDAS, and its data quality control, as well as impacts of its wind data on the NWP for heavy rainstorms.

2. System configuration and characteristics of WINDAS

2.1 Selection of radio frequency

One of the parameters to evaluate performance of wind profilers is height coverage (height range) of wind measurement. Height coverage of wind measurement strongly depends on radio frequency being used in wind profilers (Röttger and Larsen 1990; Dibbern et al. 2001). VHF atmosphere radars, operated at frequencies around 50 MHz have high capability of wind measurement from the troposphere to the stratosphere, and even to the mesosphere (Fukao et al. 1985), but they need relatively high expenses, and a large site for their construction facility. UHF wind profilers, using frequencies around 400 MHz, have capability to measure winds in the whole troposphere, and then are most suitable for operational upper-air measurement in weather services. Actually, NPN of NOAA consists of 404 MHz wind profilers (NOAA 1994). However, use of frequencies of the 400-MHz band for wind profiling is strictly limited in Japan, particularly in areas nearby medical facilities, because the frequency bands are also used in medical equipment.

Wind profilers operated at frequencies from 915 MHz to 1.3 GHz (1 GHz-band wind profilers), started to be used in research activities in the early 1990s. Height coverage of 1 GHz-band wind profilers had been initially limited to the top of the boundary layer, usually up to 2 to 3 km in height (Ecklund et al. 1990; Carter et al. 1995; Hashiguchi et al. 1995; Ohno 1995), but was improved to be beyond the top of the boundary layer in the late 1990s (Winston 2000; Hashiguchi et al. 2004). Water vapor producing rain clouds is concentrated below the middle level of the troposphere, approximately below 5 km in height. Hence, we thought that it is a necessary condition to observe airflows in the layer from the surface to around 5 km in height in order to monitor behavior of rainfall systems. Considering the cost performance (cost of a 400 MHz-band wind profiler is estimated to be twice or three times higher than that of a 1.3 GHz-band wind profiler), as well as the restriction of radio frequency allocation in Japan described above, the JMA selected 1.3 GHz-band wind profilers for the network,
rather than 50 MHz-band atmospheric radars, or 400 MHz-band wind profilers. The WINDAS is the first operational wind profiler network consisting of 1.3 GHz-band wind profilers.

2.2 Network of the wind profilers

As illustrated in Fig. 1, the JMA selected the site locations of thirty-one wind profilers, giving the high priority on the middle and western Japan, where severe rainstorms occur almost every year due to typhoons, the Baiu-front and midlatitude cyclones. The distances from each wind profiler site to its neighboring wind profiler site are ranged from 67 to 262 km, and 130 km on the average over the four main islands of Japan. Particularly, at the south and west coasts of the main islands of Japan, the wind profilers are distributed with higher spatial resolution, so as to correspond to the horizontal scale of meso-β weather systems. The spatial resolution of upper-air wind observation in Japan has been extensively improved with the start of operation of the WINDAS.

2.3 System configuration

Figures 2a and 2c show photographs of one of the wind profilers, and the Control Center of WINDAS, respectively. Figure 3 is the system configuration of the WINDAS as illustrated in a block diagram. The wind profilers composing the WINDAS were selected in 2000, through an international tender of procurement. The main unit of the wind profilers was designed with the technologies developed at the Radio Science Center for Space and Atmosphere (currently the Research Institute for Sustainable Humanosphere) of the Kyoto University (Hashiguchi et al. 2004) in collaboration with the Mitsubishi Electric Corporation (Wakayama et al. 2000).

Table 1 summarizes the main characteristics of the WINDAS. The wind profilers have the transmitting peak power as large as 2 kW, and antenna gain of 33 dBi, by use of 4 m × 4 m active phased array antenna, consisting of 96 sub-antennas (Fig. 2d). The phase-coded pulse compression technique, with the 8-bits binary code developed by Spano and Ghebrebrhan (1996) is used to avoid range sidelobe at the first range gate (usually at 400 m in height) of wind measurements. More detailed description of the structure and mechanism of the wind profiler is presented by Hashiguchi et al. (2004). A clutter fence, 2 m in height surrounds the array antenna in order to prevent ground clutter contamination. Loss of radio wave power in case of snow accumulation of 10 cm depth over the antenna, is estimated to be 1 dB. As shown in Fig. 2b, semi-globe radar domes made of FRP are installed over the array antennas at nine wind profilers, which are located in the heavy snowfall areas, in order to prevent heavy snow accumulation over the antenna. All the wind profilers of the WINDAS are in remote operation from the Control Center, located in Tokyo.

2.4 Signal/data processing and data quality control

Figure 4 illustrates the schematic chart of signal processing and data processing, including data quality controls of the WINDAS. Data of the WINDAS are used in real-time for operational weather services, and then they have to be kept in high quality as much as possible. One of the prominent features of the WINDAS is the strict quality control at the stages of signal and data processing. After the FFT processing in the signal processor, removal of ground clutter is made by eliminating spectral components around zero-velocity in the Doppler velo-
ity spectrum. Removal of migration-bird echo, described in Section 2.5, is then done. In the data processor, vertical profiles of spectral moments on the five beams are estimated every minute. One of the specific procedures to the WINDAS is its estimation scheme of Doppler spectral moments, using the Gaussian-function fitting method (Hashiguchi et al. 1995). The scheme has an advantage that spectral moments are available even in the case of low signal to noise ratio. After the Doppler spectrum width check, homogeneity among Doppler velocities on four oblique beams is examined. The homogeneity is distorted in some cases, particularly at the edge of severe convections, where some beams among the five beams are penetrated into precipitation clouds, and the other beams stay in clear sky. 10-minute averages of three components of wind \((u, v, w)\) over each wind profiler site, are finally calculated from Doppler velocities, using the four-beam method (Adachi et al. 2005).

The 10-minute averaged wind data and data quality flag are sent to the Control Center every hour, by using the JMA telecommunication lines, or public digital telephone lines. The quadratic surface check for \(u\) and \(v\) components (Sakota 1997) is made in the computer of the Control Center. The check is based on continuity of \(u\) or \(v\) components on a time-height domain, and has shown high performance to eliminate erroneous data automatically. One to two percent of the total amount of obtained data has been judged erroneous data, in the sequence of the data quality controls. The quality-assured data are then sent to the JMA central computer (Numerical Analysis and Prediction System: NAPS) by 20 minutes after
each hour, and are used as initial values of numerical predictions. Being coded into BUFR (Binary Universal Form for the Representation of Meteorological Data), the wind profiler data have been put onto the Global Telecommunication System (GTS) for global exchange on an operational basis since April 2002.

### 2.5 Migrating-bird echo removal

After the operation of the WINDAS was started, it was revealed that a significant error of wind measurements occasionally occurred due to migrating birds. The erroneous data due to migrating birds appeared mostly at nights of spring and autumn under fair weather condition, as reported in the profiler networks of the U.S. and of Europe (Wilczak et al. 1995; Engerbart and Gorsdorf 1997). As indicated in Fig. 5, the amount of data contaminated by migrating birds in the WINDAS shows distinct seasonal change, with peaks of spring and autumn. The directions of migration of birds are mainly northeastward in spring and southwestward in

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**Table 1. Main characteristics of the WINDAS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1357.5 MHz</td>
</tr>
<tr>
<td>Antenna</td>
<td>coaxial colinear arrays with gain of 33 dBi and size of 4 m × 4 m</td>
</tr>
<tr>
<td>Peak Power</td>
<td>1.8 kW</td>
</tr>
<tr>
<td>Beam width</td>
<td>4 degree</td>
</tr>
<tr>
<td>Beam configuration</td>
<td>5 beams</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.67, 1.33, 2.00*, 4.00 × 10⁻⁶ sec.</td>
</tr>
<tr>
<td>PRF</td>
<td>5, 10*, 15, 20 kHz</td>
</tr>
<tr>
<td>Side robe level</td>
<td>−40 dB or −60 dB at elevation angles of 0–10 degree</td>
</tr>
<tr>
<td>Data processing height</td>
<td>400 m to 9.1 km*</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>291 m*</td>
</tr>
<tr>
<td>Basic data</td>
<td>Doppler moments every 1 minute</td>
</tr>
<tr>
<td>Distributed data</td>
<td>*u, v, w-components of wind, S/N ratio and data quality flag every 10 minutes</td>
</tr>
</tbody>
</table>

*Default values in the operational mode*
autumn, along the main islands of Japan. In the most prominent case of bird-migration, deviation of false “winds” of the WINDAS from true winds observed with radiosondes, extends up to 90 degrees in direction, and to 10 ms\(^{-1}\) in speed. In October 2001, when birds actively migrated over about half the numbers of the profiler sites, 12% of the total amount of data obtained from the WINDAS were contaminated by migrating birds. The percentage of the contamination was much larger than what we had presumed before the start of the operation of the WINDAS. Doppler spectrum width of migrating-bird echoes is, in general, larger than that of atmospheric echoes (Wilczak et al. 1995). Using this characteristic of migrating-bird echoes, wind data with relatively large Doppler spectrum width under clear air condition, were judged to be bird-contaminated data and were removed, during the period from December 2001 to March 2003.

A more sophisticated algorithm of migrating-bird echo removal was developed in March 2003 (Kobayashi et al. 2005), and was installed into the signal processors of the wind profilers. The algorithm is based on the fact that echo intensity from migrating birds is generally greater than that from the atmosphere, and that migrating-bird echoes are fluctuated more rapidly than precipitation echoes. In the WINDAS, incoherent integration is made using twenty-eight Doppler spectra, obtained during 0.4 seconds as shown in Fig. 4. A set of twenty-eight Doppler spectra prepared for the incoherent integration are examined. When spectrum densities of the spectra set show low time-fluctuation, it is judged that the spectra come from the atmosphere or precipitation, and then all the spectra will be used in the
following incoherent integration. On the other hand, when time-fluctuation of spectrum densities in a spectral set is large, it is judged that atmospheric spectra and migrating-bird spectra, are mixed in the spectra set. Since spectra with relatively large spectrum density are originating from migrating birds, they are abandoned from the spectra set. Then, the incoherent integration is made, using the remained spectra, which are originated from the atmosphere. This algorithm has been successfully worked, and true winds are retrieved from nearly half of bird-contaminated data. Wilczak et al. (1995), and Pekour and Coulter (1999), examined shapes of a spectrum before incoherent integration and eliminated the spectral peaks, which are not fitted to the Gaussian distributions as migrating-bird echoes. Their method is excellent, to find migrating-bird echoes, but is thought to use relatively long calculation time in the signal processing. The algorithm developed in the WINDAS is relatively simple and shows practical effectiveness for removal of migrating-bird echoes in operational use.

3. Performance of the WINDAS

3.1 Height coverage of wind measurement

The wind profilers of the WINDAS have four operation modes, with height resolutions of 100, 200, 300 and 600 m, corresponding to four pulse lengths. We here define “height coverage of wind measurements” as the maximum height up to where wind measurements are available. In general, the longer pulse length that is used, the better height coverage is obtained, due to higher transmitting power in spite of less height resolution. Relationship between height coverage, and height resolution was actually examined in the period from May to June 2001, prior to the full operation of the WINDAS. The mean height coverage in 100, 200, 300 m height resolution modes during the period were 3.0 km, 5.4 km and 6.4 km, respectively. Hence, we selected the 300 m mode, as the default operation mode, because this mode has the highest coverage and enough height resolution, to be used for initial values of the latest NWP models operated in JMA.

Signal intensity of 1.3 GHz-band wind profilers highly depends on the weather conditions, and then shows pronounced temporal variation. Figure 6 shows the monthly means of height coverage of wind measurement at 25 wind profilers, during the period from April 2003 to March 2004. The height coverage attains 6 to 7 km in summer, and decreased to 3 to 4 km in winter, being 5.3 km for the annual mean. It is thought that this seasonal variation of the height coverage mainly results from change of water vapor amount contained in the lower troposphere. At the stage of the initial planning of the WINDAS, we made a goal that the annual mean of height coverage in wind measurements should reach 5 km. It was confirmed from this statistical evaluation of height coverage, that the goal has been accomplished.

3.2 Data accuracy and system reliability

The wind measurement accuracy of the WINDAS was evaluated by comparisons with winds forecasted by the NWP model in June and July 2001 (Tada 2001). As shown in Fig. 7, biases and root mean square errors (RMSEs) of wind speed deviation of profiler winds from model winds are the same as those of radiosonde winds from model winds. There is no significant difference between profiler winds and radiosonde winds in the biases and RMSEs. This means that the accuracy in the wind measurement, with the WINDAS is comparable to that from radiosonde observations. ECMWF (2004) reported that the quality of the WINDAS data was consistently good, and the standard deviation was low with few outliers.

In order to evaluate the reliability of the operation of the WINDAS, the percentage of data
received in real-time at the Control Center was examined. The monthly means of data availability over all the wind profiler have been more than 98.8% since May 2001. This indicates that stable operation of the system has been accomplished in the WINDAS.

4. Data applications

4.1 Impact on NWS models

The upper-air wind data from the WINDAS have been used as an initial value in all the NWP models, being operated in the JMA, since June 2001. The WINDAS data particularly contribute to the initial value for the hydrostatic MSM during 2001 to 2004, and to the non-hydrostatic MSM (Saito et al. 2006) from 2004 with 10 km horizontal resolution (the horizontal resolution has been farther improved to 5 km from March 2006). The data assimilation in MSM is made using a full forecast-analysis system, with a 4-dimensional variational (4D-VAR) method (Ishikawa 2001; Koizumi 2002). Numerical forecasts by MSM are currently made eight times a day using hourly WINDAS wind data, during six hours before each initial time. The amount of upper-air data being provided to MSM has been significantly increased since the start of the operation of the WINDAS, particularly in the lower troposphere. 4D-VAR makes the best use of the ability of wind profilers that provide temporally and spatially denser observation data of upper-air winds, than data from conventional radiosonde observations.

The impact of the WINDAS data on the MSM numerical forecasts of rainfalls, was statistically examined using threat scores (Tada 2001). The threat scores of 3 to 6 hour forecast of MSM, were examined in the period from 27 June to 26 July 2001. The threat scores for rainfalls smaller than 10 mm h\(^{-1}\) were not clearly improved, by using wind data obtained from the WINDAS. On the other hand, the threat score for rainfalls greater than 30 mm h\(^{-1}\), in the case of using only conventional upper-air observation data was 0.02, and the score was improved to 0.05 by adding wind data obtained from the WINDAS. This verified that the WINDAS data are effective for forecasting heavy rainfalls by providing wind data in the lower troposphere.

An impact experiment (observation system experiment) was conducted with MSM using the WINDAS data, and the 4D-VAR method for a severe rainstorm which occurred in western Japan in June 2001 (Ishikawa 2001). As shown in Fig. 8a, the forecasted location of the rainstorm, using only conventional upper-air observation data, is shifted approximately 60 km to the north of the true location of the rainstorm. On the other hand, the forecasted location of the rainstorm, with wind profiler data, well agrees to the true location as shown in Fig. 8b. This is because the northerly component of winds around the storm, forecasted from only radiosonde data (Fig. 8d) was larger than that in the case of adding the WINDAS data (Fig. 8e). Namely, the advection effect on the storm by environment winds, simulated without the WINDAS data, was overestimated, but the assimilation of the WINDAS data into MSM using the 4D-VAR method accurately forecasted the advection effect. This example practically indicated that data of the WINDAS, improved the accuracy of the NWP models of the JMA.

4.2 Hourly wind analyses

The JMA developed a new product, named the “Hourly wind analysis data”, corresponding to the start of operation of the WINDAS. The product is made out of the first guess of MSM wind data, on 5 km-horizontal grids, and is corrected by wind data from the WINDAS, commercial aircraft and Doppler radars at the airports. The product is a forcefull tool to illustrate three-dimensional kinematic fields in
mesoscale weather systems, being mainly used for nowcasting of significant weather events in forecast services, as well as in aviation weather services.

4.3 Example of analysis using the WINDAS data

An example showing the advantage of wind profiler data for analysis of kinematic aspects of a tropical storm is presented here. The 16th typhoon occurred in 2004 (Chaba), crossed over Japan from the southwest to the northeast, from 29 to 31 August 2004 as shown in Fig. 9a, changing its structure from a tropical cyclone into an extratropical cyclone (Yamashita and Ishihara 2005). The WINDAS data obtained near the track of the typhoon inner core, depicted tilting of the typhoon vortex, due to the influence from the midlatitude westerly flow. Figure 9b–d shows the time-height cross sections of winds from the wind profilers located at 31.7°N, 32.8°N and 34.9°N, respectively. The typhoon vortex at 31.7°N (Fig. 9b) was vertical through the surface to the upper troposphere. The vortex at 32.8°N (Fig. 9c) was started to tilt below the 4 km level, and the tilting was clearly recognized at 34.9°N (Fig. 9d). This tilting of the typhoon vortex, was thought to be resulted from the increase of environmental vertical shear around the typhoon as it intruded into the midlatitude westerly flow (Jones et al. 2003). This is a typical example
showing usefulness of the wind profiler network, for analyzing kinematical structure of mesoscale weather systems.

5. Conclusions

The JMA started the operation of the wind profiler network “WINDAS” in April 2001. The WINDAS consists of thirty-one 1.3 GHz-band wind profilers, and is characterized with dense spatial resolution of 130 km on the average over the main islands of Japan, high data accuracy due to strict data quality control and high data availability. Height coverage of wind measurement is 6–7 km in summer, 3–4 km in winter and 5.3 km on the average through a year. The wind data from the WINDAS has significantly contributed to improve accuracy of the numerical weather prediction of the JMA, mainly for mesoscale weather systems. Being put on GTS, the wind data are distributed to the world in real-time. Although a problem of data contamination from migrating birds had occurred in the first year of its operation of the WINDAS, it was practically solved by developing a removal algorithm. Extending uses of the WINDAS, such as physical retrieval, or direct data assimilation to numerical models for obtaining vertical profile of water vapor amount
from the wind profiler signal, will be the next issues in the operation of the WINDAS.

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