Measurement Performance Assessment of Future Space-Borne Doppler Wind Lidar for Numerical Weather Prediction

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Abstract

Global wind profile observation is important to improve initial conditions for numerical weather prediction (NWP), general circulation model, and various other meteorological studies. A space-borne Doppler wind lidar (DWL) is one of promising remote sensing techniques for global wind measurement.

We describe a study based on simulated satellite measurements for assessing the measurement performances of a Japanese coherent DWL. Global simulations are performed using pseudo-truth atmospheric model of an observing system simulation experiment (OSSE) conducted using the global NWP system of the Japan Meteorological Agency. Wind profile retrieval simulations have been performed for 1 month (August, 2010) and the results show that the percentage of good quality estimates is 40% below 8 km, and it decreases to 10% at 8–20 km in the southern hemisphere and is 20–50% in the northern hemisphere. Expected line-of-sight wind speed errors for good quality estimates are 0.5 m s^{-1} below 8 km and 1.1 m s^{-1} at 8–20 km.

In the future, the simulated observations will be used in the OSSE to quantitatively infer the potential impacts on NWP accuracy. To illustrate such analysis, results are shown from an initial validation test using a simple wind measurement model instead of the realistic DWL simulations.

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1. Introduction

Numerical weather prediction (NWP) and general circulation model (GCM) have improved over the last few decades. However, it is crucial to improve the initial conditions for NWP on synoptic and regional scales and GCM (Baker et al. 2014). Current space-borne observing systems are unbalanced toward temperature- and water-vapor-related measurements in comparison with wind measurements (Baker et al. 2014). Global wind profile observation is important to significantly improve the initial conditions (WMO 2012). Table 1 shows current user requirements of wind profile observation for global NWP (WMO, on-line). While the requirements are requested for globally homogeneous wind profile

observation, current global wind observing systems do not satisfy the requirements. Wind profile observations are measured mainly by radiosonde networks. Weather observation points on oceans and remote land areas are sparsely distributed. Single-layer wind measurement can be made by satellite-borne microwave scatterometers and polarimetric microwave radiometers. The vector winds called the atmospheric motion vector (AMV) are estimated from cloud and water vapor motions derived from geostationary and polar-orbit satellite images. The AMV achieves a large coverage area and high temporal resolution. However, the AMV cannot retrieve vector winds under thick clouds, and the vertical resolution is relatively low (2–4 km). Bias and root-mean-square (RMS) vector difference of the AMV retrieval verified against radiosonde wind observations as shown in previous studies (e.g. Hayashi and Shimoji 2013; Otsuka et al. 2015) are relatively large (bias less than 2 m s^{-1} and RMS vector difference worse than 4 m s^{-1}) compared to those expected from the space-borne Doppler Wind Lidar (DWL) as discussed in this study (expected precision and vertical resolution better than 2 m s^{-1} and 1 km, respectively). Global wind observing system with higher vertical resolution, low-bias and high precision is necessary to fill the gap of the current observations.

The European Space Agency is planning to launch the first space-borne DWL called ADM-Aeolus for obtaining global wind profiles (ESA 1999, Stoffelen et al. 2005). The current target year of the launch is 2016 (ESA, on line). It will provide profiles of line-of-sight (LOS) wind speed. A working group for a future space-borne DWL mission was organized in Japan in 2011 to discuss a space-borne coherent DWL (CDWL) for vector wind measurement. JAXA is developing a new type of satellites flying in a circular orbit at an altitude of 180–250 km and has a plan to launch the first new satellite after 2016 (Nagano et al. 2009). It will be a precursor mission for future advanced passive optical remote sensing and active remote sensing. Being at the low altitude allows the electrical power consumption required for the active remote sensing systems to be reduced, which is a promising approach for next-generation Earth observation missions. Target observation period of the space-borne CDWL is more than 3 years, and target satellite life is 5 years. In order to enhance the feasibility of the space-borne CDWL, the working group studies the feasibility of a super-low-altitude-satellite-borne CDWL. The concept of the future space-borne CDWL is to demonstrate its applicability to wind profile observation based on two LOS wind speed measurements and to show its usefulness for NWP and GCM, by improving prediction of typhoon and heavy rain and studies on meteorology and atmospheric transport. For the mission definition, it is necessary to objectively evaluate whether the performance characteristics of the instrument satisfy the requirements on NWP. Here, numerical simulations of the measurement are used for the purposes. An observing system simulation experiment (OSSE) is an evaluation method using data assimilation system

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Table 1. Ideal (Goal), breakthrough (BT), and threshold (TH) observational user requirements of wind profiling observation for global numerical weather prediction

Target atmosphere	Horizontal resolution (km)			Vertical resolution (km)			Wind accuracy (m s^{-1})		
	Goal	BT	TH	Goal	BT	TH	Goal	BT	TH
Lower Troposphere									5
High Troposphere	15	100	500	0.5	1	3	1	3	8
Low stratosphere									5

and simulated observations. The OSSE especially allows us to quantitatively estimate the impacts of the observations on NWP by simulated observational values. In Section 2, we describe the implementation of the OSSE using a simple lidar simulator and its validation is discussed. The numerical simulation setup and a first assessment of the measurement performances of the space-borne DWL are described in Section 3. Discussion and conclusion are presented in Section 4.

2. Potential impact of global wind profiling on numerical weather prediction

We constructed an OSSE system based on the sensitivity observing system experiment (SOSE) (hereafter, SOSE-OSSE, Marseille et al. 2008; Ishibashi 2014) using the JMA's global NWP system as of 2010 (JMA 2013). Pseudo-truth atmospheric field was created by SOSE and used in a full-fledged lidar simulator such as the Integrated Satellite Observation SIMulator (ISOSIM-L) for a space-borne CDWL, described in Section 3. The preparation is underway to implement SOSE-OSSE and to assess the impacts from space-borne CDWL wind profiles. Before implementing the comprehensive full SOSE-OSSE, we performed a simple, single SOSE-OSSE where a simple lidar simulator instead of ISOSIM-L was employed. It is worth describing the results of this simple SOSE-OSSE to validate the SOSE-OSSE system and to illustrate the potential impacts obtained from hypothetical global wind profile observations. This article presents this preliminary result and future companion papers will describe a more comprehensive SOSE-OSSE that assimilates realistic simulations from ISOSIM-L.

The simple simulator produces LOS wind profiles from the SOSE pseudo-truth assuming a space-borne observing system onboard a polar orbiting satellite crossing the equator at 0930 local time. The simple operator interpolates longitudinal and latitudinal wind components of the pseudo-truth to observation locations in the horizontal interval of 250 km of 2,000 km swath at 100, 300, 500, 700 and 900 hPa every hour, converts them into wind speed in the LOS direction at azimuthal angle of 45 degree, and then adds random errors with 1 m s^{-1} standard deviation to mimic real observations. We define the converted LOS wind profile as a synthetic wind profile. This simple simulator does not account for observation sampling determined by clouds and aerosols. Note that the vertical resolution is coarser and horizontal width is greater than that for the future space-borne CDWL we planned (see Section 3.1). We carried out an assimilation experiment using a low-resolution version ($\sim 60 \text{ km}$) of the JMA NWP system at 00 UTC on 1 August 2010, and then ran an 84-hour forecast. Figure 1 shows the data distribution of the simulated winds in a 6-hour data assimilation window from 21 UTC on 31 July to 03 UTC on 1 August 2010 and the forecast improvement rate (IR) for wind speed at 850 hPa for 36-hour forecast. The IR is defined as the normalized RMS error difference between the control experiment where only operational datasets are assimilated and the test experiment where the simulated wind profile observations are assimilated in addition to the operational dataset as of 2010. The normalized RMS error is computed against the operational analysis at the valid time. This may not be appropriate when verifying very short-range forecasts (e.g. at 6-hour) but it can be assumed that the analysis is accurate enough to verify forecasts at longer ranges (Garand et al. 2013). There are positive or negative IR's where the

Fig. 1. (a) Distribution of the synthetic wind observations. (b) Improvement rate IR , defined by normalized difference of root-mean-square forecast error by assimilating synthetic wind profiles, for horizontal wind speed at 850 hPa at 36-h forecast. Positive values or warmish shaded areas indicate smaller forecast errors.

synthetic winds are assimilated. A positive IR , indicating a reduction in the normalized RMS error or an improvement in the wind speed forecasting, is more evident especially in the middle and high latitudes of the southern hemisphere. Figure 2 shows a global averaged IR for 24- to 84-hour forecast ranges. The highest IR is in the short forecast range from 24- to 48-hour (dashed line with two arrows). The IR becomes smaller after a 48-hour forecast but is still positive at most pressure levels. These results are reasonable in that they are consistent with many studies on satellite data assimilation that produces positive impacts for the short-range forecast in the southern hemisphere. These encouraging results tell us that our SOSE-OSSE properly works and that global wind profile observations could give us additional positive impacts on the NWP system where many other observations are already assimilated. We are constructing a more sophisticated SOSE-OSSE system to discuss in detail DWL impacts that includes realistic aerosol and cloud models that are consistent with a pseudo-truth meteorological field, simulating much more realistic space-borne

Fig. 2. Time sequence of global averaged *IR* for horizontal wind speed from 24-h to 84-h forecasts. Solid (dotted) contour lines show positive (negative) *IR*.

DWL wind measurements based on the ISOSIM-L. In addition, the magnitude and detailed forecast ranges and meteorological variables of the improvement we obtained in this study can vary with different seasons and periods of assimilation experiment. We plan to implement the assimilation experiments for longer period such as one month in different seasons to perform robust impact studies.

3. Potential performance of space-borne Doppler Wind Lidar observation

3.1 Setup for numerical simulations

We developed an end-to-end Doppler lidar simulator called ISOSIM-L to study the performance of a space-borne CDWL and to evaluate the rate and distribution of good quality observations as well as their random errors and biases for various wind observation geometries. The ISOSIM-L considers all laser shots transmitted continuously to the atmosphere along a simulated orbit. Each simulated LOS measurement is decomposed into narrow range gates of 100 m length. For each range gate, the ISOSIM-L assumes the theoretical power spectral density of the measured signal and computes the theoretical time-domain signal. The ISOSIM-L calculates the backscattered signal characteristics (power, Doppler-shifted frequency, spectral width, random time signal and its power spectrum) under the assumption that atmospheric conditions are homogeneous inside each range gate. The power spectra of the time-domain signals are averaged to match the desired spatial resolution, and the Doppler-shifted frequency is retrieved (Zrinć 1979). The retrieval method is based on the periodogram maximum likelihood estimator (Frehlich and Yawlosky 1994). A Doppler-shifted frequency of 1 MHz corresponds to a LOS wind speed of about 1 m s^{-1} at $2 \mu\text{m}$. The total error of a DWL wind measurement is determined by measurement noise, a retrieval bias and error, a frequency search band, and a bad estimates ratio (Frehlich 2004). More details on simulation algorithms and errors of the ISOSIM-L are given in Baron et al. (2015).

Here, we use an observation geometry based on previous feasibility studies (Ishii et al. 2012). The DWL looks off nadir to detect a Doppler-shifted LOS wind. A nadir angle of 35° is selected for the ISOSIM-L simulations. Azimuthal angles of 45° and 135° along the satellite track are used to obtain effective wind vectors. The altitude of the satellite is set to 220 km. The ISOSIM-L computes virtual space-borne DWL observations with a horizontal resolution of 100 km and vertical resolutions of 500 m in the altitude range of 0.1–3 km (lower troposphere), 1 km between 3–8 km (middle troposphere) and 2 km between 8–20 km (upper troposphere and lower stratosphere). The LOS wind speeds observed at altitudes below 0.1 km are not used in this analysis because of surface-return contaminations. Laser pulse energy, receiver efficiency, telescope diameter, and other system parameters are based on previous feasibility studies and specifications

Table 2. System parameters used for ISOSIM-L simulations

Wavelength (μm)	2.05
Pulse energy (mJ)	125
PRF (Hz)	30
Pulse duration FWHM (ns)	200
Telescope diameter (m)	0.4
Receiver efficiency	0.08
Sampling frequency (MHz)	400
Sampling point	256
Azimuth angle (deg)	45, 135
Nadir angle (deg)	35
Satellite altitude (km)	220
Speed of satellite (km s^{-1})	7.8

for a ground-based coherent lidar developed at NICT (Ishii 2009; Ishii et al. 2010). The details of DWL parameters are summarized in Table 2.

The ISOSIM-L simulations use the SOSE pseudo-truth global atmospheric state (wind, temperature, pressure and, liquid water) given for one month of August 2010 and the aerosol data set calculated for the same period using a global aerosol model named the Model of Aerosol Species IN the Global Atmosphere (MASINGAR, Rev. 2) (Tanaka et al., 2003) (see Fig. S1(a)). The horizontal and temporal resolutions of the atmospheric and aerosol models are $1.125^\circ \times 1.125^\circ$ and 1 hour. The vertical resolutions of the atmospheric and aerosol models are 20 m near the surface to 2 km in the lower stratosphere (60 vertical levels) and 100 m to 1 km (48 vertical levels), respectively. Clouds are randomly generated from the pseudo-truth liquid water, temperature and cloud coverage on an ISOSIM-L grid defined along the orbit track with a horizontal resolution of $10 \times 10 \text{ km}^2$ and a vertical resolution of 200 m (see Fig. S1(b)).

3.2 Results

The comparison of Doppler-shifted frequency estimates with respect to the true state determines the measurement performance of a DWL. The probability density function (PDF) of the retrieved Doppler-shifted frequencies is composed of a localized component of “good” estimates around the true mean frequency and a uniformly distributed “bad” estimates over the full bandwidth (= sampling frequency/2). In this study, we use a bad estimate ratio b given by Eq. (E15) of Frehlich (1997). Figure 3 shows the wind speed error with respect to the signal to noise ratio *SNR* for ideal conditions (homogenous atmosphere) and for various average number of range gates N . Only data for $b < 50\%$ are shown. Dashed lines show the theoretical values based on the Cramer-Rao lower bounds *CRLB* (Scharf 1991) on the standard deviation of Doppler-shifted frequency estimates defined by Eq. (10) of Rye and Hardesty (1993). Errors decrease with $\sqrt{N}$. Errors are constant

Fig. 3. Relationship between signal to noise ratio *SNR* and wind speed error for various average number of range gates N . The bad retrieval ratio b is lower than 50%. Dashed lines are the Cramer-Rao lower bounds.

in the region of $SNR > 0.1$ because of the effect of speckle noise. The speckle noise is the dominant noise source in the region, and it limits the measurement performance of a CDWL. For the region of $SNR < 0.1$, errors are near the theoretical values and increase with a law in $1/SNR$.

Figure 4a shows the ratio of bad estimates derived statistically from the one-month ISOSIM-L simulations for the three altitude ranges of 0-3, 3-8, and 8-20 km. The results are representative of realistic conditions with non-homogeneous atmosphere. When $SNR \cdot \sqrt{N}$ is larger than 0.1 and b is smaller than 1%, retrieval data are considered as “good quality estimates”. For a pulse rate frequency PRF of 30 Hz and a horizontal resolution of 100 km, N increases from about 2000 to 8000 for vertical resolutions of 500 m and 2 km, respectively. SNR 's associated with good quality estimates are larger than 0.002 and 0.001 for $N = 2000$ and 8000, respectively.

Figure 4b shows the percentages of good quality estimates for the three altitude ranges over different latitudes. The percentage is defined as the ratio of good estimates to the total number of estimates in narrow bins of SNR and N . The percentage is about 40% for all latitudes except for the altitude range of 3-8 km in the latitude range of 30S-Eq. For the altitude range of 8-20 km, the percentage is about 10% in the southern hemisphere and 20-50% in the northern hemisphere. These differences are due to the aerosol concentration and the probability of occurrence of clouds. Figure 4c shows the expected wind speed error for good quality estimates in the three altitude ranges and the different latitude ranges. The expected LOS wind speed errors for the lower and middle troposphere, and upper troposphere are about 0.5 and 1.1 $m s^{-1}$ over the latitudes, respectively. Errors found from the ISOSIM-L are larger than those estimated for homogeneous atmosphere. The measurement performances are limited by the variability of the atmospheric wind and to a lesser extent by that of the single-range SNR 's. The variability of the atmosphere is defined as a representative error (Frehlich 2001). It is important to discuss the seasonal dependency of our results. For example, CALIOP data show seasonal and geographical features of aerosol loads (Winker et al. 2013), and MODIS also suggest seasonal and terrestrial contrasts of cloud fraction (King et al. 2013). The measurement performance related to SNR can vary with the aerosol concentration and the probability of occurrence of clouds. This study evaluated the measurement performances using a global one-month dataset of August 2010, which contained various meteorological conditions including geographical contrast of the aerosol loads and cloud fractions. Thus, we suppose that our result is valid for different seasons. In order to prove our supposition, however, further studies must be conducted for longer period and different seasons in future.

4. Discussion and conclusion

Direct space-borne DWL wind measurement is one of the promising approaches for global wind profile observation. In this paper, we described the concept of a future space-borne CDWL, the validation of the SOSE-OSSE using synthetic wind profile data, and the measurement performance of the space-borne DWL using ISOSIM-L. Typical percentages of good quality estimates are 40% in the altitude range of 0-8 km, and 10% in the altitude range of 8-20 km for the southern hemisphere and 20-50% for the northern hemisphere, which depends on the aerosol concentration and the probability of occurrence of clouds. The expected LOS wind speed errors for good quality estimates are about 0.5 $m s^{-1}$ below 8 km and 1.1 $m s^{-1}$ at 8-20 km over the latitudes.

Since the AMV is a major source of the global wind observation for current NWP systems, it is worth comparing the characteristics of the AMV and the space-borne DWL. We would like to discuss the advantages of having simultaneous the AMV and DWL wind data. The space-borne DWL could perform wind measurements with a small bias, a high precision, a high vertical resolution but with a limited coverage area and temporal resolution. Although the AMV makes large horizontal wind distribution at a

Fig. 4a. Relationship between $SNR \cdot \sqrt{N}$ and b calculated for (black line) 0-3 km, (dark grey line) 3-8 km, and (light grey line) 8-20 km. SNR is the signal to noise ratio. N is the average number of range gates.

Fig. 4b. Percentage with good quality estimates for different latitude ranges: (black bar) 0-3 km, (dark grey bar) 3-8 km, and (light grey bar) 8-20 km.

Fig. 4c. Expected wind speed error for good quality estimate in various altitude ranges over the different latitude ranges: (black bar) 0-3 km, (dark grey bar) 3-8 km, and (light grey bar) 8-20 km.

horizontal resolution of $0.5^\circ \times 0.5^\circ$, it cannot retrieve vector winds under thick clouds and only provides us a limited wind profile (single or a few observation heights) with a low vertical resolution of 2 km. The AMV can hardly retrieve the vector winds over dry regions, clear-sky or fewer cloud regions, atmosphere near Earth's surface over inland areas, and low wind speed regions. On the other hand, although the space-borne DWL cannot make wind measurement under/inside thick clouds, it can provide us with a full wind profile at along-track horizontal and vertical resolutions better than 100 km and 1 km, respectively. The measurement characteristics of the space-borne DWL are complementary to the AMV retrieval and very helpful for their algorithm improvements. The synergy between the AMV and space-borne DWL wind mea-

surements would improve the initial conditions for NWP, GCM, and meteorological studies.

In the future, a SOSE-OSSE will be conducted using wind measurements simulated with ISOSIM-L in order to assess the potential impacts of the space-borne DWL on NWP and GCM. In this paper the SOSE-OSSE has been introduced and results of its validation using synthetic space-borne observations have been presented. The results using ISOSIM-L data will be discussed in future companion papers.

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Supplement

Supplementary materials include Figs. S1(a) and S1(b) and more detailed information.

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