Assimilation of wind speed and direction observations: a new formulation and results from idealized experiments

Xiang-Yu Huang[1], Feng Gao[1,2], Neil A. Jacobs[3] and Hongli Wang[1]

[1]National Center for Atmospheric Research, Boulder, CO, USA; [2]Nanjing University of Information Science & Technology, Nanjing, China; [3] Panasonic Weather Solution, Morrisville, NC, USA

Introduction

Current data assimilation systems, including the Weather Research and Forecasting Data Assimilation (WRFDA, Huang et al., 2009; Barker et al., 2012), do not consider wind direction errors when assimilating wind observations. Despite being collected in the form of speed (*sp*) and direction (*dir*), wind observations are transformed to their longitudinal and latitudinal components, *u* and *v*, prior to assimilation. The observation errors of *u* and *v*, which may be estimated from the wind speed error, are used in the assimilation. Although the *dir* errors can impact the uncertainty of *u* and *v*, they cannot be considered during the assimilation process, and therefore have no independent influence on the assimilation results. A new method of directly assimilating *sp* and *dir* observations, referred to as asm_sd, is proposed and compared with the conventional method, referred to as asm_uv, in Huang et al. (2013) and is briefly presented by this poster.

WRFDA and new formulation

WRFDA employs the incremental formulation of Courtier et al. (1994). The analysis increment minimizes a cost function,

$$J(\delta x)=\frac{1}{2}\delta x^T\mathbf{B}^{-1}\delta x+\frac{1}{2}(\mathbf{H}\delta x-\mathbf{d})^T\mathbf{R}^{-1}(\mathbf{H}\delta x-\mathbf{d})$$

where the superscripts -1 and T denote inverse and adjoint of a matrix or a linear operator, $\delta\mathbf{x}=\mathbf{x}^a-\mathbf{x}^b$ is the analysis increment, $\mathbf{x}^a$ is the analysis, $\mathbf{x}^b$ is the background, $\mathbf{d}=\mathbf{y}-H(\mathbf{x}^b)$ is the innovation vector, $\mathbf{y}$ is the observation vector, H is the nonlinear observation operator, $\mathbf{H}$ is the linearized H, $\mathbf{B}$ is the background error covariance, $\mathbf{R}$ is the observation error covariance.

Here, we only discuss the items related to wind observations. The model state vector, $\mathbf{x}$, contains, among other variables, u and v,

$$\mathbf{x}=(\cdots,u,v,\cdots)^T$$

In asm_uv, wind observations largely collected in the format of dir^o and sp^o, are transformed to u^o and v^o before being assimilated; and in asm_sd, wind observations are assimilated in their original form of dir^o and sp^o :

$$\mathbf{y}_{asm\_uv}=(\cdots,u^o,v^o,\cdots)^T;\quad \mathbf{y}_{asm\_sd}=(\cdots,dir^o,sp^o,\cdots)^T$$

For asm_sd, the nonlinear observation operator, H_t, tangent-linear operator, $\mathbf{H}_t$ and adjoint operator $\mathbf{H}_t^T$ are expressed as:

$$\begin{pmatrix}sp\\dir\end{pmatrix}=H_t\begin{pmatrix}u\\v\end{pmatrix}\qquad \begin{pmatrix}\delta sp\\\delta dir\end{pmatrix}=\mathbf{H}_t\begin{pmatrix}\delta u\\\delta v\end{pmatrix}\qquad \begin{pmatrix}\delta u^*\\\delta v^*\end{pmatrix}=\mathbf{H}_t^T\begin{pmatrix}\delta sp^*\\\delta dir^*\end{pmatrix}$$

$$sp=(u^2+v^2)^{1/2}\qquad \mathbf{H}_t=\begin{pmatrix}\frac{u}{\sqrt{u^2+v^2}} & \frac{v}{\sqrt{u^2+v^2}}\\ \frac{v}{u^2+v^2} & \frac{-u}{u^2+v^2}\end{pmatrix}\qquad \mathbf{H}_t^T=\begin{pmatrix}\frac{u}{\sqrt{u^2+v^2}} & \frac{v}{u^2+v^2}\\ \frac{v}{\sqrt{u^2+v^2}} & \frac{-u}{u^2+v^2}\end{pmatrix}$$

$$dir=n\pi+\arctan\left(\frac{u}{v}\right)$$

H_t computes *sp* and *dir* from *u* and *v*; n is chosen to confine *dir* part of **d** within [-180°,180°].

$\mathbf{H}_t$ computes perturbations in *sp* and *dir* from perturbations in *u* and *v*,

$\mathbf{H}_t^T$ computes the gradients in *u* and *v* from the gradients in *sp* and *dir*

The errors of most observation types are assumed to be uncorrelated; thus, the observation error covariance, $\mathbf{R}$, becomes a diagonal matrix with observational error variance on the diagonal. In the asm_uv or asm_sd formulations, $\mathbf{R}$, is expressed in form of *u*, *v or sp*, *dir* as:

$$\mathbf{R}_{asm\_uv}=\begin{pmatrix}\ddots&0&0&0\\0&\sigma_u^2&0&0\\0&0&\sigma_v^2&0\\0&0&0&\ddots\end{pmatrix}\qquad \mathbf{R}_{asm\_sd}=\begin{pmatrix}\ddots&0&0&0\\0&\sigma_{sp}^2&0&0\\0&0&\sigma_{dir}^2&0\\0&0&0&\ddots\end{pmatrix}$$

In contrast to the approximations and assumptions made for $\mathbf{R}$ in asm_uv, the estimation of $\mathbf{R}$ in asm_sd can be made directly.

Idealized Case

Assuming *u*, *v*, *dir* and *sp* can be analyzed univariately and the ratio between **B** and **R** is 1. From the same OBS and BG, asm_uv leads to analysis:

$$u^a_{uv}=\tfrac{1}{2}(u^b+u^o)$$
$$v^a_{uv}=\tfrac{1}{2}(v^b+v^o)$$

asm_sd leads to analysis:

$$sp^a_{sd}=\tfrac{1}{2}(sp^b+sp^o)$$
$$dir^a_{sd}=\tfrac{1}{2}(dir^b+dir^o)$$

which could be very different, as shown in Fig.1.

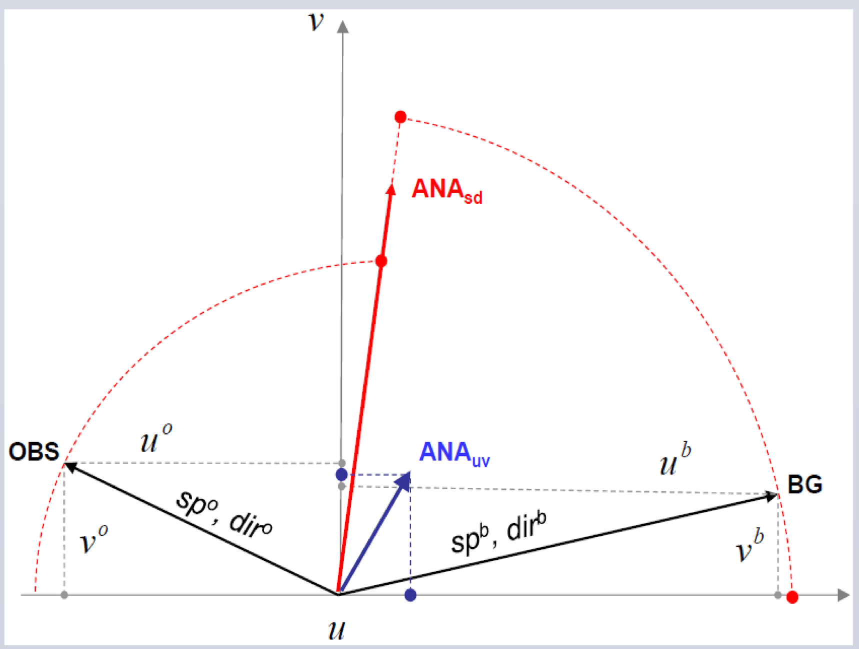


Fig. 1 The background (BG), observation (OBS) and analyses wind vectors obtained by asm_uv (ANA_{uv}) and asm_sd (ANA_{sd}).

Single Observation Experiments

The results from three experiments, with (sp^o, dir^o) = (16.2, 111.8) and (sp^b, dir^b) = (25.5, 258.7), are shown in Fig. 2. We use 1.5 m s^{-1} for both *u* and *v* observational errors, and use 1.5 m s^{-1} for the *sp* observation error and 10°/2.9 ° for *dir* observation errors as the comparison.

As discussed, the observational *dir* error should influence the analysis, and it is demonstrated in this test with asm_sd.

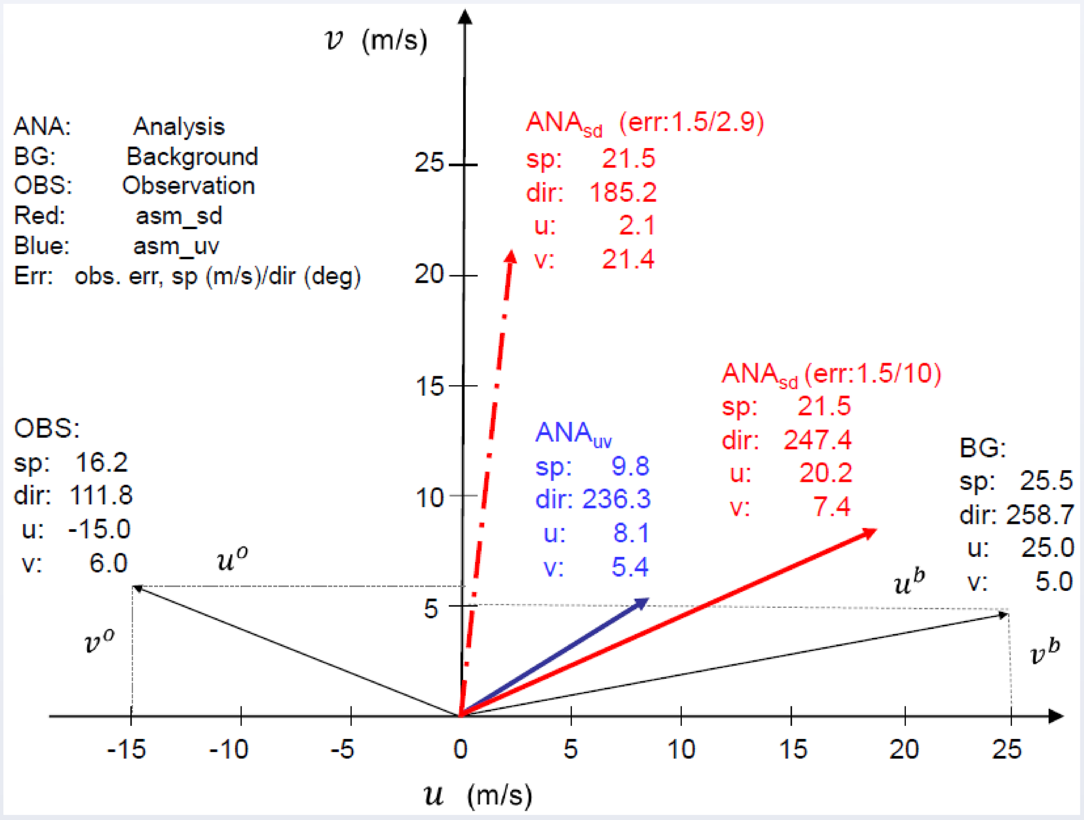


Fig. 2 The background (BG), observation (OBS) and analyses wind vectors obtained by asm_uv (ANA_{uv}) and asm_sd (ANA_{sd}). The same as Fig.1, but from single observation experiments.

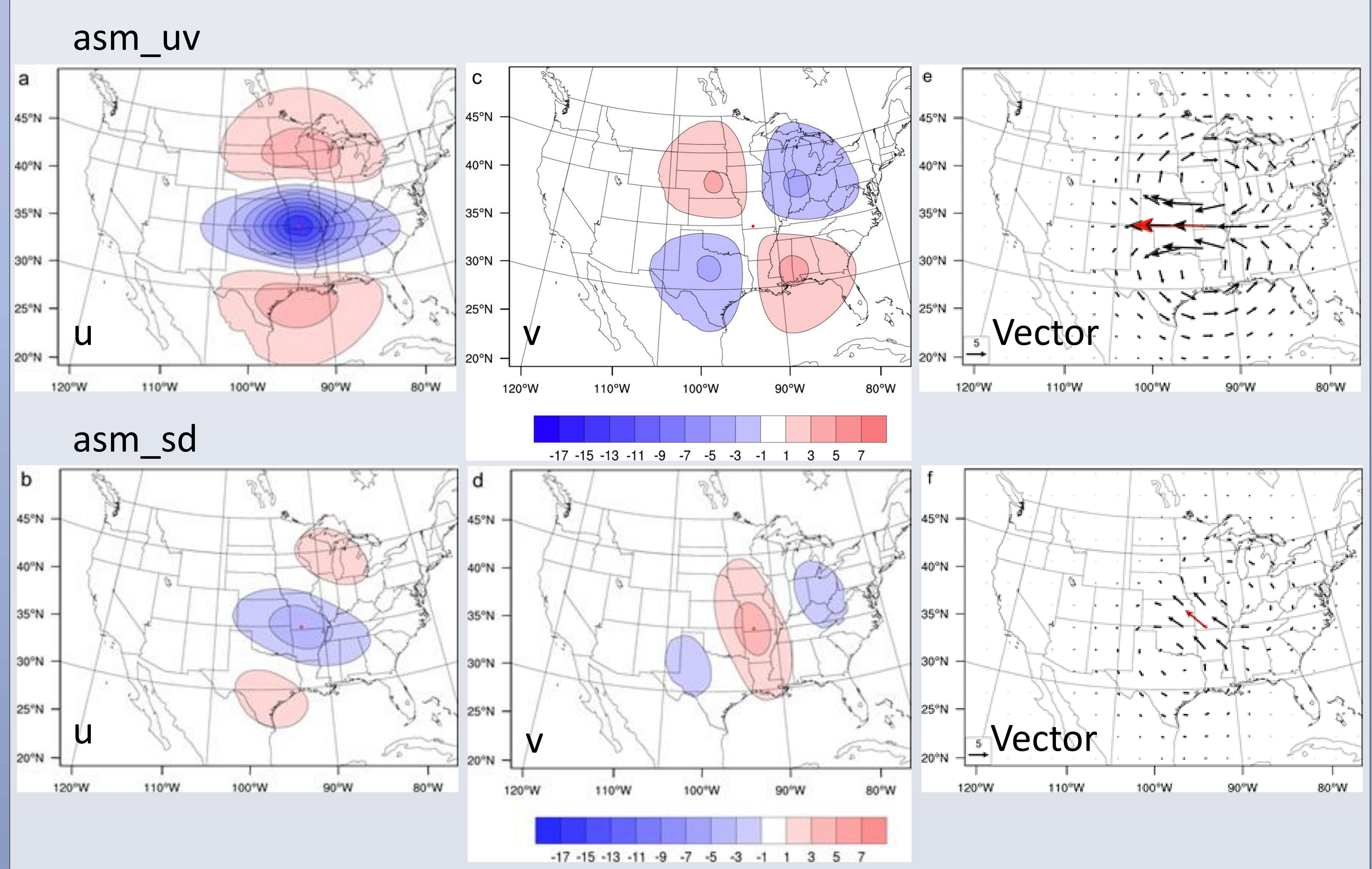


Fig. 3. The wind analysis increments due to a single wind observation pair (-15.0 m s^{-1}, 6.0 m s^{-1}) or (16.2 m s^{-1}, 111.8°) by asm_uv (upper; a, c, e) and by asm_sd (bottom; b, d, f).

Stronger wind

Under the assumptions made for the idealized case, it is easy to show that the analysis wind vector obtained by asm_sd is always longer than the analysis wind vector obtained by asm_uv when the background wind vector and the observation wind vector do not point in the same direction, as shown in Fig.4a.

$$sp^a_{uv}=\sqrt{(u^a_{uv})^2+(v^a_{uv})^2}=\tfrac{1}{2}\sqrt{(u^b+u^o)^2+(v^b+v^o)^2}$$

$$sp^a_{sd}=\tfrac{1}{2}(sp^b+sp^o)=\tfrac{1}{2}\left(\sqrt{(u^b)^2+(v^b)^2}+\sqrt{(u^o)^2+(v^o)^2}\right)$$

We also reached the same qualitative confusion, without the above assumptions, by running single wind observation experiments using WRFDA, as shown in Fig.4b.

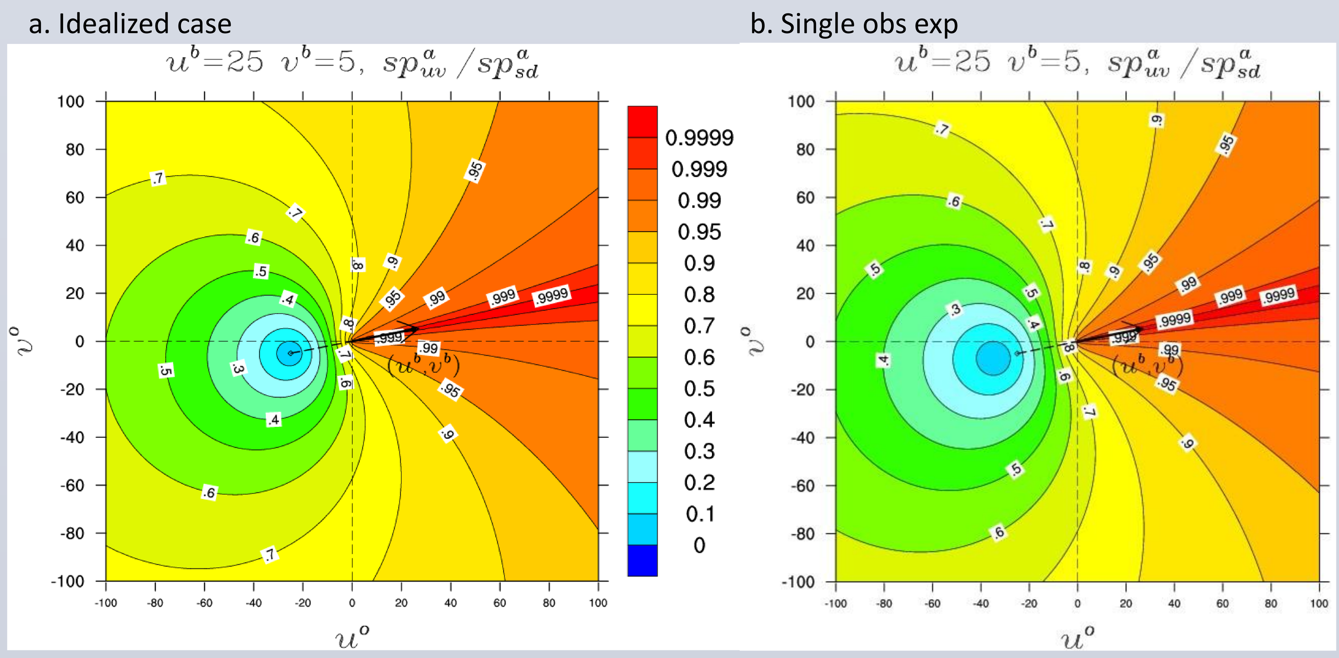


Fig. 4. The ratio of wind speed analysis of asm_uv to that of asm_sd as a function of u^o and v^o.

Observing System Simulation Experiments

1) Generate a reference atmosphere calling a "nature" run, by using a higher-resolution model

The experiment configuration:

	Model	Resolution	IC/BC	Sigma level	Cycle
Nature run	WRF	6 km	FNL	57	No
Control run	WRF	18 km	GFS	37	6 hours

Assimilation starts at 0000 UTC 16 Dec, 2011, and runs 9 cycles in two days.

2) Generate simulated observations using "nature" combined with realistic observational errors

From the reference atmosphere, we extract *sp* and *dir* at observation locations, and add observation errors (Gao et al., 2012), to simulate observations, sp^o and dir^o, over the entire network.

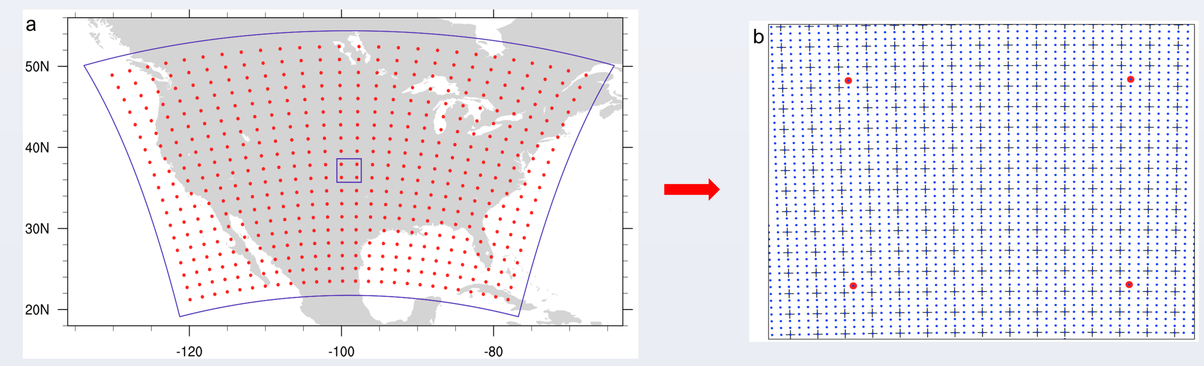
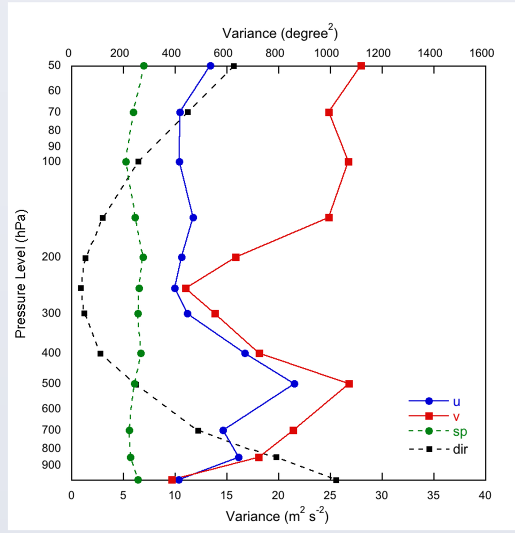


Fig. 5 Model domain and the distribution of simulated observations and an enlarged view (b) of the small box in (a), with "nature run" grid points (small dots), "control run" grid points (crosses) and observation locations (large dots)

3) Compute observation errors

The observation errors for sp^o, dir^o, u^o and v^o are then computed by comparing the simulated observations against the reference atmosphere. The observation errors are shown in Fig.6.

Fig. 6 The observation variances for sp^o, dir^o, u^o and v^o.



4) Assimilate the simulated observations

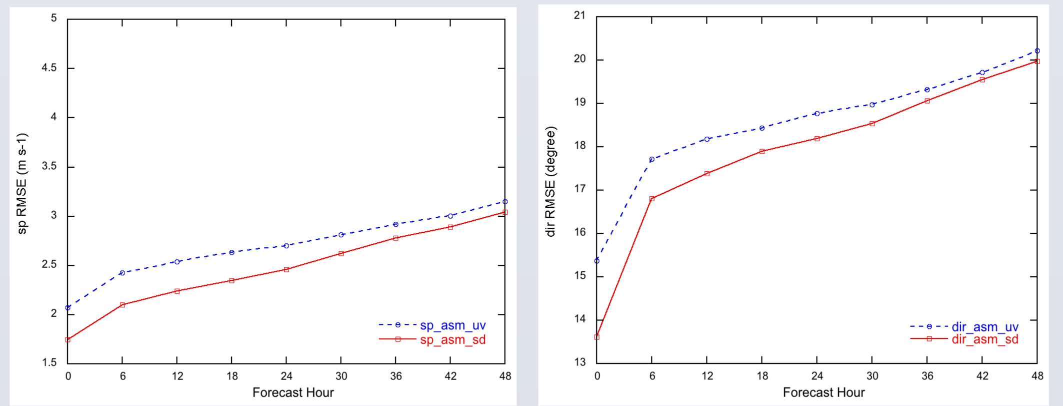


Fig. 7 The average RMSE of analyses and 48-h forecasts over the 9 data assimilation cycles against nature run.

Summary

The formulation of asm_sd ensures that the analysis vector falls between the background and observation in terms of *sp* and *dir*. Its analysis can be influenced by the wind direction observation error, which should play an important role in most data assimilation systems. The results presented in OSSE show that the asm_sd method produces a more accurate analysis, and as a result, can also lead to a better forecast when compared to the asm_uv method.

Because the scope of this paper focuses on the idealized configurations, the quality control aspect of the data assimilation has not been directly addressed. The real observation experiments show that the quality control and the assimilation method itself both have the ability to improve the analysis, which will be published in a following paper.

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