NOTES AND CORRESPONDENCE

The Impact of Surface Wind Data Assimilation on the Predictability of Near-Surface Plume Advection in the Case of the Fukushima Nuclear Accident

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Abstract

We investigated the predictability of plume advection in the lower troposphere and the impact of AMeDAS surface wind data assimilation by using radioactive cesium emitted by the Fukushima nuclear accident in March 2011 as an atmospheric tracer. We conducted two experiments of radioactive plume predictions over eastern Japan for March 15, 2011 with a 3-km horizontal resolution using the Japan Meteorological Agency non-hydrostatic weather forecast model and local ensemble transform Kalman filter (JMANHM-LETKF) data assimilation system. The assimilated meteorological data were obtained from the standard archives collected for the Japan Meteorological Agency operational numerical weather prediction and the AMeDAS surface wind observations. The standard archives do not contain land-surface wind observations. The modeled radioactive cesium concentrations were examined for plume arrival times at 40 observatories. The mean error of the plume arrival times for the standard experiment (assimilating only the standard archives) was 82.0 min with a 13-h lead-time on an average. In contrast, the mean error of the AMeDAS experiment (assimilating both the standard archives and AMeDAS surface wind observations) was 72.8 min, which was 9.2 min (11 %) better than that of the standard experiment. This result indicates that the plume prediction has a reasonable accuracy for the environmental emergency response and the prediction can be significantly improved by the surface wind data assimilation.

Keywords surface wind data assimilation; plume advection predictability; Fukushima nuclear accident; environmental emergency response

1. Introduction

The advection of minor constituents in the troposphere (e.g., water vapor, oxidants, and aerosols) is one of the key processes for numerical weather or environment prediction. Advection, emission, deposition, and chemical/physical changes define constituent distributions. For weather prediction, the distribution of water vapor influences the coverage and strength of precipitation. Moreover, the distributions of oxidants, aerosols, and their precursors directly impact human health and indirectly modify the weather and climate. However, it is difficult to simulate advection in the lower troposphere due to poor reproducibility of near-surface wind velocities in numerical weather simulations. Numerical weather forecast models cannot explicitly resolve fine-scale structures of real surface wind velocities due to the topographical heterogeneity and the instability (or nonlinearity) of the atmospheric boundary layer (ABL). These sub-grid scale features cause discrepancy between the measured and forecast-
ed variables. Therefore, the observational datasets of surface wind velocities are usually very limited or are avoided for operational weather prediction (e.g., Japan Meteorological Agency (JMA) 2015, in Japanese) to prevent the degradation of initial conditions. To improve near-surface wind prediction, recent studies tried to assimilate surface wind observations over land (e.g., Hacker and Snyder 2005; Benjamin et al. 2010; Hacker and Rostkier-Edelstein 2007; Hacker et al. 2007; Rostkier-Edelstein and Hacker 2010; Ancell et al. 2011, 2015; Ingleby 2015; Bédard et al. 2015, 2017). In these studies, however, the surface wind observations have an influence only on extremely short-term and local forecasts (less than 6 h) even if they have a positive impact. Besides, these past studies have not particularly investigated the predictability of constituent advection.

In this context, validating constituent advection predictions and understanding the impact of surface wind data assimilation have garnered increasing attention. Especially, the predictability of near-surface plume advection is a crucial factor for the environmental emergency response (EER), in which we have to prepare for the dispersion of hazardous materials emitted from a point source on the ground to the ABL. If the plume prediction has a reasonable accuracy like weather forecast, the area in danger will have to be evacuated in advance (World Meteorological Organization 2006). As mentioned above, the surface wind data assimilation is often very limited or avoided for weather analyses and predictions, although nudging of surface wind observations has been performed for lower tropospheric advection simulations (e.g., the WRF-CMAQ ozone simulation conducted by Li et al. 2016). However, the impact of surface wind data assimilation has not been well investigated for these advection simulations, especially for predictions incorporating high-performance data assimilation.

The investigation of plume advection requires widespread tracer observations with a fine time resolution. Therefore, we used radioactive cesium emitted by the Fukushima nuclear accident in March 2011 as the atmospheric tracer. The radioactive cesium plume was dispersed from a single source (the Fukushima Daiichi Nuclear Power Plant). The surface concentration of the plume was measured at many locations at a high frequency and with high accuracy (Tsuruta et al. 2014; Oura et al. 2015). This point source plume is advantageous due to its simple tracer isolation and validation without cross-dispersion. This paper shows the accuracy of the $^{137}$Cs plume advection prediction and the impact of surface wind data assimilation on the predictability of the $^{137}$Cs plume advection in the following sections.

2. Methodology

In general, atmospheric advection models require a gridded point value (GPV) dataset that contains a meteorological analysis or prediction that is precalculated via a high-performance data assimilation system. For example, the JMA operational meso-GPV dataset was used by all regional models that participated in the multimodel intercomparison of Fukushima nuclear pollution predictions (Science Council of Japan (SCJ) 2014) except for two models. One was our model (Sekiyama et al. 2015), which used an original meteorological dataset. The other model used the European Centre for Medium-Range Weather Forecasts (ECMWF) operational global GPV dataset. All models except Sekiyama et al. (2015) utilized the GPV datasets that were prepared by others (i.e., JMA or ECMWF). However, for the purpose of our investigation, the GPV datasets have to be prepared by our own data assimilation system because we need to arrange a comparison of meteorological analyses performed in the presence or absence of surface wind data assimilation. Hence, we utilized the meteorological data assimilation system of Sekiyama et al. (2015) in this study to prepare the GPV datasets with and without land-surface wind data assimilation.

The meteorological data assimilation system of Sekiyama et al. (2015) was developed by Kunii (2014) and is composed of the JMA's non-hydrostatic regional weather prediction model (JMANHM, cf., Saito et al. 2006, 2007) and the local ensemble transform Kalman filter (LETKF, cf., Miyoshi and Aranami 2006). In this study, this system was driven by 20 ensemble members and a 3-km horizontal resolution within the model domain of eastern Japan ($215 \times 259$ grids, cf., Fig. 2b of Sekiyama et al. 2015). The covariance localization parameters were set to 50 km in the horizontal, 0.1 natural-logarithm-pressure coordinate in the vertical, and 3 hours in the time dimension for all observations. The boundary conditions for the model domain were provided by the JMA operational global analysis and prediction. Incidentally, JMANHM has been used to produce the JMA operational meso-GPV dataset at a 5-km horizontal resolution since before March 2011 with a four-dimensional variational (4D-Var) data assimilation method. This weather forecast system is known as JNoVA (Honda et al. 2005).

Using the abovementioned JMANHM-LETKF data assimilation system, two types of meteorological
The initial conditions were prepared from March 11 to 31, 2011 at 3-h intervals. One was the standard analysis (STD), which was produced by assimilating only the observations archived for the JMA operational analysis of JNoVA. These observations were collected by land-surface observatories (pressure measurements only), satellites (including sea surface wind), radiosondes, pilot balloons, wind profilers, aircrafts, ships, and buoys. The satellite radiances and radar precipitation analyses were excluded from this study. This JNoVA dataset does not contain land-surface wind-velocity observations.

The other analysis was produced by assimilating the JNoVA dataset and the land-surface wind-velocity observations collected by AMeDAS. AMeDAS is the acronym of the automated meteorological data acquisition system managed by JMA, which is a land-surface observation network that comprises approximately 1,300 stations throughout Japan with an average interval of 17 km. In this study, we assimilated the land-surface wind velocities from more than 200 AMeDAS stations within the model domain (shown in Fig. 1).

For the surface wind data assimilation of the AMeDAS experiment, the height of the surface wind velocity was intended to be fixed at 10 m, because almost every AMeDAS anemometers are installed at a height of 10 m according to the World Meteorological Organization guideline. All observed velocities $U_{obs}$ were transformed into $U_{10}$ by using the following formula:

$$U_{10} = \frac{\ln \left( \frac{10}{z_0} \right)}{\ln \left( \frac{z_{obs}}{z_0} \right)} U_{obs},$$

where $z_{obs}$ is the height of the anemometer installation and $z_0$ is a constant roughness length (1 m). However, the transformation was negligible in the experiment. The observation errors of the AMeDAS surface wind velocity were set to 2 m s$^{-1}$, which is a comparable level to the root mean square errors (RMSEs) of the STD experiment shown in Fig. 2. The RMSEs and correlation coefficients ($r$) in Fig. 2 were calculated by 1-h forecasts of the STD and AMeDAS experiments that were performed every 3 h from 00:00 UTC on March 11 to 12:00 UTC on March 15, 2011 at the AMeDAS stations used in this study.

Using these meteorological analyses as the initial conditions, two forecast runs (STD and AMeDAS experiments) were performed with the same JMANHM configuration for 48 h. The boundary conditions were provided by the JMA operational global prediction with the same initial time as JMANHM. The forecast initial time was set to 12:00 UTC on March 14 to reproduce the radioactive cesium plume behavior over the inland area of eastern Japan. According to Nakajima et al. (2017), the radioactive plumes moved primarily over the ocean during the Fukushima nuclear accident in March 2011. However, on March 15–16 and 20–21, the plumes moved deeper inland. However, because there was a widespread precipitation over the Tohoku and Kanto regions on March 20–21, we investigated only the case of March 15–16 in this study. When the precipitation is strong and widespread, the influence of wet deposition on the plume concentration becomes extremely large. The model simulations of precipitation strength and wet deposition are complicated and challenging. Therefore, we plan to investigate the March 20–21 event in future.

Plume advection simulations were then driven by the 48-h meteorological forecast runs by using the Eulerian regional air quality model version 2 (RAQM2). RAQM2 was developed by Kajino et al.
The emission of radioactive cesium was fixed at a constant value (1 Bq h\(^{-1}\)), because we intended to validate only the plume arrival time at each station to rigorously examine the plume advection predictability. The Fukushima radioactive cesium plume was emitted from the point source; the background concentration was nearly zero before March 2011. The modeled concentration contrast between the background and the edge of arriving plume was larger than ten orders of magnitude. Therefore, we were easily able to identify the plume arrival time in simulations. We tried many
settings of the Fukushima nuclear pollutant simulation (e.g., Adachi et al. 2013; SCJ 2014; Sekiyama et al. 2015) by using realistic emission rate datasets (e.g., Chino et al. 2011) and confirmed that we need only relative concentration values if we want to define the edge of radioactive plumes. This is because the background concentration of anthropogenic nuclear products is zero in simulation models; thus, the plume edge has a jump of values by more than ten (or sometimes twenty) orders of magnitude. Furthermore, wet deposition in the model was turned off to avoid a plume disappearance caused by the erroneous precipitation in the model.

The modeled plume arrival times were validated by comparing them with the hourly averaged radioactive cesium concentrations measured by Tsuruta et al. (2014) and Oura et al. (2015). Tsuruta et al. (2014) developed a method to retrieve the hourly averaged concentrations of radioactive cesium in the lower atmosphere using suspended particulate matter (SPM) sampling tapes with a detection limit of less than 0.6 Bq m$^{-3}$ during the Fukushima nuclear accident. The SPM tapes were collected from the air pollution monitoring network managed by the national government and maintained by prefectural governments. Tsuruta et al. (2014) and Oura et al. (2015) reported the concentration data at 99 SPM-tape sampling stations. However, we screened these stations to clearly detect the radioactive plume arrival, which is discussed in the next section. Consequently, the data from 40 stations of the 99 stations were used in this study, as shown in Fig. 3.

3. Results and discussion

The plume arrival times at the SPM-tape sampling stations were determined with a threshold of 1 Bq m$^{-3}$ for the observations and $1 \times 10^{-15}$ Bq m$^{-3}$ for the model experiments. In general, when the plume arrived, the concentration rose sharply because the background was nearly zero (e.g., Fig. 4a). The observed concentrations changed rapidly from less than the detection limit (approximately 0.6 Bq m$^{-3}$) to more than 1 Bq m$^{-3}$. The modeled concentrations increased by more than 10 orders of magnitude. Note that the highest modeled concentrations at the SPM tape sampling stations were on the order of $10^{-13}$–$10^{-11}$ Bq m$^{-3}$. Hence, the threshold for the modeled plumes was set to $1 \times 10^{-15}$ Bq m$^{-3}$. For example, the observed plume arrival time and the STD forecasted plume arrival time are shown in Fig. 4a at Station #49 in Kuki City, Saitama Prefecture, based on Oura et al. (2015).

When a concentration surge was not clearly observed, e.g., as in Fig. 4b (Station #59 in Chiba City), arrival time data were not used. In addition, more than one increase in concentration over a short period of time was also observed in a few cases, e.g., as in Fig. 4c (Station #81 in Ota Ward, Tokyo). In this case, the edge of the observed plume could not be clearly identified and compared with modeled plumes. Thus, we omitted these data from the statistical calculations. After the screening, 40 out of the 99 stations of Oura et al. (2015) remained, as shown in Fig. 3. Fortunately, most of the 40 stations were located inland; therefore, it was expected that we could distinctly observe the influence of land-surface wind observations on the plume simulation.

The STD experiment did not assimilate the land-surface wind observations; namely, it assimilated the observation dataset regularly used in the operational JNoVA system, except for the satellite radiance and radar precipitation data. We have confirmed that the difference between the STD experiment analysis and
the operational JNoVA analysis is small. The influence of the satellite radiance and radar precipitation data was negligible for surface wind predictability in this study. The averaged difference (mean error) in the plume arrival times at the 40 SPM-tape sampling stations between the observational data and the STD experiment was 82.0 min (Table 1). Here, the average forecast length was 13 h. As indicated by the standard deviation (83.4 min) compared to this average, the forecasted plume arrival time was often very close to the observations. However, there were a few instances of errors exceeding 3 h. This is thought to represent the realistic ability of state-of-the-art operational weather forecast models and data assimilation systems to predict plume advection for emergency evacuations.

Conversely, the mean error of the AMeDAS experiment was 72.8 min, which was 9.2 min (11%) smaller than that of the STD experiment, with a statistical significance level of p-value of 0.008 (Table 1). This result indicates that the land-surface wind data assimilation significantly improved the predictability of near-surface plume advection even after a half-day forecast. Although the AMeDAS surface wind observations had only a small positive impact on the surface wind reproducibility as shown in Fig. 2, the impact on the plume predictability was large with a high statistical significance. The accuracy of a half-day plume prediction depends on not only the accuracy of 12-h-forecasted wind velocities in the vicinity of the plume but also very short-term wind-velocity forecasts near the emission source. Therefore, there is possibility that the improvement of the plume arrival time predictability is caused by only the improvement of very short-term forecasts near the emission source. However, at least from the viewpoint of advection prediction, the improvement of the plume predictability was surely maintained for longer than 6 h by the AMeDAS surface wind data assimilation. Besides, the 72.8-min error will be acceptable for the EER evacuation if the prediction is available with a half-day lead time.

4. Summary

The assimilation of AMeDAS surface wind data has a positive impact on the predictability of plume advection in the lower troposphere, at least in cases of wintertime air pollution over complex terrain, e.g., the Fukushima nuclear accident. The plume arrival prediction has a 72.8-min error with a half-day lead time for Tohoku and Kanto regions for March 15, 2011 by using the AMeDAS surface wind data assimilation. Besides, the 72.8-min error will be acceptable for the EER evacuation if the prediction is available with a half-day lead time.

**Table 1. Mean plume arrival time errors at the 40 SPM-tape sampling stations.**

<table>
<thead>
<tr>
<th></th>
<th>STD experiment</th>
<th>AMeDAS experiment</th>
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<tr>
<td>mean error (min)</td>
<td>82.0</td>
<td>72.8</td>
</tr>
<tr>
<td>standard deviation (min)</td>
<td>83.4</td>
<td>79.6</td>
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<td>significance level (p-value)</td>
<td>0.008</td>
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Fig. 4. Examples of time series of the radioactive cesium ($^{137}$Cs) concentrations derived from the SPM-tape sampling observations and two model experiments (STD and AMeDAS) from 12:00 UTC on March 14 to 12:00 UTC on March 15, 2011. The advection of the plumes was examined using the data from (a) Kuki City, Saitama Prefecture, and not using the data from (b) Chiba City, Chiba Prefecture, or (c) Ota Ward, Tokyo.
improving advection predictability would be applicable to near-surface water vapor, oxidant, and aerosol predictions by using surface wind data assimilation.

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