Mesoscale Ensemble Experiments on Potential Parameters for Tornado Outbreak

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Abstract

Energy Helicity Index (EHI), defined by the product of Convective Available Potential Energy (CAPE) and Storm Relative Environmental Helicity (SREH), is one of potential parameters to diagnose the possibility of tornado outbreak. In this study, probabilities that EHI exceed some criteria were examined with a mesoscale ensemble prediction system, whose grid interval was 15 km, in two tornado events in Japan (Nobeoka and Saroma tornado events). High probability regions (HPR) of large SREH existed in the northeastern quadrants of a typhoon or a low-pressure system, while HPRs of large CAPE extended along the warm humid airflow from the Pacific Ocean. In the two events, the tornados were formed near HPRs of large EHI, where HPRs of large SREH and CAPE were overlapped. This result indicates the possibility of the probability forecast of the potential parameter for tornado outbreak.

1. Introduction

A tornado with Fujita scale of 2 occurred in Nobeoka, southeastern part of Kyushu, on 17 September 2006. A limited express train was derailed and more than 1,000 houses were damaged. Another tornado with Fujita scale of 3 occurred in Saroma, Hokkaido on 7 November 2006. Nine people were claimed and 26 people were injured by this tornado. Hereafter, these tornados are referred to as Nobeoka and Saroma tornados, respectively.

Several numerical studies have been performed with the cloud resolving models to clarify the structure and formation mechanisms of tornados (e.g., Mashiko et al. 2008; Kato and Niino 2007). Mashiko et al. (2008) succeeded in the reproduction of the Nobeoka tornado that was formed in the mini-super cell storms within the rain band of the typhoon. Kato and Niino (2007) pointed out that the Saroma tornado was formed in the environmental condition in which the super cell storm could be easily organized. They also showed that the gust front formed the rotating updraft by upraising the low-level airflow that had the vertical shear. The super cell storms, which sometimes cause the tornado outbreaks, are generated in the environmental condition of the moderate vertical wind shear and unstable atmosphere. Thus, the parameters of SREH and CAPE are focused on in this study.

Because intense tornados often cause severe disasters, quantitative potential forecasts of tornados, as well as the understanding of the mechanisms, are important. Potential parameters to diagnose the tornado formation have been investigated with upper sounding data and operational analysis data. For instance, Sakurai and Kawamura (2008) proposed a new parameter KHI, which is composed of K-index and SREH, and showed the usefulness of this parameter. When outputs of the numerical weather prediction are used, potential parameters can be obtained with a lead time. An operational warning system has been developed by the Japan Meteorological Agency (JMA) using the forecasted parameters and the observed reflectivity distribution of operational radars. In their system, potential parameters are estimated from the forecast of the operational mesoscale model (MSM) of JMA, of which the horizontal grid interval is 5 km. However, the deterministic forecast does not always express the real atmosphere state, because the initial condition and the numerical model include errors.

Errors in the initial condition can be considered in ensemble forecasts. Enomoto and Yoshida (2008) conducted an ensemble forecast using an AGCM with a grid interval of 80 km, and pointed out the possibility of the probabilistic forecast of tornado outbreak using potential parameters.

In this study, potential parameters are obtained from outputs of a mesoscale ensemble prediction system, whose grid interval is 15 km. Initial perturbations of ensemble members are produced by the JMA’s operational one-week ensemble forecast to reflect large scale perturbations which affect the potential parameters for the tornado outbreak.

The following three merits are expected in the ensemble forecast of the potential parameter of tornado outbreaks. (1) Probability information on the potential parameters (e.g., EHI) is obtained using the outputs of ensemble forecasts. (2) Detection rate of severe phenomena is increased, because the ensemble forecast covers several scenarios of weather events. (3) Ensemble mean is statistically more accurate than the deterministic forecast.

The goal of our study is to validate the ensemble forecast from the above points of view. As for the third point, it is difficult to show it by only two experiments.
of Nobeoka and Saroma tornadoes because many experiments on tornado outbreaks are needed. Thus, only the comparison between the HPRs of control run and ensemble mean are shown in this study.

In the next section, the design of experiment is briefly explained. Results of the ensemble forecasts are shown in Section 3. Section 4 provides the summary and discussions.

2. Specification of the ensemble experiment

The ensemble forecasts were performed with the non-hydrostatic model of JMA (NHM; Saito et al. 2006a). The domain size and horizontal grid interval of the model were 3300 km × 3000 km and 15 km, respectively. Vertically, 40 levels terrain-following coordinates are employed, where depths of layers vary from 40 m to 1180 m with height. The Kain-Fritsch convective parameterization scheme modified by JMA and the 3-ice bulk cloud microphysics scheme were used.

Initial conditions were produced by adding the normalized perturbation of operational one-week ensemble forecast of JMA to the initial fields of the regional spectrum model (RSM) of JMA. In the normalization, magnitudes of perturbations were adjusted to 80% of the statistical background errors in the operational mesoscale analysis (Saito et al. 2006b). The number of ensemble members was 11 including the control run whose initial condition was not perturbed. Boundary conditions were provided by the operational RSM forecast. Rationality of this method was checked by the comparison of the control run and the ensemble mean (Seko et al. 2007). In their 12-day statistics on the ensemble forecast over Japan area, the root mean square errors (RMSEs) of the ensemble mean were smaller than those of the control run, and threat scores of 3-hour rainfall were improved except for 0.1 mm when the ensemble mean was used. This ensemble system was applied to the Nobeoka and Saroma tornadoes.

Initial times of the numerical forecasts were 12 UTC 16 September and 12 UTC 06 November 2006, respectively. Potential parameters, such as CAPE etc., at the forecast time of 18 hours were computed from the outputs of the ensemble forecasts with the program of CAPE7m (Suzuki 2007), which is used in the operational warning system at JMA.

3. Results of ensemble experiment

Figure 1 shows the ensemble mean distributions of the sea-level pressure and mixing ratio of rainwater at the height of 20 m. The typhoon and low-pressure system were well reproduced in both cases. Namely, their reproduced positions were in good agreement with the observed ones. Magnitudes of ensemble spreads of sea-level pressures and horizontal winds were large near the centers of the typhoon and low-pressure system, due to the difference of their positions and intensities among ensemble members.

Figure 2 shows the ensemble mean and probability distributions of CAPE, SREH and EHI in the Nobeoka tornado case. CAPE is the energy that an air parcel gets from the buoyancy between the LFC (level of free convection) and the equilibrium level. Because the convective available potential energy depends on the level from which the air parcel is lifted, it was evaluated by lifting the air from every vertical level, and then the maximum value among them was adopted as ‘CAPE’.

In the estimation of SREH, the moving speed and direction of the storm were assumed as follows. (1) The moving speed is 80% of the average of the horizontal wind. (2) The moving direction is shifted rightward by 20 degrees from the average of the horizontal wind. The average range of horizontal wind was 10 km from the surface. CAPE and SREH are potential parameters that indicate how intense convection can be generated and how intense vorticity is produced by the environmental airflow, respectively. Because EHI is proportional to the product of CAPE and SREH, EHI includes both effects.

The region of large CAPE extended over the Pacific Ocean off the southern coast of Western Japan (Fig. 2a). This region coincided with the southerly airflow region in the south of the western Japan and the confluence region of easterly and westerly airflows. On the other hand, large SREH existed in the northeastern quadrant of the typhoon (Fig. 2b). Although these large CAPE and SREH regions existed near the tornado outbreak point, their maximum positions were located at the northwestern or southern sides of Nobeoka. However, the region of large EHI became narrower, covering the position where tornado was formed (Fig. 2c).

Probability distributions of CAPE, SREH and EHI are shown in Figs. 2d–2f. The magnitudes of 1000, 300 and 2.5 of CAPE, SREH and EHI were used as the criteria. It is conceivable that the magnitudes of CAPE, SREH and EHI are varied with seasons, latitudes of tornado outbreaks and resolutions of numerical models. Thus, their criteria should be determined statistically. Because the estimation of proper criteria is not within the scope of this study, the criteria of this study was determined by trial and error so that some members of the ensemble forecast cover the positions of the tornado outbreaks.

Because the probability contains the information of all ensemble members’ forecasts, the following features of probability are common with those of the ensemble mean. (1) High probability regions (HPRs) of large CAPE extended to the southern side of Western Japan. (2) HPRs of the large SREH existed at the northeastern quadrant of the typhoon. (3) HPRs of large EHI, which corresponds to the overlapped area of HPRs of large CAPE and SREH, covered Nobeoka. Similar relationships between the tornado outbreak position and CAPE, SREH and EHI were seen in the Saroma tornado case (Fig. 3), although EHI near Saroma (Fig. 3c) was smaller than that at Nobeoka (Fig. 2c). Compared with the Nobeoka tornado case, the Saroma tornado was formed in a cooler season and at more northern part of Japan. The large CAPE and its HPRs were mainly located to the southeast of Japan, and CAPE near Saroma was smaller than that of the Nobeoka case. As for SREH, the region of large SREH became wider, and its maximum point was located to the east of Hokkaido, far from Saroma. These distributions may suggest that these potential parameters are not a proper index of tornado outbreak. On the other hand, HPRs of large EHI existed near Saroma, although the magnitude of EHI was smaller than that of the Nobeoka tornado case due to the difference of the magnitudes of CAPE.

In this study, values of 2.5 and 1.5 were used as the criteria of EHI in Nobeoka and Saroma tornado cases, respectively. Since averages in top 25% of EHI are 1.0 and 0.2, respectively (Ehibara and Kitamura 2007), our criteria are much larger than climatological values of EHI.

In both tornado events, HPRs of large EHI cover or are located near the positions of the tornado outbreaks. These results suggest that the probability information provided by the ensemble forecast is useful for the diagnoses of tornado outbreaks.

Besides the probability, the maximum value among
the ensemble members is important for the disaster prevention, because the tornados cause severe disaster such as the loss of life. Figures 4a and 4b show the maximum value of EHI and the contour lines of 2.5 and 1.5 in the Nobeoka and Saroma cases, respectively. We assume that these magnitudes are the criteria for tornado outbreak. The regions where the maximum values exceed the criteria (blue lines) were wider than those of the ensemble mean (red lines) and control run (black lines). In Fig. 4b, the regions of large EHI in ensemble mean and control run were located not at Saroma but at southeast of Saroma. Considering the severity of tornado disasters, the warning should be issued based on the maximum value of EHI, rather than EHI by the single deterministic run. This usage of the maximum EHI corresponds to the second merit of the ensemble forecast mentioned in the introduction.

Because the number of ensemble member in this study was 11, the counters of maximum values illustrate the region with the probability of 9.1% in Figs. 2
and 3. When the number of the ensemble member is not enough, this lowest probability expressed in the probability forecast is not negligible. The maximum value of EHI can show the degree of the risk outside of the lowest probability counters. Thus, this parameter is expected to be useful when the number of the ensemble member is small.

Another advantage of the ensemble forecast is that the ensemble means are statistically more accurate than the deterministic runs. However, in our cases, the regions of large EHI in the ensemble means were similar to those of the control runs (Fig. 4), and this advantage was not necessarily clear. This seems attributable to the fact that the control runs were accurate enough. The tornadoes were simulated in both cases by the simple downscale modeling without data assimilation (Kato and Niino 2007; Mashiko et al. 2008). In this paper, the statistical advantage cannot be discussed because the ensemble forecasts were applied to only two tornado cases.

As mentioned in the introduction, the lower atmosphere played the important processes for the outbreak of the Saroma tornado. To see the usefulness of other parameter, after Thompson et al. (2005), the Significant Tornado Parameter (STP) was examined (Supplement 1). STP consists of the normalized terms of mean layer CAPE in the lowest 500 m (MLCAPE), SREH at 6 km, LCL, vertical shear in the lowest 3 km and mean layer CIN in the lowest 500 m (MLCIN). Here, the terms LCL and MLCIN indicate easiness of the condensation occurrence, and the low level vertical shear can change to the vertical vorticity by the updraft. The distributions of large STP regions were similar to those of EHI. However, if we compare HPRs of large STP with those of the products of the terms of MLCAPE and SREH, HPRs of large STP were located at closer positions to the tornado outbreak Similar features were also seen in the Nobeoka case. These results suggest that other parameters are also applicable to the ensemble forecast.

4. Summary

In this study, the probabilities of CAPE, SREH and EHI were predicted by the ensemble forecast, and the usefulness of the ensemble forecast was shown by the probability and maximum distributions of EHI in Nobeoka and Saroma tornado cases. However, the number of experiments was not enough and the experiments of the tornado with Fujita scale of 1 or 0, which account for most of number of tornados, were not performed. Experiments in many tornado cases are needed to ensure the usefulness of the ensemble forecast. There are many other parameters that have been proposed as the potential parameters of tornado outbreaks. Thus, the experiments on other parameters are also desired.

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Supplement

1. Probability of STP and the difference distribution of probability between STP and CAPE and SREH parts of STP.

References


