

Ensemble Sensitivity Analysis Applied to a Heavy Rainfall Event in Beijing

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Abstract—A high-impact heavy rainfall event occurred in Beijing, China on 16 July 2018, which is a typical warm sector heavy rainfall associated with Mesoscale Convective System (MCS) of multi cells. To clarify the key factors influencing the heavy rainfall, ensemble sensitivity analysis (ESA) is conducted using the state-of-the-art European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system. The ESA is a new efficient tool utilizing the information contained in ensemble forecast to calculate a linear relationship between a forecast metric and model perturbation variable. Results show that the low-level southwesterly moist flow plays a significant role in the heavy rainfall in Beijing which is favorable for abundant water vapor and dynamic lifting.

Keywords—ensemble sensitivity analysis; heavy rainfall; ensemble prediction system

I. INTRODUCTION

Heavy rainfall in Beijing of China cause great threat to safety for life and property. Forecasting of extreme heavy rainfall is challenging given its relative low predictability. During 15-18 July 2018, a severe heavy rainfall event occurred in Beijing which caused large economic losses and great impact. The rainfall event lasted almost 60 hours and the short duration intensity of rainfall is also very high. As for heavy rainfall over China, Zhang and Cui [1] summarized advances in understanding the heavy rainfall. Sun et al. [2] overviewed the features of extreme severe rainfall events during 2006-2013 in the Beijing area. Most previous works focused on the weather systems that were likely involved in the occurrence and development of the heavy rainfall event in the Beijing area qualitatively, but the dominant or key synoptic features influencing the heavy rainfall as well as their predictability by operational ensemble prediction system remains further study.

Ensemble sensitivity analysis (ESA) is a new efficient tool to gain quantitative insights and determine the dominant factors for the dynamics of weather systems [3,4,5]. Many studies have successfully applied ESA to heavy rainfall [6,7], the genesis and development of mesoscale vortices as well as tropical cyclones [8,9]. Other sensitivity analysis method (e.g., singular vectors, ensemble Kalman filter, adjoint sensitivity) have also been used to examine the impact of model-state perturbations on forecast error [10,11,12]. One of the most significant advantages of ESA is that it is not necessary to linearize the mathematical

representation of the processes in the underlying atmospheric model which is required by the adjoint approach. So the ESA method is preferred for its relative simplicity.

Present study uses archived operational global ensemble forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) to diagnose the dynamics of a heavy rainfall event on 16 July 2018 over Beijing and to assess the forecast uncertainty. The data and the ESA method used in this study are described in detail in section 2. The overview of the heavy rainfall event is provided in section 3. Section 4 presents the results of ensemble-based analyses.

II. DATA AND METHODOLOGY

A. Data

The rainfall observations and radar data were provided by the China Meteorological Administration (CMA). The ensemble forecasts with 50-km horizontal resolution from the ECMWF Ensemble Prediction System are used in this study. NCEP Final (FNL) $1^\circ \times 1^\circ$ Operational Global Analysis data are utilized as the analysis of circulation background in this case.

B. Ensemble Sensitivity Analysis

ESA is typically performed as a linear regression between a chosen forecast metric J and a model perturbation state X_i at an earlier time, with the sensitivity measured by the slope as [3]

$$\frac{dJ}{dX_i} = \frac{\text{cov}(J, X_i)}{\text{var}(X_i)} = \text{cor}(J, X_i) \times \frac{\sqrt{\text{var}(J)}}{\sqrt{\text{var}(X_i)}} \quad (1)$$

Where cov and var denote the covariance and variance of the given variables, respectively, cor is a correlation coefficient. The slope of the regression depends both on the amount of the variance in the forecast response that is explained by the perturbation variable and the actual variance of the perturbation variable. At any given forecast time, the variance of the forecast response variable is constant. However, the variance of the perturbation state variable X_i can vary from one location to another. Using the correlation coefficient in place of the slope has desirable property that interpreting the results is easier. We

will use only the correlation coefficient as our sensitivity measure hereafter.

III. OVERVIEW OF THE HEAVY RAINFALL EVENT

On 15–18 July 2018, heavy rainfall occurred in the Beijing area of China. The heavy rainfall event started at 1500 BJT 15 July and ended at 0600 BJT 18 BJT July which lasted 58 hours. The maximum rainfall amount occurred in Miyun county (351.3mm). In this study we focus on the period of 16 July. For 24 hour accumulated precipitation from 0800 BJT 16 to 0800 BJT 17 July, the heavy rain band exhibited northeast-southwest orientation with rainfall of many stations exceeding 100 mm (Fig.1).

Analysis of the radar composite images shows that strong radar echo (>50 dBz) during the morning on 16 July located near central Beijing area and Miyun county indicating very high rainfall intensity. This heavy rainfall event includes both warm sector heavy rainfall and frontal heavy rainfall. The development of mesoscale convective cells was typical of train effect which caused extreme heavy rainfall for whole period.

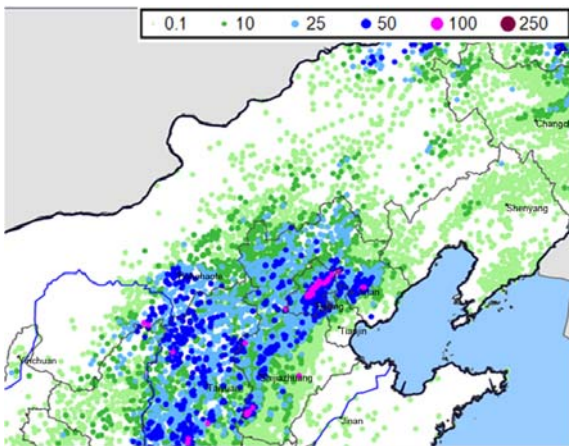


FIGURE 1. 24 HOUR OBSERVED ACCUMULATED PRECIPITAITON FROM 0800 BJT 16 JULY TO 0800 BJT 17 JULY (UNIT: MM)

Fig. 2 depicts the large-scale circulation background of this heavy rainfall event. On 2000 BJT 15 July, subtropical high was very strong and the 588 dagpm line extended northward to the southern Beijing area (Fig.2a). The trough at 500 hPa located over Inner Mongolia and Gansu province. On 2000 BJT 16 July, the trough and subtropical high moved eastward while the winds at 850 hPa intensified especially to the southwest of the Beijing area (Fig.2b). The heavy rainfall area was in front of the trough. So the rainfall before 17 July was featured as warm sector heavy rainfall. The long-lasting southwest jet brought abundant water vapor favorable for the heavy rainfall. The precipitable water at 2000 16 BJT 16 was more than 55 mm over most area of Beijing (not shown). The rainfall distributions are almost parallel to the axis of low level jets similar as the summarized extreme severe rain events associated with MCS of multi cells (type II) in the Beijing area.

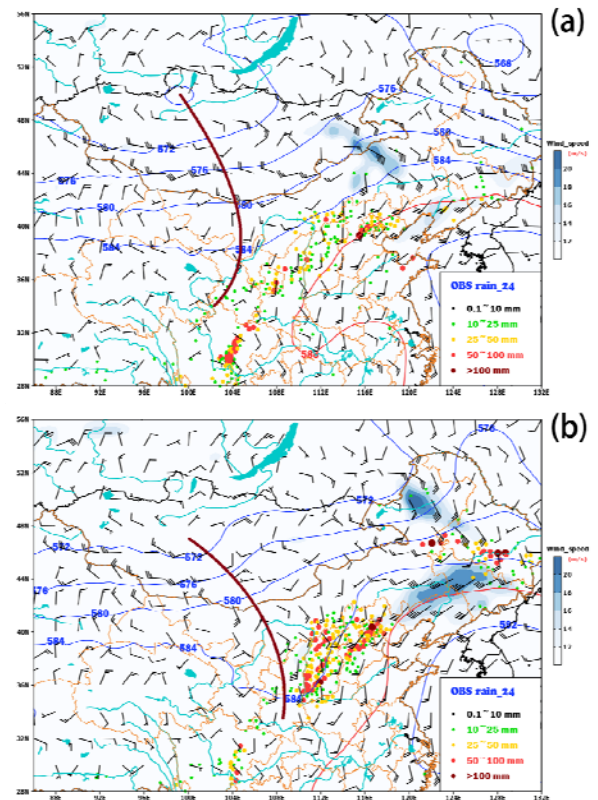


FIGURE II. THE 500 HPA GEOPOTENTIAL HEIGHT (CONTOUR, UNIT: DAGPM), 850 HPA WIND (BARB, UNIT: M/S) AND WIND SPEED (SHADED, UNIT: M/S), OBSERVED 24 HOUR ACCUMULATED PRECIPITATION (DOT, UNIT: MM) AT (A) 2000 BT 15 JULY AND (B) 2000 BT 16 JULY

IV. PERFORMANCE OF THE ENSEMBLE FORECAST

The ensemble and the control deterministic forecasts of the 24-h accumulated rainfall from 0800 BJT 16 July to 0800 BJT 17 July provided by ECMWF (Fig. 3) showed a quite large uncertainty in terms of the pattern, location and amount. It is clear that most of the ensemble members predicted moderate or heavy rain with an apparent underestimation of the peak magnitude of rainfall. However, member 18 and 29 predicted torrential rain (≥ 50 mm) which is similar as the observed rainfall pattern. Some members such as member 8 and 38 predicted torrential rain to the northwest of the Beijing area that the error are more associated with the location.

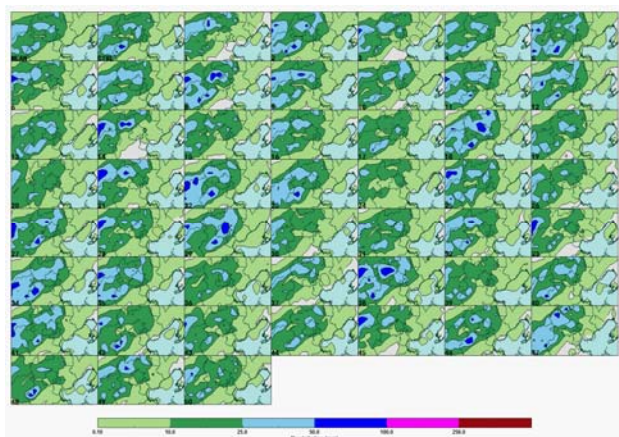


FIGURE III. THE DISTRIBUTION OF 24 HOUR RAINFALL OF CONTROL, ENSEMBLE FORECASTS AND ENSEMBLE MEAN OF ECMWF FROM 0800 BJT 16 JULY TO 0800 BJT 17 JULY BY ECMWF INITIALIZED AT 20:00 BJT 15 JULY (UNIT: MM)

V. ENSEMBLE SENSITIVITY ANALYSES

Here sensitivity is calculated using the ECMWF 51-member ensemble. We calculate linear correlations between area-averaged precipitation with several atmospheric variables at each grid point. The correlations with magnitudes greater than 0.36 are statistically different from zero at the 95% confidence level using a two-tailed significance test.

Fig. 4 presents the correlation coefficient between area-averaged 24-h rainfall from 0800 BJT 16 July to 0800 BJT 17 July and 850-hPa wind speed at 0800 BJT 16 July. The box indicates the area for calculating the forecast metric. It can be seen that large positive area is around southeast of Beijing, Tianjin and south of Hebei province. The correlation coefficient is larger than 0.36 which is statistically significant. Given the observed southern wind over this area, the correlation pattern suggest that the stronger the southwest of low-level wind in the morning of 16 July, the heavier rainfall will be predicted by the ECMWF ensemble system for the following 24 hours.

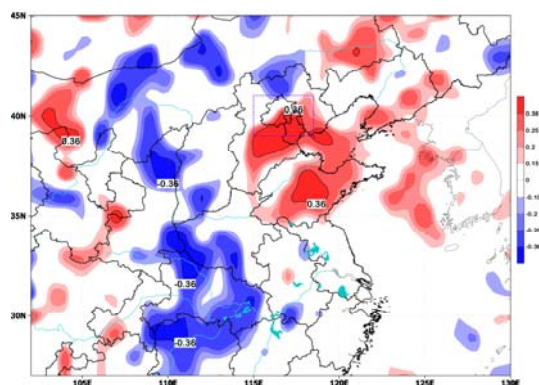


FIGURE IV. THE CORRELATION COEFFICIENT (SHADED) BETWEEN THE AREA-AVERAGED 24-H RAINFALL (0800 BJT 16 JULY TO 0800 BJT 17 JULY) AND 850-HPA WIND SPEED AT 0800 BJT 16 JULY. THE BOX INDICATES THE AREA USED FOR CALCULATING THE AREA-AVERAGED RAINFALL

Fig. 5 gives the correlation coefficient between the area-averaged 24-h rainfall from 0800 BJT 16 July to 0800 BJT 17 July and the precipitable water at 0800 BJT 16 July. It is obvious that significant positive areas dominate southern Beijing, middle and south of Hebei province as well as parts of Henan and Shanxi province. These correlations suggest that stronger water vapor is associated with greater precipitation in the Beijing area. These results are consistent with previous studies showing that the southern wind and water vapor play a key role in the development of type II heavy rainfall in the Beijing area [2].

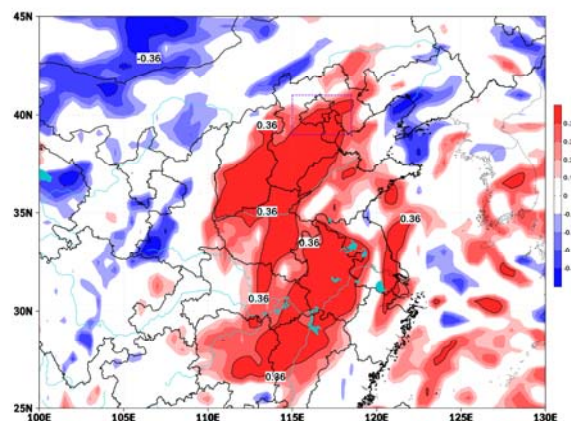


FIGURE V. SAME AS FIGURE 4, BUT FOR PRECIPITABLE WATER AT 0800 BJT 16 JULY

VI. SUMMARY

This work examined quantitatively the key synoptic features influencing the high-impact heavy rainfall event in Beijing, China, on 16 July 2018 by using a new efficient tool - Ensemble sensitivity analysis (ESA). The heavy rainfall event is a typical warm sector heavy rainfall associated with Mesoscale Convective System (MCS) of multi cells. Correlation coefficients between the 24 hour area-averaged precipitation in Beijing and various variables were calculated based on the state-of-the-art ECMWF forecasting system. The results showed that the key synoptic system was the low level southwesterly moist flow which caused abundant water vapor and strong dynamic lifting.

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