Predictability of Record-Breaking Rainfall in Japan in July 2018: 
Ensemble Forecast Experiments with the Near-Real-Time 
Global Atmospheric Data Assimilation System NEXRA

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Abstract

This paper is the first publication presenting the predictability of the record-breaking rainfall in Japan in July 2018 (RJJ18), the severest flood-related disaster since 1982. Of the three successive precipitation stages in RJJ18, this study investigates synoptic-scale predictability of the third-stage precipitation using the near-real-time global atmospheric data assimilation system named NEXRA. With NEXRA, intense precipitation in western Japan on July 6 was well predicted 3 days in advance. Comparing forecasts at different initial times revealed that the predictability of the intense rains was tied to the generation of a low-pressure system in the middle of the frontal system over the Sea of Japan. Observation impact estimates showed that radiosondes in Kyusu and off the east coast of China significantly reduced the forecast errors. Since the forecast errors grew more rapidly during RJJ18, data assimilation played a crucial role in improving the predictability.

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1. Introduction

The record-breaking rainfall in Japan in July 2018 (hereafter RJJ18) was successive torrential rains occurred in Hokkaido and western Japan from late June to mid July 2018. As of 21 August 2018, 221 fatalities were reported across 14 prefectures (Government of Japan 2018). RJJ18 caused a number of floods and debris flows throughout western Japan, making it the severest flood-related disaster in Japan since the Nagasaki flood in 1982. Japan has experienced many disastrous heavy rainfall events. Following these events, efforts have been made to understand their meteorological mechanisms at convective, synoptic, and planetary scales. For emergency management, it is also important to explore the predictability of such disastrous events by numerical weather prediction (NWP, Pantillon et al. 2017; Nystorm et al. 2018). The Japan Meteorological Agency (JMA) issued “special heavy rainfall warnings” to 11 prefectures on 6 and 7 July 2018. Improving the predictability of heavy rainfalls could enable the JMA to issue such warnings earlier and provide people with more time for evacuation.

The objective of this study is to extend our understanding of this record-breaking rainfall and its synoptic-scale predictability by NWP. For this purpose, we use a data assimilation (DA) system comprising the Nonhydrostatic ICosahedral Atmospheric Model (NICAM; Satoh et al. 2008, 2014) and the Local Ensemble Transform Kalman Filter (LETKF; Hunt et al. 2007). The NICAM–LETKF system was developed by Terasaki et al. (2015) and has been extended continuously to assimilate satellite radiance and precipitation data (Terasaki and Miyoshi 2017; Kotsuki et al. 2017a), to estimate model parameters (Kotsuki et al. 2018a), to improve its variance inflation method (Kotsuki et al. 2017b), to diagnose assimilated observations (Kotsuki et al. 2018b), and to accelerate its computation for high-performance computing systems (Yashiro et al. 2016). Recently, a 100-member near-real-time NICAM–LETKF system started running on the Japan Aerospace Exploration Agency (JAXA)’s second-generation supercomputer system (JSS2). The near-real-time system was named NEXRA representing NICAM–LETKF at JAXA Research Analysis and has been in operations routinely since June 2017.

This study investigates the predictability of RJJ18 by ensemble forecasts using the recently-developed NEXRA system. As we describe in Section 2, there were three heavy precipitation stages during RJJ18; we focus on the predictability of the third stage, in which most western prefectures experienced disastrous heavy rainfall. Here we discuss the synoptic-scale predictability of RJJ18 using a relatively coarse global DA system at 112-km horizontal resolution. It is also important to investigate impacts of assimilated observations to forecast error reductions as in the previous studies by e.g., Wu et al. (2010), Jung et al. (2012), and Kunii et al. (2012) for The Observing System Research and Predictability Experiment’s Pacific Asian Regional Campaign. Here, we examine the contributions of assimilated observations in RJJ18 using the Ensemble Forecast Sensitivity to Observations (EFSO) method, as the first application to stationary heavy rainfall events.

This paper is organized as follows. Section 2 briefly introduces RJJ18. Section 3 describes the experimental settings. The results are presented and discussed in Section 4. A summary is provided in Section 5.

2. Record-breaking rainfall in Japan in July 2018 (RJJ18)

RJJ18 comprised successive downpours across Japan from late June to mid July 2018. Figure 1 shows the 24-h accumulated precipitation by the JMA radar and rain gauges (a.k.a. Radar/Raingage-Analyzed precipitation), for a 12-day period during RJJ18. We divided this heavy rainfall event into three stages. In the first stage (27 June–1 July), the seasonal stationary Baiu front extended from...
DA and subsequent forecasts to investigate the synoptic-scale predictability of RJJ18. We use NICAM at 112-km horizontal resolution with 38 vertical layers up to approximately 40 km. Due to the relatively coarse model resolution, we employed the Arakawa and Schubert (1974) scheme for cumulus parameterization, and the Berry’s parameterization (1967) for large-scale condensation. A number of mesoscale systems (e.g., linear rain bands) constituted RJJ18, but this paper focuses on synoptic-scale predictability as the first step.

The LETKF conducts DA every 6 h. Relaxation to prior spread (RTPS; Whitaker and Hamill 2012), a variant of the original relaxation method known as relaxation to prior perturbation (Zhang et al. 2004), is used for variance inflation in the LETKF. The assimilated observations are conventional observations from the National Centers for Environmental Prediction (NCEP) operational system (data known as NCEP PREPBUFR), satellite radiances of Advanced Microwave Sounding Unit-A (AMSU-A), and a near-real-time version of Global Satellite Mapping of Precipitation (GSMaP_NRT). For further details of the NICAM–LETKF system, refer to Terasaki et al. (2015), Terasaki and Miyoshi (2017), and Kotsuki et al. (2017a).

3.2 Experimental setting

This study performs the 100-member NICAM–LETKF experiment succeeding the NEXRA system after 0000 UTC 1 June 2018. In this study, we modified the LETKF of the NEXRA system slightly as follows: switching off temporal localization and increasing the RTPS parameter from 0.90 to 0.95. The first modification enables the LETKF to compute the analyses in the observation space; these analyses are necessary for the EFSO to quantify the observation impacts. Without temporal localization,
the ensemble becomes more contracted, and we increased the RTPS parameter to compensate for the contraction. We confirmed that these two modifications did not significantly change the forecast accuracy measured by the departure (observation – first guess) for global radiosondes (not shown).

We conduct 10-day ensemble forecasts from the analysis ensemble. These ensemble forecasts are also used in the EFSO. Due to the linear error growth assumption, the forecast lead time of EFSO is usually limited up to 36 h for global systems. This study uses 24-h forecasts for the EFSO, but the 24-h forecast improvement would result in an improvement of longer forecasts. The advection of the localization center (Ota et al. 2013) is not applied. The EFSO impact estimates were not very sensitive to the choice of the RTPS parameter in the NICAM-LETKF (Kotsuki et al. 2018b).

As we reviewed in Section 2, the third-stage heavy rainfall caused the largest amount of precipitation and severest disaster. Therefore, this study focuses on the third-stage precipitation in western Japan (128.0°E–139.0°E and 32.0°N–37.5°N, hereafter the WJ domain) for 24-h accumulated precipitation over 0000 UTC on 6–7 July 2018 (Fig. 1j, dashed rectangle).

4. Results and discussion

4.1 Ensemble precipitation forecasts

Figure 2 shows the ensemble-mean precipitation accumulated over 0000 UTC on 6–7 July 2018 for 16 forecasts initialized every 12 h. Compared to JMA's observations (Fig. 1j), the predicted Baiu front was biased northward, resulting in heavy rainfall over the Korean Peninsula by 0000 UTC 2 July (Figs. 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h, and 2i). Figure 3 shows sea level pressure (SLP) at 0000 UTC July 4 for 8 deterministic forecasts initialized every 12 h. The northward Baiu front would be caused by the north-westward track forecasts of Typhoon 1807 by 0000 UTC 2 July (Figs. 3a, 3b, 3c, 3d, and 3e). Because of DA at 0000 and 1200 UTC 2 July, the predicted precipitation areas moved southward and remained over the WJ domain probably due to improved typhoon track forecasts (Figs. 3f, 3g, 3h, 3i, and Supplemental Fig. S1b). It is important to improve typhoon track forecasts for predicting typhoon-monsoon severe rainfall events (e.g., Zhang et al. 2010; Xie et al. 2013). However, precipitation forecasts in the WJ domain were still weak even with the corrected typhoon track in RJJ18 (Figs. 2j and 2k). After 1200 UTC 3 July, intense precipitation cores (≥ 75 mm) appeared over the WJ domain; this study investigates DA at 1200 UTC 3 July further in Section 4.3. Intense precipitation areas were biased slightly northward (Figs. 2l, 2m, 2n, 2o, and 2p), perhaps due to the coarse resolution of the model.

Here we investigate arbitrarily selected 16 members from an ensemble forecast initialized at 0000 UTC 3 July 2018 (Fig. 4). This ensemble mean forecast did not detect the intense precipitation core in the WJ domain (Fig. 2k). Except for two members 05 and 16, the ensemble forecasts predicted heavy rainfall (≥ 50 mm) off the coast of Wenzhou, China (120.0°E–126.0°E, 25.0°N–30.0°N); therefore, the ensemble mean forecast resulted in a heavy precipitation core in that region (Fig. 2k). In contrast, some members predicted heavy rainfall in the WJ domain (members 02, 07, and 16). These members predicted the development of low-pressure systems in the Sea of Japan (members 07 and 16) or near Hokkaido (member 02). Therefore, we investigate whether predicting the low-pressure system was important to predict heavy rainfall in the WJ domain in the next Section 4.2.

4.2 Ensemble correlation analysis

Here, we explore the role of $L_{\text{sea}}$ in predicting heavy rainfall
in the WJ domain using a 100-member ensemble forecast initialized at 1200 UTC 3 July 2018. Figure 5 shows the ensemble-based correlations between accumulated precipitation over 0000 UTC on 6–7 July 2018 in the WJ domain, and forecast SLP at four forecast validation times. Figures 5c and 5d show significant negative correlations between forecast SLP and accumulated precipitation, suggesting that LNoto development have led to intense precipitation in the WJ domain. No clear correlation was detected at 0000 UTC 6 July (Fig. 5b) because LNoto had not started to develop by that time (Fig. 5c). Relatively large positive correlations (≥ 0.25) were seen near the coastline of southern China (Figs. 5c and 5d). This implies that the convective activities in that region would have related to precipitation in the WJ domain. Notably, large positive correlations (≥ 0.25) were also continuously seen over the Tibetan Plateau (Fig. 5a, 5b, 5c, and 5d). The Tibetan monsoon system might have affected the development of LNoto.

Fig. 3. Sea level pressure (hPa) at 0000 UTC 4 July for 8 deterministic forecasts initialized every 12 h from (a) 0000 UTC 30 June to (b) 1200 UTC 3 July 2018.

Fig. 4. Four-day-lead forecasts of arbitrarily-selected 16 ensemble members initialized at 0000 UTC 3 July 2018, showing 24-h accumulated precipitation (mm, color shades) over 0000–2400 UTC 6 July 2018. Black contours show the sea level pressure (SLP) of 1000 hPa at 0000 UTC 7 July 2018. Magenta arrows denote the low-pressure system that developed near Noto Peninsula.
Figure 6a summarizes forecast rainfall over the WJ domain as a function of forecast lead time (FT). JMA’s observation (54.97 mm) is indicated by a dashed blue line. Ensemble mean and deterministic precipitation forecasts were similar to each other; they increased as FT decreased. Before 1200 UTC 3 July, all members underestimated rainfall amounts. The forecast precipitation was substantially increased by two DA at 1200 UTC 3 July and 0000 UTC 4 July 2018. Ensemble-mean precipitation forecasts were almost the same as JMA’s observation after 0000 UTC 4 July.

Figure 6b shows the number of ensemble members that predicted L_{Noto}, which is defined by the following two conditions: a low-pressure system (≤ 1000 hPa and four or more successive model grids) was predicted near the Noto Peninsula (125.0°E−140.0°E, 30.0°N−45.0°N) and was not connected with the low-pressure system (≤ 1000 hPa) off the coast of Wenzhou, China. More ensemble members predicted L_{Noto} by two DA at 1200 UTC 3 July and 0000 UTC 4 July 2018. The results suggest that these two DA play an important role in predicting the development of L_{Noto} and subsequent heavy rainfall over the WJ domain. Fewer ensemble members predicted L_{Noto} in the DA at 1200 UTC 4 July 2018. This reduction was the result of some members failing to satisfy the second condition of L_{Noto} due to the strongly developed low-pressure systems (Supplemental Fig. S4). Consequently, the precipitation forecast initialized at 1200 UTC 4 July was biased northward (Fig. 2n) compared with the two forecasts that were 12 h apart (Figs. 2m and 2o).

### 4.3 EFSO impact estimates

Finally, we investigated the DA at 1200 UTC 3 July 2018 using EFSO impact estimates. Specifically, we evaluated assimilated observations whether they improved or degraded atmospheric fields in eastern Asia (115.0°E−145.0°E, 25.0°N−42.1°N; the domain of Fig. 2) using kinetic energy (KE), potential energy (PE), and moist energy (ME) as error norms (cf. Ota. et al. 2013). Figure 7a shows the estimated observation impacts on a 24-h forecast, showing the contribution from each type of observation.
At the given analysis time, radiosondes (ADPUPA) had the largest impact on forecast error reduction, which is consistent with a recent study on the typhoon forecast (Kunii et al. 2012), followed by radar-based wind observations (V ADWND). For comparison, Fig. 7b shows the estimated impacts averaged over a week in spring (1−7 April), 2018. Radiosondes again made the largest contribution. However, two notable differences are seen between the impact estimates for April and July 2018. First, radiosondes at 1200 UTC 3 July had larger impacts by about five times than those of 1−7 April 2018. This result indicates that the forecast error grew more rapidly in RJJ18 than during the period of 1−7 April 2018; therefore, DA was more important to capture the true atmospheric fields. Second, the ratio of error reduction in ME (69.4%) was larger than that during 1−7 April 2018 (38.7%).

Figures 7c, 7d, and 7e show the estimated vertically-accumulated impacts of radiosondes (J kg⁻¹) assimilated at 1200 UTC on 3 July 2018 for KE, PE and ME, respectively. For each observation point, the area of the circle is proportional to the absolute impact. The black open circles at the bottom right corner in each panel correspond to 1.0 J kg⁻¹.

5. Summary

The objective of this study was to improve our understanding of the predictability of the record-breaking heavy rainfall event in Japan in July 2018 (RJJ18). We focused on the third stage of the event and examined its predictability using the recently-developed near-real-time global atmospheric DA system NEXRA. Our main findings are summarized as follows.

- There were three successive stages in the RJJ18. In the western Japan (WJ), most prefectures experienced disastrous heavy rainfall (≥ 300 mm) in RJJ18. Intense precipitation areas (≥ 1,000 mm) were observed in Gifu, Kagoshima, Miyazaki, and Kochi Prefectures. The largest amount of precipitation in WJ was observed at the third stage, particularly on 6−7 July 2018.
- Ensemble-mean 24-h accumulated precipitation forecasts on 6 July 2018 were almost the same as JMA’s observation after 0000 UTC 4 July; namely, the intense precipitation over the WJ domain was well predicted 3 days in advance. DA at 1200 UTC 3 July and 0000 UTC 4 July contributed substantially to improving predictions of heavy rainfall. The predictability of the intense rains was tied to the generation of a low-pressure system L Noto in the middle of the Baiu front.
- EFSO impact estimates revealed that radiosondes in Kyusyu and off the east coast of China significantly reduced the forecast error in eastern Asia. The forecast error grew more rapidly during RJJ18 than during a typical period in April 2018; therefore, DA was extremely important in capturing the true atmospheric fields.

This study focused on the synoptic-scale predictability of RJJ18 using the global DA system. Further studies using spatially finer DA systems are necessary to investigate whether higher resolution systems can extend the predictability of RJJ18. In addition, it is of great importance to examine intrinsic and practical predictabilities of this severe rainfall event (e.g., Zhang et al. 2007; Sun and Zhang 2016). The first and second stages of RJJ18 also caused heavy rainfall, especially in northern Kyushu and Hokkaido. These stages should also be examined further.

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**Supplement**

Fig. S1. Japan Meteorological Agency (JMA) synoptic weather charts for 0000 UTC from June 27 to July 8, 2018. The black arrow indicates the low-pressure system that developed near Noto Peninsula.

Fig. S2. Geographical names in this study.

Fig. S3. Accumulated precipitation (mm) of JMA’s Radar/Rain-gauge-Analyzed Precipitation over 12 days from 0000 UTC June 27 to 0000UTC July 9, 2018.

Fig. S4. Similar to Fig. 3, but showing forecasts initialized at 1200 UTC July 4, 2018.

Fig. S5. Analysis increments at 1200 UTC July 3, 2018 for (a) temperature (K) and (b) water vapor mixing ratio (g kg⁻¹) at 1570 m above the sea level. Warm and cold colors indicate the increase and decrease due to data assimilation.

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