Improving a Precipitation Forecast by Assimilating All-Sky Himawari-8 Satellite Radiances: A Case of Typhoon Malakas (2016)

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Abstract

Tropical cyclones (TCs) and associated heavy precipitation have large impacts in Japan. This study aims to find how data assimilation (DA) of every-10-minute all-sky Himawari-8 radiances could improve the quantitative precipitation forecast (QPF) for TC cases. As the first step, this study performs a single case study of Typhoon Malakas (2016) using a regional atmospheric model from the Scalable Computing for Advanced Library and Environment (SCALE) coupled with the local ensemble Kalman filter (LETKF). The results show that the all-sky Himawari-8 radiance DA at 6-km resolution improves the representation of Malakas and may provide more accurate deterministic and probabilistic precipitation forecasts if the horizontal localization scale is chosen appropriately.


1. Introduction

Tropical cyclones (TCs) and associated heavy precipitation have attracted attention because of their severe disaster risks and profound impacts on water management. Indeed, a TC approaching Japan brings water in later summer and may be crucial to avoid droughts in dry summer years. In addition, the TC-induced precipitation strongly affects the hydroelectric power generation, especially in the late summer to fall when the number of TCs approaching Japan is the largest in climatology (e.g., Fudeyasu et al. 2014). High precision quantitative precipitation forecast (QPF) plays an essential role in safe operations of hydroelectric dams.

The horizontal distribution and amount of TC-induced precipitation depend on the TC track, intensity, and rainfall band structure. To predict them accurately, it is essential to obtain better initial conditions in terms of both large-scale circulation (steering flows) and the TC structure through data assimilation (DA). In particular, geostationary satellite radiance observations would be among the most important data sources because of their broad coverage including over the ocean where TCs develop but the number of in-situ observations is very limited. Infrared (IR) radiances observed by geostationary satellites are strongly affected by clouds (e.g., Okamoto et al. 2014; Okamoto 2017), so that assimilating all-sky (both cloud-affected and clear sky) IR radiances is a promising way to analyze TCs.

Recently, a couple of the third-generation geostationary satellites, Himawari-8 by the Japan Meteorological Agency (JMA, Bessho et al. 2016) and GOES-16 by the National Oceanic and Atmospheric Administration (NOAA, Schmitt et al. 2005; 2017), have started their full operations. Advanced imagers onboard these satellites are capable of capturing behavior of rapidly-evolving convective clouds with high spatiotemporal and spectral resolutions. Recently, Honda et al. (2018a, b, hereafter H18a and H18b) have successfully assimilated all-sky Himawari-8 satellite radiances every 10 minutes in a TC case and a TC-associated heavy rainfall case in Japan. They demonstrated that the every-10-minute all-sky Himawari-8 DA improves TC intensity forecast and enables rapid refresh of precipitation and flood forecasts. However, they did not investigate precipitation induced by a TC itself, because none of the TCs in these cases directly caused heavy precipitation in Japan.

In September 2016, Typhoon Malakas passed the southern coast of Japan (Fig. 1a) and induced a large amount of precipitation over a broad area (Fig. 1b). The heavy precipitation was observed not only in the coastal region but also in the mountain region of central Japan, where a number of hydroelectric dams have been operated for a long time. The present study aims to investigate the impact of the every-10-minute all-sky Himawari-8 DA on the heavy precipitation event associated with Typhoon Malakas (2016), with particular focus on QPF directly associated with Malakas. The rest of this paper is organized as follows. Section 2 describes experimental design. Section 3 gives the results and discussion. Summary and concluding remarks are given in Section 4.

2. Methodology

We use the SCALE-LETKF system (Lien et al. 2017) consisting of a regional numerical weather prediction (NWP) model from the scalable computing for advanced library and environment (SCALE, Nishizawa et al. 2015; Sato et al. 2015) and the local ensemble transform Kalman filter (LETKF, Hunt et al. 2007; Miyoshi and Yamane 2007). Following H18a, we set up two computational domains: the parent domain (hereafter D1) with 18-km mesh and the daughter domain (hereafter D2) with 6-km mesh. D1 and D2 cover a large area of East Asia and most of the Japanese archipelago (Fig. 1a), respectively.

Most of the model physics parameterization schemes in each domain are the same as those of H18a. Namely, we use the Tomita (2008) six-class single-moment bulk microphysics parameterization, the level-2.5 closure of the Mellor-Yamada-Nakanishi-Niino turbulence scheme (Nakanishi and Niino 2004), the Model Simulation radiation TRAnSfer code (MSTRN) X (Sekiguchi and Nakajima 2008), a Beljaars-type bulk surface-flux model (Beljaars and Holtslag 1991), and a single-layer urban canopy model (Kusaka et al. 2001). Recently, the Kain-Fritsch convective parameterization (Kain 2004) has been implemented in SCALE, we use it in both D1 and D2.

The ensemble size is fixed at 50. D1 is identical to the domain of the near-real-time SCALE-LETKF system continuously running from May 2015 (Lien et al. 2017), and the initial ensemble
Model (MSM) data are used as the reference of the surface wind radar data). In addition, the initial values of the JMA Meso-Scale (Fig. 1a), we start the D2 DA cycles at 1200 UTC 19 September (72 DA cycles). We also run forecasts in each experiment, respectively (Fig. 1b). Although Him8 outperforms NoHim8, the precipitation amount in Him8 is much smaller than that in the JMA radar data. This would be caused by insufficient TC intensity in Him8 (see Fig. 6a). In addition, it is likely that the precipitation amount of Malakas was increased by the terrain; the current model resolution (6 km) may not be high enough to resolve the terrain-induced precipitation process.

3. Results and discussion

Figure 2 presents the analyzed Himawari-8 IR radiances in each experiment and actual observations. As shown in H18a and H18b, the all-sky Himawari-8 DA significantly improves the cloud patterns associated with Malakas in Him8 compared to those in NoHim8.

The all-sky Himawari-8 DA improves precipitation forecasts as well. We conduct deterministic forecasts from the analysis ensemble mean in each experiment. Figure 3 shows horizontal maps of forecast 3-h accumulated precipitation amount and the corresponding 3-h accumulated JMA radar data. Him8 shows precipitation associated with Malakas better matching with JMA radar data than NoHim8, which completely misses strong precipitation over central Japan near Shizuoka and Nagano prefectures. This forecast failure may be crucial to the operations of hydroelectric dams in central Japan. In addition, surface wind intensity of Him8 is closer to the JMA MSM data, indicating that the surface wind associated with Typhoon Malakas is also improved by the all-sky Himawari-8 DA (Fig. 3).

Since Malakas caused a heavy precipitation in Japan after 1200 UTC 19 September (Fig. 1a), we start the D2 DA cycles at 1200 UTC 19 September after a 6-hour spin-up ensemble forecast initiated from the D1 analysis ensemble. We conduct the D2 DA cycles with and without the Himawari-8 radiance DA (hereafter “Him8” and “NoHim8” experiments, respectively) till 0000 UTC 20 September (72 DA cycles). We also run forecasts in each experiment. To evaluate precipitation forecasts, we verify against the JMA composite radar-precipitation estimates (hereafter “JMA radar data”). In addition, the initial values of the JMA Meso-Scale Model (MSM) data are used as the reference of the surface wind field.
Fig. 2. Horizontal maps of Himawari-8 brightness temperature (K) of band 13 (10.4 μm) for (left) NoHim8 and (middle) Him8 ensemble mean analyses, and (right) Himawari-8 observations at (a–c) 1800 UTC 19 September and (d–f) 0000 UTC 20 September, respectively.

Fig. 3. Horizontal maps of 3-h accumulated precipitation amount (mm) of (a) NoHim8 and (b) Him8 for 6−9-h forecasts initiated from the analysis ensemble mean at 0000 UTC 20 September, and (c) the corresponding 3-h accumulated JMA radar data. The black curves are 10-m wind speed from the (a) NoHim8 and (b) Him8 forecasts and that from the initial values of the JMA MSM data. The contour interval is 3 m s$^{-1}$ starting at 12 m s$^{-1}$.

Fig. 4. Ensemble-derived probability (%) of 3-h accumulated precipitation amount ≥ 10 mm for (a, c) NoHim8 and (b, d) Him8 forecasts initiated from the analyses at 0000 UTC 20 September 2016. Forecast times are (a, b) 6−9 h and (c, d) 9−12 h. Thick black contours show the corresponding JMA radar data of 10 mm.
forecasts are initiated at 0000 UTC 20 September 2016. Black and red curves show NoHim8 and Him8, respectively. The scores are calculated over land within the red rectangle region in Fig. 1, with the threshold values of 1.0 mm h\(^{-1}\) (solid) and 10.0 mm h\(^{-1}\) (dashed). The ensemble forecasts are initiated at 0000 UTC 20 September 2016.

for the bias scores for heavy rain in 12-h forecast lead times. However, the scores are still far from perfect even in Him8, possibly because Himawari-8 radiance observations do not directly measure precipitation. Namely, a deep cloud observed by Himawari-8 is not necessarily associated with a large amount of precipitation. Directly assimilating rainfall amount observations together with the Himawari-8 radiances will be investigated in our future study.

The improvement of precipitation forecast skill is associated with the TC representation. H18a and H18b demonstrated that the all-sky Himawari-8 IR DA could modify the structure and position of a TC. Figure 6 presents the time series of the TC intensity and tracks. Him8 shows the TC intensity analyses (thick lines) and forecasts (thin lines) closer to the best track than NoHim8, consistent with H18b. This modifies the circulation associated with the TC, especially northward moisture transport east of the TC (not shown). This leads to improved precipitation patterns in central Japan (Fig. 3) although the TC tracks are not clearly improved (Fig. 6b). The center of Malakas was unclear at 0000 UTC 20 September 2016 (Fig. 2f), so that the best-track analyses of the TC (Fig. 6b) are not necessarily optimal for forecasting TC-induced precipitation as a function of forecast lead time (h). Black and red curves show NoHim8 and Him8, respectively. The scores are calculated over land within the red rectangle region in Fig. 1, with the threshold values of 1.0 mm h\(^{-1}\) (solid) and 10.0 mm h\(^{-1}\) (dashed). The ensemble forecasts are initiated at 0000 UTC 20 September 2016.

The horizontal localization scale is one of the most important tunable parameters in an ensemble DA system. H18b reported a high sensitivity of the TC analyses and forecasts to the horizontal localization scale. Following H18b, we used 60 km, but this may not be necessarily optimal for forecasting TC-induced precipitation in this case for a decaying stage after recurvature and moving along the southern coast of Japan. In fact, H18b mainly focused on the TC intensity for a typhoon under rapid intensification over the ocean far south of Japan. Here we conduct two additional experiments with different horizontal localization scales (30 km and 90 km). Although the impacts on the analyses are relatively small (not shown), the precipitation forecast scores are sensitive to the horizontal localization scale (Fig. 7). The shortest scale of 30 km is the worst. The difference between the 60 km and 90 km experiments is not so large, but generally the largest scale of 90 km gives the best results. The 60 km experiment shows a slight advantage for strong precipitation (dashed lines) with longer forecast lead times. Comparing with NoHim8 (black), we find that all-sky Himawari-8 IR DA exhibits a clear benefit on the precipitation forecasts regardless of the setting of the horizontal localization scale with some exceptions for heavy precipitation with the shortest 30-km localization. This is not surprising if we consider that an IR radiance observation may contain a long-range correlation with other atmospheric variables in a TC (Zhang et al. 2016). However, the long-range correlation would be situation dependent. For example, it is unlikely that atmospheric variables within an isolated convective cloud are closely related to an IR radiance observation far from the cloud. Therefore, it is essential to choose an appropriate localization scale by considering target phenomena and sampling errors.

4. Summary and concluding remarks

It is important to predict TCs and associated heavy precipitation as accurately as possible. In this study, we investigated the potential of all-sky Himawari-8 IR DA for improving not only the TC representation but also TC-induced precipitation forecasts in a single case of Typhoon Malakas (2016). The results showed that all-sky Himawari-8 IR DA provided more accurate deterministic and probabilistic precipitation forecasts. This was not shown by the previous studies (Honda et al. 2018a, b) because they focused on TC intensity forecasts and deterministic precipitation forecasts, but not on probabilistic precipitation forecasts. In addition to the
precipitation forecasts, TC intensity and associated surface wind intensify were improved by all-sky Himawari-8 IR DA. Positive impacts of all-sky Himawari-8 IR DA on the precipitation forecasts were also verified by the threat scores and bias scores. Both of the scores of Him8 outperformed those of NoHim8, except for Him8 with the small horizontal localization scale of 30 km.

Improved precipitation forecasts would contribute to efficient operations of hydroelectric dams. H18a showed that Himawari-8 DA improved river discharge forecasts. They used river discharge observations only for verification of the river model forecasts, but recently, Sawada et al. (2018) demonstrated the potential of river discharge observations for improving the atmospheric state using a strongly coupled river-atmosphere DA system. It is an interesting future work to apply their idea to a real-world precipitation event. In addition to river observations, assimilating other types of atmospheric observations such as the JMA radar data with all-sky Himawari-8 IR radiances simultaneously is another important direction.

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