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.

(Citation: Honda, T., S. Takino, and T. Miyoshi, 2019: Improving a precipitation forecast by assimilating all-sky Himawari-8 satellite radiances: A case of Typhoon Malakas (2016). SOLA, 15, 7–11, doi:10.2151/sola.2019-002.)

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. In Japan, QPF for TC cases would be crucial.

The horizontal distribution and amount of TC-induced precipitation depend on the TC track, intensity, and rainfall 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 (Seigiuchi 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...
for D1 is adopted from the analysis ensemble at 0000 UTC 11 September 2016 of the near-real-time SCALE-LETKF system which also has 50 ensemble members. Following H18a and considering the SCALE version difference, we run a 1-day spin-up ensemble forecast before starting 6-hourly DA in D1. Six-hourly conventional PREPBUFR observations obtained from the National Centers for Environmental Prediction (NCEP) are assimilated in D1. The boundary conditions for D1 analyses and forecasts are given by the NCEP Global Forecasting System (GFS) analysis and forecasts, respectively. Following Lien et al. (2017) and H18a, the localization scales in D1 are chosen to be 400 km in the horizontal and 0.3 of the natural logarithmic pressure (ln $p$) in the vertical, and covariance inflation in D1 is a combination of multiplicative inflation (coefficient of 1.25) and the relaxation to prior perturbation (RTTP, Zhang et al. 2004) (coefficient of 0.8).

For D2, we follow H18b and conduct DA cycles every 10 minutes with three types of observations: NCEP PREPBUFR observations (split into every-10-minute bins), band 9 (6.9 µm) of Himawari-8 IR radiance observations, and hourly TC vital observations (split into every-10-minute bins), band 9 (6.9 µm) data into 0.06° × 0.06° resolution, close to the model resolution ($6$ km) for D2. Next, similar to H18a and H18b, we thin the 0.06° × 0.06° Himawari-8 IR radiance data into 0.24° × 0.24° resolution. H18b estimated that the observation error correlation becomes low if the observation distance is larger than 0.2°. As in H18a and H18b, a radiative transfer model known as RTTOV 11.2 (Saunders et al. 2013) is used for the observation operator of the Himawari-8 radiances. Following H18b, the horizontal and vertical localization scales are chosen to be 60 km and 0.5 ln $p$, respectively, and the observation errors are set to be 3 K (clear sky) and 6 K (cloudy sky). The center of the Himawari-8 vertical localization function is assigned by taking the cloud top height into account (H18b). The localization scales for the NCEP PREPBUFR (TC vital) observations are chosen to be 50 km (200 km) in the horizontal and 0.3 ln $p$ (no localization) in the vertical.

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.

### 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).

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.

Forecast uncertainty estimates are important outcomes of ensemble prediction, especially for practical use including hydroelectric power generations. Indeed, to provide uncertainty estimates, JMA plans to start operational mesoscale ensemble forecasts. Here we conduct 50-member ensemble forecasts and compute probability of precipitation (Fig. 4). The Him8 forecasts well predict the major precipitation over central Japan with higher probabilities (> 70%), whereas the NoHim8 forecasts fail. The NoHim8 forecasts have a relatively high probability region southeast of Japan, where the JMA radar observation did not observe rainfall. The improvement by assimilating Himawari-8 radiances would be caused by an appropriate reduction of the ensemble spread by the Himawari-8 observations including over the ocean.

Here we perform quantitative comparisons of the precipitation forecasts by using threat scores and bias scores verified against the JMA radar data. Since the ensemble mean makes the precipitation forecasts biased toward a broader area of weaker precipitation than individual ensemble members, we first compute these scores for each ensemble member and then take the ensemble mean. The scores are computed only over land within the rectangle shown in Fig. 1b. Figure 5 depicts threat scores and bias scores as a function of forecast lead time. Him8 clearly outperforms NoHim8, so that the Him8 threat scores are higher and bias scores are closer to 1 than those of NoHim8 for both weak rain and heavy rain, except...
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. This leads to improved precipitation patterns in central TC, especially northward moisture transport east of the TC (not shown). This modifies the circulation associated with the TC. Figure 6 presents the time series of the TC intensity and all-sky Himawari-8 IR DA could modify the structure and position with the TC representation. H18a and H18b demonstrated that the potential of all-sky Himawari-8 IR DA for improving not only the TC intensity forecasts and deterministic precipitation forecasts, 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 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).
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.

Acknowledgements

We thank two anonymous reviewers for their constructive comments. This study was performed as part of a collaborative research project between RIKEN and Tokyo Electric Power Company Holdings for advancing hydroelectric dam operations. The authors thank the members of this collaborative research project.

This work was partly supported by JST CREST (Grants JPMJCR 1312), FOCUS Establishing Supercomputing Center of Excellence, RIKEN Incentive Research (FY2018), and FLAGSHIP2020, MEXT within the priority issue 4 “Advancement of meteorological and global environmental predictions utilizing observational ‘Big Data.’” TH and ST conducted the experiments and analyzed the results. TM is the PI and directed the research. The Himawari-8 radar data were provided by the National Institute of Information and Communications Technology (NICT) Science Cloud. The NCEP PREPBUIFR observation is available online from http://rda.ucar.edu/datasets/ds337.0/. The JMA radar and MSM analysis data were collected and distributed by the Research Institute for Sustainable Humanosphere, Kyoto University (http://database.rish.kyoto-u.ac.jp/index-e.html). The results were obtained by using computational resources of the K computer, provided by RIKEN.

Edited by: S.-H. Chen

References

Beljaars, A. C. M., and A. A. M. Holtslag, 1991: Flux parameterization over land surfaces for atmospheric models. J. Appl. Meteor., 30, 327–341.

Bessho, K., and co-authors, 2016: An introduction to Himawari-8/9 – Japan’s new-generation geostationary meteorological satellites. J. Meteor. Soc. Japan, 94, 151–183.

Fudeyasu, H., S. Hirose, H. Yoshiooka, R. Kumazawa, and S. Yamasaki, 2014: A global view of the landfall characteristics of tropical cyclones. Trop. Cyclone Rev. Res., 3, 178–192.

Hunt, B. R., E. J. Kostelich, and I. Szunyogh, 2007: Efficient data assimilation for spatiotemporal chaos: A local ensemble transform Kalman filter. Physica D, 230, 112–126.

Honda, T., S. Kotsuki, G.-Y. Lien, Y. Maejima, K. Okamoto, and T. Miyoshi, 2018a: Assimilation of Himawari-8 all-sky radiances every 10 minutes: Impact on precipitation and flood risk prediction. J. Geophys. Res., 123, 965–976, doi: 10.1002/2017JD027096.

Honda, T., and co-authors, 2018b: Assimilating all-sky Himawari-8 infrared radiances: A case of typhoon Soudelor (2015). Mon. Wea. Rev., 146, 213–229.

Kain, J. S., 2004: The Kain–Fritsch convective parameterization: An update. J. Appl. Meteor., 43, 170–181.

Kusaka, H., H. Kondo, Y. Kikegawa, and F. Kimura, 2001: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound.-Layer Meteor., 101, 329–358.

Lien, G.-Y., T. Miyoshi, S. Nishizawa, R. Yoshida, H. Yashiro, S. A. Adachi, T. Yamaura, and H. Tomita, 2017: The near-real-time SCALE-LETKF system: A case of the September 2015 Kanto-Tohoku heavy rainfall. SOLA, 13, 1–6.

Miyoshi, T., and S. Yamane, 2007: Local ensemble transform Kalman filtering with an AGCM at a T159/L48 resolution. Mon. Wea. Rev., 135, 3841–3861.

Nakanishi, M., and H. Niino, 2004: An improved Mellor–Yamada level-3 model with condensation physics: Its design and verification. Bound.-Layer Meteor., 112, 1–31.

Nishizawa, S., H. Yashiro, Y. Sato, Y. Miyamoto, and H. Tomita, 2015: Influence of grid aspect ratio on planetary boundary layer turbulence in large-eddy simulations. Geosci. Model Dev., 8, 3393–3419.

Okamoto, K., 2017: Evaluation of IR radiation simulation for all-sky assimilation of Himawari-8/AHI in a mesoscale NWP system. Quart. J. Roy. Meteor. Soc., 143, 1517–1527.

Okamoto, K., A. P. McNulty, and W. Bell, 2014: Progress towards the assimilation of all-sky infrared radiances: An evaluation of cloud effects. Quart. J. Roy. Meteor. Soc., 140, 1603–1614.

Sato, Y., S. Nishizawa, H. Yashiro, Y. Miyamoto, Y. Kajikawa, and H. Tomita, 2015: Impacts of cloud microphysics on trade wind cumulus: Which cloud microphysics processes contribute to the diversity in a large eddy simulation? Prog. Earth Planet. Sci., 2, 23.

Saunders, R., and co-authors, 2013: RTTOV-11: Science and Validation Report. NWP-SAF Rep. NWPSAF-MO-TV-032, Met Office, United Kingdom, 62 pp. (Available online at https://nwpsaf.eu/oldsite/deliverables/rtn/docs_rttov11/rttov11_svr.pdf, accessed 24 September 2018).

Sawada, Y., T. Nakaegawa, and T. Miyoshi, 2018: Hydrometeorology as an inversion problem: Can river discharge observations improve the atmosphere by ensemble data assimilation? J. Geophys. Res., 123, 848–860, doi:10.1002/2017JD027531.

Schmitt, T. J., M. M. Gunshor, W. P. Menzel, J. J. Gurka, J. Li, and A. S. Bachmeier, 2005: Introducing the next-generation Advanced Baseline Imager on GOES-R. Bull. Amer. Meteor. Soc., 86, 1079–1096.

Schmitt, T. J., P. Griffith, M. M. Gunshor, J. S. Goodwin, and W. J. Lebarbier, 2017: A closer look at the ABI on the GOES-R series. Bull. Amer. Meteor. Soc., 98, 681–698.

Sekiguchi, M., and T. Nakajima, 2008: A k-distribution-based radiation code and its computational optimization for an atmospheric general circulation model. J. Quant. Spectrosc. Radiat. Transfer, 109, 2779–2793.

Tomita, H., 2008: New microphysical schemes with five and six categories by diagnostic generation of cloud ice. J. Meteor. Soc. Japan, 86, 121–142.

Zhang, F., C. Snyder, and J. Sun, 2004: Impacts of initial estimate and observation availability on convective-scale data assimilation with an ensemble Kalman filter. Mon. Wea. Rev., 132, 1238–1253.

Zhang, F., M. Minamide, and E. Clothiaux, 2016: Potential impacts of assimilating all-sky infrared satellite radiances from GOES-R on convection-permitting analysis and prediction of tropical cyclones. Geophys. Res. Lett., 43, 2954–2963.

Manuscript received 18 October 2018, accepted 2 December 2018 SOLA. https://www.jstage.jst.go.jp/browse/sola/