Importance of ocean prediction for heavy rainfall prediction over Japan in July 2020

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Abstract
Hindcast experiments were performed for heavy rainfall events over Japan in July 2020 using a regional atmospheric model and a regional coupled model to examine the importance of ocean prediction for predicting heavy rainfall events. Both models were able to predict the first peak of accumulated rainfall over western Japan occurring in the first half of July. However, only the coupled model predicted the second peak that occurred in the second half of July. Sea level pressure (SLP) and low-level moisture inflow originating from an existing atmospheric river (AR) were found to differ in each model. In the regional atmospheric model, the error associated with the inaccurate low-level moisture inflow grew with rising excessive latent heat flux, which enhanced convection and resulted in incorrect SLP patterns. This trend seems to be enhanced by having a prescribed sea surface temperature (SST), which affects the surface heat flux. When ocean conditions are predicted as in the coupled model, such error growth is suppressed by changes in SST that adjust surface heat flux, and it leads to generation of the correct SLP patterns. With correct SLP especially for Pacific high in this case, favorable conditions for inflow from the AR can also be predicted, thus making it possible to predict the heavy rainfall. In conclusion, considering the atmospheric feedback on SST, ocean prediction can improve the predictability of heavy rainfall over Japan, the conditions for which are influenced by the nearby AR. Ocean prediction may therefore extend the range of weather forecasting.

KEYWORDS
numerical methods and NWP, physical phenomenon, rainfall, scale, convection, tools and methods, synoptic

1 | INTRODUCTION

Heavy rainfall events over Japan are becoming more and more significant. The total amount of accumulated rainfall and its occurrence frequency have been reported to have increased 1.4–1.7 times in the past 30 years because of increasing water vapor in the atmosphere due to the climate change (Ministry of Education, Culture, Sports, Science, and Technology & Japan Meteorological Agency, 2020). With damage caused by the increasing
heavy rainfall becoming increasingly serious, there is a rising demand for more precise heavy rainfall prediction.

Recent studies have endeavored to improve heavy rainfall prediction by updating the prediction systems and adopting assimilation techniques (e.g., Kawabata et al., 2013; Kunii, 2014; Ono et al., 2021). However, heavy rainfall over Japan is sometimes difficult to predict, even with newer prediction systems, because these events consist of localized quasi-stationary band-shaped convective system (QBCS), especially in summertime. Their occurrence tends to be influenced by many factors. For example, Kato (2020) suggested that possible favorable conditions for QBCS development include low and middle-level moisture content, a large-scale environment, and local wind properties. To reduce model’s uncertainty and achieve more accurate heavy rainfall prediction, Duc et al. (2021) recently performed an ensemble forecast with 1000 ensemble members that outperformed the operational forecast. However, this process is computationally too expensive for practical use, so other ways to improve the accuracy of heavy rainfall forecasting need to be considered.

In July 2020, there was heavy rainfall over Japan, particularly western Japan. The integrated amount of rainfall was the highest in the area since 2009 (Hirockawa et al., 2020). Heavy summer rainfall in Japan is considered to be closely related to the abundance of moisture supplied from the East China Sea to the southwest. The inflow of moisture toward Japan in recent years has been recognized as an atmospheric river (denoted as AR hereafter, Zhu & Newell, 1998; Gimeno et al., 2014). Some recent studies have highlighted the relationship between heavy rainfall events and ARs (Araki et al., 2021; Kamae et al., 2017; N. Zhao et al., 2021). Liu et al. (2021) very recently revealed that sea surface temperature (SST) patterns along with Kuroshio extension can affect AR and rainfall behaviors in western north America. Due to the SST patterns surrounding Japan, a similar situation is believed to occur near Japan, where the AR may have significant impact on the heavy rainfall. Thus, predicting ocean condition changes may be important for increasing the accuracy of heavy rainfall prediction.

The purpose of this study is to evaluate the importance of ocean prediction for improving heavy rainfall prediction in Japan. To achieve this, we conducted hindcast experiments for heavy rainfall events in July 2020, using a regional atmospheric model and a regional coupled model. The remainder of this paper is structured as follows. Section 2 describes the models used for the hindcast experiments and the experimental setup. Section 3 presents the results and discussion. Section 4 provides summary and conclusions.

2 | MODEL AND EXPERIMENTAL SETUP

2.1 | Regional coupled model

A regional coupled model was used to conduct the hindcast experiments. The atmospheric part of the model was based on the regional configuration of a non-hydrostatic atmospheric model (Baba, 2020a; Baba et al., 2010) with a recently developed convection scheme (Baba, 2019, spectral scheme hereafter). This spectral scheme can simulate convective clouds better than existing schemes for intraseasonal variability, tropical cyclones, and diurnal cycle of precipitation (Baba, 2020a, 2020b, 2021; Baba & Giorgetta, 2020). Other atmospheric parameterizations used are almost identical to those used by Baba (2020a). The ocean portion of the model is the Nucleus for European Modeling of the Ocean (NEMO, Madec, 2008) version 3.6. The configuration of this ocean model follows Baba (2020b), except for the regional configuration and different horizontal diffusion settings that were changed depending on the horizontal resolution. The atmospheric and oceanic models were coupled with the Ocean Atmosphere Sea Ice Soil version 3 coupler, Model Coupling Toolkit (OASIS3-MCT, Valcke, 2013). The regional atmospheric model, which was used for comparison with the regional coupled model, was configured from the regional coupled model by removing the ocean model and introducing a prescribed SST.

The horizontal resolution of the atmospheric portion of the model was set to 30 km. This resolution is 1.5 times larger than the minimum needed for capturing daily precipitation (20 km, Takayabu & Hibino, 2016). The variability of intra-daily precipitation is greatly dependent on the convection scheme, and the spectral scheme used is able to simulate this variability (Baba, 2020a). The present study focuses on regional-scale precipitation over Japan (Kawase et al., 2019), so this resolution was used even though it cannot resolve the convective cells of QBCS (Duc et al., 2021; Kato, 2020). The total number of vertical layer is 34 which model top is set to 25 km. The horizontal resolution of the ocean model was 0.25° in the curvilinear coordinate, and 31 vertical z-coordinate levels were used. The time interval for each flux exchange between atmospheric and oceanic models was set to every 30 min. The model outputs were recorded every 3 h.

2.2 | Experimental setup

For the present demonstration, two different configurations were used for the hindcast experiments, as
described above. The one is regional atmospheric model, and the another is regional coupled model (each model run is referred to as RUN-ATM and RUN-CPL, respectively, hereafter). When the regional atmospheric model is used, the SST within the prediction period is generally unknown. In this case, SST is given by the climatological SST, and an SST anomaly at the starting time of prediction. The time variation of the given SST follows that of climatological SST. This SST anomaly persistence method has been used for atmospheric-model-only predictions and forecasts (M. Zhao et al., 2010), and a similar method has been employed in the prediction of Japan Meteorological Agency (JMA, 2019). On the other hand, although ocean conditions are directly simulated in RUN-CPL, they should be initialized before prediction. The temperature and salinity of the initial state were determined via monthly Simple Ocean Data Assimilation (SODA) version 3 reanalysis data (Carton et al., 2018). Some preliminary experiments were performed to investigate the effect of different ocean spin-up terms, and the results did not change even with 1-year of spin-up before the prediction start time. This spin-up term was thus employed for RUN-CPL.

The computational domain was chosen as the western north Pacific surrounding Japan area (105°E–177°W and 6°N–66°N) so as to be similar to that used in Japan Coastal Ocean Predictability Experiment 2 (JCOPE2, Miyazawa et al., 2009). To minimize the model bias of outer models, the lateral boundary conditions for both the atmosphere and the ocean were determined by reanalysis data in this demonstration. For the atmospheric model, the lateral boundary condition is supplied by daily ERA5 reanalysis (Hersbach et al., 2020), while the lateral boundary condition for the ocean model is given through monthly SODA reanalysis. These reanalysis data were also used to initialize the atmospheric and oceanic conditions for the initial state. The hindcast experiments started on June 30, 2020 and continued to July 31, 2020. To further reduce model-derived uncertainty, eight time-lagging ensemble members were considered for the hindcast. The ensemble members were generated using different initialization times at the following hours: 0, 3, 6, 9, 12, 15, 18, and 21 h on June 30.

**Figure 1** (a) Time evolution of total daily accumulated rainfall (3-day running mean) over western Japan (defined as land regions west of 138°E). The dashed lines indicate the accumulated rainfall from each ensemble member. (b)–(d) Comparison of horizontal distributions of total accumulated rainfall (mm) between July 20 and 31, 2020. The observed values (Obs) were computed using reanalysis data from the Meso-Scale Model (MSM) of JMA.
3 | RESULTS AND DISCUSSION

3.1 | Accumulated rainfall

The time evolution of total daily accumulated rainfall over western Japan for each case is compared in Figure 1a. The heavy rainfall event in July 2020 has two peaks, one in the first half and one in the second half of July, with the rise and fall associated with each peak lasting for approximately 2 weeks. Although peak values were slightly delayed compared with the observed values, both RUN-ATM and RUN-CPL successfully predicted the first peak of the accumulated rainfall. However, RUN-ATM failed to predict the second peak, while RUN-CPL did successfully predict it. The distributions of total accumulated rainfall during July 2020 were qualitatively similar (Figure S1 in the supporting information), but the distributions in the second half of July were much different (Figure 1b–d). According to the observed values, large accumulated rainfall occurred in several regions in western Japan. RUN-ATM failed to predict the correct distribution of rainfall over Japan; it simulated little rainfall over the land, while predicting widespread rainfall over the western north Pacific. On the other hand, although RUN-CPL overestimated the rainfall in some regions, it successfully predicted narrow rainfall distributions along the islands of Japan. Because the models mainly differ in their treatment of the ocean, the properties of rainfall originating from the ocean may cause these different results.

3.2 | Moisture supply

As shown above, the time evolution of daily accumulated rainfall had two main peaks during July 2020, and the largest difference between the predicted rainfall and the observational data was evident for the second peak. To identify the impact of ocean conditions on the heavy rainfall, atmospheric conditions that might be affected by the ocean were analyzed. Figure 2 compares the distributions of precipitable water and low-level wind velocities averaged between July 15 and 31, 2020. ERA5 is used as the reference (Obs), and hindcast results are given by an ensemble mean.
correctly predicted in RUN-CPL but not predicted well in RUN-ATM. The precipitable water indicate that the moisture over western Japan in RUN-ATM was less than both the observed and those in RUN-CPL. Such lack of low-level moisture inflow was not in fact observed in the first half of July (Figure S2). Thus, these results indicate that RUN-ATM failed to predict accumulated rainfall during extended range predictions, because of the incorrect low-level moisture inflow. This also suggests that ocean prediction may enable correction for these failures.

3.3 | Ocean condition

Differences in the predicted ocean conditions seems to cause the different low-level moisture inflows, suggesting that the ocean conditions also give rise to different low-level pressure patterns. To clarify this point, corresponding SST and sea level pressure (SLP) patterns are compared for the second half of July in Figure 3. A Pacific high (one of the subtropical highs) in the southeast of Japan is evident in the image of observed values. In contrast, RUN-ATM predicted low pressure at this locality, meaning that this model failed to predict the Pacific high, although its SST pattern is similar to that observed. RUN-CPL predicted a lower SST compared with the observed values, but predicted high pressure in the region of the Pacific high. These results suggest that surface heat flux transitions from the ocean, rather than SST, may be important for the formation of the pressure pattern, which is favorable for the formation of low-level moisture inflows. In other words, this means that considering atmospheric feedback on SST is more important than providing prescribed SST in the prediction.

3.4 | Sea level pressure pattern and surface heat flux

To confirm the importance of surface heat flux, latent heat flux transitions were compared with the SLP for the period before the second peak of rainfall (Figure 4a). A high-pressure region was observed in the region southeast of Japan throughout the transitions. A remarkable point in the transition is that the latent heat flux from
the ocean did not increase, even when the ocean surface is exposed to the drier atmospheric conditions of the high-pressure region (Figure S3). This may be because the increase in SST was suppressed by a heat loss via surface heat flux and radiative cooling (see outgoing longwave radiation [OLR] in Figure S3), which is also believed to suppress any increase in latent heat flux. In RUN-ATM, high pressures remained in the southeast on July 14, with large prolonged latent heat flux in the south. This large latent heat flux did not disappear as the time passed; rather, the latent heat flux increased further on July 16, leading to a low SLP in the southeast. This low SLP implies unrealistically enhanced convection in the location of Pacific high. In these features, RUN-ATM predicted constantly low-level wet conditions reacting with the latent heat flux increase, even within higher OLR regions (Figure S3). Originally, the latent heat flux should be decreased by the SST decrease due to a heat loss by surface heat flux and radiative cooling, but RUN-ATM cannot consider these effects. This means that an adjustment of SST responding to the atmospheric condition is essentially needed, but when SST is prescribed, the results is a decline in prediction fidelity for low-level moisture inflow formation. RUN-CPL could not predict the observed pressure pattern exactly, but it did predict a high-pressure region in the south and southeast over the western Pacific, and showed suppression of latent heat flux as well.

These results imply that considering the atmospheric feedback on SST can avoid further error growth in the prediction. Wang et al. (2005) found similar findings for prediction of Asian summer monsoon rainfall. They revealed that prediction skill of atmosphere-only model decreased where the atmospheric feedback on SST was significant by analyzing the correlations between rainfall and SST anomalies. Also in this study, the area of heavy rainfall is included in the region where the atmospheric feedback on SST is significant (Figure 4b). The Japan area in July is basically covered by negative correlation coefficients, so it means that a coupled model prediction is necessary to accurately predict heavy rainfall events in this area.

The SST and surface heat flux adjustments cause differences in the low-level moisture inflows just before heavy rainfall. The pressure patterns and incoming moisture from the southwest region on July 20, just before the second peak of rainfall, are compared in Figure 5a–c. Low-level southwesterly wind formed according to the observed values and RUN-CPL, while this was not predicted in RUN-ATM, where the high pressure corresponding to the Pacific high was not present. RUN-CPL could not predict the exact similar pressure pattern and moisture fields observed, but it qualitatively modeled the correct flow fields near Japan. The wind and moisture fields in the observation and RUN-CPL conform with typical AR features, so the fields present favorable
conditions for heavy rainfall, and this indicates why RUN-CPL was able to predict the heavy rainfall in the second half of July 2020. In this feature, RUN-CPL overestimated the flow pattern. This may be due to too large pressure gradients originating from the underestimated SST in the southern region that generated a higher SLP there (Figure 4a). Therefore, introducing an ocean assimilation is expected to further improve the flow pattern in the prediction.

Pacific high is considered a key to form the suitable flow pattern for AR, and so it may have a good correlation to the rainfall amount shown in Figure 1a. Analyzing the area averaged SLP for the Pacific high, it was found that the difference in the SLP between the cases started to appear since July 15 when the SLP of the Pacific high in the observation started to increase slightly. Then, the difference became significant between RUN-ATM and RUN-CPL by July 20 (Figure 5d, corresponding SLP patterns are shown as in Figure 5a–c). RUN-CPL could not predict SLP increase as observed, but it predicted higher SLP as observed than RUN-ATM. Therefore, the time series of Pacific high’s SLP correlate to that of rainfall amount, meaning that a higher Pacific high after July 20 as observed can cause the heavy rainfall in correct location, and it realizes better heavy rainfall prediction.

4 | SUMMARY AND CONCLUSIONS

The importance of ocean prediction for predicting heavy rainfall over Japan was demonstrated through hindcast experiments using a regional atmospheric model (RUN-ATM) and a regional coupled model (RUN-CPL). SST was prescribed using the persistent anomaly method in RUN-ATM, which is a similar procedure used by the Japanese operational weather forecast, while the ocean conditions were directly simulated in RUN-CPL. Both models could predict the first peak of accumulated rainfall well, but only RUN-CPL succeeded in predicting the second peak of heavy rainfall observed in second half of July 2020.
The successful prediction by RUN-CPL was analyzed by examining the mean low-level moisture inflows toward Japan. The observed data showed a moisture inflow over Japan from an existing AR, which RUN-ATM failed to predict during the second peak of the heavy rainfall. This was found to be related to the sea level pressure (SLP) patterns; RUN-CPL predicted a qualitatively correct high-pressure pattern corresponding to the Pacific high, while RUN-ATM predicted low pressure in the same area. This failure originated from the inability of the prescribed SST to adjust surface heat flux. The prescribed SST did not decrease even when a heat loss due to surface heat flux or radiative cooling occurred by the high-pressure pattern. This led to more latent heat flux, which enhanced convection in the region where the Pacific high should exist. This difference caused a lack of low-level moisture inflows in RUN-ATM and resulted in a prediction failure, while RUN-CPL successfully predicted the second heavy rainfall peak. Fidelity for the Pacific high was found to be closely related to the failure or success of the prediction, since behavior of the AR was much influenced by this subtropical high.

If the error growth is suppressed in RUN-ATM, these differences may not occur. The evolution of flow fields in RUN-ATM indicated that this case first failed to predict low-level moisture, as the conditions were too wet, keeping excessively high latent heat flux by the prescribed SST, and generating low pressures in the Pacific through enhanced convection. If this overestimated moisture was avoided in RUN-ATM, this case succeeded in predicting the Pacific high and the late July heavy rainfall. However, an error growth is inevitable in numerical prediction even with assimilation techniques, so it may be difficult to avoid the overestimation and following error growth. In addition, as the analysis on the significance for feedback effects presented, the atmospheric feedback on SST is essentially significant in Japan area during summertime. Thus, it is difficult for atmosphere-only model prediction to further increase the prediction accuracy. If ocean prediction is included in the prediction model, it can mitigate unrealistic error growth, especially that associated with SST, which can adjust surface heat flux.

The results of this study indicate that the ocean prediction is useful for improving the predictability of heavy rainfall for extended range forecasts, especially for heavy rainfall events in summertime where ARs play an important role. With the ocean prediction, consideration for atmospheric feedback on SST can suppress the error growth in the prediction. This concurs with recent studies, which reveal that ARs have had an important influence on heavy rainfall in the past, and ocean prediction can thus be useful for future regional-scale heavy rainfall prediction in Japan. Going forward, research should evaluate the importance of resolving the convective cells of QBCSs for rainfall forecasting with ocean prediction.

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