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	Mesoscale OSSE to Evaluate the Potential Impact from a Geostationary
	Hyperspectral Infrared Sounder
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Abstract

35

34

36	Herein, the impact of a hyperspectral sounder on a geostationary satellite (GeoHSS)
37	in a regional numerical weather prediction system is investigated during the Baiu
38	seasons, including heavy rainfall cases, in 2017, 2018, and 2020. The reanalysis-based
39	observing system simulation experiment (OSSE) technique uses ERA5 as the
40	pseudo-truth atmospheric profile. Temperature and relative humidity
41	pseudo-observations are generated using the one-dimensional variational retrieval
42	scheme based on the spectral characteristics of the GeoHSS. Verification with
43	radiosonde observations shows an improvement over various altitudes and forecast
44	times (FTs), including wind impacted through the assimilation cycle and forecasts. The
45	precipitation forecasts also show an improving trend with a notable impact to extend the
46	forecasts' lead time. Case studies show impacts on precipitation primarily during longer
47	FTs, accompanied by an improved prediction of depressions on the Baiu front and
48	upper-level troughs. These are due to large-scale impacts from the pseudo-observations
49	with a comprehensive coverage over clear-sky areas, propagating to precipitation areas
50	through the assimilation cycle and forecasts. However, the prediction of an event of
51	small-scale localized heavy rain is insufficient even at short forecast ranges owing to a
52	limited resolution. Experiments show that extracting information in the lower atmosphere
53	is critical, and that the impact on upper-level environments is sensitive to using

⁵⁴ observations in cloudy areas.

- 56 **Keywords:** data assimilation; observing system simulation experiment; hyperspectral
- 57 infrared sounder; geostationary satellite

59 **1. Introduction**

Observation data from satellite-borne instruments provide homogeneous atmospheric 60 information over a wide area that conventional observations cannot cover, significantly 61improving the accuracy of numerical weather predictions (NWPs). Recent advances in 62 remote sensing technology have improved the quality of satellite observations, resulting in 63 the procuring of enormous amounts of high-resolution data. In particular, the advent of the 64hyperspectral infrared sounder (HSS) has drastically improved the spectral resolution and 65allowed acquiring detailed vertical structures of the atmosphere. Observation data from 66 HSSs, such as the cross-track infrared sounder (CrIS) and infrared atmospheric sounding 67 interferometer (IASI), implemented on low-earth-orbiting (LEO) satellites are widely used at 68 operational NWP centers globally, resulting in high impacts on the improvement in NWPs 69 (Menzel et al. 2018). 70

Geostationary satellites can perform high-frequency measurements over a wide fixed 71area, whereas LEO satellites can only observe a specific location twice a day. Many 72 geostationary satellites, including the geostationary operational environmental satellite 7374(GOES; Schmit et al. 2017), Meteosat (Schmetz et al. 2002), and Himawari (Bessho et al. 2016), have been equipped with imagers operated at high horizontal and temporal 75resolutions because of significant advances in instrument performance. They provide 76helpful information on atmospheric phenomena that cause severe weather events involving 77localized and rapid atmospheric changes. Furthermore, the HSS on a geostationary 78

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79satellite (GeoHSS) should provide detailed information on the temporal evolution of the atmosphere's three-dimensional structure, and is expected to significantly improve the 80 prediction accuracy of high-impact weather events. In the World Meteorological 81 Organization (WMO) Integrated Global Observing System's (WIGOS's) vision in 2040 82 (WMO 2020), GeoHSS is one of the high-priority instruments to be installed on 83 geostationary satellites, and it plays a vital role in constructing the global atmospheric 84 observation network. With this background, the geostationary interferometric infrared 85 sounder (GIIRS) was installed on the Chinese geostationary satellite FY-4A launched in 86 2016 (Yang et al. 2017). The plan has materialized in Europe and thus the infrared sounder 87 (IRS) is going to be installed on the Meteosat Third Generation (MTG) satellite (Holmlund et 88 al. 2021); additionally, GeoHSS has also been considered for installation on the 89 geostationary extended observations (GeoXO) satellite in the United States (Adkins et al. 90 2021; Lauer et al. 2021). The Japan Meteorological Agency (JMA) also aims to start the 91 operation of the next geostationary satellite around 2029 after Himawari-8 and Himawari-9, 92 currently in operation, and GeoHSS is a promising candidate to be an onboard instrument 93 (Bessho et al. 2021). 94

As GeoHSS is to be installed on geostationary satellites, several impact evaluations in NWPs have been conducted using observing system simulation experiments (OSSEs), with the results showing the expected data assimilation (DA) impact of this high-frequency, widely distributed, and high-resolution three-dimensional observational data (Guedj et al.

2014, Jones et al. 2017, Li et al. 2018, Wang et al. 2021a). A recent DA experiment using
 actual data from GIIRS with a global four-dimensional variational (4D-Var) system in an
 intensive typhoon case reported improved forecast accuracy (Yin et al. 2021).

Okamoto et al. (2020) investigated the expected impact of GeoHSS located over Japan 102 on NWPs via OSSE using an integrated global and regional NWP system for the next 103operational geostationary satellite to replace Himawari-8 and Himawari-9. Their experiment 104applied the reanalysis-based (RA) OSSE (RA-OSSE) technique using the fifth generation 105of the European Centre for Medium-Range Weather Forecasts (ECMWF) RA (ERA5; 106Hersbach et al. 2020) data as the pseudo-truth atmospheric profile. The OSSE results 107showed that the GeoHSS improved representative weather field and typhoon track 108prediction in the global NWP system, whereas it improved heavy rainfall event prediction in 109the regional NWP system. 110

This study extends to evaluating the impact of the GeoHSS on the regional NWP system. In this work, we increased the number of cases to understand the more general and robust characteristics of GeoHSS's impact, focusing on torrential rainfall events in Japan. A one-week DA cycle is conducted over three rainy seasons to understand the impacts, including the benefits obtained through cycling. To isolate the effect of GeoHSS, we investigate the following cases, in which the mechanism of the phenomenon has been well analyzed in the literature.

• The heavy rainfall event of July 2018 (Tokyo Climate Center (TCC) 2018, JMA 2018a,

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119	Tsuguti et al. 2019): A case with precipitation over a wide area caused by a continuous
120	large-scale warm moisture inflow into the Baiu front. We focus on precipitation
121	forecasting improvement through the impact of widely distributed GeoHSS data on
122	large-scale environments.
123	• The July 2017 northern Kyushu heavy rainfall event (Meteorological Research Institute
124	(MRI) 2017, JMA 2018b, Kawano and Kawamura 2020): A case with the localized
125	concentration of precipitation that is stagnant for hours, which is challenging to forecast
126	using the NWP with limited resolution. We focus on the impact on the precipitation
127	environment forecast based on the scale of the environmental phenomena.
128	• The July 2020 heavy rainfall event (TCC 2020, Hirockawa et al. 2020, and Araki et al.
129	2021): A case where a small low-pressure system over the Baiu front has a large
130	impact on heavy rainfall. We focus on the precipitation forecast improvement consistent
131	throughout the DA cycle.
132	In Okamoto et al. (2020), the regional DA used the temperature (T) and relative humidity
133	(RH) vertical profiles from ERA5 as pseudo-observational data, regarded as representative
134	atmospheric information obtained from GeoHSS. However, although the
135	pseudo-observations include ERA5's analysis error, this method might overestimate the
136	accuracy and information of the GeoHSS observations compared to the actual available

137 data. A more realistic approach to consider a variety of observation error sources was

138 necessary.

There are primarily two methods for the actual data use in DA: one is to directly 139assimilate the brightness temperature (BT) measured by GeoHSS, and the other is to 140assimilate retrievals (such as T and RH) diagnosed from the BT. The DA of HSS BT has not 141been introduced into the operational regional DA of JMA, and its practical use, including 142handling bias correction, will require significant effort (Okamoto et al. 2020).¹ Thus, we 143choose to assimilate retrievals in this study, adopting an approach similar to those of Jones 144et al. (2017), Li et al. (2018), and Wang et al. (2021a). We first derive BT from the ERA5 145vertical profile using the radiative transfer for TOVS (RTTOV; Saunders et al. 2018) and 146apply the 1D-Var retrieval system (Hayashi et al. 2021a,b; Oyama et al. 2019) considering 147the spectral characteristics of GeoHSS on the BT to obtain T and RH retrievals. The 148retrievals are the pseudo-observations of GeoHSS for the OSSE. 149Section 2 describes the experiments conducted in this study. In Section 3, we investigate 150the impact of GeoHSS using the RA-OSSE technique for three periods, including heavy 151

rainfall cases during the Baiu seasons in 2017, 2018, and 2020. A summary of the study is
 provided in Section 4.

154

155 **2. Method**

¹ JMA is currently using HSS BT data from LEO satellites in the regional DA starting in March 2023.

157 2.1 RA-OSSE

In this study, similar to that in Okamoto et al. (2020), we conduct an RA-OSSE using 158ERA5 as the pseudo-true atmospheric profile, which has high accuracy and should be 159highly independent of the JMA system used in the experiment. In the conventional OSSE, a 160 nature run is first created as the true state. Then, pseudo-observations are simulated from 161the nature run for all existing observations and those to be evaluated. However, the 162RA-OSSE uses the actual data for the existing observations and generates 163 pseudo-observation data only for the unacquired GeoHSS to be evaluated. Therefore, 164actual observations can verify RA-OSSE, allowing direct discussion of the impact on 165predicting severe weather events such as torrential rains. However, we need to select 166cases where the prediction initiated with the ERA5 is more accurate than that with the JMA 167analysis, so that the impact of the pseudo-observations can be noticeable. Similar 168approaches based on the RA-OSSE are also used in the works of Wang et al. (2021a) and 169Wang et al. (2021b). 170

This study's OSSE used an experimental system based on the former mesoscale analysis (MA; JMA 2019), which was in operation until March 2020, applying the JMA nonhydrostatic model-based variational (JNoVA) DA (Honda et al. 2005). This system runs a three-hourly 4D-Var DA cycle with a three-hour assimilation window on a 4080 × 3300 km domain covering Japan and its surroundings. The 4D-Var uses the incremental approach, optimizing the increments at a horizontal grid spacing of 15 km with 38 vertical layers while

generating the first guess and the analysis at a horizontal grid spacing of 5 km with 48 vertical layers, both with the model top at ~22 km. Various conventional observations as well as satellite and ground-based remote sensing data, which are the same with the data used in MA (JMA 2019), are assimilated in addition to the pseudo-observations of GeoHSS to generate the initial condition for 39-h forecasts at a horizontal grid spacing of 5 km on the same domain using the JMA's operational nonhydrostatic model ASUCA as the forecast model (Ishida et al. 2022).

184

185 2.2 GeoHSS pseudo-observations

The T and RH GeoHSS pseudo-observation data are generated as 1D-Var retrievals 186(Hayashi et al. 2021a, b; Oyama et al. 2019) from ERA5. The ERA5 data are provided at a 187horizontal grid spacing of ~31 km, with 137 vertical layers, a model top of ~0.01 hPa, and a 1881-h time interval. In the 1D-Var, the all-sky BT calculated from ERA5 is used as the 189observation. RTTOV version 12 (Saunders et al. 2018) is used to simulate the BT from 190 temperature, specific humidity, cloud fraction, specific cloud ice and liquid water content, 191ozone mass mixing ratio, 10-m horizontal wind components, 2-m temperature, skin 192temperature, and surface pressure obtained from ERA5. The geostationary satellite's 193position is the same as that of Himawari-8 and Himawari-9 (140.7°E). The spectral 194characteristics are the same as those of the IRS to be installed on MTG as specified in the 195RTTOV version 12, which measures 1738 channels in the long- and mid-wave infrared 196

bands at a spectral resolution of 0.625 cm⁻¹, including temperature channels (700–742 cm⁻¹) and water vapor channels (1660–1984 cm⁻¹), similar to that shown in Okamoto et al.
(2020).

In 1D-Var processing, the channels are prioritized according to Rodgers (1998) to 200 maximize the information content, and 100 channels are selected considering the 201information content and computational cost. However, clouds affect the channels, and the 202channels are rejected when the difference between the BTs without and with cloud 203 scattering calculations exceeds 1 K (Okamoto et al. 2020). As discussed by Okamoto et al. 204(2020), this cloud detection scheme cannot be applied in an actual situation because the 205BT without cloud scattering is unknown. Thus, this scheme assumes that the estimation of 206cloud effect will become available with high accuracy. 207

The observation error in the 1D-Var is ~0.3 K for temperature channels and 1 K for water vapor channels based on the observation-minus-background statistics in clear-sky areas without correlation between channels.

To increase the independence between the 1D-Var pseudo-observations and the first guess of the OSSE mesoscale DA, forecasts from JMA's global spectral model (GSM; JMA 2019) are used as the first guess of the 1D-Var. The GSM has 100 model layers, a model top of 0.01 hPa, and a horizontal grid spacing of ~20 km. The background error covariance is based on GSM prediction statistics. The RTTOV version 12 (Saunders et al. 2018) runs in the observation operator to estimate clear-sky BT from temperature and specific humidity

in the 1D-Var.

In DA, the T and RH pseudo-observations are rejected when the diagonal part of the 2181D-Var averaging kernel, which describes how the retrieval changes with respect to 219changes in the true atmospheric state (Maddy et al. 2009), for the pseudo-observation is 220smaller than 0.03. This indicates that they are derived using only few BT 221pseudo-observation channels in the 1D-Var, for example, in the presence of clouds. The 222observation error used in DA is based on the standard deviation statistics of the retrieval 223pseudo-observations from ERA5 and varies from 0.5 to 1.3 K for T (Fig. 1 black filled 224circles) and from 10% to 15% for RH (Fig. 1 gray filled circles). 225

226

227 2.3 Processing of pseudo-observations in DA

In DA, pseudo-observations are horizontally thinned to ~45 km, as is done for radiance 228observations of Himawari-8 in the operational system. In the vertical direction, the 229pseudo-observations are used at GSM's model layer nearest to each of the 13 altitudes 230(1000, 920, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa) for T and the 231232seven altitudes up to 300 hPa for RH. In the time direction, pseudo-observations are assimilated on an hourly basis. As done in Okamoto et al. (2020), we apply quality control 233(QC) on the pseudo-observations as that of the conventional observations in MA (JMA 2342019; Onogi 1998). 235

The pseudo-observations are not explicitly perturbed, considering they include the

237	ERA5 analysis errors and the representation errors due to differences between ERA5 and
238	JMA's DA system. However, this might overestimate observation accuracy, as discussed in
239	the research conducted by Okamoto et al. (2020) and Wang et al. (2021a), with Okamoto et
240	al. (2020) noting that a trial with perturbed pseudo-observations resulted in smaller but
241	positive impacts. Future work will evaluate these impacts by carefully estimating the
242	GeoHSS observation error, including measurement errors.
243	
244	2.4 Experimental scenarios
245	The following experiments were conducted in this work.
246	CNT: no pseudo-observation assimilation.
247	 1DVar: assimilate the 1D-Var retrieval pseudo-observations.
248	Similar to the approach adopted by Okamoto et al. (2020), herein, an experimental system
249	is used to generate the lateral boundary conditions (LBCs) based on the operational global
250	DA system of the JMA as of 2018 (JMA 2019). Two global experiments were conducted
251	here, as listed below.
252	 global CNT: generating LBCs for CNT. No pseudo-observation was assimilated.
253	• global BT: generating LBCs for 1DVar. This global experiment assimilated hourly BT
254	GeoHSS pseudo-observations simulated from ERA5 using RTTOV 12 (Okamoto et al.
255	2020).
050	

257 **3. OSSE results**

258 This section focuses on the three aforementioned periods (Section 1) and investigates 259 the impact of GeoHSS on them.

260

3.1 The heavy rain event of July 2018

This section investigates the case of July 2018, in which heavy rainfall occurred over a wide area, primarily in western Japan. TCC (2018), JMA (2018a), and Tsuguti et al. (2019) provided detailed analyses of the meteorological conditions at the time of this event (the JMA surface weather chart for this period is available at the JMA website, https://www.data.jma.go.jp/fcd/yoho/data/hibiten/2018/1807.pdf). A DA cycle is run from 0000 UTC July 1 to 2100 UTC July 7, 2018 to study the impact of GeoHSS pseudo-observations on the forecast.

269

a. Distribution of pseudo-observation data

There are only few pseudo-observations above 200 hPa (Fig. 2a black bars) because few channels are sensitive to these altitudes. In this study, the lower limit of the wavenumber observed by the GeoHSS is 700 cm⁻¹ for creating BT observations for the 1D-Var, based on the IRSs' spectral characteristics as described in Section 2.2. If the spectral band can be extended to the lower-wavenumber side, it should enhance the sensitivity in the upper levels. The 1D-Var retrieval pseudo-observations increase from 200 to 300 hPa as the number of sensitive channels increases.

Below 300 hPa, the QC-passed data decrease at the lower levels as the area under clouds increases. Specifically, clouds are widely distributed from southeastern China to the East China Sea, where the convection is active, and around Honshu, primarily in western Japan, where the Baiu front is stagnant, and these areas have few pseudo-observations (Fig. 2b). However, areas with pseudo-observations occur even in the lower levels from northeast China to the Yellow Sea, around Primorsky Krai and Hokkaido, and over the ocean far southeast of Japan (Fig. 2c).

Below 850 hPa, the use of channels sensitive to water vapor decreases, and the number of RH 1D-Var retrieval pseudo-observations is small (Fig. 2a gray bars). Developing a method for effectively extracting information on water vapor in the lower levels is critical as this might significantly affect severe weather events.

Taking into account the GeoHSS spectral characteristics and the retrieving process, the number of the 1D-Var pseudo-observations is smaller than that of the vertical profile ones in Okamoto et al. (2020) above 200 hPa for T and below 850 hPa for RH. However, for 250–500 hPa, the cloud detection assumed in the 1DVar pseudo-observations allows more data than that assumed in the vertical profile ones, which excludes all data below the level with an ERA5 cloud fraction exceeding 0.03 in each vertical column (Okamoto et al. 2020).

b. The difference from ERA5

295

The ERA5 data time series is a consistent time evolution of the meteorological field that provides the GeoHSS pseudo-observations. We adopt ERA5 as a reference and compare 1DVar's deviation from the reference with CNT. This helps us understand the distribution characteristics of the atmospheric information added by the GeoHSS and the extent to which the impact of the added information persists. The deviation from ERA5 is evaluated using the root-mean-square difference (RMSD).

Figure 3 shows the difference between the deviation of 1DVar and CNT for RH at 500 303 hPa. 1DVar decreases the deviation across the domain at the initial forecast time (FT; Fig. 304 3a) because of the assimilation of pseudo-observations. However, the distribution is 305nonuniform. A significant decrease in RMSD occurs over areas corresponding well to 306 where the pseudo-observation data are assimilated (Fig. 2b for T). The impact extends 307 along the atmospheric flow through the DA cycle to areas where there are few 308pseudo-observations because of clouds, which is noticeable from the east coast of China to 309 the northern East China Sea. 310

As the FT progresses, the effect of GeoHSS gradually reduces. However, this effect persists over a wide range even at an FT of 21 h (hereafter denoted as FT = 21; Fig. 3b). It is unlikely that the pseudo-observation data directly affect precipitation areas with clouds. This suggests that their impact reached these areas primarily through time evolution.

315

316 c. Verification against radiosonde observations

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317	In terms of verification against radiosonde T observations, 1DVar (Fig. 4a) shows
318	persistent improvement from the CNT, especially in the upper levels (200–300 hPa) of the
319	atmosphere. 1DVar also significantly decreases the root-mean-square error (RMSE) over
320	the middle (400–500 hPa) levels at short forecast ranges. The impact tends to weaken as
321	the FT progresses, but significant improvements are still observed beyond FT = 24 in the
322	upper and lower levels. The decrease in RH RMSE is centered around 300 hPa in 1DVar
323	(Fig. 4b), although the impact is smaller than that on T (Fig. 4a). At FT = 0, the increase in
324	RH RMSE is statistically significant at 1000, 300, and 250 hPa. The reason for the
325	degradation is unclear, although a decrease in the number of RH 1D-Var
326	pseudo-observations at lower and upper levels might contribute to it. The degradation is not
327	noticeable in the July 2017 and July 2020 statistics (not shown), suggesting that this result
328	is not necessarily robust. As discussed in Section 3.1a, the number of RH 1D-Var retrieval
329	pseudo-observations decreases at the lower levels. Correspondingly, the impact of the
330	1D-Var pseudo-observations on T RMSE (Fig. 4a) is smaller than that of the vertical profile
331	pseudo-observations as in Okamoto et al. (2020), especially in the lower levels at shorter
332	FTs (not shown).

The impact of GeoHSS extends to wind components that are not directly assimilated as the pseudo-observations, indicating that the improvements in T and RH are propagated through the DA cycle and forecast. A significant improvement in U and V occurs in the upper levels (200–300 hPa; Figs. 4c, d). Figure 5a shows the substantial improvement rate

of 1DVar from CNT from northeastern China through the Korean Peninsula reaching to the
 northern coast of western Japan (solid black ellipse) in U at 250 hPa, where 1DVar shows a
 sustained improvement in Fig. 4c. The mean wind field during the experiment (Fig. 5b)
 corresponds to the jet stream path (solid black ellipse), indicating that the regional and
 global GeoHSS assimilations improve the large-scale structure of the upper-level wind field,
 including LBC.

Persistent improvement in V is observed for 1DVar (Fig. 4d) in the lower levels (700– 925 hPa). The spatial distribution at 850 hPa for 1DVar shows improvements (Fig. 5c solid black rectangles) corresponding to the flow over northeastern China influenced by a mountain range, the flow from the South China Sea into the East China Sea, and the flow from the limb of the Pacific High toward the southern coast of Japan (Fig. 5d solid black rectangles). Specifically, the latter two flows can influence heavy rainfall in western Japan, which is the focus of this study.

Thus, in this study, the meteorological field's overall accuracy is improved by adding the ERA5 information to the JMA system, indicating that it is appropriate to use ERA5 as the pseudo-true atmospheric profile for the RA-OSSE. Okamoto et al. (2020) found the same improvement as in this study by assimilating GeoHSS pseudo-observations from the verification using only forecasts initiated at 0000 UTC July 2–7, 2018 (six forecasts). Compared to the verification in Okamoto et al. (2020), the verification in this study using a larger number of statistical samples shows significant improvements for RH and upper-level

wind components in addition to T over a broader range. An additional experiment without
the regional assimilation of pseudo-observations but with the use of LBCs from the global
BT shows a similar trend of improvement.

360

d. Verification of precipitation forecast

362 1) Statistical verification

The impact also extends to the precipitation forecast, reflecting the improved meteorological field shown in the radiosonde verification. Verifying the precipitation accumulated over 3 h against the analyzed radar/rain gauge precipitation shows that the threat score (TS; Fig. 6a) for 1DVar (red) is higher than the CNT (blue) at all thresholds (black), with significance at most thresholds. The bias score (BI; Fig. 6b) also tends to approach 1 at many thresholds, mitigating excess precipitation in CNT.

The experiment without the regional assimilation of pseudo-observations shows a similar improvement compared to 1DVar as observed in the verification against radiosonde observations (not shown). Okamoto et al.'s (2020) verification with six forecasts also showed the impact of GeoHSS pseudo-observations similar to this study.

373

374 2) Time evolution of verification score

The improvement from CNT in the TS and BI of 1DVar (Figs. 7a, b) is primarily distributed at longer FTs (solid black ellipses). The assimilation of GeoHSS

pseudo-observations increases the forecast lead time. As shown in Fig. 3, the impact from 377 distant clear-sky locations propagates through the DA cycle and forecast, spreading to the 378surrounding area and reaching the precipitation area, which may have improved 379 precipitation at longer FTs. A sensitivity experiment shows that reducing the 380 pseudo-observation frequency from 1 to 3 h degrades the TS in the longer FTs (not shown), 381 indicating that the repeated pseudo-observation assimilation at a high frequency of 1 h 382enhances the propagation of information from the pseudo-observations without dissipation 383 in the DA cycle and forecast. 384

385

e. Prediction of heavy rainfall in the Chugoku region

387 In this experimental period, the TS of 1DVar shows that forecasts have a long lead time, particularly at lower thresholds, persisting throughout the DA cycle (Fig. 8a), indicating that 388the forcing of convection from a large-scale environment is vital in precipitation. The Baiu 389 front stalled near the main island of Japan during this period, resulting in heavy rainfall over 390 a wide area, especially in western Japan. The observation (Fig. 9a) of the precipitation 391392accumulated over 3 h at 2100 UTC July 6, 2018 (Fig. 8a solid white rectangle) shows that the rainfall intensifies in the Chugoku region (Fig. 9a solid black ellipse). In this section, the 393 forecast initiated at 0000 UTC July 6 (Fig. 8a solid yellow rectangle) is investigated near FT 394 = 21 (light blue arrow), where high TS persists at the threshold of 30 mm/3 h in 1DVar. 395The intense rainfall in Chugoku is not predicted in the 21 h forecast from CNT (Fig. 9c). 396

However, 1DVar (Fig. 9b) shows an improvement compared to CNT, intensifying precipitation over the Chugoku region, although the peak location is shifted to the north. The experiment without the regional assimilation of pseudo-observations also shows intense rainfall over the Chugoku region, although the intense precipitation area is slightly smaller, and the peak is shifted to the northeast (not shown) compared to the observation (Fig. 9a).

1DVar predicts that a low-pressure area passes through the northern part of Kyushu and reaches the western part of the Seto Inland Sea near Hiroshima at FT = 18 (Fig. 10b solid black ellipse), which is not predicted in CNT (FT = 18). The short-range forecast from CNT (FT = 3) initiated at 1500 UTC July 6 (Fig. 10a) shows an overall increase in pressure but also gives the low-pressure area over the western Seto Inland Sea (solid black ellipse), indicating the reliability of the low-pressure area in 1DVar (FT = 18). This low-pressure area could enhance the precipitation over the Chugoku region (Fig. 9b).

The JMA surface weather chart (available at the same JMA website as mentioned in Section 3.1) at 0000 UTC 7 July, 2018 indicates that a surface pressure trough extends to the southwest along the front from a low-pressure system located at the eastern Sea of Japan. This trough reaches the Chugoku region where the front curves in a smoothed kink-shape. The JMA global analysis at 925 hPa at 1800 UTC 6 July, 2018 (e.g., Fig. A2.2 of TCC 2018) shows cyclonic circulation around the Chugoku region. These indicate the localized low-pressure area can intensify the lower-level moist air flow into the Chugoku For Peer Review

417	Region from the southeast. Shimpo et al. (2019) also pointed out the important contribution
418	of the meso-scale low-pressure system on the Baiu front, that enhanced moisture inflow
419	from the south, to the torrential rainfall over the Chugoku region.
420	In contrast, CNT (FT=18) predicts a low-pressure system over the central East China
421	Sea (Figs. 10a, b white arrows), whereas 1DVar weakens it (Fig. 10b). The short-range
422	forecast of CNT (FT = 3) does not show a corresponding low-pressure system (Fig. 10a),
423	indicating that its CNT (FT = 18) forecast reliability is low.
424	Considering the difference between 1DVar and CNT of the lower levels' water vapor
425	flux, 1DVar at FT = 18 enhances the flux from the southwest near Hiroshima (Fig. 10c black
426	arrow) and that enters western Japan from the ocean southeast of Kyushu (Fig. 10c solid
427	black ellipse). These correspond to the passage of the low-pressure area described above,
428	enhancing the precipitation in 1DVar.
429	These phenomena associated with the small low-pressure area over the Baiu front
430	occur in the lower-level cloud areas, where GeoHSS pseudo-observation data are not
431	assimilated, indicating the impact propagation discussed in Section 3.1d 2.
432	
433	3.2 The July 2017 northern Kyushu heavy rainfall event
434	This section presents the results of applying the OSSE on the case of torrential rain in
435	northern Kyushu in July 2017. MRI (2017), JMA (2018b), and Kawano and Kawamura
436	(2020) present detailed analyses of the atmospheric condition during this heavy rainfall

21

437	event (the JMA surface weather chart for this period is available at the JMA website,
438	https://www.data.jma.go.jp/fcd/yoho/data/hibiten/2017/1707.pdf).
439	The DA cycle is run from 0000 UTC July 1 to 2100 UTC July 7, 2017. The TS of 1DVar
440	during this period (Fig. 8b) is lower than that in July 2018 (Fig. 8a). Furthermore, the
441	forecast accuracy varies depending on cases, and the persistence of high TS over DA
442	cycles and FTs is short. This period includes cases in which the precipitation phenomena
443	are not determined only by forcing from large-scale environments, and contributions from
444	localized environments are crucial. We investigate the impact of the GeoHSS
445	pseudo-observations, focusing on its dependence on the scale of precipitation forcing.
446	

a. Statistical Verification 447

Verification against radiosonde observations shows a similar overall decrease in 448RMSE for 1DVar as observed in July 2018 (Fig. 4), but with a more widespread 449 improvement in July 2017 (not shown). As for precipitation, 1DVar outperforms CNT in TS 450at all thresholds (Fig. 11a). The improvement is primarily at longer FTs (not shown), as 451452observed in July 2018 (Fig. 7a). However, as shown by the solid red rectangles in Fig. 8b, the high TS persists for thresholds above 10 mm/3 h after FT = 24 mostly in the case of 453Typhoon Nanmadol (Fig. 8b light blue rectangle) which crossed western Japan and then 454moved off the Tokai coast on July 4. Thus, this typhoon case primarily contributes to the 455forecast characteristics over this range. BI is above 1 in July 2018 (Fig. 6b), whereas it is 456

below 1 in July 2017 (Fig. 11b), indicating an overall underestimation of precipitation.
1DVar slightly mitigates the underestimation of CNT at many thresholds (Fig. 11b). The
improvement is primarily at longer FTs as in TS (not shown).

460

461 b. Prediction of Typhoon Nanmadol

1DVar shows improvement from CNT in the 30-h forecast (Fig. 8b light blue arrows) of 462precipitation due to the Baiu front, affected by Typhoon Nanmadol's approach at 0600 463 UTC July 4 (Fig. 12a solid black ellipse) discussed in Section 3.2a. In 1DVar, the 500-hPa 464trough (not shown) deepens over the Sea of Japan and accelerates its eastward 465propagation compared to CNT, extending the low-pressure area northeast of the typhoon 466 (Fig. 12d solid black ellipse). As a result, compared to CNT (Fig. 12b), the 1DVar forecast 467(Fig. 12c) enhances precipitation over land in Hokuriku, whereas it weakens the 468precipitation band extending from northern Niigata to the Noto Peninsula, consistent with 469 the observation (Fig. 12a). The impact is more noticeable than in an experiment using the 470 vertical profile pseudo-observations (Okamoto et al. 2020), which has less data at ~500 471hPa as discussed in Section 3.1a, suggesting that it is important to effectively use data at 472upper cloud altitudes (not shown). 473

474

475 c. Prediction of heavy rainfall in northern Kyushu

476 In this case, the forecast lead time of precipitation is severely limited especially at

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higher thresholds (Fig. 8b solid white rectangles), indicating that the forcing from 477large-scale environments alone did not necessarily link to the precipitation phenomena. 478Figure 13 displays the two shortest-range forecasts (FT = 3, 6; Fig. 8b dashed yellow 479rectangle) of the precipitation accumulated over 3 h from 1DVar and CNT valid at 0600 480 UTC July 5, 2017, the time of torrential rainfall in northern Kyushu. The observation (Fig. 48113a) shows intense rain concentrated in a small area near Asakura. The intense 482precipitation area's spatial scale is small, indicating that detailed topographic effects 483 contribute to precipitation concentration and persistence (Takemi 2018; MRI 2017; Kawano 484and Kawamura 2020). 485

Both 1DVar and CNT (Figs. 13b–e) predict the precipitation intensification over northern Kyushu consistent with the observation. However, the precipitation concentration area is displaced from the observation, and its peak intensity is weak in all forecasts. Furthermore, the forecast variation is large, depending on the initial times. Because the small-scale precipitation areas and topography can only be simulated by a fine grid spacing, the NWP model with a grid spacing of 5 km used in this study has difficulty predicting this localized precipitation's concentration and long duration.

⁴⁹³ During this heavy rainfall event, the atmospheric environment was characterized by ⁴⁹⁴ strong cold air in the upper level, forming persistent strong stratiform instability (MRI 2017, ⁴⁹⁵ JMA 2018b). The analysis (FT = 0) of 400 hPa T for CNT (Fig. 14c) indicates that a cold ⁴⁹⁶ airmass of ~-18°C approaches the northern Kyushu region (solid black ellipse).

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Longer-range forecasts give weaker cold air, with delayed eastward propagation. However,
1DVar (Fig. 14a) strengthens the predicted cold air from a longer range than CNT (Fig.
14b), bringing it closer to the analysis (Fig. 14c).

MRI (2017) and JMA (2018b) highlighted that the warm moisture flows from the 500southwest in the lower levels toward Kyushu, which is another vital factor for this heavy rain 501event. In water vapor flux at 950 hPa, the analysis (FT = 0) of CNT (Fig. 14f) shows warm 502moisture flow from the southwest toward northern Kyushu (solid black ellipse). 503Longer-range forecasts give weaker warm moisture flow concentrations and intensity. On 504the other hand, 1DVar (Fig. 14d) strengthens the warm moisture flow compared to CNT 505(Fig. 14e) around FT = 12–18, and makes longer-range forecasts closer to the analysis 506(solid black ellipses). 507

508 For this case study, the assimilation of GeoHSS pseudo-observations improves 509 large-scale environments, such as the upper-level cold air and low-level water vapor flux, 510 extending the forecast lead times. However, the localized heavy rainfall is insufficiently 511 reproduced only with the assimilation of the GeoHSS pseudo-observations, probably due to 512 the limited resolution of the OSSE in this study.

513

3.3 The July 2020 heavy rainfall event

This section applies the OSSE to the period of heavy rain in Kyushu in July 2020 (TCC 2020; Hirockawa et al. 2020; and Araki et al. 2021). The DA cycle is run for 0000 UTC June

517	30-2100 UTC July 7, 2020. In this period, TS and its persistence (Fig. 8c) are between
518	those in July 2018 (Fig. 8a) and July 2017 (Fig. 8b). Two terms of high TS persisted for
519	several days (Fig. 8c solid black ellipses), corresponding to when the Baiu front covered a
520	wide area of Japan and stagnated (the JMA surface weather chart for this period is
521	available at the JMA website,
522	https://www.data.jma.go.jp/fcd/yoho/data/hibiten/2020/2007.pdf).
523	In the verification against radiosonde observations for this period (not shown), 1DVar
524	improved from CNT, as observed in July 2018 and July 2017. 1DVar also outperforms CNT
525	overall in the verification of precipitation forecasts (not shown), and the improvement
526	distributes primarily at longer FTs, as observed in July 2018 and July 2017.
527	Figure 15 displays 6–12 h forecasts (Fig. 8c yellow rectangle) of 3-h accumulated
528	precipitation valid at 0000 UTC July 4, 2020 (Fig. 8c light blue rectangle). A precipitation
529	band extends from the central Kyushu region to the Shikoku region, and a precipitation
530	concentration area is observed in the Kumamoto Prefecture (Fig. 15 left panels). In CNT
531	(Fig. 15b), the precipitation band and concentration area are displaced to the north. 1DVar
532	(Fig. 15a) mitigates the northward shift in CNT and predicts a precipitation area closer to
533	the observation, which is consistent further up to the forecast of FT = 21 (not shown). A
534	similar impact persists over successive forecast updates, indicating the impact propagation
535	through the DA cycle.

536 A closer examination of the forecast (not shown) indicates that 1DVar weakens a small

537 low-pressure system moving eastward over the Baiu front passing through northern Kyushu compared to CNT. Consequently, the low-level warm moisture flow near the low toward the 538north from the southwest of the precipitation area weakens. Thus, the low-level wind's 539convergence line, which is formed between the flow due to the low and the flow of warm 540moisture from the southwest, shifts to the south. Araki et al. (2021) pointed out that this 541convergence line was an important factor for the heavy rainfall in Kumamoto. This effect 542might shift the precipitation band and concentration locations to the south in 1DVar (Fig. 54315a) compared to CNT (Fig. 15b). 544The case without regional assimilation of pseudo-observations also improves the 545precipitation location (not shown) compared to CNT. However, the forecast varies, 546

⁵⁴⁷ depending on the initial values, and 1DVar shows better consistency with the observation.

In another case of precipitation forecast with a long lead time (Fig. 8c solid white rectangle), an improvement of 1DVar from CNT is observed in the Kyushu and Chugoku regions around 1800 UTC July 6, 2020, which is also related to a small low over the Baiu front, and may be due to its accelerated eastward propagation near the Tsushima Strait.

552

553 **4. Summary**

This study investigated the impact of GeoHSS in a regional NWP system for the period of heavy rainfall cases during the Baiu season in 2017, 2018, and 2020. The RA-OSSE technique was applied using ERA5 as the pseudo-true atmospheric profile.

The OSSE was conducted using pseudo-observations from 1D-Var retrieval as a realistic impact evaluation. The pseudo-observation considered the measurement process of BT, the amount of atmospheric information due to the GeoHSS's spectral band and the selection of channels used (including maximizing information content and rejecting cloud-affected channels), and the retrieval process.

562 Compared to the vertical profile pseudo-observations presented by Okamoto et al. 563 (2020), the number of 1D-Var retrieval pseudo-observations herein was smaller at and 564 above 200 hPa for T and below 850 hPa for RH because of the limited number of sensitive 565 channels based on the IRS spectral characteristics and 1D-Var processing's limited 566 capability. However, the number of 1D-Var retrieval pseudo-observations increased for the 567 250–500 hPa range with a wider coverage because of the difference in handling 568 cloud-affected data.

The verification against radiosonde observations showed an improvement in T and RH over several altitudes and FTs. Wind components, not directly assimilated as pseudo-observations, were also impacted through the DA cycle and forecast. In verifying precipitation forecasts, the impact was stronger at longer FTs, extending the forecast lead time.

The impact was also confirmed in several heavy rainfall event case studies. The assimilation of pseudo-observations with wide coverage had an impact at relatively long FTs (up to ~30 h), indicating the improvement of several atmospheric fields through the DA

577 cycle. Many improvements were associated with lows over the Baiu front, owing to 578 improvement in large-scale environments, including the low-level warm moisture flow and 579 upper-level trough. There were cases with similar impacts that continued for a series of 580 forecasts in the DA cycle update. However, there was a case wherein small-scale 581 phenomena, such as localized precipitation concentration and its persistence, were 582 insufficiently predicted even at short forecast ranges, in experiments with or without 583 pseudo-observations.

In the radiosonde verification, a decrease in accuracy of the case using the 1D-Var 584pseudo-observations from the case using the vertical profile ones in Okamoto et al. (2020) 585was observed at shorter FTs in the lower levels, where the RH pseudo-observations of 5861D-Var decrease. Developing an effective method for extracting information from the lower 587atmosphere in retrieval and DA processes is necessary. Regarding the upper-level 588environments, the impact on the 500 hPa trough in the July 2017 typhoon case was larger 589for the 1D-Var pseudo-observations than for the vertical profile ones, where the 590cloud-detection assumed in the 1D-Var pseudo-observations allows more data at ~500 591592hPa. Effective use of the GeoHSS data in cloud areas should become a critical issue.

In this study, we assumed the assimilation of GeoHSS data as 1D-Var retrievals. Further enhancement of the retrieval algorithm and the direct assimilation of BT are possible. The impact that can be achieved by GeoHSS assimilation depends on how effectively the atmospheric information can be extracted. This study focused on the Baiu

597 season, where the Baiu front is stagnant and GeoHSS observations are unlikely to be assimilated around the precipitation area, particularly in the middle and lower levels. Thus, 598the impact was primarily through the DA cycle and forecast. In the case where no clouds 599occur upstream of the precipitation area, a smaller scale and more direct impact on 600 precipitation can be obtained. In this study, the ERA5 resolution (~31 km) and the thinning 601 spacing of the pseudo-observations (~45 km) are coarse compared to the expected 602resolution of a real GeoHSS measurement (~4 km), which limits the evaluation of the direct 603 impact from these high-resolution data. However, the inner model resolution of the 4D-Var 604is limited (~15 km) in this study, which requires to thin data accounting for the correlation of 605 the representation errors (Janjić et al. 2018). An impact that takes advantage of these data 606 607 can be obtained by using a high-resolution DA and forecast system that properly handles correlated observation errors. Research on these issues is a future task. 608

609

610 Data Availability Statement

The output data from this study have been archived and are available upon request to the corresponding author. The observational data and the data assimilation system are made available under a contract with the Japan Meteorological Agency because these are collected and developed for operational purposes. The ERA5 data used in this study are available from https://apps.ecmwf.int/data-catalogues/era5/?class=ea.

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Fig. 9 Three-hour accumulated precipitation at 2100 UTC July 6, 2018. (a) Radar/rain gage
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Fig. 10 (a) The difference between sea-level pressure of CNT FT = 3 (initiated at 1500

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Fig. 11 As in Fig. 6 but for forecast statistics initiated from 0000 UTC July 2 to 2100 UTC July 7, 2017. The results are displayed for (a) TS and (b) BI.

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Fig. 12 Observation and forecasts valid at 0600 UTC July 4, 2017. (a) 3 h accumulated precipitation from radar/rain gage analyzed precipitation, (b) as in (a) but for CNT FT = 30, (c) as in (b) but for 1DVar, (d) sea-level pressure from 1DVar FT = 30 (contoured every 1 hPa in black) and CNT FT = 30 (contoured every 1 hPa in green), and the difference in sea-level pressure between 1DVar FT = 30 and CNT FT = 30 (1DVar (FT = 30) – CNT (FT = 30)) (shaded).

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Fig. 13 Observation and forecasts of 3 h accumulated precipitation valid at 0600 UTC July
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Fig. 14 Forecasts and observations valid at 0600 UTC July 5, 2017. (a) T (shaded and

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Fig. 1 The observation error of temperature (black) and relative humidity (gray) used in the assimilation during 0000 UTC July 1 to 2100 UTC July 7, 2018, for 1DVar pseudo-observations.

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Fig. 2 (a) The number of T (black) and RH (gray) pseudo-observations assimilated in the
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Fig. 3 The difference between the deviations (RMSDs) of 1DVar and CNT from ERA5,
RMSD (1DVar) - RMSD (CNT), for 500 hPa RH. Statistics of forecasts initiated from
0000 UTC July 2 to 2100 UTC July 7, 2018. For (a) FT = 0 and (b) FT = 21.



[RMSE(1DVar) - RMSE(CNT)] / RMSE (CNT)

Fig. 4 RMSE improvement rate against radiosonde observations of 1DVar from CNT; i.e.,
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Fig. 5 (a) RMSE improvement rate against radiosonde observations of 1DVar from CNT, 906 [RMSE (1DVar) - RMSE (CNT)] / RMSE(CNT), averaged over forecasts initiated from 907 0000 UTC July 2 to 2100 UTC July 7, 2018, and 0-39 h forecast times for 250 hPa U. (b) 908 Averaged 250 hPa wind (barbs) and wind speed (shaded) from 1DVar. The average is 909 910 taken over the initial value of forecasts initiated from 0000 UTC July 2 to 2100 UTC July 7, 2018. Short barbs, long barbs, and pennants indicate 5 m s⁻¹, 10 m s⁻¹, and 50 m s⁻¹, 911 respectively. (c) As in (a) but for 850 hPa V. (d) As in (b) but for 850 hPa. Short barbs, 912 long barbs, and pennants indicate 1 m s⁻¹, 2 m s⁻¹, and 10 m s⁻¹, respectively. 913 914



Fig. 6 Verifying 3 h accumulated precipitation against radar/rain gage analyzed
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Fig. 7 Difference in the verification score of 3 h accumulated precipitation from CNT. Results are plotted against forecast time (h) and threshold (mm/3 h). Forecast statistics were initiated from 0000 UTC July 2 to 2100 UTC July 7, 2018 (48 forecasts). (a) TS 1DVar–CNT, (b) BI 1DVar–CNT.



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Fig. 8 (a) TS of 3 h accumulated precipitation from 1DVar for forecasts initiated from 0000
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Fig. 9 Three-hour accumulated precipitation at 2100 UTC July 6, 2018. (a) Radar/rain gage
analyzed precipitation, (b) 21 h forecast initiated at 0000 UTC July 6, 2018, for 1DVar,
and (c) as in (b) but for CNT.



valid = 2018.07.06 1800 UTC

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Fig. 10 (a) The difference between sea-level pressure of CNT FT = 3 (initiated at 1500 943 UTC, hereafter denoted as 15INI in the figures) and CNT FT = 18 valid at 1800 UTC July 9446, 2018, (CNT (FT = 3) - CNT (FT = 18); shaded), sea-level pressure of CNT FT = 3 945(contoured every 1 hPa in black), and sea-level pressure of CNT FT = 18 (contoured 946 every 1 hPa in green). (b) The difference between sea-level pressure of 1DVar and CNT 947 (1DVar - CNT; shaded), and sea-level pressure of 1DVar (contoured every 1 hPa). 948 Forecast initiated at 0000 UTC July 6, 2018, FT = 18. (c) The difference between water 949 vapor flux at 850 hPa of 1DVar and CNT (shaded), and the wind of 1DVar (barbs). 950 Forecast initiated at 0000 UTC July 6, 2018, FT = 18. Short barbs, long barbs, and 951pennants indicate 1 m s⁻¹, 2 m s⁻¹, and 10 m s⁻¹, respectively. 952



Fig. 11 As in Fig. 6 but for forecast statistics initiated from 0000 UTC July 2 to 2100 UTC
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valid at 2017.07.04 0600 UTC

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Fig. 12 Observation and forecasts valid at 0600 UTC July 4, 2017. (a) 3 h accumulated
precipitation from radar/rain gage analyzed precipitation, (b) as in (a) but for CNT FT =
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difference in sea-level pressure between 1DVar FT = 30 and CNT FT = 30 (1DVar (FT =
30) - CNT (FT = 30)) (shaded).



Fig. 13 Observation and forecasts of 3 h accumulated precipitation valid at 0600 UTC July
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Fig. 14 Forecasts and observations valid at 0600 UTC July 5, 2017. (a) T (shaded and contoured) at 400 hPa 1DVar FT = 24 (forecast from 0600 UTC July 4), (b) as in (a) but for CNT FT = 24, (c) as in (b) but for FT = 0 (forecast from 0600 UTC July 5), (d) water vapor flux (shaded) at 950 hPa 1DVar FT = 12 (forecast from 1800 UTC July 4), (e) as in (d) but for CNT FT = 12, and (f) as in (e) but for FT = 0 (forecast from 0600 UTC July 5). Contour interval is 1°C in (a), (b), and (c).



3h accumulated precipitation valid at 2020.07.04 0000 UTC

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Fig. 15 Forecasts and observations of 3 h accumulated precipitation valid at 0000 UTC July 4, 2020. (a) From left to right, observation from the radar/rain gage analyzed precipitation, and 6, 9, and 12 h forecasts of 1DVar initiated at 1800, 1500, and 1200 UTC July 3, 2020, respectively. (b) As in (a) but for CNT. The dashed lines indicate the position of Kumamoto where the torrential rain was observed.

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