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Air-sea coupled data assimilation experiment for Typhoons Kilo, Etau and the September 2015 Kanto-Tohoku Heavy Rainfall with the Advanced Microwave Scanning Radiometer 2 sea surface temperature

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Abstract

The September 2015 Kanto-Tohoku heavy rainfall occurred in a stationary linear convective system between Typhoons Kilo and Etau. We investigated the influence of sea surface temperature (SST) on the local heavy rainfall event using a regional air-sea strongly coupled data assimilation system based on the local ensemble transform Kalman filter (LETKF) and a nonhydrostatic atmosphere model (NHM) coupled with ocean-surface wave model and a multilayer ocean model together with the Advanced Microwave Scanning Radiometer 2 (AMSR2) level 2 (L2) SST product. From the validation of SST analyzed by the coupled data assimilation system with the Japanese geostationary satellite multi-functional transport satellite 2 hourly SST product and in situ observations at the moored buoy, we demonstrated that the coupled system with AMSR2 L2 SST led to improvement of the SST analysis. From the verification by using radiosonde observations and radar-raingauge rainfall analysis, the analysis of the lower-atmospheric components were improved by the air-sea coupled NHM-LETKF.

The local torrential rain occurred around 37°N in the Tochigi prefecture was embedded in a stationary linear convective system. The location of the linear convective system corresponded to the synoptic-scale convergence area between the cyclonic circulation associated with Etau and easterly lower-tropospheric winds. Strong southerly winds associated with Etau caused enhancement of local convection periodically along the convergence area on the upwind side of the linear convective system and resulted in a
wave-like train of the total water content around 4-8 km altitudes on the leeward side. The improvement of SST analysis could change not only the transition of Etau to the extratropical cyclone but also lower-tropospheric wind field and thereby the location of the stationary linear convective system with embedded local torrential rain.

**Keywords** air-sea coupled data assimilation, sea surface temperature, linear convective system, typhoon

1. **Introduction**

Current numerical weather forecasting system is constructed based on atmospheric observation data, atmospheric data assimilation system and atmospheric numerical model. The state-of-the-art numerical weather forecasting system is a mission-critical system and needs to be improved continuously to prevent natural disasters and to mitigate the damage. Advancements in the supercomputer system enable the numerical model to have higher resolution and to be more sophisticated with the advance of observational technology and a variety of observation data (Brunet et al. 2010; Bauer et al. 2015). In particular, with the progress of satellite technology, various satellites such as geostationary / polar orbiters have been launched. Since the observation area is limited spatially and temporally, however, incorporating the data appropriately into the atmospheric analysis is important for improving weather forecasts. The Global Change Observation Mission-Water “Shizuku” (GCOM-W) satellite with the Advanced Microwave Scanning
Radiometer-2 (AMSR2) microwave radiometer (e.g. Tomita et al. 2015) is one of the progressive microwave satellites with multi-frequency channels. The satellite can observe the amounts of precipitation, water vapor, sea surface temperature (SST), and near surface wind speed over the global ocean.

An analysis field of SST, required as the lower boundary condition of the atmosphere model, has been conventionally created by an ocean data assimilation system (e.g. Kurihara et al. 2006) and is not directly linked with an atmosphere data assimilation system (e.g., Kunii 2014). For this reason, the atmospheric field analyzed by the atmosphere data assimilation system is not always consistent with the oceanic field analyzed by the ocean data assimilation system. Lea et al. (2015) studied air-sea weakly coupled data assimilation, which used forecasts calculated by an atmosphere-ocean coupled model to provide the background field, while the analysis of the atmosphere and the ocean was updated in each assimilation system. Since atmospheric physical components are interacted with SST, an air-sea strongly coupled assimilation system which takes the covariance between the atmosphere and the ocean into account is expected as a next-generation numerical weather forecasting system (Brunet et al. 2010). In an air-sea strongly coupled system, observational information is shared between the atmosphere and ocean models (Liu et al. 2013; Sluka et al. 2016; Smith et al. 2015, 2017).

Previous studies investigated the role of ocean coupling in the atmospheric analysis using the atmospheric data assimilation system based on the local ensemble
transform Kalman filter (LETKF) (Miyoshi and Kunii 2012; Kunii and Miyoshi 2012) and the
data assimilation system of which forecast part was a nonhydrostatic atmospheric model
(NHM) coupled with a 1-dimensional ocean model (Kunii et al. 2017). Here we present
new development of the regional air-sea strongly coupled system based on NHM-LETKF
(Wada and Kunii 2017) although a control variable in the ocean part is limited to SST.
Wada and Kunii (2017) constructed a regional air-sea strongly coupled data assimilation
system for the first time and demonstrated the advantage for analyzing a tropical cyclone
and an SST field as well as their predictions for Typhoon Sinlaku (2008).

One of the challenging subjects is to accurately predict extreme rainfall events with
a longer lead time. Such events have a large and sometimes devastating effect on social
communities. It is no exception in the developed countries. According to a nationwide
survey in the United States, two of the most important aspects are when and where
precipitation will occur (Lazo et al. 2009). Here this study focuses on the linear convective
system in Japan that occurred along 140°E and had not changed the location for about 36
hours in September, 2015 (Fig. 1). Local torrential rain was continuously embedded inside
the stationary linear convective system around 37°N at the Kanto region on 9-10 September.
The system moved eastward on 11 September and the linear convective system turned to
be stagnated at the Tohoku area.

The synoptic structure surrounding the linear convective system was characterized
by Typhoon Kilo (2015) and the extratropical cyclone transited from Typhoon Etau (2015)
Fig. 2). Regarding the analysis and predictability of the stationary linear convective system and local torrential rain, the possibility of improving the numerical forecast by assimilating Himawari-8 rapid-scan atmospheric motion vectors (Kunii et al. 2016) and by a sophisticated atmosphere data assimilation system (Lien et al. 2017; Honda et al. 2018) has been reported so far. Lien et al (2017) pointed out that a high-resolution atmospheric model with horizontal resolution of a few kilometers is needed to improve the forecast. However, the effect of diabatic heating caused by changes in SST on the stationary linear convective system has not been investigated in these studies, while previous studies pointed out the importance of SST (Tsuguti and Kato 2014a; Manda et al. 2014; Kunoki et al. 2015; Sato et al. 2016), lower-tropospheric moisture (Peters et al. 2017; Schumacher 2015; Schumacher and Peters 2017) and warm air advection (Peters and Schumacher 2015a, b) for such heavy rainfall events.

The purpose of this study is to demonstrate the effect of accurate SST analysis on the analysis of the September 2015 Kanto-Tohoku heavy rainfall occurred in a stationary linear convective system over the Japanese archipelago between Kilo and the extratropical cyclone transited from Etau, particularly focusing on the stationary linear convective system across the Tochigi prefecture. This study used the air-sea strongly coupled data assimilation system developed by Wada and Kunii (2017) with AMSR2 SST product. Also, our concern is the effect of SST on the linear convective system and how the extremely heavy rainfall occurred at a specified local area in the Tochigi prefecture (Fig.
1). This is the first attempt that the air-sea strongly coupled data assimilation system is applied to analyze a stationary linear convective system with embedded local torrential rain.

This paper consists of five sections. After the introduction, the following Section 2 describes data and method used in this study. Sections 3.1 and 3.2 present the results of assimilation and validation of SST and atmospheric components such as hourly rainfall, winds, temperature and relative humidity. Section 3.3 and 3.4 shows the results of the analysis regarding the linear convective system occurred over the Japanese archipelago between Kilo and the extratropical cyclone transited from Etau. Section 4 discusses roles of SST and ocean coupling on the analysis of the linear convective system. Section 5 is devoted to concluding remarks.

2. Data and method

This section explains data and method used in this study. The air-sea strongly coupled data assimilation system is briefly explained as a schematic diagram in Fig. 3. New developments are in the analysis part that satellite SST data are able to be incorporated into the assimilation system as one of control variables and in the forecast part that the coupled atmosphere-wave-ocean model (Wada et al. 2010, 2013) is used instead of the NHM (Kunii 2014). The coupled model can simulate tropical cyclones realistically as well as storm-induced sea surface cooling (Wada et al. 2014) and level off of drag coefficients under high winds (Wada et al. 2013). The analysis system takes the background error
covariance between atmospheric and oceanic components into account, so that it is called the air-sea strongly coupled assimilation system (Liu et al. 2013; Sluka et al. 2016; Smith et al. 2015, 2017; Wada et al. 2017).

The Group for High Resolution Sea Surface Temperature (GHRSST) Project Data Processing Specification version 2 format specifications (GDS2.0) version 2.1 Level 2P (L2P) Global Skin Sea Surface Temperature from AMSR2 on the GCOM-W satellite (http://suzaku.eorc.jaxa.jp/GHRSST/index.html) were used every hour within ±3 hours in each 6-hourly cycle in conjunction with atmospheric observation data archived in the Japan Meteorological Agency (JMA). Hereafter, the SST is called AMSR2 L2P SST. In addition, hourly SST retrieval derived from the Japanese geostationary satellite multi-functional transport satellite 2 (MTSAT-2) with a horizontal grid spacing of 0.04° was used in order to validate SST analyzed by the coupled system (Hereafter, it is called ‘analyzed SST’). It should be noted that MTSAT-2 SST is independent of AMSR2 L2P SST, so that it is useful to validate the analysis. Table 1 shows a list of SST and ocean datasets used in this study.

The coupled data assimilation system covered the area of 4000 km x 3300 km with the number of grid points 273 x 221 in the Lambert conformal projection. The configuration is the same as Kunii (2014). The horizontal grid spacing was 15 km. The number of the vertical levels was 50, with different intervals ranging from 40 m for the near-surface layer to 1180 m for the uppermost layer. The top height was approximately 26 km. The number of the ensemble members was 50. To prevent underestimation of ensemble spreads near
lateral boundaries, lateral boundary uncertainties as well as uncertainties at the initial time were created from global objective analysis by adding perturbations derived from the JMA operational one-week ensemble prediction system. The variables controlled and analyzed in NHM-LETKF and the air-sea coupled system were three-dimensional wind components \((u, v, w)\), temperature \((T_a)\), pressure \((p)\), water vapor mixing ratio \((q_v)\), water/ice microphysics variables such as mixing ratio of cloud \((q_c)\), rain \((q_r)\), snow \((q_s)\), cloud ice \((q_{ci})\), graupel \((q_g)\), and SST \((T_s)\). The covariance localization scales used in this study were set to be 200 km in the horizontal, 0.2 in the vertical in the log \(p\) coordinate system, and 3 hours in time. The localization parameters corresponded to the one-sigma length at which the Gaussian localization function became \(e^{-0.5}\). These specifications are the same as Wada and Kunii (2017) except the setting of the assimilation domain and the number of the ensemble size.

We call the experiment with the original NHM-LETKF ‘CNTL’ and the experiment with the air-sea strongly coupled data assimilation system (Hereafter it is called ‘the coupled NHM-LETKF’) together with AMSR2 L2P SST ‘CPL’.

The Merged Satellite and In-situ Data Global Daily Sea Surface Temperatures (MGDSST) dataset with the horizontal resolution of 0.25° (Kurihara et al. 2006) was used as the SST boundary condition in the CNTL experiment. SST was fixed within four cycles in a day, which was the same as the configuration on SST in the original NHM system (Kunii 2014). It should be noted that AMSR2 L2P SST was used for creating MGDSST product.
after cutting the component shorter than 27 days.

The oceanic initial conditions in the CPL experiment were created with the JMA objective analysis in 2015 and four-dimensional Variational Ocean ReAnalysis for the Western North Pacific over 30 years (FORA-WNP30) dataset (Usui et al. 2017: http://synthesis.jamstec.go.jp/FORA/e/index.html) in the different year data of the reference date (1 September) and the data 5 days before the reference date (27 August) from 1990 to 2014 to create initial perturbation (25 years x 2 days = 50 member) on the ocean side. The five days corresponded to the assimilation window of FORA-WNP30. The observation error of AMSR2 L2P SST was set to be 3°C in consideration of diurnal variation of SST (Kawai and Wada 2007). The assimilation window length of the coupled NHM-LETKF was 6 hours. Note that AMSR2 L2 SST data were directly assimilated without any bias corrections in the CPL experiment. Assimilated observation data included radiosonde, pilot balloon, wind profiler, aircraft, ship, buoy, total precipitable water obtained from the Global Navigation Satellite System and atmospheric motion vectors derived from MTSAT-2. The relaxation to prior spread method (Whitaker and Hamill 2012) was adopted. We set the relative weight of the background (analysis) to 0.95 (0.05). The assimilation experiments were started from 1200 UTC on 1 September and were ended at 1800 UTC on 13 September in 2015.

3. Results

3.1 SST analysis and validation

Since the coupled NHM-LETKF is able to analyze SST every 6 hours, the analyzed
SST field includes variations shorter than a day: Diurnal cycle of SST can be analyzed. In addition to the analysis of diurnal cycle of SST, it is expected that the analyzed SST field will be improved overall. Now, we focus on how the analyzed SST field was improved by the coupled NHM-LETKF with AMSR2 L2 SST (Fig. 4). The analyzed SST field at 1800 UTC on 9 September 2015 in the CPL experiment (Fig. 4b) was compared with the SST field at 1800 UTC on 9 September 2015 in the CNTL experiment (Fig. 4a) and the SST field derived from AMSR2 L2P SST (Fig. 4c) observed from 1500 UTC to 2100 UTC on 9 September 2015. The time 1800 UTC was selected because the SST field in the CNTL experiment was updated at 1800 UTC every four cycles.

We can find some areas in Fig. 4 where there is no AMSR2 L2 SST data due to thick clouds. The comparison revealed that the characteristics of AMSR2 L2P SST (Fig. 4c) was analyzed in the CPL experiment (Fig. 4b) better than in the CNTL experiment (Fig. 4a) in the following points: [1] Around 25°N, 125°E, SST in the CNTL experiment was ~1°C higher than SST in the CPL experiment. [2] Around 30-35°N, 145°E, SST was relatively low in the CPL experiment due to strong surface winds associated with Kilo. [3] Relatively high SST areas were found around the coastal area in the Sea of Japan in the CNTL experiment where the extratropical cyclone transited from Etau passed over.

Assimilated SST by the coupled NHM-LETKF was validated by using in situ SST observations at the Kuroshio Extension Observatory (KEO) buoy moored at 32.3°N, 144.6°E. From the time series of SST at the grid corresponding to the location of the moored buoy,
the diurnal variation in SST could be analyzed in the CPL experiment, while the diurnal variation could not be seen in the CNTL experiment (Fig. 5). The improvement of the amplitude of the diurnal SST variation led to the improvement of SST analyzed in the CPL experiment (Fig. 4b). Moreover, SST in the CNTL experiment had positive biases compared with analyzed SST in the CPL experiment and in situ SST observations at the moored buoy. Analyzed SST in the CPL experiment, however, had relatively small negative biases compared with in situ SST observations even though AMSR2 L2 SST data were directly assimilated without any bias corrections.

As described in Section 2, MTSAT-2 SST was independent of AMSR2 L2 SST. This is the reason that MTSAT-2 SST was used to validate SST at 1800 UTC 9 September 2015 in the CNTL and CPL experiments (Fig. 6). SST in the CNTL experiment was relatively high compared with MTSAT-2 SST when SST was higher than 24°C (Fig. 6a). This is one of the causes of deteriorating the square of correlation coefficient (0.54) and the slope (0.67) of the linear regression function in the CNTL experiment. These values were improved in the CPL experiment (Fig. 6b). The square of correlation coefficient and slope increased to 0.69 and 0.75, respectively. The result suggests that the verification by using hourly MTSAT-2 SST supported the improvement of the quality of analyzed SST in the CPL experiment.

3.2 Analysis and validation of atmospheric components

Hourly radar-raingauge analyzed rainfall shown in Fig. 1 was estimated from total rainfall amount within an hour based on radar observations calibrated with rain-gauge
measurements from the JMA automated meteorological data acquisition system (Makihara 1996). Figure 1 captured the evolution of the stationary linear convective system and local torrential rain occurred at the Kanto region. The precipitation pattern shown in Figs. 7a-b was a result of 6-hour forecasts initiated at 1200 UTC on 9 September in the CNTL (Fig. 7a) and CPL (Fig. 7b) experiments. Hereafter, the results of the forecast experiments initiated from the ensemble mean (see Fig. 1 in Miyoshi and Kunii 2012) were used for the analyses because the precipitation was a forecast variable both in the original and the coupled NHM-LETKF. The orientation of the linear convective system in the CNTL experiment (Fig. 7a) was close to that in the radar-raingauge analysis (Fig. 1). However, the location of the linear convective system over the Japanese archipelago in the CNTL experiment shifted westward compared with that shown in Fig. 1. The location of the linear convective system with embedded local torrential rain around 37°N in the Tochigi prefecture was successfully predicted in the CPL experiment (Fig. 7b).

Figure 8 shows the time series of total hourly rainfalls from 0000 UTC on 9 September to 1800 UTC on 10 September in 2015. The hourly radar-raingauge analyzed rainfall dataset used in this study was originally created with the method used in Tsuguti and Kato (2014a, b). The analysis area was a rectangular surrounded by 36-37°N, 139-140°E where the local torrential rain occurred. The total hourly rainfalls over the area of 36-37°N, 139-140°E were calculated by summation of hourly radar-raingauge analyzed rainfall, hourly rainfall obtained in the CNTL experiment and hourly rainfall obtained in the CPL
experiment, respectively. At 1800 UTC on 9 September, the total hourly radar-raingauge analyzed rainfall had a peak, while a peak of the total hourly rainfall was found at 1200 UTC on 9 September in the CPL experiment, six hours earlier than the occurrence of the peak of the total hourly radar-raingauge analyzed rainfall. In the CNTL experiment, there is no peak found from 1200 UTC to 1800 UTC on 9 September in 2015.

Figure 9 shows scatter diagrams on hourly rainfall amounts between hourly radar-raingauge analyzed rainfall and hourly rainfall in the CNTL (Fig. 9a) / CPL (Fig. 9b) experiment, respectively. It should be noted that the analysis area is different from that in Fig. 8. The analysis area was a rectangular surrounded by 33-38°N, 138-141°E, including the stationary linear convective system with embedded local torrential rain. Since the analysis area expanded, the number of data samples increased although only the result of the forecast initiated from the ensemble mean was used. There was no correlation between hourly radar-raingauge analyzed rainfall and hourly rainfall in the CNTL experiment, while the correlation was significant between radar-raingauge analyzed rainfall and hourly rainfall in the CPL experiment with the p-value much smaller than 0.05. The result suggests that the improvement of the SST field analyzed by the coupled NHM-LETKF leads to the improvement of hourly rainfall forecast.

Kunii et al. (2016) evaluated threat and bias scores for the 3-hourly accumulated precipitation averaged over eight different initial times. Following Kunii et al. (2016), we evaluated mean thread score for a threshold of 3-hourly precipitation amount from 0 to 20
mm/h averaged from 0000 UTC 9 to 1800 UTC 10 September 2015 every 6 hours (Fig. 10). The evaluated area was a relatively large rectangular surrounded by 28-42°N, 134-141°E.

Predictions of 3-hourly precipitation amount in the CPL experiment were improved at a threshold over 5 mm compared with those in the CNTL experiment although the threat score was degraded at the thresholds of 1 and 2 mm. This result is consistent with the result shown in Fig. 7. It should be noted that mean bias score in the CPL experiment was not improved (not shown) probably due to insufficient horizontal resolution (15 km) in both NHM-LETKF and the coupled NHM-LETKF even though SST analysis was improved in the CPL analysis. In fact, Wada et al. (2017) conducted forecast experiments on the September 2015 Kanto-Tohoku heavy rainfall with a 3-km mesh atmosphere-ocean coupled model and showed that hourly accumulated rainfall was quantitatively simulated to some extent.

The results of the analyses in the CNTL and CPL experiments were also verified with radiosonde observations during the period from 0000 UTC on 8 to 1800 UTC 13 September. The physical components were zonal ($U$) and meridional winds ($V$), air temperature ($T$) and relative humidity ($RH$). Although the radiosonde observations were used in the assimilation, here we checked to what extent the assimilation result was close to the observations. Regarding the root mean square error (RMSE) of $U$, $V$, $T$ and $RH$, RMSE in the CPL experiment was improved in the low-to-mid troposphere below 500-hPa level (Fig. 11) except near the surface. The exception implies that there was a problem regarding the bias of air temperature in the CPL experiment in that the lowermost
temperature became low and dry due to some problems regarding the surface boundary layer scheme and air-sea interfacial processes in the NHM. However, the atmospheric boundary processes played an essential role in the improvement in the low-to-mid troposphere below 500-hPa level. The improvement led to better expression of both the linear convective system and embedded local torrential rain occurred around 37°N in the Tochigi prefecture. The improvement of the analysis is considered to serve as in-depth understanding of the formation mechanism of both the stationary linear convective system and local torrential rain.

### 3.3 Etau and upper-tropospheric trough

As shown in Fig. 2, Etau moved northward and became an extratropical cyclone in the Sea of Japan and then moved northeast over the ocean. Etau had a primary rainband (Houze 2010) in the eastern side during the passage over the Japanese archipelago. After the passage, the rainband turned to be changed into the stationary linearly convective system with embedded local torrential rain continuously around 37°N, 140°E in the Tochigi prefecture (Fig. 1). Here we address a relation between the extratropical transition of Etau and the linear convective system and the difference of the relation between CNTL and CPL experiments.

First, we address the effect of synoptic conditions on the linear convective system. To examine the impact of the air-sea coupled assimilation on the synoptic condition particularly in the upper troposphere, the concept of potential vorticity (PV) (e.g., Hoskins et
al. 1985) is introduced. PV is proportional to the product of absolute vorticity and stability. Because it behaves as a flow tracer on an isentropic surface, PV is a useful concept for understanding the effect of synoptic conditions such as upper-tropospheric trough on the linear convective system through the adiabatic process. In fact, PV has been utilized in studies on TC-trough interactions and transitioning TCs (e.g., Atallah et al. 2007).

According to RSMC best track data, Etau appeared over the ocean south of Japan at 0000 UTC 8 September (not shown). Figure 12 shows horizontal distributions of potential vorticity and winds on the 345K isentropic surface together with sea-level pressures at 00UTC on 8 September, 00 UTC and 18 UTC on 9 September analyzed in the CNTL and CPL experiments. It should be noted that this study defines the center position of Etau by the point at which the sea-level pressure is minimum. As shown in Fig. 12a, on the 345K isentropic surface, southwesterly winds were strong at the southeastern side of high PV region in the CNTL experiment. Etau moved along the southwesterly steering flow and made landfall in the central part of Japan at 0000 UTC 9 September (shown in a circle in Fig. 12b). At 1800 UTC, the extratropical cyclone was finally absorbed in the upper-tropospheric trough. The extratropical cyclone transited from Etau was stationary in the Sea of Japan (shown a typhoon mark in Fig. 12c) and then changed the moving direction northeastward. The central pressure of the extratropical cyclone was 995.8 hPa at 1800 UTC in the CNTL experiment.

Compared with the central pressure of Etau in the CNTL experiment (Fig. 12a), the
central pressure in the CPL experiment was not significantly changed at 0000 UTC 8 September (Fig. 12d). However, the central pressure of Etau (996.0 hPa) increased to some extent in the CPL experiment before the storm made landfall compared with the central pressure (995.1 hPa) in the CNTL experiment (Fig. 12e). At 1800 UTC on 9 September, the central pressure of the extratropical cyclone (Fig. 12f) was higher (998.3 hPa) in the CPL experiment than that (995.8 hPa) in the CNTL experiment (Fig. 12c). Like the results in the CNTL experiment, the extratropical cyclone was absorbed in the upper–tropospheric trough.

In Fig. 12, there was no significant difference in the distribution of the upper–tropospheric trough between CNTL and CPL, whereas there was a clear difference in the negative PV distribution on a meso-beta scale formed east of the upper-tropospheric trough.

Figure 13 shows vertical sections of potential vorticity, winds and potential temperature across the line A-B shown in Fig. 12 analyzed in the CNTL and CPL experiments. The upper–tropospheric trough and the meso-beta scale PV system moved from A to B in Fig. 13. The meso-beta scale PV profile had an upstanding structure over the Japanese archipelago. The profile involved a minimum in the lower troposphere and a maximum directly above in the CNTL experiment, while it involved a maximum in the lower-to-mid troposphere and a minimum directly above in the CPL experiment where the linear convective system appeared. In the CPL experiment, the distribution of lower-to-mid tropospheric maximum PV and directly above minimum PV regarding a creation of the updraft axis from the lower troposphere was consistent with a conceptual model of Fritsch.
et al. (1994) and Houze (2004) although these studies showed the model for explaining mesoscale convective vortex following a tropical cyclone. In the CNTL experiment, a meso-beta scale warm core structure also appeared like the result in the CPL experiment, although the height of the warm core became relatively high compared with that in the CPL experiment. The location of the minimum PV with the warm core corresponded to that of strong divergence on a meso-beta scale (Fig. 14). In the CPL experiment, strong convergence area in the lower-to-mid troposphere was located above the cold pool near the relatively strong lower tropospheric easterly. Also the relatively high divergence area appeared west of the convergence area, indicating the existence of outflow boundary condition. These are consistent with the mesoscale convective system shown in the conceptual diagram in Fritsch et al. (1994) and Houze (2004). In addition, the vertical wind profile west of the PV maximum/minimum pattern found in the CPL experiment was also consistent with the environmental vertical wind shear in that the profile had a deep layer of a weak flow and weak shear in the mid-to-upper troposphere (Fritsch et al. 1994, Houze 2004). By using the air-sea coupled data assimilation, the meso-beta scale PV may be modified system through a change in environmental vertical wind profiles.

3.4 Lower-tropospheric moisture flux and convection

As described in Section 3.3, the meso-beta scale PV distribution was changed by using the coupled NHM-LETKF as a data assimilation system (Fig. 7). In particular, lower-tropospheric winds associated with environmental vertical wind shear and formation
of an updraft are important in that they directly affect estimates of turbulent heat fluxes, horizontal moisture transport in the lower troposphere and variations in SST. This section addresses the effect of analyzed SST on the lower-tropospheric moisture fluxes and associated convection. The lower-tropospheric moisture flux was calculated by specific humidity multiplying a horizontal wind speed at each grid and level, while convection was detected from upward vertical velocity. Tsuguti and Kato (2014a) pointed out the importance of lower-tropospheric moist airs and air-mass transformation associated with high SST and air-sea latent heat flux to the formation and maintenance of the heavy rainfall event occurred on Amami-Oshima Island, Japan in 2010 when Typhoon Megi (2010) made landfall in the Philippines and moved to the South China Sea. Yoshida and Itoh (2012) reported that a large moisture flux south of Kyushu led to a heavy rainfall event in the vicinity of Kyushu when Typhoon Maggie (1999) caused the northward advection of a separate tropical disturbances during the northwestward translation.

The horizontal moisture fluxes in the CNTL (Fig. 15a) and CPL (Fig. 15b) experiments were relatively high around the extratropical cyclone, along the linear convective system and east of the linear convective system north of 30°N. South of Japan, in contrast, horizontal moisture fluxes analyzed in the CPL experiment were relatively low (< 50 g m⁻² s⁻¹) compared with those in the CNTL experiment. The vertical cross section across the Japanese archipelago in the CNTL experiment (Fig. 15c) indicates that the lower-tropospheric horizontal moisture flux transported from east of Japan to the Japanese
The lower-tropospheric convergence resulted in upward moisture flux in the middle and east of the Japanese archipelago. The upward moisture transport was analyzed only east of the Japanese archipelago in the CPL experiment (Fig. 15d) due to relatively weak lower-tropospheric easterly winds (Fig. 11b). The difference of winds at 20-m height between the CNTL and CPL experiments clearly increased around the location of the linearly convective system (Fig. 16). This led to increases of the difference of the lower-tropospheric convergence. In fact, air-sea latent heat fluxes were relatively high around the extratropical cyclone, the linear convective system, and Kilo in the CNTL experiment (Fig. 17a), while air-sea latent heat fluxes reduced around these areas in the CPL experiment (Fig. 17b). In particular, the reduction in air-sea latent heat fluxes around the extratropical cyclone and Kilo was caused by storm-induced sea surface cooling in the CPL experiment. In the coupled NHM-LETKF, the storm-induced sea surface cooling could be predicted by the atmosphere-wave-ocean coupled model even under deep clouds’ condition (Wada and Kunii 2017). The reduction in air-sea latent heat fluxes in the CPL experiment led to not only a decrease in the lower-tropospheric equivalent potential temperature but also a change of the horizontal distribution of the lower-tropospheric equivalent potential temperature (not shown). The change did affect the horizontal moisture fluxes in the lower troposphere. These differences between the CNTL and CPL experiments are one of factors that could change the location of the linear convective system.
Hereafter, this section focuses on the linear convective systems calculated in the CNTL and CPL experiments. Both linear convective systems in the CNTL and CPL experiments were sustained within a cycle of data assimilation (for 6 hours). Vertical cross sections of vertical wind velocity and total water content (defined as a summation of rain, cloud, snow, ice and graupel) and their evolution are shown along the linear convective system in the CNTL (Fig. 18) and CPL (Fig. 19) experiments. The area of relatively high upward vertical velocity, representing the occurrence of convection, corresponded to the area where total water content was high. The total water content became high around 6-km height in the CPL experiment because of an increase in snow. Arrows in Figs 18 and 19 show that convective area with high total water content extended northward (from ‘B’ to ‘A’ in Fig. 18 and from ‘D’ to ‘C’ in Fig. 19) like a wave train that propagated to the downstream (‘A’ in Fig. 18 and ‘C’ in Fig. 19) side. The wave train began to be enhanced over the Japanese archipelago where southerly winds became strong at the southeastern edge of the upper-tropospheric trough (Figs. 12c and 12f). A single cell was dominant in the CNTL experiment, while the cells seemed to be linked as a stationary linearly convective system in the CPL experiment. In other word, the moving speed of a convective cell in the CNTL experiment was faster than that in the CPL experiment. The relatively fast moving speed was related to the relatively fast southerly winds throughout the vertical profile in the CNTL experiment (Fig. 18). It should be noted that the area of high total water content appeared locally in the horizontal distribution (not shown), indicating that the effect of the horizontal
advection on the occurrence of high total water content was relatively small. Around the Tochigi prefecture, negative vertical wind velocity was continuously found in the lower troposphere (Figs. 19a-c). In addition, the convergence was relatively strong and a deep layer of a weak flow existed in the mid-to-upper troposphere around the Tochigi prefecture (Fig. 14). This indicates formation of stationary stratiform area around the location of local torrential rain.

Roles of upper-tropospheric trough, lower-tropospheric winds and the SST field in formation and maintenance of the linearly convective system are summarized in Fig. 20. The upper-tropospheric trough, lower-tropospheric winds and SST field modified by the coupled NHM-LETKF played an important role in determining the location of the lower-tropospheric convergence area, the occurrence and maintenance of the linearly convective system. It should be noted that easterly winds associated with Kilo were closely related to the transport of the lower-tropospheric moisture fluxes toward the linear convective system that played a crucial role in determining the location of the convergence area over the Japanese archipelago, although the difference in the easterly winds between CNTL and CPL was small. The linearly convective system in the CPL experiment had a common characteristic with that assimilated in the CNTL experiment: Convective area extended south to north like a wave train over the Japanese archipelago due to strong winds at the eastern side of the upper-tropospheric trough. In addition, the system was sustained for six hours in both the CNTL and CPL experiments. The difference between the
two experiments appeared not only in the location of the linear convective system but also in the lower-troposphere where negative vertical winds were sustained and local torrential rain occurred.

Therefore, more accurate SST analysis by the coupled NHM-LETKF leads to improvement of analyzing the location of the linearly convective system with the embedded local torrential rain occurred between Kilo and the extratropical cyclone transited from Etau. This is consistent with the effect of lower-tropospheric moisture (Peters et al. 2017; Schumacher 2015; Schumacher and Peters 2017) on the formation, location and longevity of the linear convective system. In addition, the area of high lower-tropospheric moisture in the Pacific Ocean corresponded to the area of high equivalent potential temperature (not shown). In that sense, the effect of warm air advection (Peters and Schumacher 2015a, b) is also important on the formation, location and longevity of the linear convective system.

4. Discussion

The impact of SST modification due to ocean coupling on the lower troposphere is considered to be generally small on a weather-forecasting time scale except for severe weather such as tropical cyclones. The impact of the storm-induced oceanic response (Price, 1981) on tropical cyclones differs from that of preexisting synoptic SST conditions on atmospheric disturbances. The latter has ever been investigated synoptically on heavy rainfalls under the Asian summer monsoon (Manda et al. 2014), storm tracks (Kuwano-Yoshida and Minobe 2017; Sasaki et al. 2012) and extratropical cyclone (Xu et al.
In addition, this has been examined by using an atmosphere-ocean coupled model (e.g., Berthou et al. 2014; Lebeaupin Brossier et al. 2013). These studies have found that local changes in SST and the difference of a SST field such as a horizontal gradient of SST have some impacts on the atmosphere. The effect of a change of the SST field analyzed every cycle of the data assimilation by the coupled NHM-LETKF with AMSR2 L2 SST is essentially consistent with these previous studies. This study implicitly supports that the ocean plays an active role in driving the atmosphere (e.g., Small et al. 2008; Kelly et al. 2010; Kwon et al. 2010).

However, sea surface cooling and reduction in air-sea latent heat flux by passage of Etau and Kilo can be understood as the occurrence of ‘negative feedback’ effects caused by the oceanic response to tropical cyclones (e.g. Chang and Anthes 1979; Zhu et al. 2004; Wu et al. 2005; Bender et al. 2007; Wada 2009; Wada et al. 2010, 2014; Kanada et al. 2018). The coupled NHM-LETKF with AMSR2 L2 SST reproduced the sea surface cooling realistically so that the analysis of the SST field was improved.

In this study, no bias correction was conducted for AMSR2 L2 SST when running the 6-hour cycle of the analysis by the coupled NHM-LETKF with AMSR2 L2 SST although the verification result shown in Fig. 5 was reasonable for the analyzed SST. In fact, the ocean model in the atmosphere-wave-ocean coupled model used in this study has a problem for simulating a diurnal cycle of SST. More realistic analysis of a diurnal cycle of SST in the CPL experiment may lead to the improvement of the analysis of SST. The
improvement of the analysis of SST will lead to the improvement of the location of the linearly convective system and the strength of local torrential rainfall.

It should be noted that it was necessary to spin up about one week for analyzed SST to be consistent with the observed SST (Wada and Kunii 2017). The amount of the observation data (the amount of AMSR2 L2P SST per cycle of the analysis in this study) may be related to this spin-up period in view of the rate of data coverage to the analysis region. When performing target observation like the Observing System and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC) (see Wada and Kunii 2017) and conducting both atmospheric and oceanic analyses by the coupled NHM-LETKF or another air-sea strongly coupled data assimilation system, it is necessary to take the spin-up time adequately.

This study demonstrates that improvement of the lower troposphere by improving the SST analysis contributed to the improvement of the analysis of the September 2015 Kanto-Tohoku heavy rainfall. This suggests that synoptic SST field and the lower troposphere play a crucial role in formation and maintenance of the linear convective system. However, the role of SST played in the accuracy of the analysis of the linear convective system might be changed when the horizontal resolution of NHM-LETKF (15 km) becomes high (e.g. 5 km or less) and cumulus convection scheme is not used in a forecast model. Moreover, this kind of regional data assimilation system is greatly influenced by the lateral boundary condition when analyzing the stagnation / deformation
processes of the upper trough, which is considered to play a crucial role in the stagnation of the linear convective system and associated local torrential rain (Kitabatake et al. 2017). Due to the constraint of computational resources, in the present study, it is difficult to identify the relation of the stagnation and deformation processes to the upper-tropospheric trough and the linear convective system. In order to clarify the relation, we expect that a global air-sea coupled data assimilation system will be developed in the future.

5. Concluding remarks

In September 2015, the linear convective system that originated from the primary rainband of Typhoon Etau was stagnated and caused local torrential rain continuously around 37˚N, 140˚E in the Tochigi prefecture on 9-10 September. The area of the linear convective system moved to around the Tohoku region on 11 September. The linear convective system occurred between Typhoon Kilo and the extratropical cyclone transited from Etau (Fig. 2). This study addresses the effect of the analysis of sea surface temperature (SST) on the analysis and prediction of the linear convective system with embedded local torrential rain by using the air-sea coupled data assimilation system based on a local ensemble transform Kalman filter (LETKF), a nonhydrostatic atmosphere model (NHM) coupled with ocean-surface wave model and a multilayer ocean model, and Advanced Microwave Scanning Radiometer 2 (AMSR2) level 2 (L2) SST data. This study also addresses the difference of the relation of Kilo and the extratropical cyclone transited from Etau to the linear convective system by applying the air-sea strongly coupled data
assimilation system based on NHM-LETKF (Kunii 2014), but the forecast part of the original system is replaced with an atmosphere-wave-ocean coupled model (coupled NHM-LETKF).

The analysis of SST is improved by the coupled NHM-LETKF with AMSR2 L2 SST for Kilo, Etau and the September 2015 Kanto-Tohoku heavy rainfall. In addition, the coupled NHM-LETKF with AMSR2 L2 SST successfully improve the precipitation forecasts of the location of the stationary linear convective system with embedded local torrential rain. The coupled NHM-LETKF could change the extratropical cyclone transited from Etau but also change the synoptic field associated with the lower-tropospheric dynamic / thermodynamic conditions, although there was no significant difference in the upper-tropospheric trough. These changes result in the difference of the analyzed location of the linear convective system. Synoptic SST field did affect the location of lower-tropospheric convergence area with changes in air-sea latent heat fluxes and equivalent potential temperature in the lower troposphere.

The SST analysis by the coupled NHM-LETKF is validated with in situ observations and MTSAT-2 SST. The correlation of SST analyzed by the coupled NHM-LETKF with in situ observations and MTSAT-2 SST was significantly higher than that of SST used in the original NHM-LETKF. The improvement of SST analysis led to the improvement of atmospheric analysis particularly in the lower troposphere. The improvement of the analyses of both SST and the lower troposphere is important to improve the analysis of the
linearly convective system with the embedded local torrential rain. It should be noted that
there still remains a problem regarding the bias of air temperature in that the lowermost
temperature became low and dry. To improve the analysis of air temperature near the
surface using NHM-LETKF, we need to improve the surface boundary layer scheme and
air-sea interfacial processes in the NHM.

Extremely heavy rainfall event is very rare, so that it is difficult to pile up case
studies to verify the effectiveness of the coupled NHM-LETKF. However, as to tropical
cyclones, the number of genesis is in the order of 20-30 in the western North Pacific. It is
necessary to pile up case studies of severe weather such as tropical cyclones to further
develop the coupled NHM-LETKF. In addition, predictability studies regarding tropical
cyclones and extremely heavy rainfall events by using the coupled NHM-LETKF with new
datasets obtained from new observational technologies such as more sophisticated satellite
observations (e.g. Bessho et al. 2016; Ruf et al. 2016) and new in situ observations (e.g.
Yonehara et al. 2016; Wada et al. 2017) will contribute to the progress of weather forecasts
by advanced numerical prediction system.

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<td>daily</td>
<td>North Pacific (Usui et al., 2006)</td>
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