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Analysis of the Factors that Led to Uncertainty of Track Forecast of Typhoon Krosa (2019) by 101-Member Ensemble Forecast Experiments Using NICAM

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Abstract

Typhoon Krosa (2019) formed in the eastern part of the Philippine Sea and ~1400 km east of another typhoon Lekima on 6 August and made landfall in the western part of Japan’s mainland on 15 August. The operational global model forecasts, which were initialized just after Krosa’s formation, showed a very large uncertainty and totally failed to predict the actual track of Krosa. In this study, we investigated the causes of this large uncertainty through 101-member ensemble forecast experiments by using a 28-km mesh global nonhydrostatic model. The experiments initialized at 1200 UTC 6 August, showed a large uncertainty. An ensemble-based lagged correlation analysis indicated that the western North Pacific Subtropical High (WNPSH) retreated further east in the members with large track forecast errors than in the members with small errors. For the members with a large track forecast error for Krosa, Krosa and Lekima approached each other by 250 km and Krosa moved northward faster than the observation in 36 hours from the initialization time. For the members with a small track forecast error for Krosa, two typhoons approached each other by only 50 km, and the northward moving speed was comparable with that of the observation. The typhoon-center relative composite analysis exhibited that at the initialization time, the members with a large Krosa track forecast error had a larger horizontal size of Krosa and the difference in Krosa’s size was kept during the forecast period. This difference in size led to a stronger interaction between the two typhoons and retreatment of the WNPSH, thus resulting in a fast northward moving speed for the members with a large Krosa track error.
Keywords tropical cyclone; track forecast; Fujiwhara effect; forecast bust;
western North Pacific subtropical high
1. Introduction

Tropical cyclones (TCs) often cause destructive disasters and threaten human lives and socioeconomics. To mitigate the damages caused by TCs, continuous efforts are needed to improve track forecasts. By 2030, the Japan Meteorological Agency (JMA) aims at reducing the track forecast errors of typhoons on forecast day 3 to less than 100 km, which is approximately half the current forecast error (see Fig 4.1 of JMA 2020). The forecasting of TC tracks has significantly been improved in recent decades. However, the forecasts occasionally experience unusual large errors or uncertainties, which are sometimes called “forecast busts.” Thus, to further improve the track forecasts of TCs, it is necessary to understand what causes such unusual large forecast errors or uncertainties.

The thick color line surrounded by black in each panel of Fig. 1 shows the best track data for Typhoon Krosa (2019). Krosa formed at 0600 UTC 6 August, in the eastern part of the Philippine Sea under the convective envelope associated with the boreal summer intraseasonal oscillation (BSISO; Wang and Rui 1990; Wang and Xie 1997; Kikuchi 2021). Afterward, by 8 August, it moved northwestward, and by 11 August, it slowed down and made a complex trajectory. Subsequently, it moved northwest/north-northwest again and, on 15 August, made landfall on the Hiroshima prefecture, the western part of the mainland of Japan. It should be noted that at the formation time of Krosa, another typhoon, Lekima, was located at ~1400 km west of Krosa. Lekima moved northwestward and made landfall on the central part of the mainland of China on 9 August.
The operational models initialized at 1200 UTC 6 August, showed a very large uncertainty in forecasting Krosa’s track (Figs. 1a, 1e, and 1i). For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) and JMA models barely captured the observed Krosa’s track within the uncertainty range. However, the spread was very large; the westernmost track would hit Korea, and the easternmost track would go through the oceanic area east of Japan without making landfall (Figs. 1a and 1e). The National Centers for Environmental Prediction (NCEP) model showed a small uncertainty; however, it totally failed to predict the actual track of Krosa; all members predicted that Krosa would go through to the east of Japan without making landfall (Fig 1i).

For the later model initialization time, the uncertainty of Krosa’s track forecast decreased, and the forecasts of the three models converged to the observed track in the experiments initialized at 1200 UTC 9 August (Figs 1d, 1h, and 1i).

In the western North Pacific (WNP) region, it is well known that the WNP subtropical high (WNPSH) strongly modulates TC tracks in various time scales. TC tracks are modulated by the convective activity in the tropics since it affects the westward extension of WNPSH (Lu and Dong 2001). Nakazawa and Rajendran (2007) found that the seasonal number of TCs approaching Japan or making landfall on it is strongly modulated by the presence of an anticyclonic anomalous circulation east of the Philippines due to the shifting of the WNPSH westward, resulting in a lower-than-normal TC frequency over Japan. Choi et al. (2010) showed that the Pacific–Japan pattern (Nitta 1987) changes the TC activity in WNP. In addition, Nakano et al. (2021) showed that the suppressed and enhanced convection associated with BSISO affects TC tracks, and this impact is well reproduced by the ECMWF model. Camp et al.
(2019) showed the potential of TC landfall seasonal forecasts by using WNPSH indices predicted by UK MetOffice’s global seasonal forecast system in June–August. It is worth noting that a TC creates anticyclonic anomaly northeast of its location due to the Rossby response to its convective heating (Kawamura and Ogasawara 2006), resulting in WNPSH enhancement.

In the cases when two or more TCs closely coexist, they interact with each other (a.k.a. “Fujiwhara effect”; Fujiwhara 1921, 1923). Brand (1970) showed that the interaction characteristics depend on the separation distance between such TCs; rotating cyclonically within each other when the separation distance is less than 750 NM (~1390 km) and attracting each other when the separation distance is less than 400 NM (~740 km). Peng and Reynolds (2005) showed that an interaction can occur even when the separation distance is 1861 km. Moreover, Brand (1970) mentioned that the track forecast errors for TCs the Fujiwhara effect taking place were larger than average in the 1960’s. The forecast bust cases associated with such storms can still be seen in state-of-the-art numerical weather prediction systems (e.g., Choi et al. 2017).

The ensemble-based sensitivity analysis (Ancell and Hakim 2007; Torn and Hakim 2008) and clustering the ensemble members by using a ranking of a metric or the characteristics of predicted TC tracks are used to diagnose the main cause of forecast bust. Nakashita and Enomoto (2021) performed an ensemble sensitivity analysis for Typhoon Hagibis (2019) and found that the ensemble members with large track errors have an initial perturbation to weaken the ridge of WNPSH. Magnusson et al. (2014) explored the main causes of the uncertainties in the forecasting of Hurricane Sandy (2012), which made landfall on the eastern coast of the US from the Atlantic, by grouping the
ensemble members into landfall members and moving to the east members and suggested that weaker extension of the subtropical ridge resulted in eastward track.

In this study, we investigated the main causes of the large uncertainty in Krosa’s track forecasting through 101-member ensemble forecast experiments by using a global nonhydrostatic model. The rest of this paper is organized as follows. Section 2 describes the experimental setup of the ensemble forecast experiments. Section 3 introduces the data utilized in this study except for the model experimental data and explains the analysis methods. Section 4 shows the results of the experiments, a discussion, and a comparison of the operational model data. Section 5 presents the summary and conclusions of this study.

2. Model Experiment

The model used in this study is a 28-km mesh Nonhydrostatic ICosahedral Atmospheric Model (NICAM [version NICAM.18]; Satoh et al. 2014; Kodama et al. 2021). The number of vertical layers was set to 38, and the model top was located at 37 km. The moist convection was explicitly calculated using a single-moment cloud microphysics scheme (Roh and Satoh 2014) without any cumulus parameterization. The atmospheric initial condition was provided by an operational weather analysis system called NICAM-LETKF JAXA Research Analysis (NEXRA, https://www.eorc.jaxa.jp/theme/NEXRA/index_e.htm, Kotsuki et al. 2019). NEXRA’s core data assimilation system is NICAM-LETKF (Terasaki and Miyoshi 2017; Kotsuki et al. 2017), and it combines the ensemble
simulation obtained by NICAM and the in situ/satellite observations by LETKF (local ensemble transformed Kalman filter, Hunt et al. 2017). Note that neither TC position and intensity analysis data (so-called TCVITAL) nor Synthetic Tropical Cyclone Bogus Reports (SYNDAT) are assimilated for NEXRA production. The ensemble size and horizontal resolution of NEXRA were 100 and 112 km, respectively. We used all the ensemble analysis members (100) and their mean for the model initialization. Thus, there were 101 members in total. SST was predicted by a slab ocean model with a constant depth of 15 m. Moreover, SST was nudged toward the initial values with an e-folding time of 7 days. The initial value of SST (1°×1° horizontal resolution) was obtained from the Global Data Assimilation System of NCEP. The SST data was also used in NEXRA's data assimilation cycle. The model simulations were initialized at 1200 UTC from the 6th to the 9th of August and integrated for 10 days to examine whether the model can reproduce a large uncertainty.

3. Data and Method

The best track data of the Regional Specialized Meteorological Center (RSMC; Tokyo) was used as observational data of the TC location and minimum sea level pressure. The operational ensemble forecasts of ECMWF, JMA, and NCEP (see Table 1), which were taken from the International Grand Global Ensemble archive (TIGGE; Bougeault et al. 2010; Swinbank et al. 2016), were used for the comparison with the NICAM forecasts and discussion. As the resolution of archived data varies by the operational center and is the coarsest for JMA data, the other center’s data was regridded to the same resolution, 1.25
As analyzed by Nakano et al. (2017), the TCs in the model were tracked by searching the sea level pressure (SLP) minimum nearest to the observed TC center at the initial time and by connecting the nearest SLP minimum along with the forecast period. Before searching the SLP minimum, the SLP field was smoothed 100 times using a Gaussian (1-2-1) filter to avoid tracking a meso-vortex embedded in the typhoon scale vortex (e.g., Nolan et al. 2001) or a spurious minimum, which can be caused by numerical noise (e.g., so-called grid storm). To define the TC center in NEXRA, the geopotential height at 925 hPa was used instead of the SLP because the SLP for each ensemble member was not available.

Because JMA issues 5-day TC track forecast, reducing TC track error, the distance between the TC center positions analyzed in the best track data and forecasted by the model, 5 days later of Krosa’s genesis is of interest. To examine the sensitivity of Krosa’s track forecast, we performed an ensemble-based lagged correlation analysis and a best-worst comparison. The lagged correlation is formulated with track forecast error at 1200 UTC 11 August 2019, about 5 days later from Krosa’s genesis \((J)\) and the atmospheric fields \((F)\) of interest at any time \(t\) including initial time as

\[
\text{Corr}(x, y, t) = \frac{\text{cov}(J, F(x, y, t))}{\sigma(J)\sigma(F(x, y, t))}
\]

Where \(\text{cov}\) is the covariance between two arguments and \(\sigma\) is the standard deviation. In the best-worst comparison, the best 20% and worst 20% ensemble members in terms of the TC track forecast errors for Krosa at 1200 UTC 11
August 2019 were selected. Then, the difference in the ensemble mean of each group was analyzed.

4. Results and Discussion

4.1 General results

Figure 2 shows the predicted Krosa’s track in all the ensemble simulations by NICAM. The simulations initialized at 1200 UTC 6 August (Fig. 2a) represent a large uncertainty in Krosa’s track; the westernmost track makes landfall on the Korean Peninsula, and the easternmost track passes through the east of the Japanese Islands without making landfall. The uncertainty decreases with a later model initialization date with a slight eastward bias. The simulations initialized at 0000 UTC 9 August (Fig. 2d) reasonably capture the observed Krosa’s track. This uncertainty reduction in the latter model initialization date was also seen in the operational ensemble forecast system (Fig. 1). Thus, the main uncertainty cause can be analyzed in detail using the NICAM simulation data initialized at 1200 UTC 6 August.

TC tracks are generally affected by vertically averaged flows, which are also called steering flows. The steering flow can be roughly represented as a geostrophic flow at 500 hPa, although the depth of steering flow is sensitive to the TC intensity (Velden and Leslie 1991). Therefore, the ensemble-based sensitivity analysis was performed using the geopotential height at 500 hPa (Z500) and Krosa’s track forecast error at 1200 UTC 11 August (Fig. 3). There was no high sensitivity region in NEXRA, which was used at the model initialization time (Fig. 3a). At 0000 UTC 7 August (Fig. 3b), the lagged
correlation between Z500 and Krosa’s track forecast error on 11 August became low between the two typhoons of Krosa and Lekima, and the region extended toward the Japanese Islands along with the forecast time (Figs 3c and 3d). This result indicates that Z500 is relatively low (high) in the member with a large (small) Krosa track forecast error. In addition to the negative correlation region, two positive correlation regions appeared in the northwest of Lekima’s center and southeast of Krosa’s center. This indicates that Z500 is relatively high (low) in the members with large (small) track forecast errors for Krosa. These results suggest that Krosa’s track forecast is sensitive to the distance between the two typhoons.

To examine the mechanism behind this forecast sensitivity, the best 20% and worst 20% members (20 members for both) in terms of Krosa’s track forecast errors at 1200 UTC 11 August were selected and compared with each other. The best (worst) members had a forecast track error of less than 600 km (more than 1700 km) at 1200 UTC 11 August. Figure 4 represents Krosa and Lekima’s track forecasts for the best, worst, and other members. The best members (Fig. 4a) predicted a stall in Krosa from the 9th to the 11th of August and subsequent northwestward or north-northwestward track. The worst members (Fig. 4b) predicted a fast northward movement of Krosa two days after the model initialization time and movement toward the east of Japan. For Lekima’s track forecast, the best members (Fig. 4c) well captured the observed track. However, the worst members (Fig. 4d) predicted the recurvature of Lekima toward Japan. These results suggest that the main cause of the track forecast errors of both typhoons is the same.

Figure 5 shows that 5860-m (approximating the edge of WNPSH) and 5760-
m (indicating Krosa and Lekima) contours simulated by the best and worst members. Although there was a little difference between the ensemble means of the best and worst members at 0000 UTC 7 August (Fig 5a), the differences became apparent afterward. With the worst members at 0000 UTC 8 August, Krosa was predicted northwest of the Krosa predicted with the best members and Lekima shifted slightly east of that predicted with the best members (Fig 5b). Thus, the distance between the two typhoons was small with the worst members. In addition, the WNPSH over Japan retreated further east with the worst members. These differences became larger at 0000 UTC 9 August (Fig 5c). These results are consistent with those of the ensemble-based sensitivity analysis (Fig. 3).

Figure 6a shows the ensemble mean of six-hourly positions of the two typhoons predicted with the best and worst members. Whereas Krosa moved northward fast with the worst members, the northward migration with the best members was slow and was almost stalled after forecast time of 48 hours (FT = 48 h). With the best members, Lekima moved northwestward faster than with the worst members. In addition, with the worst members, the recurvature of Lekima was predicted at approximately FT = 48 h. Krosa’s track forecast error (Fig. 6b) with the worst members rapidly grew after FT = 18 h and became greater than 1000 km at FT = 66. However, Krosa’s track forecast error was not so large (~220 km) with the best members at FT = 72 h. It is worth noting that the position error at FT = 1 h is slightly larger with the worst members than that with the best members. Lekima’s track forecast error was almost the same among the best and worst members at FT = 6 h. However, the error with the worst members became greater in the latter forecast time and rapidly grew.
starting from FT = 48 h. The distance between the two typhoons (Fig. 6c) with
the worst members was 1400 km at FT = 1 h. Afterward, it decreased to 1150
km by FT = 36 h and then increased at the later forecast time. The best
members had little distance changes until FT = 24 h. However, the distance
rapidly increased at a later forecast time. Assuming that both groups represent
the same vortex structure of the typhoons, the interaction between both
typhoons could occur easily when the distance between the two typhoons was
close. Thus, the interaction between the two typhoons would be stronger with
the worst members than with the best members. The predicted Krosa’s central
minimum pressure (Fig. 6d) is deeper than the best track data from the initial
time to FT = 30 h with both members. The model represented Lekima to be
shallower in both members than analyzed with the best track. Thus, the bias in
the central pressure for both typhoons seems not to be related to the track
forecast error.

These results suggest that the degree of interaction between the two
typhoons and the retreatment of WNPSH affected the uncertainty of Krosa’s
track forecast. These two points are discussed in the following subsections.

4.2 Why did the strong interaction occur in the worst members?

Figure 7 shows the locations of the typhoons’ centers for both the best and
worst 20 members and the ensemble mean SLP distributions. The existence
frequency of the typhoons’ centers in the east-west and south-north directions
are also shown. At FT = 1 h (Fig. 7a), the low SLP area associated with Krosa
for the worst members located slightly to the west of that of the best members.
Corresponding to this westward shift, the existence frequency of Krosa’s center
in the east (west) of 142°E was less (more) with the worst members than with the best members, whereas the frequency was almost the same in the south-north direction for both members. It is worth noting that simulated Krosa’s centers are biased to the northwest of the best track even in the best members. This bias is originated from analysis fields in NEXRA (not shown). It suggests that there is room to improve analysis fields further. These points are discussed later. At FT = 12 h (Fig. 7b), the SLP distributions of Krosa with the worst members shifted to the northwest of those with the best members. The analyzed center location was well captured by the simulated existence frequency with the best members. However, it is out of range of the simulated existence frequency by the worst members, especially in the east-west direction. Nevertheless, the SLP distribution and existence frequency of the typhoon center for Lekima were almost the same with both the best and worst members (Figs. 7c–d). These results suggest that differences in the TC structure or environments of Krosa may lead to the strong interaction between Krosa and Lekima in the worst members.

To examine the differences in the typhoon structure, a composite analysis relative to the typhoon’s center was performed. Figure 8 shows the composite around Krosa’s center in NEXRA at the model initialization time (1200 UTC 6 August) for the best and worst members. The low geopotential height at 925 hPa (Z925) area near the western edge represents the eastern part of Lekima. The 680-m contour of Z925 was separated in the composite of the best member (Fig. 8a); however, it was connected to Lekima in the composite of the worst members (Fig. 8b). The differences in Z925 (Fig. 8c) indicate that there was an anticyclonic anomaly north of Krosa’s center with the best members in
comparison with the worst members. The lagged correlation analysis (Fig. 8d) showed consistent results; Z925 is lower (higher) when the track forecast error at 1200 UTC 11 August is larger (smaller). The 10-m wind speed was larger at the east of Krosa’s center with both the best and worst members than at the west (Figs. 8e and 8f). The small wind speed was induced by a confluence of the northerly wind by Krosa and the southerly wind by Lekima. The difference between the best and worst members indicates the weak wind speed anomaly in the eastern semicircle (Fig. 8g). The lagged correlation analysis (Fig. 8h) showed the consistent results; the 10-m wind speed is higher (lower) when the track forecast error at 1200 UTC 11 August is larger (smaller). These results indicate that the Krosa in the worst members had a larger circulation than that in the best members.

Although apparent differences in the vortex structure of Krosa could be found between the best and worst members, a very little difference in Lekima’s structure was found (Fig. 9). The anomaly of 10 degrees east of Lekima’s center can be related to the differences in Krosa’s position and size. The Z925 was higher in the best members (Fig. 9c). This result is consistent with the lagged correlation analysis (Fig. 9d). The confluence region of Krosa’s northerly and Lekima’s southerly was shifted to the west more with the worst members than with the best members. The lagged correlation analysis indicates this feature by the dipole structure east of the TC center (Fig. 9h), whereas the difference between the best and worst members showed negative anomaly only there (Fig. 9g).

How the difference in the initial conditions affects the forecast? Figure 10 shows that SLP at 1800 UTC 6 August (FT = 6 h) in the east and west of
Krosa’s center is lower (Fig. 10a) and 10-m wind speed of the outer region, especially from east to south, is larger (Fig. 10b) in the members with larger Krosa’s track forecast error at 1200 UTC 11 August. These results indicate that Krosa’s size is larger in the members with larger track error. The negative correlation for SLP (Fig. 10c) and the positive correlation for 10 m wind speed (Fig. 10d) became stronger and surrounded the storm center at 1200 UTC 7 August. These results suggest that Krosa’s structure at the initial condition affected the vortex structure in the model forecast. The initial vortex structure, which was larger in size with the worst members, led to active convection in the outer region. Thus, the larger vortex structure and stronger interaction with Lekima with the worst members were withheld.

4.3 Why did a difference in WNPSH occur?

The variation of the WNPSH should be influenced by whether the mass concentration/dissipation had occurred near the Japanese Islands. Figures 11 and 12 show the divergence and the geopotential height for the best and worst members at 200 and 925 hPa, respectively. In the best members (a–c of Figs. 11–12), the trough at 200 hPa existed to the northeast of Krosa. Therefore, Krosa was embedded in northerly wind environment at 200hPa induced by the trough and anticyclonic circulation above Lekima existing to the west of Krosa. At 925 hPa, the WNPSH existed to the east and north of Krosa. Thus, Krosa was embedded in southerly wind environment caused by the WNPSH and cyclonic circulation of Lekima. Thus, Krosa was embedded in, generally, northerly vertical wind shear environment (Fig. 13a). Recall that the convective activity enhanced downshear/downshear left quadrant (Corbosiero and Molinari...
2002; Ueno 2007), Krosa’s convection, thus convergence at 925 hPa and the
divergence at 200 hPa, biased to the south to southeast of the storm center.
The best members well reproduced these features (a–c of Figs 11–12). In the
worst members (d–f of Figs 11–12), convergence at 925 hPa and the
divergence at 200 hPa, biased to the south quadrant at 0000 UTC 7 August and
these shifted to the east quadrant two days later. It is attributed to changes in
direction of vertical wind shear, from northerly to westerly (Fig. 13b),
accompanied by northward movement of Krosa and presumably begin to be
affected by the jet stream (Ito and Ichikawa 2021). This eastward-biased
divergence at 200 hPa in the worst members may resulted in eastward-biased
difference in Z925 (Fig. 12i) leading to the WNPSH retreatment.

It should be noted that the area of divergence at 200 hPa is larger in the
worst members than that in the best members. This larger area of divergence
near the tropopause may cause wider area pressure decrease in the lower-
levels. In fact, Fig. 12i shows that larger area of positive Z925 anomaly (best
member – worst member). This supports that decreases in geopotential height
in wider area occurred in the worst members. Fig 14 shows time series of the
lagged correlation between divergence within 6 degrees (inner area) and 6–9.5
degrees away (outer area) from the Krosa’s center and TC track forecast error
at 1200 UTC 11 August. In the inner area (Fig. 14a), lower-level convergence
and upper-level divergence are large (small) when the Krosa’s track forecast
error is small (large) after 1200 UTC 7 August (FT = 24 h). In the outer area,
lower level convergence and upper level divergence are small (large) when the
Krosa’s track forecast error is small (large) after 1200 UTC 7 August (FT = 24
h). Sun et al. (2015) demonstrated that significant 500 hPa height decrease
leading to the breaking of WNPSH occurred after 2–3 days integration when the initial storm size is large. Our results also suggest that the larger storm size in the worst members leads to retreat of the WNPSH.

4.4 Did the same situation happen in the operational models?

The readers may wonder whether the proposed mechanism worked in the operational ensemble forecast systems. The operational centers’ forecasts were grouped into best and worst and then compared to speculate this point. However, analyzing the mechanism in detail using operational model data is beyond the aim of this paper, as the archived data resolution is much coarser than the actual model resolution except for ECMWF (Table 1). Figure 15 shows the spaghetti diagram of Z500 for the best and worst members for each operational system initialized at 1200 UTC 6 August. There is no obvious difference at 0000 UTC 8 August, whereas NICAM showed apparent differences (Fig. 5). However, by 10 August, WNPSH retreated more eastward with the worst members than with the best members. In addition, Krosa’s northward movement was faster at all centers, and Lekima’s northward movement was slower at all centers with the worst members except for JMA. Thus, with the worst members, Krosa and Lekima would rotate around each other in an anticlockwise direction. Overall, these results suggest that, as found in the NICAM simulations, at least the stronger interaction between Krosa and Lekima would occur with the worst members than with the best members and that it is associated with the eastward retreat of WNPSH.
5. Summary and Conclusion

In this study, the main cause of the uncertainty in forecasting Krosa’s track, as seen in the operational ensemble forecast data, was examined by a 101-member ensemble forecast by NICAM, which was initialized using the LETKF-based data assimilation product NEXRA. The large uncertainty in the model initialized at 1200 UTC 6 August and the decrease in uncertainty as the model initialization time went by, as predicted by the operational systems, were successfully reproduced by NICAM. The ensemble-based sensitivity analysis of Krosa’s track forecast error suggested that the track error was sensitive to the intensity of WNPSH over Japan and the distance between Krosa and Lekima.

The best and worst members (20 for each) in terms of Krosa’s forecast track error were compared. The westward extension of WNPSH was stronger with the best members, and the northward movement of Krosa was faster with the worst members. The distance between Krosa and Lekima decreased by 250 km in 36 hours after the model initialization time with the worst members, whereas the distance was almost constant in 24 hours after the model initialization time with the best members. These results suggest that a strong interaction between Krosa and Lekima occurred with the worst members, leading to a fast northward movement and a large track forecast error.

The difference in the composite fields between the best and worst members indicates that Krosa had a larger vortex size with the worst members than with the best members at the initial conditions. However, little differences were found around Lekima. The Krosa’s larger vortex size with the worst members at the model initial time led to larger vortex size with the worst members of the NICAM forecasts. This larger storm size with the worst member should result in retreat
of the WNPSH through the mechanism proposed by Sun et al. (2015) and lead
to faster northward movement of Krosa. These results suggest that the analysis
error of the meteorological field including the TC position around Krosa in
NEXRA, which was used in the NICAM forecasts, determines whether a strong
interaction between Krosa and Lekima and the retreat of WNPSH would occur
or not. The analysis of the operational models suggests that at least strong
interaction between two TCs occurred with the worst members also worked in
these models whereas the timing is later than NICAM.

Considering that BSISO sometimes causes multiple TC formations, such as in
the present case, examining whether the track forecast busts associated with
BSISO occur or not is the next step to further improve TC forecasting. Lekima
and Krosa were formed under a convective envelope associated with BSISO.
There is a possibility that it was difficult to obtain enough observational data to
constrain the model, especially at the initial phase of Krosa. Recent studies
have shown that assimilating all-sky radiance data improves TC forecasting
(Honda et al. 2018; Minamide and Zhang 2018). Assimilating satellite-based
synthetic aperture radar (SAR) is also promising because SAR can retrieve high
surface wind speed (> 20 m s\(^{-1}\)) even in cloudy/rain areas. Thus, implementing
such advanced methods to NEXRA as well as increasing special resolution of
NEXRA for better use of these data and quantifying the improvement rate of TC
forecasting under many cases (e.g., Nakano et al. 2017) would be useful in
future works.
**Data Availability Statement**

The NEXRA analysis data are available upon request to the NEXRA development team (Z-NEXRA_ADMIN@ml.jaxa.jp). All the data from ensemble experiments by NICAM will be provided from M.N. upon request.

**Supplement**

None

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**References**


Fig. 1. Track forecast for Krosa (2019) by the ECMWF (a–d), JMA (e–h), and NCEP (i–l) models, initialized at 1200 UTC 6 August (a, e, i); 1200 UTC 7 August (b, f, j); 1200 UTC 8 August (c, g, k); and 1200 UTC 9 August (d, h, l), respectively. The color indicates the valid date (day of August starting from 1200 UTC). The best track is also shown by thick color line surrounded by black.

Fig. 2. Track forecast for Krosa by NICAM initialized at 1200 UTC 6 August (a); 1200 UTC 7 August (b); 1200 UTC 8 August (c); and 1200 UTC 9 August (d), respectively. The color indicates the valid date (day of August starting from 1200 UTC). The best track is also shown by thick color line surrounded by black.

Fig. 3. Ensemble-based lagged correlation (shade) between the 500-hPa geopotential height for 1200 UTC 6 August (a); 0000 UTC 7 August (b); 1200 UTC 7 August (c); and 0000 UTC 8 August (d) and Krosa’s track forecast error at 1200 UTC 11 August. The contours show the 500-hPa geopotential height (m) simulated in the experiment initialized with the ensemble-mean of 100-member analyses.

Fig. 4. Clustered track forecast for Krosa (a–b) and Lekima (c–d), initialized at 1200 UTC 6 August by the track forecast error for Krosa at 1200 UTC 11 August. Best 20 members (a and c), worst 20 members (b and d). The color
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Fig. 5. Spaghetti diagram of the 500-hPa geopotential height valid for 0000 UTC of (a) 7 August; (b) 8 August; and (c) 9 August, respectively. The orange (aqua) contours are forecasted by the worst (best) 20 members, and the thick lines are ensemble means of the best and worst members. The contours for 5760 (broken line) and 5860 (solid line) m are shown.

Fig. 6. Six-hourly ensemble means of the best (blue) and worst members (red) (a) Track forecast, (b) track forecast error (km), (c) distance between Lekima and Krosa (km), and (d) minimum sea level pressure (hPa). The plus (+) and cross (x) symbols in (a, b, and d) are for Lekima and Krosa, respectively. The minimum sea level pressure in the best track data is also shown by black curves and symbols in d.

Fig. 7. Distributions of the TC center position (cross symbols) and SLP (contours; hPa) at FT = 1 h (a, c) and FT = 12 h (b, d) for Krosa (a−b) and Lekima (c−d) simulated for the best (blue) and worst (red) members. The black cross symbols indicate Krosa’s (a−b) and Lekima’s (c−d) position analyzed in the best track at 1200 UTC 6 August (a and c) and 0000 UTC 7 August. The existence frequencies of TC center for each latitude and longitude bin (size = 0.5°) are also shown in the left and bottom sub-panel, respectively.

Fig. 8. Ensemble means of (a-b) the geopotential height at 925 hPa (Z925; m),
(e-f) 10-m winds (vector; m s$^{-1}$) and 10-m wind speed (shade; m s$^{-1}$), analyzed in NEXRA for the ensemble mean of the best (a, e) and worst (b, f) 20 members at 1200 UTC 6 August and their differences (c, g) around Krosa. The x and y axes represent the eastward and northward distance (degree) from Krosa’s center, respectively. The ensemble-based lagged correlation between (d) Z925 and (h) 10-m wind speed and Krosa’s track forecast error at 1200 UTC 11 August are also shown. The thick black contours in a and b are for 680 m of Z925.

Fig. 9. Same as Fig. 8 but for around Lekima.

Fig. 10. TC-center relative ensemble-based lagged correlation between (a, c) SLP and (b, d) 10-m wind speed and Krosa’s track forecast error at 1200 UTC 11 August for (a, b) 1800 UTC 6 August (FT = 6 h) and (c, d) 1200 UTC 7 August (FT = 24 h). The x and y axes represent the eastward and northward distance (degree) from Krosa’s center, respectively.

Fig. 11. Ensemble mean of the horizontal winds (vector; m s$^{-1}$), divergence (shade; s$^{-1}$) and geopotential height (contour; m) at 200 hPa for the best (a–c) and worst (d–f) members and their difference (g–i) at 0000 UTC 7 August (a, d, g); 0000 UTC 8 August (b, e, h); and 0000 UTC 9 August (c, f, g), respectively. The blue and red crosses are ensemble mean of TC centers for the best and worst members, respectively. Thick broken lines in a–f show the radius of 6 and 9.5 degree from the Krosa’s center for reference.
Fig. 12. Same as Fig. 11 but for 925 hPa.

Fig. 13. The vertical wind shear of horizontal winds between 11988 m and 1500 m at 0000 UTC 7 August (red); 8 August (green); and 9 August (blue), respectively. The x and y axes are the zonal and meridional component (m s\(^{-1}\)).

Fig. 14. Ensemble-based lagged correlation between the divergence averaged (a) within 6 degrees and (b) between 6 and 9.5 degrees from the Krosa’s center and Krosa’s track forecast error at 1200 UTC 11 August, respectively.

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Table 1. Specifications of the operational ensemble prediction data archived at TIGGE.
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<th>NCEP</th>
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