Effect of Initial Vortex Intensity Correction on Tropical Cyclone Intensity Prediction:
A Study Based on GRAPES_TYM

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ABSTRACT

Predicting the intensity of tropical cyclones (TCs) is challenging in operational weather prediction systems, partly due to the difficulty in defining the initial vortex. In an attempt to solve this problem, this study investigated the effect of initial vortex intensity correction on the prediction of the intensity of TCs by the operational numerical prediction system GRAPES_TYM (Global and Regional Assimilation and Prediction System_Typhoon Model) of the National Meteorological Center of the China Meteorological Administration. The statistical results based on experiments using data for major TCs in 2018 show that initial vortex intensity correction can reduce the errors in mean intensity for up to 120-h integration, with a noticeable decrease in the negative bias of intensity and a slight increase in the mean track error. The correction leads to an increase in the correlation coefficient of $V_{\text{max}}$ (maximum wind speed at 10-m height) for the severe typhoon and super typhoon stages. Analyses of the errors in intensity at different stages of intensity (including tropical storms, severe tropical storms, typhoons, severe typhoons, and super typhoons) show that vortex intensity correction has a remarkable positive influence on the prediction of super typhoons from 0 to 120 h. Analyses of the errors in intensity for TCs with different initial intensities indicate that initial vortex correction can significantly improve the prediction of intensity from 24 to 96 h for weak TCs (including tropical storms and severe tropical storms at the initial time) and up to 24 h for strong TCs (including severe typhoons and super typhoons at the initial time). The effect of the initial vortex intensity correction is more important for developing TCs than for weakening TCs.

Key words: vortex intensity correction, intensity bias, intensity error, tropical cyclones

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1. Introduction

Vortex initialization is one of the key elements in operational systems used to predict the intensity of tropical cyclones (TCs), such as the GRAPES_TYM (Global and Regional Assimilation and Prediction System_Typhoon Model) numerical prediction system of the National Meteorological Center of the China Meteorological Administration (CMA) and Hurricane Weather Research and Forecast (HWRF) model of the NCEP. This is because most TCs occur over open oceans where there are insufficient observations to define the precise structure of the inner core and the intensity of TC. Although many studies have focused on how to initialize the vortex of TCs via data assimilation (Wu et al., 2006; Pu et al., 2009, 2016; Xiao et al., 2009; Zhang and Weng, 2015; Zou et al., 2015), the initialization methods still have limitations in resolving the three-dimensional structure of TC and few have been used in operational applications. As a result, various new initialization methods have been developed to improve the initial vortex in operational models for the forecast of TCs.

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The vortex initialization of TCs can be classified into four different types of methods. The first is the so-called bogus vortex, which is generated by the empirical function for sea-level pressure (Zou and Xiao, 2000; Xiao et al., 2009) and the gradient wind balance equation based on the analyzed minimum sea-level pressure and the location of the TC center. The vortex is used to replace the vortex in the global analysis (Ueno, 1989; Wang, 1998; Ma et al., 2007). The second method is bogus data assimilation, which produces the initial vortex by assimilating the data generated by the first method (Zou and Xiao, 2000; Chou et al., 2008; Qu et al., 2016). The second method is dynamic initialization by model integration (Peng et al., 1993; Kurihara et al., 1995; Hendricks et al., 2011; Nguyen and Chen, 2011; Zhang et al., 2012; Cha and Wang, 2013). The TC vortex generated by dynamic initialization is consistent with the dynamics and physics of the model, which avoids spin-up or spin-down during the first few hours of integration, but additional integration time will be needed for the intensification of TC to match the observations by cycle integration.

The fourth method is vortex intensity correction (VIC), which is often used in operational models such as HWRF and GRAPES_TYM. This method obtains the initial vortex either from the forecast model itself or from a global model that provides the initial and boundary conditions for the forecast model (Qu et al., 2009a, b; Gopalakrishnan et al., 2012; Liu et al., 2012; Ma, 2019) and then corrects the intensity and structure based on observations such as the minimum sea-level pressure, the maximum wind speed at 10 m and the radius of TC. The HWRF model applies a more advanced vortex initialization method by blending the TC vortex with environmental fields from the NCEP Global Forecast System (NCEP-GFS). The TC vortex is obtained either from the HWRF model itself or from the NCEP-GFS, depending on the intensity and structure of TC at the initial time (Tallapragada et al., 2015, 2016). GRAPES_TYM obtains its initial vortex from the NCEP-GFS analysis and corrects its intensity to match the observations using the scheme proposed by Wang (1995).

The objectives of this work were to introduce the vortex initialization scheme used in GRAPES_TYM and to investigate the effect of this scheme on the prediction of the intensity and track of TCs in Northwest Pacific and the South China Sea using a case study and statistical analysis of the results from major TCs in 2018. This paper focuses on how initial VIC affects the prediction of the intensity of TCs at different stages of intensity and with different initial intensities. General information from GRAPES_TYM and the vortex initialization scheme are introduced in Section 2. The experimental design is described in Section 3 and the results are presented in Sections 4 and 5. A summary and discussion are given in Section 6.

2. GRAPES_TYM and its vortex intensity correction scheme

2.1 GRAPES_TYM

GRAPES_TYM is a regional model for predicting the tracks and intensities of TCs in Northwest Pacific and the South China Sea. It was developed by the National Meteorological Center of the CMA and has been in operation since 2012. The model has been improved in terms of the model dynamics and physics as well as the vortex initialization scheme (Zhang et al., 2017; Ma et al., 2018). GRAPES_TYM uses a terrain-following height coordinate in the vertical direction and an Arakawa-C grid in the horizontal direction. The model physics include the single-moment 6-class microphysics scheme (WMS6), the scale-aware Simplified Arakawa–Schubert cumulus convection scheme, the Yonsei University planetary boundary layer scheme, the Goddard shortwave radiation scheme, and the rapid radiative transfer model longwave radiation scheme. The horizontal grid space is 0.09° with 75 levels in the vertical direction.

2.2 Vortex intensity correction scheme

GRAPES_TYM uses the forecast fields of the NCEP-GFS as its initial and boundary conditions. The resolution of the NCEP-GFS input is 0.5° × 0.5° in the horizontal direction and 26 levels in the vertical direction. No relocation is performed in GRAPES_TYM because it has no positive effect on the prediction of the mean track of TCs in the first 48 hours (Ma et al., 2018, 2019).

Correction of the initial intensity of TC was only applied if the minimum sea-level pressure around the center of TC ($p_{min}$) in the initial field was greater than the central pressure from the objective analysis of the forecaster ($p_{obs}$). The difference between $p_{min}$ and $p_{obs}$ is $\Delta p$ ($\Delta p = p_{min} - p_{obs}$) and the corrections to the initial field from NCEP-GFS ($U_{org}$, $V_{org}$, $H_{org}$, and $T_{org}$) are $\Delta U$, $\Delta V$, $\Delta H$, and $\Delta T$. The function used to calculate the tangential wind is defined by:
where $V_m$ is the velocity of the maximum wind at 10-m height, $r_m$ is the radius of the maximum wind, $r$ is the radius from the center of the vortex, $r_0$ is the outermost radius of the wind (set to $r_0 = 4^\circ$ in this study), and $b$ is a parameter determining the horizontal shape of the wind profile, which is related to the radius of 15 m s$^{-1}$. The vertical profile of the tangential wind is given as a sine function of the vertical coordinate $\sigma$. The parameter $\sigma$ is calculated by:

$$\sigma = \frac{p - p_{\text{top}}}{p - p_{\text{bas}}},$$

(2)

where $p_{\text{top}} = 100$ hPa and $p_{\text{bas}} = 1010$ hPa.

The VIC was calculated at each pressure level and the result was interpolated into the terrain-following height coordinate. The parameters $\Delta p$, $\Delta U$, $\Delta V$, $\Delta H$, and $\Delta T$ were calculated by using the following steps:

1) Calculate $V_T (\Delta U, \Delta V)$ using Eq. (1) starting from a smaller value of $V_m$ such as 0.5 m s$^{-1}$.

2) Obtain the sea-level pressure ($p_{\text{sea}}$) using a nonlinear balance equation through Poisson iteration and calculating $\Delta p_1$ as $p_{\text{bas}} - p_{\text{sea}}$.

3) If $\Delta p_1 < \Delta p$, then add a small increment $\Delta V_m$ to $V_m$: $V_m = V_m + \Delta V_m (0 < \Delta V_m < 1)$ and repeat steps 1–3 until $\Delta p_1 \geq \Delta p$.

4) Calculate $\Delta U$ and $\Delta V$ based on $V_m$.

5) Obtain the geopotential height ($\Delta H$) using a nonlinear balance equation.

6) Obtain the temperature ($\Delta T$) using a hydrostatic balance equation.

The initial $U$, $V$, $H$, and $T$ are calculated by: $U = U_{\text{org}} + \Delta U$; $V = V_{\text{org}} + \Delta V$; $H = H_{\text{org}} + \Delta H$; and $T = T_{\text{org}} + \Delta T$. TC1822 (Super Typhoon Mangkhut in 2018) was used as an example to show the modification to the initial fields from the NCEP-GFS using this process. Mangkhut was classified as a tropical depression at 1200 UTC 7 September 2018 and ended at 0900 UTC 17 September 2018. The peak intensity was 65 m s$^{-1}$ at 1800 UTC 12 September 2018 and lasted for 60 h (Fig. 1).

Figure 2 shows profiles of the mean sea-level pressure across the center of TC1822 along 162.5°E with and without VIC at the initial time 0000 UTC 8 September 2018. The minimum sea-level pressure decreased from 1004 to 997.5 hPa after VIC, close to the pressure in the best-track data (998 hPa).

The $U$-wind latitude–height cross-sections along 162.5°E before (Fig. 3a) and after (Fig. 3b) VIC show that the $U$-wind increased and there was no change in the location of $V_{\text{max}}$, which was located at about 900 hPa. The difference in $U$ between before and after intensity correction ($\Delta U$) (Fig. 3c) shows that the maximum $\Delta U$ is 14 m s$^{-1}$ at 1000 hPa with a symmetrical structure and no boundary layer. This may cause the sudden initial change in the central pressure of the tropical cyclone and maximum wind speed at 10 m (Wang, 1998).

The temperature cross-sections before and after VIC are plotted in Figs. 4a, b. There is a warm core at the mid-level at about 400 hPa before VIC (Fig. 4a) and at about 450 hPa after VIC (Fig. 4b). The maximum $\Delta T$ after VIC is about 1.1 K within 500–600 hPa (figure omitted).

### 3. Experimental design

Two experiments were carried out for major TCs in 2018. One used the NCEP-GFS forecast fields as the initial condition of the model (hereafter referred to as ORG) and the other used the NCEP-GFS forecast fields modified by VIC within the inner core region as the initial condition (hereafter VIC). The integration time was

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Fig. 1. (a) Track and (b) $V_{\text{max}}$ of Super Typhoon Mangkhut.
120 h with 12-h intervals at 0000 and 1200 UTC. Fourteen TCs (TC 1808, 1810, 1812, 1814, 1816, 1817, 1818, 1819, 1820, 1821, 1822, 1824, 1825, and 1826) were studied, all with lifetimes > 72 h. There were 150, 143, 130, 111, 96, and 64 samples at 0, 24, 48, 72, 96, and 120 h, respectively.

The track and intensity errors were calculated against the best-track data from the Shanghai Typhoon Institute of the China Meteorological Administration. The analysis included the mean track and intensity errors for all samples and for the stratified samples by different initial intensities and different stages of intensity. The TCs in the Northwest Pacific Ocean are divided into six categories: tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), severe typhoon (STY), and super typhoon (SUTY). The samples with the same intensity category at the initial time (TS-IN, STS-IN, TY-IN, STY-IN, and SUTY-IN) are shown as Table 1. Stratified analysis provided a clear picture of how the VIC affected the prediction of the track and intensity of TC by GRAPES_TYM. Because there were only three
samples for the category of tropical depression, this category was removed from the statistical analysis (Table 1).

The relative skill and positive population rate (percentage of samples of VIC with smaller errors than ORG to the total samples) were calculated by using the following equation:

\[
\text{Skill} = \frac{\text{error}_{\text{VIC}} - \text{error}_{\text{ORG}}}{\text{error}_{\text{ORG}}}. \tag{3}
\]

4. Case study of Super Typhoon Mangkhut in September 2018

Two initial times were chosen to analyze the impacts of the initial VIC on the prediction of the track and intensity of Mangkhut with different intensities at the initial time: (1) 0000 UTC 8 September 2018 when Mangkhut was a TS (TS-IN); and (2) 0000 UTC 12 September 2018 when Mangkhut was an SUTY (SUTY-IN).

Figure 5 shows the forecast track and intensity initiated at 0000 UTC 8 September 2018. The track (Fig. 5a) from VIC was similar to the ORG track and a little bit better after 48 h, whereas the deepening rate of the minimum sea-level pressure (\(p_{\text{min}}\)) (Fig. 5b) and increasing rate of maximum wind speed at 10 m (\(V_{\text{max}}\)) from VIC were larger than those from the ORG track and closer to the best-track data. The peak values of \(p_{\text{min}}\) and \(V_{\text{max}}\) were 907 hPa and 58.9 m s\(^{-1}\) for VIC and 931.6 hPa and 51.2 m s\(^{-1}\) for ORG. The effects of the intensity correction on \(p_{\text{min}}\) and \(V_{\text{max}}\) lasted throughout the 120-h integration, although there was a stronger spin-up in the first 12-h integration of \(V_{\text{max}}\) compared with the ORG track (Fig. 5c).

Figure 6 presents forecast track and intensity initiated at 0000 UTC 12 September 2018 when Mangkhut was an SUTY. The impact of the initial intensity correction on the track was negligible (Fig. 6a). Compared with the

Table 1. Categories of tropical cyclone in the Northwest Pacific Ocean

| Category | \(V_{\text{max}}\) (m s\(^{-1}\)) | Scale of wind | No. of samples |
|----------|-------------------------------|--------------|---------------|
| TS-IN    | 17.2–24.4                     | 8–9          | 45            |
| STS-IN   | 24.5–32.6                     | 10–11        | 20            |
| TY-IN    | 32.7–41.4                     | 12–13        | 17            |
| STY-IN   | 41.5–50.9                     | 14–15        | 25            |
| SUTY-IN  | \(\geq 51.0\)                 | \(\geq 16\)  | 43            |

Fig. 5. Predicted (a) track and (b, c) intensity initiated at 0000 UTC 8 September 2018. OBS: best track, ORG: no vortex intensity correction, VIC: vortex intensity correction, and Fst: forecast.
results from the initial time 0000 UTC 8 September when Mangkhut was a TS, the impact on the intensity prediction was mainly observed within 24-h integration. The results also indicate that, for an SUTY, there is a stronger spin-down and the impact reduces rapidly, even if the initial intensity is adjusted to match the observations. This is possibly because the corrected vortex is not coordinated with the model dynamics and physics and the model resolution of 0.09° is not high enough for the prediction of the intensity of such an intense tropical cyclone.

Figure 7 shows the mean errors for track, $p_{\text{min}}$, and $V_{\text{max}}$ from ORG and VIC. The mean track errors from VIC are smaller than those from ORG, except at 48 h (Fig. 7a); the skills are 12.9% for 24 h, −5.7% for 48 h, 6.9% for 72 h, 13.3% for 96 h, and 17.7% for 120 h. The mean $p_{\text{min}}$ and $V_{\text{max}}$ errors are noticeably reduced for 0, 72, and 96 h and slightly reduced for 24 and 48 h after the initial intensity correction.

The large differences in $p_{\text{min}}$ and $V_{\text{max}}$ between ORG and VIC at 0 h are mainly from the forecasts when Mangkhut was an SUTY and $V_{\text{max}}$ was much weaker than the analyzed value at that time (Figs. 8a, c). VIC effectively reduced the negative bias at the initial time, but there was a large spin-down after integration (Figs. 8c, d). The improvement for 72 and 96 h mainly came from the forecasts when Mangkhut was a TS and an STS, but there was a stronger spin-up compared with ORG (Figs. 8c, d).

5. Statistical results

5.1 Mean track and intensity errors

To evaluate the impact of the initial VIC on the prediction of the track and intensity of TC by GRAPES_TYM from a statistical perspective, we carried out an experiment using the major TCs that lasted for longer than 72 h. Figure 9 shows the mean track and intensity errors of 150 samples. There was no clear difference in the mean track errors, apart from the errors being slightly larger than that of the ORG for times < 96 h (Fig. 9a). The VIC increased the track error by up to 10.8% (11.49 km) for 48 h. This supports the conclusions of Ma (2019), which were drawn by using a version of GRAPES_TYM with a coarser resolution of 0.12° and 50 vertical levels. VIC had a positive effect on the prediction of intensity from the initial time to the whole integration period (0–120 h; 120 h not included; Fig. 9b), up to a maximum of 19.8% (1.41 m s$^{-1}$) improvement at 84 h. These results indicate that the VIC is
crucial in the prediction of the intensity of TCs, but has not a positive effect on the prediction of the mean track.

Figure 10 reveals the relationships between the predicted and observed values of $V_{\text{max}}$. There is a larger initial intensity error for almost all stages of intensity, except for tropical storms. The initial $V_{\text{max}}$ is weaker than the observed value, especially for severe typhoons and super typhoons (Fig. 10a). The initial negative biases reduced from $-4.34$ to $0.15$ m s$^{-1}$ and the correlation coefficient increased from 0.94 to 0.99 after the correction of the initial intensity (Fig. 10b). For the prediction of the following 48 and 72 h, the predicted values of $V_{\text{max}}$ with initial VIC were closer to the observational data for severe typhoons and super typhoons. The negative biases decreased from $-2.61$ to $-1.08$ m s$^{-1}$ at 48 h (Figs. 10c, d) and from $-1.72$ to $-0.45$ m s$^{-1}$ at 72 h (Figs. 10c, f). The correlation coefficient increased from 0.88 to 0.91 at 48 h (Figs. 10c, d) and from 0.86 to 0.91 at 72 h (Figs. 10c, f).

5.2 Impacts on the prediction of the stage of TCs with different intensities

Further analyses were carried out for different stages of TC intensity. For example, for the super typhoons, 0 h represents the samples with an SUTY intensity at the initial time and 12 h indicates the samples with an SUTY intensity at the 12-h forecast. The results show that VIC is most important for the prediction of super typhoons:
The VIC has a positive skill for all forecast times of 0–120 h (Fig. 11a), can reduce the large initial intensity errors and has a skill of 87.37% compared with ORG at the initial time. After 0–18 h spin-down, a steady positive skill > 25% was found for the forecasts around 72–108 h, with a peak value of 39.04% at 84 h. These results suggest that the initial intensity correction is most important for the prediction of SUTY intensity in GRAPES_TYM. The application of the initial VIC can significantly reduce the negative bias from 0 to 120 h (not shown): the initial negative bias was about −7.27 and −8.13 to −6.17 m s$^{-1}$ for the following integration (24–120 h) for ORG.

The prediction of TS from VIC had a positive skill >10.0%, except at 120 h, and the peak value (35.68%) appeared at 72 h (Fig. 11b). The skill for STY was positive until 108 h, although the magnitude was smaller than for TS and SUTY. Negative skills existed for STS and TY after 60 and 48 h.

5.3 Impacts on the prediction of intensity for TCs with different initial intensities

To evaluate the impacts of initial VIC on the prediction of the track and intensity of TCs with different initial intensities, the five categories of TC grouped by initial intensity (Table 1) were analyzed. The results show that samples with TS-IN and STS-IN (63 samples) showed a similar behavior, as did the samples with STY-IN and SUTY-IN (68 samples). The 63 samples were placed in a group named weak-TC, and the 68 samples were placed in a group named strong-TC. The remaining 17 samples with TY-IN were intentionally omitted due to their statistical insignificance. Figure 12 shows that there
was no clear difference in the mean track errors between ORG and VIC for the weak-TC group (Fig. 12a) and that the mean track errors of VIC were slightly larger for the strong-TC group (Fig. 12b). VIC can greatly reduce mean intensity errors by reducing the negative bias for 00–120 h (120 h not included) for the weak-TC group (Figs. 12c, e). For the strong-TC group, a large reduction in the mean intensity error and bias appeared before 24 h,
after which the difference narrowed rapidly (Figs. 12d, f). This may be because the corrected vortex is not coherent with the model and there is strong spin-down. Alternatively, the resolution of GRAPES_TYM (0.09°) may not be sufficiently high to resolve very intense TCs, such as STY and SUTY, even if the initial intensity was corrected to the observations.

5.4 Impacts on developing and weakening TCs

The TCs were classified as developing TCs before they reached their peak intensity and as weakening TCs after they had reached their peak intensity. For the developing TCs, the mean intensity errors for 0–120 h (120 h not included) were greatly reduced by the correction of the initial intensity; the reduction was less than 10% from 24 to 108 h. A larger decrease in the intensity error was seen at 72 and 84 h, with improvements of 25.04% and 28.16%, respectively. The forecast skill decreased rapidly after 84 h and was −1.4% at 120 h. This indicates that the model dynamics and model physics play an important part in the prediction of intensity over longer time periods (Fig. 13a). Correction of the vortex initial intensity also reduced the negative bias in intensity from 0 to 120 h (Fig. 13b).

The impacts were positive for the whole integration period for weakening TCs, but the major impacts were mainly within a prediction time of 48 h and especially within a prediction time of 24 h (Fig. 14a). The prediction skill was improved by 25.4% for 24 h and 20.4% for 48 h. The intensity bias was greatly reduced for the initial time and the following 24 h of prediction (Fig. 14b).

6. Summary and discussion

This study investigated the impacts of correcting the initial vortex intensity on the operational prediction of the track and intensity of TCs by GRAPES_TYM. The initial intensity of TCs in the NCEP-GFS initial fields was corrected to match the best-track data using the revised method proposed by Wang (1995). The correction process was applied when the minimum sea-level pressure of the NCEP-GFS initial fields was larger than that of the best-track data and the correction was limited within $r_0 = 4^\circ$, as indicated in Eq. (1).

Statistical evaluations indicated that the initial vortex correction had a negative impact on the prediction of tropical cyclone tracks by −3.71% to −10.8% (11.4 km) for 24–48 h, but effectively reduced the negative bias of the NCEP-GFS initial vortex and had a positive impact from 0 to 96 h. The mean absolute intensity errors were decreased by 17.0% (24 h), 17.1% (48 h), 18.4% (72 h),
and 14.6% (96 h). The correlation coefficients between the predicted $V_{\text{max}}$ and the best-track data were increased from 0.88 to 0.91 for 48 h and from 0.86 to 0.91 for 72 h.

An analysis of the mean $V_{\text{max}}$ errors of different stages of intensity shows that VIC is more important in the super typhoon stage and has a positive impact from 0 to 120 h via a reduction in the negative bias. A positive skill > 25% is seen in the 72–108-h forecast, with a peak value of 39.04% at 84 h.

Stratified analyses of the absolute errors in intensity based on the different initial intensity of TCs show that the initial vortex correction improved the forecast of intensity from 24 to 108 h by reducing the negative bias over the whole integration period for initially weak TCs. However, the results were different for initially strong TCs, for which the large reductions in the mean intensity error and bias appeared before 24 h, after which the difference narrowed rapidly. This may be because the cor-

![Fig. 12. Mean error and bias of intensity for the weak-TC and strong-TC groups. (a, c, e) Weak-TC group and (b, d, f) strong-TC group; (a, b) mean track error; (c, d) mean intensity error; and (e, f) intensity bias.](https://example.com/fig12)

### Fig. 13.
(a) Mean intensity error and skill (numbers) and (b) bias of intensity for deepening tropical cyclones.

![Fig. 13. (a) Mean intensity error and skill (numbers) and (b) bias of intensity for deepening tropical cyclones.](https://example.com/fig13)
rected vortex is inconsistent with the model dynamics and physics. There is strong spin-down, but the model resolution of GRAPE_TYM (0.09°) is not sufficiently high to resolve very intense TCs, such as STY and SUTY, even if the initial intensity is corrected to the observations.

The results also show that the mean intensity errors of 00–120 h (not included) were reduced significantly for developing TCs, but the reduction in the mean intensity errors were mainly within 48 h for weakening TCs.

Initial VIC is important for the prediction of intensity by GRAPE_TYM. The vortex correction scheme applied in GRAPE_TYM is a relatively simple scheme aimed at correcting the storm intensity in the NCEP-GFS initial fields to match the best-track data. There is no size correction to the NCEP-GFS initial vortex for the radii of \( V_{\text{max}} \) and 15 m s\(^{-1}\), and the boundary layer is not considered during the correction. An improvement in the intensity correction scheme is ongoing and the vortex predicted by the preceding 6–12-h integration from GRAPE_TYM will be considered to replace the NCEP-GFS initial vortex in the HWRF model.

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