A Dynamical Initialization Scheme for Binary Tropical Cyclones

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ABSTRACT

This paper reports on a dynamical initialization scheme for binary vortices (BVDI) that was developed to improve the initial conditions supplied to the models used to forecast binary tropical cyclones (TCs). For binary TCs, one TC can be regarded as the environment for the other TC’s development. Based on the dynamical initialization scheme for a single vortex (SVDI), a specified multistep iteration of SVDI was introduced in the BVDI scheme to ensure that each TC develops under conditions of realistic binary vortices interaction during the 6-h cycle run. In the BVDI scheme, each TC is initialized twice within a continuously adjusted environmental flow. Four clusters of forecast simulations with different initial conditions were run for 11 pairs of binary TCs over the northwest Pacific. The forecasts of binary TCs by the BVDI scheme reduced the position and intensity errors associated with the forecast TCs by 35.2% and 56.6%, respectively, compared with those without initialization, and also performed better than the direct extension of the SVDI scheme to binary TCs. The representation of binary vortices interaction will need to be improved for initialization and future forecasts of binary TCs.

1. Introduction

The interaction between two (or more) tropical cyclones (TCs) may change the track, intensity, and structure of each, and renders the forecasting of binary TCs more difficult than for a single TC (Brand 1970; Dong and Neumann 1983; Lander and Holland 1993; Carr and Elsberry 1998; Jang and Chun 2013). The interaction of binary TCs (i.e., the Fujiwhara effect) was first described in a series of experiments by Fujiwhara (1921, 1923, 1931). When two cyclonic vortices are in close proximity they both rotate counterclockwise and move toward each other. Most binary TCs rotate counterclockwise, and their interaction can occur when they each satisfy specific criteria (e.g., separation distance and rotation rate; Brand 1970; Dong and Neumann 1983; Lander and Holland 1993; Carr and Elsberry 1998). Dritschel and Waugh (1992) identified five regimes that describe the interaction of two isolated vortices, based on the contour dynamics. Prieto et al. (2003) then extended the work of Dritschel and Waugh (1992) to develop the partial merger regime on both the f plane and sphere of a nondivergent barotropic model. They found that the interaction of the vortices could result in episodic exchanges of vorticity. Kuo et al. (2004, 2008) found that a weaker vortex could contribute to the concentric eyewall formation of a nearby TC core. Jang and Chun (2015) investigated suitable environments for binary TCs in the western North Pacific (WNP), and obtained six representative trajectories for binary TCs in the WNP. In addition, Yang et al. (2008) and Jang and Chun (2013) observed the interaction of binary TCs and analyzed the effects of this interaction on their tracks and intensities in real TC simulations. Even though these previous studies provide objective criteria, occurrence conditions, and dynamical explanations for the interaction of binary TCs, the forecasting of binary TCs remains a considerable challenge.

If we are to improve the forecasting of binary TCs, the initial conditions of each TC must be as accurate as possible. However, TC initial conditions are not well represented in numerical models because there are few observations of TCs over the open ocean, and several initialization methods have been developed to reduce the errors associated with these initial conditions. The first
method inserts a bogus vortex into the analysis field after the original vortex is removed, and results fit the general structure of TC (e.g., Holland 1980; DeMaria 1987; Hubbert et al. 1991; Mathur 1991; Kwon and Cheong 2010; Rappin et al. 2013). However, inserting a bogus vortex into the initial conditions may not be consistent with the numerical prediction model. To solve this problem, the second method, the bogus data assimilation technique, was developed to assimilate the bogus vortex into the initial conditions (e.g., Goerss and Jeffries 1994; Davidson and Weber 2000; Zou and Xiao 2000; Pu and Braun 2001; Zhang et al. 2007; Wang et al. 2008). The dynamical initialization is the third method, first proposed by Kurihara et al. (1993), in which the initial three-dimensional TC structure, including the moisture field and balanced dynamics, is generated by axisymmetric model integration and incorporates the numerical forecast model. In general, the dynamical initialization is only applied to a single vortex (SVDI). Recently, different approaches have been used in the application of the SVDI scheme (e.g., Nguyen and Chen 2011; Cha and Wang 2013; Hendricks et al. 2013; Nguyen and Chen 2014). Cha and Wang (2013, hereafter CW13), for example, used 6-h cycle runs in a numerical model to deepen the vortex before the initial forecast time, and conducted a series of forecast experiments to test the performance of their SVDI scheme. The CW13 scheme eliminated the inconsistency between the new initial conditions of the TC and the prediction model. Moreover, the spectral nudging technique used in CW13 reduced the bias in the large-scale environmental field (Cha et al. 2011).

As shown by observational and theoretical studies of binary TCs, the state of each vortex of the binary TCs depends mainly on the development of each isolated vortex itself and the possible impact of the other vortex as the environmental field (i.e., the interaction between the binary TCs). Thus, the initialization of binary TCs must include these two aspects if possible. To the best of our knowledge, the initialization of binary TCs has yet to be explored in the literature. In this study, a dynamical initialization scheme for the binary vortices (BVDI) is proposed to improve the forecasting of binary TCs. As outlined above, the BVDI scheme must consist of at least two parts: one related to the initialization for each TC for a given environmental flow, which could be operated by the SVDI scheme; the other being the contribution from the interaction of the binary TCs (i.e., the environmental flow forcing). Therefore, the advantage of SVDI scheme has an important role in the application of BVDI scheme. To this end, based on the CW13 scheme an improved hurricane/typhoon dynamical initialization scheme (HTDI) was introduced by including the initial scale adjustment, and moist bogus that could deepen the weak vortex in the cycle runs. In addition to the initialization scheme for the binary TCs without the contribution from their interaction, a direct application of SVDI scheme is also described comparing with the BVDI scheme.

The objectives of this paper are to introduce the BVDI schemes and investigate the effects of dynamical initialization schemes on the forecasting of binary TCs. The HTDI and BVDI schemes are introduced in section 2. In section 3 the numerical model and experimental design are described. A case study of a pair of binary TCs, Super Typhoon Saomai (2006) and Tropical Storm Bopha (2006), is provided in section 4. Simulations of 11 pairs of binary TCs over the northwest Pacific between 2002 and 2012, with 4 different initial conditions, are presented in section 5, and section 6 presents a summary of our findings.

2. Vortex dynamical initialization

As discussed in the introduction, the dynamical initialization of binary TCs follows a similar procedure to the SVDI scheme; that is, the cycle runs with a 6-h window are continuously conducted to spin up each individual TC, but the vortex–vortex interaction must be included in the cycle runs. Therefore, the following questions arise: How does the SVDI scheme affect the dynamical initialization for the binary TCs? How best to reflect the contribution of the interaction between the binary TCs to the dynamical initialization for each TC in the cycle runs? In this section, a modified SVDI scheme based on CW13 is first introduced, which is incorporated in the BVDI and then dynamical initialization schemes for binary TCs are proposed.

2.a. A modified dynamical initialization for a single vortex

In general, the SVDI scheme typically contains two steps. First, the TC initial conditions derived from global analysis are separated into an environmental field, axisymmetric vortex component, and asymmetric vortex component over a certain radius centered on the position of the vortex center of the analysis field at the initial time (Kurihara et al. 1993). The separated vortex variables include the zonal and meridional wind components, perturbation geopotential, perturbation pressure, perturbation potential temperature, and water vapor mixing ratio (e.g., Nguyen and Chen 2011; Cha and Wang 2013). Second, the cycle runs are conducted to deepen the single vortex through the numerical forecast model 6-h forward integration from the initial time $t_0$ to $t_0 + 6 \text{ h}$ until the vortex intensity is close to the best track data (hereafter OBS; i.e., the minimum surface pressure is less than, or equal to, the OBS). The initial conditions of each cycle run consist of the environmental field,
asymmetric component, and the weighted average of the axisymmetric vortex components from the analysis and 6-h integration field as follows:

\[
F_{in}^{N}(x, y, \sigma, t_0) = F_t(x, y, \sigma, t_0) + F_{vas}(x, y, \sigma, t_0) + (1 - \omega)F_{vax,N-1}(x, y, \sigma, t_0 + 6),
\]

where \( \sigma \) is the height of the terrain-following hydrostatic pressure vertical coordinate system; \( F_{in}^{N} \) is the initial condition of the \( N \)th cycle run, where \( 2 \leq N \leq 20 \); \( F_t \) is the environmental field of the original initial conditions (hereafter \( F_{in}^{1} \)) obtained from the global analysis; \( F_{vas} \) and \( F_{vax} \) are the asymmetric and axisymmetric vortex components, respectively, of \( F_{in}^{1} \); \( F_{vax,N-1} \) is the axisymmetric vortex component of the model output from the \( N - 1 \) times cycle run; and \( \omega \) is the matching function based on Eq. (26) in Kwon and Cheong (2010). The radius of the separated TC is 600 km. Similar to CW13, spectral nudging was applied to the wind field above 850 hPa in each cycle run.

In the cycle runs described in CW13, even though the vortex intensity can increase, its initial scale may not be adapted to the OBS. Consequently, the radius of maximum wind (RMW) of the TC must be modified to improve the structure of the initial vortex. Therefore, we introduced a modified SVDI scheme, the HTDI, which improved the CW13 scheme for the initial vortex size and moist bogus vortex (Fig. 1). When the central pressure of the vortex \( P_{min}^{N} \) derived from the initial conditions of the \( N \)th cycle run decreases to half the sum of the central pressure of \( F_{in}^{1} \) \( (P_{min}^{1}) \) and OBS \( (P_{obs}) \), a linear interpolation is used to adjust the RMW of the axisymmetric tangential wind \( F_{vax,N-1} \) in Eq. (1) to that of the OBS and construct the initial conditions for the next cycle run \( (F_{in}^{N+1}) \). This procedure ensures that both the intensity and structure of the initial vortex are consistent with the OBS (Fig. 1).

In addition, if the difference in the central pressure of the initial conditions between the \( (N - 1) \)th and \( N \)th cycle runs is less than 1 hPa, the axisymmetric tangential wind of \( F_{in}^{1} \) is replaced by a dry bogus as the initial condition for the \( (N + 1) \)th cycle run. Following DeMaria (1987), a bogus vortex is given as

\[
u(r, \sigma) = v_m(r, \sigma) \left( \frac{r}{r_m} \right)^b \left\{ 1 - \left( \frac{r}{r_m} \right)^b \right\},
\]

where \( v_m(r, \sigma) \) is the maximum tangential wind, and twice as large as that of the vortex in the original analysis.

**Fig. 1.** Procedure for the new hurricane/typhoon dynamical initialization scheme for a single vortex (HTDI).
field at each level, \( r_m \) is the RMW and equal to \( F_1^{in} \) vortex at each level, and \( b = 1.6r_m \times 10^{-5} \) and is the deformation coefficient.

If the difference in the central pressure of the initial conditions between the \((N + M - 1)\)th and \((N + M)\)th cycle runs is still less than 1 hPa after the dry bogus is inserted into the initial conditions of the \(N\)th cycle run \((M \geq 1)\), then a moist bogus vortex, which couples the bogus vortex mentioned in Eq. (2) and a water vapor profile, is added into \( F_1^{in} \) for the \((N + M + 1)\)th cycle run. Following Rappin et al. (2013), the radial profile of water vapor is given as follows:

\[
q(r, \sigma) = q(r, \sigma) + q'[v(r, \sigma)/v_{\text{max}}],
\]

where \( q \) on the right-hand side is the axisymmetric component of the water vapor mixing ratio from the vortex of \( F_1^{in} \), \( q' = 0.002 \) is the moisture enhancement, and \( v_{\text{max}} \) is the maximum tangential wind at each level. Note that in Eq. (3), the moisture perturbation is large at the RMW. This setup generates more heating near the RMW and deepens the vortex efficiently during the \((N + M + 1)\)th cycle run (Shapiro and Willoughby 1982; Pendergrass and Willoughby 2009; Hendricks et al. 2014).

Compared with the CW13 scheme, the HTDI scheme effectively improves the cycle run by inserting the dry and/or moist bogus vortex, as well as adjusting the size of the initial vortex of the TC, and produces a suitable initial TC. Moreover, these features of the HTDI scheme could also help to build an efficient BVDI scheme.

### b. A dynamical initialization for the binary vortices

Fig. 2. The dynamical initialization scheme for binary TCs. (a) Direct extension of SVDI scheme to spin up binary TCs and (b) the BVDI scheme.
The first is a direct extension of the SVDI scheme into the binary TC situation (Fig. 2a), in which without the environmental field update in the cycle runs. The second uses a multistep iteration to update the environmental field to take account of the interaction between the binary TCs (Fig. 2b).

Figure 2a shows a direct extension of the SVDI scheme to deal with the binary TCs’ dynamical initialization. As shown in Fig. 2a, the two vortices of the binary TCs could be initialized alone using the SVDI scheme. The weak TC1 and TC2 in the analysis field (Fig. 2a1; IC0) is deepened alone by a SVDI scheme to the OBS, and obtain new initial conditions for TC1 (Fig. 2a2; IC1TC1) and TC2 (Fig. 2a3; IC1TC2), respectively. Then the axisymmetric components of TC1 and TC2 in the new initial conditions (Figs. 2a2, 2a3) replace those in Fig. 2a1, obtaining new initial conditions for the binary TCs (Fig. 2a4; IC1TC1,TC2). Even though the above steps are simple to initialize each TC individually, the improvement in the intensity and structure of each TC in the cycle runs does not occur at the same time; consequently, the interaction of the two TCs is not completely incorporated into this scheme. Therefore, directly using a SVDI scheme to spin up binary TCs does not consider the impact of the interaction between the binary TCs on their initial vortex structure, which is equivalent in essence to the single vortex dynamical initialization.

We propose here a new dynamical initialization for binary vortices (BVDI), which includes the interaction between the binary TCs to improve the initial conditions for their simulation (Fig. 2b). In comparison with the direct extension of the SVDI method, in the BVDI scheme, both TCs can be seen as the environmental field for each other when conducting the initialization of each TC, and then their interaction can be reflected during the cycle runs. The BVDI scheme contains the following two steps.

- **Step 1:** Similar to the SVDI scheme, the initial condition for each one of binary TCs can be separated into a vortex component and an environmental component. For a pair of binary TCs, TC1 and TC2 coexisted in the original initial condition, and TC2 (TC1) exists in the environmental component of TC1 (TC2) (Fig. 2b1; IC0). The interaction could occur between the vortex component and environmental component. First TC1 is initialized by the SVDI scheme, and then the improved initial conditions for TC1 are obtained (IC1TC1; Fig. 2b2). Then, TC2 is initialized same as TC1, but in the environmental flow IC1TC1, not in the original initial condition (IC0). Note that the improved TC1 in IC1TC1 could modify the environmental flow for the evolution of TC2 in the cycle runs. Therefore, during the cycle runs for TC2 initialization, the improved TC1 can influence the evolution of TC2, and TC2 deepens in a more realistic environment, and then a new initial condition, referred to as IC2TC1,TC2 (Fig. 2b3) is obtained. This is a key step for the BVDI scheme, in which the binary TCs interaction is partly included in the initial conditions.

- **Step 2:** To produce a more realistic TC1 in the initial condition, the axisymmetric vortex component of TC2 in original initial condition (IC0) is replaced by that in IC2TC1,TC2, and then we obtain IC2TC1 (Fig. 2b4). With IC2TC2, TC1 is initialized by the SVDI again, but in a more realistic environment and then we obtain a new initial condition IC3TC1,TC2 (Fig. 2b5). Similarly, during the second initialization of TC1, the environmental field of TC1 is changed by the improved TC2 and TC1 develops in a more realistic environment in the cycle runs. Therefore, compared with the initial condition IC2TC1,TC2, the initial condition of TC1 was improved in the IC3TC1,TC2. Again to improve the initial condition of TC2, the axisymmetric vortex component of TC1 in the original initial condition (IC0) is replaced by that in IC3TC1,TC2, and then to obtain IC3TC1 (Fig. 2b6). Finally, TC2 is initialized again by the SVDI in IC3TC1, and then to obtain the improved initial conditions of the binary TCs IC4TC1,TC2 (Fig. 2b7).

### 3. Numerical model and experimental design

In this study, the Weather Research and Forecasting (WRF) Model, version 3.4 (Skamarock et al. 2008), was used for the cycle runs in the dynamical initialization of the TCs, and also for the subsequent numerical simulations. In the simulation experiments, four two-way nesting domains (D01/D02/D03A/D03B) were contained in the model. The domains contained 331 × 301 (D01), 811 × 721 (D02), 421 × 421 (D03A), and 421 × 421 (D03B) grid points with horizontal resolutions of 18, 6, 2, and 2 km, respectively. The outer two domains (D01 and D02) covered the tracks and large-scale environment of the binary TCs. The two domains with the finest resolution (D03A and D03B) were interpolated from D02 to cover each of the primary vortex circulations of the binary TCs, and followed their vortices at the beginning of the simulations. These two moving nests might overlap visually when the two TCs were close. But for the model integration, the overlapping in the physics did not exist because each moving nest only exchanged the information with D02 and both nests were independent. Figure 3 shows the locations of the model domains for binary TCs Saomai and Bopha (2006) at 0000 UTC 8 August 2006. There are 35 vertical levels between the surface and the upper boundary at 30 hPa. The time steps for the model integration for the four
domains were 72, 24, 8, and 8 s. All simulations were integrated for 72 h. All four domains start at the same time. Physical parameterizations included the Thompson graupel microphysics scheme (Thompson et al. 2008), the rapid radiative transfer model scheme (Mlawer et al. 1997), the Goddard shortwave radiation scheme (Chou and Suarez 1994), and the Mellor–Yamada–Janjic TKE scheme (Janjic´ 1994) for planetary boundary layer physics. These schemes were used for all domains. The Tiedtke scheme (Tiedtke 1989; Zhang et al. 2011) for cumulus parameterization was applied only to the outermost domain (D01).

Initial and lateral boundary conditions for the model were obtained from the National Centers for Environmental Prediction (NECP) Final Analyses (FNL) and have a horizontal resolution of 1°. Sea surface temperatures were also obtained from the FNL data and fixed in each experiment. The best track data were provided by the Joint Typhoon Warning Center (JTWC). In the cycle run of the initialization, only D01 and D02 were onset and forward integrated for 6 h. The configurations of the cycle runs at initialization in the remaining models were the same as for the simulation experiments.

For the simulations of the binary TCs, four experiments were conducted using the different initial conditions, which were produced by the different initializations of the binary TCs (Table 1). In the CTRL run (without dynamical initialization), the initial conditions were interpolated directly from the FNL data. In the SV-CW (SV-HT) experiment, the initial conditions of binary TCs were directly spun up alone by the CW13 (HTDI) scheme as in Fig. 2a. These two experiments would help us to evaluate which SVDI scheme was a better choice to be incorporated in the BVDI scheme. For the BV-HT experiment, the initialization of the binary TCs was taken from the BVDI scheme along with the HTDI scheme to deepen each TC as in Fig. 2b, which could explain the advantage of the BVDI scheme comparing with the SV-HT run.

### 4. Case study

In this section, we use a pair of binary TCs—Super Typhoon Saomai and Tropical Storm Bopha (2006)—to test whether the BVDI scheme provides any advantage for the initialization of binary TCs and the subsequent forecasts.

Super Typhoon Saomai formed over the WNP and then moved northwestward; it developed into a typhoon at 1200 UTC 6 August 2006 and underwent rapid intensification (RI) to become a super typhoon by 1200 UTC 9 August. Saomai had a maximum surface wind speed of 71.9 m s\(^{-1}\) and a minimum SLP of 898 hPa, and made landfall at Zhejiang, China, at 1200 UTC 10 August 2006 before weakening rapidly. Tropical Storm Bopha was generated 11° east of Taiwan over the WNP at 0000 UTC 5 August 2006, and then moved westward. Bopha developed into a tropical storm at 0600 UTC 6 August. It had a maximum surface wind speed of 28.3 m s\(^{-1}\) and a minimum SLP of 984 hPa. Bopha passed over Taiwan between 1800 UTC 8 August and 0000 UTC 9 August 2006 and then began to weaken. This storm turned twice over the South China Sea and died out at 0000 UTC 11 August 2006. As binary TCs, Saomai coexisted with Bopha for 5 days between 0600 UTC 6 August and 0000 UTC 11 August 2006.

#### a. Initial conditions of Saomai and Bopha

Four sets of initial conditions for Saomai and Bopha were produced using the different initialization schemes in the CTRL (without dynamical initialization), SV-CW, SV-HT, and BV-HT experiments. The intensities of Saomai and Bopha in each cycle run with the different SVDI schemes are shown in Fig. 4. In CW13, after 10 cycle runs, the minimum SLP of Saomai was close to the OBS (967 hPa). However, that of Bopha did not decrease.
significantly and remained around 997 hPa during the 10 cycle runs, even though a dry bogus vortex was inserted at the beginning of the third cycle run, which indicates that the CW13 scheme was unable to improve all initial conditions of the TCs. By contrast, the minimum SLP of Saomai (963.3 hPa) was a little less than the OBS after eight cycle runs with the HTDI scheme. This is a result of the increase in intensity in the last cycle run, which is also in line with the OBS. Also, the minimum SLP of Bopha after seven cycle runs was close to the OBS. Therefore, in the respect of initial condition, the HTDI scheme was a better SVDI scheme introducing in the BVDI scheme for binary TCs forecasting than the CW13 scheme. In BV-HT (Figs. 6g and 6h), the initial TC structures of Saomai and Bopha were similar to the SV-HT run. The whole vortex structure is compact and the initial vortex intensity is also comparable with the OBS.

**b. Simulation of Saomai and Bopha**

The 72-h simulations of Saomai and Bopha using the four different sets of initial conditions described above were carried out to examine the impact of initialization on the simulation of binary TCs. Figure 7 shows the simulated tracks of this pair of binary TCs from 0000 UTC 8 August to 0000 UTC 11 August 2006. In CTRL, the 72-h simulated track of Saomai deviated to the north (red line in Fig. 7), and the mean position error was 152.6 km. In the other dynamical initialization runs, the simulated tracks were similar and close to the OBS. BV-HT had the smallest position errors, with a value of 50.7 km for Saomai. The track of Bopha in CTRL had large errors because it moved quickly after passing Taiwan. In the other three dynamical initialization runs, the position errors of Bopha were smaller than those for CTRL. Among all the simulations, the track of Bopha in BV-HT was the closest to the OBS, with a mean position error of 49.4 km. In summary, for this pair of binary TCs, BV-HT showed the best performance with respect to the track forecasts, with a mean position error for Saomai and Bopha of 52.9 km.

The changing intensities of Saomai and Bopha over the 72-h period are shown in Fig. 8. At the initial time in CTRL, Saomai’s maximum wind speed at a height of 10 m was about 8.1 m s\(^{-1}\) (Fig. 8a, red line), which was less than the 38.6 m s\(^{-1}\) seen in the OBS, and attains a maximum surface wind speed of 31.9 m s\(^{-1}\) after 48 h, which looked like a tropical storm and was a 30-h delay compared with the OBS. In SV-CW and SV-HT runs (Fig. 8a, green and orange lines), the intensity evolutions of Saomai were
closer to the OBS than the CTRL run. But we note that the rate of intensification in the SV-CW run did not match the RI (Kaplan and DeMaria 2003). While the rate of intensification in the SV-HT run was comparable with the OBS. In BV-HT (Fig. 8a, blue line), Saomai’s RI onset time, RI rate (21.4 m s\(^{-1}\) day\(^{-1}\)), and the maximum surface wind speed (65.6 m s\(^{-1}\)) were the closest to the OBS. However, the intensity between 0600 and 1800 UTC 8 August was 5 m s\(^{-1}\) stronger than the OBS because of the vortex-scale adjustment in the HTDI scheme, which caused excessive spinning up of the vortex.

For Bopha (Fig. 8b), the intensity evolutions of Bopha in CTRL and SV-CW were similar because the CW13 scheme cannot deepen the initial vortex of Bopha in SV-CW, so the initial intensity of Bopha in both experiments was similar. Therefore, both CTRL and SV-CW cannot reflect the real intensity evolution of Bopha. Compared with CTRL and SV-CW, in SV-HT and BV-HT (Fig. 8b, orange and blue lines), the intensity evolutions were similar to the OBS. Note that Bopha intensified again after 24 h in the simulation when it moved away from Taiwan. This may be because Bopha obtained energy from the ocean. Among all the experiments, BV-HT showed the smallest intensity errors for Saomai and Bopha, with a mean error of 5.4 m s\(^{-1}\). Most importantly, the initial conditions initialized with the BVDI scheme generated a more accurate intensity development for Saomai and Bopha, which indicates that incorporating the interaction between binary TCs and initial vortex-scale adjustment helps to reduce the intensity errors associated with the forecast of binary TCs.

The secondary eyewall formation and eyewall replacement cycle are the dynamical mechanisms that produce the variability in the structure and intensity of strong typhoons (e.g., Qiu and Tan 2013; Yang et al. 2013). The radar observations suggested that during the development of Saomai, a concentric eyewall developed between 0400 and 0900 UTC 10 August (Zhao et al. 4794 MONTHLY WEATHER REVIEW VOLUME 144...
FIG. 6. Zonal–vertical cross sections of azimuthal-mean tangential wind (m s$^{-1}$, contours) and radial wind (m s$^{-1}$, shading) from the initial conditions of (left) Saomai and (right) Bopha for the (a),(b) CTRL; (c),(d) SV-CW; (e),(f) SV-HT; and (g),(h) BV-HT runs at 0000 UTC 8 Aug 2006 from D02. Solid lines indicate counterclockwise and dashed lines indicate clockwise directions; purple shading indicates negative and inflow, and red shading indicates positive and outflow.
2008). Figure 9 shows the Doppler radar observations and simulated radar echo at a height of 3 km at 0500 UTC 10 August in the different experiments. The concentric eyewall of Saomai formed at 0500 UTC 10 August. At this time, the main eyewall had a gap in the south, and the eyewall diameter was about 45 km. The secondary eyewall was closed, and a moat with a weak echo below 30 dBZ occurs between the primary and secondary eyewalls. The primary rainbands were connected the west sector of the secondary eyewall and extend to the north-east (Fig. 9a). The complete primary eyewall was not simulated in CTRL because Saomai failed to develop into a typhoon (Fig. 9b). SV-CW only showed one closed eyewall with a radius of about 40 km, which was significantly larger than the primary eyewall in the observations. The primary rainbands were connected to the east side of the eyewall and extend to the southwest (Fig. 9c). This is mainly related to the large initial size and almost no contraction of the eyewall that limit the development of an obvious concentric eyewall in Saomai. In SV-HT and BV-HT (Figs. 9d and 9e), the size of the eye was consistent with the radar observations and the primary eyewall was surrounded by a closed high-echo band, while its tangential wind had the secondary maximum wind speed (not shown). The closed high-echo band could, therefore, be considered to be a secondary eyewall. With the help of the adjustment of the initial size in the HTDI scheme, both the SV-HT and BV-HT runs were able to capture the features of Saomai’s rainbands seen in the radar observations.

Furthermore, we also conducted four experiments for Saomai and Bopha using another three different initial times (i.e., 1200 UTC 7 August, 1800 UTC 7 August, and 0600 UTC 8 August). The simulated tracks that extend from these different initial times are shown in Fig. 10. The position and intensity errors associated with Saomai and Bopha based on these different initial times were generally similar. CTRL had large position errors compared with the OBS. Saomai moved farther northward before 1200 UTC 9 August. Bopha initialized at 1200 UTC 7 August and 1800 UTC 7 August looped when Saomai moved northwest. Bopha, when initialized at 0000 UTC 8 August and 0600 UTC 8 August, moved...
faster and more westward than the OBS and made a landfall in error. The position errors of Saomai in the SV-CW run were significantly less than those in CTRL. The simulation of Bopha in SV-CW is similar to CTRL, but the track error was not as large as in CTRL. In SV-HT and BV-HT, the tracks of Saomai and Bopha with four different initial times accord with the OBS, but BV-HT was the more accurate of the two. The mean
absolute position errors of the CTRL, SV-CW, SV-HT, and BV-HT runs were 268.6, 178.6, 124.6, and 111.0 km, respectively, which suggests that there is a remarkable improvement in the track forecasts when using the BVDI scheme.

The intensity forecasts based on the four different initial times are shown as Fig. 11. The maximum speeds of Saomai and Bopha in CTRL (Fig. 11a) were less than the OBS during the whole simulation period, suggesting that the initial intensities of these binary TCs were too weak to spin up. The SV-CW and SV-HT run (Figs. 11b and 11c) significantly reduced the intensity errors compared with CTRL, with the result that the initial vortex of Saomai was deepened by the SVDI schemes. However, the intensity evolution of Bopha in the SV-CW run did not perform as well as Saomai because the CW13 scheme could not improve the initial intensity of Bopha at 1200 UTC 7 August and 0000 UTC 8 August; while the HTDI scheme could improve the CW13 scheme. The initial intensity of BV-HT was all in good agreement with the OBS, and the intensity evolution of this pair of binary TCs was realistically captured. Compared with SV-HT, the intensity evolutions of Saomai and Bopha in BV-HT were more consistent with the OBS. The averaged absolute intensity errors of the CTRL, SV-CW, SV-HT, and BV-HT runs were 23.9, 10.8, 7.1, and 6.6 m s\(^{-1}\), indicating that the BVDI schemes showed the best performance in the forecasting of Saomai and Bopha.

In summary, comparing the simulation of the tracks, intensities, and structures, it is clear that the BVDI scheme performs the best of the dynamical initialization for Saomai and Bopha. This suggests that in the initialization of binary TCs, a full consideration of the effect of the interaction of binary TCs on their initial conditions plays an important role in the accuracy of the subsequent forecasting.

5. Simulations of binary TCs over the western North Pacific

In this section we have selected another 10 pairs of binary TCs that developed over the WNP between 2002 and 2012 to test the performance of the three dynamical initialization schemes for binary TCs (see Table 2). During the forecast period, the distance between the binary TCs was all less than 1400 km, which matches the objective criteria for binary TCs (Brand 1970; Carr and Elsberry 1998). The absolute position and intensity errors calculated for domain D02 are shown in Tables 3 and 4. Evidently, CTRL had the largest average position error of all of the forecast runs. Similar to SV-CW, SV-HT had larger
average position errors, but smaller than those in CTRL. Therefore, HTDI as one SVDI scheme cannot substantially decrease the errors associated with the track forecasts of binary TCs. Furthermore, the average position error of BV-HT was about 90.2 km and is the smallest of these four runs. In comparison with SV-HT, BV-HT not only generated a suitable initial vortex but also reflected the interaction between the binary TCs during the cycle runs. It also reduced the mean position errors by 35.2%, 21.4%, and 19.2% compared with CTRL, SV-CW, and SV-HT, respectively.

Comparison with the CTRL, the absolute intensity error in the SV-CW was reduced to about 8.3 m s⁻¹, which is 42.0% smaller than that of CTRL (Table 4). However, Typhoon Fungwong (2002), Tropical Storm Bopha (2006), and Tropical Storm Hagibis (2007) were not deepened in SV-CW by the CW13 scheme with the result that the above three TCs weakened during the cycle runs. These storms could be deepened successfully in the SV-HT by using of HTDI scheme, because the initial moist bogus deepens the weak vortex during the cycle runs. As with the position errors, BV-HT had smaller intensity errors than that in SV-HT. The average absolute intensity error in BV-HT was the smallest in the four experiments, and was 13.8%, 25.3%, and 56.6% less than that in SV-HT, SV-CW, and CTRL, respectively. Therefore, the SVDI scheme and the interaction between the binary TCs have an important role in the dynamical initialization of the binary vortex.

FIG. 11. Temporal evolution of the maximum wind speed (m s⁻¹) at a height of 10 m for Saomai and Bopha. Dashed lines with different markers are simulated intensities from D02 started at 1200 UTC 7 Aug, 1800 UTC 7 Aug, 0000 UTC 8 Aug, and 0600 UTC 8 Aug 2006. The gray solid line in each panel corresponds to the best track data. (a) CTRL, (b) SV-CW, (c) SV-HT, and (d) BV-HT.
Figure 12 shows the temporal evolution of the mean position errors and intensity errors of 14 pairs of binary TCs simulations including 4 initial times of Saomai and Bopha and another 10 pairs of binary TCs. In Fig. 12a, the position errors of the four experiments increase with the forecast time. The mean position error of CTRL was about 43.0 km at the initial time, which means that the FNL data fail to center the TCs. Similar to SV-HT, the mean initial position errors in BV-HT were 3.8 km because the developed vortices were inserted at the location that matches the OBS. During all of the forecast times, BV-HT showed the smallest position errors, which indicates that improving TC evolution itself in the cycle run using the HTDI scheme, as well as considering the influence of the interaction of the binary TCs during cycle runs, helps to reduce the track errors of the binary TCs. Based on the Student’s *t* test and 95% confidence level of correctly rejecting the null hypothesis, the SV-CW run had significantly smaller position errors than the CTRL run at the initial time to 6 h, and the final time. The position errors of the SV-HT run were significantly smaller than the SV-CW run only at initial time. But the BV-HT run had significantly smaller position errors than the SV-HT run at the initial time, 48 h, and 60 h to the final time. In Fig. 12b, the mean initial intensity error in CTRL was large because the relatively coarse FNL data cannot accurately represent the true TC intensity, although the errors decreased as the forecast time increased. Compared with the SVDI scheme, the initial error in BV-HT was reduced to 5.9 m s\(^{-1}\). The average intensity errors in the dynamical initialization runs changed little with the forecast time. BV-HT had the smallest intensity errors of all four runs. Compared with the CTRL run, intensity errors of the SV-CW run were significantly smaller at all forecast time except between the initial time and 18 h. The smaller intensity errors of the SV-HT run were significant at initial time, and 18–72 h compared to the SV-CW run. And the BV-HT had significantly smaller intensity errors than the SV-HT run at all forecast time except at 24 and 42 h. In short, the BVDI scheme performed better than directly using the SVDI

### Table 2. The 11 pairs of binary TCs from the WNP for the period 2002–12.

<table>
<thead>
<tr>
<th>Year</th>
<th>Binary TCs</th>
<th>Forecast period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial time</td>
</tr>
<tr>
<td>2002</td>
<td>Fengshen and Fungwong</td>
<td>0600 UTC 24 Jul</td>
</tr>
<tr>
<td>2004</td>
<td>Conson and Chanthu</td>
<td>1800 UTC 8 Jun</td>
</tr>
<tr>
<td>2005</td>
<td>Mawar and Guchol</td>
<td>1200 UTC 20 Aug</td>
</tr>
<tr>
<td>2006</td>
<td>Saomai and Bopha</td>
<td>0000 UTC 8 Aug</td>
</tr>
<tr>
<td>2007</td>
<td>Nari and Wipha</td>
<td>0600 UTC 14 Sep</td>
</tr>
<tr>
<td>2007</td>
<td>Hagibis and Mitag</td>
<td>1200 UTC 24 Nov</td>
</tr>
<tr>
<td>2008</td>
<td>Jangmi and Mekkhala</td>
<td>1800 UTC 27 Sep</td>
</tr>
<tr>
<td>2009</td>
<td>Parma and Melor</td>
<td>1800 UTC 5 Oct</td>
</tr>
<tr>
<td>2010</td>
<td>Lionrock and Kompasu</td>
<td>1800 UTC 30 Aug</td>
</tr>
<tr>
<td>2011</td>
<td>Roke and Sonca</td>
<td>1800 UTC 17 Sep</td>
</tr>
<tr>
<td>2012</td>
<td>Saola and Damrey</td>
<td>0000 UTC 31 Jul</td>
</tr>
</tbody>
</table>

### Table 3. Absolute position errors (km) of binary TCs in CTRL, SV-CW, SV-HT, and BV-HT.

<table>
<thead>
<tr>
<th>Year</th>
<th>Binary TCs</th>
<th>Absolute position error (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BV-HT</td>
</tr>
<tr>
<td>2002</td>
<td>Fengshen and Fungwong</td>
<td>125.3</td>
</tr>
<tr>
<td>2004</td>
<td>Conson and Chanthu</td>
<td>112.4</td>
</tr>
<tr>
<td>2005</td>
<td>Mawar and Guchol</td>
<td>50.9</td>
</tr>
<tr>
<td>2006</td>
<td>Saomai and Bopha</td>
<td>52.9</td>
</tr>
<tr>
<td>2007</td>
<td>Nari and Wipha</td>
<td>154.4</td>
</tr>
<tr>
<td>2007</td>
<td>Hagibis and Mitag</td>
<td>90.9</td>
</tr>
<tr>
<td>2008</td>
<td>Jangmi and Mekkhala</td>
<td>67.9</td>
</tr>
<tr>
<td>2009</td>
<td>Parma and Melor</td>
<td>58.1</td>
</tr>
<tr>
<td>2010</td>
<td>Lionrock and Kompasu</td>
<td>107.9</td>
</tr>
<tr>
<td>2011</td>
<td>Roke and Sonca</td>
<td>124.0</td>
</tr>
<tr>
<td>2012</td>
<td>Saola and Damrey</td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>Avg</td>
<td>90.2</td>
</tr>
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</table>
scheme for binary TCs, and generated significant reductions in the track and intensity errors on the forecasting of binary TCs.

6. Summary

This study developed a dynamical initialization scheme for binary TCs, the BVDI scheme. First, a modified dynamical initialization for a single TC, referred to as the HTDI scheme, was developed based on the scheme proposed by Cha and Wang (2013). In contrast to the CW13 scheme, the HTDI scheme introduces a moist bogus constraint and an initial vortex-scale constraint for the effective initial development of TCs. The moist bogus contributes to the subsequent development of TCs through the cycle runs for weak TCs in the initial analysis field. The initial vortex-scale adjustment generates a more realistic vortex structure and intensity for the initial conditions of the forecast.

In light of the interaction between binary TCs, which can affect the initial conditions of each TC, we developed an initialization scheme suitable for binary TCs. In the BVDI scheme, one TC (i.e., TC1) is first deepened using the SVDI scheme. The developed TC1 is then inserted into the analysis as the environment for the other TC (i.e., TC2), and the SVDI is then run for TC2. The SVDI scheme is then run again for TC1 with the developed TC2 now incorporated into the analysis. Finally, TC2 is deepened a second time using the SVDI.

<table>
<thead>
<tr>
<th>Year</th>
<th>Binary TCs</th>
<th>Absolute intensity error (m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BV-HT</td>
</tr>
<tr>
<td>2002</td>
<td>Fengshen and Fungwong</td>
<td>4.1</td>
</tr>
<tr>
<td>2004</td>
<td>Conson and Chanthu</td>
<td>5.4</td>
</tr>
<tr>
<td>2005</td>
<td>Mawar and Guichol</td>
<td>8.8</td>
</tr>
<tr>
<td>2006</td>
<td>Saomai and Bopha</td>
<td>5.4</td>
</tr>
<tr>
<td>2007</td>
<td>Nari and Wipha</td>
<td>5.8</td>
</tr>
<tr>
<td>2007</td>
<td>Hagibis and Mitag</td>
<td>6.5</td>
</tr>
<tr>
<td>2008</td>
<td>Jangmi and Meckhala</td>
<td>7.2</td>
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<tr>
<td>2009</td>
<td>Parma and Melor</td>
<td>8.1</td>
</tr>
<tr>
<td>2010</td>
<td>Lionrock and Kompassu</td>
<td>5.7</td>
</tr>
<tr>
<td>2011</td>
<td>Roke and Sonca</td>
<td>5.6</td>
</tr>
<tr>
<td>2012</td>
<td>Saola and Damrey</td>
<td>8.7</td>
</tr>
<tr>
<td>Avg</td>
<td></td>
<td>6.2</td>
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</tbody>
</table>

**Table 4. Absolute intensity errors (m s\(^{-1}\)) of binary TCs in CTRL, SV-CW, SV-HT, and BV-HT.**

**Fig. 12.** The temporal evolution of (a) absolute position and (b) intensity errors for 14 pairs of binary TCs simulations from the four experiments: CTRL (red line), SV-CW (green line), SV-HT (orange line), and BV-HT (blue line). The value of every 6 h is the average of the error for each pairs of binary TCs, which is half the sum of errors in the binary TCs. Solid points indicate forecast times when the BV-HT run is significantly better than the SV-HT runs at the 95% confidence level, hollow points indicate forecast times when the SV-HT run is better than the SV-CW run, and crisscrosses indicate forecast times when the SV-CW run is better than the CTRL run.
scheme with the newly developed TC1 in the analysis to obtain the binary TCs initial conditions.

An initialization scheme for binary TCs (i.e., BVDI) was used to generate a set of initial conditions combined with the HTDI schemes. A case study of binary storms Saomai and Bopha (2006) showed that the BVDI scheme that incorporated the HTDI scheme simulated more accurate storm tracks, intensities, and structures than that did in CTRL, SV-CW, and SV-HT, especially for the rapid intensification onset time, intensification rate, and maximum intensity of Saomai. Meanwhile, both SV-HT and BV-HT were able to reproduce the rainbands of Saomai, but overestimated the intensity of Bopha.

Another 10 pairs of binary TCs over the WNP that developed between 2002 and 2012 were selected to test the four sets of initial conditions (CTRL, SV-CW, SV-HT, and BV-HT). Compared with CTRL, SV-CW showed significant improvements in the track and intensity forecasts of the binary TCs, and led to a decrease in the absolute position and intensity errors by 17.9% and 42.0%, respectively. As with the case study of Saomai and Bopha, the results obtained from BV-HT were superior. This approach reproduced the tracks and intensities of binary TCs more accurately than did the CTRL run, and reduced the absolute errors associated with the tracks and intensities of the binary TCs by 35.2% and 56.6%, respectively, compared with CTRL.

In conclusion, the proposed binary TCs dynamical initialization scheme, which incorporates the HTDI scheme, was able to both reconstruct the observed track, intensity, and structure of binary TCs, as well as providing useful support for simulations of vortex interaction, rapid intensification, and the cause of the concentric eyewall of TCs. However, the BVDI scheme requires almost double the computing resources of directly using the SVDI scheme for the initialization of binary TCs.

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