Part I: Assimilation of T-PARC Data Based on the Ensemble Kalman
Filter (EnKF)

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Abstract

Typhoon Sinlaku (2008) is a case in point under T-PARC (THORPEX – Pacific Asian Regional Campaign) with the most abundant flight observations taken and with great potentials to address major scientific issues in T-PARC ranging from structure change, targeted observations to extra-tropical transition. A new method for vortex initialization based on EnKF data assimilation and the WRF model is adopted in this study. By continuously assimilating (with an update cycle every 30 minutes) tracks, the mean surface structure of Sinlaku and all available measurement data, this study constructs a unique high-spatial/temporal-resolution and model/observation-consistent dataset for Sinlaku during a 4-day period. Simulations of Sinlaku starting at different initial times are further investigated to assess the impact of the data. It is striking that some of the simulations are able to capture Sinlaku’s secondary eyewall formation, while others starting the simulation earlier with less data assimilated are not. This dataset provides a unique opportunity to study the dynamical processes of concentric eyewall formation in Sinlaku. In part I of this work, results from the data assimilation and simulations are presented, including concentric eyewall evolution and the precursors to its formation, while detailed dynamical analyses are conducted in follow-up papers.
201. **Introduction**

Concentric eyewall (CE) and the eyewall replacement cycle (ERC) in tropical cyclones (TCs) have been widely documented by aircraft observations and high-resolution satellite imagery. Many previous observational studies (e.g., Willoughby et al. 1982; Black and Willoughby 1992; Samsury and Zipser 1995; Willoughby and Black 1996; Hawkins and Helveston 2008; Houze et al. 2006, 2007; Kossin and Sitkowski 2009; Kuo et al. 2009) have depicted the evolution of CE structures. Features easily identified in such a structure include a nearly cloud-free region (moat), and a quasi-circular convection maximum often associated with the horizontal wind maximum outside of the primary eyewall. Statistical analyses based on a ten-year dataset (1997-2006) showed that on average 70% of the Atlantic, 50% of the eastern Pacific, 40% of the southern hemisphere and 80% of the western Pacific intense storms (>120 kts) underwent at least one ERC (Hawkins and Helveston 2008), in which short-term intensity change and expansion of the gale-wind radius can be significant. Coherent statistical results were also obtained in other studies, such as Kossin and Sitkowski 2009 and Kuo et al. 2009. These observational studies have identified CE formation as an important issue in TC forecasting. In addition, numerical simulations have been extensively applied to investigate CE formation in many previous studies (e.g., Willoughby et al. 1984;
Nong and Emanuel 2003; Houze et al. 2006, 2007; Kuo et al. 2004; Terwey and Montgomery 2008; Wang 2009; Qiu et al. 2010. From dynamical analyses and sensitivity experiments among those observational and numerical studies, a number of factors or mechanisms have been suggested as contributors to CE formation. However, forecasting and simulating the formation of CE remain a challenging issue. To better understand and forecast CE formation, it is critical to clarify key mechanisms and factors for secondary eyewall formation (SEF).

Several studies have indicated that the topography influences eyewall structure and perhaps the formation of secondary eyewall (e.g., Hawkins 1983; Wu et al. 2003, 2009). A series of papers (Willoughby 1979; Willoughby et al., 1982, 1984) have shown that several processes are likely to play important roles in CE formation, including asymmetric friction due to the storm’s motion, updrafts triggered by nearby downdrafts associated with the moat, and ice microphysics. Recently, Terwey and Montgomery (2008) pointed out that the topographic effect, the asymmetric friction due to TC motion and model ice-microphysics are not essential for CE formation based on their numerical simulations. However, these factors can have impact on CE formation and the evolution of a CE cycle. For instance, in contrast to the control experiment in Terwey and Montgomery (2008), the secondary eyewall formed a couple of hours earlier along with a more intensive outer eyewall
in their no-ice experiment. More recently, Zhou and Wang (2011) studied the impacts of ice-phase microphysics on the evolution of ERC, including its formation time, duration, radii of eyewalls and the associated intensity change. They also found that the adopted microphysics scheme can have considerable influence on the intensity change and evolution of the CEs. Other observations and numerical simulations (e.g., Nong and Emanuel 2003; Ortt and Chen 2006, 2008; Hill and Lackmann 2009; Wang 2009) suggested that external forcing relevant to high environment humidity can influence storm size, rainband structure and hence may also provide an ambient condition favorable for CE formation. Nong and Emanuel (2003) indicated that sustained eddy angular momentum fluxes arising from interactions between a mature TC and its environment could develop secondary eyewall features, which may invigorate the WISHE (Wind-Induced Air-Sea Heat Exchange; Yano and Emanuel 1991) process that is likely to contribute to the establishment of a secondary eyewall. Wang (2009) and Hill and Lackmann (2009) showed that high ambient humidity can enhance latent heat release in the vortex outer-core region, which may further provide a favorable environment for expansion of storm size, rainband(s) formation/intensification and even CE formation.

Meanwhile, internal forcing has also been investigated and has been suggested to play a role during CE formation from various aspects in the literature. It has
been proposed that the accumulation of energy near the stagnation or critical radii of vortex Rossby waves (VRWs; e.g., Montgomery and Kallenbach 1997; Brunet and Montgomery 2002; Montgomery and Brunet 2002) can have impacts on the outer rainband structure and perhaps on CE formation (e.g., Chen and Yau 2001; Chen et al. 2003; Wang 2002a, b; Corbosiero et al. 2006; Qiu et al. 2010; Abarca and Corbosiero 2011; Martinez et al. 2011). Houze et al. (2007) found that simulation of ERC failed when the model resolution decreased from 1.67 km to 5 km. Meanwhile, they noticed that during the ERC in Rita, the small-scale features captured by the radar in the inner-core region, may be related to the VRWs dynamics. Accordingly, they suggested the importance of high model resolution to better simulate small-scale internals of a TC vortex, and the importance to target the small-scale structures in a TC by aircraft surveillance.

The role of axisymmetrization process has also been shown important. For instance, extending from studies on fundamental vortex dynamics (Melander et al. 1987; McWilliams 1990; Dritschel and Waugh 1992; Fuentes 2004) and based on the barotropic nondiaguergent model, Kuo et al. (2004) suggested that the primary vortex can axisymmetrize weak PV vorticity patches into the secondary vortex ring, provided that the primary vortex is strong enough (compared to the outer disturbances). However, recent studies (e.g., Terwey and Montgomery 2008; Moon
et al. 2010) noted that PV patches outside the eyewall can be of comparable magnitude to that in the eyewall region both in the real TC environment and in their simulations with more realistic physical processes included (such as the moist convection). In particular, Moon et al. (2010) indicated that the interaction between the TC core vortex and the convection-induced small vorticity dipoles of considerable strength in two-dimensional flows does not lead to the formation of a coherent concentric vorticity ring. Thus the axisymmetrization process under a simplified two-dimensional incompressible flow appears incomplete for describing SEF in the real atmosphere. The role of the three-dimensional moist process in the maintenance of a vorticity ring has also been indicated in the study of eyewall evolution by Wu et al. (2009).

Terwey and Montgomery (2008) presented a new moist-based BSA (β-skirt axisymmetrization) formation hypothesis, as an intrinsic CE formation mechanism. This hypothesis requires a region with long filamentation time (Rozoff et al. 2006) and a sufficient low-level radial PV gradient (β) associated with the primary swirling flow, moist convective potential, and the follow-up WISHE process. Meanwhile, Wang (2008) indicated that inner rainbands are present in regions with filamentation time shorter than 30 minutes, suggesting that the filamentation process has an entirely different role from that in Rozoff et al. (2006). Instead of suppressing the
convection, the filamentation effect is argued to cause the axisymmetrization of vorticity in the rapid filamentation zone.

As introduced in this section, some studies found that intrinsic mechanisms are important, while others suggested that external forcing and environmental conditions are crucial. Moreover, with pervious works mostly based on limited observations or numerical simulations with idealized settings, it is still not well understood what key mechanisms or conditions are for CE formation in the real atmosphere. CE cycles in a real TC are neither fully documented by observation nor well simulated by numerical models. One of the major difficulties is insufficient spatial and temporal coverage of TC observations, especially the coverage of data over the inner-core region, which is important for validation and for construction of the initial vortex in a model. Another major roadblock is the insufficient understanding of the physical processes in the evolution of TCs which are critical in constructing adequate model physics for numerical simulations. These concerns reveal that the integration of good data, a capable numerical model, an efficient data assimilated methodology and an effective vortex initialization scheme is indispensable for investigation of the dynamics of CE formation and for improvement of the model forecast in a real case.

In 2008, an international field experiment, T-PARC (Elsberry and Harr 2008)
was conducted, providing an opportunity to investigate extensive TC research issues, from genesis, structure change, targeted observation, to extra-tropical transition. Typhoon Sinlaku (2008), a case in point under T-PARC, has the most abundant flight observations conducted and possesses great potentials in addressing major scientific issues in T-PARC, such as targeted observation (Chou et al. 2011; Harnisch and Weissmann 2010; Weissmann et al. 2010; Wu et al. 2011). Meanwhile, a new TC vortex initialization method based on the ensemble Kalman filter (EnKF) (Wu et al. 2010), which effectively provides well balanced initial TC vortex structure dynamically consistent with the model, is employed in this study. By continuously assimilating (with an update cycle every 30 minutes) all available data, including conventional soundings, 159 dropwindsondes and SFMR (Stepped Frequency Microwave Radiometer) data from 9 T-PARC flight missions during Sinlaku from September 9 to 13, this study constructs a unique high-spatial/temporal-resolution and model/observation-consistent dataset for Sinlaku. This dataset provides a unique opportunity to investigate key mechanisms and conditions of CE formation in Sinlaku.

Following our study, a series of papers will be presented to show results of our investigation in the intensity and structure evolution in Sinlaku during the CE cycle based on model results from data assimilations and simulations. This paper (part I)
presents general features of the assimilations and simulations. Detailed dynamical analyses and physical examinations for the CE process are discussed in follow-up papers [e.g., part II: axisymmetric dynamical processes (Huang et al. 2011)]. In the following section (section 2), methodology and data will be introduced. The results will be presented in section 3, including the track, intensity and structure evolution in Sinlaku, particularly during the CE cycle. The CE structure and evolutionary are shown with various diagrams (time-radius diagrams, vertical cross-sections, horizontal structure, etc) using different parameters, including wind fields, (potential) vorticity, and rainrate, etc. Conclusions and issues to be further investigated are provided in section 4.

2. Methodology and data

a. A new vortex initialization method based on EnKF along with additional data

Ensemble Kalman filter, first proposed by Evensen (1994), has been shown to have potential applications in data assimilations of weather systems, including TCs, in a number of studies (Snyder and Zhang 2003; Zhang et al. 2004, 2006, 2009; Chen and Snyder 2007; Zhang and Snyder 2007; Fujita et al. 2008; Meng and Zhang 2007, 2008a, b; Torn and Hakim 2009; Yussouf and Stensrud 2010). Following previous works using EnKF for TC forecasts (e.g., Chen and Snyder 2007, Torn and Hakim 2009 and Zhang et al. 2009), Wu et al. (2010) developed a new vortex
initialization method on a WRF-based EnKF data assimilation system (Meng and Zhang 2008a, b). Three special observational parameters of TCs, TC center position, storm motion vector and axisymmetric surface wind profile, are adopted and assimilated via the EnKF methodology. TC center position and storm motion vector are mainly estimated from satellite imagery and are available from major operational centers. Axisymmetric surface wind profile can be constructed with an empirical formula from Willoughby et al. (2006) based on any kinds of observation products available, such as satellite imagery, conventional radiosondes and buoys data, and in-situ measurement from aircraft observations, etc. Amid these, data obtained from aircraft surveillance provide particularly valuable information on the TC structure and intensity, especially when the TC is over an open ocean area. Analyses of the case of Typhoon Fung-wong (2008) in Wu et al. (2010) demonstrated that this new method can effectively make use of the three key TC parameters previously mentioned to establish a dynamically balanced vortex structure for follow-up TC simulations.

With the two key items in place, i.e., the TC initialization method from Wu et al. (2010) and plentiful data for Sinlaku during T-PARC, this paper provides a means to assimilate detailed T-PARC data based on the continuous EnKF update cycles to reconstruct the trajectory and evolution of Sinlaku, and thus offers an opportunity to
investigate the CE structure and physical processes of SEF. Benefited from the efficiency of the EnKF method, fast update cycle ensemble simulations can be conducted without expensive computation costs. Available data on Sinlaku (Table 1 and Fig. 1), including 623 conventional radiosondes from GTS (Global Telecommunication System), 159 dropwindsondes and SFMR data from 9 T-PARC flight missions [e.g., DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the TAIwan Region; Wu et al. 2005, 2007)/ASTRA, DLR/Falcon and NRL/P-3; see Elsberry and Harr 2008] are integrated and assimilated into the model every 30 minutes with 28 ensemble members for each experiment. As shown in Fig. 1, locations of the adopted data are marked by symbols shaded with different colors for different observations or flight missions. Information on the structure of Sinlaku is shown in Fig. 2., including wind profiles observed by C-130's α-pattern reconnaissance flights, dropwindsonde data from DOTSTAR, and the radii of 34-, 50-, 64-kt wind and maximum wind analyzed at JTWC. Spiral rainbands with significant convective activities are found outside the eyewall prior to SEF (Fig. 2d), while no coherent secondary wind maximum is found (Fig. 2c). The double eyewall structure of Sinlaku is documented by the two wind maxima in the C-130 mission at 1207 UTC and 1331 UTC 11 September (Fig. 2e) and by satellite images from 0445 UTC to 2132 UTC on 11 September (e.g., Fig. 2f). After this period,
C-130 data and satellite images show the dissipation of the inner eyewall and the appearance of an ERC (Figs. 2g, h).

These abundant data of Sinlaku during T-PARC undoubtedly help define the axisymmetric surface wind structure, one of the three TC parameters for the new vortex initialization method in Wu et al. (2010). In this study, Sinlaku’s center position and motion vector are obtained based on the best track from JMA. The axisymmetric surface wind profiles assimilated into the simulations (thick line in the left panel of Fig. 2) are mainly based on the SFMR surface wind data from four C-130 eyewall-penetrating reconnaissance missions (the α-pattern flight path shown in the right panel of Fig. 2), along with the 10-m surface winds estimated by dropwindsonde data from two DOTSTAR targeted surveillance observation missions (path shown with black lines in Figs. 2d, f).

b. Model settings and experimental design

The Advanced Research WRF (ARW) model (version 2.2.1) is employed to perform update cycle ensemble simulations. The horizontal grid spacing is 45 km (81 × 76 grid points), 15 km (88 × 100 grid points) and 5 km (82 × 82 grid points) for the 1st (D1), 2nd (D2) and 3rd (D3 or D3’) domains, respectively (Fig. 3). The 3rd domain is a moveable nest with two-way feedback, centered at the vortex center to ensure that the TC inner-core region is resolved by the finest grid. The two-way
vortex-following nest technique is implemented in both forward model simulations and the EnKF update. The model is run with 35 vertical levels in the terrain-following sigma coordinate (same as those in Wu et al. 2010). The final analysis (FNL, $1^\circ$ x $1^\circ$) taken from the National Center for Environment Prediction (NCEP) and the optimally interpolated microwave SST (OISST) are utilized for the initial and boundary conditions.

The adopted parameterization schemes are the same as those in the simulation of Fung-wong in Wu et al. (2010). WRF Single Moment (WSM) 6-class graupel microphysics scheme (Hong et al. 2004, Hong and Lim 2006) is used in the simulation. Other parameterization schemes adopted in the model are the Rapid Radiative Transfer Model (RRTM) scheme (Mlawer et al. 1997) for long wave radiation, the simple short wave scheme (Dudhia 1989) for short-wave radiation, and the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006). The cumulus convection is parameterized with the Grell-Devenyi ensemble scheme (Grell and Devenyi 2002) only in the coarser domains, namely, D1 and D2 (Fig. 3). NCEP FNL at 1200 UTC 08 September 2008 is taken as the initial ensemble mean to construct the 28 ensemble members (see the subsection 2b in Wu et al. 2010, for the methodology used while creating the initial perturbations).

After the prerun in the first 5 hours, the cycling assimilation run is carried out from
1700 UTC 08 September to 0300 UTC 13 September. To reduce computation costs, the vortex-following nest is initiated at 0300 UTC 09 September before the additional aircraft data are included. The overall assimilation period is more than 4 days, covering Sinlaku’s lifetime, from formation to development, intensification, and the CE cycle.

The ensemble simulations with all data assimilated throughout the integration are regarded as the control experiment (CTL), which contains 28 ensemble members updated and integrated independently during a typical EnKF cycle. In this paper, most figures showing the results of a single storm are derived from the ensemble mean of multiple storms (the average of the 28 ensemble member; hereafter CTL_m). The CE cycle in CTL_m is investigated in details in section 3. To assess the impact of cumulative data in different amounts, forecasting experiments are performed with assimilation paused at different times. Several ensemble forecasts, EXP1103, EXP1015 and EXP1003, are performed with initial conditions taken from CTL at 0300 UTC 11 September, 1500 UTC 10 September and 0300 UTC 10 September, respectively (Table 2). The results (mostly with the ensemble mean) are discussed in section 3.e.

3. Results

a. Track and minimum sea level pressure for all ensemble members and the
As introduced in the previous section, conventional data and three special parameters of TCs are assimilated into the model throughout the integration in CTL. Fig. 4a shows tracks of the 28 ensemble members and their ensemble mean (CTL_m) superposed on the best-track from JMA, indicating that all ensemble members closely follow the best-track of Sinlaku throughout the integration with a limited ensemble spread. Moreover, evolution of the minimum sea-level pressure is also well simulated (Fig. 4d) (except at around 0800 UTC 10 September, when the minimum sea-level pressure is over-simulated) as compared with the independent measurement from C-130 reconnaissance flights (black circles in Fig. 4d), which is not used as observation operator for data assimilation. The result indicates that the central sea-level pressure of Sinlaku in CTL continuously deepens before around 1700 UTC 10 September, the time when the axisymmetric upward motion (its ensemble mean is shown in Fig. 5b) in the outer region begins to strengthen. Afterwards, the storm intensity remains stable for 19 hours. At the time when an ERC is completed (at 1800 UTC 11 September, as discussed in the following subsection), the central sea-level pressure rises significantly from 945 to 960 hPa in 3 hours. With their capability to capture the evolution of Sinlaku’s track and intensity, these ensemble runs from CTL are further analyzed as shown below.
b. Azimuthally-mean structure of CTL_m

First, we investigate the overall axisymmetric structure of CTL_m. Major azimuthal mean variables, including tangential wind ($\overline{v}$), radial velocity ($\overline{u}$), vertical velocity ($\overline{w}$), relative vorticity ($\overline{\zeta}$), potential vorticity ($\overline{q}$) and total column rainrate, are shown both in time-radius diagrams (Fig. 5) and in vertical cross sections (Fig. 6). Information in time-radius diagrams is shown at the lowest model level (about 10-m height) for $\overline{v}$, at an altitude of 0.5 km for $\overline{w}$ (for the purpose of investigating the friction-induced upward motion within the boundary layer, which is relevant to part II of this study) and 2 km for $\overline{\zeta}$ and $\overline{q}$. The CE cycle is particularly worth-noting in these figures. All the azimuthally-mean parameters in Fig. 5 well demonstrate the secondary eyewall structure in Sinlaku, with differences in the formation time between secondary maxima using different parameters. The SEF time in this paper is defined by $\overline{v}$ at the lowest model level ($\eta = 0.99885$). By examining the $\overline{v}$ profile (such as those in the left panel of Fig. 2) at different times (figures not shown), we can precisely recognize the SEF (the persistent secondary maximum) and define its formation time in each simulation. For instance, the SEF time is 0700 UTC 11 September in CTL_m. Based on the time-radius diagram of $\overline{v}$, the outer (secondary) eyewall is initially present at the radii of about 80 to 120 km from the storm center (Fig. 5a). During the CE process,
from 0700 to 1800 UTC 11 September, both inner and outer eyewalls experience sporadic intensification and weakening. During later stages of the CE cycle (between 1200 and 1800 UTC 11 September), competition between the inner and outer eyewalls is observed. Finally, the outer eyewall replaces the disintegrated inner eyewall and becomes the new primary eyewall at 1800 UTC 11 September, and thus an ERC is completed. As to the evolution of the azimuthally-mean vertical velocity ($\bar{w}$) and total column rainrate, it can be found that convective activities outside the primary eyewall intensify significantly around 0700 UTC 11 September (Figs. 5b, e), showing the enhancement of the organized convection outside the inner eyewall. A moat region where convection is suppressed is also found between the two eyewalls. Convection associated with the inner eyewall decays after about 1400 UTC 11 September. Eventually, the inner eyewall is replaced by the new outer convection while Sinlaku becomes a storm with a larger eye. These features of the CE cycle are consistent with those on $\bar{v}$. However, the secondary maxima of $\bar{w}$ and the total column rainrate appear much earlier than that of $\bar{v}$. In the following subsection, the plan view demonstrates those weak secondary maxima of convective activities featuring spiral rainbands, rather than a CE structure. Other variables, such as $\bar{\zeta}$ (Fig. 5c) and $\bar{q}$ (Fig. 5d), indicate also the presence of SEF in Sinlaku. Both $\bar{\zeta}$ and $\bar{q}$ at 2-km height show a coherent
secondary maximum which increases significantly around the SEF time, showing
the CE structure.

With regard to the evolution of the storm’s vertical structure, the azimuthal
average of radius-height cross sections for CTL_m is also investigated (Fig. 6).
After the spinup process (figures not shown), vertical structures in terms of \( \bar{v} \), \( \pi \),
\( \bar{w} \), \( \bar{\zeta} \) and \( \bar{q} \) show a unique observation/model consistence with the CE evolution
processes. The radius of the maximum tangential wind (about 40 m s\(^{-1}\)) (RMW)
near the surface is located around 30 km from the storm center before SEF (Fig. 6a),
indicating a compact vortex structure. The double eyewall structure is clearly
shown at lower levels (approximately below 5 km) in terms of \( \bar{v} \), with the radii of
the inner and outer eyewalls at about 35 and 100 km (Fig. 6b), respectively. After
ERC, the new eyewall is located at around 100 km from the typhoon center (Fig. 6c),
showing a big-eye structure in Sinlaku. Then, the vortex intensifies and the new
eyewall contracts with time. The \( \bar{v} \) maximum near the surface in Fig. 6d, for
example, is about 45 m s\(^{-1}\) and is located at the radius of 60 km from the storm
center. This reintensification and contraction are also present in Fig. 5a. The
secondary maximum of the radial inflow is first shown at 2100 UTC 10 September
(Fig. 6e), but the magnitude is weaker than that in the eyewall. It is worth-noting
that the intensification of boundary layer inflow occurs over the region where the
secondary eyewall forms and establishes prior to SEF. After the secondary eyewall forms, inflow over the outer eyewall becomes much larger than that in the inner eyewall (Fig. 6f). The maximum inflow in the inner eyewall weakens and disappears eventually (Figs. 6g, h), demonstrating the completion of an ERC. As for \( \bar{w} \), the eyewall features a slantwise convection from the surface to about 16-km altitude, associated with a broad but weak upward motion region outside the radius of 75 km prior to SEF (e.g., Fig. 6i). After SEF, convection in the inner eyewall becomes shallower and much weaker, while an upward motion substantially develops in the outer eyewall (e.g., Fig. 6j). After ERC, the outer convection becomes a new primary eyewall located at a larger distance from the storm center. Then, convection in the new eyewall moves radially inward and strengthens with time. The structure and intensity evolution in terms of \( \bar{v} \), \( \bar{u} \) and \( \bar{w} \) are consistent with those in a typical CE cycle.

Furthermore, the vertical structure on \( \bar{\zeta} \) and \( \bar{q} \) show similar evolution during the CE cycle (Figs. 6m-p, 6q-t). Both \( \bar{\zeta} \) and \( \bar{q} \) decrease with radius. \( \bar{\zeta} \) and \( \bar{q} \) gradients are larger within the eye and eyewall region ( \( r < 50 \) km in Figs. 6m, q), while being smoother outside the eyewall region. A local maximum appears just inside the radius of the secondary maximum \( \bar{v} \) in both the \( \bar{\zeta} \) and \( \bar{q} \) fields during the CE episode, and is confined to levels below 2.5 km (Figs. 6n, r). After
the ERC (Figs. 6o, s), the gradient over the eye and inner eyewall region decreases significantly, and the low-level maximum over the outer eyewall vanishes. However, a local maximum appears in the middle level from around 2.5 to 5 km. During the eyewall contraction period, the magnitude of $\zeta$ and $\bar{q}$ in the eye continue decreasing, and their gradients over the eye region become very small, demonstrating a nearly homogeneous structure in $\zeta$ and $\bar{q}$ (Figs. 6p, t). In all, the axisymmetric structure of CTL_m demonstrates the features of a double eyewall structure and a CE cycle in terms of various variables, including $\bar{v}$, $\bar{w}$, $\zeta$, $\bar{q}$ and the total column rainrate (Figs. 5 and 6).

Regarding the SEF issue, what we are concerned about are the features prior to SEF. One of the interesting features is that the secondary maxima of $\bar{w}$ (Fig. 5b), $\bar{\zeta}$ (Fig. 5c) and $\bar{q}$ (Fig. 5d) initially appeared around 1800 UTC 10 September, which is about 13 hours earlier than the SEF time defined by a persistent secondary maximum of $\bar{v}$. About 6 hours before the secondary maxima of $\bar{\zeta}$ and $\bar{q}$ are established at the radii of the secondary eyewall, the weak secondary maxima of $\bar{w}$, $\bar{\zeta}$ and $\bar{q}$ is found to move outward radially from the inner eyewall between 1200 UTC and 1800 UTC 10 September. Meanwhile, the outer tangential wind field ($\bar{v}$; Fig. 5a) keeps broadening since about 1200 UTC 10 September, corresponding to the outward shift of these outer maxima prior to SEF. The broadening of outer
tangential wind is mostly confined to lower levels (Fig. 6a), while radial inflow in
the boundary layer considerably strengthens over the same region (Fig. 6e). These
features occurring prior to SEF are speculated to serve as key precursors to SEF.
Detailed dynamical analyses (such as the energy collection of VRWs, the upscale
process of the eddy kinetic energy on the \(\beta\)-skirt, boundary layer dynamics, and the
role of the environmental moisture, etc) are to be presented in part II and part III of
this study.

While the azimuthally-mean structure highlights general features of a CE
structure, to provide a more detailed eyewall structure, plan views are also examined
in the following subsection to explore the evolution of the CE structure.

c. Plan views of CTL\_m

The plan views of each dynamical variable investigated in the previous
subsection, such as \(v\), \(w\), \(\zeta\), \(q\) and total column rainrate, are examined at a
30-minute time interval. The evolution of Sinlaku’s structure in CTL\_m in
different fields is shown by 2-hour plots from 1800 UTC 10 September to 0000
UTC 12 September (Figs. 7-11). In the \(v\) field, the storm is intense, compact (small
eye) and quite symmetric at 1800 UTC 10 September (Fig. 7a). Tangential wind
field broadens over the northwestern and southeastern quadrants between 1800 UTC
10 September and 0000 UTC 11 September (Figs. 7a-d), consistent with the
broadening wind field previously obtained from the axisymmetric view (Figs. 5a and 6a). The secondary maximum of the swirling circulation becomes more organized and develops along with time in the northwestern quadrant (Figs. 7e, f) while the primary eyewall becomes relatively asymmetric. Afterwards, the outer circulation gradually surrounds the primary eyewall, and nearly completely encloses the inner eyewall from 0600 UTC to 1200 UTC 11 September (Figs. 7g-j), demonstrating a typical CE structure. Between 1200 UTC and 1800 UTC 11 September, some disturbances show up near the secondary eyewall, and the CE structure becomes less distinct (Figs. 7j-l). This transition period of eyewall evolution is also shown in \( w \), \( \zeta \) and \( q \) fields (see Figs. 8, 10, and 11), corresponding to the sudden weakening of secondary eyewall near 1200 UTC 11 SEP in Fig. 5. During the development of the outer swirling circulation (Figs. 7e-g) and the CE period (Figs. 7g-l), the original primary eyewall (inner eyewall) weakens and the eye enlarges slightly. After 1800 UTC 11 September, the inner eyewall dissipates (Fig. 7m), and the overall vortex intensity weakens. The outer eyewall replaces the original one and becomes the new primary eyewall with a bigger eye (Figs. 7m-p).

Similar evolution can be found in \( w \) and total column rainrate fields (Figs. 8 and 9). Convection cells form sporadically in rainbands outside of the eyewall. Not well organized to begin with (Figs. 8a-e and 9a-e), they eventually dissipate or
merge into the eyewall. However, after 0400 UTC 10 September, these rainbands become more organized outside and along the (inner) eyewall (Figs. 8f-g and 9f-g). The intense but sporadic convective activities in spiral rainbands project a weak maximum onto the azimuthal-mean structure prior to SEF (Figs. 5b, e). This implies that the secondary maximum in the azimuthal-mean of convective activities is not a robust index for defining a CE structure. Eventually, the rainbands coalesce to form an annular convection ring outside the inner eyewall (Figs. 8h-j and 9h-j). As in ν field, the distribution of w also becomes disturbed and the CE structure is less distinct between 1200 UTC and 1800 UTC 11 September (Figs. 8j-l). After this short-term adjustment, deep convection rings over the inner and outer eyewall regions are again recognizable (Fig. 8l). Convection in the inner eyewall gradually collapses (Figs. 8m-o), and the secondary eyewall becomes the new primary eyewall (Fig. 8p). In contrast, the rainrate distribution is much less disturbed between 1200 UTC and 1800 UTC 11 September (Figs. 9j-l). The less disturbed mass fields (for instance, temperature and water contents; figures not shown) can be part of the reasoning. Besides, it is also important to have the fact in mind that the total column rainrate reflects the integrated column property composed of multiple variables. The heavy precipitation region over the inner eyewall quickly dries out, and turns into a non-precipitation area (Figs. 9k, l) when
the CE structure becomes less distinct. After that, an annular precipitating region forms along with the establishment of a new primary eyewall (Figs. 9l-p).

\( \zeta \) and \( q \) fields have very similar patterns in the simulation (Figs. 10 and 11).

Before the eyewall replacement, the vorticity (and PV) field has a monopole structure with a prominent radially negative gradient with its maximum at the center. Small-scale vorticity or PV patches grow and decay sporadically outside the eyewall before 2300 UTC 10 September (figures not shown). However, at a point between 2000 UTC and 2200 UTC 10 September (Figs. 10b, c, and 11b, c), these vorticity patches become considerably organized into a belt-like structure (Figs. 10d-g and 11d-g). Being wrapped up, they form a vorticity ring outside the primary core from 0800 UTC to 1000 UTC 11 September (Figs. 10h-i and 11h-i). Similar to the wind field, the ring structure in \( \zeta \) and \( q \) fields outside the parent vortex becomes less distinct and contains high-wavenumber disturbances between 1200 and 1600 UTC 11 September (Figs. 10j-l and 11j-l). Then, the ring structure in \( \zeta \) and \( q \) dissipates, and a monopole with a smaller radial gradient is found (Figs. 10m-p and 11m-p), indicating the completion of an ERC. Particularly important is that the precursory small vorticity eddies outside the primary vorticity core before SEF are of comparable magnitude to those over the primary eyewall. These vorticity patches are about 3 times weaker than the average vorticity over the core vortex (e.g., \( r < 50 \)
km in Figs. 6m, q, 10c-f and 11c-f). For instance, as to PV, the patches range from 3 to 10 PVU (Figs. 11c-f), while those near the eyewall range from 5 to 15 PVU (Figs. 6q and 11c-f) and the averaged value in the core vortex is about 15 PVU. As suggested in Moon et al. (2010), these characteristics of the vorticity wrap-up process cannot be demonstrated by an axisymmetrization process in the framework of two-dimensional dry barotropic dynamics (e.g., Kuo et al. 2004) and require an interpretation based on a more sophisticated model with a three-dimensional dynamical core.

d. The CE cycle in each ensemble member

The time-series plots of the radius of maximum tangential wind ($\overline{v}$) (RMW) at the lowest model level in all the 28 ensemble members of CTL are displayed in Fig. 12, showing that vortices in each member undergo a CE cycle. The ensemble spread of RMW shows a $\pm 10$ km deviation from the ensemble mean. Despite the small differences in SEF time, length of the CE cycle, and radii of the eyewalls from the vortex center in different ensemble simulations, all the ensemble members in the control experiment successfully capture the CE cycle of Sinlaku.

e. Sensitivity to the amount of assimilated data

To evaluate the impact of data, ensemble forecasts of Sinlaku are carried out at different initial conditions. EXP1103, EXP1015 and EXP1003 stand for ensemble
simulations initialized at 0300 UTC 11 September, 1500 UTC 10 September and 0300 UTC 10 September, respectively (Table 2). Note that the ensemble means of these experiments (i.e. EXP1103_m, EXP1015_m, and EXP1003_m) without data assimilation are not averaged from the corresponding ensemble members at each time because TC tracks tend to spread out quickly (Figs. 4b, c), disqualifying the averaged fields as indicators for the overall TC intensity and structure. Instead, the ensemble means denote corresponding simulations initialized in CTL_m.

The time-radius diagrams of $\bar{v}$, $\bar{w}$, $\bar{\zeta}$, $\bar{q}$ and the total column rainrate demonstrate that a CE structure is present in EXP1103_m (Fig. 13) and EXP1015_m (Fig. 14), while the CE feature in EXP1015_m is not as robust as that in EXP1103_m. Tracks (Fig. 4b) and intensity (Figs. 4e and 13a) in EXP1103 are well simulated, although missing the sharp deepening of the central sea-level pressure prior to SEF (Fig. 4e). The SEF time for EXP1103_m is 0700 UTC 11 September, the same as that in CTL_m. SEF in EXP1015_m occurs 30 minutes later than CTL_m and EXP1103_m. Although the secondary eyewall establishes at around the same time in these three different experiments, the duration of CE cycles differs from each other. The eyewall replacement is completed at 1800 UTC, 2300 UTC and 1400 UCT 11 September in CTL_m, EXP1103_m and EXP1015_m, respectively. In other words, the CE cycles of the ensemble means in CTL_m,
EXP1103_m and EXP1015_m last for 11, 16 and 7 hours, respectively. The above differences in the duration of CE cycles show the run-to-run variability amid the experiments with different amount of data assimilated.

As shown in the plan view plots for CTL_m (Figs. 7-11), 5 hours after SEF, a transition period (between 1200 and 1800 UTC 11 September) occurs where the CE structure becomes less distinct. During the same period, however, the CE structure in EXP1103 remains evident in terms of either tangential wind or PV, except at 1400 UTC 11 September (Fig. 15). It is not clear why such transition of eyewall evolution occurs. Further investigation on possible factors still needs to be carried out, such as the involved PV dynamics (e.g., barotropic instability) and the impact of data assimilation (especially the assimilated azimuthal-mean surface wind).

With the least cumulative data assimilated, the storm track (Fig. 4c), intensity and structure are not well captured in EXP1003 (Fig. 16). Without assimilating enough updated data, the storm vortex in EXP1003 weakens significantly during early stages of the integration (Fig. 16). The RMW (Fig. 16a) at 0000 UTC 11 September is about 60 km, approximately 30 km larger than that at the initial time (0300 UCT 10 September). Later, the vortex starts to intensify since 0500 UTC, which is close to the SEF time in other experiments. At the beginning of the intensification, the RMW of the storm persistently expands, but its intensity does not
change significantly (Fig. 16a). Eyewall contraction starts after 1200 UTC 11 September, along with a significant increase in intensity until the end of the integration (Fig. 16a). All the dynamical variables in Fig. 16, such as $\bar{v}$, $\bar{w}$, $\bar{\zeta}$, $\bar{q}$, and the total column rainrate show that there is no coherent CE structure in EXP1003. These results demonstrate that when less data are assimilated (such as in EXP1003), the storm is weaker (Figs. 4f and 16), and that the simulated tracks have a large northeastward bias as compared to the best track (Fig. 4c), as well as a higher spread among the ensemble members as compared to that in CTL.

4. Concluding remarks

Many possible mechanisms and conditions for SEF have been suggested in the literature. However, insufficient data on a TC vortex and the incomplete understanding on TC dynamics limit our ability to investigate the issue of SEF, leaving the exploration of SEF a challenging issue. Typhoon Sinlaku (2008) is a case in point under T-PARC with the most abundant aircraft observations taken and with great potentials to address major scientific issues in T-PARC ranging from structure change, targeted observations to extra-tropical transition. Meanwhile, an effective TC initialization method featured with three key TC parameters (TC position, motion vector and axisymmetric surface wind profile) has been developed in the WRF-based EnKF data assimilation system (Wu et al. 2010).
high-temporal/spatial resolution and model-observation-consistent dataset is thus constructed by continuously assimilating all available conventional soundings, dropwindsondes and SFMR data from 9 T-PARC flight missions during Sinlaku from September 9 to 13.

The CE cycle of Sinlaku is demonstrated in the CTL experiment in terms of several different parameters ($v$, $u$, $w$, $\zeta$, $q$ and the total column rainrate). Forecast experiments with more data assimilated, such as in EXP1103 and EXP1015, also depict a coherent CE cycle in Sinlaku. It is interesting that the SEF of Sinlaku can be captured in simulations with 5-km horizontal resolution, which is coarser than the critical resolution suggested in previous numerical studies (e.g., Houze et al. 2007).

This finding indicates that the assimilation of the valuable extra data into the model along with an appropriate vortex initialization scheme provides special added value to better reconstruct a model/observation consistent dataset for Sinlaku. This dataset sketches a path to the investigation on Sinlaku’s CE formation and evolution. Meanwhile, coherent precursory features of SEF are presented, such as the broadening of the tangential wind, intensification of inflow in the boundary layer, and the weak secondary maximum in azimuthal averages of $\tilde{w}$, $\tilde{\zeta}$, and $\tilde{q}$ projected by sporadic convective activities in spiral rainbands.

Simulations of Sinlaku are performed at different initial times to assess the
impact of cumulative data in different amounts. It is striking that some of the simulations are able to capture secondary eyewall cycles (e.g., EXP1103 and EXP1015), while others starting earlier with less data assimilated (e.g., EXP1003) are not. The simulations that are unable to reproduce Sinlaku's CE cycle actually show an overall poor performance on the storm evolution, including its movement and intensity. This result demonstrates that without sufficient data assimilated, numerical simulations of a TC, in particular the structure and intensity change, can be considerably constrained by the model resolution and the detailed physical processes in the model setting. On the other hand, results among these simulations demonstrate also the added value of the assimilated data in the framework with 5-km model resolution and a 30-min update cycle. However, quantitative evaluation of impacts of these cumulative data on the vortex and the environmental conditions still requires more sensitivity experiments with suitable numerical design.

We herein stress that although continuous data assimilation significantly affects this dataset of Sinlaku, it is an influence accumulated over a period of time. The applied data assimilation strategy and its corresponding settings do not generate sharp changes at each update cycle (figures not shown). In other words, new data are progressively picked up by the model. The evolution of the continuous model data does not deviate from the model dynamics too much but instead, resembles the
results from observation. In addition, concerning the vortex structure, only surface symmetric wind profiles, which are 1-dimensional data, are used as a special TC parameter for data assimilation. For this reason, a numerical model must have played a very important role in constructing the 3-dimensional evolution of a vortex, the development of asymmetry features and the associated wave-mean flow interaction. In short, a good data assimilation method and a capable model work together to compensate the deficiencies of limited observation samplings both temporally and spatially, while good data from observation and an effective data assimilation methodology improve the model output. It is the coordination of observation, the data assimilation method and the numerical model that generates such a special model/observation consistent dataset for Sinlaku and constructs an applicable and effective numerical system.

In upcoming papers, we aim to explore the formation of secondary eyewall with data that can best assess the real atmosphere. In part II (Huang et al. 2011), the precursors to SEF are investigated in detail and a new paradigm for SEF in terms of an axisymmetric view is presented. Model output data with a finer time interval (e.g., 2 min) during model simulations and the innovation data during an update cycle of an individual ensemble member are being investigated for further dynamical analyses and will be presented in other upcoming papers. We herein
believe that this dataset, which agrees well with the observation, can shed light on our understanding about the formation of secondary eyewall.
Acknowledgement: This work is supported by the National Science Council of Taiwan Grants (NSC 98-2111-M-002-008-MY3 and NSC 97-2111-M-002-016-MY3), Central Weather Bureau Grant (MOTC-CWB-97-6M-01), Office of Naval Research Grant (N00173-08-1-G007) and the Academia Sinica. Team efforts (Pat Harr and Tetsuo Nakazawa) in collecting the data during T-PARC and helpful discussions on EnKF data assimilation with Fuqing Zhang are highly appreciated.
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Table 1. T-PARC data assimilated into simulations of Typhoon Sinlaku (2008)

<table>
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<tr>
<th></th>
<th>Conventional radiosondes</th>
<th>Dropwindsondes</th>
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<tr>
<td></td>
<td></td>
<td>DOTSTAR ASTRA</td>
<td>DLR Falcon</td>
<td>NRL P-3</td>
<td>USAF C-130</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>inner core</td>
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<tr>
<td>Total available</td>
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<td>36 (2 flights)</td>
<td>34 (2 flights)</td>
<td>12 (1 flight)</td>
<td>20</td>
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### Table 2. Experimental design: CTL and the forecasting experiments.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Assimilation of new data</th>
<th>SEF time (defined in terms of $\bar{y}$ at the lowest model level in their ensemble mean)</th>
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<tbody>
<tr>
<td>CTL</td>
<td>Throughout the integration</td>
<td>0700 UTC 11 September</td>
</tr>
<tr>
<td>EXP1103</td>
<td>Terminated after 0300 UTC 11 September</td>
<td>0700 UTC 11 September</td>
</tr>
<tr>
<td>EXP1015</td>
<td>Terminated after 1500 UTC 10 September</td>
<td>0730 UTC 11 September</td>
</tr>
<tr>
<td>EXP1003</td>
<td>Terminated after 0300 UTC 10 September</td>
<td>No SEF</td>
</tr>
</tbody>
</table>
Figure captions:

Fig. 1. Observation data assimilated into the model. Conventional radiosondes are denoted by red circles, and dropwindsondes deployed from several aircrafts are denoted by other symbols shaded in different colors.

Fig. 2. Left panels (a, c, e, g): The tangential wind profiles assimilated into the model (thick lines) are constructed mainly based on data from C-130 (grey lines for the flight level wind and black lines for SFMR wind) along with combined information from the JTWC (RMW: black squares; wind radii of 34, 50, 64 kts: grey squares) and the available DOTSTAR dropwindsonde data (triangles). Right panels (b, d, f, h): Polar-orbiting satellite images from 85 GHz sensors, superposed with the flight path (the α-pattern is C-130, and the other is DOTSTAR) and deployed locations of the DOTSTAR dropwindsondes (black dots).

Fig. 3. Model domains: D1, D2, and D3 (D3’). D3 (D3’) is a moving nest which is activated from 0300 UTC 09 September (D3) to the end of the simulation (0300 UTC 13 September; D3’).

Fig. 4. Simulated tracks in (a) CTL, (b) EXP1103 and (c) EXP1003. The best track obtained from JMA is in black. The thick color line refers the ensemble mean in each experiment. Thin lines indicate each ensemble member, while the colors represent different levels of intensity (see the color bar). The multiplication mark
in (b) and (c) indicates the initial time of the forecast experiment. (d)-(f) are the corresponding minimum sea level pressure to each experiment. Black and grey lines are for the results in the ensemble mean and ensemble members, respectively. The black circles represent the minimum sea level pressure from the C-130 observation.

Fig. 5. For CTL, time-radius diagrams of the azimuthally-mean (a) tangential wind \((\text{m s}^{-1})\) at the lowest model level, (b) vertical velocity \((\text{m s}^{-1})\) at 0.5-km height, (c) relative vorticity \((10^{-3} \text{ s}^{-1})\) at 2-km height, (d) potential vorticity \((10 \text{ PVU})\) at 2-km height, and (e) the total column rainrate \((\text{mm hr}^{-1})\) in the ensemble mean (average of 28 ensemble members, also denoted by CTL_m). SEF time is indicated by an arrow on the y-axis.

Fig. 6. The radius-height cross-sections of the azimuthally-averaged variables in CTL_m. (a)-(d): tangential winds, contour interval is 5 m s\(^{-1}\), and cyclonic winds are shaded. (e)-(h): radial winds, inflow is shaded with a 2-m s\(^{-1}\) contour interval, and the contour interval for outflow is 1 m s\(^{-1}\). (i)-(l): vertical velocity, contour interval is 0.1 m s\(^{-1}\), and upward motion is shaded. (m)-(p): relative vorticity, contour interval is \(10^{-3} \text{ s}^{-1}\) when it is larger than \(1 \times 10^{-3} \text{ s}^{-1}\), and is \(1 \times 10^{-4} \text{ s}^{-1}\) when it is smaller than \(0.5 \times 10^{-3} \text{ s}^{-1}\). Values of \(0.5 \times 10^{-3}\) and \(0.75 \times 10^{-3} \text{ s}^{-1}\) are additionally plotted, and values larger than \(0.1 \times 10^{-3} \text{ s}^{-1}\) are shaded. (q)-(t):
potential vorticity, contour interval is 5 PVU when it is larger than 5 PVU, and 1 PVU when it is smaller than 5 PVU. Values larger than 1 PVU are shaded.

Fig. 7. Plan view of the tangential winds (m \( s^{-1} \)) at the lowest model level in CTL_m from 1800 UTC 10 September to 0000 UTC 12 September with 2-h time intervals.

Fig. 8. Same as Fig. 7, except for the vertical velocity (m \( s^{-1} \)) at 0.5-km height. Upward motion is shaded with grey colors, while descent motion is marked by contours.

Fig. 9. Same as Fig. 7, except for the total column rainrate (mm hr\(^{-1}\)).

Fig. 10. Same as Fig. 7, except for the relative vorticity (10\(^{-3}\) s\(^{-1}\)) at 2-km height.

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Fig. 13. Same as Fig. 5, but for EXP1103_m.

Fig. 14. Same as Fig. 13, but for EXP1015_m. Note that the shading interval for (a) is slightly different from that in Fig. 13 to better present the CE structure in
Fig. 15. Plan view of the (a) tangential winds at the lowest model level and (b) Potential Vorticity at 2-km height in EXP1103_m from 0800 UTC 11 September to 2200 UTC 11 September with 2-h time intervals.

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