Sensitivity of the Simulated Tropical Cyclone Inner-Core Size to the Initial Vortex Size*

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ABSTRACT

The multiply nested, fully compressible, nonhydrostatic tropical cyclone model version 4 (TCM4) is used to examine and understand the sensitivity of the simulated tropical cyclone (TC) inner-core size to its initial vortex size. The results show that although the simulated TC intensity at the mature stage is weakly dependent on the initial vortex size for the general settings, the simulated TC inner-core size is largely determined by the initial vortex size. The initial vortex size is critical to both the energy input from the ocean and the effectiveness of the inward angular momentum transport by the transverse circulation driven by eyewall convection and diabatic heating in spiral rainbands.

Strong outer winds in a storm with a large initial size lead to large entropy fluxes to a large radial extent outside the eyewall, favoring the development of active spiral rainbands. Latent heat released in spiral rainbands plays a key role in increasing the low-level radial inflow and accelerating tangential winds outside the eyewall, leading to outward expansion of tangential wind fields and thus increasing the inner-core size of the simulated storm. On the contrary, a storm with a small initial size has weaker outer winds and smaller surface entropy fluxes outside the eyewall and is accompanied by less active spiral rainbands and thus a much slower increase in the inner-core size. The effectiveness of the inward transport of absolute angular momentum to increase the tangential winds outside the eyewall is largely determined by the radial extent of the vertical absolute vorticity, which is shown to be higher in a large size vortex.

The relative importance of the initial vortex size and the environmental relative humidity (RH) to the TC inner-core size is also evaluated. It is found that the inner-core size of the simulated storm at the mature stage depends more heavily on the initial vortex size than on the initial RH of the environment.

1. Introduction

The horizontal extent of damaging wind and torrential rain induced by a tropical cyclone (TC) is not only determined by the TC’s intensity but also its size, in particular, its inner-core size. In addition to its importance to disasters, the TC size also affects the TC motion (e.g., Fiorino and Elsberry 1989; Fovell et al. 2009) and determines the meridional transport of heat, moisture, and momentum, affecting the tropical–extratropical interactions and thus the atmospheric general circulation (Emanuel 2008). The TC size is also an important parameter for storm surge models and an important factor affecting the ocean upwelling under the TC (Irish et al. 2008; Price 1981). Because it is important to the distribution of disasters, the inner-core size and its change in a TC and the associated physical mechanisms have received increasing attention in recent years (Wang 2009; Hill and Lackmann 2009; Xu and Wang (2010, hereinafter XW10).

The size of a TC can be measured in different ways. Among them the radii of the eye, maximum wind (RMW), gale-force wind (17 m s⁻¹), damaging-force wind (25.7 m s⁻¹), hurricane-force wind (33 m s⁻¹), and the outmost closed isobar are frequently used in operational forecasts and statistical analyses (Merrill 1984; Weatherford and Gray 1988a,b; Kimball and Mulekar 2004; Moyer et al. 2007; Knaff et al. 2007; Maclay et al. 2008). Weatherford and Gray (1988a) defined the “inner core” and “outer core” of a TC. The former extends from

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the TC center to 1° latitude radius, while the latter is defined as the region between radii of 1° and 2.5° latitudes. By their definition, the inner-core region of a strong TC generally includes the eye, RMW, and the radius of hurricane-force wind (RHW). The outer-core region may cover the area with both the damaging-force winds and gale-force winds. Weatherford and Gray (1988b) showed that changes in the inner-core strength often occur independently from those in the outer-core strength. While the inner-core strength is closely related to the storm intensity, the outer-core strength seems to be affected greatly by the synoptic environmental conditions (Merrill 1984; Holland and Merrill 1984; Weatherford and Gray 1988b; Cocks and Gray 2002).

Previous studies have shown that the TC size varies with the season, region, latitude, environmental pressure, and even the time of the day (Kimball and Mulekar 2004; Moyer et al. 2007). Merrill (1984) found that on average TCs in the western North Pacific are twice as large as those in the Atlantic and that TCs increased in size during their recurvature in the western North Pacific. Similar size increase was found by Kimball and Mulekar (2004) for recurving hurricanes in the North Atlantic. Liu and Chan (2002) indicated that different TC sizes are associated with various synoptic flow patterns. The size of a TC also varies with time considerably. Maclay et al. (2008) examined the evolution of TC inner-core kinetic energy based on wind fields from aircraft reconnaissance flight level data. They found two processes that may lead to the growth of TC inner-core size, namely, the secondary eyewall formation and the associated eyewall replacement cycle and the external forcing from the synoptic environment, such as the vertical shear.

The difference in the observed TC size was dominantly attributed to the angular momentum transport associated with the synoptic environment in early studies (Holland 1983; Merrill 1984), but mainly with the focus on the storm-scale size. Wang (2009) emphasized the importance of latent heat release in outer spiral rainbands to the increase in the inner-core size of TCs. This led him to hypothesize that the TC inner-core size should be sensitive to the environmental relative humidity (RH), which can modify heating/cooling rate due to phase changes in outer spiral rainbands. He indicated that a deep moist layer in the near-core environment may favor the activity of strong outer spiral rainbands and thus the development of large TCs while a relatively dry environment may favor small, compact TCs. This possible effect has been studied in detail by Hill and Lackmann (2009) based on a potential vorticity (PV) perspective. They showed that the generation of diabatic PV in spiral rainbands in the moisture-rich environment is critical to outward expansion of tangential wind fields and thus to the increase in TC inner-core size. XW10 studied the sensitivity of the TC inner-core size and intensity to the radial distribution of surface entropy flux by artificially removing surface entropy flux outside a given radius in their idealized numerical simulations. They found that surface entropy flux outside the eyewall could be either positive or negative to TC intensity but contributes to the activity of spiral rainbands and thus the increase in the TC inner-core size, in agreement with the hypothesis of Wang (2009) and the results of Hill and Lackmann (2009).

The above studies all emphasize the importance of active spiral rainbands and diabatic heating outside the eyewall to the inner-core size of TCs. Both the high environmental RH and large surface entropy flux outside the eyewall are identified to be critical to the large inner-core size of a TC. Spiral rainbands and thus diabatic heating outside the eyewall can be affected by many dynamical and physical processes. In addition to the environmental RH, they may be determined by the initial size of the vortex, the interaction with mesoscale, synoptic systems in the environment, and so on. Therefore, complex internal dynamics and external forcing may affect the inner-core size of TCs. Cocks and Gray (2002) showed that small TCs were smaller than the medium and large TCs early on and throughout their respective life cycles. In an axisymmetric model simulation, Rotunno and Emanuel (1987) found that the size of the mature storm was largely determined by the size of the initial disturbance. However, it is not clear how the initial size of the disturbance/vortex controls the inner-core size of the simulated mature storm. Furthermore, both the environmental RH and the initial vortex size have been reported to be critical to the TC inner-core size, but it is unknown what their relative importance is in affecting the TC inner-core size.

The objective of this study is to address the above two issues by extending our previous studies to see how the initial vortex size controls the inner-core size of the simulated TC at its mature stage and to evaluate the relative importance of the initial vortex size and the environmental RH in determining the inner-core size of the simulated TC. Strictly speaking, the near-core environmental RH may be affected by the radial distribution of surface winds, which determines the surface entropy fluxes and is in turn determined by the size of the TC itself. Here we focus on the difference in the initial conditions of the given environmental RH and the given vortex size so that the subsequent evolution will be understood in terms of different dynamical and thermodynamic feedbacks. As in XW10, both the RMW and the radius of the azimuthal mean damaging-force wind (RDW; 25.7 m s\(^{-1}\)) are used as measures of the inner-core...
size of the simulated TCs in this study. The rest of the paper is organized as follows. Section 2 describes the numerical model and the experimental design. Section 3 discusses the model results with the focus on the effect of the initial vortex size on the size changes of the modeled TC. The relative importance of the initial vortex size and the initial environmental RH to the evolution of the inner-core size of the simulated TC is discussed in section 4. The main conclusions are given in the last section.

2. Model and experimental design

The model used in this study is the fully compressible, nonhydrostatic, tropical cyclone model version 4 (TCM4) developed by Wang (2007). A full description of TCM4 can be found in Wang (2007) and its applications to the studies of the inner-core dynamics of TCs can be found in Wang (2008a,b, 2009), Wang and Xu (2010), and XW10. The model domain is quadruply nested with two-way interactive nesting and with the inner meshes that automatically move to follow the model storm as in its hydrostatic counterpart, the tropical cyclone model version 3 (TCM3; Wang 2001). The horizontal grid intervals of 67.5, 22.5, 7.5, and 2.5 km have domain sizes of $251 \times 151, 109 \times 109, 127 \times 127,$ and $163 \times 163$ grid points for the four meshes, respectively. Since no large-scale environmental flow is included in the experiments, convection is active in both the inner-core region and the spiral rainbands that occur mainly within about 200 km from the TC center and thus are covered by the finest innermost domain. The model has 30 levels in the vertical with an unperturbed surface pressure of 1010 hPa and a top at about 38 km, with relatively high resolution both in the lower troposphere and near the tropopause.

The model physics include an E–e turbulence closure scheme for subgrid-scale vertical turbulent mixing (Langland and Liou 1996), a modified Monin–Obukhov scheme for the surface flux calculations (Fairall et al. 2003), an explicit treatment of mixed-phase cloud microphysics (Wang 2001), a nonlinear fourth-order horizontal diffusion for all prognostic variables except for that related to the mass conservation equation, a simple Newtonian cooling term that is added to the perturbation potential temperature equation to mimic the radiative cooling in the model (Rotunno and Emanuel 1987), and the dissipative heating due to molecular friction related to the turbulent kinetic energy dissipation rate $e$ directly from the prognostic $E$–$e$ turbulent closure scheme. As in Wang (2007, 2008a,b, 2009), the same model physics are used in all meshes. Cumulus parameterization is not considered even in the two outermost meshes in this study.

The experimental design follows Wang (2008a,b, 2009). The model is initialized with an axisymmetric cyclonic vortex on an $f$ plane of 18°N in a quiescent environment over the ocean with a constant SST of 29°C. The initial thermodynamic structure of the unperturbed model atmosphere is defined as the western Pacific clear-sky environment given in Gray et al. (1975). The initial cyclonic vortex has the maximum tangential wind speed of 20 m s$^{-1}$ near the surface and decreases sinusoidally with pressure to vanish at 100 hPa [see Wang (2007) for details]. The mass and thermodynamic fields were obtained by solving the nonlinear balance equation as shown in Wang (2001). The model was run for 240 h for all experiments described below. The TC center is defined in this study as the center of axisymmetric circulation along which the azimuthal mean wind at the lowest model level reaches the maximum at a given time.

Seven numerical experiments were designed in which the initial vortex size or the initial environmental RH were varied (Table 1). In the four initial size experiments, the initial RMW was given: 40, 60, 80, and 100 km in S40, S60, S80, and S100, respectively. Compared with S80, the RMW of the initial vortex in other experiments was varied by a factor of ±25% in S100/S60, and 50% in S40 (See Table 1). The choice of these initial RMWs roughly reflects the variability of the RMW in the observed weak tropical cyclones as can be seen in Fig. 1 (Willoughby and
Rahn 2004). Figure 2 shows the radial profiles of the tangential wind and absolute vorticity of the initial vortices at the lowest model level in these four experiments. We can see that the initial vortex in S100 (S40) has a larger (smaller) size both in the inner core and outside of the inner core.

To examine the relative importance of the initial environmental RH to the inner-core size of the simulated TC, three other sensitivity experiments were carried out. To have a proportional increase or decrease in the initial environmental RH comparable to that used in the initial size experiments, in these three experiments we simply multiplied the initial environmental RH at all model levels used in the initial size experiment S80 by 112.5% in RH1125, 75% in RH75, and 50% in RH50. Therefore, the environmental RH is initially 12.5% higher in RH1125 and 25% and 50% lower in RH75 and RH50 than that in experiment S80, respectively. Note that we only included an experiment with the initial environmental RH increased by 12.5% because if a factor of 25% was used, the lower troposphere would become saturated, which was unrealistic for the large-scale environment. The initial RMW in these RH experiments was set at 80 km, the same as that used in S80 in the initial size experiment (Table 1). Figure 3 shows the vertical profiles of the initial RH used in the initial size S80 (or RH100) and the initial environmental RH experiments.

3. Influence of the initial vortex size

a. Storm evolution

Figure 4 shows the time evolution of storm intensity in terms of the maximum azimuthal mean wind at the lowest model level (about 35.6 m above the sea surface) and the minimum surface pressure of the simulated storms with different initial vortex sizes. Storms in all 4 experiments experienced a rapid intensification after about 9–12-h spinup. The spinup time was shorter for smaller initial size vortex and the subsequent intensification rate was the largest for smallest initial size vortex in S40. Storms with larger initial vortex size generally took longer time to reach their quasi-steady intensity evolution. The storm in S40 ended its rapid intensification after only about 108 h, while those in S60, S80, and S100 ended their rapid intensification after about 80, 96, and 108 h, respectively. Although the storm intensity during the mature stage was similar for the initial large and medium size vortices in S60, S80, and S100, the storm with smallest initial size in S40 was much weaker than the storms in other experiments. This indicates that a disturbance with a small initial size may not be able to develop into a strong TC. Nevertheless, the storm intensity at the mature stage would not be too sensitive to the size of the initial vortex except for too small size.
vortices, such as the one in experiment S40. Although the dependence of the simulated storm intensity on the initial size of the storm itself is an interesting topic, we will leave it for another study since our focus in the present study is on the sensitivity of the inner-core size of the simulated storm to the initial size of the vortices.

Figure 5a shows the time evolution of the RMW at the lowest model level in all four experiments. The RMW in each experiment contracted rapidly with time initially and then evolved slowly. For example, initial RMWs of 40, 60, 80, and 100 km in S40, S60, S80, and S100 decreased to 10, 15, 25, and 32.5 km, respectively, in the first 24-h initial spinup period (Figs. 4 and 5a). This initial contraction resulted mainly from the asymmetric contraction because of the development of asymmetric convective cells near the original RMW and the breakdown of the quasi-symmetric convective ring formed early in the simulation (see Fig. 10 in Wang 2007 for details). After the initial rapid contraction, the RMW decreased slowly to about 7.5, 12.5, 17.5, and 22.5 km in S40, S60, S80, and S100, respectively, after 72 h of simulation. At any given time, the storm with a larger initial RMW remained larger in the simulation, indicating that the storm’s RMW at the mature stage is largely determined by the initial vortex size in the model (Fig. 5a). For example, increasing the initial RMW by 25% in S100 compared with that in S80 resulted in an increase of RMW by about 43% (25 vs. 17.5 km) averaged during the last 24 h of simulation, while a 25% decrease in the initial RMW of the vortex led to a 29% decrease of the RMW (12.5 vs. 17.5 km) in the mature stage (Table 1).

Figure 5b shows the evolution of the RDW in each of the simulated TCs. Since the maximum azimuthal mean wind reached 25.7 m s$^{-1}$ at different times in different experiments (Fig. 4a), the RMW started to show up in the simulations at different times accordingly (Fig. 5b). Although the RDW for the initially small size vortex in S40 appeared earlier than that in any other experiment, it grew very slowly and remained almost a constant around 20 km after the storm reached its steady state by about 38 h of integration (Figs. 4 and 5b). As a result, the storm with the small initial size in S40 was not only the weakest but also the smallest storm among the four experiments. Nevertheless, the storm still showed the characteristics of a TC, resembling the so-called midget TC in the western North Pacific (Brand 1972; Merrill 1984; Harr et al. 1996). As noticed by Harr et al. (1996), midget TCs generally formed in the subtropical region from relatively small-scale initial disturbances with the lack of significant background environmental vorticity.

The RDW in S60 appeared after about 24 h of integration and only increased by 10 km from 35 to 45 km from 72 to 240 h. In S80, RDW appeared about 3 h later than that in S60, but increased sharply as the storm...
intensified rapidly to reach 55 km after 78 h of integration. The RDW kept a constant until about 144 h when it started to increase slowly with time and reached its maximum value of about 72.5 km in the last 24 h of simulation. The largest initial size vortex in S100 intensified less rapidly than either the initially medium size vortex in S80 or the small size vortex in S60 (Fig. 4a) with its RDW appearing after about 33 h of integration (Fig. 5b). In contrast to the storms in S80 and S60, the RDW in S100 increased very quickly to reach 60 km after about 72 h and then increased with time throughout the simulation and reached 100 km by 240 h of simulation, which is about 38% larger than that in S80. The RDW in S60 was about 38% smaller than that in S80. Therefore, a 25% increase (decrease) in the initial RMW would result in roughly 38% increase (decrease) in the RDW of the simulated storm at the mature stage (Table 1).

The inner-core size together with the sizes of the eye and eyewall can be easily inferred from the surface rain rate. As examples, we show in Fig. 6 the surface rain rates in the 4 experiments after 120 and 240 h of simulations together with the isotach of 25.7 m s\(^{-1}\) in km at the lowest model level. We can see that the size of the eye (the nearly clear area near the storm center), the width of the eyewall (with heavy rainfall encircling the eye), and the area covered by considerable rainfall are roughly proportional to the RDW or equivalently the inner-core size at given times in these simulations. In general, larger storms have larger eyes, wider eyewalls, and wider and more outward-extended spiral rainbands. This implies that the radially extended, active spiral rainbands may play important roles in affecting the inner-core size of the simulated storms. This has been studied in some details in Wang (2009) and XW10 and will be discussed further in section 3b.

Figure 7 shows the radial distributions of several azimuthal mean variables/parameters averaged between 192 and 216 h of simulation in the 4 initial vortex size experiments. Consistent with the storm inner-core size, larger storms have not only stronger tangential winds but also stronger radial wind outside the RMW (Figs. 7a,b). We can see that the column-integrated azimuthal mean heating rate due to phase change extends farther outside the eyewall in the larger storms but is limited within a radius of about 60 km in the small storms in S40 and S60, an indication of possible contribution to the boundary layer inflow by diabatic heating in active, outward-extended, spiral rainbands in larger storms. Note that in addition to the high rain rate in the small eyewall region of the smallest storm in S40, a second maximum heating rate occurred between radii of 30 and 60 km (Fig. 7c), which is consistent with the tightly wound spiral rainbands outside the eyewall in S40 (Fig. 6). Stronger winds outside the eyewall in larger storms contributed to larger surface entropy flux outside the RMW, supporting more energetic larger storms (Fig. 7d). The smaller storm looks more compact with its potential vorticity inside the eyewall (Fig. 7e) and shows much smaller absolute angular momentum outside the eyewall (Fig. 7f). In particular, the PV in the smallest storm in S40 showed a monopole structure with the maximum PV at the storm center in the mid–lower troposphere. The angular momentum increases radially outward in all experiments, indicating the loss of angular momentum to surface friction in the inflow boundary layer.

Changes in the inner-core size of the simulated storms with various initial vortex sizes can be seen from the time evolution of the azimuthal mean surface rain rate and the azimuthal mean tangential wind at the lowest model level given in Fig. 8. For a close comparison, the time evolution of the isotach of the damaging-force wind (25.7 m s\(^{-1}\)) in each experiment is also shown in Fig. 8. Both the surface rain rate and the RMW contracted steadily with time up to about 96 h of simulation in both S80 and S100 and up to only about 48 h in S40 and 72 h in S60. The contraction occurred both in the spinup period and in the rapid intensification stage of the simulated storm in each of the experiments (Fig. 4). As we discussed above (Fig. 5b), the damaging-force wind appeared after
FIG. 6. The plan view of the rain rate (mm h$^{-1}$) at the surface after (a) 120- and (b) 240-h simulations in experiments S40, S60, S80, and S100. Contours show the isotachs of 25.7 m s$^{-1}$ at the lowest model level.
about 22 h of simulation in S40, 24 h in S60, 27 h of simulation in S80, and 33 h in S100. The damaging-force wind outside the RMW then expanded radially outward rapidly in S100 and gradually in S80 but at a much smaller rate in S60, while almost negligible in S40 (Fig. 8). The outward expansion rate of the RDW was consistent with that of surface rain rate throughout the simulation in both S80 and S100 (Figs. 8c,d). The rain rate was mostly confined in a radius of about 40–60 km in either S40 or S60 (Figs. 8a,b), which is consistent with the constantly small RDW in the two storms.

An interesting feature was the periodic appearance of outward-propagating surface rain rate, in particular in experiments S40 and S60 (Figs. 8a,b). This is related to the periodic activity of outward-propagating spiral rainbands, as indicated in Wang (2009). Note that the occurrence of the periodic outward-propagating spiral rainbands was more regular in the smaller storms with a period of about 24 h. However, such a periodic occurrence of outward-propagating spiral rainbands was not obvious in the large storms in S80 and S100 (Figs. 8c,d) because the spiral rainbands were always active in both experiments (e.g., Fig. 6). The quasi-periodic appearance of rain rate has some similarity to the observed diurnal oscillation in hurricanes (Kossin 2002). However, since no solar radiation was included in these simulations, the
FIG. 8. Radius–time cross section of the azimuthal mean rain rate (mm h$^{-1}$, shading) and tangential wind speed (contours of 50, 60, and 70 m s$^{-1}$ h$^{-1}$). The isotachs of damaging-force wind (25.7 m s$^{-1}$) at the lowest model level in experiments (a) S40, (b) S60, (c) S80, and (d) S100 are highlighted (thick contours).
quasi-periodic behavior should be a dynamical and ther-
modynamic feature other than the diurnal solar forcing. We
found that this quasi-periodic behavior was related to
the stabilization of the boundary layer due to downdrafts
from an existing rainband and the recovery of the
boundary layer from the effect of downdrafts. A full
discussion of the periodic behavior of the spiral rain-
bands in the simulations will be reported separately in
a future study.

b. Physical mechanisms

Wang (2009) showed that both intensity and inner-
core size of the simulated TCs could be affected by
diabatic heating in active outer spiral rainbands. He found
that diabatic heating in outer spiral rainbands (outside of
a radius of about 90 km) generally weakens the storm
but contributes to the outward expansion of tangential
winds and thus increases the inner-core size of a TC.
XW10 showed how the surface entropy flux outside the
eyewall contributes to the activity of spiral rainbands,
affecting the inner-core size of a TC. Therefore, a natu-
ral extension of our current understanding is to examine
whether the initial vortex size affects the subsequent
activity of spiral rainbands and thus the storm inner-core
size in the simulations presented in section 3a. Indeed,
this has already been seen in Figs. 6, 7c, and 8. The larger
initial size vortex developed into a larger inner-core size
storm with more active spiral rainbands extending out-
ward to larger radii, while the small initial size vortices in
$S40$ and $S60$ developed into small inner-core size storms
with spiral rainbands mainly confined within much smaller
radii.

The remaining question is why the larger initial size
vortex developed more active spiral rainbands that ex-
tended outward to larger radii. This can be understood
from the results discussed in XW10, who showed that
surface entropy fluxes outside the eyewall are very im-
portant to the activity of spiral rainbands. Since the larger
initial size vortex has stronger circulation outside the RMW
(Fig. 2a) at initial time, the stronger surface winds would
produce larger surface entropy fluxes outside the RMW
(e.g., Fig. 7d). The latter can then support stronger con-
vection and thus active spiral rainbands. Diabatic heating
in spiral rainbands, in turn, can contribute to the outward
expansion of tangential wind fields (Wang 2009; Hill and
Lackmann 2009). This becomes a positive feedback to
increase the inner-core size of the simulated storm with
the large initial size vortex. In the following we will
focus on how the outward expansion of the tangential
wind fields depends on the initial vortex size in differ-
ent experiments.

Following XW10, we performed a momentum budget
analysis that can provide some physical insights into the
evolution of the inner-core size of the simulated storms.
The azimuthal mean radial and tangential momentum
equations can be rewritten as

$$\frac{d\bar{u}}{dt} = -\frac{1}{\bar{\rho}} \frac{\partial \bar{p}}{\partial r} + \frac{\bar{V}^2}{r} + f\bar{V} + \bar{F}_u + \mathcal{D}_u,$$  

(1)

$$\frac{\partial \bar{V}}{\partial t} = -\bar{u} \bar{\zeta}_u - \bar{w} \frac{\partial \bar{\zeta}}{\partial z} + \bar{F}_\bar{V} - \bar{w} \bar{\zeta}' - w' \frac{\partial \bar{\zeta}'}{\partial z} + \mathcal{D}_\bar{V},$$  

(2)

where $r$ is radius; $z$ is height; $t$ is time; $\bar{u}$, $\bar{V}$, and $\bar{w}$ are
azimuthal mean radial, tangential, and vertical wind
speeds, respectively; $\bar{\zeta}_u$ is the vertical absolute vorticity
of the azimuthal mean flow; $\bar{p}$ and $\bar{\rho}$ are air density and
pressure, respectively; $f$ is the Coriolis parameter; $u'$, $w'$,
$\bar{V}'$, and $\zeta'$ are deviations of radial, vertical, tangential
winds, and the vertical relative vorticity, respectively, from
their corresponding azimuthal means; and $\bar{F}_u$, $\bar{F}_\bar{V}$,
$\mathcal{D}_u$, and $\mathcal{D}_\bar{V}$ are parameterized subgrid-scale vertical diffusion,
including surface friction of radial and tangential winds,
and horizontal diffusions of radial and tangential winds,
respectively. Note that contributions by eddy-related
processes in the radial momentum equation are
quite small and thus were not included in (1). Our results
also show that contributions to the tangential momentum
budget by the eddy transport and horizontal diffusion in
(2) are quite small and negligible after the initial spinup
stage.

Figure 9 shows the radial–time cross section of the
azimuthal mean surface pressure and pressure gradient
throughout the 240-h simulation in the four initial vortex
size experiments. The initial pressure field and its sub-
sequent evolution varied with the initial size of the model
vortex although with the same initial intensity in terms of
the maximum tangential wind speed. The larger initial
size vortex showed broader distributions in pressure and
its radial gradient fields (Fig. 9) but with smaller pressure
gradients near the RMW. Although the pressure field
expanded radially outward continuously after about 24-h
spinup in the simulation, the maximum inward pressure
gradient contracted as the storm was intensifying in all
experiments, consistent with the contraction of the RMW
(Fig. 5a). Note that the inward pressure gradient in the
small initial size vortex in $S40$ was the largest among the
four experiments even though the maximum wind speed
was weaker than that in other three experiments. This
is mainly due to the fact that the smaller RMW corre-
sponds to larger centrifugal force. Therefore, the larger
inward pressure gradient in the smaller storm did not
imply stronger inward acceleration of the boundary layer
inflow.

Acceleration of the boundary layer inflow showed a
typical radial distribution in TCs (Fig. 10). In general,
FIG. 9. Radius–time cross section of the azimuthal mean surface pressure (hPa; shading), azimuthal mean radial pressure gradient (white contours, m s$^{-1}$ h$^{-1}$), and isotachs of damaging-force wind 25.7 m s$^{-1}$ (black contours) in experiments (a) S40, (b) S60, (c) S80, and (d) S100.
Fig. 10. Radius–time cross section of the azimuthal mean acceleration of radial wind at the lowest model level \(\frac{du}{dt}\) in experiments (a) S40, (b) S60, (c) S80, and (d) S100. The radius of maximum wind in each experiment is shown by thick white dashed line. Positive values are shaded and negative contours are dashed in \(-5\), \(-10\), \(-20\), and \(-40\).
acceleration occurred outside the eyewall while deceleration appeared near and immediately inside the RMW. The change from acceleration to deceleration indicates large convergence of boundary layer inflow and upward motion near the RMW in the eyewall (not shown). An important feature is the inward acceleration of the radial wind extended to larger radii in larger storms (Fig. 10), consistent with the broader pressure gradient shown in Fig. 9. The outward expansion of both the pressure and pressure gradient fields was accompanied by a similar outward expansion of the inward acceleration of boundary layer inflow outside the eyewall. Note that the inward acceleration of radial wind was the strongest immediately outside the eyewall in the small storms in S40 and S60 (Fig. 10), seemingly contributing to the contraction of the RMW and the smallest inner-core size in the two simulations.

The azimuthal mean tangential wind budget in (2) can provide insights into the physical processes that lead to the outward expansion of tangential wind fields and determine the inner-core size of the simulated storms. Figures 11 and 12 show the azimuthal mean tangential wind budgets averaged between 48 and 72 h of simulations in S100 and S40, respectively. For the initially large size vortex in S100, positive tendencies in azimuthal mean tangential winds are dominant in the lower troposphere outside a radius of about 15 km, indicating the spinup of the azimuthal mean circulation both near the eyewall and outside the eyewall (Fig. 11a). The radial mean advection of the absolute angular momentum contributes predominantly to spin up the tangential wind in the inflow boundary layer (Fig. 11c). The vertical advection contributes to spin up the tangential wind in the eyewall except for the lower part of the inflow boundary layer where the tangential wind increases with height (Fig. 11b). The surface drag is the major sink to the azimuthal mean tangential wind budget in the boundary layer, whose depth decreases toward the storm center (Kepert and Wang 2001; Fig. 11d). The two eddy terms are generally small compared to other terms and they generally compensate for each other with a small negative contribution to the azimuthal mean tangential wind tendency (not shown). For the initially small size vortex in S40 (Fig. 12), the azimuthal mean tangential wind tendency is generally positive only in the eyewall region and quite small or slightly negative outside the eyewall. Similar to the case for the initially large size vortex, the mean radial advection of absolute angular momentum is also the dominant term in the azimuthal mean tangential wind budget and is largely balanced by the surface frictional drag in the inflow boundary layer (Figs. 12c,d).

Since the radial advection of absolute angular momentum dominates the azimuthal mean tangential wind budget in the inflow boundary layer and it is a function of the radial wind and absolute vertical vorticity \((-\pi\nabla_p\)\), we first show both variables in Fig. 13. An interesting feature is that the boundary layer inflow expanded radially outward continuously while the radial intent in absolute vertical vorticity showed an initial contraction and then a similar but slower increase after about 24 h of simulation in all experiments. The large storm in S100 experienced a considerable outward expansion in the boundary layer inflow, while the boundary layer inflow in the small storms in S40 and S60 showed a much reduced outward expansion. Therefore, the outward expansion rate of the boundary layer inflow was proportional to the initial size of the model storm. These differences result in different radial distributions in the azimuthal mean tangential wind tendency due to the radial advection of absolute angular momentum \((-\pi\nabla_p\)\) at the lowest model level as shown in Fig. 14. The outward expansion of the azimuthal mean tangential wind tendency is consistent with the outward expansion of both the radial wind and the vertical absolute vorticity. The outward expansion of the radial wind is associated with the outward expansion of pressure and its inward gradient fields. The outward expansion of pressure fields is a result of diabatic heating in spiral rainbands through the hydrostatic adjustment as discussed in Wang (2009). The outward expansion of the vertical absolute vorticity is associated with the outward expansion of tangential wind field, and in turn it enhances the outward expansion of tangential wind field through enhancing the radial advection of absolute angular momentum. The consistent outward expansion of the azimuthal mean tangential wind tendency shown in Fig. 14 and the azimuthal mean tangential wind itself shown in Fig. 8 indicates that the radial advection of absolute angular momentum is the dominant process responsible for the increase in the inner-core size of the simulated storms. Therefore, the radial wind outside the eyewall induced by diabatic heating in spiral rainbands is the key to the inner-core size increase.

XW10 elaborated a positive feedback to explain the inner-core size change due to artificial modifications to surface entropy fluxes outside the eyewall. Based on the above analysis, their positive feedback can be slightly modified to explain the dependence of the inner-core size of the mature storm on the initial vortex size in our simulations as schematically shown in Fig. 15. For the storm with an initially large size, such as the one in S100, strong winds in the boundary layer extending radially outward to large radii (Fig. 2a) enhance the surface entropy fluxes outside the eyewall and favor the formation of strong spiral rainbands. Diabatic heating in spiral rainbands can result in and enhance the boundary layer inflow not only immediately outside the RMW but also
in relatively large radii. This diabatically induced radial inflow would bring large angular momentum into the inner-core region (viz., the radial advection of absolute angular momentum $-\bar{u}\zeta$), leading to the increase in tangential winds outside the eyewall and thus the outward expansion of the wind fields and the increase in the inner-core size. The increased winds in the boundary layer would further enhance surface entropy fluxes outside.
the eyewall and thus enhance convection and diabatic heating in spiral rainbands. This is a positive feedback resulting in the increase in the inner-core size of the simulated storms in S80 and S100 (Fig. 15a). In contrary, for the storm with an initially small size, such as the one in S60, winds are weak outside the RMW, limiting the surface entropy fluxes outside the eyewall and unfavorable for the development of strong spiral rainbands at larger radii. The lack of active spiral rainbands and thus diabatic heating outside the eyewall limits the outward expansion of pressure and pressure gradient fields and keeps the boundary layer inflow outside the eyewall weak. The weak radial wind and the small radial extent of the elevated absolute vertical vorticity limit the inward advection...
FIG. 13. Radius–time cross section of the azimuthal mean absolute vorticity (10^{-3} s^{-1}; shading) and the azimuthal mean radial wind (m s^{-1}, contours) in experiments (a) S40, (b) S60, (c) S80, and (d) S100. The radius of maximum wind in each experiment is shown by thick white dashed line.
FIG. 14. Radius–time cross section of the tendency of the azimuthal mean tangential wind due to radial advection of absolute angular momentum ($-\pi \sigma_r$, 10 ms$^{-1}$ h$^{-1}$) in experiments (a) S40, (b) S60, (c) S80, and (d) S100. The radius of maximum wind in each experiment is shown by thick white dashed line.
of absolute angular momentum, keeping the inner-core size small. This is a positive feedback limiting the increase of the inner-core size in the simulated storms with the small initial size in S40 and S60 (Fig. 15b).

Another positive feedback is also operating. The initial vortex size is important to the effectiveness of the inward angular momentum transport by the boundary layer inflow. An initially large size vortex has a broader absolute vertical vorticity outside the eyewall (Fig. 2b), implying an increase in tangential winds in a large radial extent resulting from the inward transport of absolute angular momentum. This favors an increase in the inner core size of the simulated storm. In turn, the increased inner-core size and outward expansion of tangential winds extend high absolute vertical vorticity radially outward, further enhancing the effectiveness of the inward angular momentum transport by the boundary layer inflow, leading to a further outward expansion of the tangential winds and the increase in the inner-core size. This positive feedback is also an important process in our simulations (Fig. 13), as shown in dashed arrows in Fig. 15. Since the absolute vertical vorticity extends outward at a relatively smaller rate than the boundary layer inflow, the positive feedback related to the boundary layer inflow and inner-core size increase is more important than that related to the effectiveness associated with the outward expansion of the absolute vertical vorticity in our simulations.

In brief, the radial extent of winds outside the eyewall determines the surface entropy fluxes and activity of spiral rainbands and thus diabatic heating outside the eyewall. Diabatic heating can affect the outward expansion of pressure and its inward gradient fields and the boundary layer inflow. The radial extent and the strength of the boundary layer inflow affect the radial advection of absolute angular momentum, which determines the rate of radial expansion of the tangential wind field. Therefore, consistent with the finding of Wang (2009), the inner-core size of the simulated storm is largely affected by the activity of spiral rainbands, which may be affected by many processes/parameters, such as the initial vortex size, the environmental RH, the large-scale vertical shear, and so on. The two positive feedback processes identified in this study are generally consistent with the mechanism discussed in Hill and Lackmann (2009), who also emphasized the importance of surface moisture flux and the inward flux of PV from active spiral rainbands in increasing the storm size due to effect of the initial environmental RH.

4. The relative importance of the initial vortex size and the environmental RH

Previous studies have demonstrated the significant impact of the environmental RH on the inner-core size of simulated TCs (Wang 2009; Hill and Lackmann 2009).
Wang (2009) indicated that the relatively dry environment favors small inner-core size TCs due to the lack of strong outer spiral rainbands, while relatively wet environment favors large inner-core size TCs due to the presence of active outer spiral rainbands and associated diabatic heating. He demonstrated that diabatic heating in outer spiral rainbands is the key to the increase in the inner-core size of a TC. By varying the initial environmental RH in their idealized numerical experiments, Hill and Lackmann (2009) showed that TCs developed large (small) inner-core size in relatively wet (dry) environment although the intensity at the mature stage was nearly the same. In section 3, we have shown how the inner-core size of the simulated TC at the mature stage depends on the initial vortex size. In this section we are interested in evaluating the relative importance of the initial vortex size and the initial environmental RH in determining the inner-core size of the simulated mature storms although both factors are not independent because the initial vortex size may affect winds and surface moisture flux and, thus, RH in the near-core environment of the storm. Nevertheless, we can get some insights into the relative importance by carefully analyzing the results from some sensitivity experiments. We carried out three additional experiments in which the initial environmental RH was artificially reduced by 25% and 50% in RH75 and RH50, respectively, and increased by 12.5% in RH1125 as listed in Table 1. We chose the relative change of 25% for the initial environmental RH to be comparable to that for the initial vortex size discussed in section 3 while we increased RH by 12.5% in RH1125 to avoid any saturation at the initial time of the experiment.

Figure 16 shows the time evolution of the azimuthal mean maximum wind at the lowest model level and the minimum sea level pressure in all initial environmental RH experiments. With the reduced initial environmental RH in RH75 and RH50, the storms took longer time to spin up and showed a delayed rapid intensification and longer time to reach the steady-state intensity evolution. For example, the storm in RH75 (RH50) started its rapid intensification phase after about 30 h (48 h) of simulation, about 18 h (36 h) later than that in RH100. This is because the initially unsaturated inner core of the storm took longer time to become saturated in a drier environment, as discussed previously by Rotunno and Emanuel (1987) and Emanuel (1989). With a 12.5% increase in the initial environmental RH in RH1125, the initial spinup became slightly shorter than that in RH100 but the subsequent evolution is quite similar until about 192 h of simulation (Fig. 16). In the last 48-h simulation, the storm in RH1125 experienced a slight weakening, which was related to the rapid increase in the storm size (see discussion below). The maximum intensity in terms of the maximum azimuthal mean wind speed at the lowest model level in these experiments was generally similar to each other, indicating that the maximum intensity is not very sensitive to the initial environmental RH (Fig. 12a), consistent with the results of Hill and Lackmann (2009).

Figure 17 shows the corresponding time evolution of the RMW and RDW at the lowest model level. The RMW in the drier initial environment decreased first and increased for a while before a rapid contraction related to the delayed rapid intensification of the simulated storms occurred (Fig. 17a). The RMW in the 4 experiments was quite similar except for the storm in an initially wetter environment in RH1125, which showed an increase in RMW in the last 48-h simulation. As a result of the delayed rapid intensification, the storm with the drier initial environmental RH reached the damage-force wind later than in RH100 (Fig. 16a), leading to the appearance of the RDW to be delayed by about 24 h for each 25% reduction in the initial environmental RH (Fig. 17b). The subsequent evolution of the inner-core size in terms of the RDW was also different in RH75 and RH50 from that in CTRL. In general, the drier the initial environment was, the smaller the RDW of the simulated storm would be. In the two drier environment simulations, the RDWs of the storms were similar to each other during 144- and
192-h simulation immediately after the storms ended their rapid intensifications, but both were smaller than that in RH100 throughout the 240-h simulation. The RDW in RH50 remained almost constant at about 50 km after the rapid intensification, while that in RH75 increased slightly with time after 192-h simulation, similar to that in RH100. As a result, the average RDWs in RH75 and RH50 in the last 24 h of simulation were 12.5 and 20 km, or about 17% and 28% smaller than those in RH100, respectively, due to 25% and 50% decreases in the initial environmental RH. A drastic increase in both the RMW and RDW occurred to the storm in RH1125 after the 168-h integration. By 240 h, the RDW and RMW reached 108 km and 27.5 km, respectively, or about 49% and 57% larger than those in RH100. Therefore, the change in the inner-core size is asymmetric to increasing and decreasing the initial environmental RH. It is more sensitive for the wetter environment than for the drier environment. This asymmetric response of the simulated storm inner-core size to changes in the environmental RH was consistent with the results of Hill and Lackmann (2009).

For the same proportional change (25% here), the initial environmental RH seems to have a relatively weaker effect on the mature storm inner-core size than the initial vortex size except for the very wet case in RH1125 in the later stage of the simulation. As we can see from Table 1, averaged in the last 24-h simulation, a 25% increase (decrease) in the initial vortex size resulted in a 38% increase (decrease) in the RDW, while a 25% decrease in the initial environmental RH led to less than 17% decrease in the RDW at most. A similar conclusion applies to the response in the RMW (Table 1). Therefore, the intensity of the simulated storm in the mature phase is not very sensitive to either the initial vortex size if the initial storm is not too small, such as in the case S40, or the environmental RH with reasonable settings in our idealized simulations. The inner-core size of the simulated storm at the mature stage is more sensitive to the initial vortex size than to the initial environmental RH. Namely, our results demonstrate that the initial vortex size plays a more important role in determining the inner-core size of TCs than variations in the environmental RH although the latter is also important.

There are still two issues here: how the near-core environmental RH is modified by the storm and what determines the initial vortex size. To address the first issue, we plot the time–radius cross section of the azimuthal mean RH vertically averaged between the sea surface and 10-km height in Fig. 18. We can see that in general RH in the larger storms is higher in the near-core environment because of the larger surface moisture flux and more active deep convection outside the eyewall. A weak inward shrinking of the radial extent of high RH in all experiments is related to the overturning subsidence associated with the secondary circulation of the simulated storm. In this sense, the inner-core size and the near-core environmental RH are not independent of each other during the evolution of the simulated storm. To address the second issue, a systematic analysis of the horizontal scale of the tropical disturbances (TDs) that developed into TCs is required in a future study. Overall, the tropical disturbances initiated in the monsoon trough over the western North Pacific are generally large, while those initiated from the easterly waves over the North Atlantic and those generated in the subtropical regions are relatively small. Furthermore, the initial size of tropical disturbances is unlikely independent of the environmental RH. Therefore, our conclusion on the relative importance of the initial vortex size and the environmental RH is only compared with varying the initial conditions specified in idealized simulations. Nevertheless, the results have implications for the initialization of initial vortex size and the environmental RH.

In addition, previous studies show that development of concentric eyewall and angular hurricane structure may lead to significant increase in TC inner-core size (Knaff et al. 2007; Maclay et al. 2008; Wang 2008b, 2009). Both phenomena are favored by the environment.
FIG. 18. Vertically averaged azimuthal mean relative humidity (%) from the surface up to 10-km height in experiments (a) S60, (b) S80, (c) S100, (d) RH1125, (e) RH75, and (f) RH50. The isotachs of 25.7 m s$^{-1}$ are shown by white contours and the RMW in each experiment is shown by the black line.
with relatively high RH (Wang 2009). The results from this study should not be misinterpreted as the environmental RH being not important to the inner-core size of TCs, but just suggests that the initial vortex size is more important than the initial environmental RH. We thus call for attention to accurately initialize both the initial vortex size and the environmental RH in order to improve the prediction of the inner-core size of TCs by numerical models.

5. Conclusions

In this study, the influence of the initial vortex size on the inner-core size of the simulated TC has been investigated using a three-dimensional cloud-resolving TC model. The study has focused on how the initial vortex size controls the TC inner-core size in the mature stage. A positive feedback mechanism responsible for the TC inner-core size is identified. The relative importance of the initial vortex size and the initial environmental RH to the inner-core size of the simulated TC has also been evaluated based on some sensitivity experiments.

The results show that a large initial size vortex has a broad tangential wind distribution outside the RMW, causing large surface entropy fluxes outside the eyewall and favoring the development of active spiral rainbands. Diabatic heating in spiral rainbands drives strong boundary layer inflow outside the eyewall. The latter brings high absolute angular momentum inward and thus contributes to the increase in tangential winds outside the eyewall, leading to the outward expansion of the wind field and the increase in the inner-core size of the simulated TC. The broadened wind field favors more surface entropy flux outside the eyewall and thus more active spiral rainbands. In addition, the large radial extent of relatively high absolute vertical vorticity in the large-size initial vortex causes the increase in tangential wind because of radial advection of absolute angular momentum effective. This is a positive feedback for the large initial size vortex to increase in its inner-core size in the simulation. On the contrary, a small initial size vortex with the same intensity has weak winds and thus small surface entropy fluxes outside the eyewall, prohibiting the development of active spiral rainbands in large radii, resulting in weak boundary layer inflow outside the eyewall and limiting the radial advection of absolute angular momentum. As a result, the increase in tangential winds outside the eyewall is suppressed, the outward expansion of the wind field is prohibited, and thus the inner-core size remains small. This is a positive feedback to maintain a small inner-core size storm. The positive feedback mechanism identified in this study can thus explain the observational results of Cocks and Gray (2002), which showed that small TCs were smaller than the medium and large TCs early on and throughout their respective composite life cycles.

Since previous studies have emphasized the role of the environmental RH in controlling the inner-core size of TCs, it was our interest to have evaluated the relative importance of the initial vortex size and the initial environmental RH to the inner-core size of the simulated TCs. Consistent with previous findings, a relatively drier initial environment leads to weaker spiral rainbands, limiting the outward expansion of wind fields and thus favoring the small inner-core size of the simulated TC. However, the results show that the initial environmental RH has a weaker control on the inner-core size of the simulated TC at the mature stage than the size of the initial vortex except for the case with very a wet initial environment. Our results thus suggest that in addition to the importance of the environmental moisture field, realistic initialization of the vortex size is critical to the skillful prediction of the storm inner-core size and the distribution of damaging winds in TCs by numerical weather prediction models.

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