Interactive Radiation Accelerates the Intensification of the Midlevel Vortex for Tropical Cyclogenesis

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ABSTRACT: Interactive radiation helps accelerate tropical cyclogenesis, but the mechanism is still unclear. Using idealized numerical modeling in the radiative–convective equilibrium framework, it is revealed that interactive radiation can bring forward tropical cyclogenesis by accelerating the development of the midlevel vortex. A strong horizontal longwave radiative warming anomaly in the layer between 6 and 11 km altitudes in the vortex region, caused by large concentration of ice-phased particles at high levels, is critical to the development of the midlevel vortex. This longwave radiative warming anomaly induces more upward water vapor flux (mainly in the nonconvective region) and then results in more latent heating at upper levels and more sublimation and melting cooling at lower levels. This leads to an increase of the vertical diabatic heating gradient, and then the intensification of the midlevel vortex. A stronger upward water vapor flux also produces more condensates at upper levels and further enhances the horizontal longwave radiative warming anomaly in the upper troposphere, constituting a positive feedback, and then accelerates tropical cyclogenesis.

KEYWORDS: Tropical cyclones; Longwave radiation; Shortwave radiation

1. Introduction

By far, understanding the mechanisms controlling tropical cyclone (TC) genesis (the formation of a strong and compact low-level circulation) remains a big scientific challenge. Processes with multiple scales are deeply involved in TC genesis. In many cases, a midlevel vortex forms ahead of the low-level vortex (e.g., McBride and Zehr 1981; Bister and Emanuel 1997; Simpson et al. 1997; Nolan 2007; Raymond et al. 2011). This midlevel vortex is usually promoted by stratiform (the stratiform region in this study includes both stratiform precipitation region and anvil-type precipitation region) dynamics in MCS regions (e.g., Raymond and Jiang 1990; Chen and Frank 1993; Bister and Emanuel 1997; Bell and Montgomery 2019). Theories on how the midlevel vortex leads to a low-level vortex generally fall into two categories: 1) “top down” thinking and 2) “bottom up” thinking. The top-down thinking argues that the downward building of the midlevel vortex could produce the low-level circulation (e.g., Bister and Emanuel 1997). However, this mechanism has rarely been validated in observational studies. On the other hand, the bottom-up thinking argues that the near-surface vortex is enhanced by the low-level convergence induced by deep convection (e.g., Hendricks et al. 2004; Montgomery et al. 2006; Houze et al. 2009). Comparing with the idea that the midlevel vortex can directly build downward to the surface in the top-down thinking, the midlevel vortex is considered as a favorable condition for low-level convergence in the

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Fig. 1. A schematic diagram showing cloud-radiative mechanisms in the vortex region. The radiative cooling rate is shown in blue, with darker colors representing stronger cooling. The cloudy area indicates the disturbance region. Pathway 1 indicates that convection can be influenced by change of lapse rate due to large-scale environmental radiative cooling. Pathway 2 indicates that convection in the disturbance region can be influenced through lapse-rate change due to cloud-top cooling and cloud-base warming in the upper troposphere. Pathway 3 indicates that convection can be affected by a secondary circulation induced by radiative heating difference between the disturbance region and the environment. Pathway 3’ is the mechanism proposed in this study, that the radiative heating difference between the disturbance region and the environment can accelerate the midlevel circulation, which indirectly influences convection.

between radiative heating above the cloud and at the cloud base (e.g., Webster and Stephens 1980; Hobgood 1986; Xu and Randall 1995; Tang et al. 2019). The radiative cooling (mostly during nighttime) at the upper-tropospheric cloud (mainly stratiform cloud) top and the warming at the cloud base could stimulate deep convection by enhancing convective instability. Last but not least, the differential radiative heating between the cloudy region (warming anomaly) and the environment (cooling anomaly) could drive a secondary circulation (e.g., Gray and Jacobson 1977; Craig 1996; Nicholls 2015; Muller and Romps 2018). The ascent branch of the circulation in the cloud region could enhance convection (Nicholls 2015). Meanwhile, when the secondary circulation is a low-level one and the lower branch of the circulation is in the boundary layer (BL), moisture could be transported from the environmental BL into the disturbance region, which then accelerates TC genesis (Muller and Romps 2018).

Previous studies show that radiation can affect convective activity and TC genesis by changing convective instability and inducing a secondary circulation. Our hypothesis is that, besides the above pathways that radiative heating structure could directly influence convective activity, radiative effect can also indirectly affect convective activity and TC genesis through the midlevel vortex in a rotational background. In a convective self-aggregation simulation of TC genesis, the occurrence and development of the midlevel vortex is very much delayed when a homogeneous Newtonian cooling profile is applied instead of an interactive radiation scheme (Davis 2015). Meanwhile, there is evidence showing that the horizontal radiative heating difference between the initial disturbance region and the cloud-free environment can accelerate the development of the midlevel vortex, especially when the vortex is weak (Smith et al. 2020). Therefore, there seems to be a pathway that horizontal radiative heating difference could accelerate the midlevel vortex before TC genesis (Fig. 1, pathway 3’), which has not been clearly revealed yet.

In this study, we intend to find out the effect of horizontal radiative heating difference on the development of the pre-TC midlevel vortex in TC genesis. This paper is organized as follows. Section 2 introduces the design of the numerical experiments and some analysis of the results. The detailed mechanisms on how radiative heating difference can accelerate the development of midlevel vortex is revealed in section 3 and summary is provided in section 4.

2. Method and analysis

The numerical experiments are designed in idealized radiative-convective equilibrium (RCE; Manabe and Strickler 1964) framework to study the effect of interactive radiation on the development of the midlevel vortex. RCE is a good approximation of the tropical atmosphere, which is a good idealization for understanding tropical atmosphere and its sensitivity to radiative and surface forcing (Bretherton et al. 2005). Rotating RCE framework has been used in many previous studies to investigate the feedbacks in tropical cyclogenesis (e.g., Nolan et al. 2007; Wing et al. 2016; Muller and Romps 2018). The numerical model used in this study is the Weather Research and Forecast (WRF) Model, version 3.7 (Skamarock et al. 2008). The horizontal grid spacing in our simulations is 3 km. There are 50 vertical levels in our domain, among which 10 levels are below 1 km altitude. The first grid level is at 38 m above the surface. The model top is at 27 km with the upper third of the model domain to be a sponge layer. All simulations are three-dimensional on a square with double periodic boundary conditions. The sea surface temperature is fixed at 302.15 K (29°C) and the surface pressure is set to be 1000 hPa. To reduce the computational cost, the Coriolis parameter is set to be 0.0001 s⁻¹ everywhere in the domain, as in Muller and Romps (2018). This is a midlatitude (43°N) Coriolis parameter, which will accelerate TC evolution compared to realistic tropical values. The Thompson microphysics scheme (Thompson et al. 2004), RRTMG longwave and RRTMG shortwave radiation scheme (Iacono et al. 2008) are used in our simulations. Since this study focuses on the horizontal radiative heating difference, the diurnal cycle is ruled out by fixing the zenith angle and the insolation to be 45° and 500 W m⁻², respectively. The YSU boundary layer scheme is used, coupled with the revised Monin–Obukhov surface-layer scheme (Hong et al. 2006). We first perform an RCE simulation in a 90 km × 90 km small domain for 100 days. Because of the domain limit, there is no convective self-aggregation or TC
genesis in this simulation. The horizontal-mean temperature and water vapor profiles averaged over the last 20 days are used to create an RCE sounding. The RCE sounding is a little bit wetter and warmer than tropical soundings from observations (e.g., Jordan 1958). This profile is then used in a larger domain \((720 \text{ km} \times 720 \text{ km})\) to initialize the control experiment (CNTL). Convection in CNTL is kicked off by adding random noise in the potential temperature field at the lowest 10 grid levels with maximum perturbation to be 0.1 K. There is no initial vortex in CNTL. The vortices (as well as the midlevel vortices) in our simulation are self-organized, which will be more physically constrained than imposed ones.

Besides CNTL, several experiments are designed to test the sensitivity of tropical cyclogenesis to different feedbacks (Table 1). In experiment UFLUX, surface flux feedback is removed by horizontally averaging sensible and latent heat flux every time step. Radiative heating difference in the horizontal is removed by horizontally averaging radiative heating at each model level every time step in experiment URAD. Finally, in experiment UBOTH, both radiative heating and surface flux differences in the horizontal are removed.

Figure 2a shows the evolution of minimum surface pressure of simulated TCs in the four experiments. Unsurprisingly, the TC in CNTL is the first to develop among the four experiments. The storm in CNTL begins to rapidly intensify after day 17 and reaches maturity around day 21. This result restates that both surface flux feedback and radiative feedback can help accelerate TC genesis. It is evident that no simulated TC ever occurs in UBOTH, corresponding to the experiment noSFC-noRAD in Muller and Romps (2018). The interesting phenomenon is that the TC in UFLUX develops much earlier than that in URAD, although its intensification rate is smaller and its final intensity is much weaker. This indicates that in the early period, compared to surface flux feedback, radiative feedback plays a more important role in TC genesis. However, surface flux feedback still controls the intensification rate and the final intensity of the storm, which is similar to the results in Zhang and Emanuel (2016).

The time evolution of the maximum tangential-mean midlevel \((5 \text{ km})\) and low-level \((1 \text{ km})\) wind velocity in the four experiments are plotted in Fig. 2b. Circulation centers at different levels are calculated individually. In both CNTL and UFLUX, a midlevel circulation develops ahead of the low-level circulations in the early stage, which matches the results in previous studies (e.g., Nolan 2007; Davis 2015). The intensity of the midlevel circulation in UFLUX is quite close to that in CNTL during the early 15 days, further indicating that surface flux feedback is not very important in the early stage.

Table 1. Experimental design.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>A 60-day natural run with full physics in the RCE</td>
</tr>
<tr>
<td>UFLUX</td>
<td>As in CNTL, with the surface latent and sensible flux horizontally averaged every time step</td>
</tr>
<tr>
<td>URAD</td>
<td>As in CNTL, with the radiative heating horizontally averaged every time step</td>
</tr>
<tr>
<td>UBOTH</td>
<td>As in CNTL, with the radiative heating and surface flux horizontally averaged every time step</td>
</tr>
<tr>
<td>RADL</td>
<td>As in CNTL, with the radiative heating horizontally averaged from 0 to 6 km height every time step</td>
</tr>
<tr>
<td>RADM</td>
<td>As in CNTL, with the radiative heating horizontally averaged in the layer between 6 and 11 km height every time step</td>
</tr>
<tr>
<td>RADQ</td>
<td>As in CNTL, but feed the radiation model with a horizontally averaged water vapor concentration every time step</td>
</tr>
<tr>
<td>RADQC</td>
<td>As in CNTL, but feed the radiation model with a horizontally averaged cloud water concentration every time step</td>
</tr>
<tr>
<td>RADI</td>
<td>As in CNTL, but feed the radiation model with a horizontally averaged ice concentration every time step</td>
</tr>
<tr>
<td>RADQS</td>
<td>As in CNTL, but feed the radiation model with a horizontally averaged snow concentration every time step</td>
</tr>
<tr>
<td>RADM1</td>
<td>Restart at 0000 LY on day 7 of CNTL, with radiative heating horizontally averaged in the layer between 6 and 11 km height every time step</td>
</tr>
</tbody>
</table>
Wing et al. (2016). On the other hand, neither URAD nor UBOOTH shows very obvious midlevel circulation in the first 15 days, indicating that radiative feedback plays a leading-order role to the formation of the midlevel vortex in the early period. To test the robustness of this result, another two sets of experiments are conducted. In extra set 1, the Morrison microphysics scheme (Morrison et al. 2009) is used instead of the Thompson (Thompson et al. 2004) microphysics scheme. In extra set 2, we substitute the RRTMG (Iacono et al. 2008) longwave and shortwave radiation schemes with the Goddard (Chou and Suarez 1999) longwave and shortwave radiation schemes. As shown in Fig. 3, the general result is not influenced when using different microphysics and radiation schemes. Although the midlevel vortices in UFLUX with the Goddard scheme show a higher intensification rate (Fig. 3b), additional tests with another initial field indicate that this is not a universal phenomenon (not shown). The experiments strongly validate the hypothesis that in the early stage, horizontal radiative heating difference can accelerate TC genesis by promoting the formation of midlevel vortices.

Figure 4 shows the plan view of the evolution of the midlevel vortices in CNTL. Each plot is a temporal average of the velocity field (5 km height) during the first three hours on its respective day. On day 7, there is a discernable vortex at the bottom-right corner of the domain (Fig. 4a), with its maximum mean tangential velocity about 2 m s\(^{-1}\) (Fig. 2b). There are areas with positive vorticity at the upper-left corner of the domain, but no counterclockwise circulations can be clearly observed. Three days later, the vortex at the bottom-right corner intensifies (Fig. 4b), with its maximum mean tangential velocity over 4 m s\(^{-1}\) (Fig. 2b). On the other hand, a weak vortex can also be observed at the upper-left corner of the domain. These two vortices then intensify together, while getting close to each other at the same time. By day 14, the centers of the two vortices are already in one bigger circulation (Fig. 4c). The vortex-merging process ends on day 16, by this time there is only one big and strong vortex in the domain (Fig. 4d). The general evolution of the midlevel vortices is very similar to those in Davis (2015), but the development is much faster due to a larger Coriolis parameter.

A “quartile analysis” is used to have an intuitive understanding of the relationship between radiative heating and the midlevel vortex (Bretherton et al. 2005). The domain area is divided into 100 equal-sized squares, with size 72 km \(\times\) 72 km. These blocks are sorted by their average midlevel (5 km) vorticity from low to high. The square with the smallest midlevel vorticity is set on the leftmost side of figure. Since it is the radiative heating difference that we are interested in, the heating that we show in the plots has subtracted its horizontal mean at each level. The midlevel vorticity-ranked horizontal radiative heating anomaly, which has been averaged from day 7 to day 10 (average of 73 snapshots), is shown in Fig. 5. In the troposphere, horizontal longwave radiative heating anomaly is quite obvious in areas with strong midlevel vorticity, with a weak warming anomaly below 6 km, a strong warming anomaly in the layer between 6 and 11 km altitudes and a strong cooling anomaly above 11 km (Fig. 5a). This vertical structure of longwave radiative heating anomaly is consistent with previous observations and numerical studies (e.g., Gray and Jacobson 1977; Tao et al. 1996). Compared with longwave radiation, horizontal shortwave radiative heating anomaly is quite weak across the whole domain (Fig. 5b). As a consequence, the total radiative heating anomaly is dominated by longwave radiative heating anomaly (Fig. 5c).

To understand the importance of the radiative heating anomaly at different levels to the acceleration of the midlevel vortex, more sensitivity experiments are conducted based on CNTL (Table 1). The experimental setting of RADL is the same as that in CNTL, except that the warming anomaly below 6 km is removed by horizontally averaging radiative heating (longwave and shortwave) below 6 km height. With the same method, the warming anomaly in the layer between 6 and 11 km altitudes is removed in RADM, and the cooling anomaly above 11 km height is removed in RADH. Figure 6 shows that removing neither warming anomaly below 6 km nor cooling anomaly above 11 km can effectively delay the development of the midlevel circulation. Removing the cooling anomaly above 11 km even accelerates the development of the midlevel vortex. However, removing the warming anomaly in the layer between 6 and 11 km altitudes can effectively suppress the development of the midlevel vortex, indicating that the horizontal radiative warming anomaly in the layer between 6 and
11 km altitudes is critical to the acceleration of the midlevel circulation.

The vertical radiative heating anomaly dipole at upper levels, which includes a warming anomaly in the cloud layer (6–11 km) and a cooling anomaly above 11 km, is a typical radiative heating structure of stratiform cloud cover (Tao et al. 1996). To understand what kind of water substance in our simulation is responsible for this radiative heating structure, Fig. 7 gives the midlevel vorticity-ranked profiles of mixing ratios of cloud water (QC), snow (QS), ice (QI), and water vapor (QV), averaged from day 7 to day 10 (average of 73 snapshots) in CNTL. Cloud water particle seems to have very little effect on radiative warming anomaly above 6 km because it mostly concentrates below 6 km (Fig. 7a). Above 6 km, particles mainly consist of snow and ice. The magnitude of snow particle concentration is one order larger than the other particles, because the Thompson scheme tends to produce more snow (e.g., Bao et al. 2019). The snow particle mainly concentrates in the layer between 6 and 11 km altitudes near the center of the midlevel circulation (Fig. 7b). Its distribution and altitude match very well with the radiative heating anomaly structure. Ice particle has a similar distribution.

Fig. 4. Plan views of the velocity field at 5 km height in CNTL on (a) day 7, (b) day 10, (c) day 14, and (d) day 16.
with snow particle, while its concentration is quite small (Fig. 7c). It is worth mention that there is an enhanced particle concentration in the lowest-ranked columns of vorticity. This might result from the usage of a relatively small domain with periodical boundary condition. The gravity waves produced by convection in the vortex region will spread outward, which converge at the areas with negative midlevel vorticity and could excite new convection due to the periodic boundary condition. The enhanced particle concentration in the lowest-ranked columns of vorticity also results in a weak radiative warming anomaly below the cloud layer (Fig. 5a). The difference of water vapor across the domain is much smaller compared to the magnitude of water vapor, so it is quite difficult to have an intuitive guess. In our simulation, graupel particle is not treated in RRTMG scheme, so it is not considered here.

The snow and ice particles near the midlevel vortex center seem to be responsible for this dipole heating anomaly structure, which is supported by previous studies (e.g., Bu et al. 2014; Fovell et al. 2016). To verify this point, four sensitivity experiments are conducted (Table 1). RAD-QS is also based on CNTL, but the snow mixing ratio feeding to the radiation (longwave and shortwave) model at each level is a horizontal domain average. RAD-QI, RAD-QC, and RAD-QV use the same method, their only differences are the averaged water variables that feed to the radiation model. Experimental results show that only when radiative effect of snow is averaged (RAD-QS) can the development of midlevel vortex be suppressed (Fig. 8). A more interesting question is: what makes snow particle so special, its concentration or its optical nature? Sensitivity experiments show that when snow particle is treated as ice particle in RRTMG radiation transfer model, the maximum tangential wind of the midlevel vortex reaches 10 m s\(^{-1}\) at the end of day 15 (not shown). However, when feeding the radiation model with a snow concentration 1/10 of the real value, the midlevel vortex grows much

![Fig. 5. Midlevel vertical vorticity-ranked (a) longwave, (b) shortwave, and (c) total horizontal radiative heating anomaly (K day\(^{-1}\)), averaged from day 7 to day 10 (73 snap shots) in CNTL.](image)

![Fig. 6. Time evolution of the mean maximum tangential wind velocity (m s\(^{-1}\)) at 5 km in CNTL (thick solid), RADL (dashed), RADM (dotted), and RADH (thin solid).](image)
slower (not shown). Therefore, it is the large concentration of ice-phased particles (in the Thompson scheme, snow) in the upper levels of the midlevel vortex that is responsible for the 6–11 km radiative warming anomaly, which further results in the acceleration of the midlevel circulation. The radiative effect of water vapor could also accelerate the development of the midlevel vortex (Fig. 8), as shown in Davis (2015), but its impact is relatively small.

3. Mechanisms of midlevel vortex acceleration

This section focuses on the mechanisms of the acceleration of the midlevel vortex by the radiative warming anomaly. The midlevel vortex corresponds to a warm anomaly above 5 km and a cold anomaly below 5 km (Fig. 9e). With the acceleration of the midlevel circulation, the temperature anomaly dipole intensifies at the same time. In fact, the midlevel positive vorticity is actually a positive potential vorticity (PV; Fig. 9g). It is more intuitive to understand the mechanism of midlevel vortex through PV thinking (Fritsch et al. 1994).

The expression of PV is written as

\[ P = \frac{1}{\rho} \eta \theta, \]  

in which \( P \) is PV, \( \rho \) is the density, \( \eta \) is the absolute vorticity vector, and \( \theta \) is the potential temperature. When friction and horizontal vorticity are ignored, the equation of PV tendency can be approximated as

\[ \frac{dP}{dt} = \frac{1}{\rho} \frac{\partial Q(f + \zeta)}{\partial z}. \]  

\[ (2) \]

![Fig. 7. Midlevel vertical vorticity-ranked concentration of (a) cloud water mixing ratio (mg kg\(^{-1}\)), (b) snow mixing ratio (mg kg\(^{-1}\)), (c) ice mixing ratio (mg kg\(^{-1}\)), and (d) water vapor mixing ratio (g kg\(^{-1}\)), averaged from day 7 to day 10 (73 snap shots) in the CNTL.](image)

![Fig. 8. Time evolution of the mean maximum tangential wind velocity (m s\(^{-1}\)) at 5 km in CNTL (black), RAD-QV (blue), RAD-QC (red), RAD-QI (light blue), and RAD-QS (pink).](image)
FIG. 9. (a),(b) Azimuthal mean of tangential wind ($\text{m s}^{-1}$), (c),(d) relative humidity ($\%$), (e),(f) horizontal potential temperature anomaly (K), (g),(h) potential vorticity ($\times 10^{-7} \text{ m}^2 \text{ K s}^{-1} \text{ kg}^{-1}$), and (i),(j) concentration of snow plus ice ($\times 10^{-2} \text{ g kg}^{-1}$), all averaged in the last 24 h on day 9. Columns represent the variables in (left) CNTL and (right) RADM1.
In Eq. (2), $f$ is the Coriolis parameter, $\zeta$ is the relative vertical vorticity, and $Q$ is the diabatic heating rate. Since the vortex that we focus on has a maximum at 5 km altitude, $\partial Q / \partial z$ at middle levels is very small (not shown). Based on this, Eq. (2) can further be approximated as
$$\frac{dP}{dt} \approx \frac{1}{\rho} (f + \zeta) \frac{\partial Q}{\partial z}. \quad (3)$$

Equation (3) indicates that the increase of potential vorticity is proportional to the increase in vertical gradient of diabatic heating ($\partial Q / \partial z$).

To have a better understanding on how radiative warming anomaly favors the increase of $\partial Q / \partial z$ in the midlevel vortex region, another sensitivity experiment RADM1 is designed. This experiment has the same setting as that in RADM, but it restarts from CNTL at 0000 LT on day 7 and run for another 3 days. During this period, the vortices in CNTL (one at the bottom right of the domain and the other one at the upper left) evolve individually, with no obvious merging process (Figs. 4a,b). Our following analysis will focus on the evolution of the stronger (bottom right) vortex. In Figs. 9a and 9b, the tangential wind profiles averaged in the last 24 h (24 snapshots) of the vortices in CNTL and RADM1 are plotted. When the radiative warming anomaly at 6–11 km is removed, the tangential-mean velocity of the midlevel vortex in RADM1 is weaker by about 1.5 m s$^{-1}$ than that in CNTL. The size of the midlevel vortex (defined to be the outer radius of 1.5 m s$^{-1}$ tangential velocity) in RADM1 is also smaller. In CNTL, the outer radius of 1.5 m s$^{-1}$ tangential wind averaged in the last 24 h is over 240 km (not shown), while the specific radius in RADM1 is about 175 km (Fig. 9b). This result is quite similar to that in Bu et al. (2014), which pointed out the importance of the in-cloud anvil radiative warming to TC size during the mature stage. The warm anomaly above 5 km and the cold anomaly below 5 km is weaker in RADM1 (Figs. 9e,f), indicating a weaker midlevel PV (Figs. 9g,h). The simulated midlevel vortex in RADM1 also corresponds to a lower midlevel relative humidity at the end of the simulation (Figs. 9c,d), validating the point that a stronger midlevel circulation often corresponds to a more humid midlevel troposphere.

The 3-day mean diabatic heating profiles in the vortex region (averaged within 120 km radius) from day 7 to day 10 in CNTL and RADM1 are plotted in Fig. 10. In CNTL the vortex region corresponds to a positive $\partial Q / \partial z$ at 5 km height during this period, with the maximum cooling at 4 km ($-0.3$ K day$^{-1}$) and the maximum warming at 7 km ($1.8$ K day$^{-1}$). This heating structure favors the intensification of the midlevel PV in CNTL. However, in RADM1 the 3-day mean $\partial Q / \partial z$ in the vortex area is nearly zero at 5 km. Blue and red curves in Fig. 10 show the diabatic heating profiles contributed from radiative process ($Q_R$) and latent heating (microphysics process, $Q_M$). In both experiments, $Q_R$ is negative in the troposphere, with maximum cooling at about 7 km. There is no big difference in $Q_R$ profiles between CNTL and RADM1. Near the PV maximum (about 5 km), both experiments show a negative $\partial Q_R / \partial z$. It indicates that from the perspective of vertical diabatic heating profile, radiative heating in the vortex region does not favor the production of the midlevel PV in both experiments. However, the upper-level horizontal radiative heating anomaly in the vortex region (Fig. 5c), small as it is, has a great impact on the increase of vertical gradient of microphysics.
The inner 120 km radius of the midlevel vortex. The concentration of snow plus ice \((0.55 \text{ K day}^{-1})\) during the intensification of the vortex (Fig. 11). This pulsing vortex region in CNTL, MCS events occur one after another through physical processes. Taking a close look at the midlevel stratiform precipitation in MCS regions strengthens the mid-level heating structure is critical to the development of midlevel convection. Schumacher et al. (2004) showed that the stratiform region of the MCS has a strong vertical gradient of diabatic heating, which is almost twice as that in RADM1 \((0.55 \text{ K day}^{-1})\). In CNTL, the strong positive latent heating gradient counteracts the negative radiative heating gradient and results in a positive \(\partial Q/\partial z\), which in turn intensifies the midlevel PV. The \(\partial Q_M/\partial z\) in RADM1 is not strong enough, so the vertical gradient of the total diabatic heating at 5 km is almost zero, resulting in a much slower development of midlevel vortex.

As revealed in previous studies, midlevel vortices (PV anomalies) are closely connected with mesoscale convective systems (MCS). Through analysis of TRMM observation, Schumacher et al. (2004) showed that the stratiform region of the MCS has a strong vertical gradient of diabatic heating, which is most pronounced at middle levels. This vertical heating structure is critical to the development of midlevel vortices. Through observational analysis into Hurricane Karl (2010), Bell and Montgomery (2019) also concluded that stratiform precipitation in MCS regions strengthens the midlevel circulation through convergence associated with ice microphysical processes. Taking a close look at the midlevel vortex region in CNTL, MCS events occur one after another during the intensification of the vortex (Fig. 11). This pulsing phenomenon is also noted in Nolan (2007), which could result from a relatively moist sounding, a small domain, and the periodic boundary condition. Figure 12 shows a typical MCS process in CNTL, indicated by the concentration of snow and ice particles near the vortex center. This MCS event starts at 0200 LT on day 7, with a burst of strong convective cells. Although convection is strong at this time, the concentration of solid particles is not very large in the vortex region. Starting from 0400 LT, the cells with very large particle concentration start to weaken. The systematic increase in solid particles in the vortex area indicates the transition from convective precipitation to stratiform precipitation. The stratiform cloud cover reaches its peak at 0500 LT and starts to decay afterward. The averaged latent heating profile from 0200 to 0900 LT is plotted as the black curve in Fig. 13a. There is a positive diabatic heating gradient at about 5 km altitude, with the maximum heating \((14.5 \text{ K day}^{-1})\) at 7.5 km and the minimum heating \((0.2 \text{ K day}^{-1})\) at 4 km. There is shallow convection throughout the whole event. The latent heating by shallow convection counteracts a part of the diabatic cooling below 4 km, finally resulting in a minimum near 4 km altitude. We further divide 0200–0500 LT to be the developing stage of the MCS, and 0500–0900 LT to be the decaying stage. The heating profile in the developing stage is a very typical convective heating structure, further indicating that convective activity dominates in this stage (Fig. 13b). Although the heating profile shows a positive \(\partial Q_M/\partial z\) tendency at 5 km in the developing stage, the magnitude of \(\partial Q_M/\partial z\) is much smaller than that in the decaying stage. The heating profile in the decaying stage is a very typical stratiform heating structure, with a heating layer above 5 km and a cooling layer below (Fig. 13c).

The red curve in Fig. 13a shows the latent heating profile averaged in the whole MCS event (0200–0900 LT on day 7) in RADM1. The maximum latent heating near the vortex center in RADM1 is about 13 K day\(^{-1}\) and the minimum heating is about 2 K day\(^{-1}\), indicating a weaker \(\partial Q_M/\partial z\). In the developing stage, RADM1 shows a weaker latent heating above 6 km compared to that in CNTL, but the difference is very small. There is no obvious difference in the heating profile below 6 km in this stage. However, in the decaying stage the heating difference is quite obvious, with a 3.8 K day\(^{-1}\) decrease of warming at 7 km and a 1.7 K day\(^{-1}\) decrease of cooling in the layer between 4 and 5 km. In general, with an upper-level radiative warming anomaly, CNTL shows a more significant stratiform (top heavy) heating structure in the decaying stage.

As revealed in previous studies (Houze 2014), the top-heavy heating structure is caused by condensates production (heating associated with deposition and condensation) at upper levels, and the sublimation and melting cooling of these condensates at lower levels. Also shown in Figs. 10 and 13, compared to the increase of cooling at lower levels, the increase of heating at upper levels is more important to the increase of \(\partial Q_M/\partial z\) in CNTL. Therefore, the increase of condensates production at upper levels is critical to having a more significant top-heavy heating structure. Due to thermal wind balance, a stronger midlevel vortex corresponds to a stronger warm anomaly above (Figs. 9e,f). A stronger warm anomaly increases saturation pressure and lowers relative humidity, which does not favor the production of condensates. In order to have more condensates production at upper levels, more water vapor must be transported to upper levels to increase the relative humidity. As shown in previous studies (e.g., Tao et al. 1996; Nicholls 2015; Bu et al. 2014), radiative warming anomaly could induce a secondary circulation. The ascent branch of the secondary circulation might transport more water vapor upward and strengthen the stratiform heating structure. We denote the accumulated vertical flux of water vapor in the vortex region (within 120 km radius) in CNTL and RADM1 as \(F_1\) and \(F_2\), respectively. The solid line in Fig. 14 shows the profile of \(F_1 - F_2\). With the radiative warming anomaly at 6–11 km, more water vapor is transported upward above 6 km during the MCS.
event (Fig. 14). We further separate the total vertical flux into contributions from convective regions and nonconvective regions. The definition of convective regions follows the technique in Rogers (2010), except that the convective radius is fixed to be 6 km in our calculation. The nonconvective regions include stratiform regions and no-rain regions. With the radiative warming anomaly, both convective and nonconvective regions show an increase in upward water vapor flux above 6 km. However, the increase in nonconvective regions is dominant, especially at higher levels. Since nonconvective precipitation dominates in the decaying stage, it also explains why the diabatic heating in RADM1 is similar to that in CNTL in the developing stage, while the diabatic heating in RADM1 is much weaker in the decaying stage (Figs. 13b,c).

Through the above analysis, it is shown that radiative heating anomaly in the upper levels of the vortex region may transport more moisture upward, leading to more diabatic heating at high levels and more diabatic cooling at low levels, increasing the vertical gradient of microphysics diabatic heating and thus accelerate the midlevel circulation. We have also tested the effect of the radiative warming anomaly in other MCS cases (restarts at their specific time), and the results are quite similar (not shown). On the other hand, the increase of the upper-level latent heating produces more condensates.

**Fig. 12.** Tangential average of the concentration of snow plus ice ($10^{-2}$ g kg$^{-1}$) at (a) 0300, (b) 0400, (c) 0500, (d) 0600, (e) 0700, and (f) 0900 LT on day 7 in the vortex region in CNTL. The black solid line indicates the melting level.
As shown in Figs. 12 and 15, the concentration of condensates in CNTL is larger than that in RADM1, especially in the decaying stage. The increase in condensates will further enhance the upper-level radiative heating anomaly, constituting a positive feedback. In the long run, a stronger midlevel vortex favors stronger convection and produces larger and thicker cloud canopy (Figs. 9i,j), which will also enhance the upper-level radiative heating anomaly in the vortex region.

4. Summary

Interactive radiation helps accelerate tropical cyclogenesis, but the detailed pathways are still unclear. In this study, it is revealed that interactive radiation could indirectly promote convective activity and bring about TC genesis by accelerating the development of the preexisting midlevel vortex as shown in Fig. 1 (3rd pathway). This pathway is shown to be robust in experiments with other physics schemes.

Before TC genesis, in the vortex region there are three horizontal radiative heating anomalies in the vertical, including a weak warming anomaly below 6 km, a strong warming anomaly in the layer between 6 and 11 km altitudes and a strong cooling anomaly above 11 km. Through sensitivity experiments, the longwave radiative warming anomaly between 6 and 11 km altitudes is shown to be critical to the midlevel vortex formation and the development in tropical cyclogenesis. In our simulation, snow particle is shown to be the reason for this radiative warming anomaly, mostly because of its large concentration at upper levels.

The strong midlevel vorticity in our study also corresponds to a large positive PV, whose increase is proportional to the vertical gradient of diabatic heating. Sensitivity experiments show that with the 6–11 km horizontal radiative warming anomaly, more water vapor will be transported upward in nonconvective regions, which leads to more heating associated with deposition and condensation at upper levels and more cooling associated with sublimation and melting at lower levels, intensifying the top-heavy diabatic heating profile in the vortex region and finally accelerating the midlevel circulation. Meanwhile, the increase in latent heat release at upper levels produces more condensates and further enhances radiative warming anomaly, constituting a positive feedback.
feedback. This positive feedback in the vortex region could accelerate the development of the midlevel vortex and then the TC genesis.

The feedback revealed in this study is an important process during the early stage of TC genesis. Since in the real atmosphere TCs are often observed to develop from a midlevel vortex, this mechanism is expected to play an important role in many TC formation events in nature. Although radiative feedback can strengthen stratiform precipitation and accelerate the midlevel vortex, the pathway from a midlevel circulation to the development of a small-scale surface vortex is not addressed in this study. The subsidence warming or drying associated with the stratiform precipitation is unfavorable for the convective initiation, which could be alleviated by using RCE soundings in this study. More effort is needed to better understand the role of the nonconvective precipitation in TC genesis.

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