Reply to "Comments on 'How much does the upward advection of the supergradient component of boundary layer wind contribute to tropical cyclone intensification and maximum intensity?'"

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Abstract

This is a reply to the comments by Smith et al. (SGM20) on the work of Li et al. (LWL20) recently published in the *Journal of the Atmospheric Sciences*. All the comments and concerns by SGM20 have been well addressed or clarified. We think that most of the comments by SGM20 are not in line with the intention of LWL20 and provide one-sided and thus little scientifically meaningful arguments. Regarding the comment on the adequacy of the methodology adopted in LWL20, we believe that the design of the thought (sensitivity) experiment is adequate to address the scientific issue under debate and helps quantify the contribution by the upward advection of the supergradient component of boundary layer wind to tropical cyclone intensification, which is shown to be very marginal. Whereas, we are open minded to accept any alternative, better methods to be used to further address this scientific issue.

1. Introduction

In a recent paper, we (Li et al. 2020, hereafter LWL20) evaluated the extent to which the upward advection of the supergradient component of boundary layer wind contributes to tropical cyclone (TC) intensification rate and final intensity through ensemble axisymmetric model experiments. As mentioned in the introduction of LWL20, the study was motivated by the unproven claim of Schmidt and Smith (2016) and Montgomery and Smith (2017), namely part of the boundary layer spinup hypothesis of TC intensification of Smith et al. (2009), which reads “*The spin-up in the boundary layer is associated with the development there of supergradient winds. The spin-up of the eyewall updraught occurs by the vertical advection of the high tangential momentum associated with the supergradient winds in the boundary layer*’’ (Schmidt and Smith 2016, p. 1515; also see Montgomery and Smith 2017, p. 555). This statement is equivalent to claim that the upward advection of the supergradient component of boundary layer wind is a primary process that spins up the eyewall updraft aloft. However, this hypothesis/claim has not been quantified in the literature while it was cited as if it were a well-proven mechanism by some researchers in our community. For example, in Gopalakrishnan et al. (2011, p1774), “Smith et al. (2009) attributed the inner-core spinup to the existence of the unbalanced flows. Specifically, the supergradient tangential winds in the region of decelerating inflow are carried upward and outward to feed into the eyewall cloud”, and in Emanuel (2018, p15.15), “This latter assumption has been questioned by Smith et al. (2009), …, who argue that vertical advection of supergradient angular momentum out of the boundary layer is a significant contributor to interior spinup".

In LWL20, we attempted to provide an initial assessment of the above hypothesis. To do so, we conducted an ensemble control experiment and compared the intensification rate and final intensity of the simulated TC with those from an ensemble thought experiment in which the upward advection of the supergradient component of boundary layer tangential wind was suppressed. Our results show that this suppression led to little effect on the intensification rate but a slight decrease in the final (quasi-steady) intensity of the simulated TC. We found that compared with the control experiment, the thought experiment largely suppressed the outflow above the inflow boundary layer. Results from the tangential wind budget analysis showed that the upward advection of the supergradient wind component from the boundary layer is primarily responsible for the development of the outflow layer, which spins down tangential wind therein. As a result, the positive tangential wind tendency due to the upward advection of the supergradient component of boundary layer wind is largely offset by the negative tangential wind tendency due to the outward advection of absolute angular momentum (AAM), giving rise to a negligible net contribution to the spinup of tangential wind in the eyewall above the boundary layer. We thus concluded that "the upward advection of the supergradient component from the boundary layer wind should not be a dominant mechanism of TC intensification."

In their comments on LWL20, Smith et al. (2020, hereafter SGM20) raised three main issues. The first issue is the motivation of LWL20, namely whether the importance of supergradient winds to TC intensification "is still under debate", or whether the two views summarized in the Abstract of LWL20 are "separate views". The second issue is the experimental design in LWL20, they commented that suppressing the upward advection of supergradient wind out of the boundary layer in our thought experiment introduces "a ring of negative impulsive torque to the tangential momentum equation", which is unrealistic. The third issue is related to "what is 'the dominant mechanism'" for spinning up the eyewall beyond the framework of the boundary layer spinup hypothesis. Our responses to the above three issues are given below.

2. Motivation

SGM20 used their Eqs. (1) and (2) to argue that "Assuming that, above the frictional boundary layer, F_λ can be neglected, the only way that v can increase locally in a cyclonic vortex $(\zeta + f > 0)$ when the radial flow is outwards $u > 0$ is if the vertical advection of tangential momentum $-w\,\partial v/\partial z$ is positive and exceeds the radial flux of absolute vorticity, $(\zeta + f)u$ in magnitude". They thus comment that "This result seems so basic, it is hard to imagine why Li et al. consider it to be 'still under debate'". We would point out that this comment is not in line with the intention of LWL20 and misinterprets the actual debate mentioned in LWL20. The central issue is not on the role of the total upward advection of high tangential momentum from the boundary layer ($-w\,\partial v/\partial z$) in spinning up the tangential wind in the eyewall above the boundary layer but on whether the upward advection of high tangential momentum *associated with the supergradient wind component* is important or not, as clarified in LWL20. The importance of the total upward advection of tangential wind from the boundary layer ($-w\,\partial v/\partial z$) to the spinup of tangential wind in the eyewall above the boundary layer was well documented by Zhang et al. (2001) based on tangential wind budget analysis (see their Fig. 2). The boundary layer spinup mechanism as reviewed by Montgomery and Smith (2017) emphasizes the importance of the high tangential momentum *associated with the supergradient wind component in the boundary layer*. However, the positive tangential wind tendency induced by the upward advection of the supergradient component of boundary layer wind can produce an outward agradient force and thus the development of a shallow outflow layer immediately above the inflow boundary layer. The outflow would result in a region with negative tangential wind tendency. The debate thus lies in whether the positive tangential wind tendency induced by the upward advection of supergradient wind is larger than the associated negative tangential wind tendency associated with the outflow, leading to the spinup of tangential wind in the eyewall above the boundary layer. The boundary layer spinup mechanisms in Smith et al. (2009) and further articulated by Montgomery and Smith (2017) implicitly assumes that the positive tangential wind tendency exceeds the negative tendency and thus contributes significantly to the spinup of tangential wind in the eyewall above the boundary layer. However, Heng et al. (2017, 2018) argued that the positive and negative tendencies may have similar magnitudes, leading to a negligible contribution to the spinup of tangential wind in the eyewall above the boundary layer. LWL20 attempted to quantify the net contribution of the above said positive and negative tendencies to the simulated TC intensification rate and final quasi-steady intensity.

SGM20 commented that "If one is really interested to quantify the amount of cancellation between the two terms on the right-hand-side of Equation (2) (or $-w\,\partial v/\partial z$ and $-(\zeta+f)u$ in their Eq. 1; our insertion), one can do this with a single calculation. One would even calculate the contribution of the agradient wind to the vertical advection term rather easily." First, as shown in LWL20, the amount of cancellation between the two total advections $-w\,\partial v/\partial z$ and $-(\zeta+f)u$ gives a net positive tangential wind tendency to spin up the tangential wind in the eyewall both in and above the inflow boundary layer during the intensification stage of the simulated TC in the control experiment, which is consistent with the results in Zhang et al. (2001). Second, we knew that it is rather easy to calculate "the contribution of the agradient wind to the vertical advection term", as shown in Fig. 1 of LWL20 (SGM20 appeared selectively not to notice it). However, it is still hard to quantify the negative contribution due to the outflow forced by the upward advection of agradient wind. As a result, it is not straightforward to quantify the net contribution of the upward advection of agradient wind from the boundary layer to the spin up of the tangential wind in the eyewall above the boundary layer, claimed as an important process by Schmidt and Smith (2016) and Montgomery and Smith (2017).

SGM20 questioned why the two views in the Abstract of LWL20 are considered being "separate" and argued that they are "part of the same picture that does not depend on the degree to which the ascending air is supergradient. If the air that exits the boundary layer is supergradient, it must surely move outwards". That is true, the two views are not separate in this sense but the issue is whether the ascending supergradient air spins up the eyewall further above or spins down as it moves outwards, causing a negligible net contribution to the overall spinup of tangential wind in the eyewall. The results in LWL20 demonstrate that the supergradient nature of the ascending air is not the key to the TC intensification of the simulated TC because the above mentioned positive and negative contributions are nearly cancelled each other.

SGM20 also mentioned in a footnote that "Li et al's calculations appear to have been motivated by a misinterpretation of the argument of Schmidt and Smith (2016) and Montgomery and Smith (2017), who did not argue that it was the vertical advection of the supergradient part of the tangential momentum alone that spins up the eyewall." We should indicate that nowhere did LWL20 argue that the vertical advection of the supergradient component of the tangential momentum is the only part to spin up the eyewall in Schmidt and Smith (2016) and Montgomery and Smith (2017). However, as mentioned in the introduction of LWL20 and this reply, the statement of Schmidt and Smith (2016) and Montgomery and Smith (2017) is equivalent to say that the upward advection of total (high) tangential wind from the boundary layer is dominated by the upward advection of the supergradient component. In LWL20, we tried to evaluate this claim through ensemble axisymmetric model experiments. Therefore, we believe that the study of LWL20 was well motivated by the latest debate as described in LWL20 and further clarified above.

3. Experimental design

To quantify the net contribution of the upward advection of the supergradient component of boundary layer wind to the overall TC intensification and final quasi-steady intensity, an axisymmetric full-physics model was used in LWL20. To make the experimental design in

LWL20 more transparent, we rewrite the tangential wind tendency equation in the axisymmetric cylindrical coordinates (Eq. 1 in SGM20) to the following form

$$\frac{\partial v}{\partial t} = -u(\zeta + f) - w\frac{\partial v_g}{\partial z} - w\frac{\partial v_{sg}}{\partial z} + F_\lambda, \tag{1}$$

where v, u, and w denote tangential, radial, and vertical wind speeds, respectively, v_g and v_{sg} are the gradient and supergradient components of tangential wind ($v = v_g + v_{sg}$), ζ is vertical relative vorticity ($= v/r + \partial v/\partial r$), t, r and z are the time, radius, and height, respectively, and f is the Coriolis parameter. The four terms on the rhs of equation (1) are the radial flux of absolute vertical vorticity or radial advection of AAM, vertical advection associated with the gradient component of tangential wind, vertical advection associated with the supergradient component of tangential wind, and subgrid scale diffusion of tangential wind including surface friction.

In the control experiment, LWL20 used the full equation (1) in the model, while in a thought experiment, LWL20 ignored the upward advection associated with the supergradient component of tangential wind (the third term on the rhs of Eq. 1 when it is positive) below 3-km height in the inner-core region (within a 50-km radius from the TC center where supergradient wind exists). The thought experiment was carefully designed to suppress the contribution of the upward advection of the supergradient component of boundary layer wind in the model atmosphere. Since the upward advection of the supergradient component is ignored, it is expected that the outward agradient force and thus its induced outflow is also greatly suppressed. As a result, the difference between the control experiment and the thought experiment can be considered being caused by the net contribution of the upward advection of the supergradient component of boundary layer wind. We think that this experimental design is adequate and often used in scientific research to address the contribution of one process to the phenomenon in which many (nonlinear) processes are at work, in particular for the process in regional scales with a relatively small amplitude, such as the process associated with the vertical advection of the supergradient wind component in this study. Note that if the perturbed thought experiment leads to a large drift of the simulation from that of the control experiment, caution needs to be given to the extent that nonlinear feedbacks may change the nature of the phenomenon under consideration. Fortunately, the issue in LWL20 is a local phenomenon and the perturbation and its impact also mainly occur in the inner-core region, as demonstrated by results in LWL20 (see their Fig. 8). This also implies that the experimental design in LWL20 is adequate to be adopted to address the scientific issue under debate.

However, in their comments, SGM20 stated that LWL20 "do not appear to have noticed that by suppressing the upward advection of the supergradient component of the tangential momentum as air ascends out of the boundary layer, they are, in effect, introducing a ring of negative impulsive torque to the tangential momentum equation", and thus "It is difficult to see what one can learn about the real world by such thought experiments, since air ascending in real storms does not experience such a ring of negative torque as it exits the boundary layer". We would point out that LWL20 clearly clarified that "we do not mean the sensitivity experiment to be a 'realistic simulation', rather it is a thought experiment that is designed to allow the above-mentioned process to be quantified". We knew well that suppressing positive $-w\,\partial v_{sg}/\partial z$ in Eq. (1) is equivalent to adding a negative torque ($w\,\partial v_{sg}/\partial z < 0$ when w >0 and $\partial v_{sg}/\partial z < 0$) to the equation. This means that the additional negative torque is introduced to suppress the process that we attempt to quantify. It is not uncommon to conduct a thought experiment by introducing or removing the term corresponding to a certain process of interest and to quantify its contribution to the phenomenon in comparison with a more realistic control experiment, as done in LWL20. Nevertheless, we would like to see any alternative strategies to be used to confirm or reject our findings in LWL20.

SGM20 also commented that the "additional eddy momentum contributions" in a three-dimensional configuration "are not present in Li et al's axisymmetric framework". While we agree that the eddy terms play some important roles in TC intensification in a three-dimensional configuration, in particular, in the early convective organization of the eyewall. The study of LWL20 focused on the primary intensification of a storm with well-developed eyewall structure in an axisymmetric configuration. Furthermore, the boundary layer spinup mechanism articulated in Montgomery and Smith (2017) is basically an axisymmetric process, as clarified in LWL20. Therefore, the use of an axisymmetric full-physics model in LWL20 is justified although it could be a topic for a future study to see the extent to which the findings in LWL20 could be applied in a three-dimensional configuration.

4. Main mechanism for axisymmetric TC intensification

In their comments, SGM20 raised a question "What other force would make the air move inwards against the positive agradient force" or "what is 'the dominant mechanism' for spinning up the eyewall in which the radial flow is outwards" if LWL20 "are arguing that the vertical advection of tangential momentum is not a dominant mechanism". First, LWL20 did not argue the important role of the total vertical advection of tangential momentum but its supergradient component as claimed by Schmidt and Smith (2016) and Montgomery and Smith (2017). Second, as stated clearly in LWL20, the existence of the "positive agradient force" and the outward flowing air are primarily tied with the upward advection of the supergradient wind component from the boundary layer, without which the "positive agradient force" and the outflow immediately above the inflow boundary layer would be greatly reduced (Fig. 3 and Fig. 8 in LWL20) and thus no "other force" is needed to against the corresponding (non-existing) "positive agradient force". In addition, we would point out that there is still a weak outflow layer above the inflow boundary layer in the thought experiment (Fig. 3 in LWL20), which is associated with the positive upward advection of gradient wind in the eyewall updraft (Figs. 5a–c in LWL20) because the gradient wind decreases with height (Fig. 1). LWL20 thus concluded that "Our results thus demonstrate that it is the upward advection of high boundary-layer tangential momentum associated with the gradient wind that is key to the spinup of the eyewall above the boundary layer" (left column on p2663 in LWL20). This statement is justified by the similar magnitudes and spatial distributions in the combined tangential wind tendency due to the radial flux of absolute vertical vorticity and vertical advection of tangential wind in the control and thought experiments shown in Figs. 4c and 5c in LWL20.

A natural question is why the ascending air is not necessarily supergradient for TC intensification. Figure 3 in LWL20 can help answer this question indeed. We can see that the radius of maximum wind (RMW) below 2-km height shows a great inward tilt toward the surface in all phases of the simulated storm in the control experiment (left column in Fig. 3 of LWL20). This large tilt is primarily due to the existence of strong supergradient wind in the boundary layer, whose core is well inside the RMW of flow above the boundary layer and well inside the radius of maximum gradient wind. As a result, when an ascending air parcel being supergradient moves upward out of the inflow boundary layer, the air parcel will turn also outward because of the outward agradient force and the lack of inflow therein. The air parcel conserves its AAM and thus experiences a deceleration of its tangential wind as it moves further outward. When the air parcel is about to arrive at the RMW above the boundary layer, its tangential wind becomes smaller than the local tangential wind near the RMW. This is evinced by the existence of a region of subgradient wind (or inward agradient force in Fig. 3 in LWL20) above the supergradient wind. As the air parcel with subgradient wind moves further upward, a weak inflow is induced by the inward agradient force as we can see from Figs. 3c,d and Figs. 8c,d in LWL20. This alternative inflow-outflow-inflow (and the associated subgradient-supergradient-subgradient wind) structure is the well-known inertial oscillation of a rotating flow with a frictional boundary layer or a process related to the gradient wind adjustment comprehended in the literature (e.g., Rotunno 2014; Stern et al. 2020). Since the outflowing supergradient air becomes subgradient near the RMW and thus does not spin up the tangential wind therein. In the thought experiment, the supergradient component is confined in the lower boundary layer and its upward advection is suppressed. As a result, the ascending air is nearly in gradient wind balance and is slightly supergradient when it moves out of the boundary layer. This leads to very weak outward agradient force and negligibly weak outflow, but overall contributing to the spinup of tangential wind near the RMW and thus the spinup of tangential wind above 2-km height in the eyewall during the primary intensification stage.

5. Some other points

There are two other points commented by SGM20, which will be discussed briefly in this section. First, in their comments on LWL20, SGM20 mentioned that "it is hard to imagine also why an ensemble of numerical experiments is required to investigate if further". This has been clearly stated in LWL20, namely, "The ensemble experiments are designed to remove internal variability and make sure of the robustness of the results from sensitivity simulations". Based on the authors' best knowledge, the simulated TC structure and intensity are often subject to internal variability because of the nonlinearity and multiscale nature of TCs. This is especially more pronounced in an axisymmetric cloud-resolving model, such as that used in LWL20. The simulated TC intensity change can be quite sensitive to even small initial perturbations. Therefore, we conducted ensemble runs with 21 members for each experiment to help see whether the difference in the ensemble means between the control and thought (sensitivity) experiments are physically meaningful. If the difference is smaller than the standard deviation of all individual ensemble runs in one of the experiments, the difference is often considered being not physically meaningful, otherwise, the difference is considered being physically meaningful. Since in LWL20 the difference in the intensification rate of the simulated TCs between the control and thought experiments is generally less than 4%, which is smaller than the standard deviation of intensification rates of individual ensemble runs in either of the two experiments (not shown), the difference is thus physically insignificant. Therefore, LWL20 concluded that the net contribution of the upward advection of the supergradient component of boundary layer wind to the overall intensification rate of the simulated TC is marginal.

Second, in their last paragraph, SGM20 mentioned that “the agradient force is positive throughout most of the eyewall and the assumption that the supergradient winds adjust rapidly back to gradient wind balance just as the air exits the top of the boundary layer during storm spin up and maturity is not correct”. We should indicate that nowhere did LWL20 assume that “the supergradient winds adjust rapidly back to gradient wind balance just as the air exits the top of the boundary layer”. Instead, LWL20 clearly showed the existence of agradient wind above the boundary layer in the control experiment but largely reduced in the thought experiment (Fig. 3 in LWL20). In contrast to what stated in SGM20, subgradient and supergradient winds (or negative and positive agradient forces) appear alternatively in the mid-lower troposphere in the eyewall (Fig. 3 in LWL20), which is associated with inertial oscillation related to the gradient wind adjustment processes in a rotating vortex in the presence of surface friction as already mentioned above (Rotunno 2014; Stern et al. 2020). Therefore, “the tangential wind in the eyewall is supergradient through the depth of troposphere” was not correct in the mid-lower troposphere, although the agradient force (wind) is mostly positive in the eyewall further above in both the control and thought experiments (Fig. 1; results are similar at other times, not shown). Note that the agradient force (wind) is related to the upward advection of not only the supergradient wind but also the gradient wind, with the latter being dominant above the boundary layer (Fig. 1).

6. Concluding remarks

SGM20 commented on the recent work of LWL20. Based on ensemble axisymmetric numerical simulations, LWL20 quantified the net contribution of the upward advection of the supergradient component of boundary layer wind to TC intensification, a process being claimed to be key to the boundary layer spinup hypothesis of TC intensification (e.g., Smith et al. 2009, Schmidt and Smith 2016, Montgomery and Smith 2017). LWL20 found that the upward advection of the supergradient wind component from the boundary layer contributes marginally to TC intensification rate. As discussed herein, most of the comments by SGM20 are not in line with the intention of LWL20 and provide one-sided and little scientifically meaningful arguments. For example, the upward advection of supergradient wind from the boundary layer can lead to a positive tangential wind tendency immediately above the boundary layer, but they did not show how much of this is used to spin up the eyewall (or increase tangential wind near the RMW) above the boundary layer because the upward advection of supergradient wind also lead to an outflow layer, which spins down the tangential wind therein.

We would like to clarify again that LWL20 did not challenge the important role of the total upward advection of tangential wind from the boundary layer in TC intensification, which was well documented in early studies (e.g., Zhang et al. 2001; Kepert and Wang 2001), but challenged the importance of the upward advection of the supergradient wind component, which is considered a key to the boundary layer spinup mechanisms of TC intensification articulated in Smith et al. (2009) and further clarified in Montgomery and Smith (2017). Based on the study of LWL20 and more recent work of Fei et al. (2020), we are confident to conclude that the upward advection of the supergradient component of boundary layer wind contributes marginally to TC intensification although the existence of supergradient wind is a distinct feature of a natural TC. However, we would restate that we do know the importance of the unbalanced nonlinear boundary layer processes to TC intensification, mainly through its key role in controlling the strength and radial location of eyewall updraft/convection but not because of its supergradient nature in the way being emphasized by the boundary layer spinup mechanism by Montgomery and Smith (2017).

One of the major critiques on the work of LWL20 by SGM20 is the design of the thought experiment. They argued that it is not as in “real storms” as it introduces a ring of negative impulsive torque. As indicated in LWL20 and further discussed in Section 3, the additional negative torque is introduced to suppress the process that we attempt to quantify and does not mean it is realistic. Rather, the methodology adopted in LWL20 allows us to quantify the contribution of one previously claimed key process to TC intensification. We believe that our approach is scientifically sound and adequate. Nevertheless, we would like to see any alternative strategies that can be used to confirm or reject the findings in LWL20.

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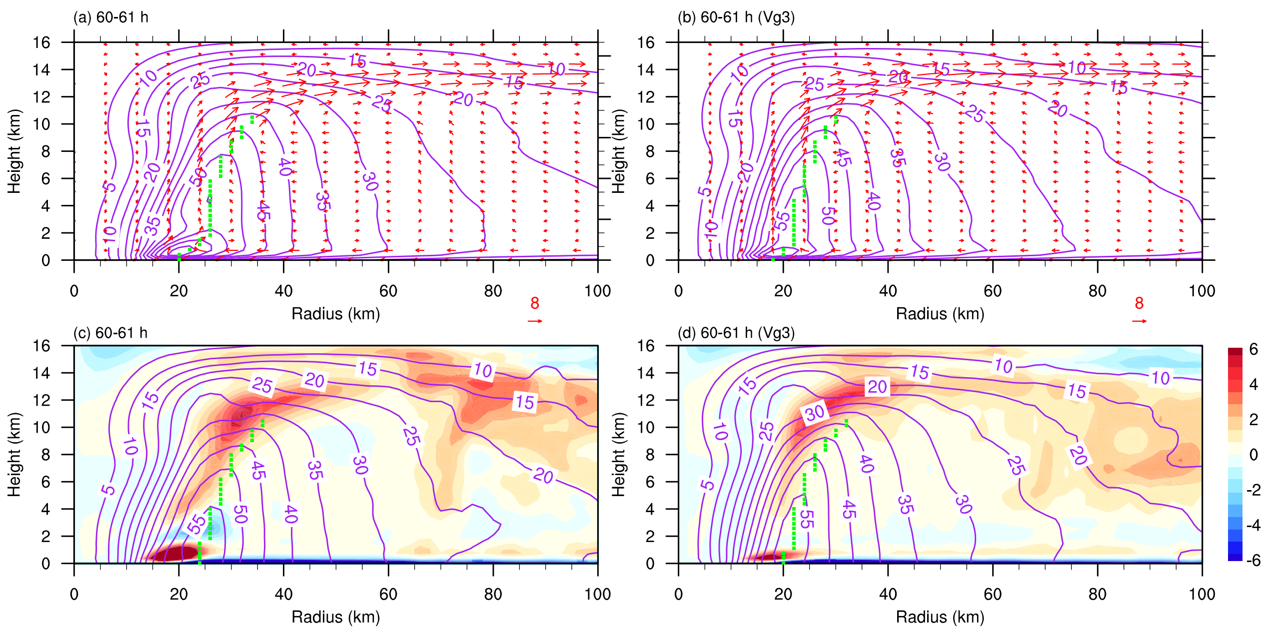

FIG. 1. The radial–vertical cross sections of the ensemble-mean tangential wind speed (purple contours; m s^{-1}) and the secondary circulation (red vectors; m s^{-1}) averaged between 60–61 h using model outputs at 6–min interval from (a) CTL and (b) Vg3. The dotted green line shows the radial location of the RMW below 10-km height. (c)–(d) As in (a)–(b), but for gradient wind speed (purple contours; m s^{-1}) with the corresponding radius of maximum gradient wind (dotted green line) and agradient wind speed (shading; m s^{-1}).