Comments on: Thermodynamic characteristics of downdrafts in tropical cyclones as seen in idealized simulations of different intensities, by J. B. Wadler, D. S. Nolan, Jun A. Zhang and Lynn K. Shay

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In their interesting paper, Wadler et al. (2021a) examine the thermodynamic effect of downdrafts on the boundary layer and nearby updrafts in idealized simulations of category-3 and category-5 tropical cyclones. These simulations are designated Ideal3 and Ideal5, respectively. The authors show that in the stronger storm, Ideal5, "downdrafts underneath the eyewall pose no negative thermodynamic influence because of eye-eyewall mixing below 2-km altitude. Additionally, a layer of higher θ_e between 1 and 2 km altitude associated with low-level outflow that extends 40 km outward from the eyewall region creates a "thermodynamic shield" that prevents negative effects from downdrafts". In the weaker storm, Ideal3, no such outflow occurs. The impact of downdrafts beyond the main eyewall in the two simulations are compared in a cartoon schematic, their Fig. 17.

In the case of Ideal5, a lower-tropospheric radial outflow jet is found to advect enhanced θ_e air outwards from the interior eyewall/eye region. Presumably, θ_e is the pseudo-equivalent potential temperature. The radial outflow jet of enhanced θ_e air is argued to act as a thermodynamic shield that modifies downdraft air descending into the boundary layer. As a downdraft attempts to pass through the shield, downdraft air would be warmed and moistened through mixing with the air in the shield. The net effect of the shield is to elevate the downdraft θ_e before it is drawn inwards by the frictional inflow. In contrast, for the case of Ideal3, there is no appreciable persistent outflow jet to shield the vortex from downdraft influences.

In the conclusions they write: "The presence of a high-θ_e air above the inflow layer in Ideal5, which is also discussed in previous observational studies (e.g., Barnes 2008; Wadler et al. 2021b), highlights the importance of storm structure in determining the thermodynamic effect of downdrafts. However, it remains unknown the exact mechanisms which lead to the formation of the high-θ_e above the boundary layer in the TC and why this layer formed in Ideal5, but not in Ideal3. This will be a topic of future work."

In this comment, we offer an explanation for this feature, which we believe to be a common feature of vortex evolution as a storm matures and decays, especially in more intense storms with a broad tangential wind circulation. The reasons are discussed in papers by Kilroy et al. (2016) and Smith et al. (2021). In essence, the evolution of a tropical cyclone at a particular stage of its life cycle depends broadly on the rate at which moist air is funnelled by the boundary-layer inflow towards the inner region, where deep convection prevails, and the rate at which this mass can be carried to the upper troposphere by the aggregate effects of this convection.

Typically, in the early stages of tropical cyclone formation and intensification, the boundary layer inflow is relatively weak and deep convection is more than capable of removing mass at the rate at which it is funnelled inwards. However, as the storm intensifies and the tangential wind field expands, the rate at which air is funnelled inwards increases, while the progressive warming of the upper troposphere tends to reduce the degree of convective instability and thereby the ability of inner-core deep convection to ventilate the mass converging in the boundary layer. This reduced convective instability may be accompanied by the reduction of effective buoyancy in the eyewall as the eyewall broadens in size (Smith and Montgomery 2022). As soon as the boundary layer inflow begins to dominate, the residual mass that cannot be ventilated by deep convection flows outwards in a shallow layer just above the boundary layer. Typically, the tangential velocity component of air ascending out of the boundary layer in the inner-core region is supergradient (Smith and Vogl 2008; Smith et al. 2008, 2009 and has a natural tendency to flow outwards. Unless this air reaches a level of free convection, it remains stably stratified which accounts for the outflow occurring in a shallow layer.

Smith et al. (2021) showed that as a tropical cyclone matures, the low-level radial outflow becomes more and more prevelant and leads ultimately to the decay of the vortex, even in a quiescent environment. At radii where the radial outflow is sufficiently large so that the radial advection of absolute angular momentum, M, exceeds the vertical advection of M out of the boundary layer, the tangential flow at the top of the boundary layer will spin down. The foregoing evolution is illustrated, for example, in Figs. 4 and 5 of Smith et al. (2021).

The difference between the two simulations Ideal3 and Ideal5 is presumably because, at the time of analysis, Ideal3 is not yet in a state where the mass influx in the boundary layer exceeds the rate at which this flux can be ventilated by deep convection. It might be possible to validate this conjecture using the ventilation diagnostic introduced by Smith et al. (2021): see their Eq. (10) and Fig. 8.

Axisymmetric balance models of tropical cyclone evolution can mimic the same effect, even though the winds in the boundary layer do not become supergradient in such a model by definition. This was shown in a series of simulations with a prognostic balance model in which the diabatic heating rate is varied in strength in relation to the frictional forcing (Smith and Wang (2018). In this model, the unbalanced forces do not exist.

On a separate topic, it is worth noting that the Wadler et al. study (p3517) demonstrates the quantitative importance of "low-level outflow from inside the eye and eye-eyewall mixing" in supporting relatively high θ_e air ascending the eyewall in their Ideal5 vortex. The "eye-eyewall mixing" of near surface boundary layer θ_e was invoked by Persing and Montgomery (2003) to explain how hurricanes could significantly exceed Emanuel's Potential Intensity (PI) theory for the maximum gradient wind. However, Bryan and Rotunno (2009) showed this process was too weak to explain the discrepancy between PI theory and numerical experiments in strictly axisymmetric model configurations. As discussed in Montgomery and Smith (2017), the dynamical origin of "super-intense storms" is now better understood. In particular, there is an important distinction between the radius of maximum gradient wind r_{gm} and the radius of maximum tangential wind r_m, the former typically lying some 10 - 20 km (or more) outside the latter. Scientific questions remain concerning the impact of "high-octane" θ_e air generated at radii inside r_{gm} (including the low-level eye of the storm) in supporting locally buoyant updrafts comprising a realistic, three-dimensional eyewall. The Wadler et al. results re-affirm the non-negligible influence of eye-eyewall mixing in a three-dimensional, category-5, hurricane.

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