Investigation of the Dynamics of Extreme Rainfall in Landfalling Tropical Cyclones

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INTRODUCTION

- While both tornadoes and flash floods individually present public hazards, when the two threats are both concurrent and collocated (refereed to here as "TORFF" events, short for "tornado and flash flood"), a unique set of concerns arise that can further jeopardize public safety (Nielsen et al. 2015, WAF)
- Among these unique concerns for dual threat scenarios, which are common in tropical cyclones (TCs), is a conflict between recommended lifesaving action for each individual hazard, which can increase confusion and lead to sub-optimal precautionary responses
- Nielsen and Schumacher (2018, JAS and 2020a, MWR) showed, using idealized and real-time simulations, respectively, of continental convection, that meso-γ-scale rotation, associated with intense 0—1 km shear, can enhance rain rates through dynamic lifting from the vertical perturbation pressure gradient forces associated with rotation (Fig. 1)
- The resulting rotational induced dynamic lifting can aide in maximizing rain rates by dynamically enhancing the updraft, lifting otherwise negatively buoyant parcels that still contain moisture and instability to their level of free convection, and enhancing warm rain production in the lowest levels of the storm (Fig. 1)

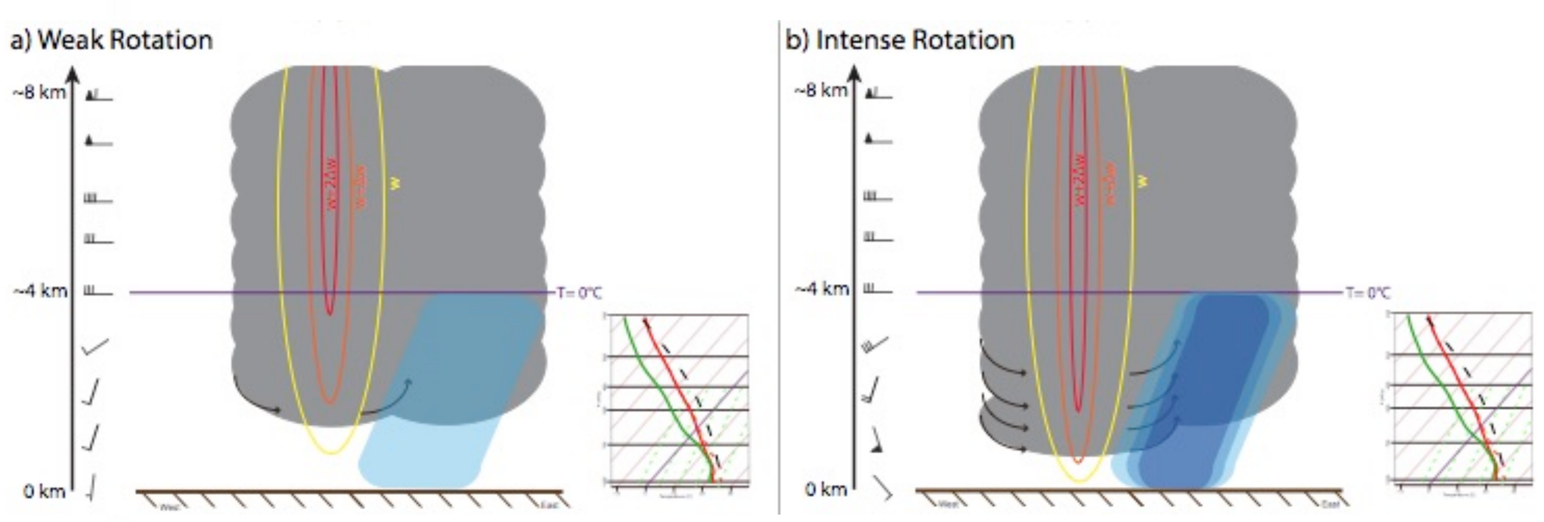

***Fig. 1** Schematic summarizing the precipitation enhancement mechanism discussed in Nielsen and Schumacher (2018, JAS). Figure shows an idealized storm system with (a) slight and (b) intense rotation in the same thermodynamic environment, which is denoted by the inset skew T–logp in each panel and has the same plotting scheme as Fig. 3. Representative kinematic profile for each case is depicted by the wind barbs following the normal convention on the left side of each panel. Rotation is indicated by arrows, with the strength proportionate to number of arrows. Blue shading represents precipitation intensity, which increases as the blue shade darkens. Warm contours represent updraft velocity contours, and purple contour represents freezing level.*

- Considering that past studies of TCs have shown the simultaneous occurrence of intense low-level shear, tornadoes, and extreme rain rates, the authors hypothesize that similar rotational enhancement mechanisms, as described above, exist in landfalling tropical cyclone rain bands
- This research serves to extend the simulations of Nielsen and Schumacher (2018, JAS and 2020a, MWR), by examining a full spatial heterogenous simulation of Tropical Storm Imelda (2019) beginning just prior to landfall

DATA AND METHODS

- Multi-radar, multi-sensor (MRMS) low-level rotation tracks (Smith et al. 2016, BAMS) and gauge corrected QPE (Zhang et al. 2016, BAMS) were utilized to investigate precipitation production of rotating storm elements
- A WRF-ARW simulation with a 800 m grid spacing (hereafter referred to as the analysis simulation) and 5-min output was initialized beginning 0000 UTC 18 September 2019 based upon the GFS analysis with the analysis simulation domain covering eastern portions of Texas (Fig. 2b)

$$\frac{\partial w}{\partial t} = \underbrace{\vec{v}\cdot\nabla_h w}_{\text{Advection}} \underbrace{-\frac{1}{\rho_0}\frac{\partial p'_B}{\partial z} \underbrace{-g\frac{\rho'}{\rho_0}}_{\text{Buoyancy (B)}} \underbrace{-\,g q_h}_{\text{Drag}}}_{\text{Total Buoyant Acc. (ACCB)}} - \underbrace{\underbrace{\frac{1}{\rho_0}\frac{\partial p'_{DL}}{\partial z}}_{\text{Linear Dynamic Acc.}} - \underbrace{\frac{1}{\rho_0}\frac{\partial p'_{DNL}}{\partial z}}_{\text{Nonlinear Dynamic Acc. (NLD-VPPGF)}}}_{\text{Total Dynamic Acc. (ACCD)}}$$

$$p' \propto \underbrace{\underbrace{e'^2_{ij}}_{\text{Splat}} \underbrace{-\frac{1}{2}|\boldsymbol{\omega}'|^2}_{\text{Spin}}}_{\text{Nonlinear dynamic } (p'_{DNL})} + \underbrace{2\mathbf{S}\cdot\nabla_h w'}_{\text{Linear dynamic } (p'_{DL})} - \underbrace{\frac{\partial B}{\partial z}}_{\text{Buoyant } (p'_B)}$$

- Buoyant and dynamic components of the vertical perturbation pressure gradient force were numerically solved at each time interval in the WRF simulation, similar to Parker and Johnson (2004, JAS) and Nielsen and Schumacher (2018, JAS), to identify the dynamic influence of meso-γ-scale rotation on the vertical structure of rotating cells

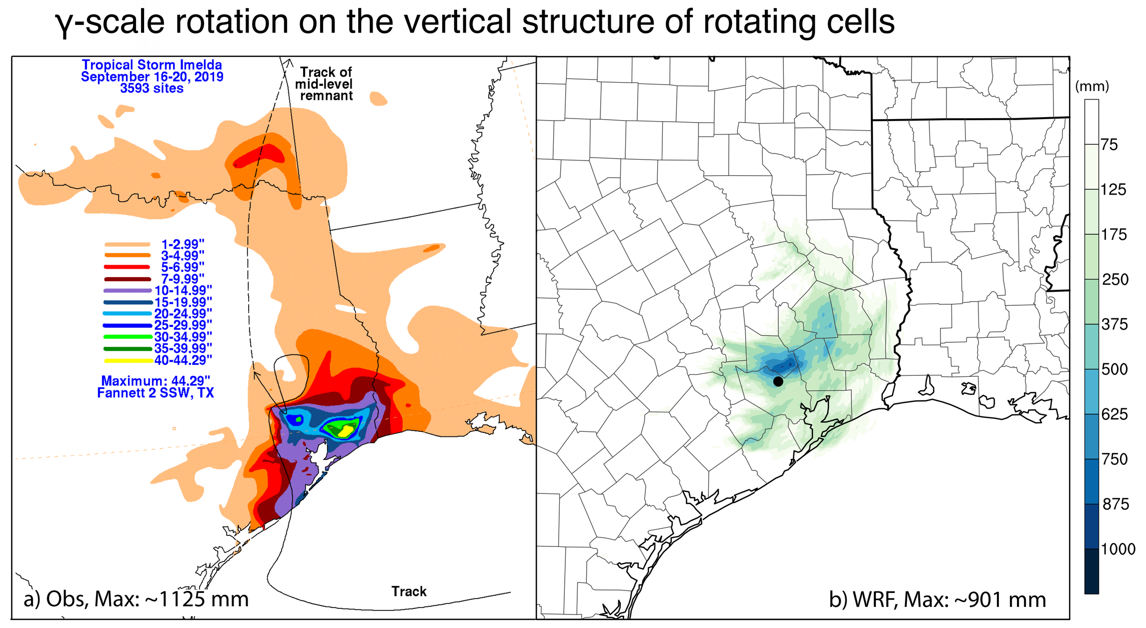

***Fig. 2:** (a) Weather Prediction Center (WPC) rainfall analysis for Tropical Storm Imelda (2019) valid from 16-20 September 2019 with storm track overlaid. (b) 48-hour accumulated precipitation valid from 0000 UTC 18 September 2019 to 0000 UTC 20 September 2019 from the analysis domain of the WRF simulation described above. Geographic extent of plot (b) matches that of the analysis simulation.*

Tropical Storm Imelda: Observations

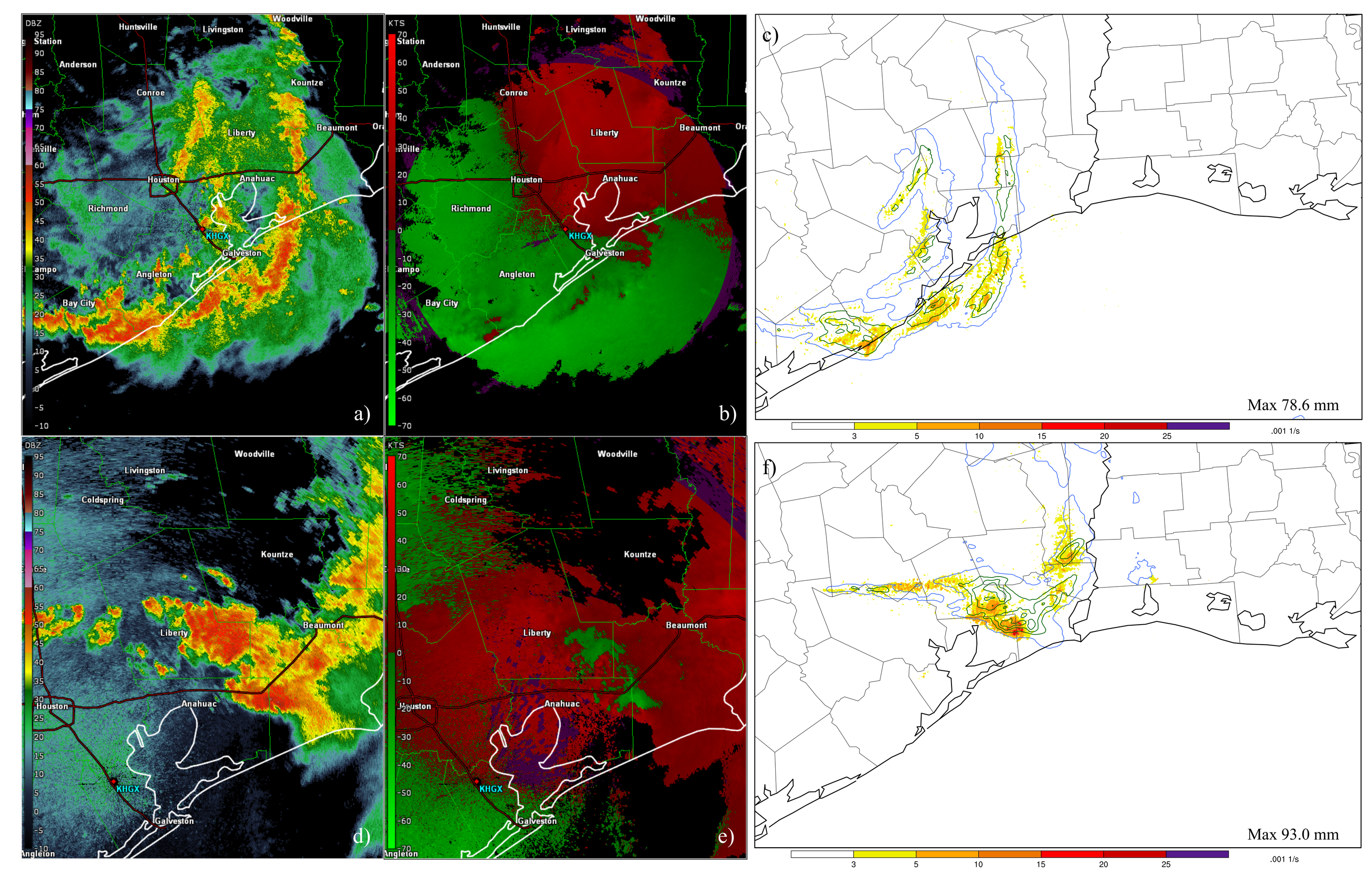

***Fig. 3:** Base radar reflectivity (a) and velocity (b) valid from Houston/Galveston WSR-88D (KHGX) valid 0852 UTC 18 September 2019. (c) Corresponding hourly MRMS rotation tracks (fill, 1/s) and hourly MRMS gauge corrected QPE (blue contour at 5 mm, green contours every 25 mm starting at 25 mm) valid 0900 UTC 18 September 2019. (d) and (e) same as (a) and (b), respectively, except valid 0416 UTC 19 September 2019. (f) as in (c), except valid 0500 UTC 19 September 2019.*

- Maximum observed accumulations over 1100 mm were seen east of Houston near Beaumont, TX (Fig. 2a) with major flooding seen across a broad area of southeast Texas
- Several periods of intense rainfall occurred over the 4 day period, including rainfall associated with a more traditional TC rainband type feature (Fig 3a-c) and an embedded stationary, back-building supercell structure (Fig. 3d-f)
- MRMS and radar data identifies several rotating features throughout the event (Fig. 3)
- A strong spatial association is seen between the rotating regions and the locations of most intense rainfall in the MRMS data for both example periods of intense rainfall above (Fig. 3c.f)

NUMERICAL MODEL RESULTS

Question to investigate:

How does rotation affect the precipitation production in various storm modes after the landfall of Tropical Storm Imelda?

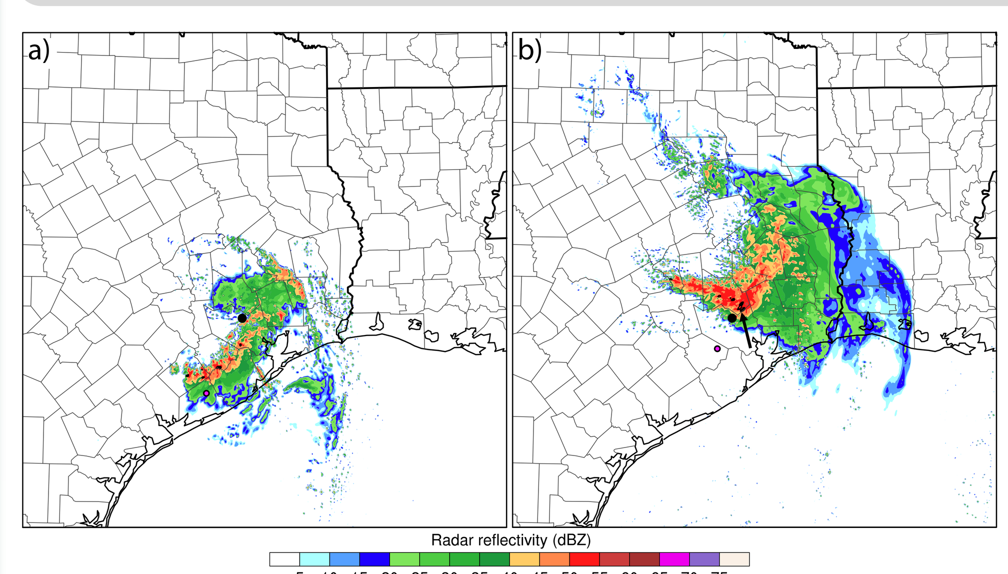

***Fig. 4:** Simulated reflectivity valid (a) 07:45 18 September 2019 and (b) 12:00 UTC 19 September 2019 in the analysis simulation. Black contour shows updraft helicity greater than 150 m^2 s^{-2}. Black marker denotes Houston Intercontinental Airport. Pink marker denotes location of soundings in Fig. 5*

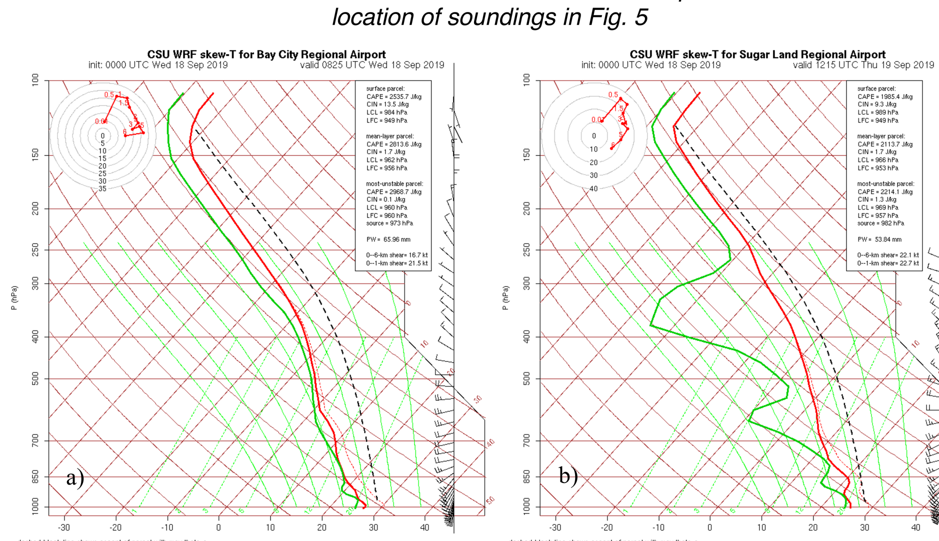

***Fig. 5:** Mean WRF model soundings valid at (a) 0825 UTC 18 September 2019 and (b) 1215 UTC 19 September 2019 centered at Bay City Regional Airport (KBYY) and Sugar Land Regional Airport (KSGR). Soundings correspond to inflow of both storm morphologies denoted in Fig. 4. Locations are also denoted by pink marker in Fig. 4.*

- The analysis simulation produced an inland evolution of Tropical Storm Imelda that was quite similar to observations (cf. Fig. 3-4), but moved the storm inland too quickly (Fig. 2)
- Similar to observations, a period dominated by a more traditional TC rainband structure with embedded rotation (Fig. 4a) and another associated with an embedded stationary, back-building supercell like structure (Fig. 4b) was produced in the analysis simulation
- Both periods were associated with enhanced environmental 0—1 km shear values capable of producing rotation in the inflow regions and slight CIN for the surface parcel
- Modeled hourly rain rates during both of these periods were similar to those recorded by the MRMS data (i.e., 75+ mm/hr)
- Low-level rotation was found to be spatially associated with regions of most intense rainfall (Fig. 6a,b) over both periods (and others not shown), as in observations (Fig. 3)

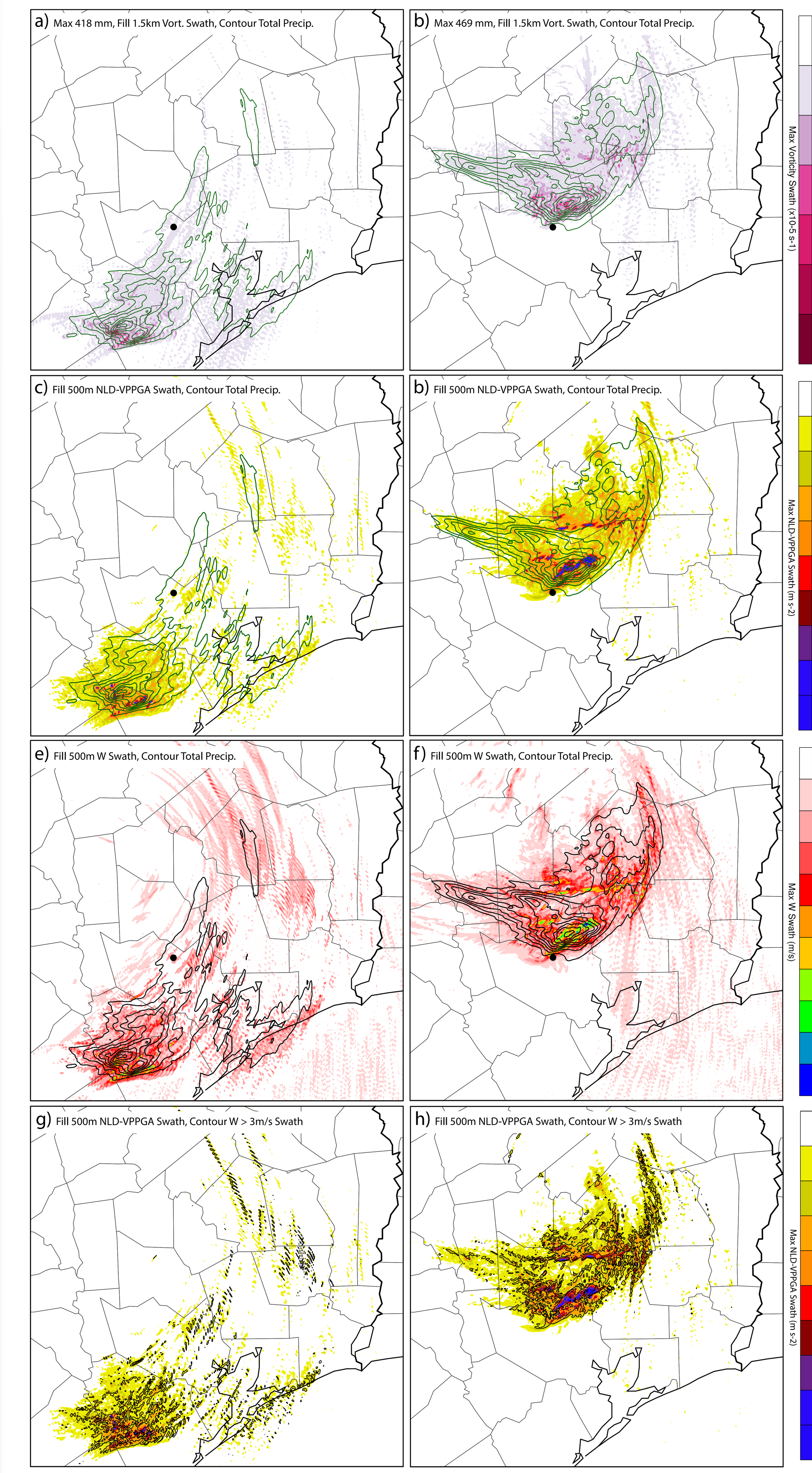

***Fig. 6:** (a,b) swath of modeled 1.5 km vorticity (fill) and period total precipitation accumulation (contours every 25 mm), (c,d) swath of 500 m non-linear dynamic vertical perturbation pressure acceleration (NLD-VPPGA; fill) and period total precipitation accumulation (contours), (e,f) swath of 500 m vertical velocity (W, fill) and period total precipitation accumulation (contours), and (g,h) swath of NLD-VPPGA (fill) and swath of 500 m vertical velocity (W, contour). Left column valid 07:15-12:30 UTC 18 September 2019 in the analysis simulation and right column valid 10:00-14:00 UTC 19 September 2019 in analysis simulation.*

- Intense, rotationally induced dynamic accelerations (NLD-VPPGA) are seen directly below the regions of low-level rotation (Fig. 6c,d)
- These accelerations induced locally intense vertical velocities in the lowest levels of the storms (i.e., ~500 m, Fig. 6e,f)
- 500 m vertical velocities over 3 m/s are almost exclusively associated with regions of rotationally induced dynamic acceleration (Fig. 6g,h), which makes sense give the surface parcel being slightly thermodynamically stable (Fig. 5)
- Buoyancy accelerations (not shown) are present in low levels in both time periods but are around an order of magnitude less than the rotationally induced accelerations
- Rotation and associated accelerations are shallow, but serve to lower the base of the updraft and increase the low-level updraft strength of rotating elements, compared to non-rotating elements (Fig. 6-7)
- An increase in low-to-mid level rain water mixing ratio is seen below the melting level in updrafts with low-level rotation compared to those without (Fig. 7)
- An expected negative vertical acceleration is seen above the level of maximum rotation (Fig. 7) that does appear to reduce mid-level vertical velocities but not below what is seen in updrafts without low-level rotation

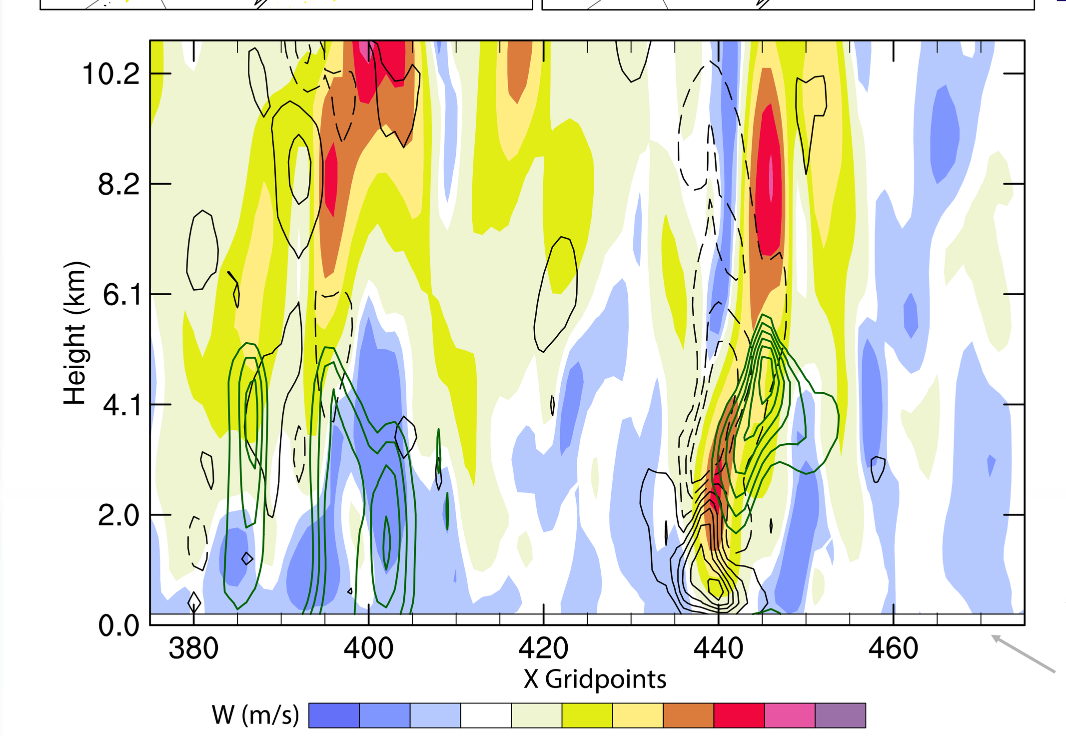

***Fig. 7:** Mean vertical E-W cross sections over 2.5-km in the E-W direction of W (fill), non-linear dynamic vertical perturbation pressure acceleration (NLD-VPPGA , black contours, dashed (negative) and solid (positive), every 0.02 m s^{-2}), and rain water mixing ratio (green contours, every .002 kg kg^{-1} starting at .004 kg kg^{-1}) valid at 1305 UTC 19 September 2019 in the analysis simulation for the vortex in Fig. 4b at a later time (denoted by arrow).*

CONCLUSIONS and ACKNOWLEDGEMENTS

- A 800 m WRF model simulation of landfalling Tropical Storm Imelda in 2019 was used to numerically solve for the buoyant and dynamical components of the vertical perturbation pressure gradient force to investigate the influence of rotation on precipitation processes
- Dynamical accelerations associated with embedded and discrete rotating cells in the simulation were found to increase low-level updraft strength, lower the updraft base, lift thermodynamically stable parcels, and increase low-level rain water production, compared to non-rotating updrafts
- These results suggest the precipitation enhancement associated with meso-γ-scale rotation seen in Nielsen and Schumacher (2018, JAS and 2020a, MWR) for continental convection is also active in TCs

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