RESEARCH TITLE:
ON THE ROLE OF COHERENT TURBULENT STRUCTURES IN INTENSE HURRICANES

Accurate prediction of hurricane intensity continues to lag behind track prediction, largely due to the lack of sufficient high resolution spatio-temporal observations of the microscale processes near the high turbulence eye-eyewall region. Incomplete representation of interacting turbulent eddy scales and their roles (in numerical weather forecast models) in flux transport is the bane of hurricane intensity forecast error, especially in the short ($\leq$24 hour) time range. This is partly because turbulent fluxes in the hurricane boundary layer modulates enthalpy, moisture and momentum exchange between the storm and the underlying ocean surface. A few flight–level and ground–based observations of the near–eyewall region in intense hurricanes have alluded to the existence of these destructive organised turbulent structures in the hurricane boundary layer. These structures, sometimes identified as coherent turbulent eddies, tornado scale vortices and/or boundary layer roll vortices based on their sizes and proximity to the storm center, can have severe implications ranging from determining the severity of damage caused by hurricanes during landfall to endangering research flight missions.

Although many important aspects of hurricane structure and behavior have been discovered using aircraft observations, the general distribution of turbulence in hurricanes has is only recently just being explored due to the intensive computational requirement. In the present study, Large Eddy Simulation (LES) of the eye–eyewall region (at an unprecedented horizontal and vertical resolution of 31.25m and 15.125m respectively) is utilized to characterize the behaviour of coherent turbulent eddies and the dominant scales responsible for vertical and horizontal fluxes within a simulated Category–5 Hurricane. Using a novel eddy-recycling methodology of Dr. George Bryan (a close collaborator from the National Center for Atmospheric Research [NCAR]) in the Cloud Model 1 (CM1), an idealized simulation of Hurricane Felix (2007) is used to study the influence of previously unresolved fine scale structures on momentum flux transfer within the storm.

The initial simulation of the eddy recycling methodology (using CM1) was ran at a coarse resolution (Δx =250m, Δy =250m, Δz =125m on 1152 $\times$ 1152 $\times$ 125 grid points), requiring over 2000 cores for an 8 day simulation on the Notre Dame Center for Computing Resource HPC queues. However, the actual dataset for which our analyses was based was ran (by Dr. George Bryan) at Δx =31.25m, Δy =31.25m, Δz =15.125m on the NCAR Yellowstone Supercomputing facility, requiring about $\approx$750000 CPU hours for a 4 hour integration (7.5 days using 4096 processors) on a 2944 $\times$ 2944 $\times$ 262 grid points. Analyses of over 4.8 Terrabytes (TB) of model output data was mostly carried out on NCAR's Casper specialized data analysis and visualization cluster.

Figure 1(a) and (b) shows a $\approx$700m vertical velocity slice for the S–W quadrant of the computational domain and simulated radar reflectivity field. From Fig. 1(a), there are a number of kilometer–scale intense updraft–downdraft couplets in the inner eyewall, with magnitudes >20m/s in some cases. The comparative sizes of these coherent eddies seem to decrease with increasing radial distance from the storm center. A vertical cross section through these structures at R$\approx$11km (inner eyewall) and R$\approx$22km (outer eyewall) is shown in Fig. 2(a) and (b) respectively. Two intense downdrafts (highlighted by the arrows in Fig. 1(a)) are identified in Fig. 2(a), showing a vertical extent of $\approx$2.5km and associated with intense vertical mixing as seen in the cross section of potential temperature at the exact same location (Fig. 2(c)). Farther from the inner eyewall (R$\approx$22km), a vertical cross section of the same variables (Fig. 2(b) and (d)) show a decrease in the vertical extent and magnitude of the updraft-downdraft couplet and a decrease in the intensity of vertical mixing induced by them. From the simulated radar reflectivity plot shown in Fig. 1(b), the high reflectivity values in the Southern part of the inner eyewall (and the associated collocated vertical velocity signature) is qualitatively identical to the Tornado Scale Vortices (TSVs) identified in the inner eyewall of Hurricane Harvey (a Category–4 storm in 2007) using the Doppler on Wheels (DOW) instrument. Detailed analyses (not shown here) using a combination of spectral/cross spectral and momentum flux analyses, we find that that an interaction between sub–kilometer to kilometer scale eddies and large scale eddies ($\approx$3 – 6.0km) dominate the vertical flux transport in the inner eyewall, with the former responsible for negative (-$\langle u^{'} w^{'} \rangle$, -$\langle v^{'} w^{'} \rangle$) and the latter responsible for positive (+$\langle u^{'} w^{'} \rangle$, +$\langle v^{'} w^{'} \rangle$) vertical flux transport. For the horizontal momentum flux ($\langle u^{'} v^{'} \rangle$), an interesting balance between the large scales ($\approx$6km) and smaller scales ($\approx$2km) is noted close to the surface, with the former driving radial inflow of high momentum air and the latter driving radial outflow.

The significance of these findings suggest that unresolved sub–mesoscale eddies in current numerical weather forecast systems lies at the core of poor intensity forecasts of hurricanes. These results call for a more physics-involved paramerization of these structures and their roles in the transfer of fluxes within the high wind hurricane environment.

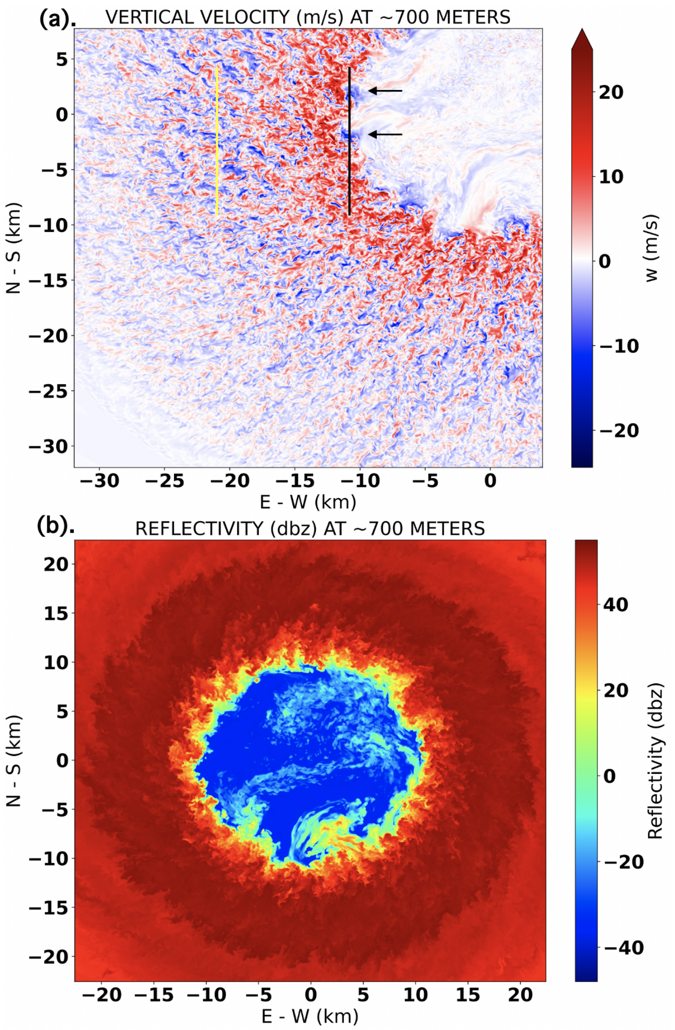

Figure 1: Two dimensional fields of, (a) vertical velocity (m/s) in the S-W quadrant of the LES model domain and (b) simulated radar reflectivity (dbz) in a 40km × 40km subset domain (at ≈700m). Vertical cross sections of the inner eyewall (solid black line) and outer eyewall (solid yellow line) are shown in 2.

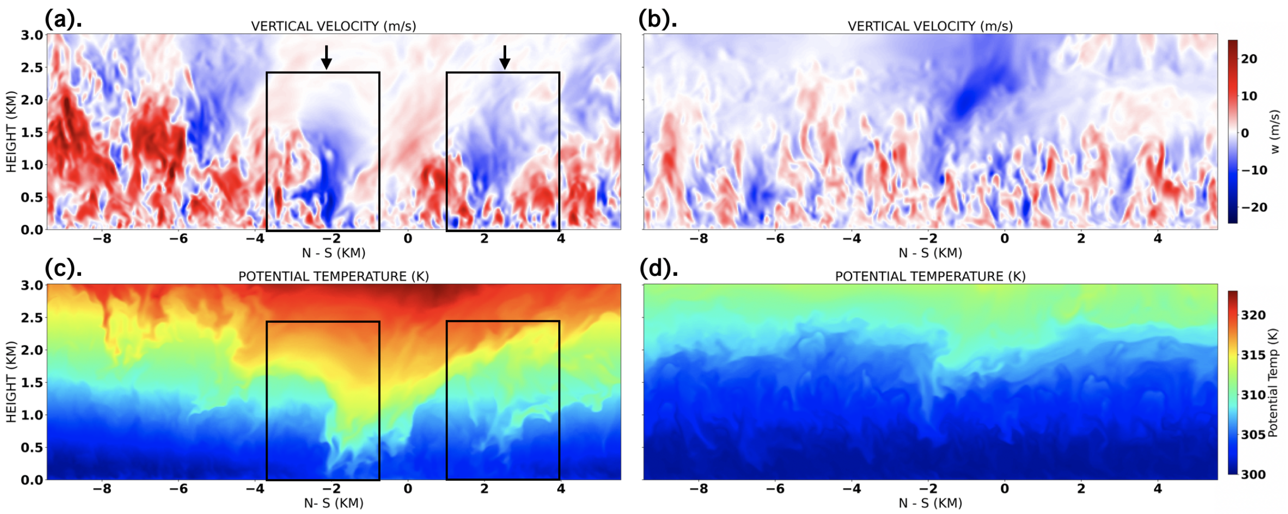

Figure 2: Cross section of, (a) vertical velocity (m/s) and (c) potential temperature (K) in the inner eyewall (R≈11km). Cross section of, (b) vertical velocity (m/s) and (d) potential temperature (K) in the outer eyewall (R≈22km). Black and yellow lines in Fig. 1 (a) represent sections (inner eyewall and outer eyewall respectively) from which (a),(c) and (d),(e) are plotted respectively.