I. Motivation

- Downdrafts and negatively buoyant outflows important for development of near surface vorticity
- Studies suggest an important role of outflow surges during tornadogenesis or on existing tornado vortices
- Little is known about how they affect tornado-strength vortices

II. Methodology

1. Highly idealized simulations of tornado vortex with CMI version 18 modified to include TKE scheme by (5), with artificial heat source and sink added as in (4)

2. In additional experiments, add heat sinks of various amplitude, timing, geometry to investigate influence on the tornado

3. Example for bubble shows cold air wrapping around the vortex (Fig. 3)

IV. Cold surges

- Possible effects:
  1. Convergence of high swirl air at lower radii
  2. Baroclinic generation
  3. Imbalance between inflow and outflow
  4. Outflow totally undercuts the inflow

III. Control simulations (CTL)

- Structure qualitatively similar to (3): Early flow symmetry, and later development of asymmetry and presence of a central downdraft (Fig. 1)

- Intensification by convergence of high swirl air to lower radii (Fig. 2)

- Example for bubble shows cold air wrapping around the vortex (Fig. 3)

- Perturbation potential temperature (shaded) at 5 m AGL and \( w = 4 \) m s\(^{-1}\) contour for a weakly cold outflow.

- Baroclinic tornadogenesis: Downdrafts

- Example for bubble shows cold air wrapping around the vortex (Fig. 3)

- Horizontal maps of angular momentum (shaded) and perturbation potential temperature (black) at 300 m AGL, \( w = 4 \) m s\(^{-1}\) contour (blue) at 300 m AGL. Yellow dot denotes the vortex. Right: Tornado (shaded), \( w \) (black), vorticity (blue).

EF0: rapid intensification by 20-35% for strong outflows then death, no significant impact when intermediate outflow (Fig. 4 left)

EF3: late intensification by 10-25% for weak outflows, death for stronger outflows (Fig. 4 right)

- Intensification coincides with correlation between updraft velocity and local convergence of high swirl air at lower radius (Fig. 5)

- Intensification by convergence of high swirl air to lower radii (Fig. 2)

V. Warm surges

- Example of warm bubble (Fig. 8, 9)

- In this case, the updraft is not disturbed, but the inflow is significantly altered at 25 min

VI. Summary and conclusions

- Simulation of tornadoes with larger domain, and more realistic forcing and boundary conditions than (3)

- Circulation analyses (not shown) reveal that the surges are not significant generators of circulation (via baroclinic horizontal vorticity generation and subsequent tilting into the vertical)

- Intensification is ideal when a balance is achieved between convergence of high swirl air and updraft intensification

- Strong cold outflow \( < 5 \) K has the potential to increase rapidly an EF3 vortex to EF4 for 10 min before killing it, but weaker outflows \( (2 \text{ K, } -1 \text{ K}) \) do not significantly alter the vortex

- Weak cold outflow produce slow convergence of high swirl air that can potentially increase an EF3 vortex to EF4, but stronger surges are detrimental

- In our simulations: \( -4 \text{ K} \) always eventually kills the vortex

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References