The impact of variations of low-level structure associated with surface drag on intensification of simulated tornadoes

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Abstract

The low-level structure is critical to transformation of low-level vorticity, which is known to be the fundamental source of rotation in updraft, and hence impact the intensification of tornadoes. Multiple convergence boundaries have been observed and simulated within surface drag by recent studies, suggesting that tornado development can occur away from the main convergence boundary separating the outflow and ambient inflow. How these variations of low-level structure under effect of surface drag contribute to long lived tornadoes are not well understood. In addition, differences in tornado intensity across different environments may yield different sensitivities to the underlying surface roughness. In this study, two environmental soundings representative of high CAPE, shallow CIN and low cape, deep CIN, respectively, are used to initialize the idealized simulation with the Bryan Cloud Model (CM1), and simulation with different surface drag strength with semi-sip boundary conditions are performed. Results of the simulations show that the inclusion of surface drag substantially alters the low-level structure in several minutes, resulting in stronger vorticity near surface and greater curvature of the convergence boundary. With the increase of surface drag, the tornado develops away from the forward convergence boundary due to the stronger angular momentum of the vortex and weaker ambient inflow. The rotating updraft tends to tilt to the area with greater convergence. The increasing distance beyond certain threshold between the relative location of tornado and convergence boundary indicates enhanced separation of maximum vorticity and maximum positive vertical pressure gradient, resulting in stronger vorticity near surface but slightly transport upward. The trajectory analysis demonstrates that, in drag conditions, most parcels travel through the rear flank downdraft area and merge to the rotating updraft, which intensifies the tilting of horizontal vorticity in that area and form the secondary convergence boundary. The low CAPE and deeper level of CIN require more dynamical vertical pressure gradient force associated with the magnitude of convergence from the low-level boundary and hence are more sensitive to the increase of surface drag.

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Introduction

Surface boundaries in supercells have long been suspected of being important in the arrangement and concentration of vorticity for the development and intensification of tornadoes. It is known that surface drag can enhance radial inflow in tornadoes (Fig. 1), but additional research is required to clarify the role of surface drag in preconditioning the near-surface environment of tornadoes. We focus on the following two questions in this study:

1. How are the formation and evolution of surface convergence boundaries affected by the presence or absence of surface drag?
2. How do these variations of low-level structure affect the development of simulated tornadoes?

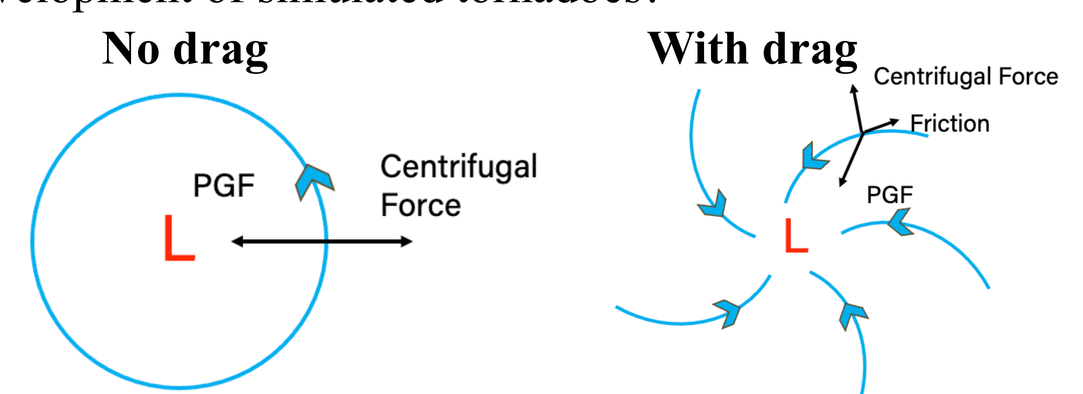

Fig.1. Surface drag disrupts cyclostrophic balance and enhances radial inflow near the surface (e.g. Howells et al. 1988)

Methodology

We use the CM1 model (Bryan and Fritsch 2002) to perform two idealized simulations at 100-m horizontal grid spacing of a tornadic supercell using an observed sounding from 31 March 2016 in northern Alabama: one without surface drag (FreeSlip) and one introducing drag (Free2Drag) 600 s prior to tornadogenesis. The goal is to focus on the impact of surface drag on the low-level structure on short time scales.

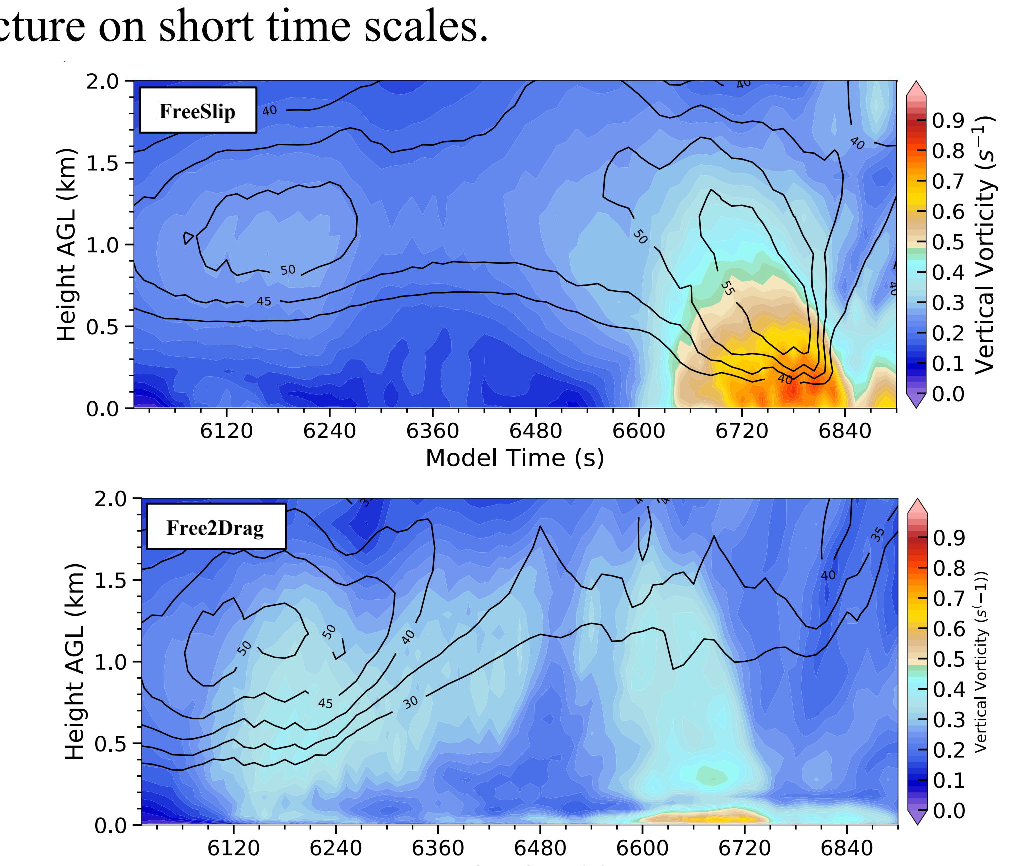

Fig. 2. Time-height plots of maximum vertical wind speed and vorticity for experiment FreeSlip and Free2Drag leading up to and during the period of tornadogenesis.

Evolution of convergence boundaries

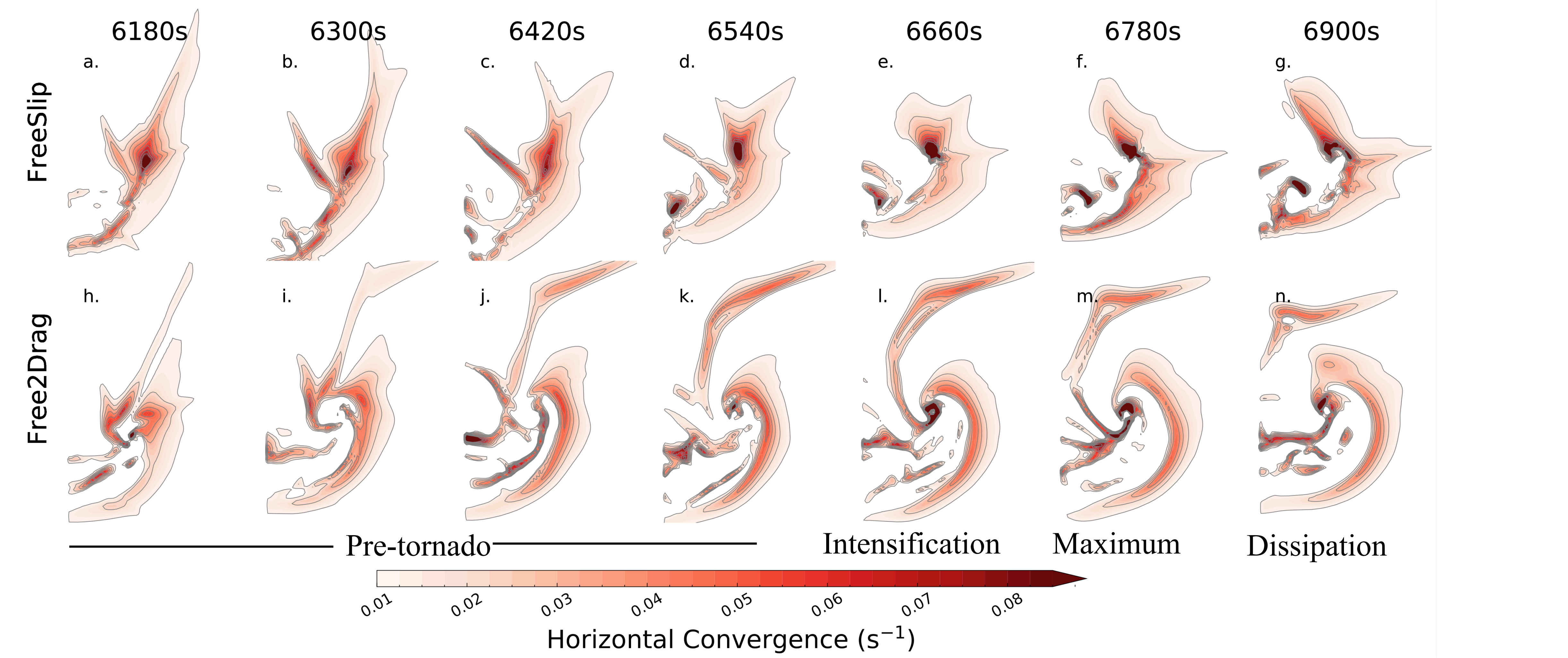

Fig. 3. Evolution of convergence boundaries at 30m AGL. Inclusion of surface drag substantially alters the low-level structure within minutes, resulting in greater curvature of the convergence boundaries, a stronger and more stable left-flank convergence boundary (LFCB; Beck and Weiss 2013), and additional transient secondary-rear flank convergence boundaries (SRFCBs).

Structure of simulated tornadoes

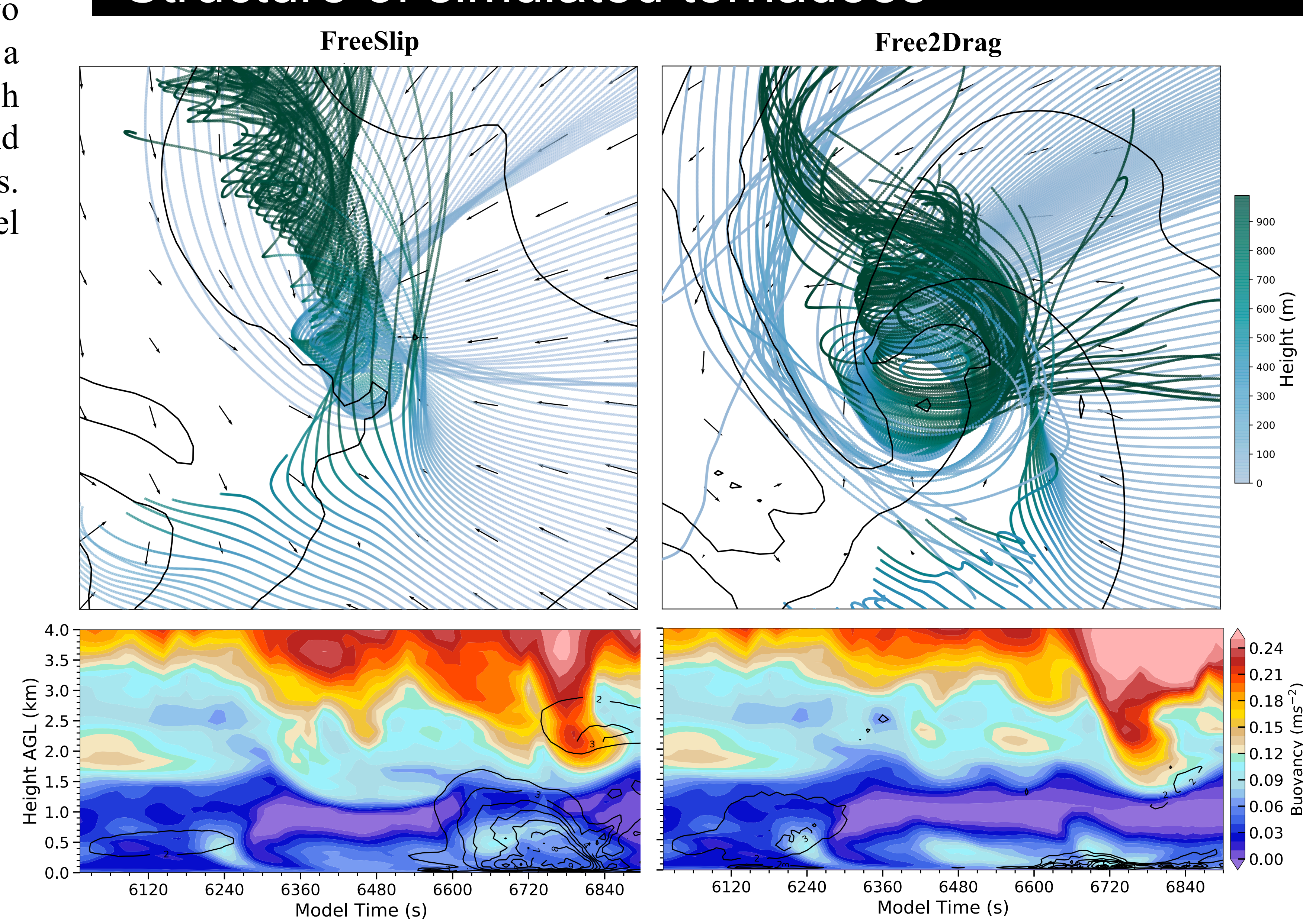

Fig. 4. (Top row) Collection of tornado source parcel trajectories; (Bottom row) time-height plot of buoyancy (shaded) and vertical perturbation pressure gradient force (VPPGF; black contour).

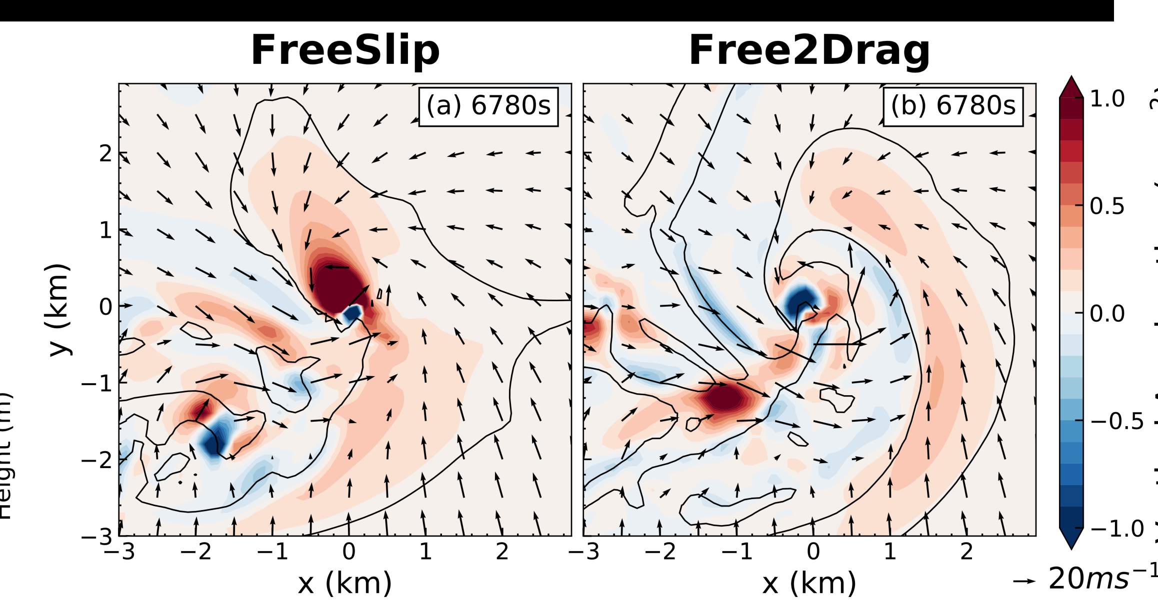

Fig. 5. vertical acceleration at 200 m AGL (shaded).

- In Free2Drag, the center of the simulated tornado near the surface develops detached from the rear flank gust front, whereas in FreeSlip, it remains embedded within the region of convergence associated with the gust front.
- The downward VPPGF associated with the stronger near-surface pressure deficit in Free2Drag suppresses vorticity stretching near the center, resulting in a weaker tornado (Fig.2 and 4).
- The tornado in Free2Drag also develops a larger horizontal circulation, suggestive of a two-cell vortex structure.

Distribution of near-surface vorticity

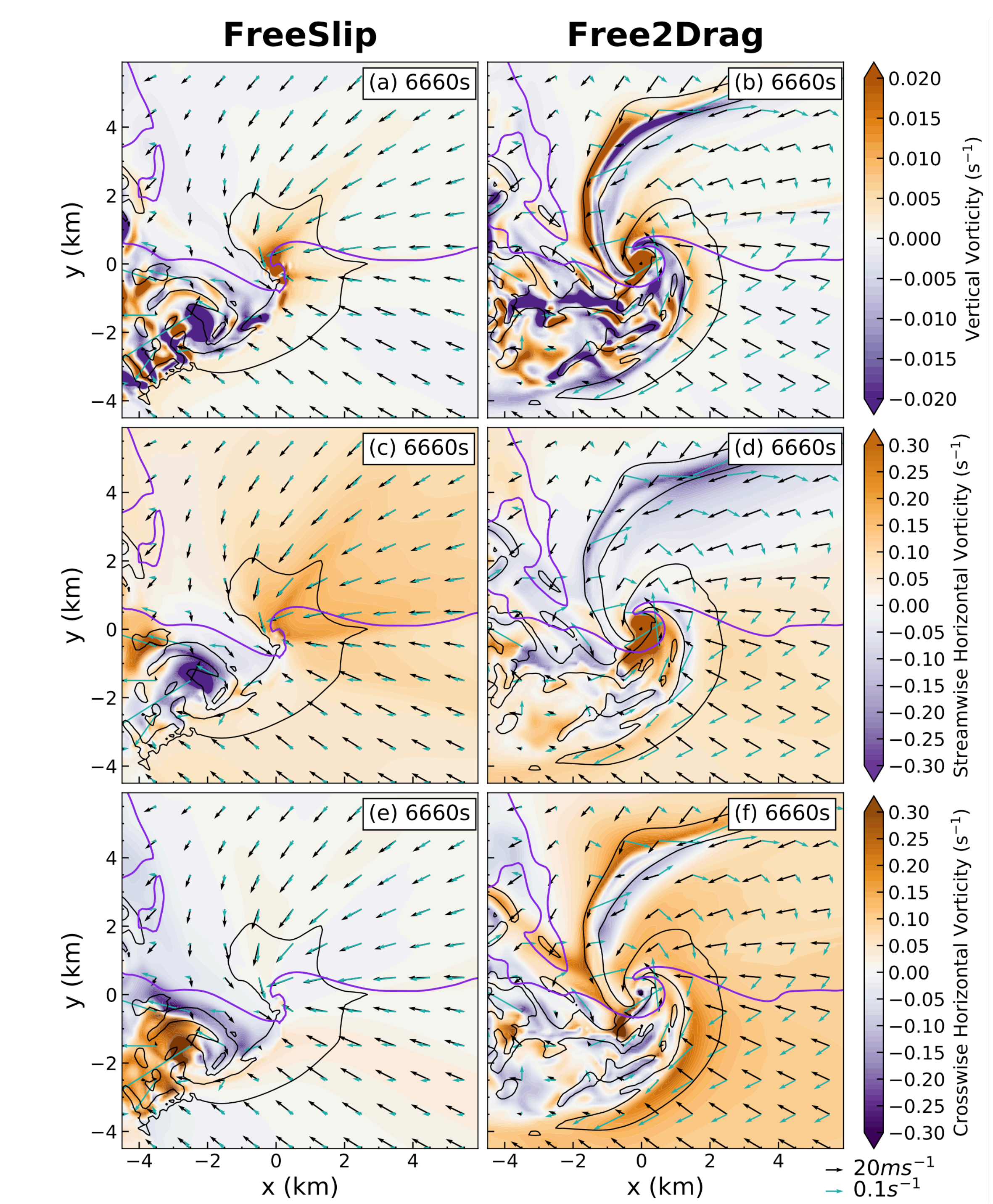

Fig. 6. Distribution (shaded) at 30 m AGL of vertical (top row), horizontal streamwise (middle row), and horizontal crosswise (bottom row) vorticity (shaded). Radar reflectivity (purple contour), storm-relative horizontal wind (black arrows) and horizontal vorticity vector (Green arrows) are also shown.

- The horizontal vorticity in FreeSlip is streamwise primarily in the forward flank region, which contributes to tornadogenesis through tilting and stretching.
- Friction-driven crosswise horizontal vorticity dominates near the surface in Free2Drag until the river-bend effect (Davies-Jones et al. 2001; Roberts et al. 2016) exchanges it into streamwise, resulting in the majority of positive streamwise vorticity located in the rear-flank region.
- The enhanced updraft associated with drag-induced convergence boundaries facilitates generation of vertical vorticity by tilting.
- Work continues to quantify the tornado vorticity sources and the role of the surface boundary evolution

Acknowledgments

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