CWE-8
June 7-11, 2026
London, ON, Canada

The influence of bottom boundary conditions on simulated mesovortex evolution

M. Schneider [a], L. Schielicke [b], D. Sills [c]

[a] *Canadian Severe Storms Laboratory, Western University, London, ON, Canada, morgan.schneider@uwo.ca*
[b] *Department of Physics and Astronomy, Western University, London, ON, Canada, lschieli@uwo.ca*
[c] *Canadian Severe Storms Laboratory, Western University, London, ON, Canada, david.sills@uwo.ca*

SUMMARY

The evolution of severe convective storms is highly dependent on physical processes in the atmospheric boundary layer, where the effects of surface drag are significant. Most prior research on the effects of surface drag on storm evolution has focused on large-eddy simulations of isolated supercell storms. These studies find surface friction to be important to storm intensification and subsequent tornado formation. Findings from other studies focusing on mesoscale convective systems (MCSs) show that friction was crucial to near-surface vorticity generation processes resulting in tornadogenesis, but only one extend this analysis to low-level (lowest 1–3 km) rotating updrafts, or mesovortices [*O*(2–20 km) wide]. In this study, we use CM1, a high-resolution idealized storm model, to simulate three MCSs using free-slip, semi-slip, and no-slip bottom boundary conditions. Comparisons between these simulations are performed to evaluate the effects of the bottom boundary condition on the development and characteristics of mesovortices.

Keywords: *Severe storms, storm dynamics, idealized numerical modelling*

1. INTRODUCTION

Surface drag is an important influence on the dynamics in the low levels (lowest ~1–3 km) of the atmosphere. Low-level physical processes are especially influential on the evolution of severe convective storms and their hazards, such as tornadoes and damaging wind. Tornadoes and severe wind in organized complexes of convective storms, or mesoscale convective systems (MCSs), are often associated with mesovortices, which are embedded storm-scale [*O*(~2–20 km) wide; Orlanski, 1975] rotating updrafts within the larger convective system that typically extend up to ~3 km above the ground. While there is no clear consensus on the exact mechanisms for the formation and maintenance of mesovortices, the importance of low-level processes to mesovortex evolution is well documented. However, most studies on the influence of surface drag have largely focused on its effects on isolated supercell storms and tornadoes rather than MCS mesovortices.

A multitude of studies have established the importance of surface drag in supercell tornado formation and evolution. Schenkman et al. (2014) and Roberts et al. (2016) additionally showed that surface drag played a direct role in simulated supercell tornadogenesis. Schenkman et al. (2014) found that a no-drag control simulation produced a significantly shorter-lived tornado, while Roberts et al. (2016) found that excluding surface drag resulted in no tornado at all. Fiedler (2017) found that using a semi-slip lower boundary condition with moderate surface roughness resulted in more realistic tornado structures compared to free-slip and no-slip boundary conditions (which neglect surface roughness). Recently, Jiang et al. (2025) found that including surface drag in simulated supercells increased the likelihood of tornadogenesis. Moderate drag strength was found to be most favorable for tornado intensification.

In addition to the past work focusing on tornadoes, Markowski (2016), Roberts and Xue (2017), and Roberts et al. (2020) examined the influence of surface drag on simulated rotating updrafts in supercell storms, referred to as mesocyclones. Markowski (2016) found that frictionally generated vorticity near the surface was the dominant contributor to mesocyclone rotation in the early stages of the supercell. Roberts and Xue (2017) and Roberts et al. (2020) found that simulated mesocyclones with surface drag intensified more rapidly and produced tornadoes, while mesocyclones without surface drag remained weaker and did not produce tornadoes. Stronger surface drag also led to earlier mesocyclone intensification in Roberts et al. (2020). Both studies proposed that frictionally generated vorticity near the surface had a direct role in mesocyclone intensification leading to tornadogenesis.

A small number of studies have studied the effects of surface drag on rotation in MCSs. Consistent with the previously discussed studies on supercell tornadoes, Schenkman et al. (2012) found that frictionally generated vorticity near the surface contributed directly to tornadogenesis in a simulated MCS, and that a control simulation without surface drag failed to produce a tornado. Xu et al. (2015) later found that surface drag in a simulated MCS produced near-surface horizontal vorticity that contributed significantly to low-level mesovortex formation. However, this study did not perform a control simulation without surface drag for comparison, leaving open questions about the specific effects of surface drag on simulated MCS mesovortices. This work seeks to address these questions using idealized simulations of MCSs with varying lower boundary conditions to examine how surface drag influences the formation and evolution of mesovortices.

2. METHODS

Numerical simulations of three idealized MCSs are generated with Cloud Model 1 (CM1), which uses a large-eddy simulation (LES) framework to model convective storms at high spatial resolution in a homogeneous base state environment (Bryan and Fritsch, 2002). The simulations are performed in a 300 km × 300 km × 15.36 km domain using a uniform horizontal grid spacing of 250 m and a stretched vertical grid with 20-m grid spacing in the lowest 600 m above the surface level. These resolutions are sufficient to resolve larger turbulent eddies and convective-scale features within MCSs such as updraft cores and mesovortices (Bryan et al., 2003; Lebo and Morrison, 2015). Convection is initiated by introducing four warm bubbles at the start of the simulation, resulting in the formation of a line of discrete supercell thunderstorms. The simulations are integrated forward in time for 7 h, allowing the discrete supercells to grow upscale into an MCS, a process that occurs frequently in nature. A summary of other select model configuration parameters is given in Table 1.

Table 1: Overview of CM1 model configuration parameters.

Parameter	Description
Horizontal grid spacing	250 m
Vertical grid spacing	20 m below 600 m 280 m above 12 km
Lateral boundary conditions	Open radiative east-west, periodic north-south
Bottom boundary conditions	Free-slip, no-slip, semi-slip
Subgrid-scale turbulence	1.5-order turbulent kinetic energy (TKE)
Cloud microphysics	Predicted Particle Properties (P3) with triple-moment ice

Bottom boundary conditions are varied between the three simulations to examine the effects of surface layer representation on low-level mesovortex evolution. In LES, including CM1, flow characteristics close to the surface are typically modelled using a free-slip, no-slip, or semi-slip boundary condition. The free-slip simulation (FREESLIP) uses a smooth bottom boundary and serves as a frictionless point of comparison. The no-slip simulation (NOSLIP) also uses a smooth bottom boundary but prescribes a thin viscous sublayer at the interface, wherein shearing stresses are dominated by viscosity and turbulent stress (drag) is negligible. The semi-slip simulation (SEMISLIP), by contrast, uses a rough surface, which lacks a viscous sublayer and allows for turbulence and therefore frictional drag to exist at the surface. The SEMISLIP simulation uses a constant drag coefficient of $C_D = 0.0014$, corresponding to a roughness length of $z_0 \approx 0.2$ mm.

3. PRELIMINARY RESULTS

Mesovortex characteristics in each simulation are evaluated initially using domain-wide model statistics. The time series of vertical vorticity at various heights in Figure 1 show clear differences in the evolution of mesovortex rotation between the three simulations.

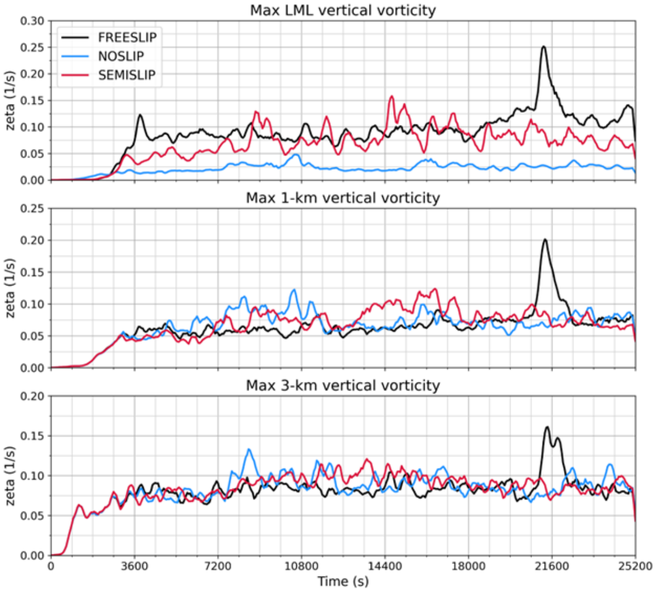

Figure 1: Top: Time series of domain-maximum vertical vorticity at the lowest model level (LML; 10 m) in the FREESLIP (black), NOSLIP (blue), and SEMISLIP (red) simulations. Middle: As in the top panel, but for the 1-km level. Bottom: As in the top panel, but for the 3-km level.

Vertical vorticity near the surface intensifies earliest in the SEMISLIP and FREESLIP simulations (top panel), with more rapid early intensification in the FREESLIP simulation. The NOSLIP simulation never develops strong near-surface vertical vorticity. As upscale growth begins after 7200 s, the SEMISLIP and FREESLIP simulations maintain similar magnitudes of near-surface vertical vorticity until a spike in vorticity appears in the FREESLIP simulation just before 21600 s. Further examination is needed to determine if this spike represents the formation of a tornado-like vortex and why this feature is absent from the SEMISLIP and NOSLIP simulations.

At a height of 1 km (middle panel), the SEMISLIP and NOSLIP simulations develop stronger vertical vorticity after 7200 s, with slightly weaker vertical vorticity in the FREESLIP simulation until the spike at 21600 s. Vorticity in the SEMISLIP simulation intensifies around 12600 s and the SEMISLIP simulation then maintains the strongest 1-km vertical vorticity of the three simulations until weakening around 18000 s. This period between 12600 and 18000 s is when the MCSs reach maturity, suggesting that the inclusion of surface drag may contribute to the enhancement of storm-scale rotation above the surface in a maturing MCS. The evolution of vertical vorticity at 3 km (bottom panel) is qualitatively similar to the 1-km evolution, with marginally stronger vertical vorticity in the SEMISLIP and NOSLIP simulations after 7200 s.

4. CONCLUSIONS

In preliminary results, the three simulated MCSs display clear differences in vertical vorticity evolution, indicating that representation of the surface layer can have a significant effect on simulated mesovortex characteristics. The SEMISLIP and NOSLIP simulations develop stronger rotation at 1 km and 3 km above the surface, with SEMISLIP having the strongest rotation at 1 km as the MCS matures, while the FREESLIP simulation appears to develop the strongest near-surface rotation. Note that since these values are domain-wide maxima, they may not represent the evolution of a single feature over time. Even so, these results warrant further study of the simulated mesovortices and the role that the bottom boundary condition plays in their differing evolution.

ACKNOWLEDGEMENTS

This work was made possible by funding from ImpactWX and Western University. Many thanks to George Bryan at NCAR/UCAR for maintaining and sharing CM1. These simulations were produced using the facilities of the Shared Hierarchical Academic Research Computing Network (SHARCNET) and Digital Research Alliance of Canada.

REFERENCES

Bryan, G. H., Fritsch, J. M., 2002. A benchmark simulation for moist nonhydrostatic numerical models. Mon. Wea. Rev. 130, 2917–2928. https://doi.org/10.1175/1520-0493(2002)130<2917:ABSFMN>2.0.CO;2.

Bryan, G. H., Wyngaard, J. C., Fritsch, J. M., 2003. Resolution requirements for the simulation of deep moist convection. Mon. Wea. Rev. 131, 2394–2416, https://doi.org/10.1175/1520-0493(2003)131<2394:RRFTSO>2.0.CO;2.

Fiedler, B., 2017. Axisymmetric tornado simulations with a semi-slip boundary. Fluids 2, 68, https://doi.org/10.3390/fluids2040068.

Jiang, Q., Dawson, D. T., Chavas, D. R., 2025. Favorability of tornado-like vortex formation and duration as a function of surface drag in idealized simulations. Mon. Wea. Rev. 153, 1841–1865, https://doi.org/10.1175/MWR-D-24-0137.1.

Lebo, Z. J., Morrison, H., 2015. Effects of horizontal and vertical grid spacing on mixing in simulated squall lines and implications for convective strength and structure. Mon. Wea. Rev. 143, 4355–4375, https://doi.org/10.1175/MWR-D-15-0154.1.

Markowski, P. M., 2016. An idealized numerical simulation investigation of the effects of surface drag on the development of near-surface vertical vorticity in supercell thunderstorms. J. Atmos. Sci. 73, 4349–4385. https://doi.org/10.1175/JAS-D-16-0150.1.

Orlanski, I., 1975. A rational subdivision of scales for atmospheric processes. Bull. Amer. Meteor. Soc. 56, 527–534, https://doi.org/10.1175/1520-0477-56.5.527.

Roberts, B., Xue, M., Schenkman, A. D., Dawson, D. T., 2016. The role of surface drag in tornadogenesis within an idealized supercell simulation. J. Atmos. Sci. 73, 3371–3395. https://doi.org/10.1175/JAS-D-15-0332.1.

Roberts, B., Xue, M., 2017. The role of surface drag in mesocyclone intensification leading to tornadogenesis within an idealized supercell simulation. J. Atmos. Sci. 74, 3055–3077. https://doi.org/ 10.1175/JAS-D-16-0364.1.

Roberts, B., Xue, M., Dawson, D. T., 2020. The effect of surface drag strength on mesocyclone intensification and tornadogenesis in idealized supercell simulations. J. Atmos. Sci. 77, 1699–1721. https://doi.org/ 10.1175/JAS-D-19-0109.1.

Schenkman, A. D., Xue, M., Shapiro, A., 2012. Tornadogenesis in a simulated mesovortex within a mesoscale convective system. J. Atmos. Sci. 69, 3372–3390, https://doi.org/10.1175/JAS-D-12-038.1.

Schenkman, A. D., Xue, M., Hu, M., 2014. Tornadogenesis in a high-resolution simulation of the 8 May 2003 Oklahoma City supercell. J. Atmos. Sci. 71, 130–154, https://doi.org/10.1175/JAS-D-13-073.1.

Xu, X., Xue, M., Wang, Y., 2015. The genesis of mesovortices within a real-data simulation of a bow echo system. J. Atmos. Sci. 72, 1963–1986. https://doi.org/10.1175/JAS-D-14-0209.1.