Utilizing a Semi-idealized Modeling Framework to Understand Meso- and Convective-scale Dynamics of Severe Lake-effect Snowstorms

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Introduction

A semi-idealized modeling framework is developed to explore what modulates long lake axis-parallel band location, shape, and intensity. Initial model experiments are used to investigate:

What caused cross-band asymmetry during the catastrophic Buffalo Snowstorm November 17-19, 2014?

Idealized lake-land geometry and simplified boundary conditions allow for controlled variations of the model state space.

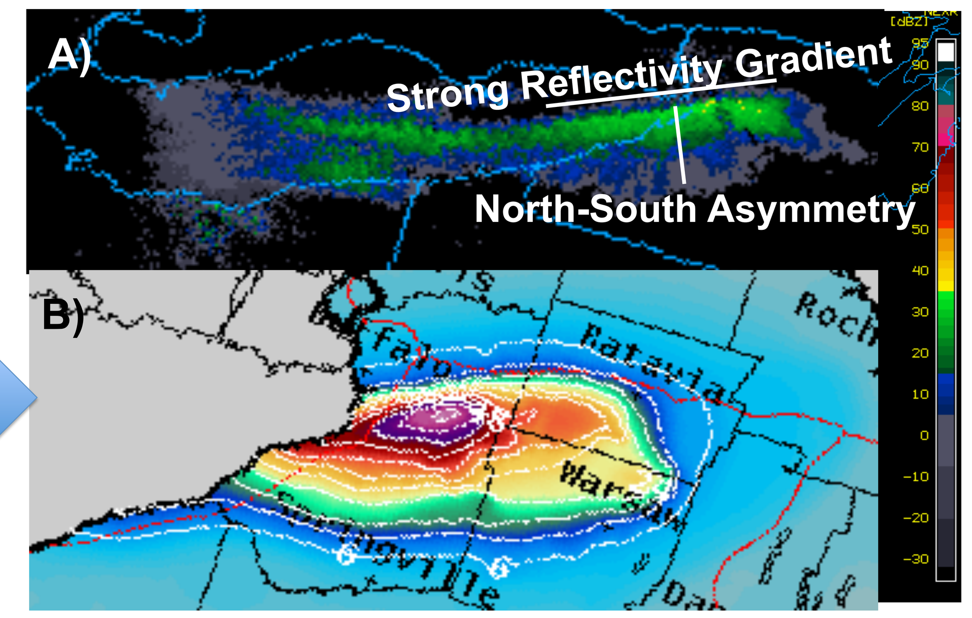


Figure 1. Observed cross-band asymmetry during the 2014 Buffalo snowstorm November 17-19, 2014. (A) NEXRAD radar reflectivity at 12:30Z 11/18/14 (UCAR, 2014). (B) Storm total snowfall in inches (NWS, 2014).

Numerical Experiment Design:

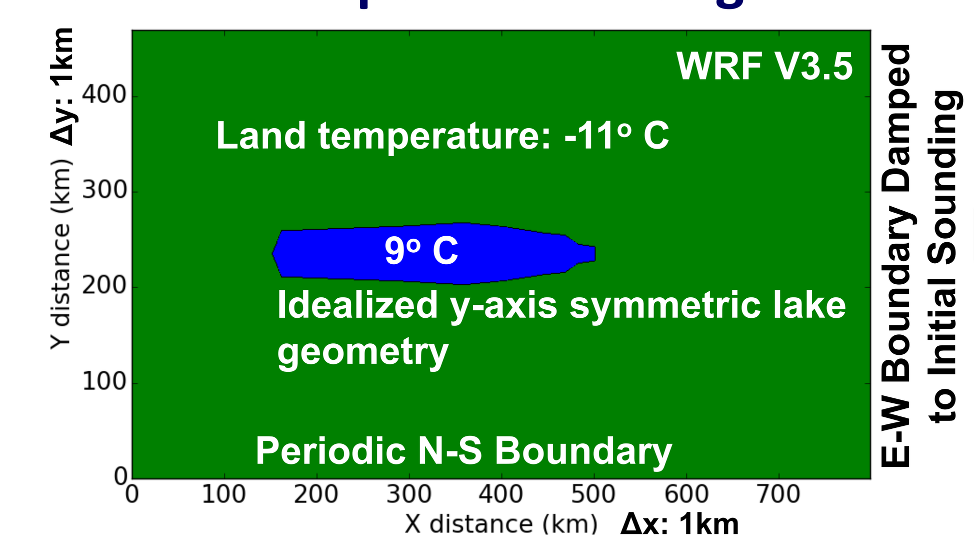


Figure 2. Model domain for semi-idealized model experiments. Land and lake surface temperatures are labeled.

Configuration

- Planetary boundary layer scheme: YSU
- Microphysics : Thompson scheme
- Terrain: None
- Radiation: None
- Land moisture flux: None
- Coriolis: f-plane, acts on perturbation winds

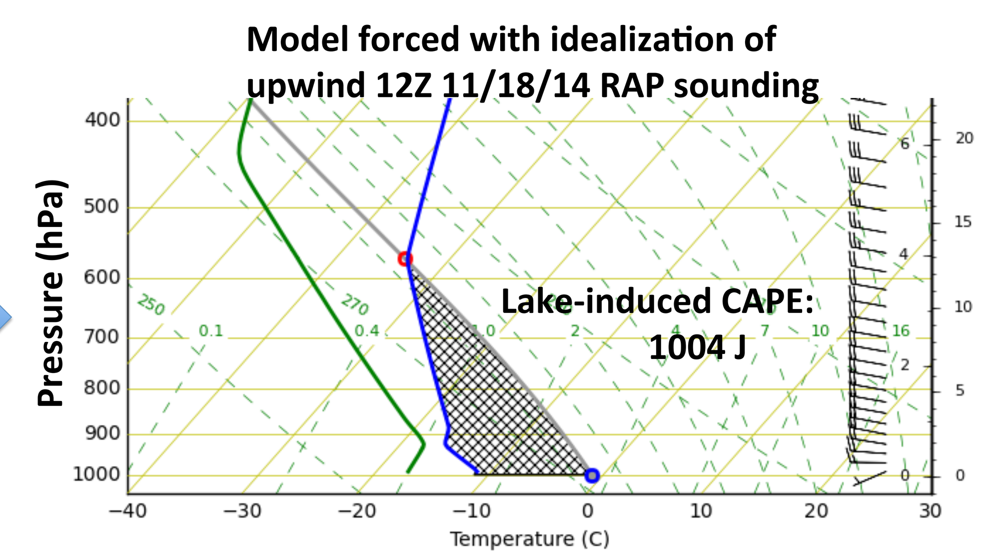


Figure 3. Initial sounding and boundary condition for incoming flow.; control simulation wind direction shown.

Suite of experiments examine controlled perturbations to wind direction:

- Winds rotated 10° CW from lake's long axis [Control]
- Winds parallel to lake's long axis [Rot0]
- Winds rotated 5° CW from lake's long axis [Rot5]
- Winds rotated 15° CW from lake's long axis [Rot15]

Simulated Lake-effect Snow-band Morphology:

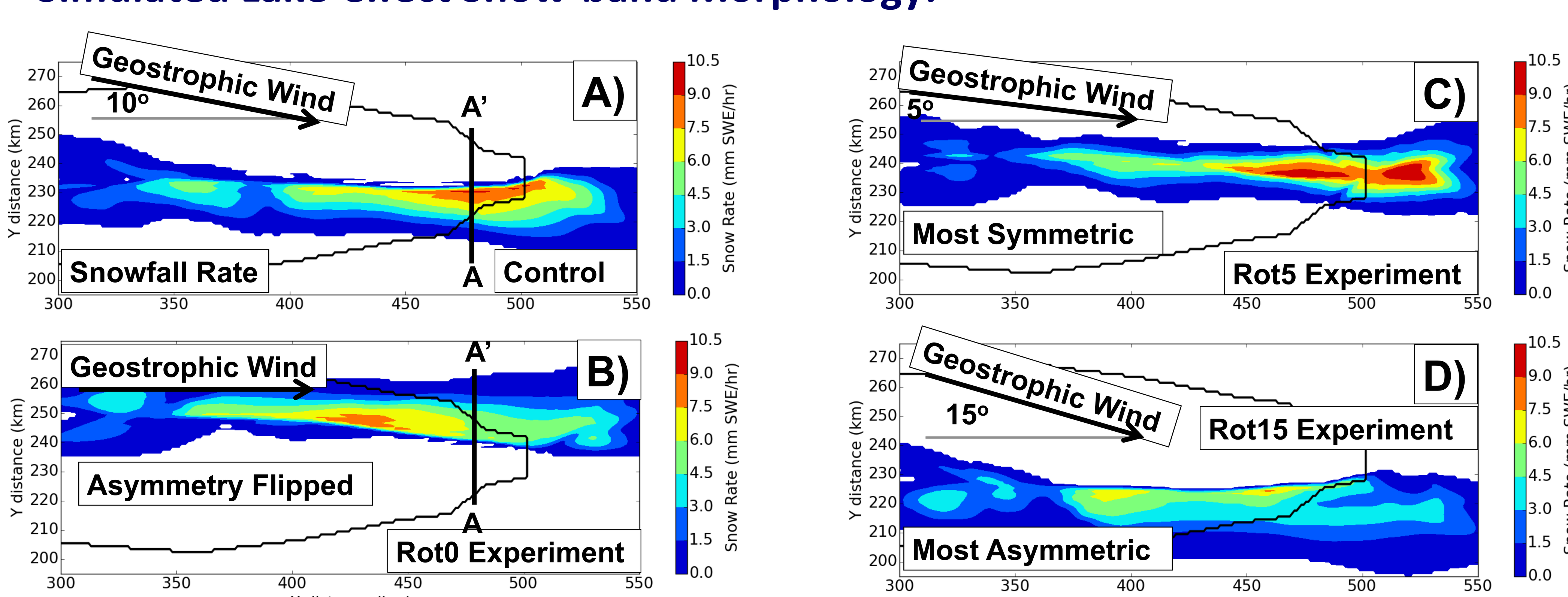


Figure 4. Modeled steady-state precipitation rates in liquid water equivalent for: A) Control experiment; B) Rot0 experiment; C) Rot5 experiment; and D) Rot15 Experiment.

- Control simulation recreates observed band asymmetry, structure, and precipitation rates without lake shape asymmetry, terrain, and lake surface temperature variability, suggesting that these characteristics are not fundamental to band morphology
- By varying the geostrophic wind direction within a range of 15 degrees, it is possible to obtain snow-bands of opposite asymmetries

The Impact of Updraft Structure on Band Morphology

***Hypothesis:* Buoyancy gradient across snow-band causes updraft to tilt, producing asymmetric morphology.**

Use horizontal vorticity budget analysis (following Rotunno, Klemp, and Weismann [1988]) to test:

$$\frac{\partial \xi}{\partial t} = -\frac{\partial v\xi}{\partial y} - \frac{\partial w\xi}{\partial z} + \frac{\partial B}{\partial y}$$

Equation 1. Simplified flux form of the zonal vorticity equation. Assumes negligible: zonal convergence of vorticity, tilting, stretching, and viscous forces. B is buoyancy; ξ is zonal vorticity.

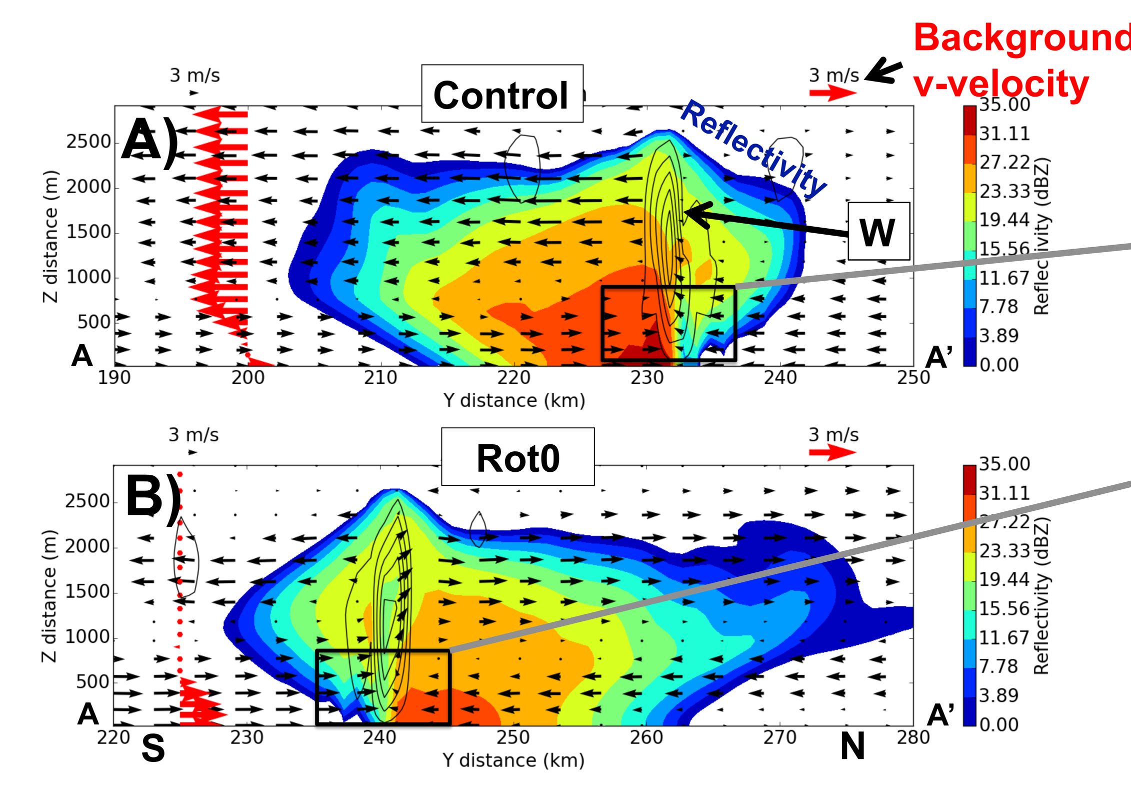
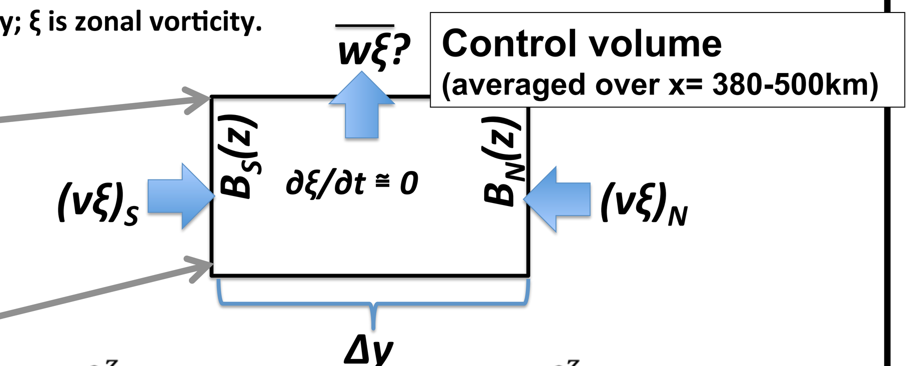


Figure 5. Cross section A – A' from Figure 4 for the Control (A) and Rot0 (B) experiments. V-W velocity vectors are drawn in black and updrafts greater than .5 m/s are contoured at intervals of 1 m/s. For reference, upwind boundary condition v-velocity components are shown in red (note difference in scale). Control volume used in vorticity budget analysis is drawn in a black box.



$$\overline{w\xi}\,\Delta y = -\int_0^z [(v\xi)_N - (v\xi)_S]dz + \int_0^z [B_N - B_S]dz$$

Equation 2: Solve for vertical vorticity flux by assuming a steady state, then integrating eqn. 1 over control volume.

- A negative (positive) vertical vorticity flux represents a tendency for upper-level outflow to the north (south).
- Asymmetric outflow can be produced by:
  1. Horizontal buoyancy gradients
  2. Horizontal vorticity flux convergence.

Horizontal Vorticity Budget Analysis:

Term (m2/s2)	Experiment Name: Rot0	Rot5	Control	Rot 15
$\overline{w\xi}\,\Delta y$	-49.11	-2.28	39.18	72.91
$-\int_0^z [(v\xi)_N - (v\xi)_S]dz$	-8.01	1.69	7.23	13.89
$\int_0^z [B_N - B_S]dz$	-41.10	-3.97	31.95	59.02

Table 1. Each term of Equation 2 calculated from model output.

- Buoyancy gradient generation explains most of the vertical vorticity flux and its variation

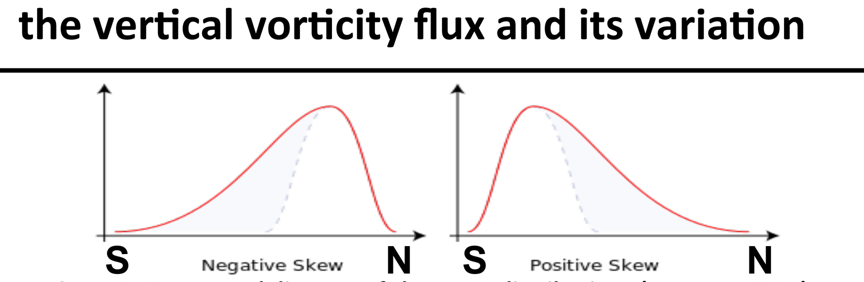


Figure 6. Conceptual diagram of skewness distributions (Hermans 2014).

Use skewness of vertically integrated ice and liquid mass to quantify cross-band asymmetry

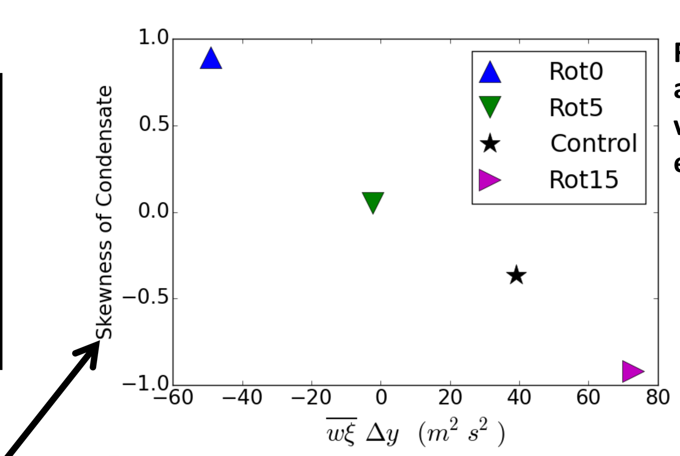


Figure 7. The relationship between corss-band asymmetry (skewness of condensate) and vertical vorticity flux for each numerical experiment.

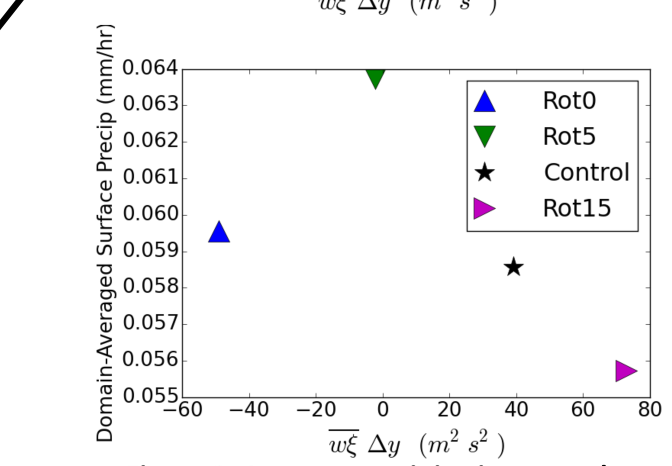


Figure 8. Average precipitation over the entire model domain.

- The relationship between vertical vorticity flux and skewness supports buoyancy gradient hypothesis
- The most symmetric and "upright" snow-bands produce more total precipitation over the model domain

Conclusions

- Simplified model recreates observed lake-effect band structure
- Buoyancy gradients across lake-effect snow bands appear to drive outflow dynamics that cause observed cross-band asymmetry
- More-symmetric snow-bands, with smaller cross-band buoyancy gradients, may create more total snowfall

Future Work

- Test the robustness of results with different physics parameterizations, higher resolution, and more complex model configurations (i.e. added wind shear, terrain, lake-temperature variations).
- Develop a conceptual model for how boundary layer flow interacts with surface fluxes to create observed buoyancy gradients and snow-band structure
- Test hypothesis using data from the Ontario Winter Lake-effect Systems field campaign

Reference: Rotunno, R., Klemp, J. B., & Weisman, M. L., 1988: A theory for strong, long-lived squall lines. *Journal of the Atmospheric Sciences*, 45(3), 463-485. Additional references available upon request.