Observations of Misovortices within a Long-lake-axis-parallel Lake-effect Snow Band during the OWLeS Project

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Introduction and Motivation

Since the winter of 2010-11, several instances of strings of misovortices have been observed in high-resolution radar data collected within long-lake-axis-parallel (LLAP) lake-effect snow bands over Lake Ontario. Previous analyses of single-Doppler data has postulated that these vortices originate owing to horizontal shearing instability (HSI) along shear zones within the bands. One such case occurred on 7 January 2014 (Fig. 1) when Arctic air, characterized by 850 mb air temperatures around -25°C, traversed Lake Ontario, with water temperatures around 3°C. Dual-Doppler wind syntheses and a high-resolution Weather Research and Forecasting (WRF) model simulation of this event are analyzed to reveal that two separate criteria for HSI are met along this shear zone, strongly suggesting that HSI is the likely generation mechanism of the string of vortices observed in this case.

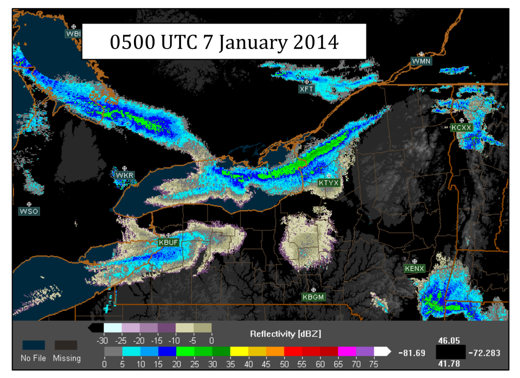
Figure 1: Multi-radar multi-sensor (MRMS) analysis over the eastern Great Lakes region at 0500 UTC 7 January 2014.

Radar Data Collection

- Data collected by two Doppler on Wheels (DOW) radars (DOW6 and DOW8) between 0400-0800 UTC 7 January 2014 (Fig. 2) were edited with Solo3 and then mapped to a Cartesian grid (Δx = 250 m) using a two-pass Barnes analysis and OPAWS software.
- The DOW radars are X-band (3-cm) wavelength radars with a beamwidth of 0.95°.

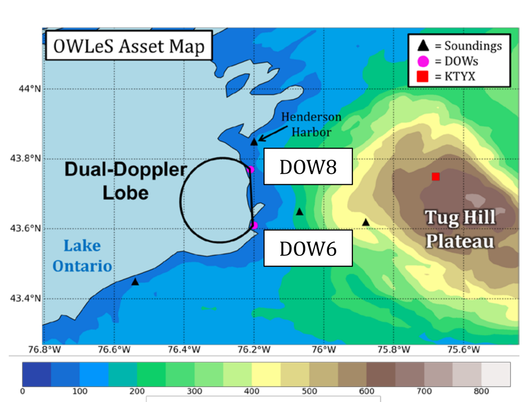
Figure 2: Map illustrating the locations of mobile radars (pink circles), mobile sounding units (black triangles), and the KTYX WSR-88D radar (red square). The dual-Doppler lobe is indicated in black and terrain height (m) is shaded.

WRF Simulation

- Three nested grids (Fig. 3)
- Δx = 3 km, 1 km, 333 m
- 60 vertical levels
- Microphysics: Thompson
- Boundary layer: Shin-Hong
- Radiation: RRTMG
- Surface layer: Monin-Obukov
- Land surface: RUC LSM
- Cumulus: None

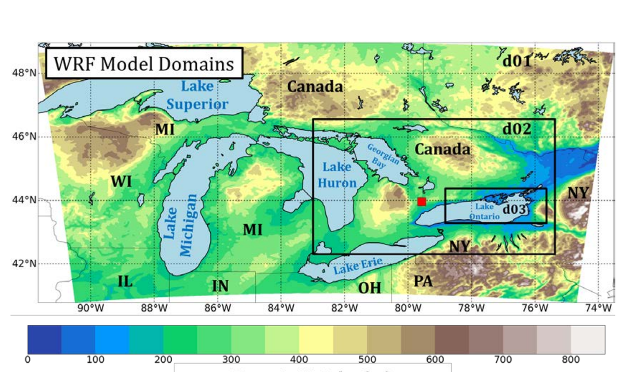
Figure 3: Map illustrating the three nested WRF domains, with horizontal resolutions of 3 km, 1 km, and 333 m, respectively. Terrain height (m) is shaded.

Dual-Doppler Analysis

- Six distinct cyclonic misovortices were tracked for a 20-minute period (Fig. 4). The vortices did not merge or interact during this time.
- The vortices formed and propagated along a cyclonic horizontal shear zone initially at the northern edge of the band (Figs. 4a-c), which later migrated toward the center of the band (Figs. 4d-f).
- The mesoscale updraft was also along the northern edge of the band (Fig. 5).
- When the connection between the upstream Georgian Bay and Lake Ontario bands (Fig. 1) terminated after 0800 UTC, the string of vortices also vanished.

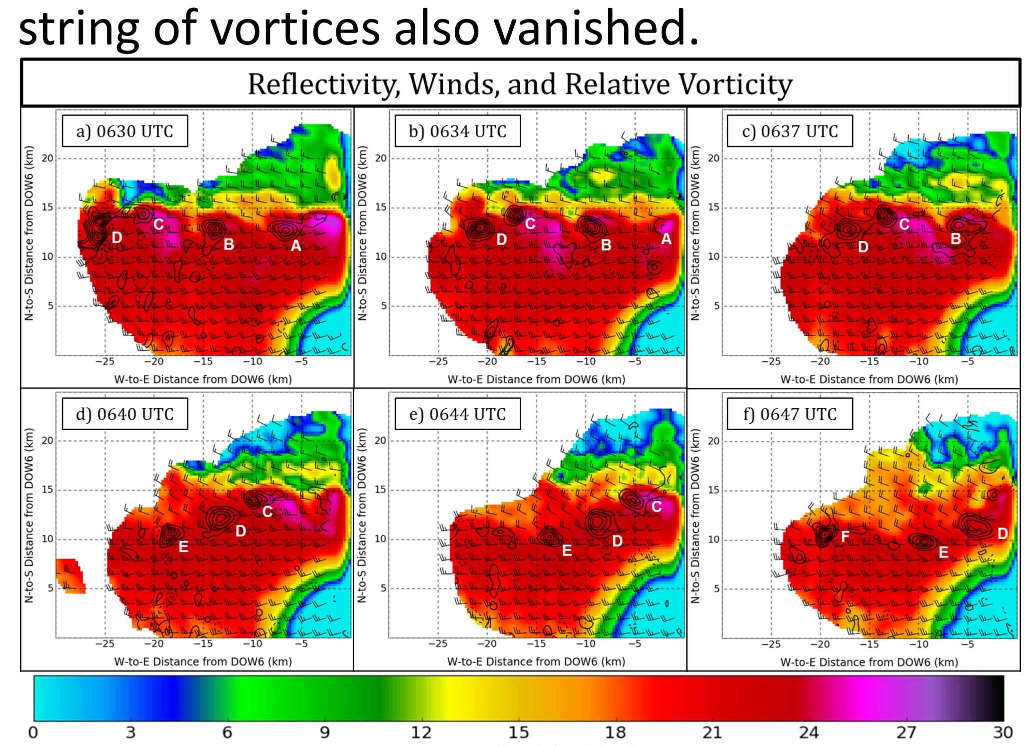
Figure 4: Dual-Doppler wind syntheses at 500 m AGL with horizontal winds (full barb = 10 m s^{-1}), DOW6 composite reflectivity (dBZ; shaded), and vertical vorticity (contoured every 0.5 x 10^{-2} s^{-1}) at: a) 0630, b) 0634, c) 0637, d) 0640, e) 0644, and f) 0647 UTC 7 January 2014. Each vortex is labeled with a capital letter.

- A vertical cross section through Vortex A (Fig. 5) reveals the transverse secondary circulation and significant overlap between the vertical velocity (white contour) and vertical vorticity (black contour) fields, enhancing vertical vorticity via stretching.
- A plan view of the stretching term in the vertical vorticity equation ($\zeta \frac{\partial w}{\partial z}$; Fig. 6) reveals that stretching occurred in most of the vortices (compare Figs. 4a and 6).
- Rayleigh's Instability Criterion (RIC) states that $\frac{\partial^2 \bar{u}}{\partial y^2}$ must change sign (an inflection point must exist) for HSI to be present ($\bar{u}$ is the mean wind component parallel to the wind shift) and is satisfied at the location of the shear zone and vortices (Figs. 4a and 7).
- Fjørtoft's Instability Criterion (FIC) states that $\frac{\partial^2 \bar{u}}{\partial y^2}(\bar{u} - \bar{u}_I) < 0$ for instability, where $\bar{u}_I$ is the mean wind component parallel to the shear zone at the inflection point and is satisfied in a broad zone encompassing the shear zone and vortices (Figs. 4a and 8).

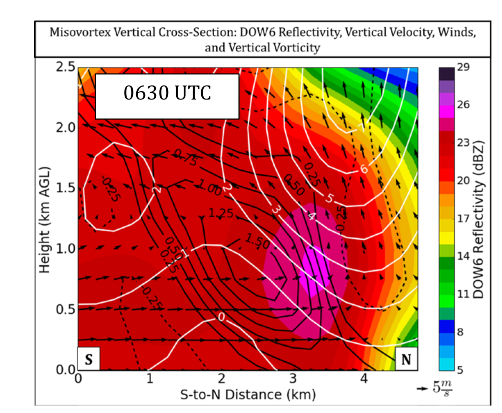
Figure 5: Vertical cross section through Vortex A at 0630 UTC with DOW6 reflectivity (dBZ; shaded), vertical velocity (white contours every 1 m s^{-1}), vertical vorticity (black contours every 0.25 x 10^{-2} s^{-1}), and wind vectors (v and w components only; m s^{-1}).

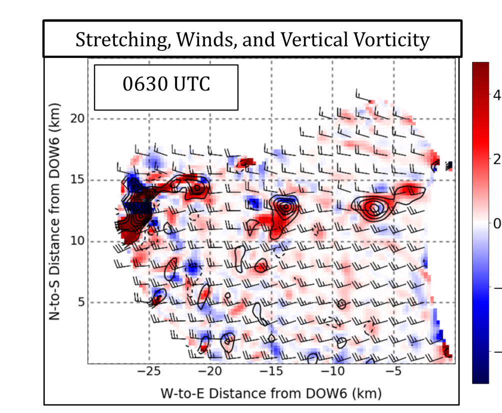
Figure 6: Stretching term in the vertical vorticity equation ($\zeta \frac{\partial w}{\partial z}$ x 10^{-4} s^{-2}; shaded), 500 m winds (full barb = 10 m s^{-1}), and vertical vorticity (contoured every 0.5 x 10^{-2} s^{-1}) at 0630 UTC.

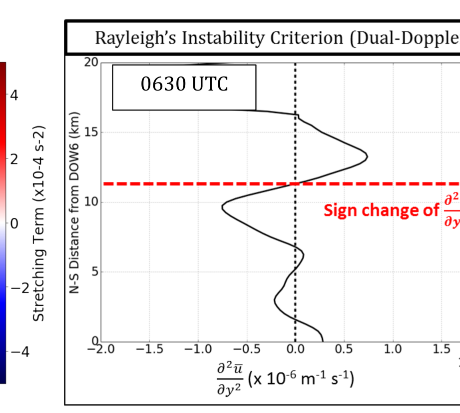
Figure 7: RIC ($\frac{\partial^2 \bar{u}}{\partial y^2}$ x 10^{-6} m^{-1} s^{-1}) vs. north-south distance (km) from DOW6 at 500 m AGL at 0630 UTC. The red dashed line indicates where RIC is satisfied.

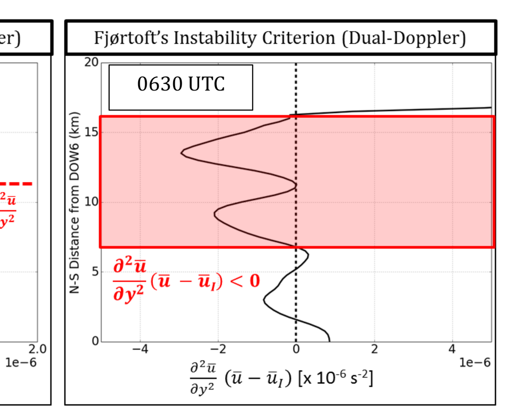
Figure 8: FIC ($\frac{\partial^2 \bar{u}}{\partial y^2}(\bar{u} - \bar{u}_I)$ x 10^{-6} s^{-2}) vs. north-south distance (km) from DOW6 at 500 m AGL at 0630 UTC. The red shading indicates where FIC is satisfied.

WRF Simulation Analysis

- The WRF simulation realistically replicates the string of vortices seen in the radar observations (Fig. 9), but slightly later than was observed.
- A vertical cross section through Vortex G (Fig. 10) illustrates that the simulated vortices are also located south of the primary updraft.
- The vortex stretching term (Fig. 11) is important to vortex maintenance over Lake Ontario. The vortices dissipate as they move inland, as surface roughness increases and stretching decreases. Stretching was 4-6x greater than tilting throughout the integration (not shown).
- Both RIC (Fig. 12) and FIC (Fig. 13) are satisfied at the location of the vortices and shear zone, strongly suggesting that HSI, not tilting, is the dominant generation mechanism of these vortices.

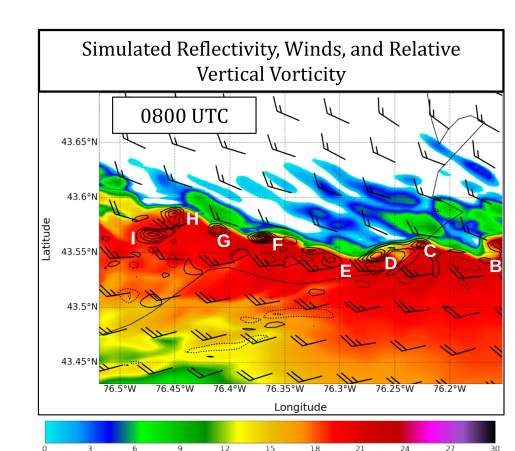
Figure 9: Simulated composite reflectivity (dBZ, shaded) with horizontal winds (full barb = 10 m s^{-1}), and relative vertical vorticity (contoured every 0.5 x 10^{-2} s^{-1}) at 500 m AGL at 0800 UTC 7 January 2014. Each vortex is labeled with a capital letter.

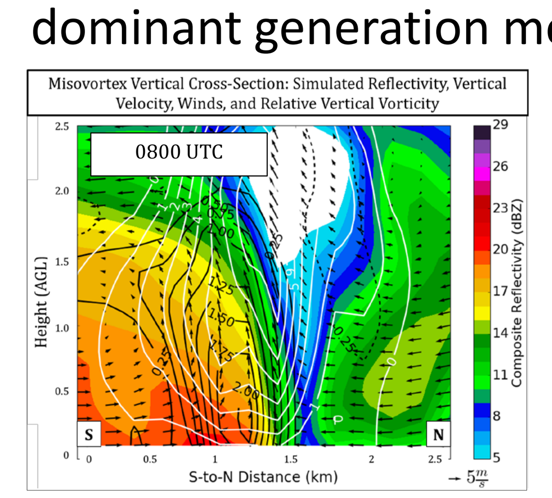
Figure 10: Vertical cross-section through simulated Vortex G at 0800 UTC. Composite reflectivity (dBZ; shaded) with vertical velocity (white contours every 1 m s^{-1}), vertical vorticity (black contours every 0.25 x 10^{-2} s^{-1}), and wind vectors (v and w components only; m s^{-1}).

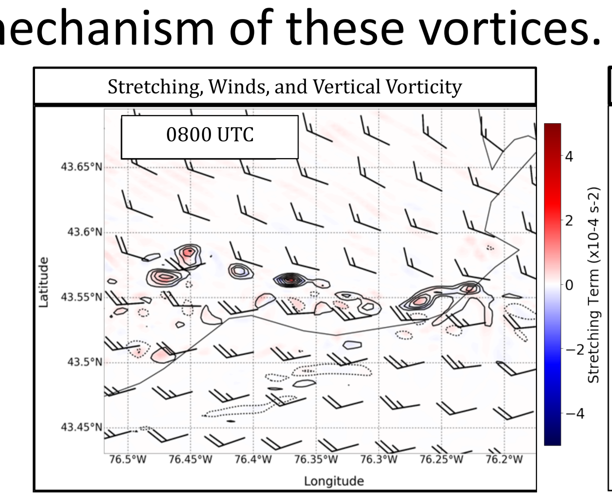
Figure 11: Stretching term in the vertical vorticity equation ($\zeta \frac{\partial w}{\partial z}$ x 10^{-4} s^{-2}; shaded), 500 m winds (full barb = 10 m s^{-1}), and vertical vorticity (contoured every 0.5 x 10^{-2} s^{-1}) from the WRF simulation at 0800 UTC.

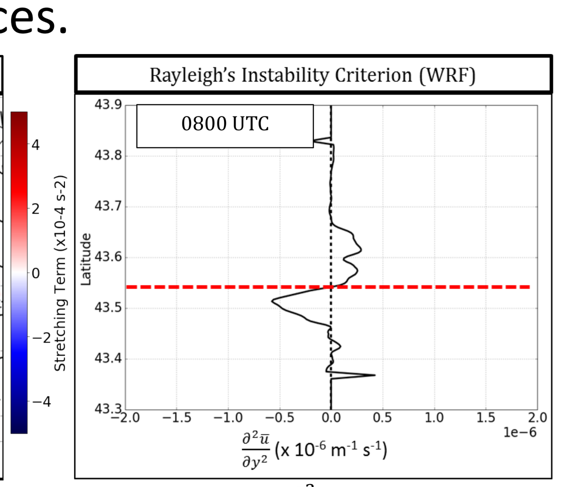
Figure 12: RIC ($\frac{\partial^2 \bar{u}}{\partial y^2}$ x 10^{-6} m^{-1} s^{-1}) vs. latitude from the WRF simulation at 500 m AGL at 0800 UTC. The red dashed line indicates where RIC is satisfied.

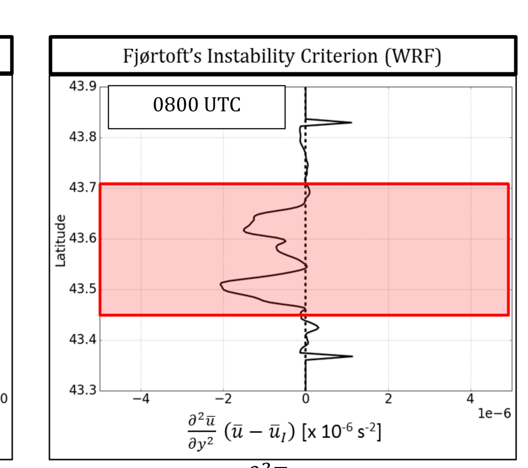
Figure 13: FIC ($\frac{\partial^2 \bar{u}}{\partial y^2}(\bar{u} - \bar{u}_I)$ x 10^{-6} s^{-2}) vs. latitude from the WRF simulation at 500 m AGL at 0800 UTC. The red shading indicates where FIC is satisfied.

Conclusions

- A string of misovortices developed along a cyclonic horizontal shear zone within a lake-effect snow band over Lake Ontario on 7 January 2014.
- The shear zone and vortices were initially co-located with the primary updraft along the northern edge of the band, but later migrated southward toward the center of the band.
- When the connection between the upstream Georgian Bay band and the Lake Ontario band dissipated, the string of vortices vanished.
- Analyses of dual-Doppler wind syntheses and a high-resolution WRF simulation reveal that two criteria for HSI are satisfied along this shear zone, strongly suggesting that HSI is the likely formation mechanism of these vortices.
- The lack of vortex couplets strongly suggests that tilting is likely not the primary driver of misovortexgenesis.
- Stretching is likely important to vortex maintenance over the warm lake waters.
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