Quantifying the Upscale Effects of Mesoscale Convective Systems and Implications to Model Biases in Large-Scale Circulation

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K. Sakaguchi[1], Z. Feng[1], J. Lu[1], L. R. Leung[1], J. Jang[2], C. Zarzycki[2], B. Skamarock[2], and R. Houze Jr.[1,3]
[1]Pacific Northwest National Laboratory, [2]National Center for Atmospheric Research, [3]University of Washington

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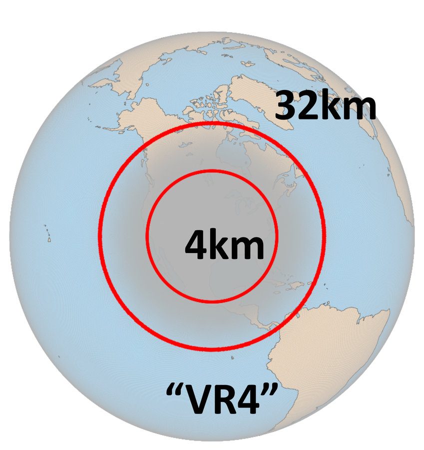
Introduction

- Previous studies suggested that Mesoscale Convective Systems (MCSs), particularly those long-lived, can alter the synoptic conditions and provide positive feedbacks to their lifetime (Yang et al. 2017; Feng et al. 2018). It implies that models not simulating MCSs miss important “upscale” effects. Our goal is to quantify the missing upscale effects.
- One approach is to use potential vorticity (PV) generated by MCSs (Davis and Weisman 1994). Intense condensational heating and wind sheer embedded in MCSs lead to strong PV anomalies, which can be used to retrieve associated wind and mass fields under an assumed flow balance: referred as PV inversion.
- We test the applicability of PV inversion for quantifying the upscale effects of MCSs in a global model. Our first step presented here is to compare two numerical experiments: one lacking MCS (used as a reference) and the other producing MCS, given a similar large-scale environment.

Experimental Design

MPAS-CAM Framework



- Model for Prediction Across Scales (MPAS) is a global, non-hydrostatic dynamical core on an unstructured Voronoi mesh (Skamarock et al. 2012)
- MPAS can be flexibly configured for quasi-uniform and variable resolutions, down to convection-permitting resolutions
- MPAS is coupled to the Community Atmosphere Model (CAM) by PNNL-NCAR collaboration for climate-oriented studies
- We use two horizontal meshes with regional refinement over the continental U.S.: VR25 and VR4.
- The CAM default deep convection parameterization by Zhang and McFarlane (1995) is used in VR25, while it is turned off in VR4 over the entire global domain.

Numerical Experiments

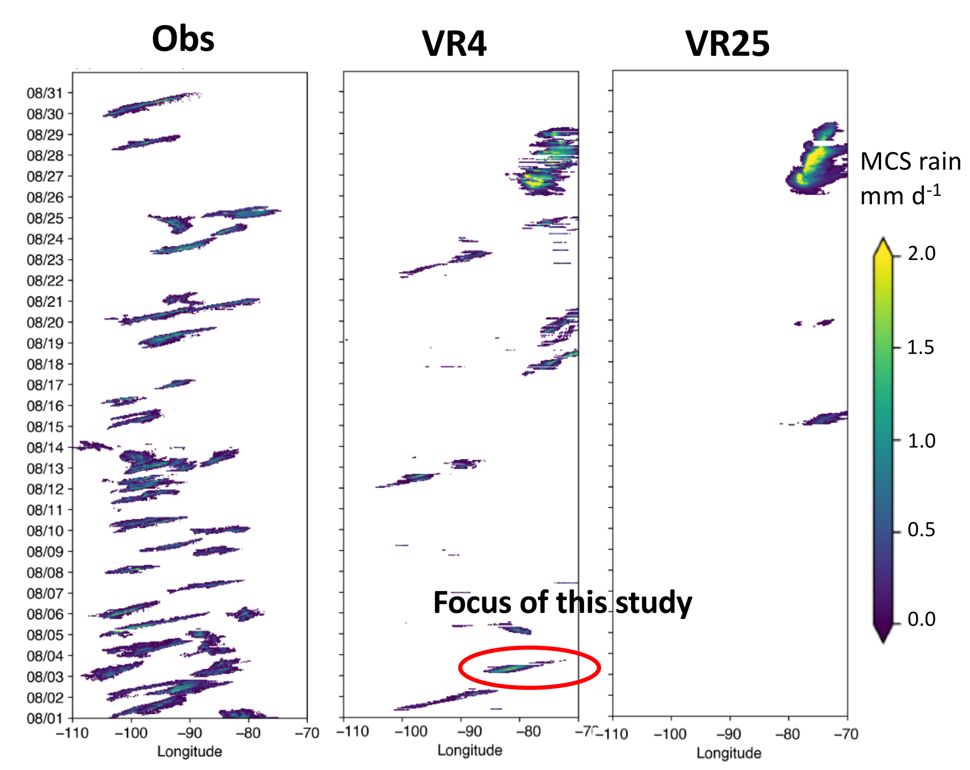
- The CAM5.4 physics parameterizations and CLM4.0 land model are used.
- Series of 7-day hindcasts are conducted for August 2011 for each resolution. The hourly (2D variables) and 3-hourly (3D) outputs are analyzed.
- The atmospheric initial condition is taken from the ERA-Interim at 07/30 00Z. The land initial condition is obtained from an off-line land simulation with observed atmospheric forcing. SST and sea ice fraction are prescribed from daily ERA-Interim data.

MCS tracking

- For VR25, we down-sampled 13-yr of 4-km MCS database produced by FLEXTRKR (Feng et al. 2018, see oral presentation on Wednesday, abstract# 413405) to 25km, and simplified FLEXTRKR to track MCSs at coarse resolutions
  - Input variables: OLR, precipitation (hourly)

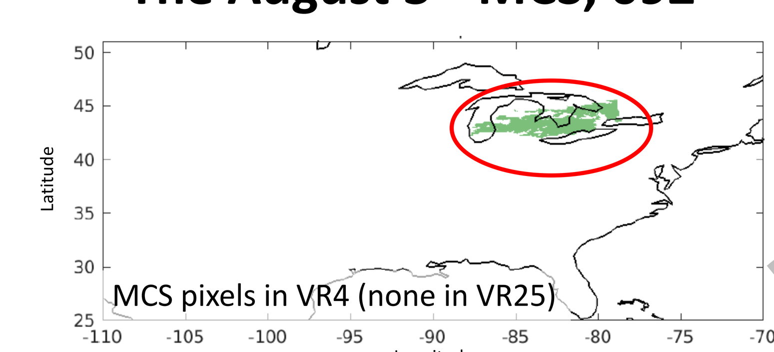
Simulated MCSs

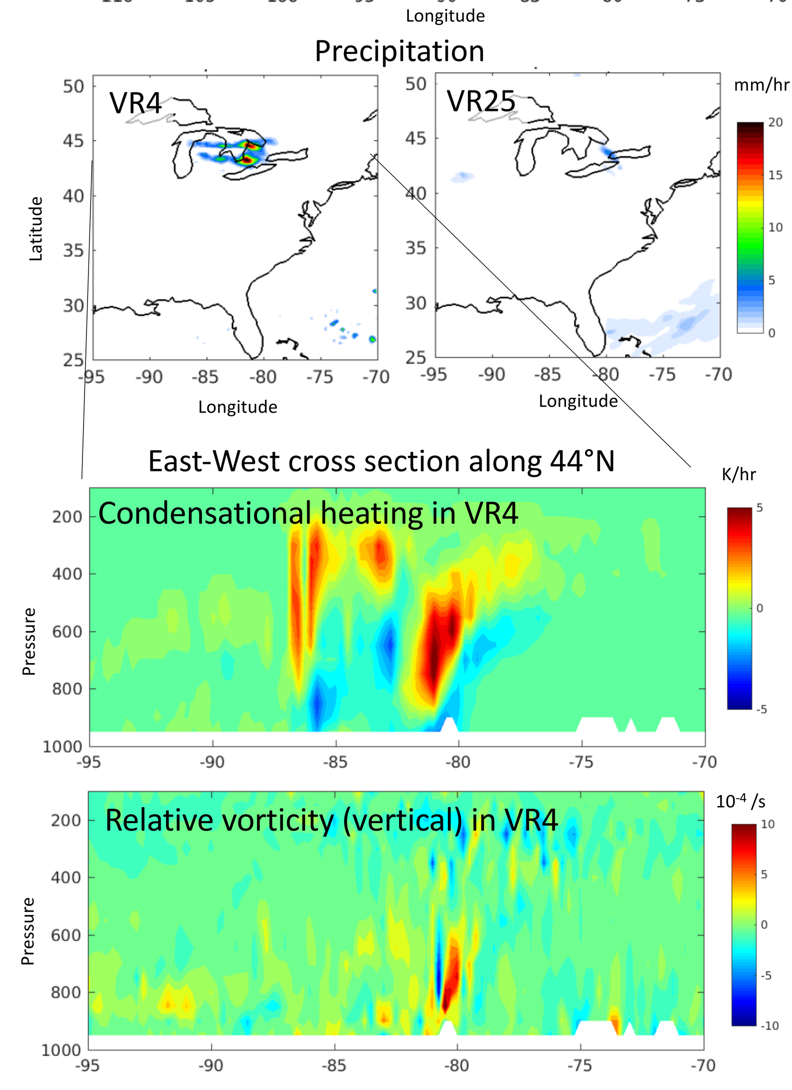
Hovmöller diagram for the precipitation from MCSs, in August. Averaged over 25– 50°N



- VR25 produces few MCSs
- In VR4, an MCS is identified at 05Z on 08/03, lasting for 11 hours (red circle)

The August 3rd MCS, 09Z



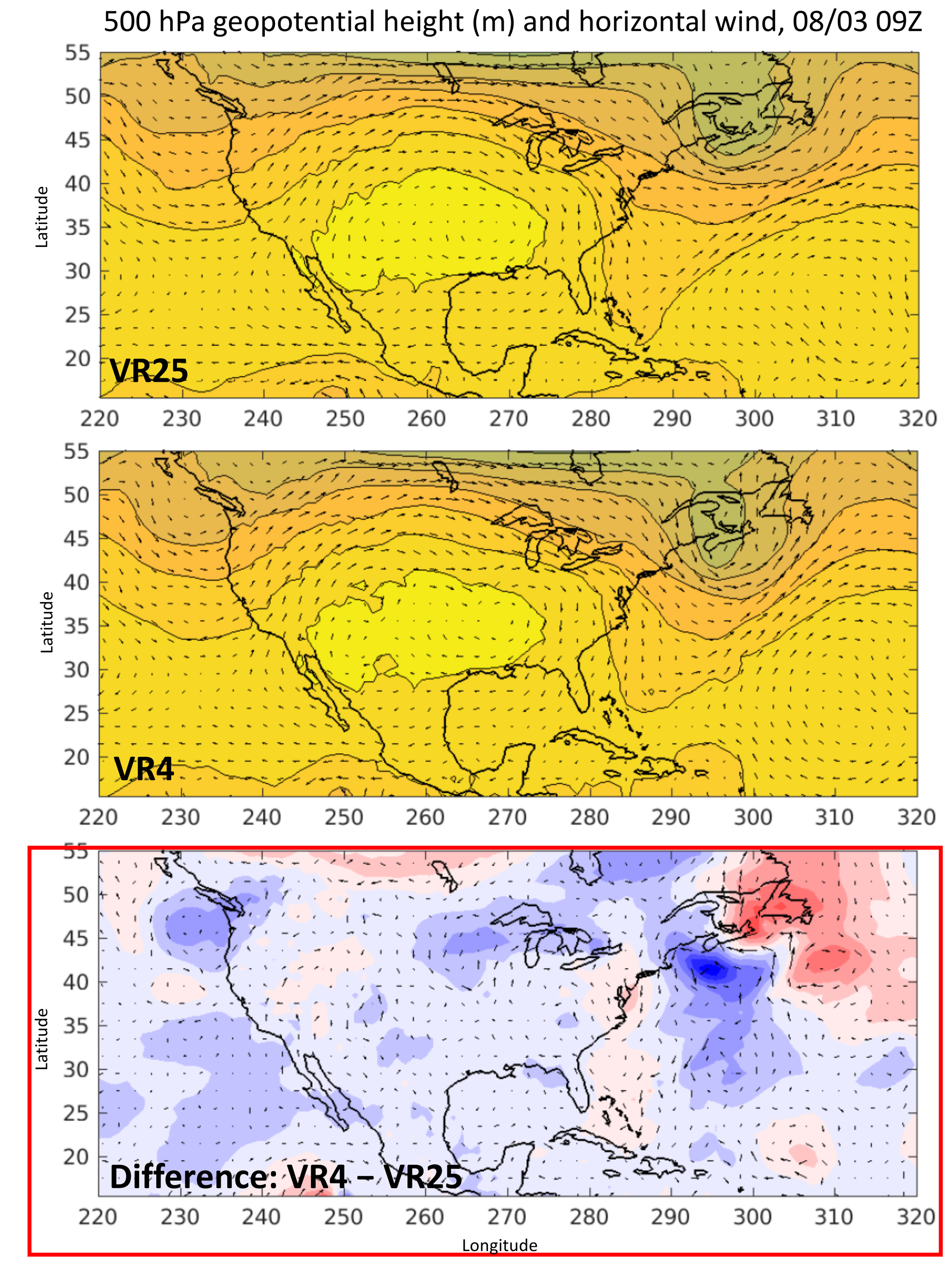


- The target MCS produces strong condensational heating and vorticity, which are missing in VR25

PV Inversion

Large-Scale Environment

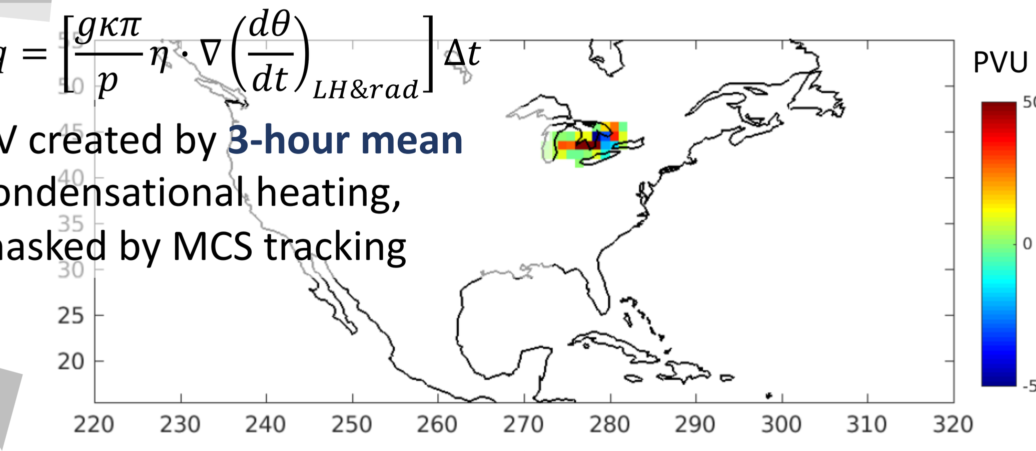
500 hPa geopotential height (m) and horizontal wind, 08/03 09Z



- After four days of integration, large-scale fields are still similar between the two resolutions. Notable differences include the low anomaly near the Great Lakes and the off-shore dipole in the northeastern part of domain.

$$\Delta q = \left[\frac{g\kappa\pi}{p}\eta \cdot \nabla\left(\frac{d\theta}{dt}\right)_{LH\&rad}\right]\Delta t$$

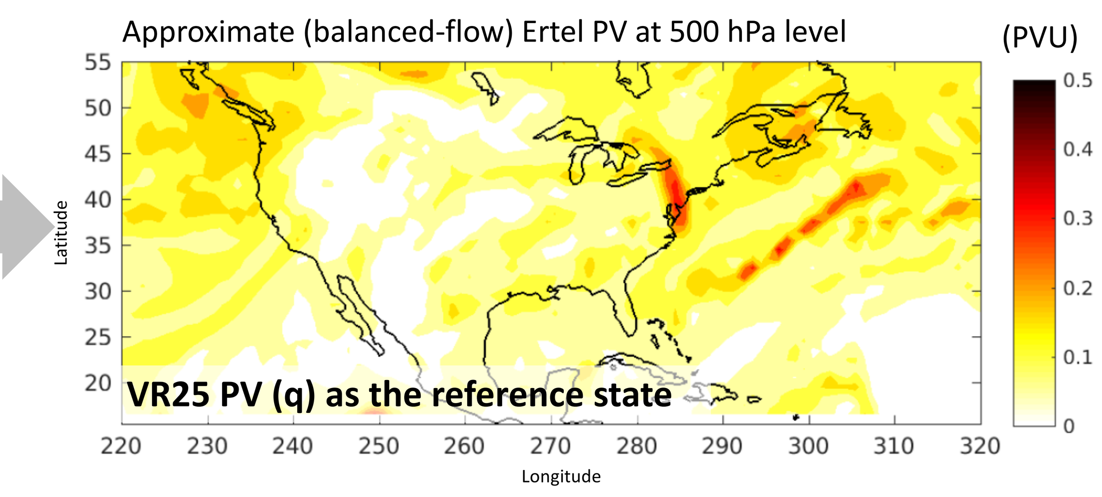
PV created by **3-hour mean** condensational heating, masked by MCS tracking



Added to the reference PV field (VR25) and inverted

Potential Vorticity and Balanced State

Approximate (balanced-flow) Ertel PV at 500 hPa level



$$q = -\frac{g\kappa\pi}{p}\left(\eta\frac{\partial\theta}{\partial\pi} - \frac{1}{a\cos\phi}\frac{\partial v}{\partial\pi}\frac{\partial\theta}{\partial\lambda} + \frac{1}{a}\frac{\partial u}{\partial\pi}\frac{\partial\theta}{\partial\phi}\right)$$

Davis and Emanuel (1991)

The “Balanced state” approximation reduces the relationship among streamfunction, geopotential height, and potential vorticity to two Poisson equations.

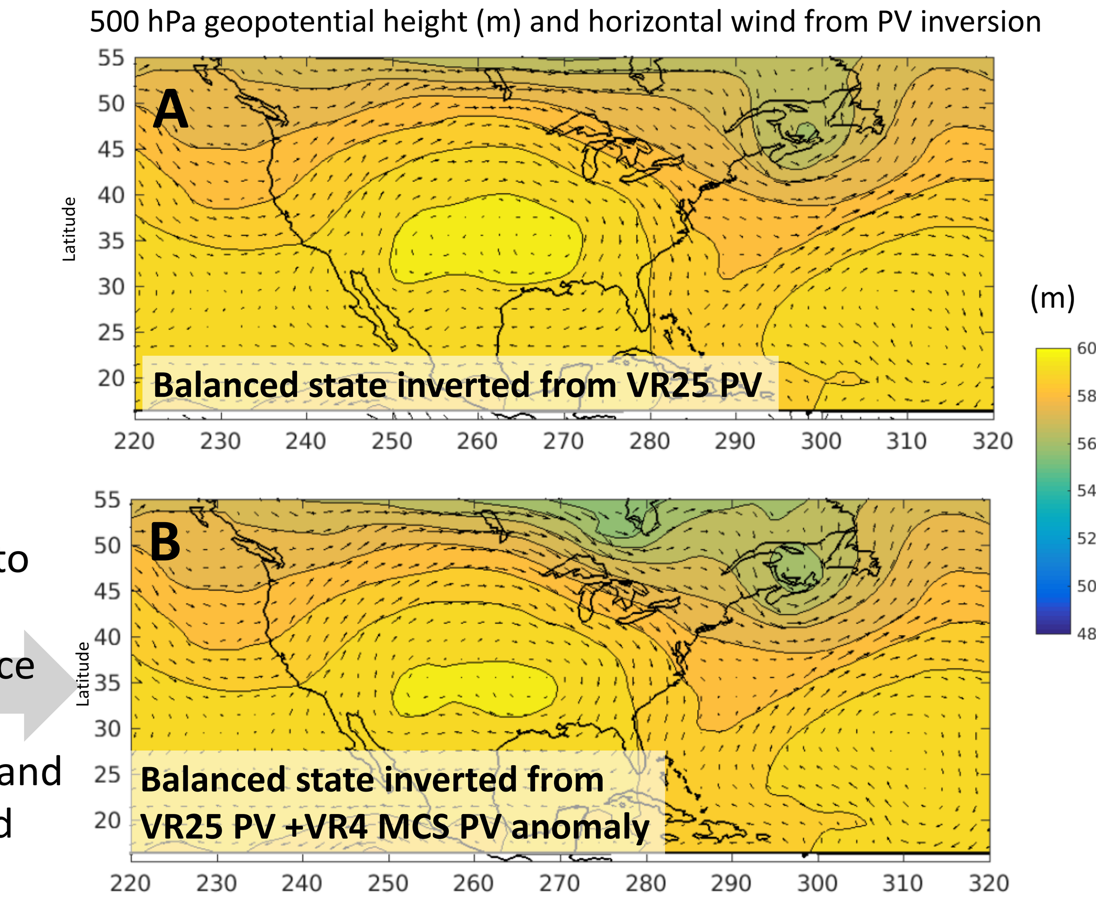
$$\nabla^2\Phi = f(q,\Psi) \qquad \nabla^2\Psi = g(q,\Phi)$$

Φ : geopotential
Ψ : streamfunction

These two equations are numerically solved together by the simultaneous overrelaxation method.

Horizontal wind velocities (u,v) are obtained from the streamfunction solution, describing a balanced atmospheric state dominated by rotational motion and consistent with the given PV field.

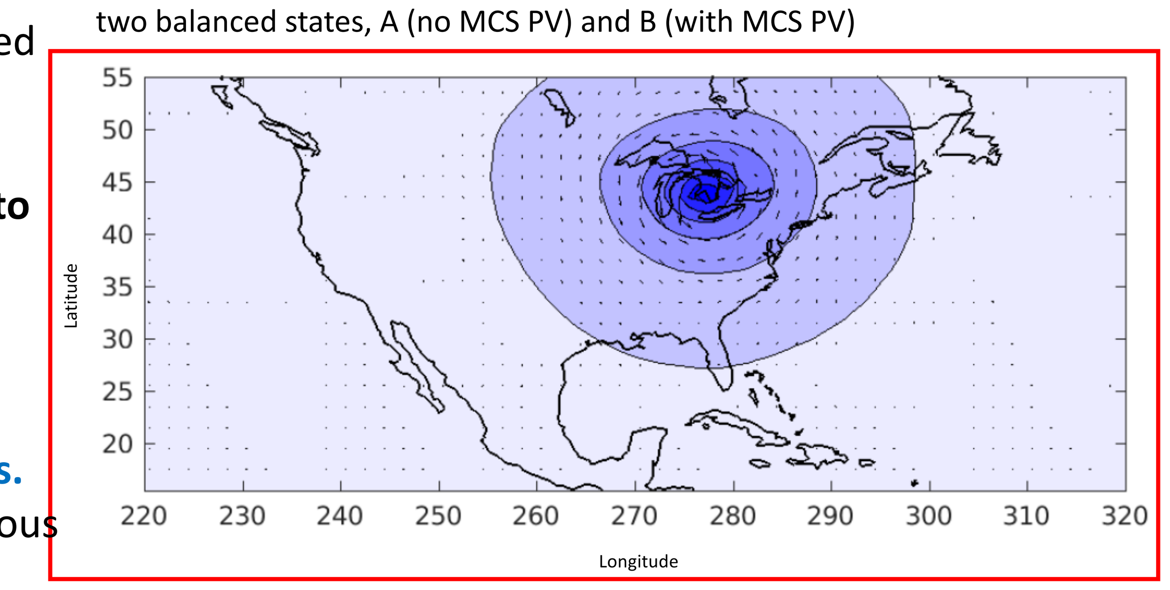
500 hPa geopotential height (m) and horizontal wind from PV inversion



- **We quantify the upscale effect by carrying out PV inversion twice**: once without the PV anomaly from the MCS (VR25) and the other with the MCS PV anomaly. The difference represents the influence of MCS’s PV on the large-scale fields under the assumed balanced state (divergent winds are negligible).
- PV anomaly from the strong heating accumulated over 3-hour period is so large that **we needed to scale it by a factor of ~100 to carry out the inversion**. Higher temporal frequency (smaller departure between the two states) and/or other compensating terms in the PV budget seem necessary.
- **The upscale effect from this particular MCS appears as a low anomaly with cyclonic circulation centered over the Great Lakes.** While it extends to the NE seaboard, other processes (e.g., previous MCSs) are more likely responsible for the dipole feature.

B – A :Inferred upscale effect from the MCS

Difference in the 500 hPa geopotential height (m) and horizontal wind from the two balanced states, A (no MCS PV) and B (with MCS PV)



Summary and Future Work

Contact: Koichi Sakaguchi, PNNL (Koichi.Sakaguchi@pnnl.gov)

Our preliminary result suggests that it is possible to quantify upscale effects from MCSs by combining non-hydrostatic variable-resolution model, MCS tracking algorithm, and PV inversion technique. However, technical and theoretical challenges remain. More case studies, degrees of consistency between the balanced state approximation and the total field, sensitivity of the upscale effect (and fidelity of MCS itself) to model configurations will be explored using realistic hindcasts as well as idealized model experiments.

U.S. DEPARTMENT OF ENERGY

Water Cycle and Climate Extremes Modeling (WACCEM) Scientific Focus Area

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

MPAS Model for Prediction Across Scales

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