A Multiscale Dynamical Assessment of the Mesoscale Convective Systems in the United States

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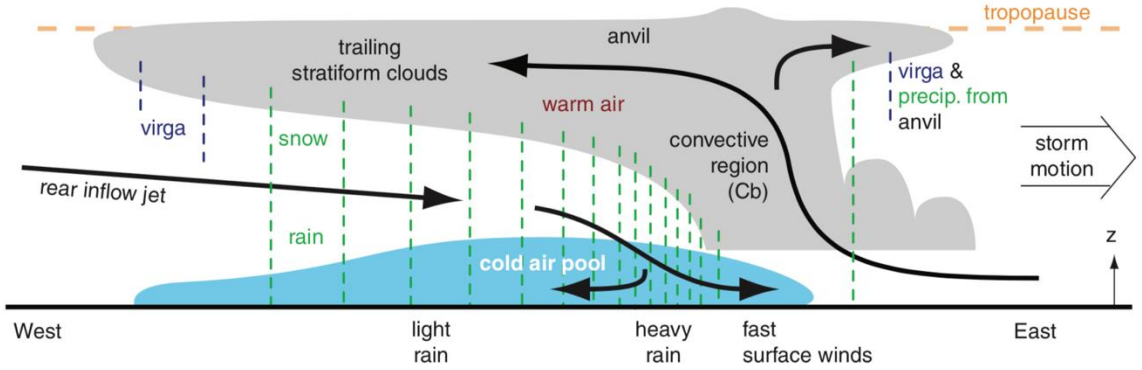
January 16th, 2025

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2 Schiller Institute for Integrated Science and Society, Boston College

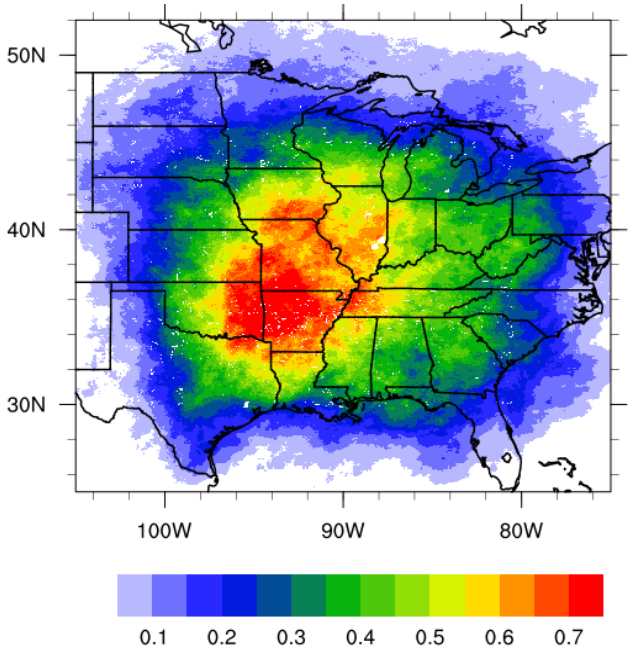
3 NOAA / Geophysical Fluid Dynamics Laboratory

Why do Mesoscale Convective Systems (MCSs) matter?

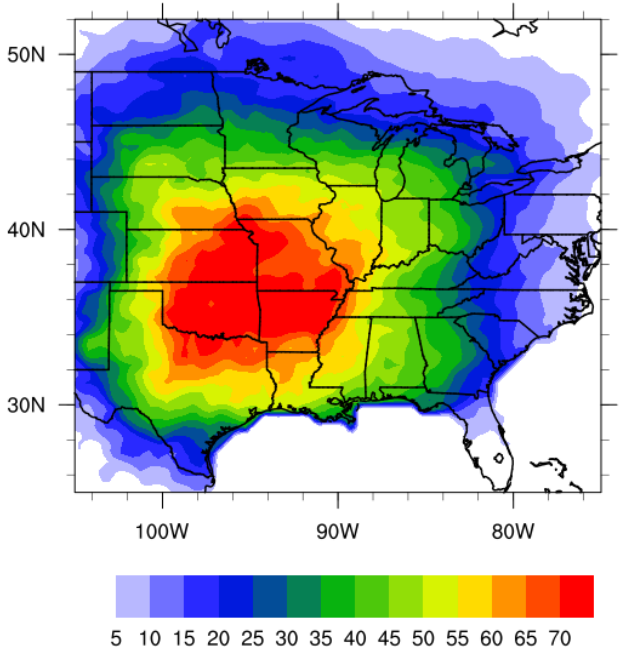


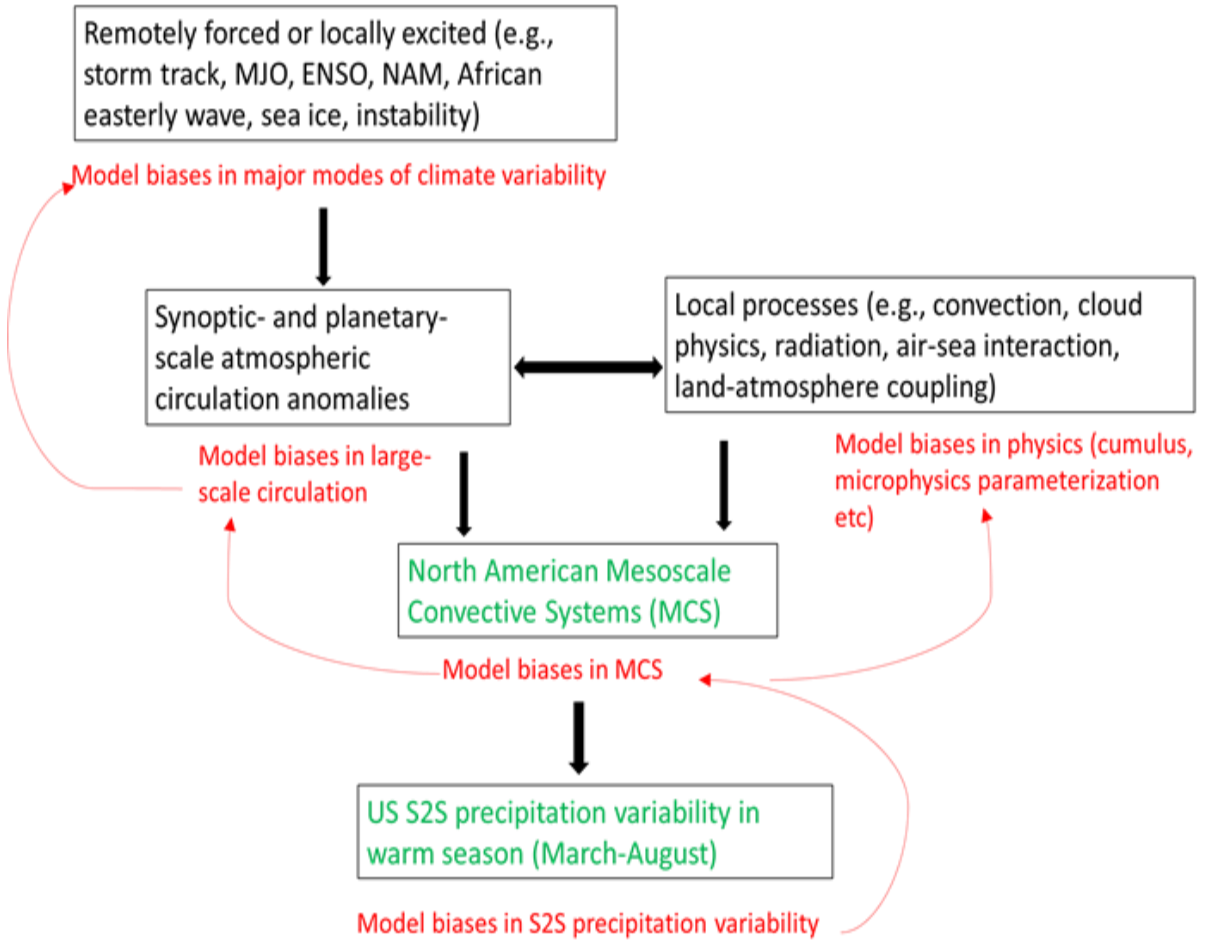
Schematic diagram of an MCS (Houze 2018)

MCS activity in boreal spring



Percentage contribution of MCS precipitation





Large-scale forcing patterns of observed MCSs

Five large-scale circulation patterns

371, 369, 335, 308, and 294 events in Clusters 1 to 5.

Broad envelope of large-scale ascent favoring MCS genesis

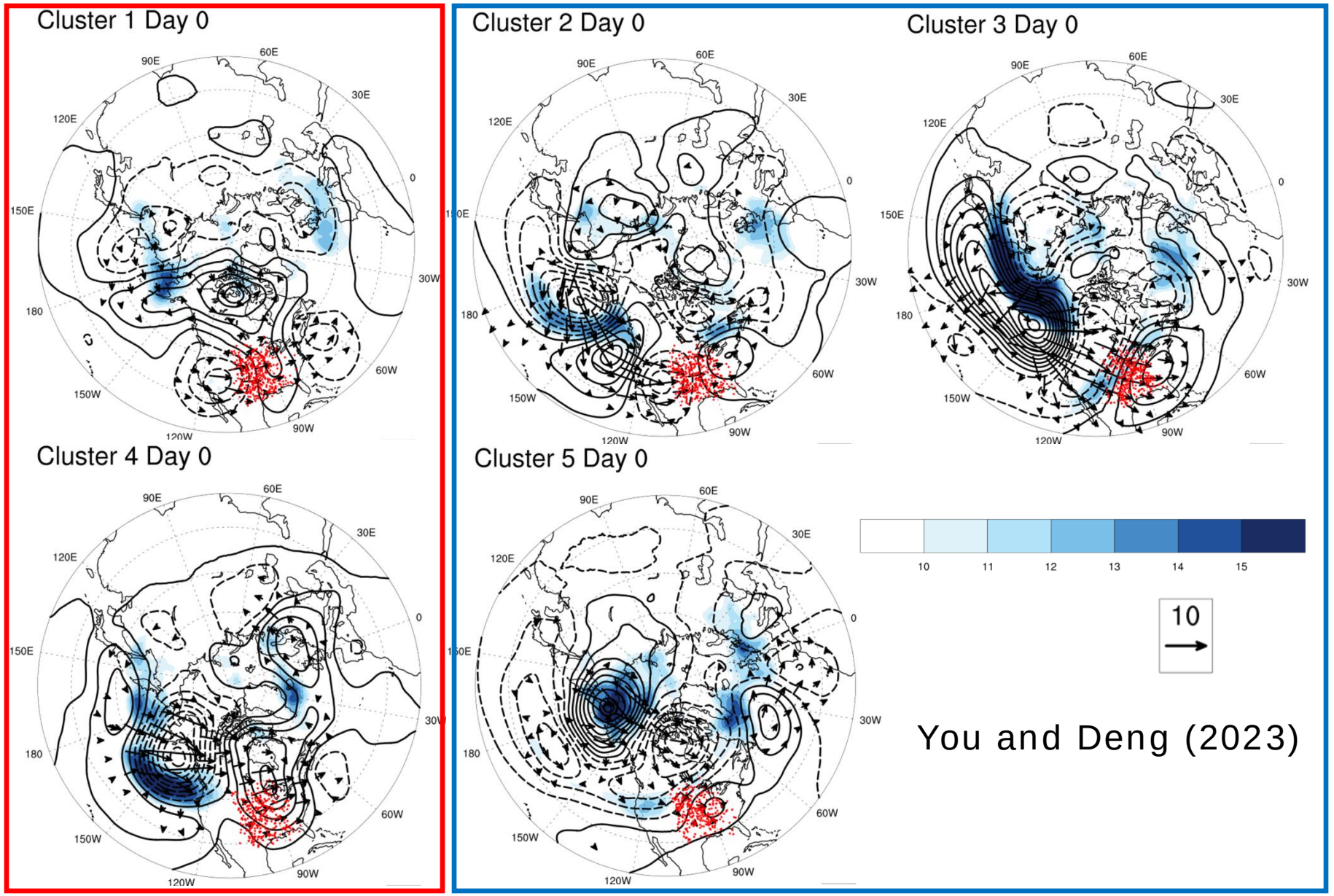
Remotely forced:

Clusters 2, 3, 5

Locally excited:

Clusters 1, 4

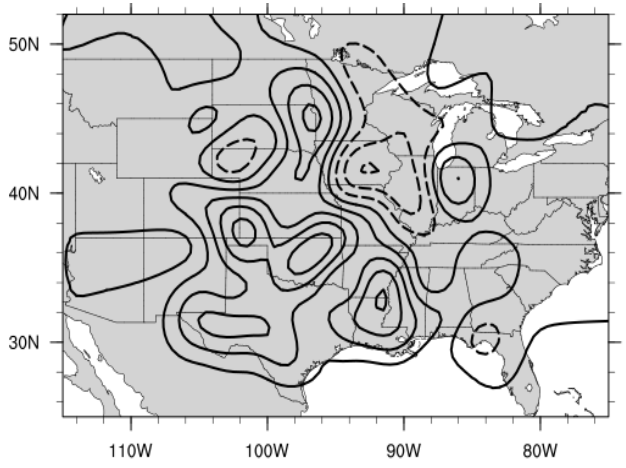
Large-scale circulation patterns on day 0 from Clusters 1 to 5



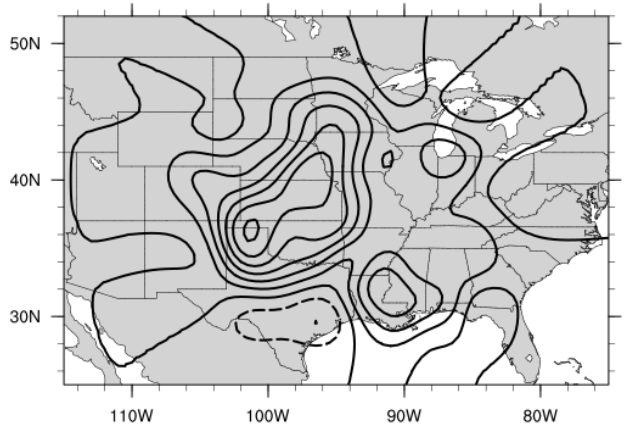
You and Deng (2023)

What contributes to the decadal trend of MCS genesis frequency?

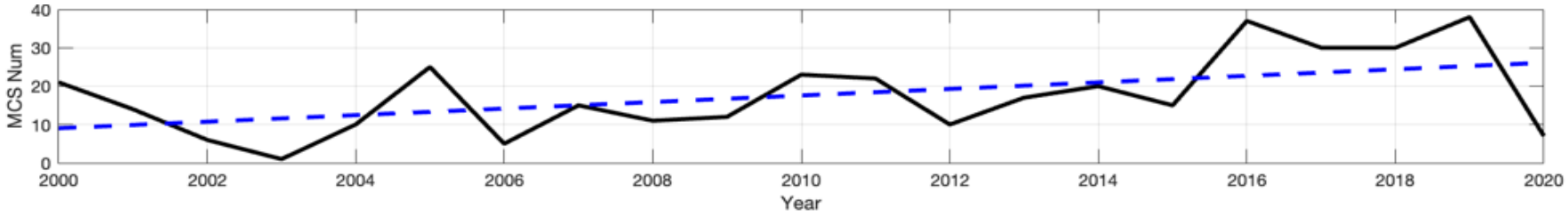
Trend of MCS genesis frequency

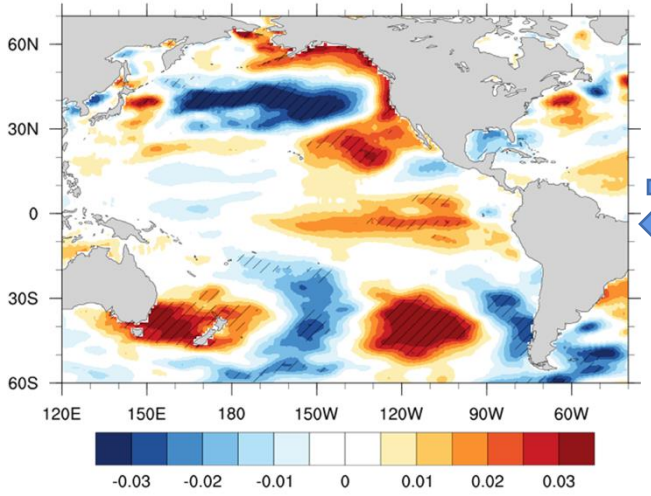


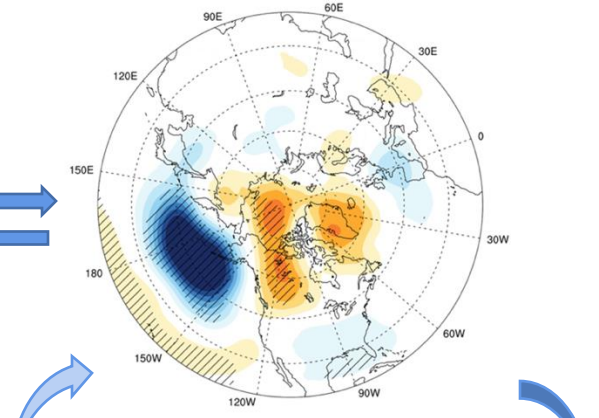
Trend of MCS genesis frequency in Cluster 2



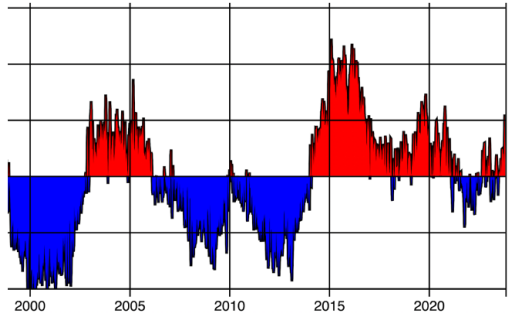
Interannual time series of MCS genesis frequency: Cluster 2



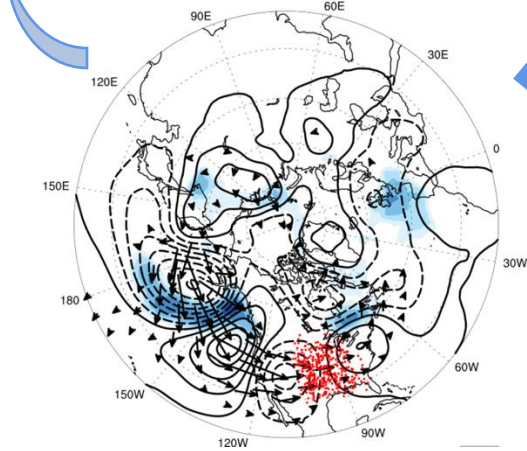




PDO Index



Source: NASA JPL



You and Deng (2023)

How can we better understand MCS biases in global climate models?

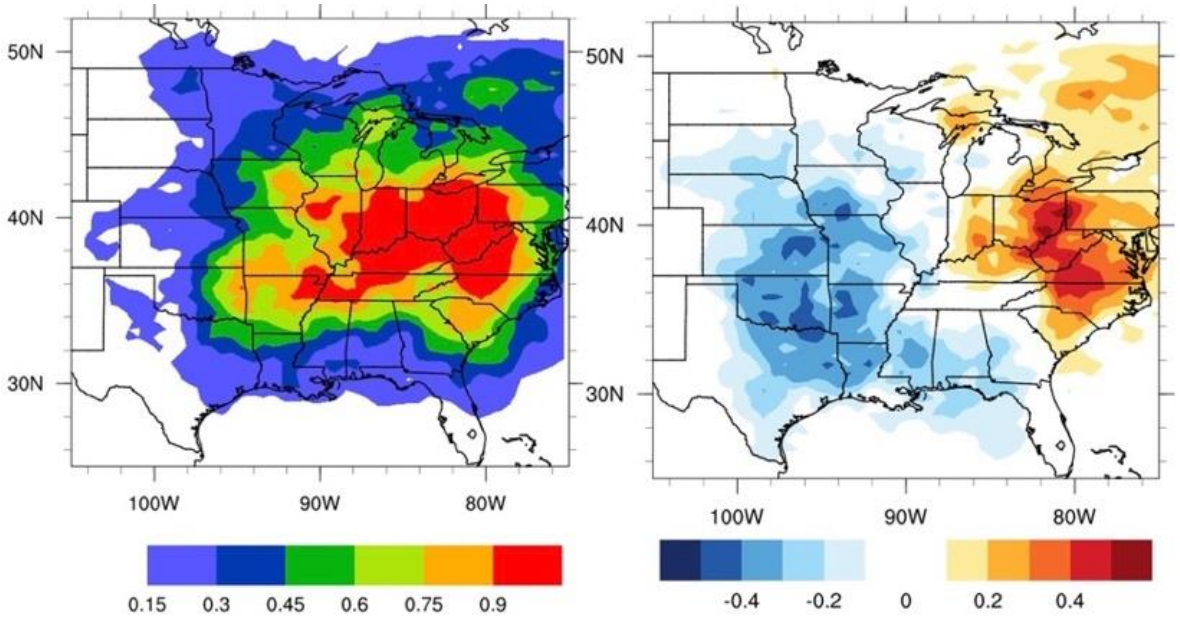
Geophysical Fluid Dynamics Laboratory (GFDL)'s Atmosphere Model version 4 (AM4)

- AMIP-type simulation; 50 km resolution
- Simulation period: 1950-2014
- Study period: Spring 2000-2014

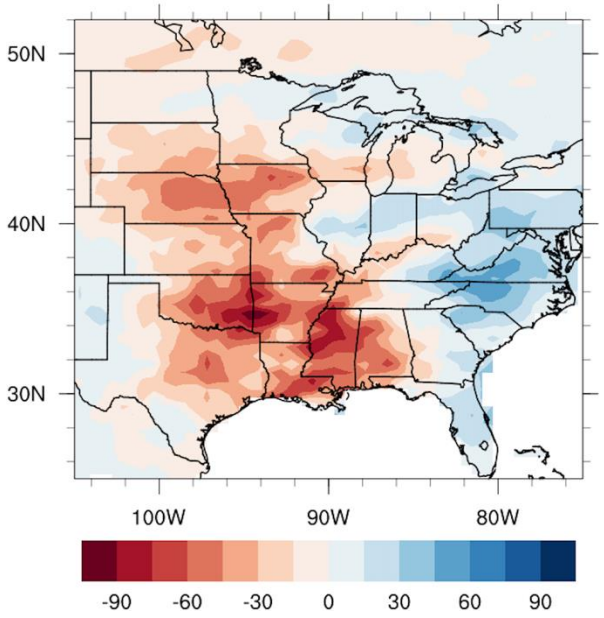
Observation - Great Plains; AM4 - Midwest

Eastward shift of MCS activity and associated precipitation

MCS activity in GFDL AM4 and its bias



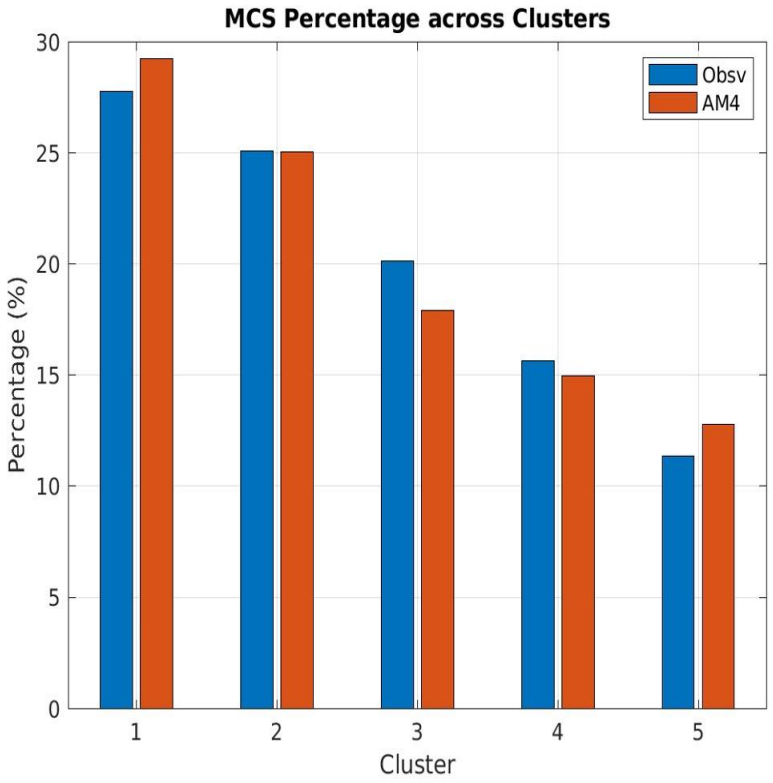
MCS precipitation bias



You et al. (2023)

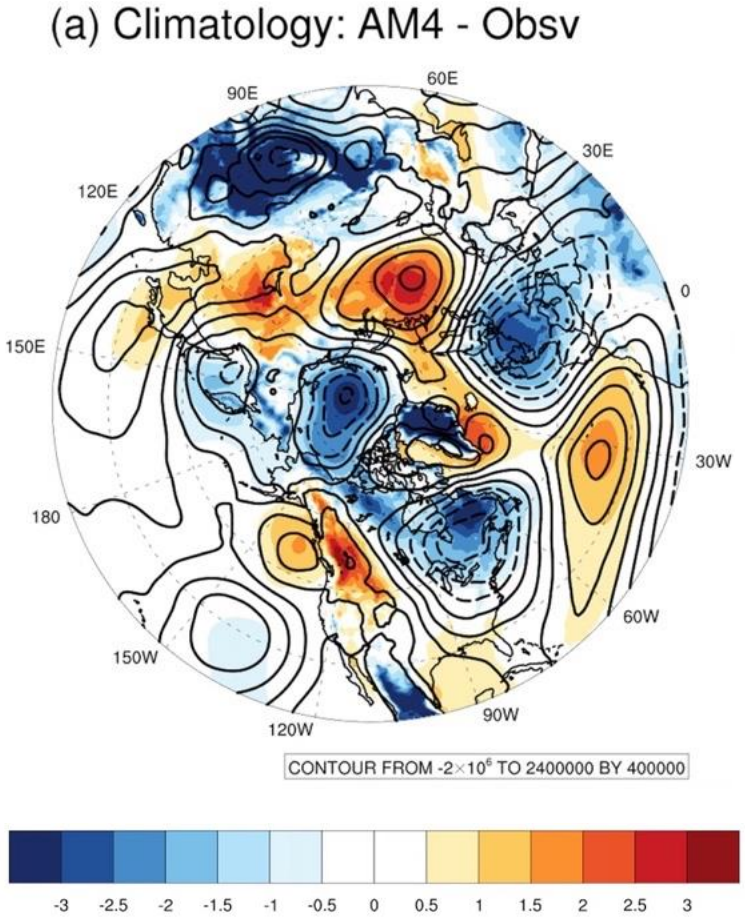
What causes the model bias in MCS location?

Comparable contribution of mix-clusters to AM4 and observed MCSs

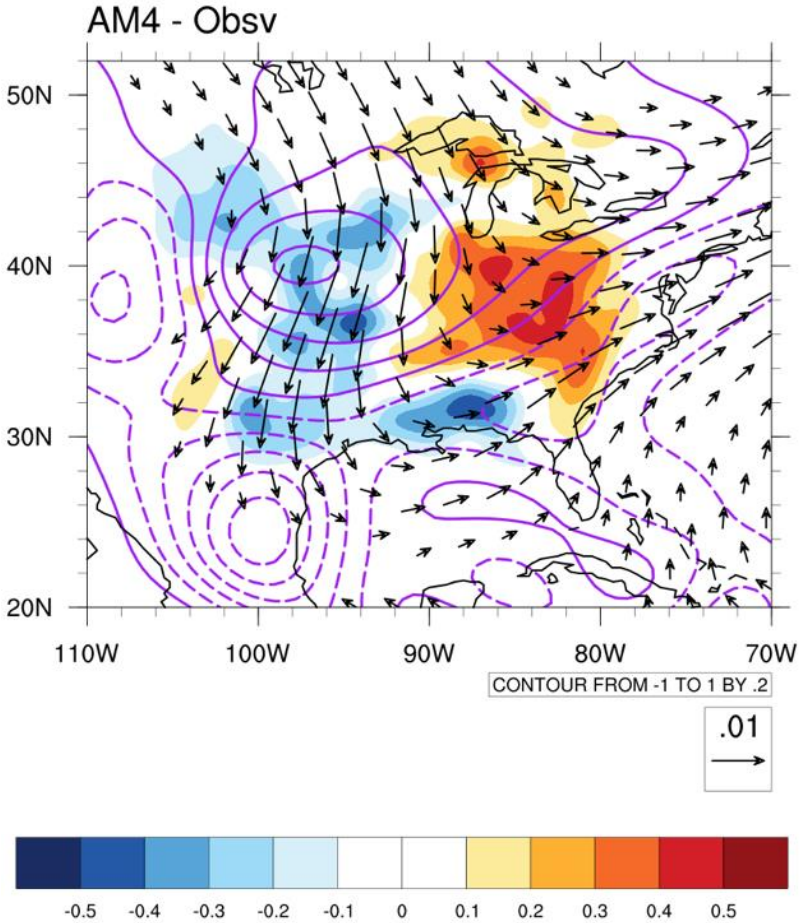


You et al. (2023)

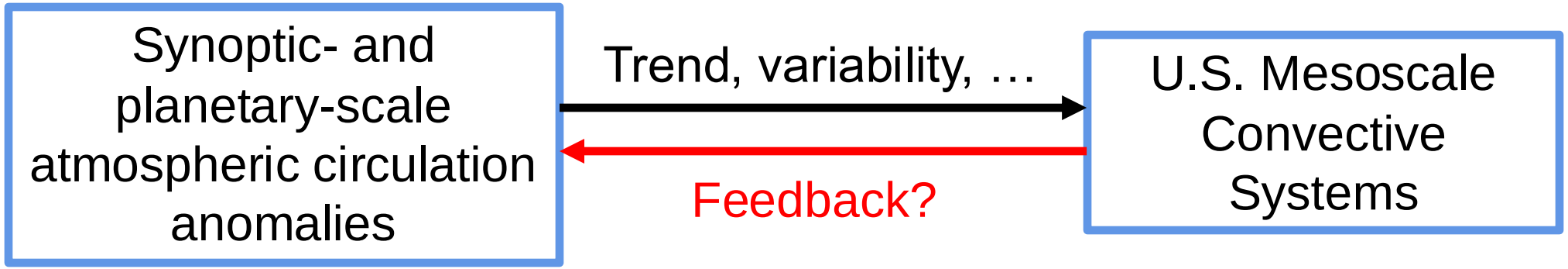
Biases in SLP (color shading) and 850mb streamfunction (contour)



Biases in MCS track density (color shading), 850mb moisture transport (vector), and its divergence (contour)



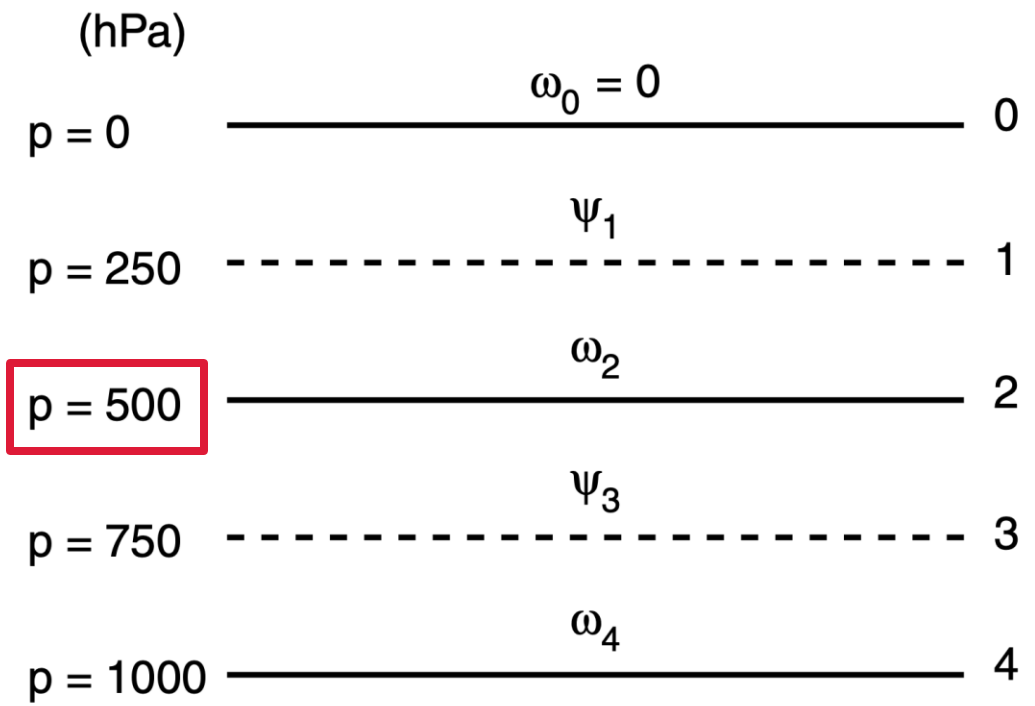
From large-scale forcing to MCS feedback



Development of a moist two-layer QG model for dynamical analysis

Model Configuration

- Upper-level – 250 hPa; lower-level – 750 hPa.
- Model domain: 20-65 N channel domain.
- Model is linearized around the basic state flow of springtime 2000-2020.



Schematic of a two-layer QG model (Holton and Hakim, 2012)

Incorporate Diabatic Heating into the Model

Thermodynamic equation at the middle level

$$\frac{\partial}{\partial t}\left[\frac{(Z_1-Z_3)}{\delta p}\right]+\frac{1}{f\delta p}J(Z_3,Z_1)=\omega_2\left(S_2+\frac{R\alpha}{C_p p_2}\right)=\omega_2\widehat{S_2}$$

"effective stability"

Linear regression $Q=\alpha\omega_2$

Thermodynamic equation at level 2

+ Vorticity equations at level 1 and 3

= QGPV equations at levels 1 and 3

(variable: geopotential).

$$\frac{\partial}{\partial t}\left[\zeta_1+\frac{f(Z_3-Z_1)}{(\delta p)^2\widehat{S_2}}\right]+f^{-1}J(Z_1,\zeta_1+f)+\frac{1}{(\delta p)^2\widehat{S_2}}J(Z_1,Z_3)=-\epsilon_1\zeta_1,$$

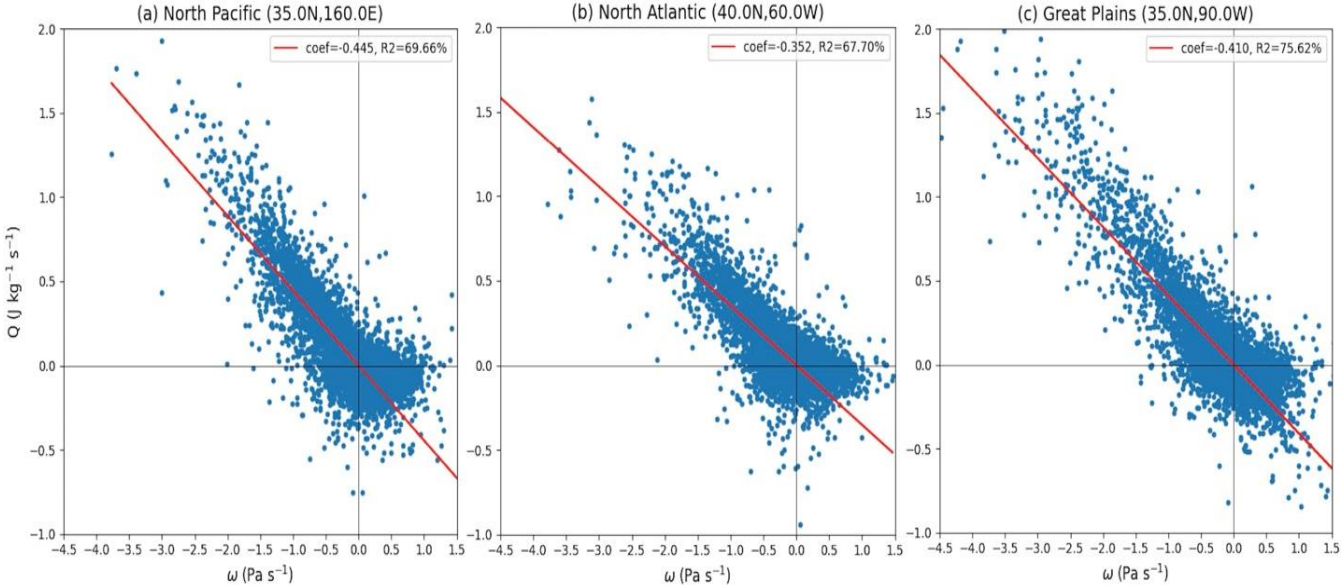
$$\frac{\partial}{\partial t}\left[\zeta_3+\frac{f(Z_1-Z_3)}{(\delta p)^2\widehat{S_2}}\right]+f^{-1}J(Z_3,\zeta_3+f)+\frac{1}{(\delta p)^2\widehat{S_2}}J(Z_3,Z_1)=-\epsilon_3\zeta_3$$

Empirical parameterization of diabatic heating

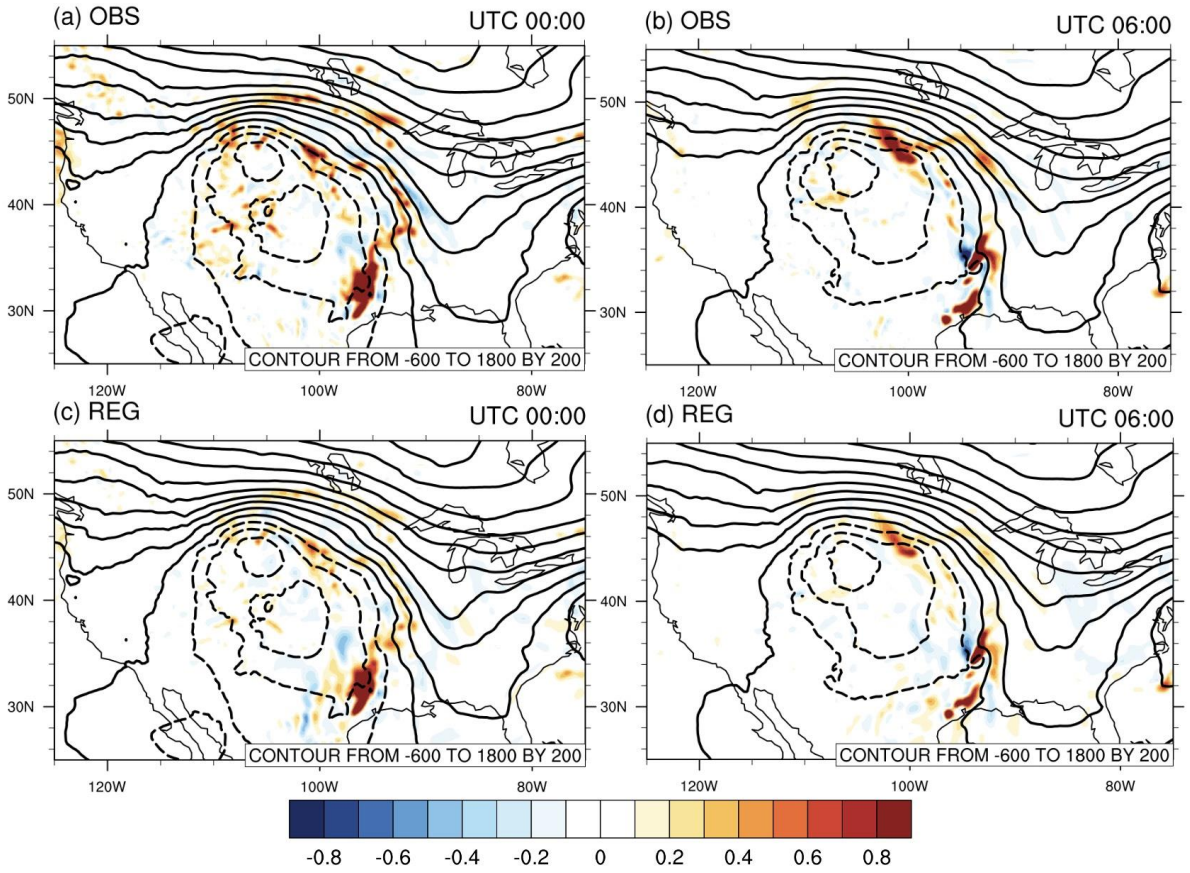
- Estimation of Q at the middle level with residual method (e.g., Nigam 1994) with ERA5 reanalysis.
- Train the linear regression model using data of 2000-2010.
- Three major heating region: North Pacific and North Atlantic storm tracks, central US.
- The model reproduces well in the magnitude and structure of diabatic heating.

$$Q = \frac{C_p T}{\theta}\left(\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} + \omega\frac{\partial \theta}{\partial p}\right)$$

Scatter plots of the Q versus ω at selected points



Q (color shading) vs 750 mb geopotential (contour) for a selected MCS case on May 21st, 2011.



Optimal mode (nonmodal instability) analysis

Optimal Mode Analysis

- Identify the most rapidly amplifying disturbances (in terms of wave amplitude) within a specific time interval (e.g., for synoptic-scale, 1 – 4 days).
- Both **global optimization** and **local optimization** over a specific region (e.g., the North American - North Atlantic sector, 20°- 65°N, 0°-130°W)

Step 1: Linearize QGPV equations and solve for normal modes $(\Phi_1, \Phi_3)^T$

Step 2: Assume **optimal disturbance** as **linear combination of normal modes**

$$\psi = (\psi_1, \psi_3) = \sum_{i=1}^{2N} (\Phi_{1i}, \Phi_{3i})\, e^{\sigma_i \tau} a_i = P\Lambda a$$

Step 3: Convert the optimization problem into an eigenvalue problem

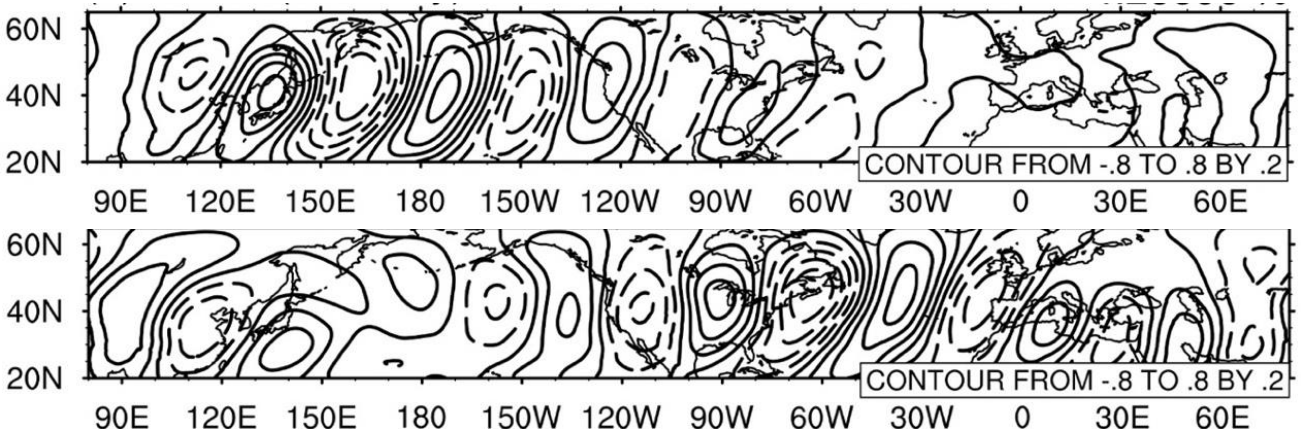
$$\mathcal{A}(\tau) = \psi^H D \psi = a^H \Lambda^H P^H D P \Lambda a = a^H B(\tau) a \qquad \psi(\lambda, \phi, t) = \sum_{i=1}^{2N} (\Phi_{1i}, \Phi_{3i})\, e^{\sigma_i t} a_i$$

$$\gamma B(0) a = B(\tau) a \qquad \gamma = \frac{a^H B(\tau) a}{a^H B(0) a}$$

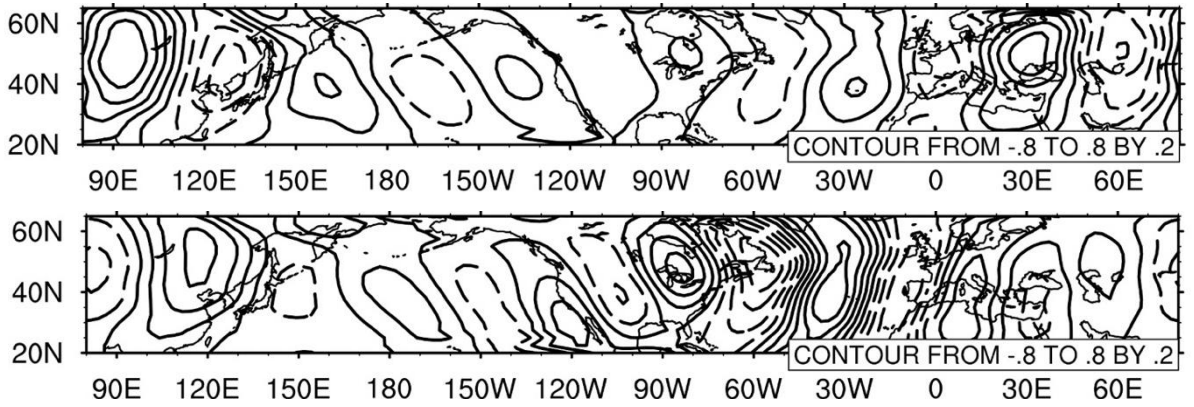
You and Deng (2025)

Impact of diabatic heating on extratropical synoptic variability

EOF 1 and EOF 3 of bandpass-filtered (2-8 days) 250 mb geopotential anomalies



EOF 1 and EOF 3 from sampled optimal modes from the dry model

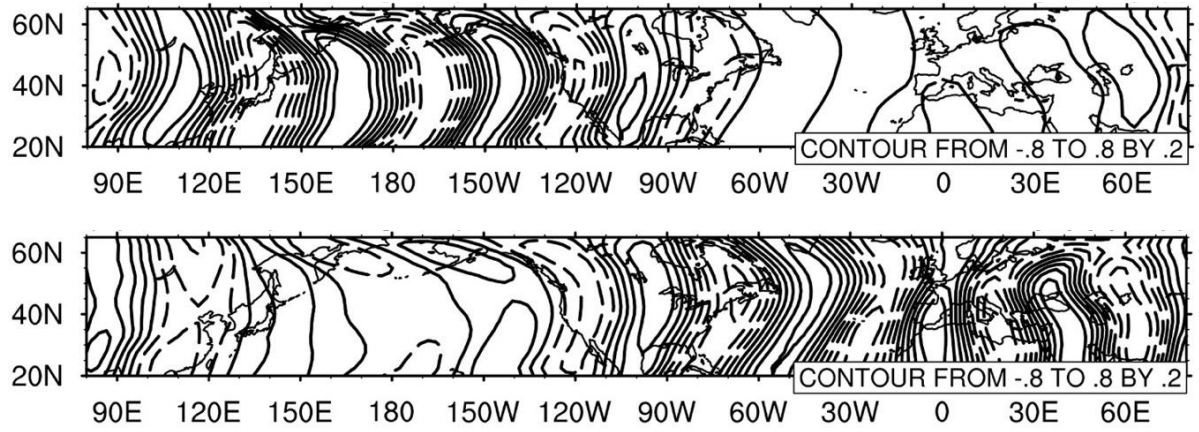


- **Sampling optimal modes**:

Random sampling from the top 50 optimal modes with τ = 1, 2, 3, and 4 days from day 1 to day 15 with replacement of 500 times. Concatenate into a hypothetical flow (15*500 = 7500 days)

- Diabatic heating in the QG model improves the model's capability in reproducing the general characteristics of the synoptic variability.

EOF 1 and EOF 3 from sampled optimal modes from the fully moist model



Impact of heating in US MCS region on extratropical synoptic variability

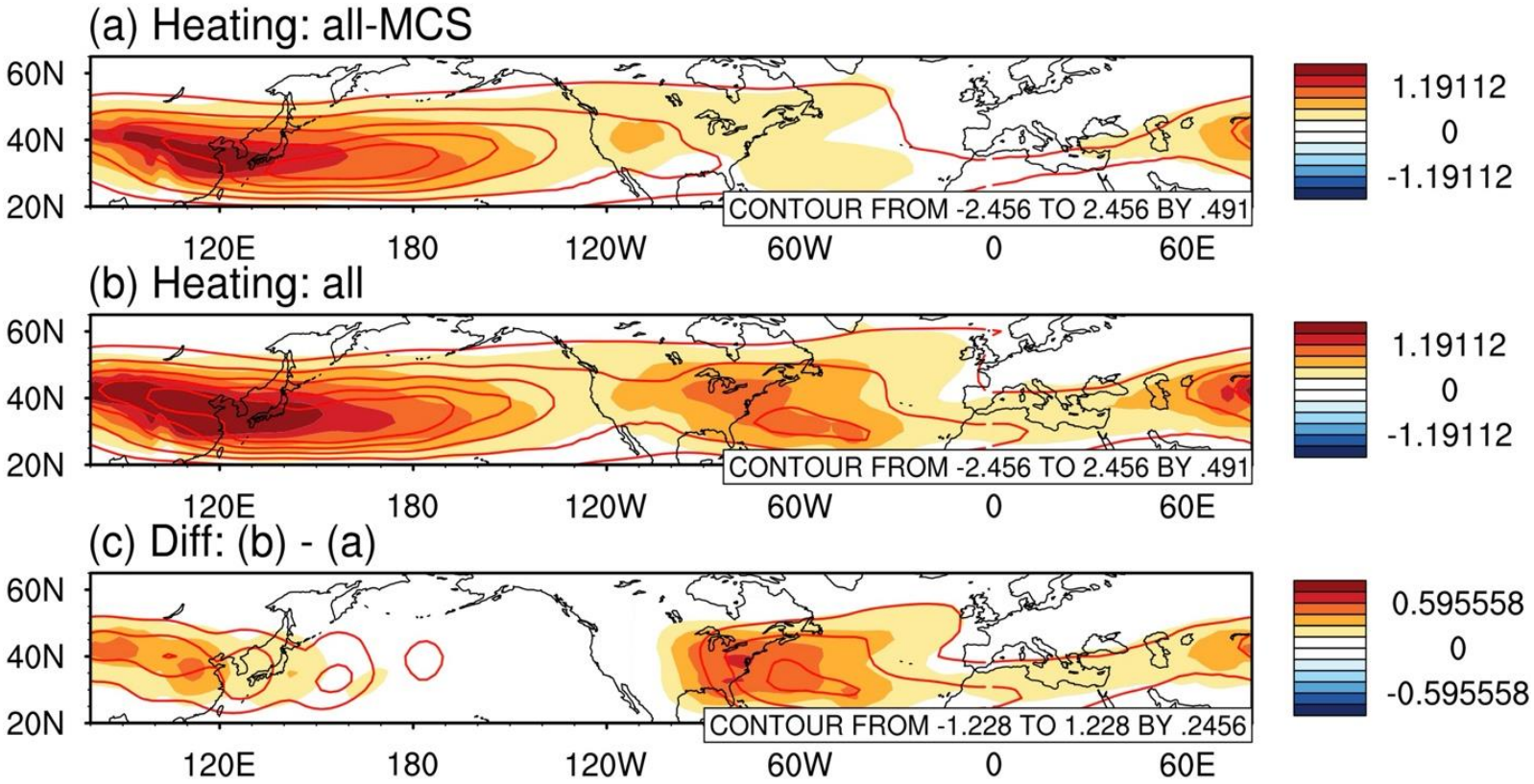
"all-MCS": all heating turned on except for the US MCS region.

"all": heating turned on everywhere (fully moist model)

Footprints of US MCS heating:

- better separation of storm tracks
- larger amplitudes of synoptic variability over North America and North Atlantic
- better organized circumglobal propagation of synoptic disturbances in the midlatitudes channel

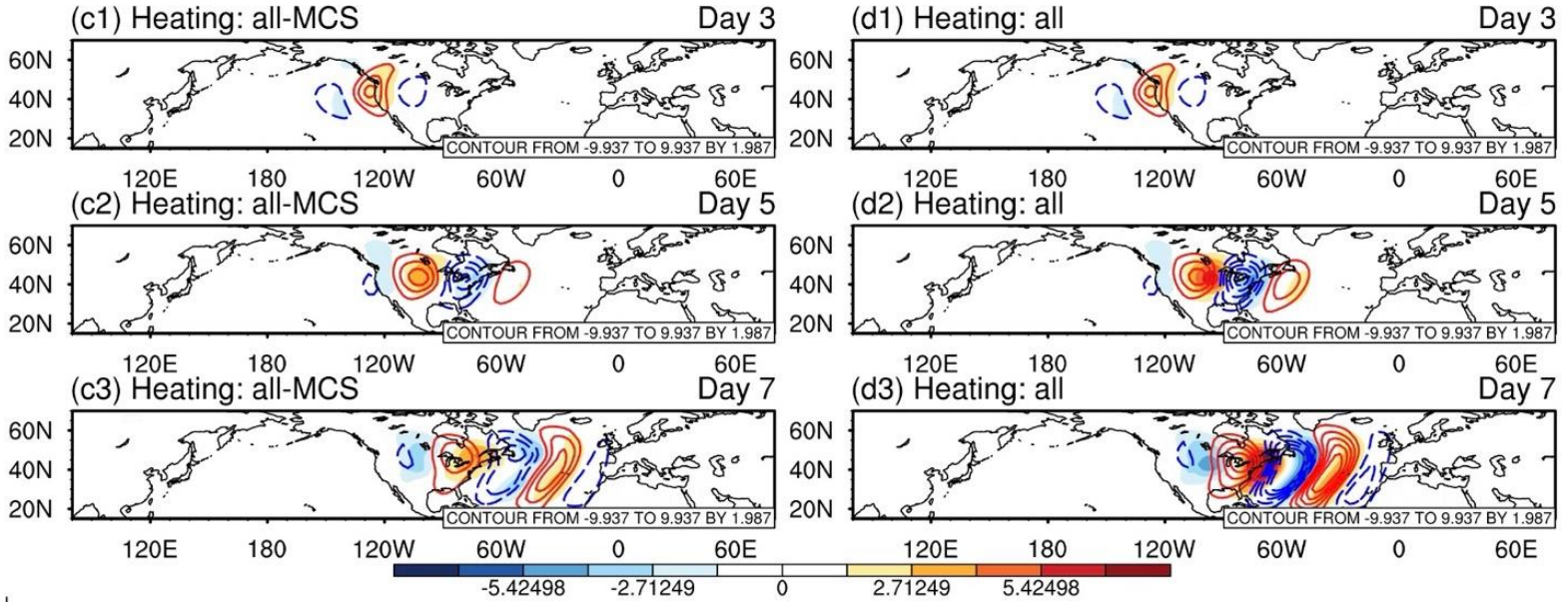
Standard deviation of sampled channel optimal modes at upper (contour) and lower (color shading) levels



Footprints of MCS heating seen in “local optimal modes”

- Local optimization over the North America – North Atlantic sector (20°- 65°N, 0°-130°W).
- Further addition of the MCS heating leads to more intense disturbances on day 5 and 7.

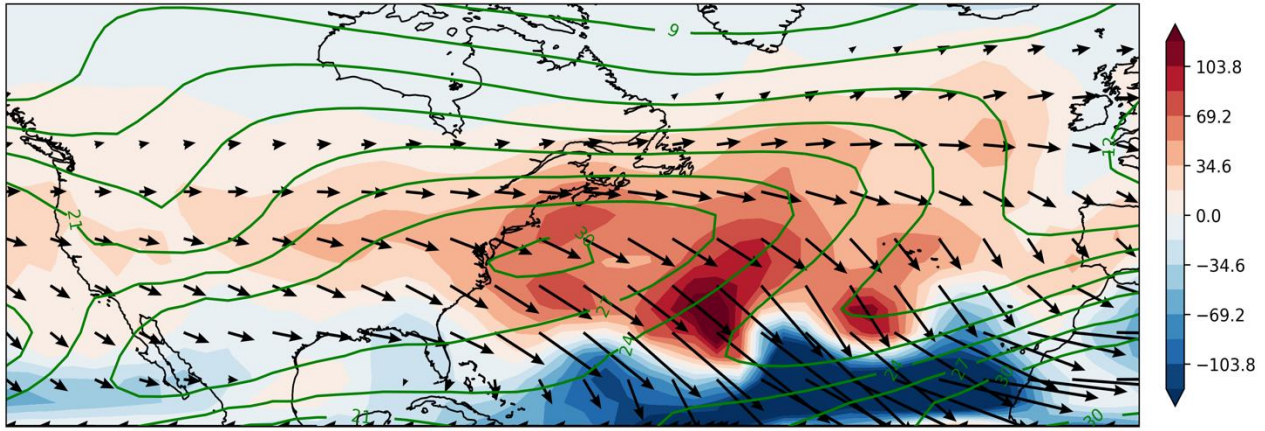
Evolution of the first local optimal mode with τ = 3 days



- stronger eddy forcing of the Atlantic jet

$$E = \left(\overline{v'^2 - u'^2}, -\overline{u'v'}\right)$$ (Hoskins et al., 1983)

Change in E vector and Div(E) (color shading) associated with MCS heating. Contours are 250 mb springtime mean zonal wind.



Concluding remarks

Large-scale forcing of MCSs:

- PDO is at least partly responsible for the positive trend of MCS genesis frequency in the period of spring 2000-2020.
- Biases in large-scale circulation due to model systematic errors and model physics contribute to the eastward-drift bias of MCSs in AM4.

Feedback of MCS heating to large-scale circulations:

- The introduction of diabatic heating reduces the zonal scale and increases the amplitude of optimal disturbances, leading to better-defined North Pacific and North Atlantic storm tracks.
- MCS convective heating not only significantly enhances synoptic variability over the eastern U.S. and North Atlantic but also promotes the circumglobal zonal propagation of synoptic-scale disturbances, extending its impact to planetary and hemispheric scales.
- The transient (synoptic) eddy forcing of the background zonal flow is amplified by MCS heating, manifested as more prominent westerly accelerations that strengthen and extend downstream the Atlantic jet.

THANK YOU

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