The University of Texas at Austin
Oden Institute for Computational Engineering and Sciences

Surface potential vorticity diagnostics for Hurricane Harvey: an application for baroclinic instability and hurricane movement

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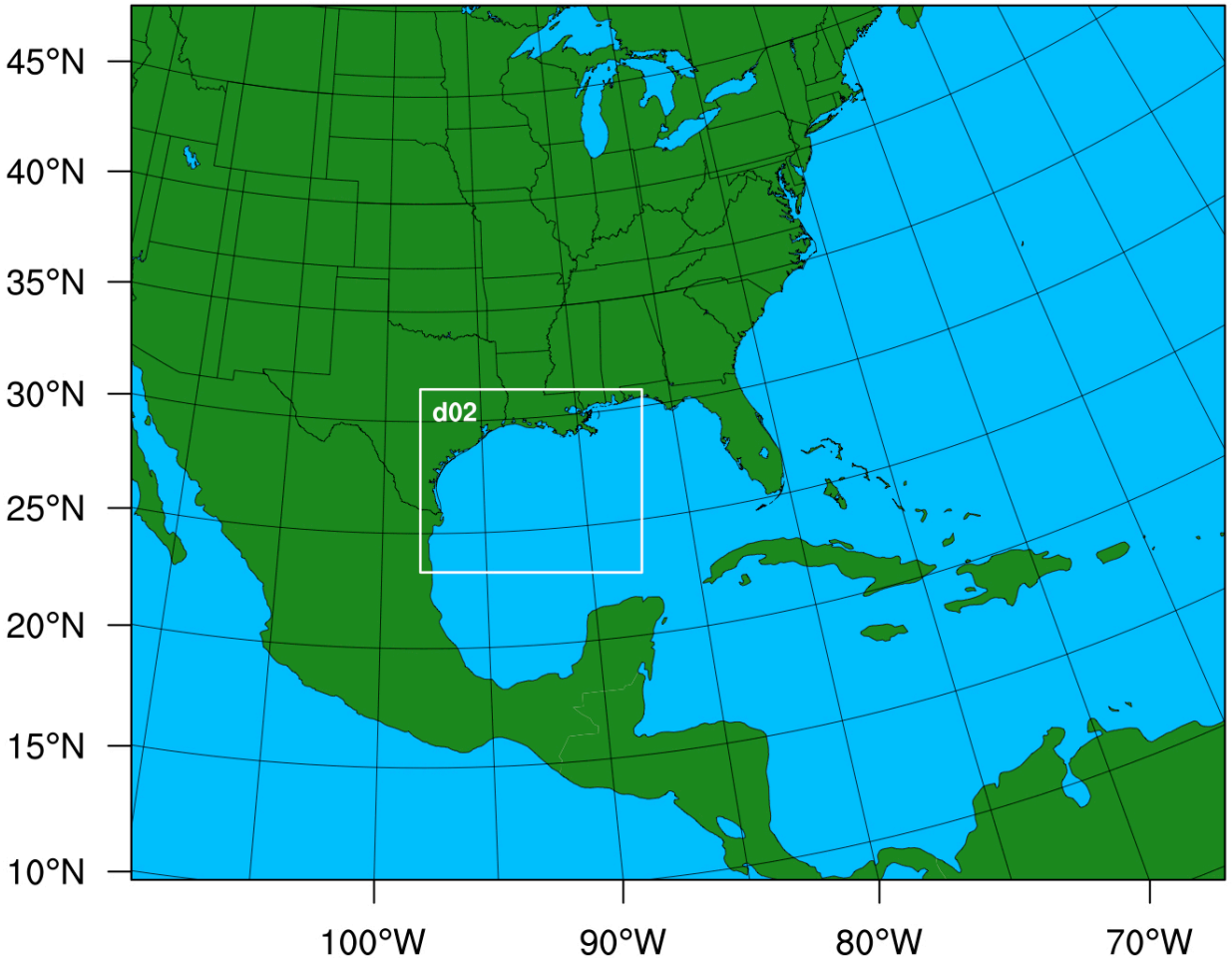
Motivation

- Develop a high-resolution configuration in the Gulf of Mexico (GoM) region to study extreme weather events using the Weather Research and Forecasting (WRF) model.
- Perform high-resolution simulations of Hurricanes Harvey (2017) and Ida (2021) in WRF using GoM with the horizontal resolution of < 4 km (current simulations include resolution of around 12 km).
- Study how meteorological data including vorticity and temperature fields can improve our understanding on tracking cyclones.
- Use meteorological data from WRF as inputs of atmospheric forcing in coastal models to improve estimates on storm surge and rainfall.
- Provide high-fidelity data for Machine Learning groups on their task for digital-twin developments.

Model Setup

High-resolution simulations of Hurricanes Harvey and Ida in the WRF model.

GoM configuration



$\Delta x_1 = 5$; 15 km

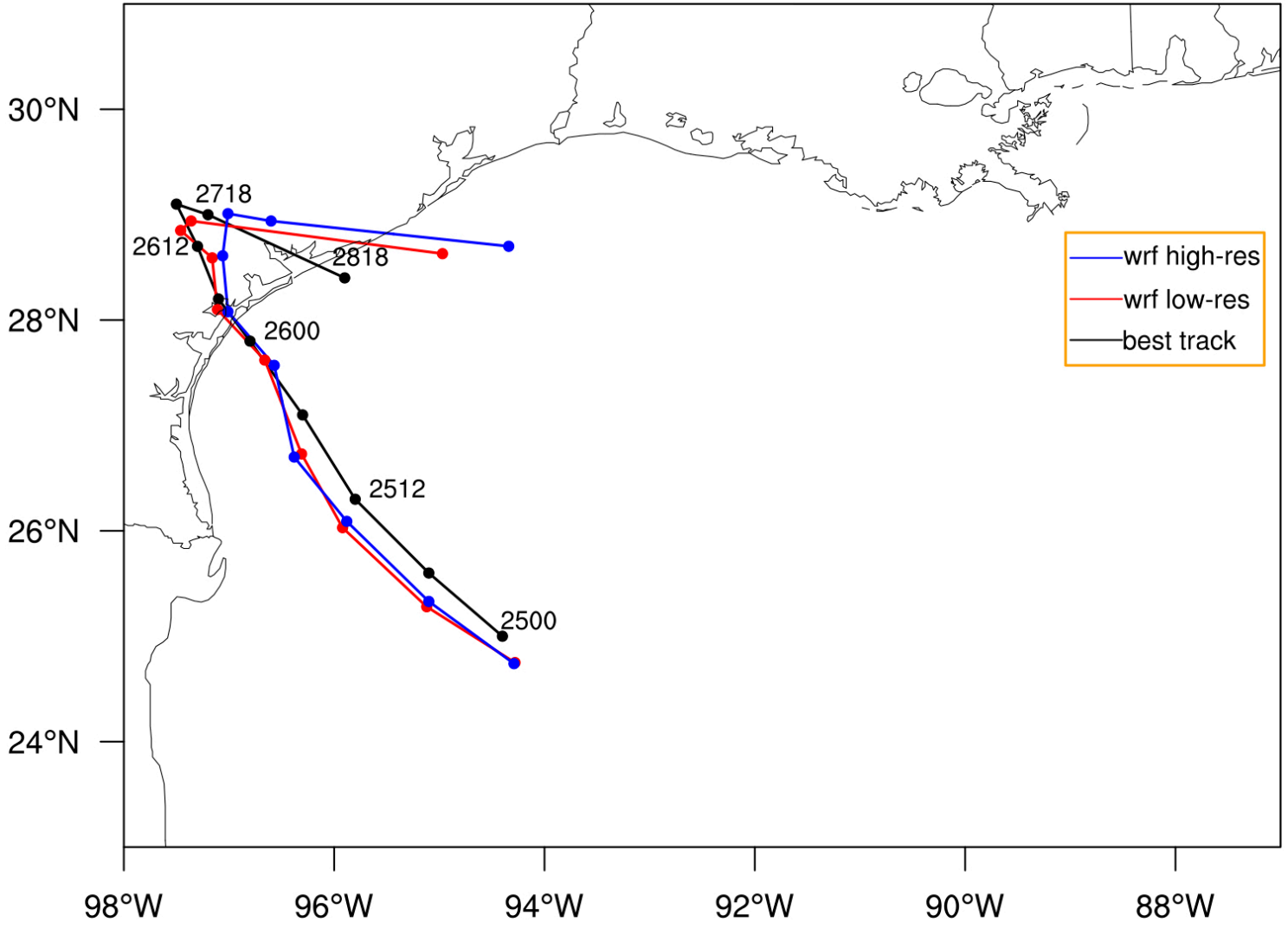
$\Delta x_2 = 1.67$; 5 km

Δt = 15 minutes

Initializing with NCEP GFS forecast with the simulation period Aug 25 – 30, 2017 (HH) and Aug 27 – 31, 2021 (HI)

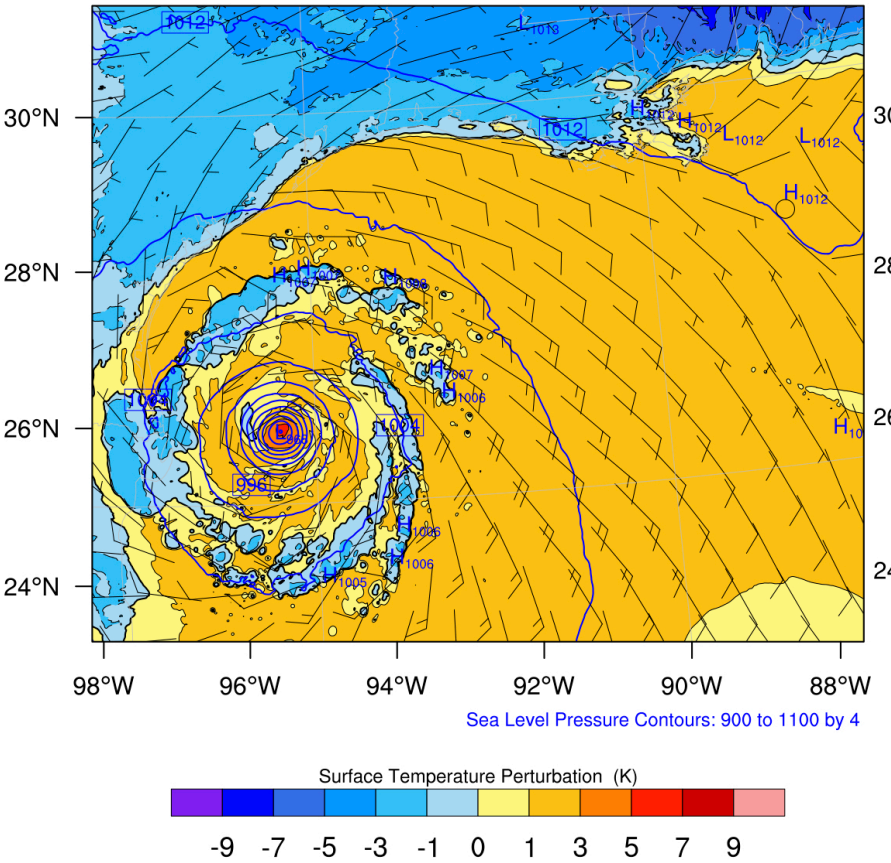
Hurricane Harvey Track

- The hurricane track in WRF simulations outperforms that in NHC-OFCL
- Track forecast error in high (low)-res is about 62% (72%) smaller than that in OFCL

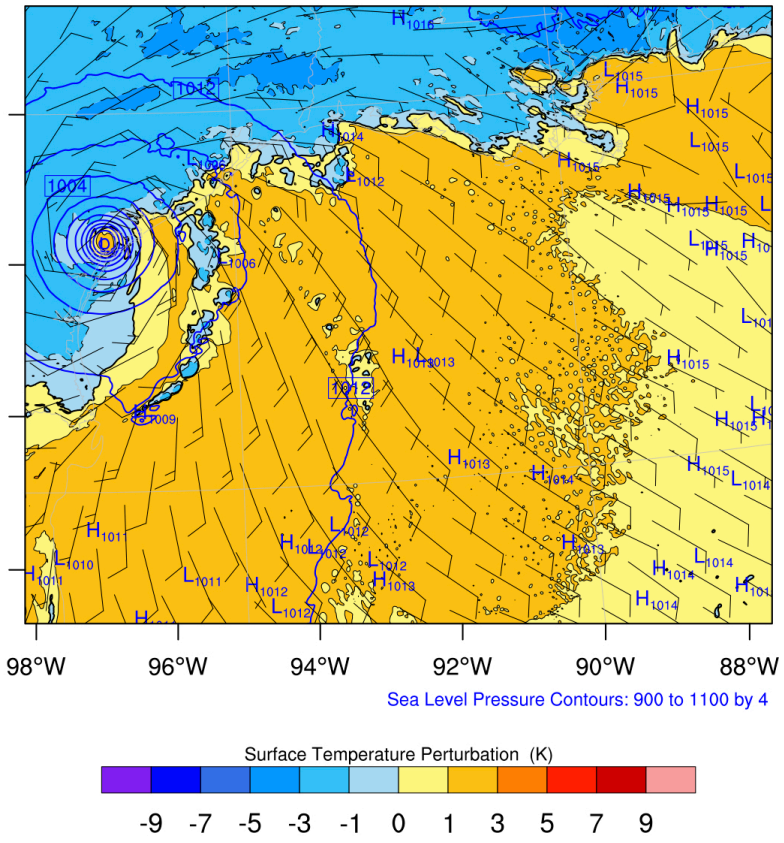


Overview of Simulations (HH)

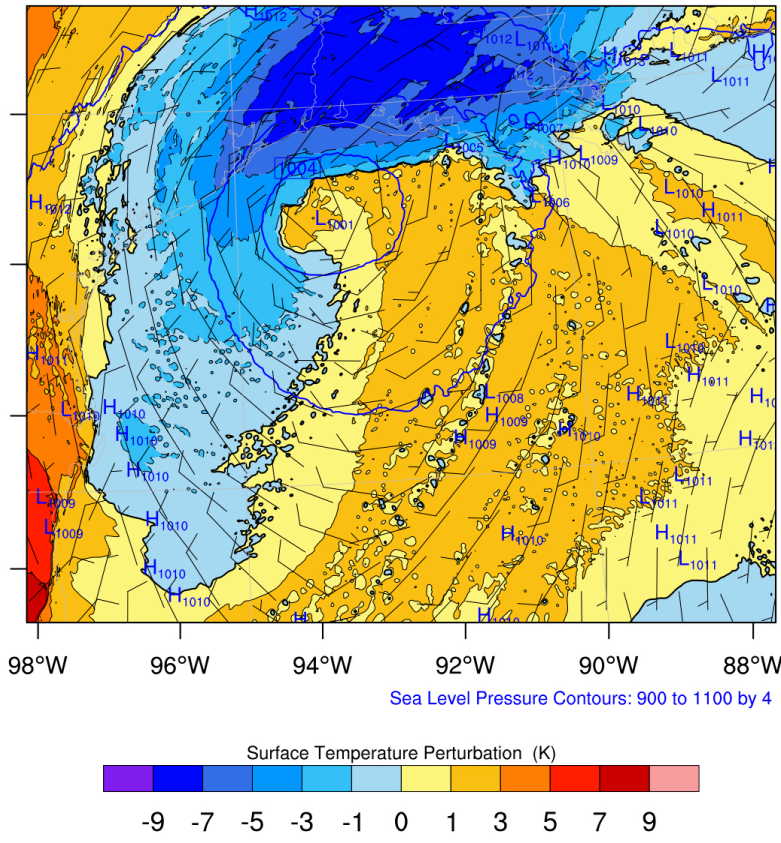
- Potential temperature perturbation field at the surface overlaid by wind velocity and sea level pressure



Aug 25, 09:00:00



Aug 26, 06:00:00



Aug 28, 21:00:00

Potential Vorticity

- Potential vorticity is combination of absolute vorticity ω_a projected on normal to the potential pressure surface n_σ and the surface temperature θ_s (Montgomery & Shapiro, JAS 52, 1995; Schneider et al., JAS 60, 2003):

$$Q_s = -g \underbrace{(f\boldsymbol{k} + \boldsymbol{\nabla}_\sigma \times \boldsymbol{v})}_{\boldsymbol{\omega_a}} \cdot n_\sigma \, \theta_s$$

- The sign of the meridional gradient of potential vorticity can be informative about the direction of the hurricane movement

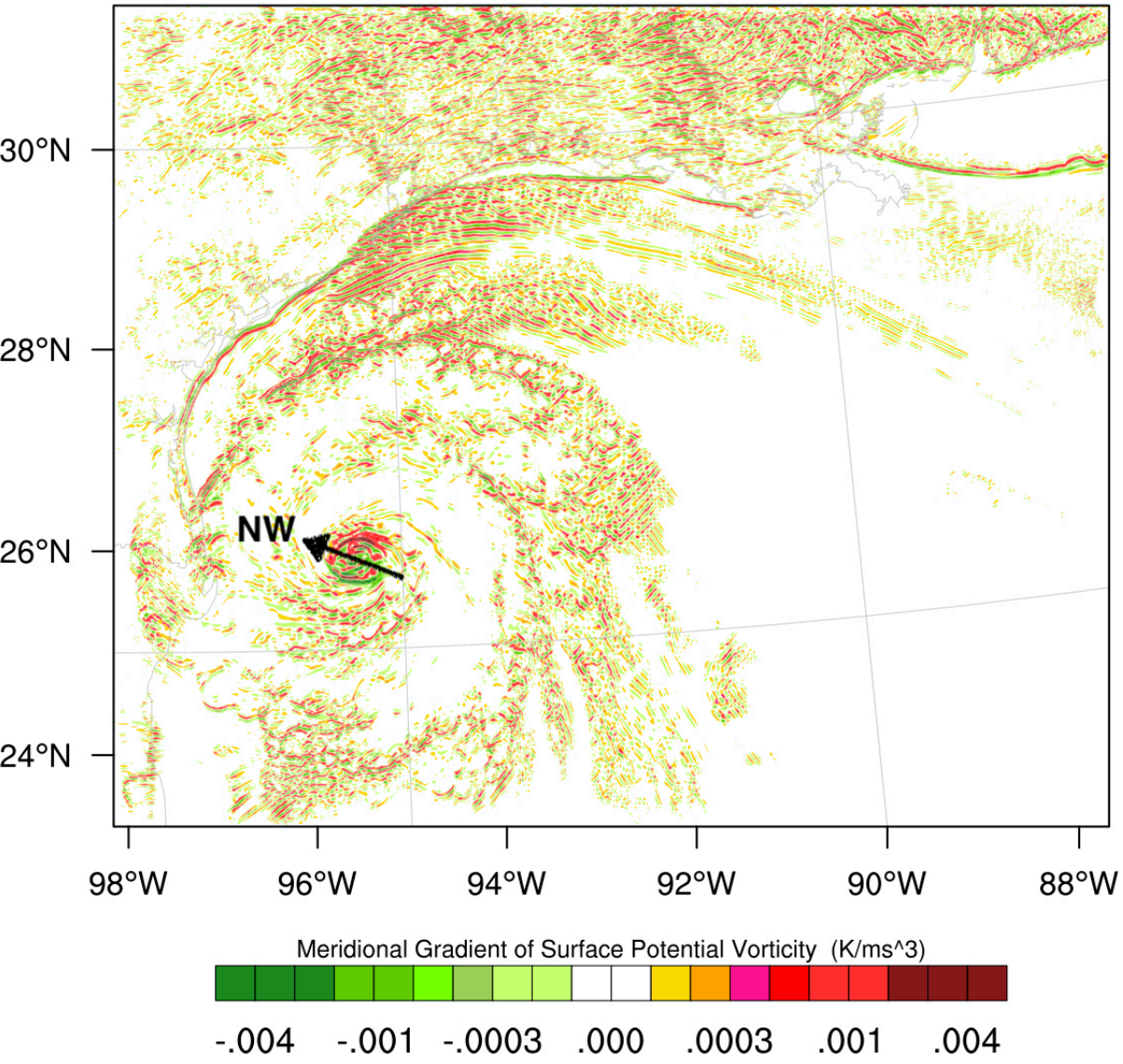
$$\frac{\partial Q_s}{\partial y}$$

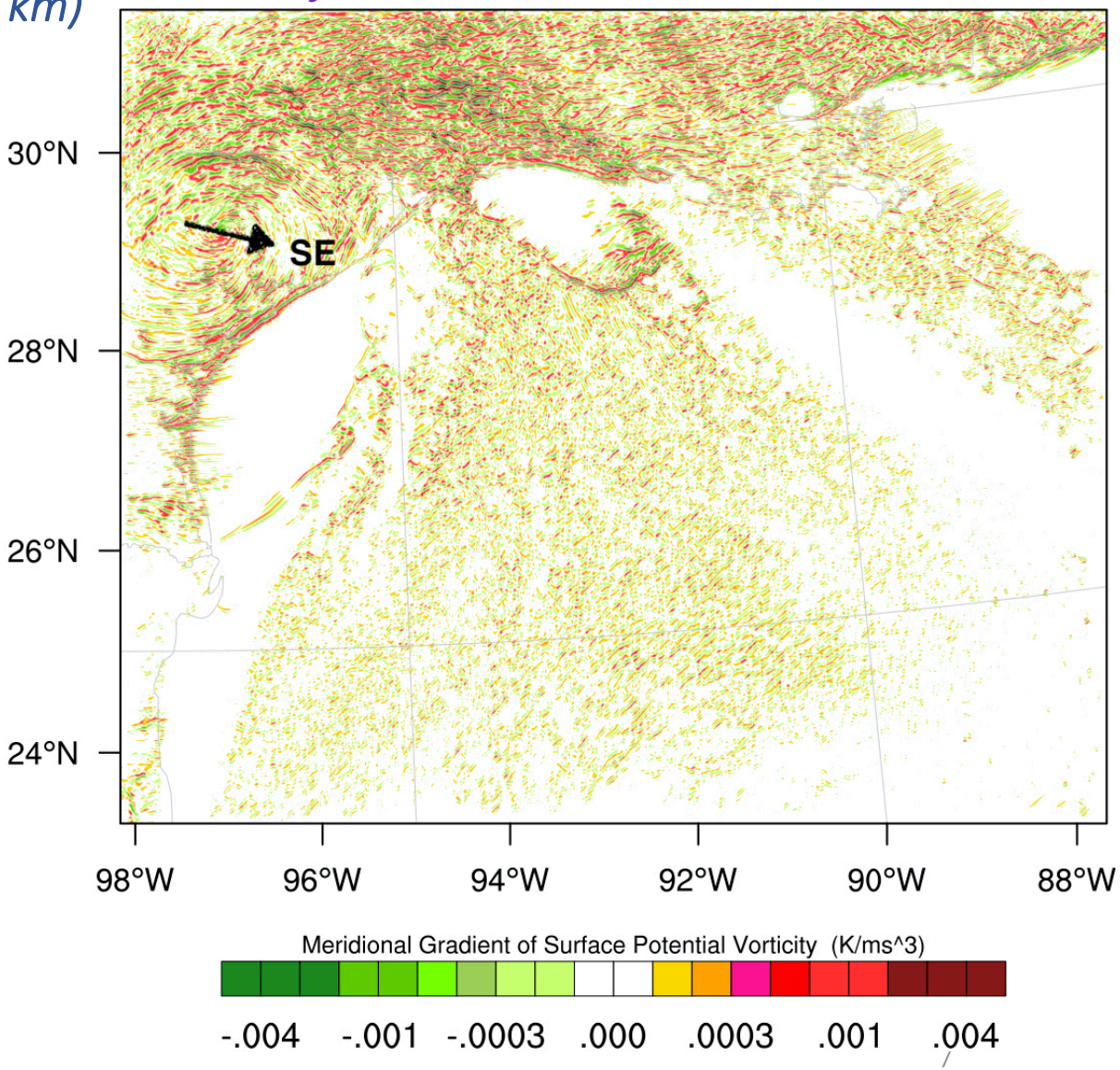
Meridional gradient of the Surface Potential Vorticity

$\frac{dQ_s}{dy}$ Over ocean @ Aug 25, 09:00:00

Higher resolution (1.67 km)

$\frac{dQ_s}{dy}$ Over land @ Aug 27, 12:00:00





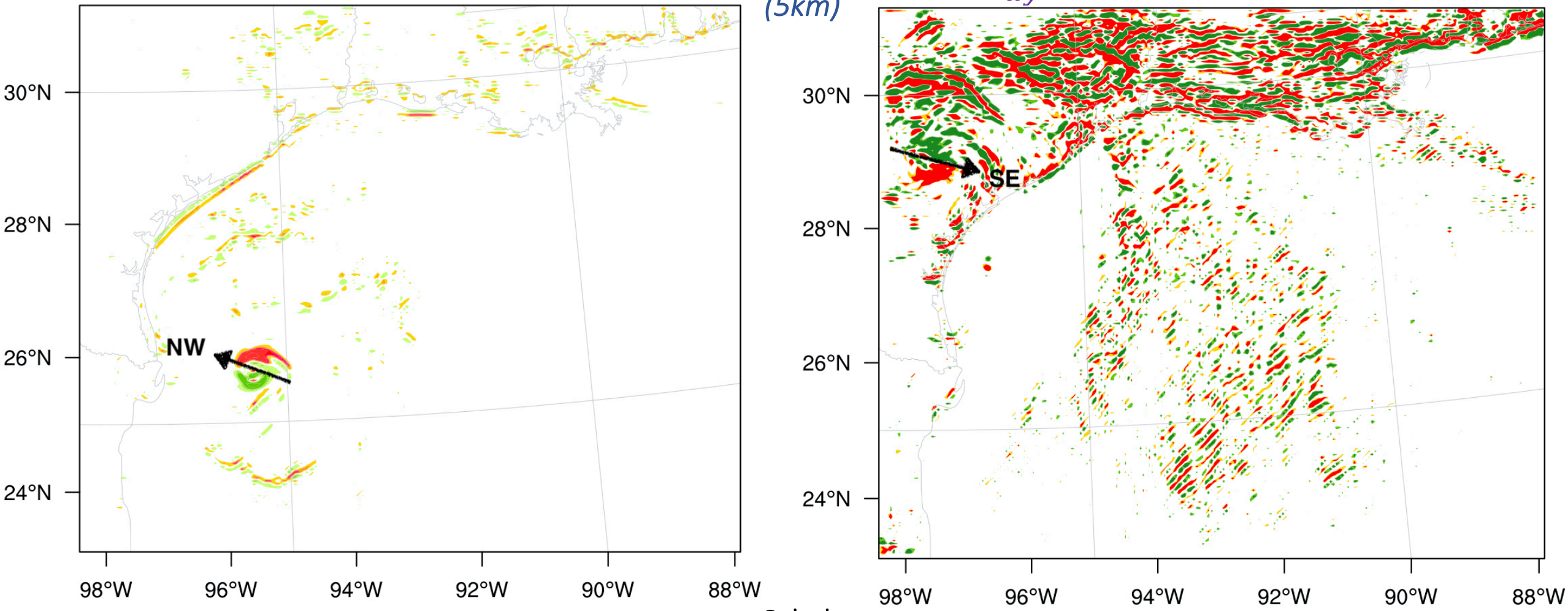
Khani & Dawson, JAS, 2023 (submitted)

Meridional gradient of the Surface Potential Vorticity

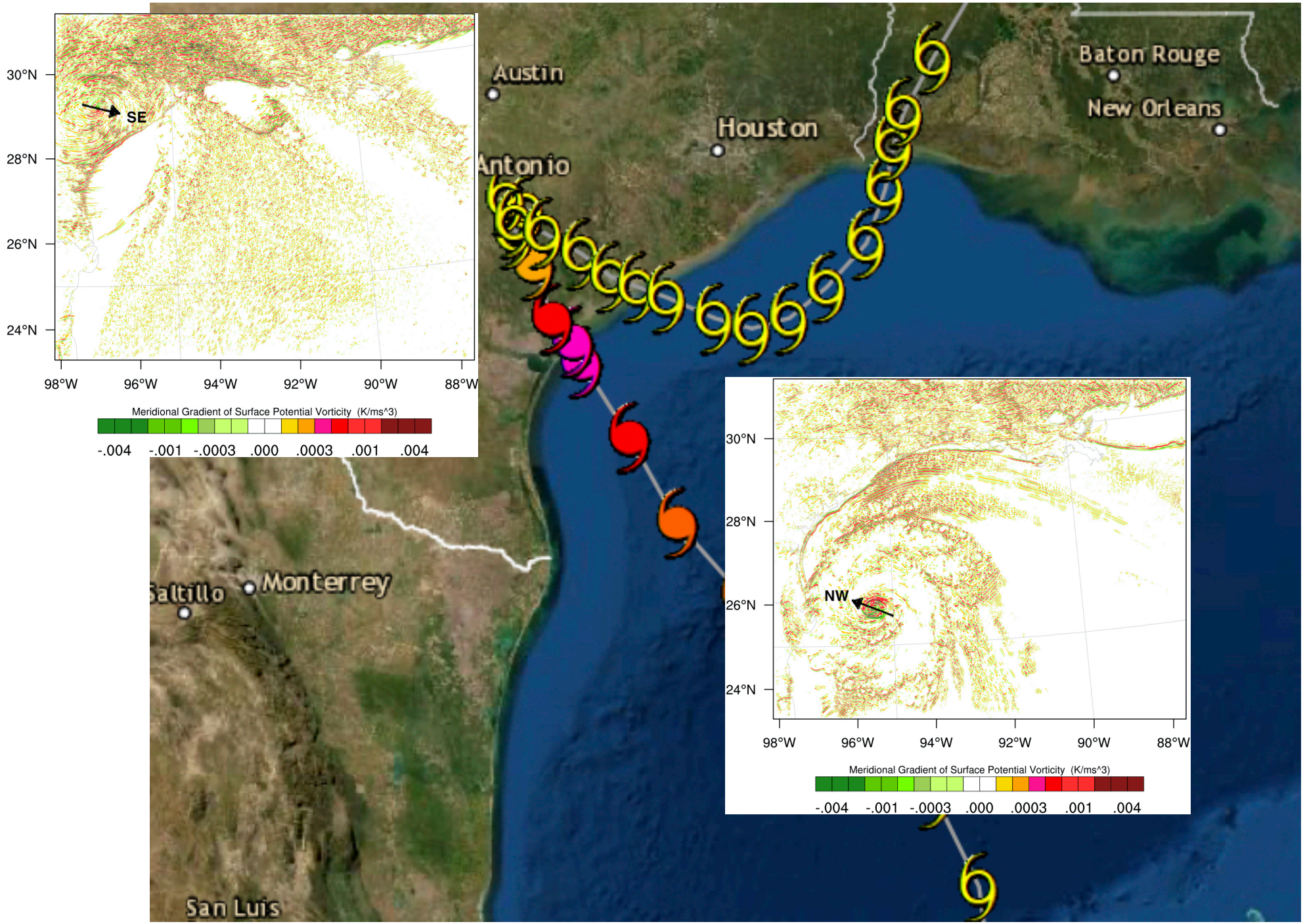
$\frac{dQ_s}{dy}$ Over ocean @ Aug 25, 09:00:00

Coarser resolution (5km)

$\frac{dQ_s}{dy}$ Over land @ Aug 27, 12:00:00



Khani & Dawson, JAS, 2023 (submitted)


Austin
Houston
Antonio
Baton Rouge
New Orleans
Monterrey
Saltillo
San Luis
SE
NW
30°N
28°N
26°N
24°N
98°W
96°W
94°W
92°W
90°W
88°W
Meridional Gradient of Surface Potential Vorticity (K/ms^3)
-.004
-.001
-.0003
.000
.0003
.001
.004

Baroclinic Instability

- Necessary condition of baroclinic instability in the continuous/layered stratified flows (as in **Pedlosky, JAS 21(2), 1964a; Pedlosky, JAS 21(4), 1964b**):

$$\int_{-\ell}^{\ell} dy \int_{\sigma_1}^{\sigma_2} \left(\frac{C^2}{g}\right) d\sigma \frac{u\partial Q}{\partial y} > 0,$$

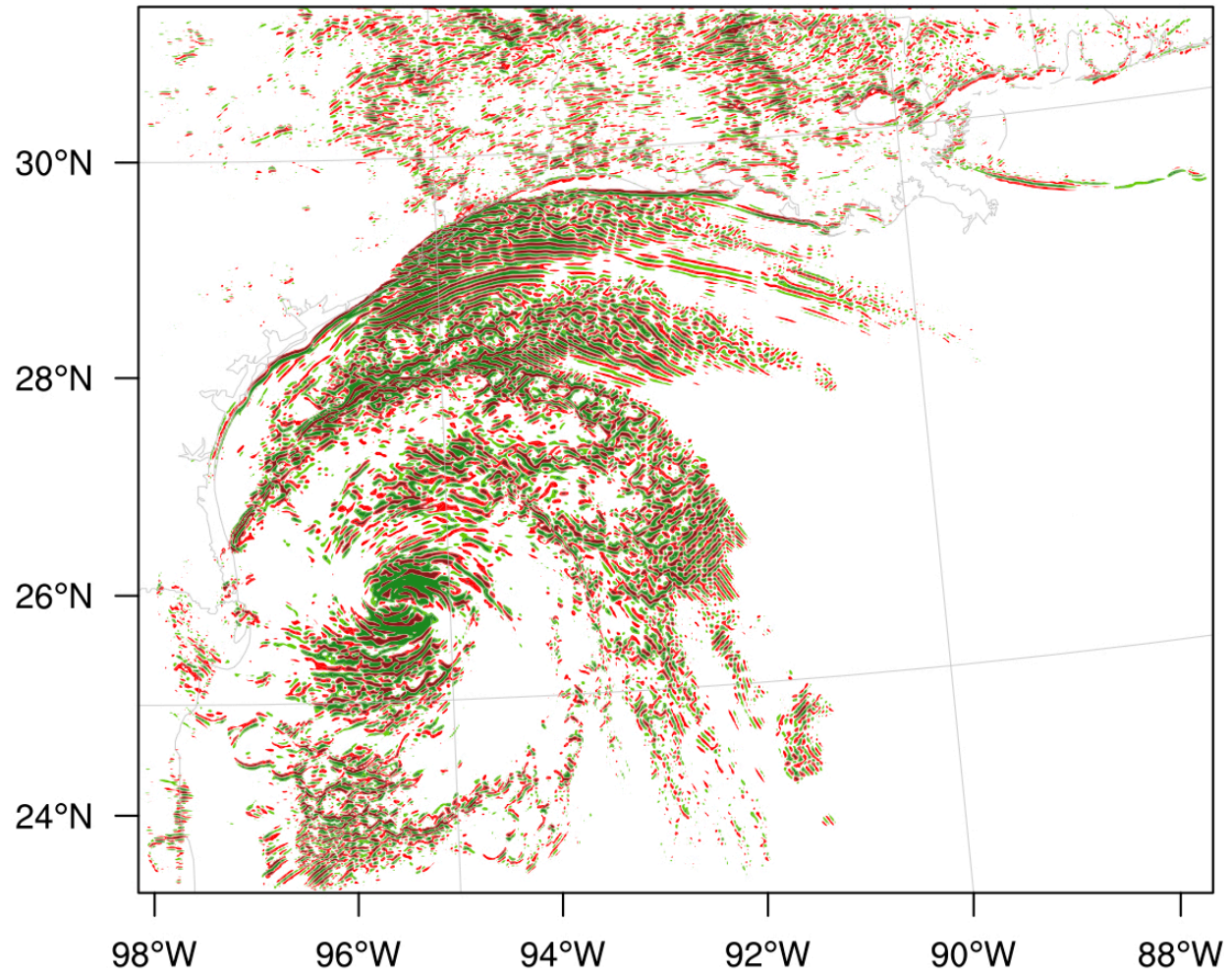
- Since $\sigma_1 > \sigma_2$ in the potential pressure coordinates in the atmosphere, we need to have

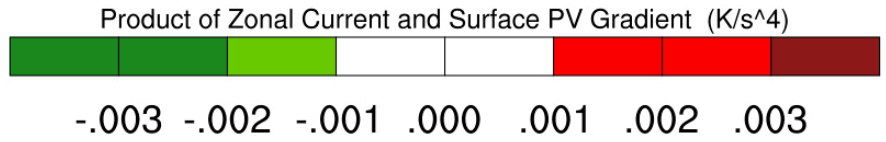
$$u\frac{\partial Q}{\partial y} < 0,$$

to hold the necessary condition of baroclinic instability.

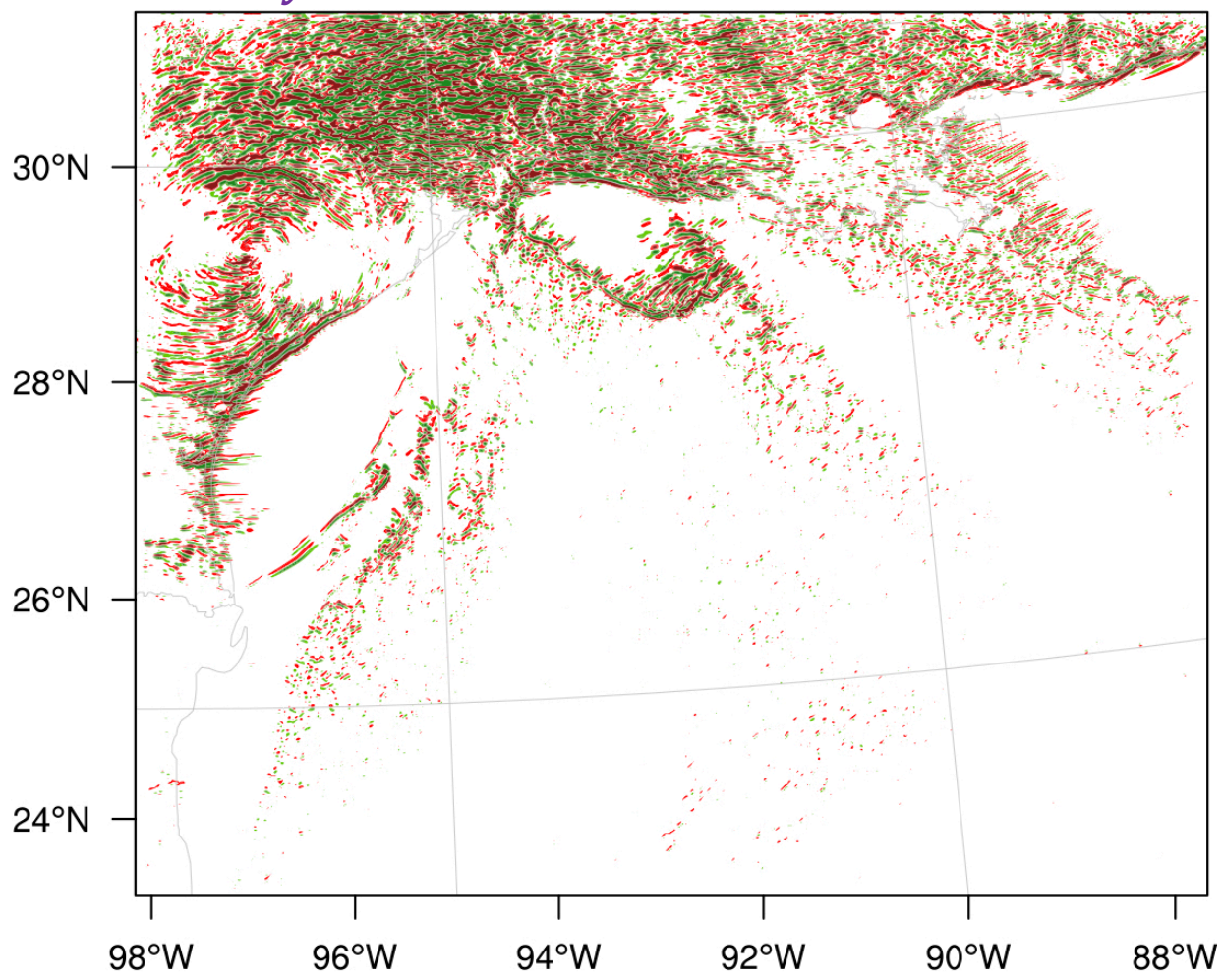
Baroclinic Instability

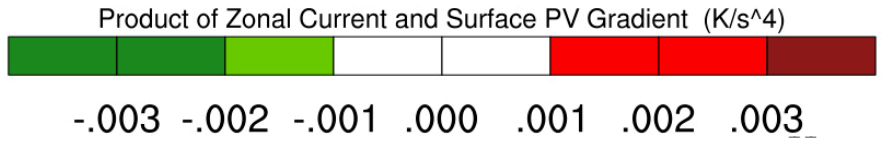
$u_s \frac{dQ_s}{dy} < 0$ Over ocean @ Aug 25, 09:00:00





$u_s \frac{dQ_s}{dy} > 0$ Over land @ Aug 27, 12:00:00



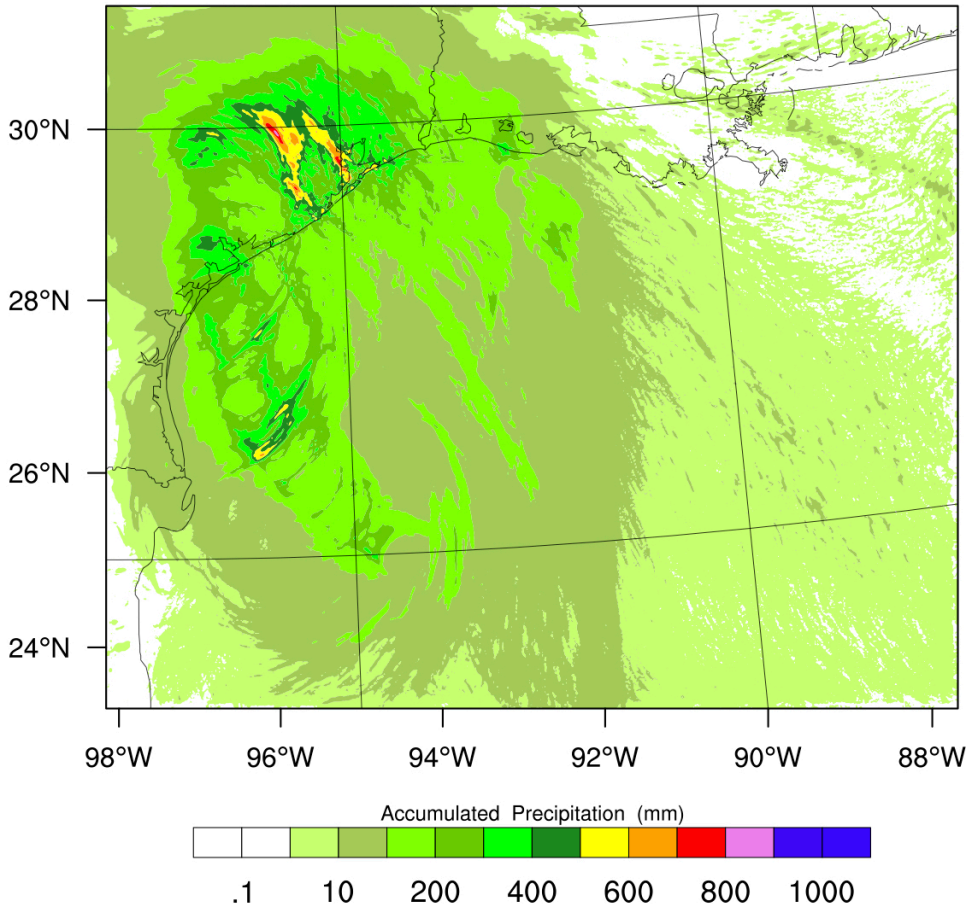


Khani & Dawson, JAS, 2023 (submitted)

Precipitation (mm)

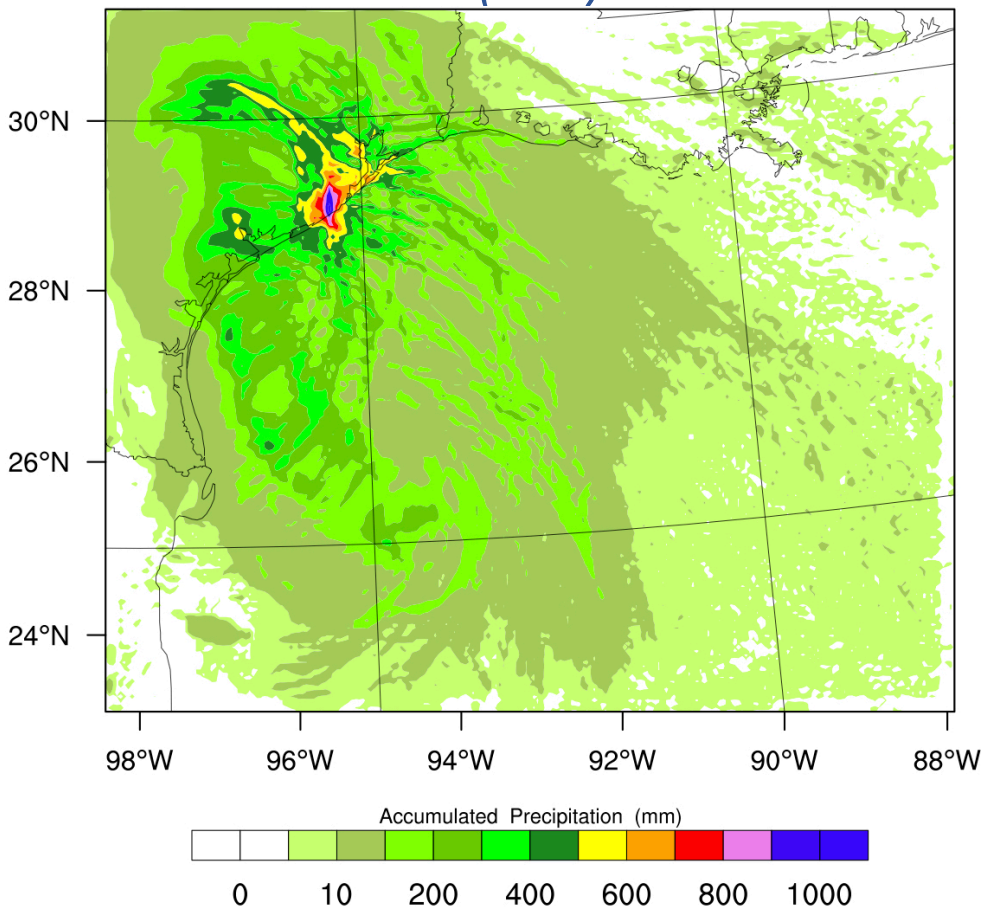
- Resolving *convective cumulus precipitation* improves the accuracy of locations and magnitudes of maximum rainfall.

Higher resolution (1.67 km)



Aug 26, 06:00:00

Coarser resolution (5km)



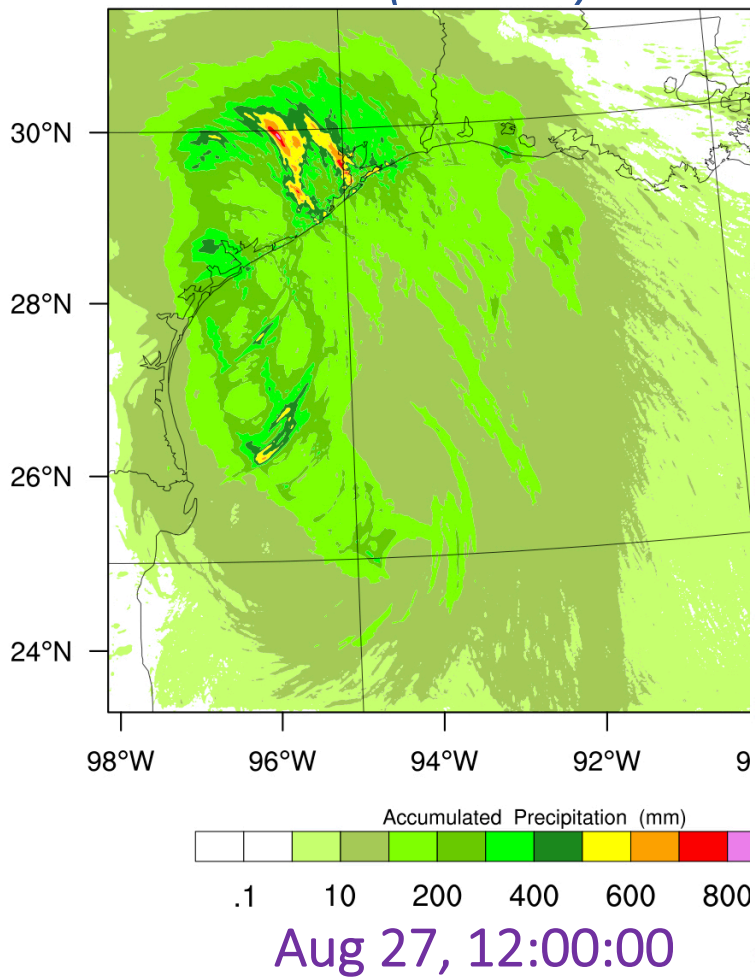
Aug 26, 06:00:00

Khani & Dawson, JAS, 2023 (submitted)

Precipitation (mm)

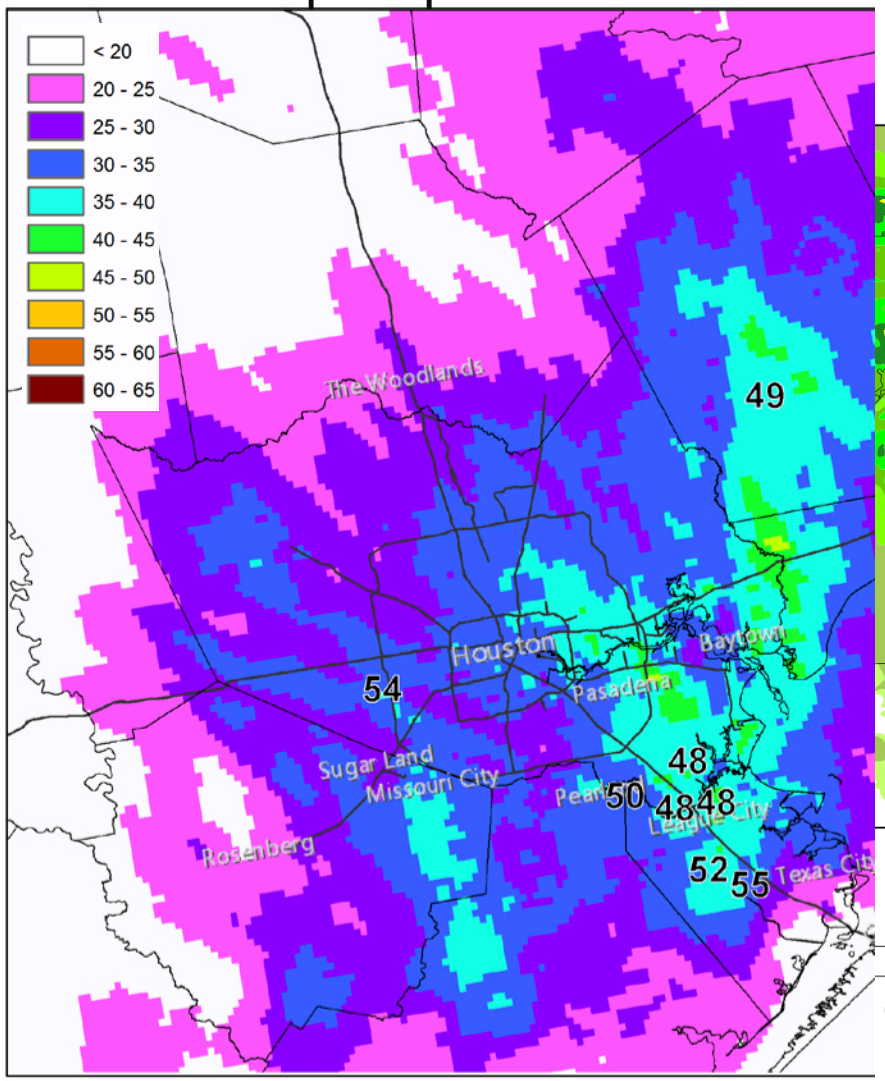
- Patterns in the high-resolution case are comparable to those from gauge data.

Higher resolution (1.67 km)

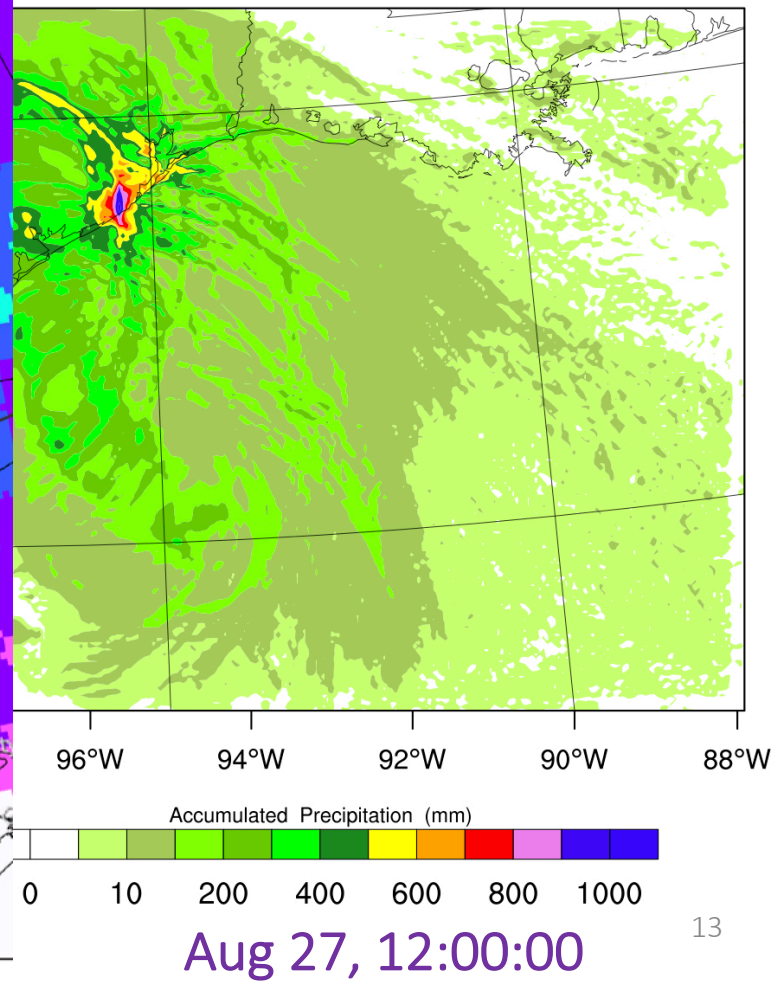


Aug 27, 12:00:00

NOAA gauge-corrected precipitation



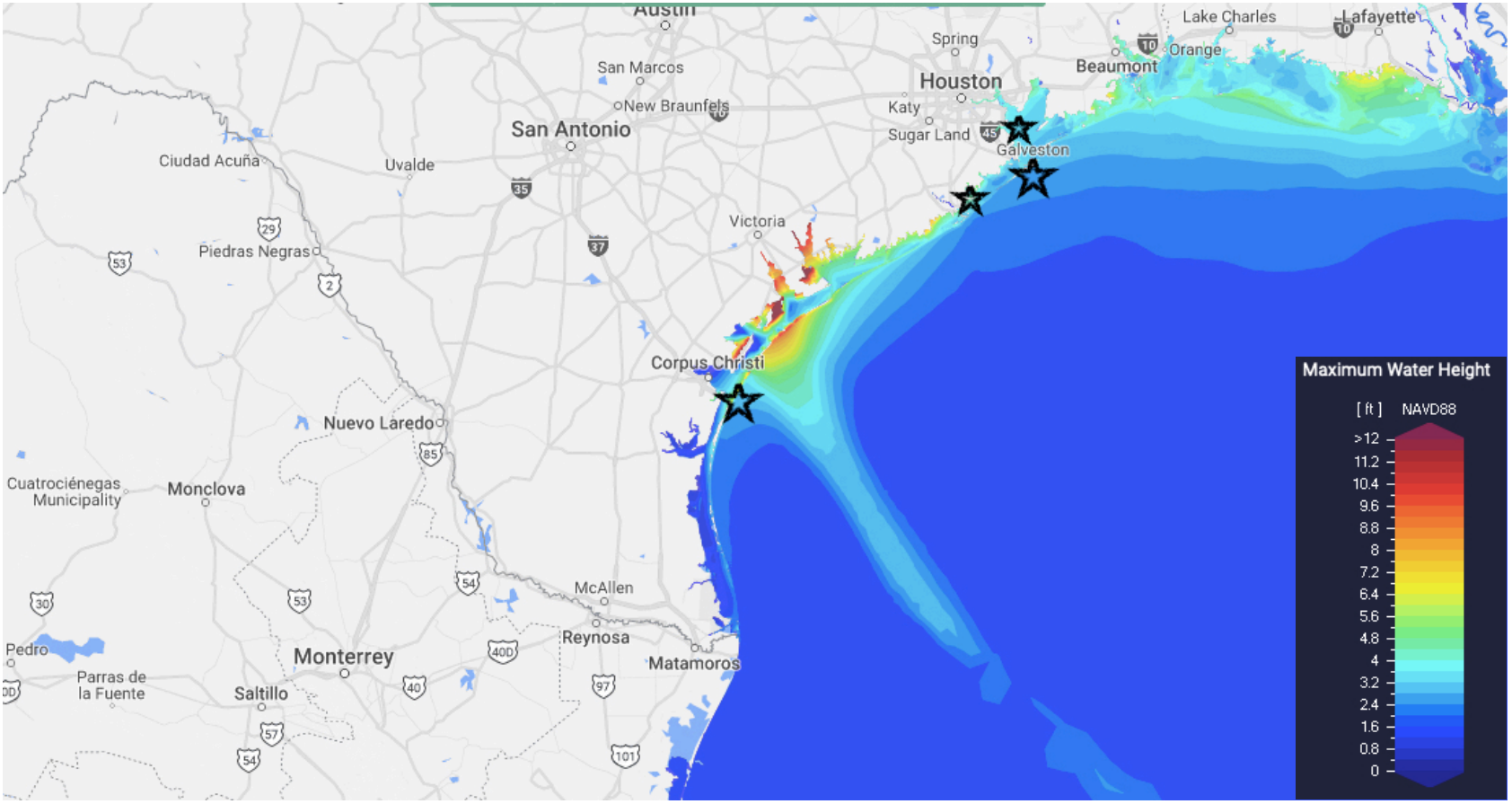
Coarser resolution (5km)



Aug 27, 12:00:00

WRF+ADCIRC (One-way coupled model)

- High-resolution WRF outputs (**surface pressure, U10 and V10 velocities & precipitation**) are used in ADCIRC model for storm surge estimates



Taken from *Coastal Emergency Risks Assessment (CERA)* webpage

Hurricane Harvey

✓ Hydrodynamics (storm surge):

- ❖ Galveston Pier 21
- ❖ Bob Hall Pier Corpus Christi
- ❖ Eagle point
- ❖ USCG freeport

✓ Hydrology (in progress):

- Precipitation
- River runoff

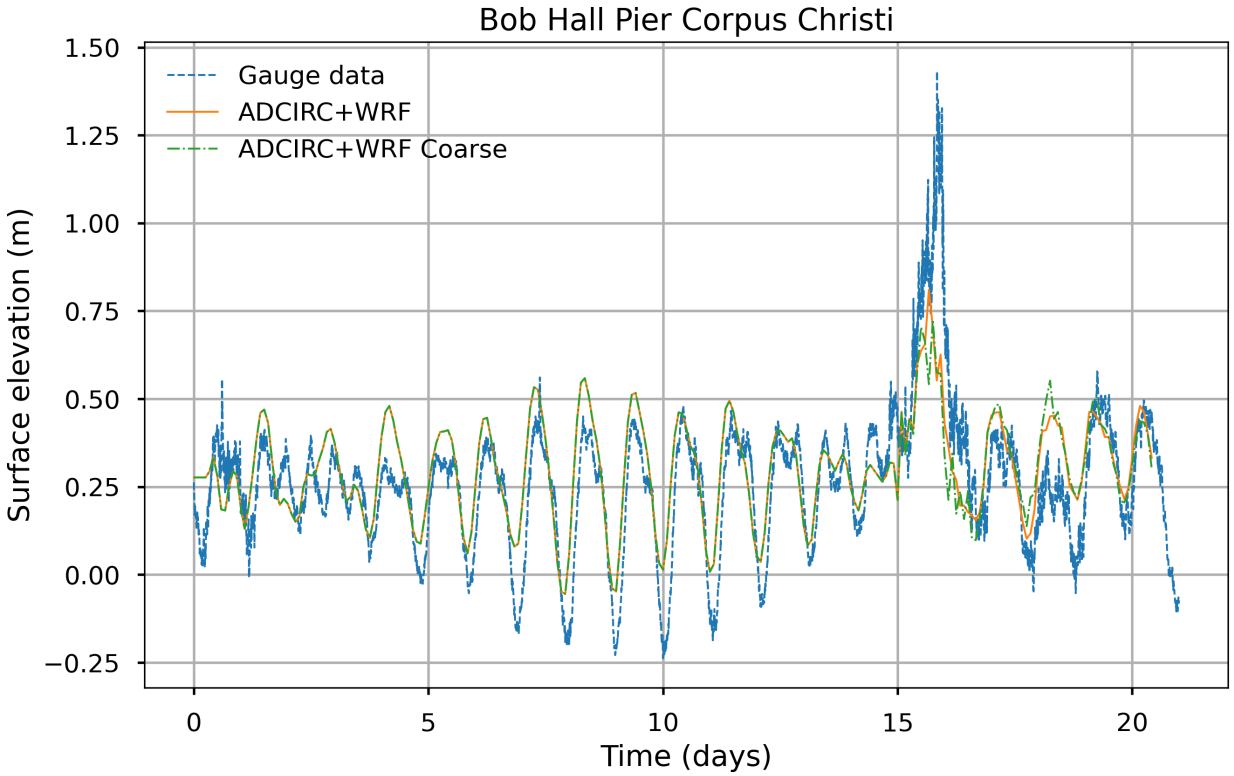
✓ Wave (in progress):

- Swan (near shore wind waves)

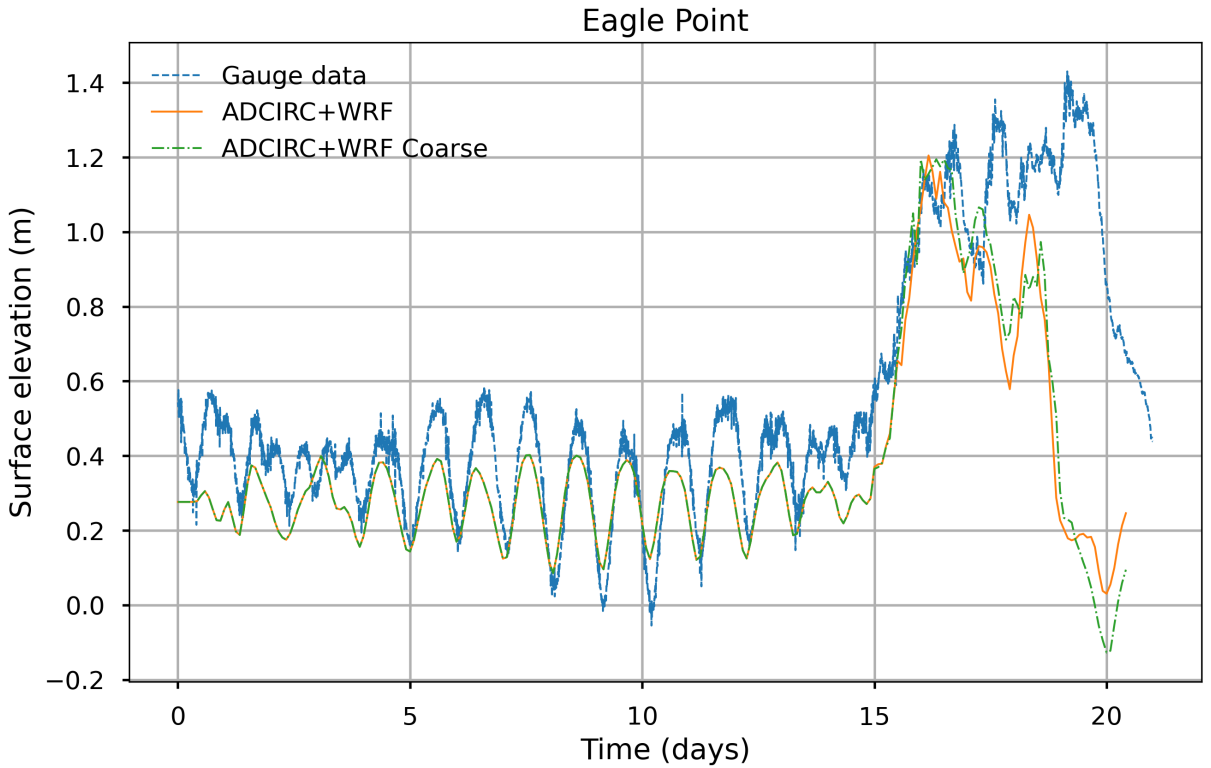
WRF+ADCIRC (Coupled Model)

- Surface elevation in WRF+ADCIRC compared with NOAA gauge data.
- To include precipitation effects.
- To employ ML to improve correlation coefficients & integral time.

Good results!



Poor results!



Work in preparation (Khani, Reich, Loveland & Dawson, 2023)

Summary

- High-resolution simulations can enhance our understanding of hurricane dynamical processes and cyclone tracks.

- Patterns for precipitation rates/rainfall are skillfully resolved at high-resolution simulations.

- High-resolution meteorological products will improve storm surge estimates in hydrodynamical models (coupled models).

Conclusions/Future Work

- High-resolution atmosphere simulations can help to improve our understanding on dynamical processes of the hurricane movement and to enhance model accuracy using state-of-the-art scale-aware parameterization in coarse-resolution simulations.

- Whether simulations with higher resolution (sub-kilometer grid spacing) can be useful to improve hurricane forecasts? Resolving KH waves, internal waves, clouds, microphysics, ….

- To develop a coupled atmosphere-ocean-coastal model including the Wind-Evaporation-SST (WES) interaction (WRF-ADCIRC-SWAN-MOM6).

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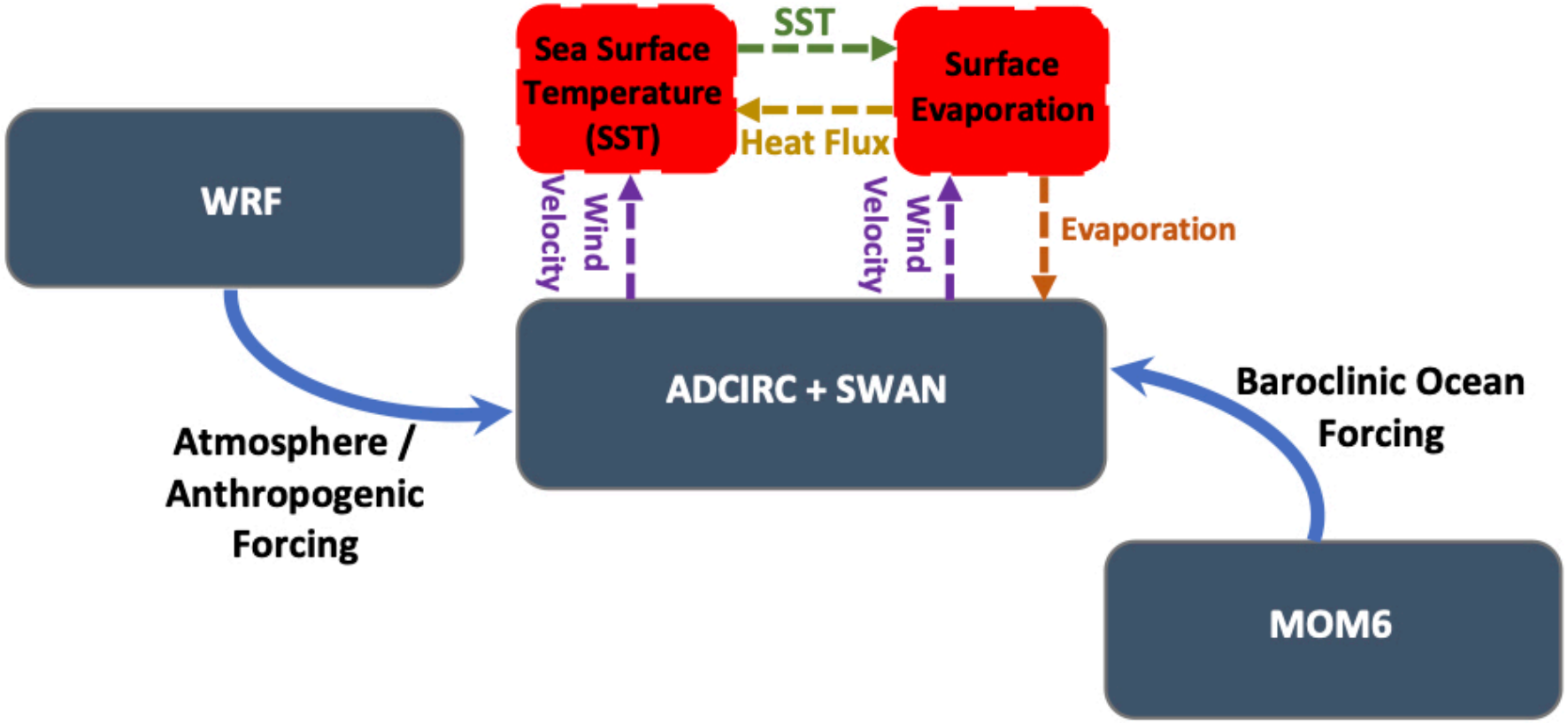
Extra slides

Coupled Atmosphere-Ocean-Coastal model

- WRF-MOM6-ADCIRC with the Wind-Evaporation-SST (WES) interaction

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}\cdot\nabla\mathbf{U} + f\mathbf{k}\times\mathbf{U} = \frac{-1}{\rho}\nabla\left(P_s + \rho g\eta^*\right) + \frac{1}{H}\left(\frac{\tau_s - \tau_b}{\rho} + \nabla M + \nabla D\right),$$

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(\mathbf{U}H) + \sigma(\eta - \eta_c) = R_t - \nabla\cdot\left(\mathbf{U}_b H\right) - \frac{Q_e}{\rho_a L c_e}.$$



Hurricane Harvey: Simulation

Model Setup

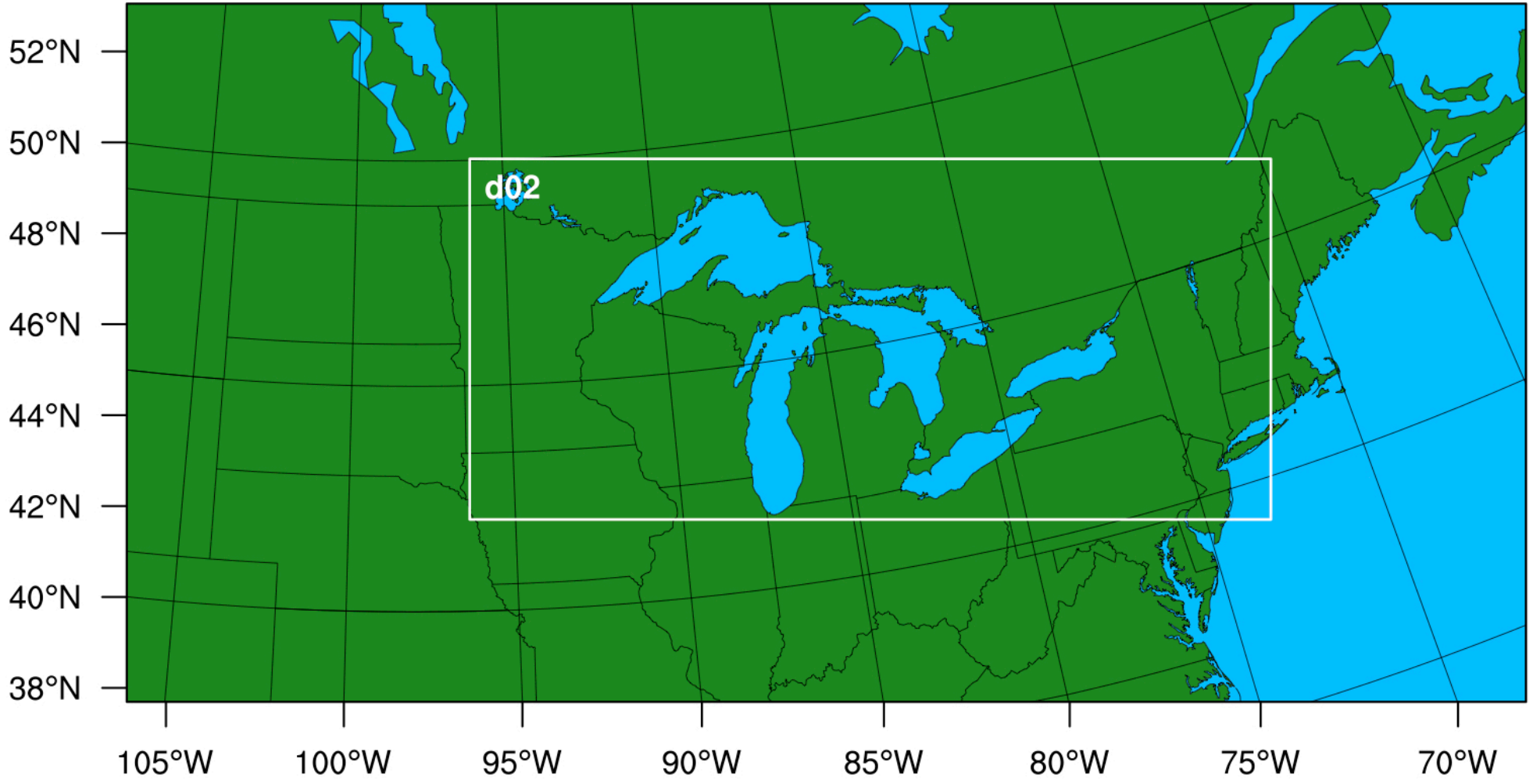
- A High-resolution configuration for Gulf of Mexico region is developed in the WRF mesoscale model to study Hurricane Harvey.

Details

- The configuration includes resolutions of $\Delta x = 1.67$ km and $\Delta x = 5$ km for the nest and main domains, respectively.
- Forecast for 132-hours (5 days + 12 hrs) of Hurricane Harvey is performed. Outputs are saved at every 15 minutes.
- Potential and absolute vorticity, potential temperature perturbation, pressure and precipitation fields are diagnosed for studying the cyclone dynamics.

WPS for Great Lakes

High-resolution weather forecasting for weather extremes



Δx_1 = 5 km

Δx_2 = 1.67 km

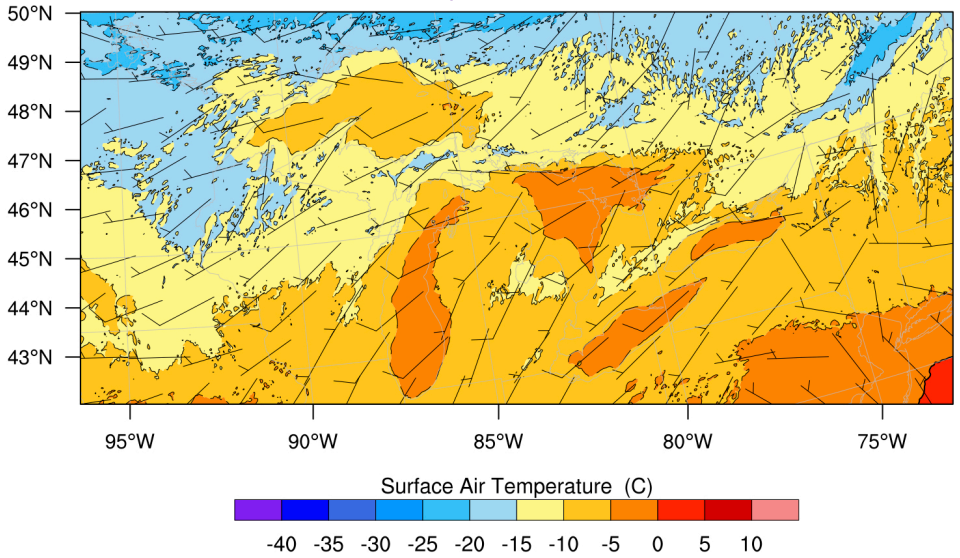
Δt = 30 mins.

Initializing with NCEP GFS forecast with the simulation period Feb 1—7, 2023

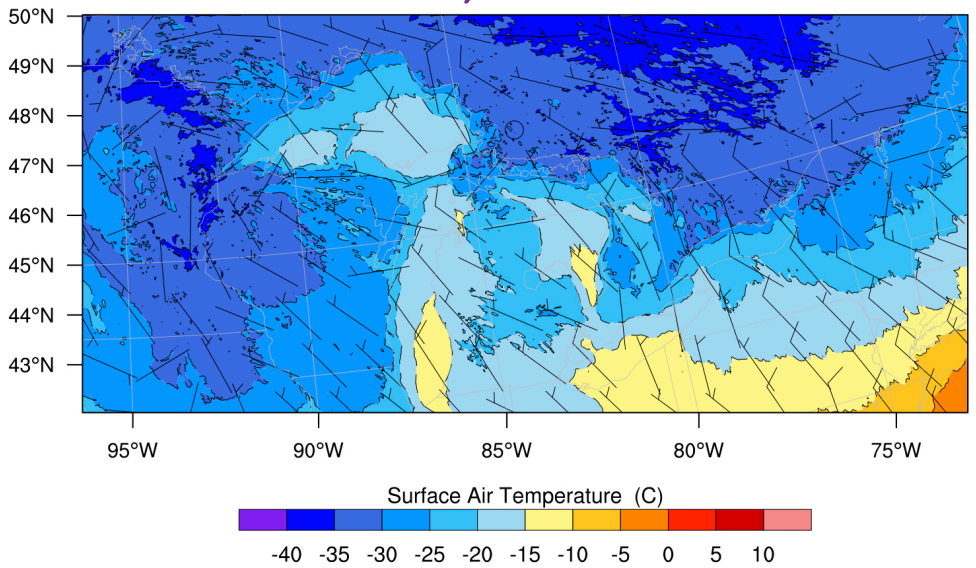
Surface Temperature

- Surface temperature indicates severe cold weather on Feb 3 in the GL.

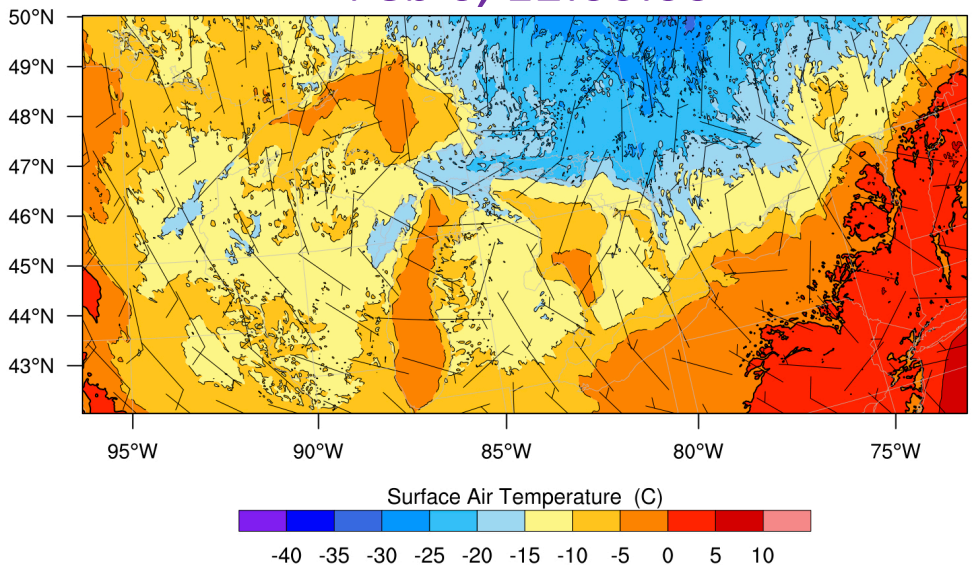
Feb 2, 03:00:00



Feb 3, 12:00:00



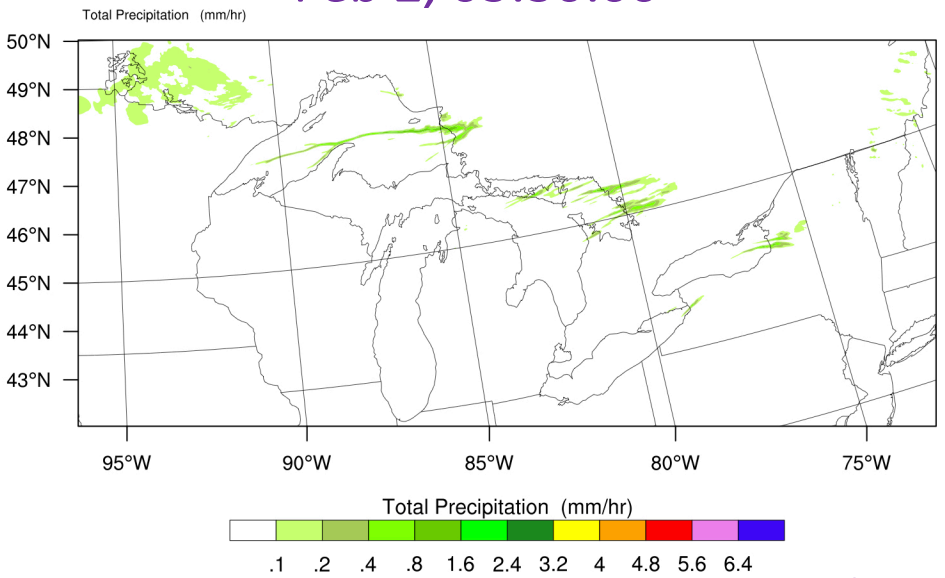
Feb 6, 12:00:00



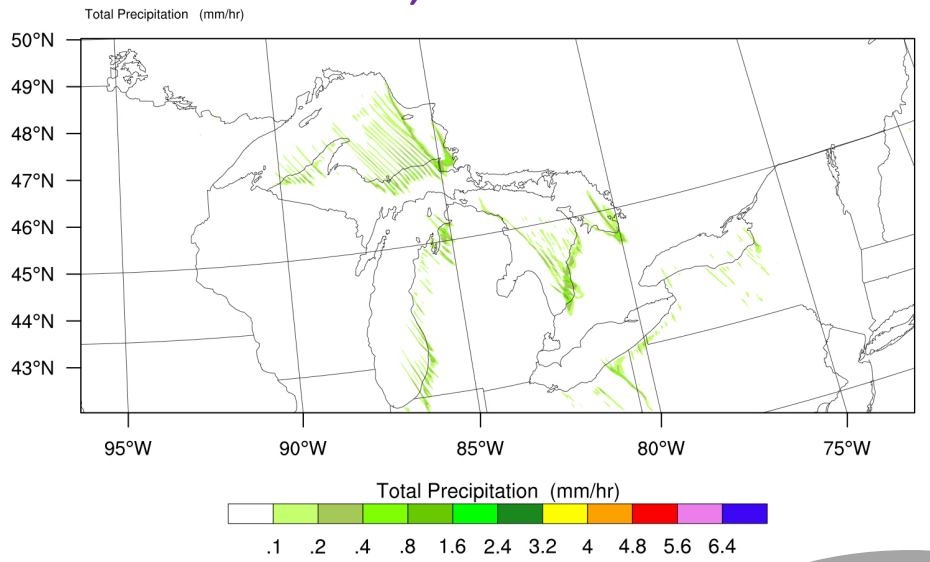
Precipitation Rates (mm/hr)

- Precipitation rate significantly increases over Ontario lake and Erie.

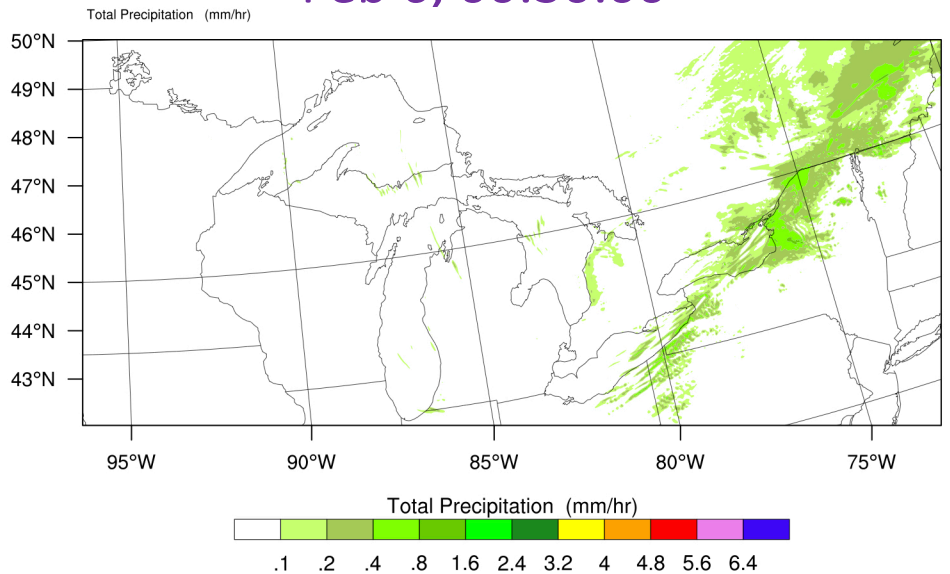
Feb 2, 03:30:00



Feb 3, 12:30:00



Feb 6, 00:30:00

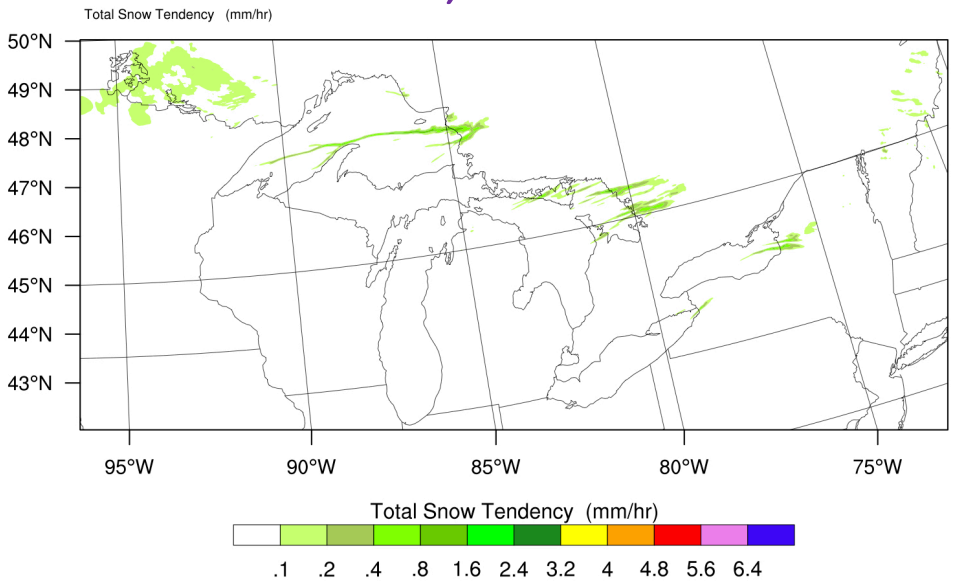


To study precipitation rates (moisture dynamics) enhanced by surface temperature extremes …

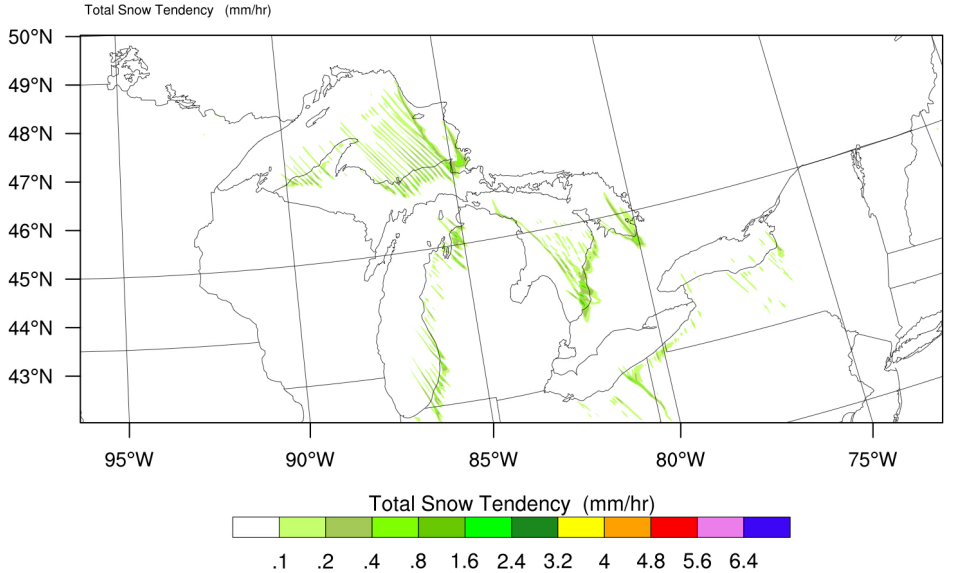
Rate for Snow & Ice precipitation (mm/hr)

- On Feb 6, snow & ice rates are mainly important at North of 49°N.

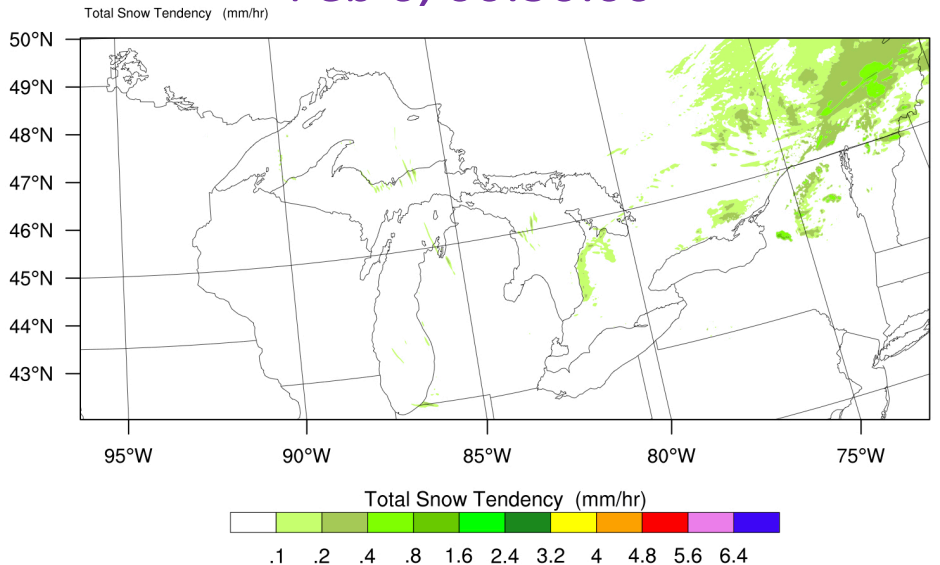
Feb 2, 03:30:00



Feb 3, 12:30:00



Feb 6, 00:30:00

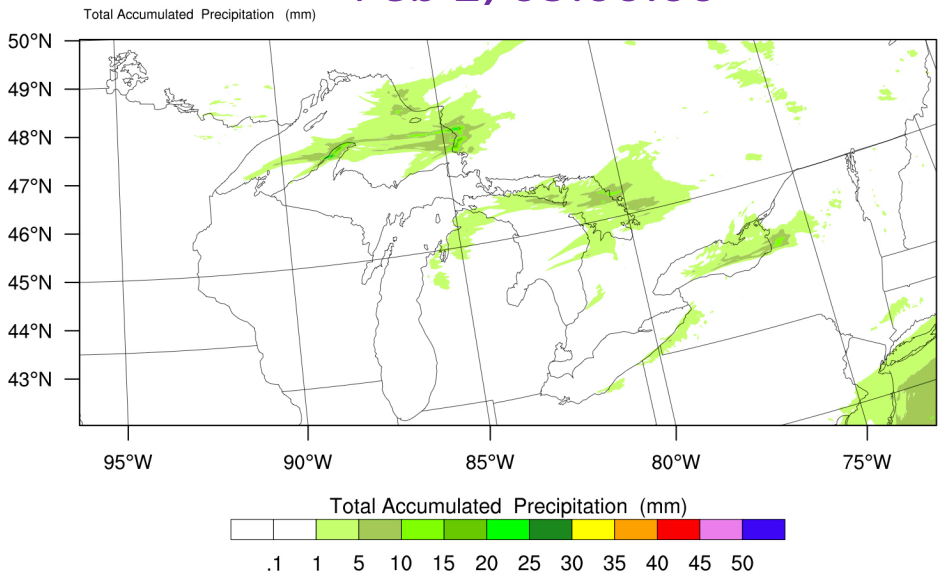


Snow and ice tendencies
versus
rainfall tendency …

Accumulated Precipitation

- Total precipitation is heavier over Superior, Ontario, Huron lakes.

Feb 2, 03:00:00



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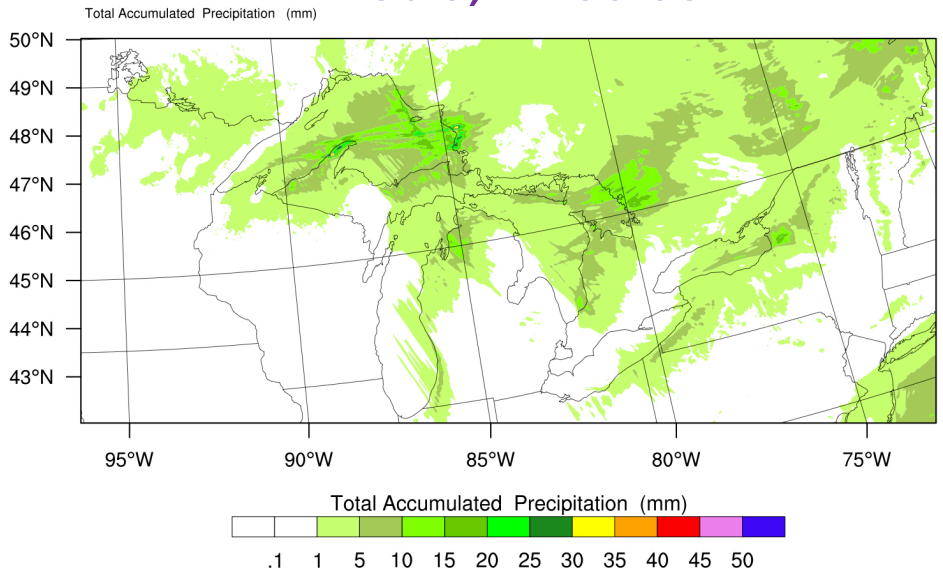

Feb 6, 12:00:00