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Machine Learning Forecast Sensitivity

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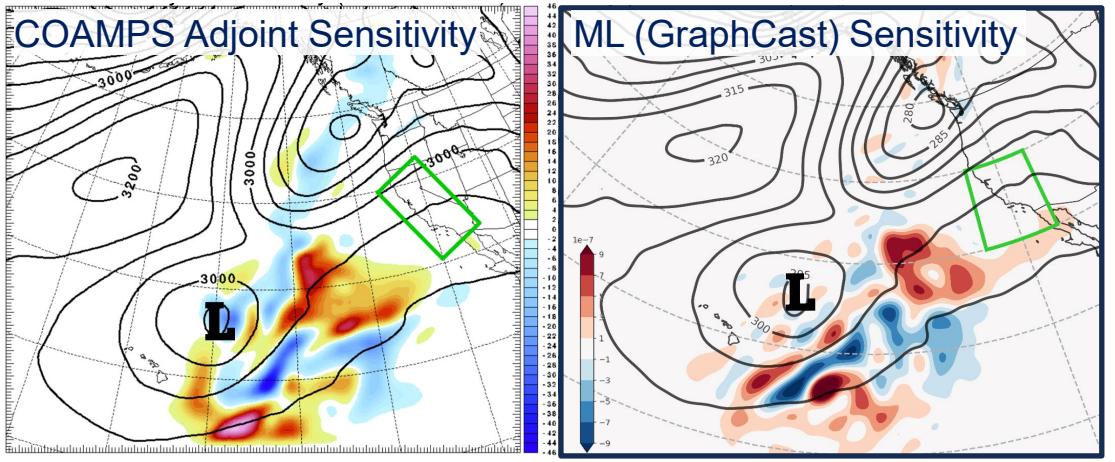
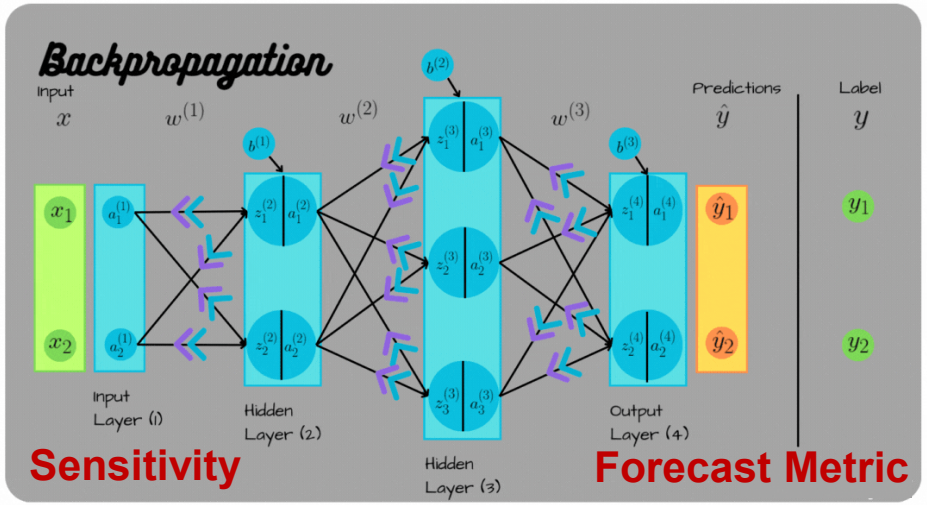
Deep Learning Sensitivity Analysis

- Where do changes in the initial conditions most strongly affect high impact weather (HIW) forecasts?
  - Observation targeting & system design, dynamics, predictability
- Adjoint sensitivity (Errico 1997; Rabier et al. 1996; Doyle et al. 2019)
  - Quantifies sensitivity of a forecast metric to initial conditions
  - Limitations: computational cost, complex code, short lead time
- ML models are ideal for sensitivity computations
  - Derivatives computed analytically via backpropagation
  - Enables long-lead sensitivities (>2 weeks) (e.g., Vonich & Hakim, 2024)
  - Agree with adjoints for ~48-h integrations (Baño-Medina et al. 2025); correlation of 0.7+ for > 100 cases between ML & NWP adjoints
- Goal: Use ML sensitivity analysis to identify HIW predictability barriers during AR-Recon, NURTURE, NAWDIC, & GARRP
  - 5-day forecast sensitivities using GraphCast (Lam et al. 2023)
  - Case study: Storm Pedro (2026)
  - Establish interpretability

48-h precipitation sensitivity to the 700-hPa water vapor
St. Valentine's Day AR and CA Flooding (2019)





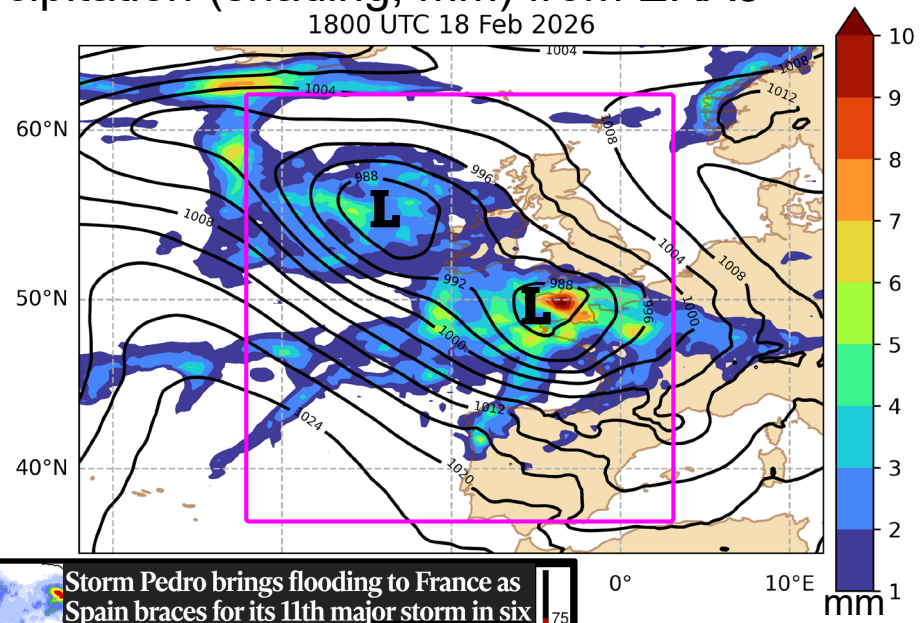
Methods

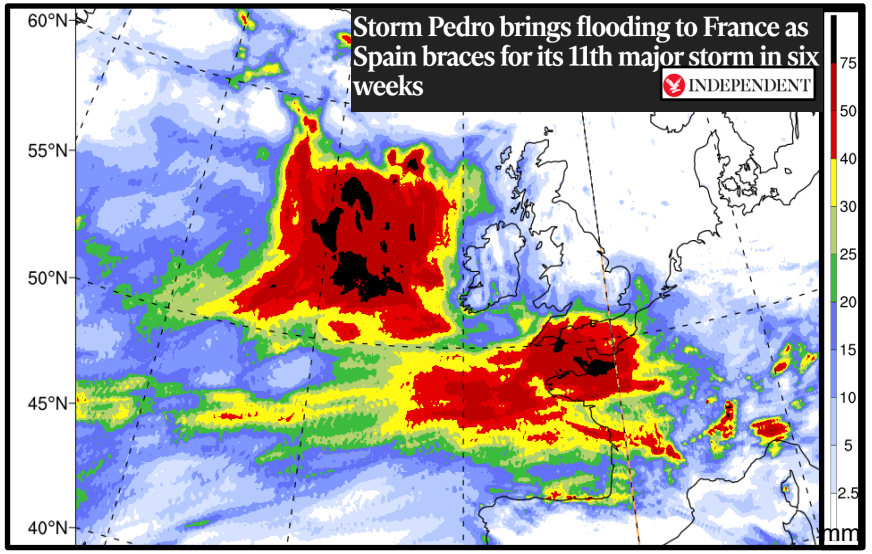
- GraphCast (1° version) used to compute 5-day sensitivities and optimal perturbations
- Loss function
  - Mean Squared Error vs ERA-5 reanalysis
  - 3D temperature, humidity, winds, geopotential, MSLP, 2-m temp., 10-m wind speed, precipitation
  - Computed over W. Europe & E. Atlantic
- Optimal perturbations
  - Iteratively apply sensitivity gradients to initial conditions (captures nonlinearities)

$$x_0^{i+1} = x_0^i - \eta \left(\frac{\partial L}{x_0} \right)^i$$

- Storm Pedro (17-20 Feb. 2026)
  - Flooding in France (100-200 mm); UK impacts
  - Wind gusts to 36 m s^{-1} (81 mph) in Spain
  - Occurred during AR-Recon, NAWDIC, NURTURE

Sea level pressure (black, hPa) and 6-h accumulated precipitation (shading, mm) from ERA5





IMERG Precipitation (mm, 17-20 Feb.)

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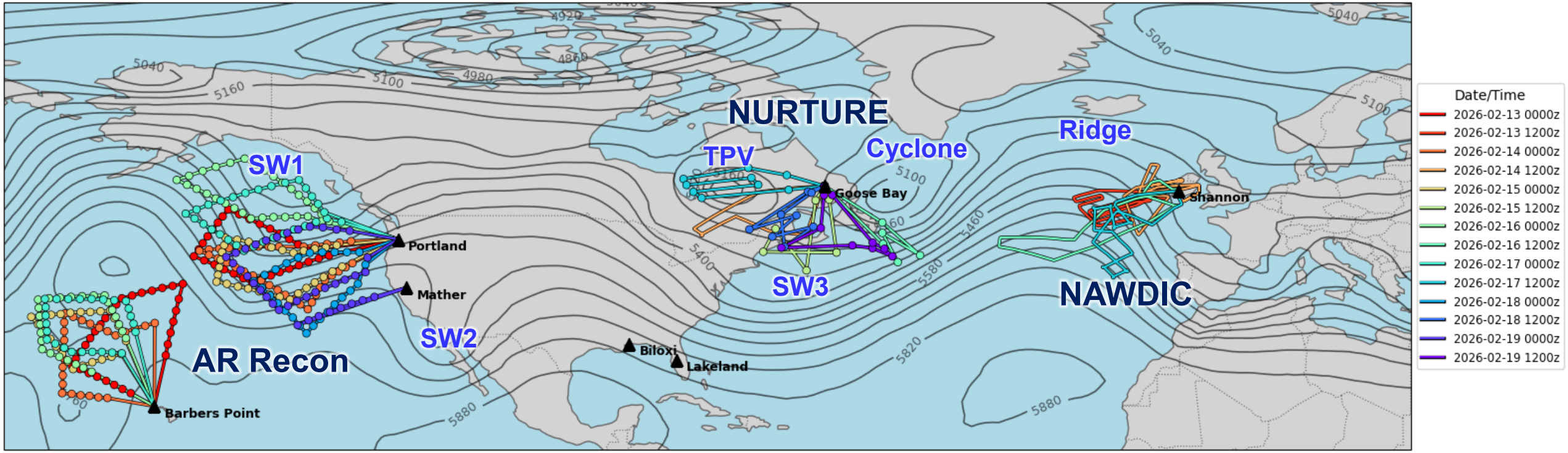
Flight Tracks during Storm Pedro Time Period

AR Recon, NAWDIC, NURTURE Flight Tracks (13-19 Feb. 2026)
1800 UTC 13 Feb. 500-hPa Geopotential Height Analysis



- During 13-19 February, > 20 research flights and many dropsondes deployed
- Excellent case to examine in the context of GARRP goals

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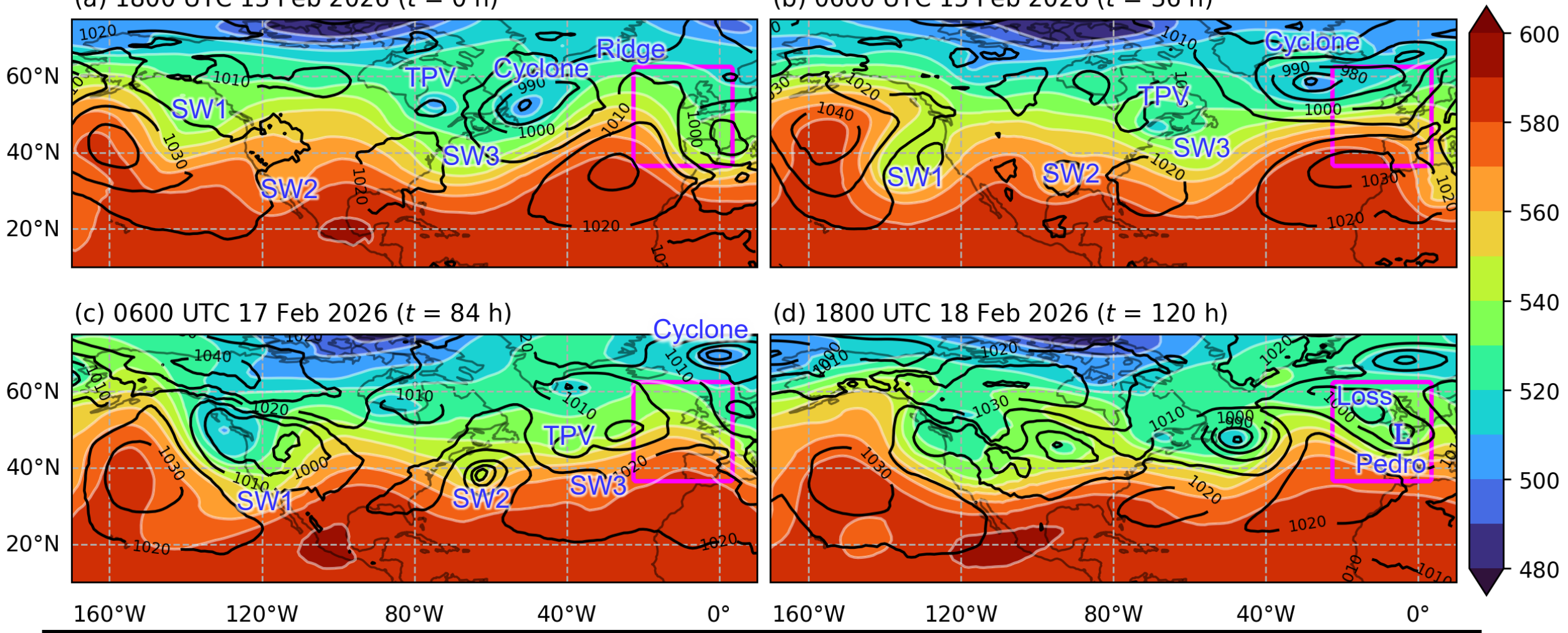
Synoptic Overview

Sea level pressure (black, hPa) and 500-hPa geopotential height (shading, dam) from ERA5



Features impacting predictability: 3 shortwave troughs (SW1-3), East Coast cyclone, ridge, TPV

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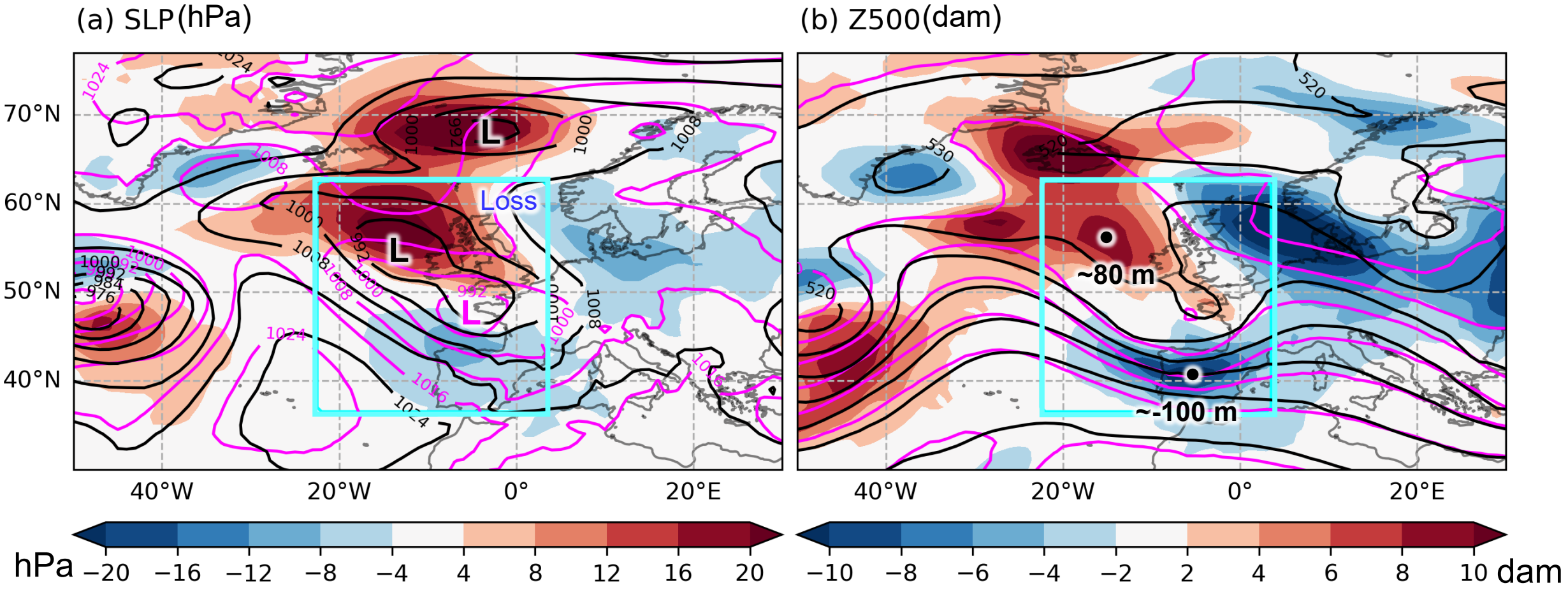
GraphCast Forecast Errors

5-day GraphCast Forecast (magenta), ERA5 (black), Forecast minus ERA5 (shading) (1800 UTC 18 Feb)



Cyan box = region over which loss function (5-day forecast error over all variables and levels) is averaged when computing sensitivity gradients

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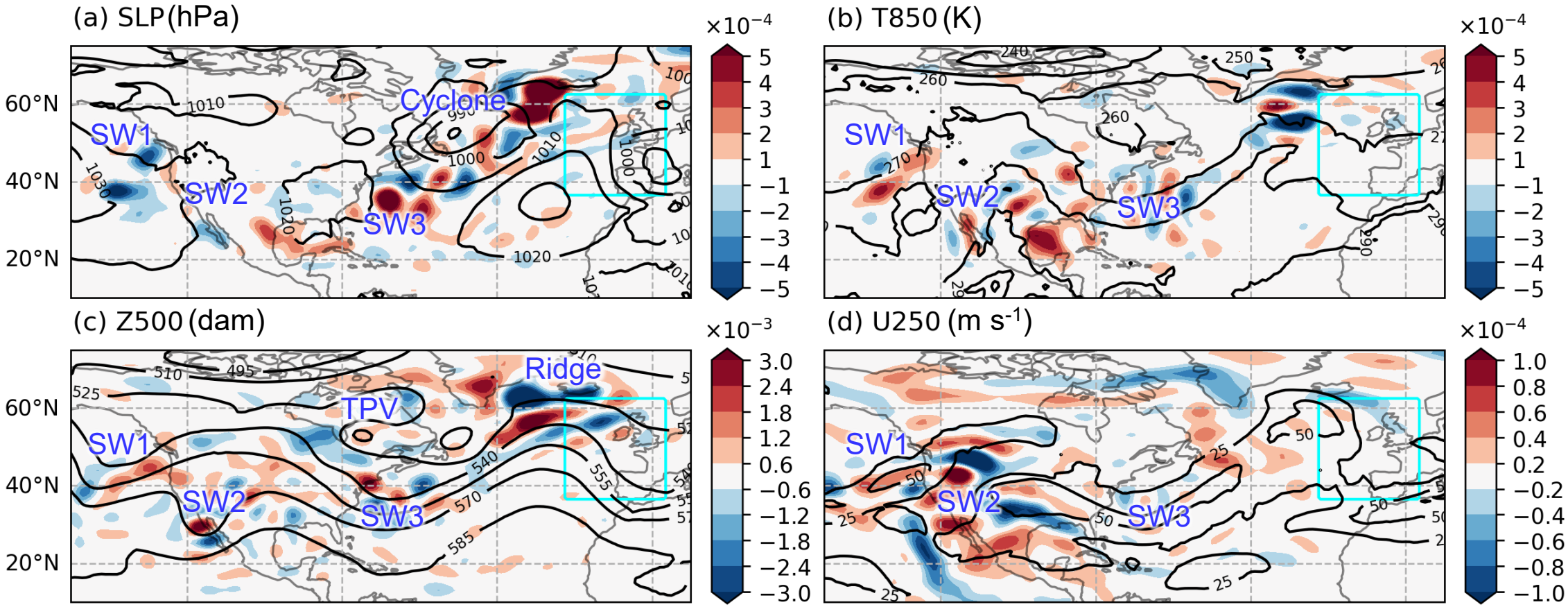
Sensitivity of 5-day Forecast Error to Initial Conditions

5-day Sensitivity (shading) and Initial Conditions from ERA5 (black) Valid at 1800 UTC 13 Feb. 2026



- SLP sensitivity occurs along the Gulf Stream corridor
- Sensitivities are tilted upstream with altitude similar to adjoints [tilted against the mean shear to maximize transient response (e.g. Orr 1907; Rabier et al. 1996)

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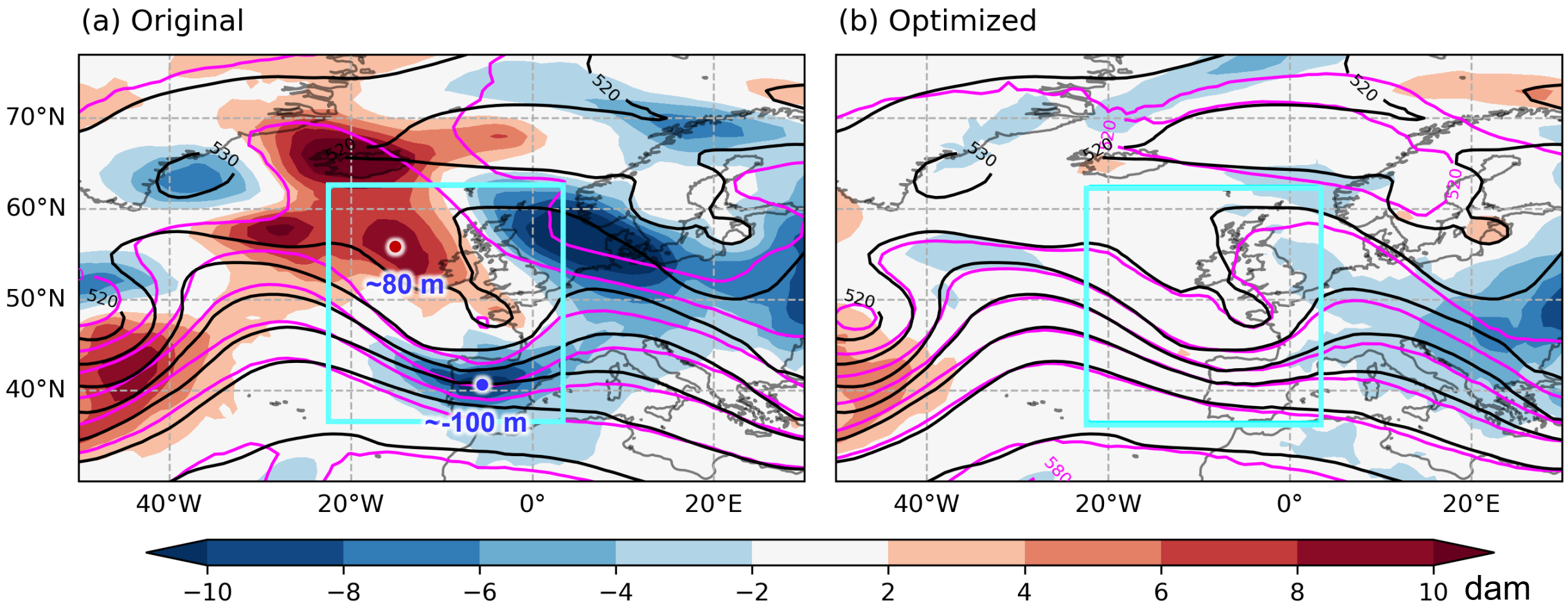
Optimal Perturbations

5-day GraphCast forecast (magenta), ERA5 (black), and Forecast minus ERA5 (shading)
for 500-hPa geopotential height (dam) valid at 1800 UTC 18 Feb 2026



Optimal perturbations are extremely impactful in and around the loss region

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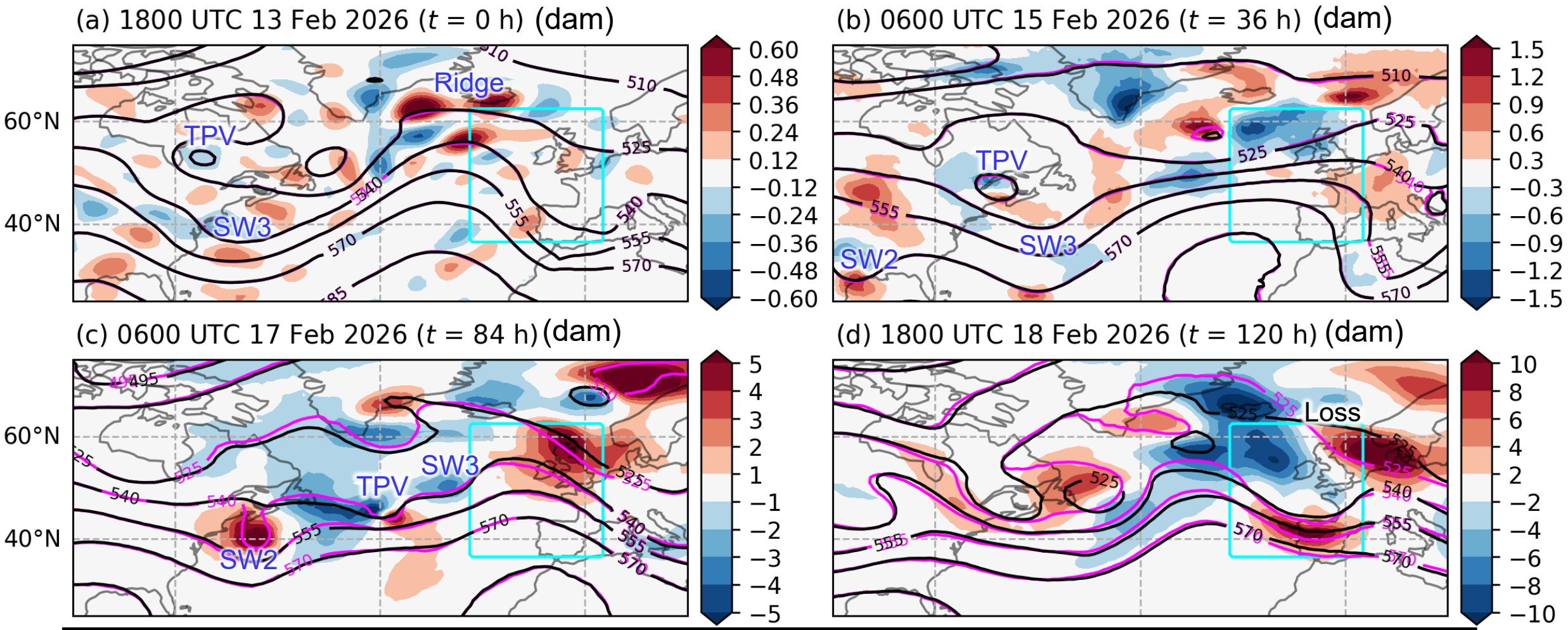
Z500 Perturbation Evolution

Original forecast (magenta), Optimal forecast (black), and Optimal minus Original (shading) (dam)



Largest initial perturbations are near the ridge, followed by rapid growth in the waveguide and SW2 & 3 consistent with Rossby wave packet dynamics and non-normal growth (Farrell 1989)

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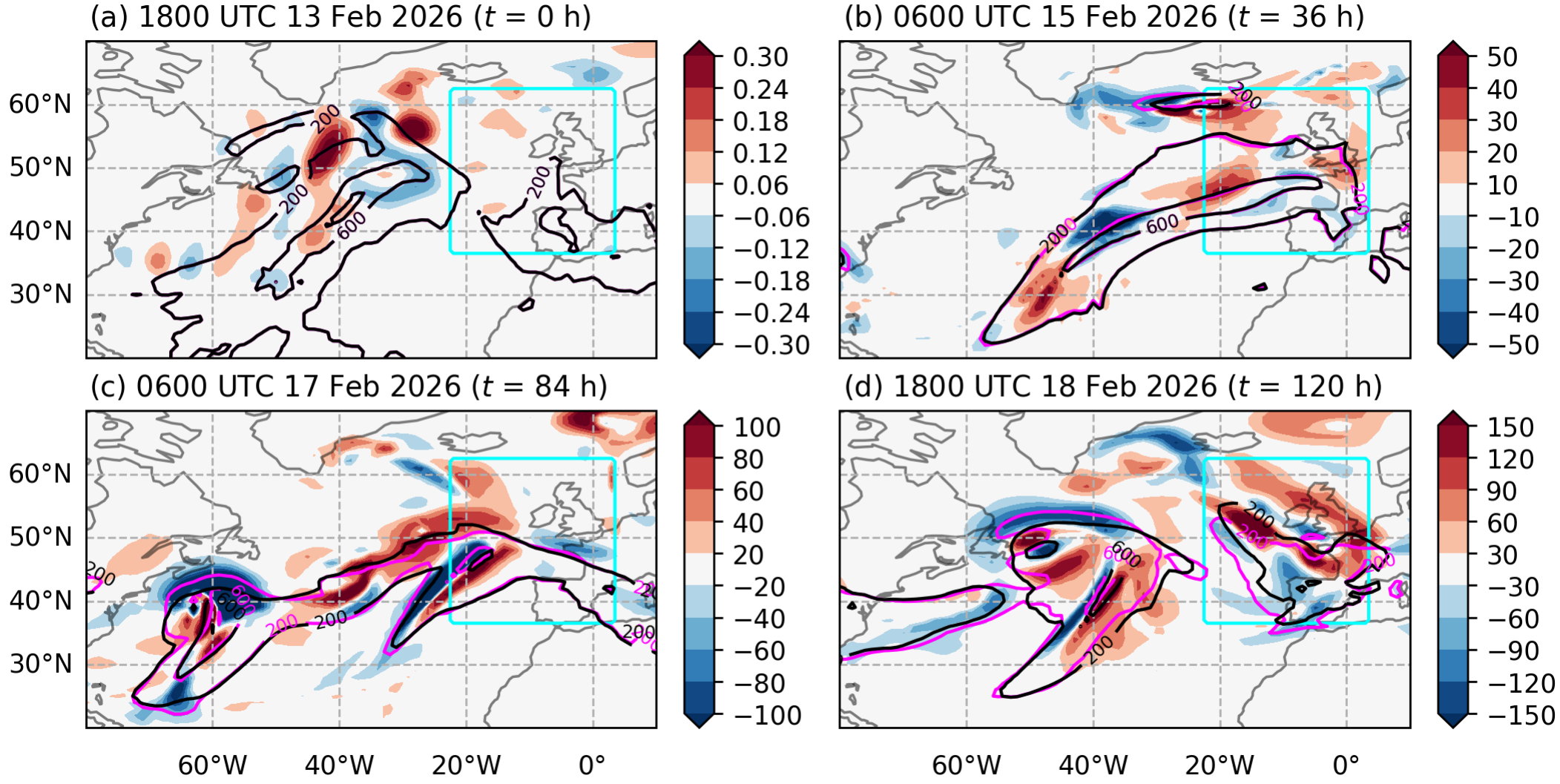
IVT Perturbation Evolution

Original forecast (magenta), Optimal Forecast (black), and Optimal minus Original (shading)



Initially small IVT perturbations grow rapidly and intensifies the AR near Europe at final time

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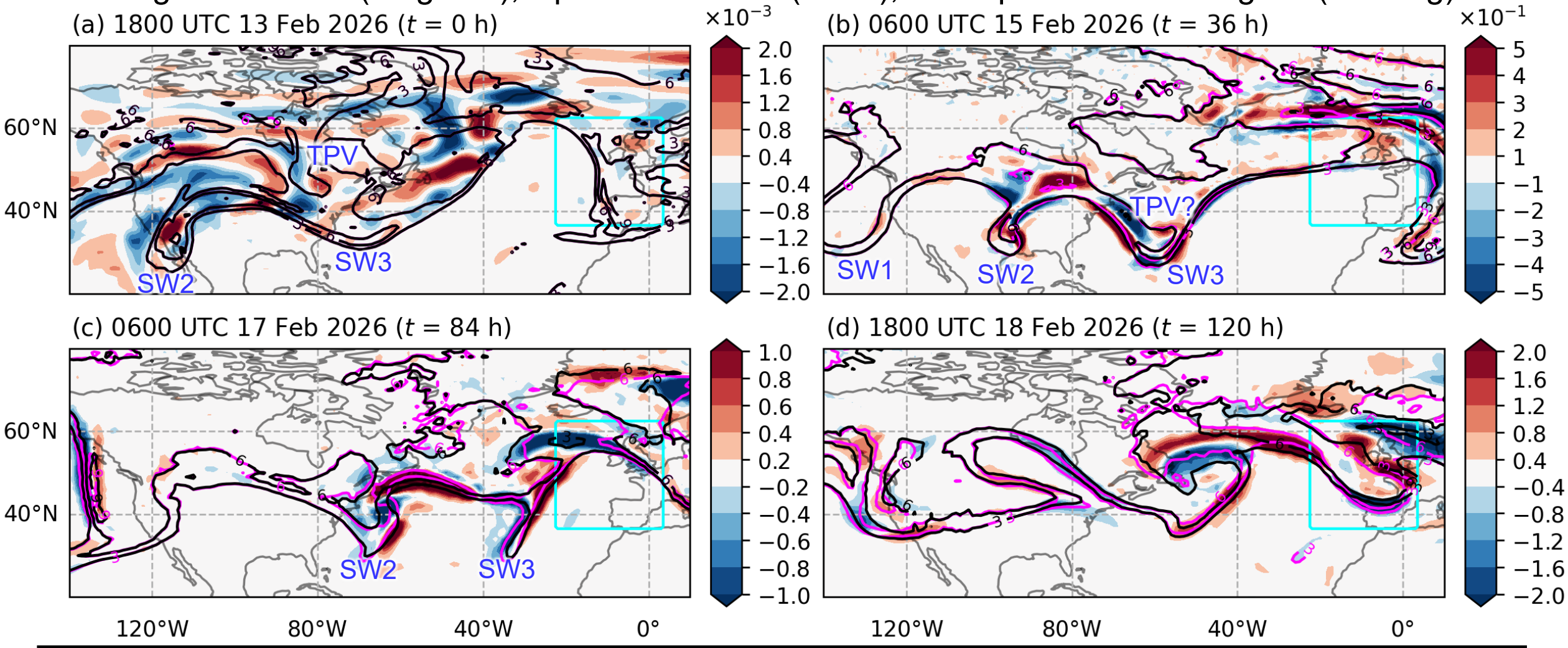
250-hPa PV Evolution

Original forecast (magenta), Optimal Forecast (black), and Optimal minus Original (shading)



PV optimal perturbations grow rapidly and propagate along the waveguide and sloping tropopause

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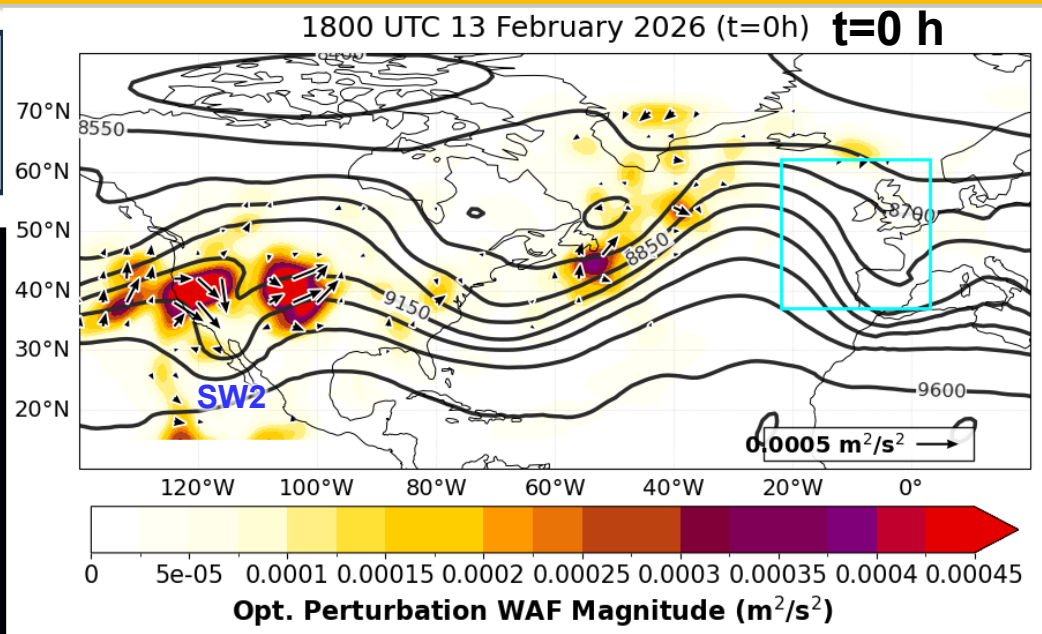
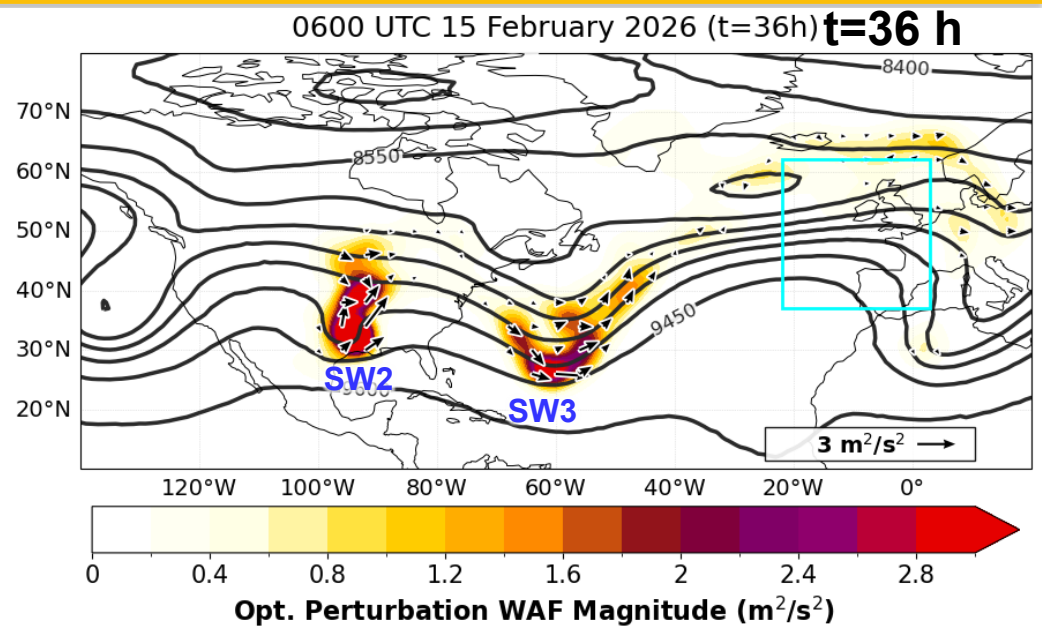
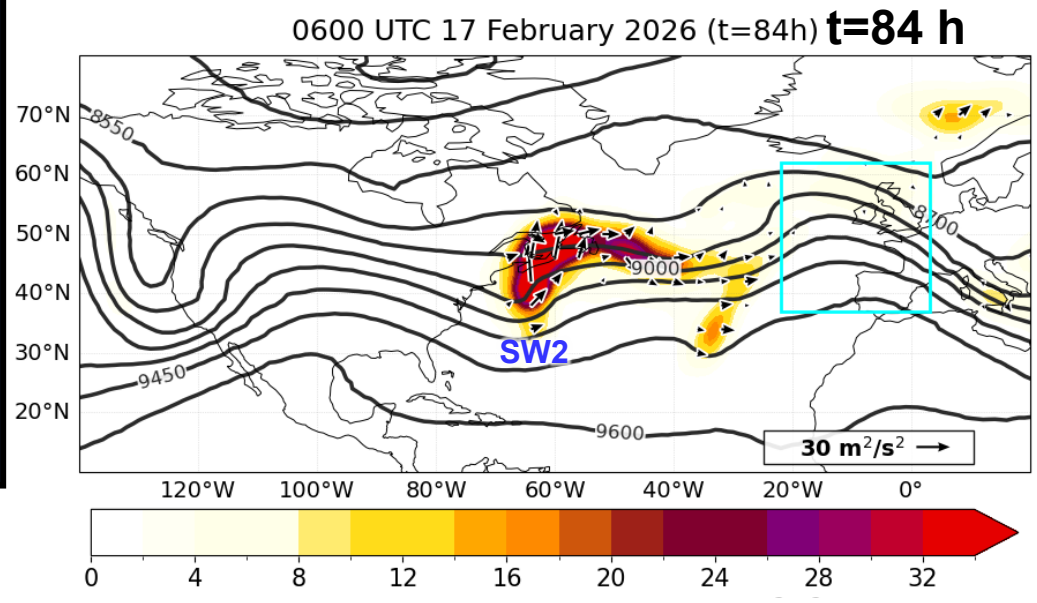
Optimal Perturbation Wave Activity Flux (WAF)

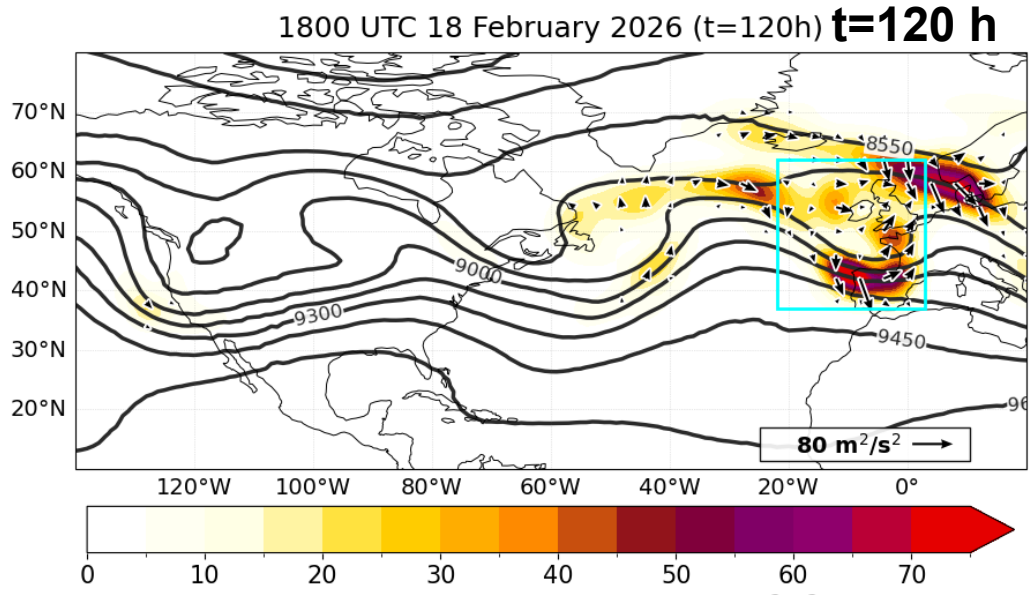
300-hPa heights
Pert. WAF magnitude
Pert. WAF vectors
Forecast WAF mag.

- Wave activity flux (WAF) (Takaya-Nakamura 2001) identifies Rossby wave packets & propagation direction
- Perturbation WAF acts to reinforce background Rossby wave packets, extract energy from background flow, and disperse energy downstream



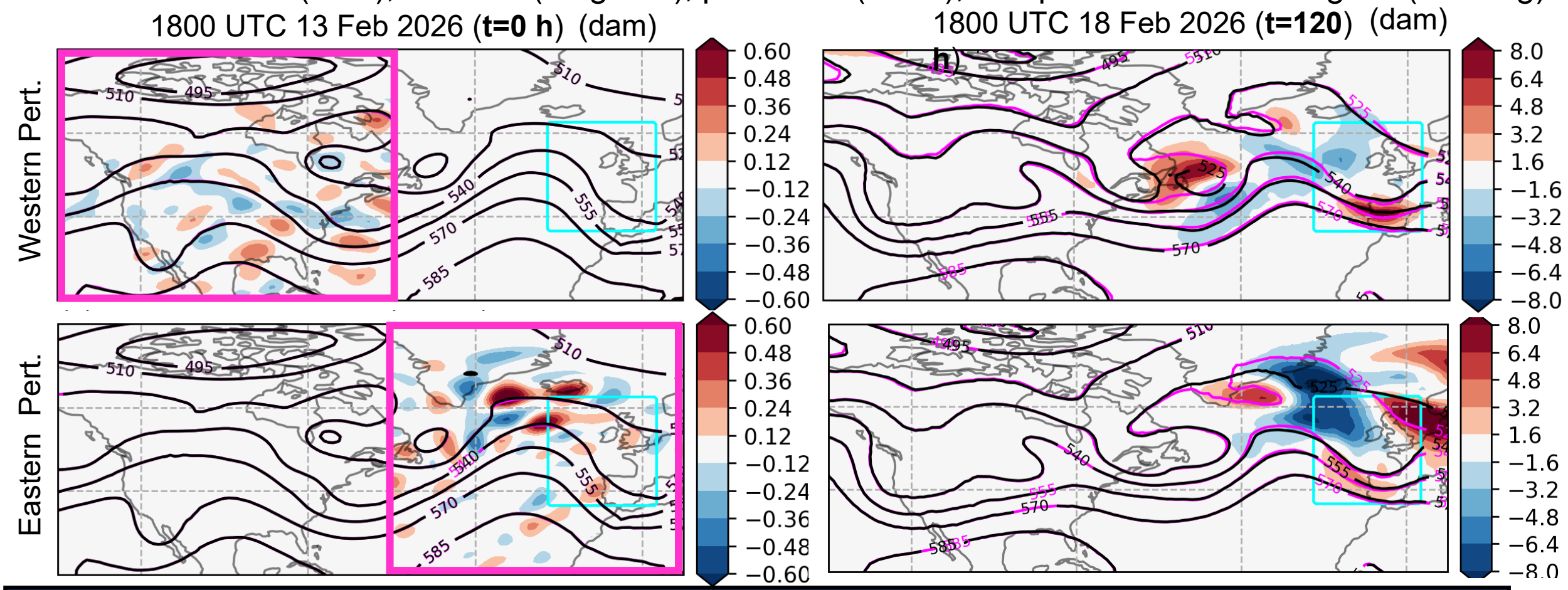






Eastern vs. Western Z500 Perturbations

Z500 Perturbations (dam); forecast (magenta), perturbed (black), and perturbed minus original (shading)



- Separating perturbations by region provides insight into the error sources and transient growth
- Western perturbations propagate and grow rapidly, impacting the jet, ARs, & downstream trough
- Eastern perturbations propagate and grow slower, modifying downstream flow north of the jet

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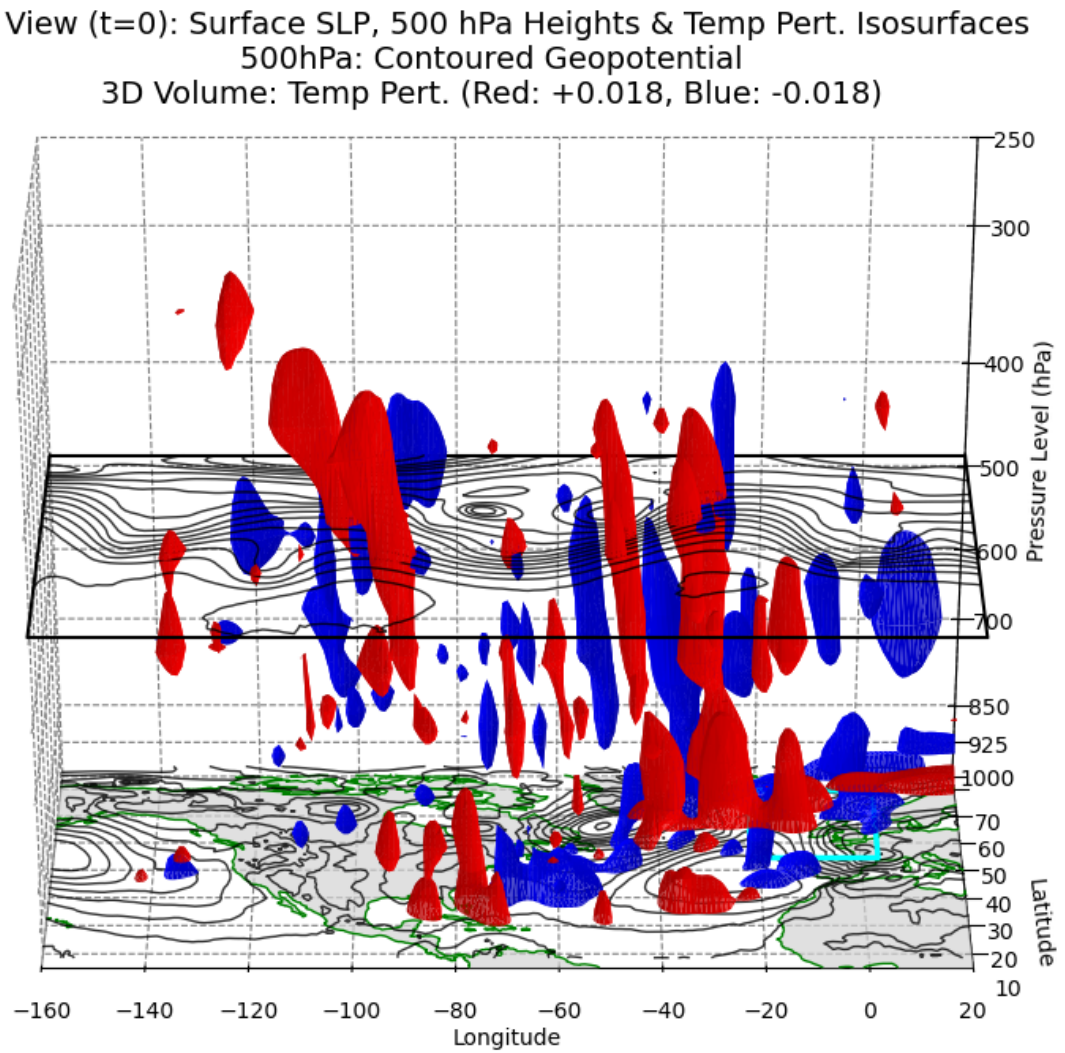
Summary

- GraphCast sensitivity gradients are dynamically-consistent and valid to ~10+ days, not possible using NWP adjoints
- Optimal perturbations grow rapidly, amplify along the jet and drive large 5-day forecast errors in downstream HIW
- Upstream error sources (troughs, ARs, and TPVs) limit predictability through Rossby wave dispersion along the jet
- ML sensitivity analysis identifies error sources, informs adaptive observations (AR Recon, NURTURE, GARRP), and advances understanding of HIW predictability
- Future:
  - ML sensitivities to NURTURE, AR Recon, GARRP to understand what limits HIW predictability
  - Linking ML Models/Sensitivity, Direct Obs. Prediction, autonomous observing systems to improve predictions



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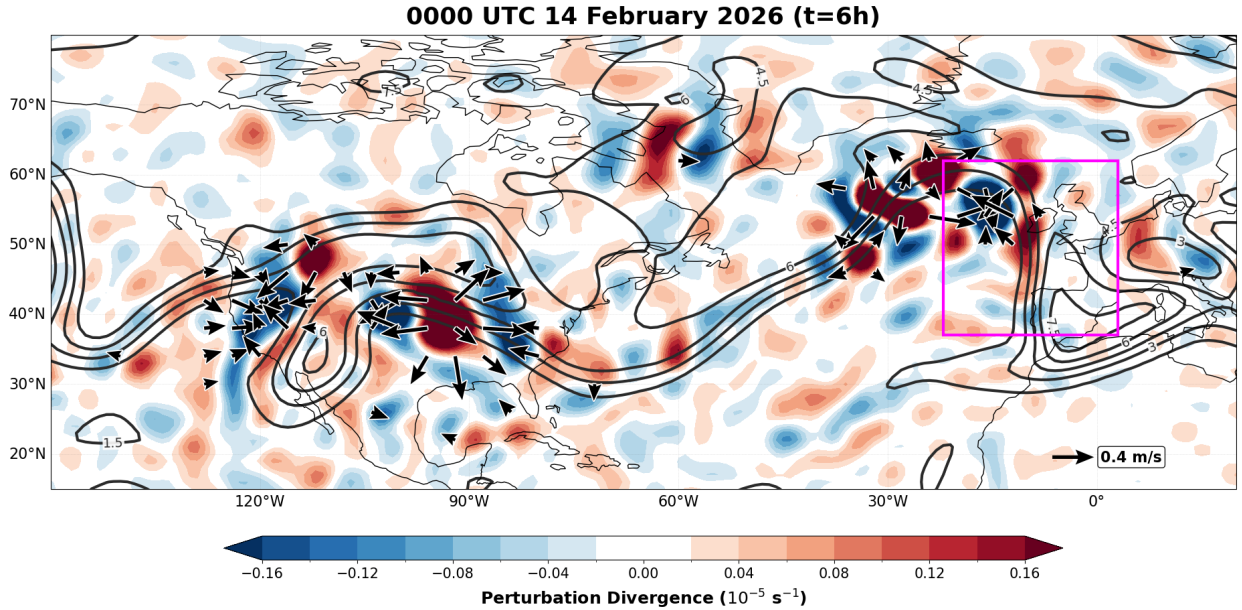
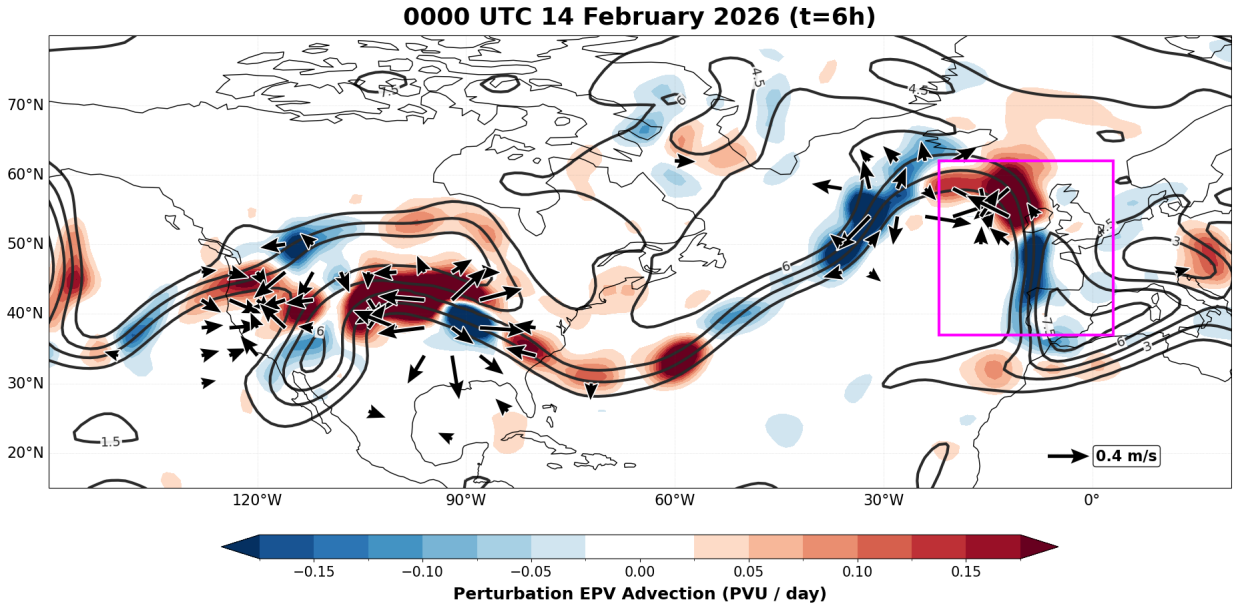
Extra Slides

250-hPa Rossby Wave Forcing

250-hPa Perturbation Divergence (shading); PV (contours), Perturbation Irrotational Wind Vectors (6 h)



PV Advection by Perturbation Irrotational Wind (shading) PV (contours); Perturbation Irrotational Wind Vectors (6h)



- Optimal perturbations increase divergent outflow early in forecast, especially near SW2 and cyclone
- Strong advection of PV by the perturbation irrotational wind near SW2

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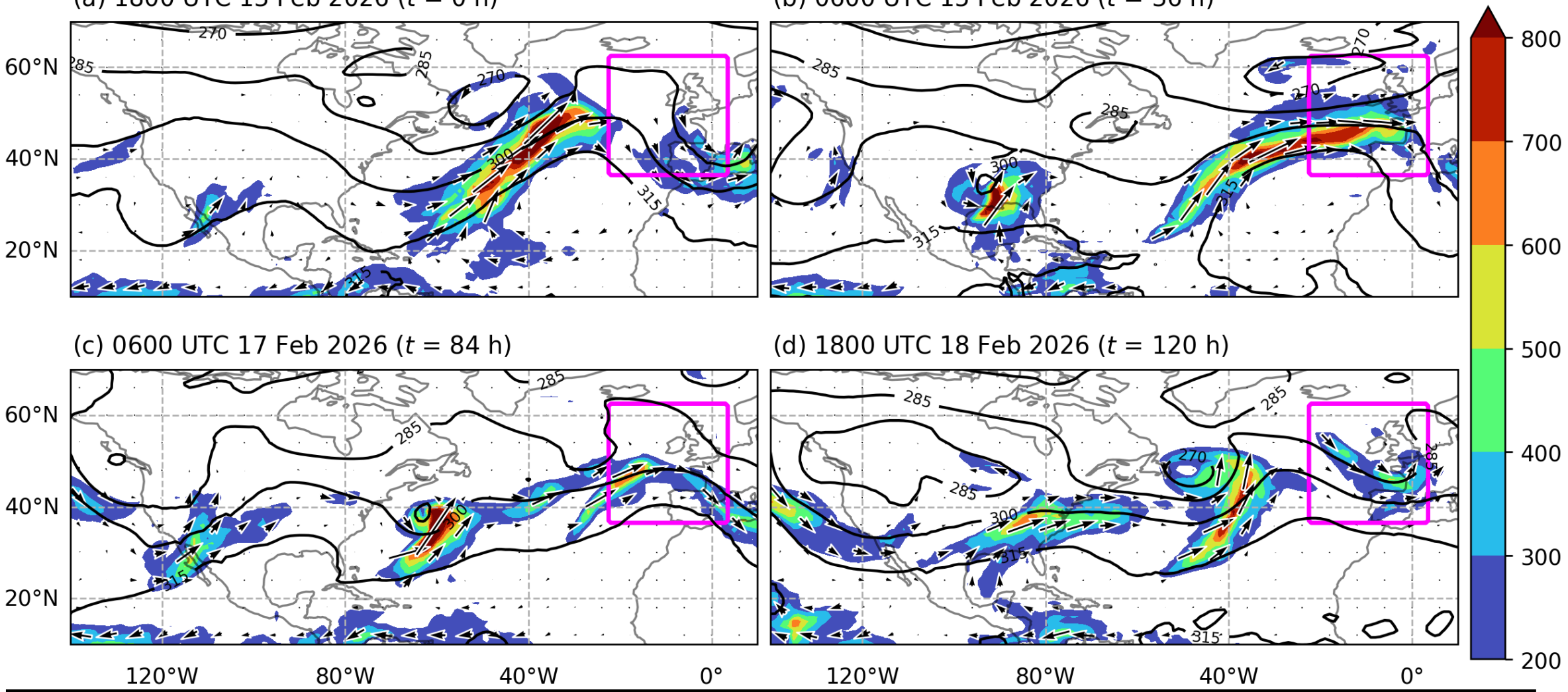
Synoptic Overview

IVT Vectors and Magnitude (shading, kg m^{-1} s^{-1}) and 700-hPa Geopotential Height (black, dam)



Atmospheric rivers were present in the East, Central, West Atlantic during the forecast

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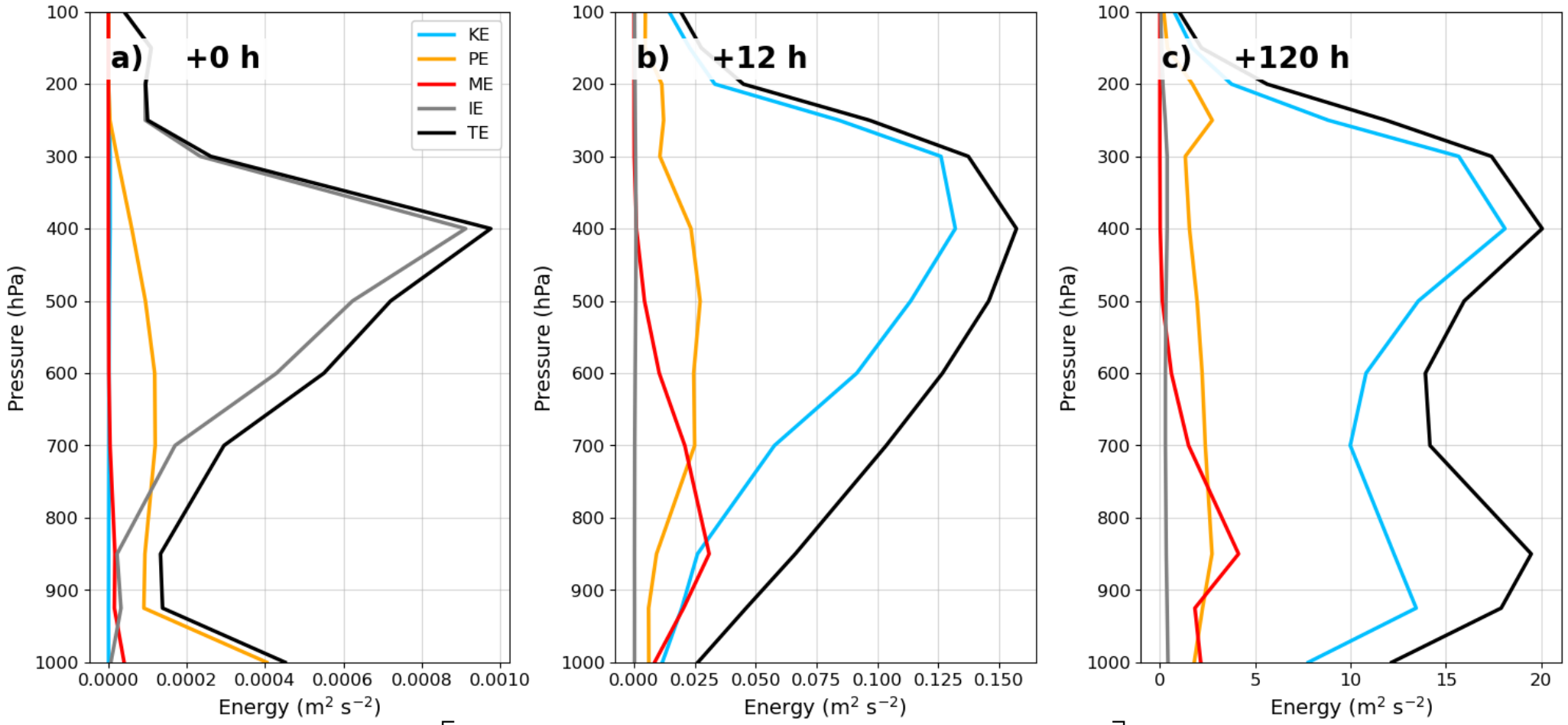
Optimal Perturbation Energy Budget

- Rapid conversion of upstream internal energy to downstream kinetic energy (non-normal transient growth)
- Energy conversion rates show that initial growth occurs via baroclinic production that is peaked in mid-levels; PE→KE conversion also contributes later

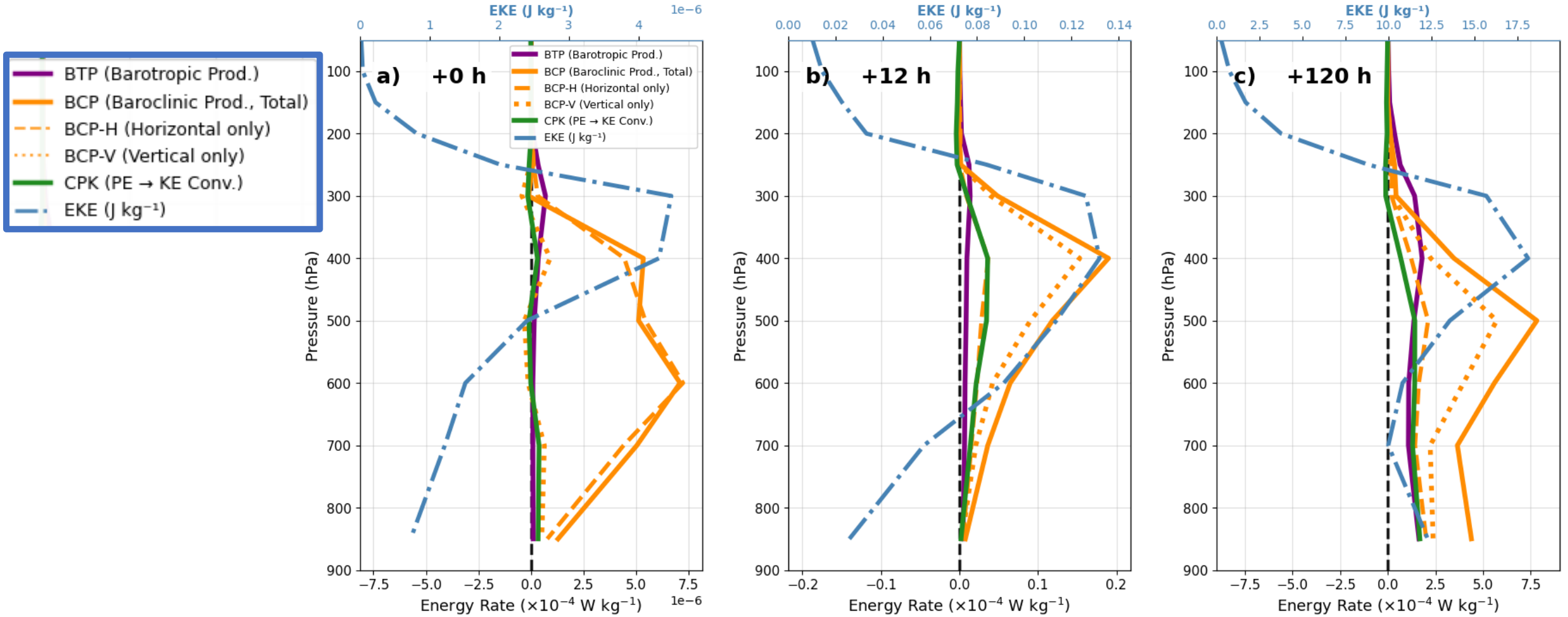


$$E = \frac{1}{2A}\int\left[(u'^2 + v'^2 + w'^2) + \frac{C_p}{T_r}T'^2 + \frac{RT_r}{p^2_{sr}}p'^2 + \frac{l_v^2}{C_pT_r}q_v'^2\right]dAd\sigma$$

Total KE PE IE Moist

Optimal Perturbation Energy Conversion Rates

Init: 2026021318 | Domain: 10°–80°N, -140°–20°E



- Diagnosis of optimal perturbation energy conversion rates [e.g., Lorenz (1955); Holton and Hakim (2013)]
- Rapid initial growth via baroclinic production peaked in mid-levels; PE→KE conversion contributes later

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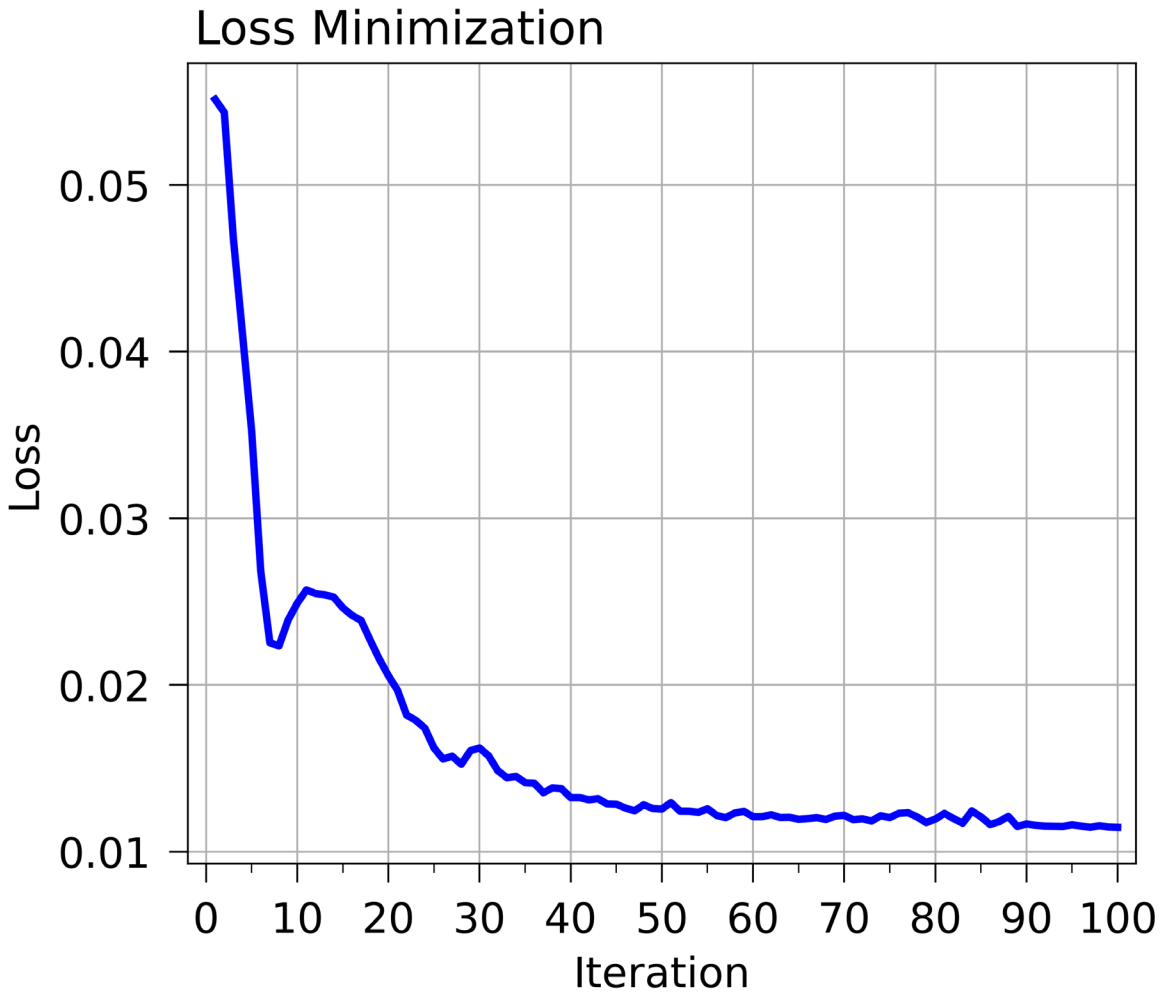
Computing "Optimal" Initial Conditions

- What are the changes (i.e., perturbations) to the initial conditions that will minimize forecast error?
- Obtain by iteratively applying sensitivity gradients to initial conditions

$$x^{i+1} = x^i - \eta \left(\frac{\partial L}{x_0} \right)^i$$

- Optimal perturbation calculation is not restricted to linear dynamics (e.g., adjoints); it captures all nonlinear effects present in the ML model
- Useful for examining how perturbations to sensitive areas evolve in space and time and over different regions



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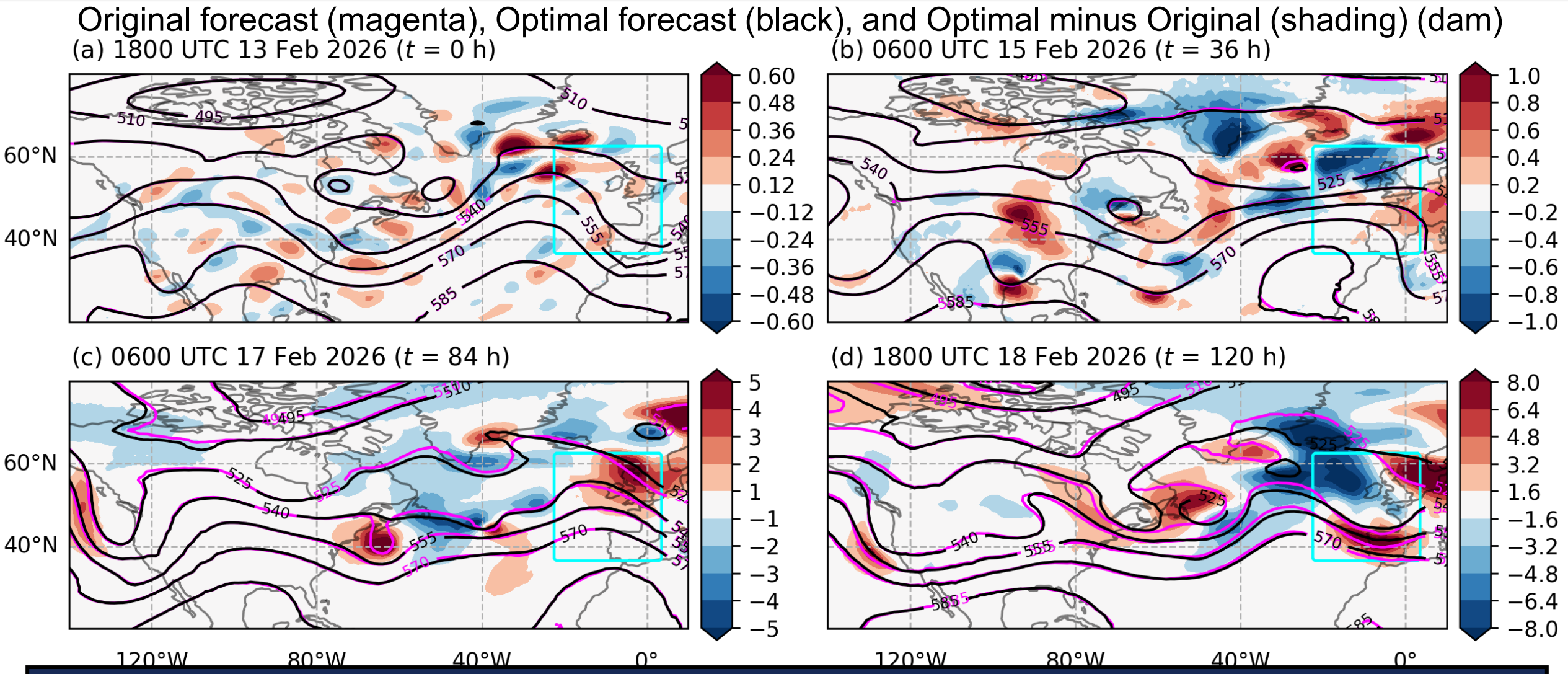
Z500 Perturbation Evolution



Largest initial perturbations are near the ridge, followed by rapid growth in the waveguide and SW2 & 3

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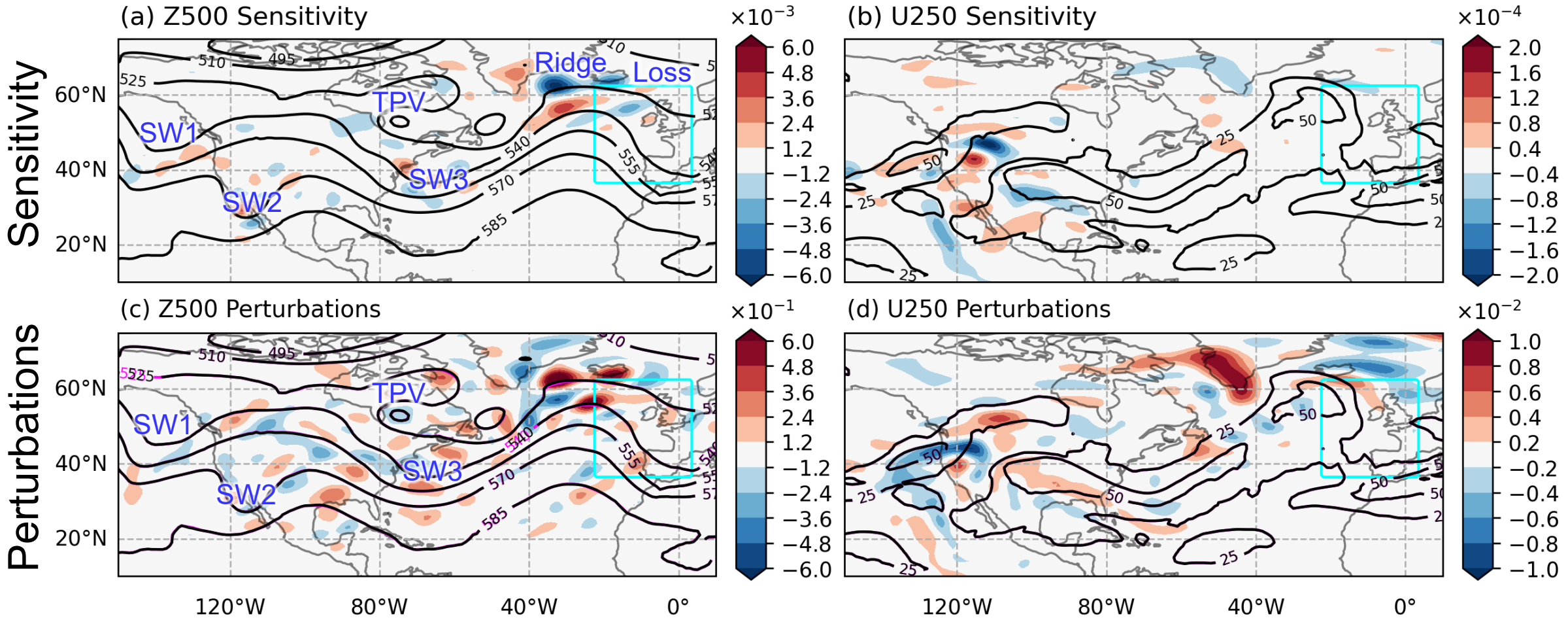
Comparing Perturbations and Sensitivity



- Perturbations resemble negative of sensitivity (sensitivity is up-gradient, optimal perturbations are down-gradient)
- Patterns change during the iterations due to nonlinearities and higher-order effects

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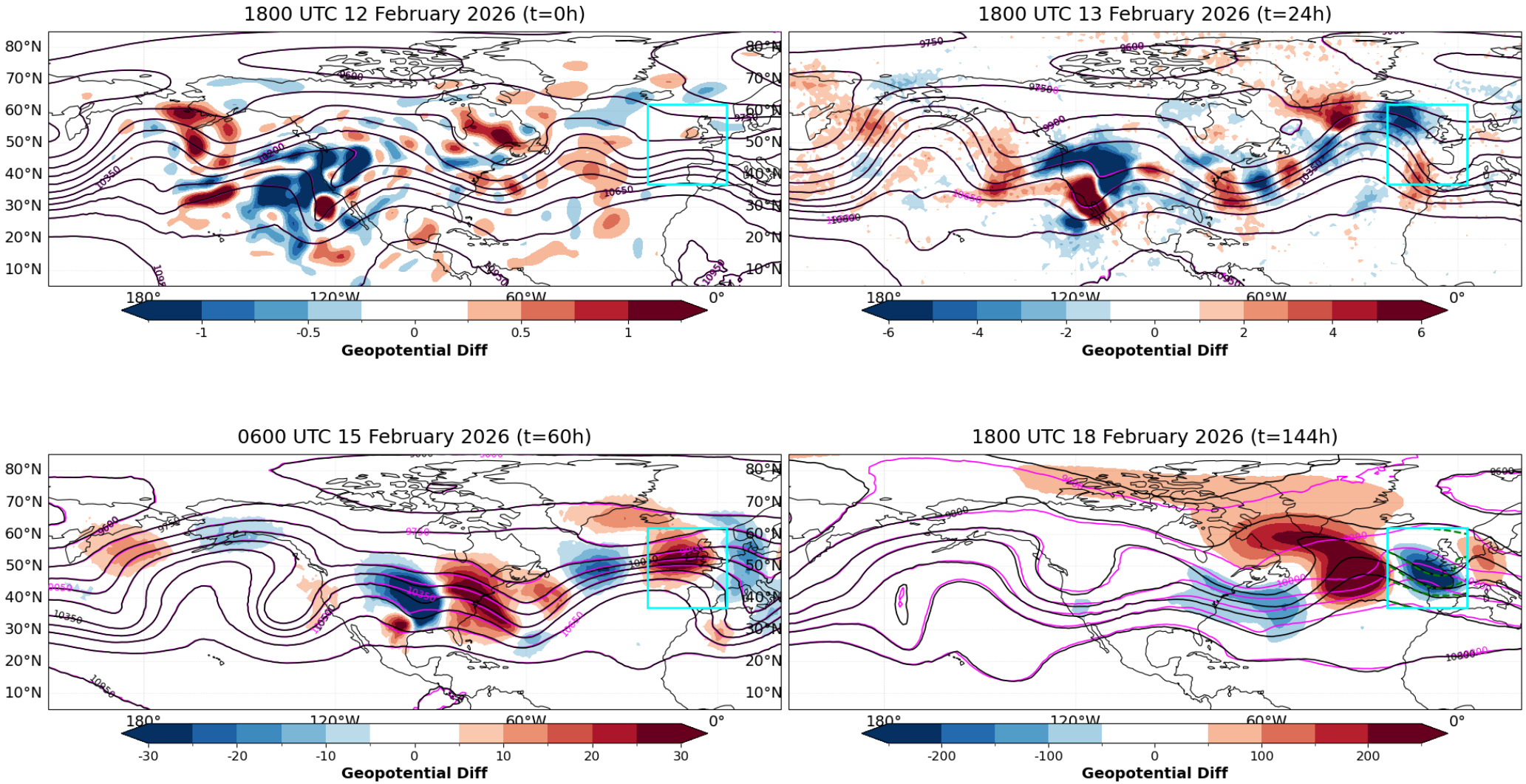
500-hPa GHT Initialized at 1800 UTC 12 Feb. (6 day)

Geopotential Height forecast (magenta), analysis (black), optimal perturbation (shading) (m)



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Optimal Perturbation Wave Activity Flux (WAF)

300-hPa heights
Pert. WAF magnitude
Pert. WAF vectors
Forecast WAF mag.

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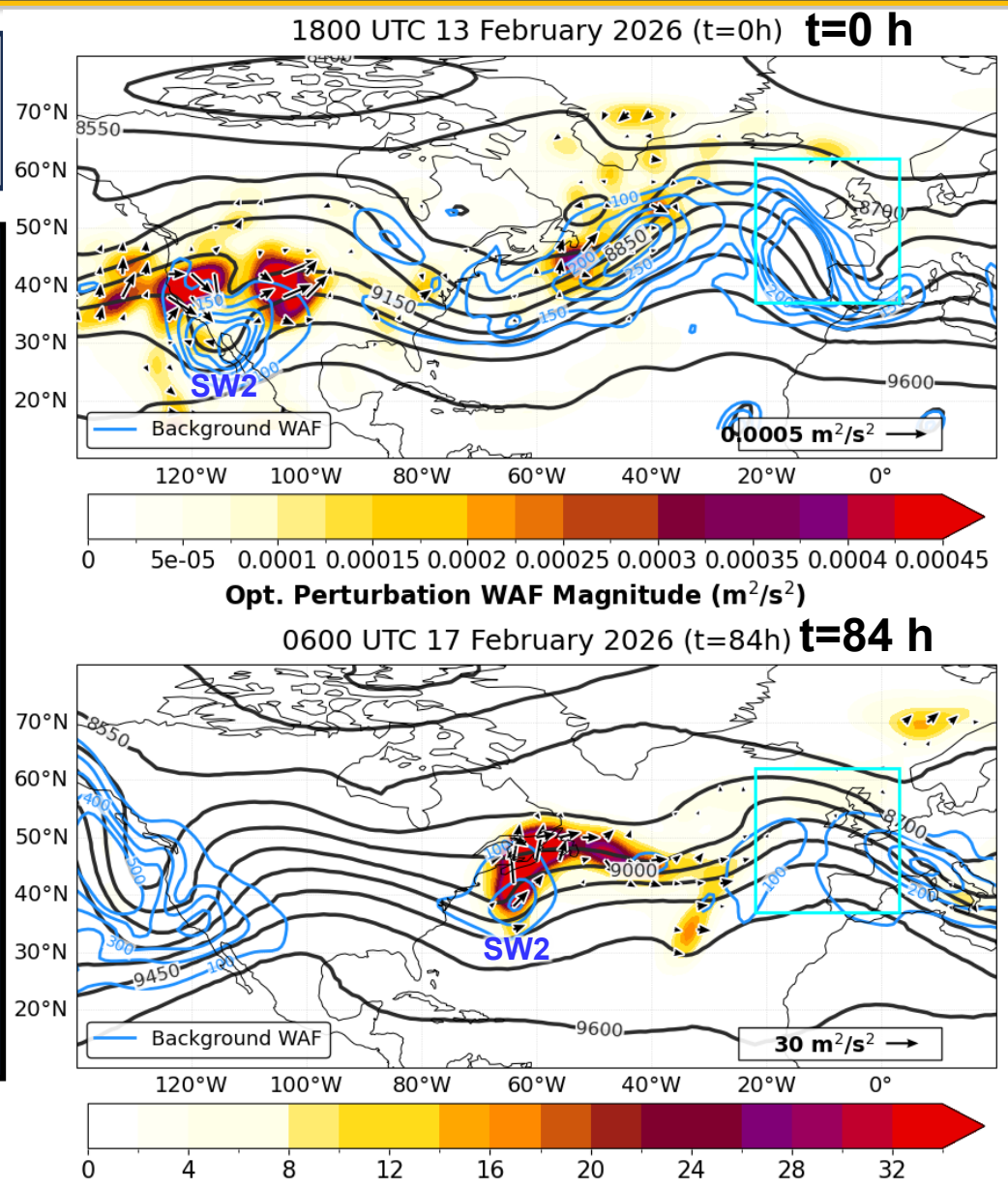
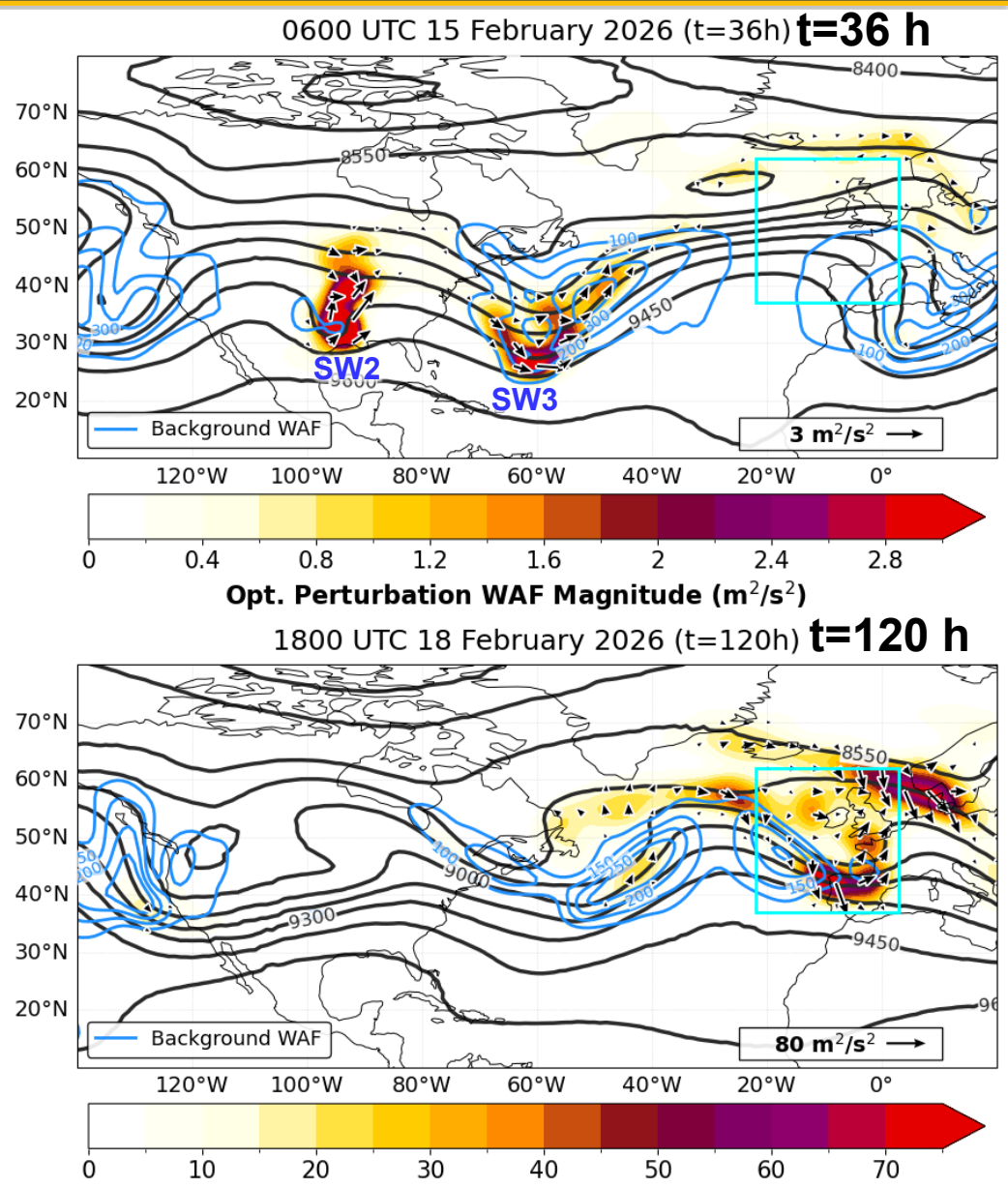
- Perturbation WAF acts to reinforce background Rossby wave packets, extract energy from background flow, and disperse energy downstream





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Optimal Perturbation
Takaya-Nakamura Wave Activity Flux

$$W_x = \frac{p\cos\phi}{2|U|}\left[U(v'^2 - \psi' v'_x) + V(-u'v' + \psi' u'_x)\right]$$

$$W_y = \frac{p\cos\phi}{2|U|}\left[U\left(-u'v' + \psi' v'_y\right) + V\left(u'^2 + \psi' u'_y\right)\right]$$

W: Horizontal Wave Activity Flux vector (Wx, Wy)
p: Pressure level (normalized by 1000 hPa)
ϕ: Latitude
U = (U, V): Basic state (background) wind vector, with magnitude |U|
(u', v'): Actual (total) perturbation wind components (includes both geostrophic and ageostrophic flow)
ψ' = Φ' / f: Perturbation geostrophic streamfunction (where Φ' is the geopotential anomaly and f is the Coriolis parameter)
Subscripts (x, y): Partial spatial derivatives in the East-West (zonal) and North-South (meridional) directions