Diagnosing Forecast Sensitivity of Atmospheric Rivers Using an Adjoint

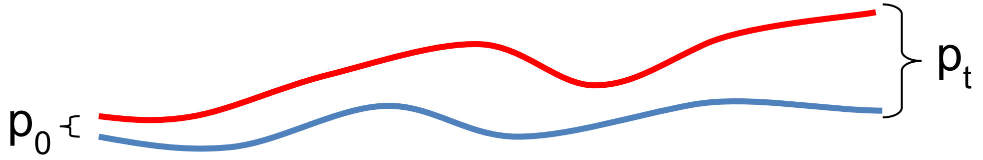
James D. Doyle and Carolyn A. Reynolds
U.S. Naval Research Laboratory, Monterey, CA

We acknowledge the support of the NRL Base Program, PE 0601153N
Computational support provided by the Navy DoD Supercomputing Resource Center

2024 Winter Season Working Group Meeting

Adjoint Sensitivity

Characterize stability of system by examining the behavior of perturbation growth in linear framework



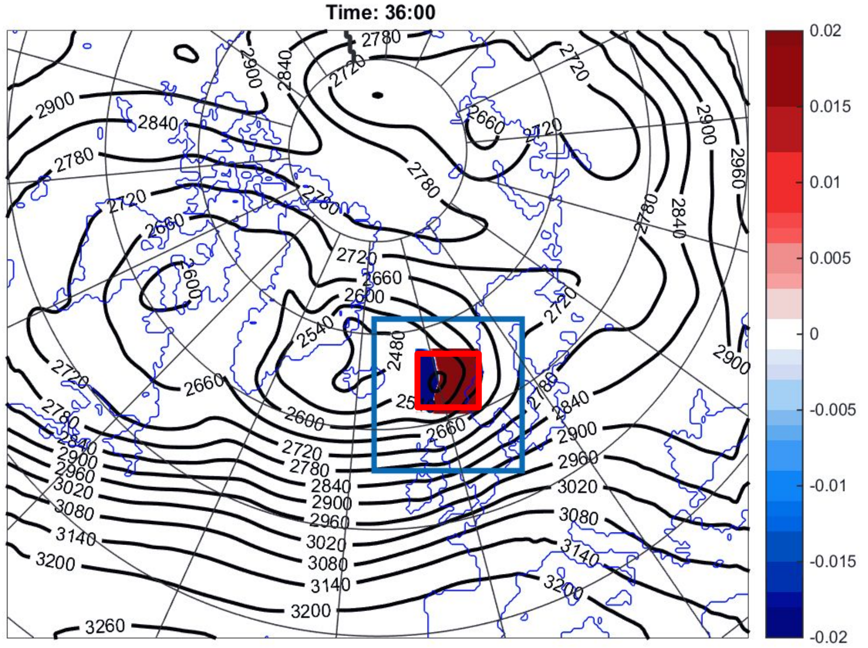
Nonlinear	Tangent Linear	Adjoint	Sensitivity of response function (J) at time t_n to the state at time t_0
$p_t = Mx_0 - M(x_0 + p_0)$	$p_t = M_{0,t}\, p_0$	$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$	
Nonlinear Model; State vector; Perturbation vector	Tangent forward propagator or Tangent Linear Model (TLM)		

Provides sensitivity of forecast aspect to changes in initial state, highlighting regions of potential rapid perturbation (and error) growth.

COAMPS® Moist Adjoint Model

- Dynamics: Nonhydrostatic (30 km resolution)
- Physics: PBL, surface flux, microphysics, cumulus
- Response Functions, *J*: Precip (others snow, IVT, PV)
- Optimal Perturbations: ~1 K, 1 m s^{-1}, 1 g kg^{-1}

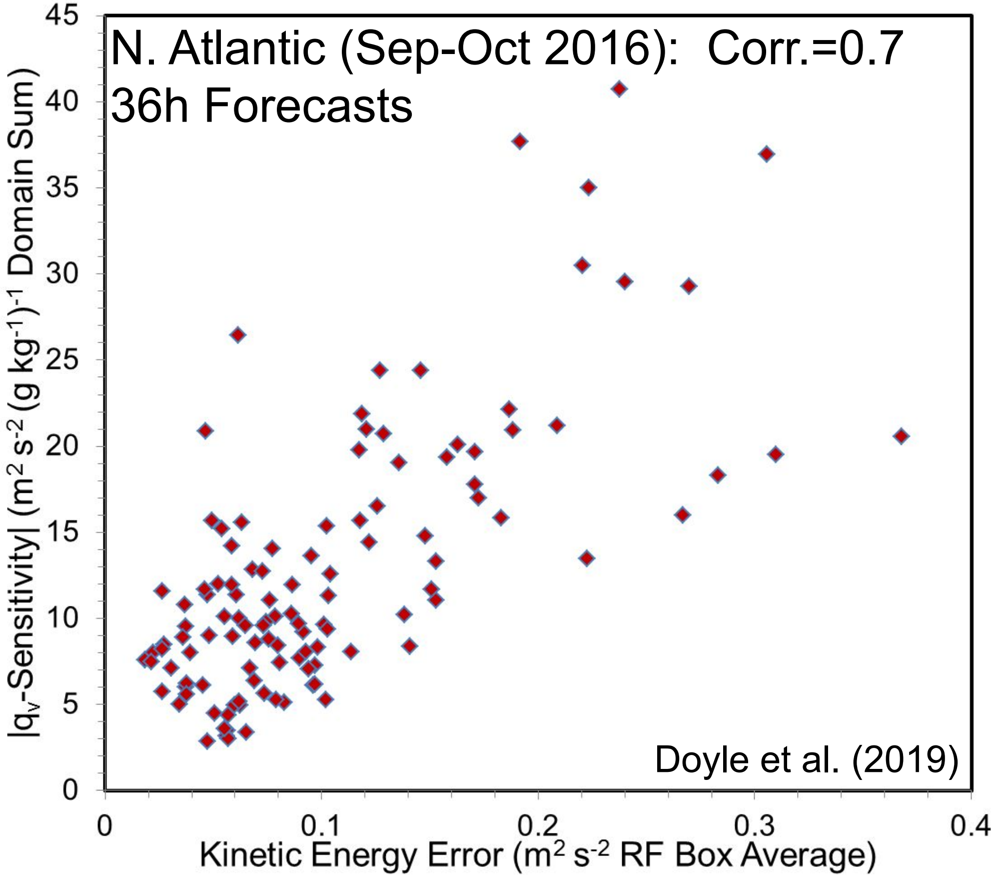
9-10 Jan 2015 (Storm Nina) (36 to 0 h)

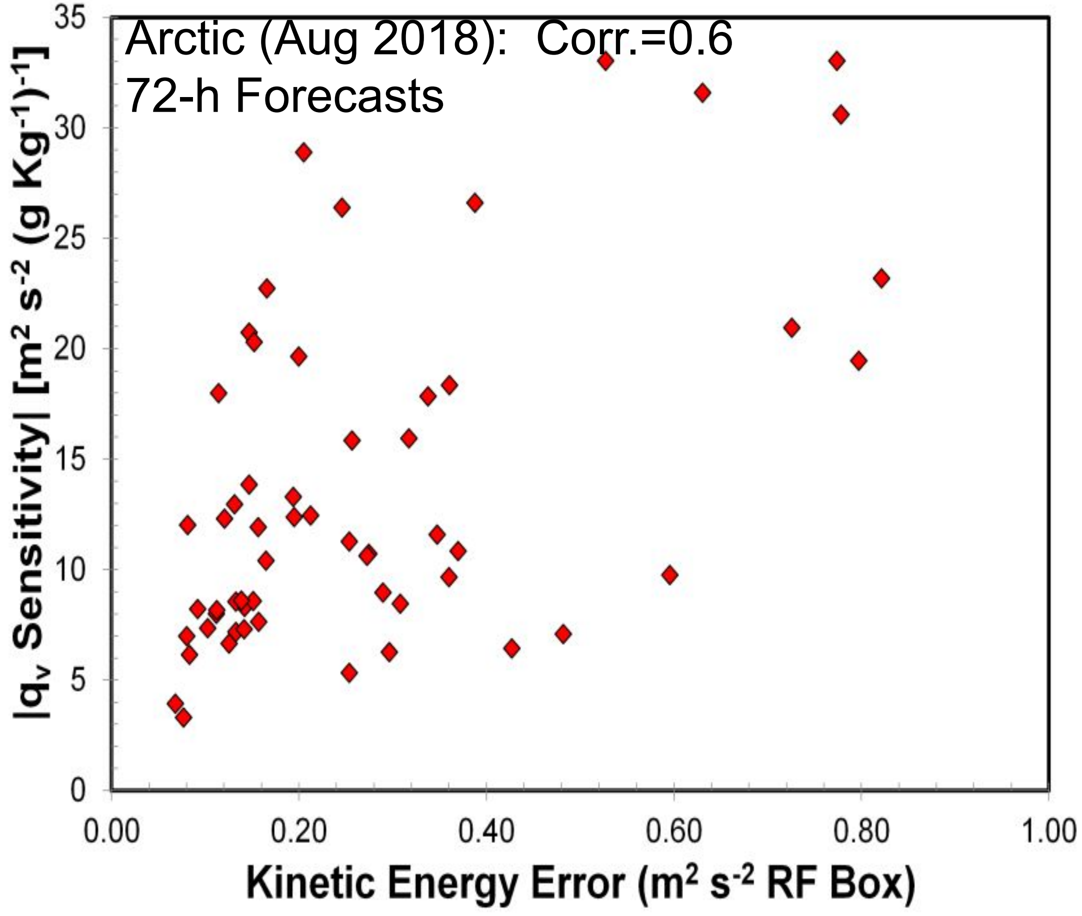


See: Errico (1997); Langland et al. (1995); Amerault et al. (2008); Doyle et al. (2014, 2019)

Adjoint Sensitivity and Forecast Errors

Low-Level Wind Forecast Error vs. Initial Vertically Integrated Moisture Sensitivity





- Sensitivity magnitude (domain-vertically integrated) & low-level kinetic energy forecast error are well correlated for multiple regions: N. Atlantic (Doyle et al. 2019), U.S. W. Coast (Reynolds et al. 2019), Arctic

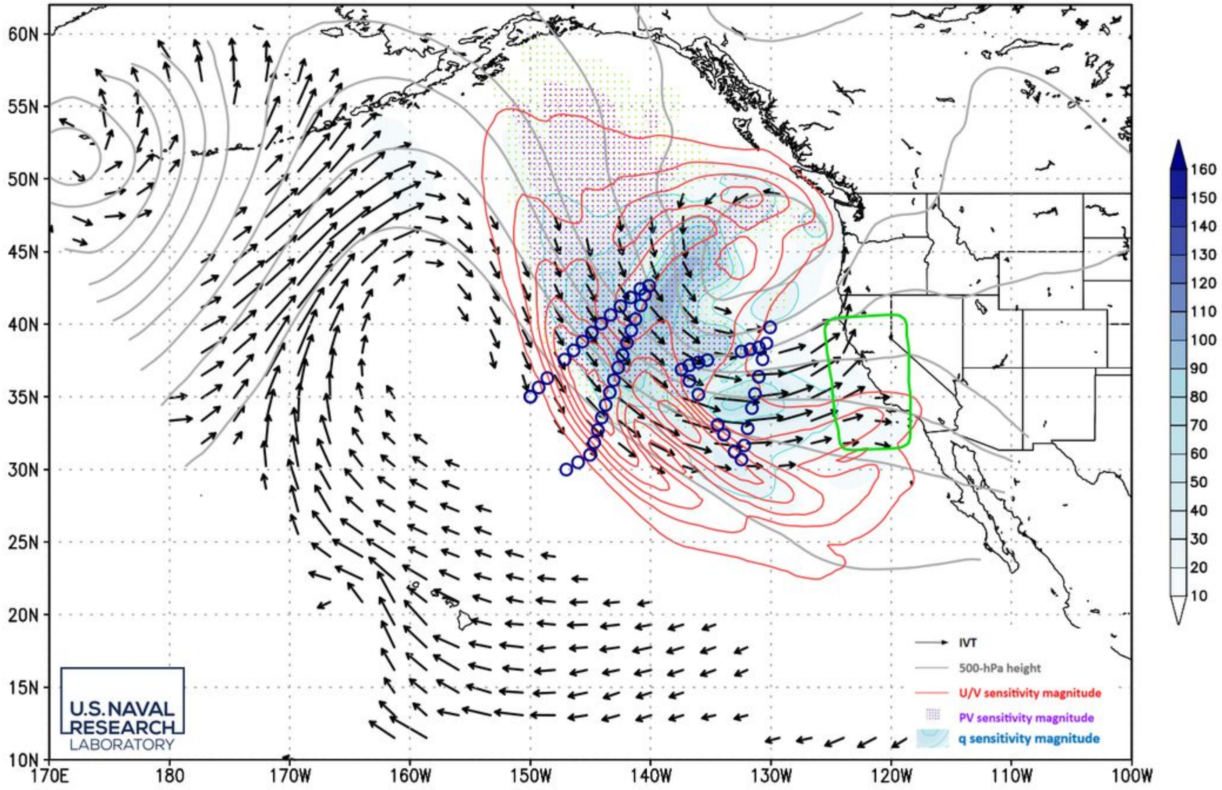
Optimization Time

How Does the Sensitivity Vary with Optimization Time?

36-h Optimization Time

Precipitation Response Function

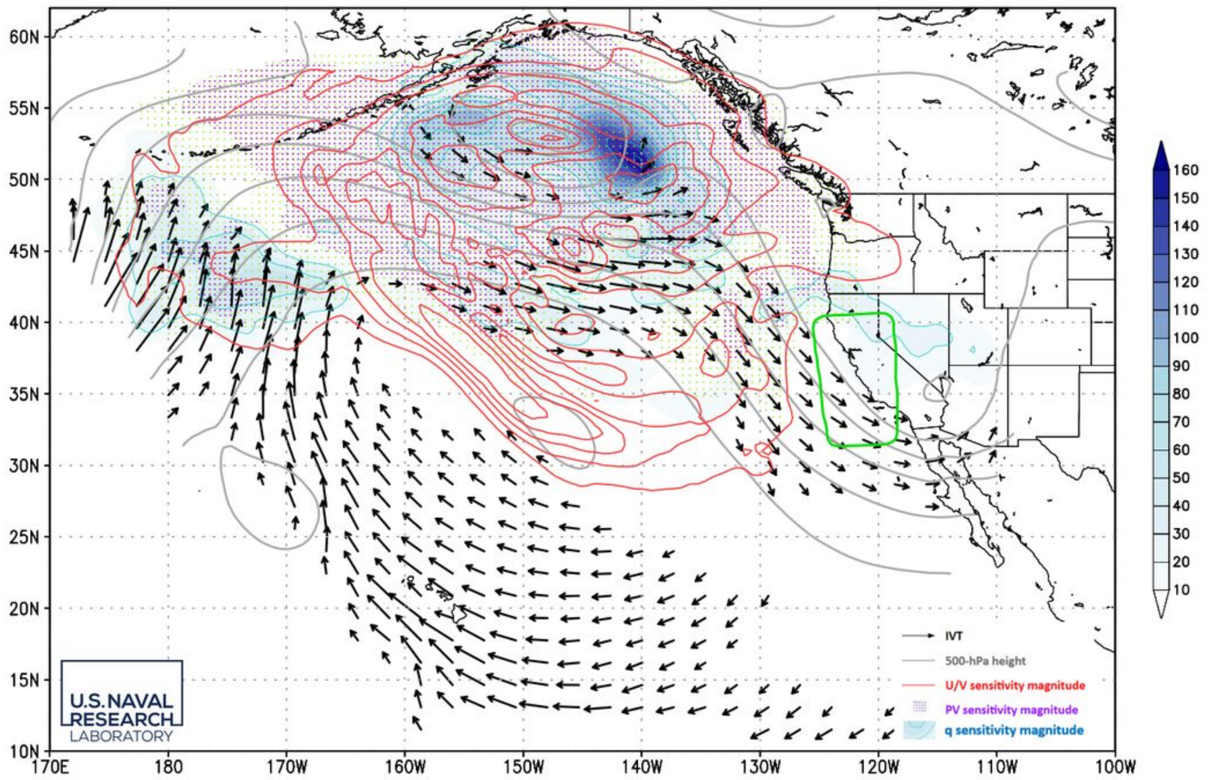
Initial: 00Z 27 Jan. 2021 Final: 12Z 28 Jan. 2021



60-h Optimization Time

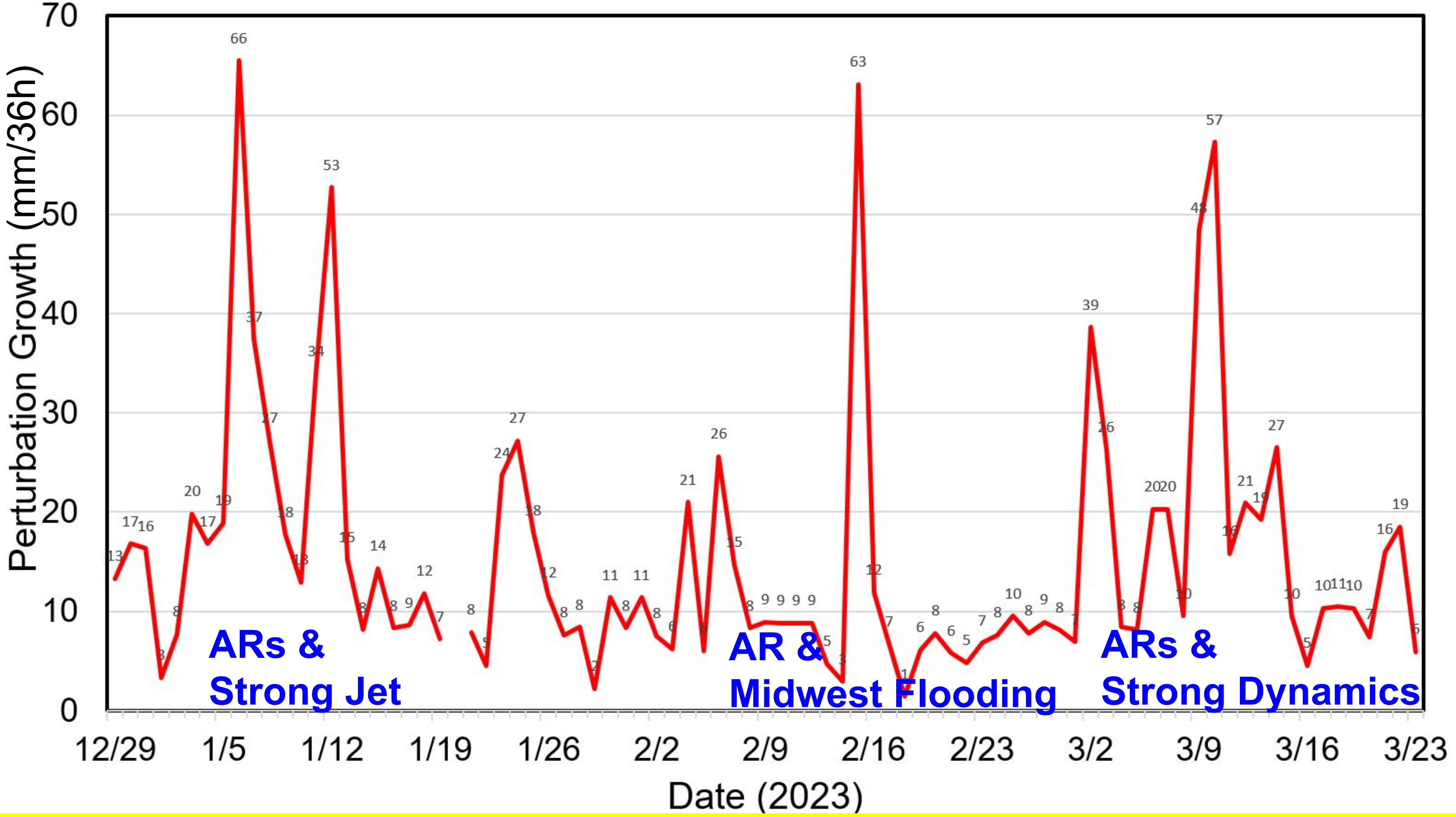
Precipitation Response Function

Initial: 00Z 26 Jan. 2021 Final: 12Z 28 Jan. 2021



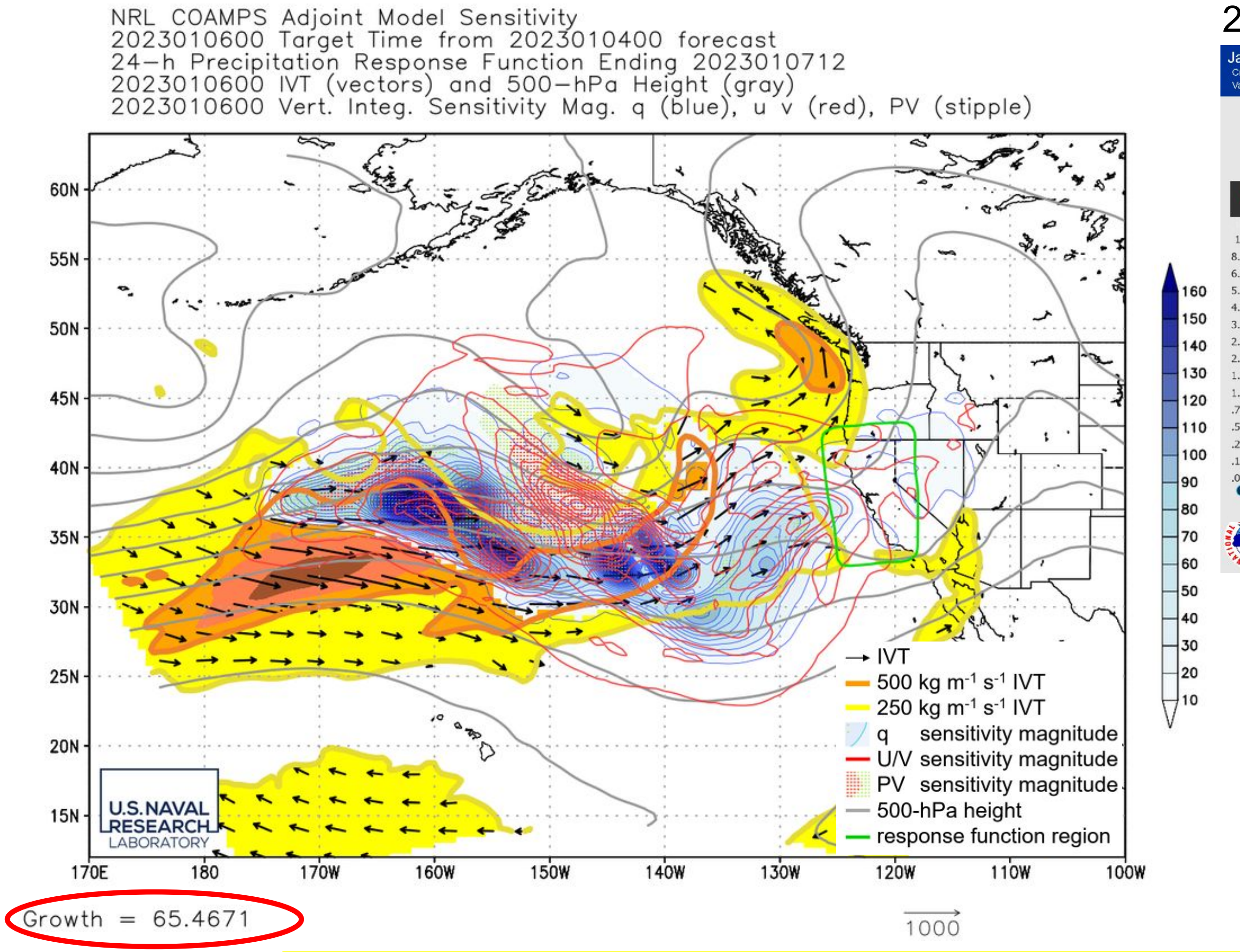
- Typical optimization times used for the COAMPS adjoint is 36-h during AR-Recon
- Longer optimization times result in sensitivity that is further upstream and difficult for aircraft to reach

Adjoint Sensitivity (AR Recon 2023)

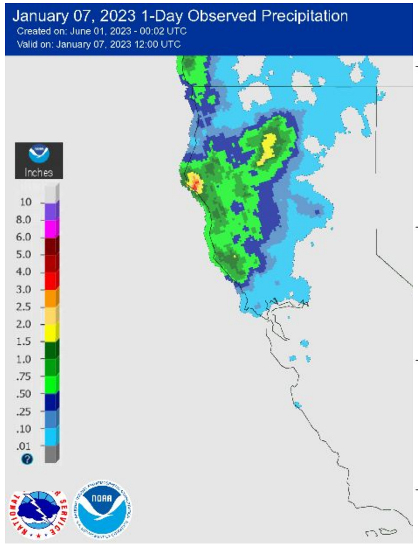


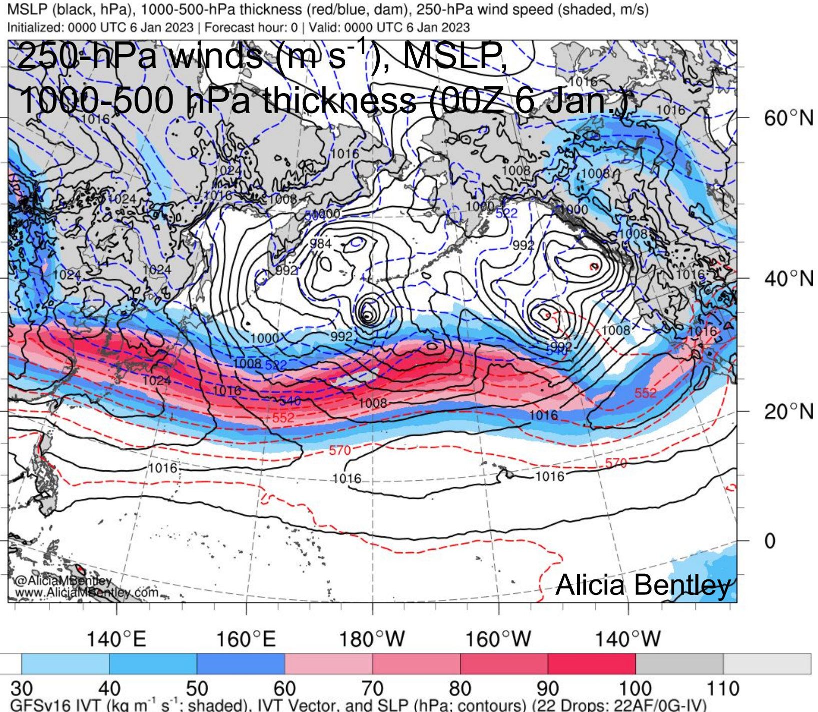
- Based on past experience in AR-Recon, precipitation perturbation growth (in non-linear model over a 36-h integration) is typically between 20-30 for strong cases (rarely above 30)
- 8 events greater than 30 in 2023 (precipitation metrics); these highlight particularly strong and damaging events

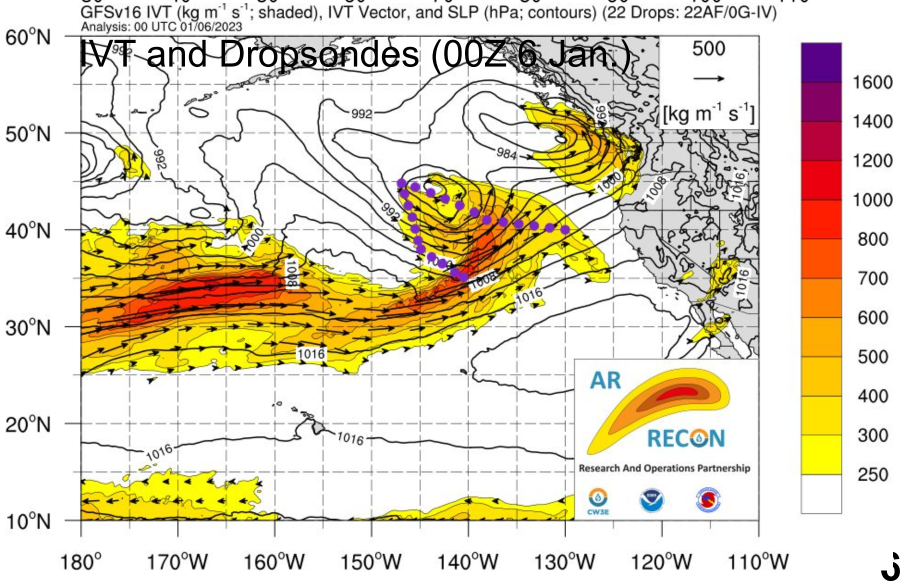
Adjoint Sensitivity: Jan. 6, 2023 (IOP 6)



24-h Precip. (12Z Jan 6)

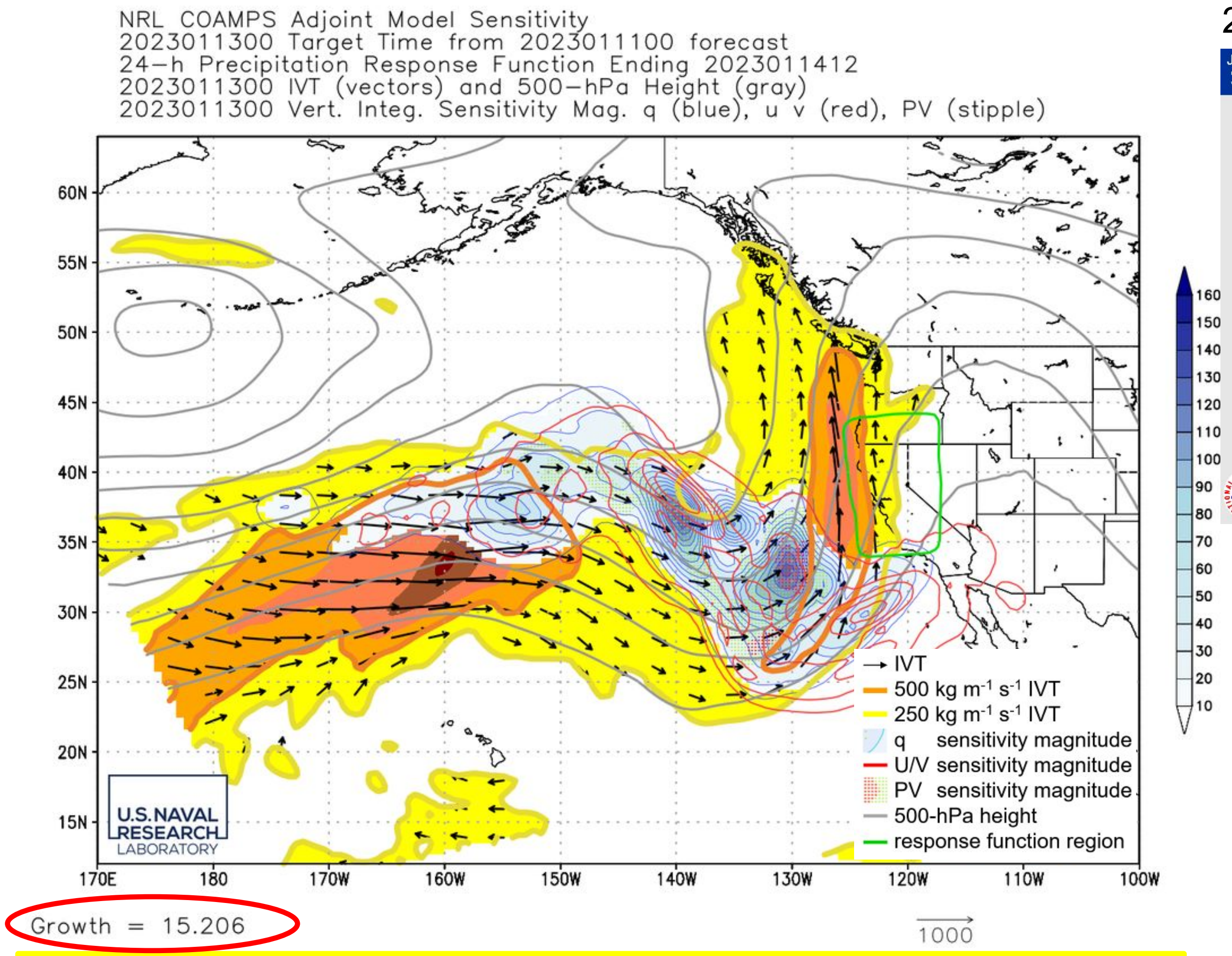




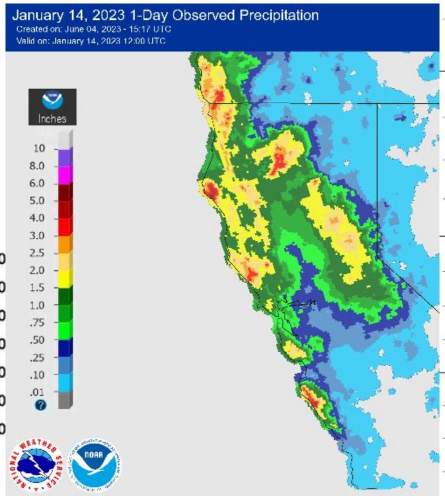


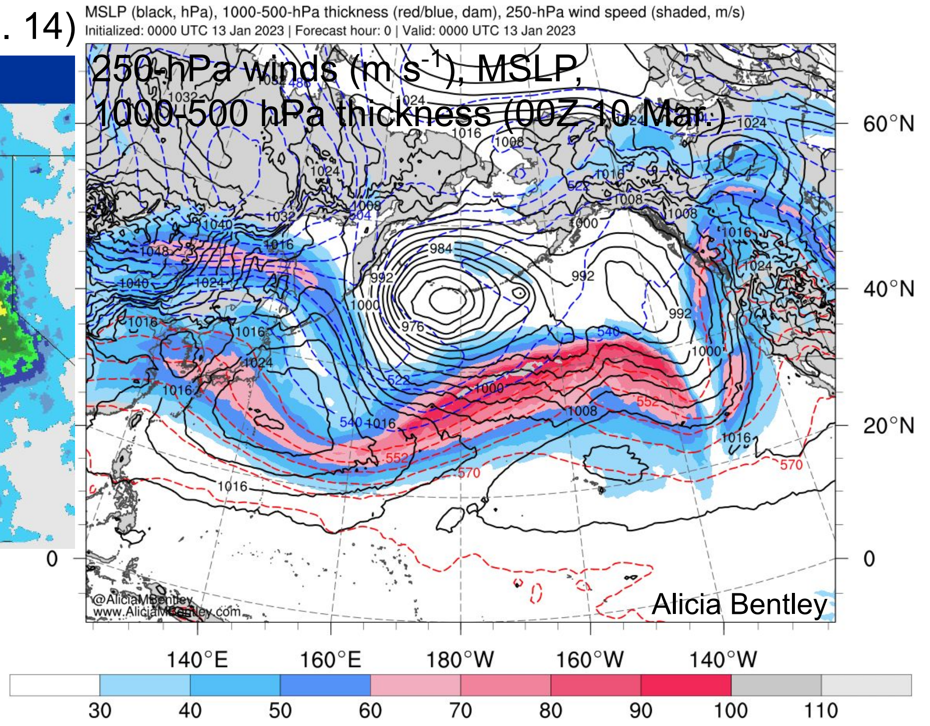
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Strong sensitivity near shortwave troughs (PV) in AR core and on cold-side near the strong dynamics

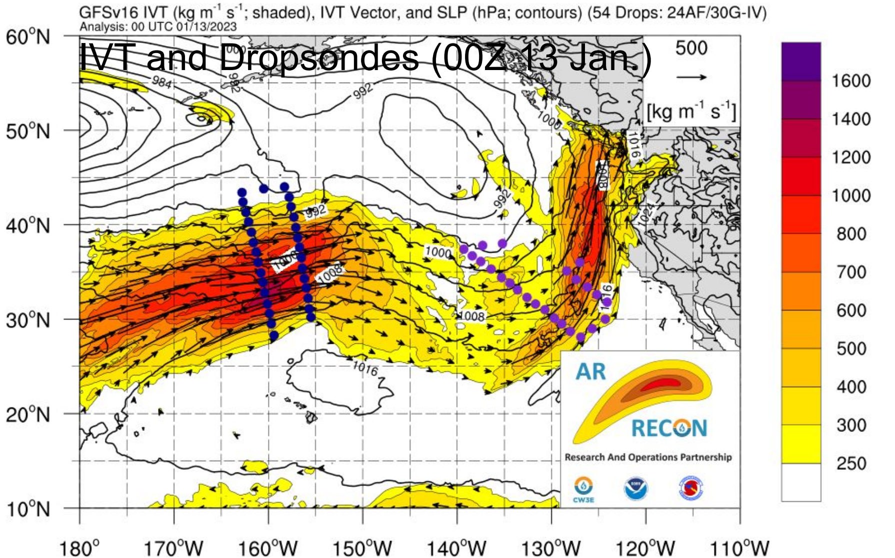
Adjoint Sensitivity: Jan. 13, 2023 (IOP 13)



24-h Precip. (12Z Jan. 14)







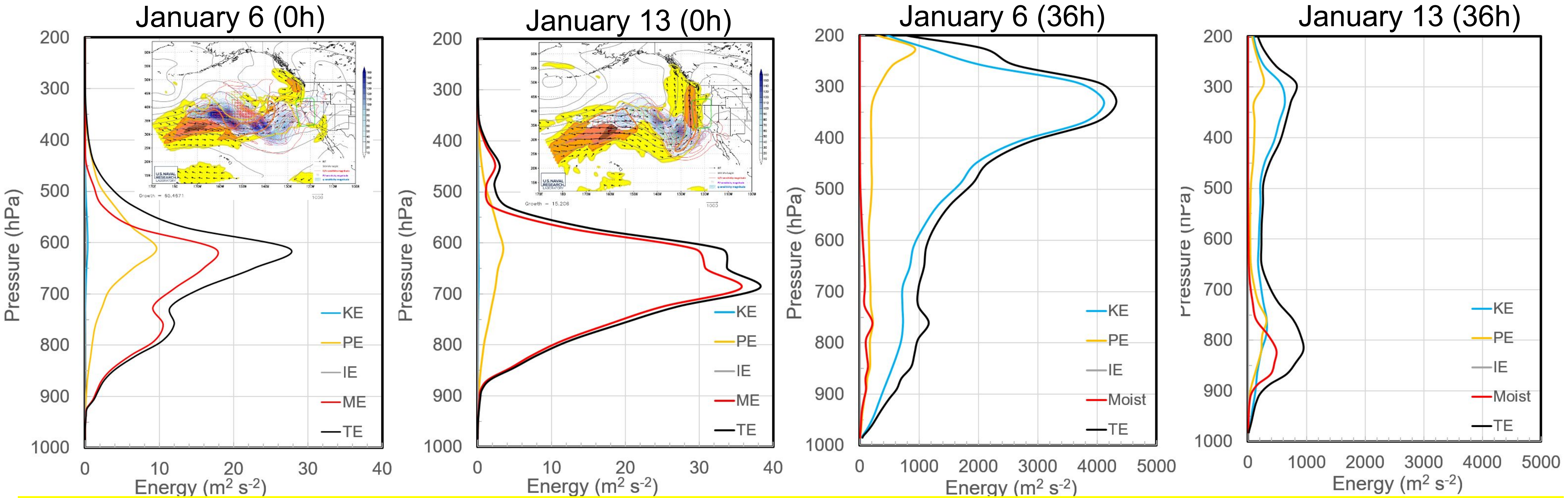
- Weaker jet along CA; AR directed from sub-tropics
- Moderate growth rate (36-h sensitivity)
- Sensitivity in AR inflow and upstream in next AR

Adjoint Optimal Perturbation Energetics

Energy Budget (Domain Average)

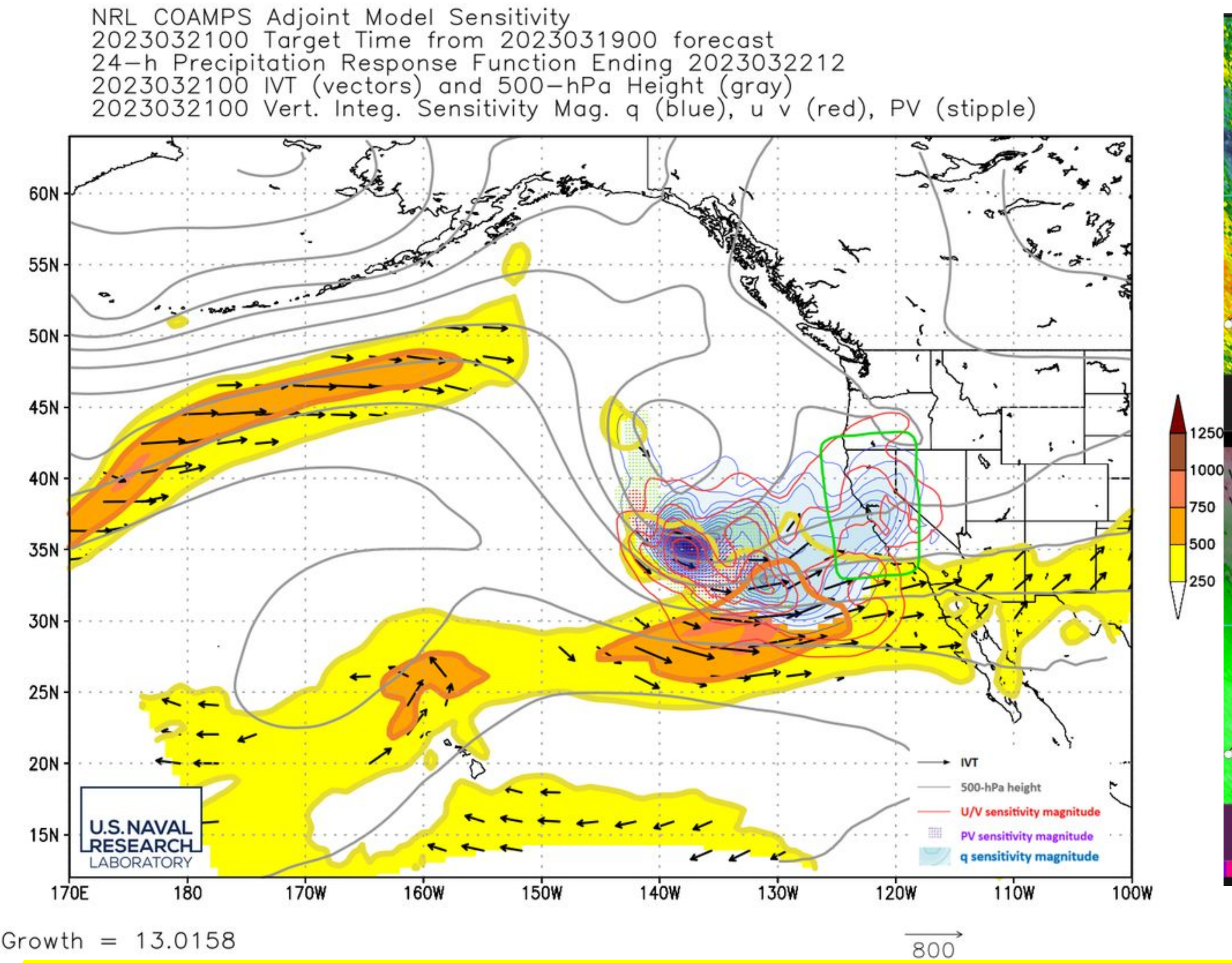
$$E = \frac{1}{2A}\int\left[(u'^2 + v'^2 + w'^2) + \frac{C_p}{T_r}T'^2 + \frac{RT_r}{p^2_{sr}}p'^2 + \frac{l_v^2}{C_p T_r}q_v'^2\right]dAd\sigma$$

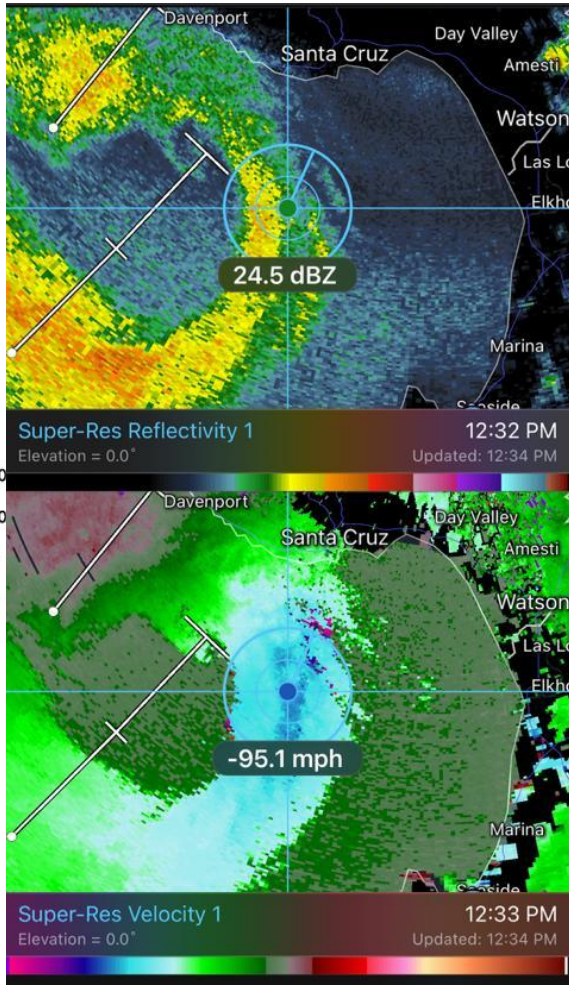
Total KE PE IE ME



- Comparison of Jan. 6 (growth rate 65) and Jan. 13 (growth rate of 15) cases
- Energy peaks in mid-levels at initial time, and grows *rapidly* in the vertical on Jan. 6 (much slower growth Jan 13)
- Jan. 6 shows much more rapid perturbation growth in NLM at jet level than Jan. 13

Adjoint Sensitivity: March 21





Dan Stern (UCAR)

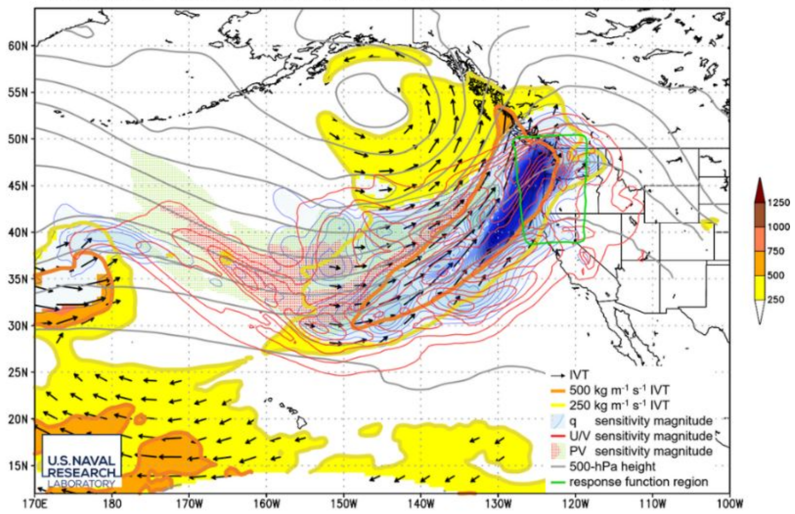
- Strong dynamic system made landfall along the Central California Coast and was a significant forecast challenge
- Multiple vortices along a bent-back warm (or occluded) front leading to extensive damage in Santa Cruz Mtns.

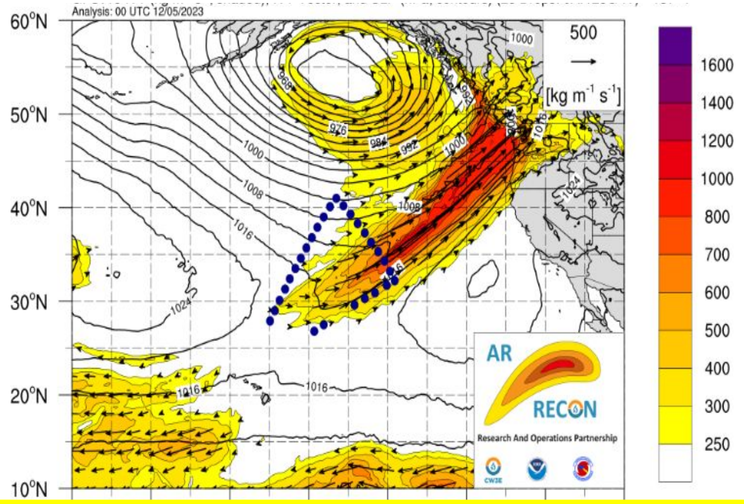
Adjoint Sensitivity: 2023-24 Winter Season

00Z Dec. 5, 2023 (IOP-4)

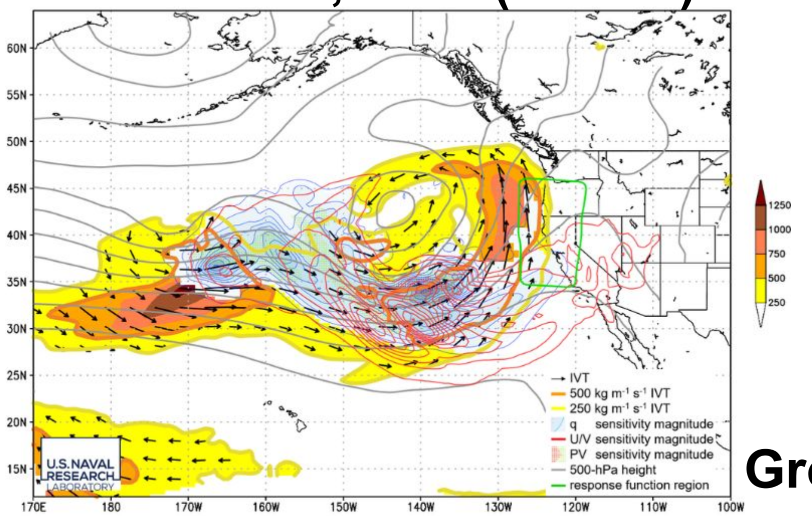
00Z Jan. 27, 2023 (IOP-27)

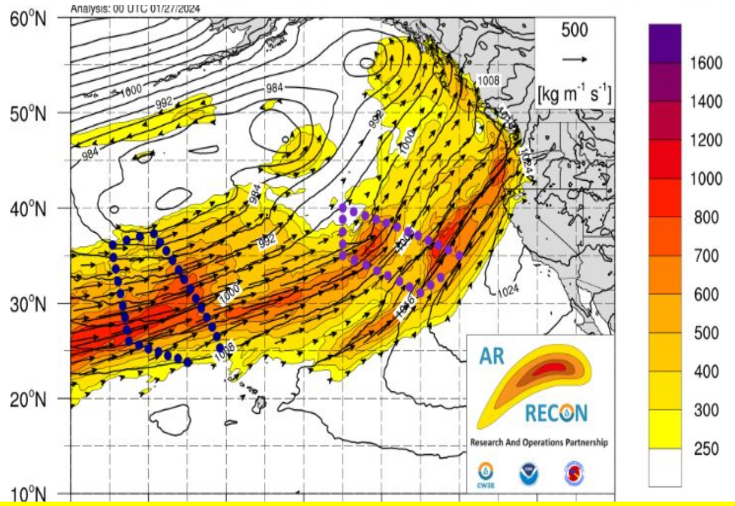
Growth 24





Growth 19

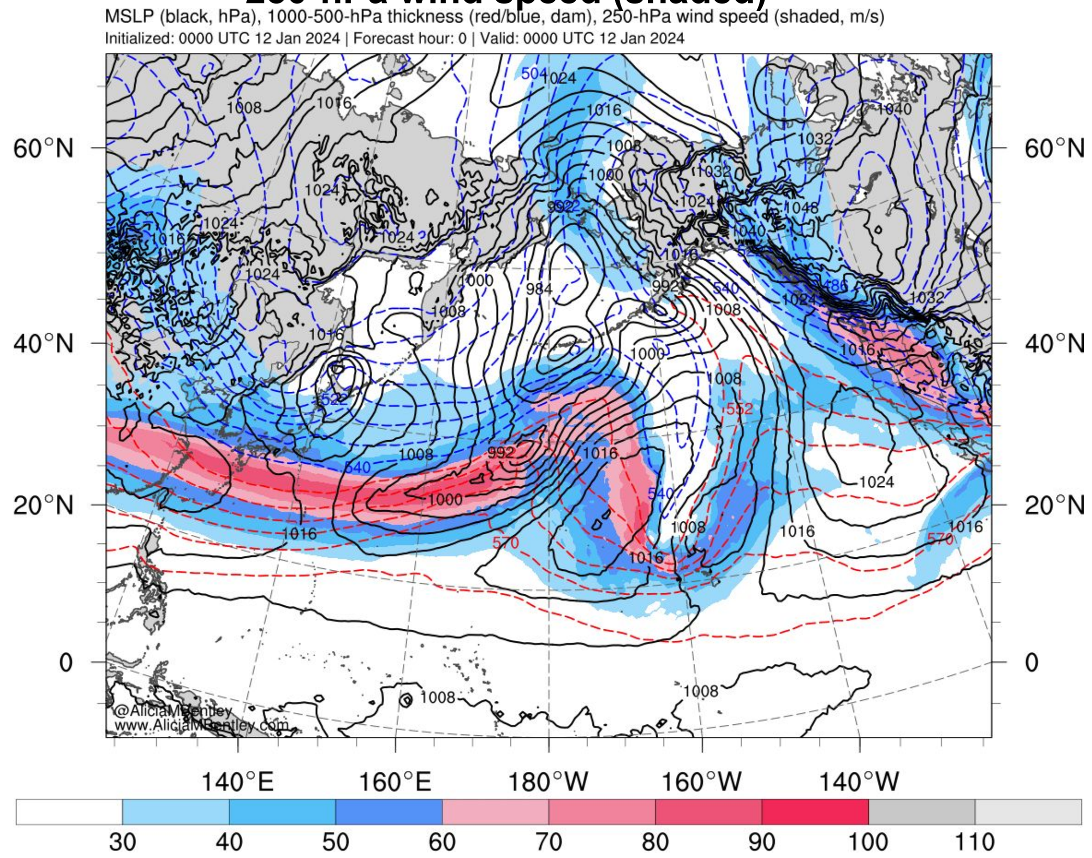




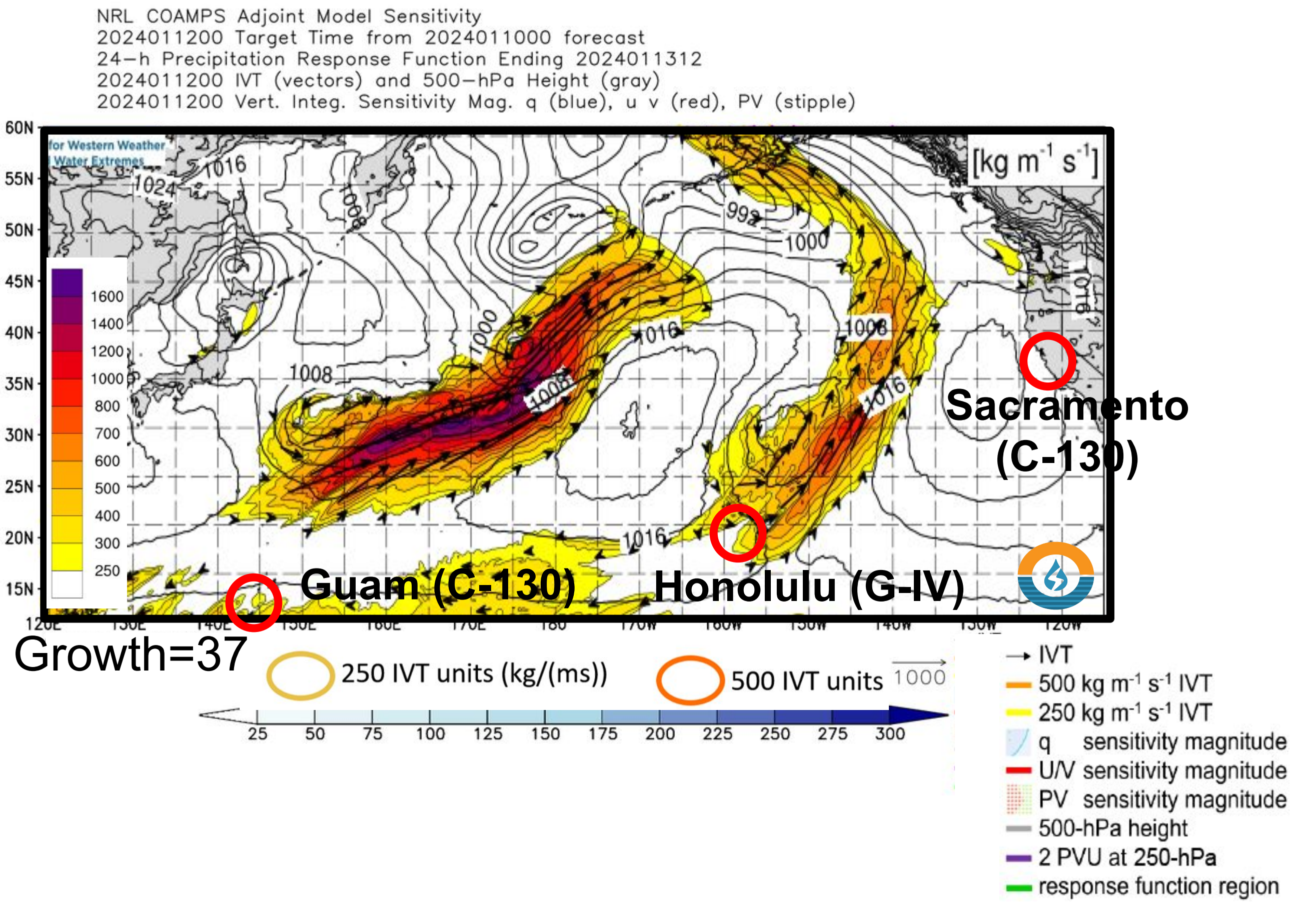
- Adjoint sensitivity provided to the AR-Recon team in 2023/24 from Nov. through Mar.
- Adaptive response function regions (W. Coast, E. Coast, W. Pacific domains)
- Response functions used in 2023/24: accumulated precipitation, accumulated snow, IVT

Adjoint Sensitivity: Western Pacific

GFS Analysis 00Z 12 January 2024
MSLP (hPa), 1000-500 hPa thickness (red/blue), 250-hPa wind speed (shaded)



Integrated Vapor Transport (color, vectors), SLP (contours) 00Z 12 January 2024



COAMPS adjoint sensitivity provided for W. Pacific targets in real time (and E. Pacific, Gulf of Mexico, E. U.S.) in Jan. 2024

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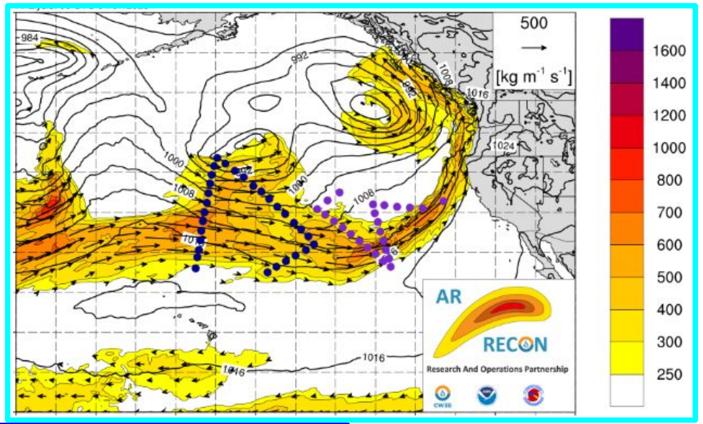
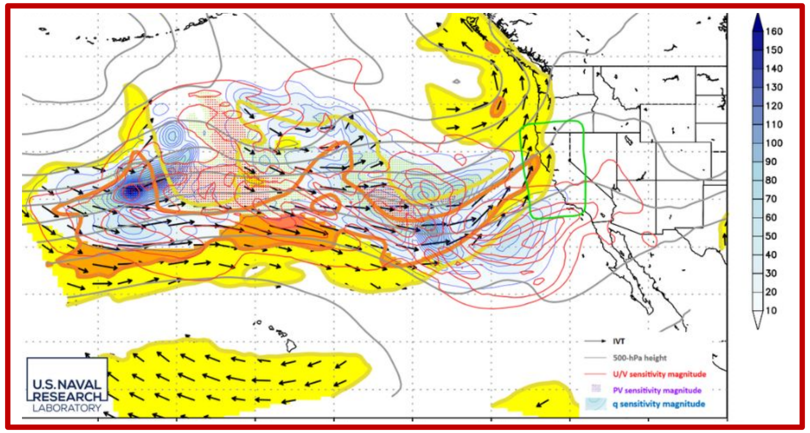
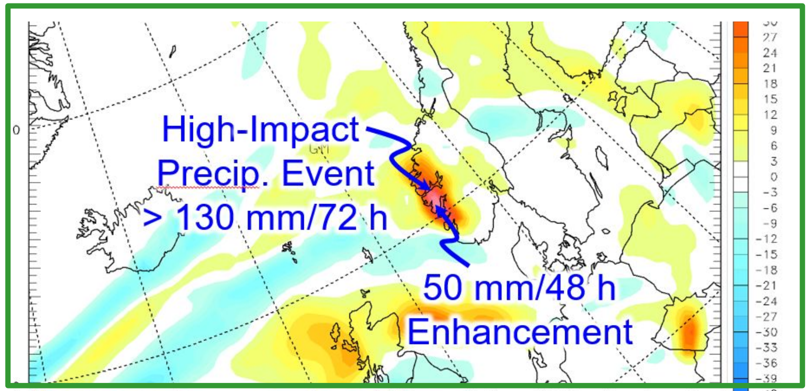
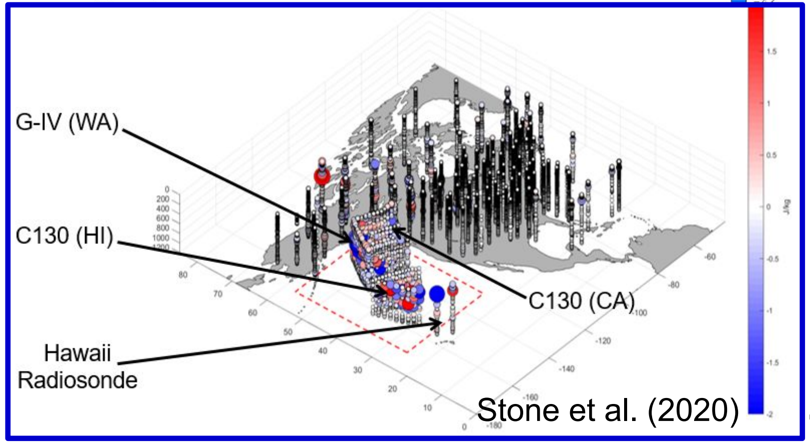
Summary

- Adjoint-based systems are powerful tools that can be used for predictability and data assimilation applications
  - Sensitivity analysis
  - Targeted observations
  - Singular vectors
  - Predictability
  - Parameter estimation
  - Forecast sensitivity observation impact (FSOI)









- Adjoint Sensitivity in ARs
  - Sensitive regions of moisture & temperature often strongly project onto diabatically-active areas (ARs & WCBs) leading to fast perturbation & forecast error growth (sensitivity correlated with forecast errors)
  - Rapid growth associated with strong jets, moist baroclinic zones, and ARs
- Future Plans
  - Understand the predictability barriers associated with ARs
  - ONR Study of Air-Sea Fluxes and Atmospheric River Intensity (SAFARI)