Diagnosing Forecast Sensitivity of Atmospheric Rivers Using an Adjoint

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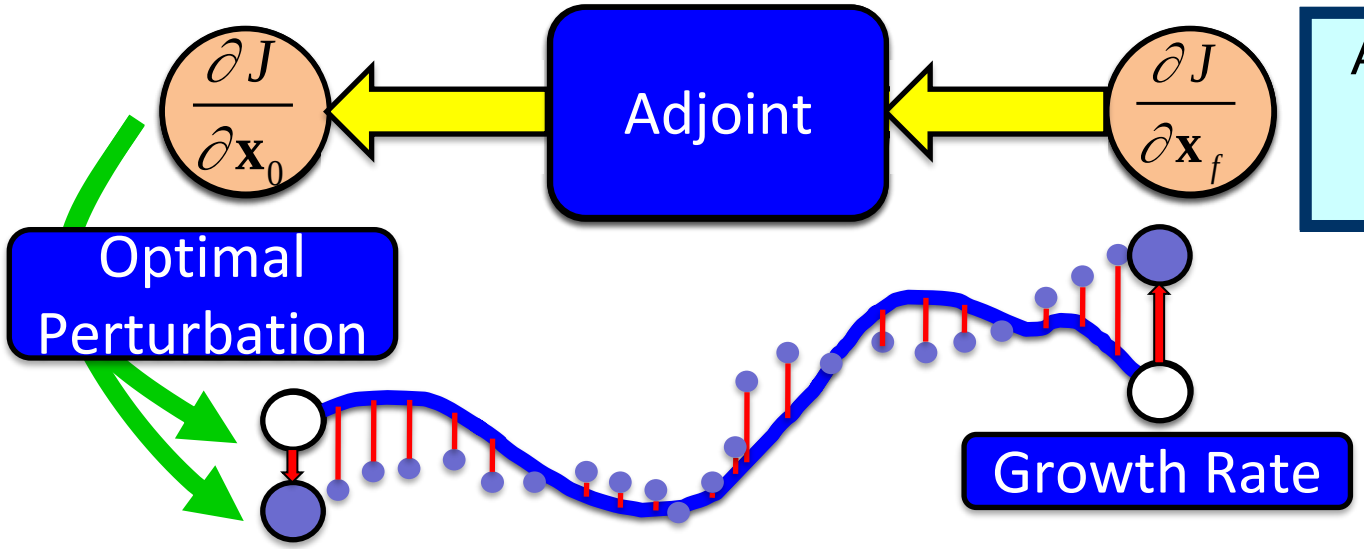
- **What are Adjoints?**
- **2023 Adjoint Sensitivity Summary**
- **Sensitivity Highlights and Energetics**
- **Summary and Future Plans**

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

Atmospheric River Reconnaissance Workshop June 27-29 2023

Adjoint Sensitivity

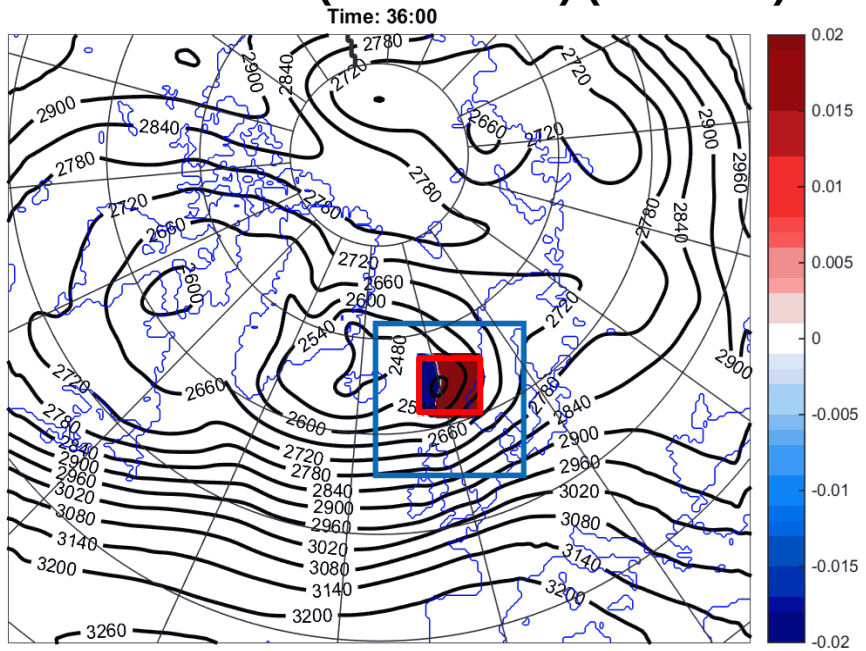


Adjoint is transpose of the TLM, and evolves the gradient of a response function (J) with respect to $\boldsymbol{x_f}$

$$\frac{\partial J}{\partial \mathbf{x}_0} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}_f}$$

Sensitivity of forecast aspect to changes in initial state, and highlights regions of large initial sensitivity.

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



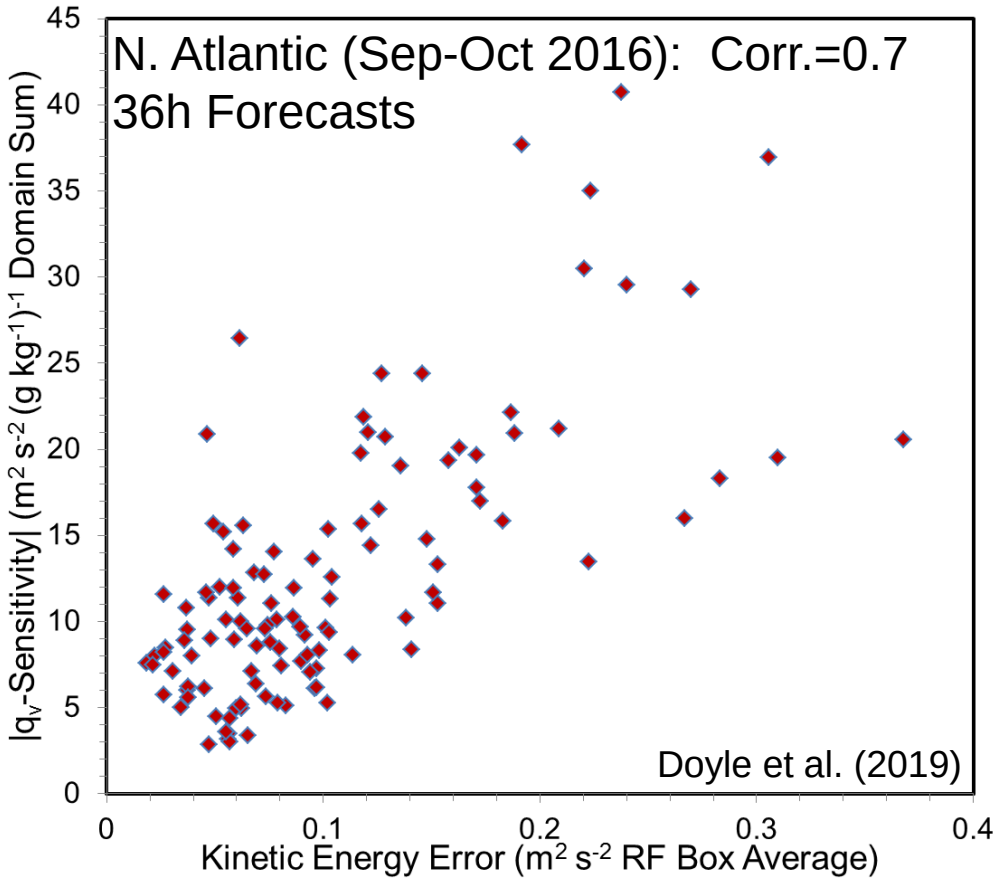
COAMPS® Moist Adjoint Model

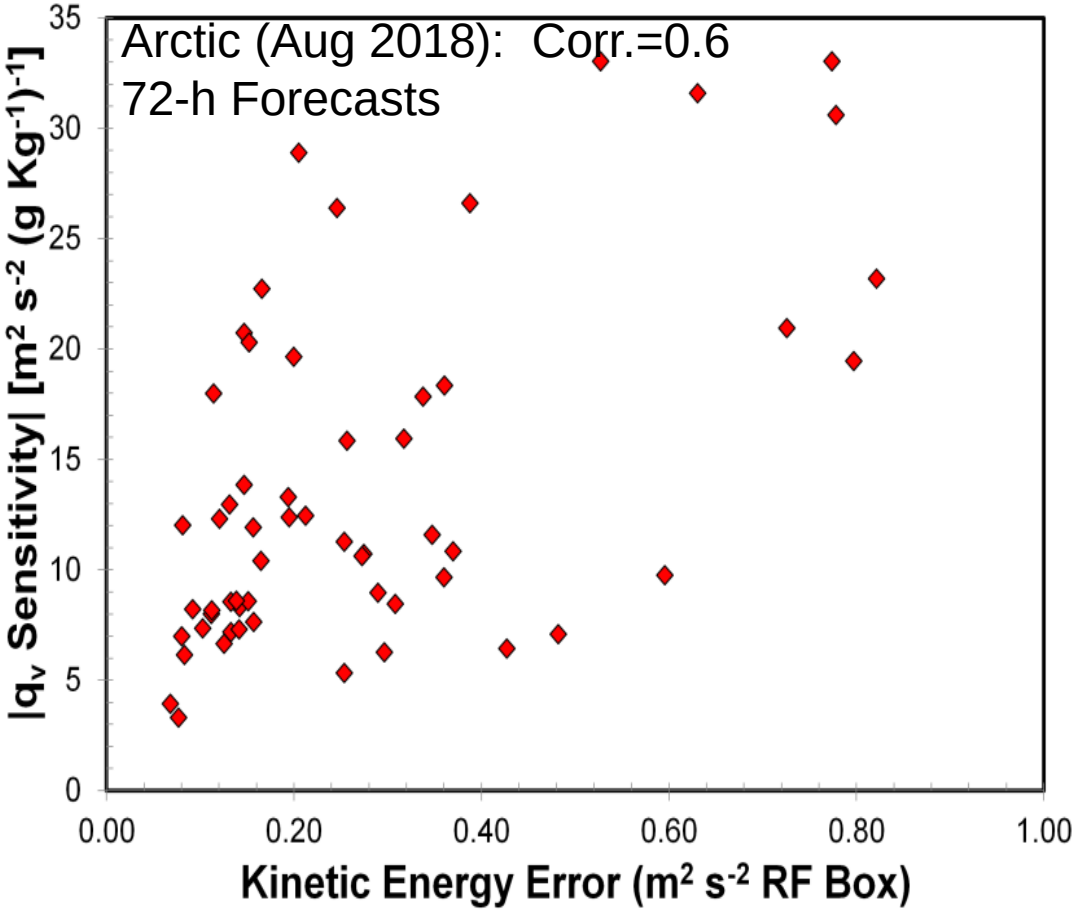
- Dynamics: Nonhydrostatic (30 km resolution)
- Physics: PBL, surface flux, microphysics, cumulus
- Response Functions, *J*: Precip (others snow, IVT, KE, PV, SST)
- Optimal Perturbations: ~1 K, 1 m s^{-1}, 1 g kg^{-1}

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





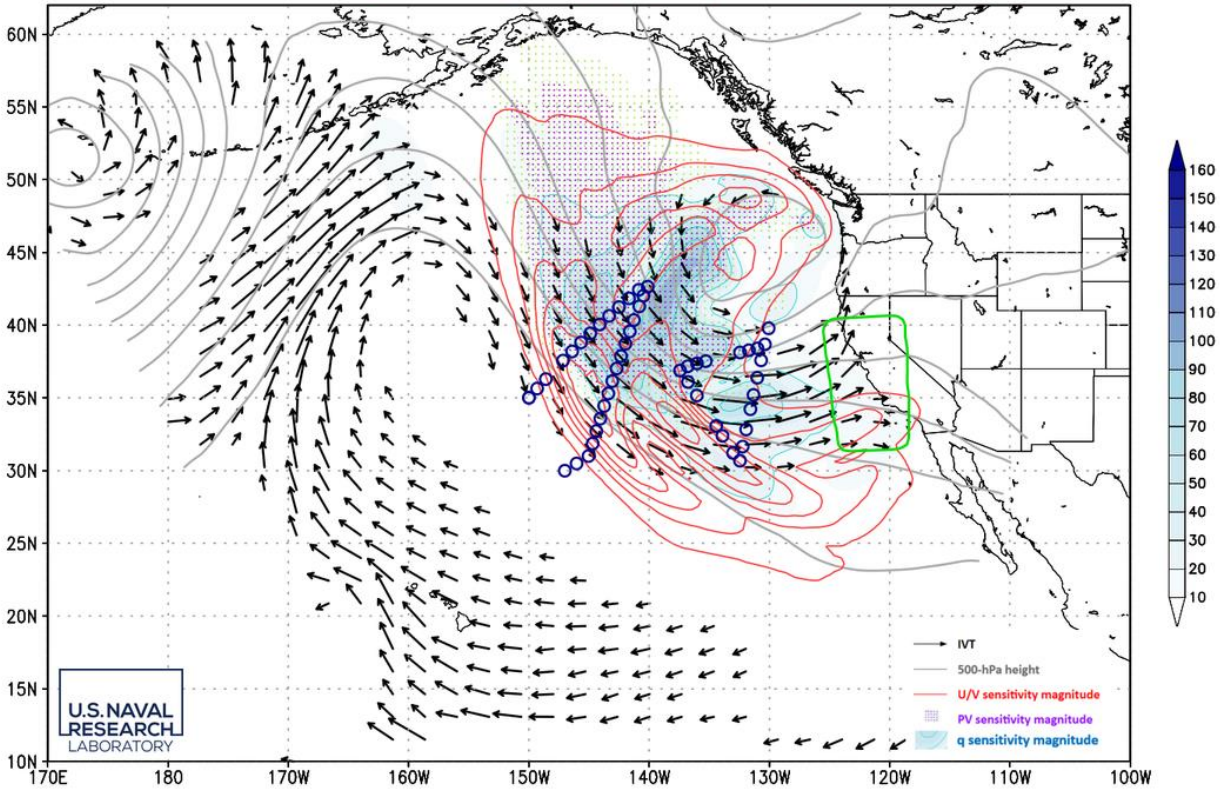
- Sensitivity magnitude (domain-vertically integrated) & low-level kinetic energy forecast error are well correlated for multiple regions: N. Atlantic (Doyle et al. 2019), U.S. W. Coast (Reynolds et al. 2019), Arctic

Optimization Time

How Does the Sensitivity Vary with Optimization Time?

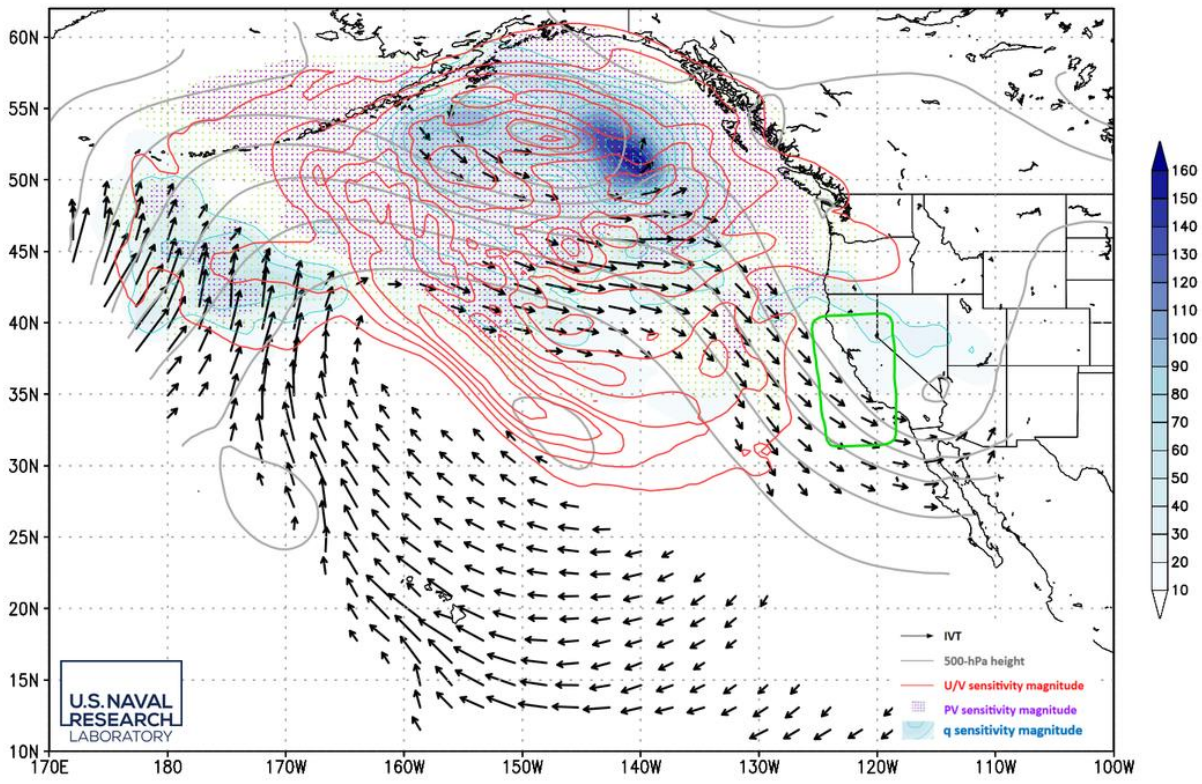
36-h Optimization Time

Precipitation Response Function
Initial: 00Z 27 Jan. 2021Final: 12Z 28 Jan. 2021



60-h Optimization Time

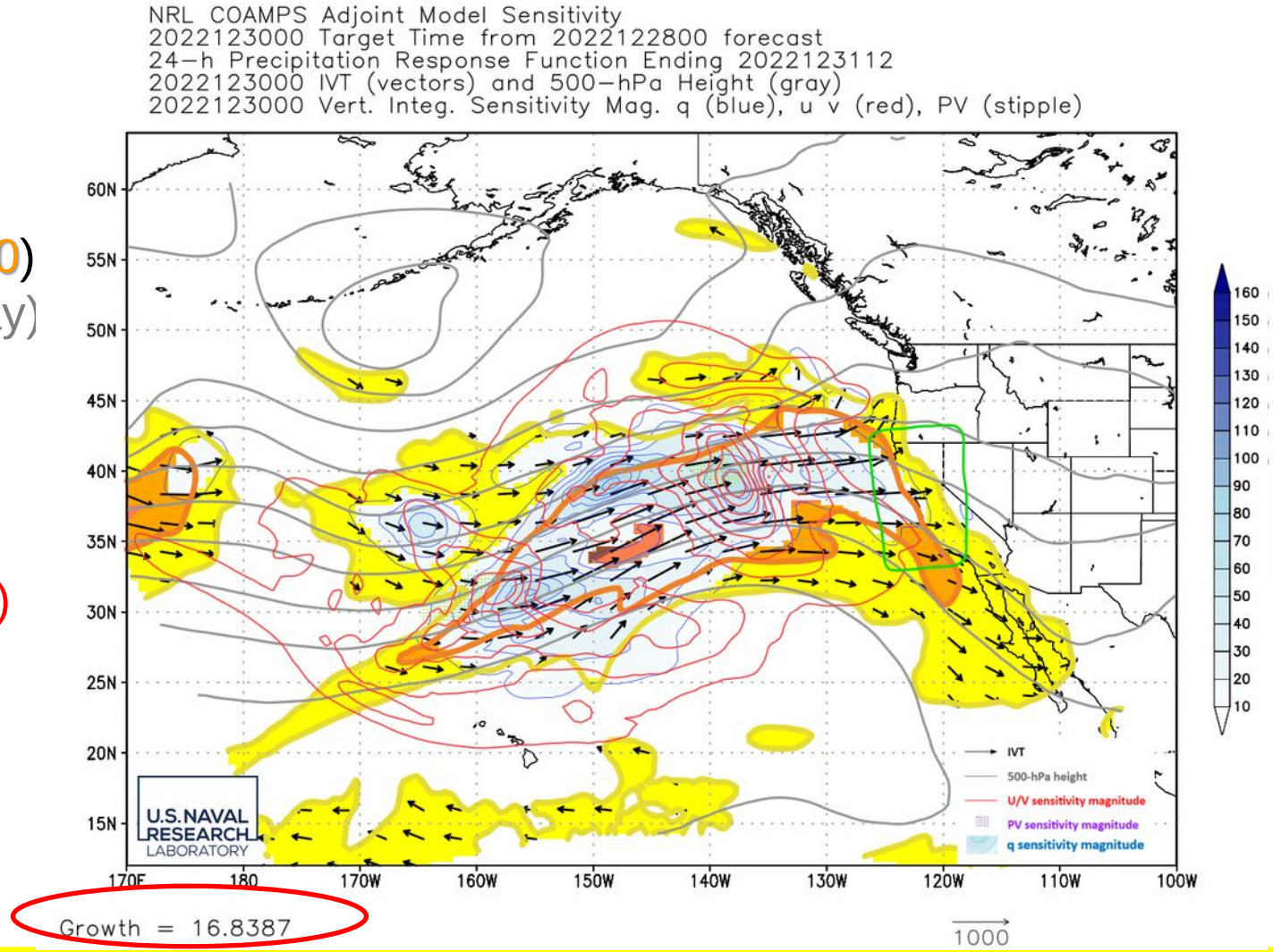
Precipitation Response Function
Initial: 00Z 26 Jan. 2021Final: 12Z 28 Jan. 2021



- 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

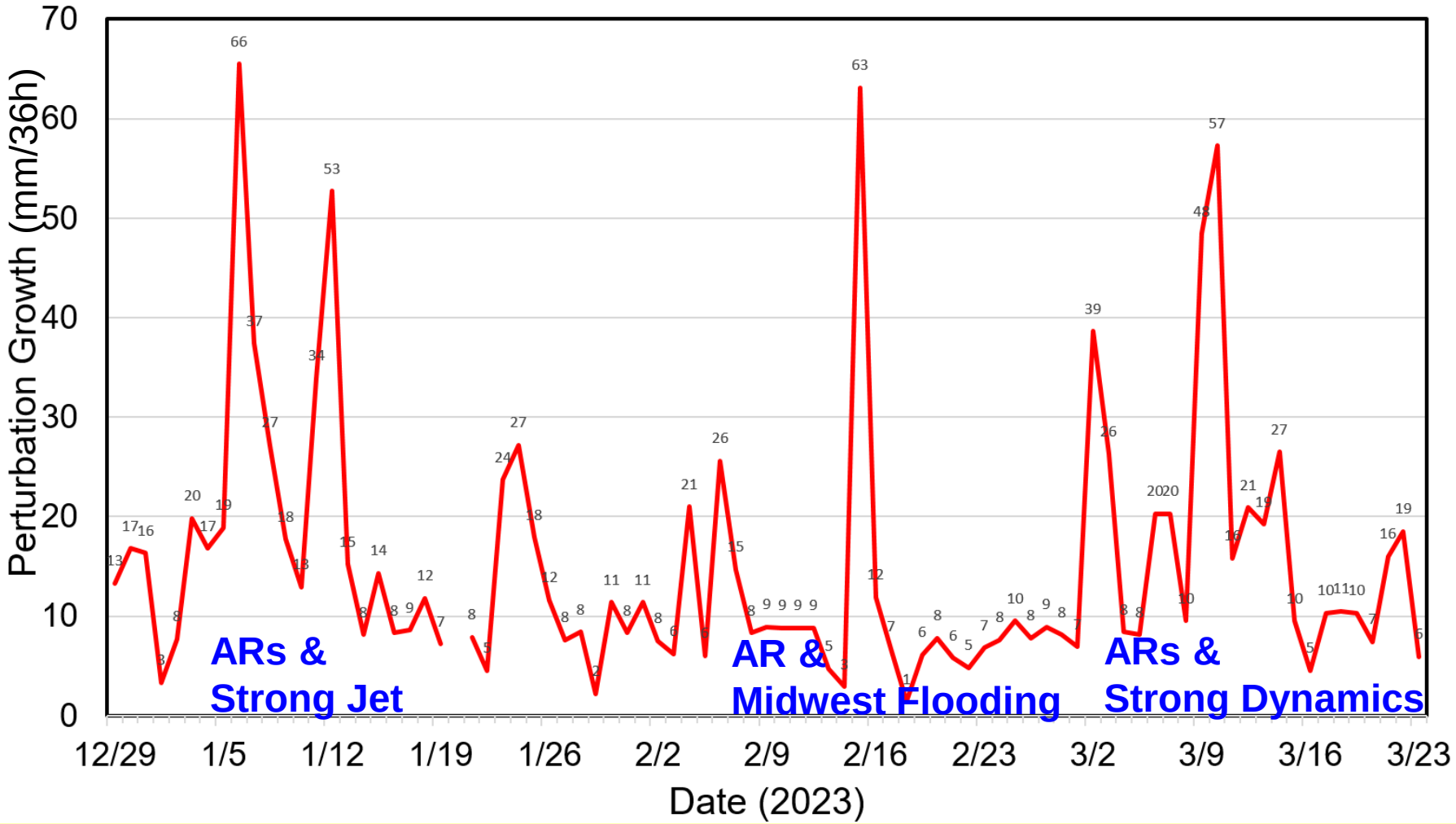
NRL Adjoint Sensitivity Summary Graphic

IVT Vectors (250/500)
500-hPa Height (gray)
Response Function
Vertically Integrated Sensitivity:
|q| (blue shading)
|u|+|v| (red contours)
|PV| (stipple)
(moderate/strong)



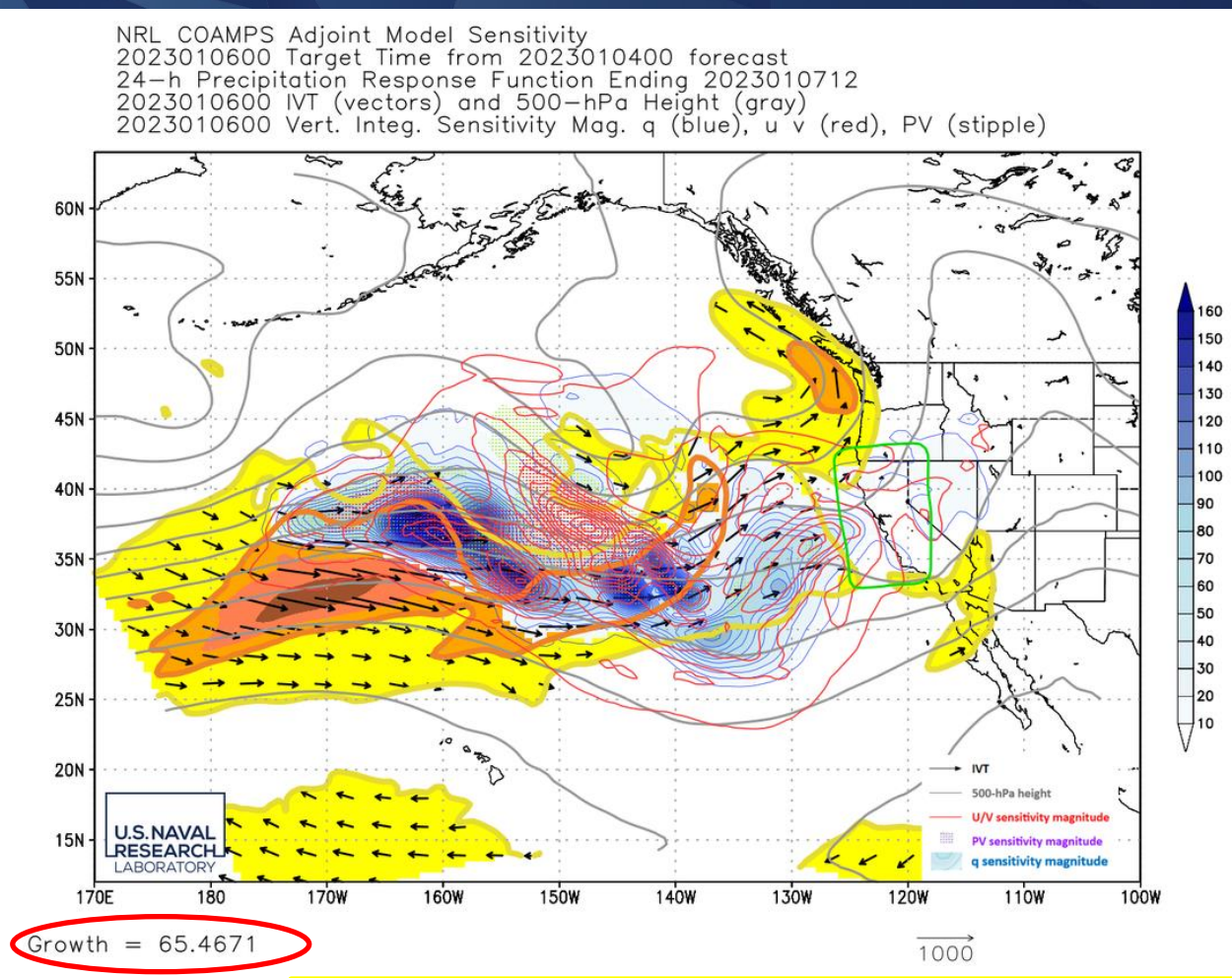
- Adjoint sensitivity provided to the AR-Recon team in 2023 from late Dec through late March
- Adaptive response function region moved daily to support different areas (W. Coast, E. Coast …)
- Response functions used in 2023: accumulated precipitation, accumulated snow, IVT

Adjoint Sensitivity (AR Recon 2023)

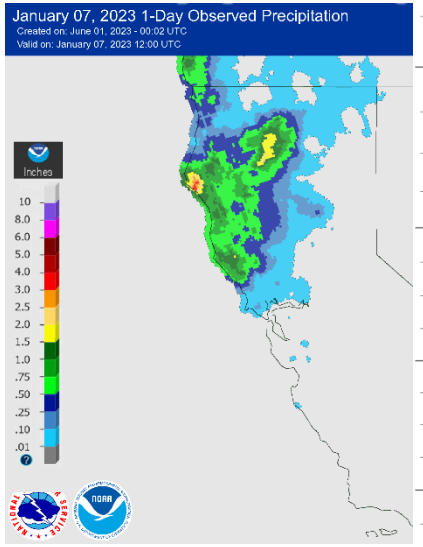


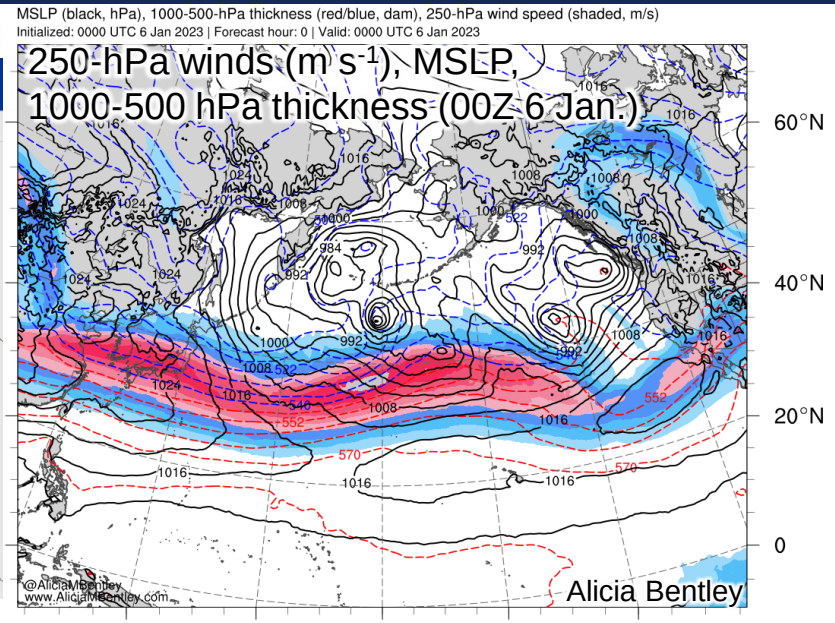
- Based on past experience in AR-Recon and NAWDEX, precipitation perturbation growth (in non-linear model over a 36-h integration) are between 20-30 for strong cases (rarely above 30 previously)
- 8 events greater than 30 in 2023 (precipitation only)

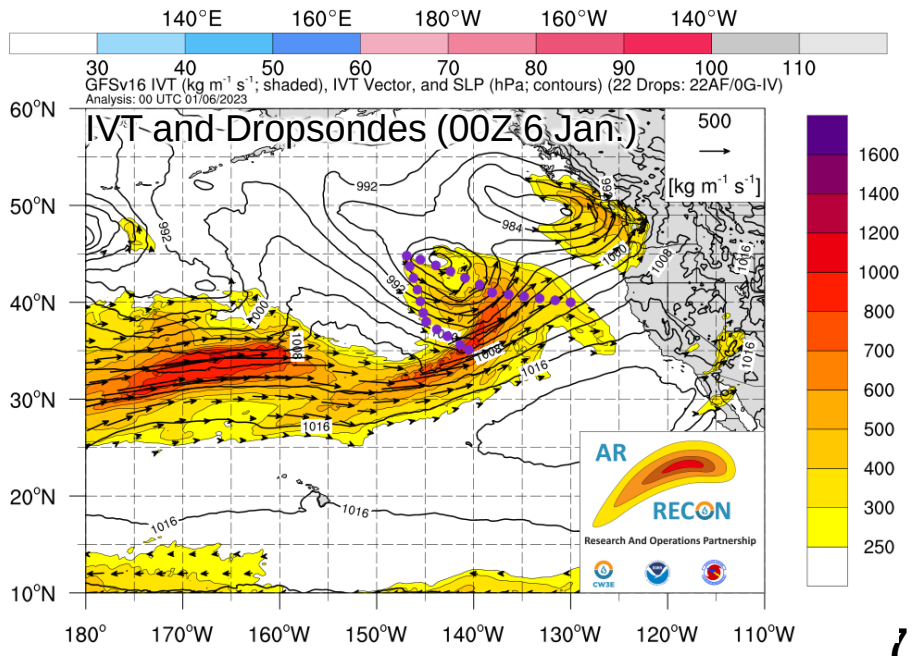
Adjoint Sensitivity: Jan. 6 (IOP 6)



24-h Precip. (12Z Jan 6)

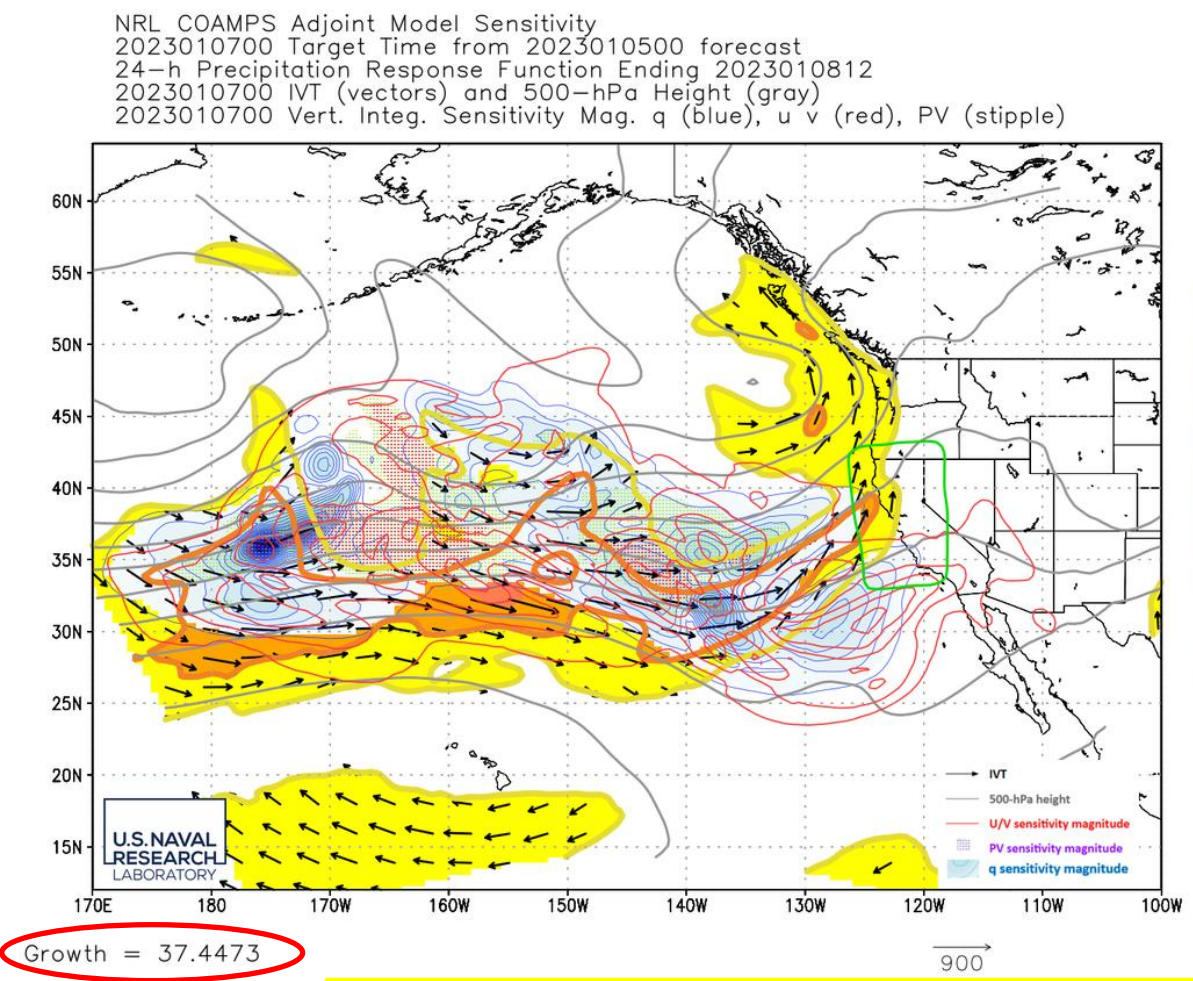




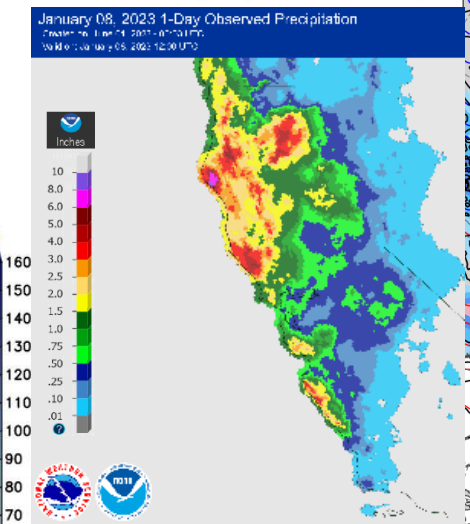


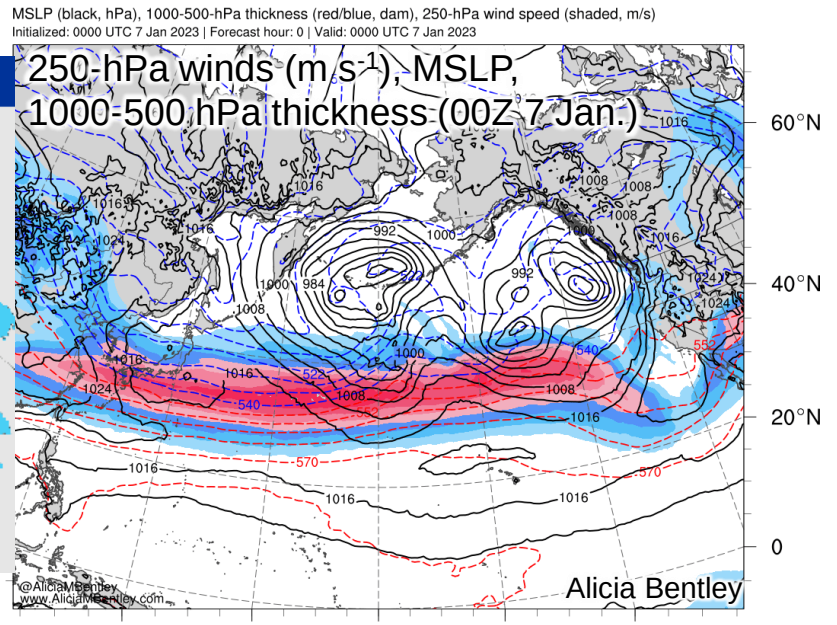
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Strong sensitivity near shortwave troughs (PV) in AR core and on cold-side near the strong dynamics

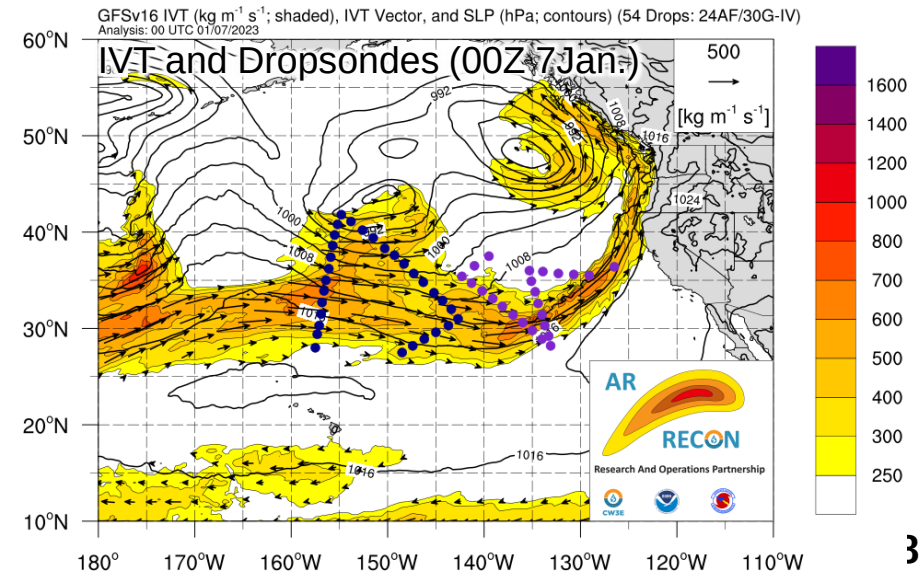
Adjoint Sensitivity: Jan. 7 (IOP 7)



24-h Precip. (12Z Jan 8)

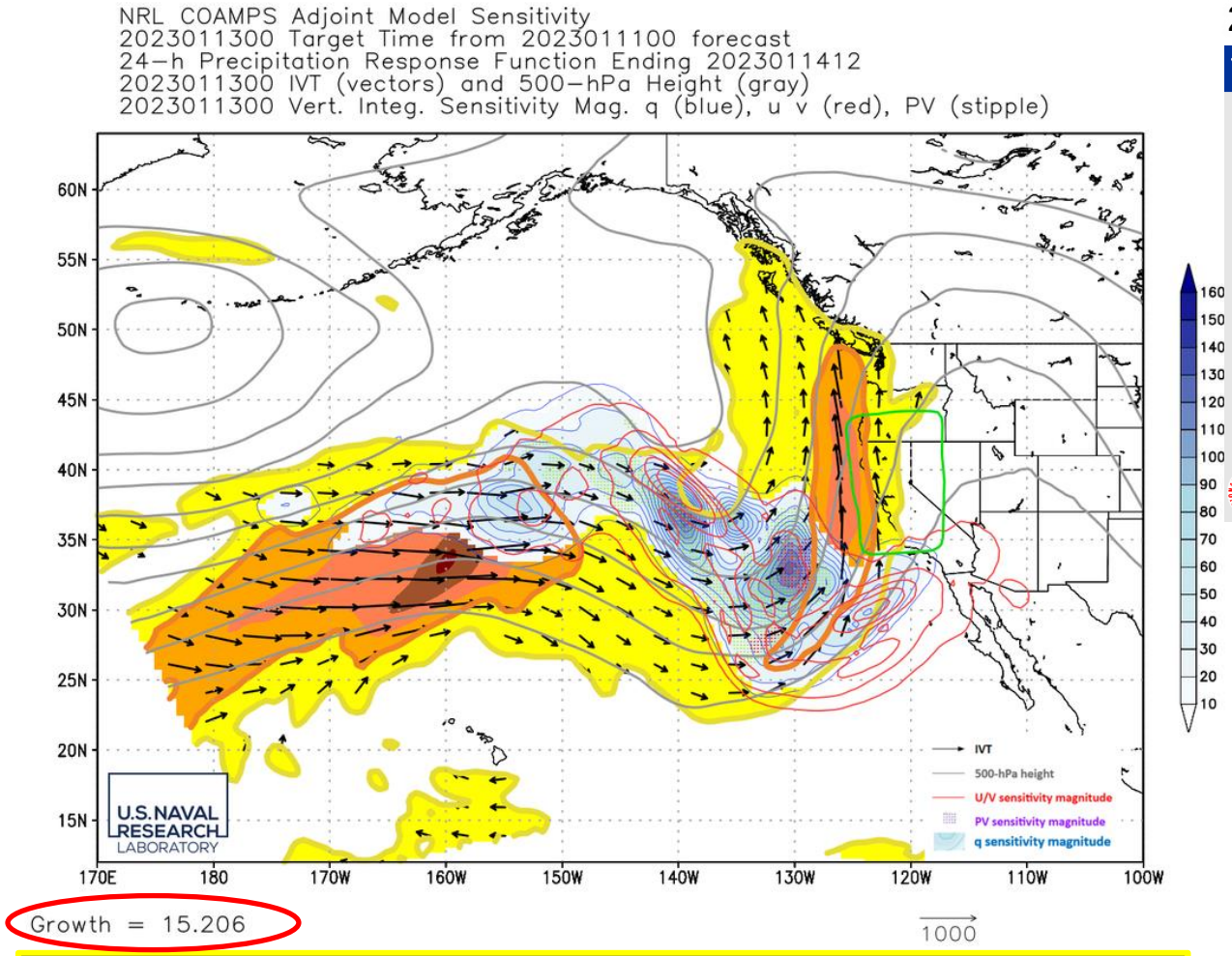






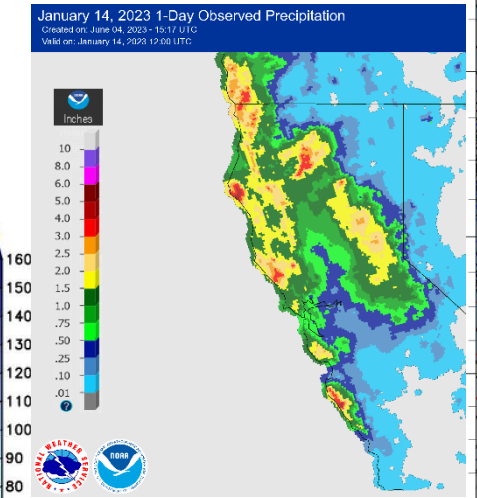
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Two prominent upstream sensitivity regions along AR (western sensitive region propagates ~38 m s^{-1})

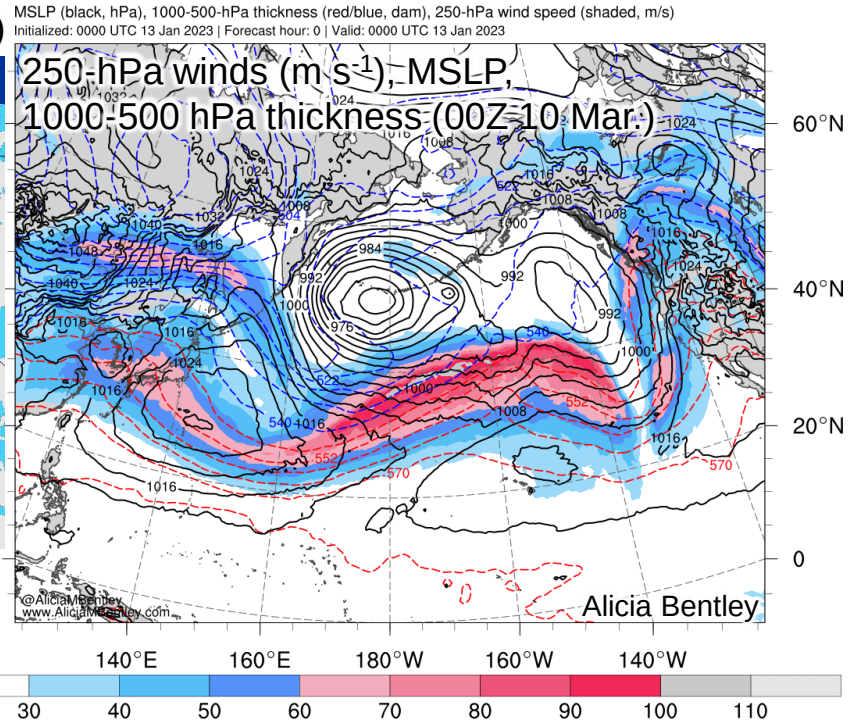
Adjoint Sensitivity: Jan. 13 (IOP 13)

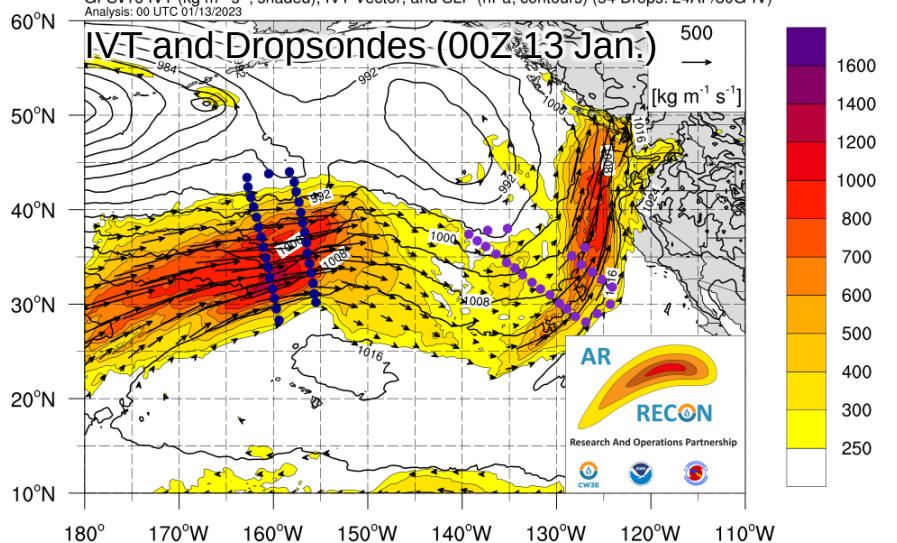


- Weaker jet along CA; AR directed from sub-tropics
- Moderate growth rate (36-h sensitivity)
- Sensitivity in AR inflow and upstream in next AR

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





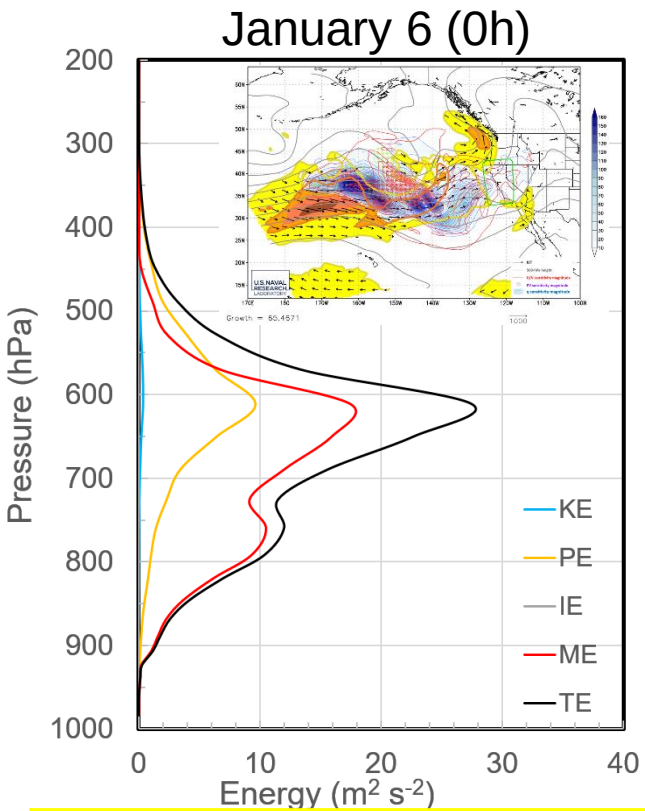


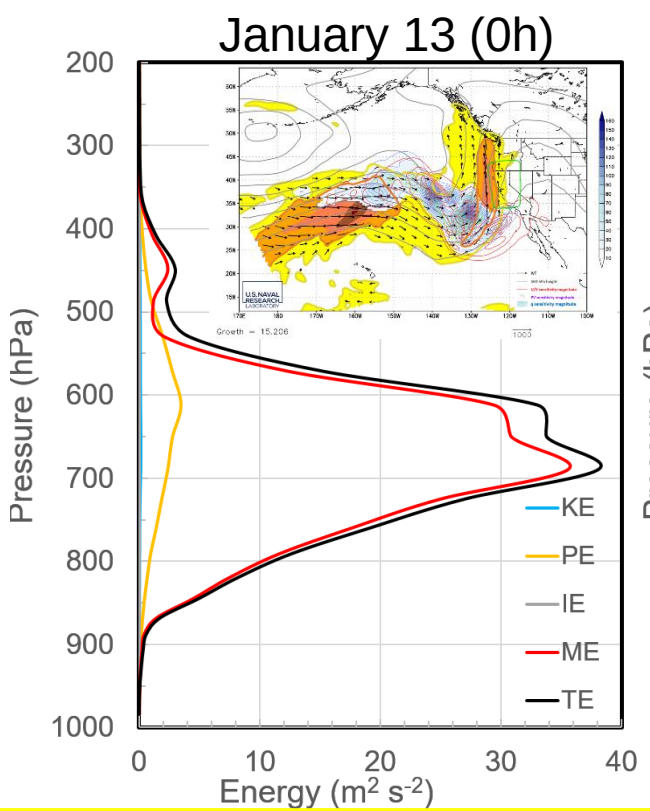
Adjoint Optimal Perturbation Energetics

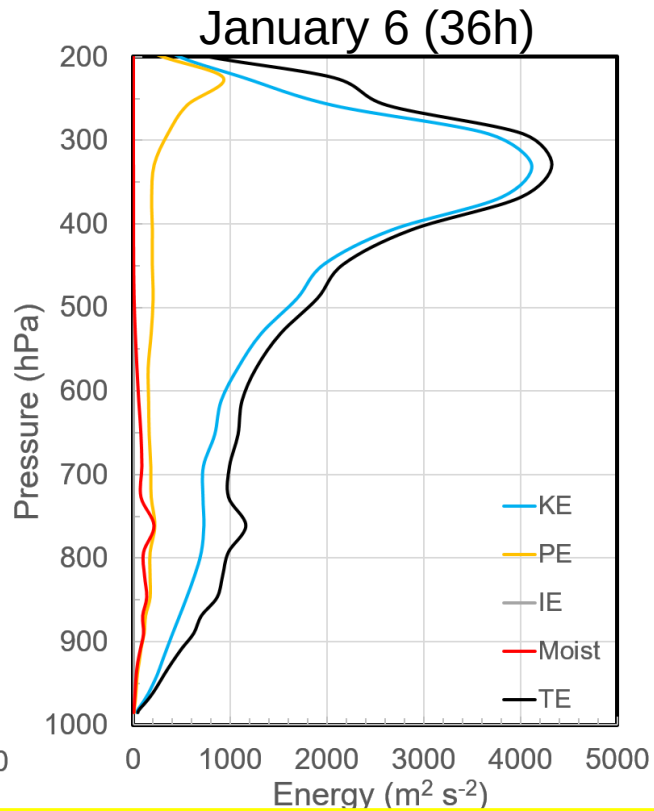
NLM Energy Budget (Domain Average)

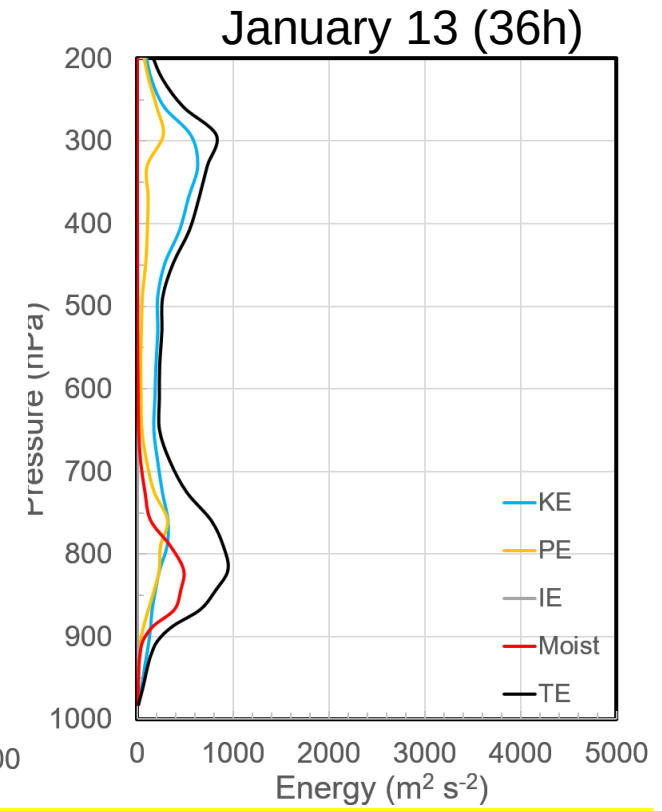
$$E = \frac{1}{2A}\int\left[(u'^2 + v'^2 + w'^2) + \frac{C_p}{T_r}T'^2 + \frac{RT_r}{p^2_{sr}}p'^2 + \frac{l_v^2}{C_pT_r}q_v'^2\right]dAd\sigma$$

Total KE PE IE ME



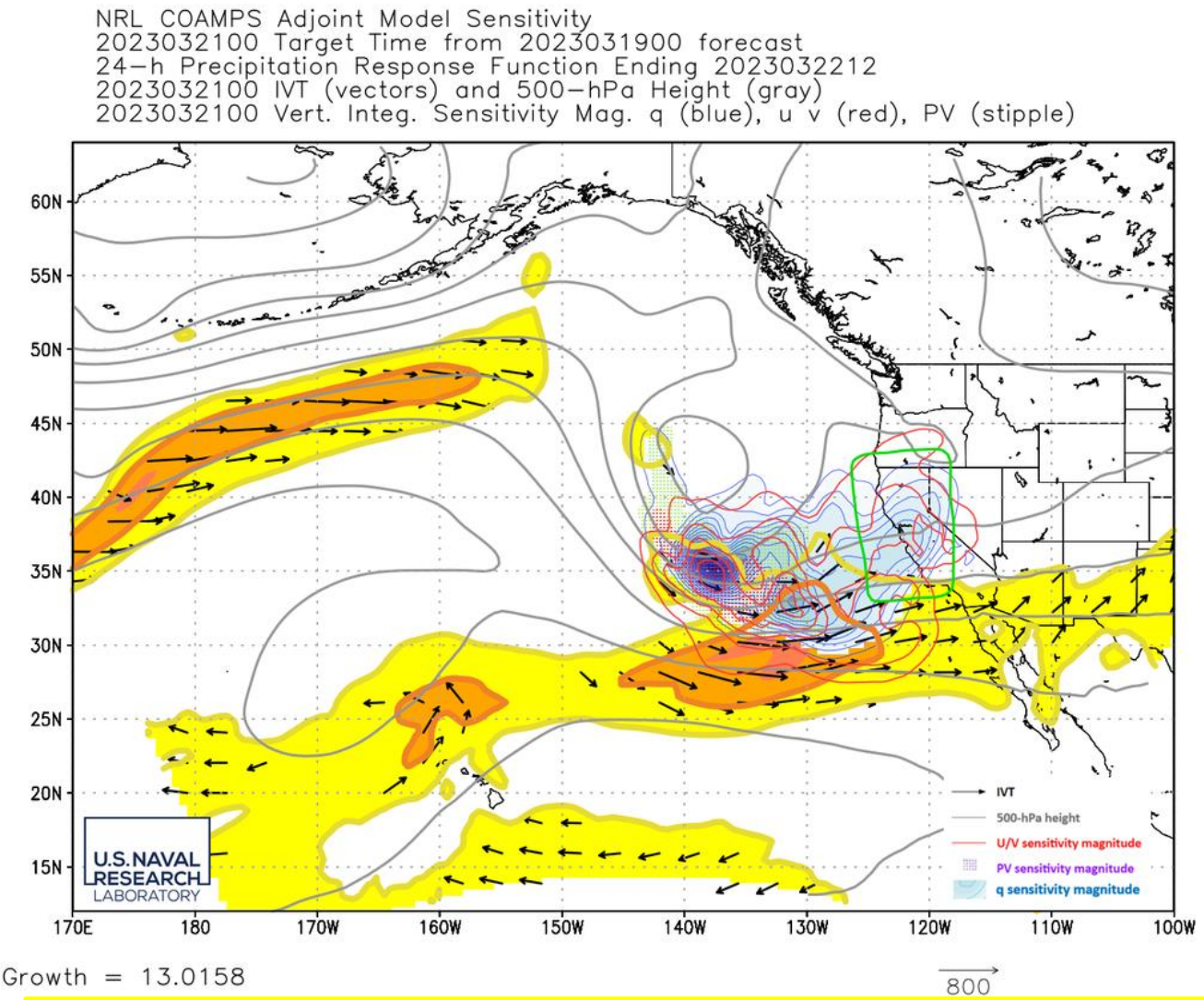


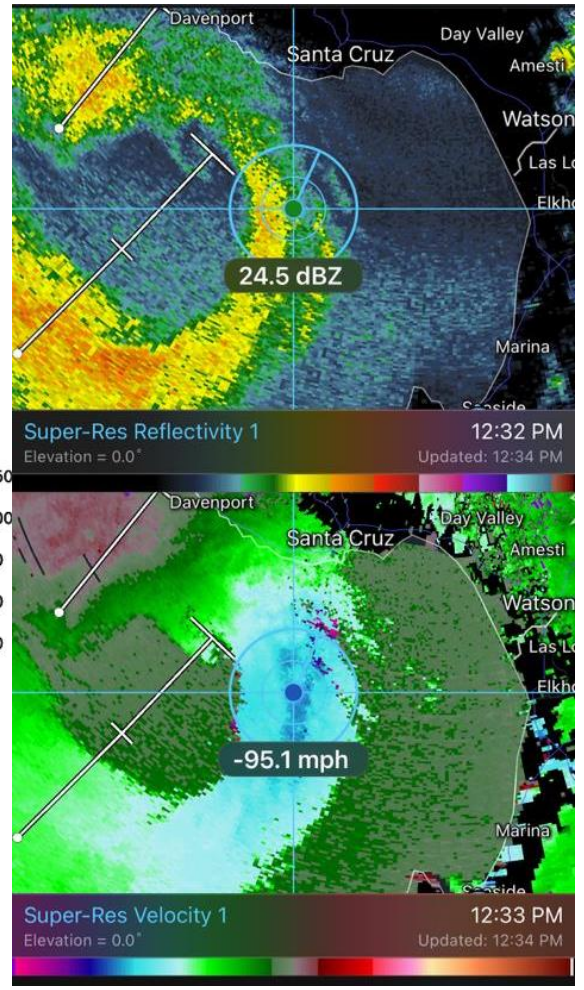




- Comparison of Jan. 6 (growth rate 65) and Jan. 13 (growth rate of 15) cases
- Energy peaks in mid-levels at initial time, and grows *rapidly* in the vertical on Jan. 6 (much slower growth Jan 13)
- Jan. 6 shows much more rapid perturbation growth in NLM at jet level than Jan. 13

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.

North Atlantic Example: NAWDEX

ET of ex-Karl

i) Strong moisture sensitivity near Karl prior to ET

ii) Vorticity sensitivity in upstream trough and near TC

Adjoint Pert.:

i) Enhancement of WCB by 20 ms^{-1} & IVT

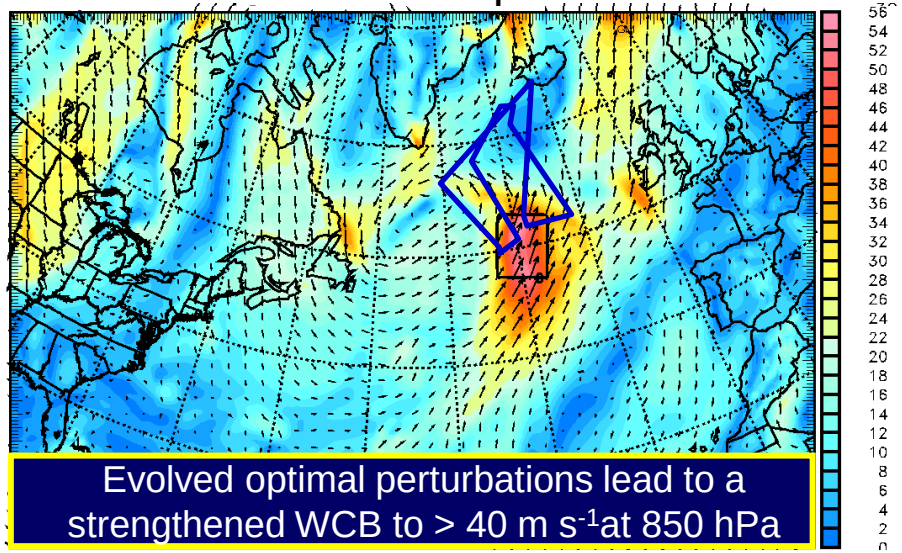
ii) Increase WCB outflow (increase irrotational winds 9 to 15 $m\ s^{-1}$)

iii) Downstream ridge building

iv) High-impact precipitation and atmos. river event

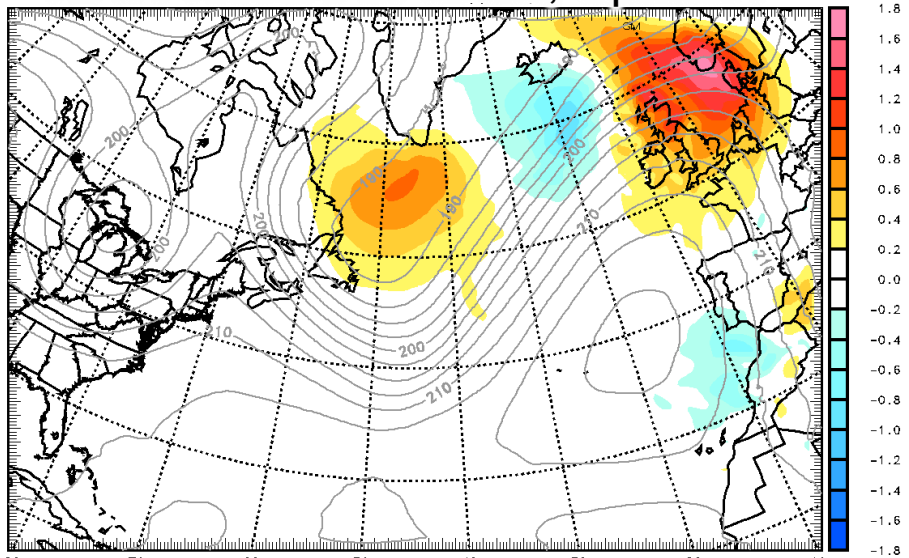
AR/WCB acts as "Amplifier"

48-h 850-hPa Optimal U'+U

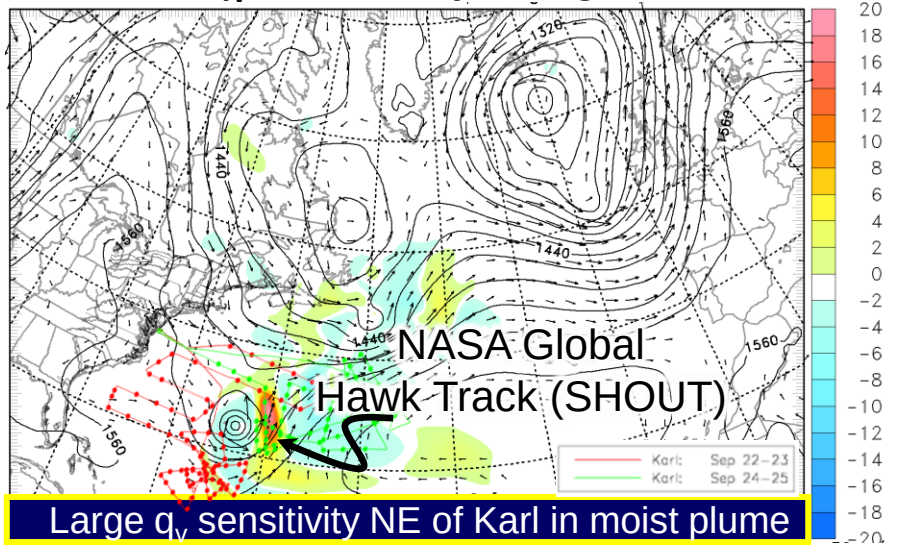


Evolved optimal perturbations lead to a strengthened WCB to > 40 m s^{-1}at 850 hPa

72-h Pressure at 12-km, Optimal P'

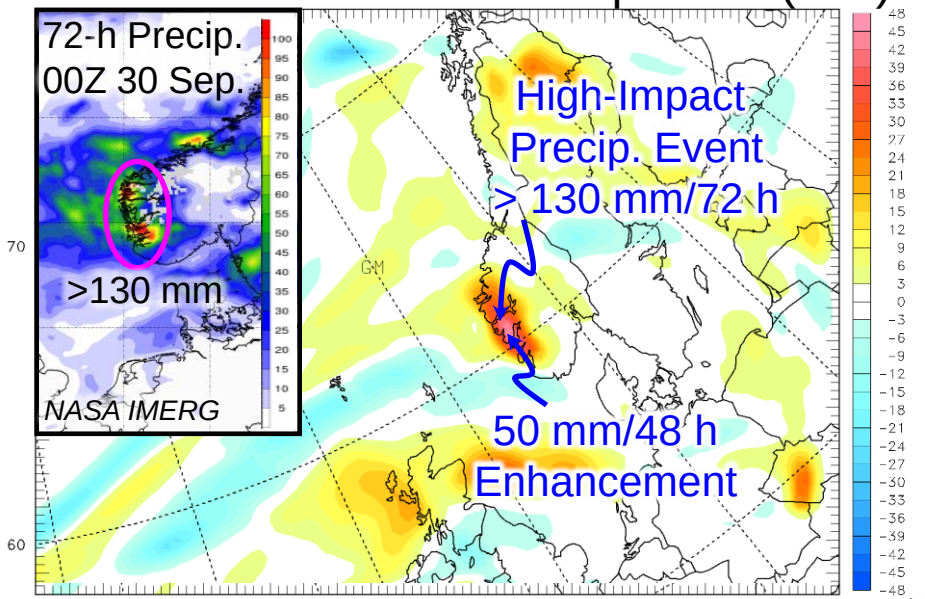


850-hPa q_v Sensitivity, Heights, & Winds



Large q_v sensitivity NE of Karl in moist plume

60-108-h Perturbation Precipitation (mm)

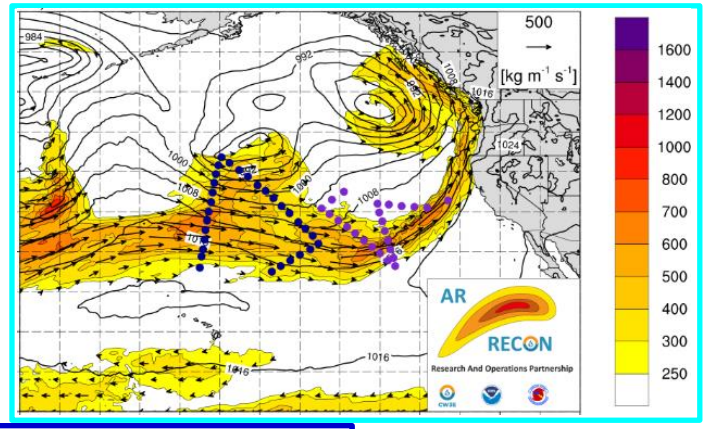


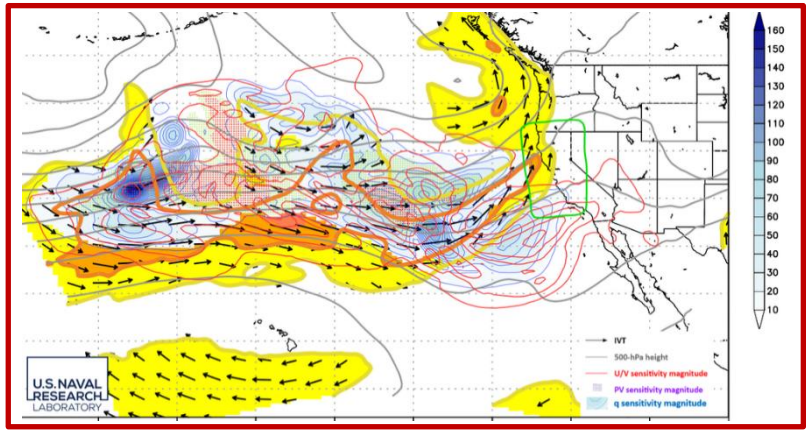
NAWDEX North Atlantic Waveguide and Downstream Impact Experiment

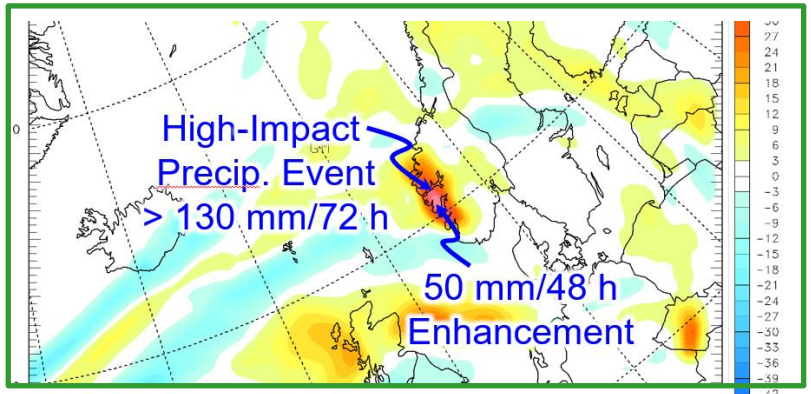
SHOUT (NOAA Sensing Hazards with Operational Unmanned Technology)

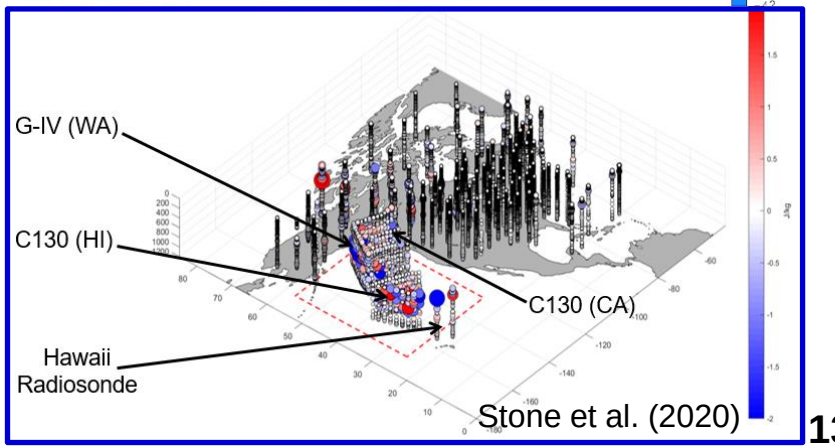
Summary

- 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)







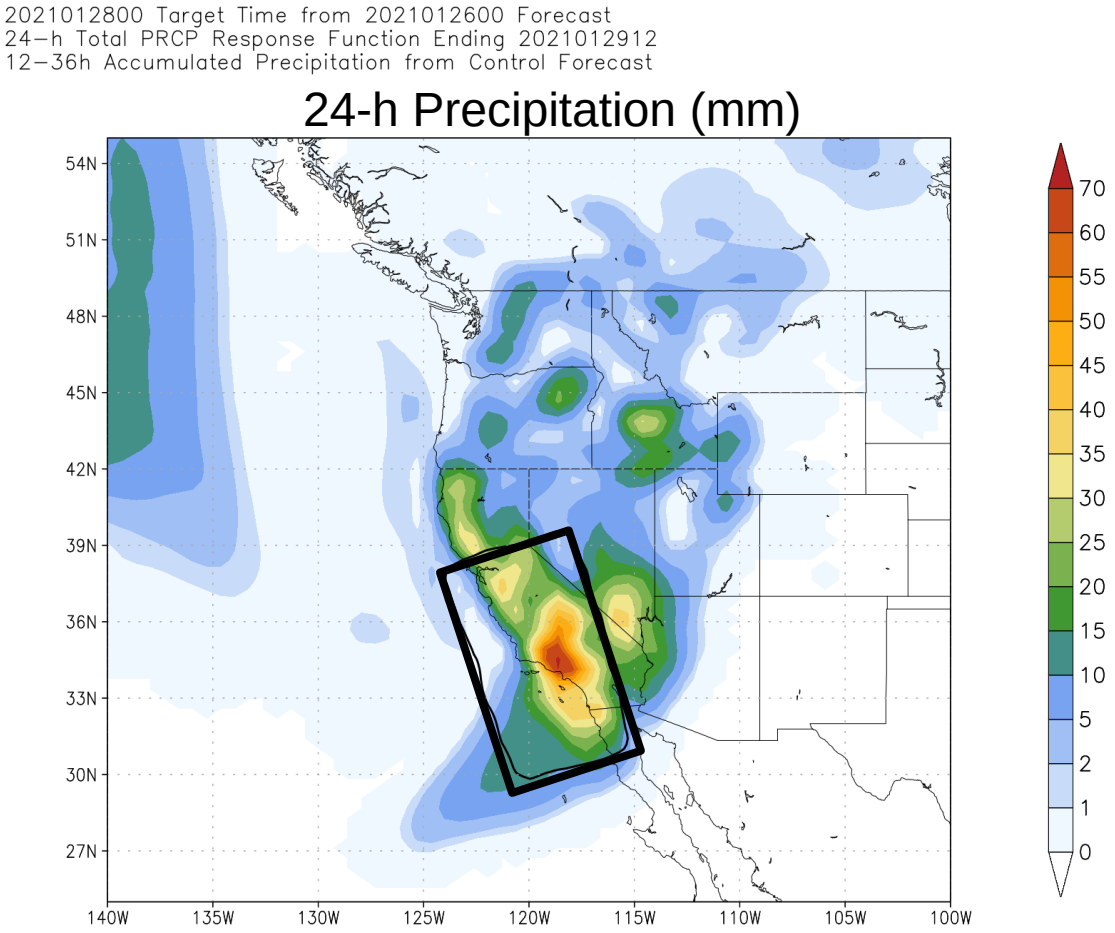


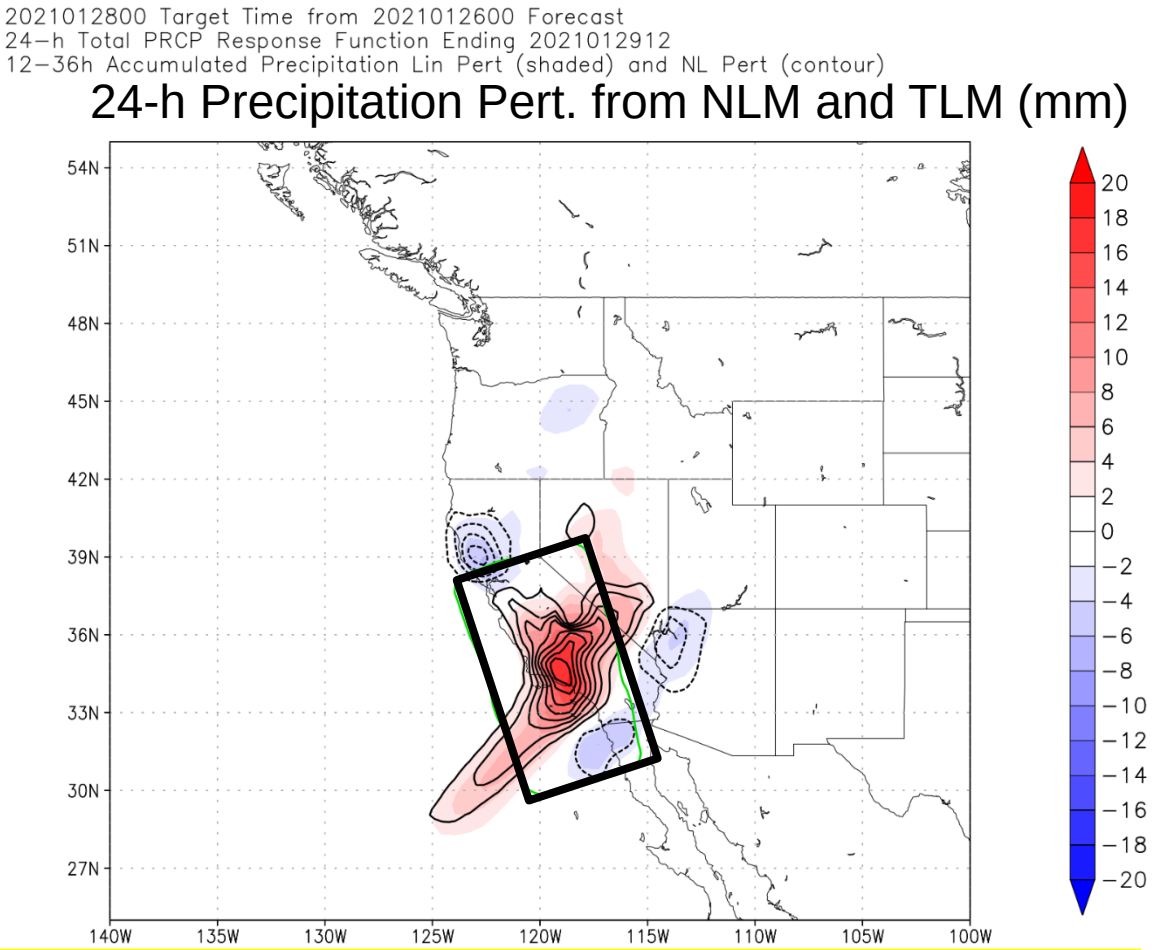
- Adjoint Sensitivity in ARs
  - Sensitive regions of moisture & temperature often strongly project onto diabatically-active areas (ARs & WCBs) leading to fast perturbation & forecast error growth (sensitivity correlated with forecast errors)
  - Rapid growth associated with strong jets, moist baroclinic zones, and ARs
- Future Plans
  - Understand the predictability barriers associated with ARs
  - Explore upstream and inflow characteristics of ARs, and air-sea interaction and boundary layer influences on AR moisture sources

U.S. NAVAL RESEARCH LABORATORY

Extra Slides

Response Function Regions

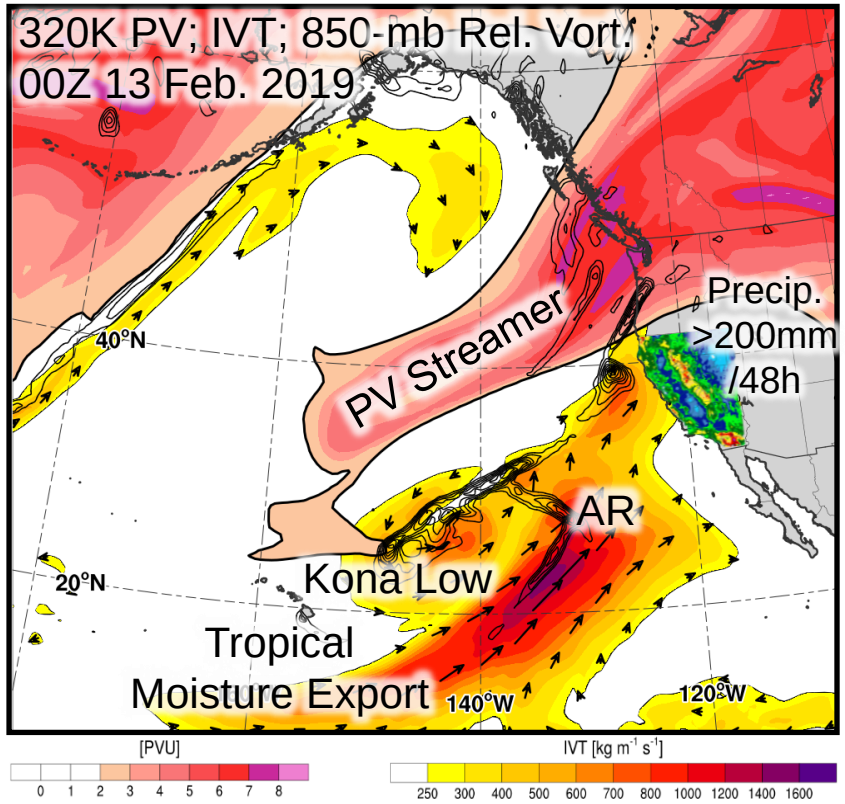




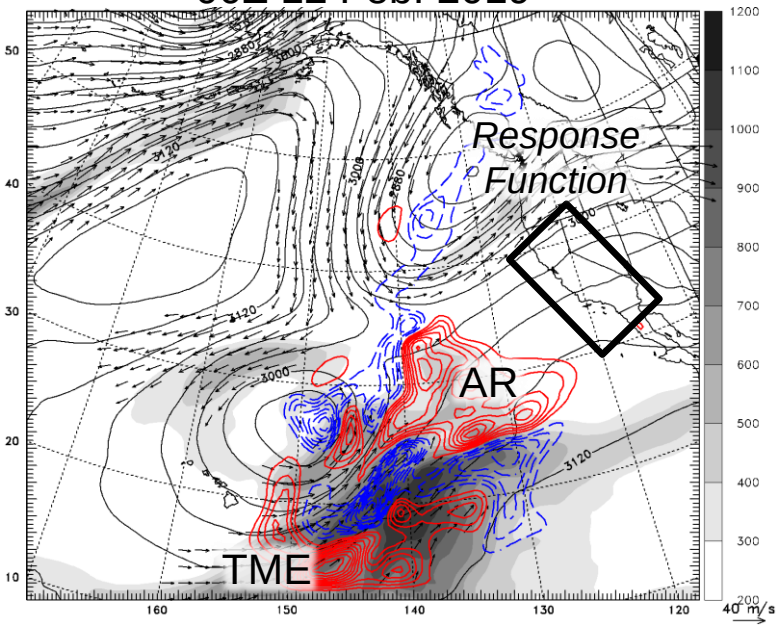
- Larger boxes are better to make sure the sensitivity represents an increase within box (and not a shifts)
- Every adjoint sensitivity run, we make sure the adjoint/TLM is valid by comparing evolved perturbations in NLM (color) and TLM (contours) and the perturbations increase the precipitation
- Growth of the perturbation precipitation is an indicator of how sensitive a forecast is.

Multi-Scale Sensitivity: Valentine's Day 2019

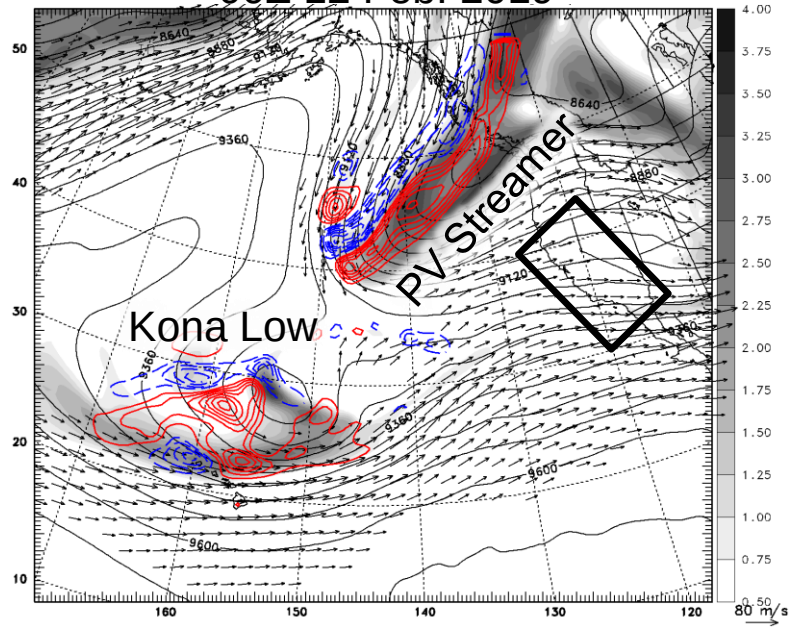
- High-impact forecasts associated with ARs can be very sensitive to the initial state, even for short-range forecasts
- We focus on a high-impact event during the AR Recon from Feb. 11-15, 2019 and utilize the NRL COAMPS® mesoscale model and moist adjoint system to explore the predictability of this heavy precipitation event.
- Goal is to quantify the predictability of this heavy precipitation event (Feb. 2019) along U.S. West Coast that featured an AR, Tropical Moisture Export (TME), Kona Low, and PV streamer
- How do multi-scale dynamics: PV Streamer, Kona Low, Tropical Moisture Export (TME), and AR impact the predictability of the downstream heavy precipitation in California?



700-hPa q_v Sensitivity (red/blue), IVT (gray), 700-hPa Heights, Winds
00Z 12 Feb. 2019



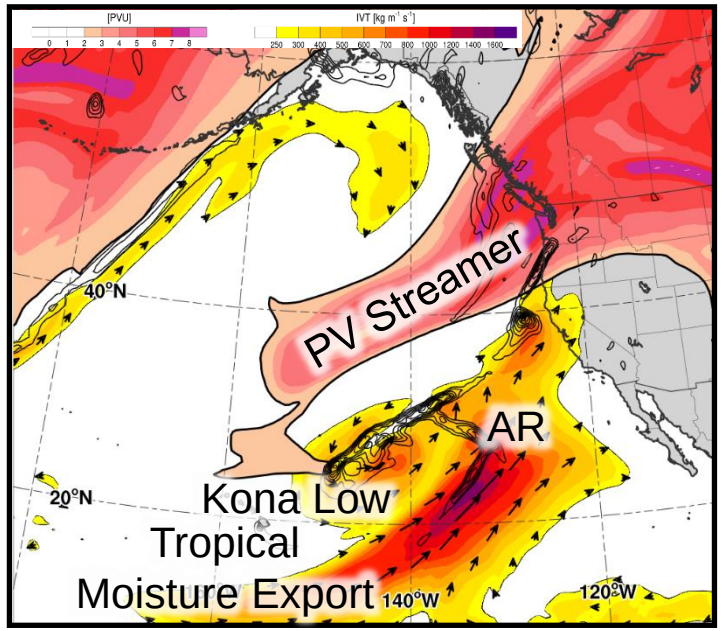
300-hPa PV Adjoint Perturbation, PV (gray), 300-hPa Heights, Winds
00Z 12 Feb. 2019



Atmospheric Rivers: AR Recon

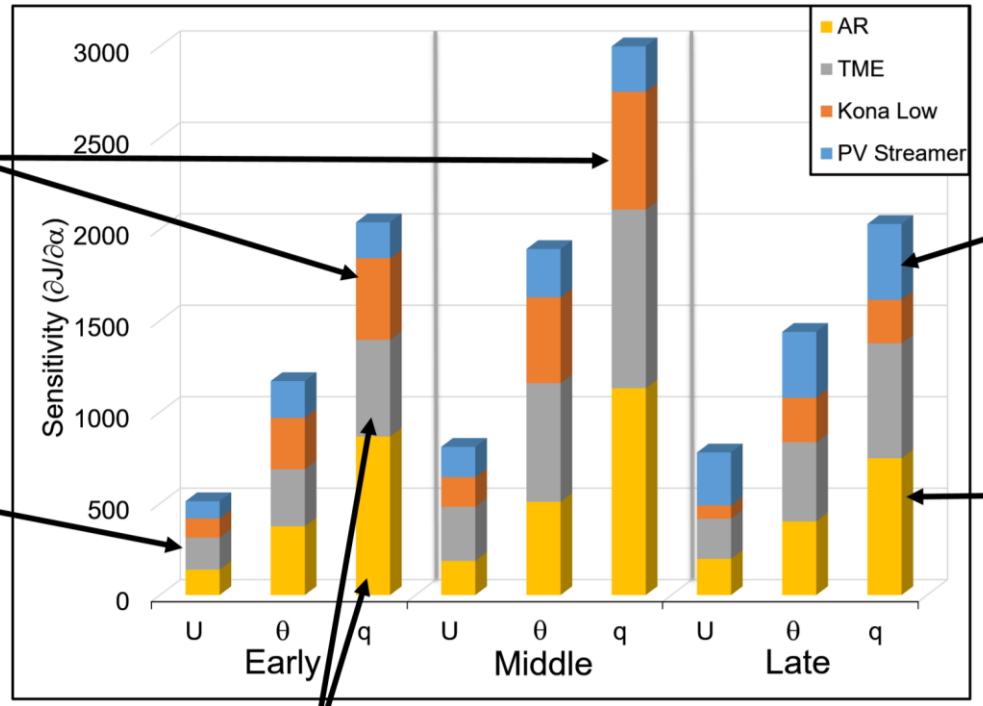
Valentine's Day Flooding Event
February 2019

320K PV; IVT 850-hPa Relative Vorticity
00Z 13 Feb. 2019



Kona Low sensitivity greatest in the early and middle periods

- Wind sensitivity smaller than θ and q sensitivity
- Moisture is most sensitive variable



PV Streamer has growing importance in late period

Moisture sensitivity is less dominant during late stage

AR sensitivity is largest followed by TME sensitivity

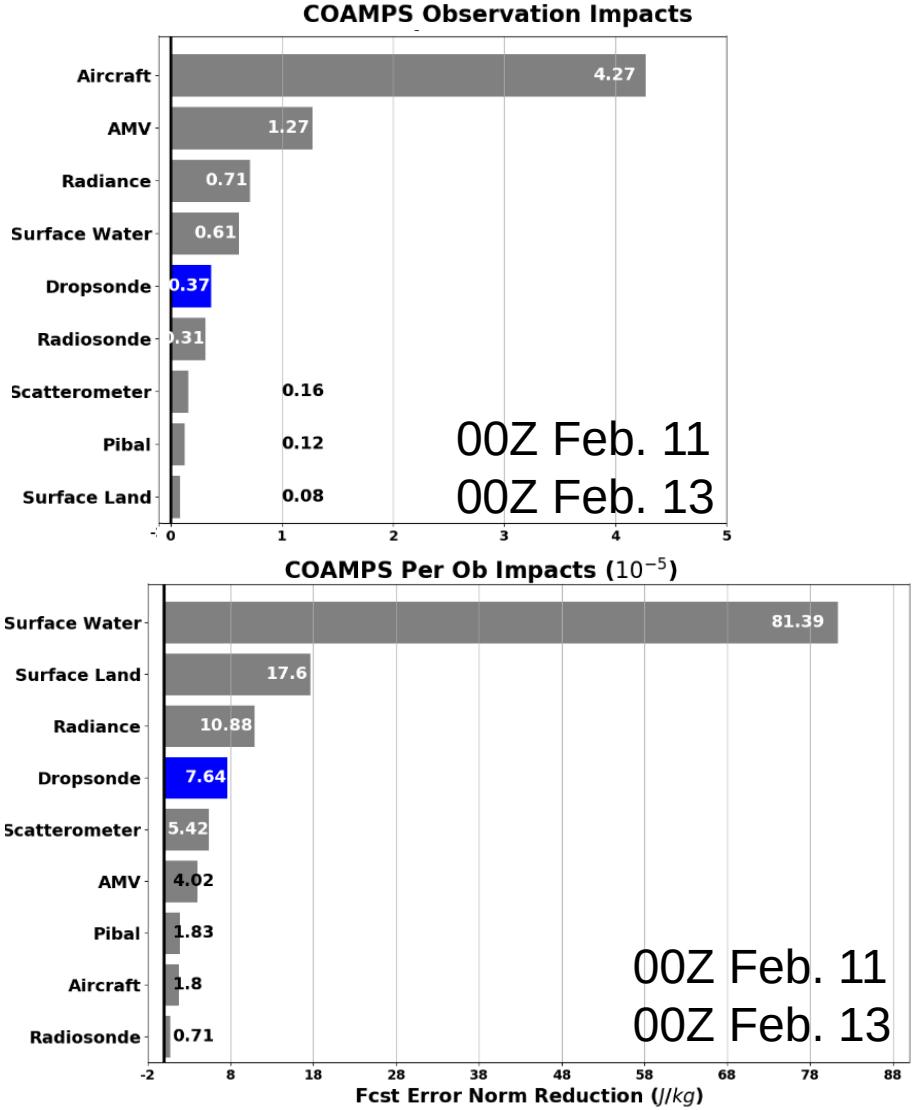
Middle period has strongest sensitivities

- AR Recon is a multi-agency effort to to improve short-term AR forecasts on the U.S. West Coast
- NRL COAMPS adjoint sensitivity was used along with other products to inform flight plans. Sensitivity typically highlighted lower-tropospheric moisture in/near ARs and Warm Conveyor Belts (WCBs)
- High-impact event exhibiting large model forecast differences. Adjoint showed sensitivity to all three features
  - Kona Low, tropical moisture export (ascending WCB), PV streamer, and phasing of PV anomalies

Observation Impact: Valentine's Day 2019

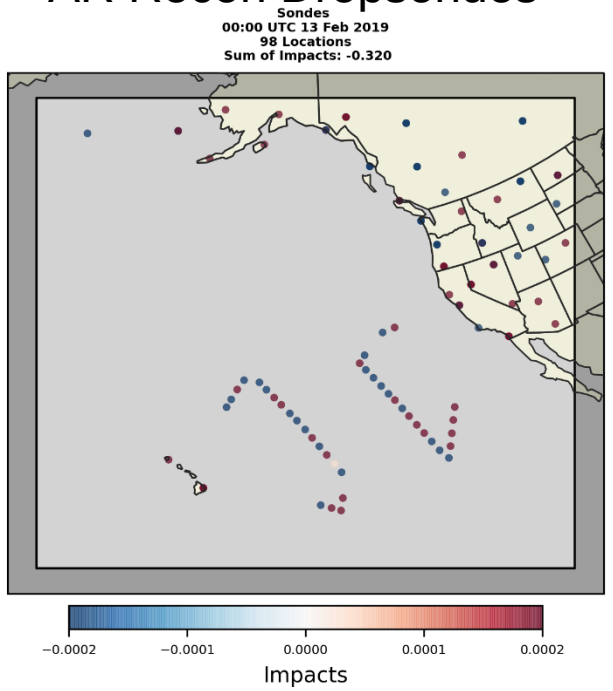
COAMPS 24-h Observation Impacts

Moist Energy Error Norm

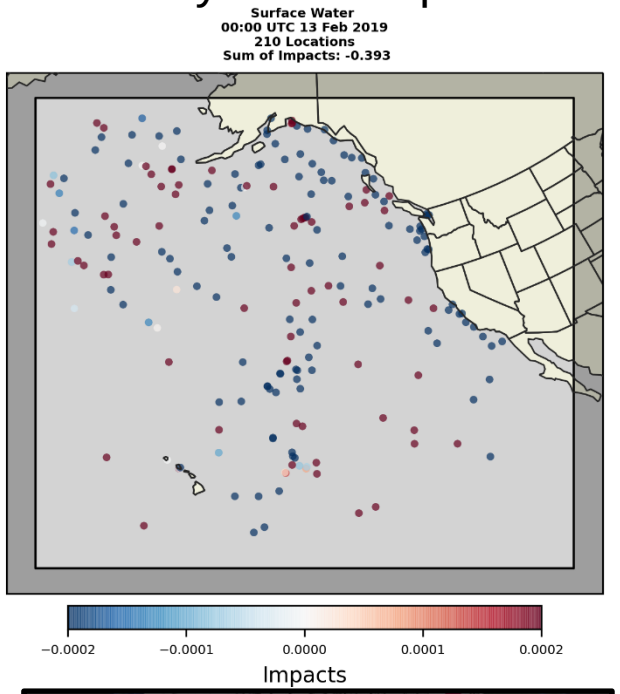


COAMPS 24 h Observation Impacts 00Z 13 Feb. 2019

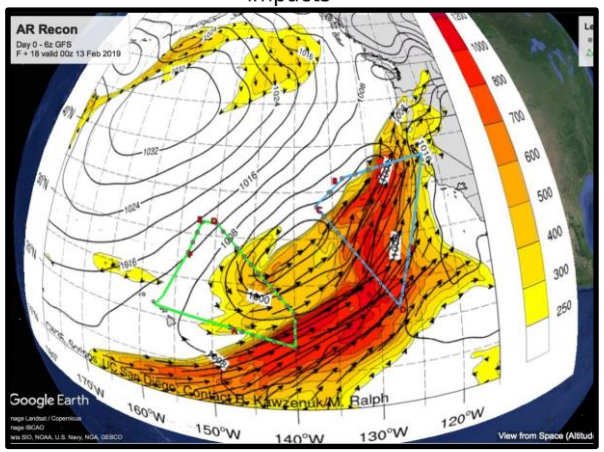
AR Recon Dropsondes



Buoys and Ships



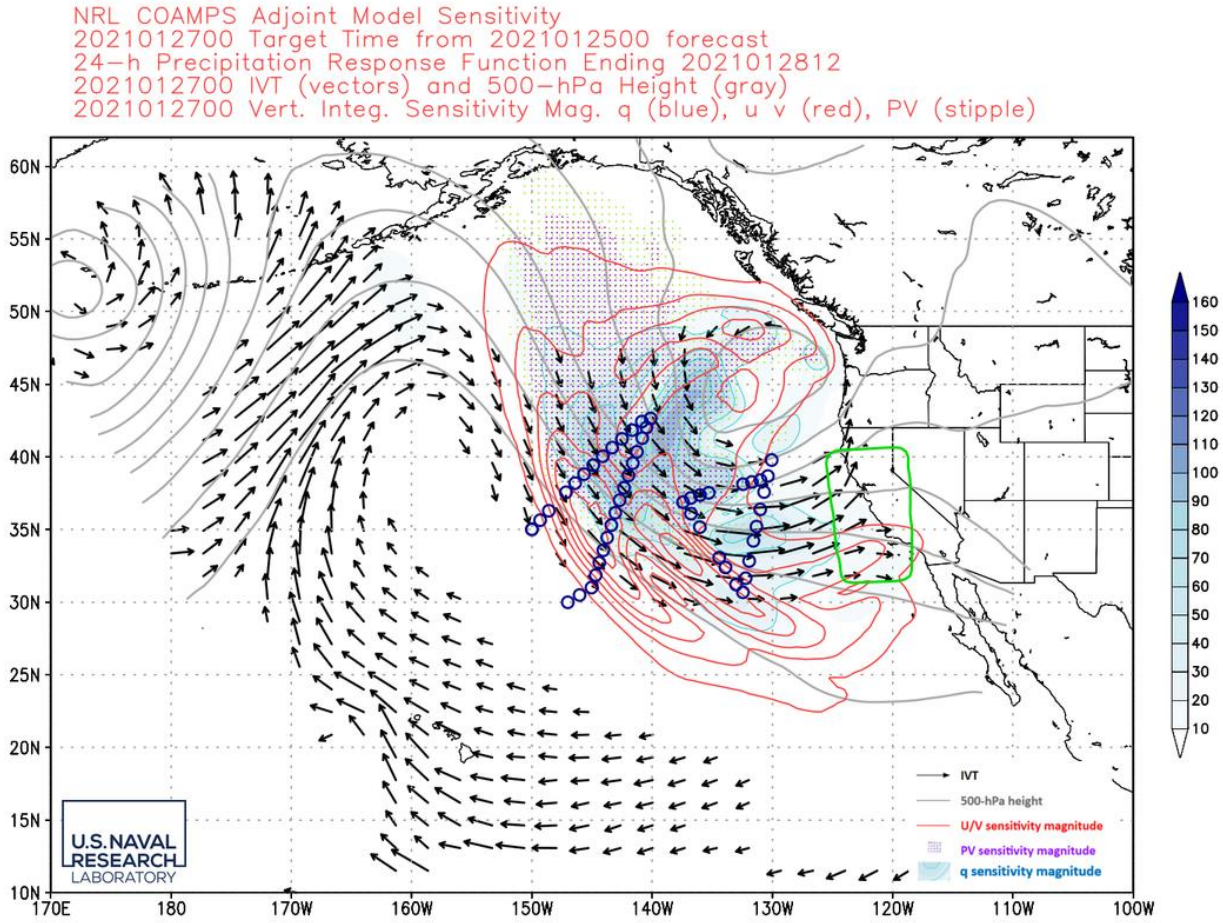
AR Recon Dropsondes are the most beneficial *in situ* profile observation (per observation and overall for the 11 & 13 Feb. IOPs)



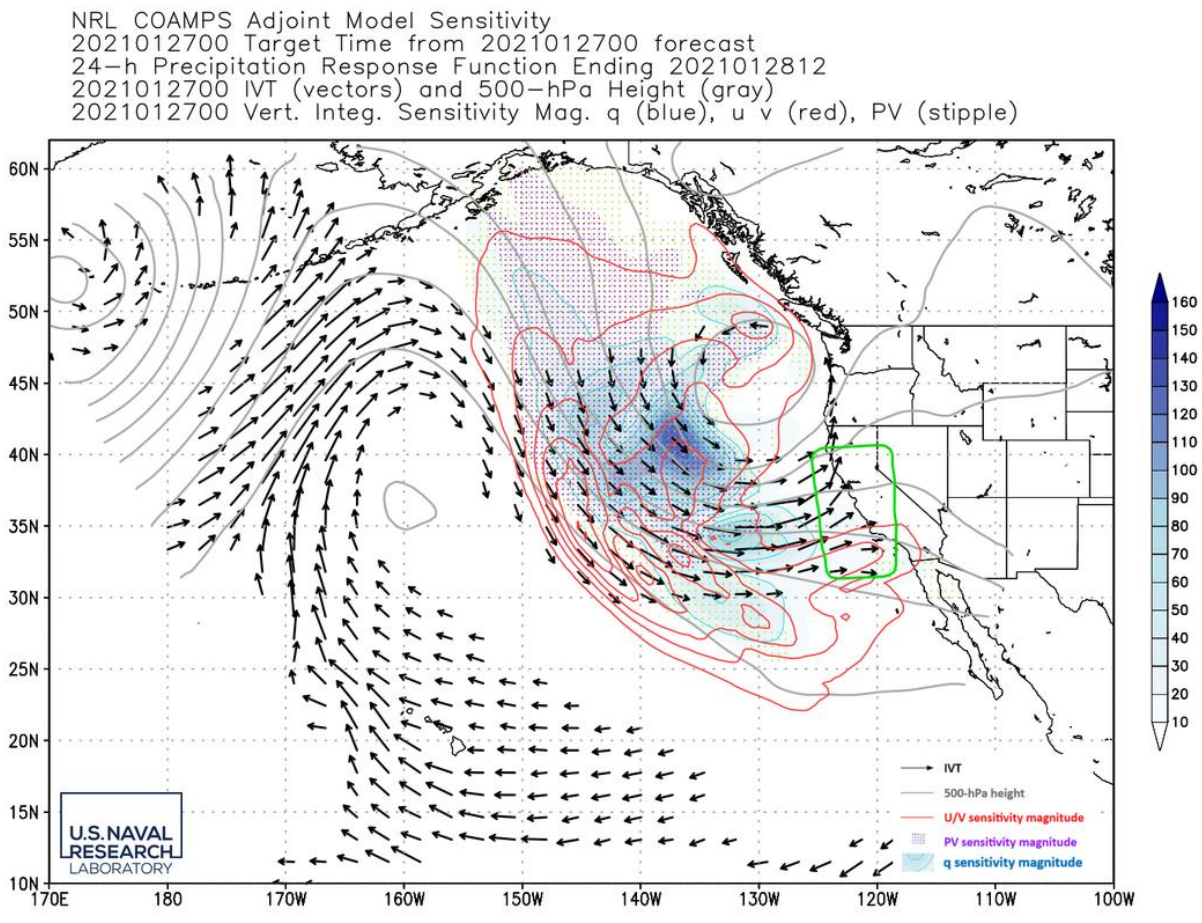
Lead Time

How Does the Sensitivity Vary with Lead Time

48-h Lead Time

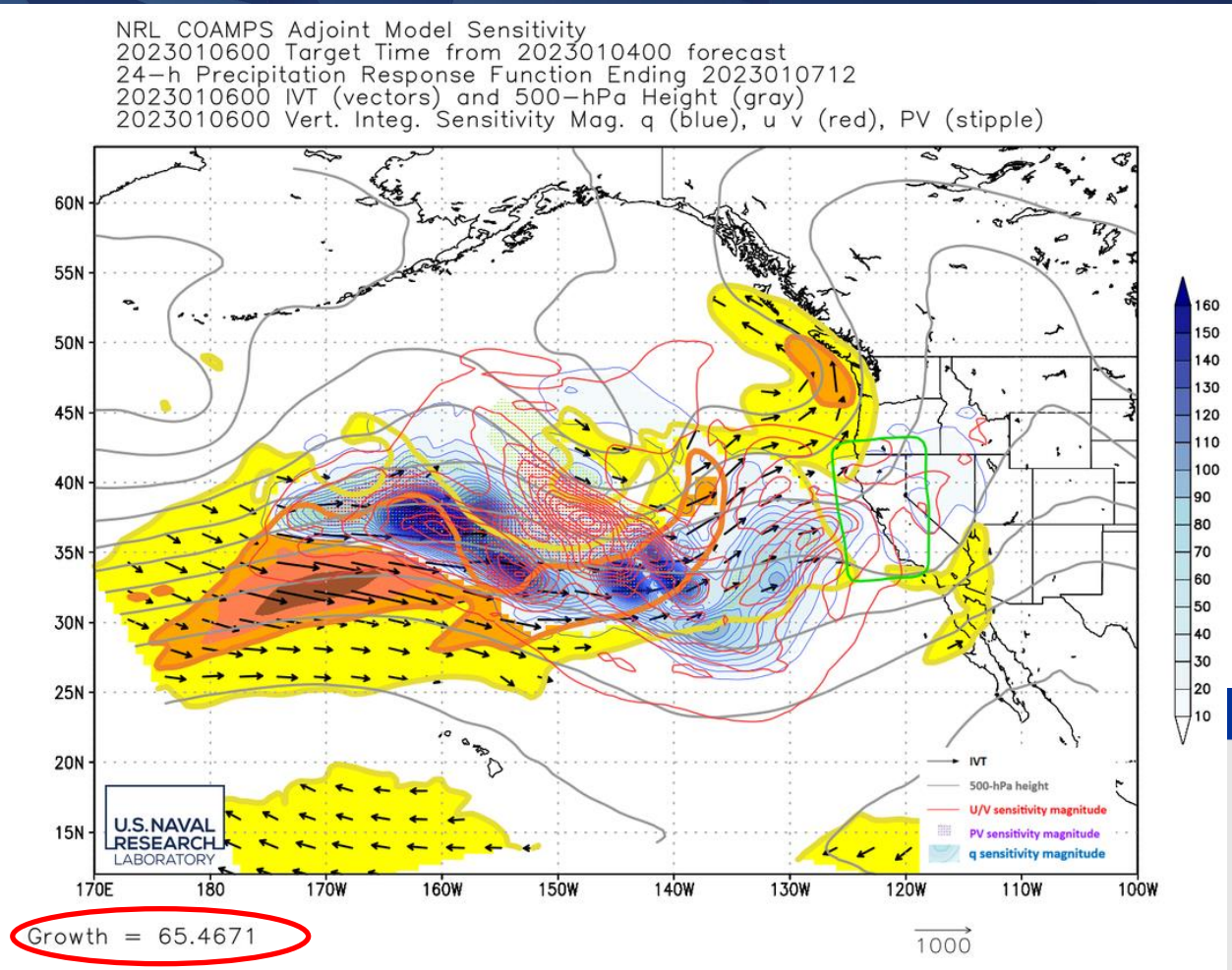


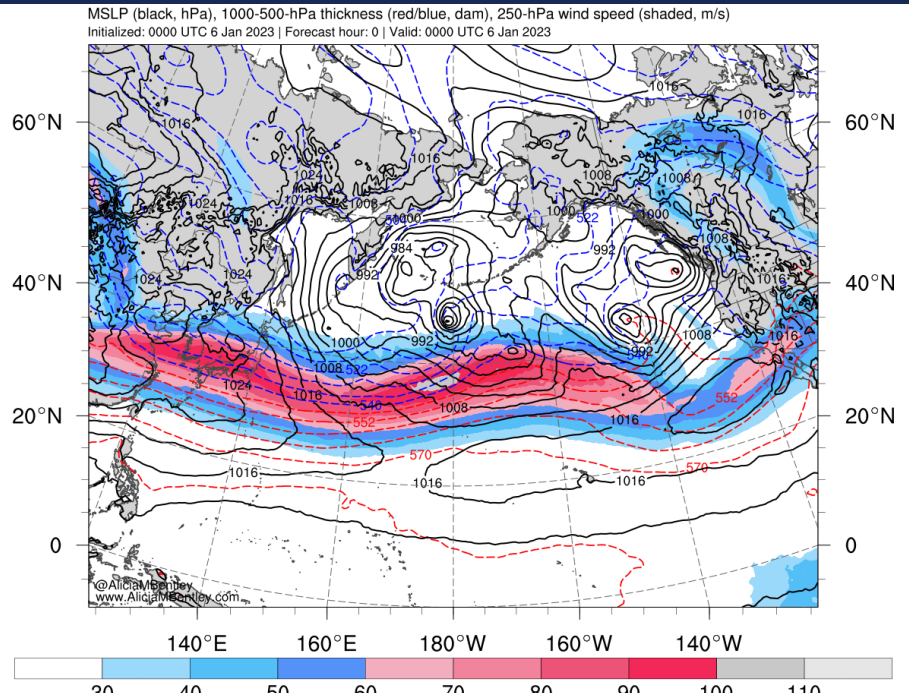
0-h Lead Time

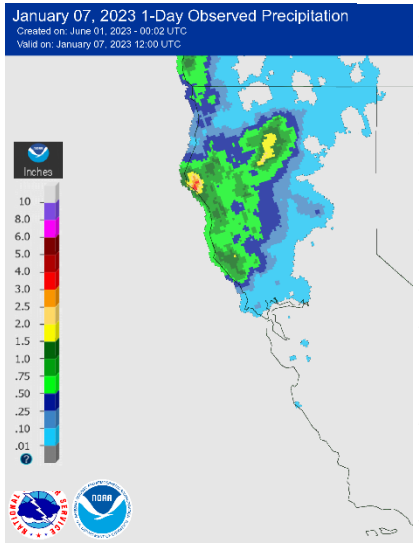


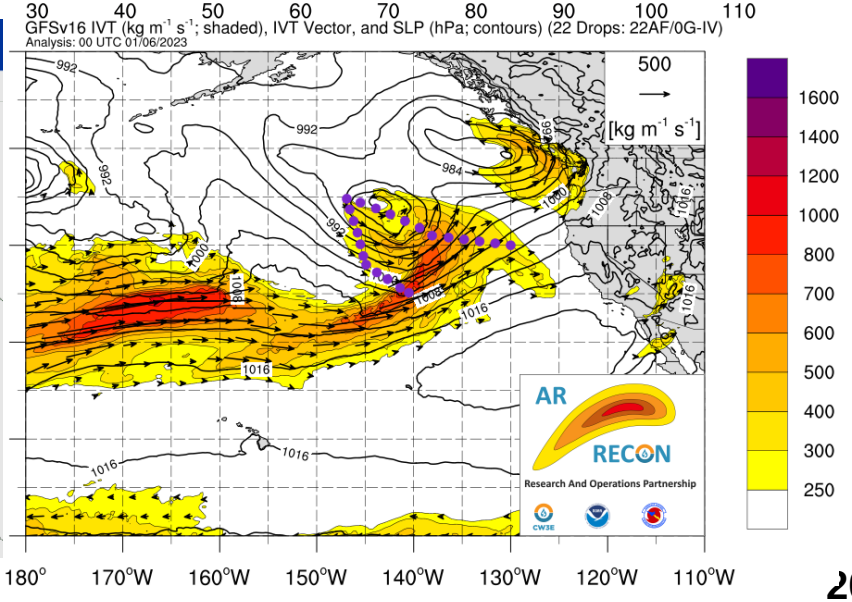
- Some difference in the sensitivity details due to the lead time used, but overall pattern similar

Adjoint Sensitivity: Jan. 6 (IOP 6)



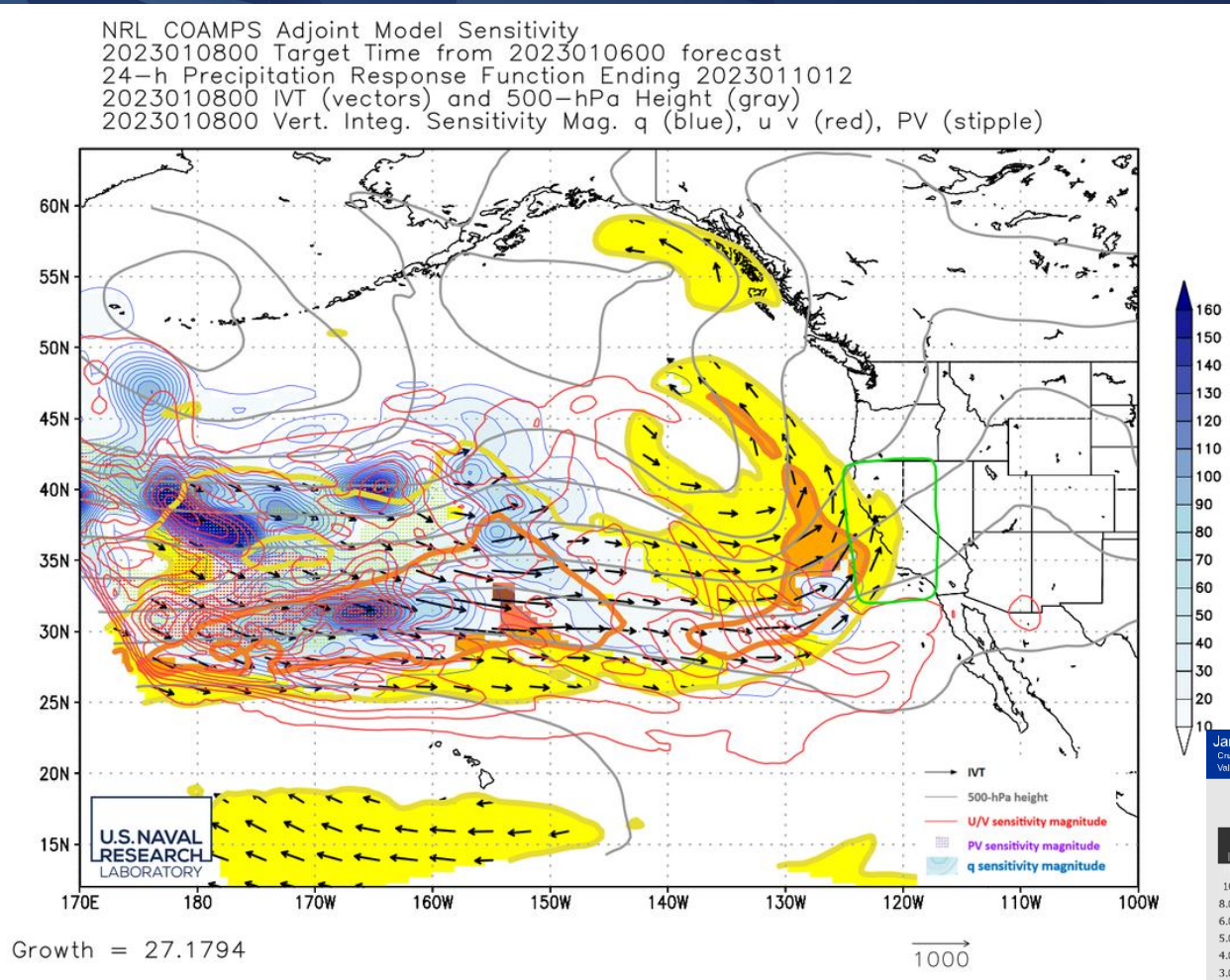


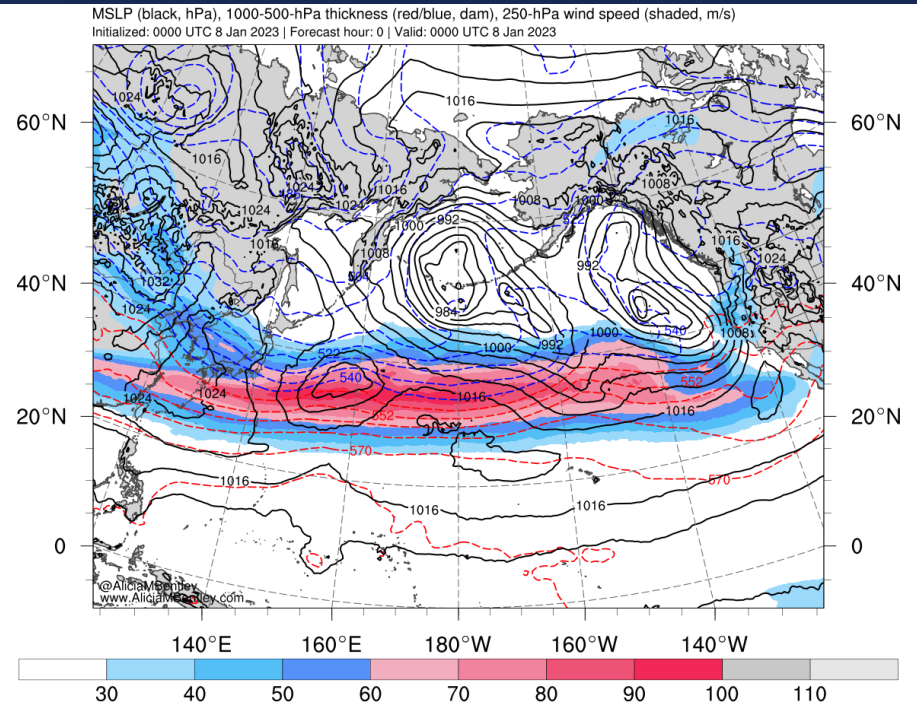


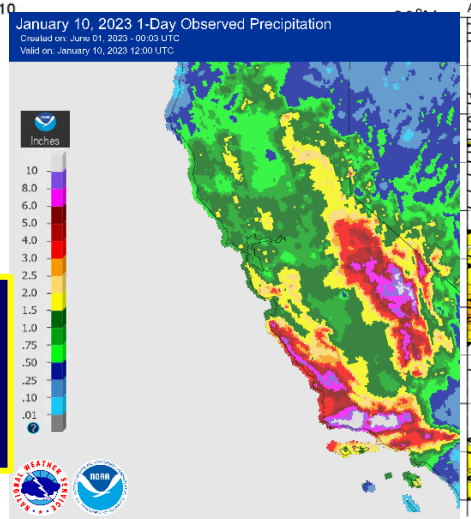


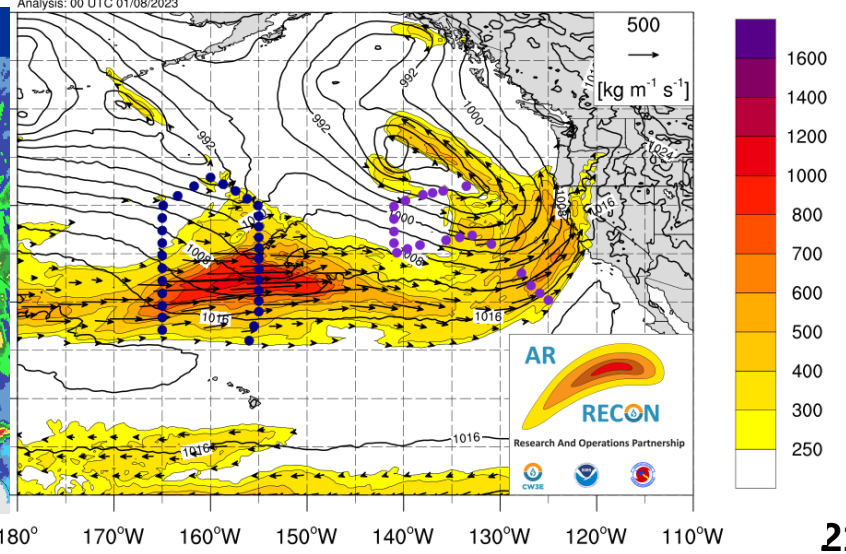
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Strong sensitivity near shortwave troughs (PV) in AR core and on cold-side near the strong dynamics

Adjoint Sensitivity: Jan. 8 (IOP 8)



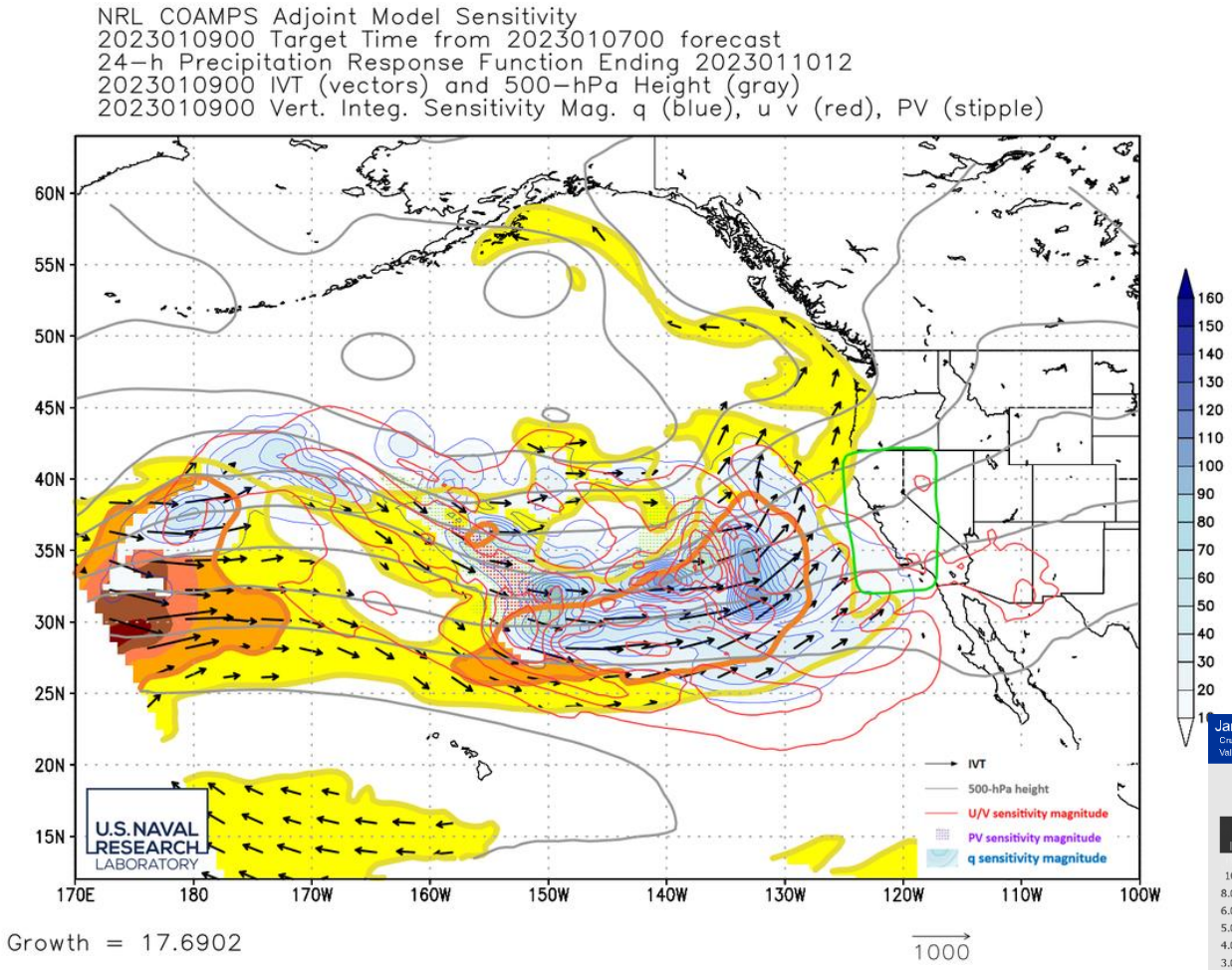


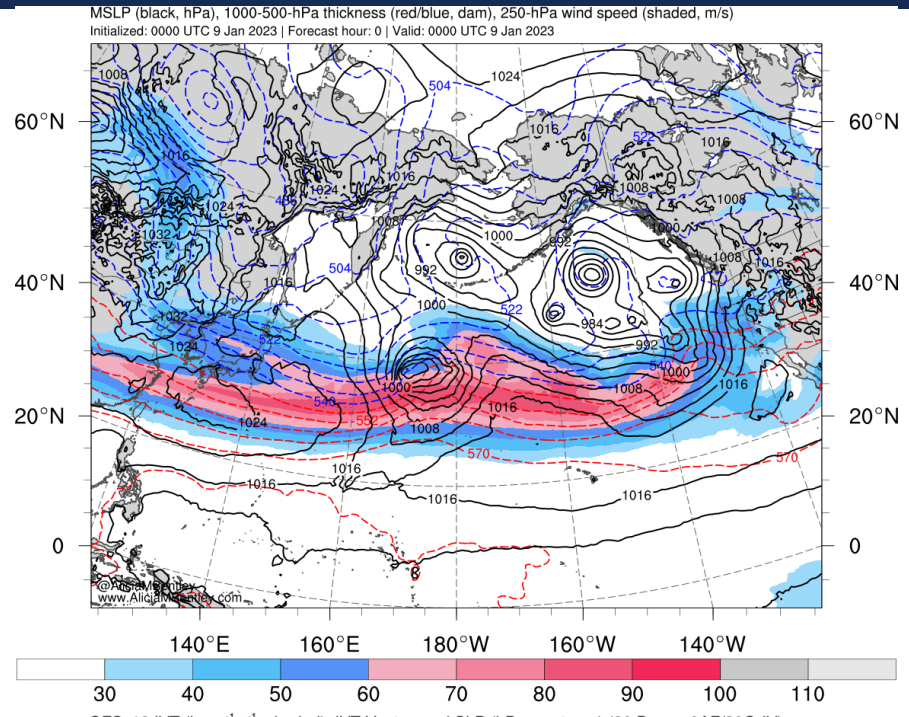


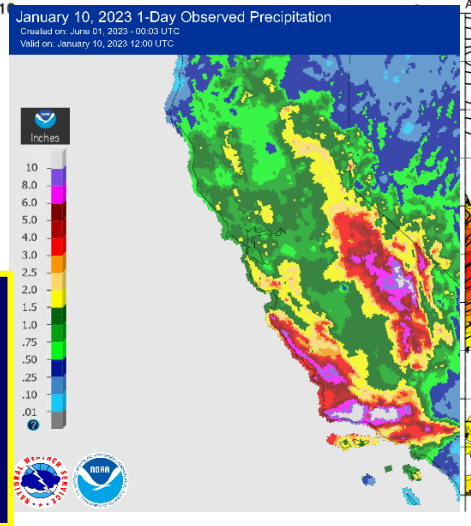


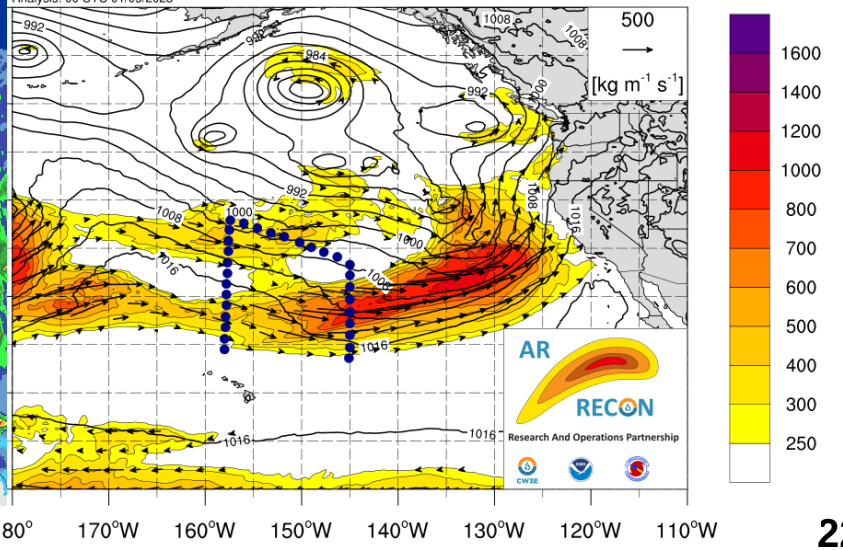
- Exceptionally strong jet and AR across the Pacific
- Strong growth rate (60-h sensitivity)
- Sensitivity located well upstream of West Coast

Adjoint Sensitivity: Jan. 9 (IOP 9)



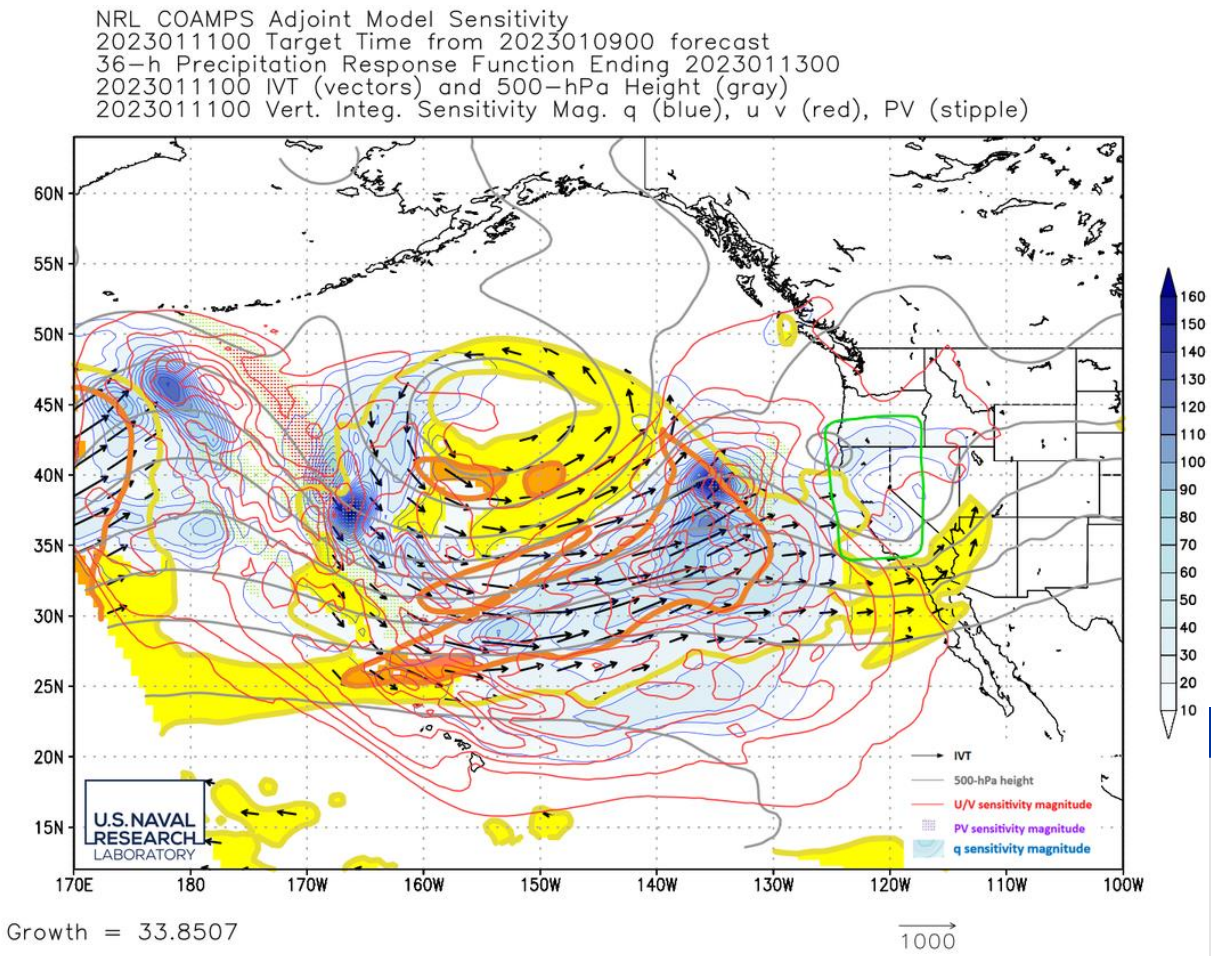


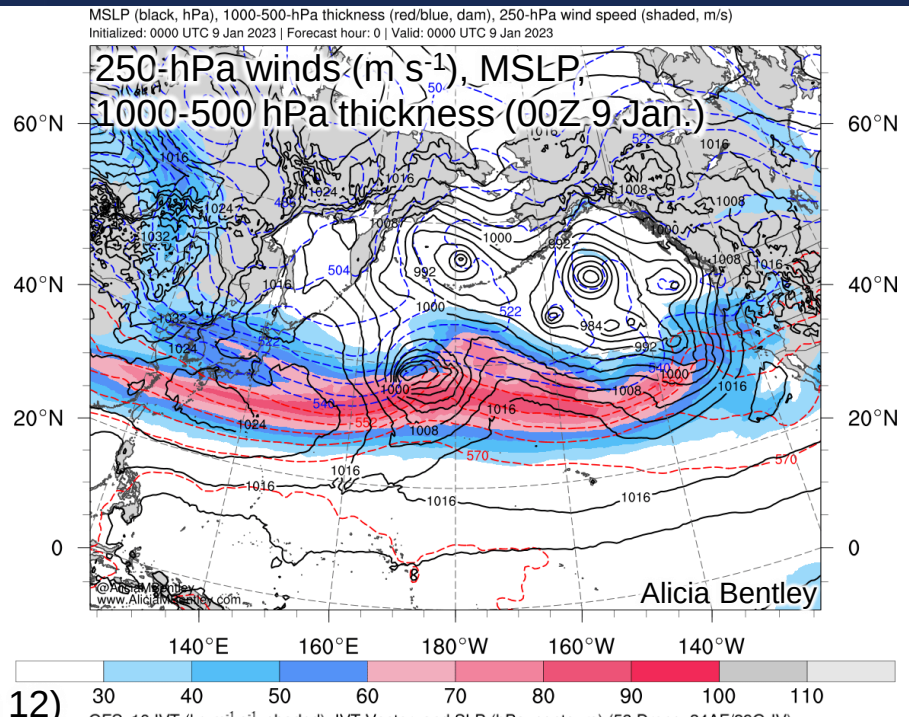


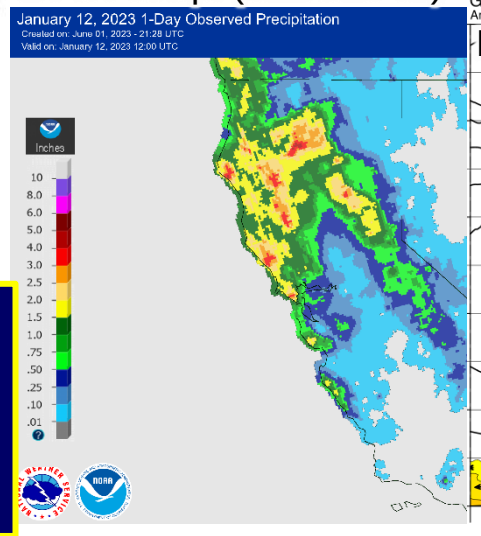


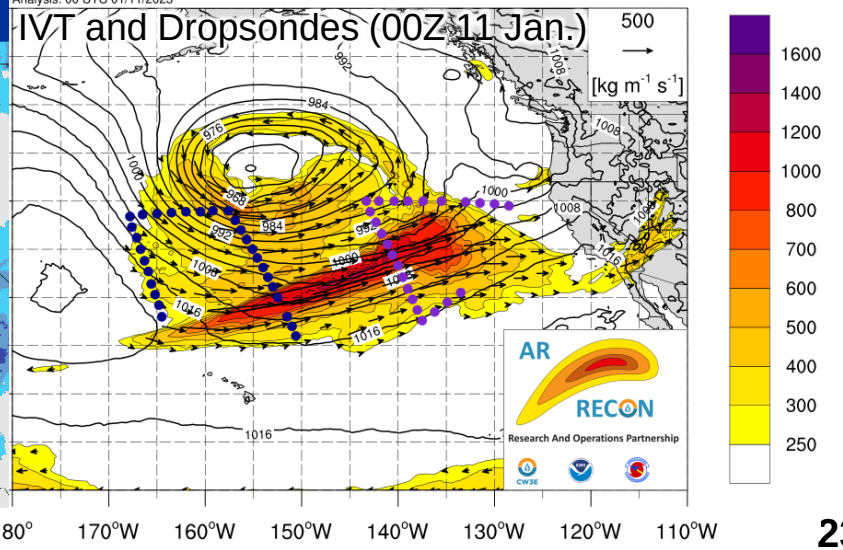
- Exceptionally strong jet and AR across the Pacific
- Moderate growth rate (36-h sensitivity)
- Sensitivity concentrated in AR and extending upstream into the next AR and shortwave

Adjoint Sensitivity: Jan. 11 (IOP 11)



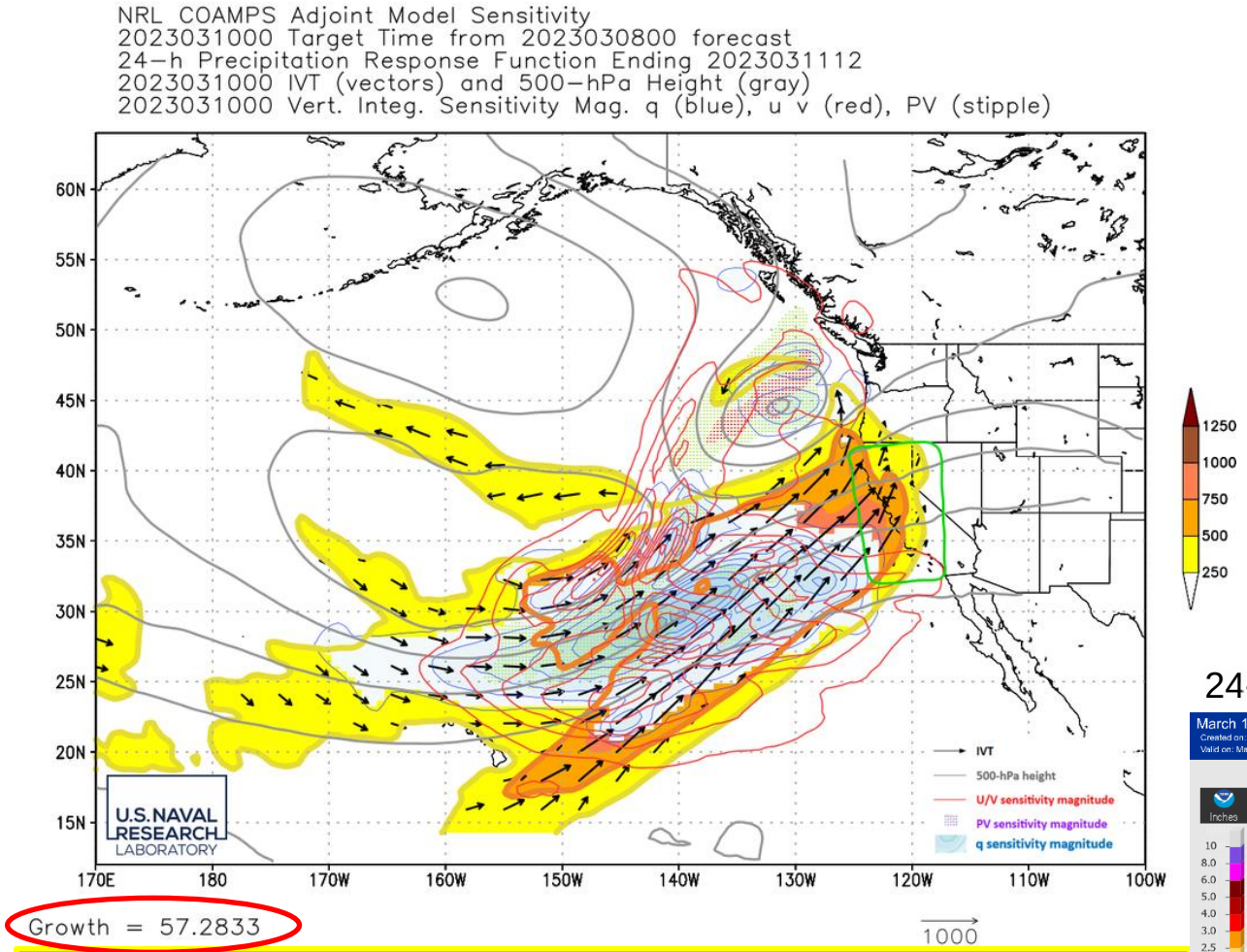


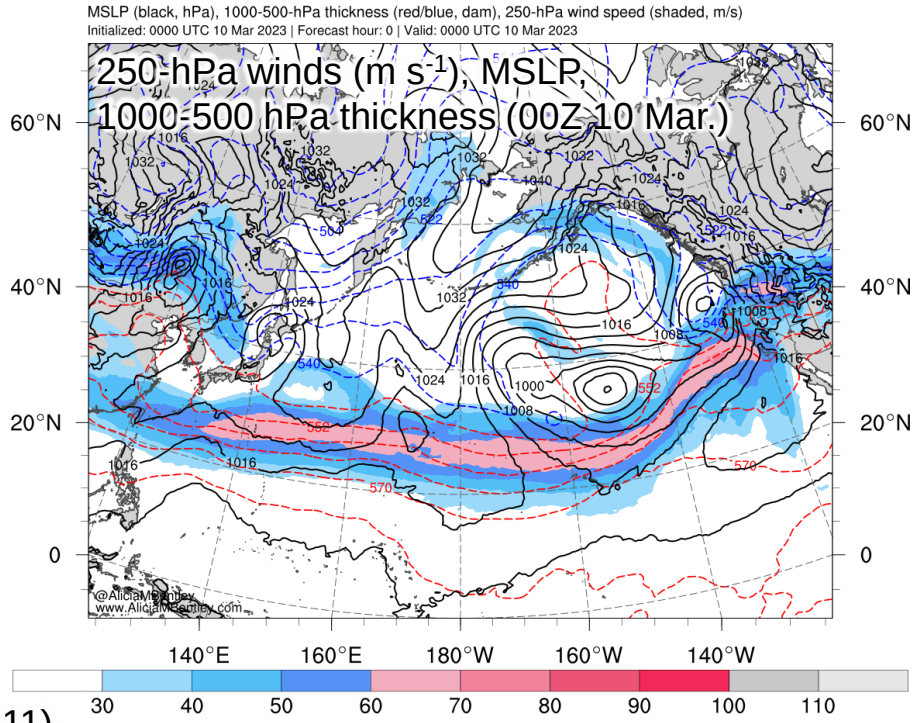




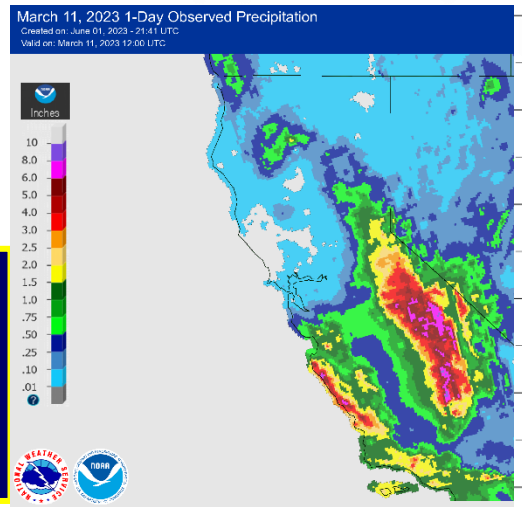
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (48-h sensitivity, 36-h RF)
- Sensitivity concentrated in AR and extends upstream ahead of the next AR and shortwave

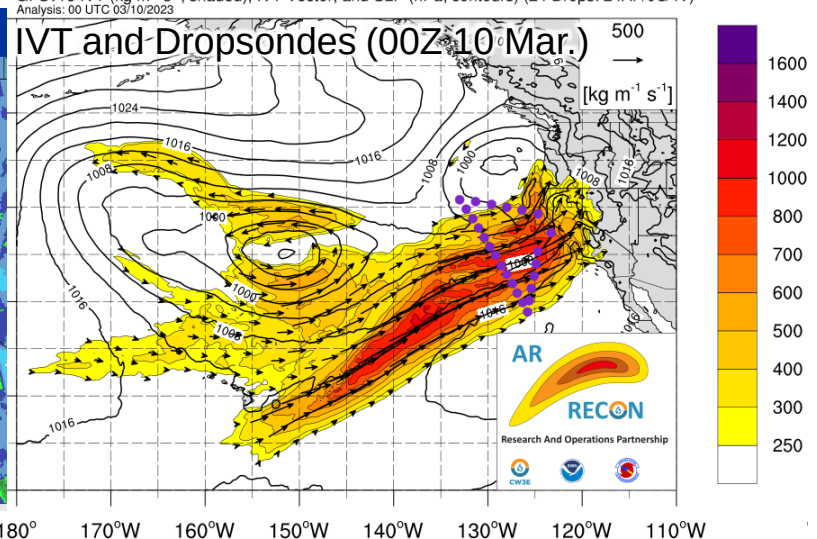
Adjoint Sensitivity: Mar. 10 (IOP 36)





24-h Precip. (12Z Mar. 11)



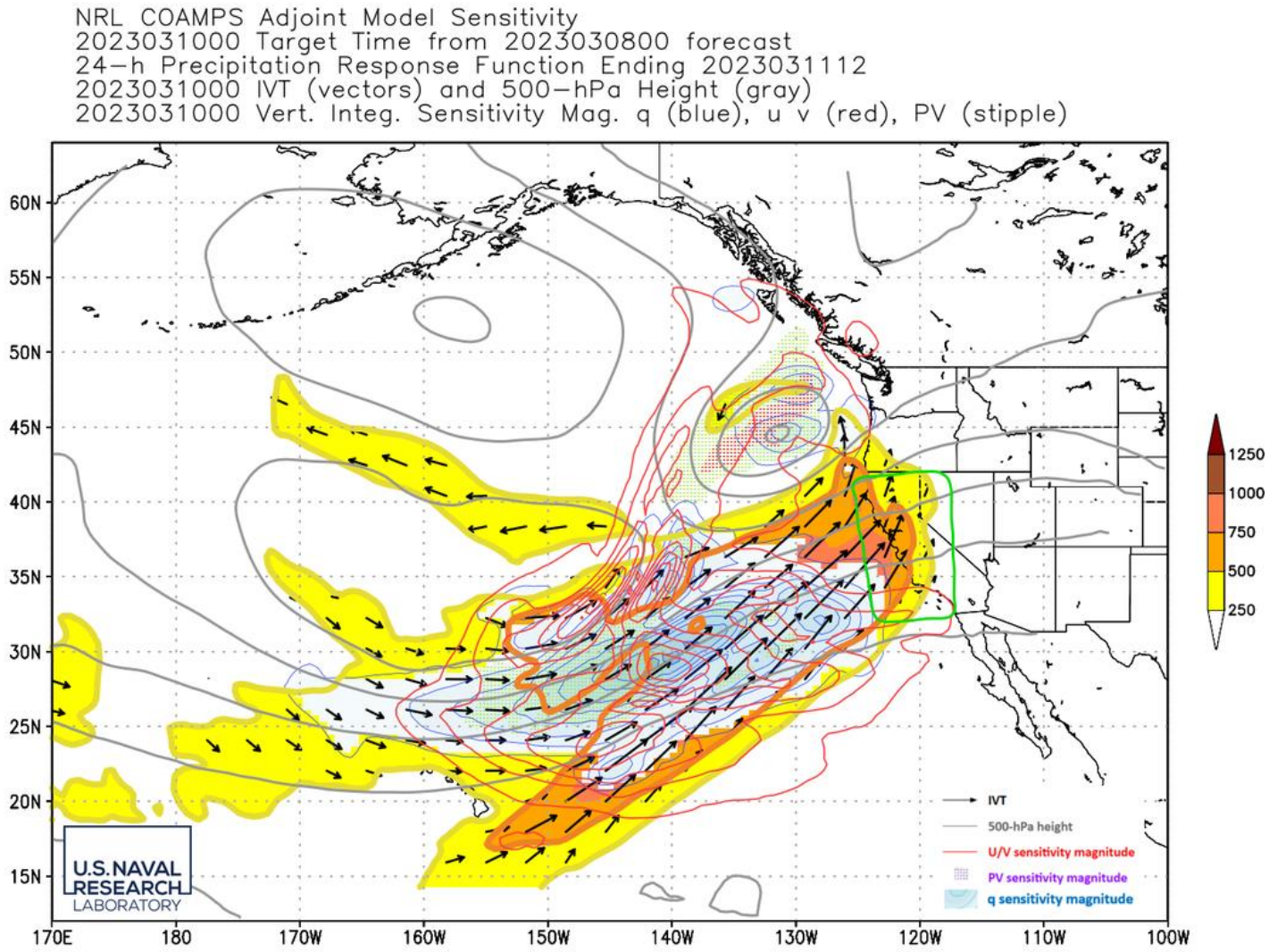


- Strong jet and AR directed from sub-tropics
- Extreme growth rate (36-h sensitivity)
- Sensitivity concentrated in AR core and in the strong shortwave trough along the NW coast

COAMPS Adjoint Sensitivity Summary Graphic

Adjoint Summary Graphic

IVT Vectors (250/500)
500-hPa Height (gray)
Response Function
Vertically Integrated
Sensitivity:
|q| (blue shading)
|u|+|v| (red contours)
|PV| (stipple)
(moderate/strong)



Growth Metric

Growth = 57.2833