

Diagnosing Forecast Sensitivity of Atmospheric Rivers Using an Adjoint

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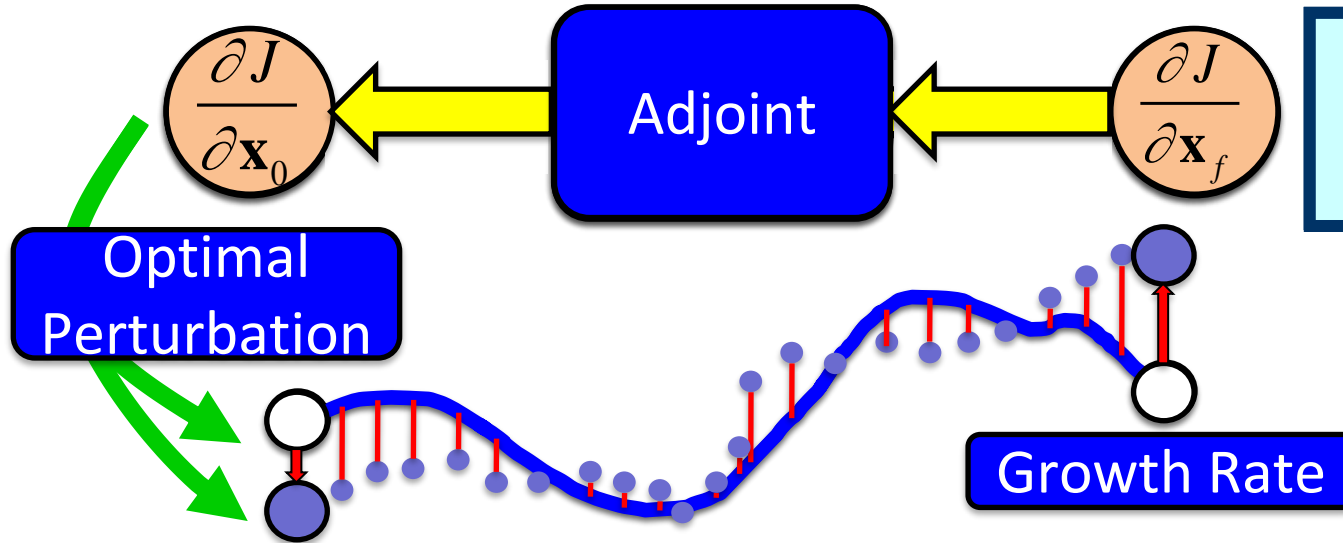
- **What are Adjoint?**
- **2023 Adjoint Sensitivity Summary**
- **Sensitivity Highlights and Energetics**
- **Summary and Future Plans**

*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

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Adjoint Sensitivity



Adjoint is transpose of the TLM, and evolves the gradient of a response function (J) with respect to \mathbf{x}_f

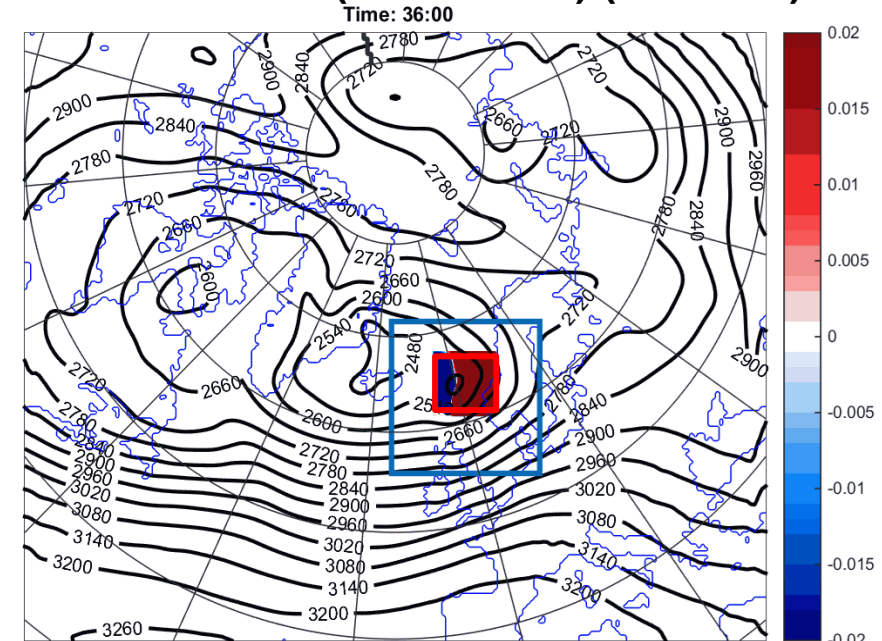
$$\frac{\partial J}{\partial \mathbf{x}_0} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}_f}$$

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

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}

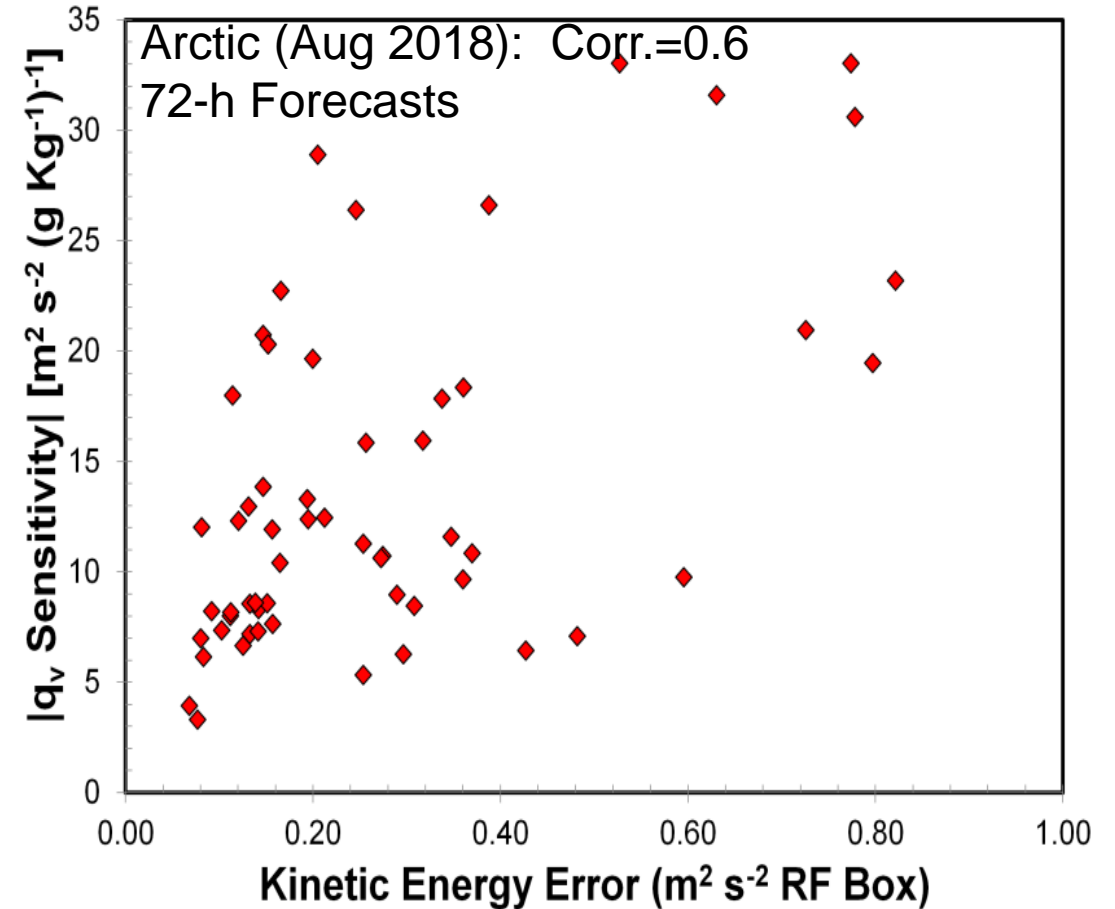
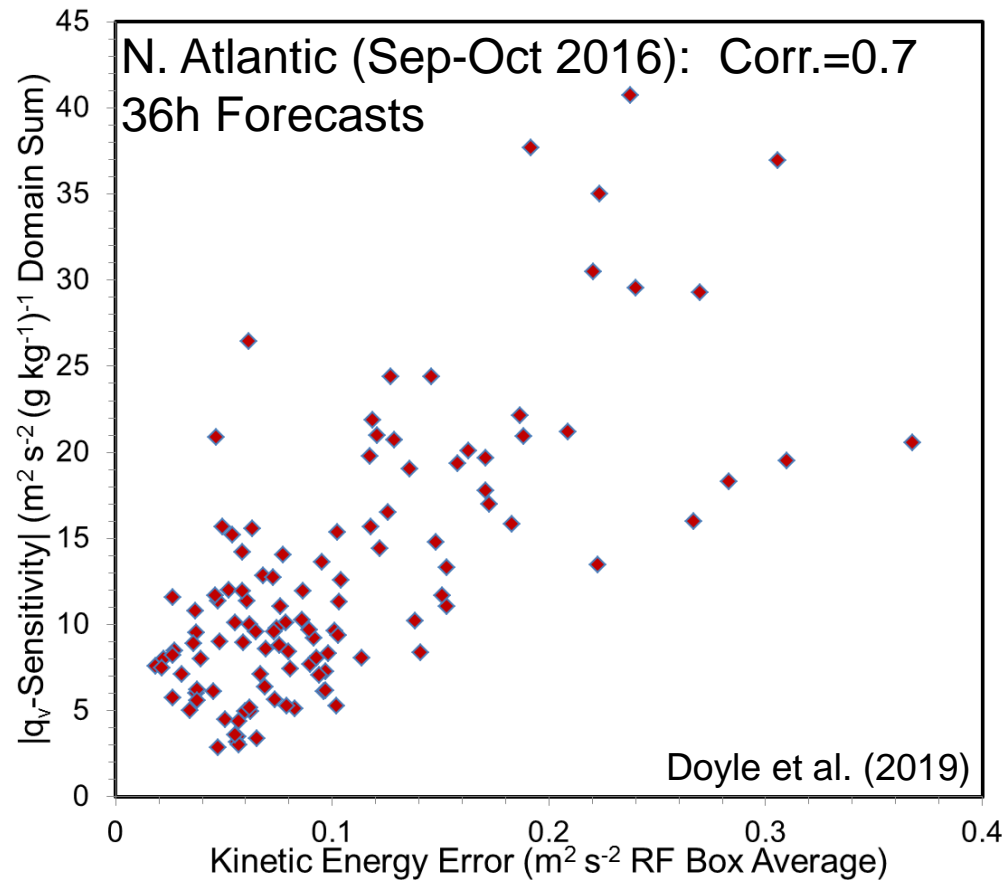
9-10 Jan 2015 (Storm Nina) (36 to 0 h)



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

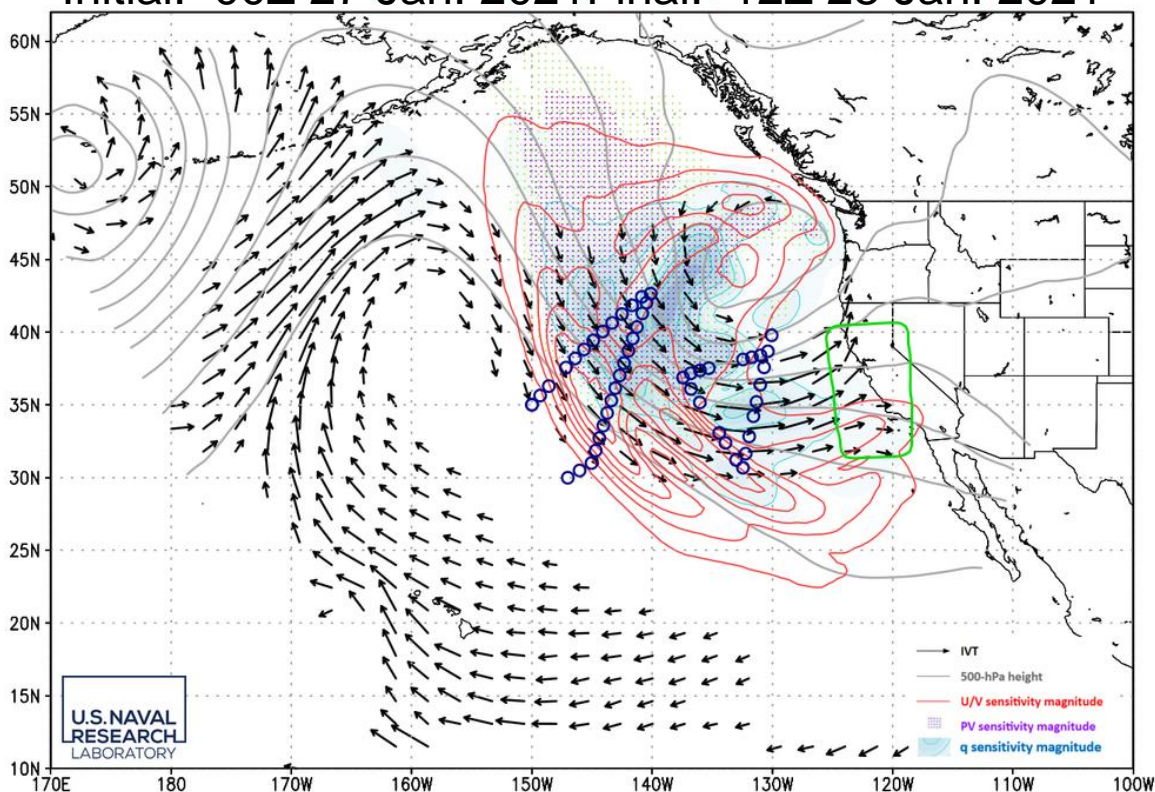
How Does the Sensitivity Vary with Optimization Time?

36-h Optimization Time

60-h Optimization Time

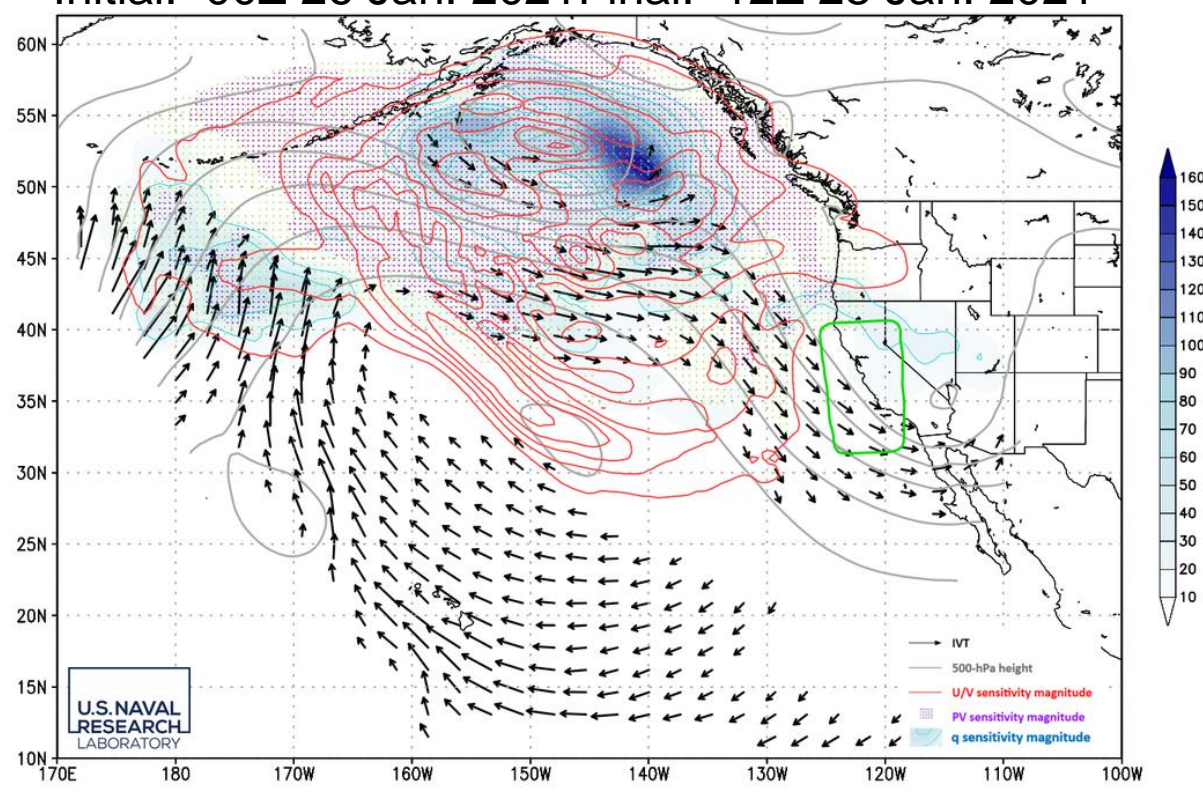
Precipitation Response Function

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



Precipitation Response Function

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

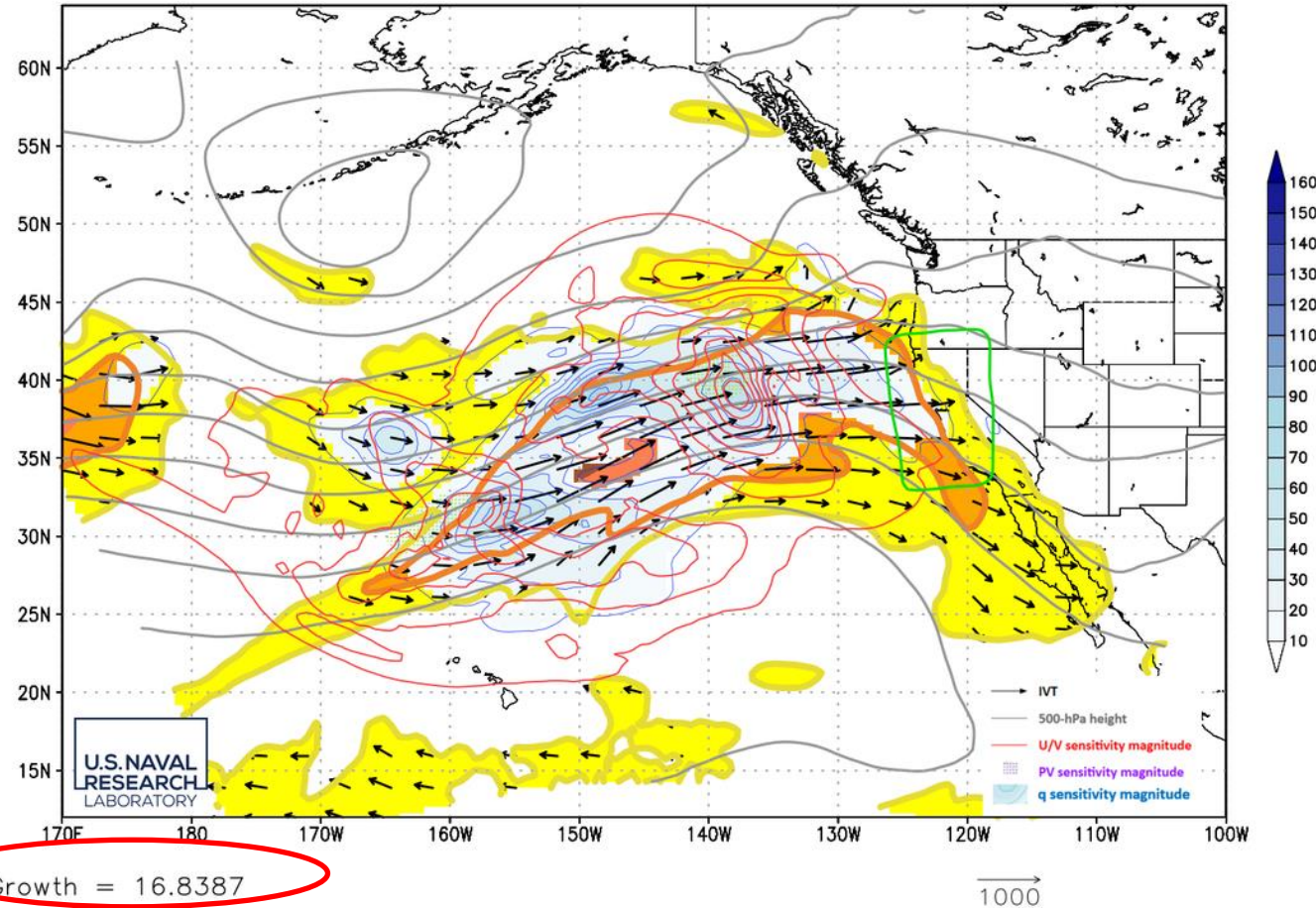


- Typical optimization times used for the COAMPS adjoint is 36-h during AR-Recon
- Longer optimization times result in sensitivity that is further upstream and difficult for aircraft to reach

NRL Adjoint Sensitivity Summary Graphic

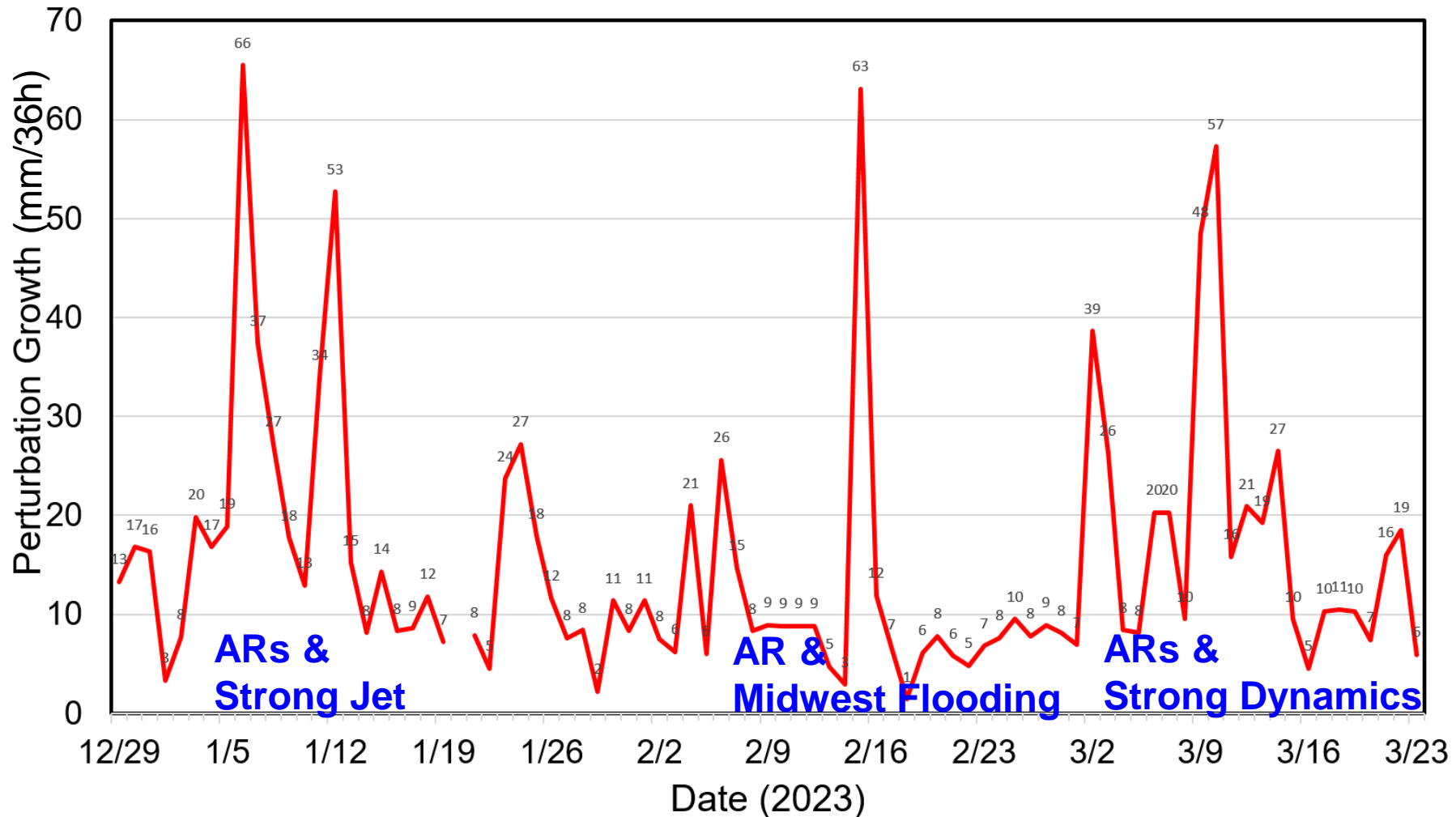
NRL COAMPS Adjoint Model Sensitivity
 2022123000 Target Time from 2022122800 forecast
 24-h Precipitation Response Function Ending 2022123112
 2022123000 IVT (vectors) and 500-hPa Height (gray)
 2022123000 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)

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

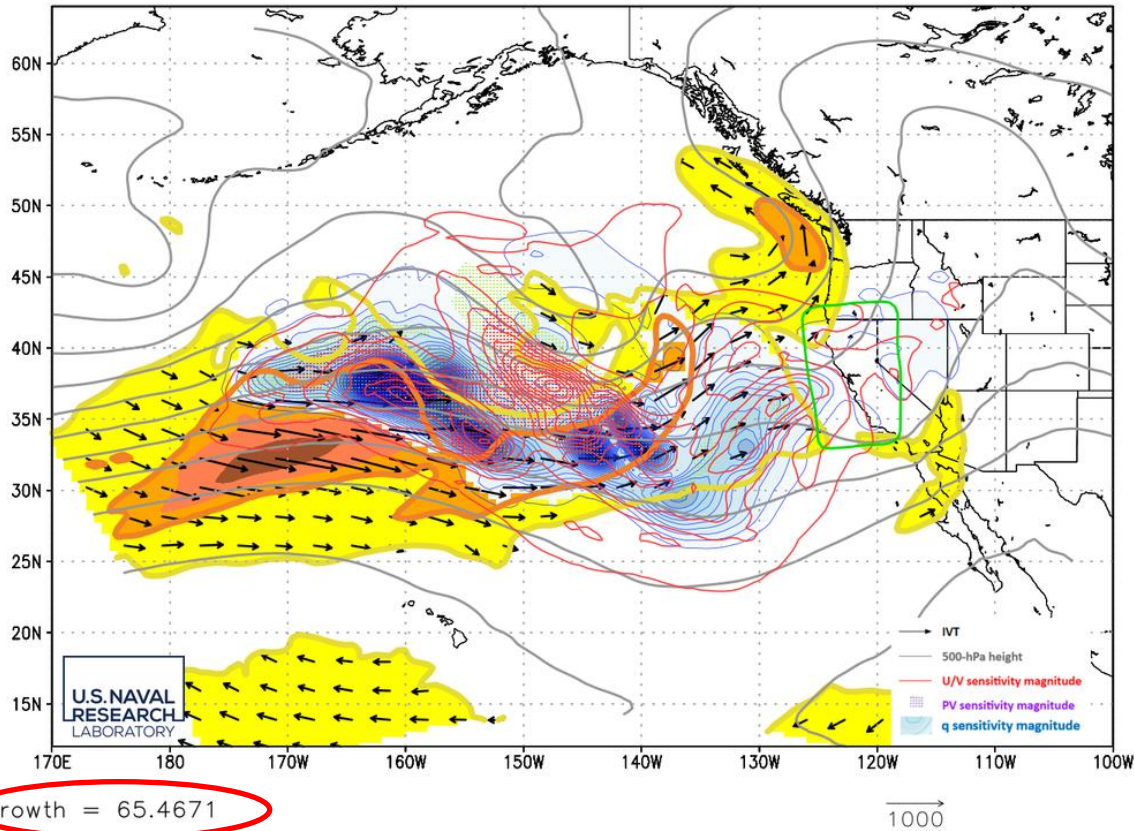
Adjoint Sensitivity (AR Recon 2023)



- 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)

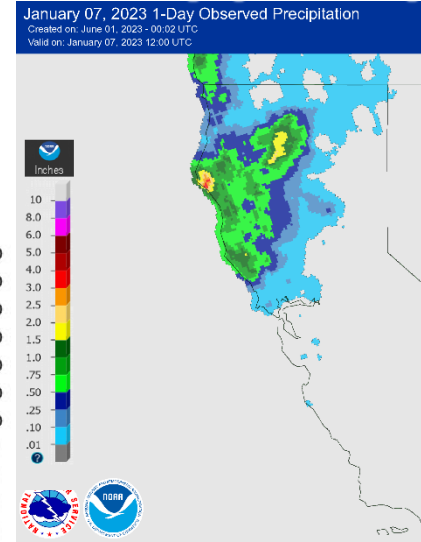
NRL COAMPS Adjoint Model Sensitivity
 2023010600 Target Time from 2023010400 forecast
 24-h Precipitation Response Function Ending 2023010712
 2023010600 IVT (vectors) and 500-hPa Height (gray)
 2023010600 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



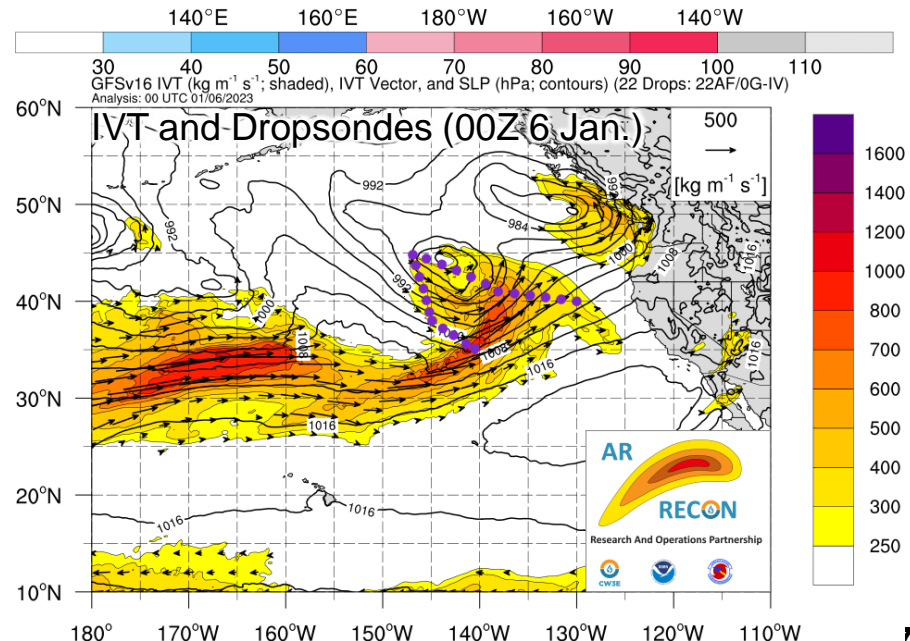
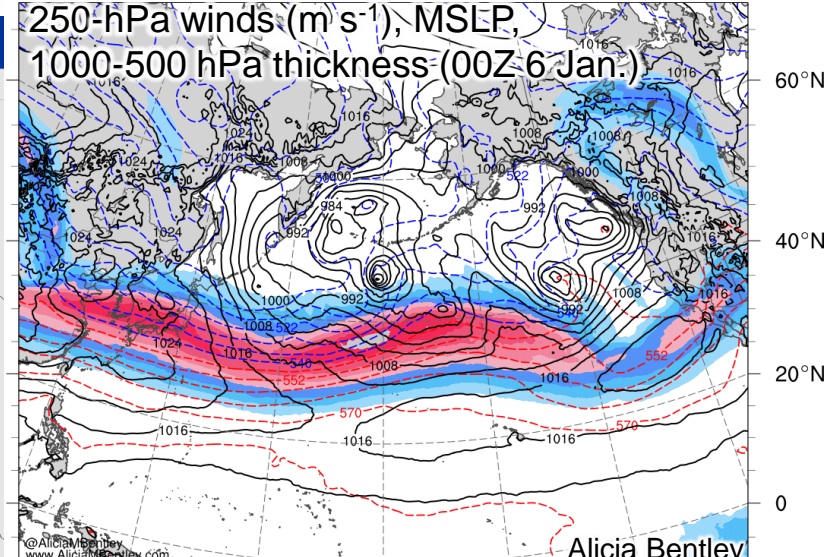
Growth = 65.4671

- 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

24-h Precip. (12Z Jan 6)

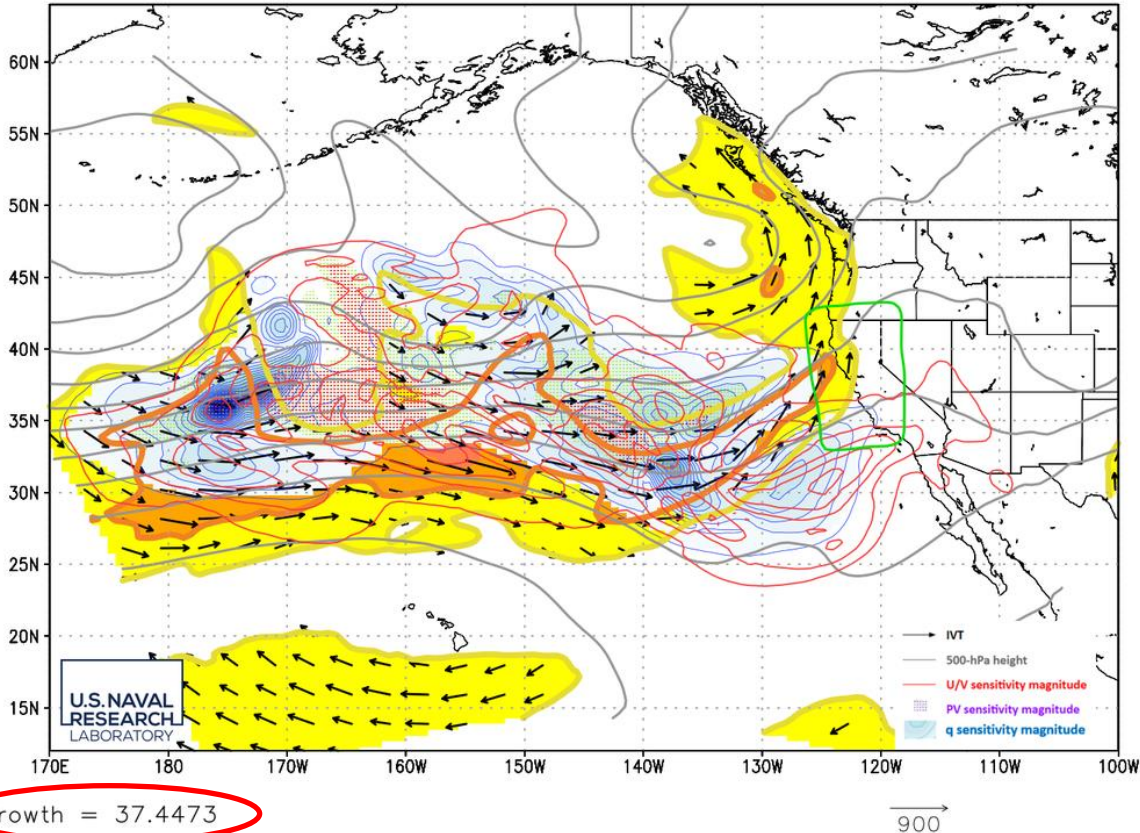


MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 6 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 6 Jan 2023



Adjoint Sensitivity: Jan. 7 (IOP 7)

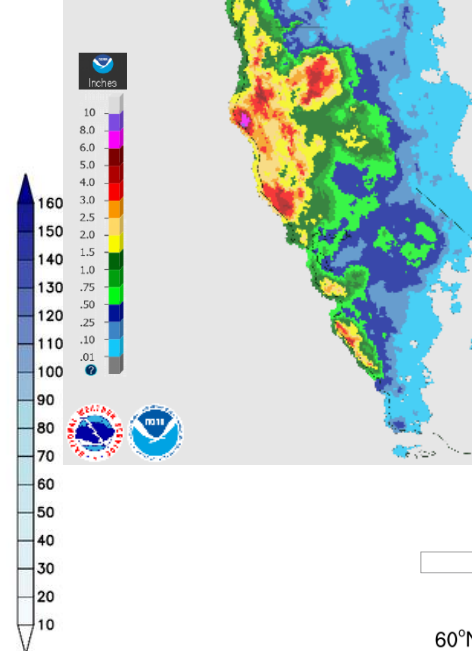
NRL COAMPS Adjoint Model Sensitivity
 2023010700 Target Time from 2023010500 forecast
 24-h Precipitation Response Function Ending 2023010812
 2023010700 IVT (vectors) and 500-hPa Height (gray)
 2023010700 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



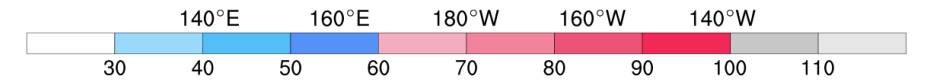
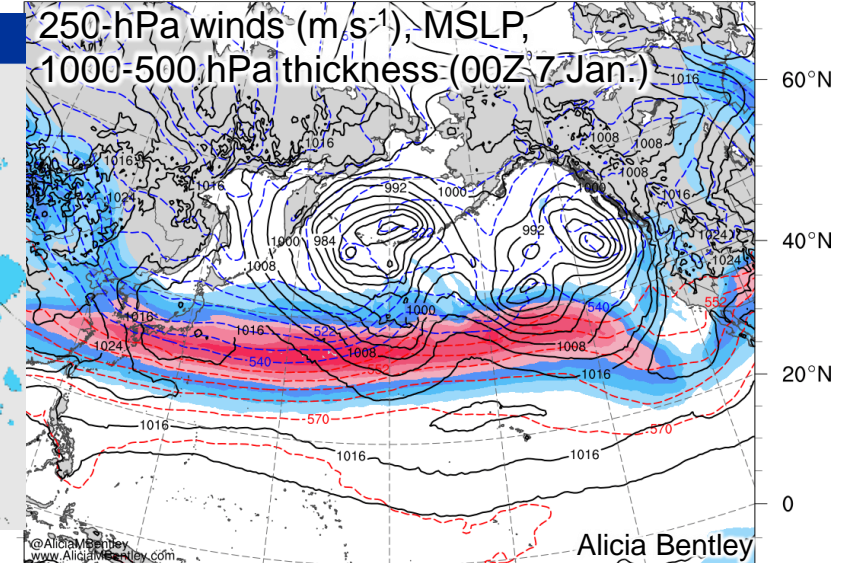
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Two prominent upstream sensitivity regions along AR (western sensitive region propagates $\sim 38 \text{ m s}^{-1}$)

24-h Precip. (12Z Jan 8)

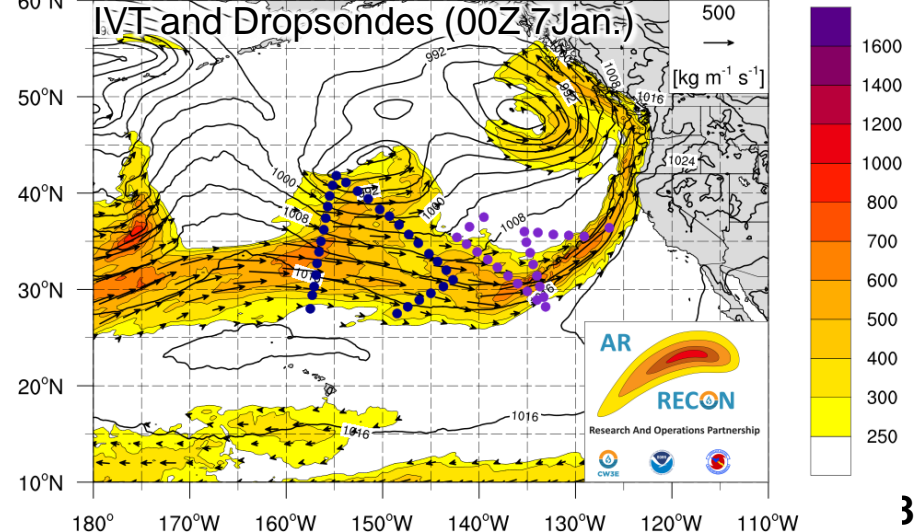
January 08, 2023 1-Day Observed Precipitation
 Forecast: 12:00 UTC 2023 - 01:00 UTC 2023
 WMO: 0000 UTC 7 Jan 2023 12:00 UTC



MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 7 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 7 Jan 2023

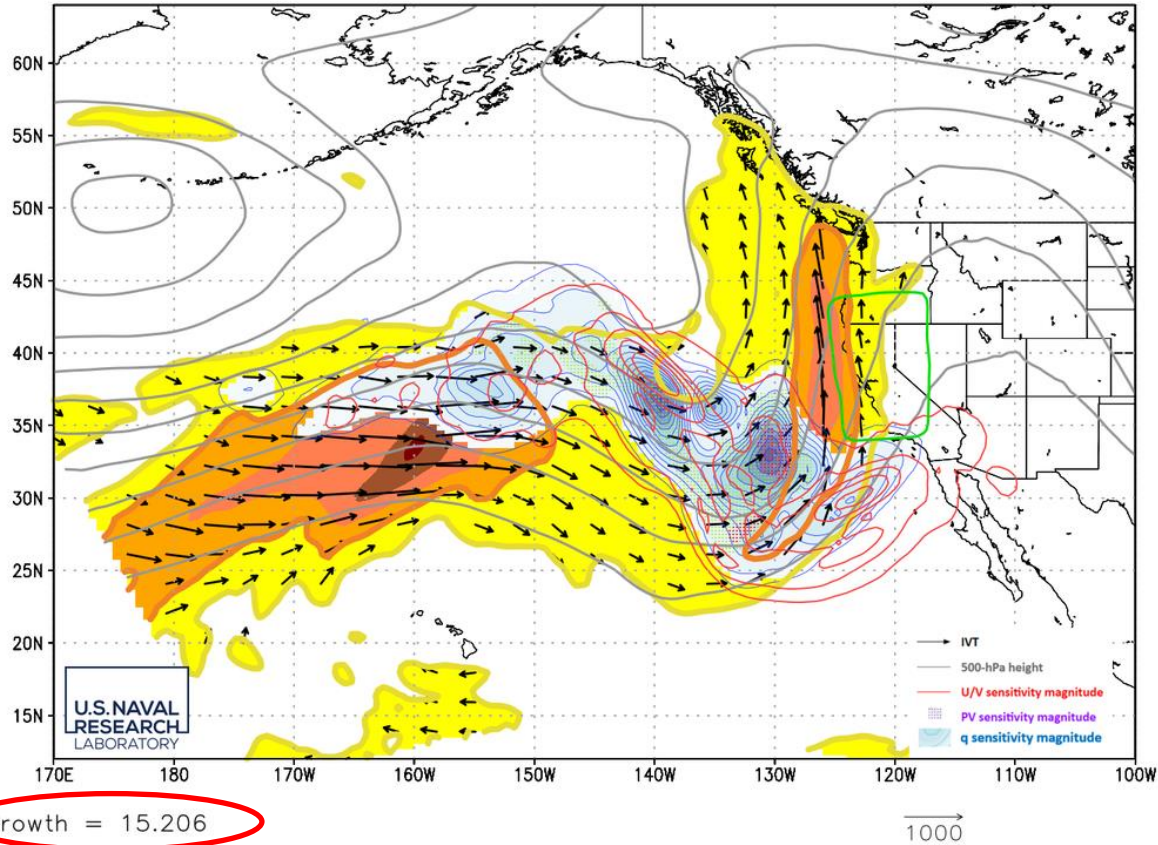


GFSv16 IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vector, and SLP (hPa; contours) (54 Drops: 24AF/30G-IV)
 Analysis: 00 UTC 01/07/2023

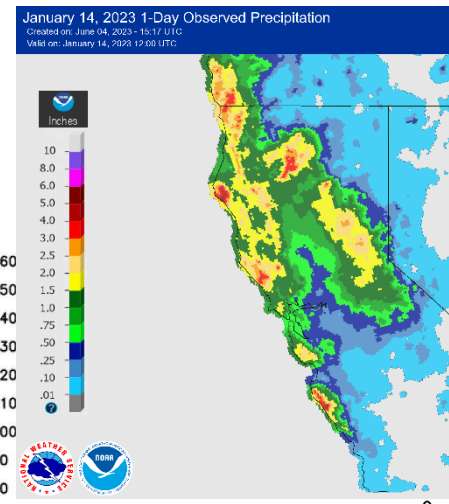


Adjoint Sensitivity: Jan. 13 (IOP 13)

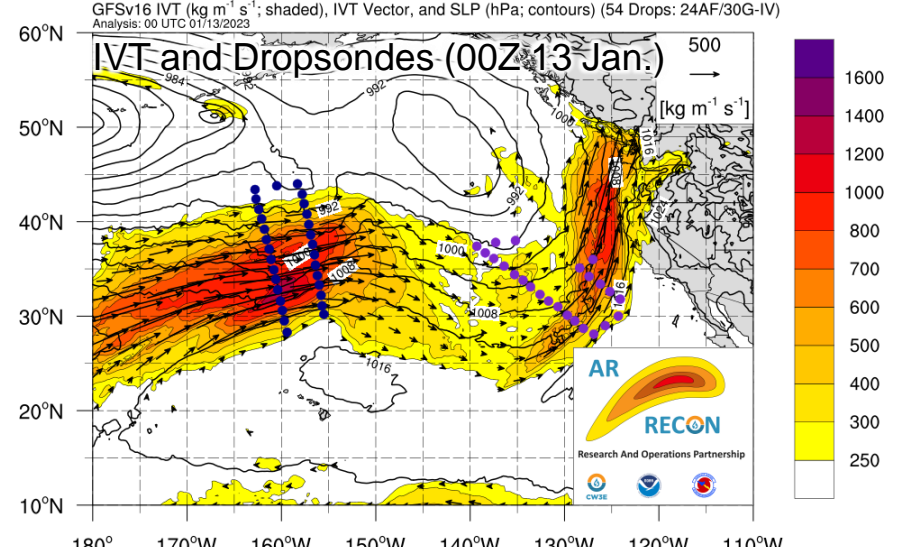
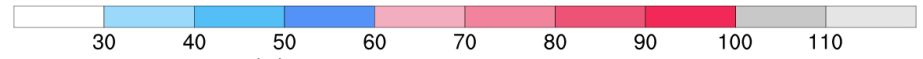
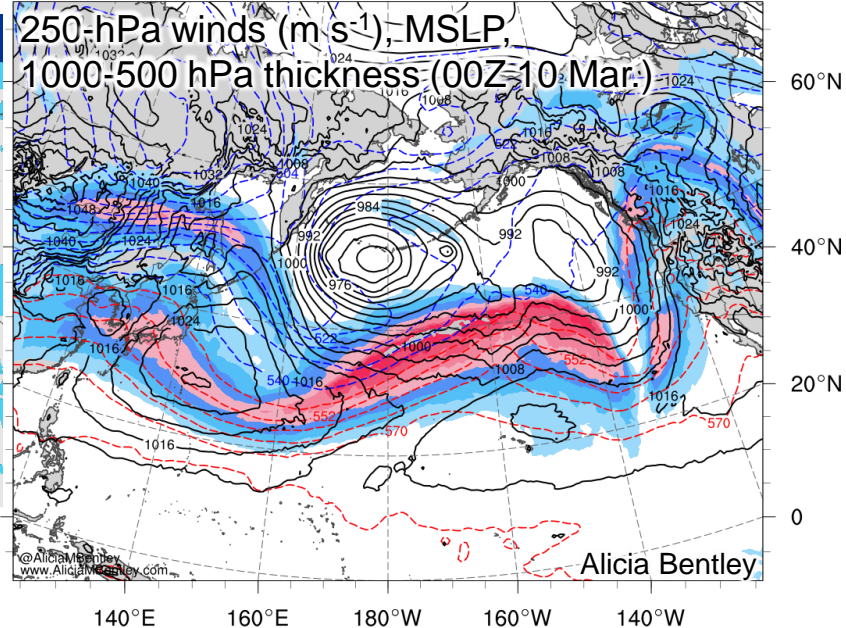
NRL COAMPS Adjoint Model Sensitivity
 2023011300 Target Time from 2023011100 forecast
 24-h Precipitation Response Function Ending 2023011412
 2023011300 IVT (vectors) and 500-hPa Height (gray)
 2023011300 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



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



MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)



- 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

NLM Energy Budget (Domain Average)

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

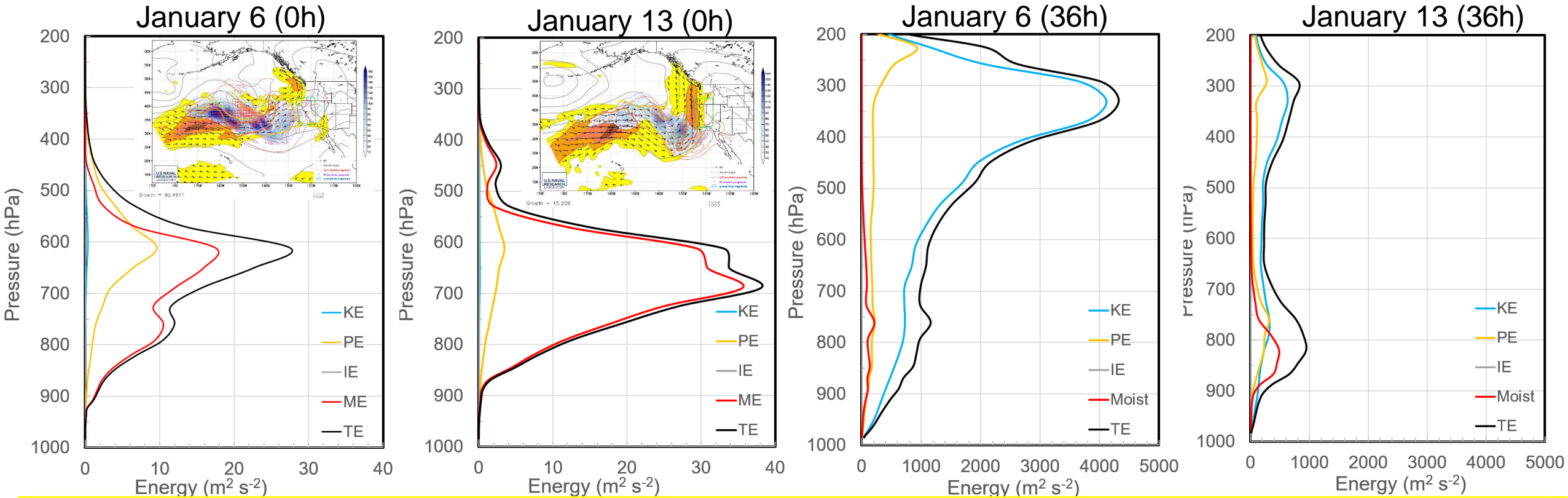
Total

KE

PE

IE

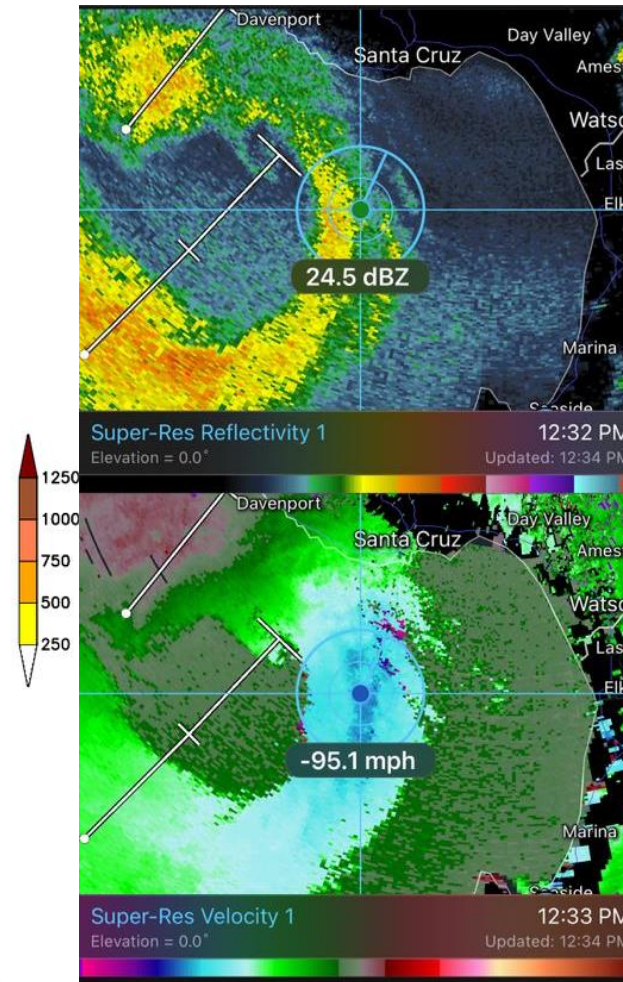
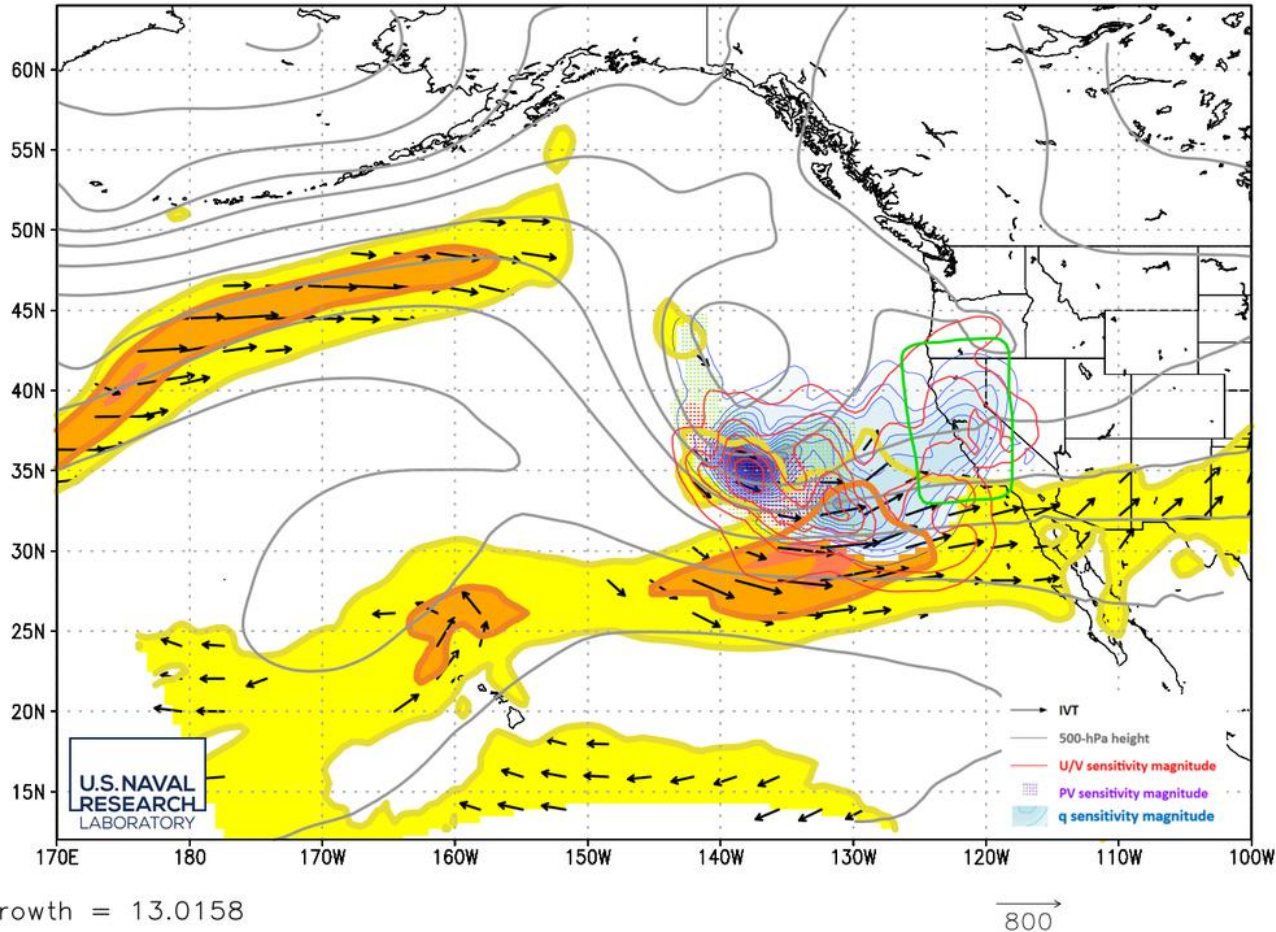
ME



- 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

NRL COAMPS Adjoint Model Sensitivity
 2023032100 Target Time from 2023031900 forecast
 24-h Precipitation Response Function Ending 2023032212
 2023032100 IVT (vectors) and 500-hPa Height (gray)
 2023032100 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



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

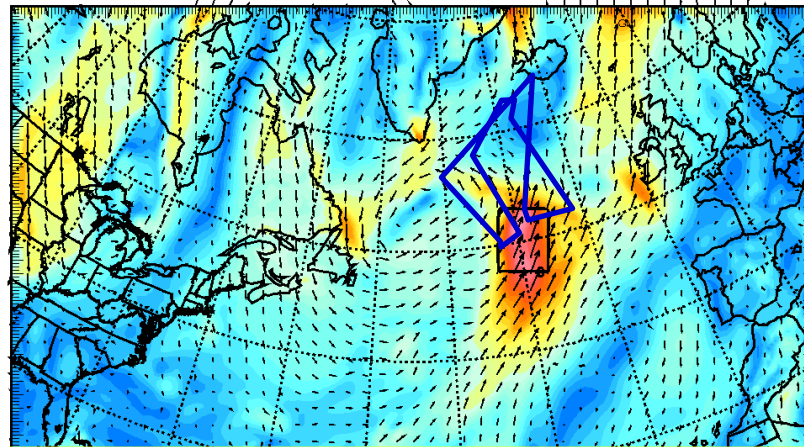
ET of ex-Karl

- i) Strong moisture sensitivity near Karl prior to ET
- ii) Vorticity sensitivity in upstream trough and near TC

Adjoint Pert.:

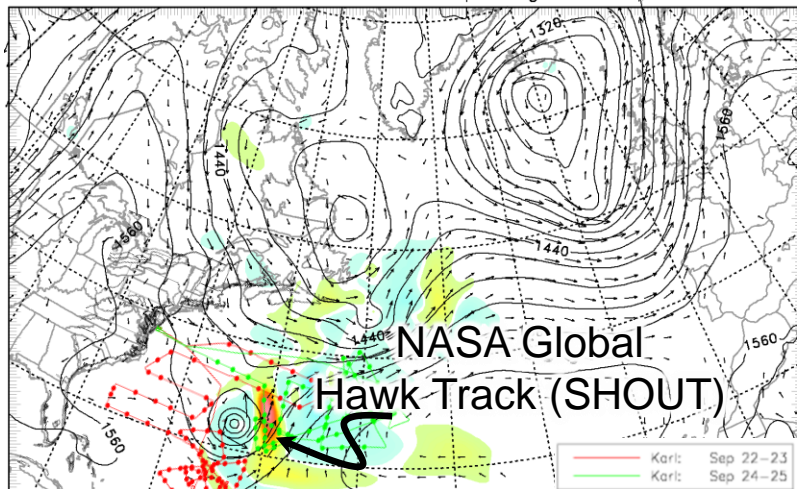
- i) Enhancement of WCB by 20 m s^{-1} & IVT
 - ii) Increase WCB outflow (increase irrotational winds 9 to 15 m s^{-1})
 - iii) Downstream ridge building
 - iv) High-impact precipitation and atmos. river event
- AR/WCB acts as "Amplifier"

48-h 850-hPa Optimal U'+U



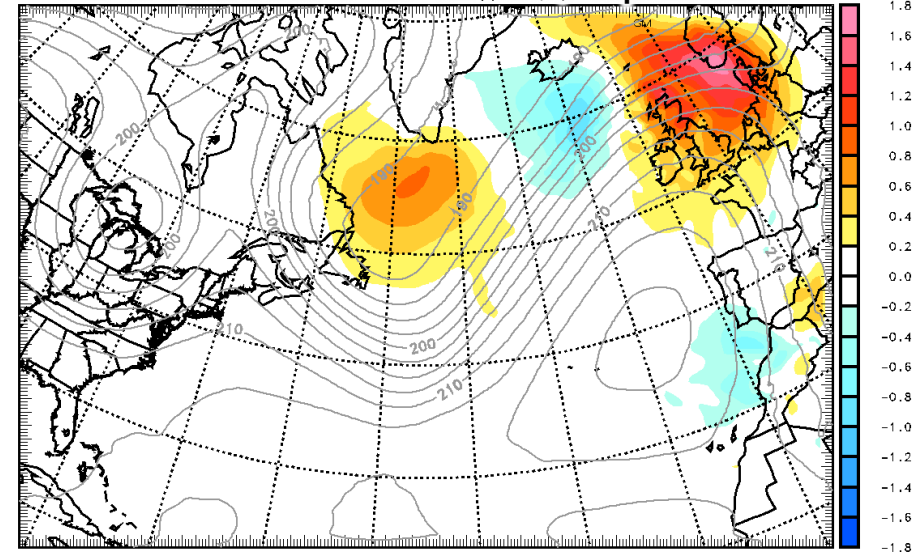
Evolved optimal perturbations lead to a strengthened WCB to $> 40 \text{ m s}^{-1}$ at 850 hPa

850-hPa q_v Sensitivity, Heights, & Winds

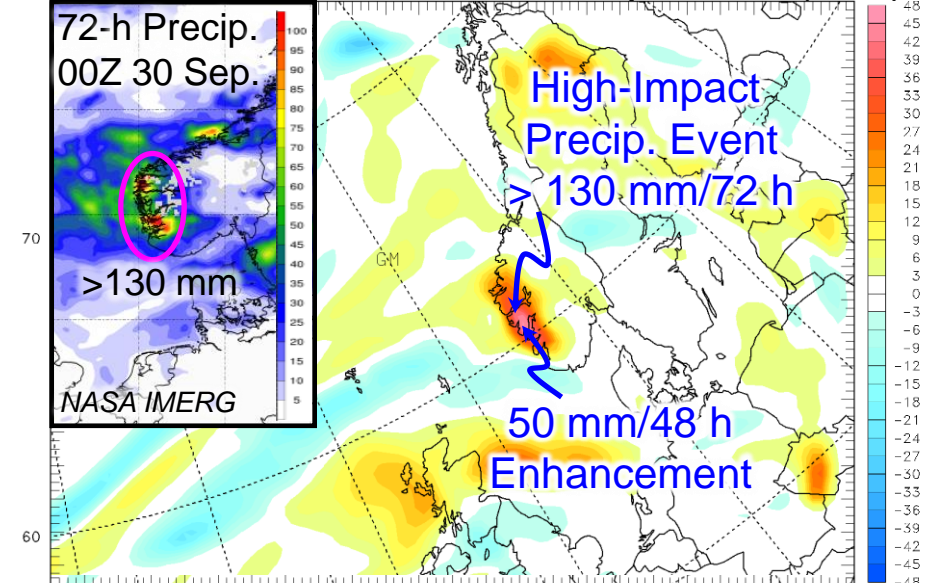


Large q_v sensitivity NE of Karl in moist plume

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



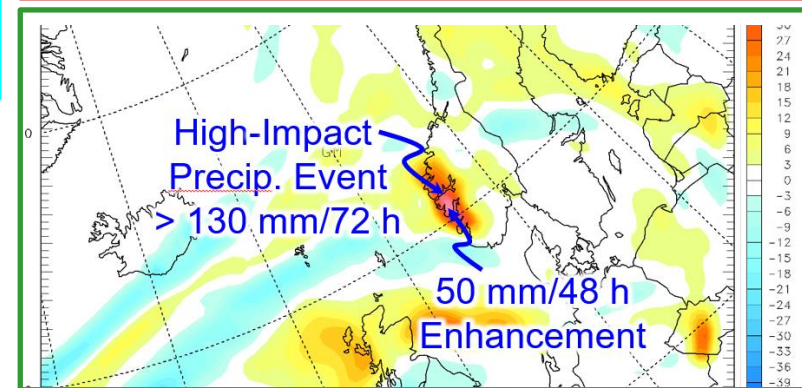
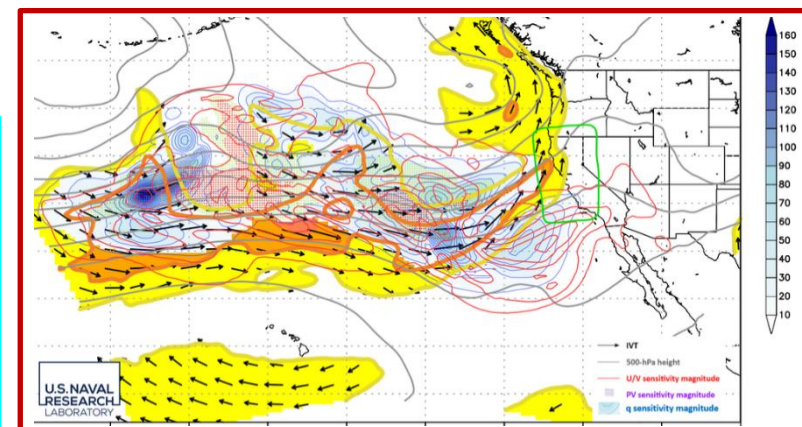
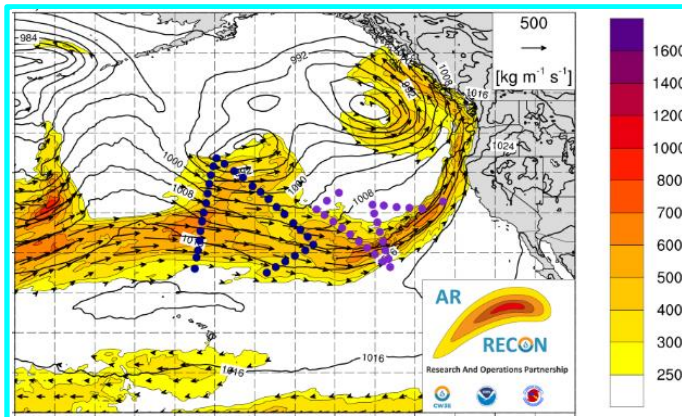
60-108-h Perturbation Precipitation (mm)



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)

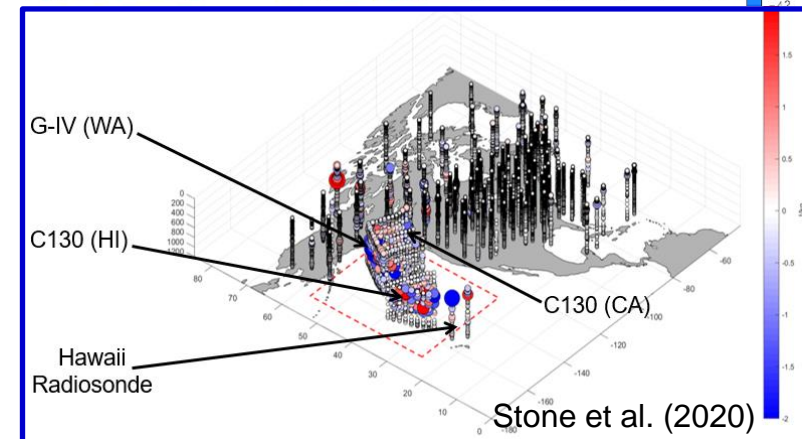


- Adjoint Sensitivity in ARs

- 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

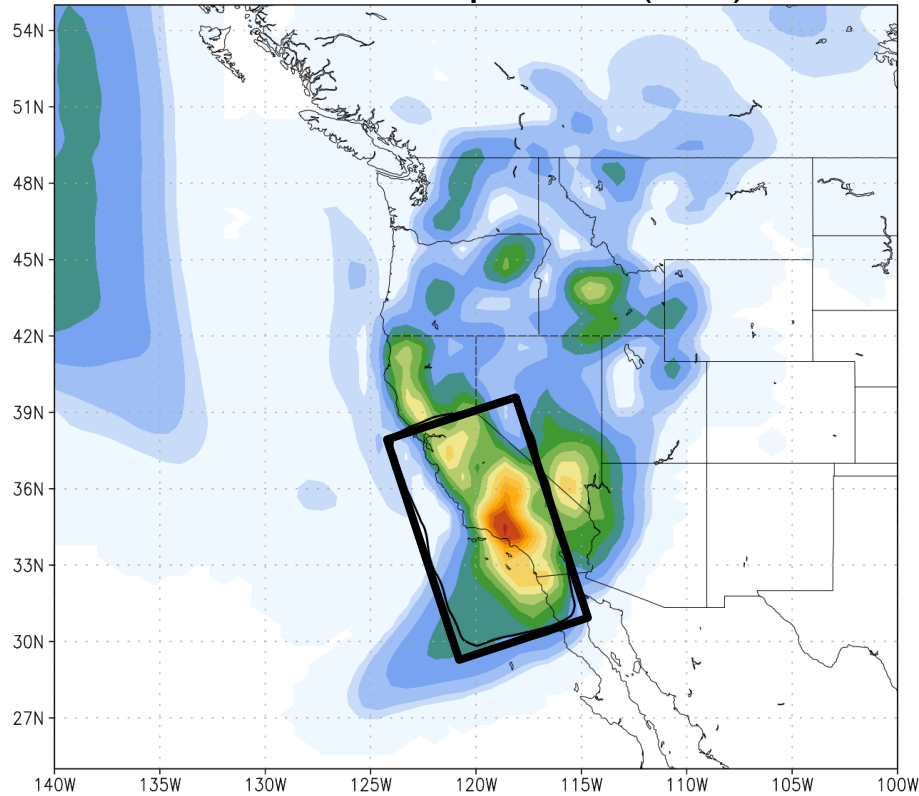


Extra Slides

Response Function Regions

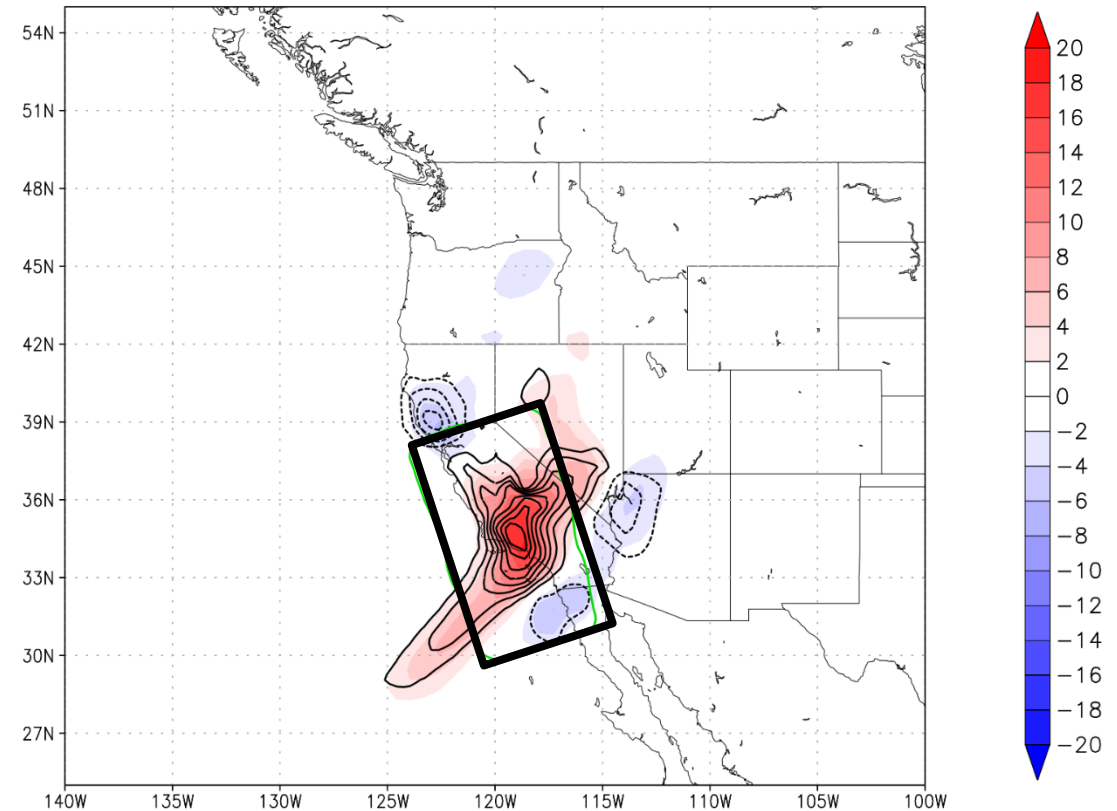
2021012800 Target Time from 2021012600 Forecast
24-h Total PRCP Response Function Ending 2021012912
12-36h Accumulated Precipitation from Control Forecast

24-h Precipitation (mm)



2021012800 Target Time from 2021012600 Forecast
24-h Total PRCP Response Function Ending 2021012912
12-36h Accumulated Precipitation Lin Pert (shaded) and NL Pert (contour)

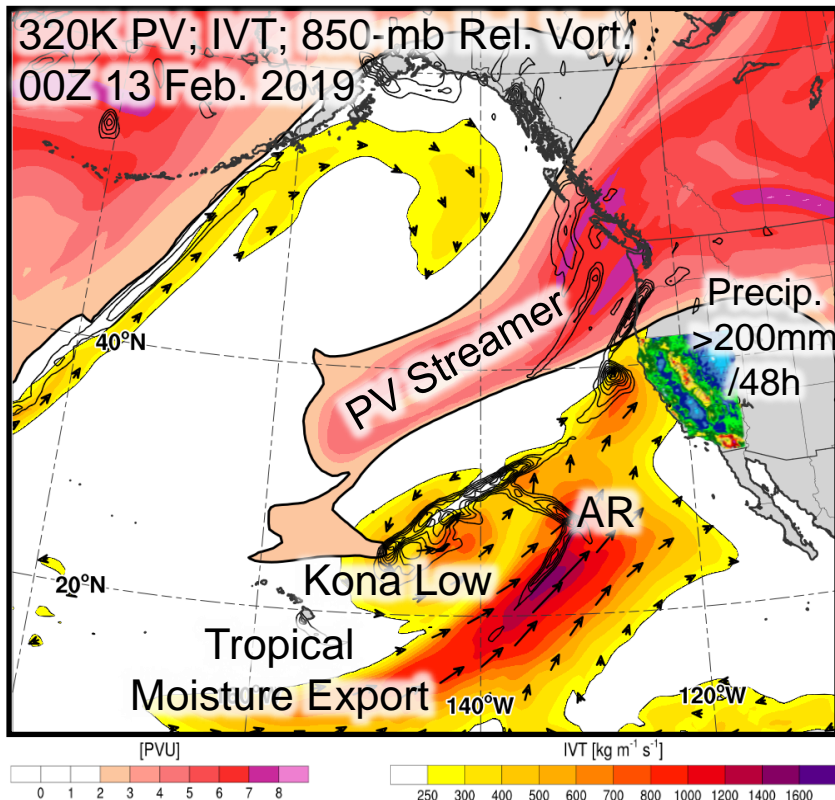
24-h Precipitation Pert. from NLM and TLM (mm)



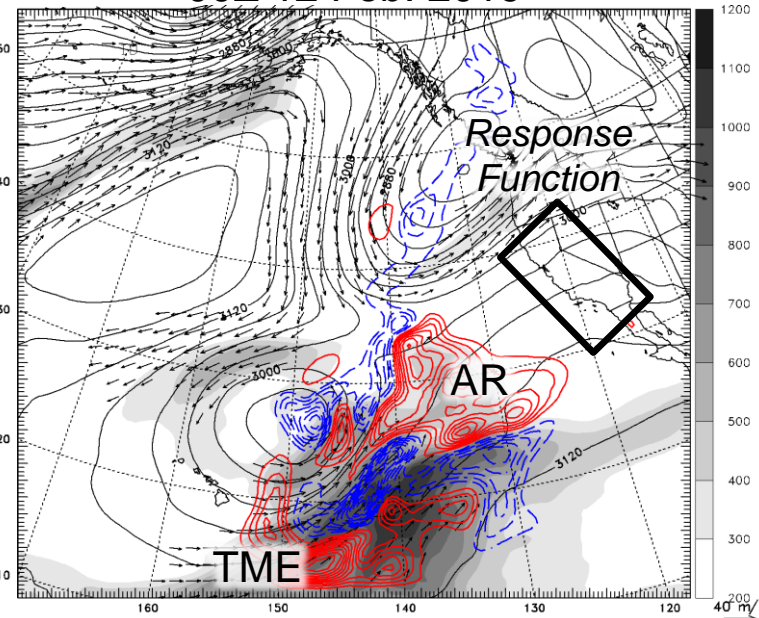
- Larger boxes are better to make sure the sensitivity represents an increase within box (and not a shifts)
- Every adjoint sensitivity run, we make sure the adjoint/TLM is valid by comparing evolved perturbations in NLM (color) and TLM (contours) and the perturbations increase the precipitation
- Growth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

Multi-Scale Sensitivity: Valentine's Day 2019

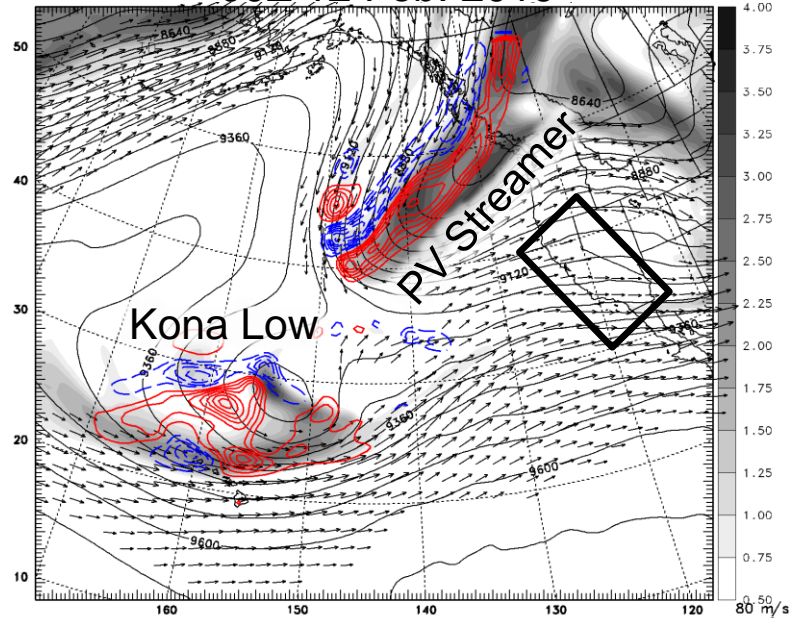
- High-impact forecasts associated with ARs can be very sensitive to the initial state, even for short-range forecasts
- We focus on a high-impact event during the AR Recon from Feb. 11-15, 2019 and utilize the NRL COAMPS[®] mesoscale model and moist adjoint system to explore the predictability of this 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



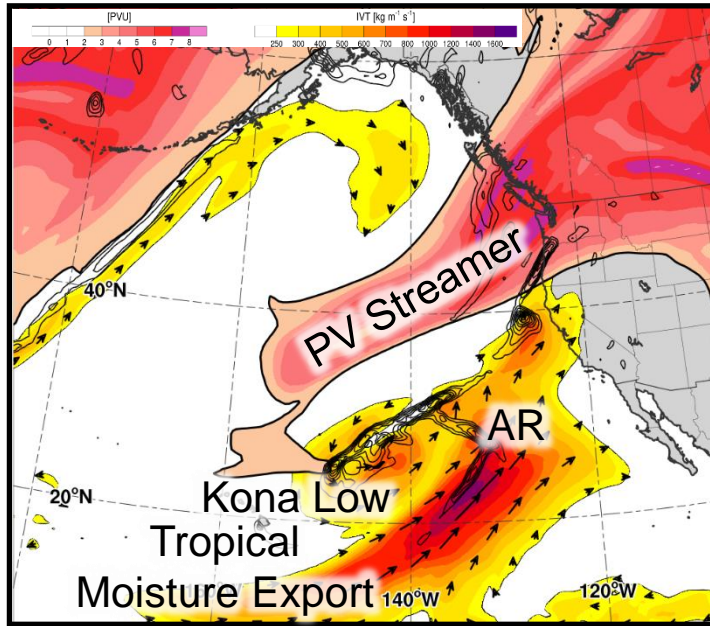
300-hPa PV Adjoint Perturbation,
PV (gray), 300-hPa Heights, Winds
00Z 12 Feb. 2019



Atmospheric Rivers: AR Recon

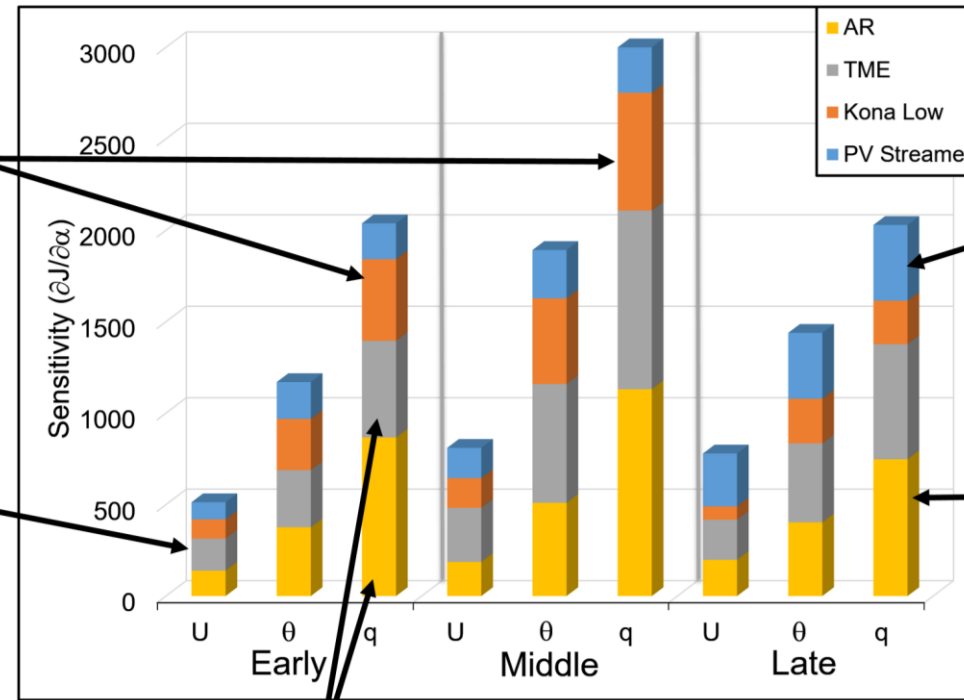
Valentine's Day Flooding Event
February 2019

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

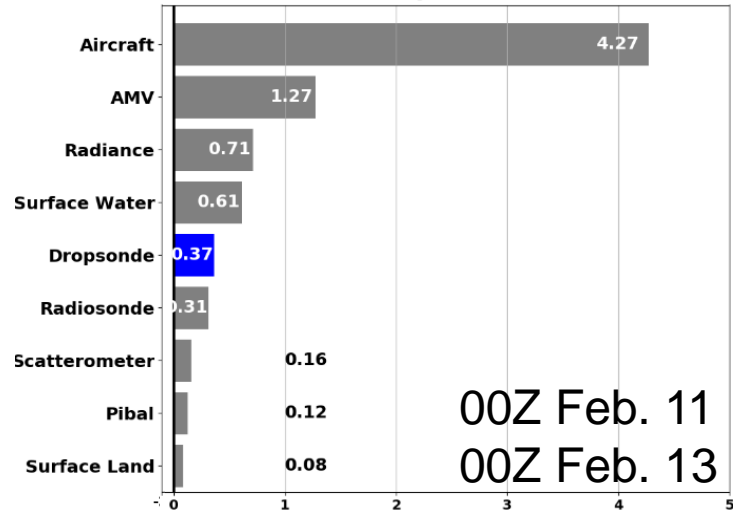
- AR Recon is a multi-agency effort to improve short-term AR forecasts on the U.S. West Coast
- NRL COAMPS adjoint sensitivity was used along with other products to inform flight plans. Sensitivity typically highlighted lower-tropospheric moisture in/near ARs and Warm Conveyor Belts (WCBs)
- High-impact 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

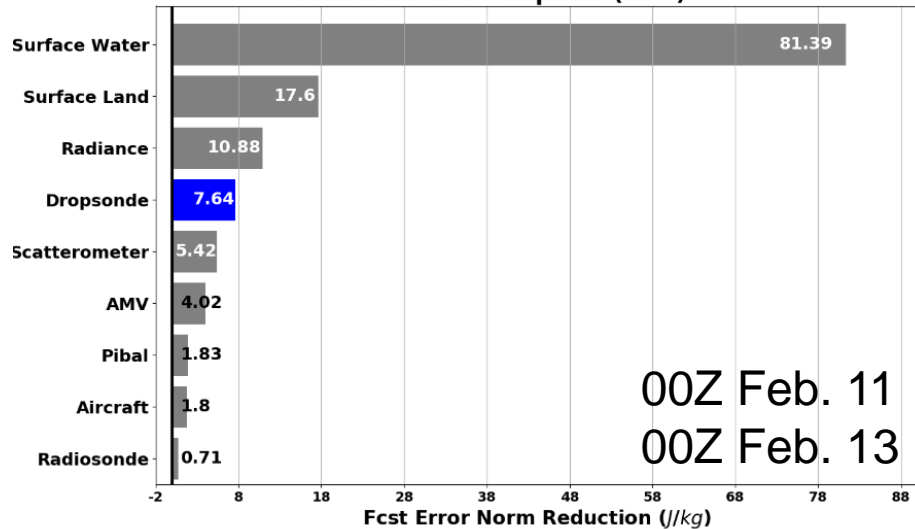
COAMPS 24-h Observation Impacts

Moist Energy Error Norm

COAMPS Observation Impacts



COAMPS Per Ob Impacts (10^{-5})

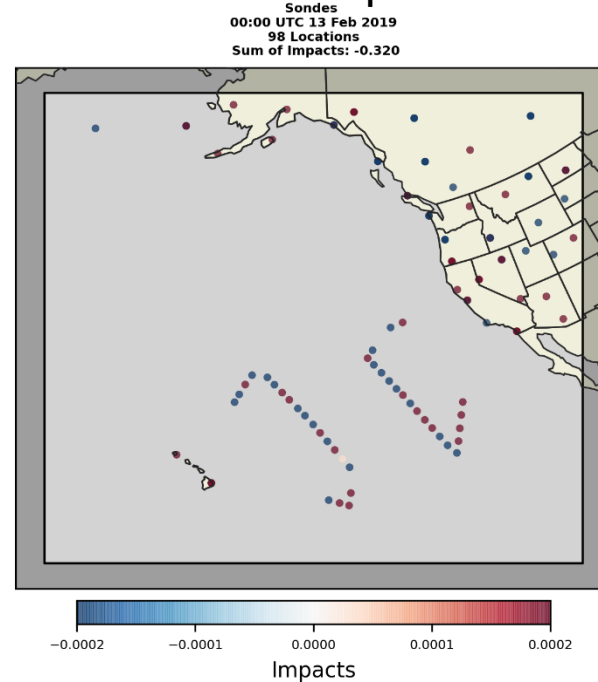


00Z Feb. 11
00Z Feb. 13

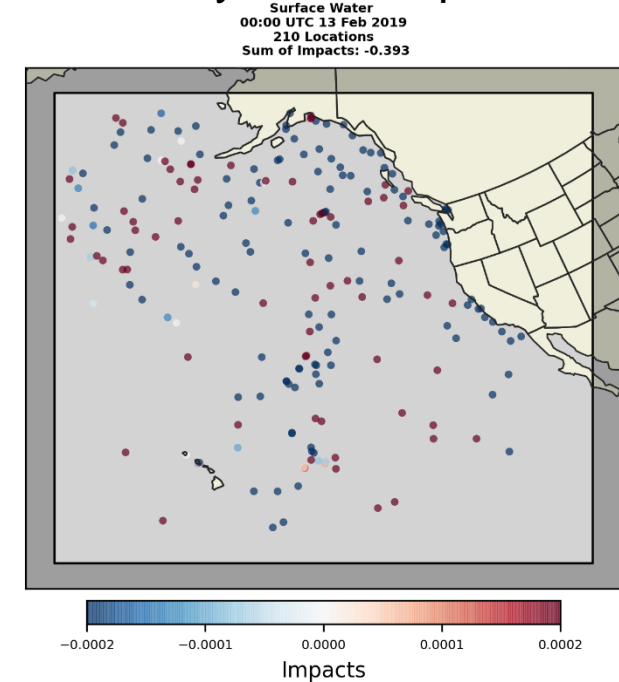
00Z Feb. 11
00Z Feb. 13

COAMPS 24 h Observation Impacts 00Z 13 Feb. 2019

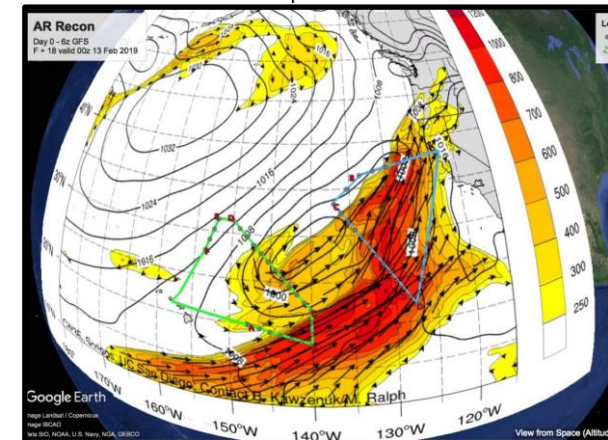
AR Recon Dropsondes



Buoys and Ships



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

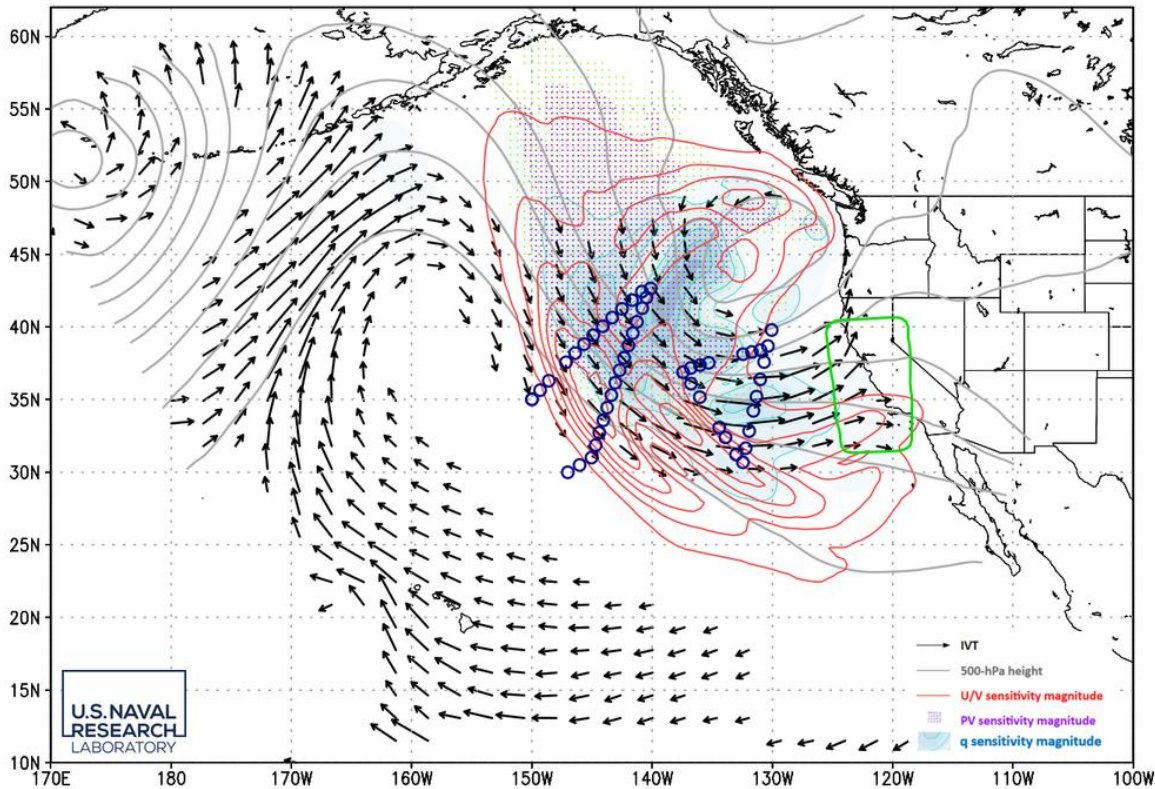


Lead Time

How Does the Sensitivity Vary with Lead Time

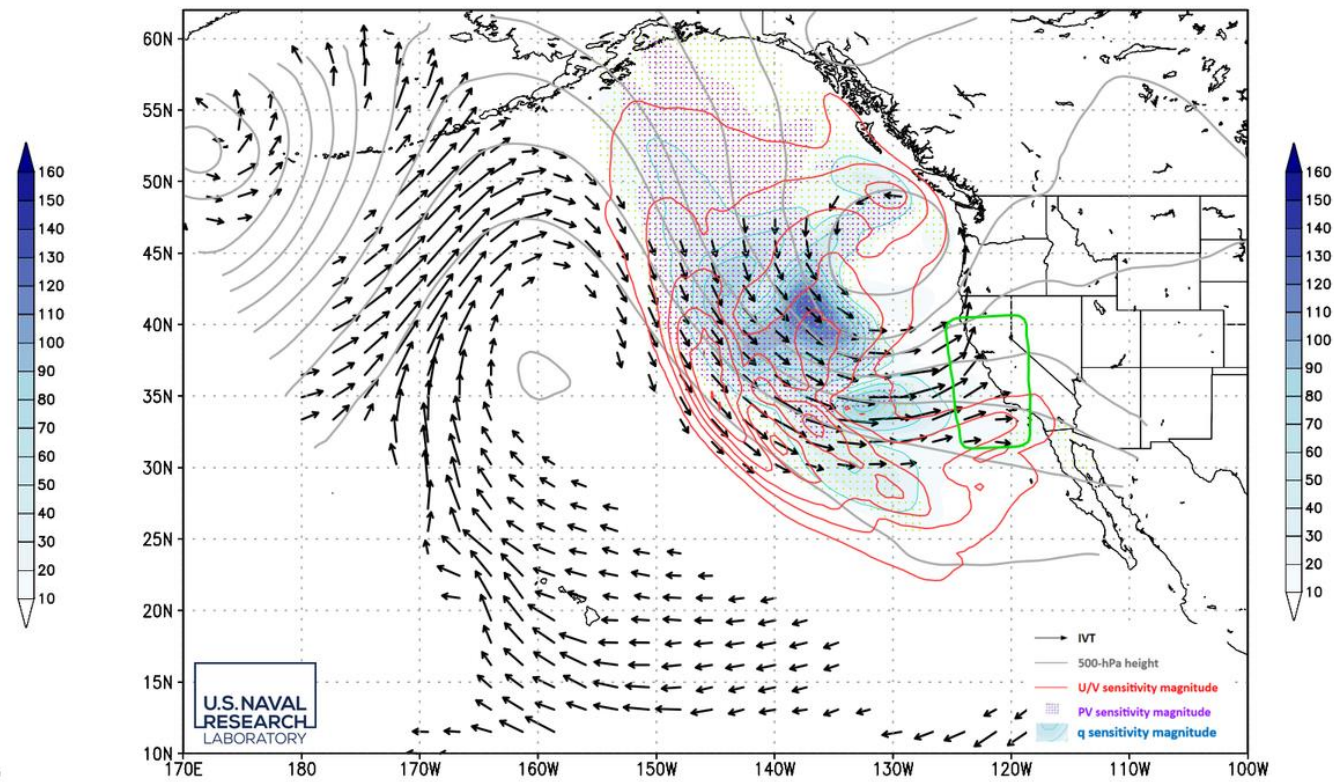
48-h Lead Time

NRL COAMPS Adjoint Model Sensitivity
 2021012700 Target Time from 2021012500 forecast
 24-h Precipitation Response Function Ending 2021012812
 2021012700 IVT (vectors) and 500-hPa Height (gray)
 2021012700 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



0-h Lead Time

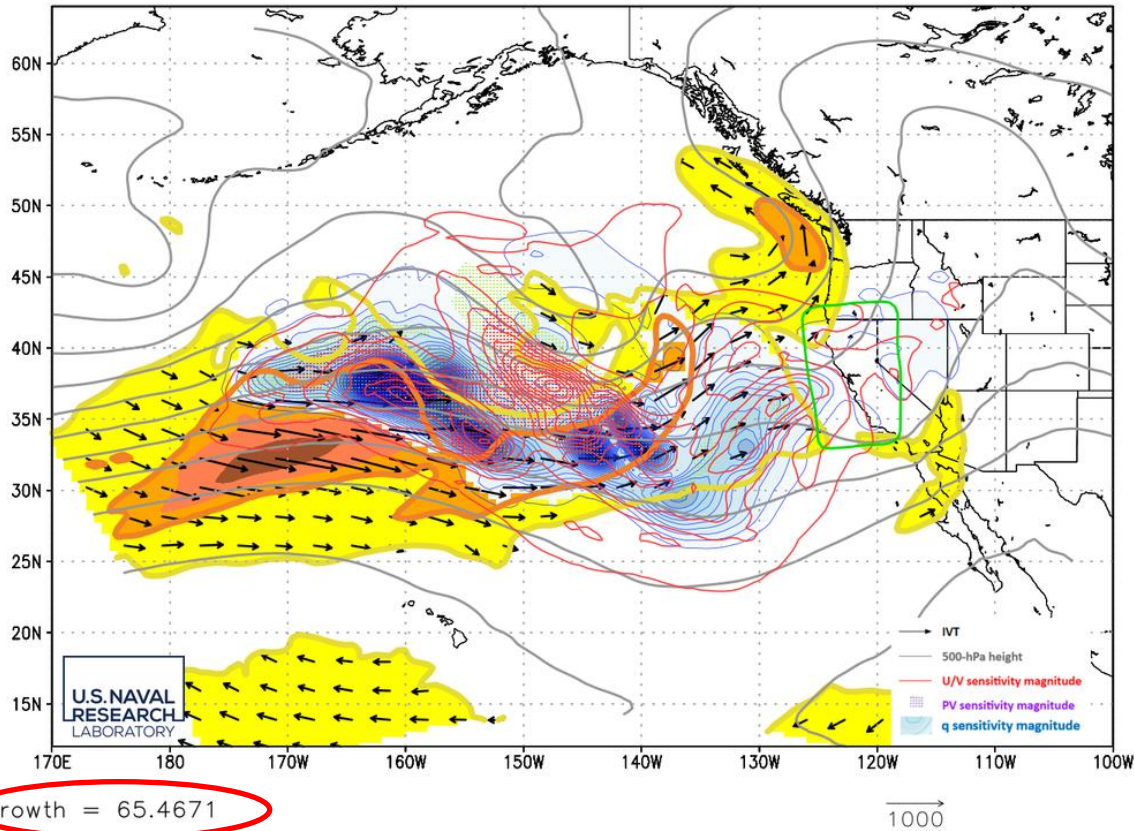
NRL COAMPS Adjoint Model Sensitivity
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 24-h Precipitation Response Function Ending 2021012812
 2021012700 IVT (vectors) and 500-hPa Height (gray)
 2021012700 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



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

Adjoint Sensitivity: Jan. 6 (IOP 6)

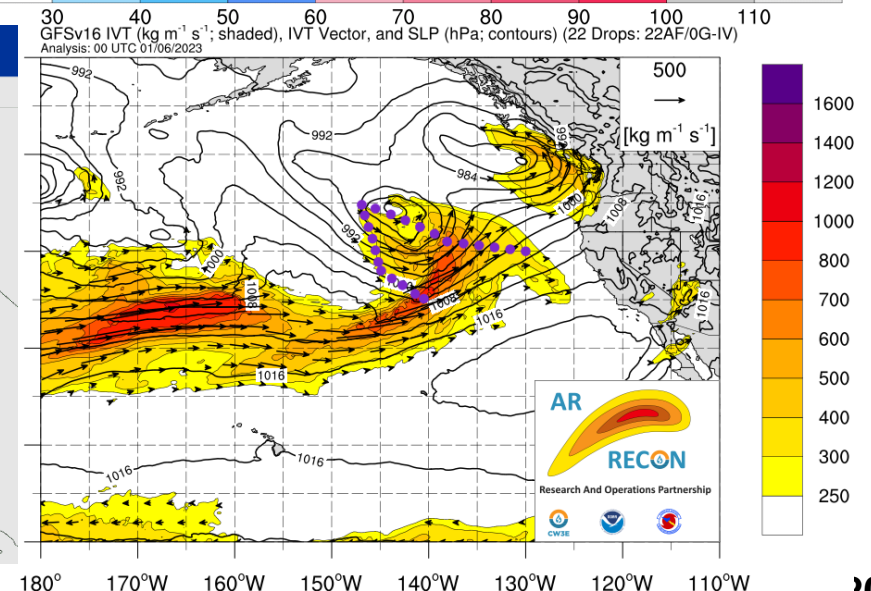
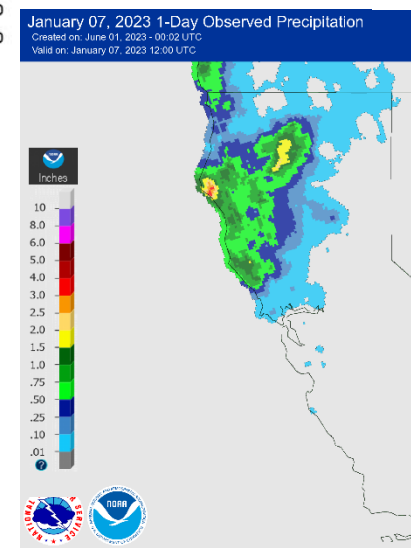
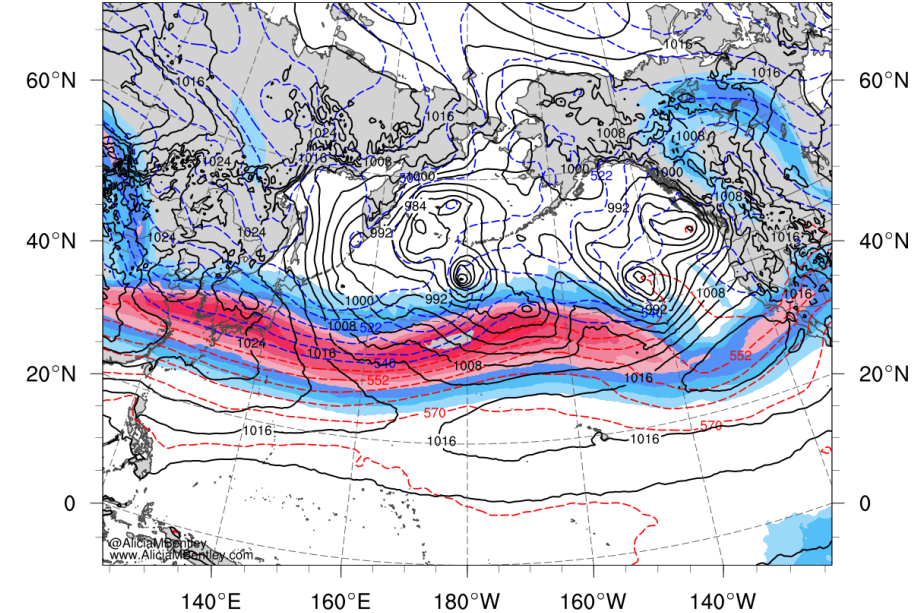
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 2023010600 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



Growth = 65.4671

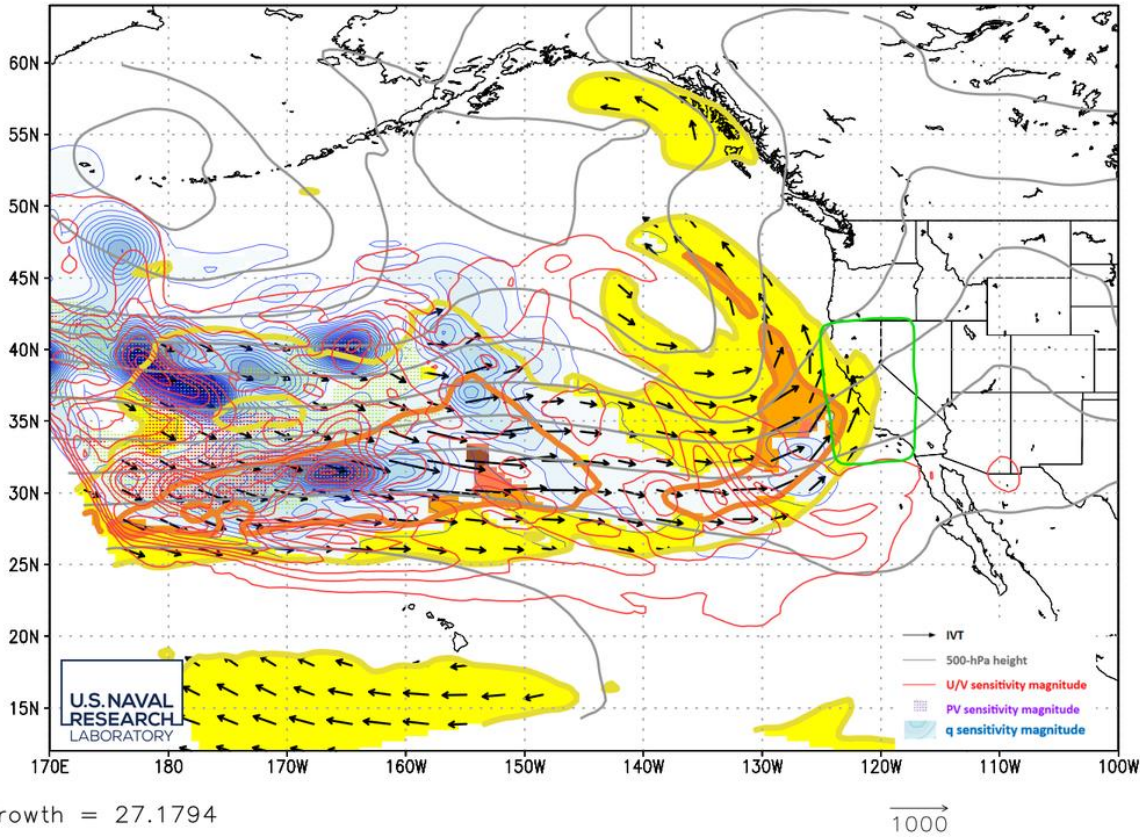
- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (36-h sensitivity)
- Strong sensitivity near shortwave troughs (PV) in AR core and on cold-side near the strong dynamics

MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 6 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 6 Jan 2023

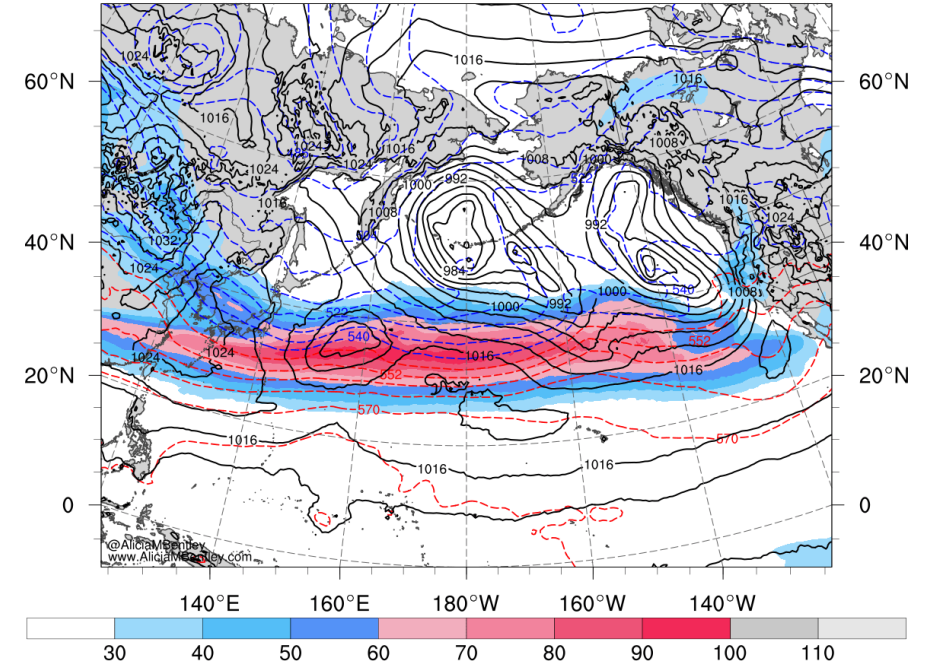


Adjoint Sensitivity: Jan. 8 (IOP 8)

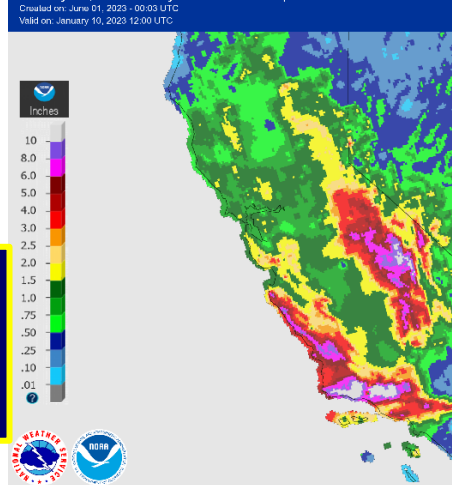
NRL COAMPS Adjoint Model Sensitivity
 2023010800 Target Time from 2023010600 forecast
 24-h Precipitation Response Function Ending 2023011012
 2023010800 IVT (vectors) and 500-hPa Height (gray)
 2023010800 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



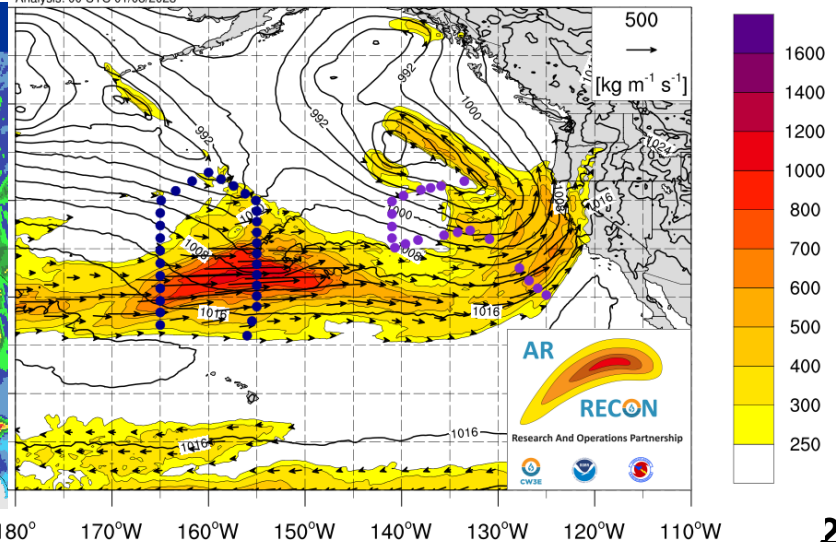
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 8 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 8 Jan 2023



January 10, 2023 1-Day Observed Precipitation



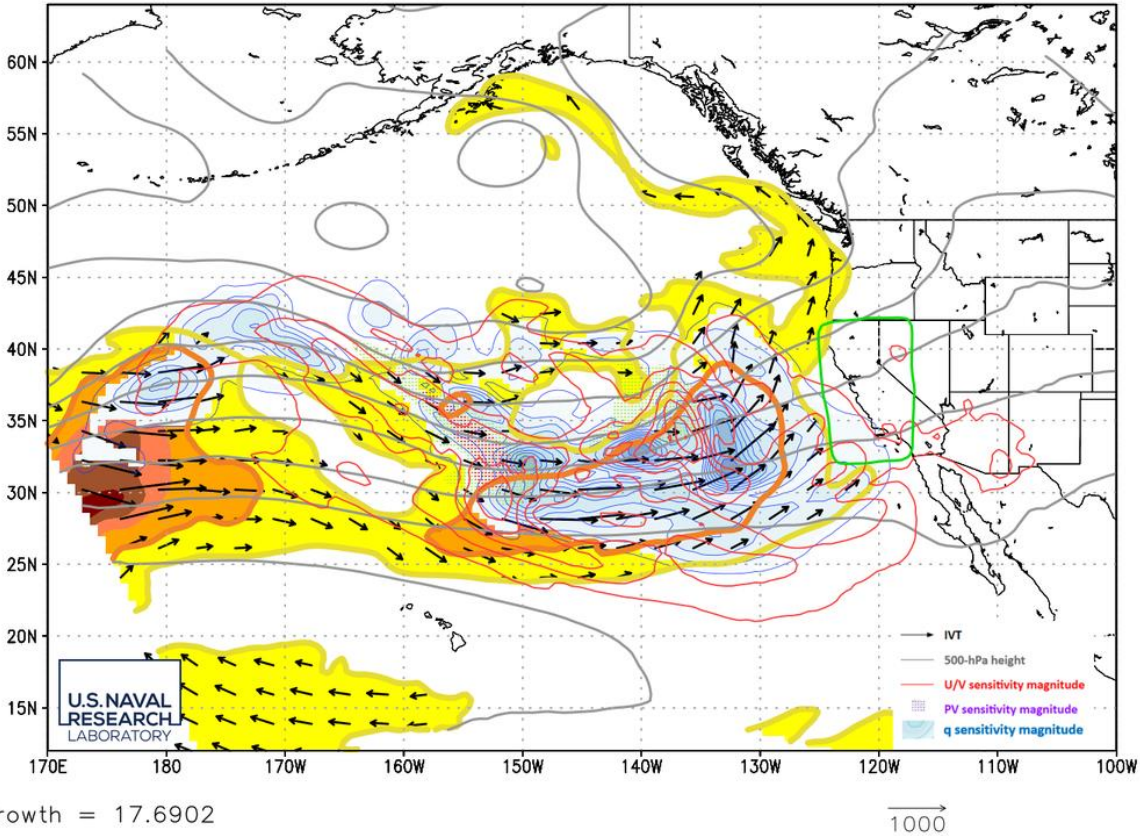
GFSv16 IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vector, and SLP (hPa; contours) (50 Drops: 20AF/30G-IV)
 Analysis: 00 UTC 01/08/2023



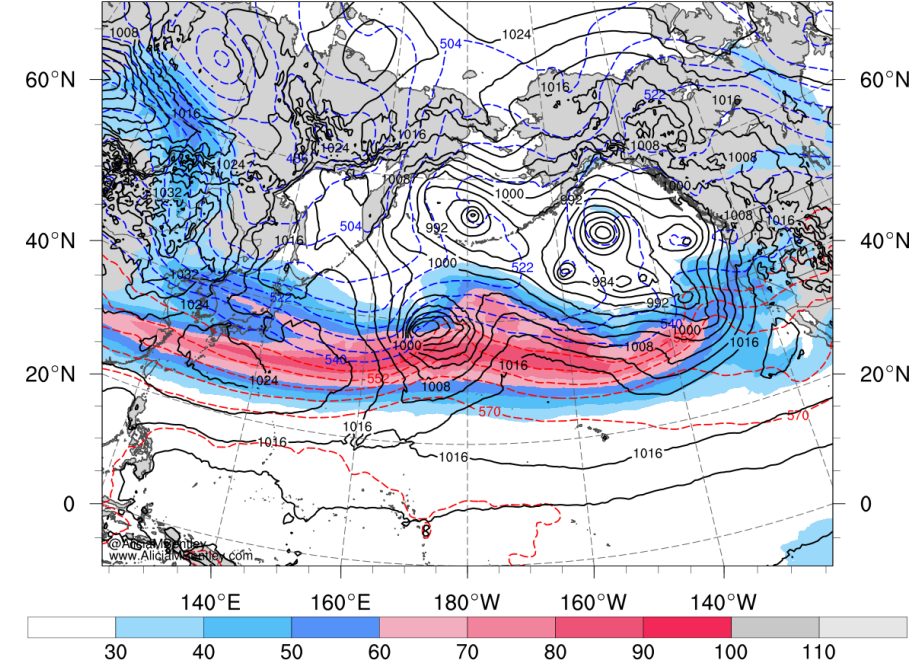
- Exceptionally strong jet and AR across the Pacific
- Strong growth rate (60-h sensitivity)
- Sensitivity located well upstream of West Coast

Adjoint Sensitivity: Jan. 9 (IOP 9)

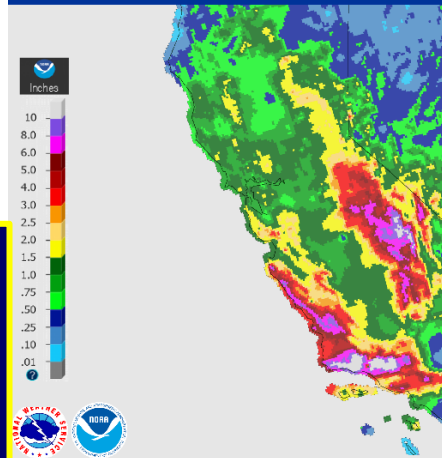
NRL COAMPS Adjoint Model Sensitivity
 2023010900 Target Time from 2023010700 forecast
 24-h Precipitation Response Function Ending 2023011012
 2023010900 IVT (vectors) and 500-hPa Height (gray)
 2023010900 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



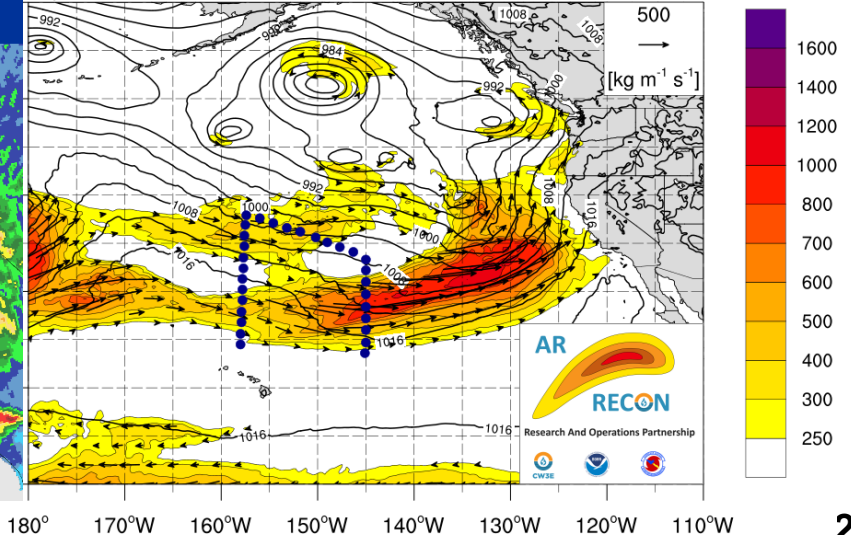
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 9 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 9 Jan 2023



January 10, 2023 1-Day Observed Precipitation
 Created on: Jan 01, 2023 - 00:00 UTC
 Valid on: January 10, 2023 12:00 UTC



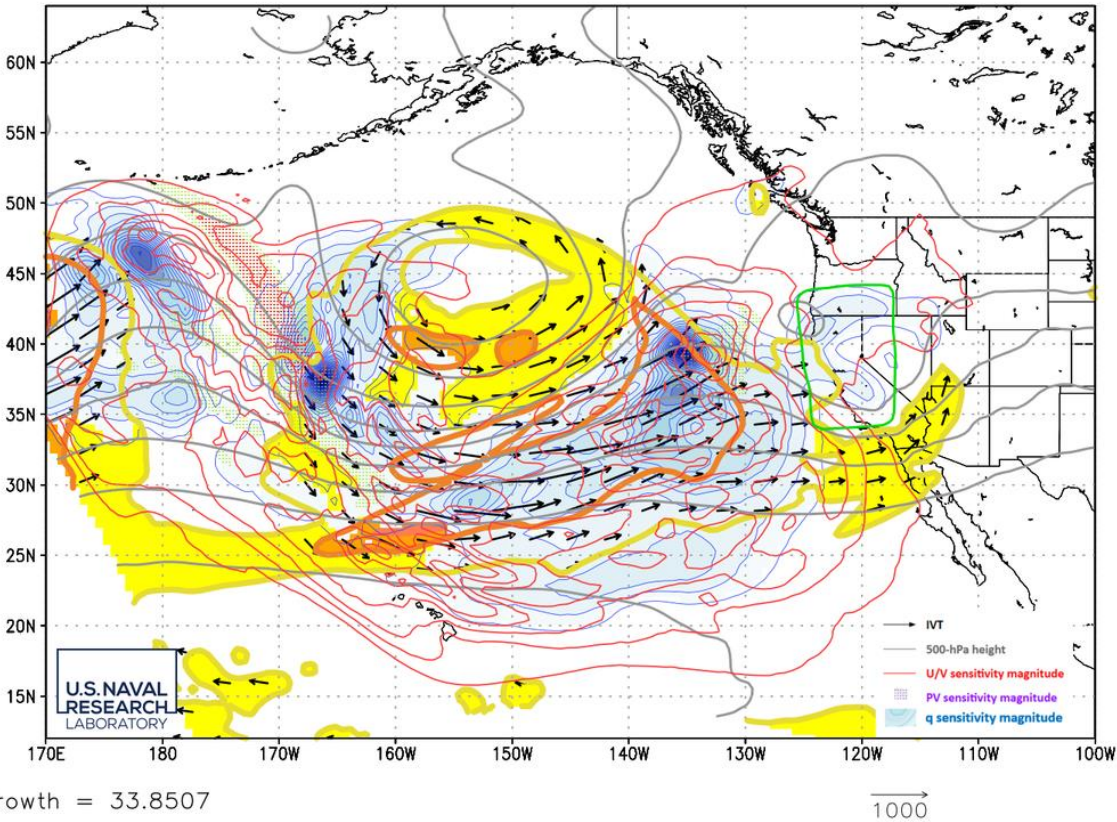
GFSv16 IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vector, and SLP (hPa; contours) (30 Drops: 0AF/30G-IV)
 Analysis: 00 UTC 01/09/2023



- 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

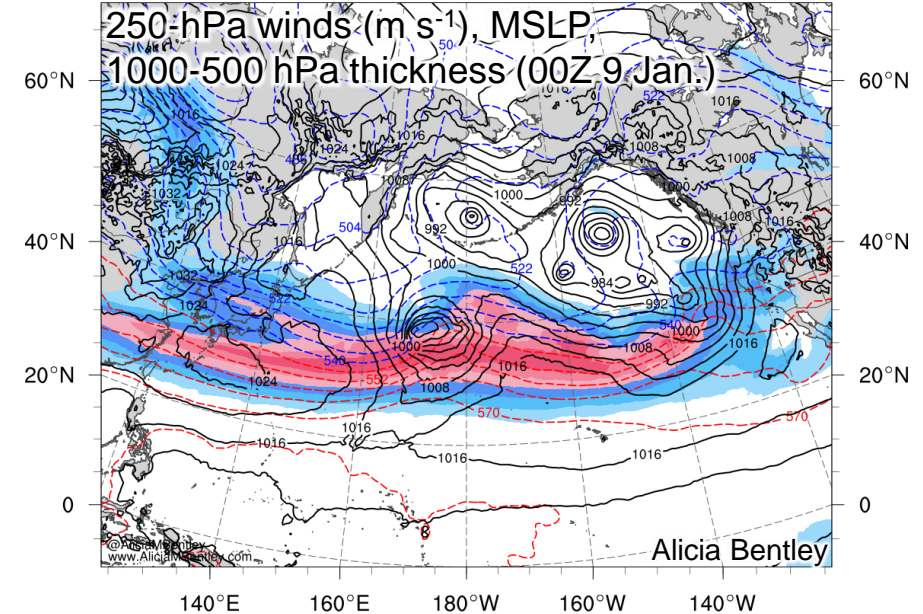
Adjoint Sensitivity: Jan. 11 (IOP 11)

NRL COAMPS Adjoint Model Sensitivity
 2023011100 Target Time from 2023010900 forecast
 36-h Precipitation Response Function Ending 2023011300
 2023011100 IVT (vectors) and 500-hPa Height (gray)
 2023011100 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)

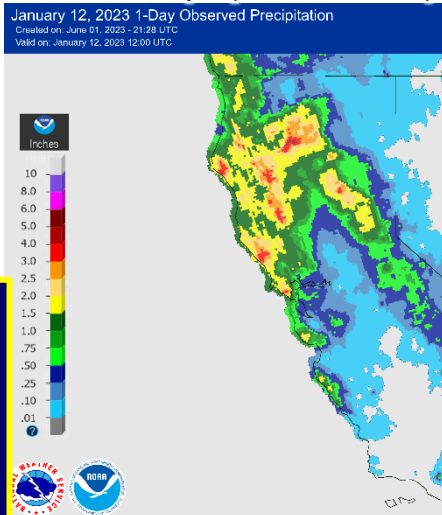


- Exceptionally strong jet and AR across the Pacific
- Extreme growth rate (48-h sensitivity, 36-h RF)
- Sensitivity concentrated in AR and extends upstream ahead of the next AR and shortwave

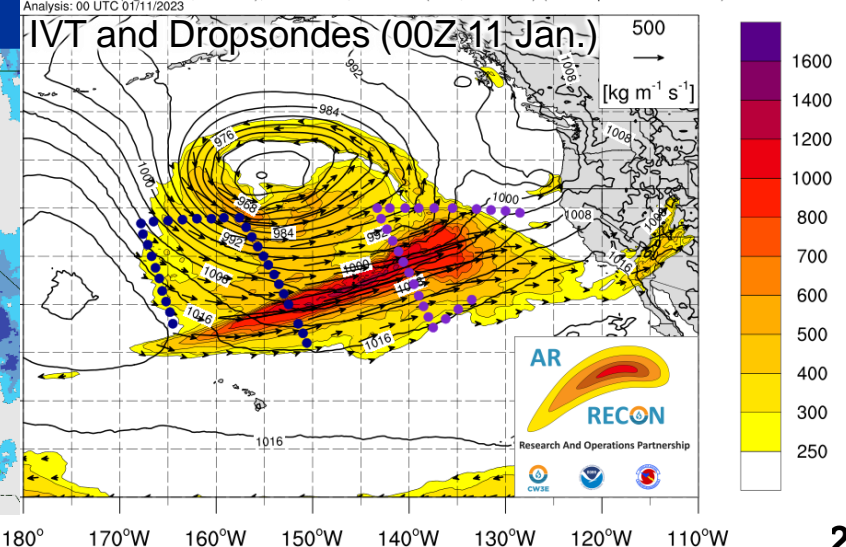
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 9 Jan 2023 | Forecast hour: 0 | Valid: 0000 UTC 9 Jan 2023



24-h Precip. (12Z Jan 12)

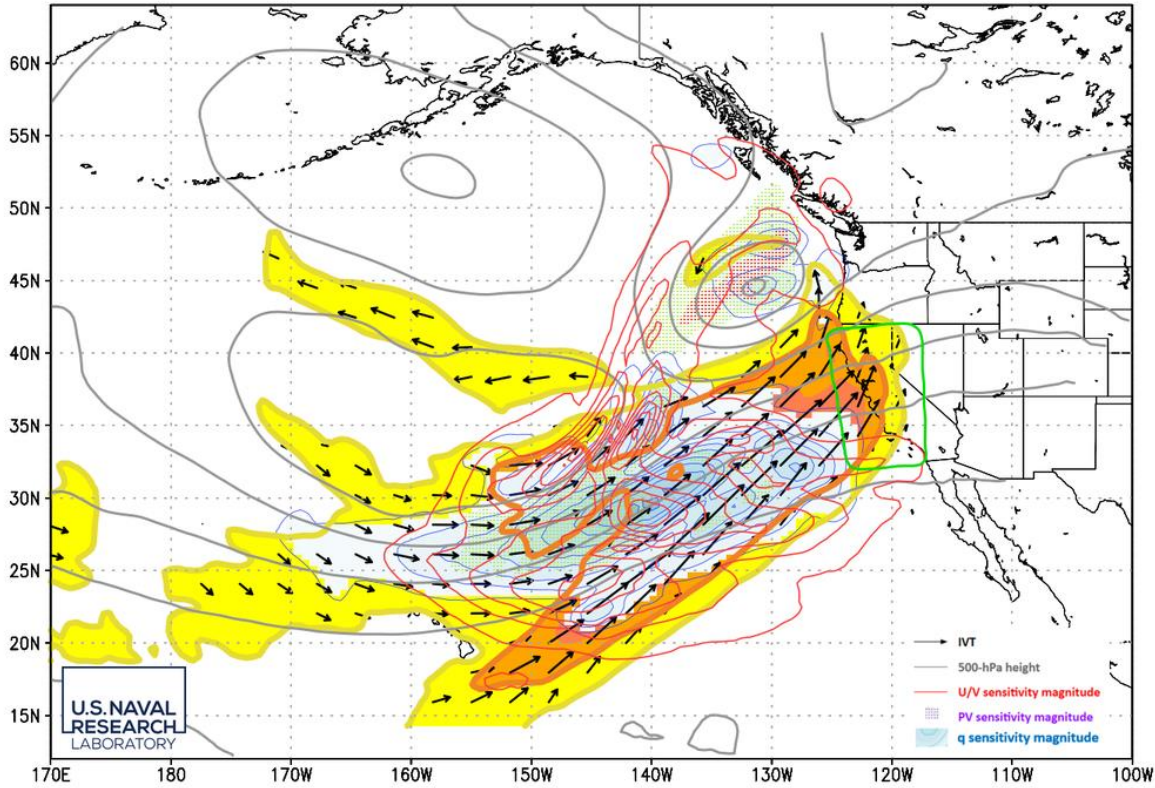


GFSv16 IVT ($kg m^{-1} s^{-1}$; shaded), IVT Vector, and SLP (hPa; contours) (53 Drops: 24AF/29G-IV)
 Analysis: 00 UTC 01/11/2023



Adjoint Sensitivity: Mar. 10 (IOP 36)

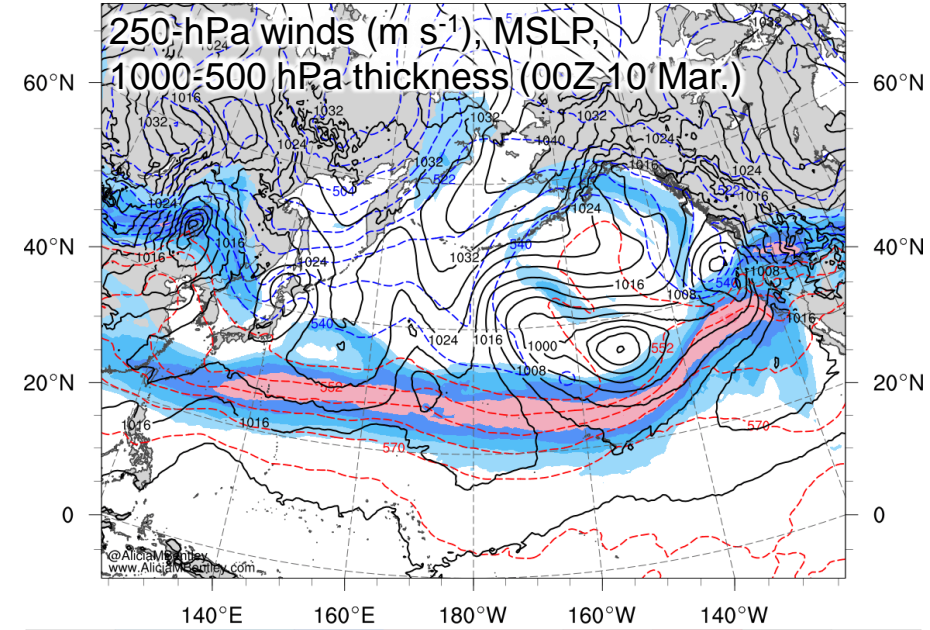
NRL COAMPS Adjoint Model Sensitivity
 2023031000 Target Time from 2023030800 forecast
 24-h Precipitation Response Function Ending 2023031112
 2023031000 IVT (vectors) and 500-hPa Height (gray)
 2023031000 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)



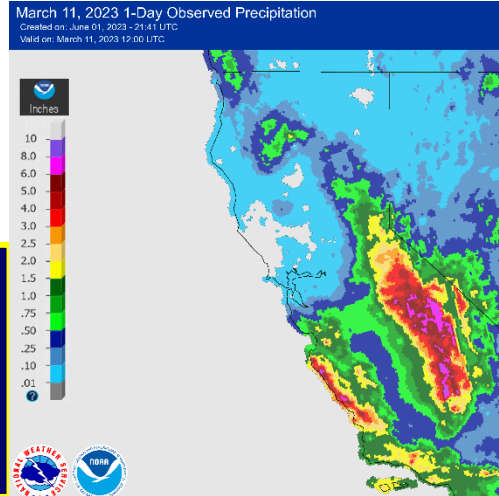
Growth = 57.2833

- 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

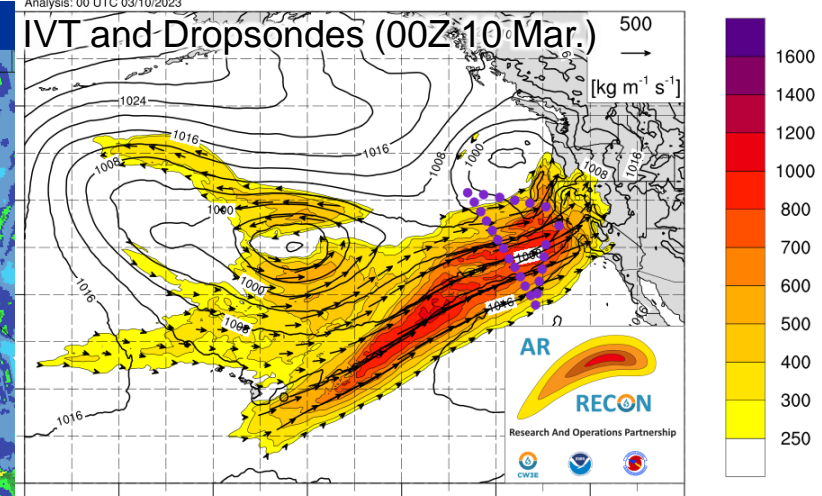
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)
 Initialized: 0000 UTC 10 Mar 2023 | Forecast hour: 0 | Valid: 0000 UTC 10 Mar 2023



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



GFSv16 IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vector, and SLP (hPa; contours) (24 Drops: 24AF/0G-IV)
 Analysis: 00 UTC 03/10/2023

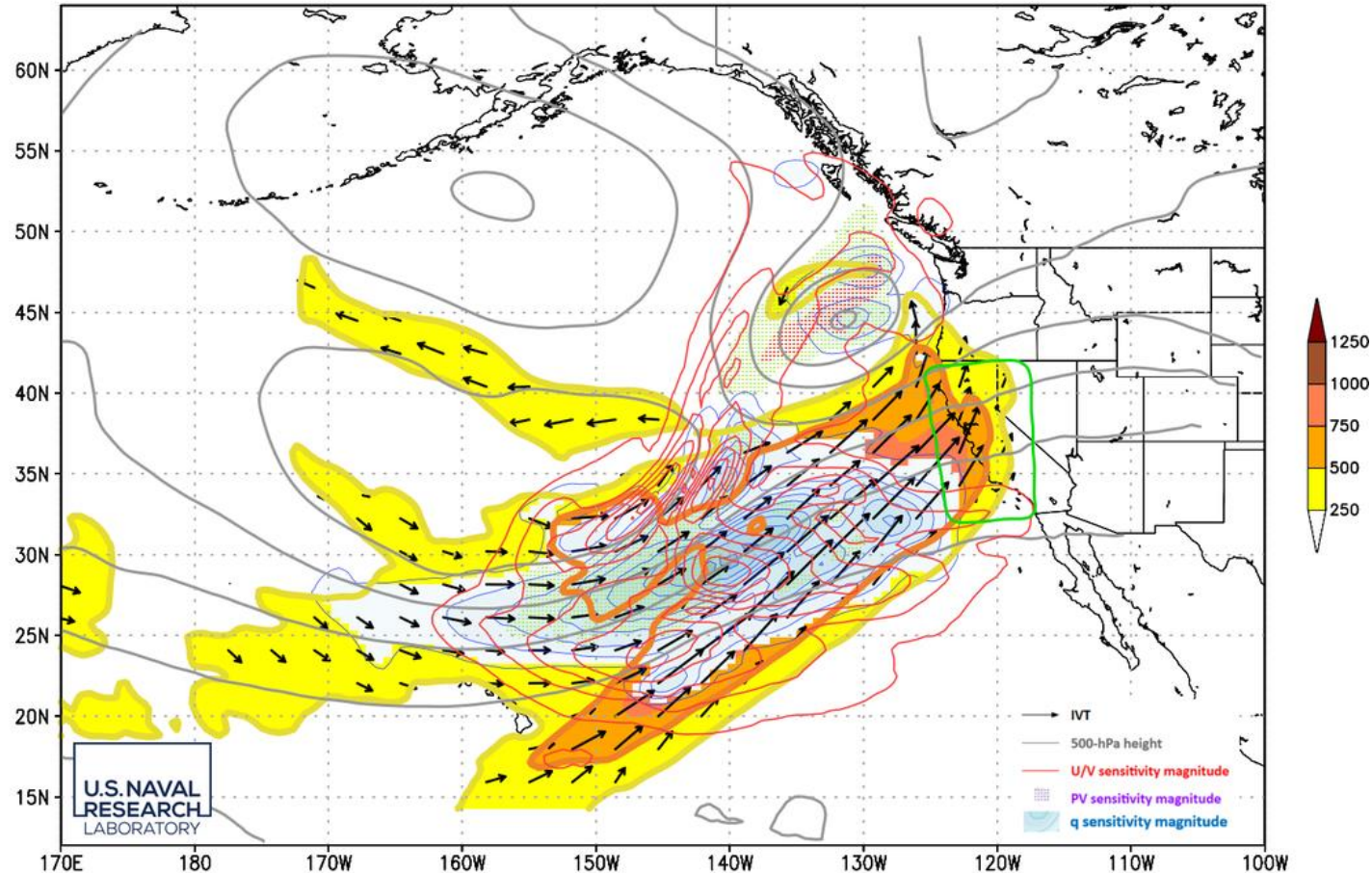


COAMPS Adjoint Sensitivity Summary Graphic

Adjoint Summary Graphic

NRL COAMPS Adjoint Model Sensitivity
 2023031000 Target Time from 2023030800 forecast
 24-h Precipitation Response Function Ending 2023031112
 2023031000 IVT (vectors) and 500-hPa Height (gray)
 2023031000 Vert. Integ. Sensitivity Mag. q (blue), u v (red), PV (stipple)

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

1000