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Dynamically Linking Two High-Impact Atmospheric River Events

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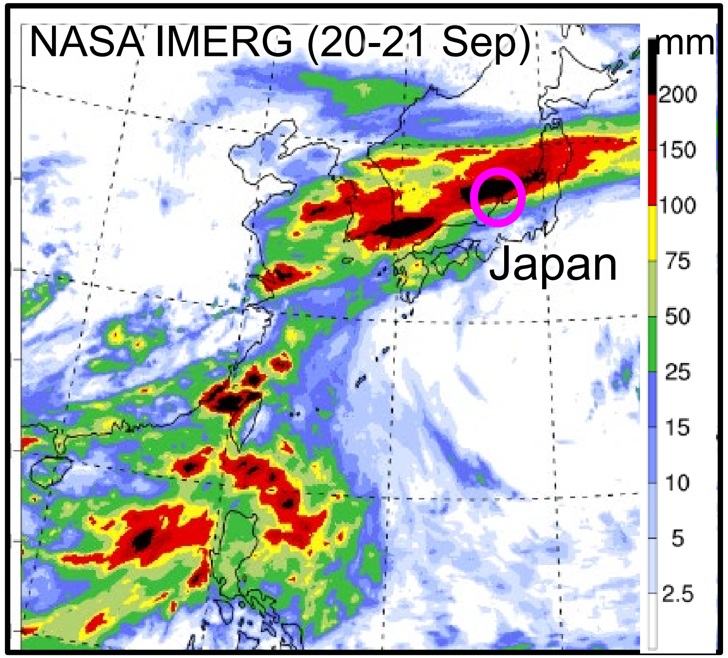
Overview
Atmospheric River (AR) High-Impact Event 20-25 Sep. 2024

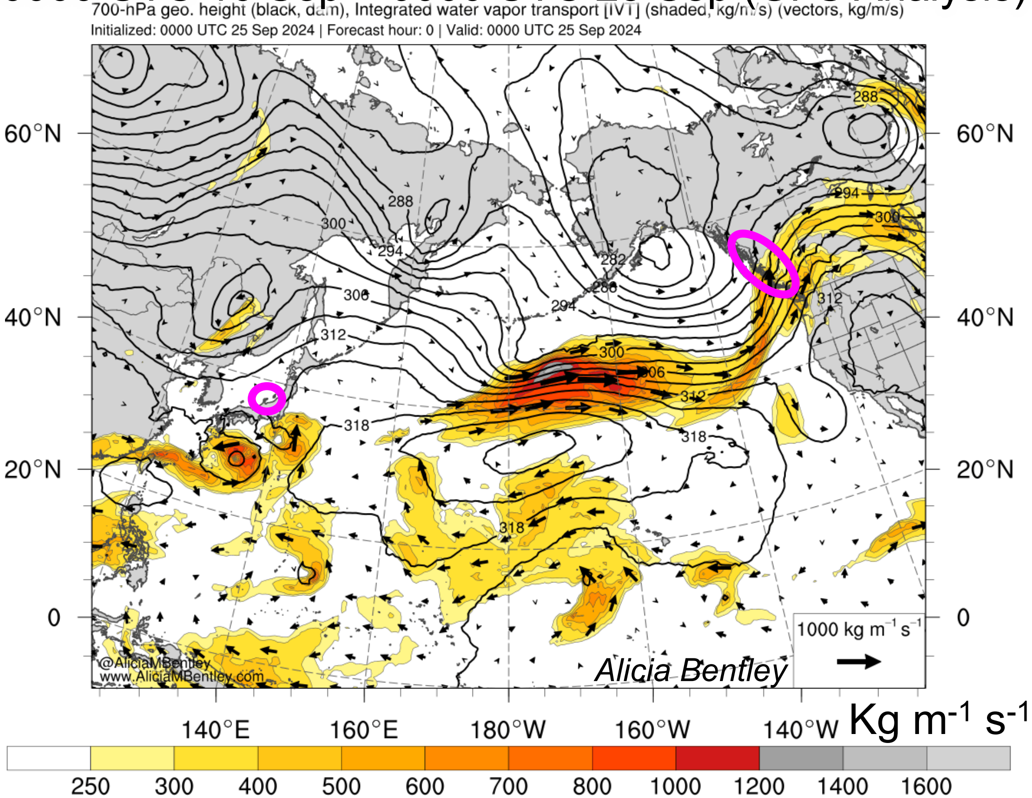
- Atmospheric Rivers (ARs) often drive High Impact Weather (HIW) and occur in families of sequential events, but the links between upstream and downstream HIW remain poorly understood (Ralph et al. 2017; Fish et al. 2019)
- We explore AR–HIW events that spanned from Japan flooding to a downstream 'extreme' AR driving AK/BC floods
- **How are these two HIW events linked and what are the predictability barriers?**
- COAMPS moist adjoint is used explore links between two HIW events
  - Adjoint Sensitivity of response function (J) at time t_n to the state at time t_0:

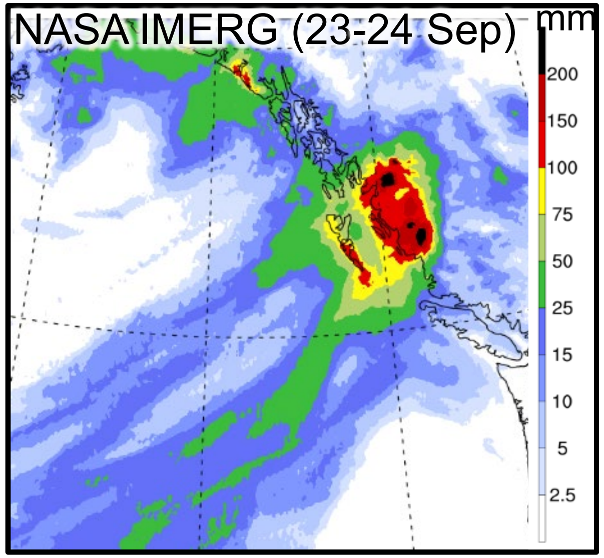
$$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$$



Monsoon moisture surge linked with a mid-latitude trough resulted in over 250 mm of precipitation in 6 h over the Noto Peninsula in Japan

IVT (shaded, kg m^{-1} s^{-1}, vectors); 700-hPa Heights
0000 UTC 16 Sep – 0000 UTC 25 Sep (GFS Analysis)





- Downstream 2.5 days later, a Category 5 AR occurred with IVT > 2100 kg m^{-1} s^{-1}
- Precipitation > 200 mm led to flooding and landslides over Alaska and British Columbia

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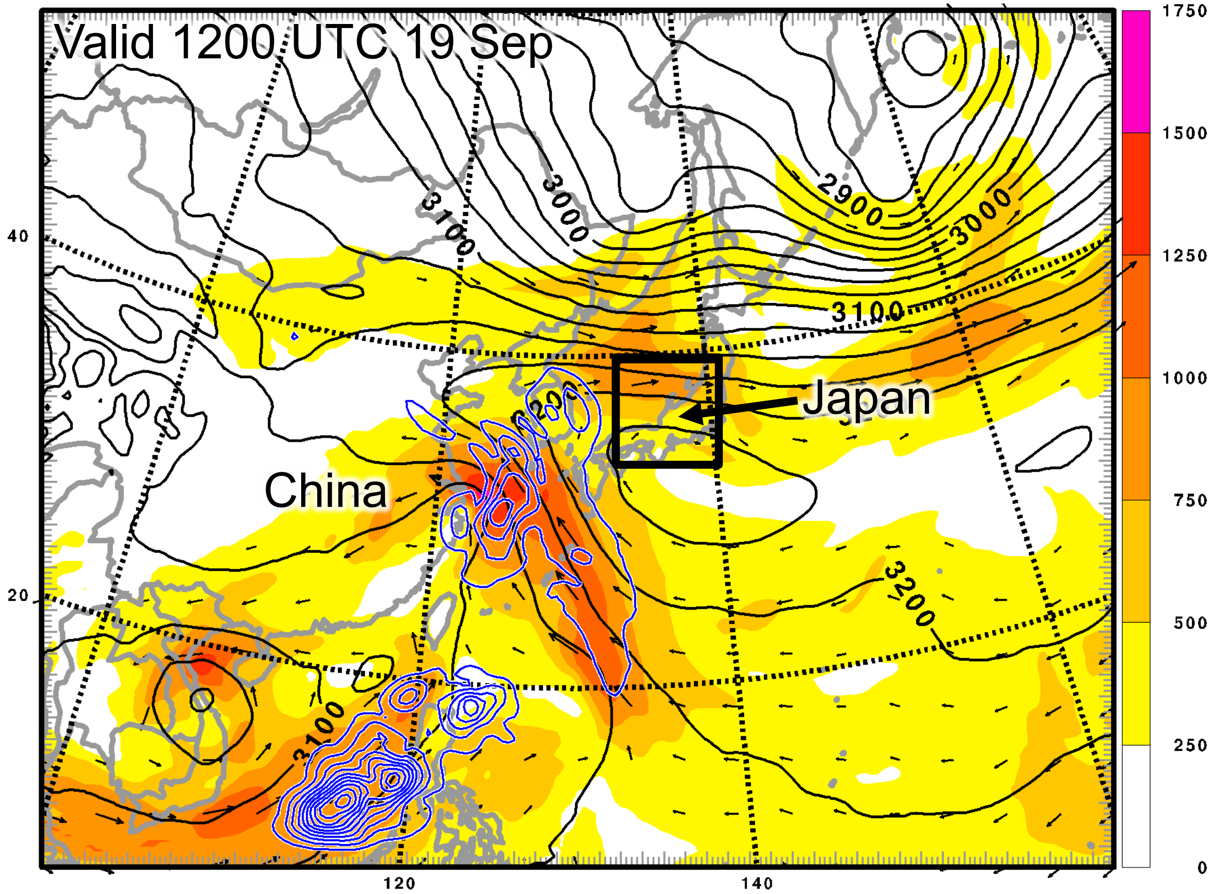
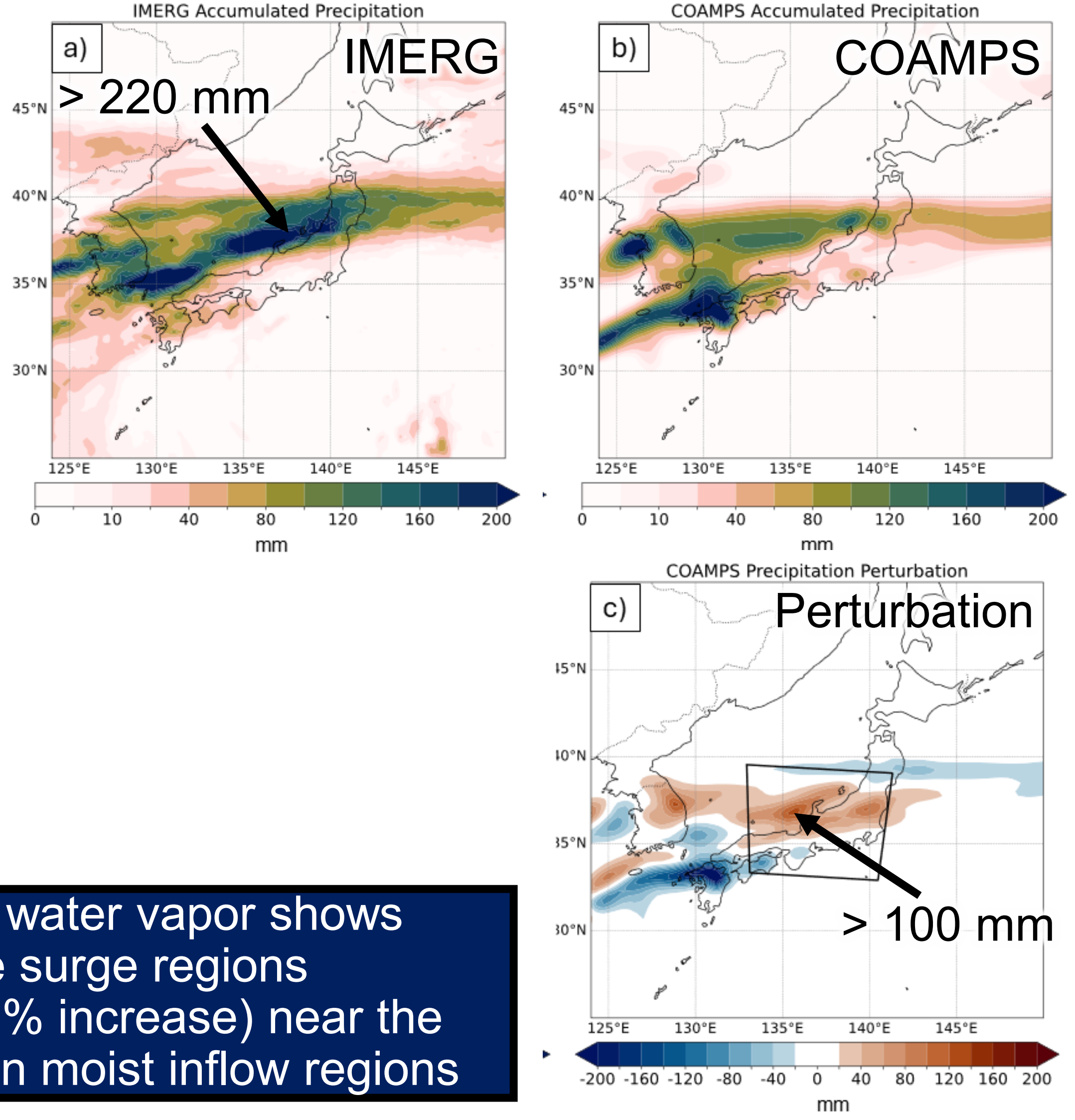
Adjoint Forecast Sensitivity for Japan Flood (60h)

1200 UTC 19 September 2024

IVT (shading, kg m^{-1} s^{-1}, vectors), 700-hPa Heights (m)
60-h Precipitation Sensitivity to the Initial Moisture [blue, mm (g $kg^{-1})^{-1}$]



48-h Accumulated Precipitation (mm) 00 UTC 22 Sep.
Adjoint Perturbation Precipitation in NLM (red/blue mm)



- Sensitivity of the 48-h accumulated precipitation to the initial water vapor shows large positive sensitivity in the monsoon trough and moisture surge regions
- Adjoint perturbations increase precipitation by > 100 mm (70% increase) near the Noto Peninsula highlighting importance of sensitive regions in moist inflow regions

Adjoint Forecast Sensitivity for Pacific NW Flood (72h)

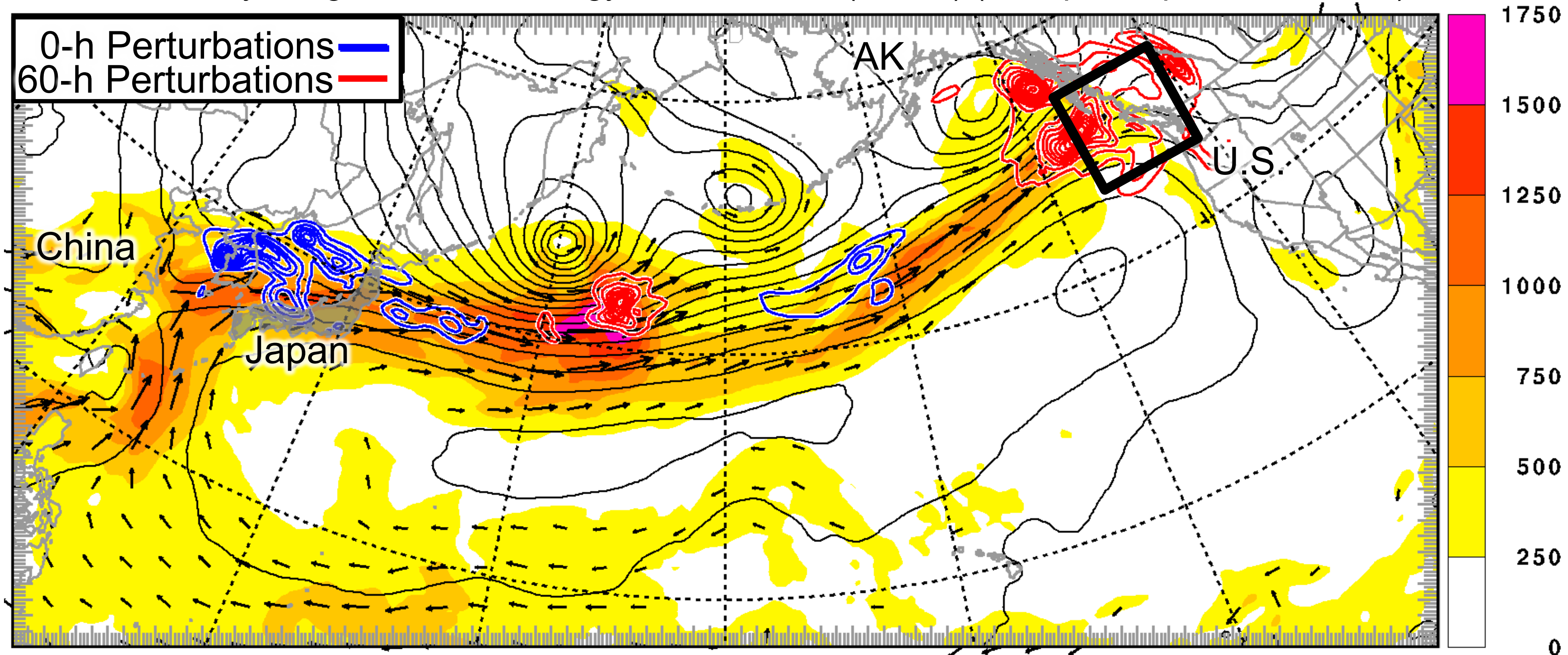
0000 UTC 21 September 2024

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

Total KE PE IE Moist

0000 UTC 21 Sep. IVT (shading, kg m^{-1} s^{-1}, vectors), 700-hPa Heights (m)

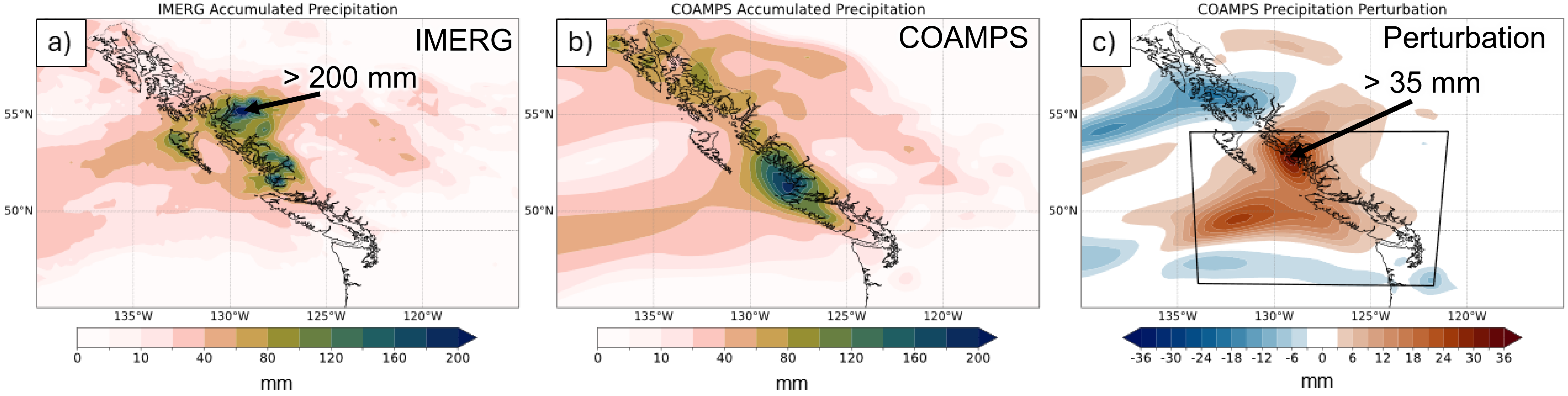
0-h Vertically Integrated Total Energy Perturbations (m^{-2} s^{-2}) (Precip. Response Function)



- Initial adjoint total energy perturbations (vertically integrated), based on the 72-h sensitivities, highlight sensitivity near the moisture surge and trough axis, mostly dominated by the water vapor sensitivity
- Adjoint perturbations grow rapidly (by 500x at 60 h) and increase the 24-72 h precipitation

Impact of Adjoint Perturbations on Precipitation
0000 UTC 21 September 2024

24-72h Accumulated Precipitation (shading, mm) Valid at 0000 UTC 24 Sep.
Adjoint Perturbation Precipitation in NLM (red/blue mm)



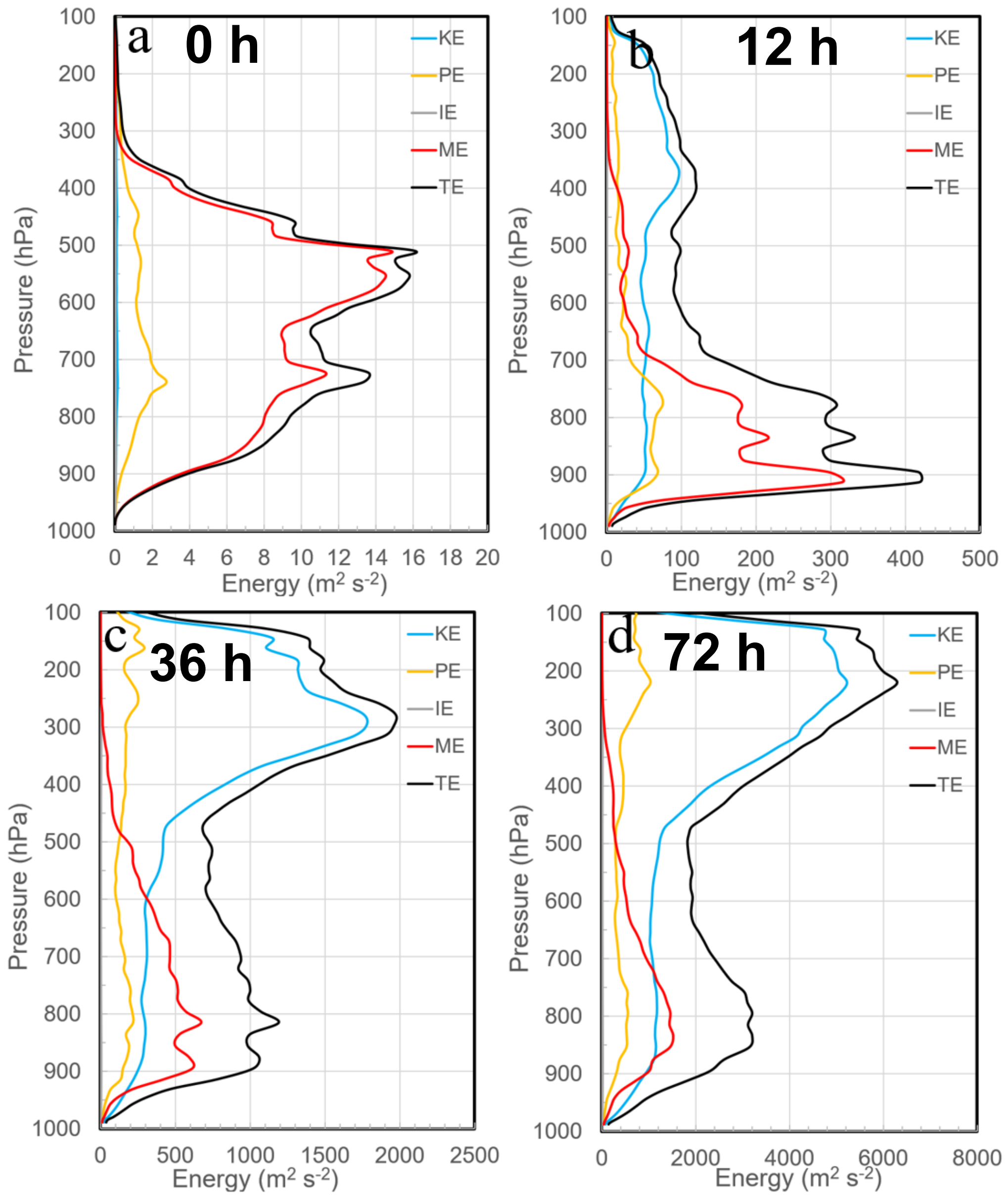
Adjoint perturbations evolved in the NLM grow rapidly (by 300x at 60 h) and increase the 24-72 h precipitation by ~25%

Optimal Perturbation Energy Budget

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

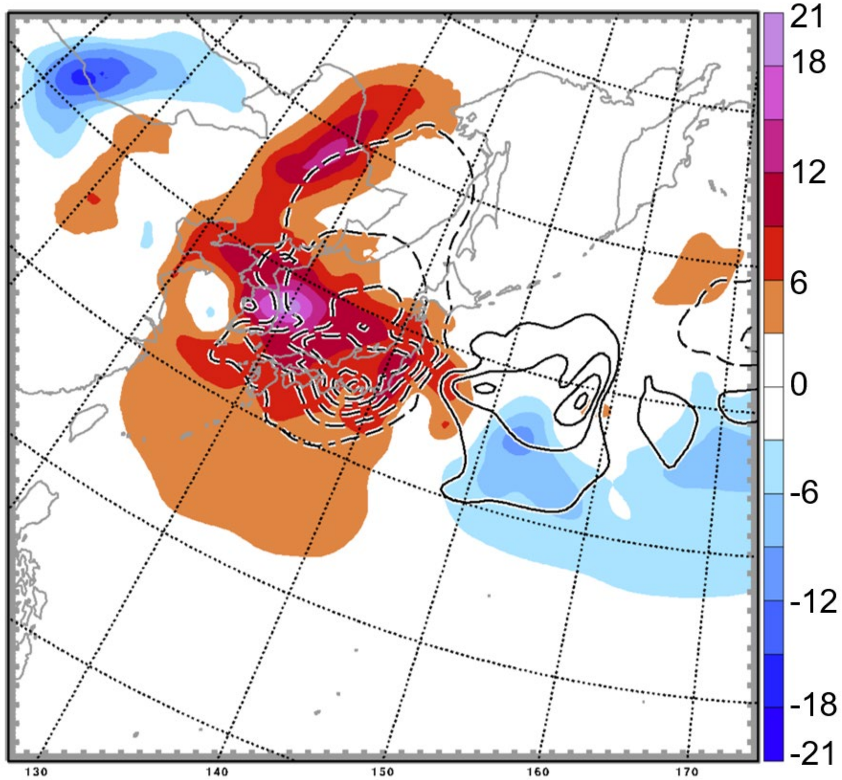
Total **KE** **PE** **IE** **Moist**

- Energy Budget: Diagnoses rapid conversion of upstream thermodynamic energy to downstream kinetic energy
- Source: Forecast uncertainty is initially concentrated in moist energy in the lower–mid-tropospheric monsoon region
- Growth: Subsequent conversion of moist energy to jet-level kinetic energy occurs within 36 h
- Pathway: Establishes a quantitative link between upstream diabatic process uncertainty and dominant forecast error modes in remote high-impact systems

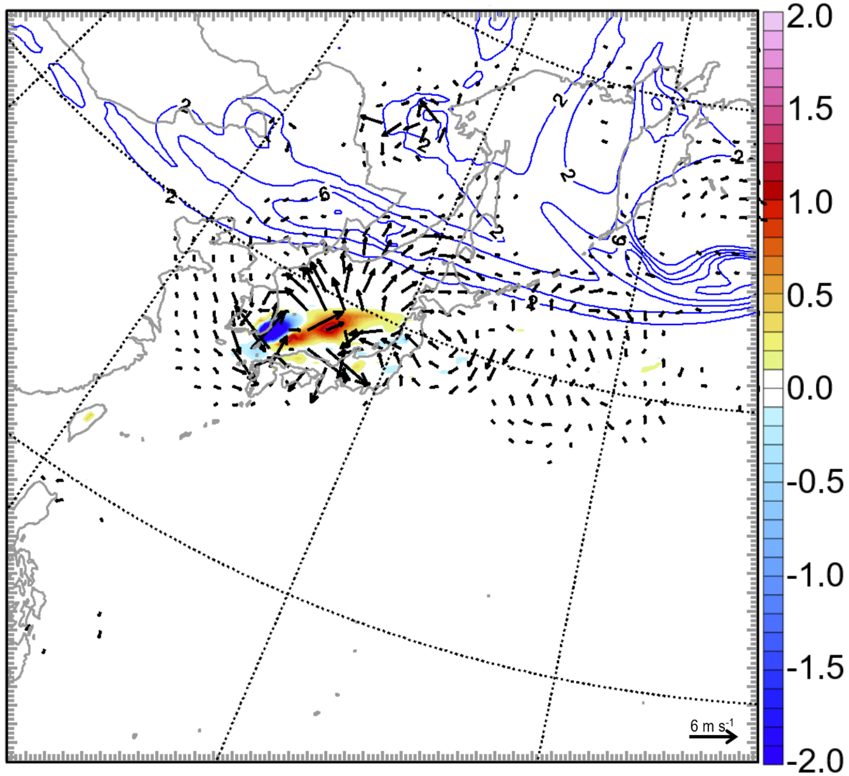


Convective-Dynamic Link
Atmospheric River Event 20-25 September 2024

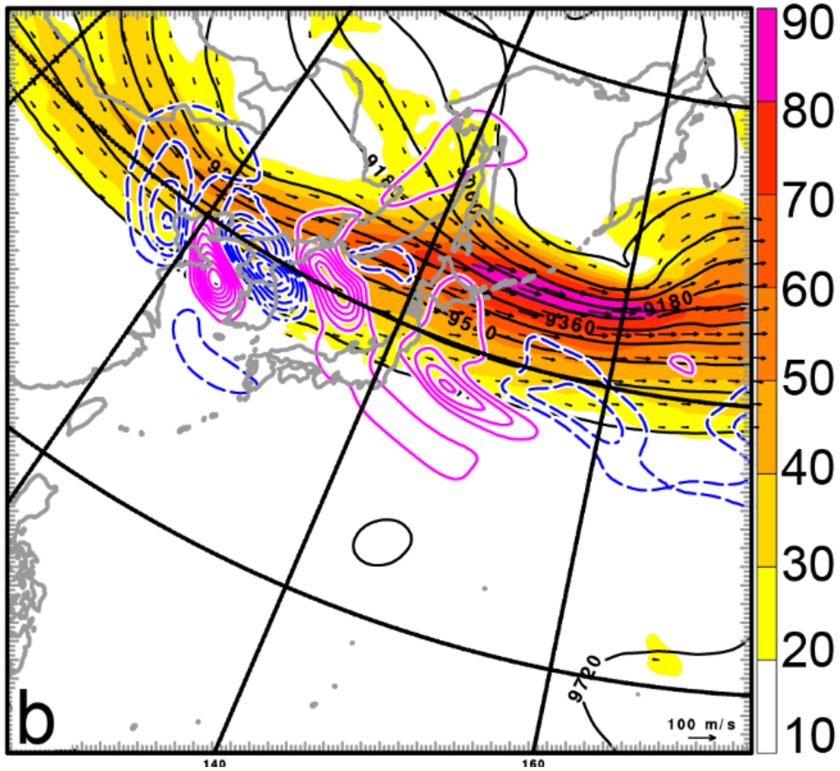
24-72-h precipitation sensitivity to 0-h 300-hPa divergence (s^{-1} mm^{-1}, color) 850-hPa divergence (s^{-1} mm^{-1}, contours) [positive (solid) and negative (dashed)]



300-hPa 12-h diabatic heating perturbation (K hr^{-1}, color), perturbation winds and vectors 12-h 300-hPa PV (every 2 PVU, contours)



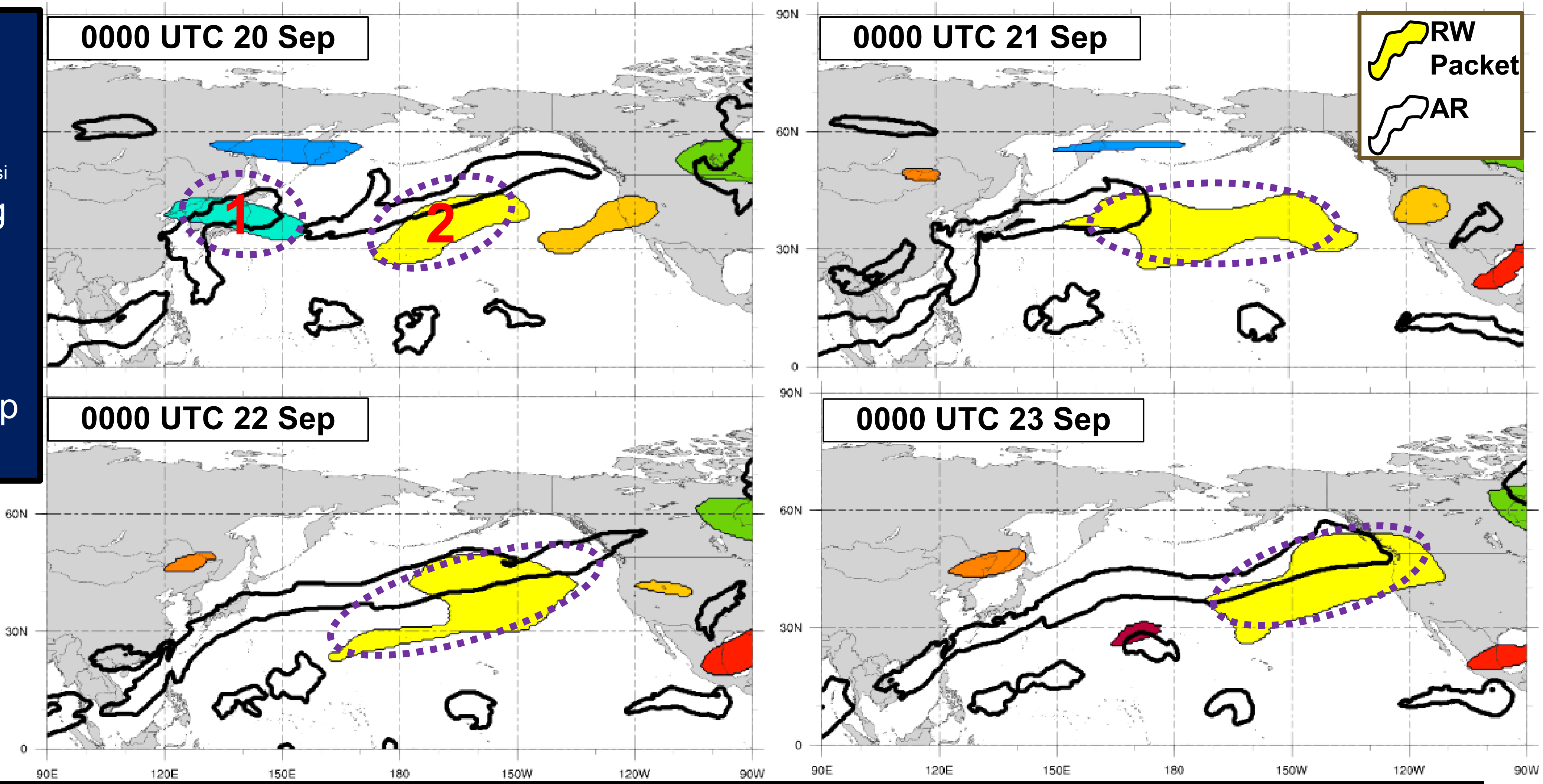
250-hPa winds (shading, vectors, m s^{-1}) 24-72 precipitation sensitivity to 0-h 500-hPa vorticity [mm s] (magenta/blue contours)



- Strong 24-72 precipitation sensitivity to the initial low-level convergence and upper-level divergence
- 12-h adjoint perturbations enhance upper-level diabatic heating and divergent outflow that project on to the irrotational winds increasing the PV advection in the waveguide
- 500-hPa vorticity sensitivity shows Rossby wave packet signature in the right entrance region of the jet

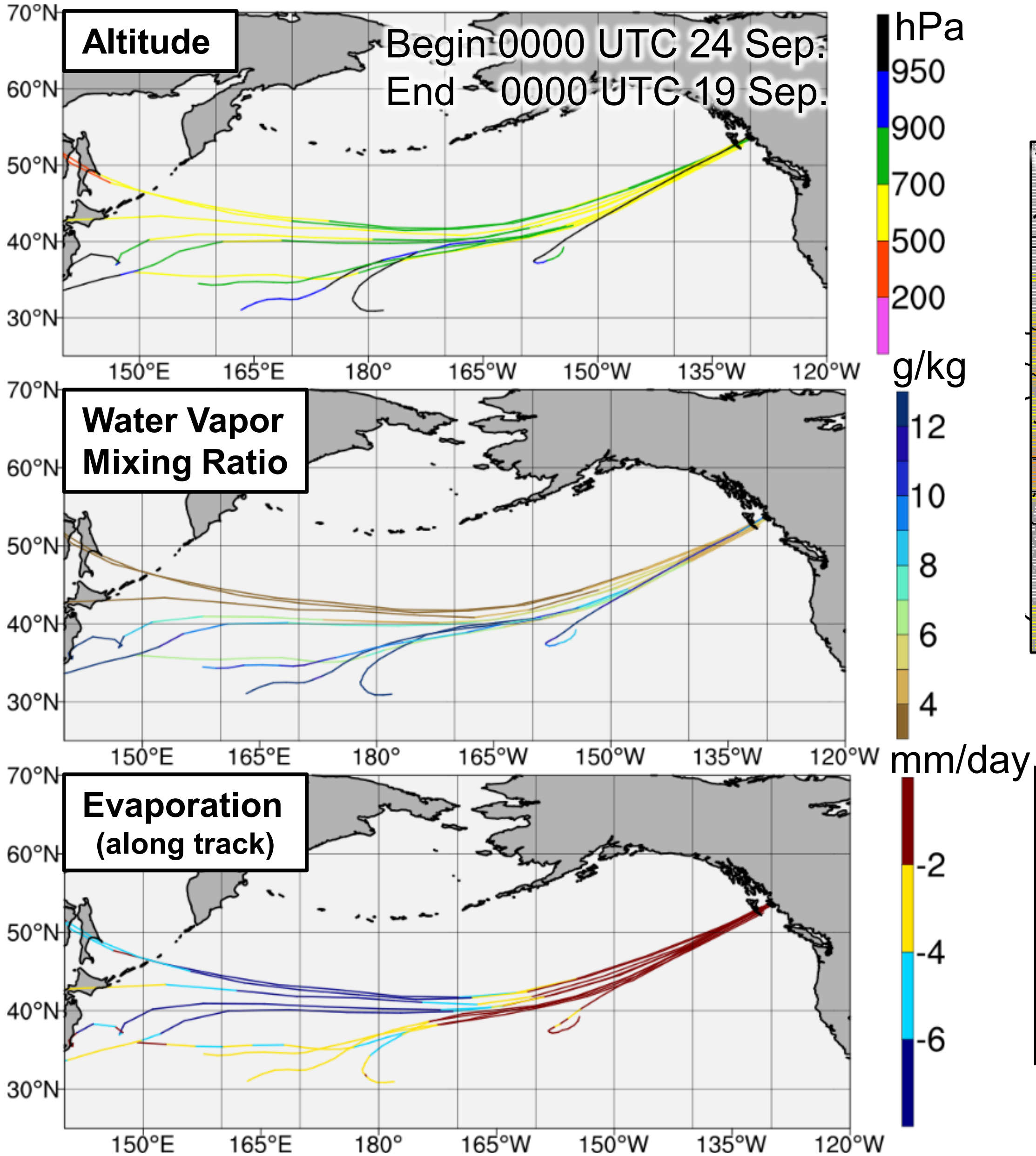
AR and Rossby Wave Packet Analysis
Atmospheric River Event 20-25 September 2024

- ERA5 Reanalysis
- ARs and Rossby Wave Packets (Ghinassi et al. 2018) tracked using TempestExtremes (Ullrich et al. 2021)
- ≥ 1 day lifetime; ≥ 35% object overlap every 6 h required

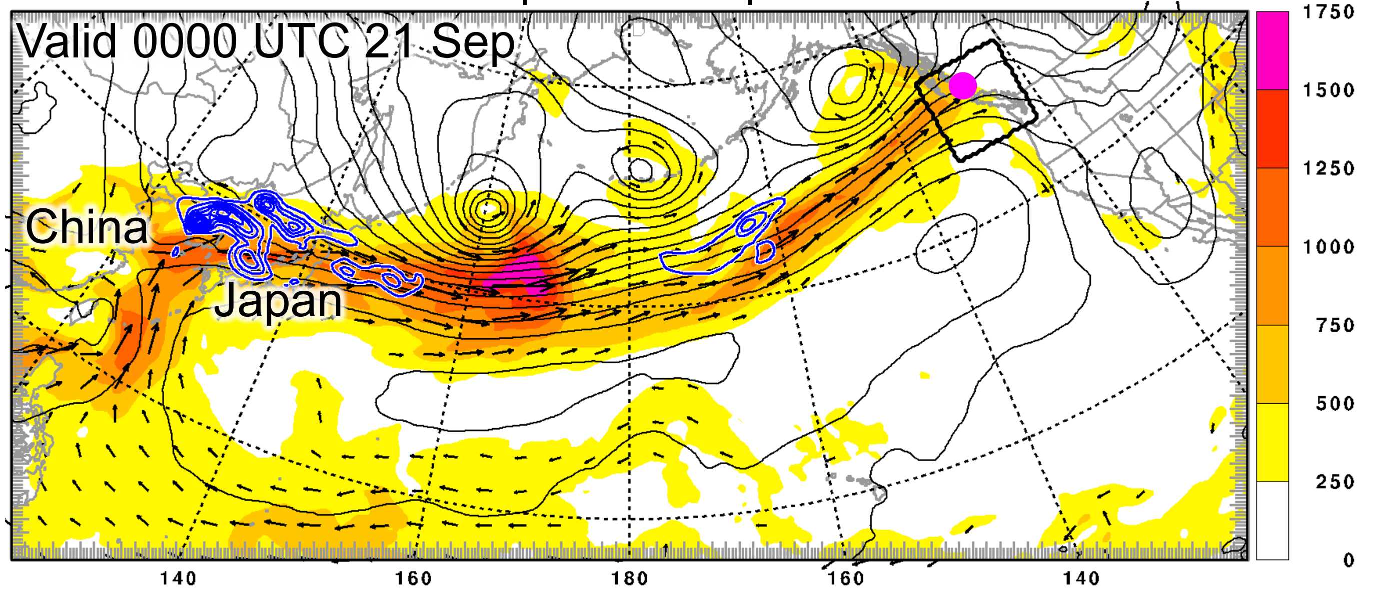


- Rossby wave packet 1 (RWP1) passes over Japan coincident with divergent outflow and is amplified
- RWP1 and RWP2 combine and propagate downstream rapidly, coincident with the trans-Pacific AR
- RWP2 makes landfall ~3-4 days later (theory ~22-32 m s^{-1} within observational estimate of 25 m s^{-1})

ERA-5 Back Trajectories



IVT (shading, kg m^{-1} s^{-1}, vectors), 700-hPa Heights (m)
0-h Vertically Integrated Total Energy Perturbations (m^{-2} s^{-2})
24-72-h Precipitation Response Function



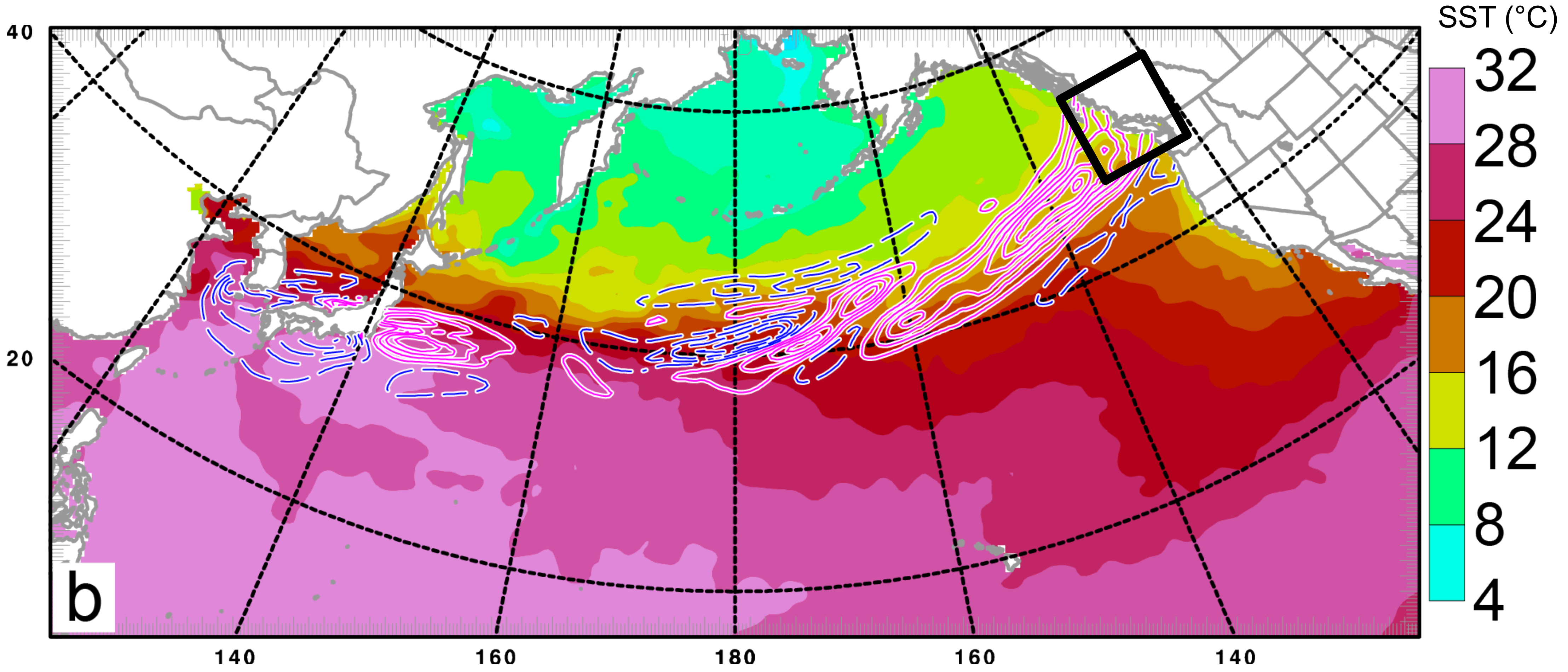
- 5-day back trajectories from ERA-5 initialized on 24 Sep.
- Trajectories are launched from the IVT maximum (using meridional component) along the B.C. coast
- Trajectories require ~5 days to transit the Pacific basin while the adjoint perturbations travel as a Rossby wave packet and impact the precipitation in 3 days

Adjoint Forecast Sensitivity (72h)

0000 UTC 21 September 2024

Sea Surface Temperature (shading, K)

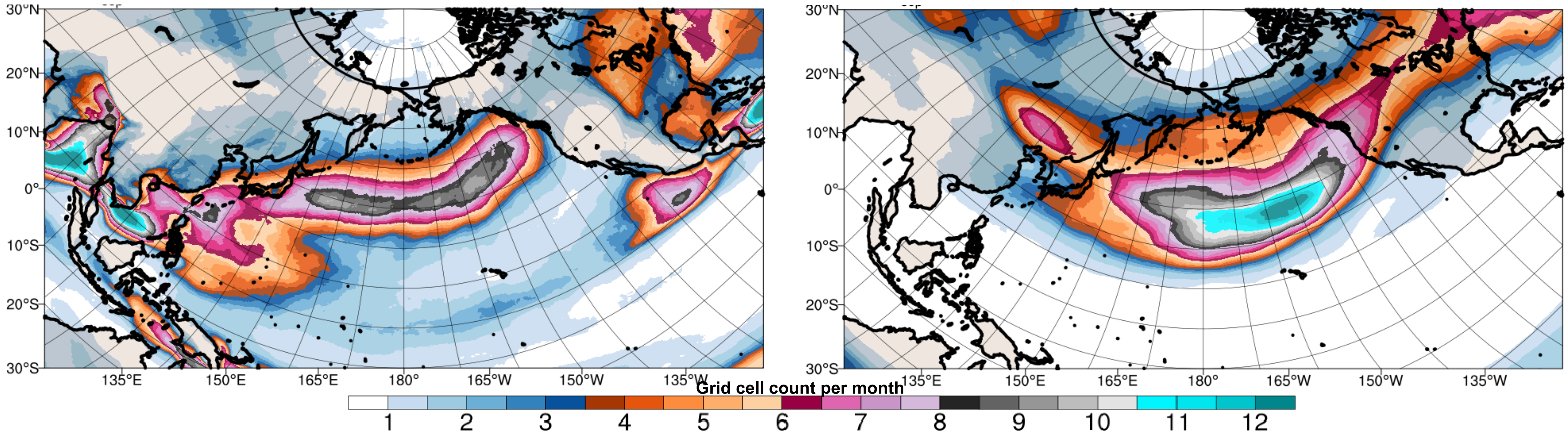
24-72-h Forecast Precipitation Sensitivity to the Initial SST (mm K^{-1})



Forecast precipitation over AK/BC is sensitive to the initial SSTs along the AR, with maxima located near baroclinic waves and to the south of the main AR corridor

AR Rossby Wave Packet Analysis
September 1998-2024

AR Frequency September 1998-2024 RWP Frequency



- September AR frequencies show an active western Pacific and a strong cross-ocean extension
- September RWP frequencies show a strong cross-Pacific extension consistent with ARs
- Spatial consistency between ARs and RWPs suggests the two may share a dynamic link

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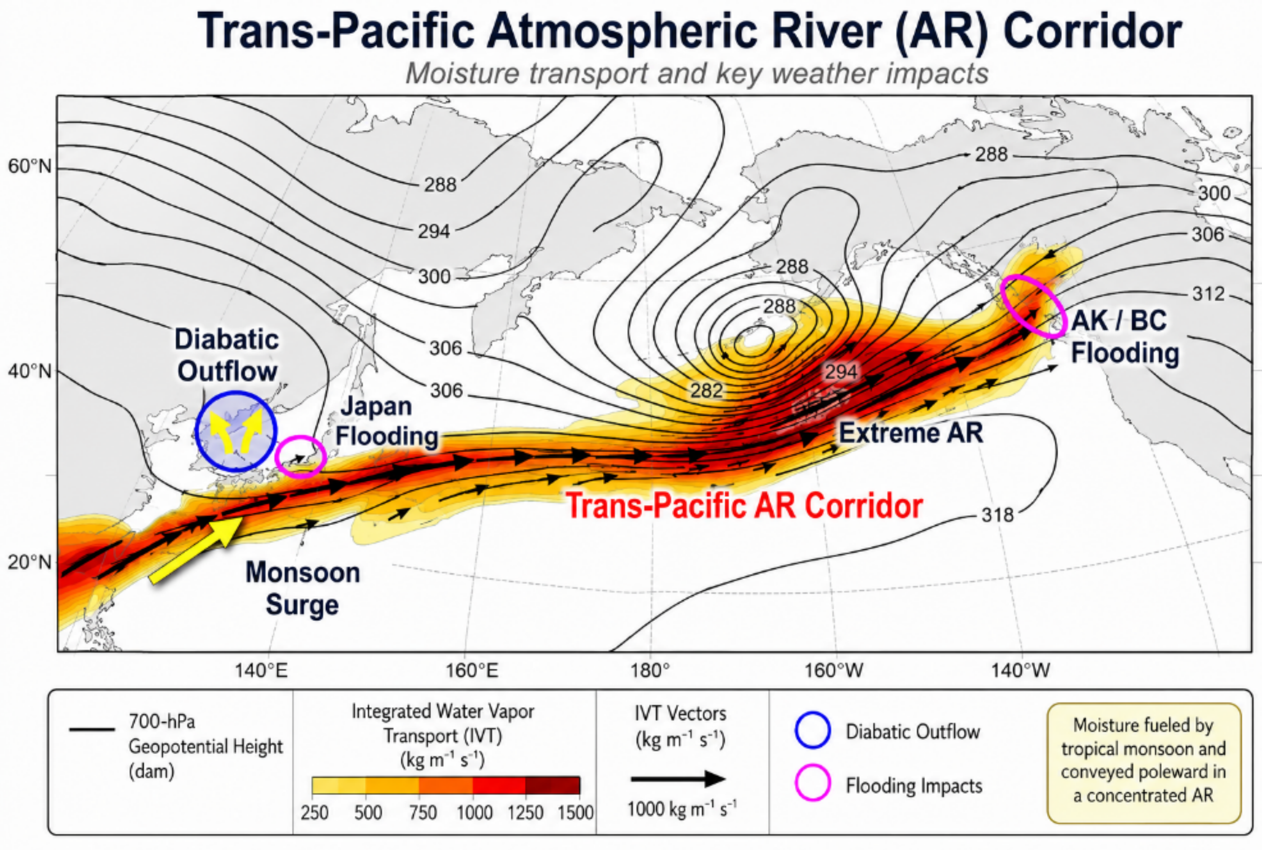
Summary

Dynamically Linked High-Impact Weather

- Japan flooding forecasts are very sensitive to the initial state moisture surge and monsoon trough
- Subsequent diabatic heating and divergent outflow amplify a RWP that propagated eastward
- Initial condition uncertainty in this region has a large impact on subsequent AK-BC flooding



Multiscale Initial Condition Uncertainty

- Large sensitivity to moist inflow & divergent outflow
- Motivates more accurate moisture analyses and HIW probabilistic prediction

Future Research

- Frequency of W. Pacific ARs triggering downstream HIW
- Dynamical coupling between RWPs and ARs
- Role of air-sea interaction in these events (SAFARI)

Doyle, J.D. , K.A. Biernat, M.G. Fearon, C.A. Reynolds: Sensitivity and Predictability of a Cross-Basin Atmospheric River: Dynamically Linking Two High-Impact Weather Events. (Mon. Wea. Rev. In Review)

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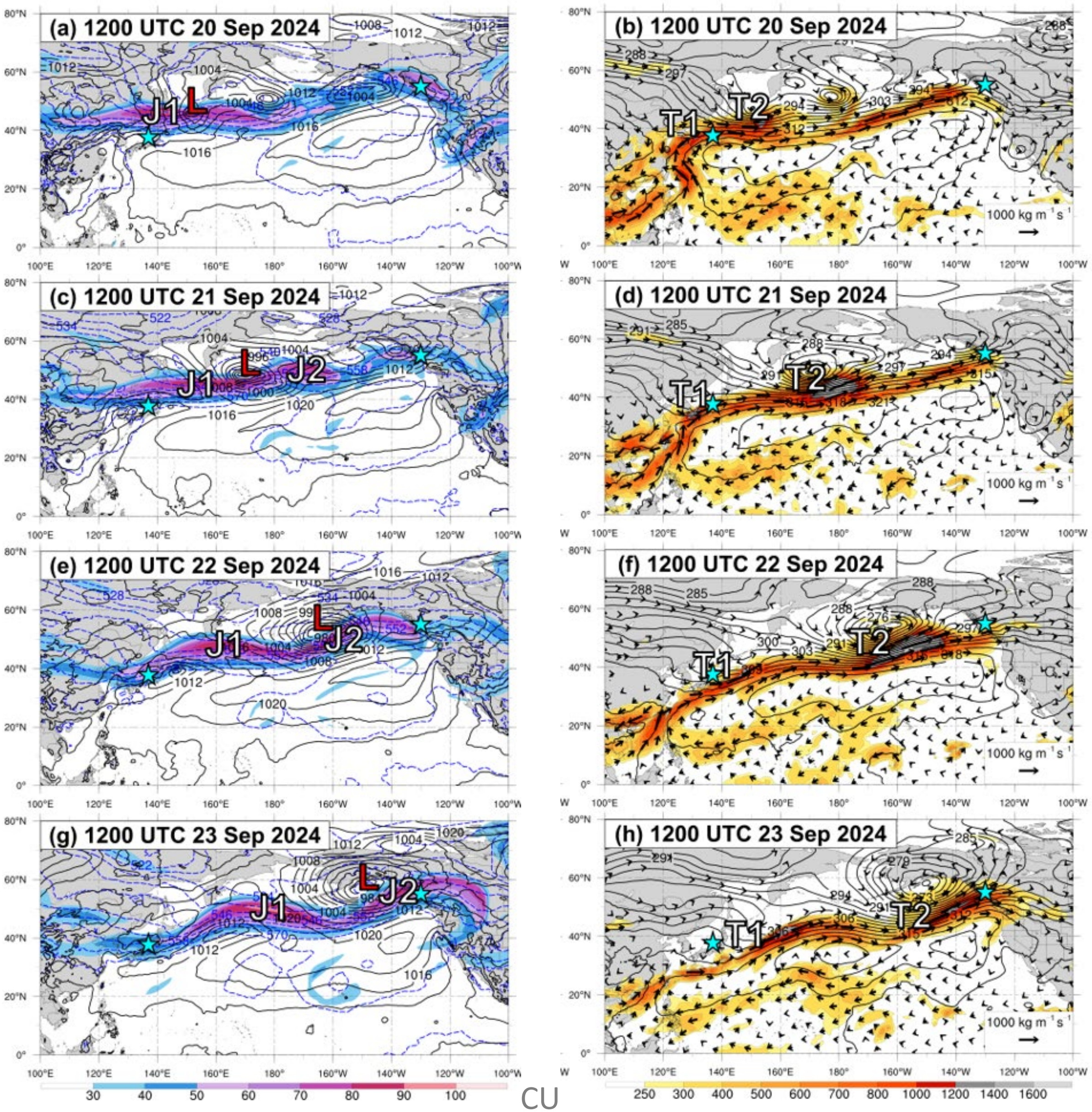
Synoptic-Scale Overview
ERA-5 Reanalysis

MSLP (black), 1000-500-hPa thickness (blue),
250-hPa wind speed (shaded)

“J1”, “J2” Jet Streaks

700-hPa geopotential height (black) and IVT (shaded and vectors)

“T1”, “T2” Troughs



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