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Sensitivity of Forecast Errors to Initial Conditions for High-Impact Atmospheric River Events using a Nonlinear Adjoint Method

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R2O Session 3B Atmospheric River Reconnaissance: Observations, Science Advances, and Impact on Forecasts and Downstream Decision-Making: Part I

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Motivation and Background

- Atmospheric rivers (ARs) are often associated with high-impact weather (HIW) such as floods and windstorms (Ralph et al. 2006; Waliser & Guan 2017; Corringham et al. 2019), with diabatic processes acting as waveguide 'triggers' or 'seeds' leading to HIW downstream (Ryoo et al. 2015) and limiting predictability (Sánchez et al. 2020)

270 mm of rain fell on the Noto Peninsula, Japan in 6 hr, doubling the previous record (20-21 Sep 2024)

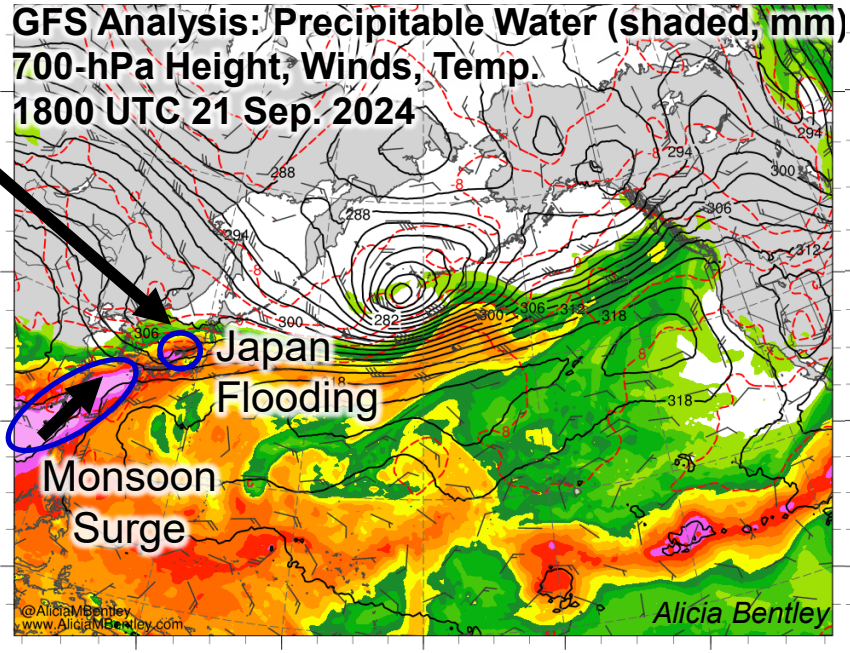

Six dead after record rain causes floods in Japan

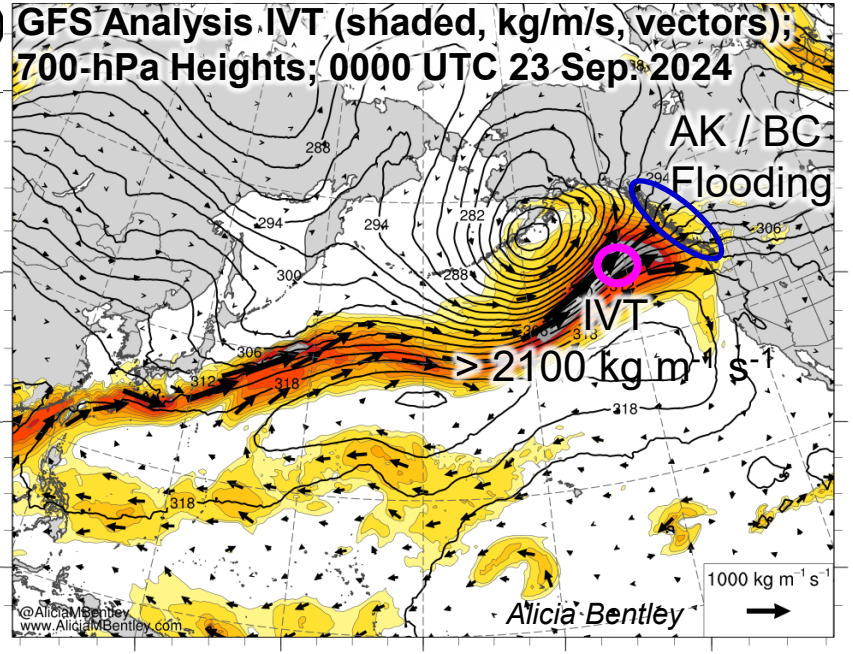
22 September 2024

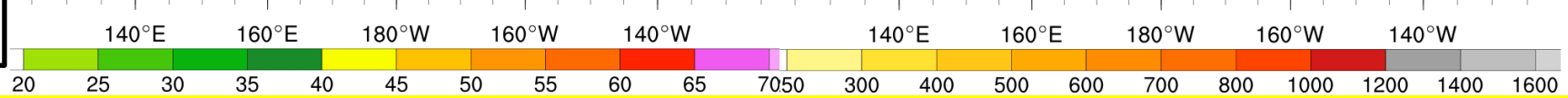
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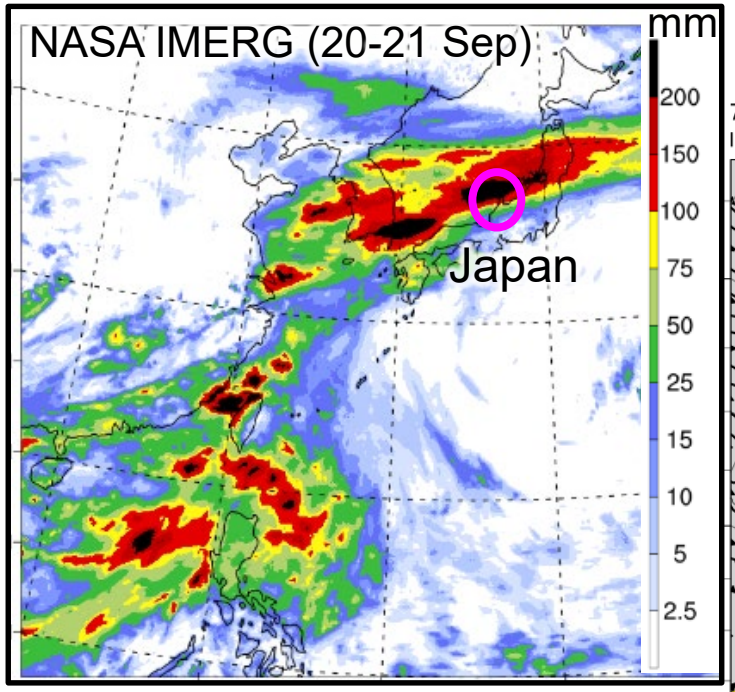


- Monsoon moisture surge linked with a mid-latitude trough contributing to record flooding in Japan
- Trans-Pacific AR corridor featured an 'extreme' AR (IVT > 2100 kg m^{-1} s^{-1}) that led to downstream flooding in AK/BC
- How are the two HIW flooding events linked and what are the predictability barriers?
- COAMPS adjoint (with nonlinear extension) 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:

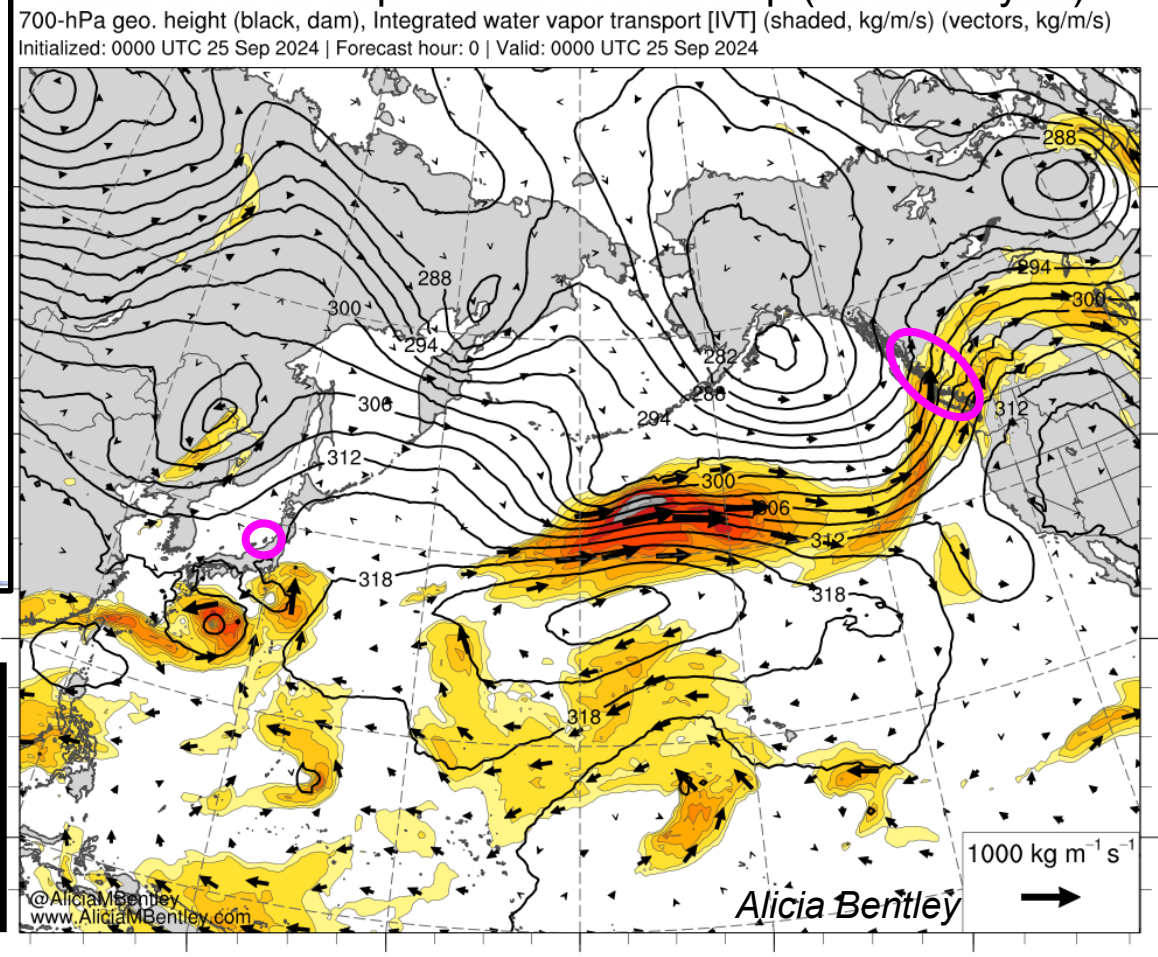
$$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$$

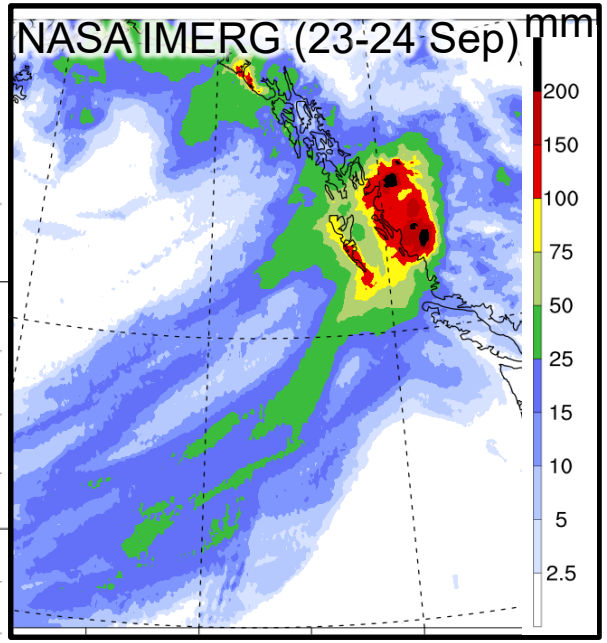
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Overview
Atmospheric River Event 20-25 September 2024



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





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

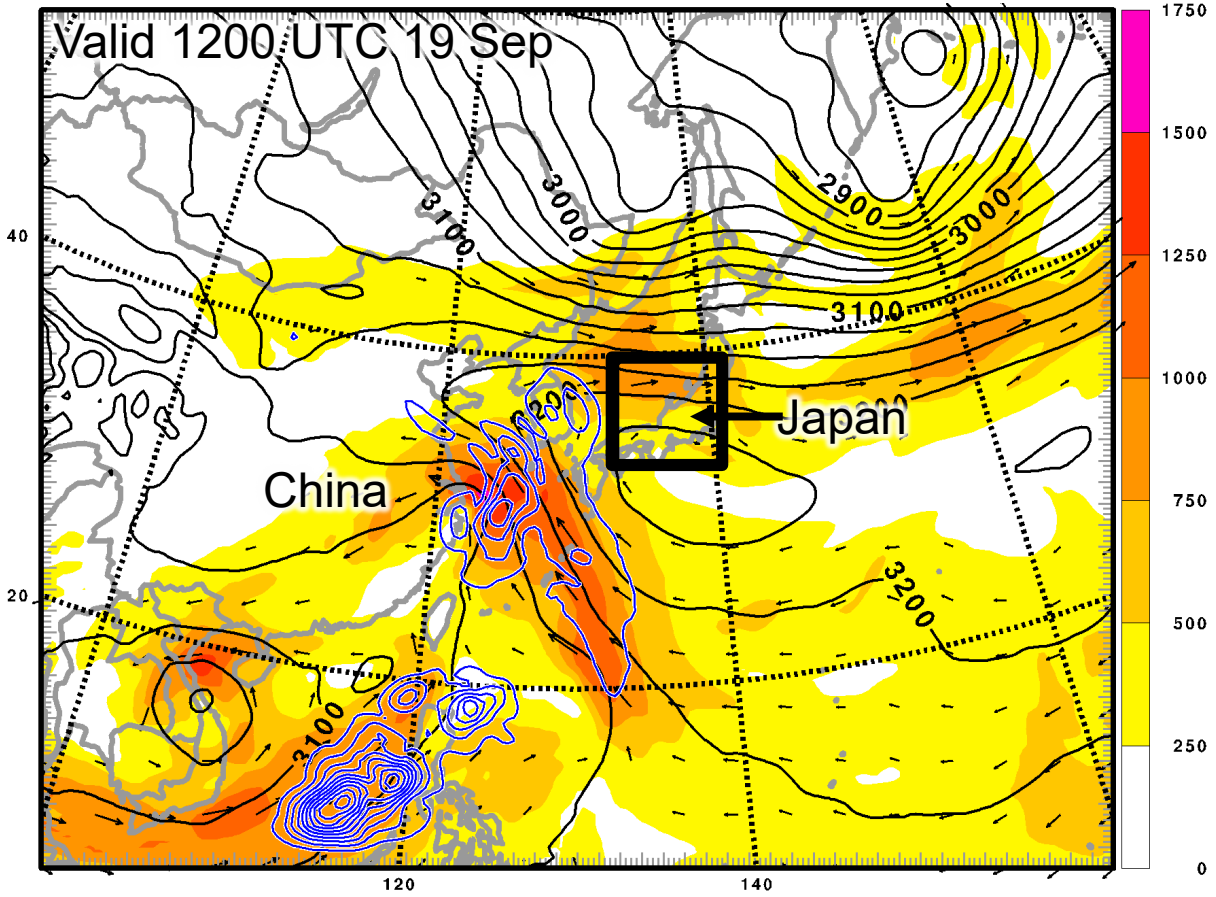
- Downstream 2.5 days later, a Category 5 AR occurred with IVTs >2100 kg m^{-1} s^{-1}
- Precipitation > 200 mm led to flooding and landslides over Alaska and British Columbia

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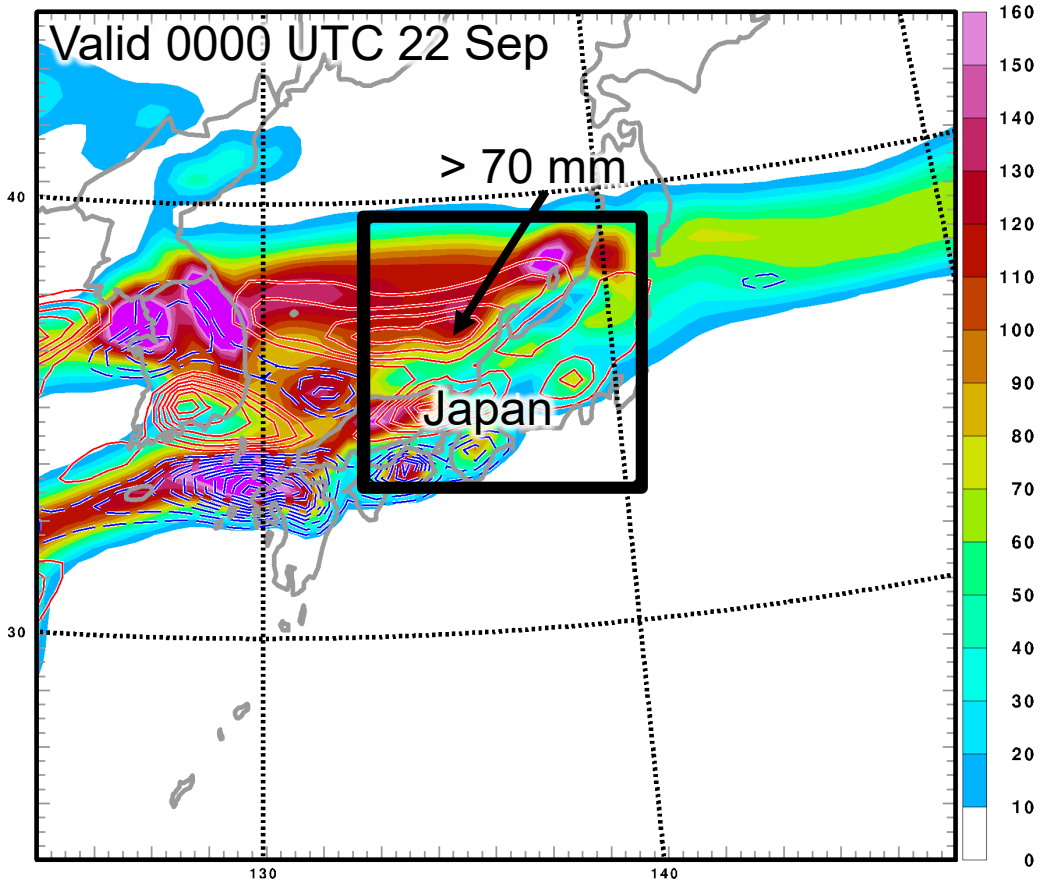
Adjoint Forecast Sensitivity for Japan Flood (60h)

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)
Adjoint Perturbation Precipitation in NLM (red/blue mm)



- Vertically integrated accumulated precipitation (60 h) sensitivity to the initial water vapor shows large positive sensitivity in the monsoon trough and moisture surge regions
- Adjoint perturbations increase the precipitation by > 70 mm (~70% increase) near the Noko Peninsula highlighting the importance of sensitive regions in the monsoon trough and moist inflow regions

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Adjoint Forecast Sensitivity for Pacific NW Flood (72h)

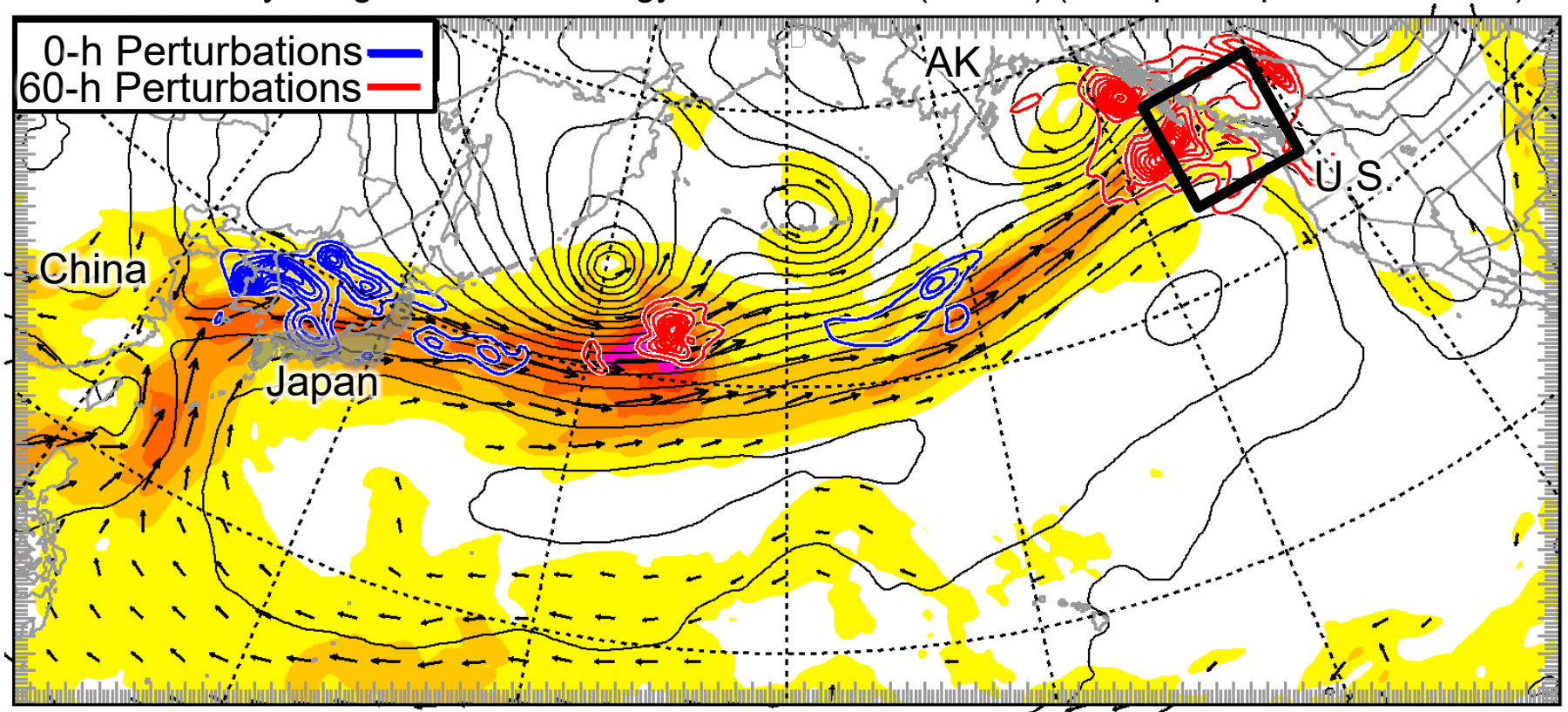
0000 UTC 21 September 2024

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

Total KE PE IE Moist

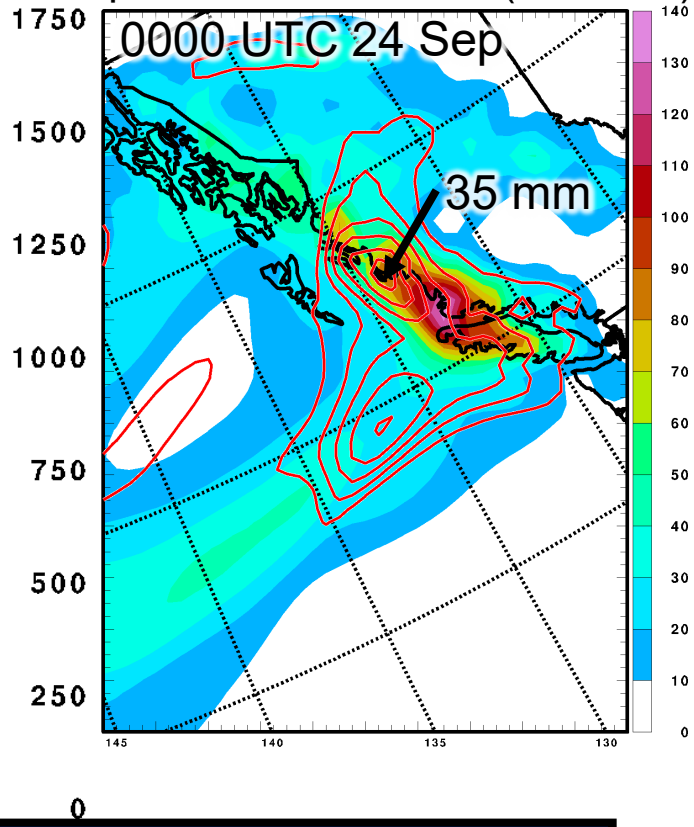
0000 UTC 21 Sep. IVT (shading, kg m^{-1} s^{-1}, vectors), 700-hPa Heights (m)

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



24-72h Precipitation (shading, mm)

Precipitation Perturbation (contours)



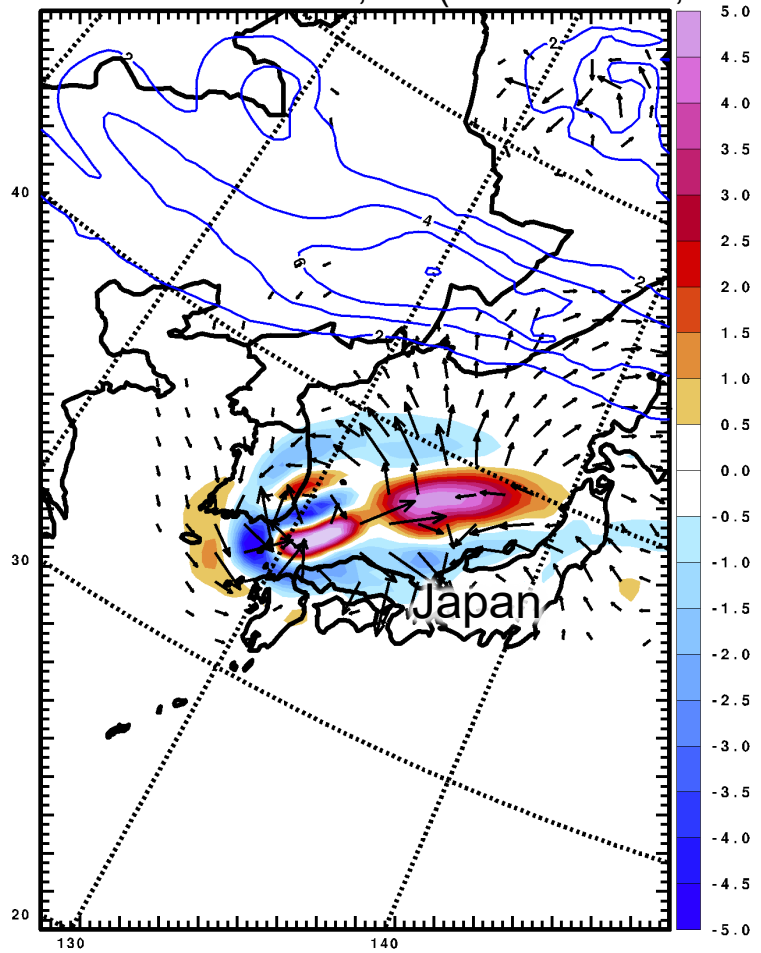
- Initial adjoint total energy perturbations (vertically integrated), based on the 72-h sensitivities, highlight sensitivity near the moisture surge and trough axis, mostly dominated by the water vapor sensitivity
- Adjoint perturbations grow rapidly (by 500x at 60 h) and increase the 24-72 h precipitation by ~25%

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

COAMPS 12-h Forecast: 1200 UTC 21 Sep. 2024

300-hPa Adjoint Perturbation Divergence (shading, 10^{-5} s^{-1})

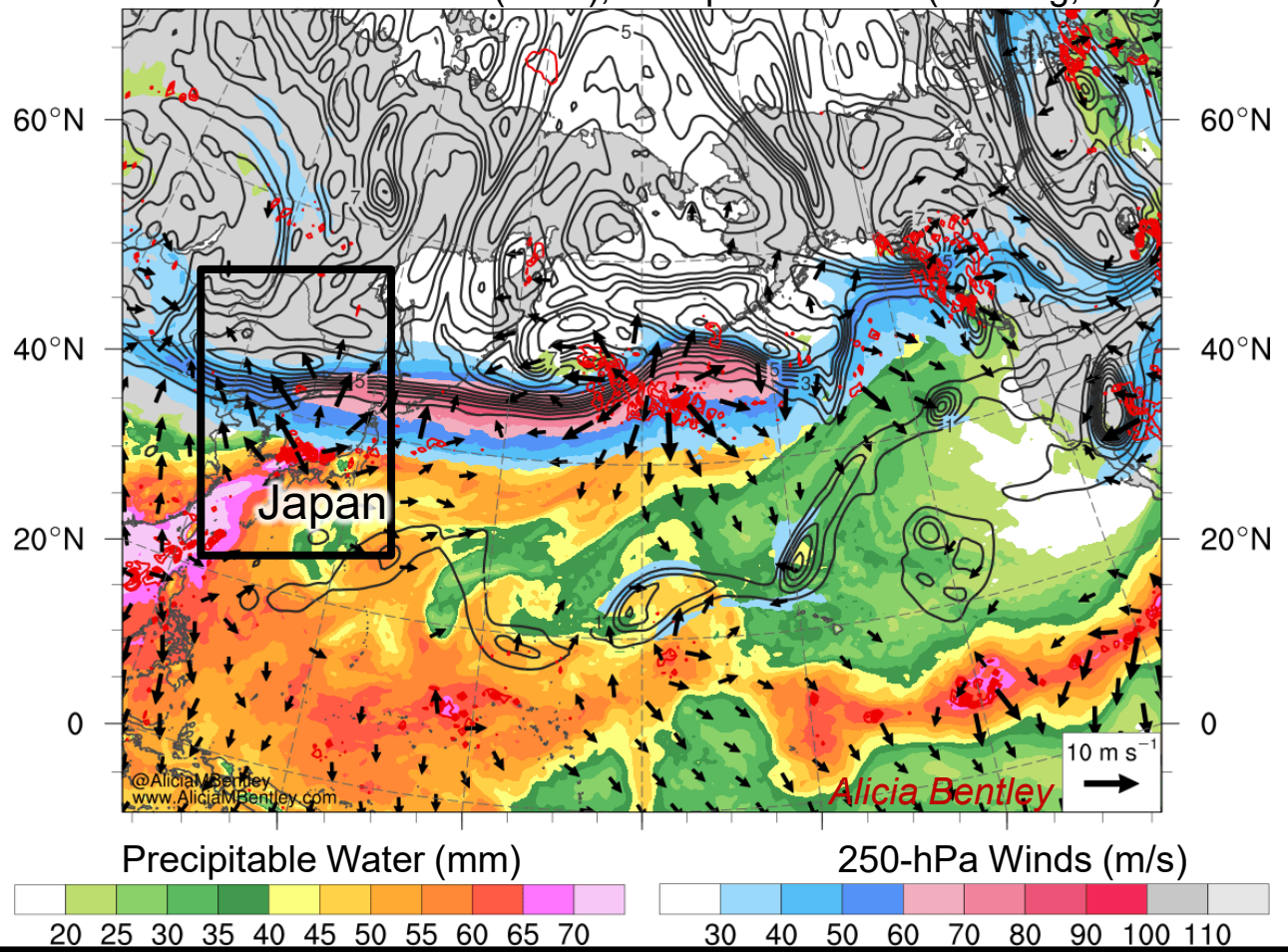
300-hPa Perturbation Winds, PV (blue contours, PVU)



GFS Analysis: 1200 UTC 21 Sep. 2024

300-200-hPa PV (black), 250-hPa wind speed (shading), 600-400-hPa ascent (red)

Irrotational wind vectors (m s^{-1}), Precipitable water (shading, mm)



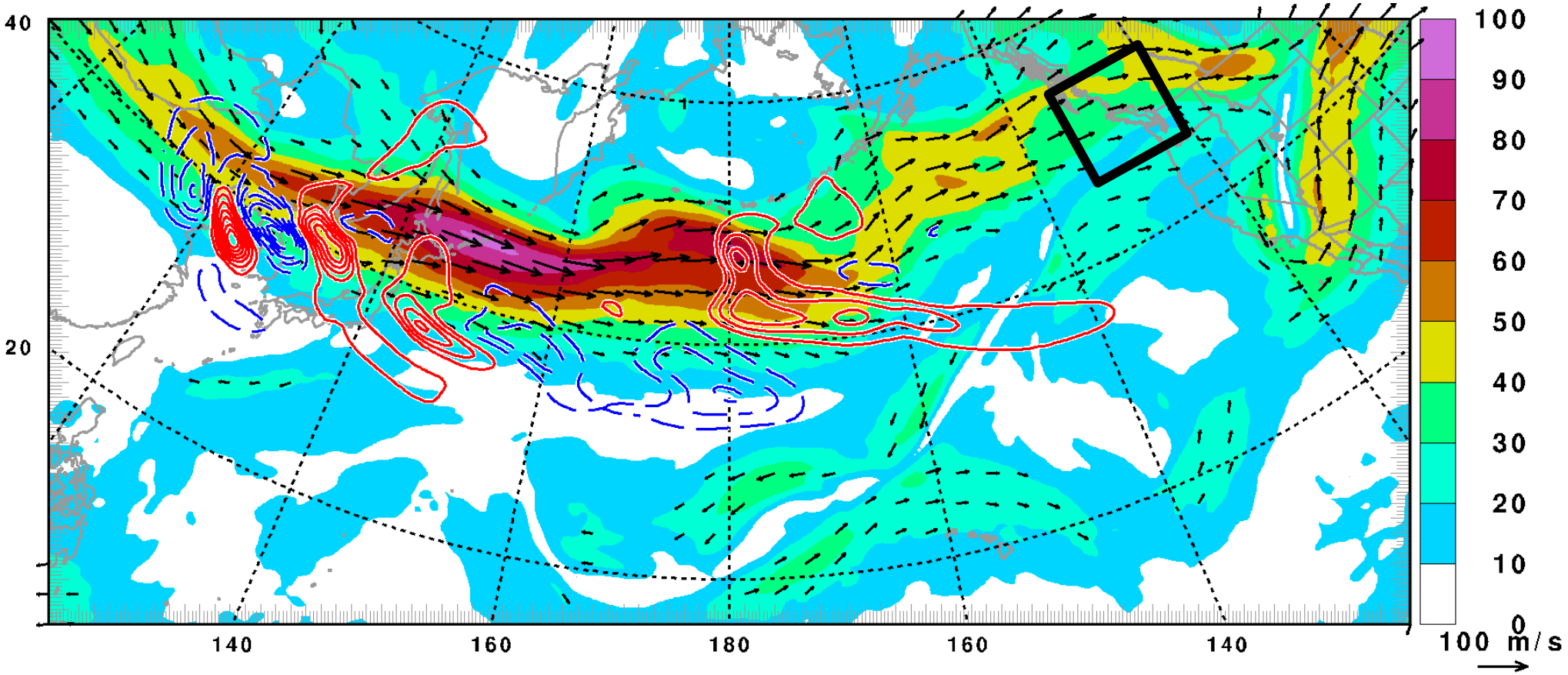
- Water vapor perturbations enhance diabatic heating and divergent outflow that project on to the irrotational winds increasing the PV advection in the waveguide
- Rossby wave packet is initiated that enhances the downstream AR event and AK/BC flooding

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Adjoint Forecast Sensitivity (72h)

0000 UTC 21 September 2024

IVT (shading, kg m^{-1} s^{-1}, vectors), 250-hPa Winds (shading, vectors, m s^{-1})
72-h Forecast Precipitation Sensitivity to the Initial 500-hPa Vorticity [mm s]



Forecast precipitation (24 h to 72 h) over S.E. AK and S.W. B.C. sensitivity to the initial relative vorticity at 500-hPa along the AR, with a wave packet signature in the right entrance region of the jet

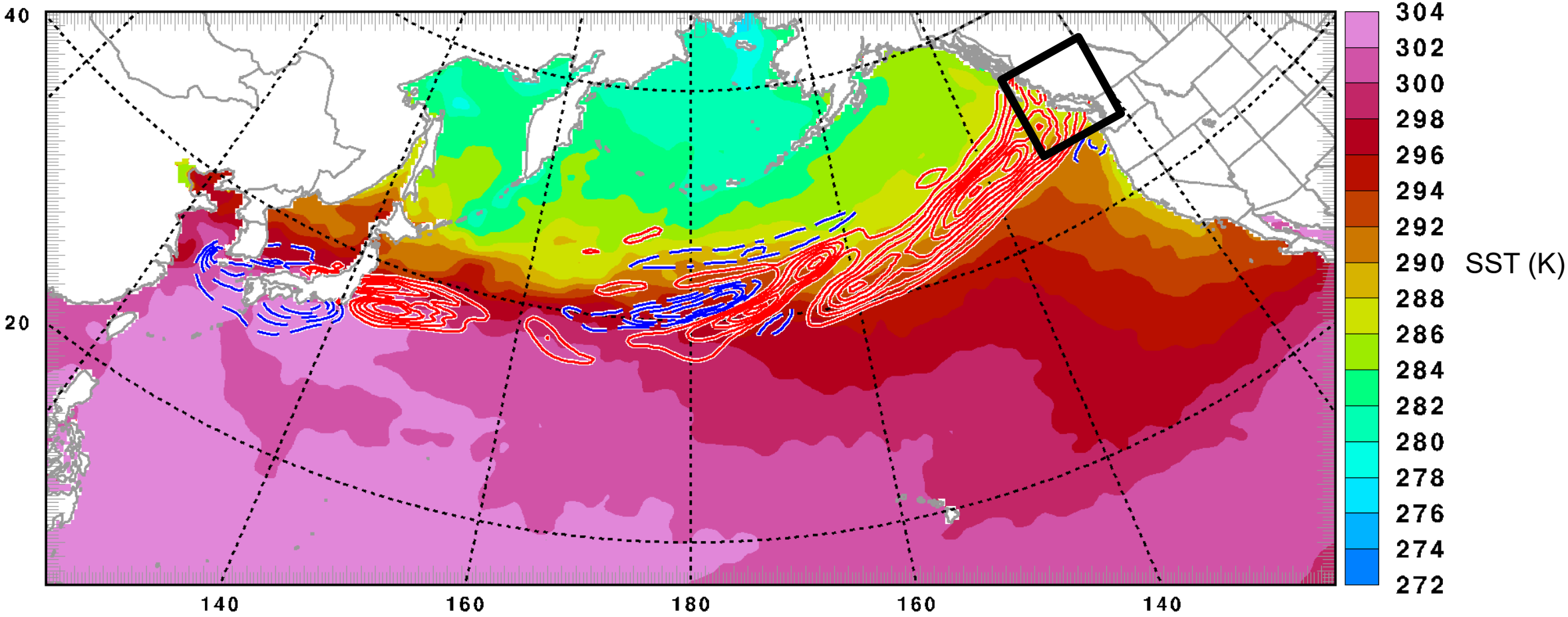
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Adjoint Forecast Sensitivity (72h)

0000 UTC 21 September 2024

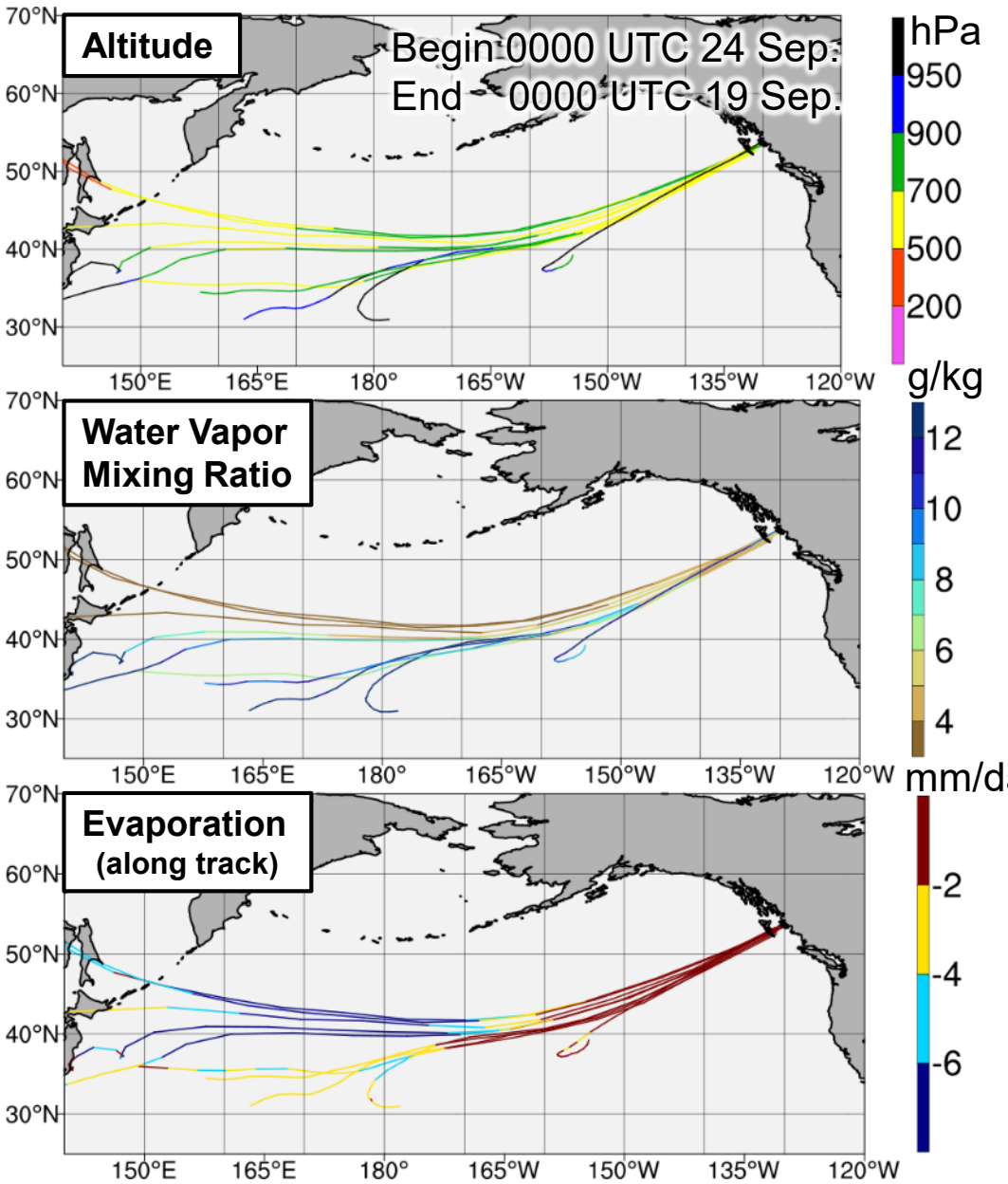
Sea Surface Temperature (shading, K)

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

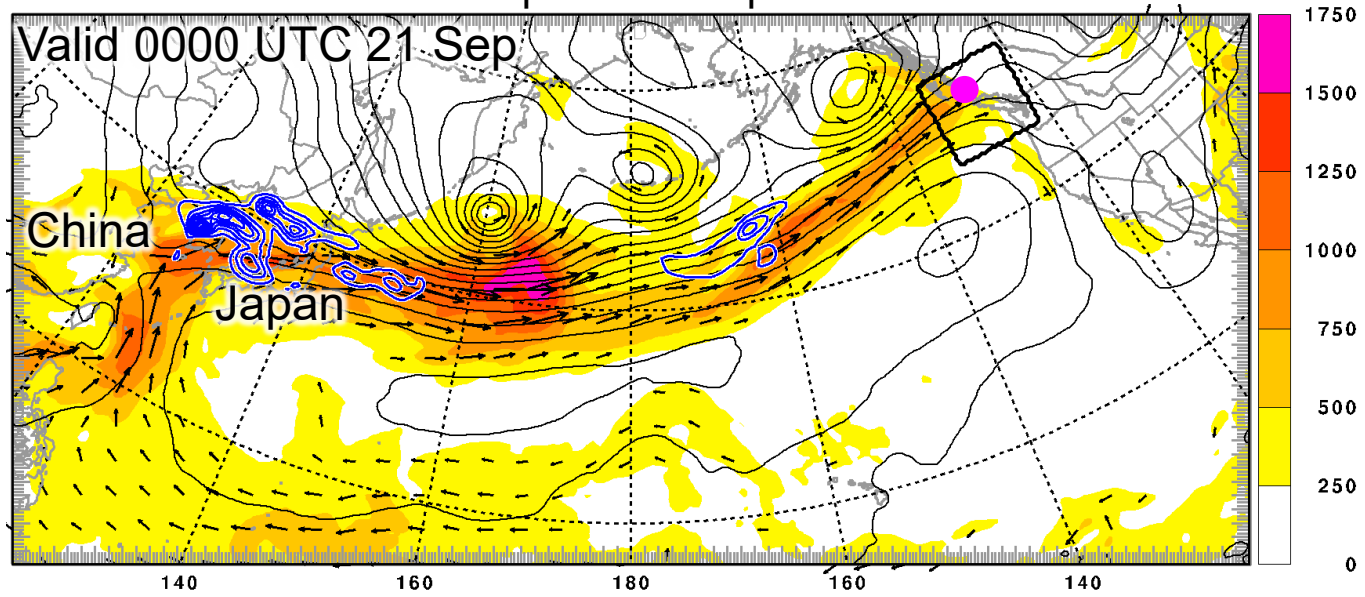


Forecast precipitation over S.E. AK and S.W. B.C. sensitivity to the initial SSTs along the AR, with maxima located near baroclinic waves and to the south of the main AR corridor

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

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Summary

Japan and AK/BC Flooding Dynamically Linked

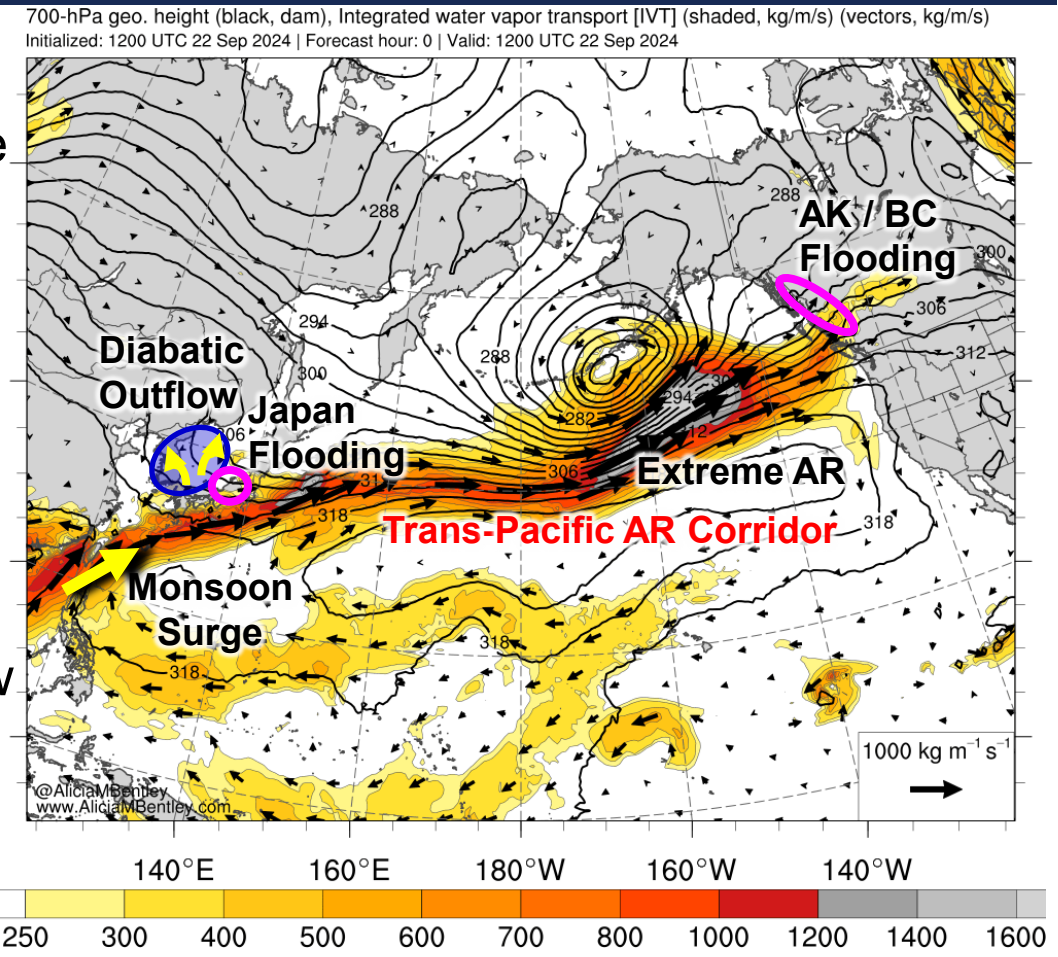
- Japan flooding forecasts are very sensitive to the initial state moisture surge and monsoon trough
- Subsequent diabatic heating and divergent outflow initiate a Rossby wave packet
- Initial condition uncertainty in these regions have a large impact on subsequent Alaska Flooding

Multiscale Initial Condition Uncertainty

- Large adjoint sensitivity to moist inflow and divergent outflow
- Need for accurate moisture analyses and probabilistic prediction

Future Research

- How often do HIW AR events in S.E. Asia trigger HIW along the U.S./Canada W. Coast? Are these ARs linked to convectively coupled equatorial Rossby waves?



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