Moisture transport during the inland penetrating atmospheric river of early November 2006 in the Pacific Northwest: A high-resolution model-based study

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Case Background & Motivation

- Series of storms in Pacific Northwest early November 2006
- 5-7 November: Record-breaking rainfall in Cascades and interior mountains (*Neiman et al. 2008*)
- Extreme rainfall and snowmelt caused destructive flooding at Montana's Glacier National Park (*Bernhardt 2006*)

- Fraction of heavy precipitation events attributable to atmospheric rivers ("AR fractions") largest along Pacific coast
- Elevated AR fractions extend to the interior of North America north and south of the High Sierras (*Rutz et al. 2015*) – including the Pacific Northwest
- **Investigate how and where water vapor penetrated the Pacific Northwest using a high-resolution weather modeling system**

Glacier National Park
Courtesy: National Park Service

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Model Configuration

Model System

- Weather Research & Forecasting (WRF-ARW)
- Version 3.6

Domain

- Single domain (2400km x 2400km)
- 4km grid spacing
- 53 terrain-following vertical levels
- No cumulus parameterization scheme

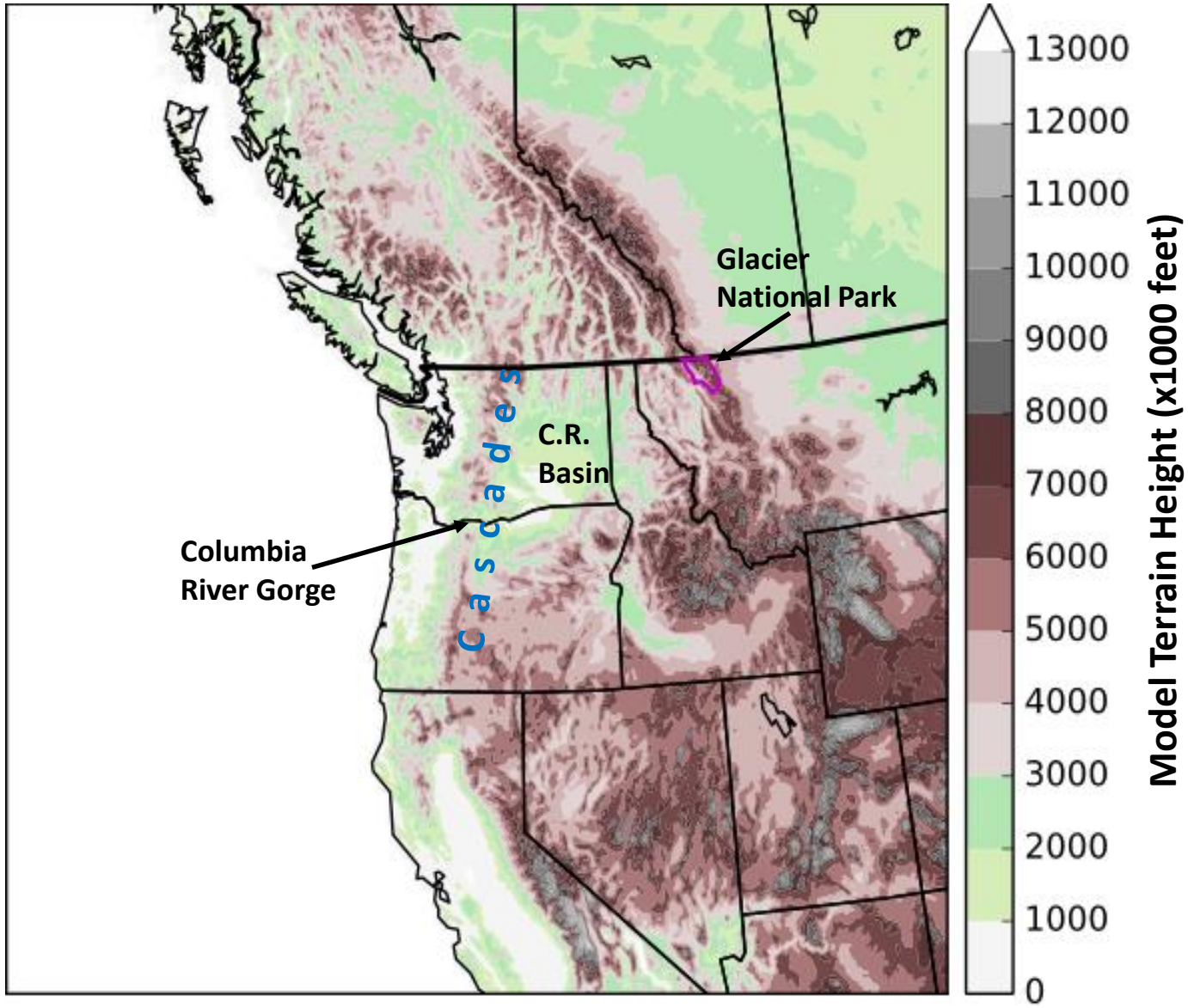
Simulation

- **00 UTC 3 November 2006 – 00 UTC 9 November 2006** *(144 hours)*
- LBC/ICs: Climate Forecast System Reanalysis

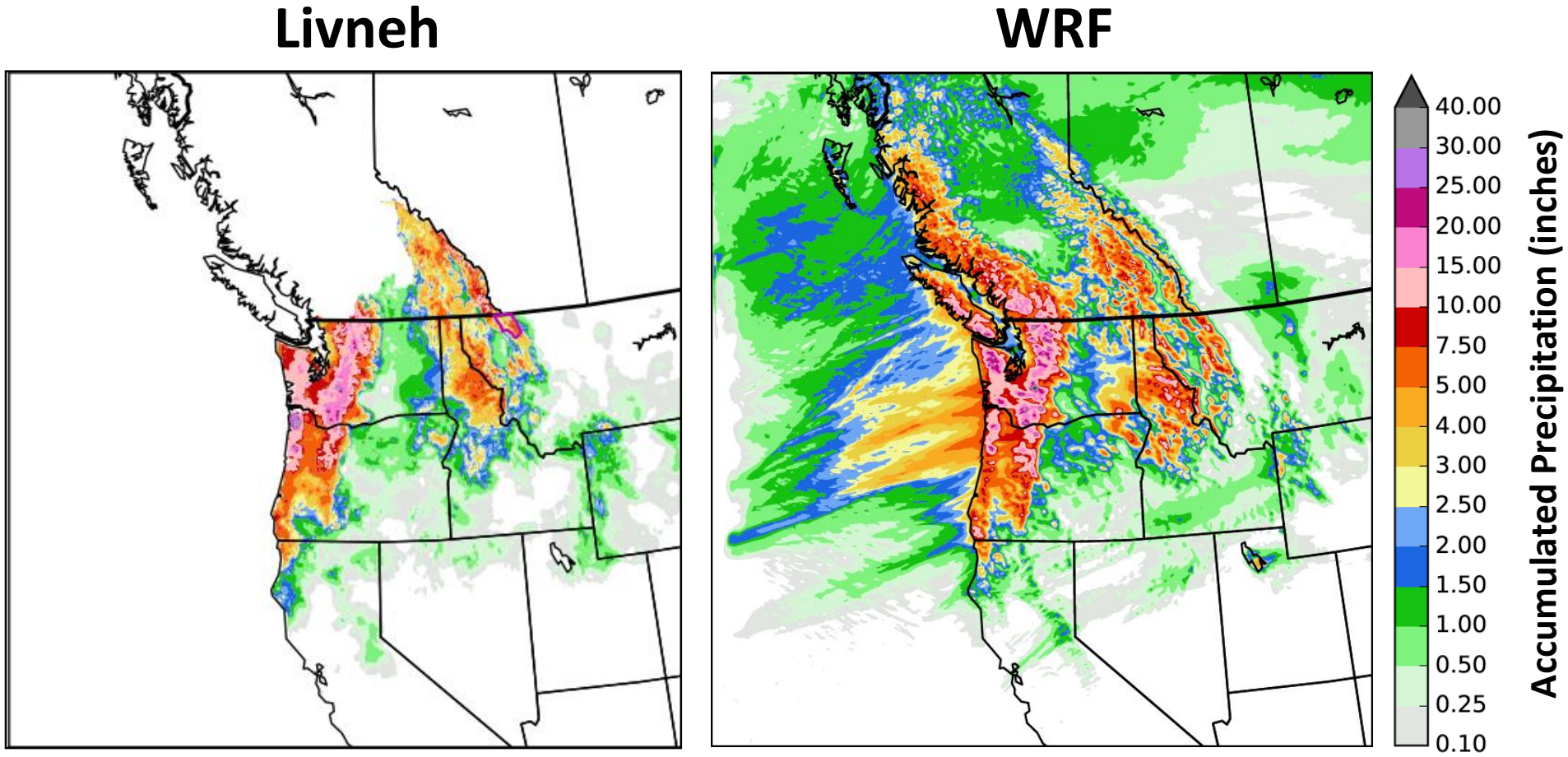
Verification

- Precipitation: *Livneh et al. (2013)* dataset based on NOAA COOP data in CONUS

WRF Model Terrain Height

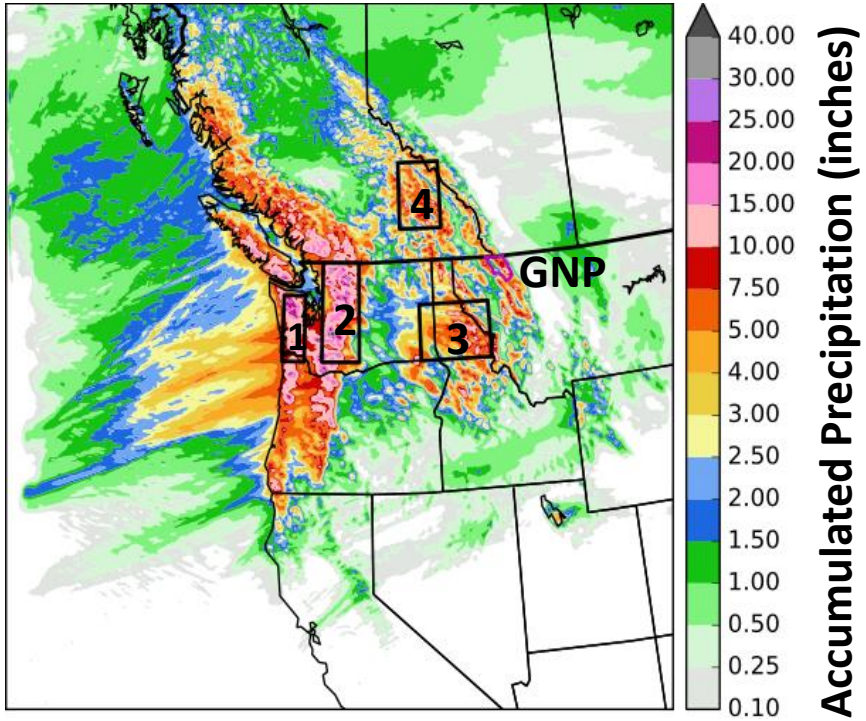


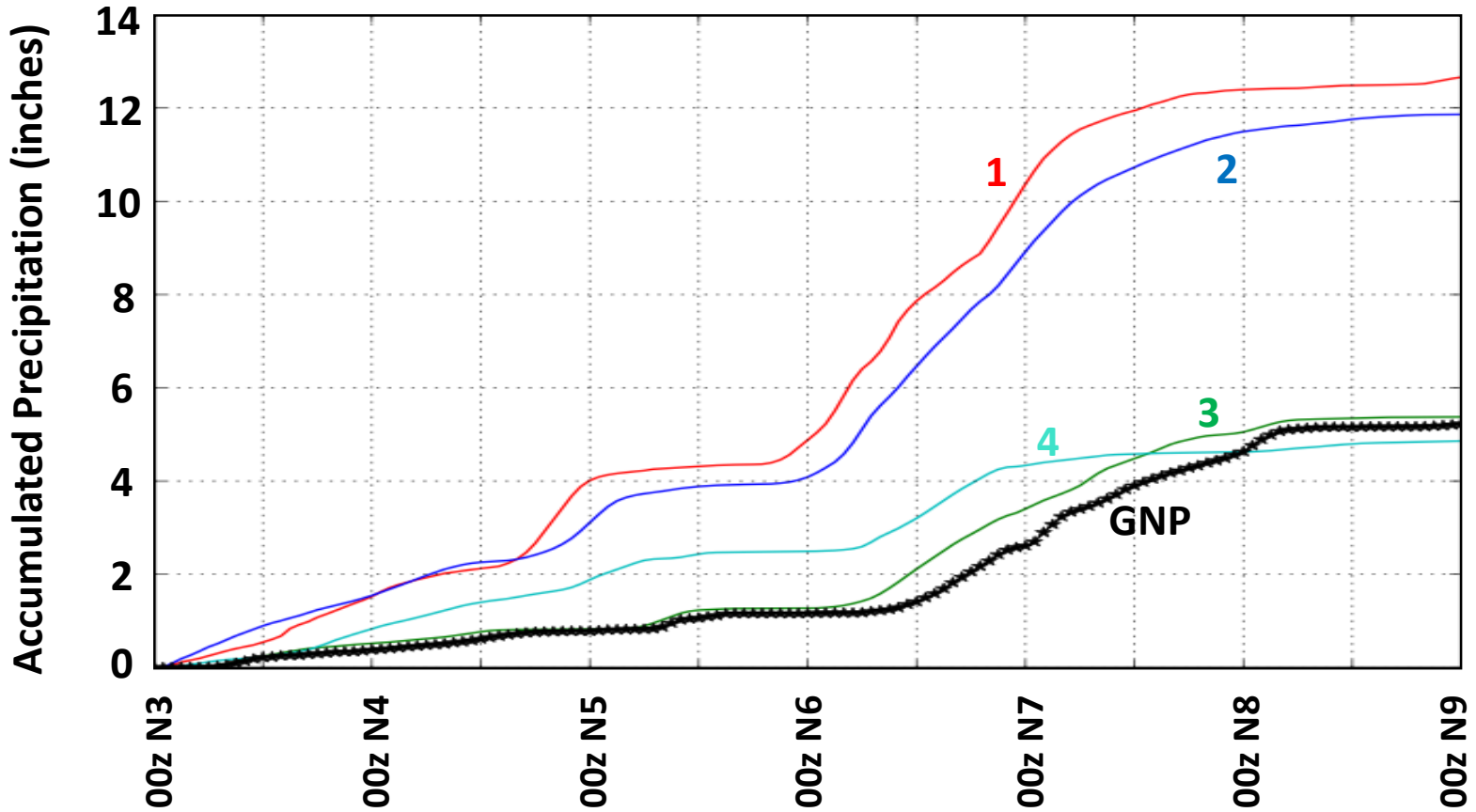
WRF Verification: Precipitation



- **General agreement in distribution and magnitude**
- Major regions of precipitation align with mountains
- Coastal Ranges: 10-15” ; 20”+ high ridges and mountains
- Interior Ranges: 5-7” ; 10”+ high ridges

WRF Precipitation Plumes



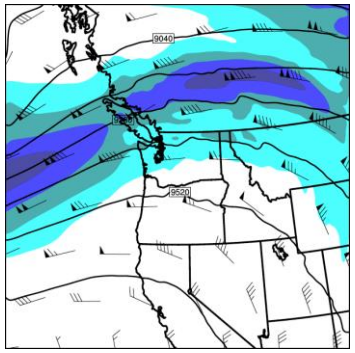


- Antecedent precipitation 1-4”
- **Main event**: ***00 UTC 6 Nov – 12 UTC 7 Nov*** (Coast)
  12 UTC 6 Nov – 00 UTC 8 Nov (Interior)

WRF Synoptic Overview: Upper Air

300 hPa

12 UTC 6 Nov



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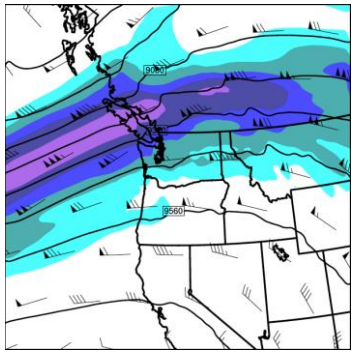

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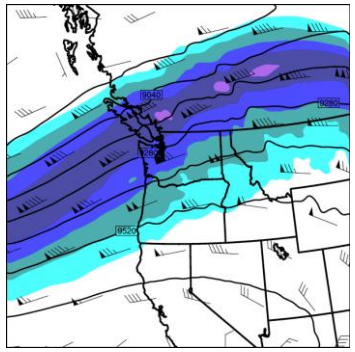

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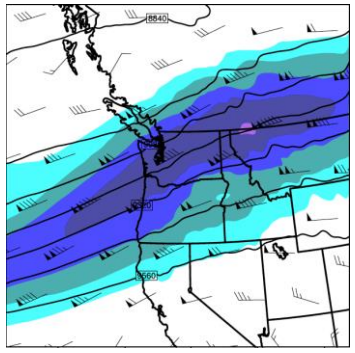

Wind Speed (knots)

500 hPa

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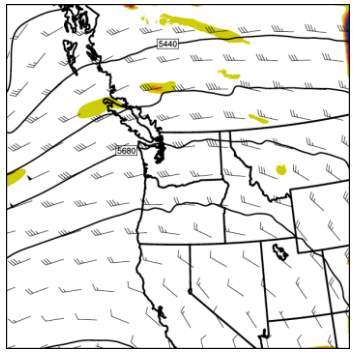

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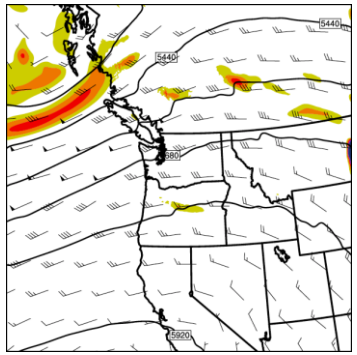

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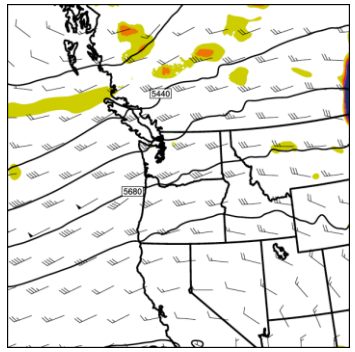

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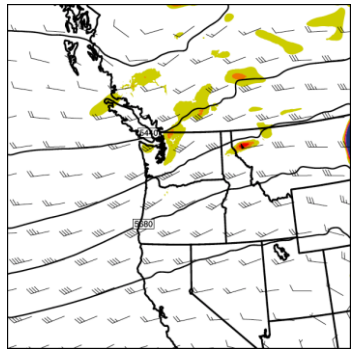
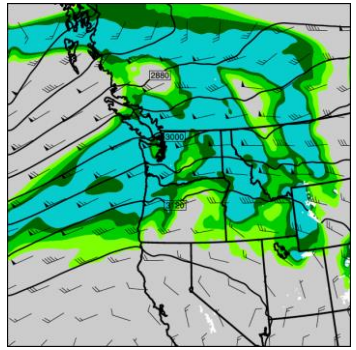


Abs. Vorticity (x10^{-5} s^{-1})

700 hPa

12 UTC 6 Nov



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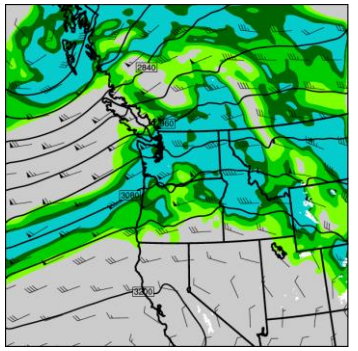

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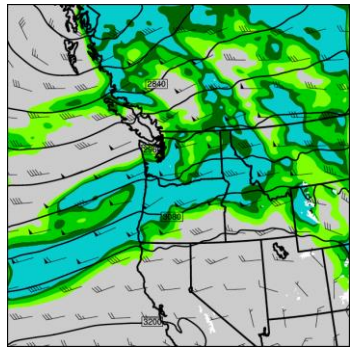

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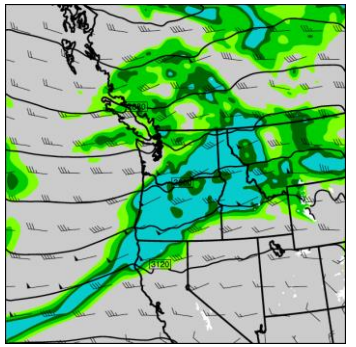
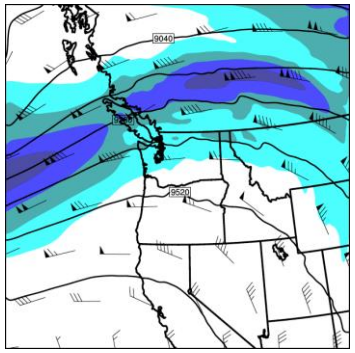


Relative Humidity (%)

WRF Synoptic Overview: Upper Air

300 hPa

12 UTC 6 Nov



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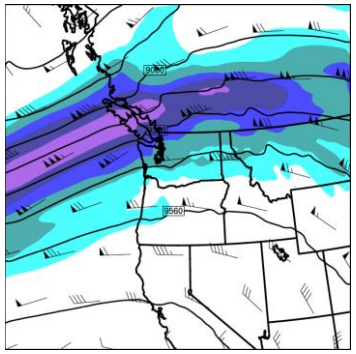

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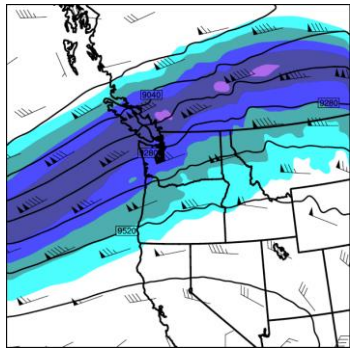

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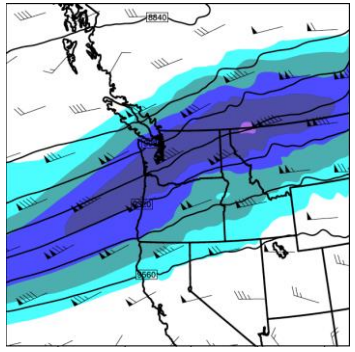

Wind Speed (knots)

500 hPa

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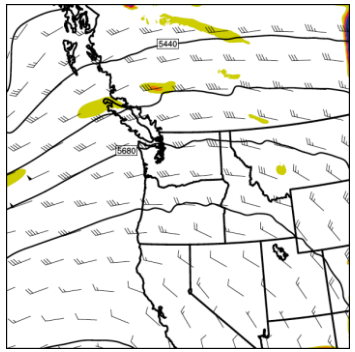

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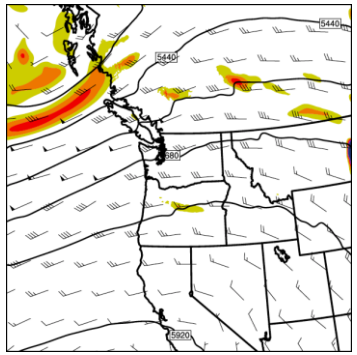

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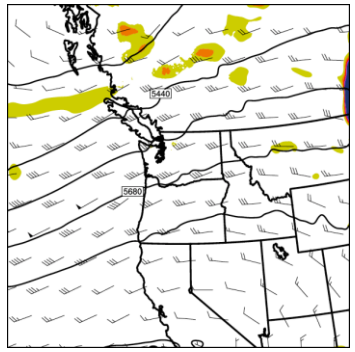

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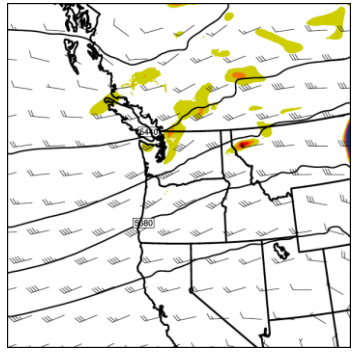

Abs. Vorticity ($x10^{-5}$ s^{-1})

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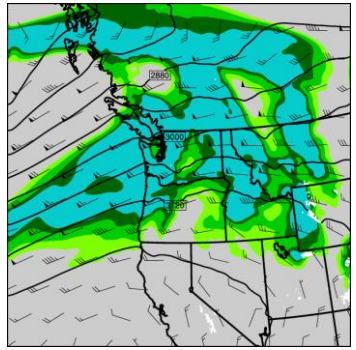

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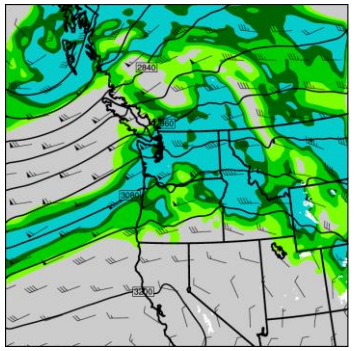

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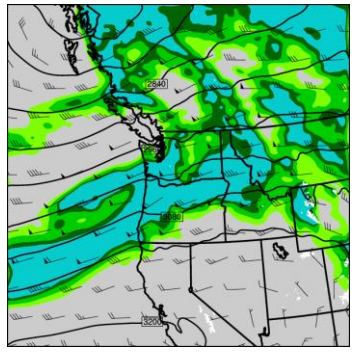

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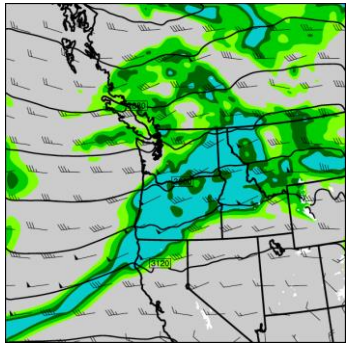

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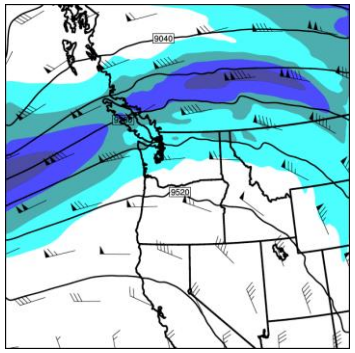

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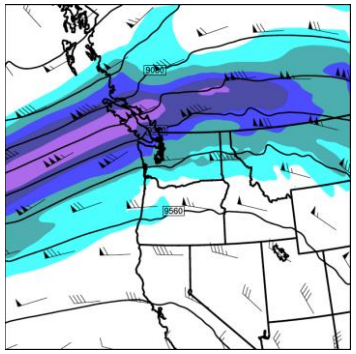

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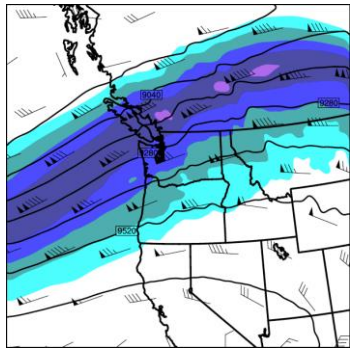

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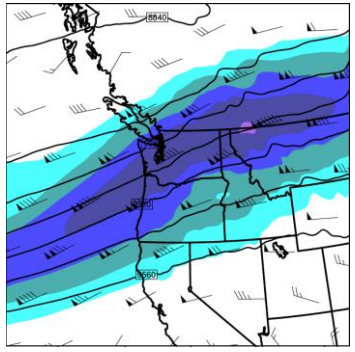

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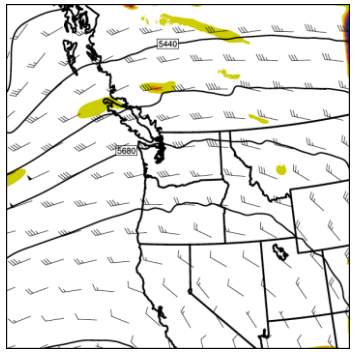

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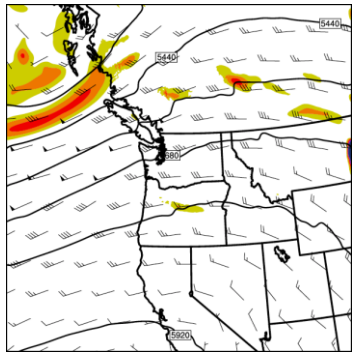

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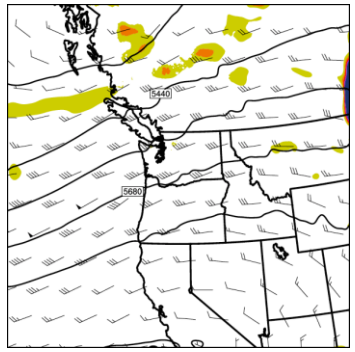

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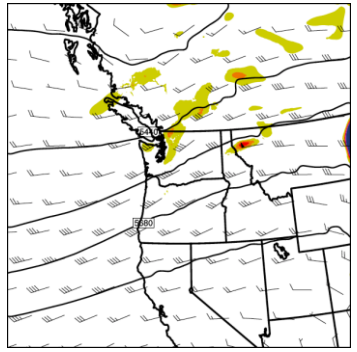

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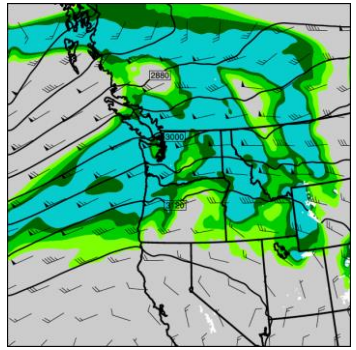

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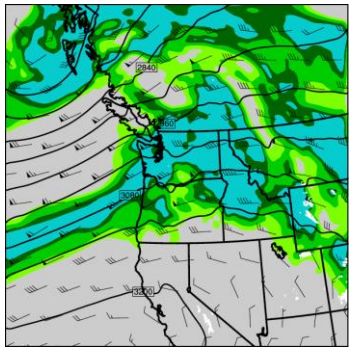

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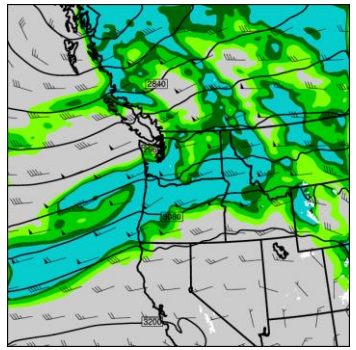

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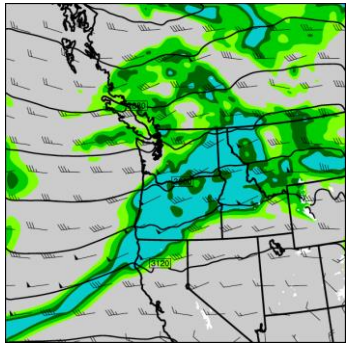
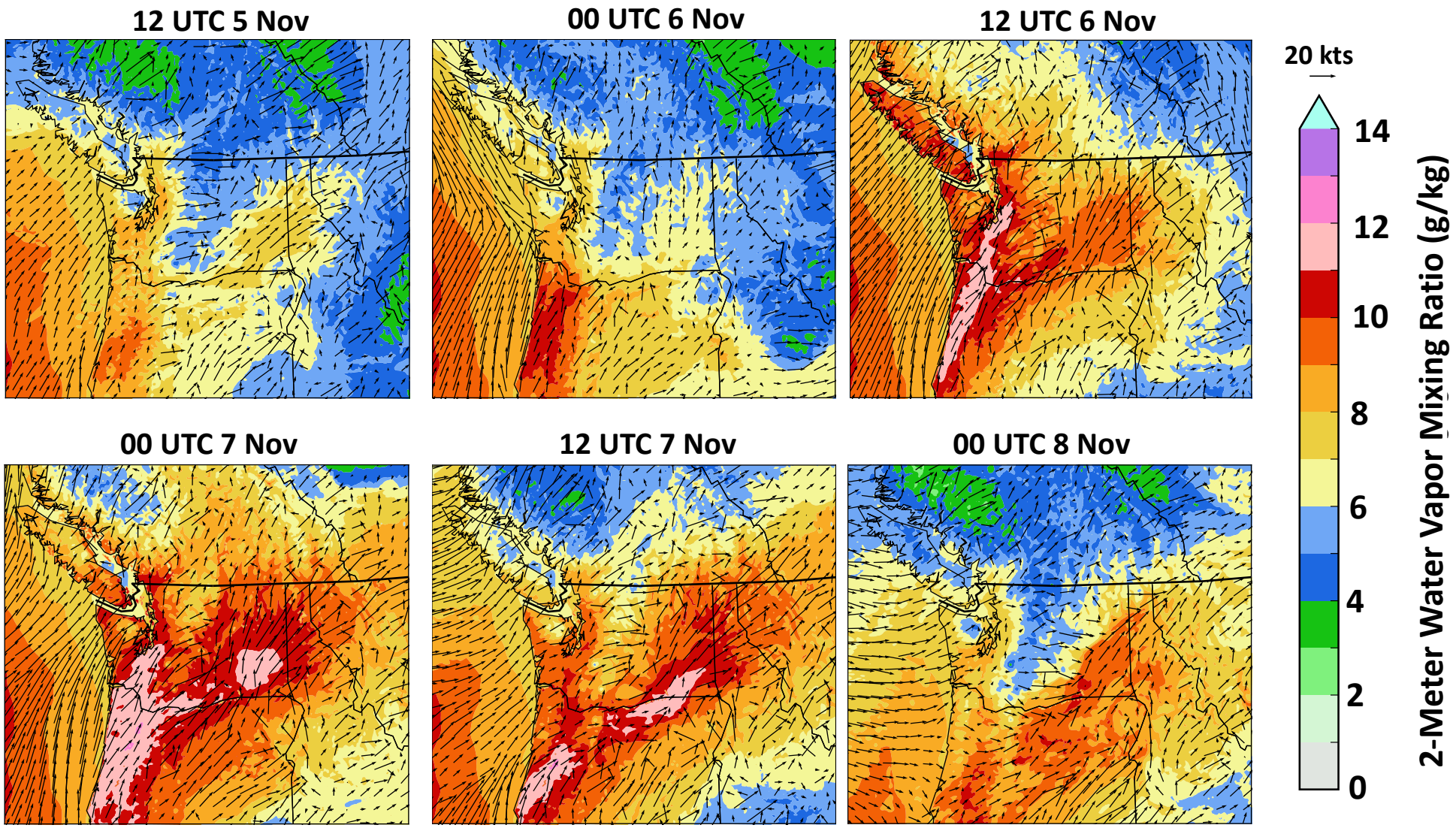


Relative Humidity (%)

WRF Synoptic Overview: Surface



Interior precip: 12 UTC 6 Nov – 00 UTC 8 Nov

Moisture Transport Diagnostics

Integrated Water Vapor (IWV)

- Total water vapor in column
- Summed over each model level
- Units: centimeters

$$IWV = \int_{sfc}^{Ptop} \left(\frac{P}{R_d T_v}\right) q dz$$

Integrated Vapor Transport (IVT)

- Horizontal water vapor flux
- Calculated as 50-hPa layer averages
- Summed over layers
- Units: kg m^{-1} s^{-1}

$$IVT = \frac{1}{g} \int_{sfc}^{200hPa} q \cdot \boldsymbol{U} \cdot dp$$

Water Vapor Mass Flux (QFLUX)

- Total water vapor mass moving through vertical unit cross section
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- Units: kg s^{-1}

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WRF Integrated Water Vapor

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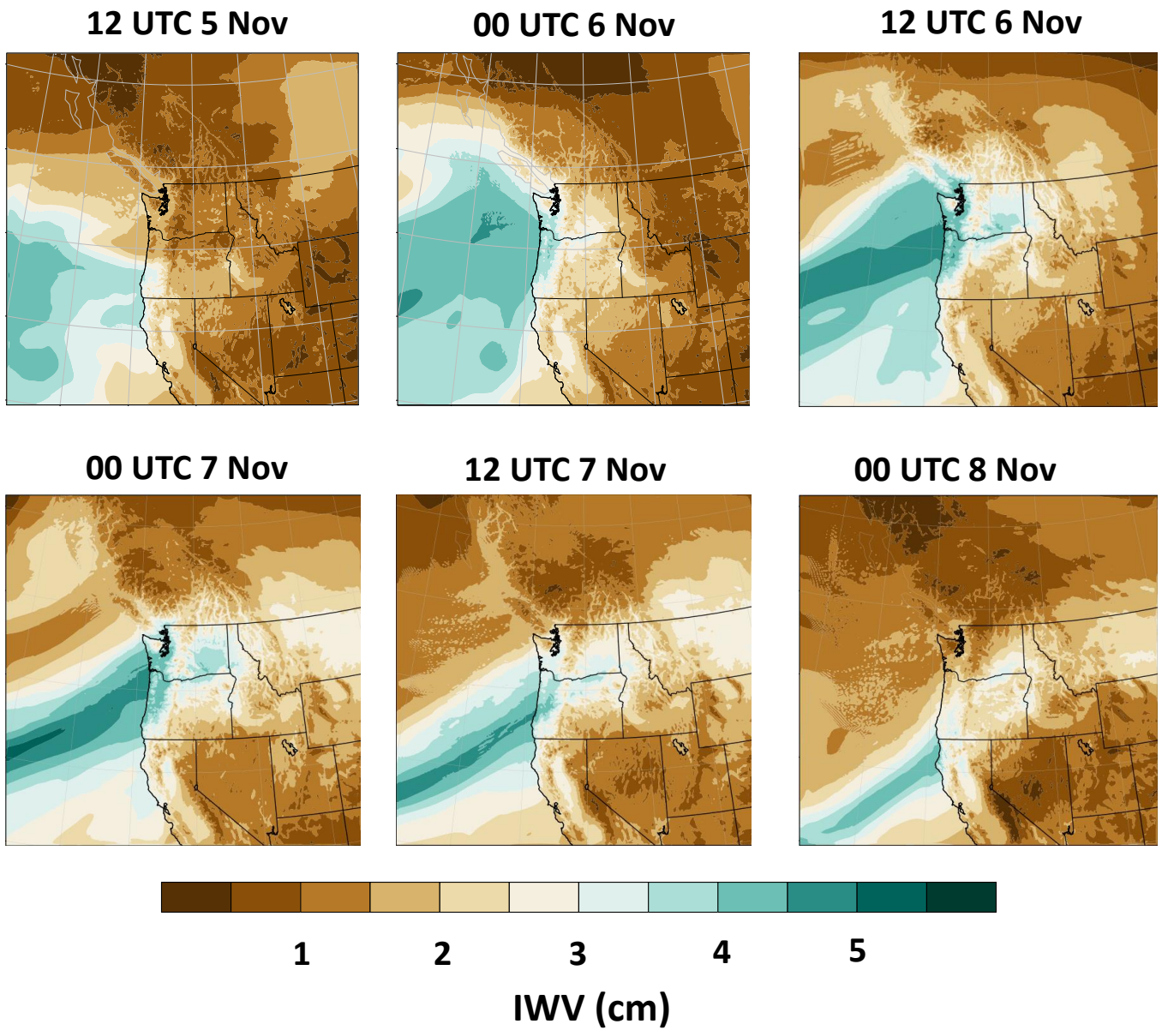


- Approach, landfall, penetration, and decay of AR
- Oriented WSW to ENE

- Most intense phase:
  - Centered on Ore./Wa. border
  - 4-5cm IWV at coast
  - 3-4cm IWV in C.R. Basin
- Decaying phase:
  - Moving south to N. Cal.
  - 3-4cm IWV at coast
  - 2cm IWV in NE Ore.

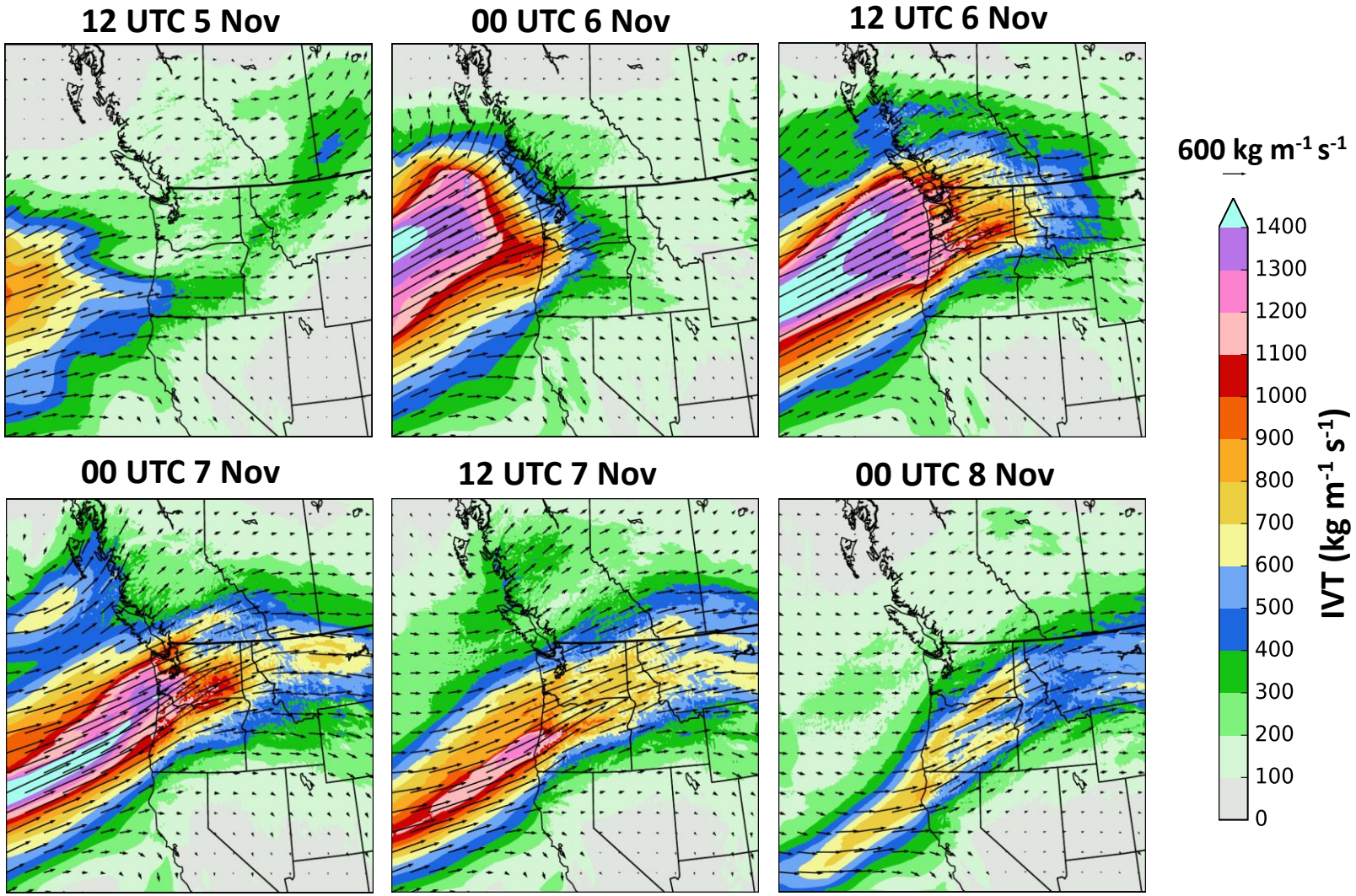
- Location of moisture, not transport

Interior precip: 12 UTC 6 Nov – 00 UTC 8 Nov

WRF Integrated Vapor Transport: Plan View

$$IVT = \frac{1}{g}\int_{sfc}^{200hPa} q \cdot \boldsymbol{U} \cdot dp$$

- Landfall at Ore./Wa. border
- Penetration occurred across length of Cascades
- Maximum penetration through C. R. Gorge and over terrain immediately south of it
- Follow this corridor with time series



Interior precip: 12 UTC 6 Nov – 00 UTC 8 Nov

WRF Integrated Vapor Transport: Temporal Plumes

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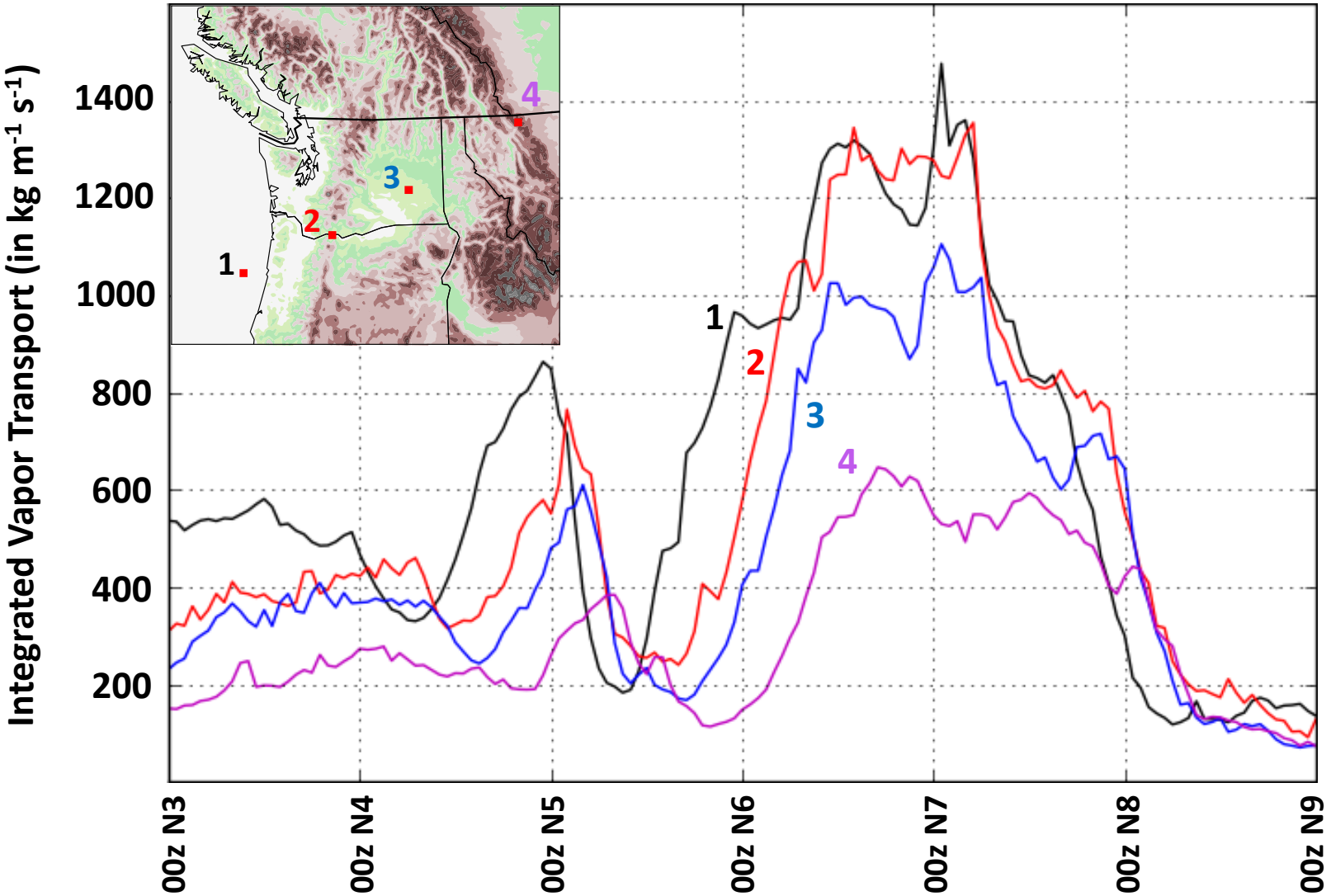
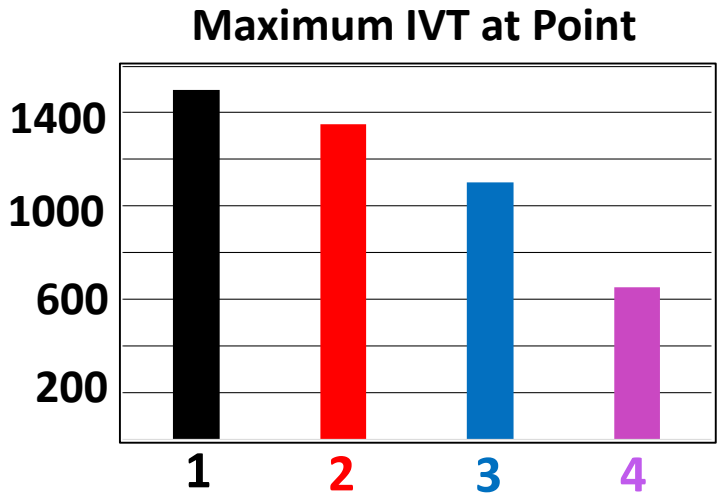


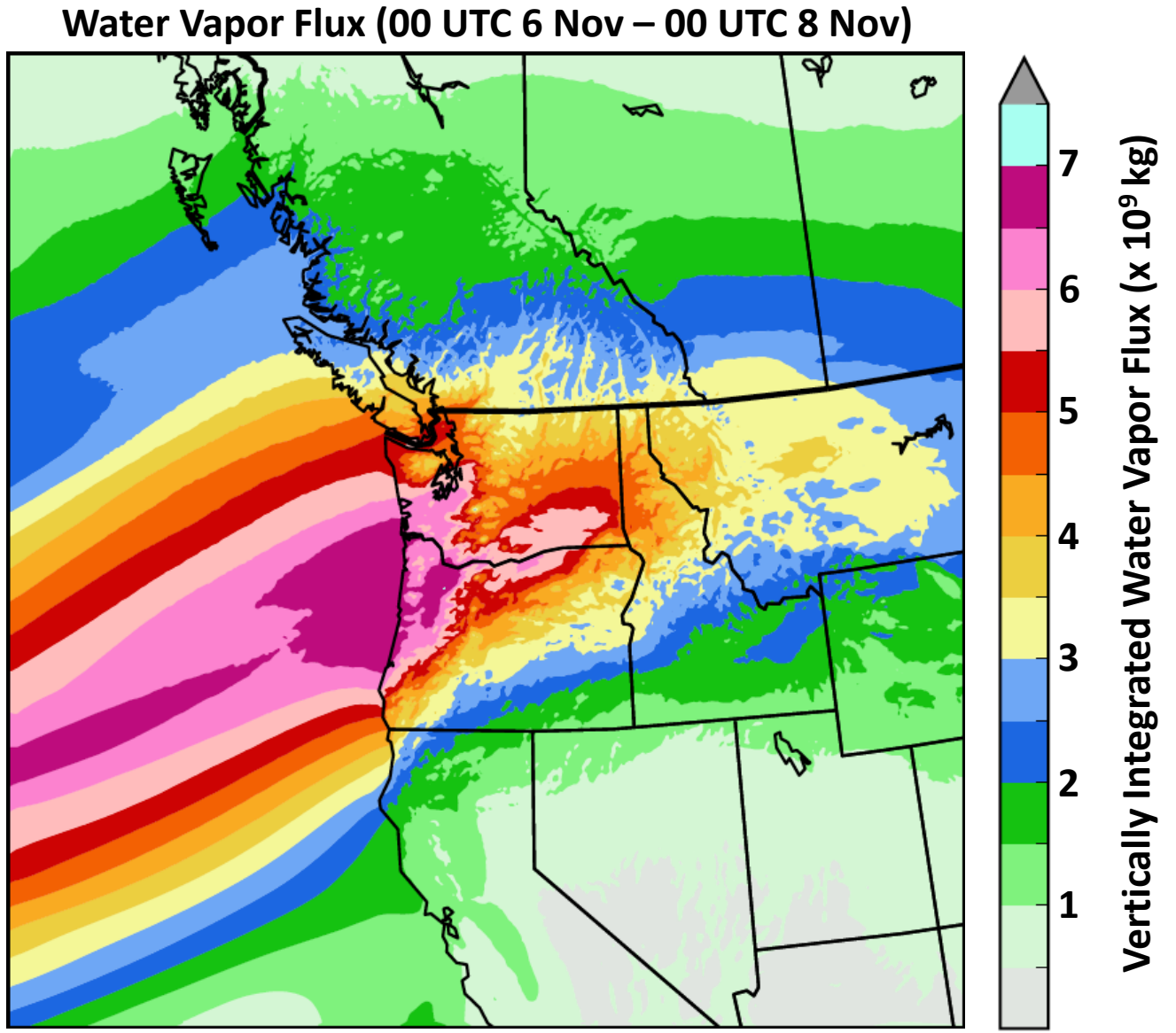
- Offshore, C. R. Gorge, C. R. Basin, Glacier Nat'l Park
- Lesser AR before main event
- Progressively less transport from Cascades eastward



WRF Water Vapor Mass Flux: Plan View

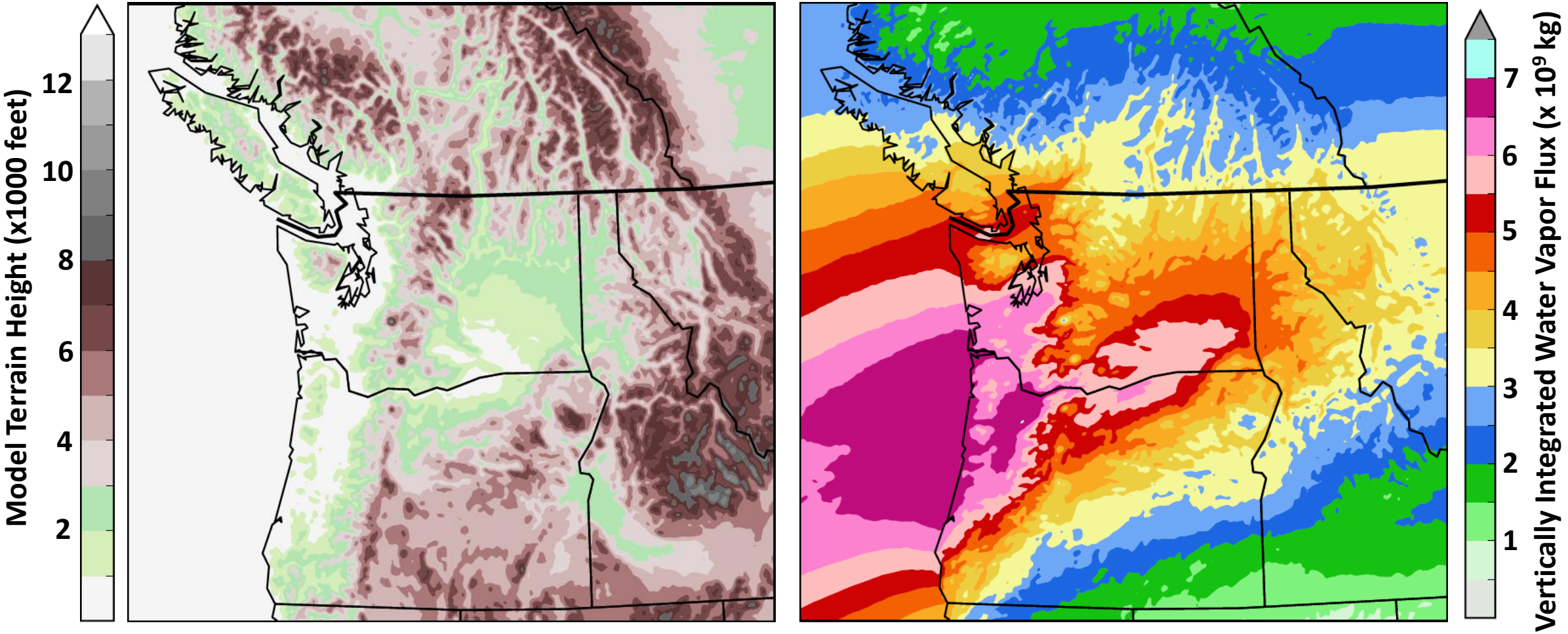
$$QFLUX = \left(\frac{P}{R_d T}\right) q \cdot \boldsymbol{U} \cdot \Delta \boldsymbol{x} \cdot \Delta \boldsymbol{z}$$

- 48-hour total water vapor flux
- Isolates main AR from initial landfall to decay
- Corridor of penetration ~150km C.R. Gorge and south
- Terrain south of Gorge 3-4k feet and ~50km wide
- Terrain north of Gorge 4-6k feet and ~100km wide



WRF Water Vapor Mass Flux: Plan View

$$QFLUX = \left(\frac{P}{R_d T}\right) q \cdot \boldsymbol{U} \cdot \Delta \boldsymbol{x} \cdot \Delta \boldsymbol{z}$$



WRF Water Vapor Mass Flux: Plan View

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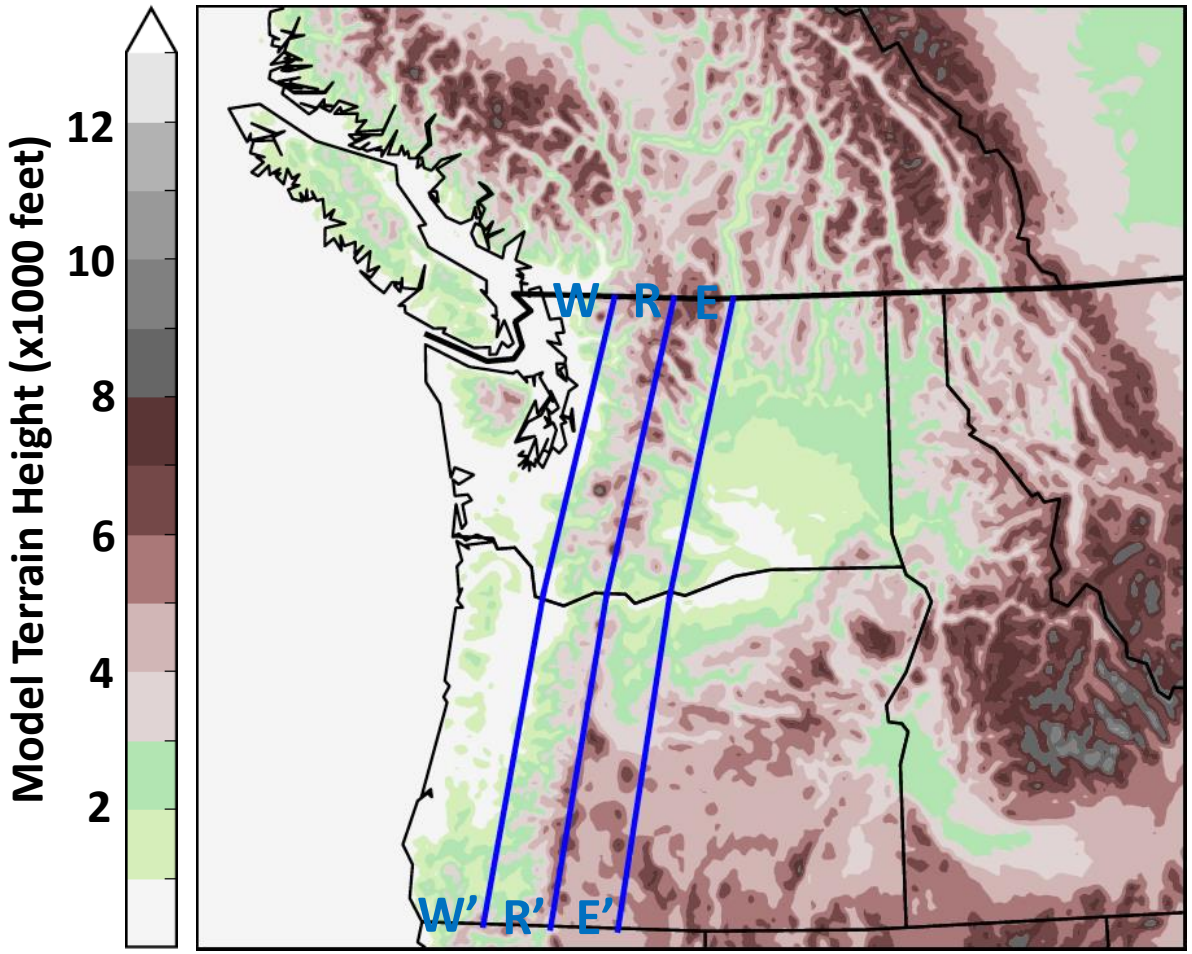
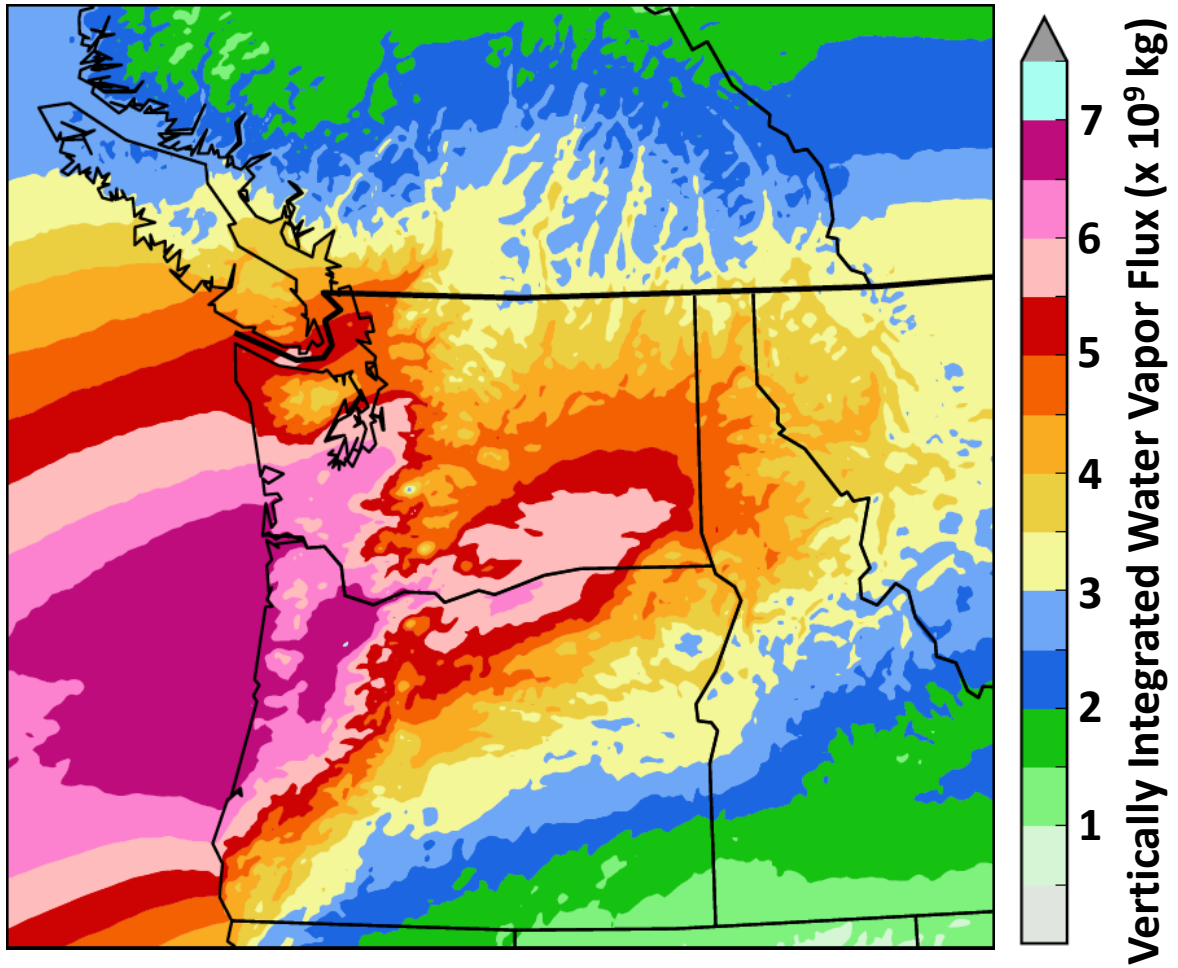
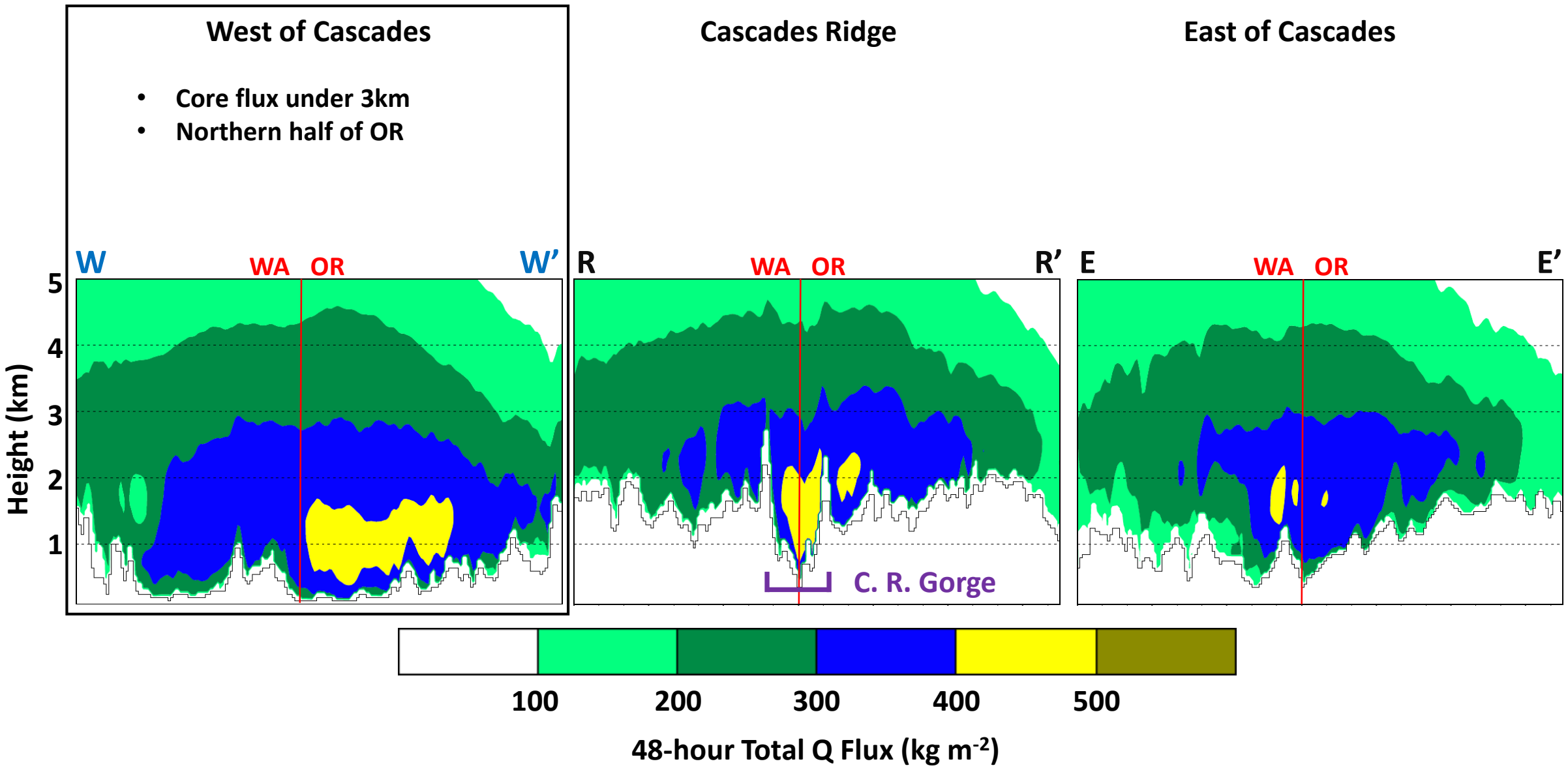


Cross-Sections



WRF Water Vapor Mass Flux: Cross-Sections



WRF Water Vapor Mass Flux: Cross-Sections

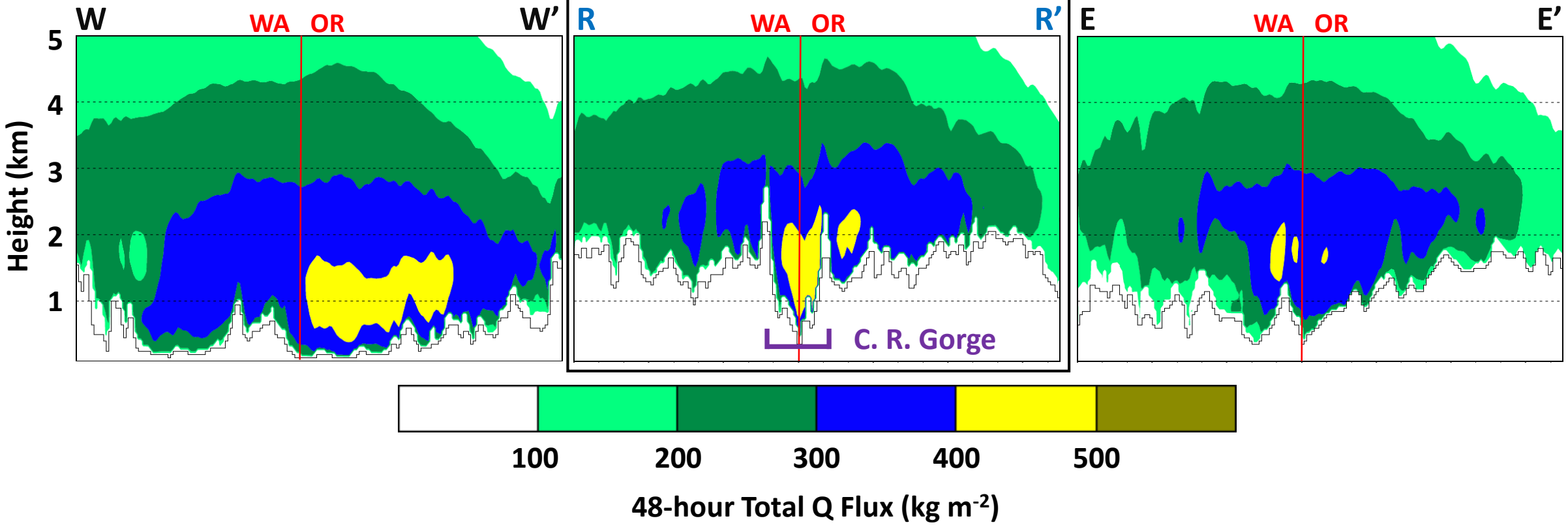
West of Cascades

- Core flux under 3km
- Northern half of OR

Cascades Ridge

- Through C.R. Gorge
- Over Cascades, esp. in OR
- Flux through Gorge similar to that west of Cascades

East of Cascades



WRF Water Vapor Mass Flux: Cross-Sections

West of Cascades

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Cascades Ridge

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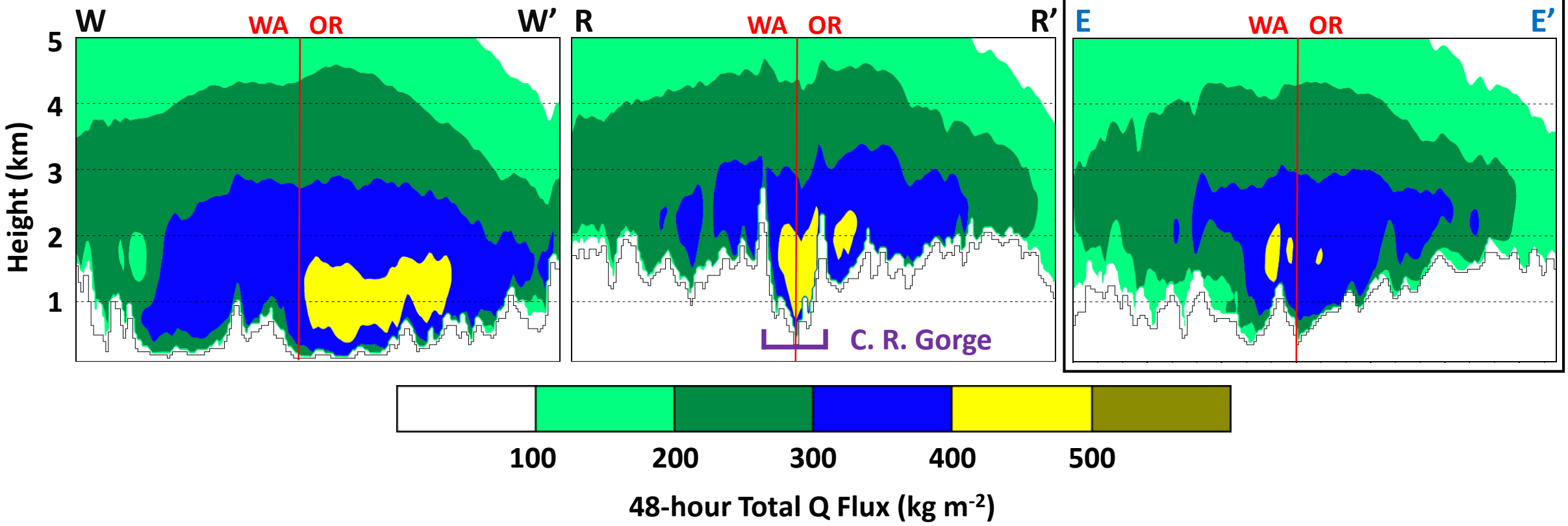
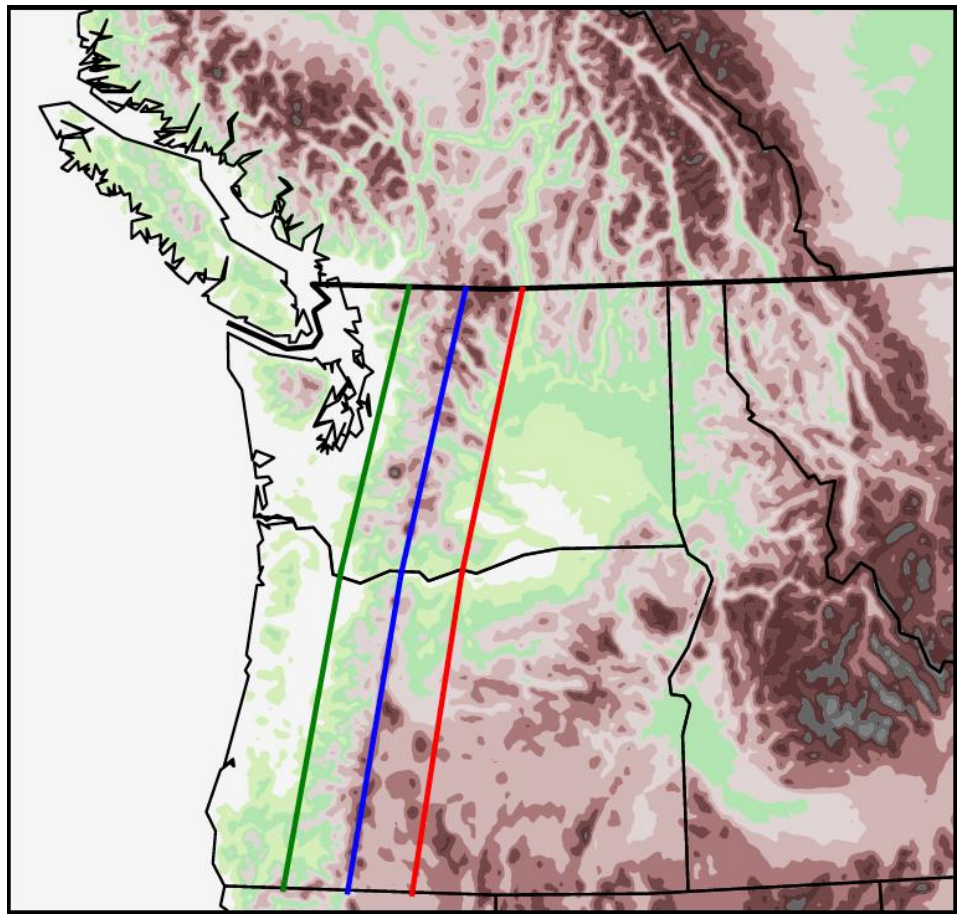
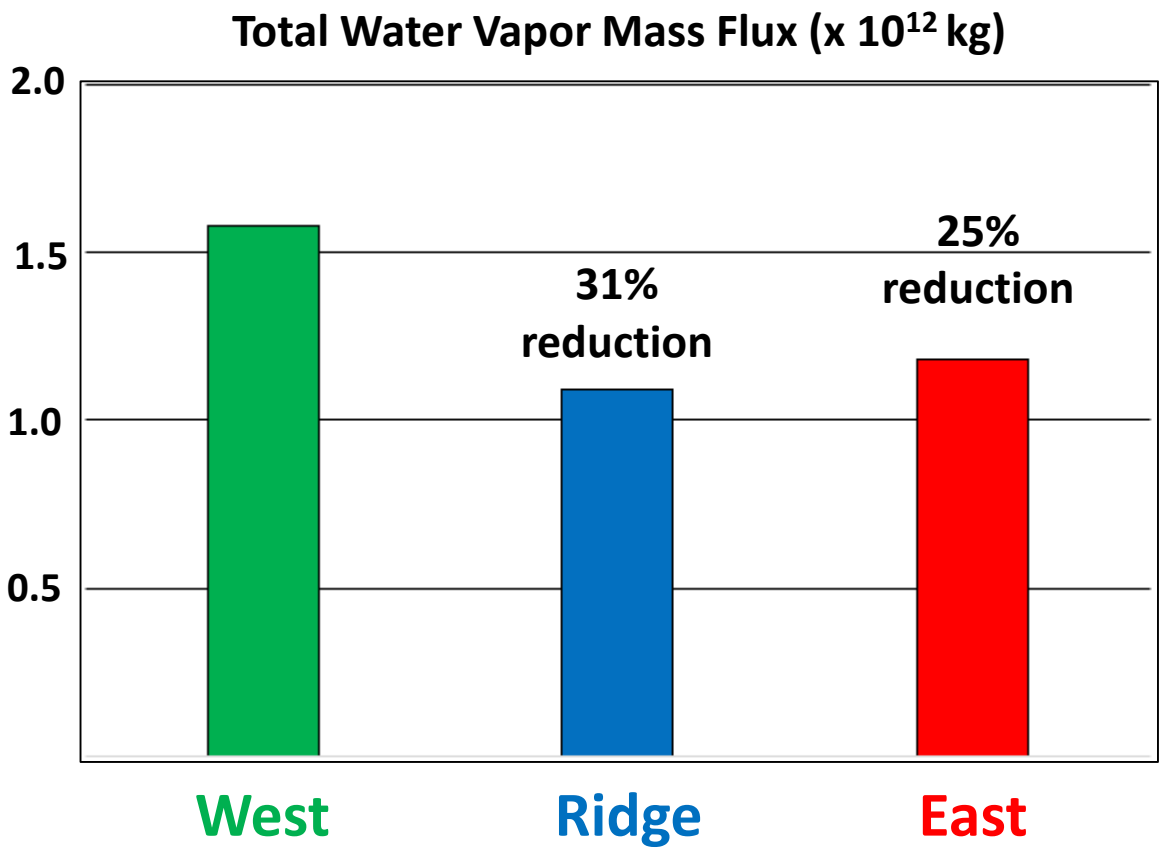
East of Cascades

- Core of flux downwind of Gorge
- Notable weakening of flux

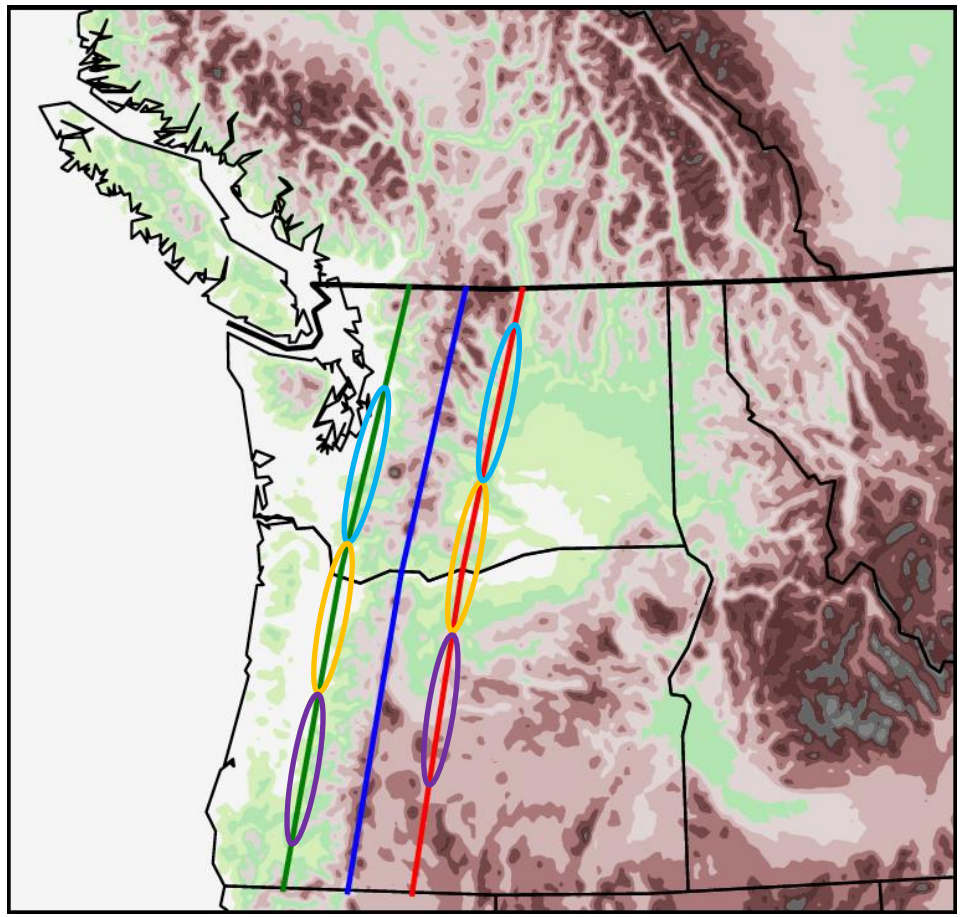


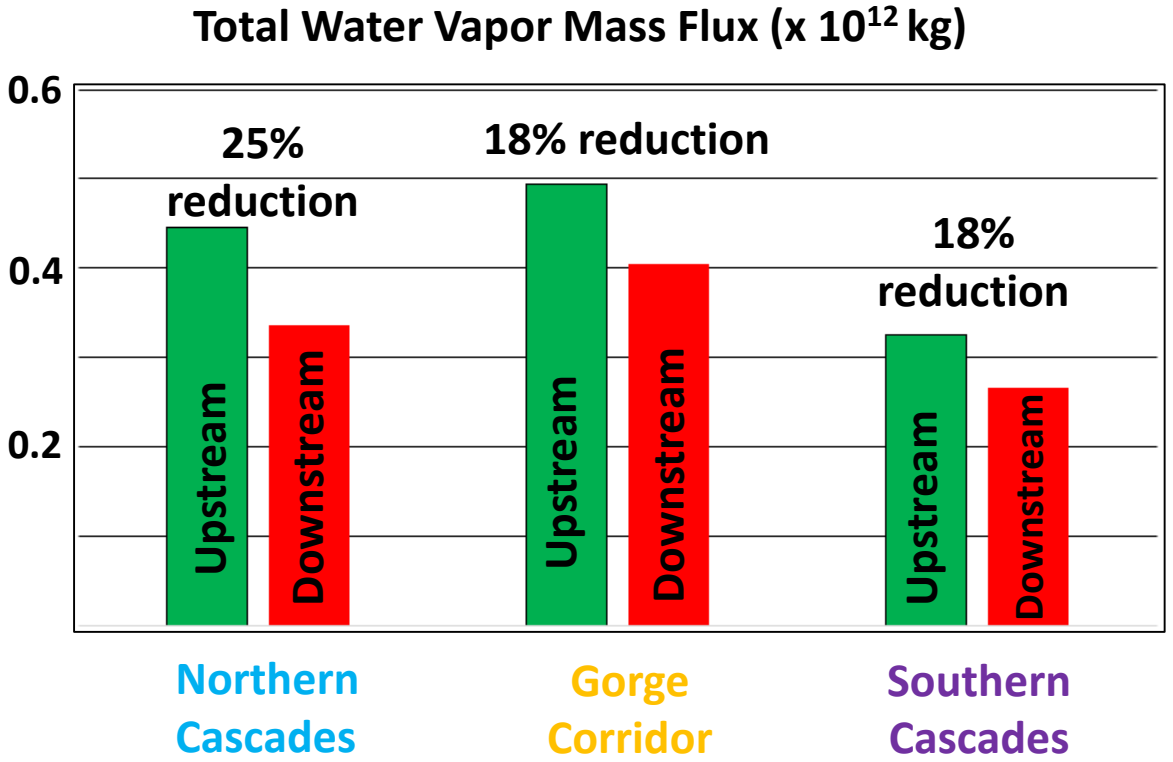
WRF Water Vapor Loss Over Cascades





WRF Water Vapor Loss: 200 km Segments





Summary

- Intense inland penetrating AR in Pacific Northwest early November 2006
- Record rainfall and flooding over interior mountains (Glacier Nat'l Park)

- Water vapor breached length of Cascades (3-7k foot ridge)
- 25% water vapor transport reduction across Cascades
- Main corridor for water vapor penetration ~150 km wide from Columbia River Gorge south
- Greater reduction north of Gorge (25%) vs. south of Gorge (18%)

Next Steps

- Follow moisture transport to interior mountains
- Calculate moisture transport including hydrometeor mass
- Modify terrain to close Gorge, increase barrier height

Acknowledgements

- Funding from the Bureau of Reclamation
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- University of Colorado's Research Computing (*Janus* supercomputer)
- Weather Research and Forecasting modeling system