On the dynamical causes of variability in the rain-shadow effect: A case study of the Washington Cascades

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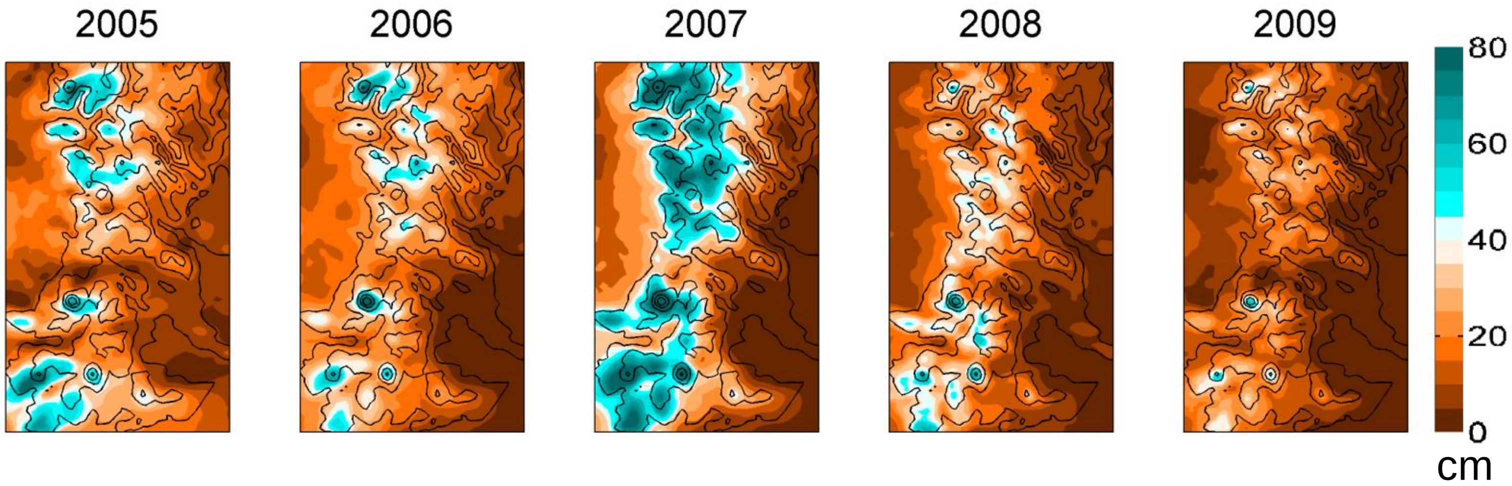
Rain shadow variability

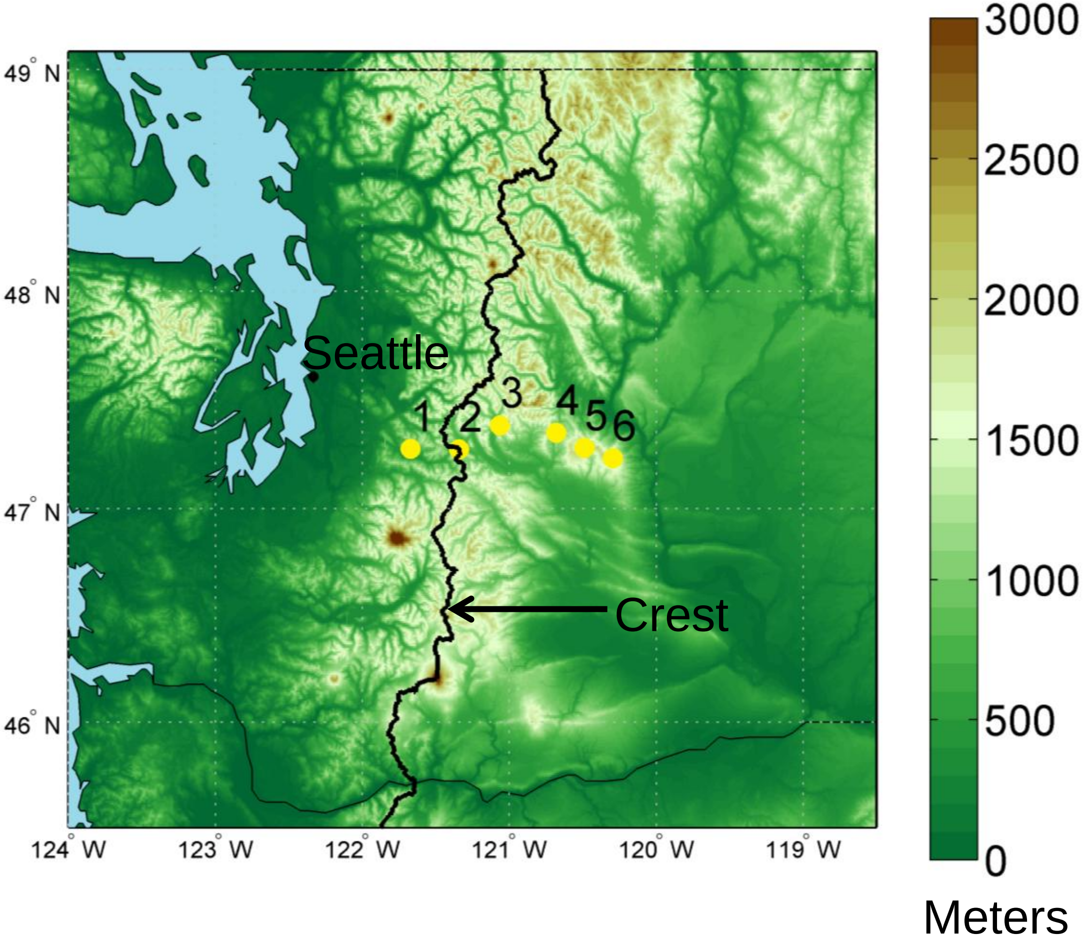
- December precipitation in the Washington Cascades



- Large interannual variability
- Significant economic impacts
  - Fish, farmers, utilities and communities depend on leeside precipitation

Snowfall Telemetry (SNOTEL) Data

- 6 stations
- 29 years of data
- 2 degrees of freedom across transect
- Well characterized by stations 1 & 6 *alone*



An orthogonal basis set for wintertime precip

- P_1 = normalized DJF precipitation at station 1
- P_6 = normalized DJF precipitation at station 6
- 2 orthogonal indices:

$P_1 + P_6$: Total Precipitation Index (T)

$P_1 - P_6$: Rain Shadow Index (R)

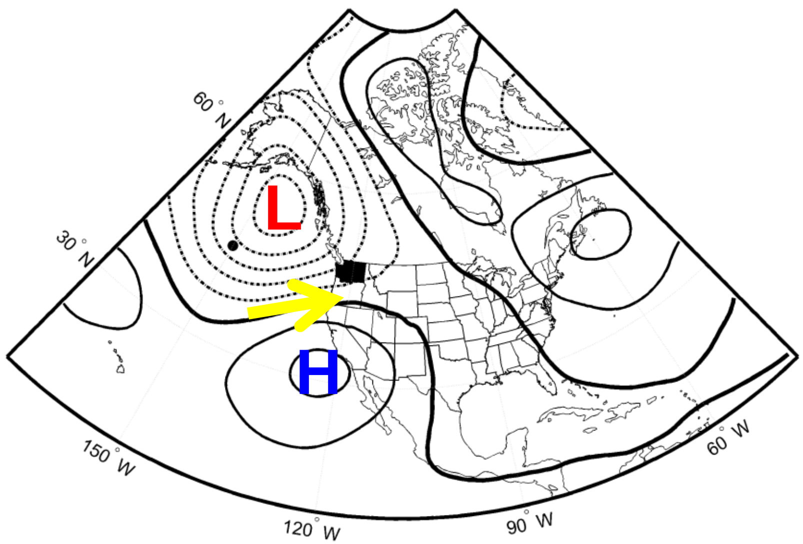
- R explains ~30% of interannual variability

Motivating questions

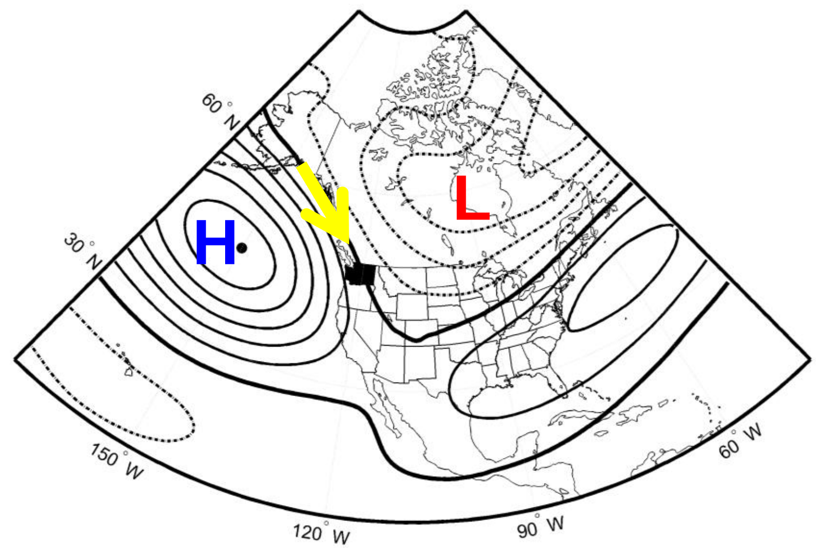
1) How is variability in T and R related to the large-scale circulation?

2) How do storm dynamics influence rain-shadow strength?

Circulation anomalies associated with *T* and *R*



Total precipitation pattern



Rain shadow pattern

- High total precip = WSW flow anom
- Strong rain shadow = NNW flow anom

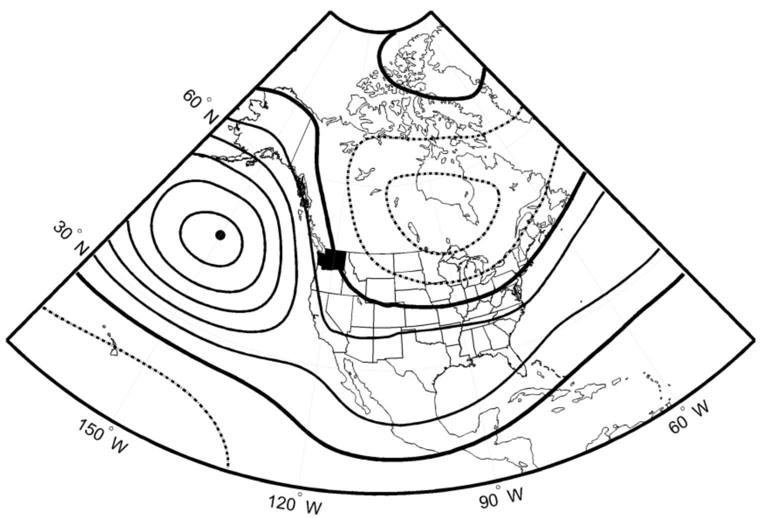
500mb height anomalies regressed on *T* and *R*. Solid (dotted) lines represent positive (negative) height anomalies. Shaded areas are statistically significant at 95% confidence level.

Rain shadow strength is related to ENSO

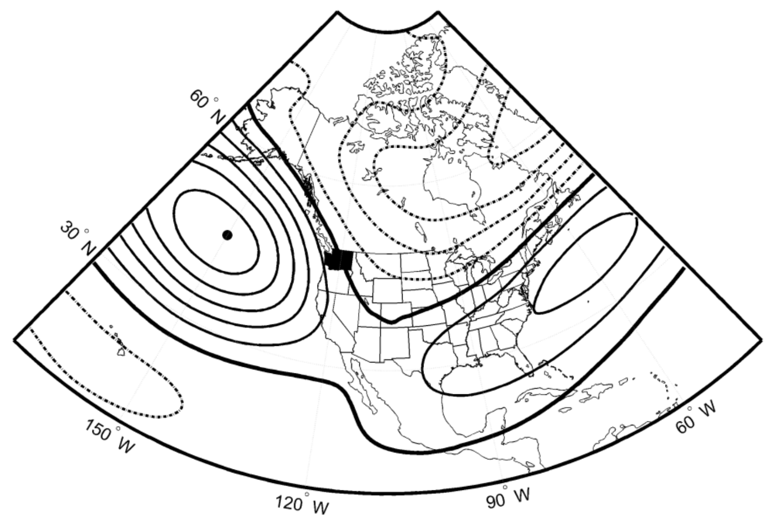
- Rain-shadow pattern closely resembles the ENSO teleconnection pattern
- Correlation table:

	T	R
DJF Niño 3 index	0.03	-0.50

- ENSO affects the rain shadow but not total precipitation



Niño 3 pattern (inverted)



Rain shadow pattern

Relevance for predictability

- ENSO is the only source of predictability beyond ~1 month
- Consequences:

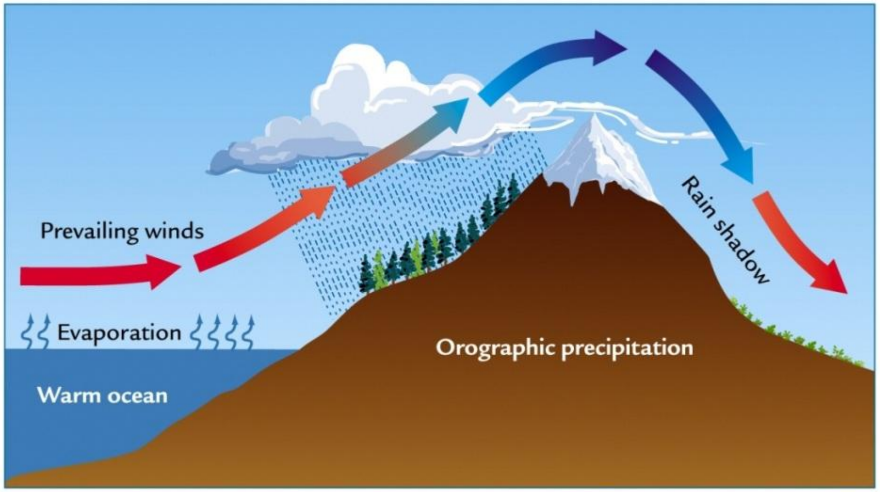
1) *R* has some predictability; *T* does not

   Correlation b/t **Nov** Nino 3 index & **DJF** rain shadow = -0.54

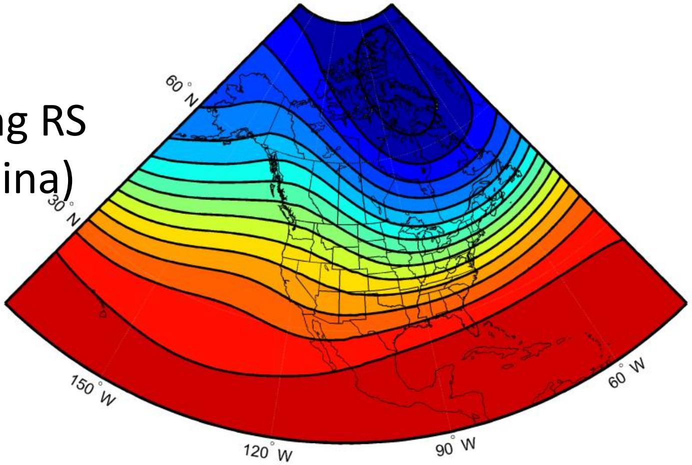
2) The pattern is more predictable than the amount

Why does ENSO do this?

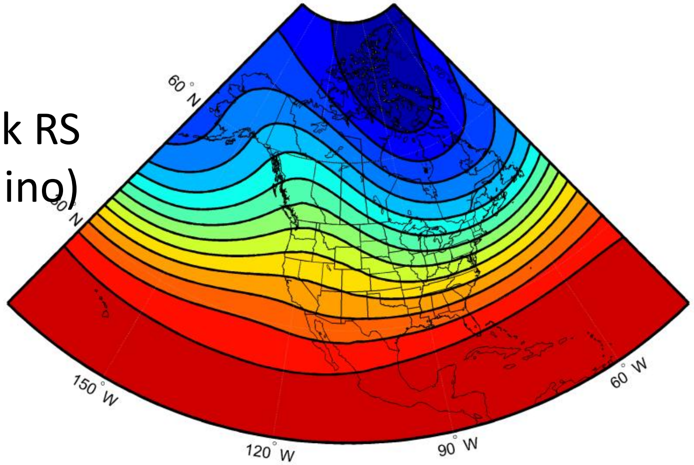
- Spillover?
  - Not consistent with ENSO wind anomalies
- Storms provide clues…



Strong RS
(La Nina)

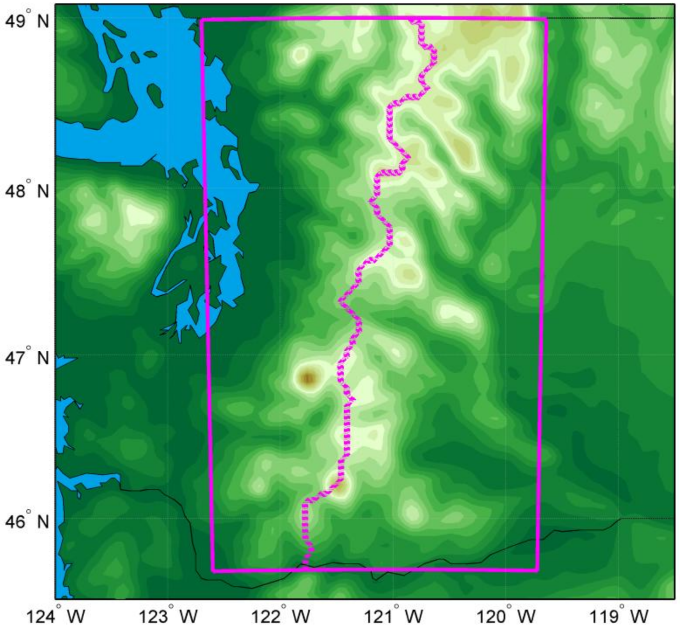


Weak RS
(El Nino)



Storm analysis

- Identified 100 strongest storms b/t 2005 and 2010
  - Based on MM5/WRF 24-hour precipitation totals in Cascades (defined as region inside pink box below)

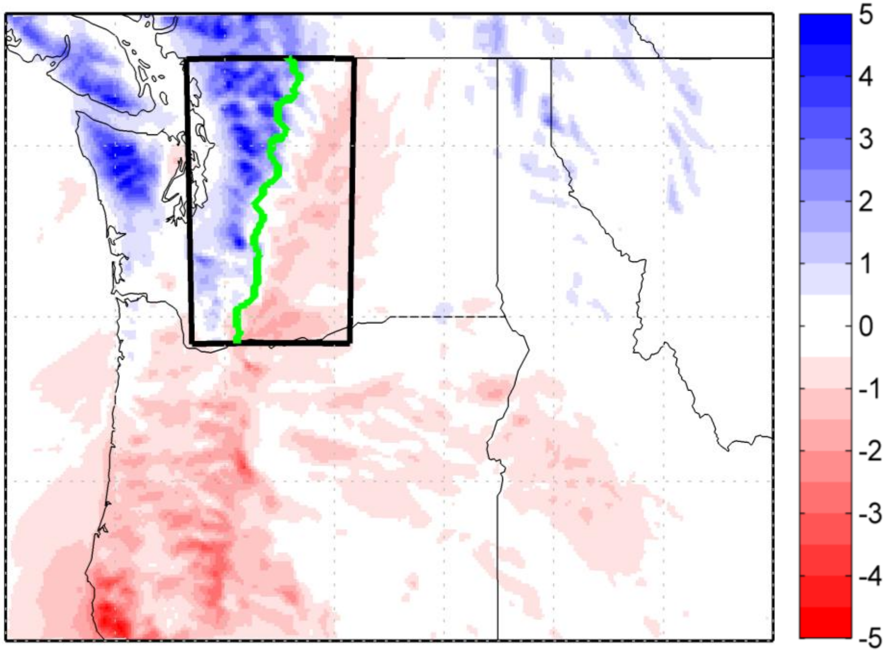


MM5/WRF 4-km grid

- Calculated rain-shadow index as before
- 3 categories
  - 33 Weak-rain-shadow storms
  - 33 Strong-rain-shadow storms
  - 34 Neutral-rain-shadow storms

Evidence of storm-track influence

1. Weak-rain-shadow storms bring more precip to south

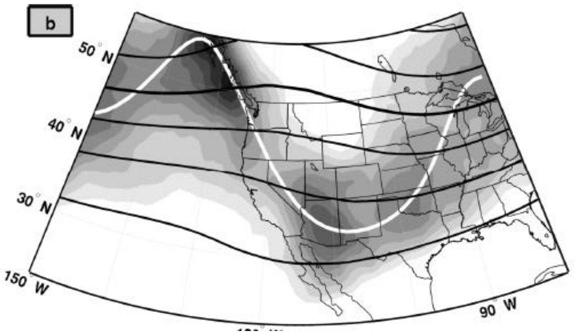


Difference in average precipitation between strong-rain-shadow storms and weak-rain-shadow storms (cm)

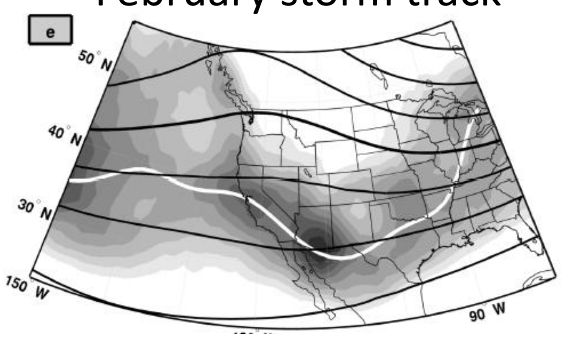
Evidence of storm-track influence

2. Weak-rain-shadow storms are more common in winter, when the storm track is further south

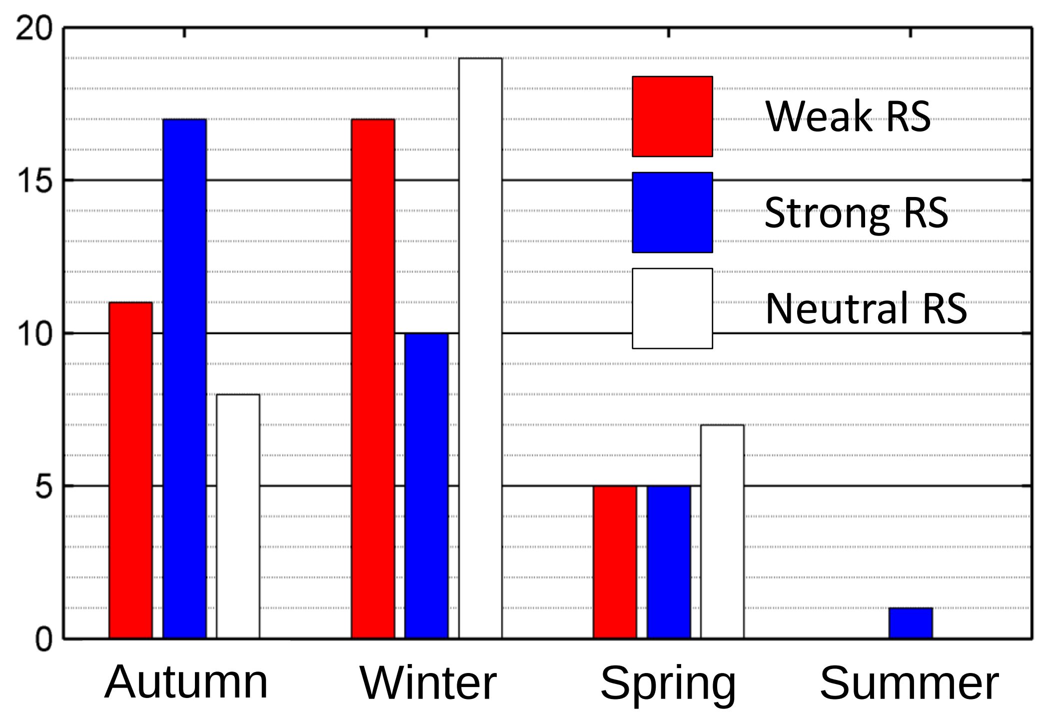
November storm track



February storm track

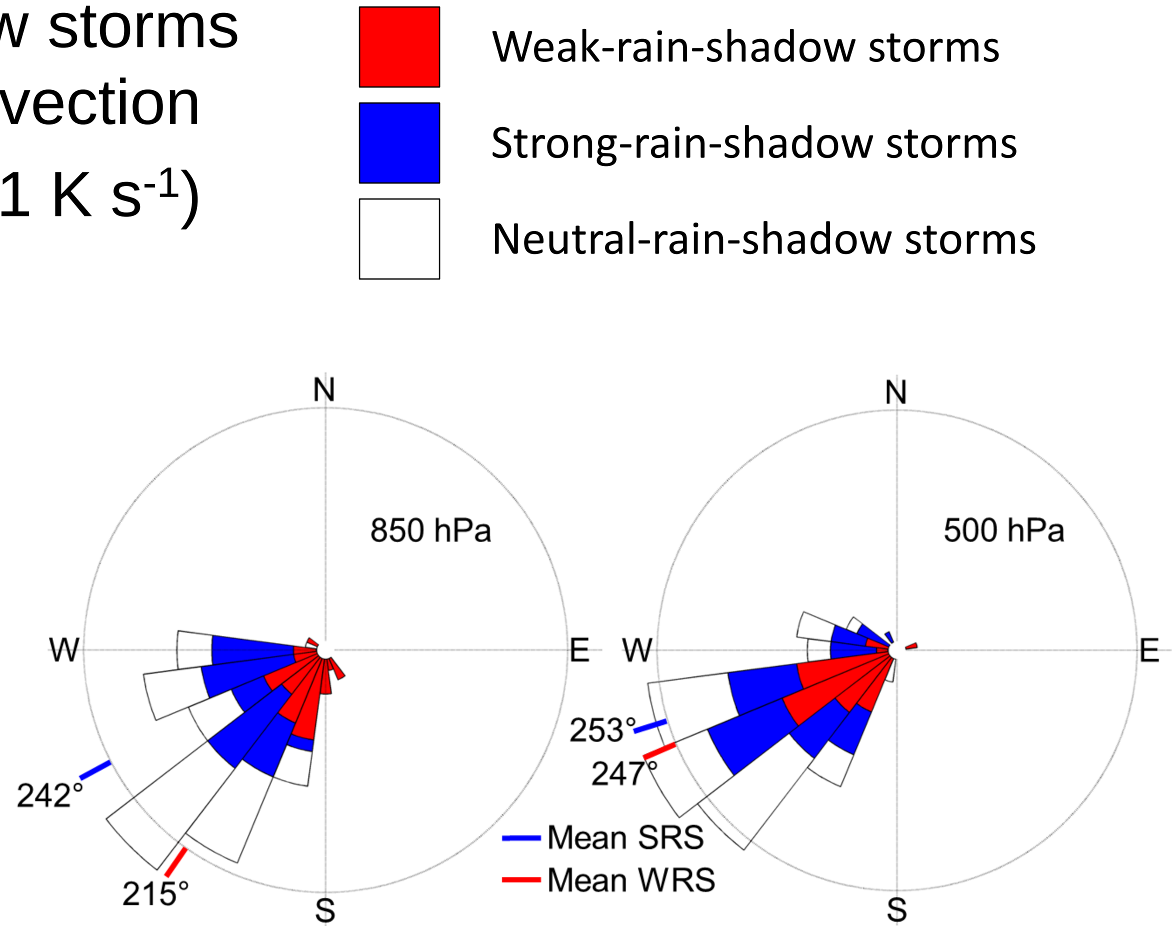


Shading: average synoptic-scale ascent
Source: Lareau & Horel, 2012



Evidence of storm-track influence

3. Weak-rain-shadow storms more warm-air advection (0.62 K s^{-1} vs. 0.31 K s^{-1})



Evidence of storm-track influence

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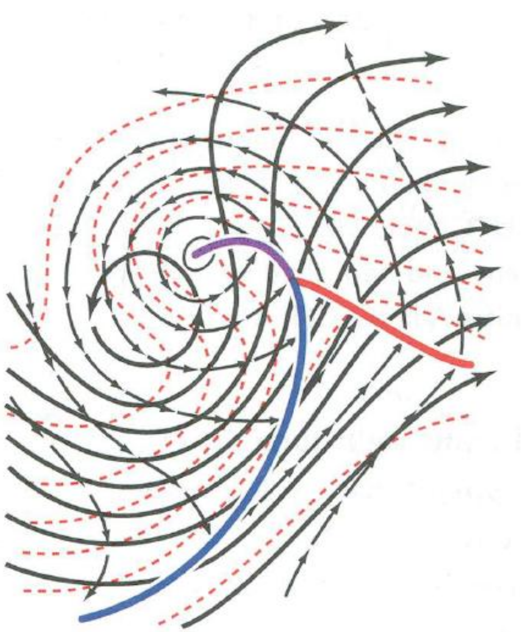
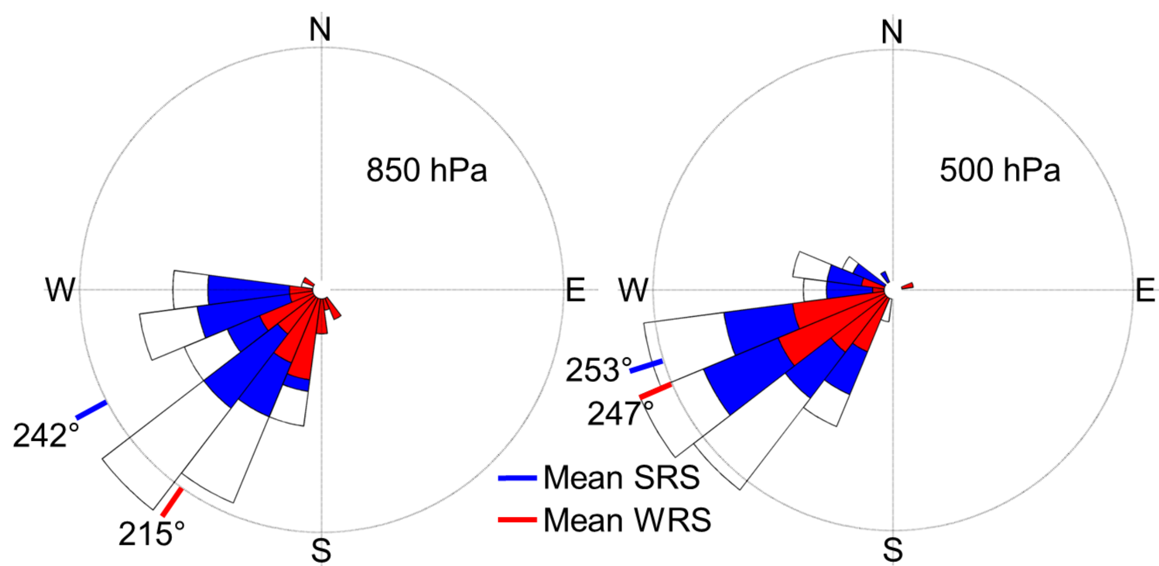
- Weak-rain-shadow storms (red)
- Strong-rain-shadow storms (blue)
- Neutral-rain-shadow storms (white)





Evidence of storm-track influence

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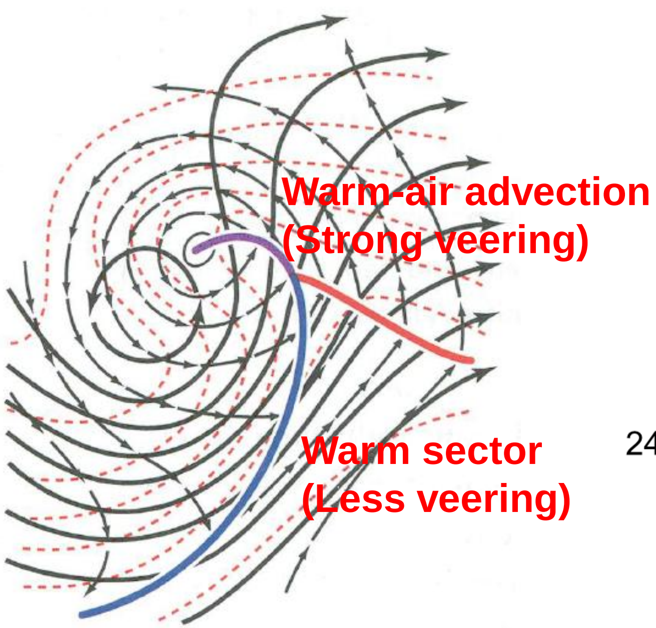
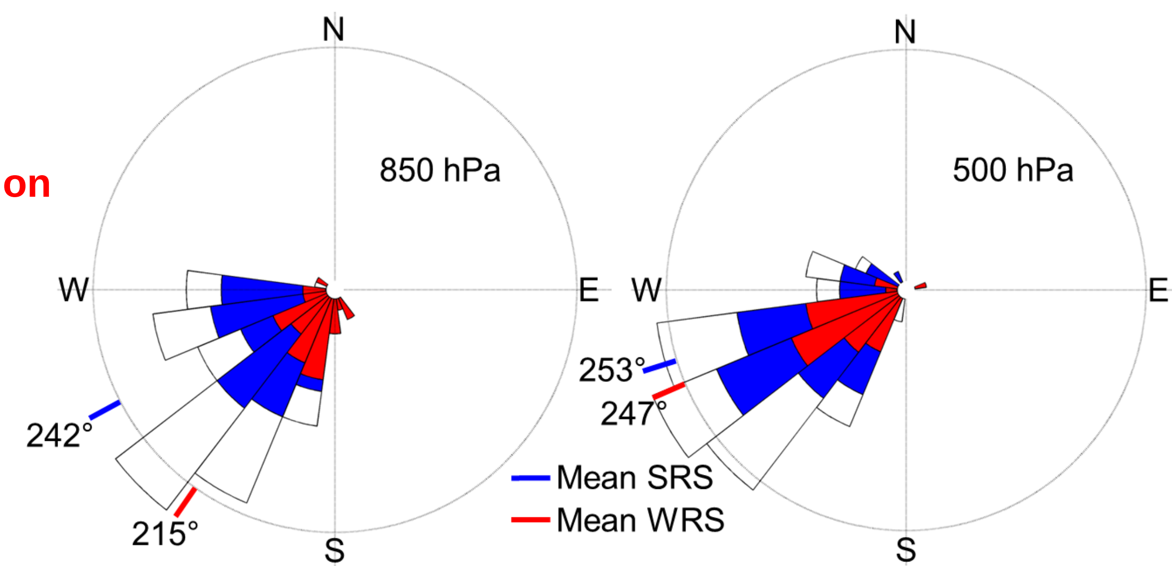
Weak-rain-shadow storms

Strong-rain-shadow storms

Neutral-rain-shadow storms





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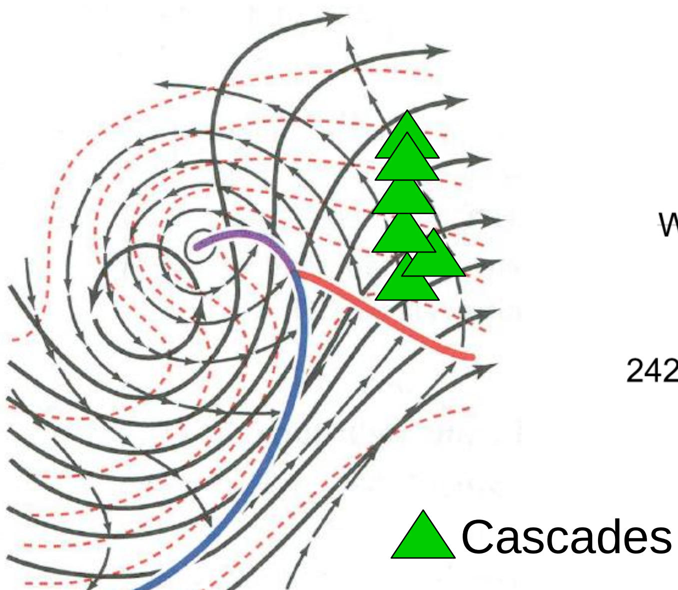
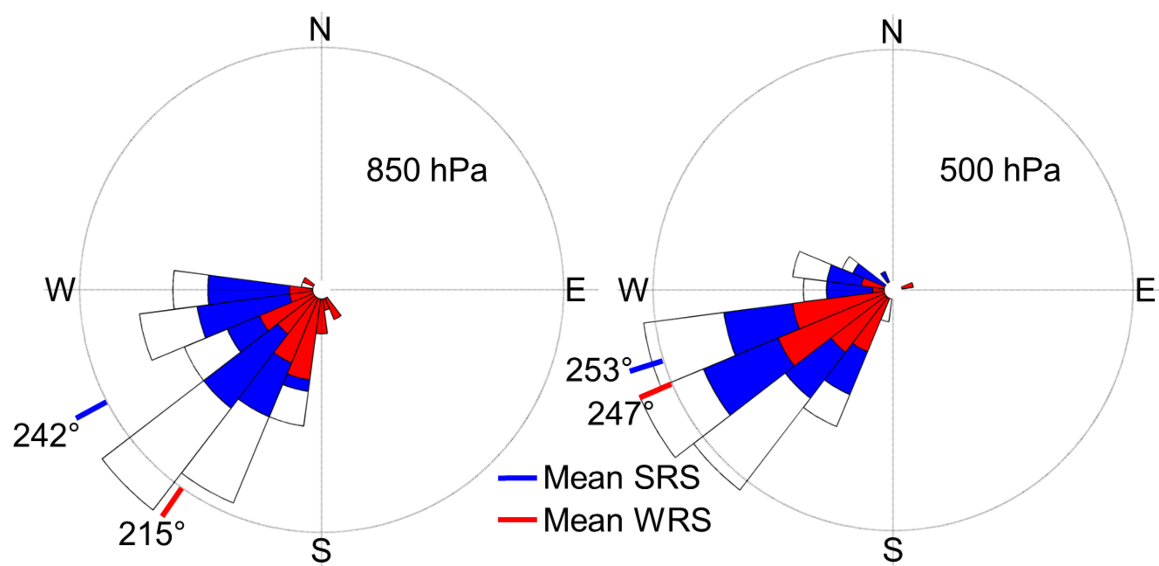
Weak-rain-shadow storms

Strong-rain-shadow storms

Neutral-rain-shadow storms

Weak rain shadow scenario





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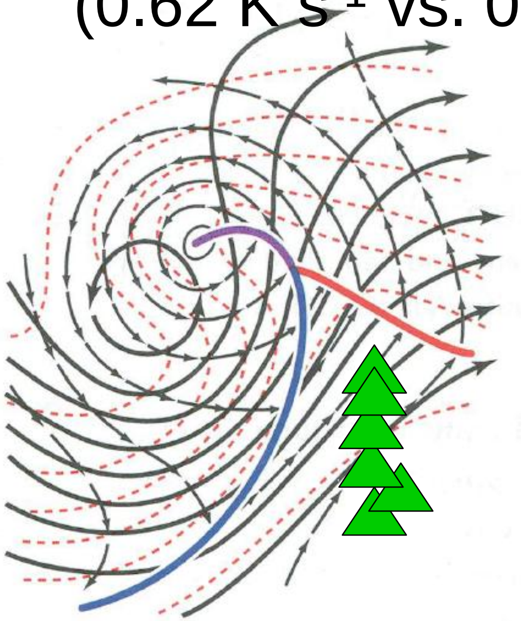
Weak-rain-shadow storms

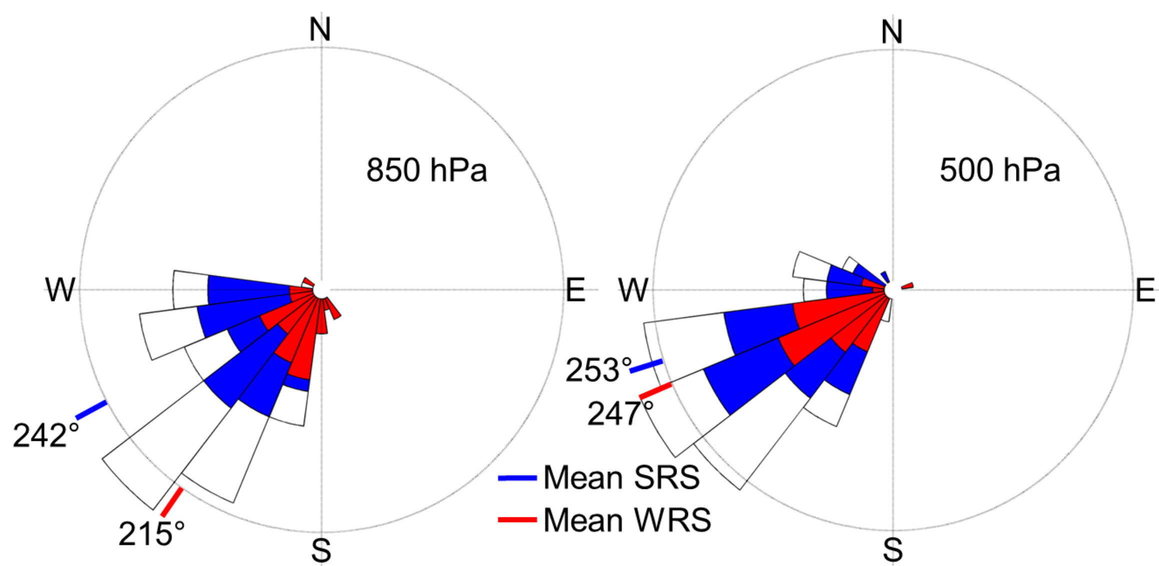
Strong-rain-shadow storms

Neutral-rain-shadow storms



Strong rain shadow scenario

Cascades



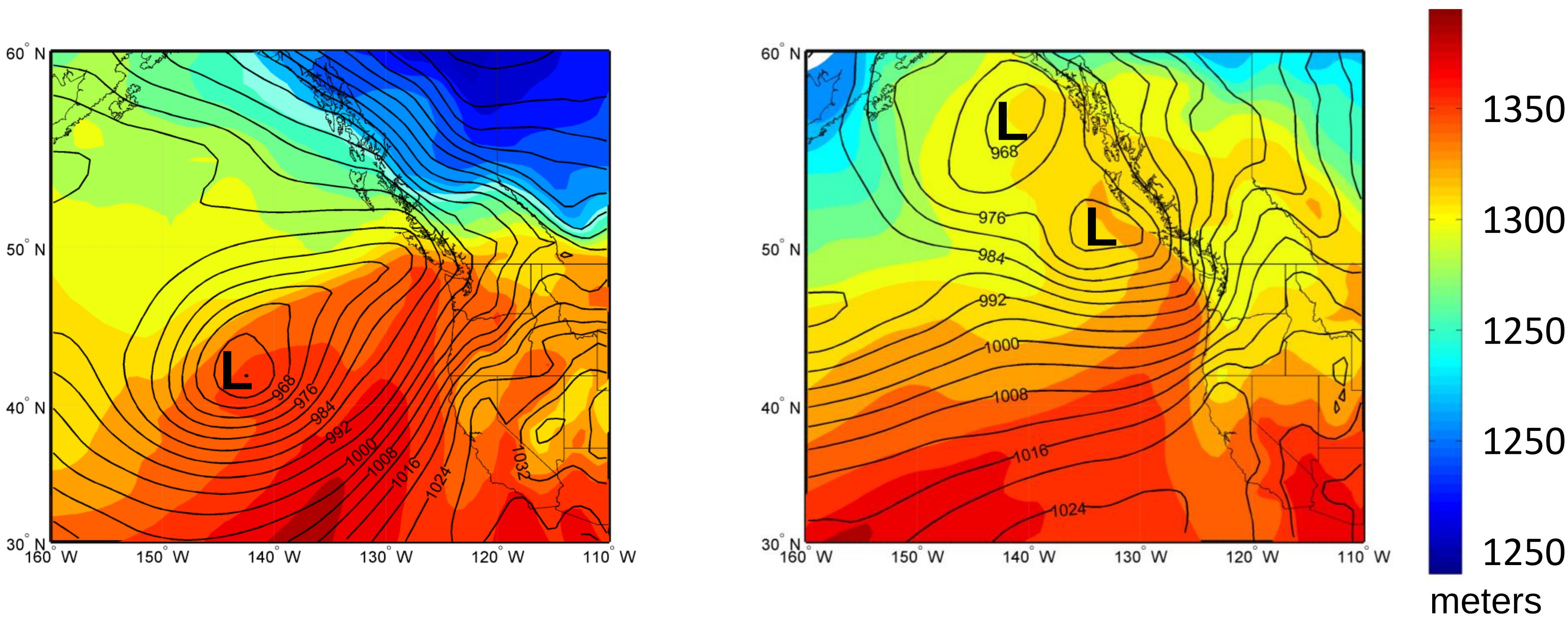
How might warm fronts act to weaken the rain shadow effect?

How might warm fronts act to weaken the rain shadow effect?

- Case studies provide some clues…

MM5 case studies

- Strong-rain-shadow case
  - Dec. 2-3, 2007
  - Cascades in warm sector
- Weak-rain-shadow case
  - Jan. 31-Feb. 1, 2006
  - Warm front crosses Cascades

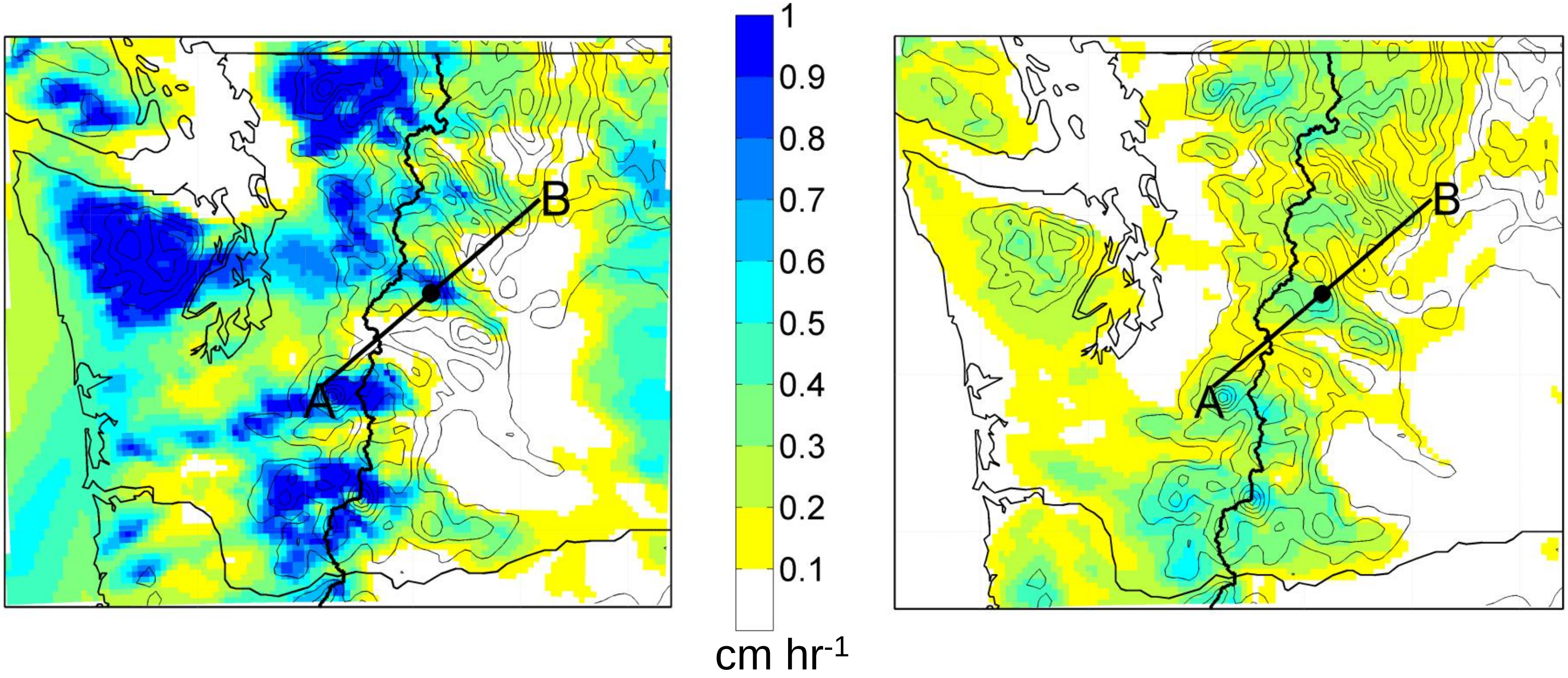


Sea level pressure (solid contours) and 1000-850 hPa thickness (colors)

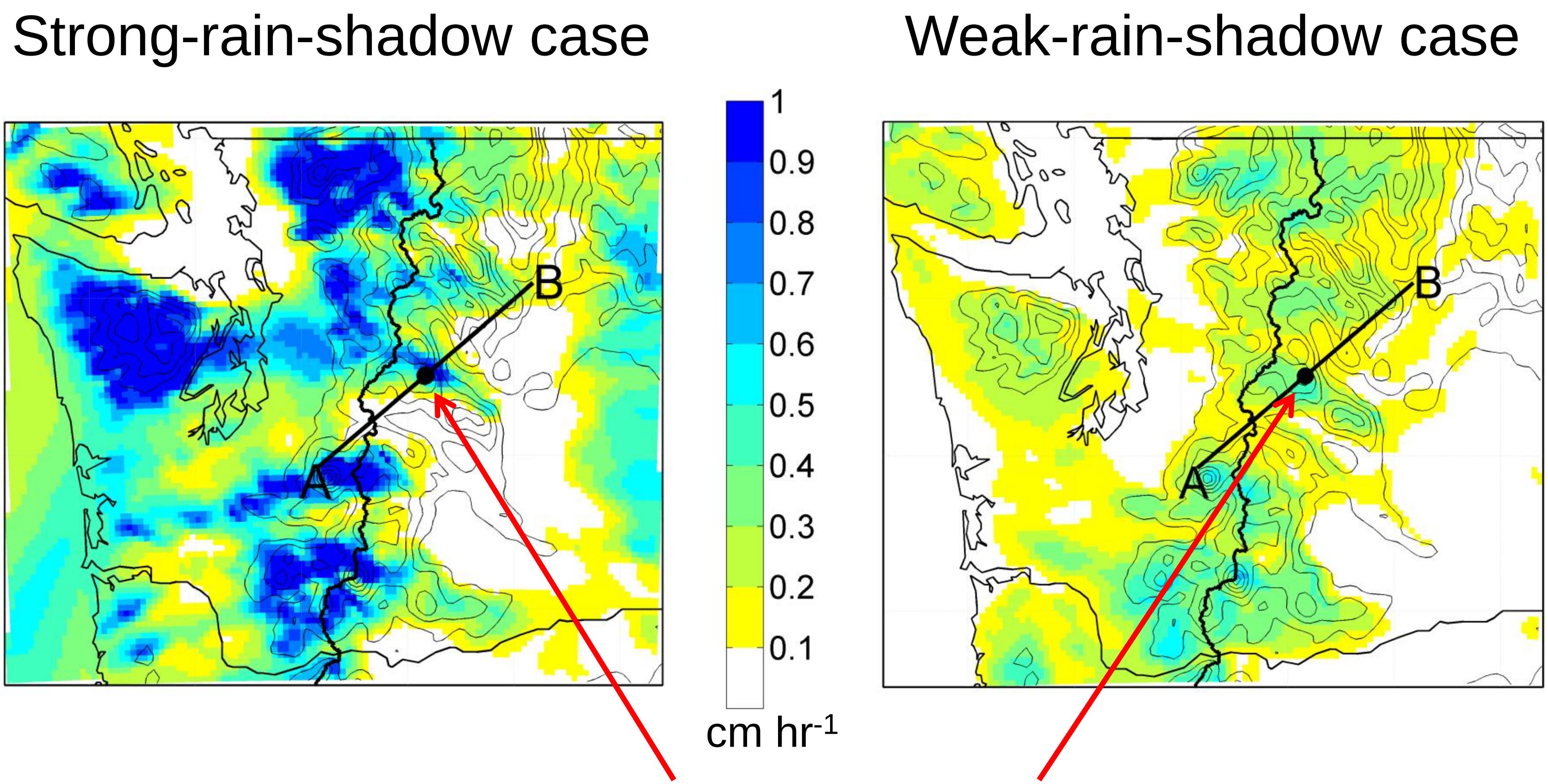
Precipitation patterns

Strong-rain-shadow case

Weak-rain-shadow case



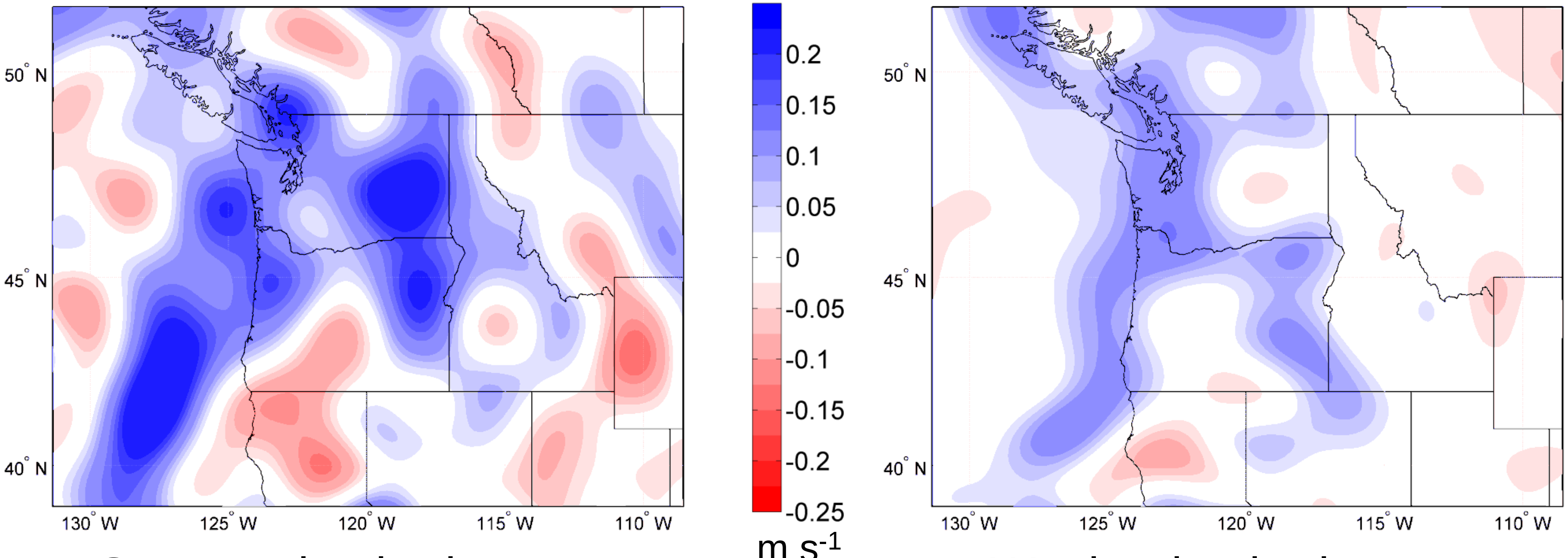
Precipitation patterns



In both cases, winds are parallel to transect at 775 hPa

Synoptic-scale w (λ > 240 km)

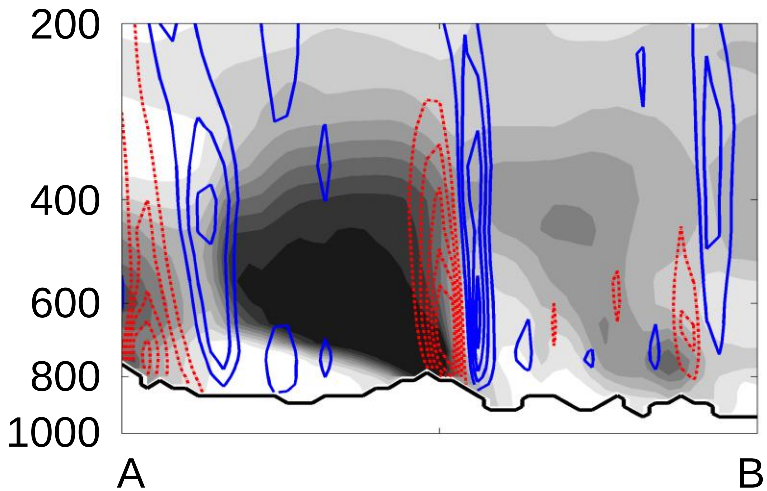
- Synoptic-scale ascent is inconsistent with rain-shadow differences
- Implicates smaller-scale processes

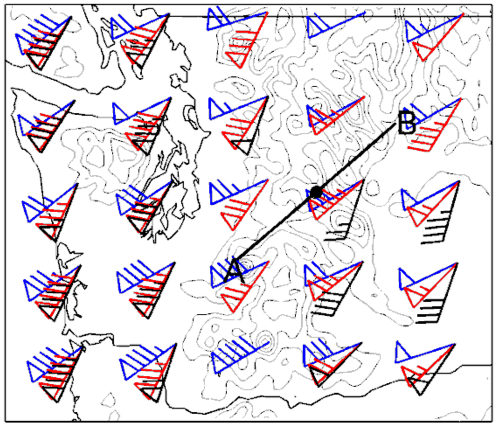


Strong-rain-shadow case

Weak-rain-shadow case

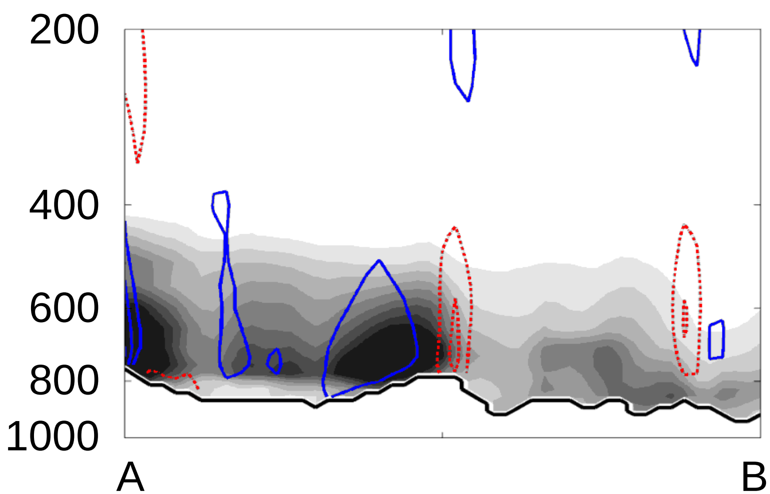
Mesoscale Dynamics

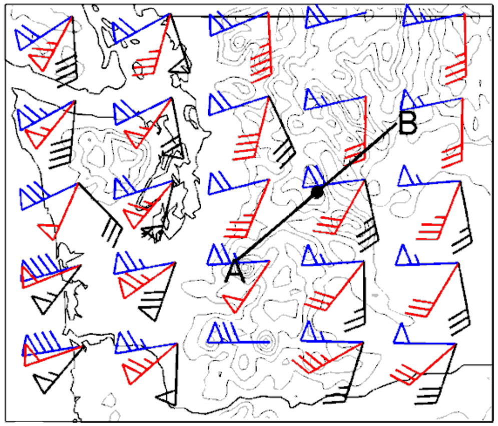




Strong RS case

- Deep mt. waves
- Downdrafts = evaporation in lee
- Little veering





Weak RS case

- Weak mt. waves
- Cloud water persists into lee
- Strong veering

Vertical velocity (red down, blue up)
Liquid/ice water content (shading)

Horizontal winds at 900 (black), 800 (red), and 500 mb (blue)

Summary

- 2 degrees of freedom in wintertime Cascade precipitation
  - Total precipitation (*T*)
  - Rain shadow (*R*)
- ENSO influences *R* via storm-track latitude
  - El Niño = southern storm track = weaker rain shadow
  - *R* is more predictable than *T*
- Warm-air advection is key to weak rain shadows
  - Mountain-wave influence is strongly suggested

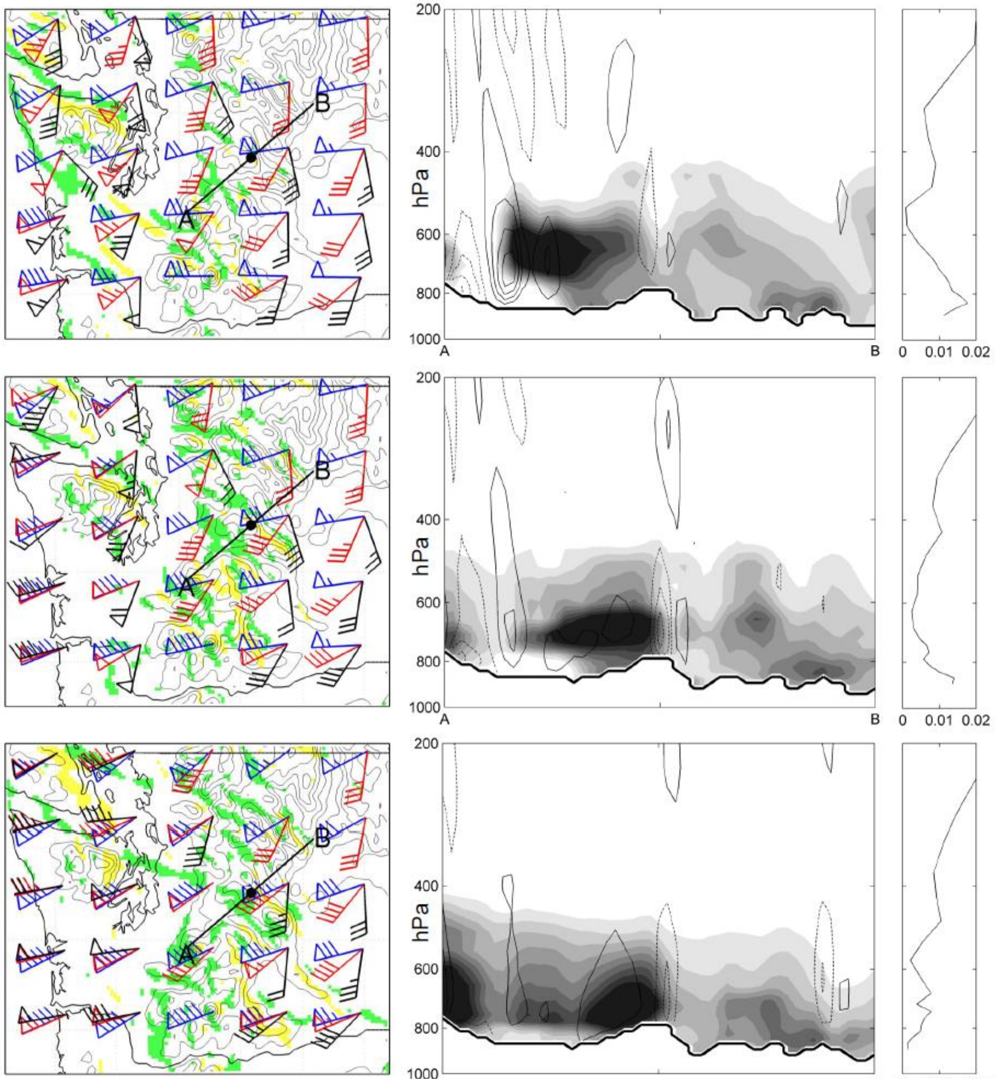
The End

Backup slides

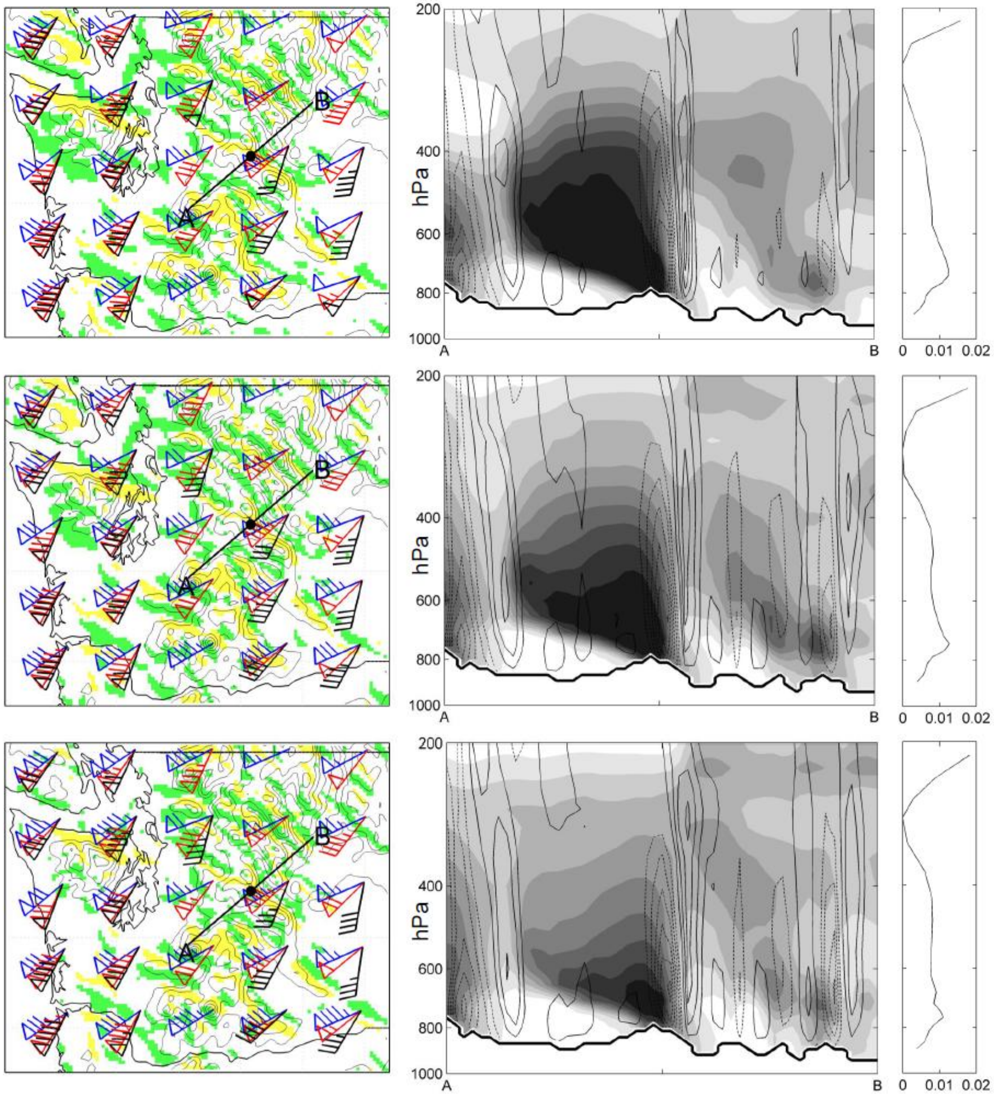
ENSO and storm-track latitude

- El Niño (La Niña) = southern (northern) storm track

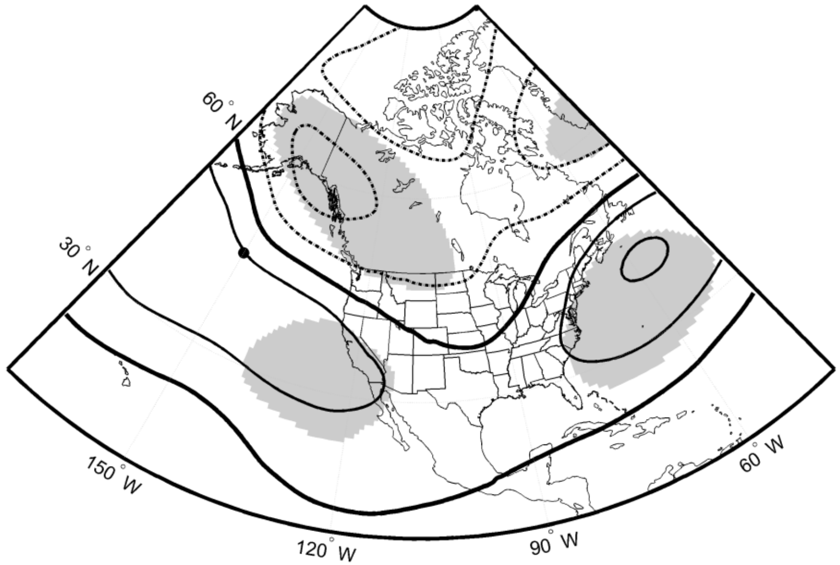
Weak RS case study



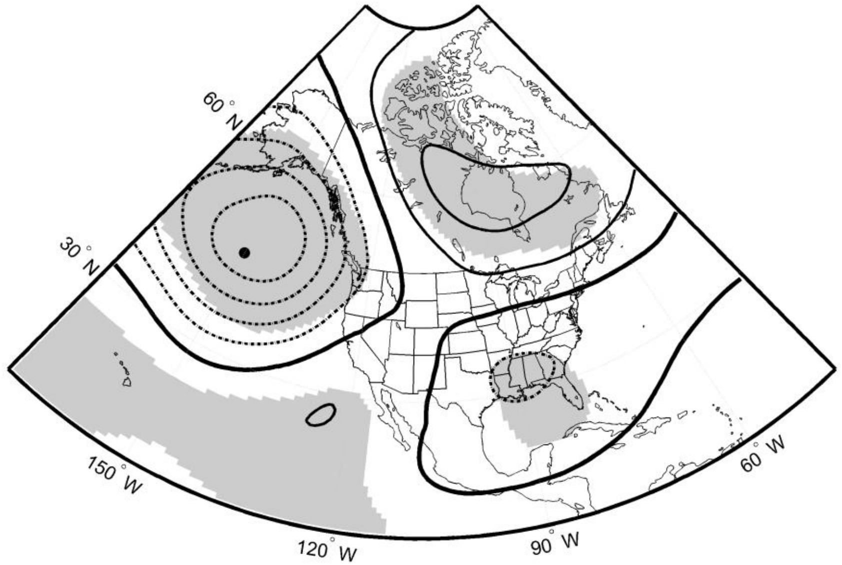
Strong RS case study



P_1 and P_6 circulation anomalies



P_1



P_6

Mountain-wave primer

From the linearized Boussinesq equations, the 2-D **steady** solution for vertical velocity in **Fourier space** is

$$\widehat{w}_{zz} + (l^2 - k^2)\widehat{w} = 0,$$

where k is the horizontal wavenumber and l^2 is the ‘Scorer parameter’:

$$l^2 = \frac{N^2}{\overline{U}^2} - \frac{\overline{U}_{zz}}{\overline{U}}.$$

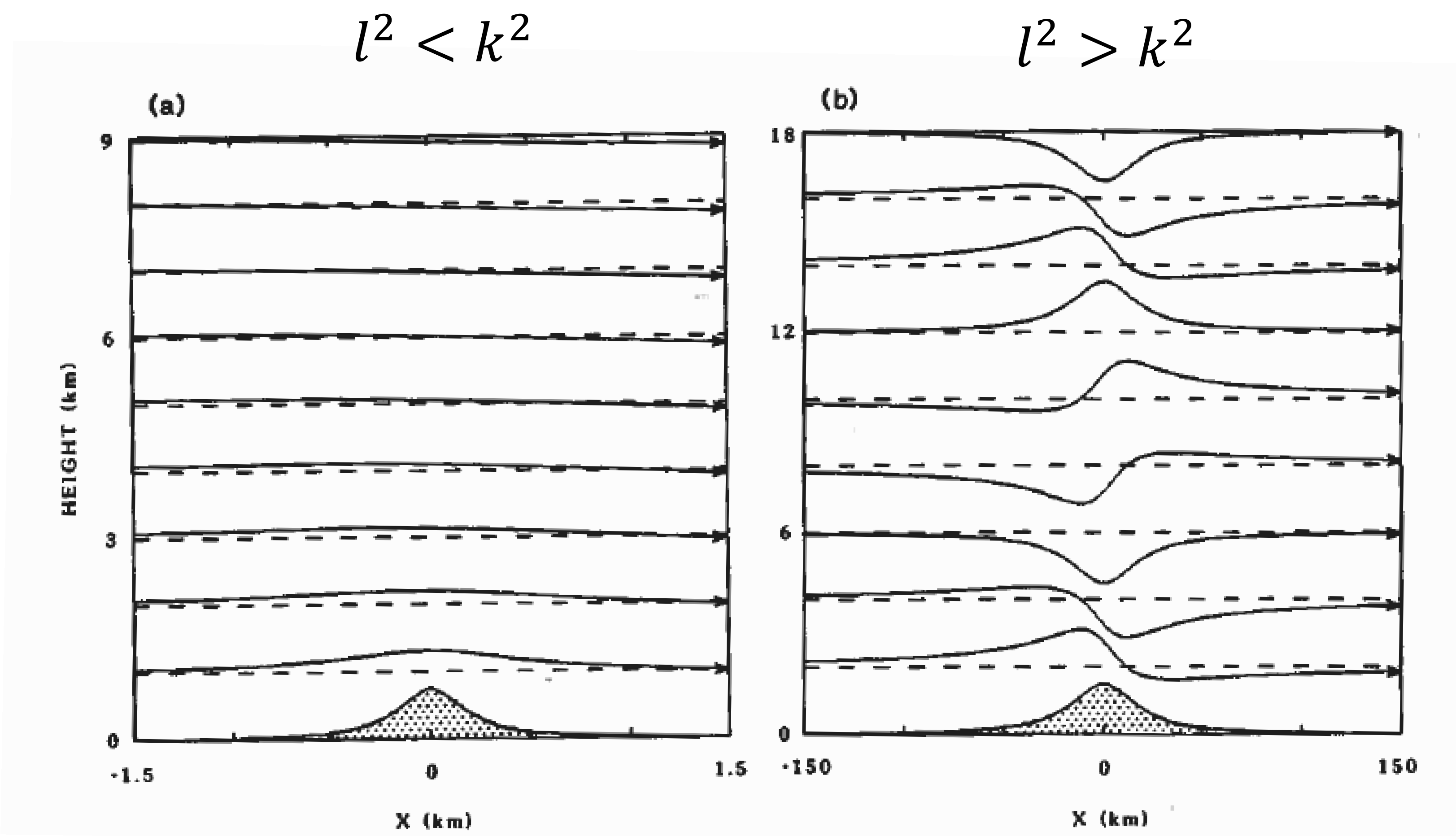
Condition for waves to propagate vertically:

$$l^2 > k^2.$$

Lower boundary condition:

$$w = \overline{U} \cdot \frac{\partial h}{\partial x}, \qquad \widehat{w} = i\overline{U}k\hat{h}(k)$$

Mountain-wave primer



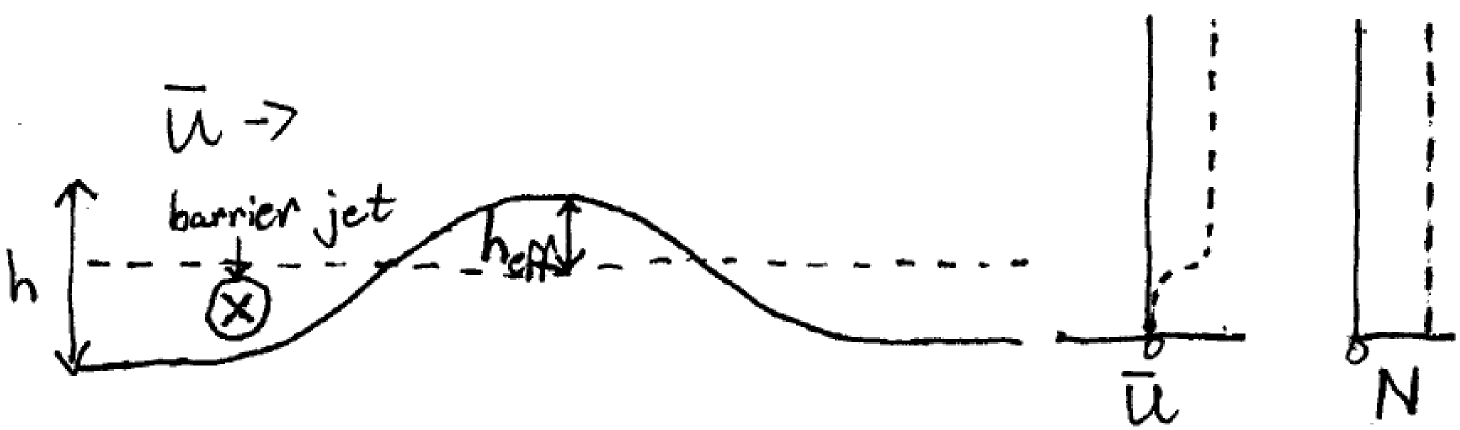
Source: Durran 1990

Mountain-wave primer

- Important points:
  1) The mountain height affects the amplitude of the vertical velocity field
  2) If $l_z < 0$, waves can become evanescent, leading to decay or reflection
  3) Waves break at a critical level where $\overline{U} \rightarrow 0$

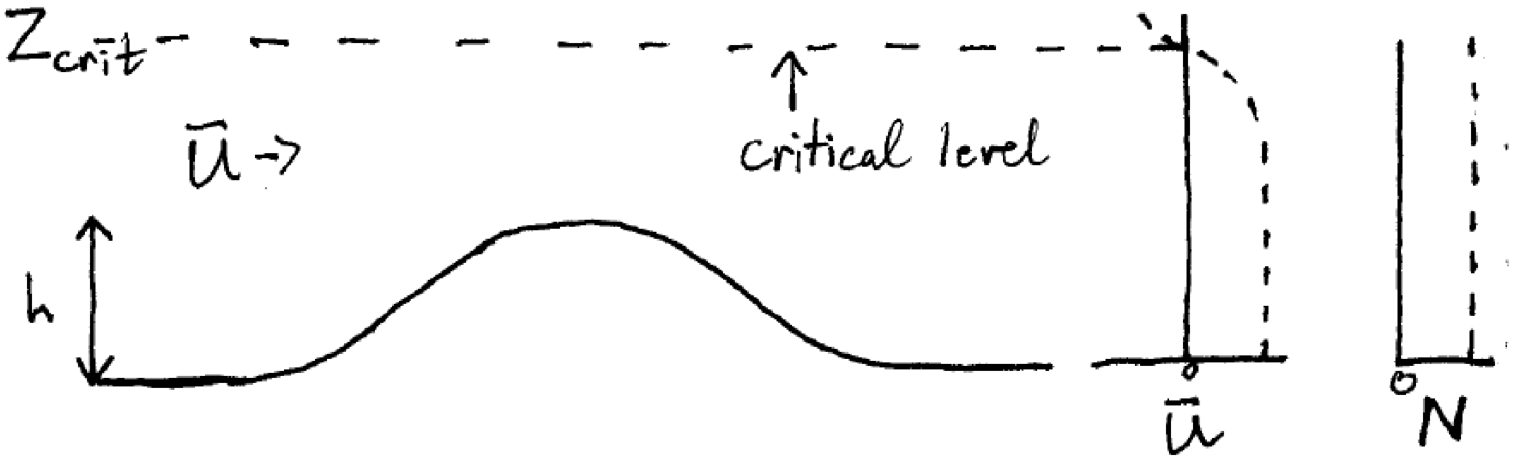
How might warm fronts lead to weaker mountain waves?

- Mechanism # 1: Blocking
  - High low-level stability can prevent the flow from ascending to the crest, and it is diverted poleward
  - Effective mountain height is reduced, leading to lower-amplitude waves (Smith 2002)



How might warm fronts lead to weaker mountain waves?

- Mechanism # 2: Directional critical level
  - Veering results in the cross-barrier component of the flow approaching zero
  - Waves cannot propagate through critical level



How might warm fronts lead to weaker mountain waves?

- Mechanism # 3: Transition to evanescent waves
  - A sharp decline in static stability above the frontal zone can result in $l^2 < k^2$
  - Waves decay or reflect back to the surface