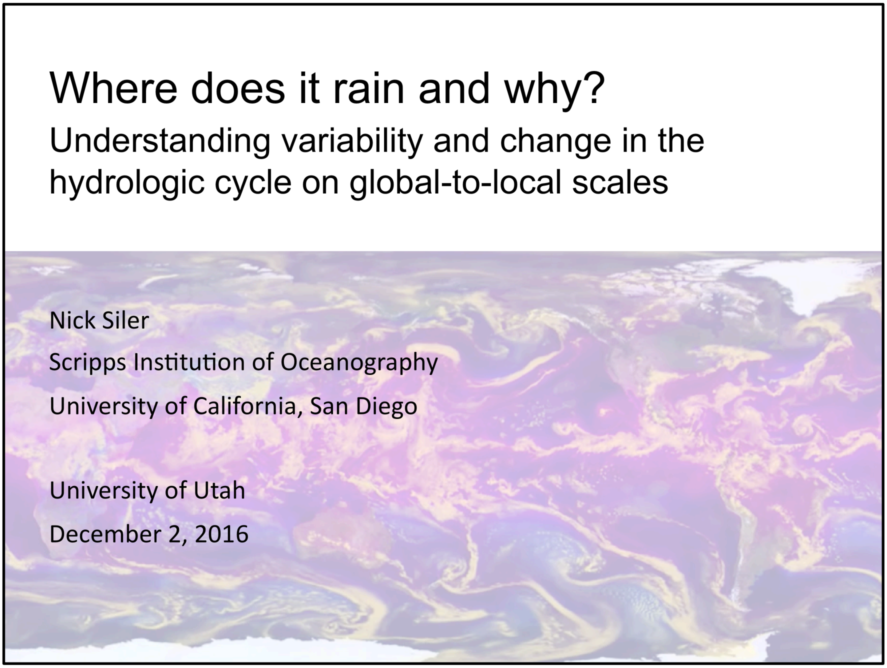
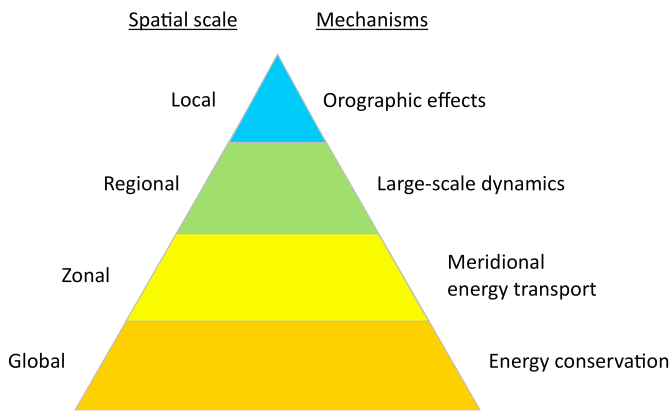


For my defense, I've chosen to focus on the piece of my research related to rain-shadow variability in the Cascades, which also has implications for other midlatitude mountain ranges across the world.

What governs the hydrologic cycle?

- The hydrologic cycle depends on mechanisms spanning a wide range of scales
- At local scale, orographic effects are important, but so are larger scales
- Calls for an integrated approach to studying the hydrologic cycle and its response to climate change

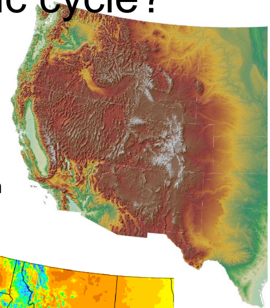


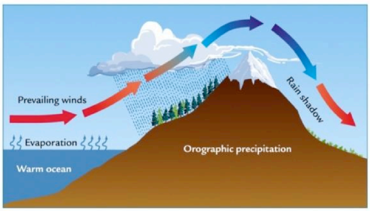
Surface tends to be warmer than the atmosphere

What governs the hydrologic cycle?

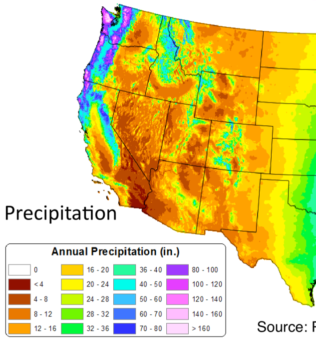
Local scale: what matters for society
- Strongly influenced by mountains ("orographic precipitation")
- Globally, mountains supply half the fresh water used by humans
- Mountains exhibit sharpest climate gradients on earth

Terrain





Precipitation



Source: PRISM

Surface tends to be warmer than the atmosphere

Today's lecture

Orographic precipitation

- What controls Cascade rain-shadow strength?

Regional predictability

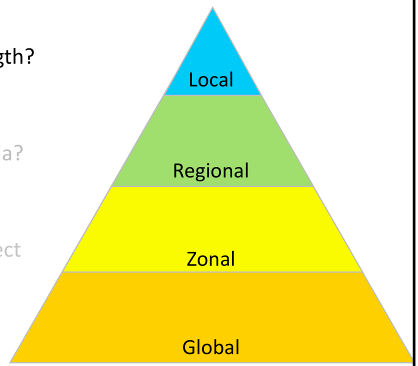
- Why did "Godzilla" El Niño betray California?

Feedbacks and energy transport

- How does spatial pattern of feedbacks affect meridional energy transport and P-E?

Global precip and climate change

- Rethinking the conventional notion of a radiative constraint



Orographic precipitation varies in space and time

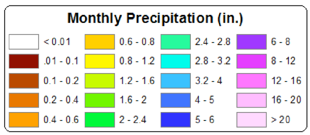
Differences

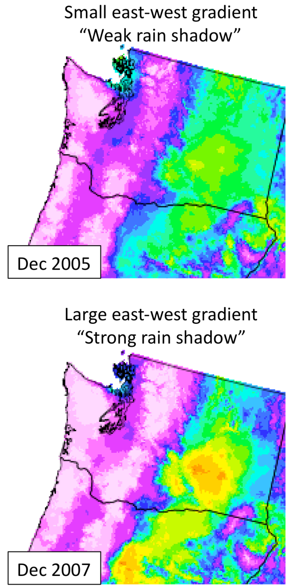
1. Amount: 2007 is wetter overall
2. Spatial pattern

Both types of variability impact society
- fish, hydropower, crops

Highest impacts in eastern half of state, where water is scarcest and 85% of crops are grown

Rain shadow literature is sparse…





Source: PRISM, OSU

Eastern Washington accounts for 85% of state's $10 Billion ag industry.

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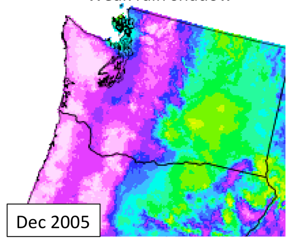
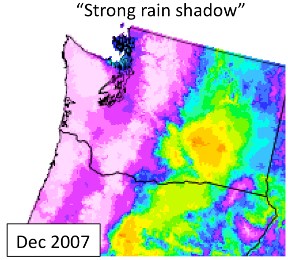
Rain shadow literature is sparse…

What causes rain shadow variability…
… from year to year?
… from storm to storm?

Small east-west gradient
“Weak rain shadow”



Large east-west gradient
“Strong rain shadow”



Source: PRISM, OSU

Eastern washington accounts for 85% of state’s $10 Billion ag industry.

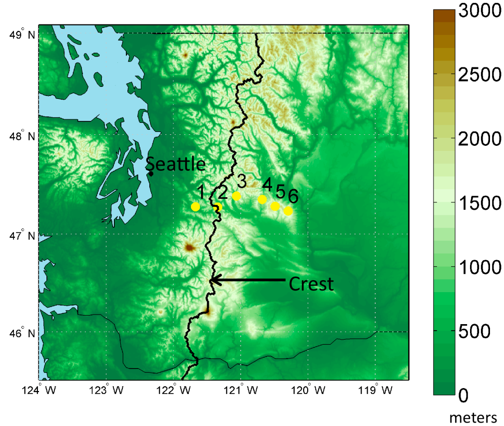
Investigating year-to-year variability in the wintertime rain shadow using SNOwfall TELemetry (SNOTEL) data

6 stations

30 years of data

2 degrees of freedom across transect

Well characterized by stations 1 & 6 *alone*



The only good source of long-term precipitation data in the Cascades comes from the SNOTEL network, and we've chosen to focus on just six stations comprising a roughly 100-km transect from east to west. These stations were chosen because of their relatively dense coverage from east-to-west, and because their records go all the way back to 1982, providing 29 years of continuous data.

Within the time series of wintertime precipitation at these six stations, we find essentially just two degrees of freedom, which are well characterized by the two time series at the westernmost site (site 1) and the easternmost site (site 6).

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:

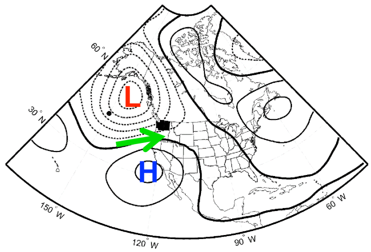
$P_1 + P_6$: Total Precipitation Index (T)

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

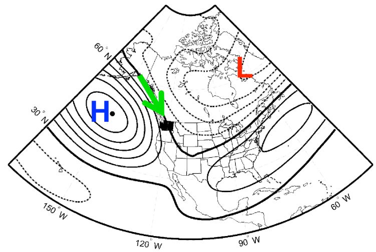
R explains ~30% of interannual variability

In light of this fact, we can construct an orthogonal basis set for wintertime precipitation from the normalized time series at stations 1 and 6, which I'll call P1 and P6 respectively. I'll call P1 *plus* P6 the Total Precipitation Index, and P1 *minus* P6 the rain shadow index, since it's a measure of the cross-barrier precipitation gradient. And because these indices are orthogonal, it's easy to show that R explains about 30% of interannual variability in precipitation, while T explains the rest.

Circulation patterns associated with *T* and *R*



Total precipitation pattern



Rain shadow pattern

WSW flow anomaly → more total precip
NNW flow anomaly → stronger rain shadow

Circulation patterns explain ~70% of variability in both modes

500 mb heights regressed on *T* and *R*. Solid (dotted) lines represent positive (negative) height anomalies.

Let’s now take a look at the circulation patterns associated with these indices. These figures show the regression maps of 500-mb height anomalies onto the Total precipitation index (left), and the rain shadow index (right). The left figure shows that high total precipitation in the Cascades is associated with a WSW wind anomaly, which is essentially an intensification of the climatological flow. In contrast, a strong rain shadow is associated with high pressure in the gulf of Alaska and low pressure over Hudson bay, resulting in a NNW wind anomaly over Washington.

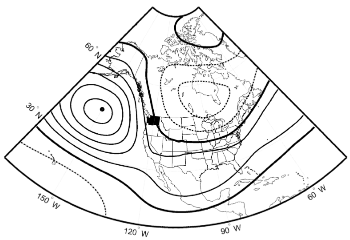
Rain-shadow strength is related to El Niño

Rain shadow pattern closely resembles El Niño's "teleconnection"

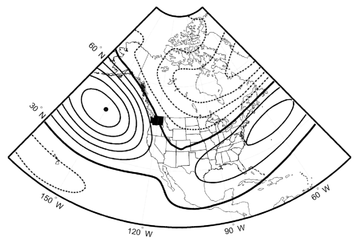
Correlation with Niño 3.4 index:

T	*R*
0.03	-0.50

El Niño affects the rain shadow but not total precipitation



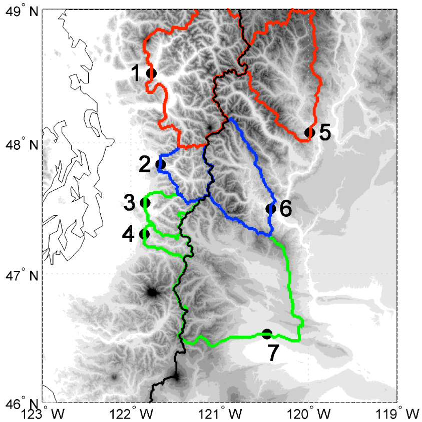
Niño 3.4 pattern (inverted)



Rain shadow pattern

And as it turns out, the RS pattern bears a striking resemblance to the ENSO teleconnection pattern, as you can see here (point to maps). Their time series are also significantly correlated at 0.5. This means that El Niño is associated with a weak rain shadow, or weak east-west precip gradient, while La Nina is associated with a strong rain shadow. In contrast, total precipitation is unrelated to ENSO. [To understand this connection between ENSO and rain shadow strength, let's take a look at individual storms.]

Watershed analysis



Watershed map
Black dots = stream gauges

- 3 “transects”: western/ eastern basin pairs

  1: Skagit
  2: Skykomish
  3: Snoqualmie
  4: Green
  5: Methow
  6: Wenatchee
  7: Yakima

- Dec-Aug streamflow used to approximate wintertime precipitation

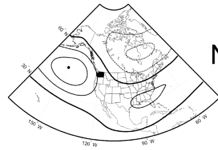
- $R = P_{west} - P_{east}$

Put in colored transects

All transects are consistent with SNOTEL results

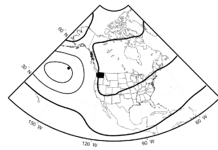
Correlations with DJF Niño 3.4 index are robust

Confirms that rain-shadow variability impacts water resources



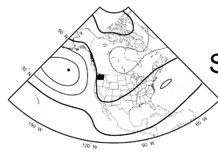
Northern transect

Niño 3.4 corr: -0.55



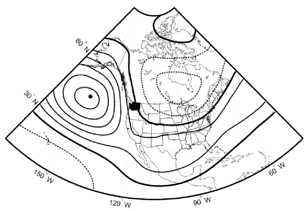
Central transect

Niño 3.4 corr: -0.54



Southern transect

Niño 3.4 corr: -0.56



Niño 3.4

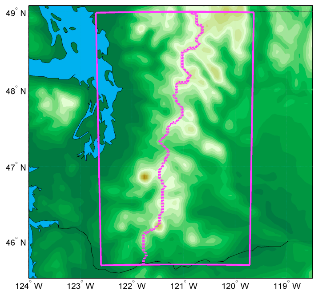
500 mb heights regressed onto rain shadow index

The contrast b/t east and west is remarkably robust, fully supportive of the SNOTEL analysis

Why does El Niño affect rain-shadow strength? Let's look at storms…

Identified 100 strongest storms over 6 years (2005-2010)

- Based on forecast 24-hour precipitation totals in Cascades (defined as region inside pink box below)



Forecast model grid

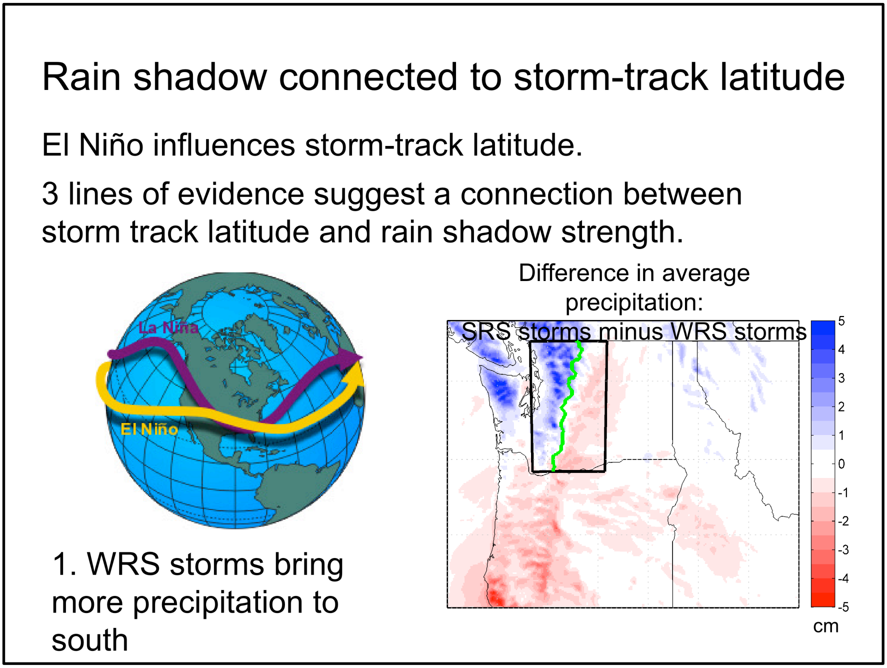
Sorted storms according to rain-shadow strength

3 categories

- 33 Weak-rain-shadow (WRS) storms
- 33 Strong-rain-shadow (SRS) storms
- 34 Neutral-rain-shadow (NRS) storms

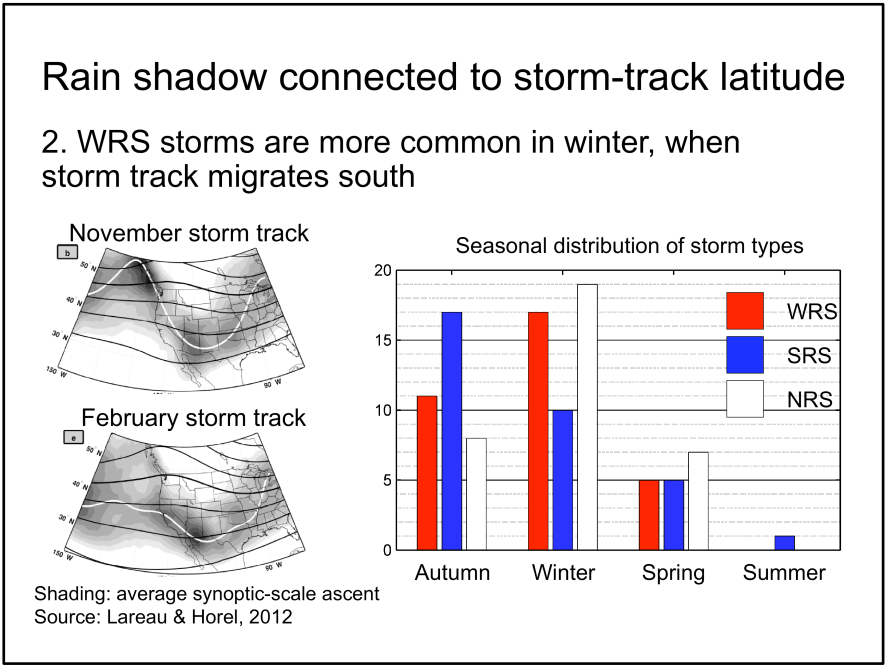
Remember these acronyms

For this portion of the analysis, I looked at 6 years of archived forecast output from Cliff's group, run at 4-km resolution. I decided to focus on just the 100 strongest storms b/t 2005 and 2010, which I defined as the 100 24-hour periods of maximum precipitation within the Cascades, defined by the pink box. We calculated a rain-shadow index just as before: by normalizing the western and eastern precipitation time series and taking their sum and difference, and we divided the storms into three categories according to rain-shadow strength. For the remainder of the talk, I'll be using WRS and SRS as abbreviations for weak rain shadow and strong rain shadow, respectively.



It's well known that El Niño is associated with a more southern storm track and La Nina a more northern storm track. And within our storm dataset, there are three pieces of evidence that suggest that ENSO's relationship to storm track latitude is in fact what accounts for its influence on rain-shadow strength.

Firstly, as you can see from this figure showing the average precipitation of strong-rain-shadow storms minus weak-rain-shadow storms, not only do weak-rain-shadow storms bring more precipitation to the east slopes of the Cascades, they also bring more precipitation to the south. This implies a more southern path of maximum precipitation during weak-rain-shadow storms, and thus a more southern storm track.

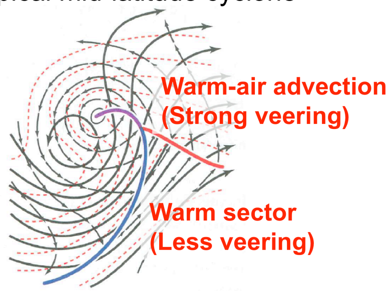


A second piece of evidence implicating storm-track latitude is the seasonal distribution of strong and weak rain shadow storms, as shown in this histogram. During the fall, strong-rain-shadow storms are more common than weak-rain-shadow storms, while in the winter, weak-rain-shadow storms are more common. This again is consistent with the storm-track-latitude hypothesis, since the storm track migrates south from fall to winter, as you can see in these figures on the left.

Rain shadow connected to storm-track latitude

3. WRS storms are associated with warm fronts
    - Stronger warm-air advection, veering (i.e., clockwise turning of winds with height)
    - More likely when the storm track is southerly

Typical mid-latitude cyclone



Finally, weak-rain-shadow storms exhibit more warm-air advection than strong-rain-shadow storms by a factor of two. This results in stronger during weak-rain-shadow storms, as is clear from this histogram showing the directional distribution of winds during weak and strong rain-shadow storms. At 850 mb, the average wind orientation during weak-rain-shadow storms is 215 degrees vs. 242 degrees for strong-rain-shadow storms. The difference is more modest at 500 mb, however, implying much stronger veering during WRS storms, consistent with stronger warm-air advection.

To understand why this also supports the storm-track hypothesis, consider this simple schematic of a mid-latitude cyclone I took from Wallace and Hobbes. The red line represents the warm front, to the north of which is strong veering and warm-air advection. In contrast, to the south of the warm front is the warm sector, where there's relatively little warm-air advection and veering.

Rain shadow connected to storm-track latitude

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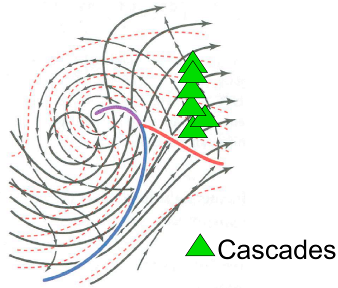
Weak rain shadow scenario



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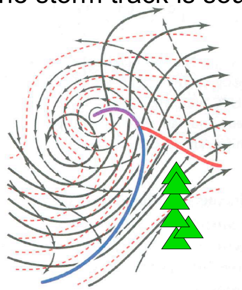

Strong rain shadow scenario

▲ Cascades

Finally, weak-rain-shadow storms exhibit more warm-air advection than strong-rain-shadow storms by a factor of two. This results in stronger veering during weak-rain-shadow storms, as is clear from this histogram showing the directional distribution of winds during weak and strong rain-shadow storms. At 850 mb, the average wind orientation during weak-rain-shadow storms is 215 degrees vs. 242 degrees for strong-rain-shadow storms. The difference is more modest at 500 mb, however, implying much stronger veering during WRS storms, consistent with stronger warm-air advection.
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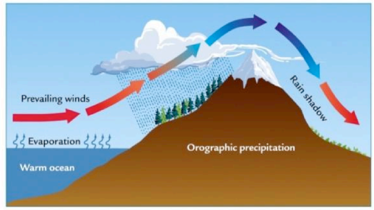
Why do warm fronts lead to weak rain shadows?

Conventional picture is inadequate
- Descent/evaporation in lee
- Rain shadow is always strong

Hypotheses:
1. Ahead of a warm front, low level winds have an easterly component.
2. Large-scale precipitation dominates orographic effects.
3. Enhanced condensation occurs over the western slopes, but more condensate spills over the crest.



In particular, there are at least three possible hypotheses for why warm fronts result in enhanced east-slope precipitation. The first is that, in some cases, ahead of a warm front, low level winds have an easterly component. And so perhaps this easterly upslope flow enhances condensation and precipitation over the eastern slope, effectively reversing the climatological rain shadow.

Another possibility is that, due perhaps to veering, or to low-level flow that's parallel to the axis of the mountain range, the overall influence of the terrain on precipitation and condensation is minimized, such that the large-scale precipitation dominates. In this picture, you have neither enhanced condensation over western slopes, nor do you have strong evaporation over eastern slopes.

And then a third possibility is that WRS storms still exhibit significant enhancement of condensation over the western slopes, but that, for reasons yet unknown, more of this condensate is allowed to spillover the crest. So now I'm going to put you on the spot, and ask which of these you think is likely to be the most important factor.

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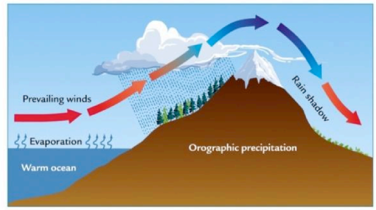
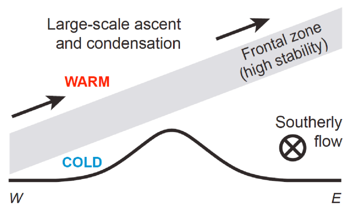
New framework
- 4 stages of warm-frontal passage



Stage 1:
- Winds from south at low levels, veering westerly in frontal zone
- Minimal orographic influence
- Ascent/condensation driven by large-scale dynamics



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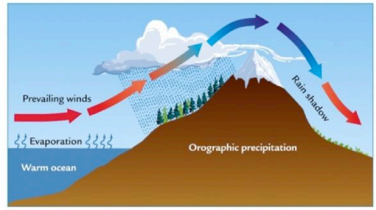
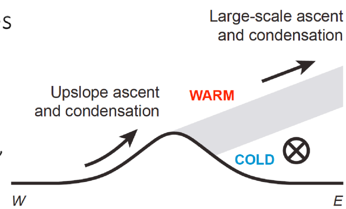


New framework

- 4 stages of warm-frontal passage

Stage 2:

- Front has passed over western slopes
  - Westerly winds → upslope ascent/condensation
- Large-scale ascent east of crest
  - Lots of condensate advected over crest, resulting in very weak rain shadow



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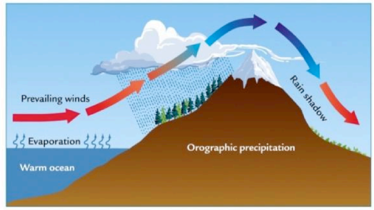
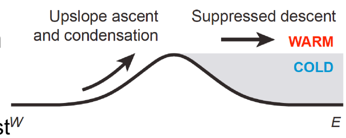


New framework
- 4 stages of warm-frontal passage

Stage 3:
- Front has fully passed
  - Upslope condensation remains strong over western slopes
- Zonally-stagnant layer persists in lee
  - Inhibits descent/evaporation, allowing weak rain shadow to persist
  - Highly stable due to warm air aloft



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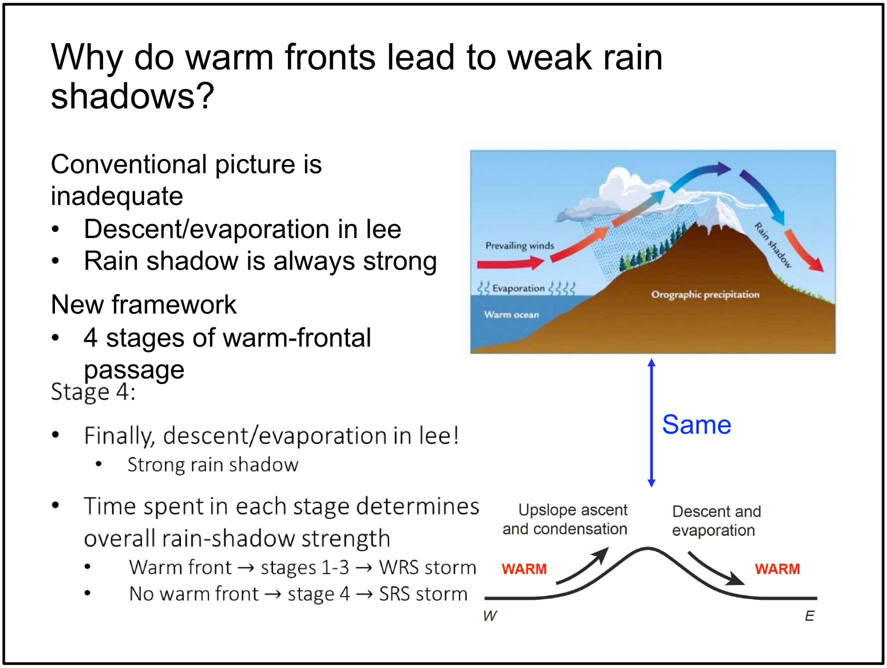

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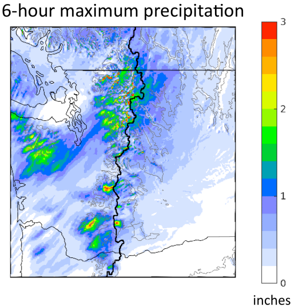
Case study of a representative weak-rain-shadow storm

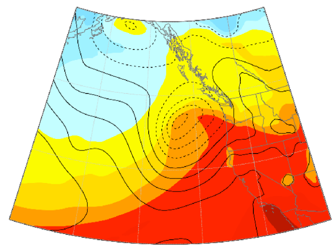
December 14, 2006

Warm front brought significant precipitation and a weak rain shadow

6-hour maximum precipitation



Lower tropospheric temperature (colors)
Sea-level pressure (contours)



The idealized simulations were useful for understanding the essential role that stable, stagnant air plays in suppressing descent, and allowing more precipitation to spill over the crest, but they provide no insight into the development and evolution of these layers in nature. So for the final section of this talk, I'll be presenting a detailed analysis of a single WRS storm (W3).

And to make our results as general as possible, we've replaced the Cascades with an idealized ridge shown here, with a height of 2 km, running from 45 to 50 degrees north.

Case study of a representative weak-rain-shadow storm

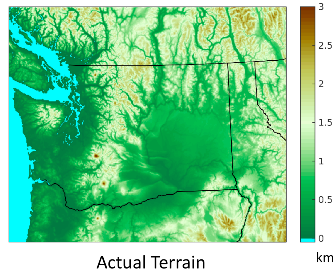
December 14, 2006

Warm front brought significant precipitation and a weak rain shadow

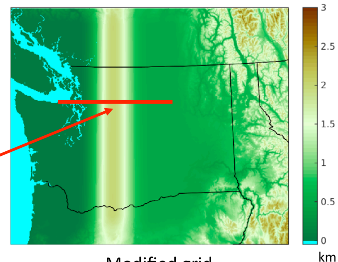
Numerical simulation (WRF model)

- 4 nested grids,
  1.33-km resolution (inner grid)
- Cascades replaced with idealized quasi-2D ridge

Let's see how the storm evolves along this transect…



Actual Terrain



Modified grid

The idealized simulations were useful for understanding the essential role that stable, stagnant air plays in suppressing descent, and allowing more precipitation to spill over the crest, but they provide no insight into the development and evolution of these layers in nature. So for the final section of this talk, I'll be presenting a detailed analysis of a single WRS storm (W3).
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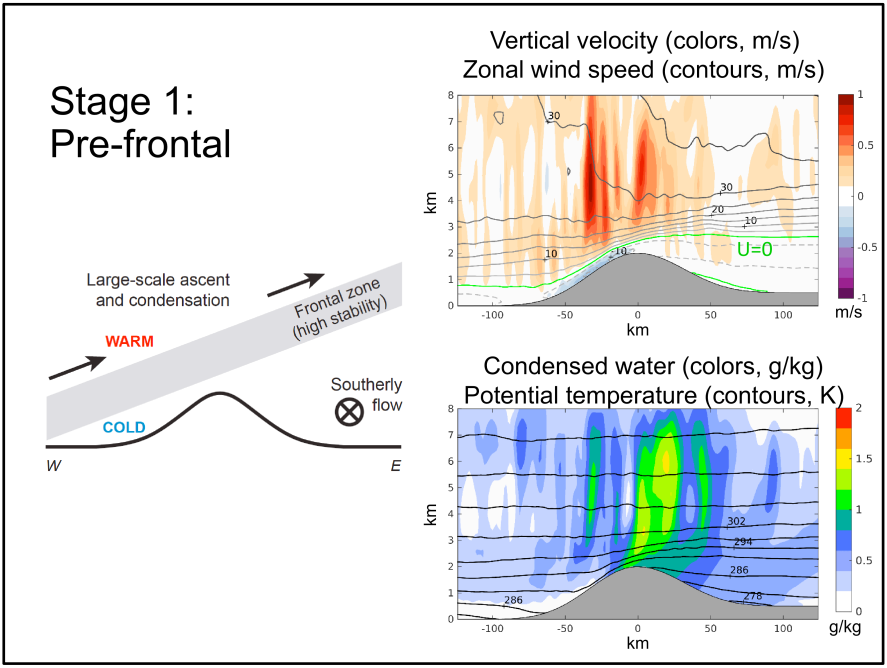
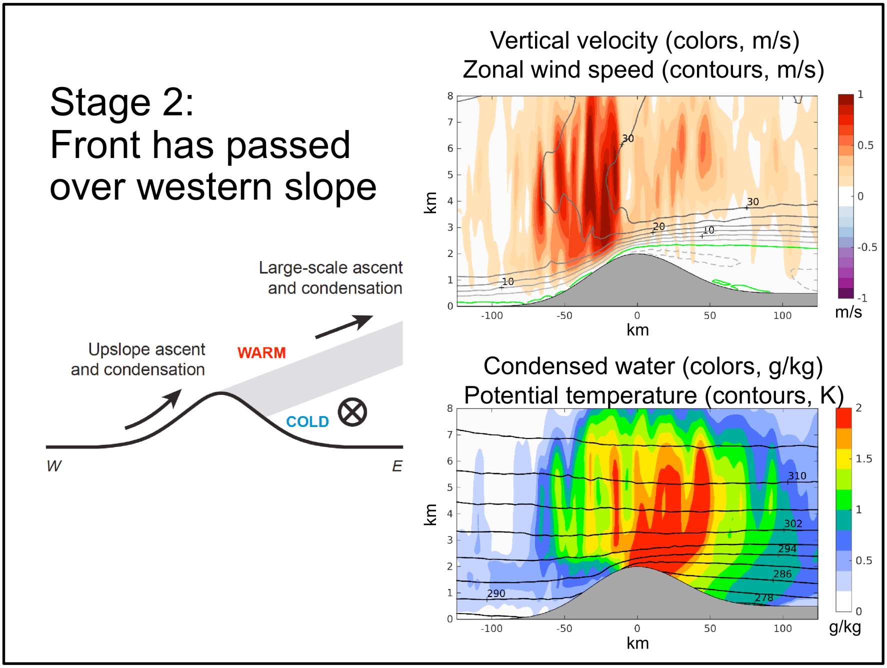
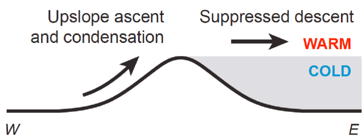


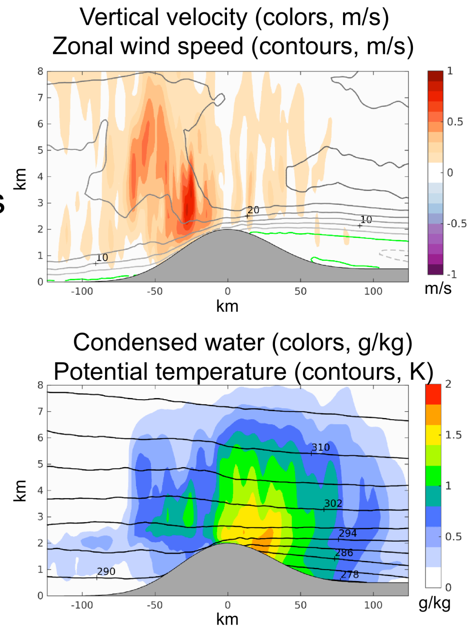
Stage 1:
Pre-frontal
Large-scale ascent
and condensation
WARM
Frontal zone
(high stability)
Southerly
flow
COLD
W
E
Vertical velocity (colors, m/s)
Zonal wind speed (contours, m/s)
U=0
m/s
km
Condensed water (colors, g/kg)
Potential temperature (contours, K)
g/kg



Stage 2:
Front has passed over western slope
Large-scale ascent and condensation
Upslope ascent and condensation
WARM
COLD
W
E
Vertical velocity (colors, m/s)
Zonal wind speed (contours, m/s)
km
m/s
Condensed water (colors, g/kg)
Potential temperature (contours, K)
g/kg

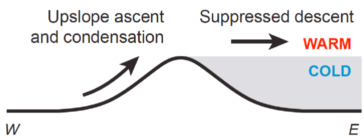
Stage 3:
Front has passed entirely, but zonally stagnant layer persists



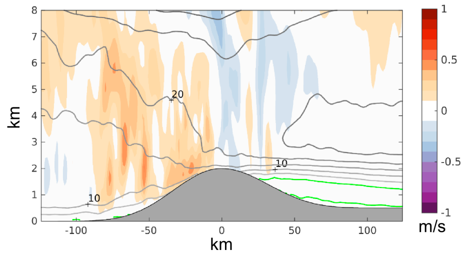


Stage 3 persists until precipitation has ended

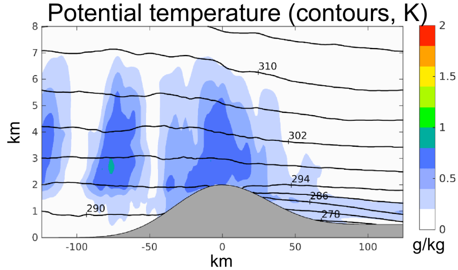
- Explains weak rain shadow for storm overall



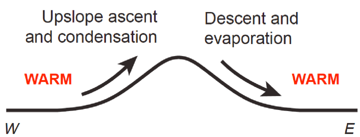
Vertical velocity (colors, m/s)
Zonal wind speed (contours, m/s)

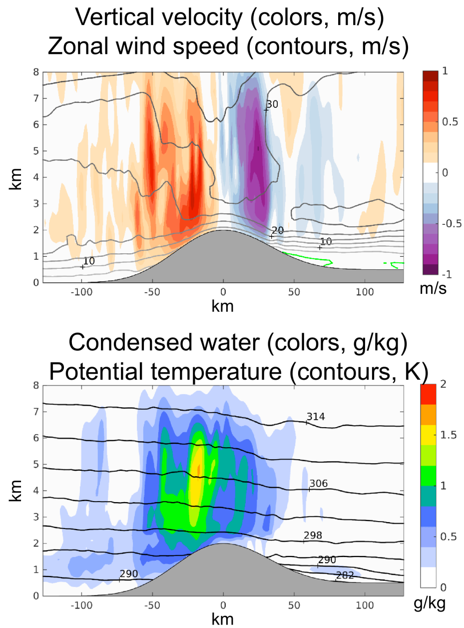


Condensed water (colors, g/kg)
Potential temperature (contours, K)



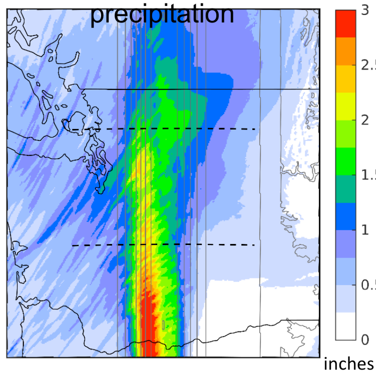
Stage 4 does occur further south, where warm front is weaker





Rain-shadow strength depends on latitude

Storm-total precipitation



Weak rain shadow in north, where warm front is strong

Strong rain shadow in south, where warm front is weaker

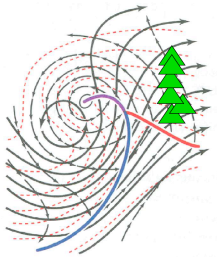
Explains connection between El Niño and weak rain shadow

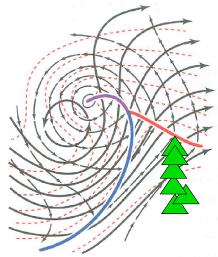
- El Niño → southern storm track → warm fronts → stages 1-3

Implications for climate change

Suggests possible strengthening of rain-shadow with poleward shift of storm tracks (Cascades, Andes, Southern Alps, etc.)

Current climate





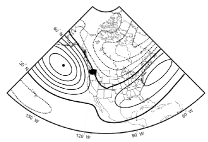
Future?

Other competing influences as well (e.g., thermodynamics)

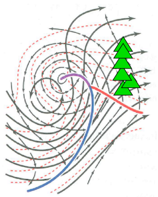
- Focus of new project on precipitation/hydrology in Sierra Nevada

Summary: understanding rain-shadow variability

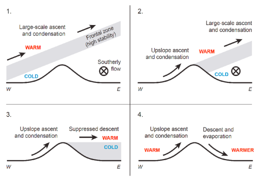
Full story involves multiple scales



Statistical association between El Niño and rain shadow



Rain shadow determined by latitude of warm front relative to mountain range



New framework for orographic precipitation

- Strength of rain shadow depends on stage of storm

Large-scale

Small-scale