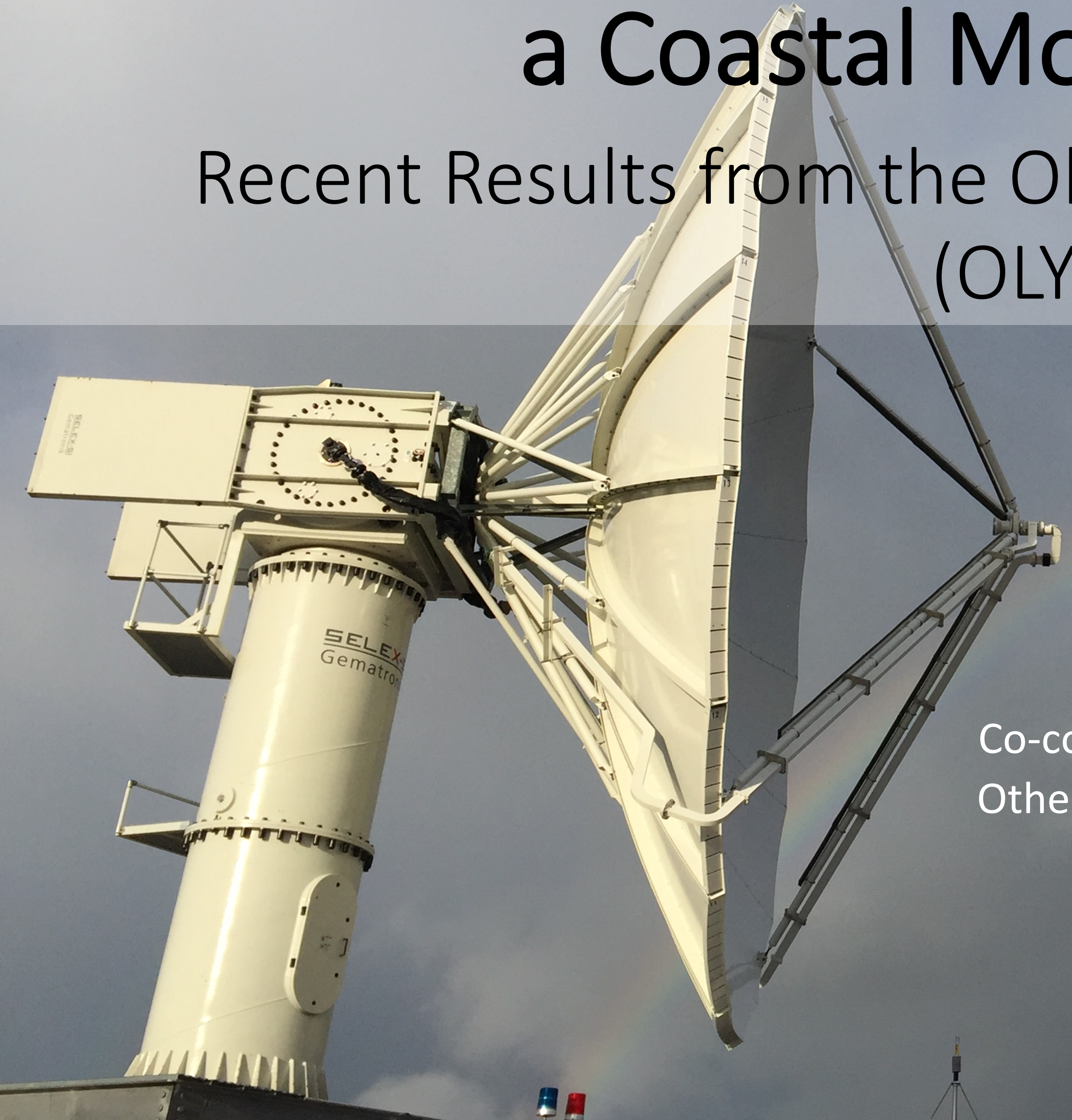
Precipitation Processes in Cyclones Passing over a Coastal Mountain Range:

Recent Results from the Olympic Mountains Experiment (OLYMPEX)



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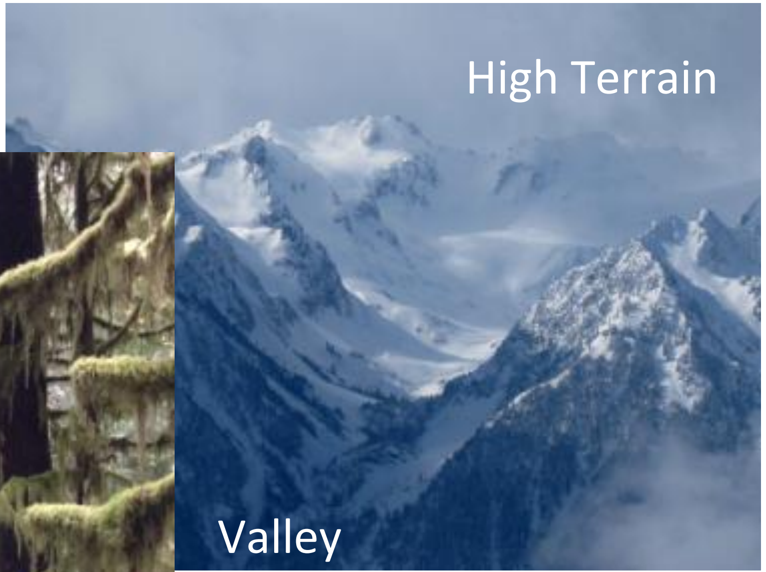
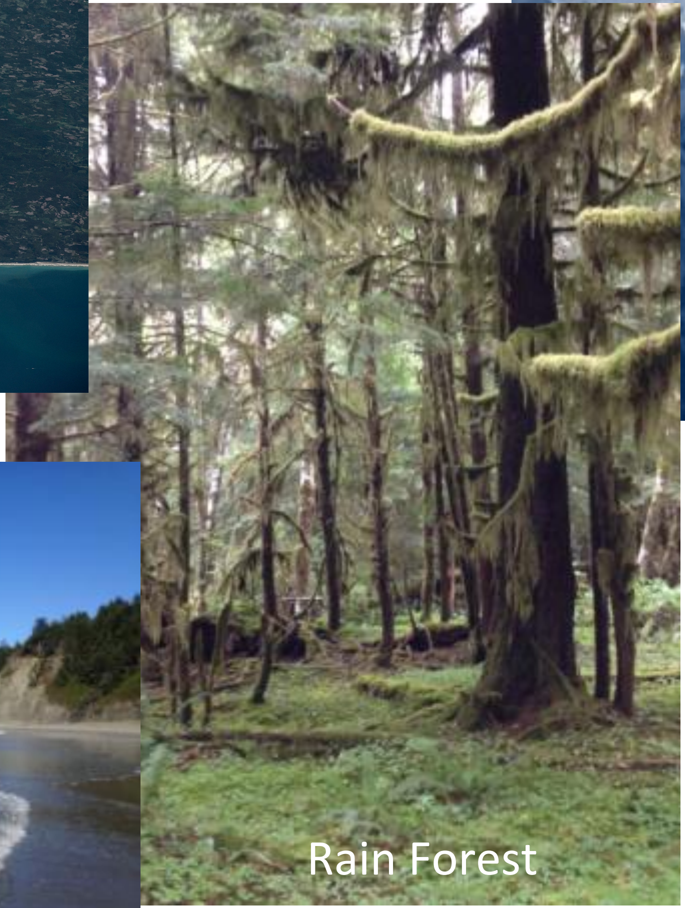
Other contributors: Stacy Brodzik, Tom Schuldt, Jamin Rader

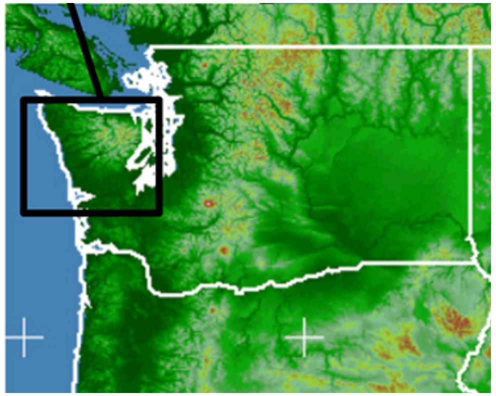
Colorado State University 18 September 2018

Why study precipitation on the Olympic Peninsula?



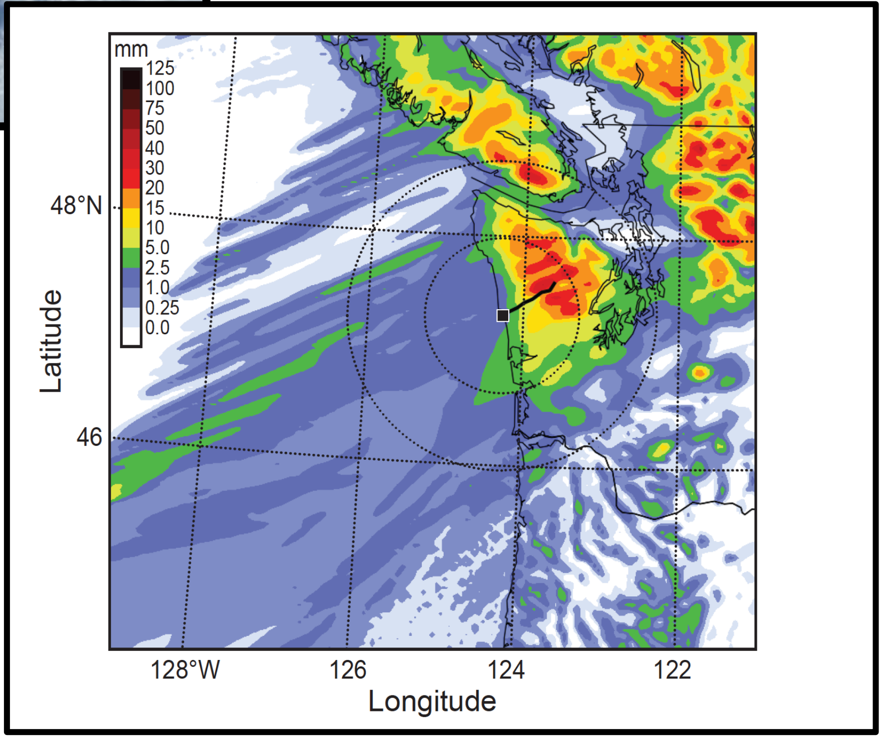


- Frequent storms
- Copious precipitation
- Rain/snow transition



Olympic Mountains Experiment (OLYMPEX)

- Two primary goals:
  - **Physical validation** of the precipitation algorithms (rain and snow) for NASA's GPM satellite.
  - **Precipitation processes** and their modification by passage over complex terrain.



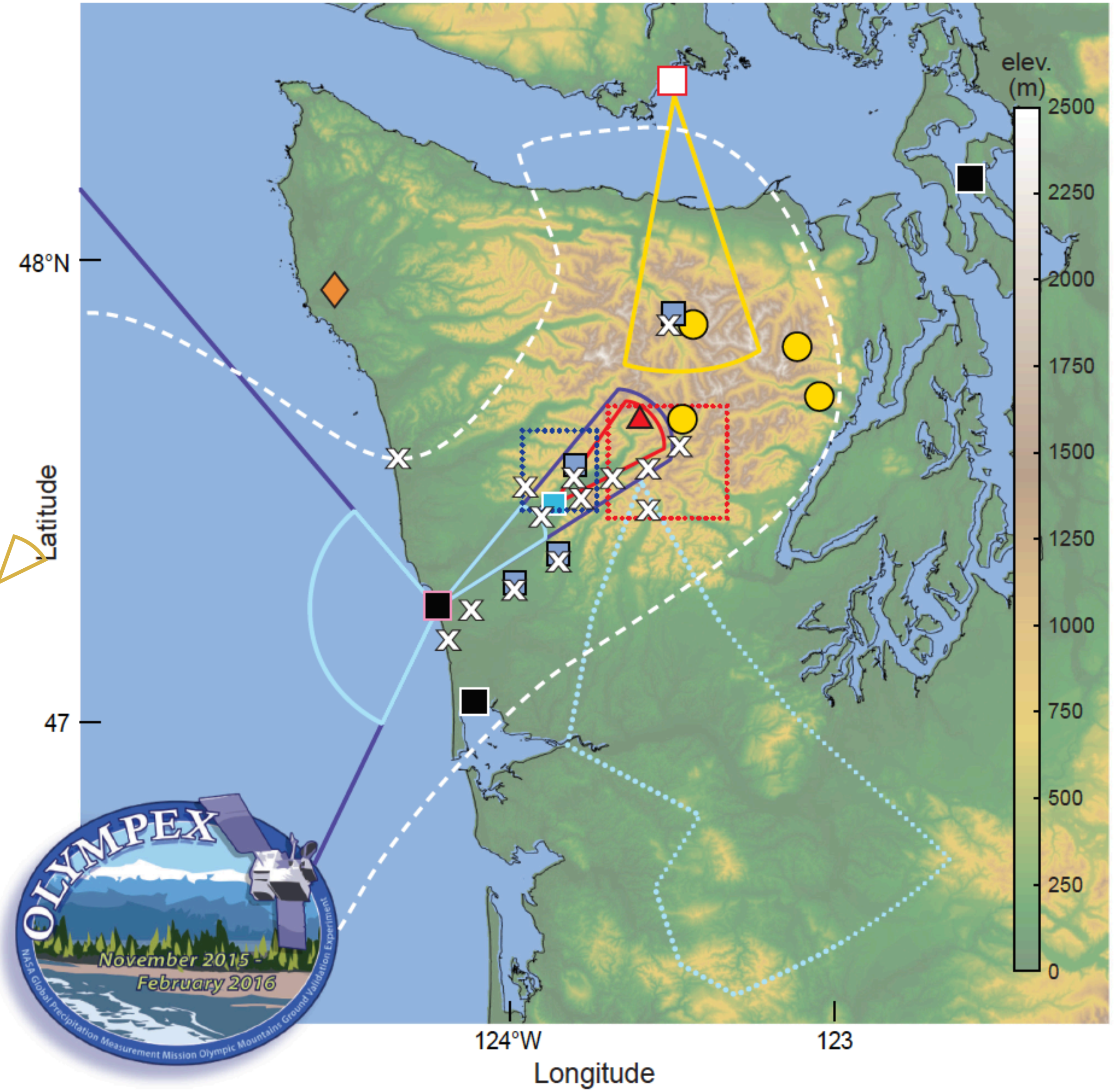
OLYMPEX Instrument Platforms

Nov-Dec 2015

Aircraft
- DC-8
- ER-2
- Citation

Nov 2015 – Jan 2016

Radars
- NPOL
- D3R
- DOW
- EC X-band
- MRRs
- WSR-88D



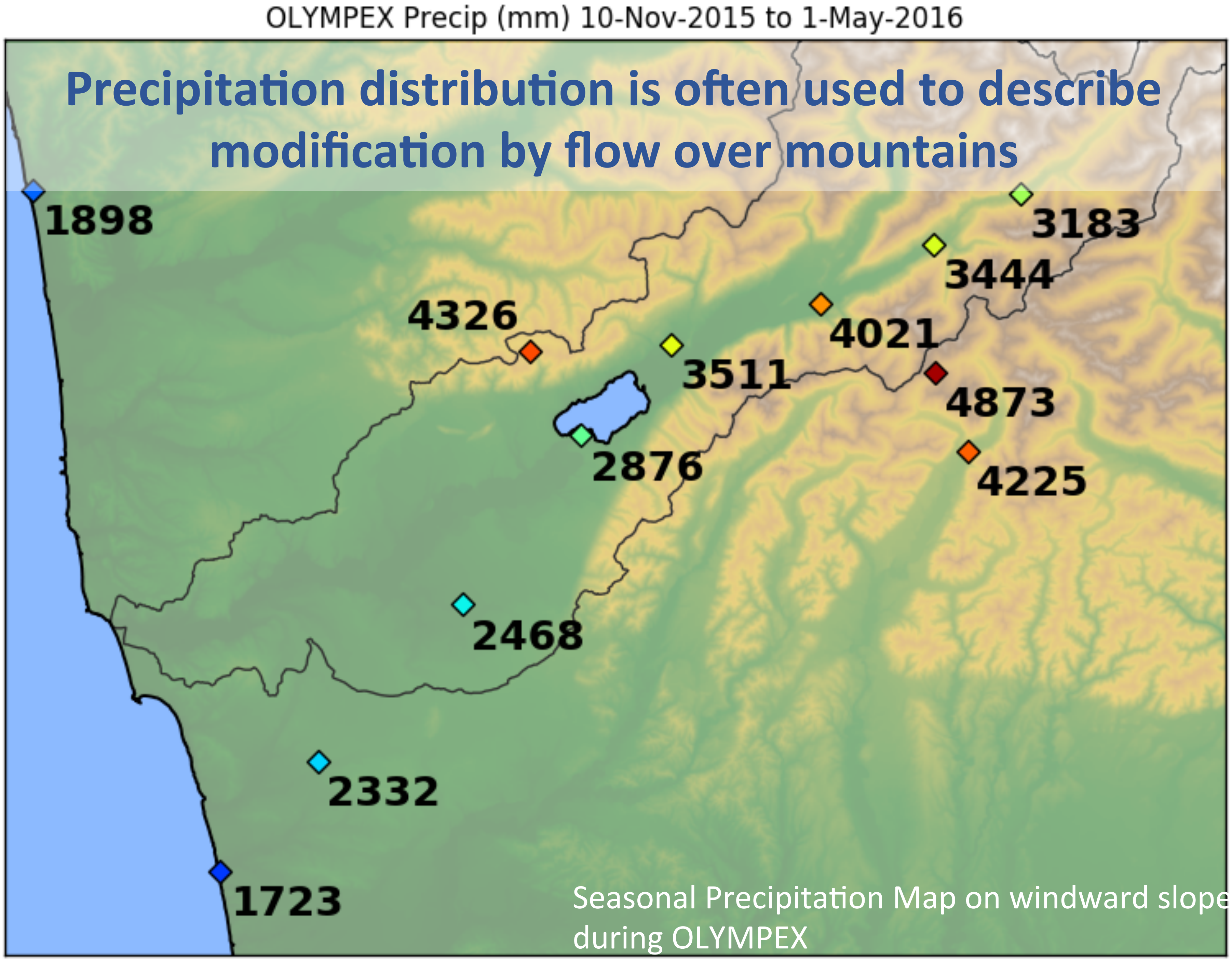
Soundings
- KUIL
- NPOL
- EC X-band

Ground Network
- Rain Gauge Networks
- Disdrometers + Gauges
- Snow Cameras

Oct 2015 – May 2016

See Houze et al. 2017, BAMS

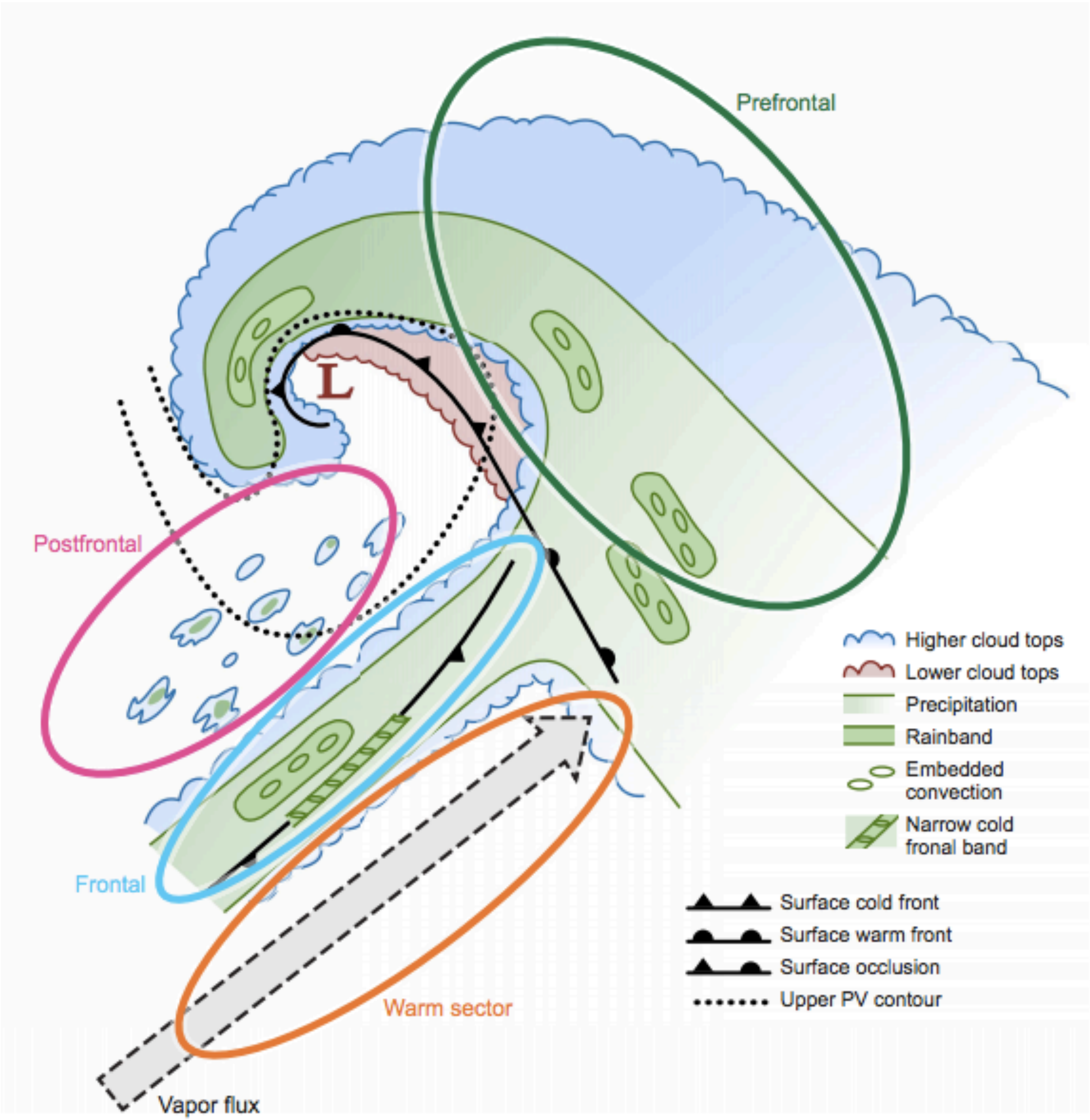
Precipitation distribution is often used to describe modification by flow over mountains

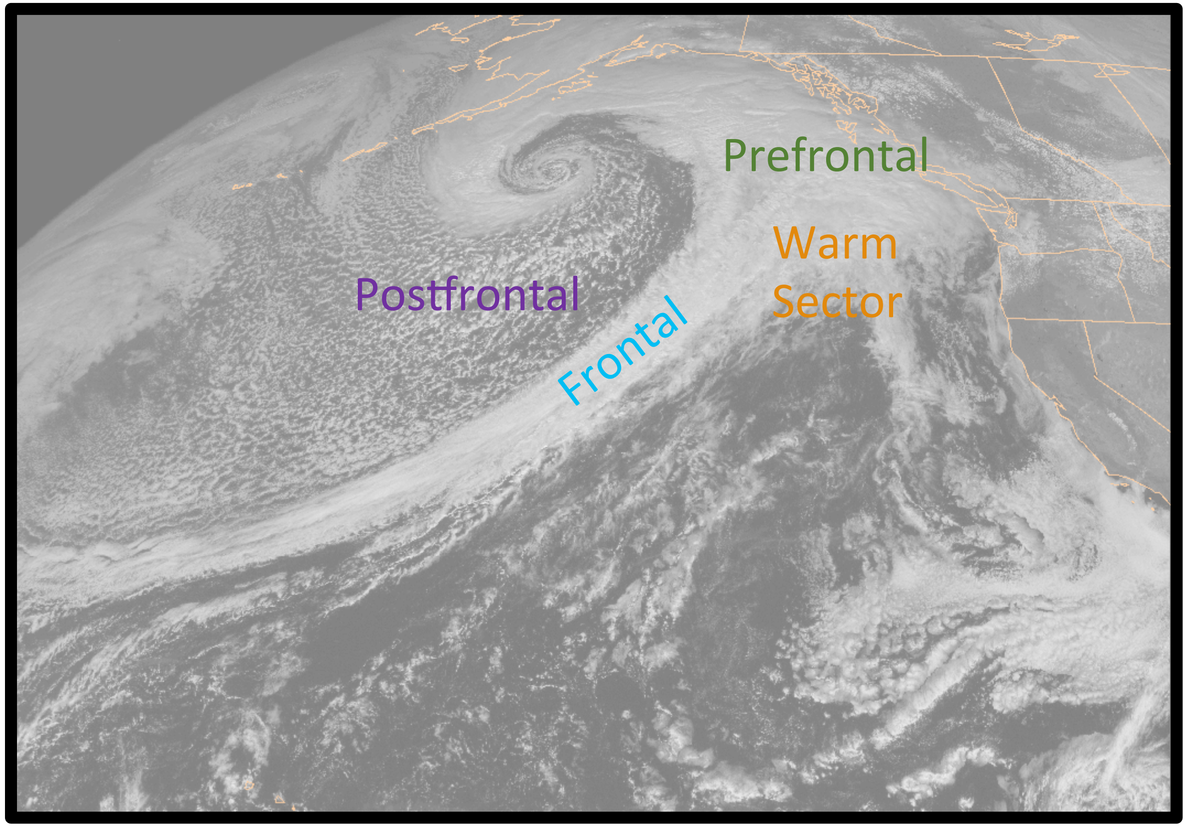


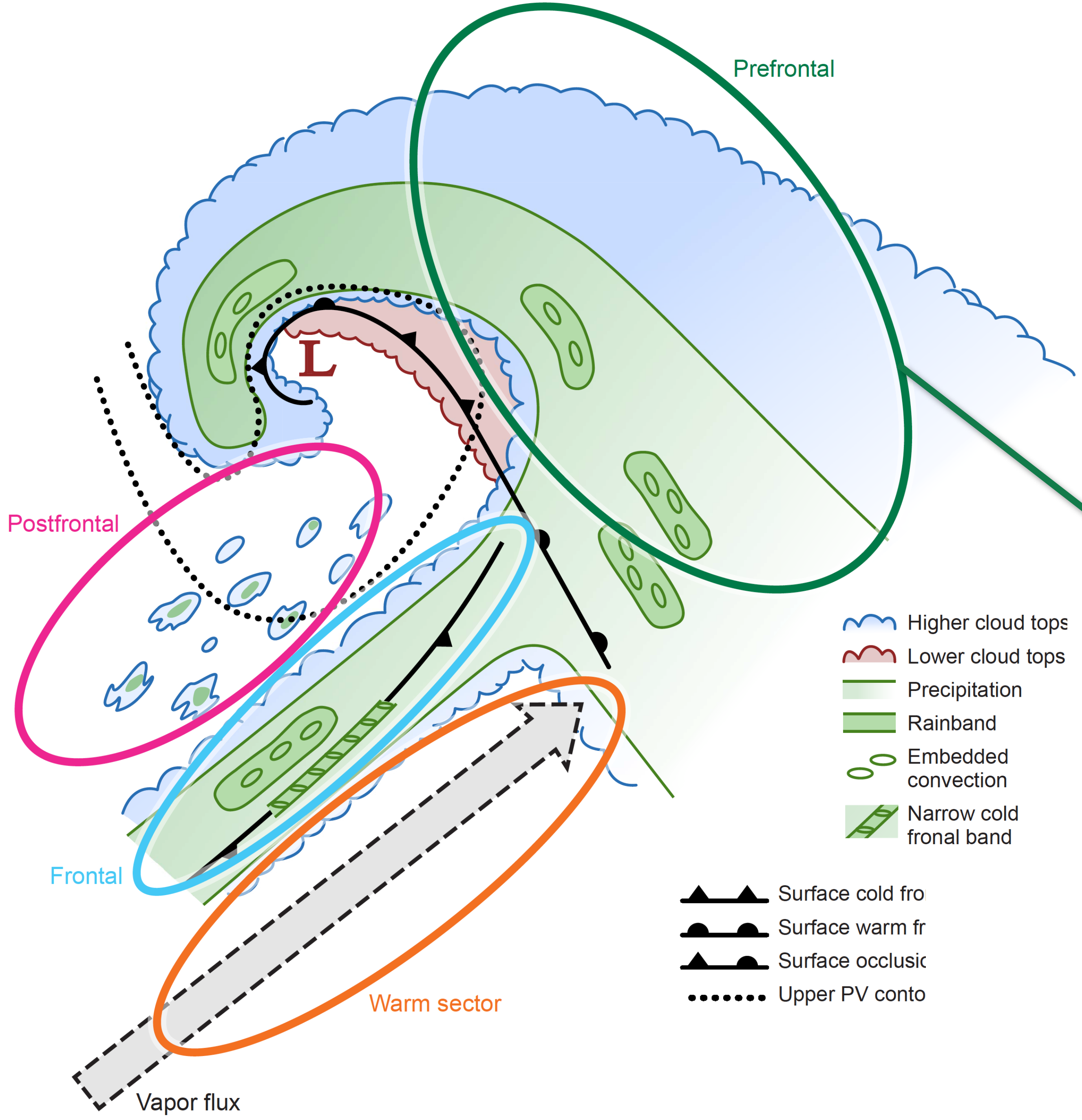
Seasonal Precipitation Map on windward slope during OLYMPEX

- Seasonal map of precipitation does not tell whole story
- What are the processes that create this distribution precipitation?
- How are the processes above and below the melting layer modified by flow over mountains?
- What are the processes controlling the leeside diminishment of precipitation?
- How does the modification vary with environmental conditions?

Precipitation is highly variable within different “sectors” of mid-latitude cyclones

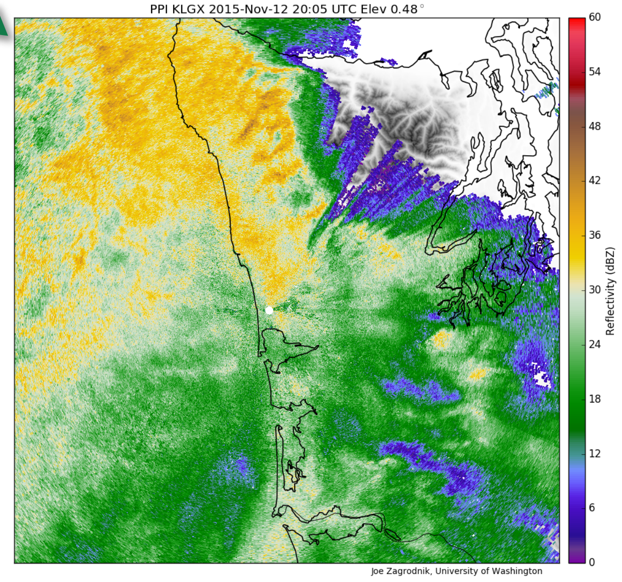


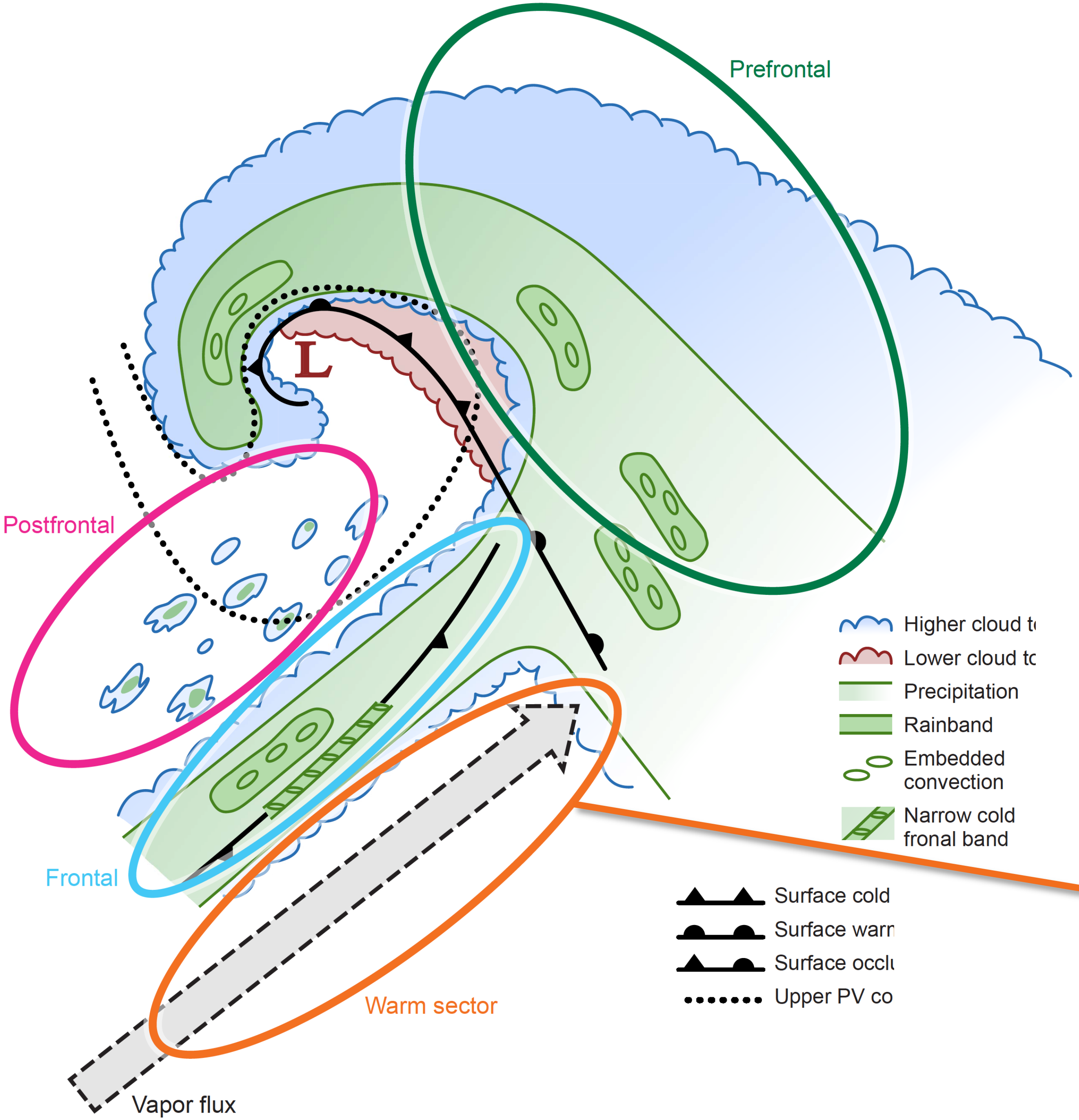




Prefrontal Environmental Characteristics

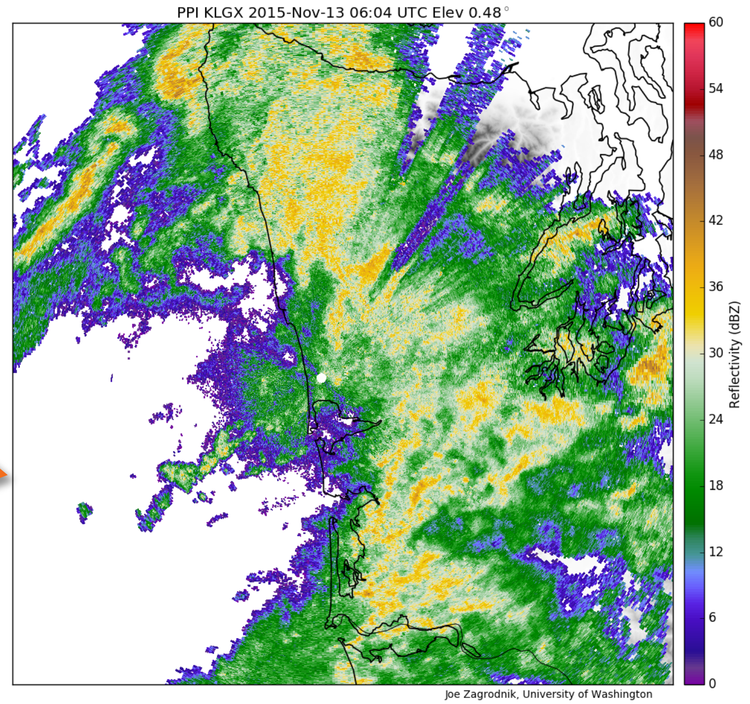
- Warm advection
- Stably stratified
- Low-level SE flow
- Increasing Integrated Vapor Transport (IVT)
- Increasing Melting Level height





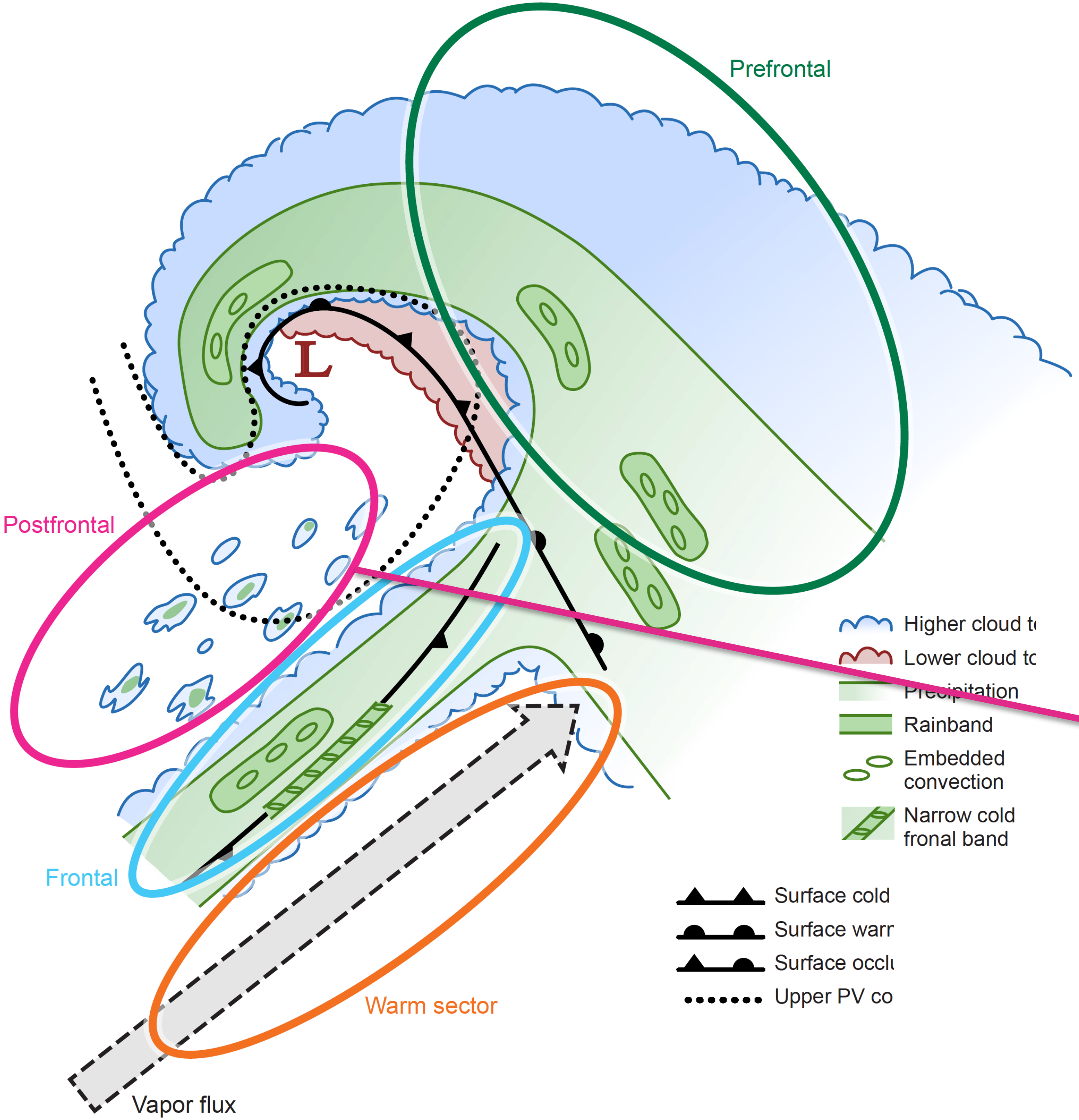
Warm Sector Environmental Characteristics

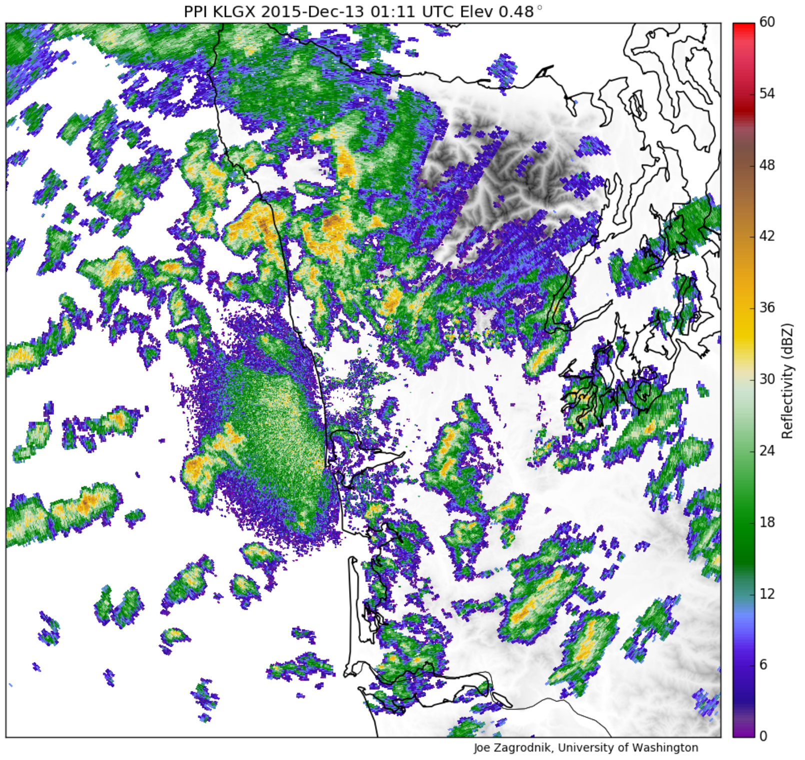
- High IVT
- Moist-neutral Stability
- S or SW flow
- High melting level



Postfrontal Environmental Characteristics

- Cold Advection
- Unstable
- W or NW flow
- Low IVT
- Low Melting Level

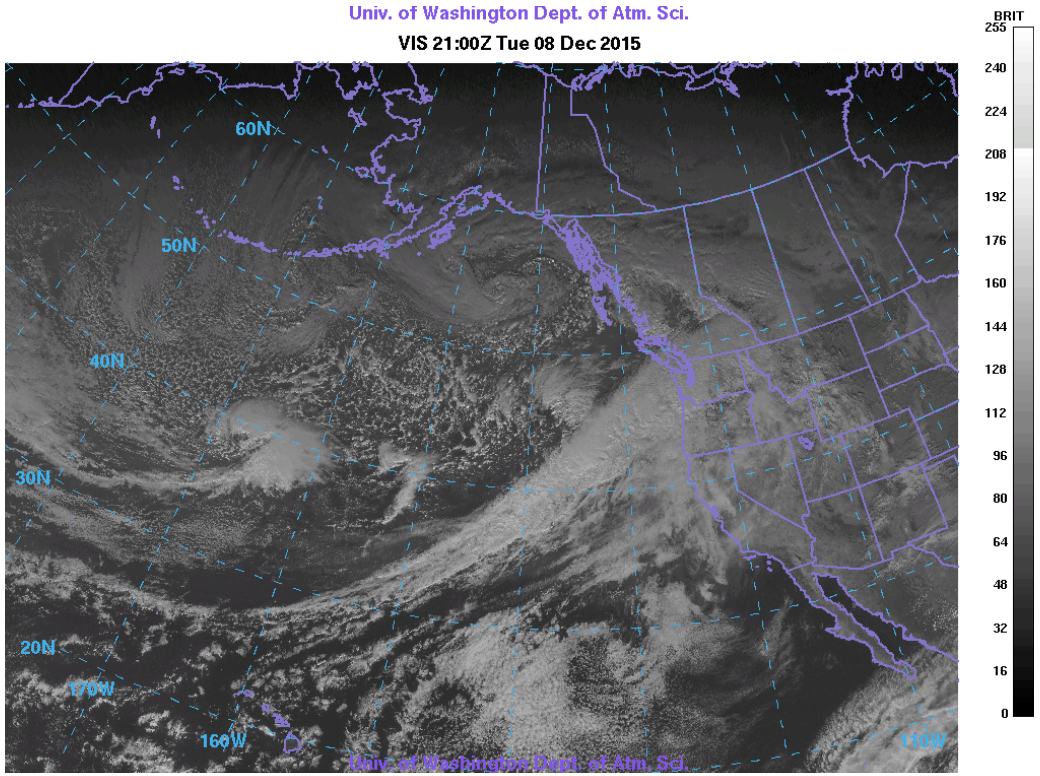




Goal of this presentation:

- Determine the large-scale environmental and microphysical processes controlling the following:

1) Windward enhancement
   (using ground-based radar and disdrometer/ rain gauge observations)
2) High terrain-lee side diminishment
   (using airborne radar and ground disdrometers)

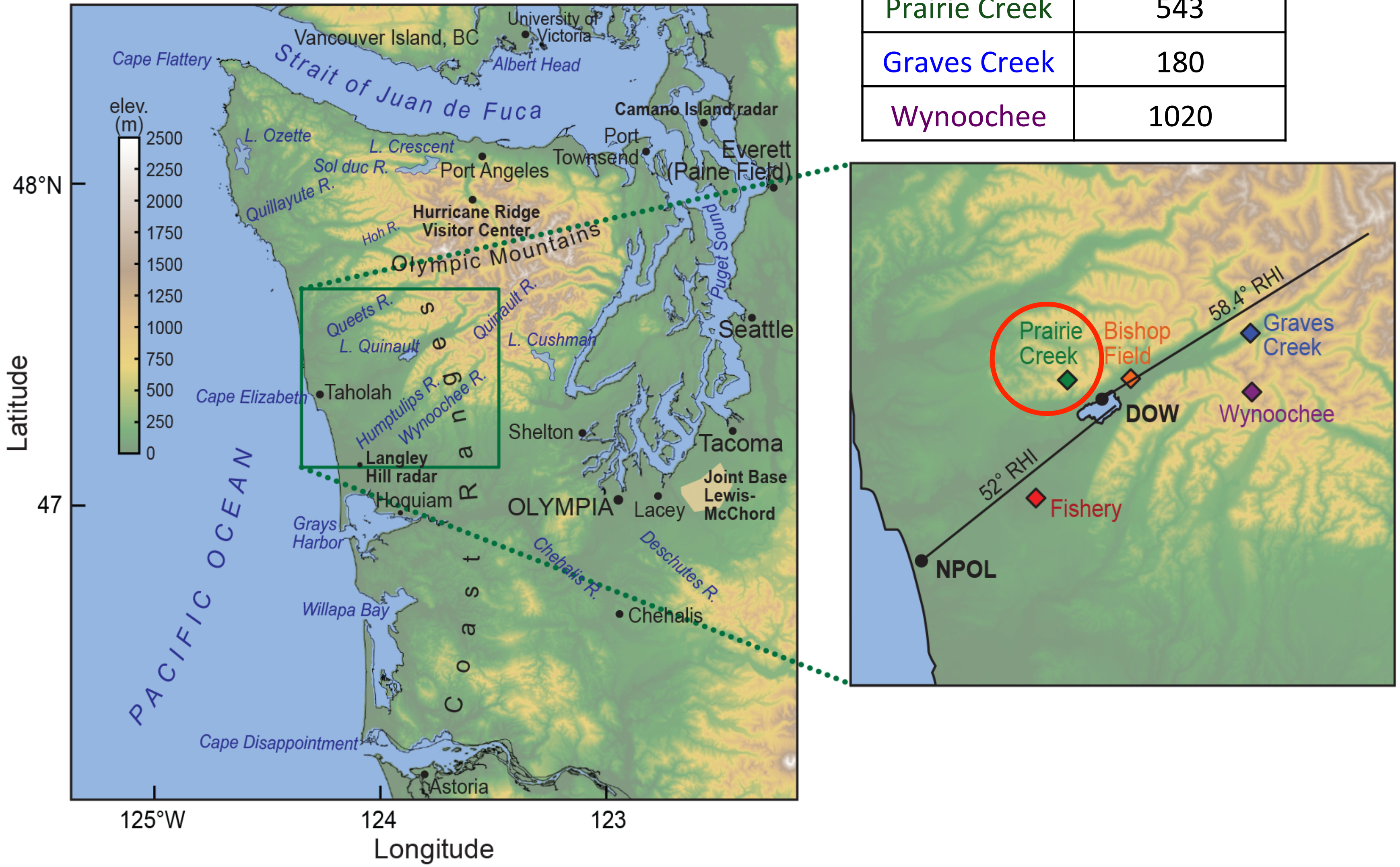


3 studies highlighted:
Zagrodnik et al. 2018 (JAS, March 2018)
McMurdie et al. 2018 (JGR, in review)
Zagrodnik et al. 2018 (JAS, in review)

Windward Enhancement:
Statistical Analysis of Disdrometer Data

- All storms Oct 2015 – Apr 2016
- Postfrontal and < 1 mm h^{-1} rain rates removed
- Divide everything into 3-hour periods centered on North American Regional Reanalysis (NARR) times (00, 03, 06 UTC etc)
  - Drop size distribution (DSD) at Prairie Creek
  - Precipitation gauges at 5 ground sites with varying elevation/distance from coast

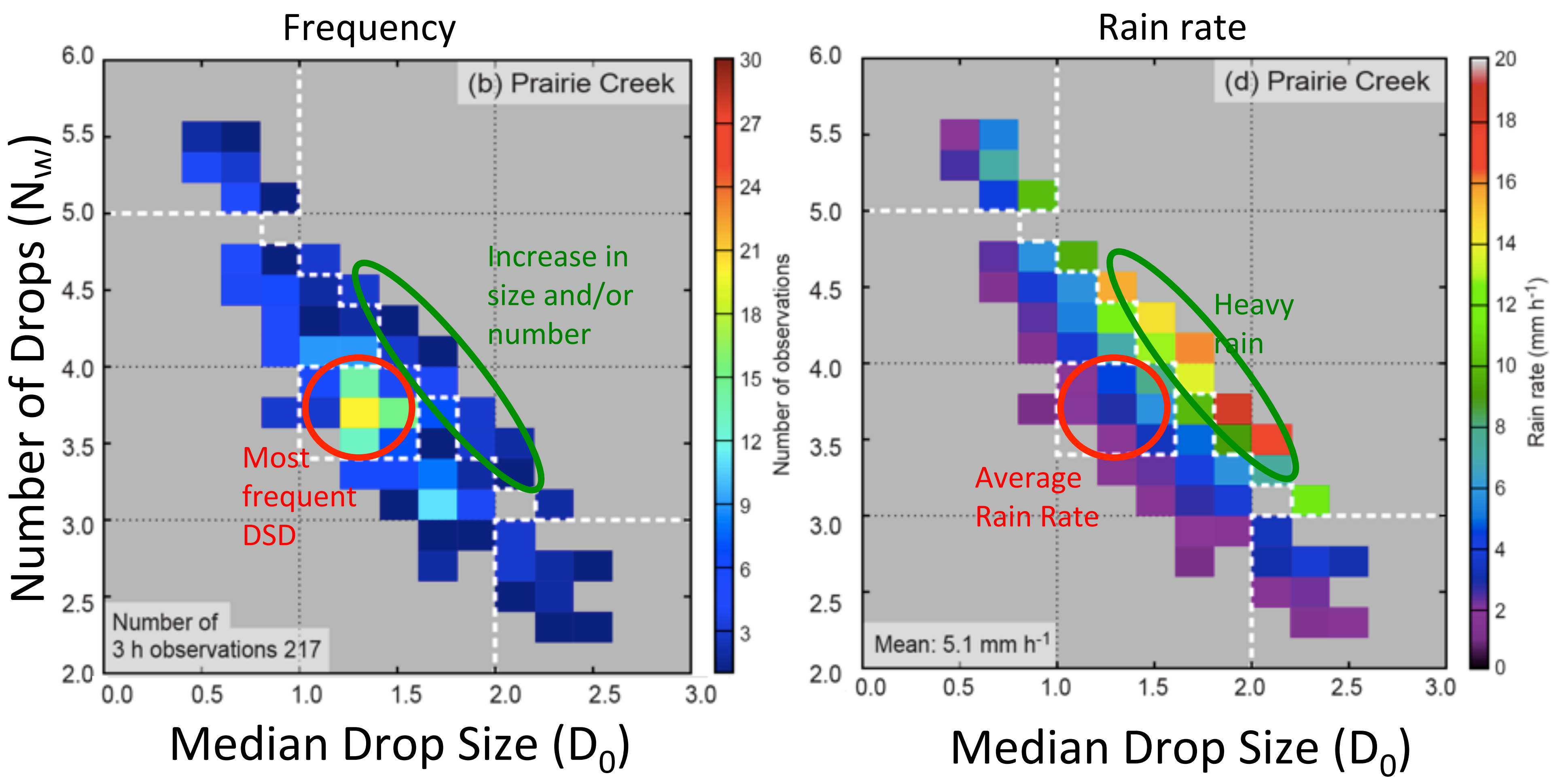
Ground Site	Elevation (m)
Fishery	52
Bishop Field	85
Prairie Creek	543
Graves Creek	180
Wynoochee	1020



Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Drop Size Distribution at Prairie Creek

Histograms of Drop Diameter vs. Drop Number:



Normalization methodology from Testud et al. (2001)

$$N_w = \frac{3.67^4 10^3 LWC}{\pi \rho_w D_0^4}$$

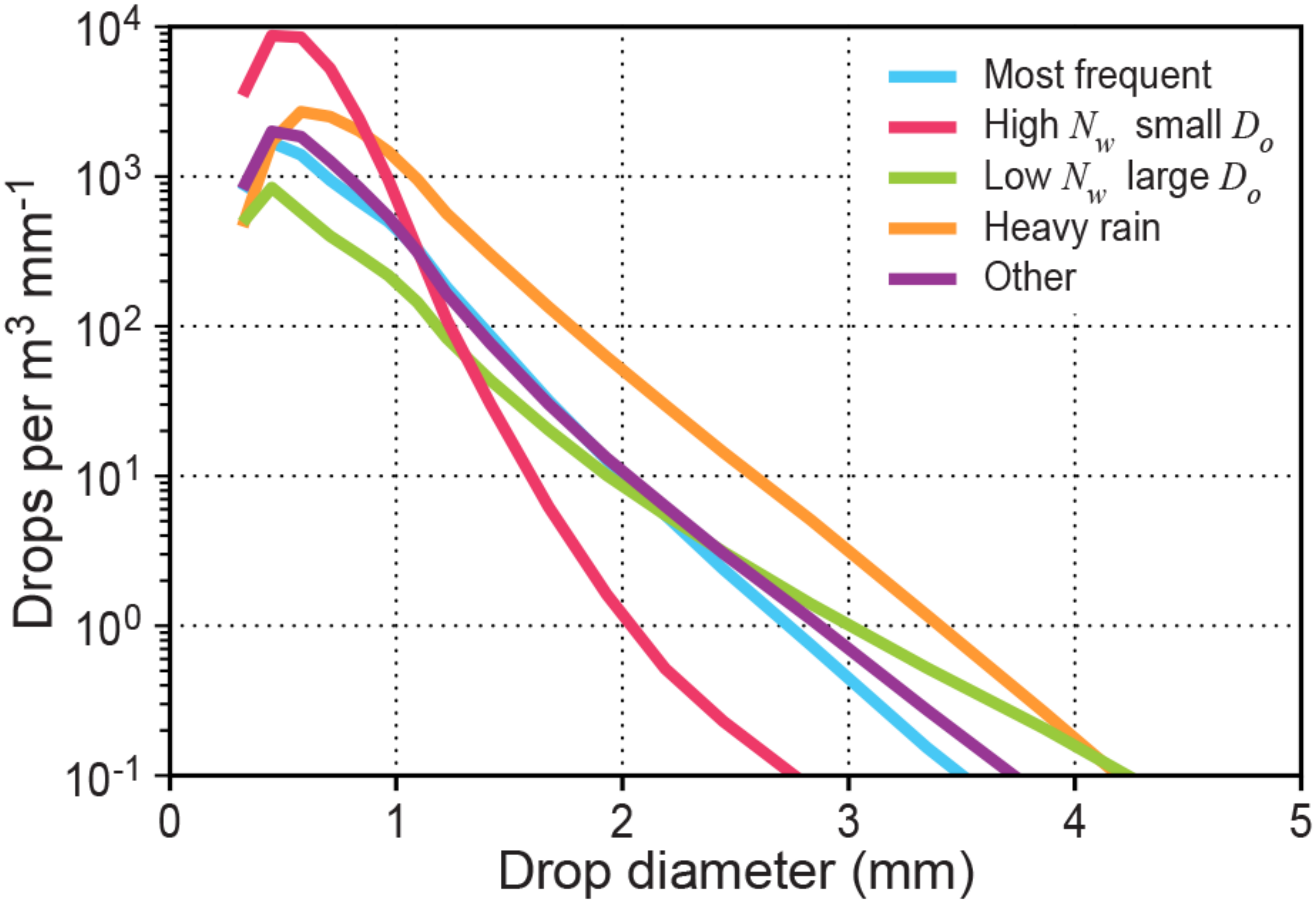
D_0 = Volume median diameter

N_w = Normalized intercept parameter

Similar DSD at near-coastal site (Fishery) but less outliers weaker rain rates

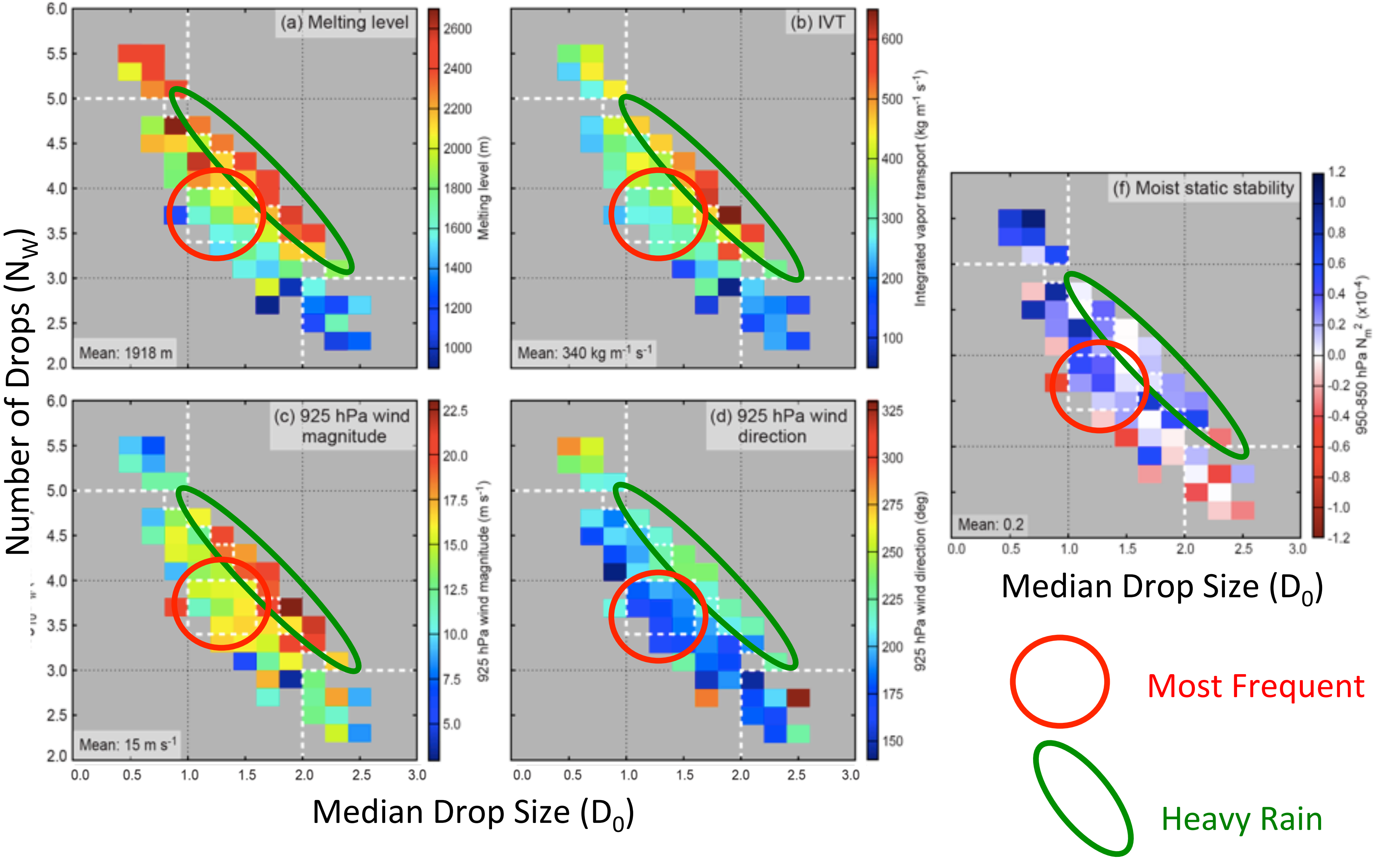
Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Average DSD of each regime



Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Prairie Creek DSD vs. Synoptic Environment

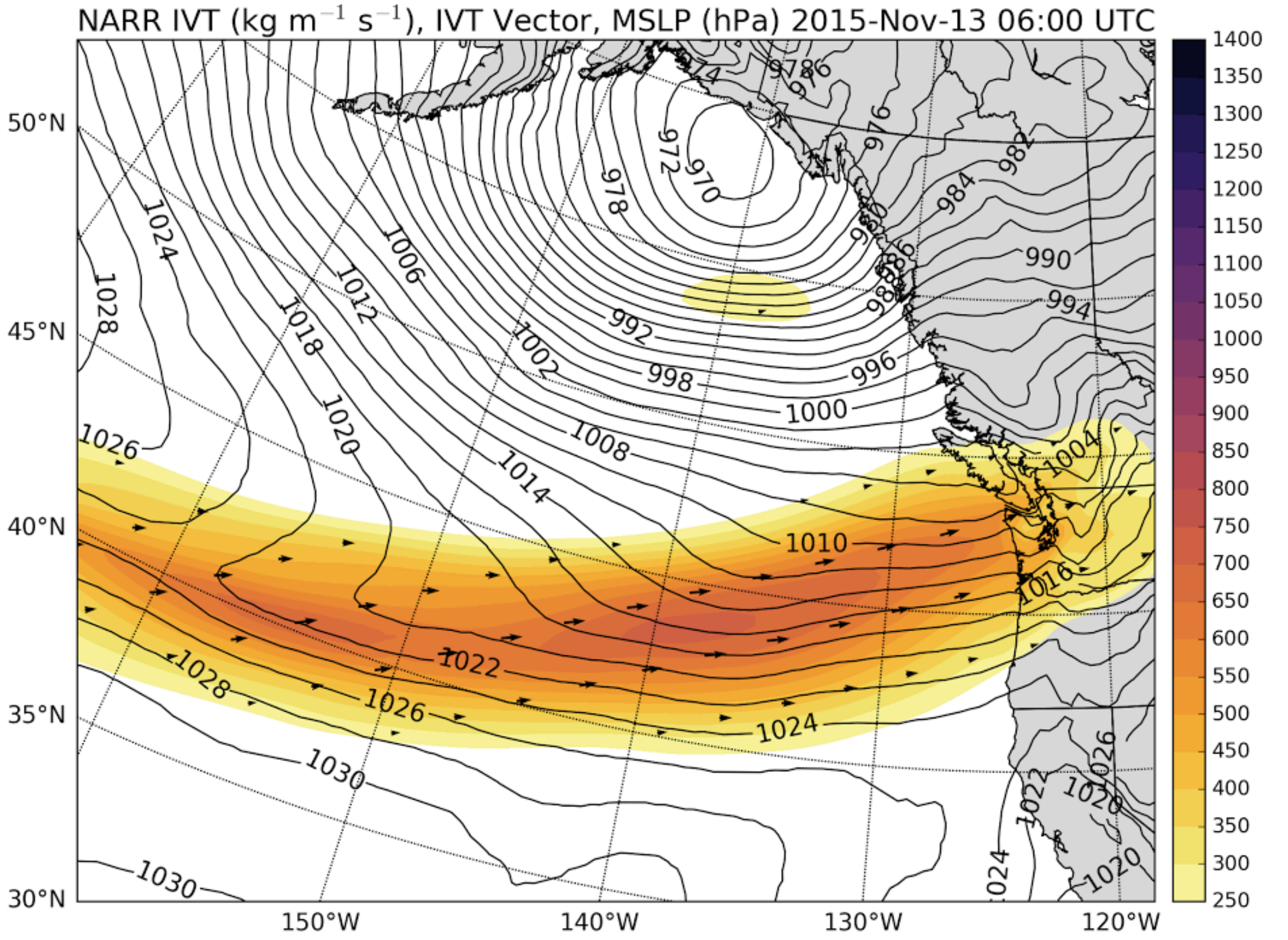


Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Case Study: Nov 12-13, 2015

- Nov 12-13, 2015 “Atmospheric River”
- High melting level
- Strong 925 hPa winds and IVT
- Moist-Neutral Stability

Integrated Vapor Transport (IVT)



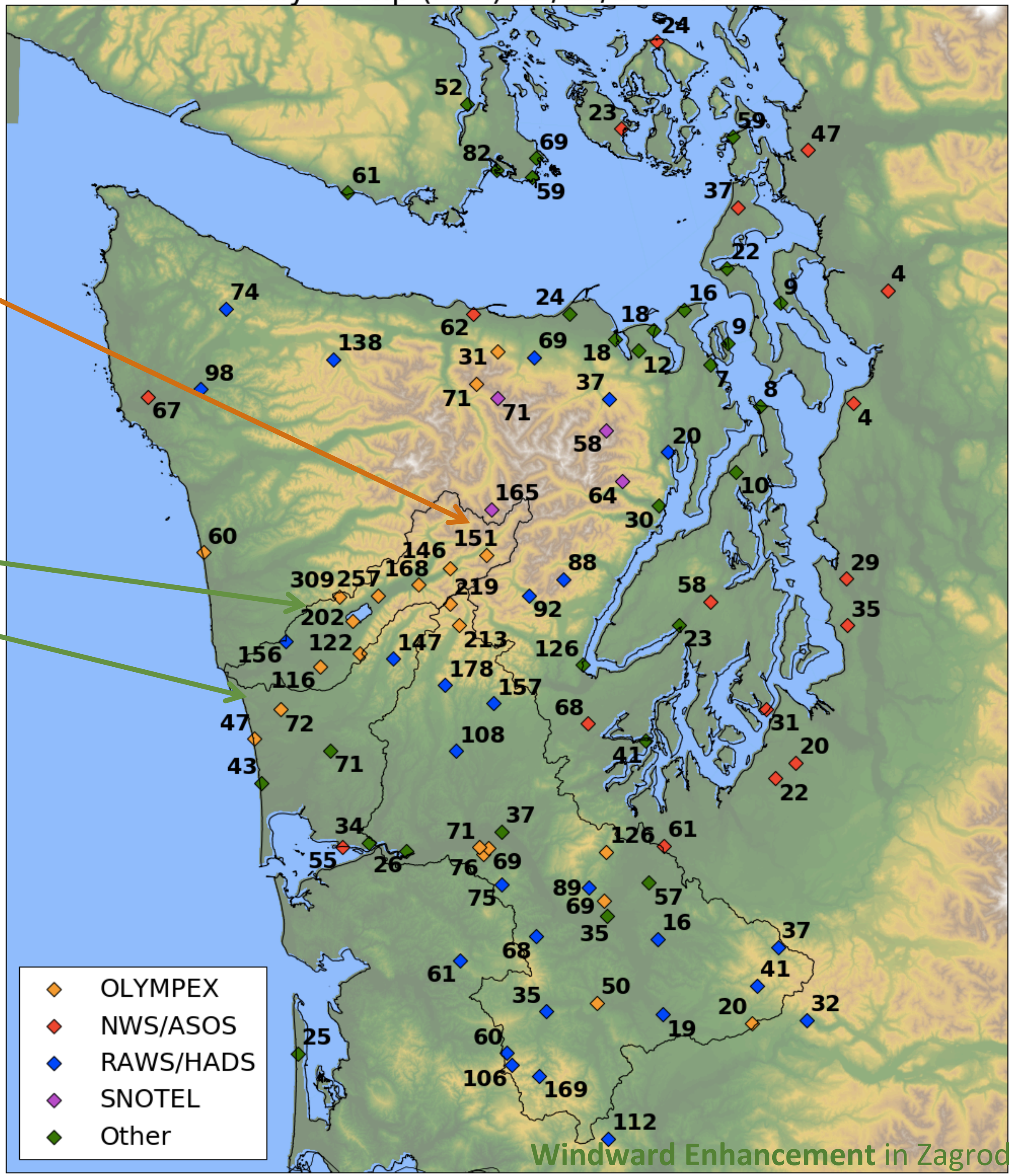
Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

High terrain less than windward slopes

Factor of 4-5 enhancement between coast and Lake Quinault

Different than climatology!

OLYMPEX Daily Precip (mm) 11/13/15 00:00 - 23:59 UTC

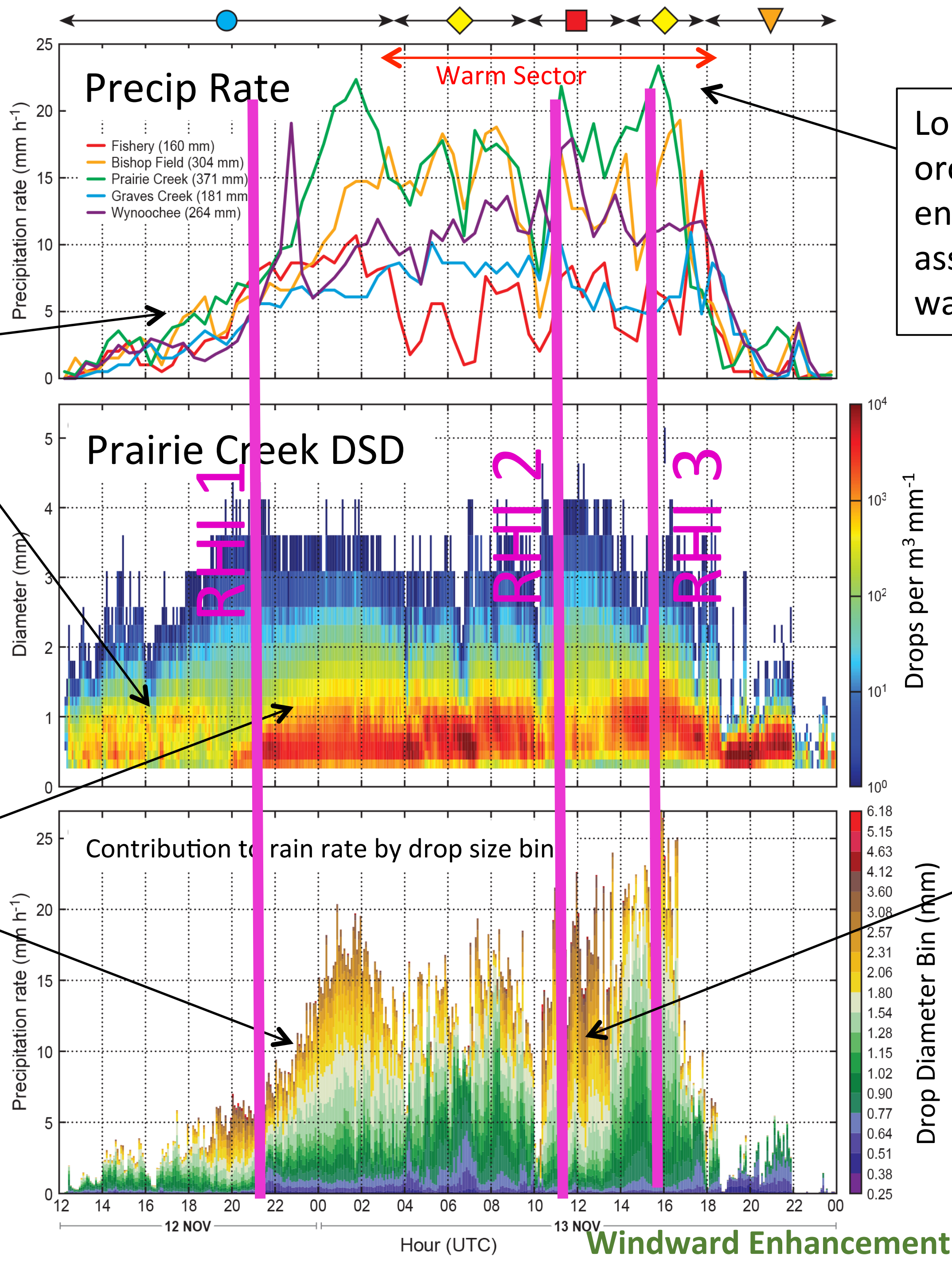


Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Time Series

Event begins with most frequent DSD. No orographic enhancement

Small-to-medium drops become dominant during transition to warm sector

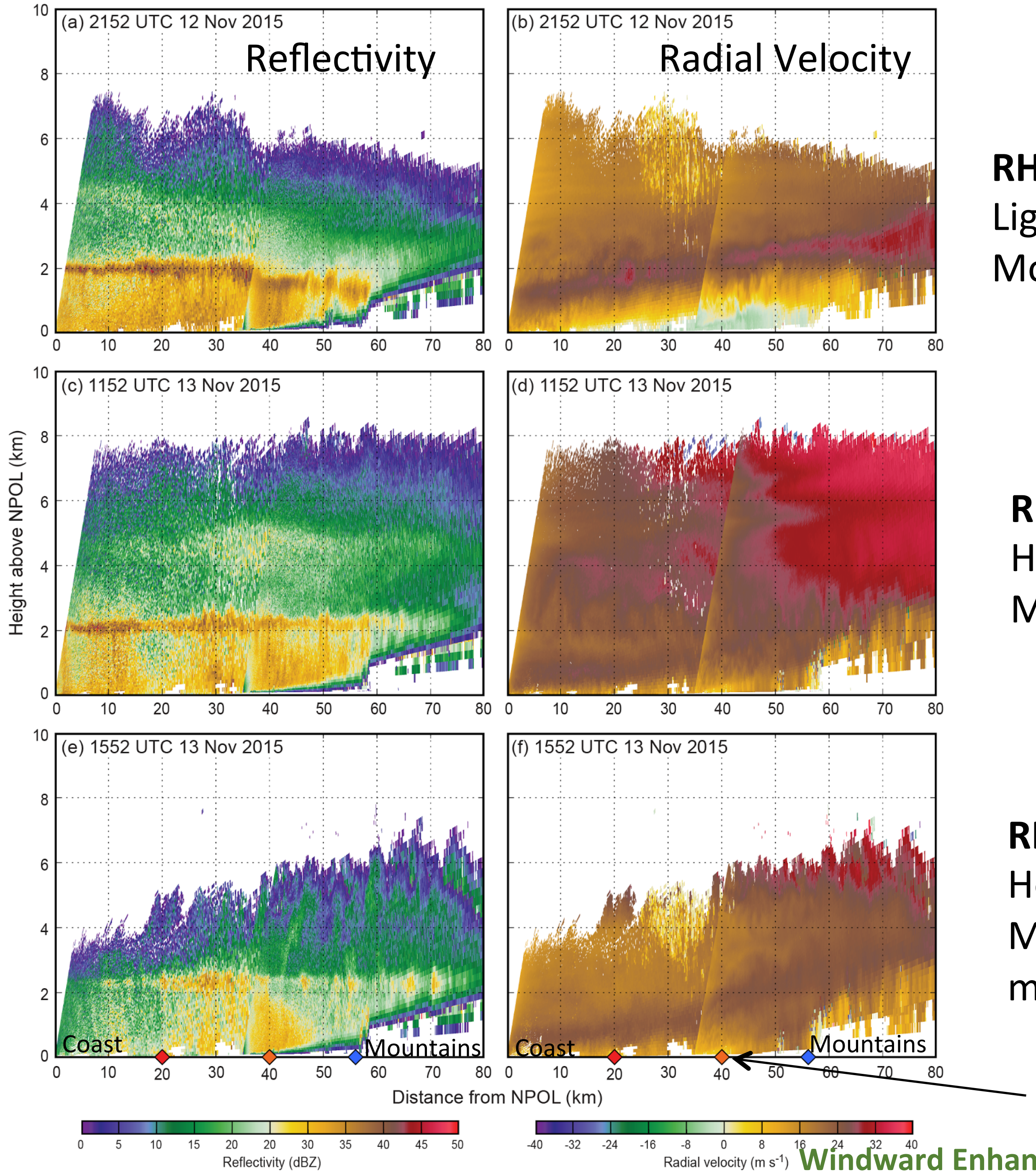


Long period of orographic enhancement associated with warm sector

Interesting period of larger drops in warm sector

Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Radar RHIs from coast to mountains



RHI 1
Light Rain
Most Frequent DSD

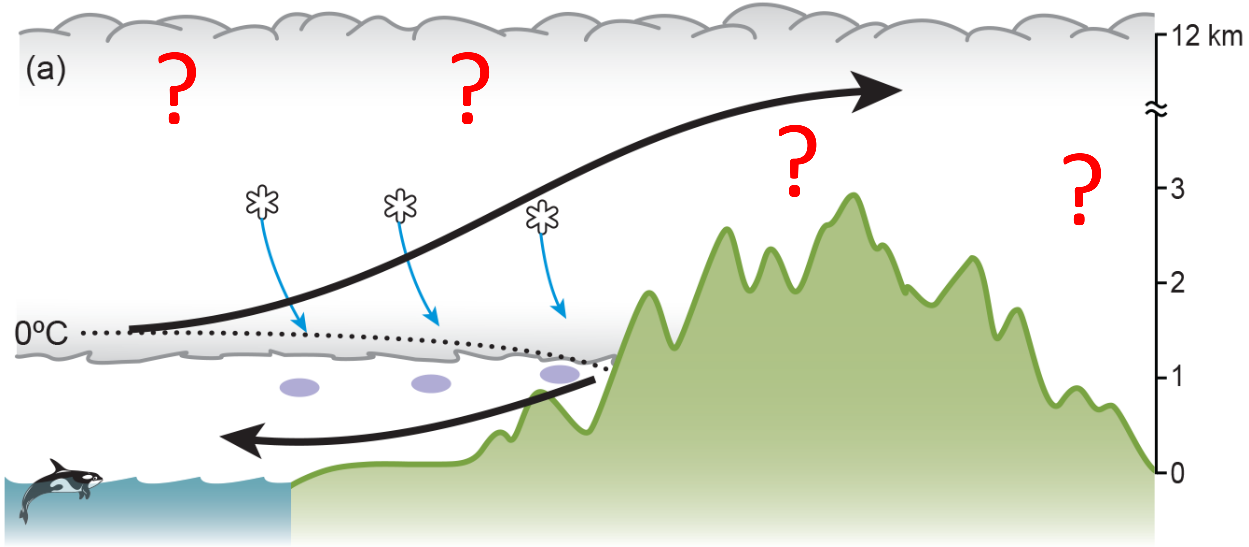
RHI 2
Heavy Rain
Mostly big drops

RHI 3
Heavy Rain
Mostly small to medium drops

Note: these images combine the NPOL and DOW radars

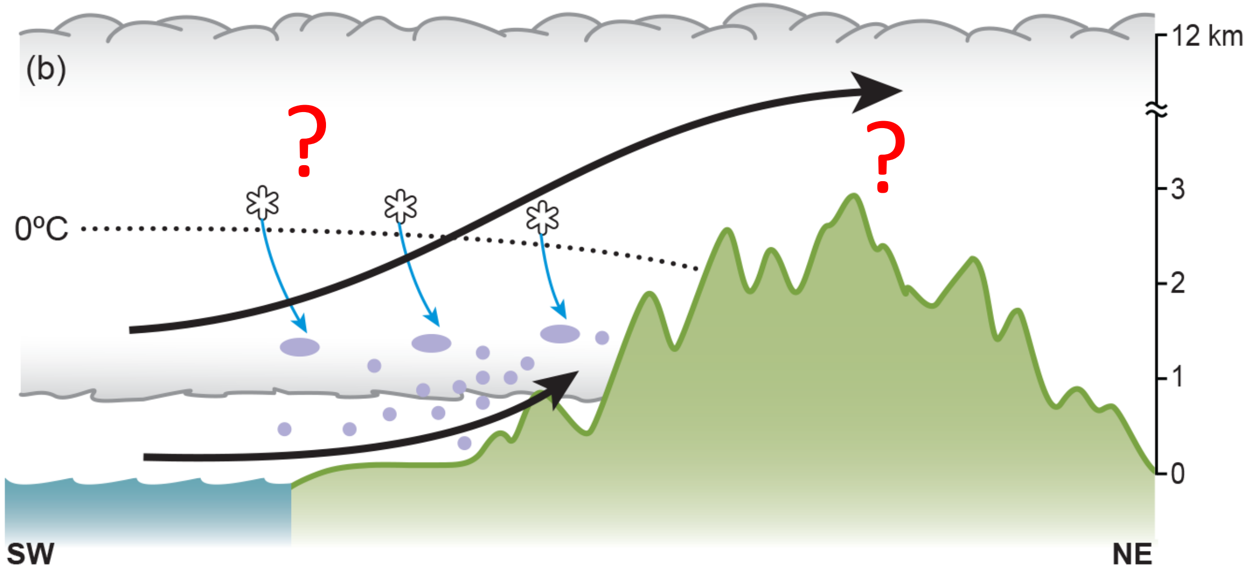
Windward Enhancement in Zagrodnik et al. 2018 (March JAS)

Windward Enhancement Summary so Far



Most Frequent DSD

- Occurs in average (prefrontal) synoptic conditions with offshore low-level flow
- Minimal windward precipitation enhancement
- Little small drop production

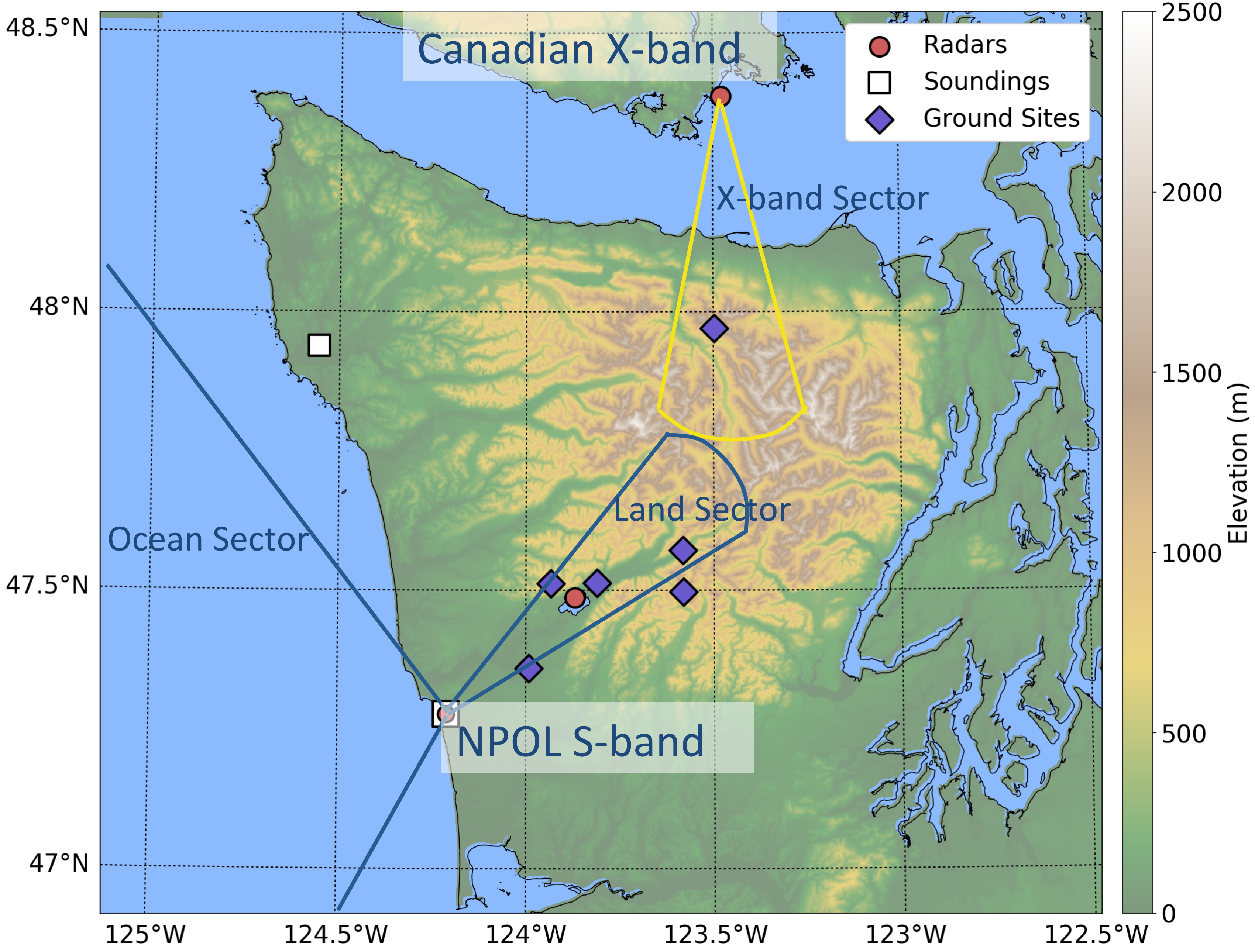


Heavy Rain DSD

- Occurs in warm sectors/atmospheric rivers
- Considerable windward precipitation enhancement
- Significant small drop production

Next: what is happening aloft and over high terrain/lee side?

Windward Enhancement in Zagrodnik et al. 2018 (March JAS)



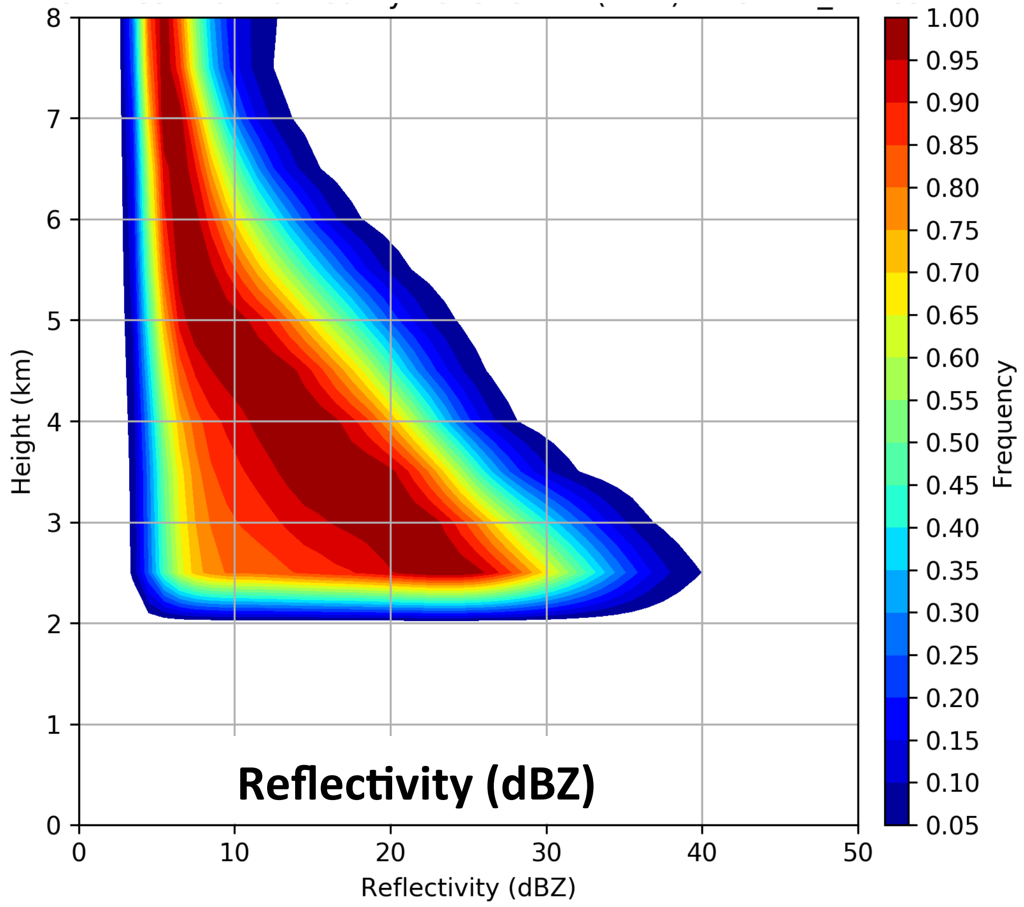
NPOL Radar Statistics

- Compare Ocean sector RHIs to Land sector RHIs
- Use all RHIs with measurable reflectivity
- Contoured Frequency by Altitude Diagrams

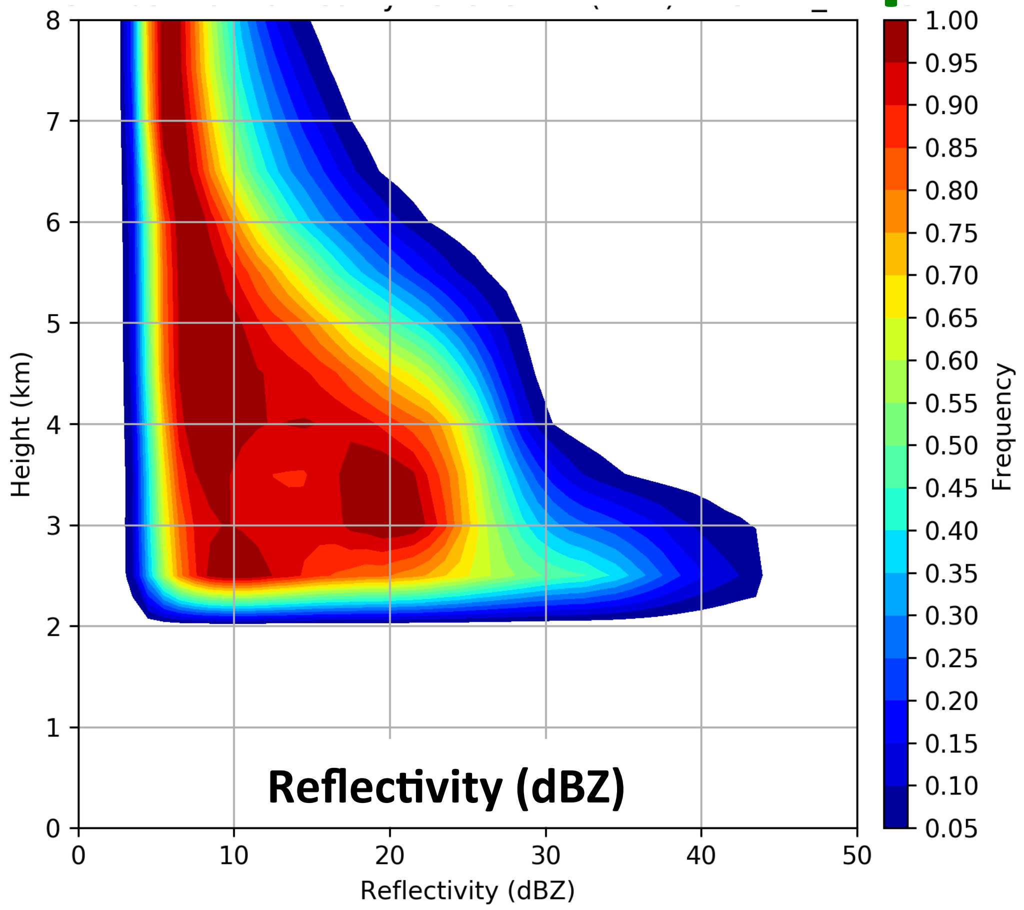
Windward Enhancement in McMurdie et al. 2018 (JGR in review)

Orographic Enhancement Aloft from Radar

Ocean



Land – Windward Slopes



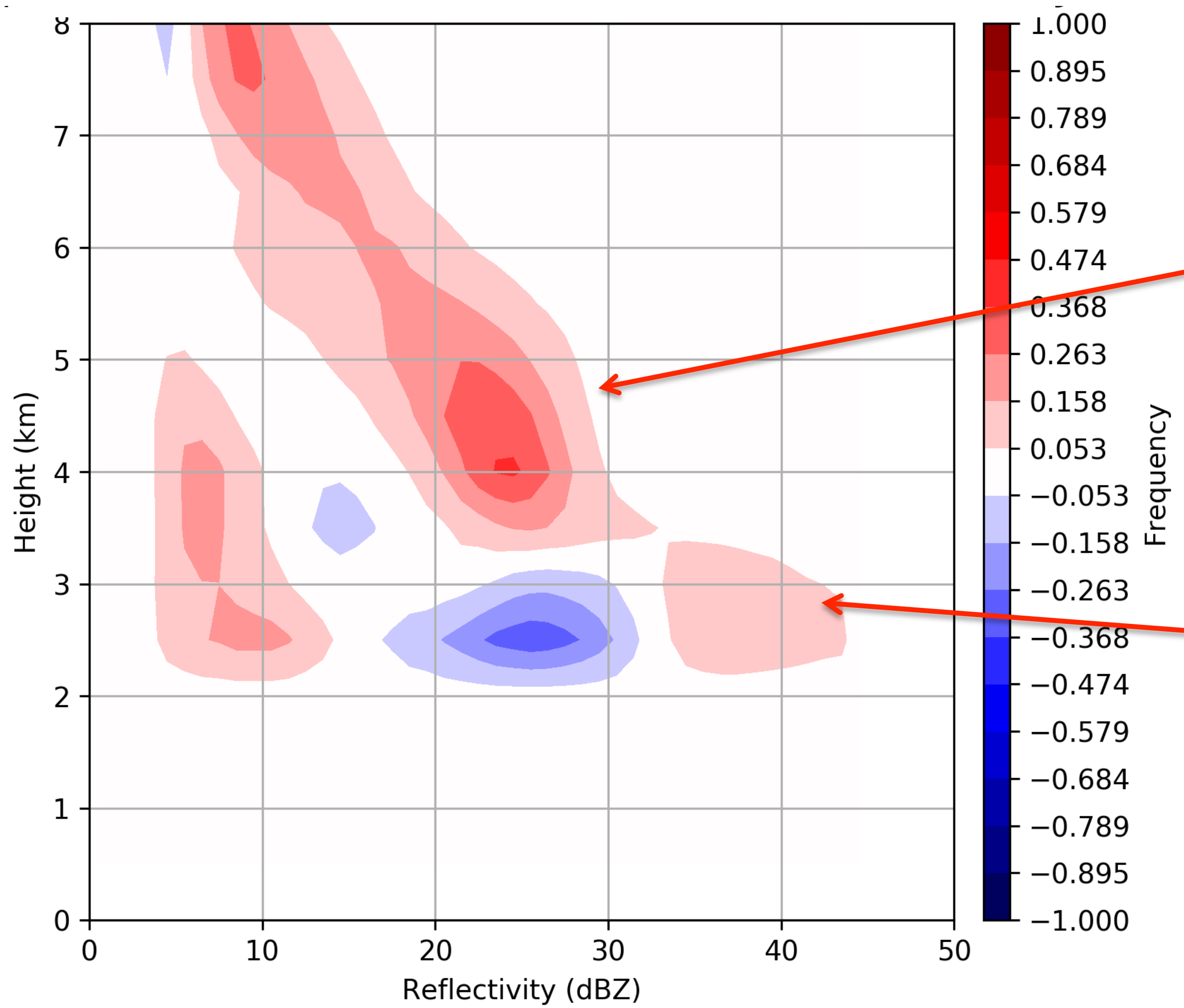
Contoured Frequency by Altitude Diagrams

Frequencies normalized by level for **all NPOL RHI data** over ocean and land above 2 km height

Windward Enhancement in McMurdie et al. 2018 (JGR in review)

Orographic Enhancement Aloft from Radar

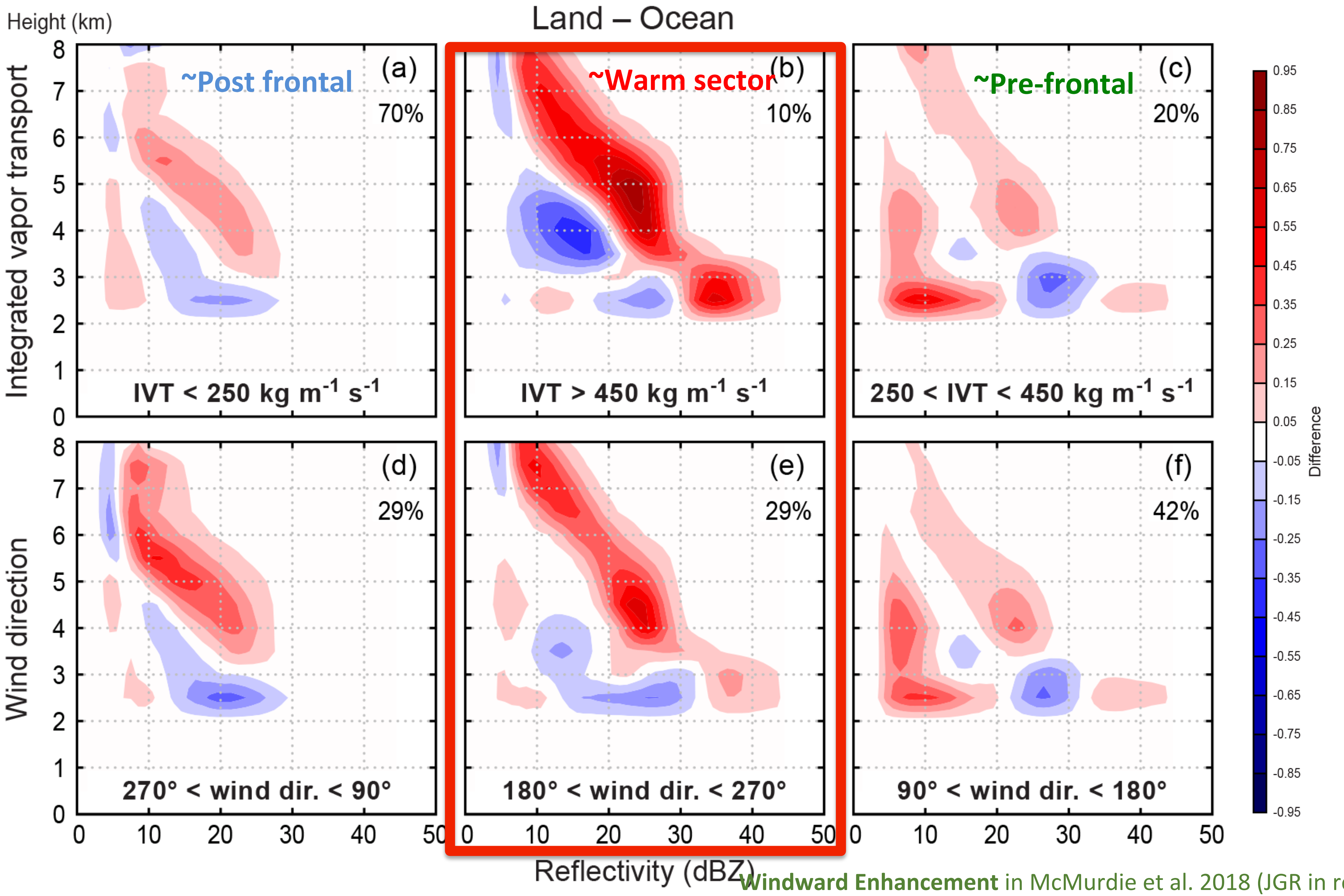
Land – Ocean **Difference** CFAD

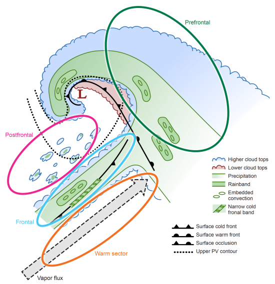


Greater frequency of higher reflectivities at all levels over windward slopes. Maximum at 4-5 km range.

Shift to higher reflectivity near melting level (2-3 km during warm events)

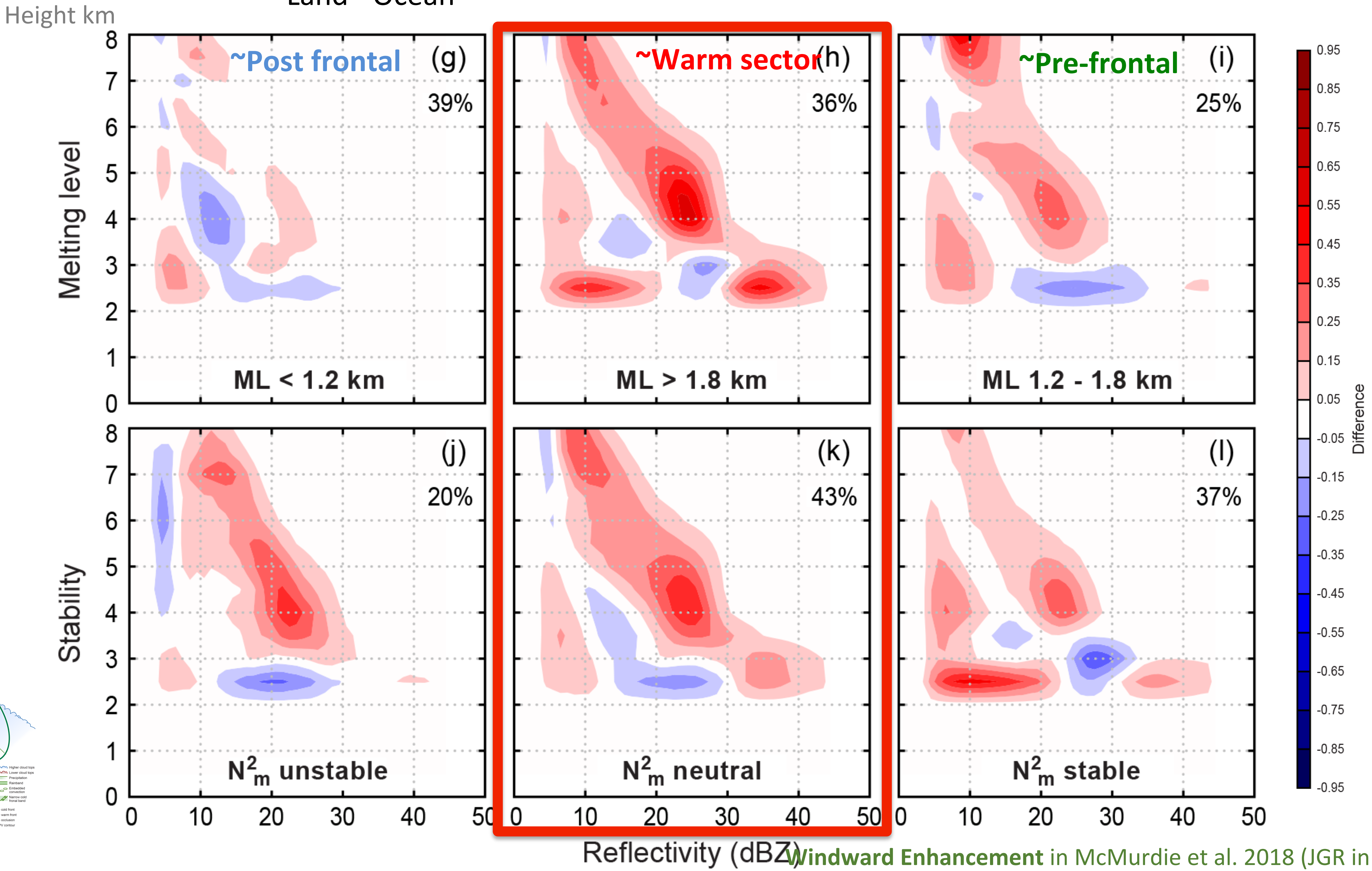
Windward Enhancement in McMurdie et al. 2018 (JGR in review)

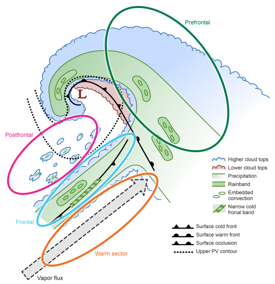




Windward Enhancement in McMurdie et al. 2018 (JGR in review)

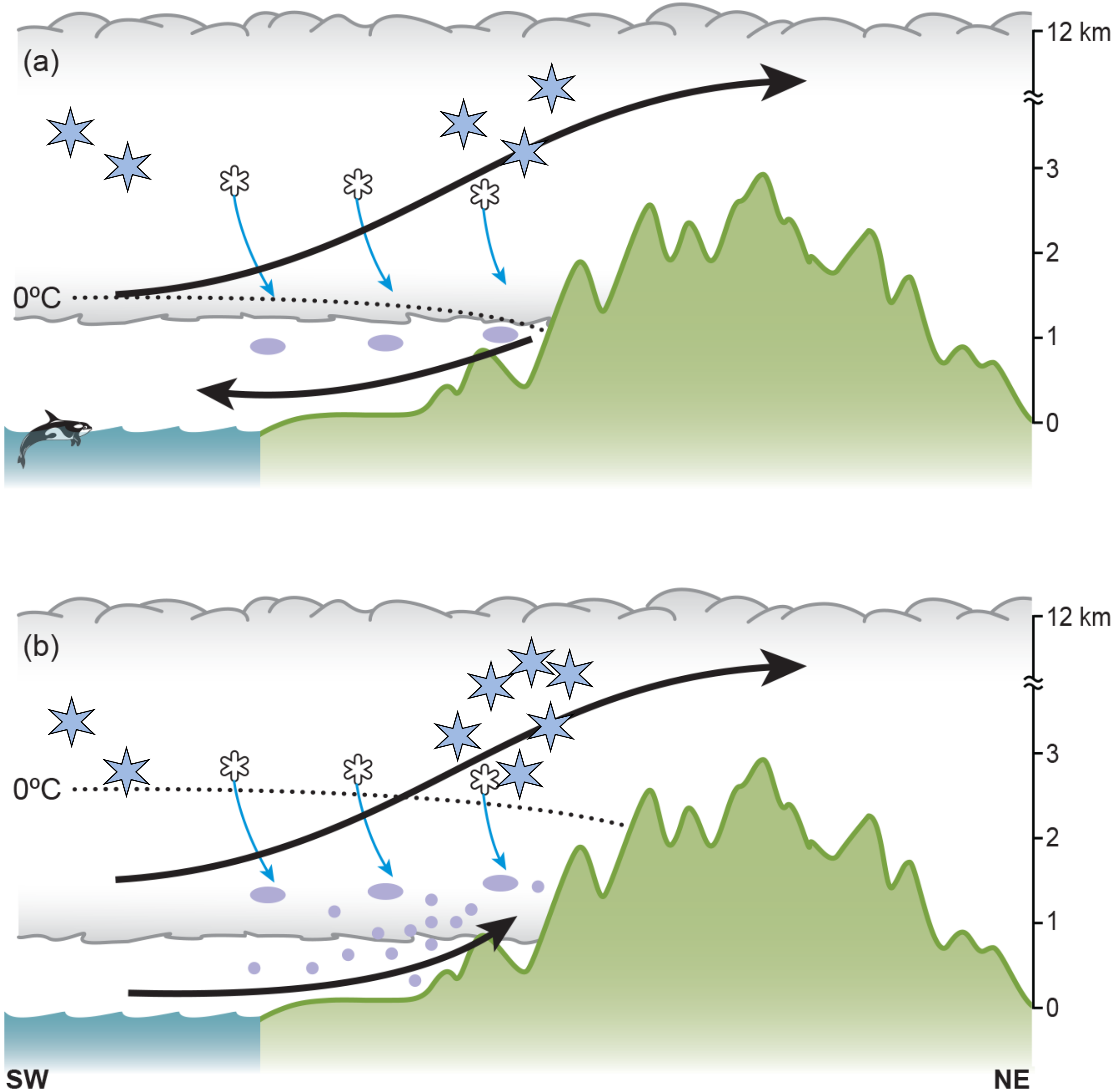
Land - Ocean





Windward Enhancement in McMurdie et al. 2018 (JGR in review)

Windward Enhancement Summary



Most Frequent DSD

- Occurs in average (prefrontal) synoptic conditions with offshore low-level flow
- Minimal precipitation enhancement
- Little small drop production

Heavy Rain DSD

- Occurs in warm sectors/atmospheric rivers
- Considerable windward precipitation enhancement
- Significant small drop production

Enhancement aloft over windward slopes

- Occurs in all atmospheric conditions
- Synoptic and environmental conditions affect the degree of enhancement
- Strongest during warm, strongly forced events (high IVT, high melting level, neutral stability and SW low-level flow)

Next: what is happening in the high terrain/lee side?

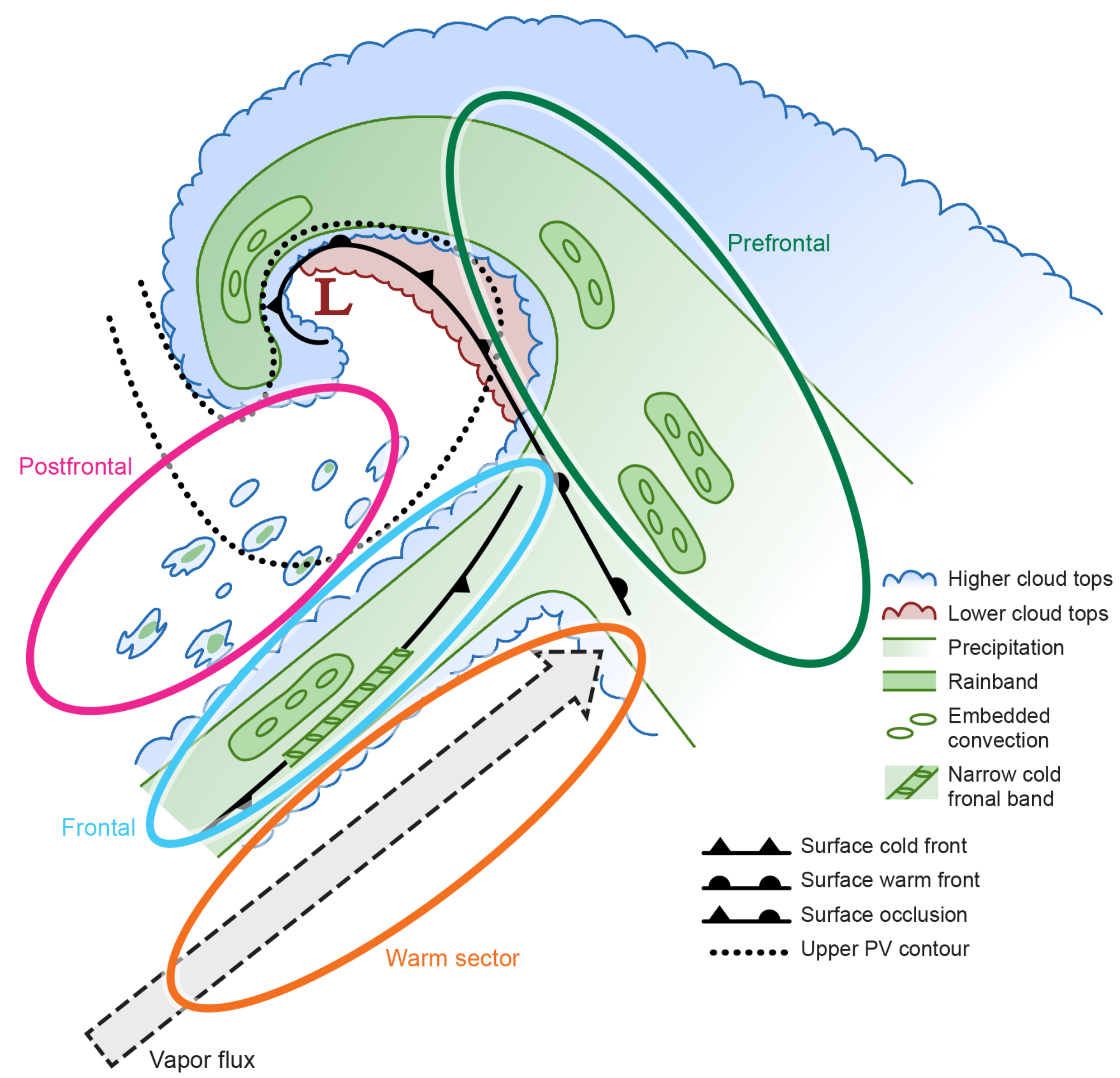
Windward Enhancement in Zagrodnik et al. 2018 (March JAS) and McMurdie et al. 2018 (JGR in review)

High Terrain/Leeside Diminishment

NASA 3rd-Gen Airborne Precipitation Radar (APR-3)

- Flies on NASA DC-8
- Triple-frequency (Ku/Ka/W-band)
- 120 m vertical resolution
- 0.2 Hz measurement frequency (~0.2 km resolution)
- Key benefit: full transects of Olympic Mountains with same instrument package!

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)



9 OLYMPEX APR-3 flights used in this portion of the study:

3 Prefrontal

- High IVT: 500-560 kg m^{-1} s^{-1}
- Stably stratified low levels ($N^2{}_m$ >0)
- Veering winds (easterly component at 925 hPa)

3 Warm Sector

- High IVT: 575-815 kg m^{-1} s^{-1}
- Moist-neutral low levels ($N^2{}_m$ = 0)
- High melting level: > 2 km

3 Postfrontal

- Low IVT: 100-400 kg m^{-1} s^{-1}
- Low melting levels: 1-1.4 km
- Unstable low levels (

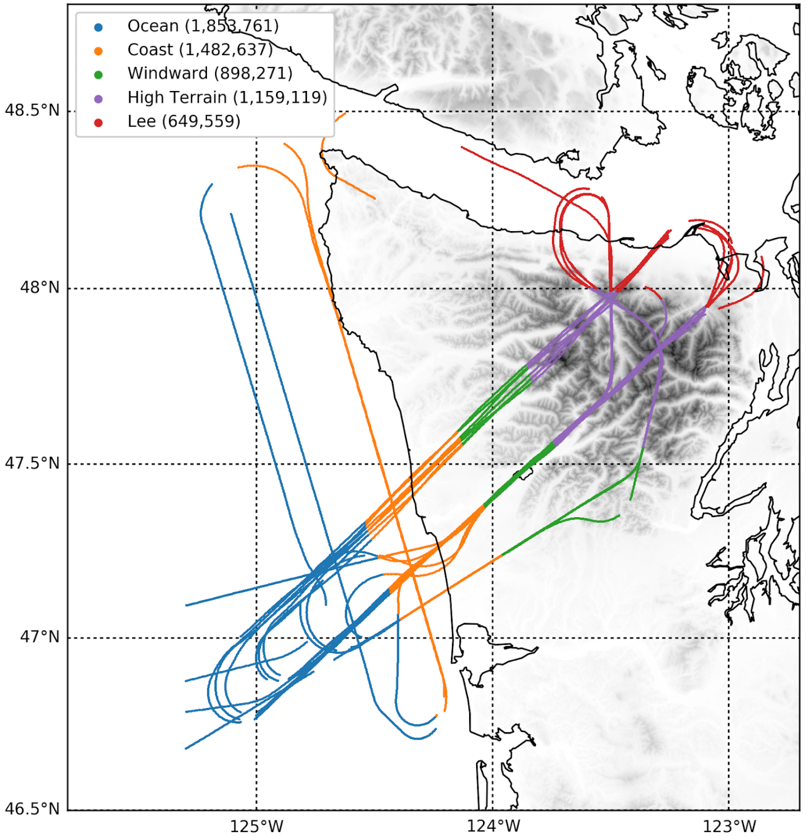
High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Flight tracks divided by storm sector and geographic region:

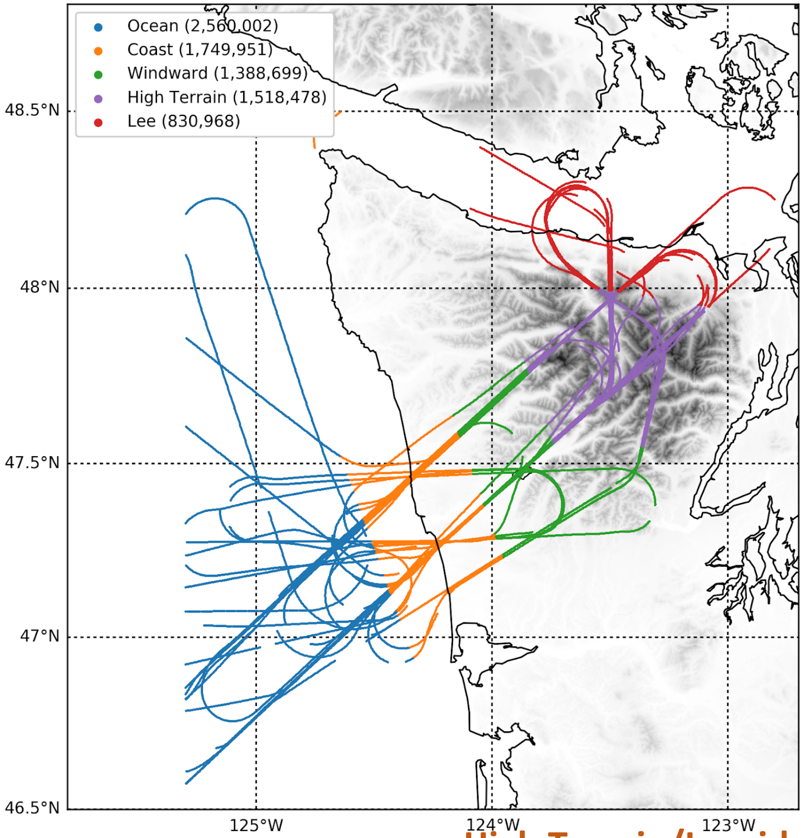
Ocean Coast Windward High Terrain Lee Side

~30 total measurement hours

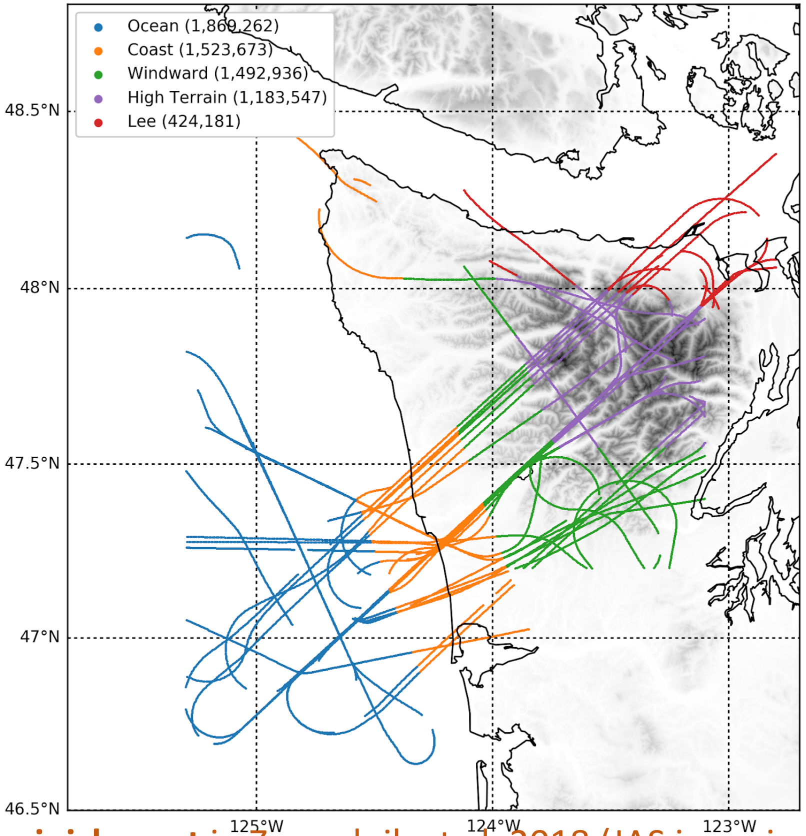
Prefrontal



Warm Sectors

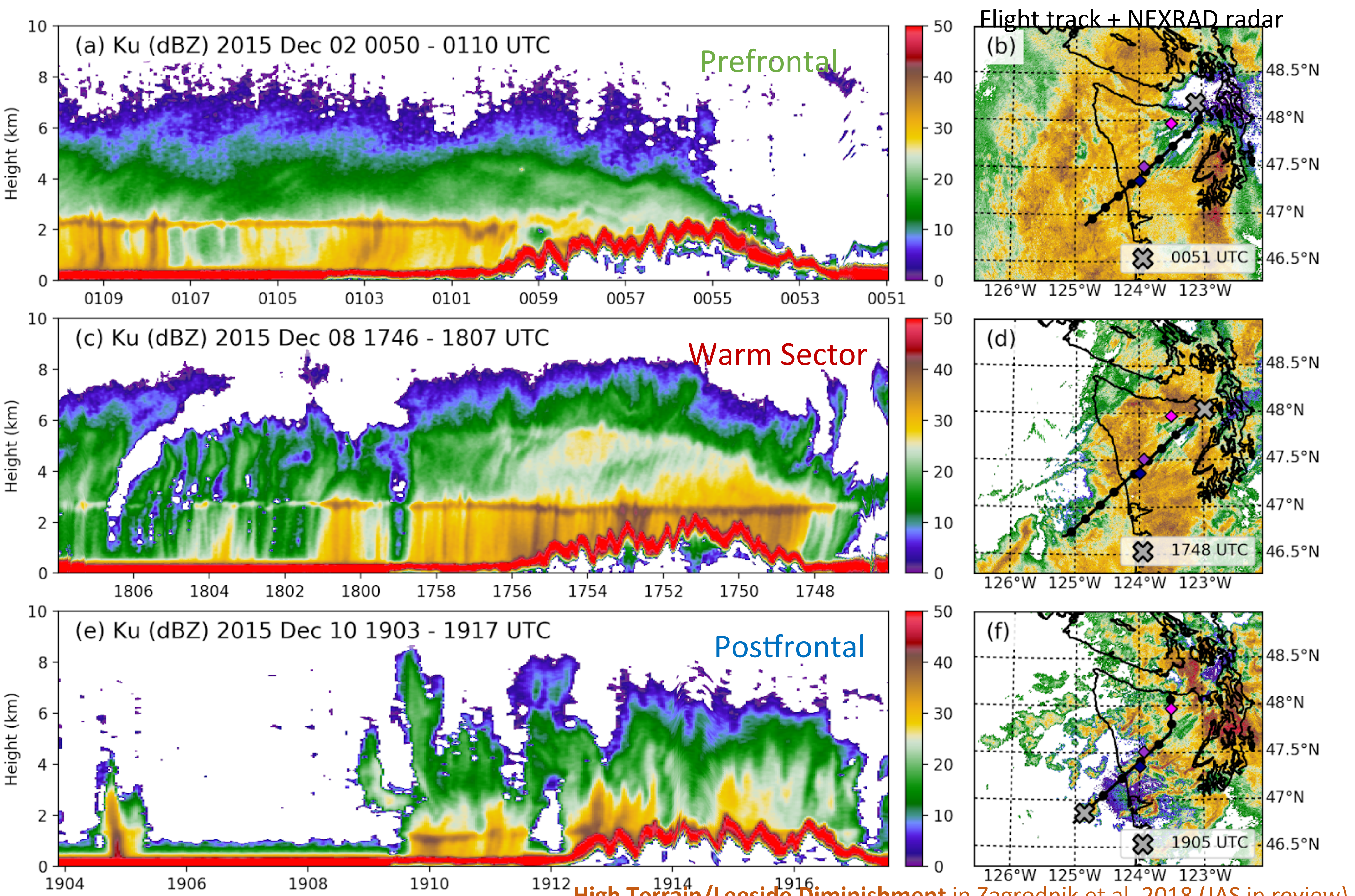


Postfrontal



High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Example APR-3 transects of Ku-reflectivity

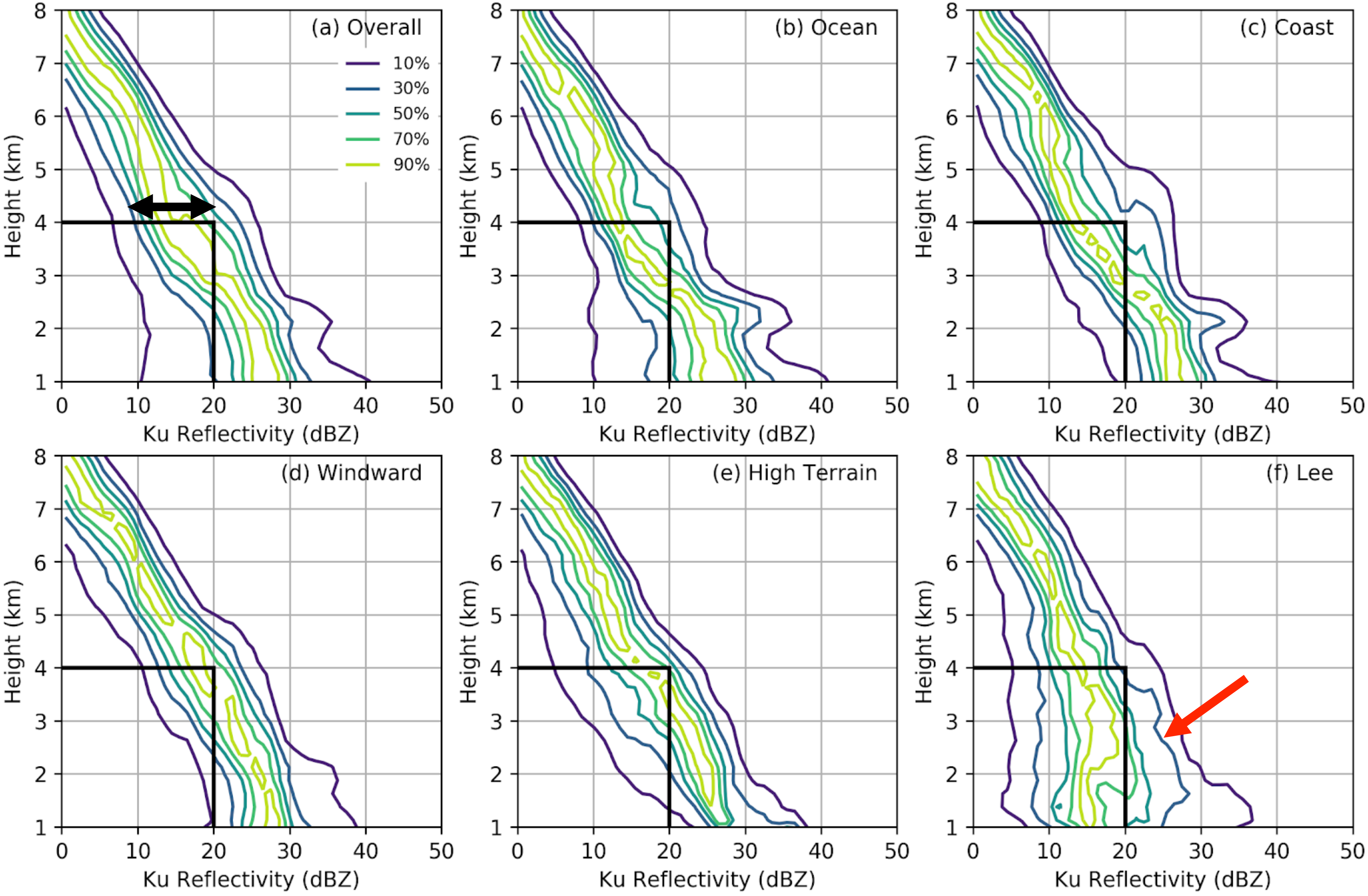


Note: the red stripe (> 50dBZ) is the ocean/land surface signature

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

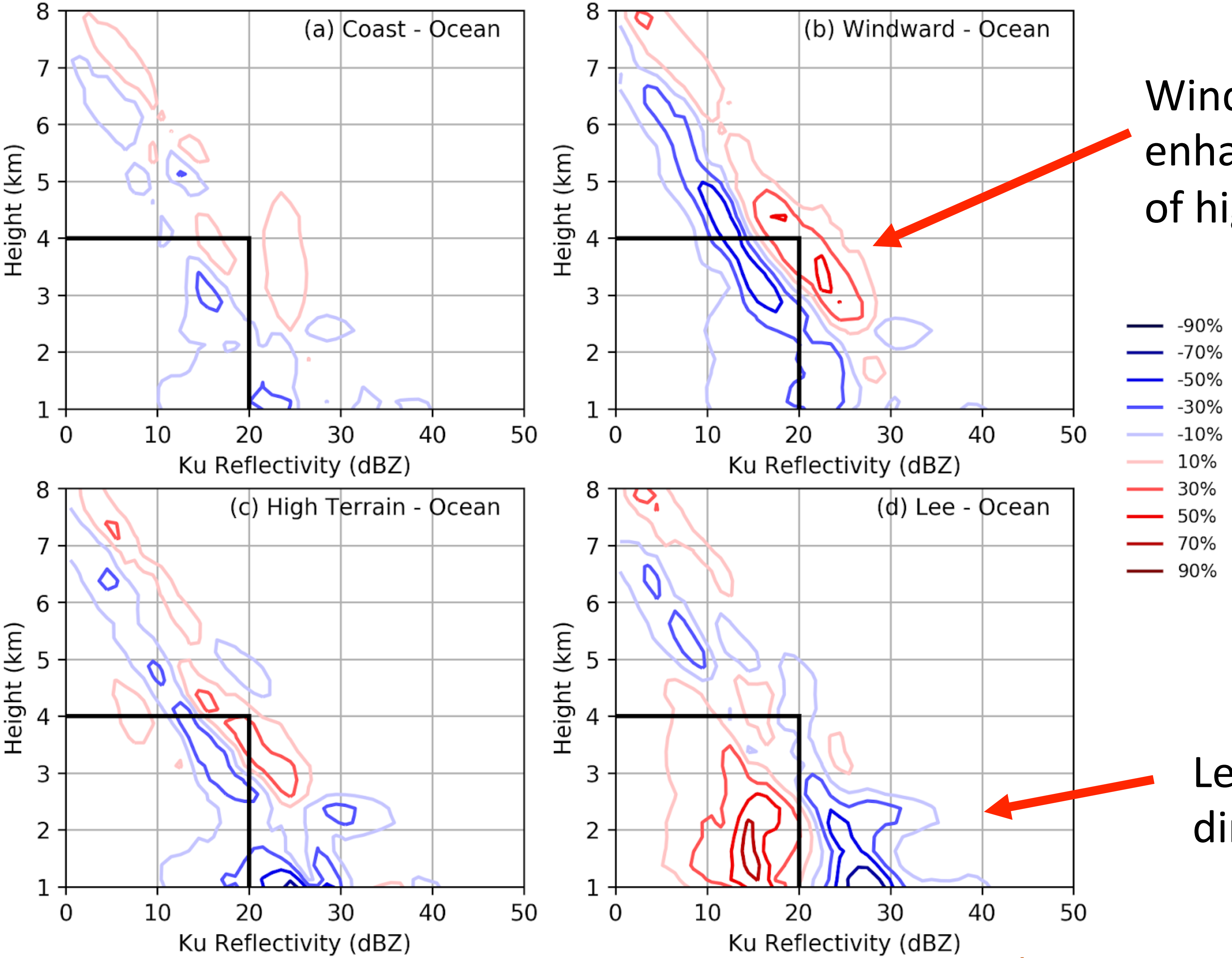
Prefrontal CFADs by geographic region (normalized by level)

Height relative to sea level



High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Prefrontal CFAD differences (relative to OCEAN)



Windward: Modest enhancement upstream of high terrain

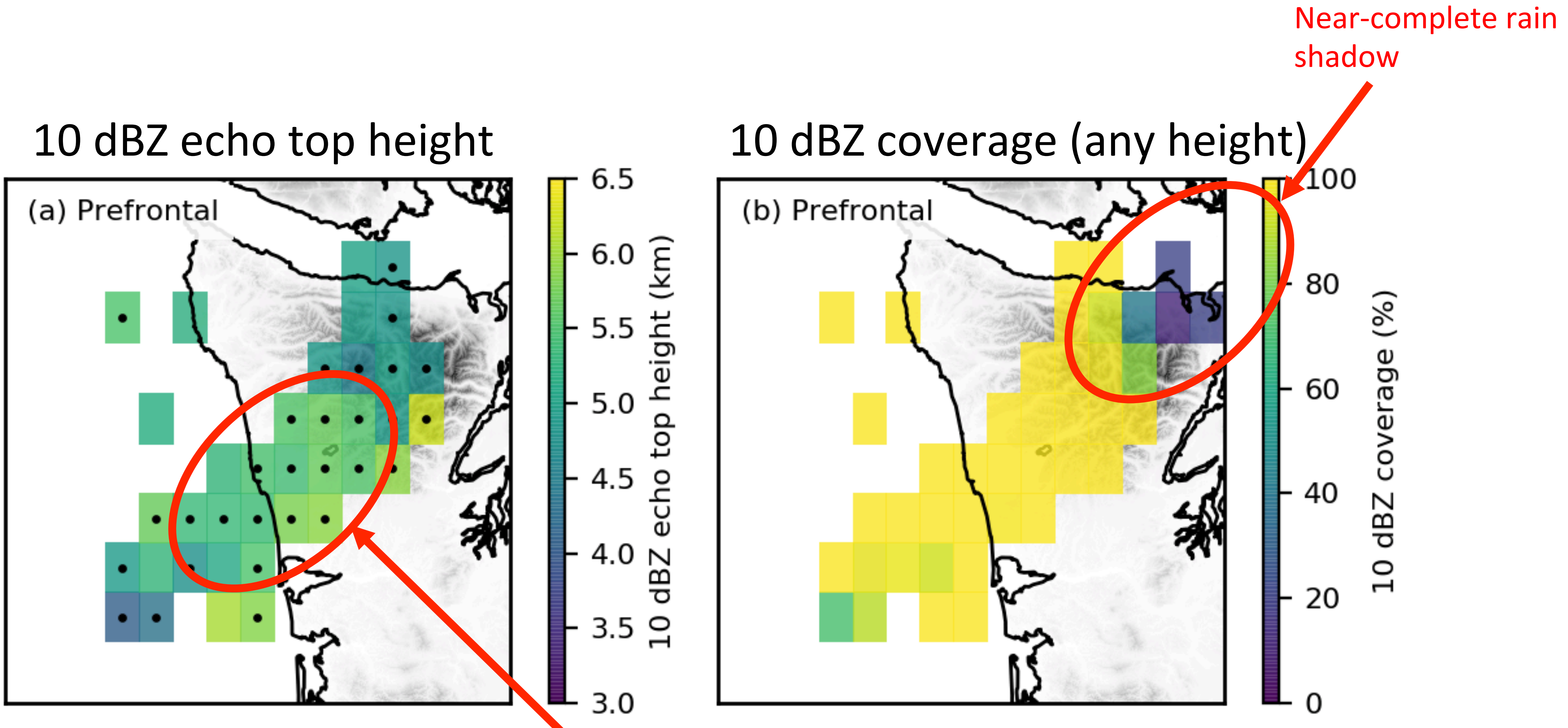
Blue: higher over ocean

Red: higher over comparison region

Lee: Significant diminishment at low levels

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Average height and coverage of 10 dBZ echo top



Dots indicate statistical significance relative to mean echo top height

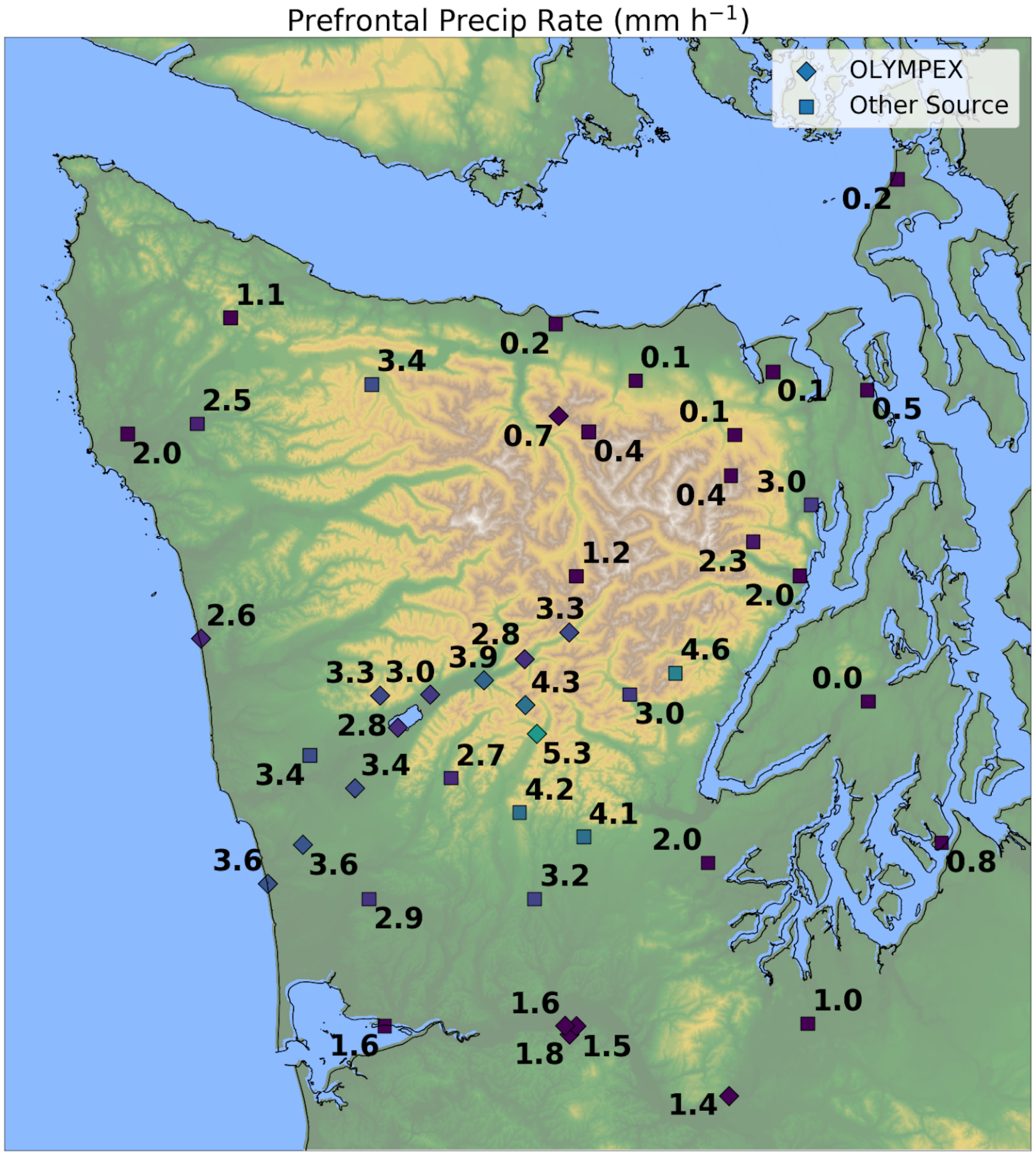
Plots generated by looking for highest 10 dBZ echo in each profile

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Uniform 3-4 mm h^{-1} over coast and windward side.

Rapid decline to < 1 mm h^{-1} at windward/high terrain boundary.

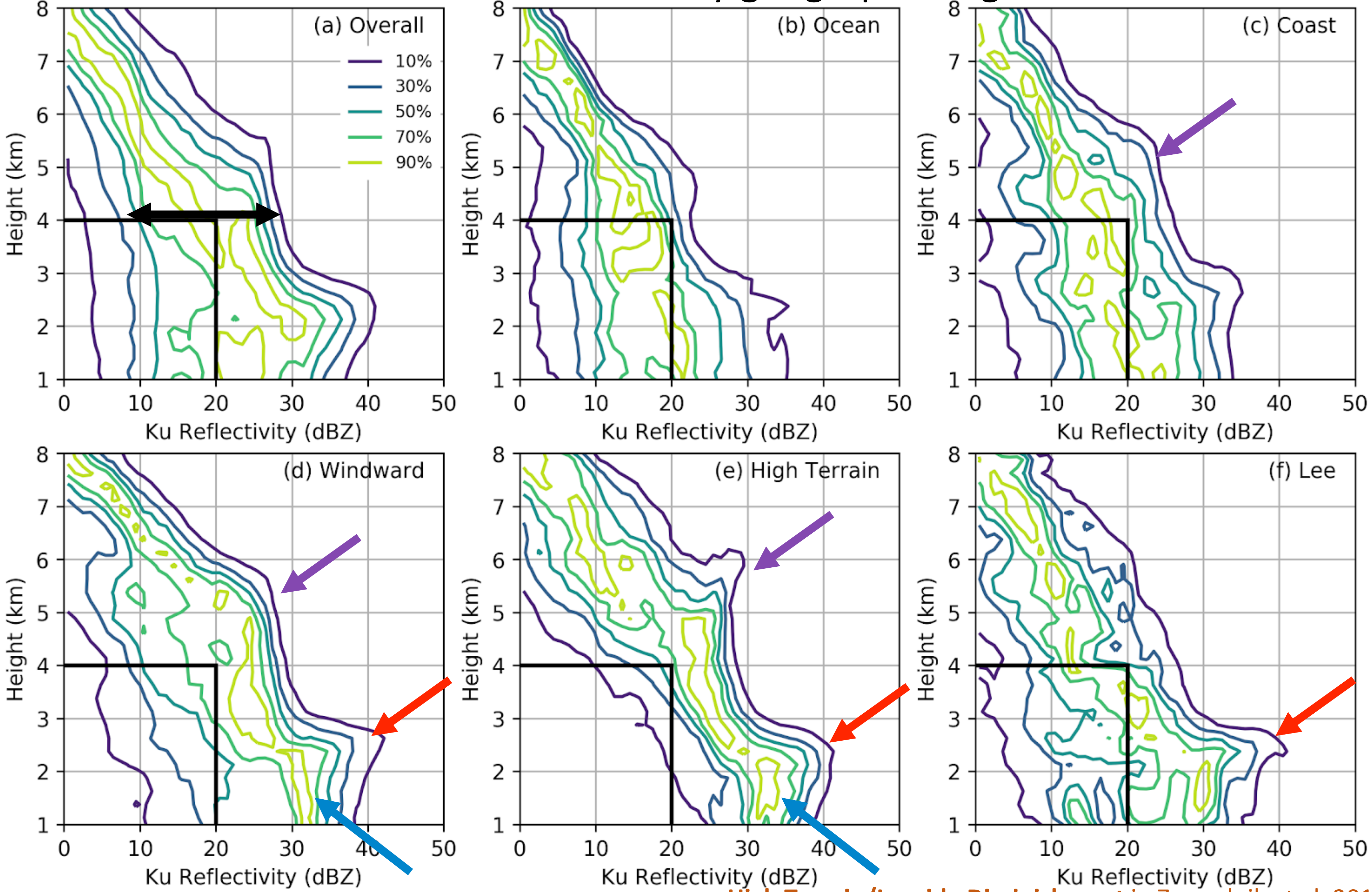
Nearly complete "rain shadow" in lee.



Average precipitation rate (mm h^{-1}) during prefrontal flights

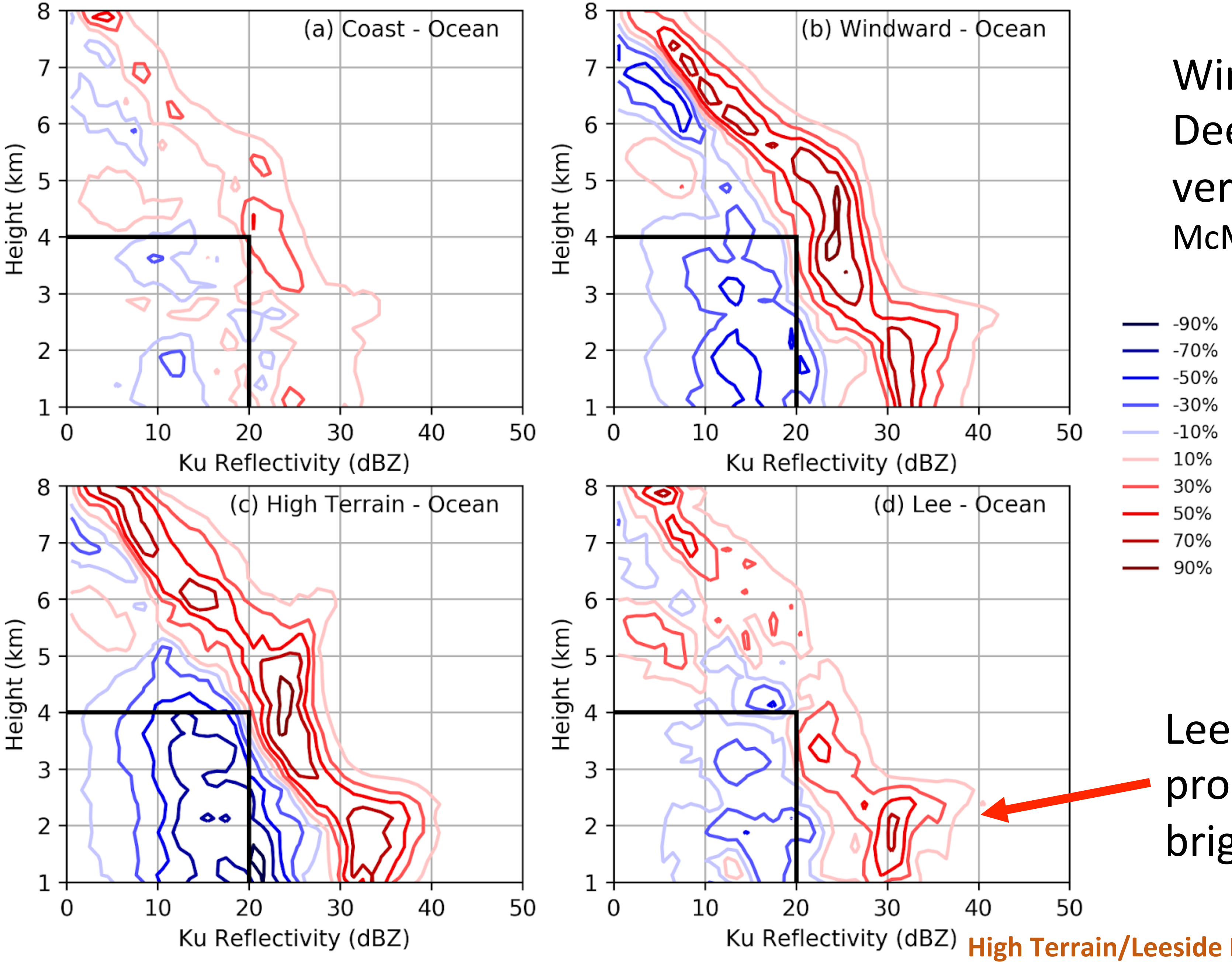
High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Warm Sector CFADs by geographic region



High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Warm Sector CFAD differences (relative to OCEAN)



Windward/High Terrain: Deep enhancement over full vertical profile (consistent with McMurdie et al. 2018)

Blue: higher over ocean

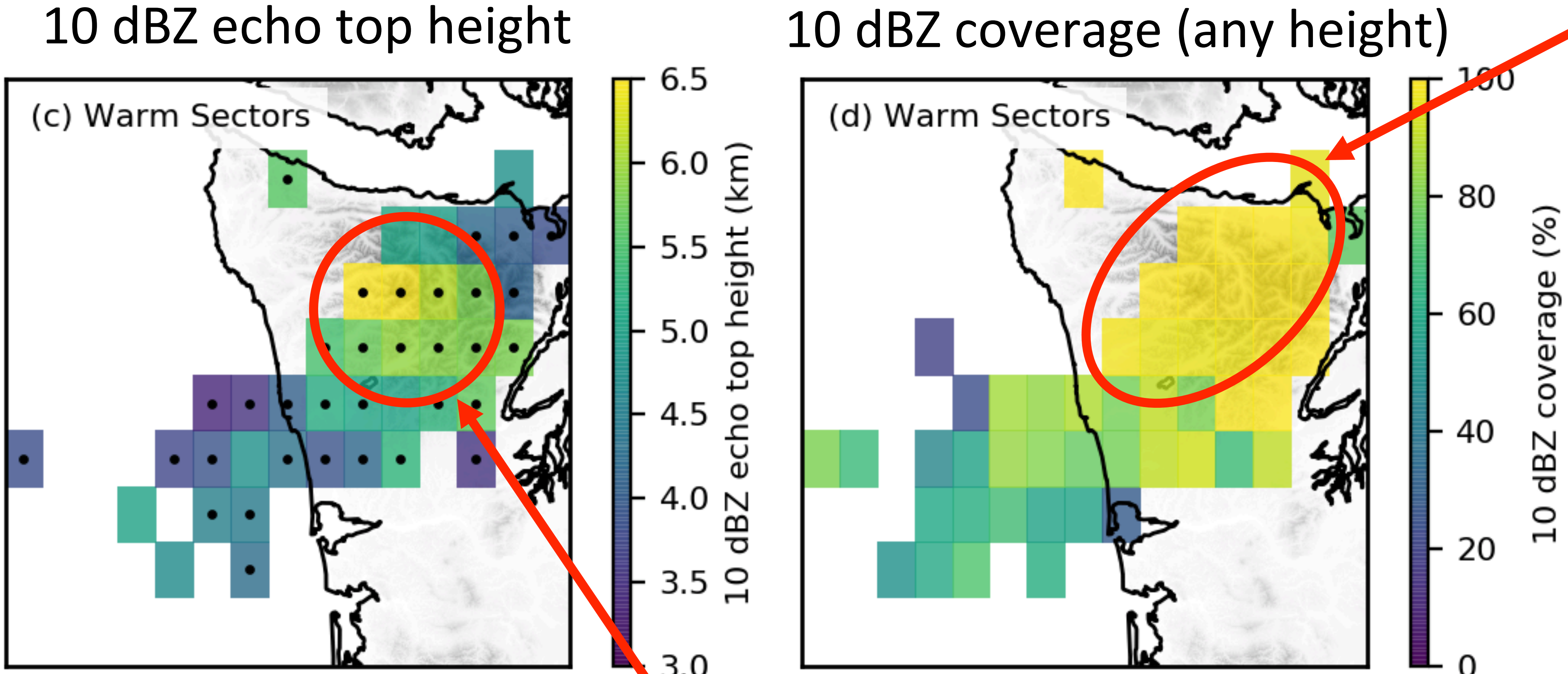
Red: higher over comparison region

Lee: Enhancement most pronounced near/below bright band--suggests spillover

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Average height and coverage of 10 dBZ echo top

Highest coverage ove
terrain also. Extends
farther to lee side



Dots indicate statistical significance relative to mean echo top height

Highest echo directly over terrain

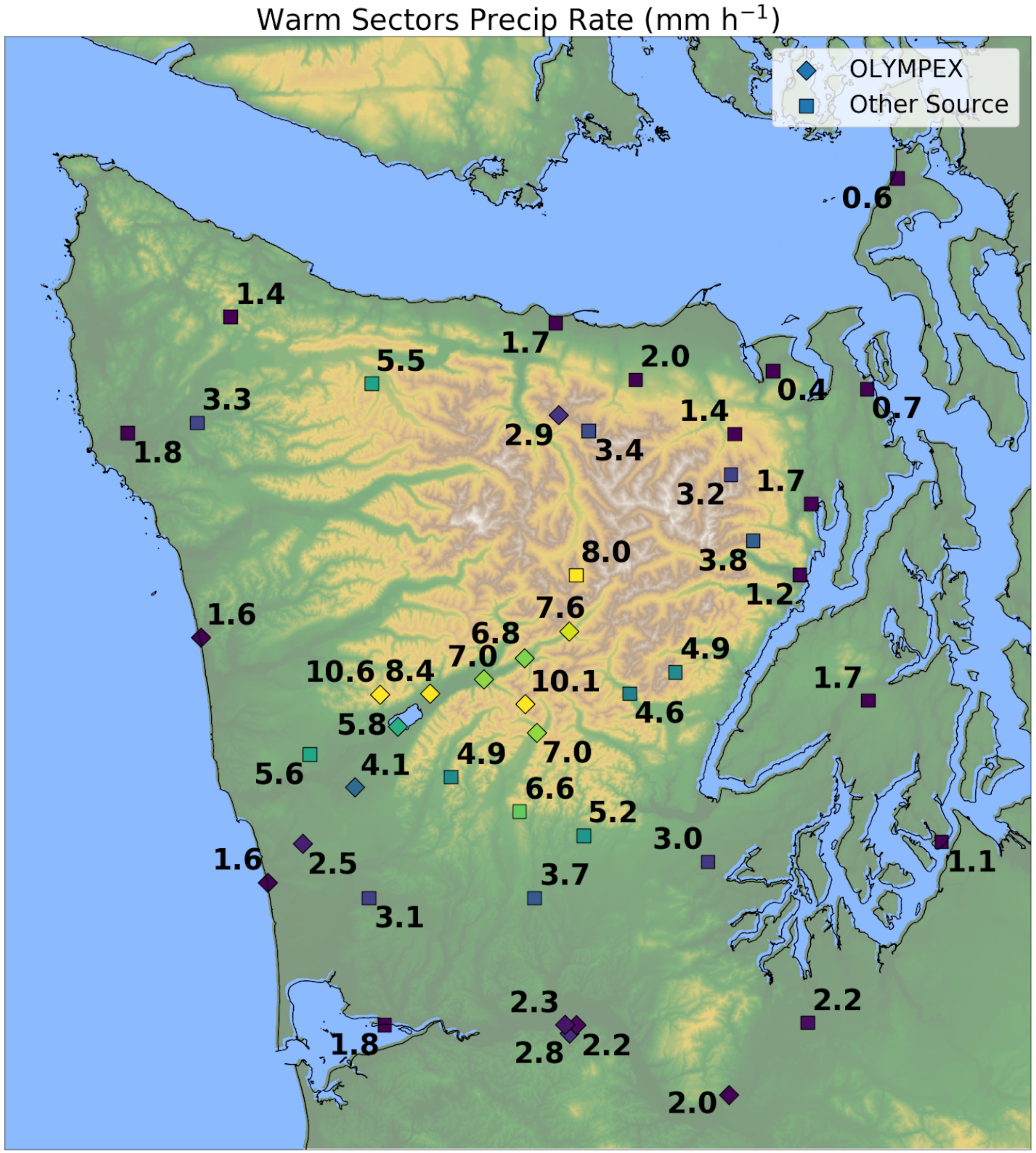
Plots generated by looking for highest 10 dBZ echo in each profile

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Factor of 6-8 times more precip on windward slopes than coast.

Sharp diminishment is located directly over high terrain, similar to climatology.

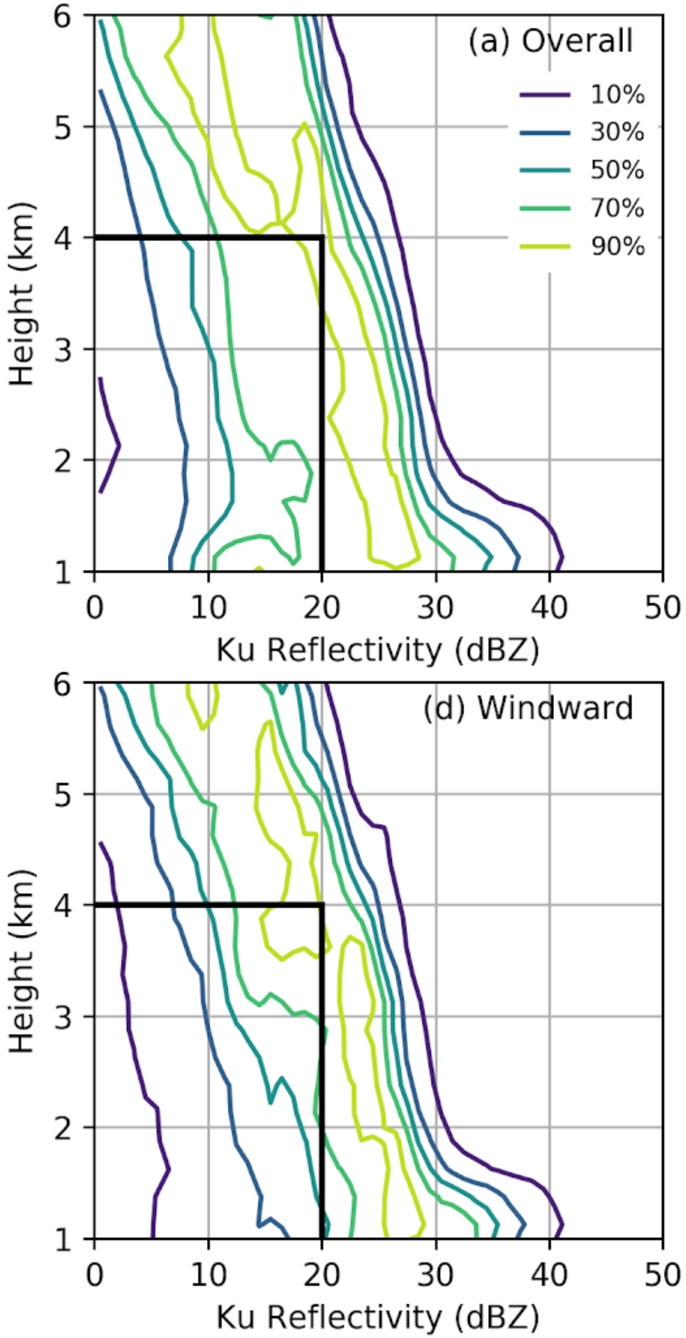
More precipitation reaches lee side.



Average precipitation rate (mm h^{-1}) during warm sector flights

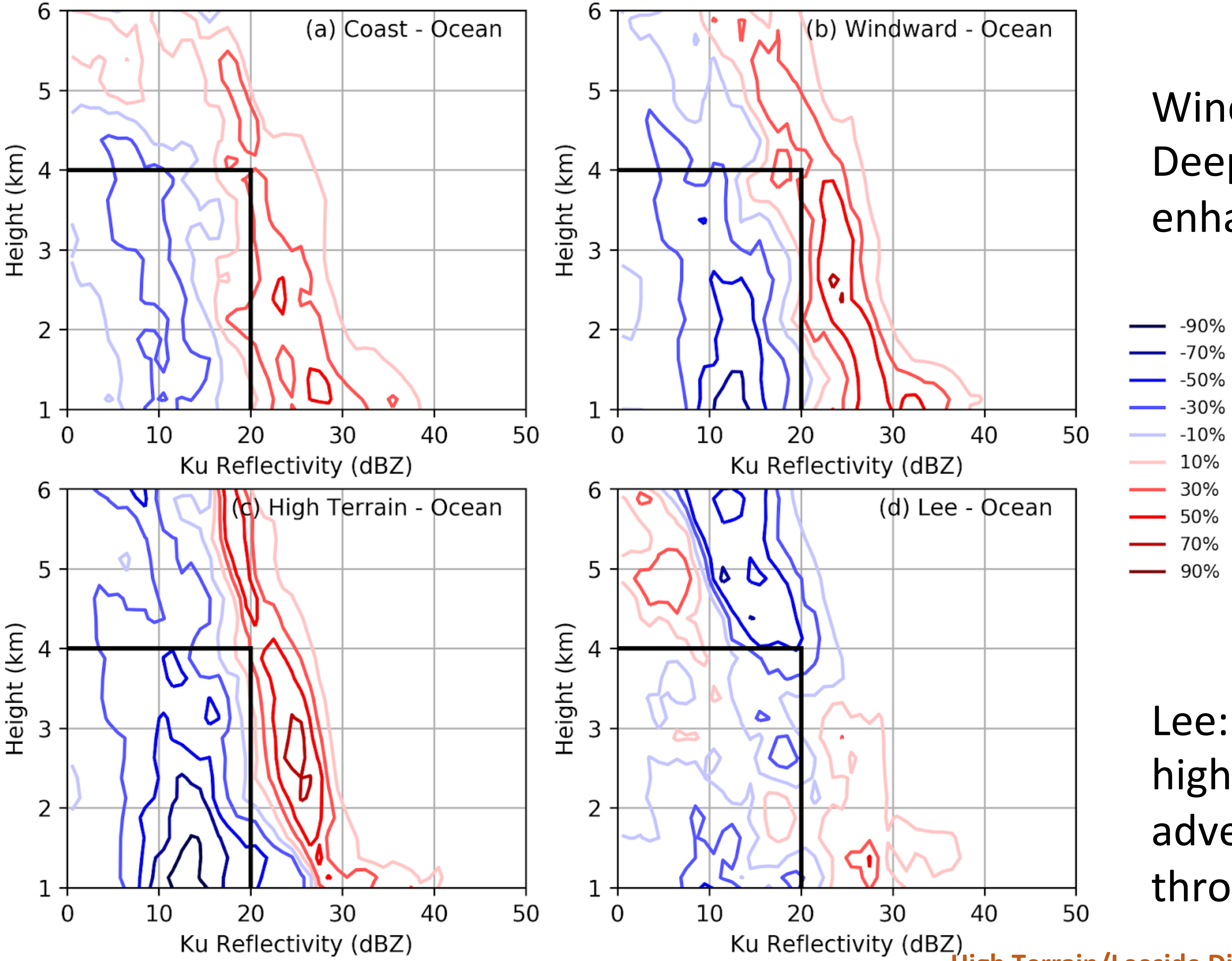
High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Postfrontal CFADs by geographic region (Note: 6 km max height)



High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Postfrontal CFAD differences (relative to OCEAN)



Windward/High Terrain: Deep layer of enhancement

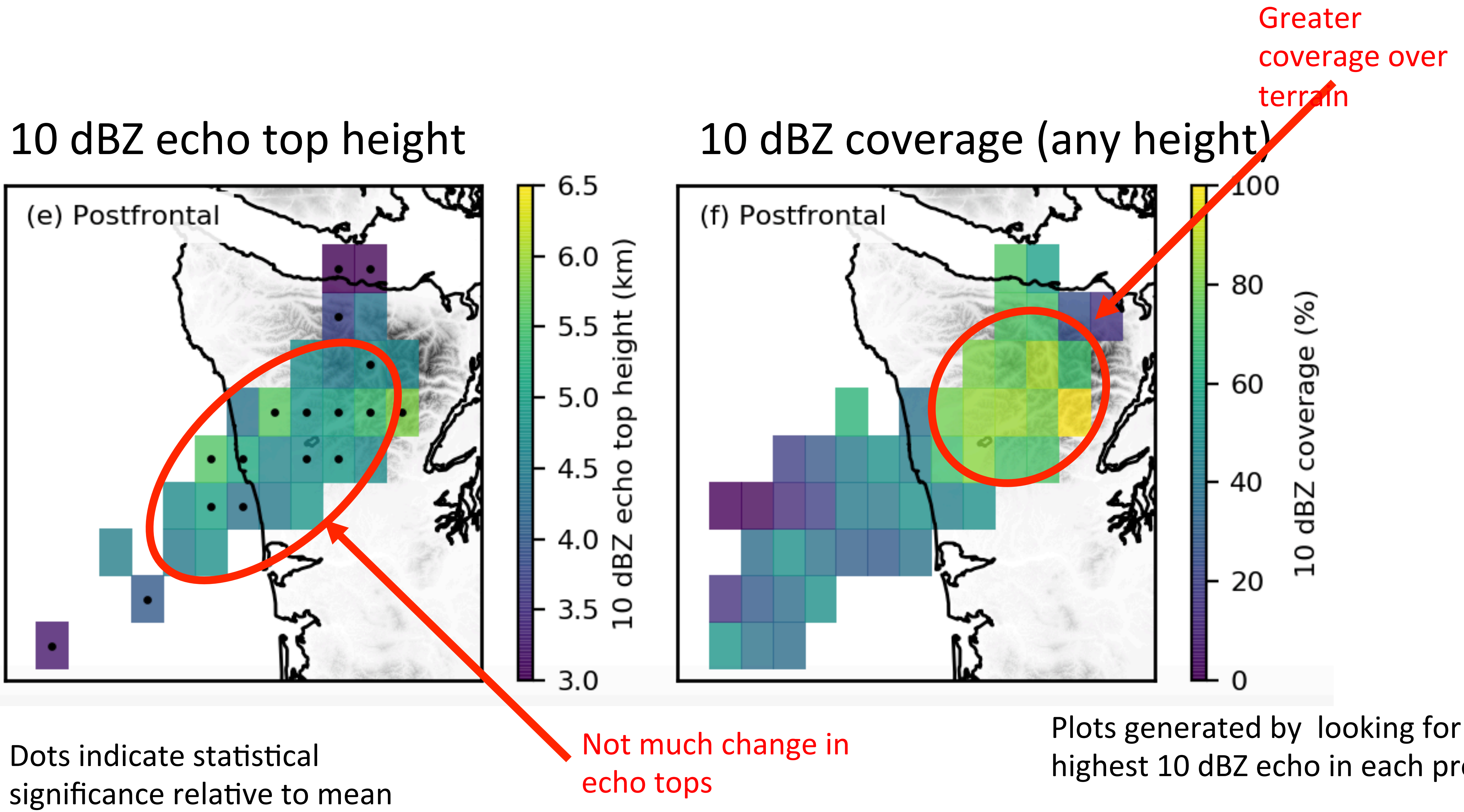
Blue: higher over ocean

Red: higher over comparison region

Lee: Diminished echo at higher levels--WNW flow advected shallow showers through Strait of Juan de Fuca

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Average height and coverage of 10 dBZ echo top



Dots indicate statistical significance relative to mean echo top height

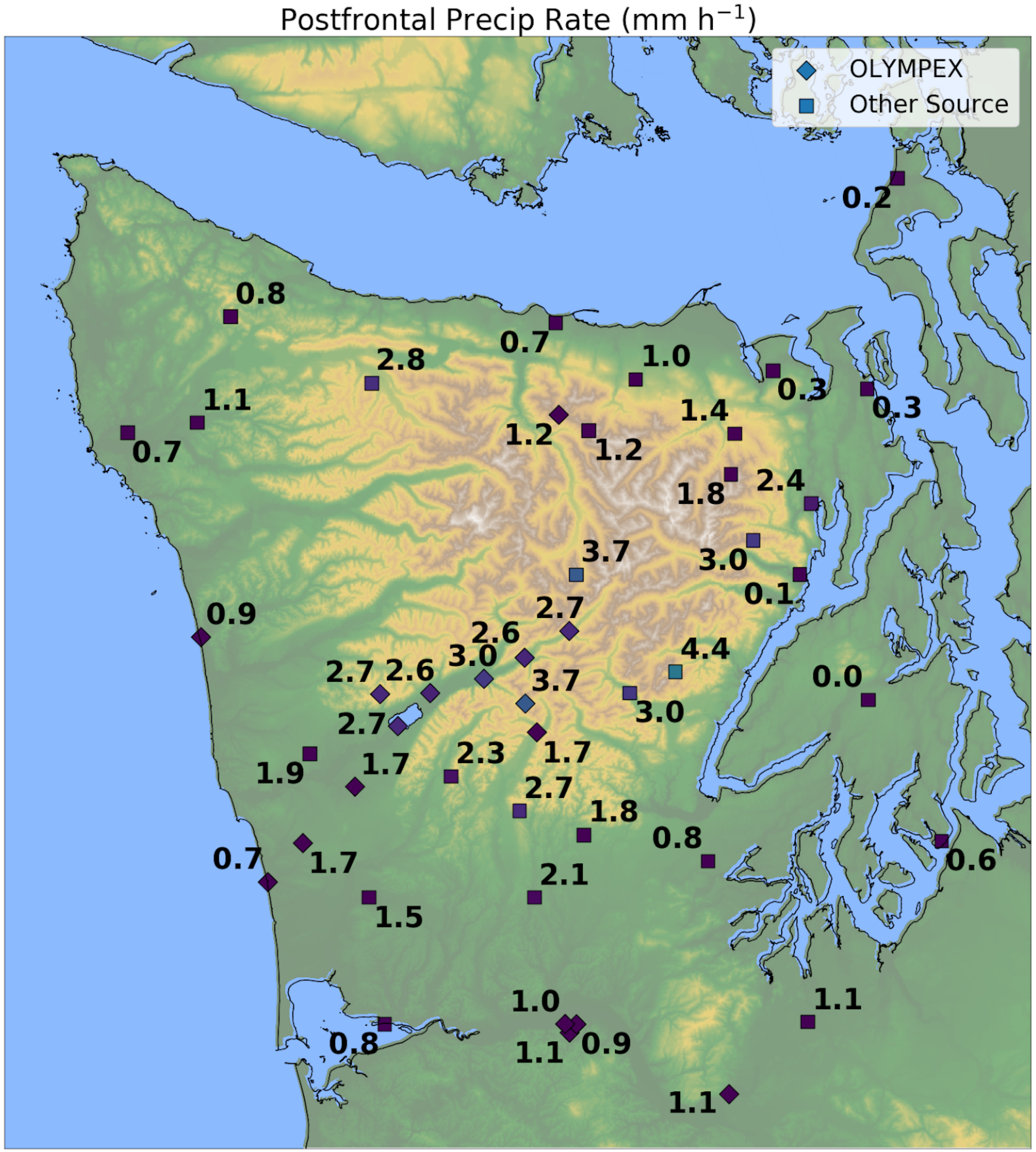
Plots generated by looking for highest 10 dBZ echo in each profile

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Windward maximum (present in all 3 sectors).

Weaker gradient of diminishment over high terrain/lee than prefrontal.

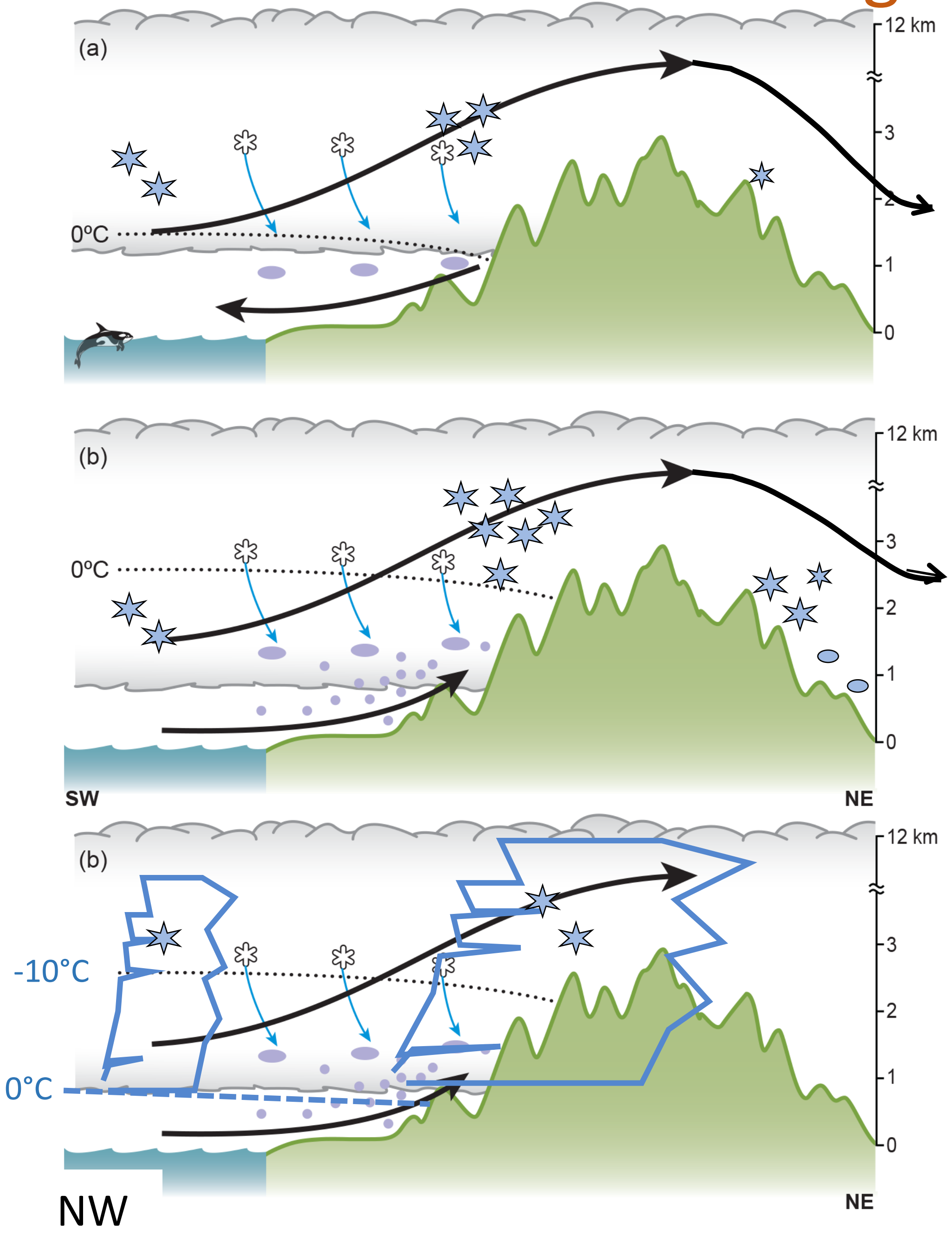
Considerable snow accumulation in postfrontal sector (low melting level + long event duration).



Average precipitation rate (mm h^{-1}) during postfrontal flights

High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

High Terrain/Leeside Diminishment Summary



Overall

- Windward enhancement/lee side diminishment omnipresent
- Degree varies with environmental conditions and storm sectors

Prefrontal

- Enhancement shifted upstream
- Near complete rainshadow

Warm Sector

- Deep intense enhancement
- Spill over onto lee side (from secondary enhancement aloft???)

Postfrontal

- Isolated convective cells over the ocean
- Transition to broader stratiform cells over the land
- Flow from W or NW, the climatological lee side is no longer the lee

Overall Conclusions

- Environmental conditions/Storm sectors regulate pattern of windward enhancement and lee side diminishment
- Windward enhancement the greatest during warm highly forced events (warm sectors, atmospheric rivers)
- Surprising result: warm precipitation processes can generate heavy rain without significant contributions from seeding by ice crystals (seeder-feeder) and shear-generated turbulence!!!
- Current/future work
- Utilize Canadian X-band radar to document lee side over full season
- Use citation aircraft to fully investigate the secondary enhancement layer
- Are warm rain processes responsible for WRF model underestimation of precipitation on windward side

Acknowledgements

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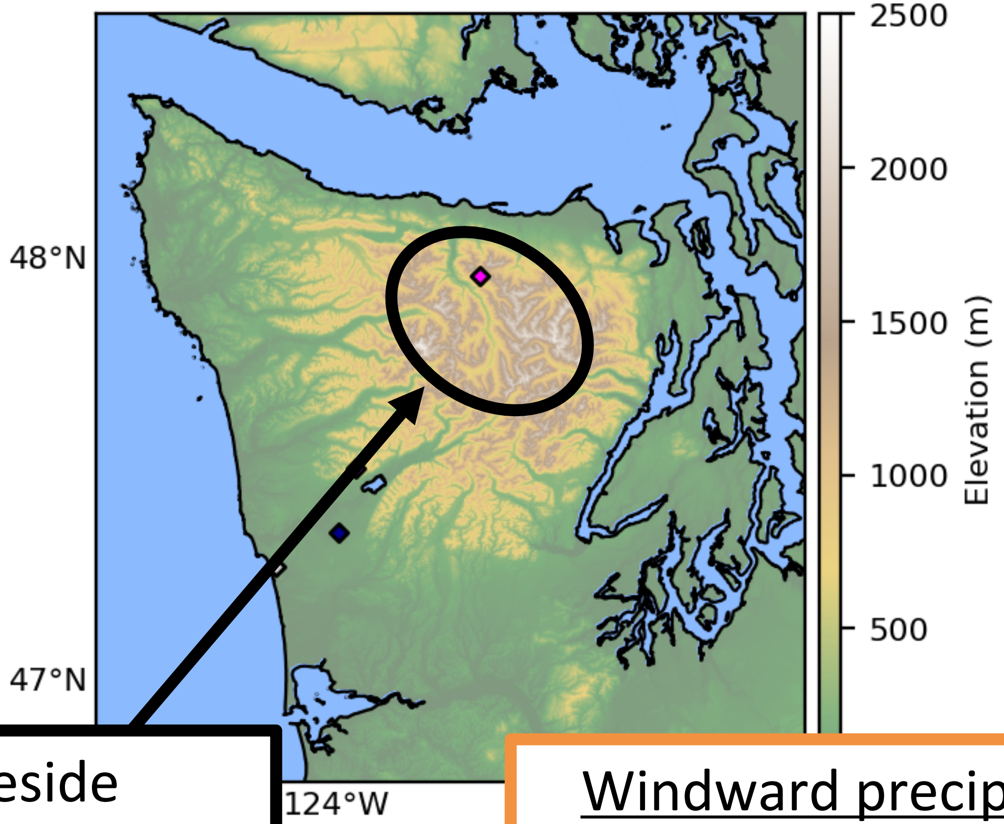
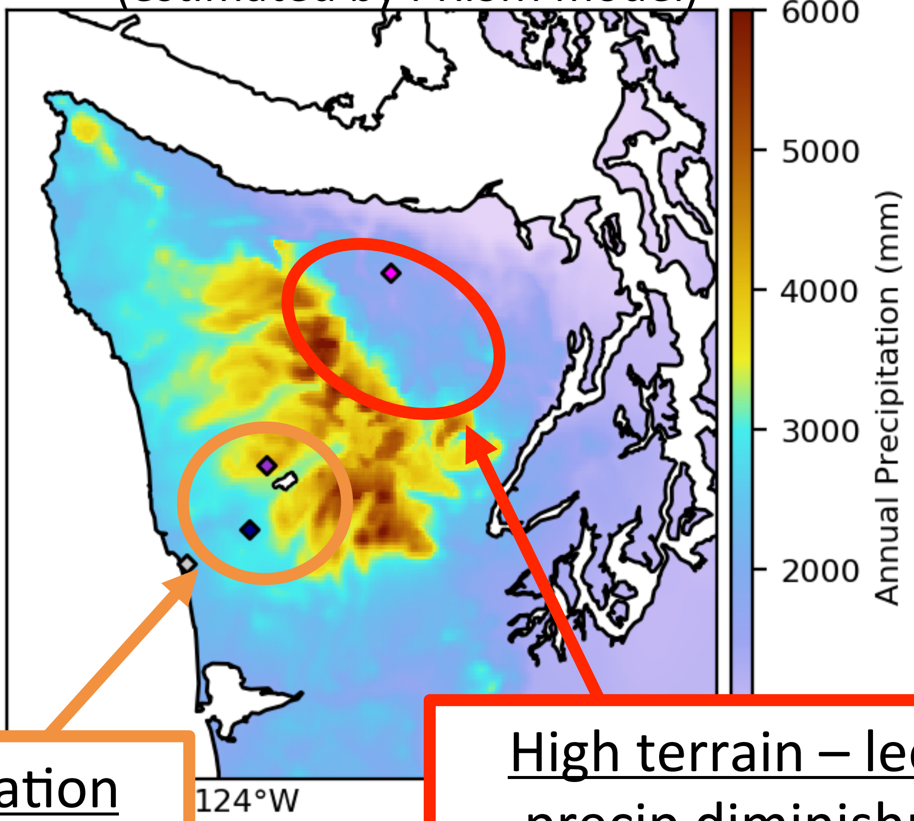
Topography



Precipitation Climatology

(estimated by PRISM model)



Leeside diminishment gradient is over high terrain

<u>Windward precipitation enhancement</u>

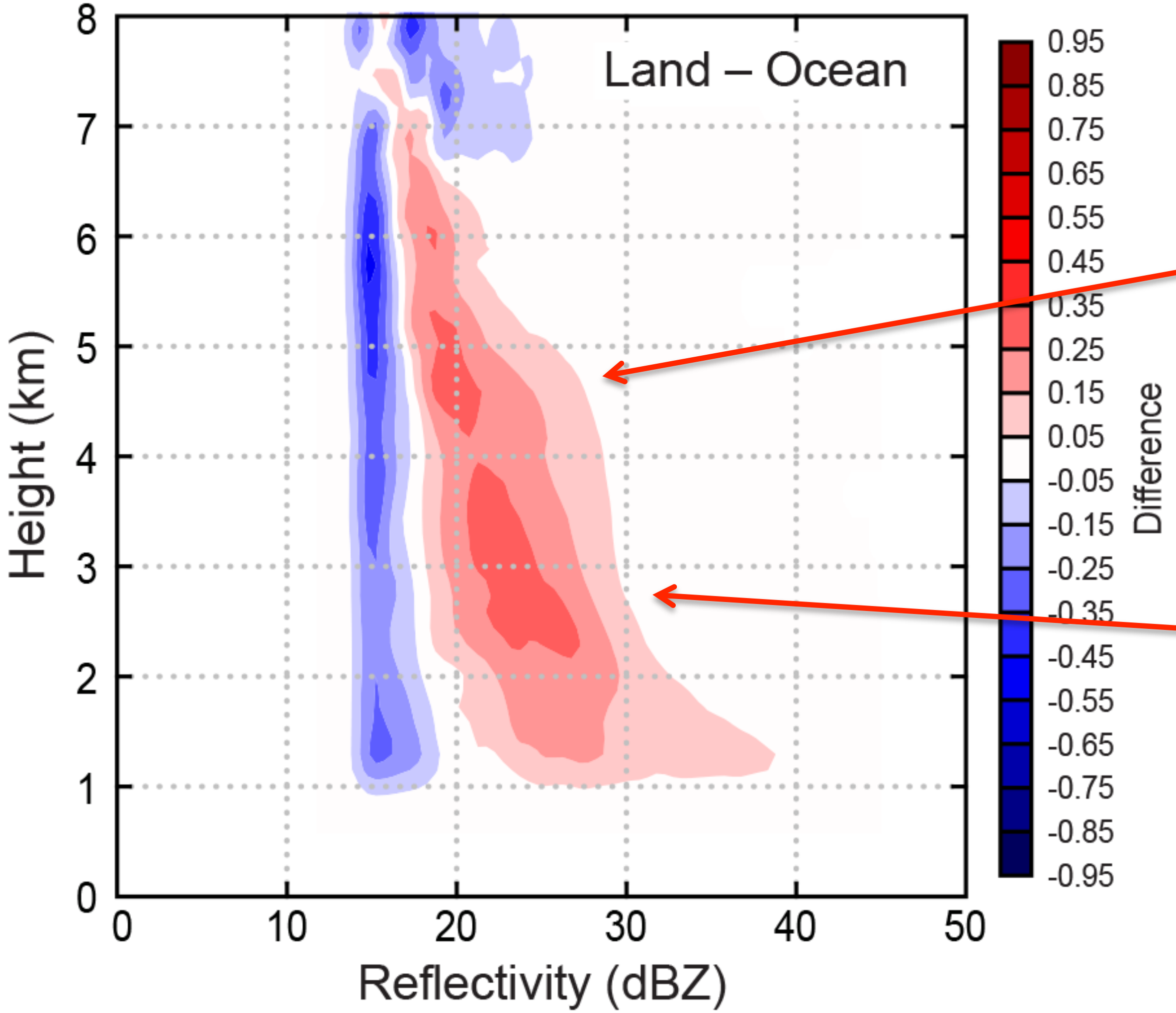
- Increase of 1.5-2x from coast to windward slopes
- Well observed by ground network + radars

<u>High terrain – lee side precip diminishment</u>

- Very strong downward precipitation gradient
- Poorly observed by ground network, well observed by aircraft

Orographic Enhancement Aloft from DPR

Land – Ocean **Difference** CFAD



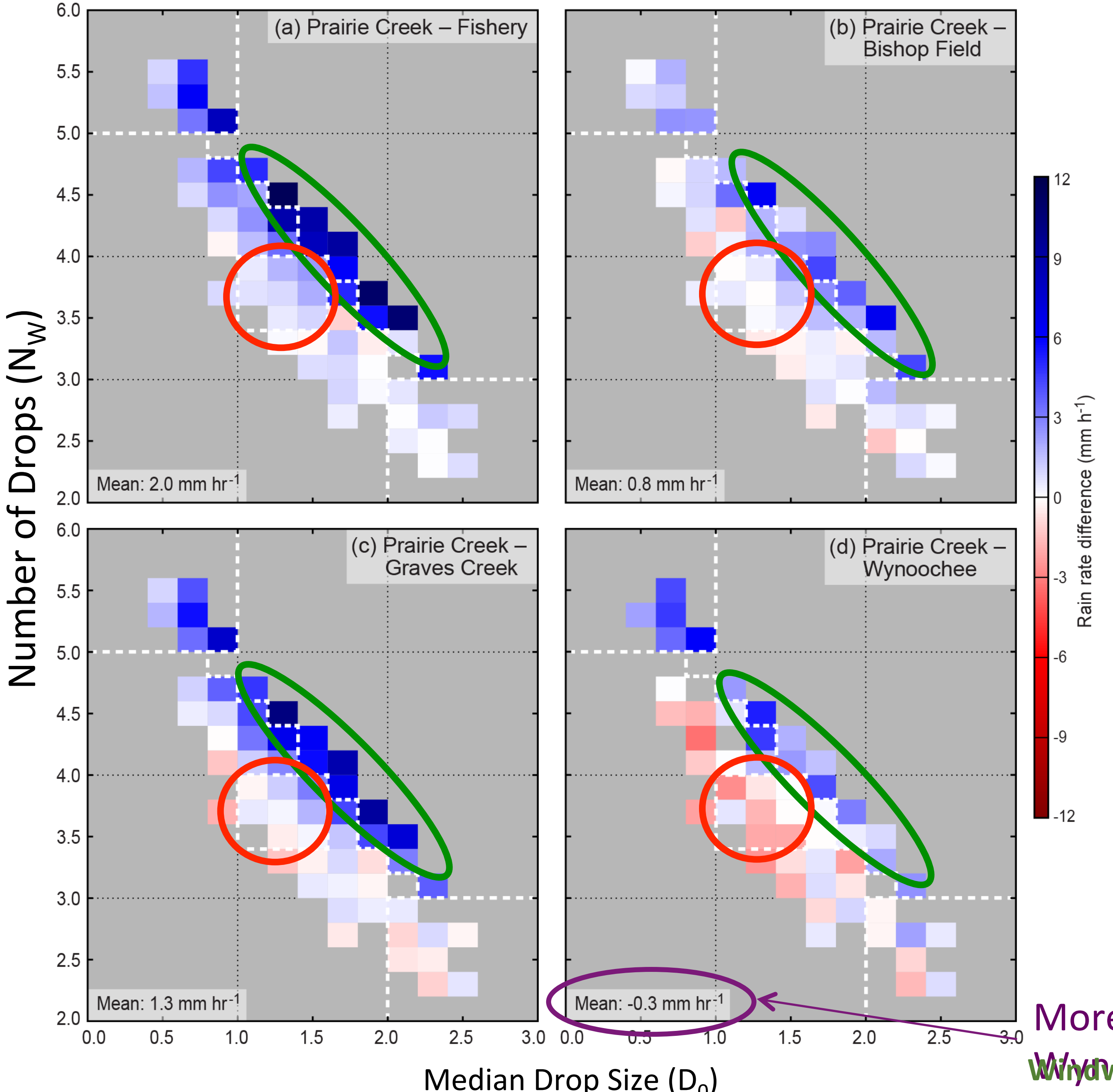
Same pattern as seen from NPOL

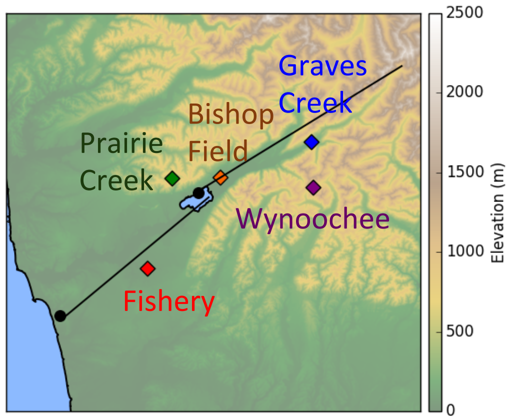
Greater frequency of higher reflectivities at all levels over windward slopes. Maximum at 4-5 km range.

Shift to higher reflectivity near melting level (2-3 km during warm events)

Windward Enhancement in McMurdie et al. 2018 (JGR in review)

Prairie Creek DSD vs. Orographic Enhancement





<u>For a given Prairie Creek DSD:</u>

Blue = more precip at Prairie Creek

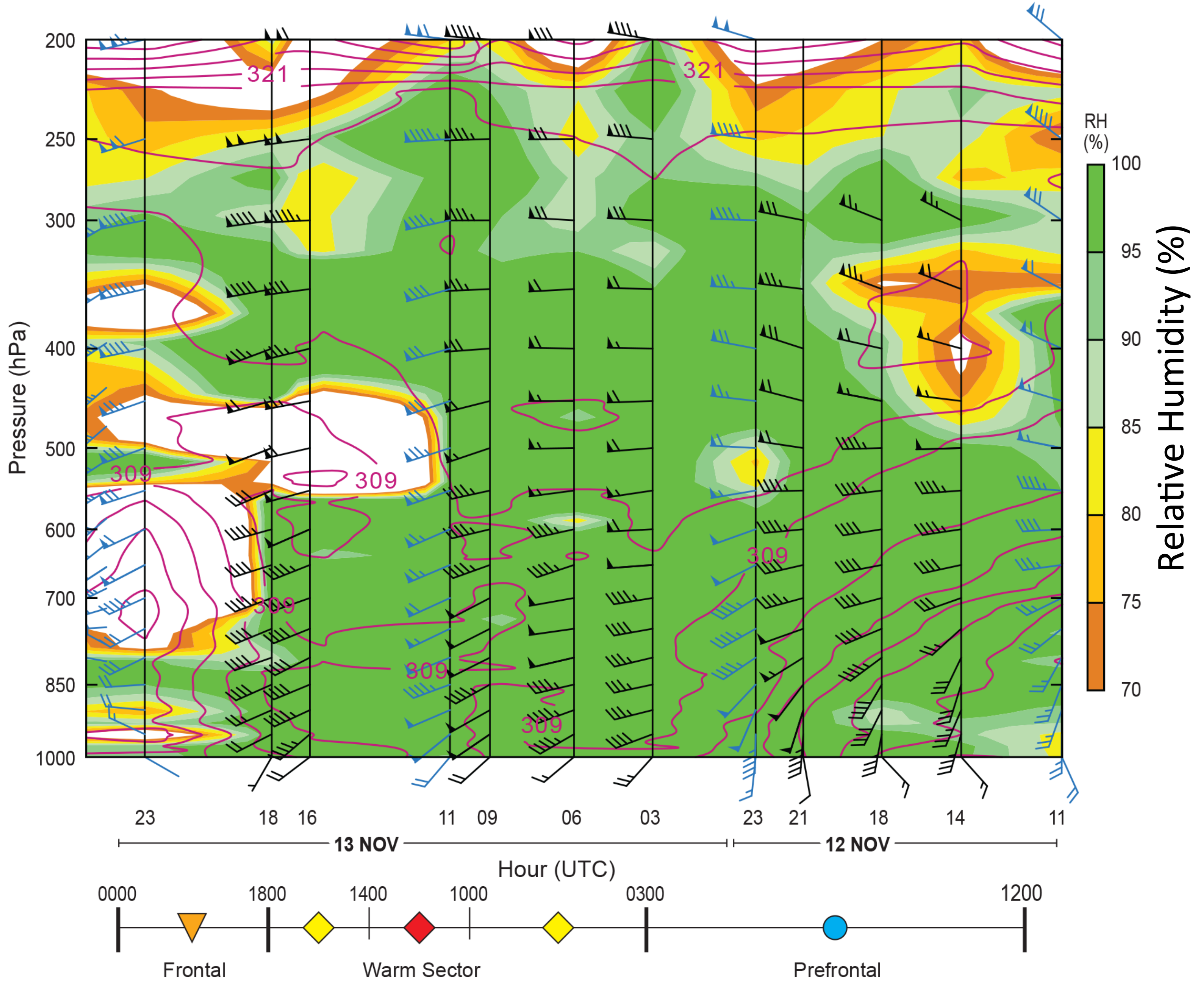
Red = less precip at Prairie Creek

White = same at both sites

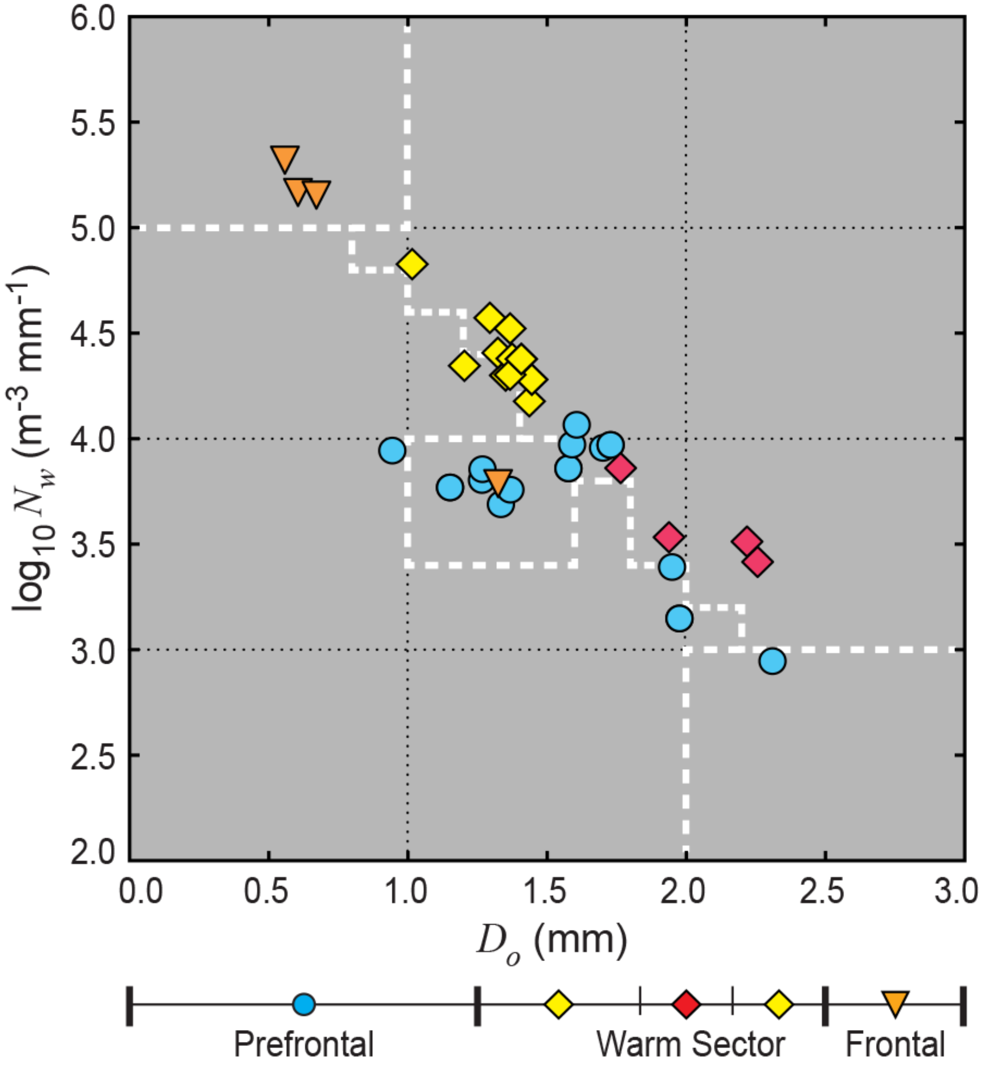
More total precip at Wynoochee

Windward Enhancement in Zagrodnik et al. 2018 (March

Cross-section of radiosonde observations at the coast



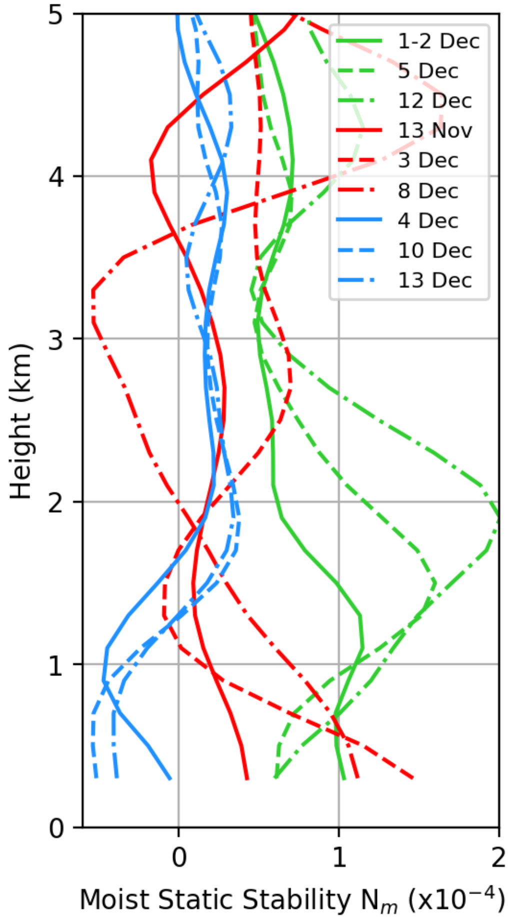
Prairie Creek 1-hour DSDs



Transitions in DSDs matched changes in storm sector
(Prefrontal -> Warm Sector -> Frontal)

Windward Enhancement in Zagrodnik et al. 2018 (March

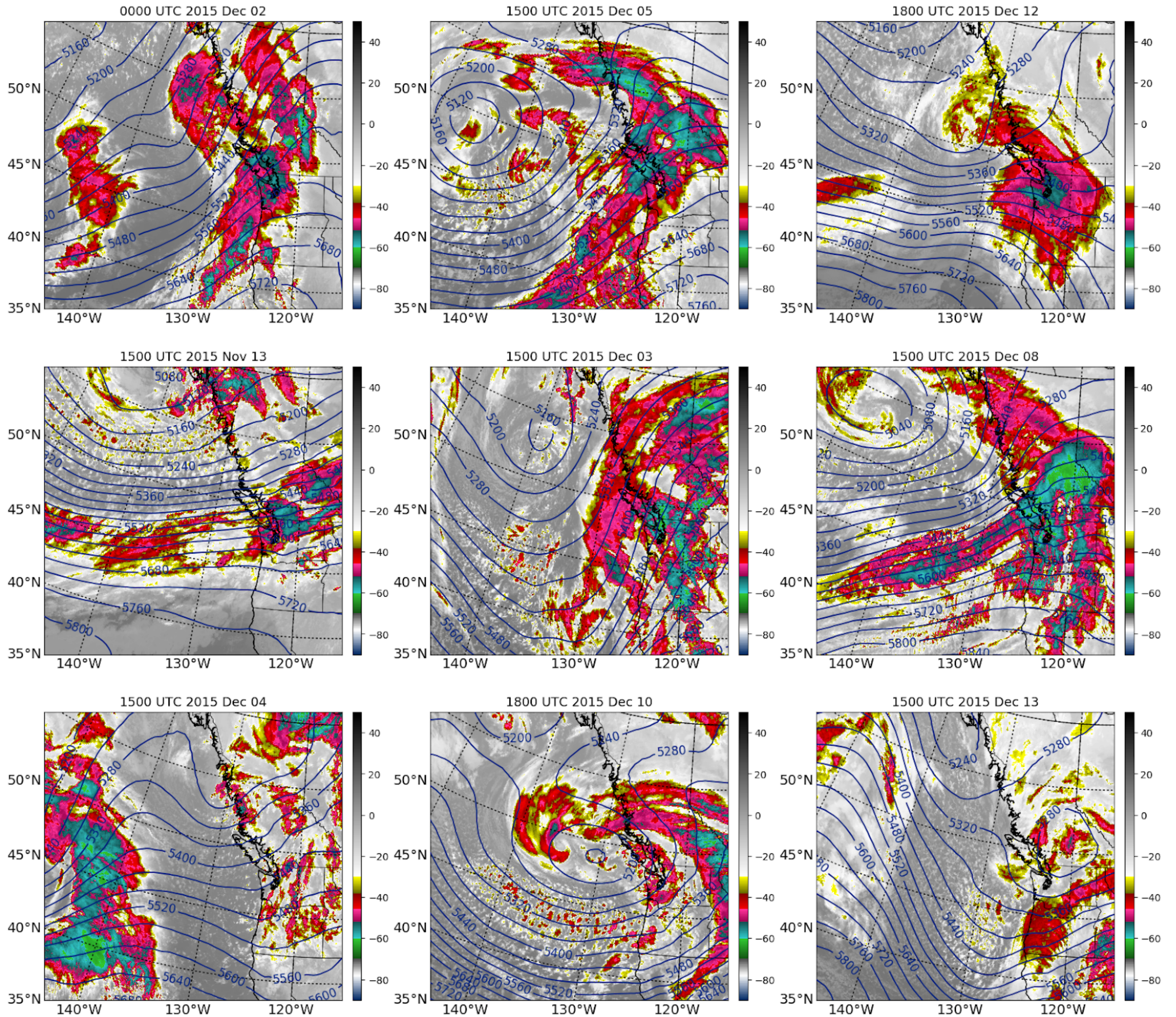
IR Satellite Imagery + 500 hPa heights during flights



Prefrontal

Warm Sectors

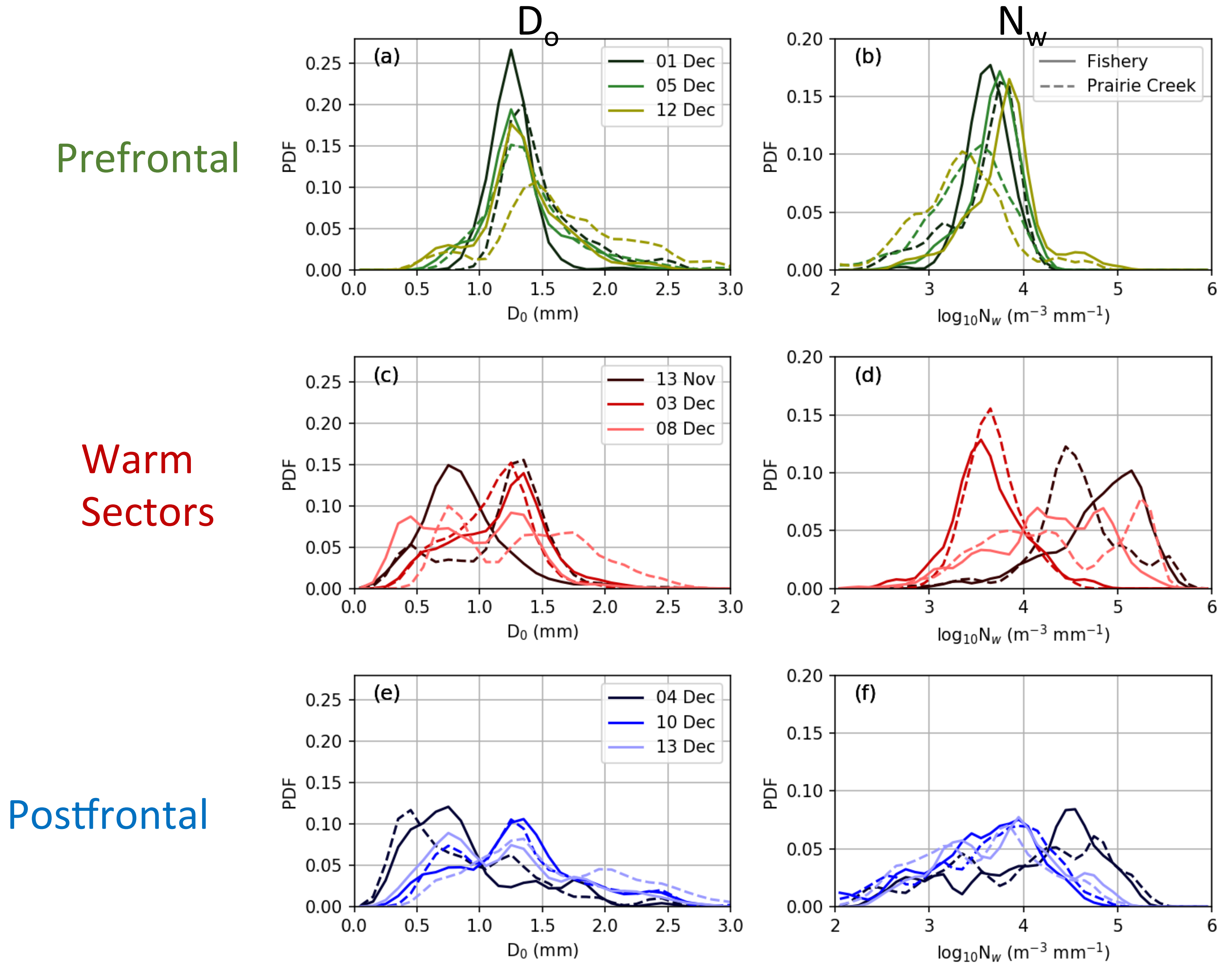
Postfrontal



Case study summary:

- Warm sector heavy rain events (Atmospheric Rivers) have most precip at low-to-mid elevations
  - Rain consists of mostly small-to-medium drops
  - Formed by condensation/collision-coalescence
  - Related to moist-neutral lifting of low-level jet
- Surprising result: warm precipitation processes can generate heavy rain without significant contributions from seeding by ice crystals (seeder-feeder) and shear-generated turbulence!!!

Windward DSD Parameter Histograms

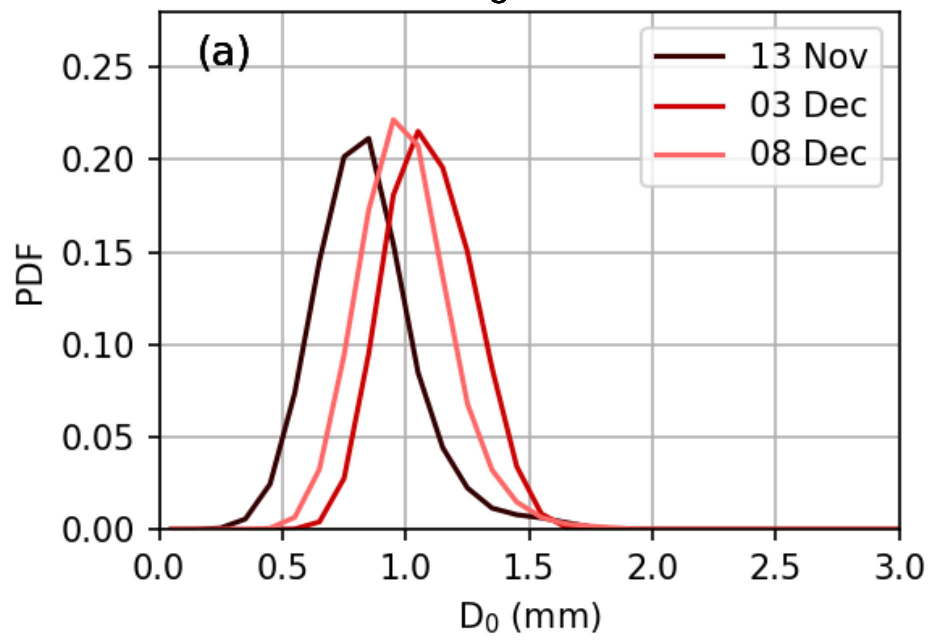


High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

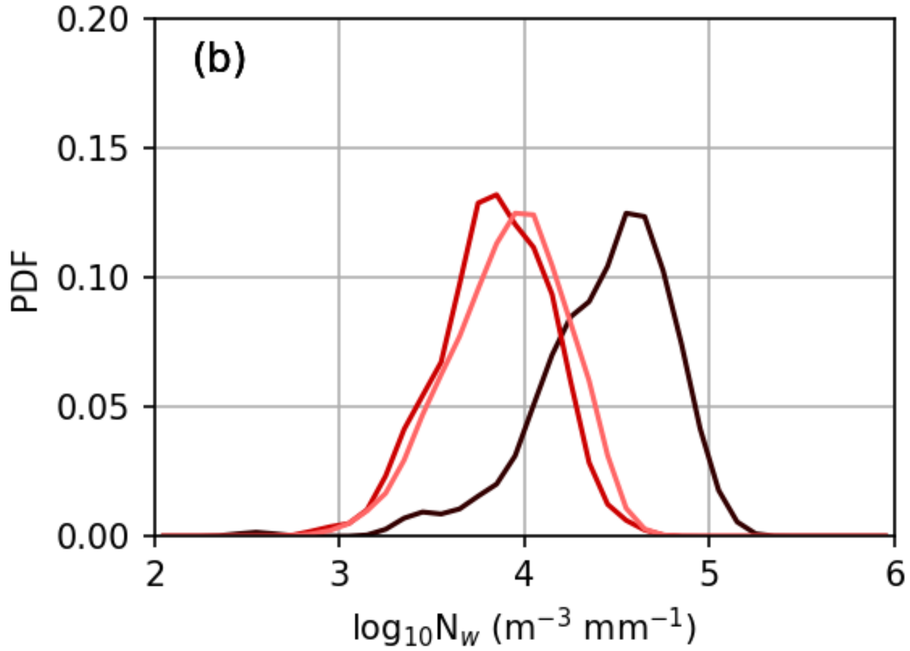
High Terrain (Hurricane Ridge) DSD Parameter Histograms

Warm Sectors

D_o



N_w



High Terrain/Leeside Diminishment in Zagrodnik et al. 2018 (JAS in review)

Conclusions from aircraft data

- Spatial distribution of precipitation modification (in horizontal and vertical) was strongly dependent on the **large-scale environment** associated with different **synoptic storm sectors**.

- **Windward enhancement** and **leeside diminishment** were omnipresent but details were **highly variable**:
  - Prefrontal: enhancement shifted upstream, near-complete lee rain shadow
  - Warm sector: deep, intense enhancement over mountains spilled over to lee
  - Postfrontal: convective to stratiform transition from coast to mountains

- Particle size distributions are highly variable in warm sectors.

Remember 12-13 November case study?