Kelvin–Helmholtz Waves in Precipitating Midlatitude Cyclones

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Outlines

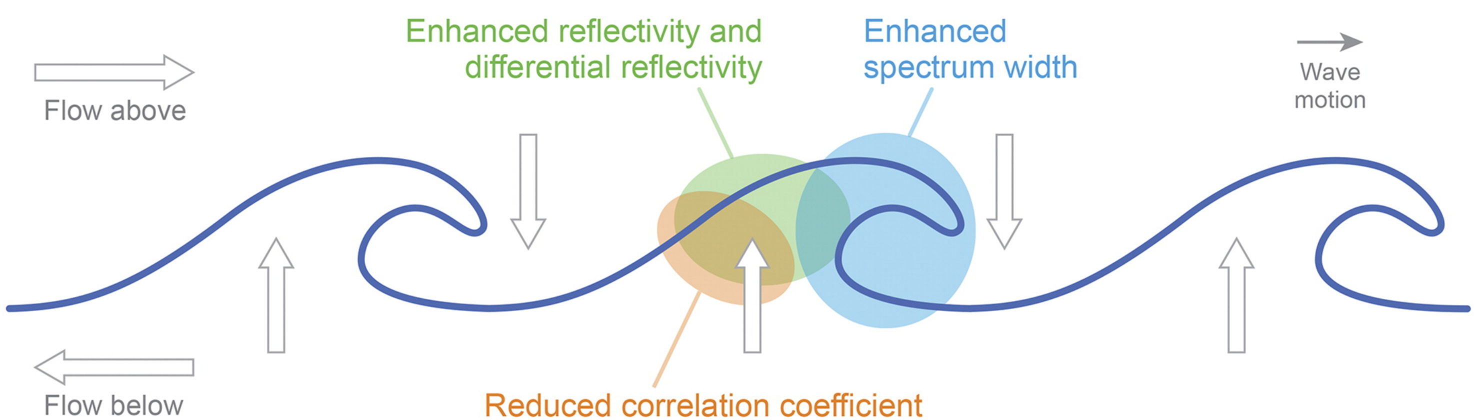
- Introductions and questions
- Data and methodology

- Large scale conditions
- PPI scans: KH waves
- RHI scans: KH waves
    - Above / within / below the melting level
- Ground observations

- Impact of topography
- summary

Introductions

- Houze and Medina (2005)
  - They provided evidence from aircraft that aggregation is increased by wave-enhanced turbulence. This aggregation in turn further enhances riming and accretion by increasing the size of the collector ice particles.
- Houser and Bluestein (2011)



Questions…

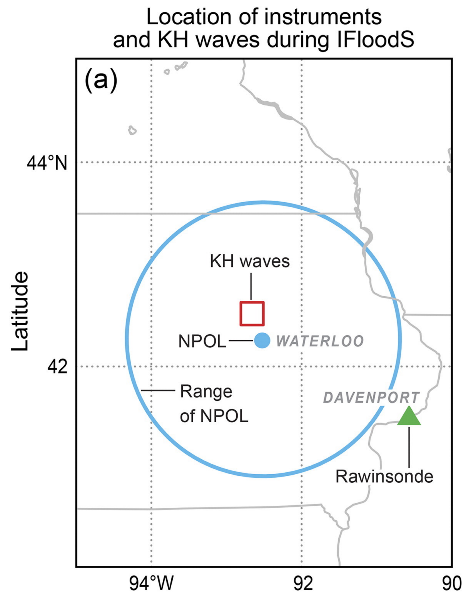
- How KH waves change microphysical processes above, within, and below the melting layer
- Whether those microphysical changes are significant enough to influence precipitation accumulations at the surface
- How terrain impacts KH waves.

Data and Cases

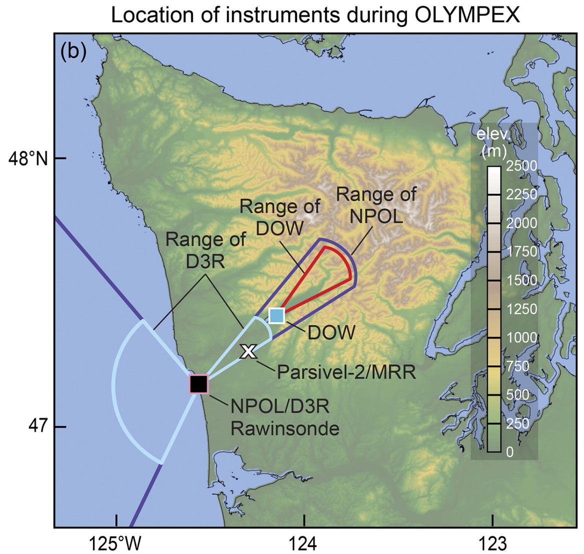
TABLE 1. Description of the time, duration, location, data available, and frontal features associated with each KH wave event.

Start date	Start time (UTC)	Duration (h)	Location	Elevation (km)	Location relative to bright band	Front
2 May 2013	1230	<1	Iowa	1–3	Within	Stationary
9 Dec 2015	0700	<1	Washington coast	4–6	Above	Nonfrontal
12 Dec 2015	2030	~1	Quinault Valley	1–3	Within	Occluded
17 Dec 2015	1200	6	Pacific Ocean, Washington coast, Quinault Valley	0–2	Below	Occluded

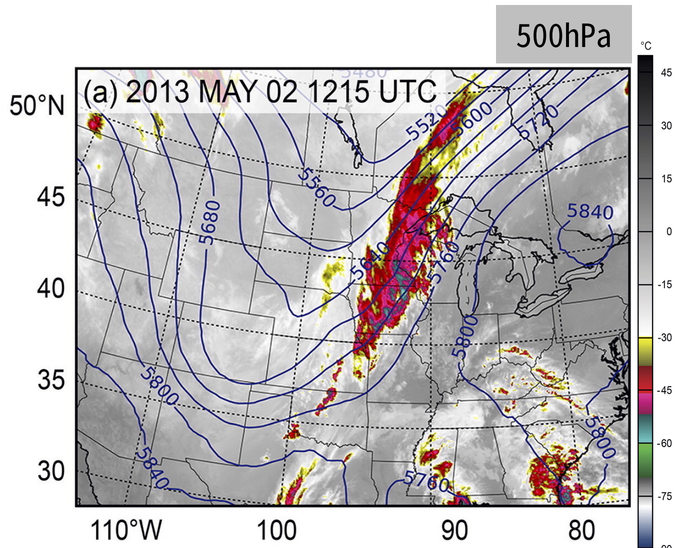
IFloodS May-Jun 2011

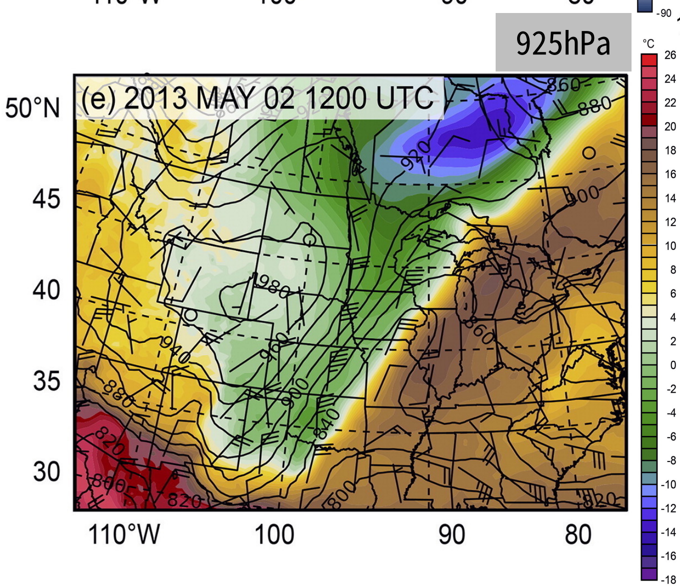


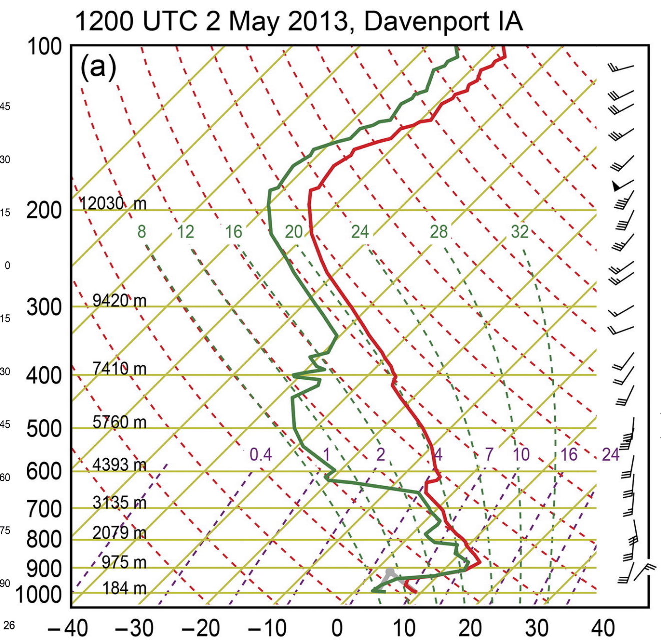
OLYMPEX 2015/16 winter

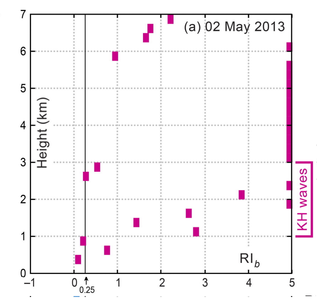


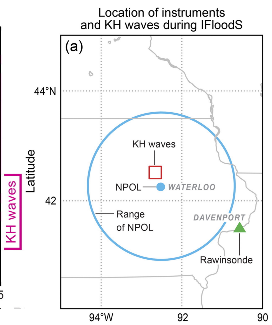
Large scale conditions: IFloodS











$$\mathrm{Ri_b} = \frac{N_d^2}{(\partial u/\partial z)^2}$$

N_d: dry Brunt-Väisälä frequency

$\mathrm{Ri_b}$: bulk Ri (0.25-km intervals)

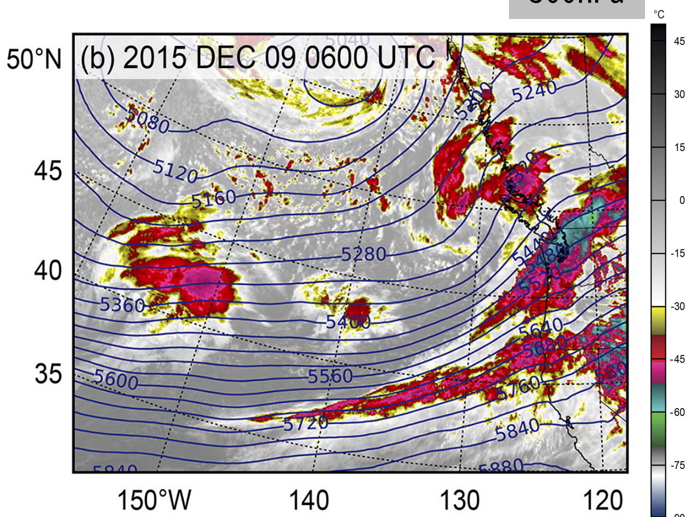
Ri<0.25: KH waves can develop (Miles and Howard 1964)

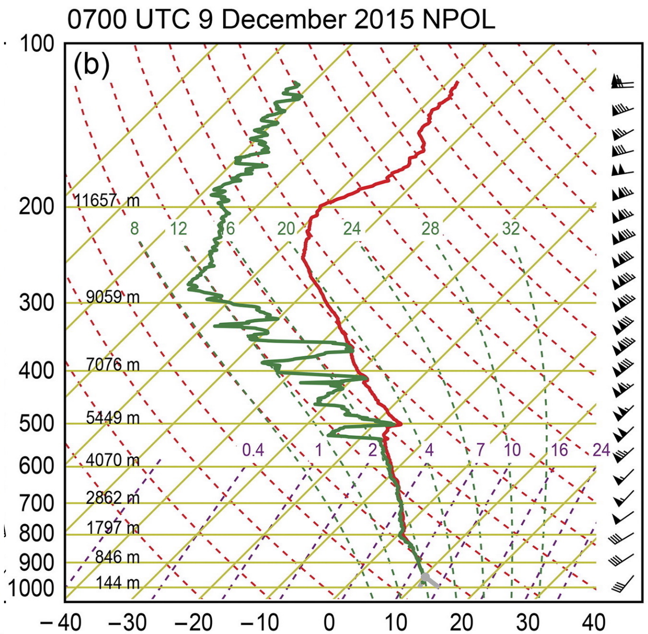
Ri<1.00: KH waves can be sustained (Weckwerth and Wakimoto 1992)

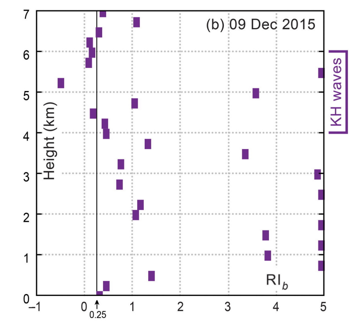
- Similar to the Oklahoma case analyzed by Houser and Bluestein (2011), which also was a snow event. The NWS noted that this was an unusually strong front. The duration is less than 1 hour.

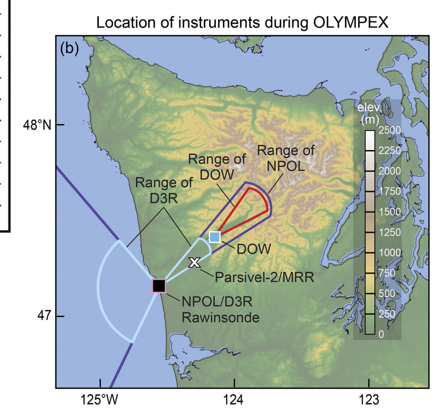
Large scale conditions: OLYMPEX [above]

500hPa

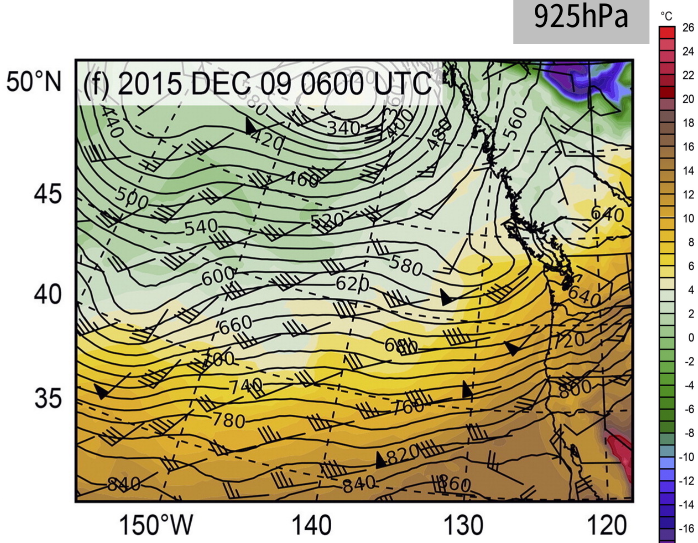








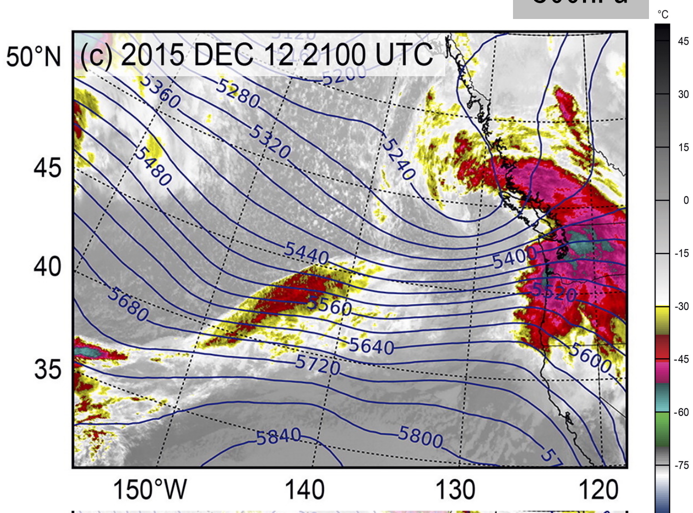
925hPa



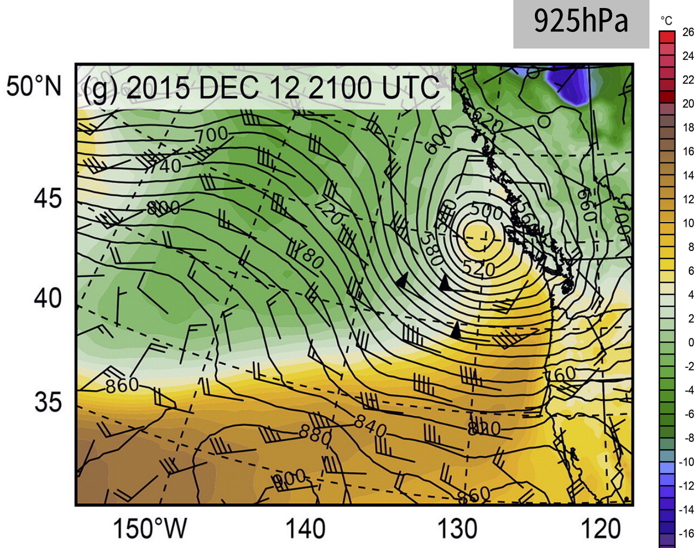
- The large scale conditions are consistent with the atmospheric river.
- KH waves are above the melting levels (4~6km). The duration was less than one hour.

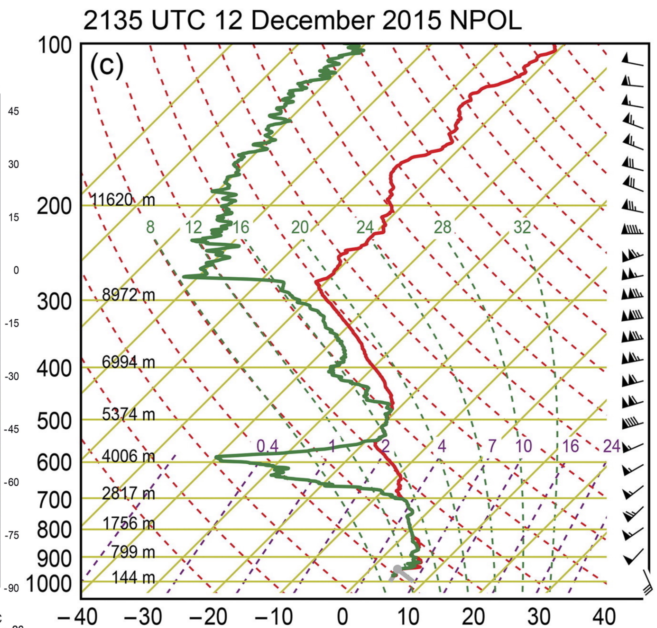
Large scale conditions: OLYMPEX [within]

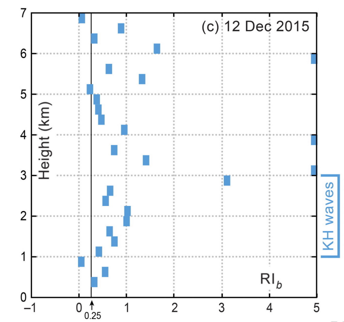
500hPa

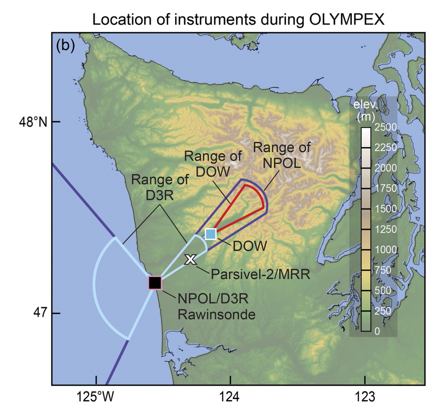


925hPa



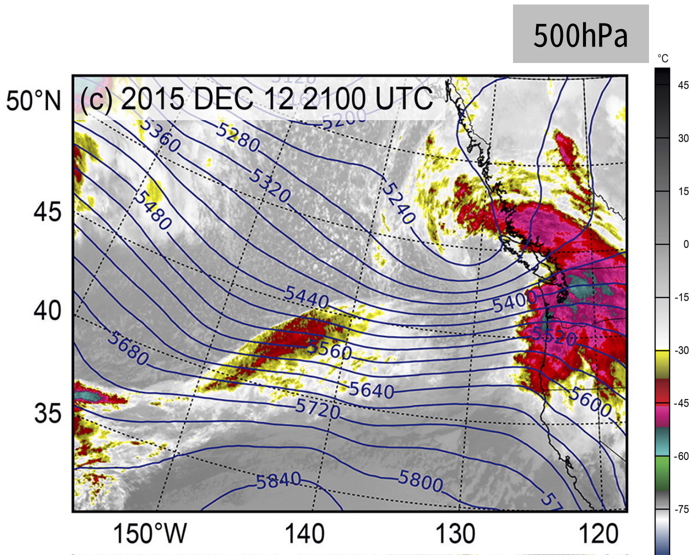


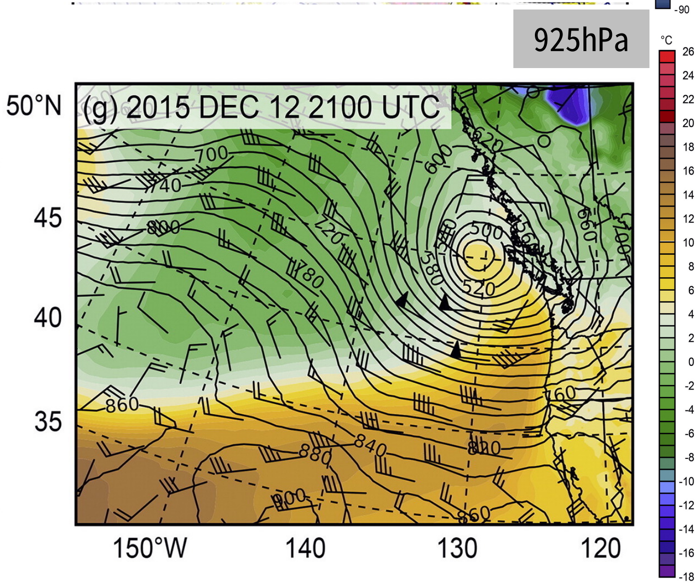


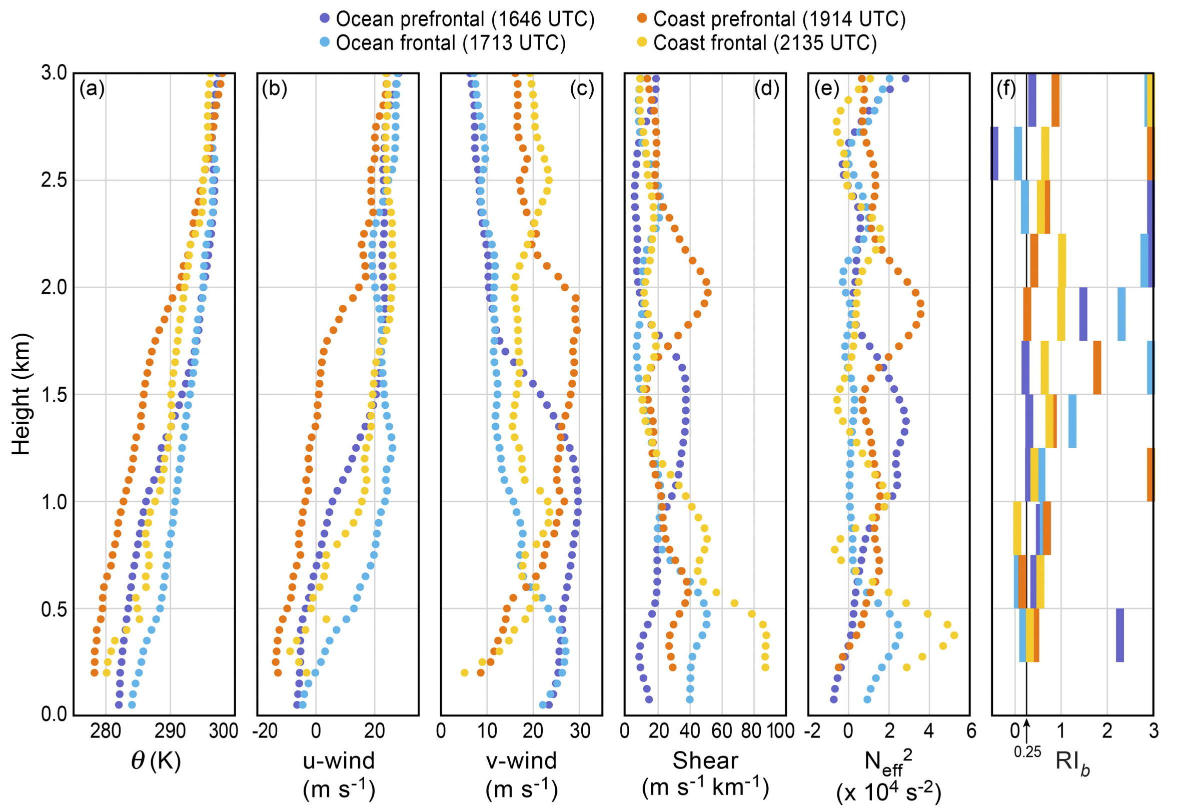


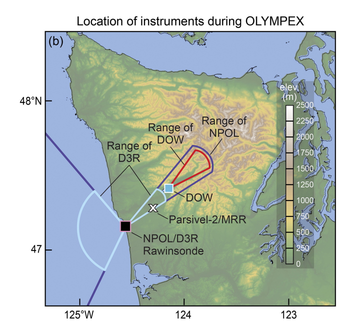
- Front was associated with a small sheared, stable layer near 925 hPa.
- KH waves are within the melting levels (1~3km). The duration was about 1 hour.

Large scale conditions: OLYMPEX [within]





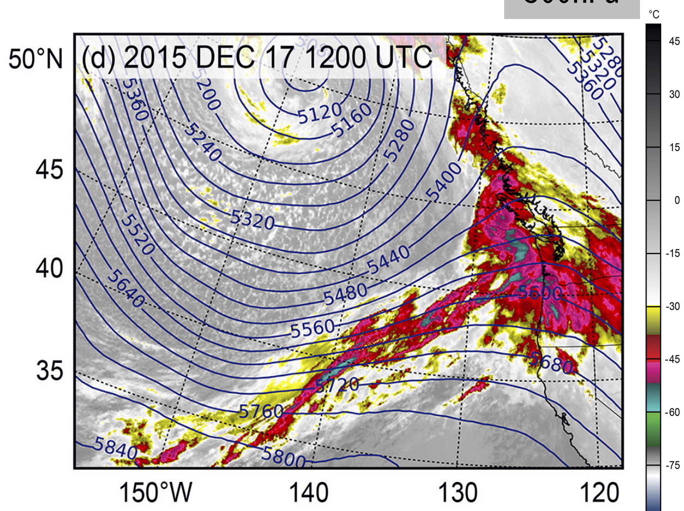




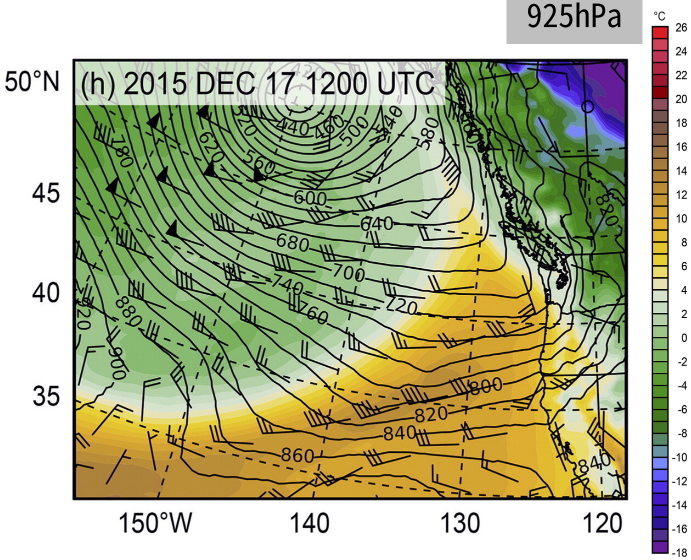
- Better condition: increased low-level shear and stability.
- KH waves was facilitated by the topography.

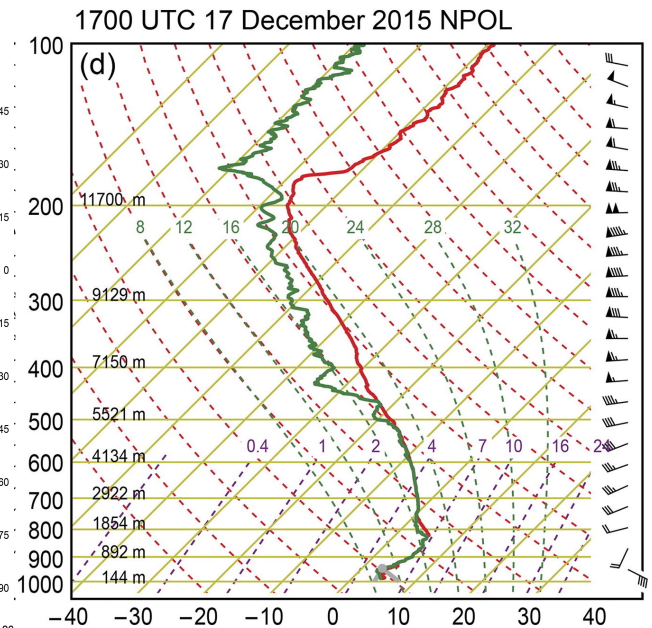
Large scale conditions: OLYMPEX [below]

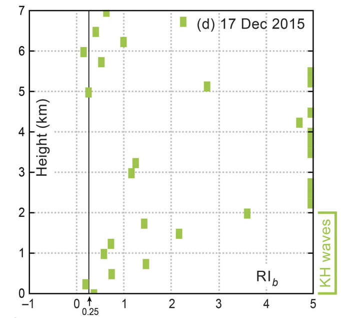
500hPa

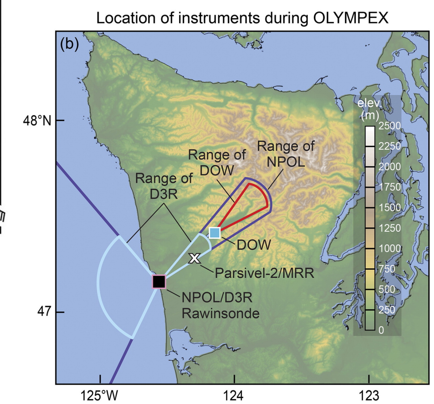


925hPa



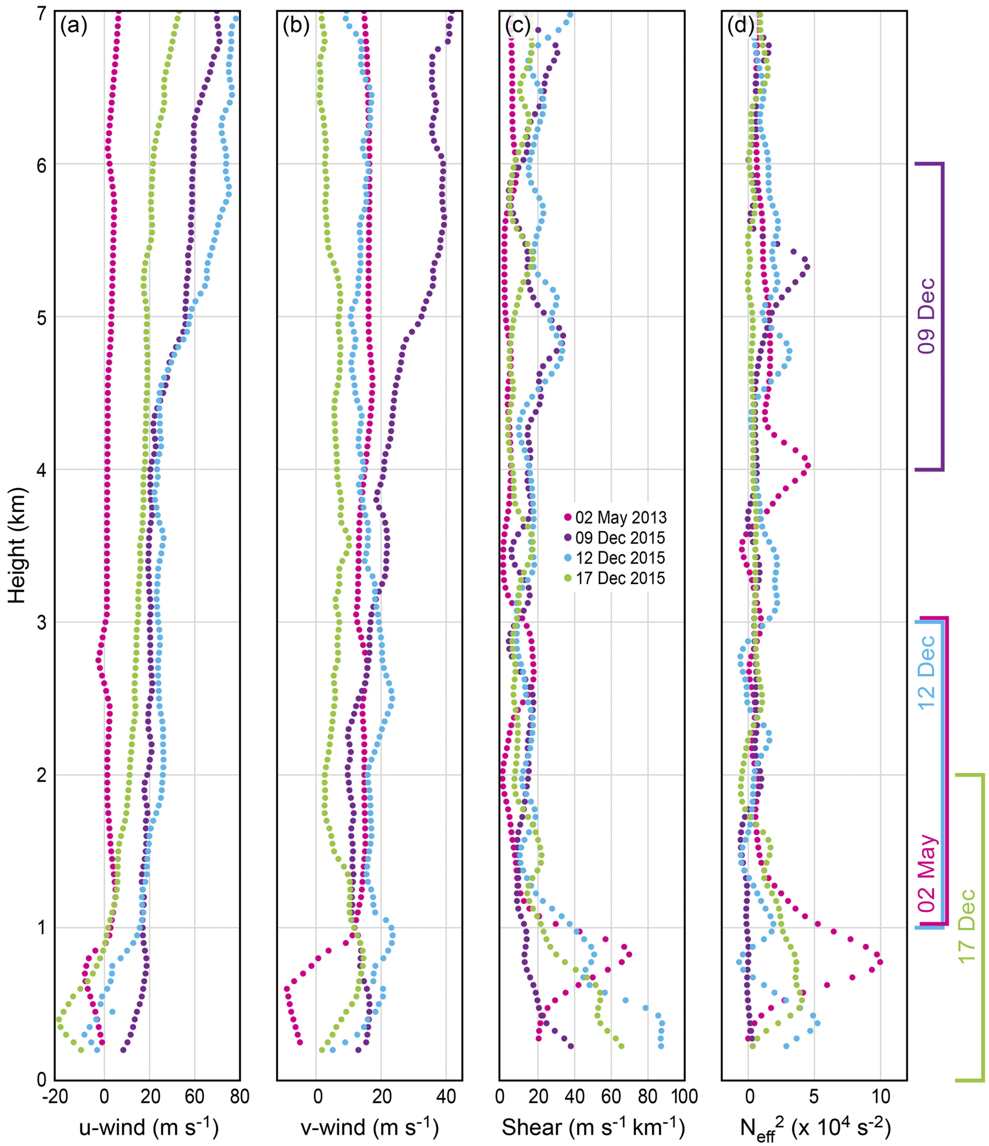






- Another occluded front.
- KH waves are below the melting levels (1~3km). The duration was 6 hours.

Large scale conditions: IFloodS, OLYMPEX



- KH waves were not unique to one type of front.
- IFloodS : much higher effective static stability (N_{eff}; N_m^2 if RH>90%, N_d^2 otherwise) and strong temperature gradient.
- OLYMPEX: lots of observed KH waves. Terrain may enhance vertical shear and thus enable KH waves to develop more easily. (Houze and Medina 2005)

PPI scans: KH waves

IFloodS: 2 May 2013 1251 UTC 3.5°

OLYMPEX:17 Dec 2015 1454 UTC 0.5°

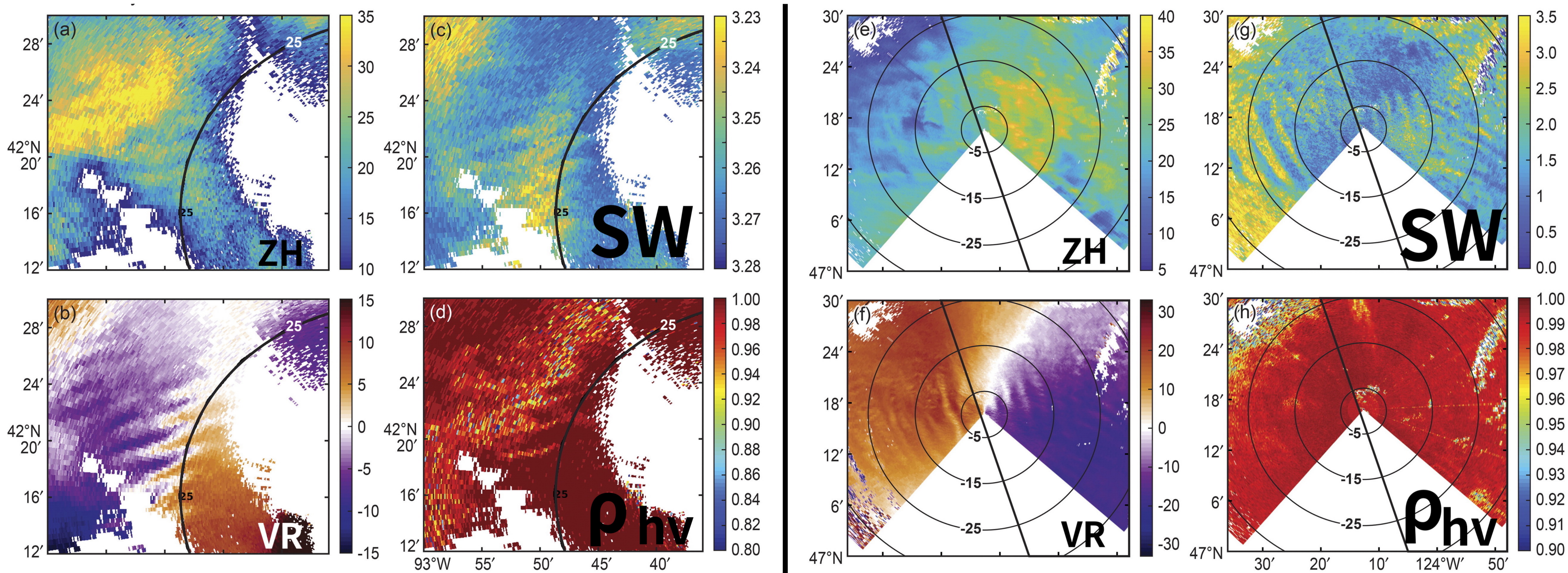
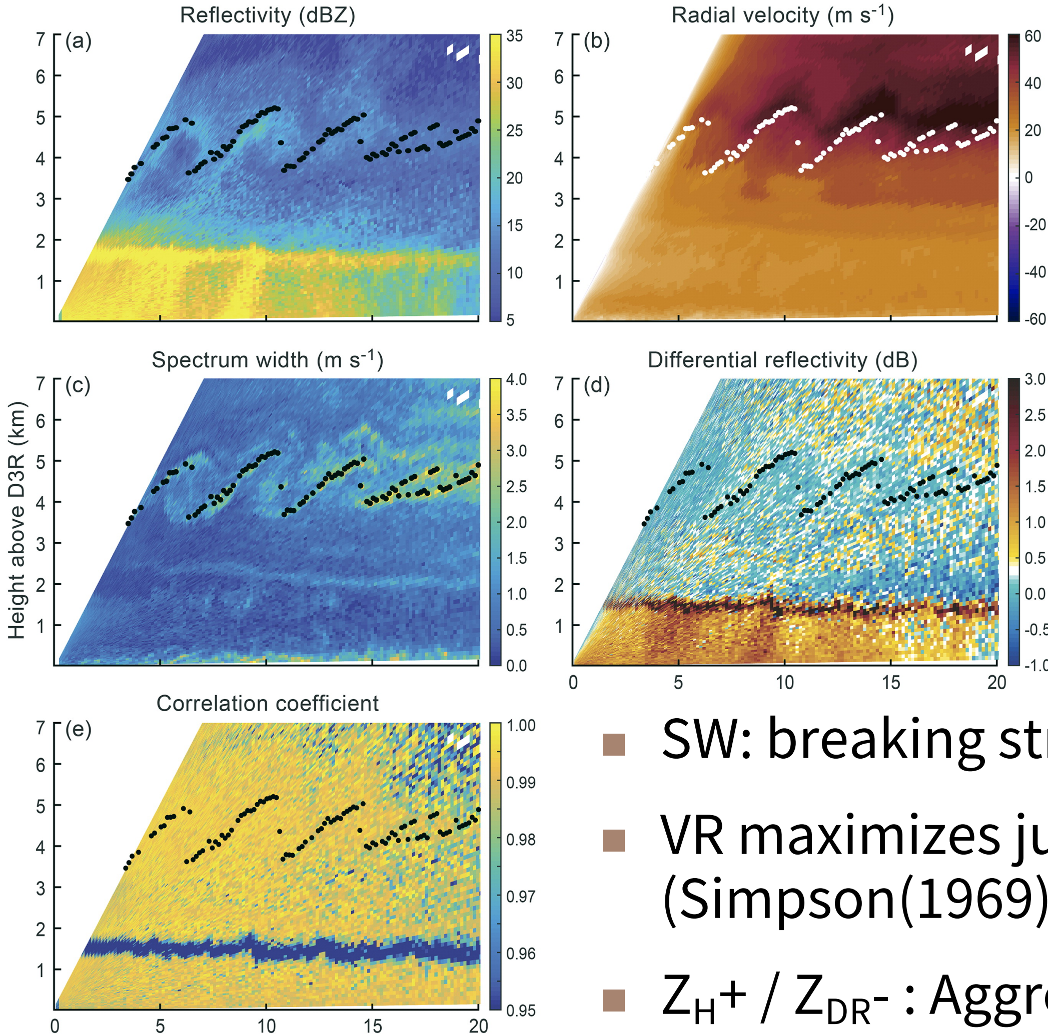
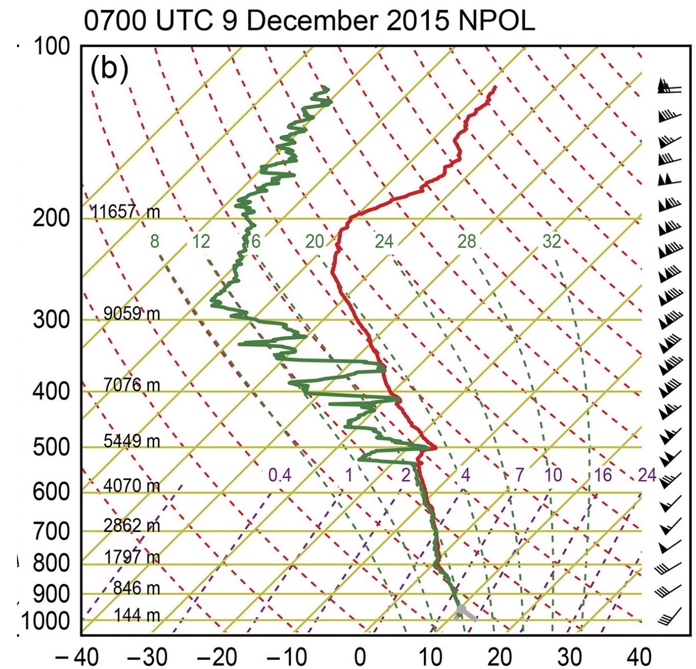


FIG. 8. (left) Radar variables from the 3.5° PPI scan from the NPOL located near Waterloo at 2151 UTC 2 May 2013: (a) reflectivity (dBZ), (b) radial velocity (m s^{-1}), (c) spectrum width (m s^{-1}), and (d) correlation coefficient. The black semicircle is the 25-km radar range ring. (right) Radar variables from the 0.5° PPI scan from the Ku band of the D3R during OLYMPEX at 1454 UTC 17 Dec 2015: (e) reflectivity (dBZ), (f) radial velocity (m s^{-1}), (g) spectrum width (m s^{-1}), and (h) correlation coefficient. The black circles show the 5-, 15-, and 25-km radar range rings. The diagonal black line represents the Washington coast.

RHI scans: KH waves (above ML)





- SW: breaking structure. (4~6 km AGL)
- VR maximizes just above crest of KH waves. (Simpson(1969) and Wakimoto et al (1992))
- Z_H+ / Z_{DR}- : Aggregation

FIG. 9. Radar variables from an RHI scan from the Ku band of the D3R at an azimuthal angle of 56° at 0706 UTC 9 Dec 2015: (a) reflectivity (dBZ), (b) radial velocity (m s^{-1}), (c) spectrum width, (d) differential reflectivity (dB), and (e) correlation coefficient. The black dots in (a) and (c)–(e) and the white dots in (b) show the location of the maximum spectrum width in each vertical column.

RHI scans: KH waves (within ML)

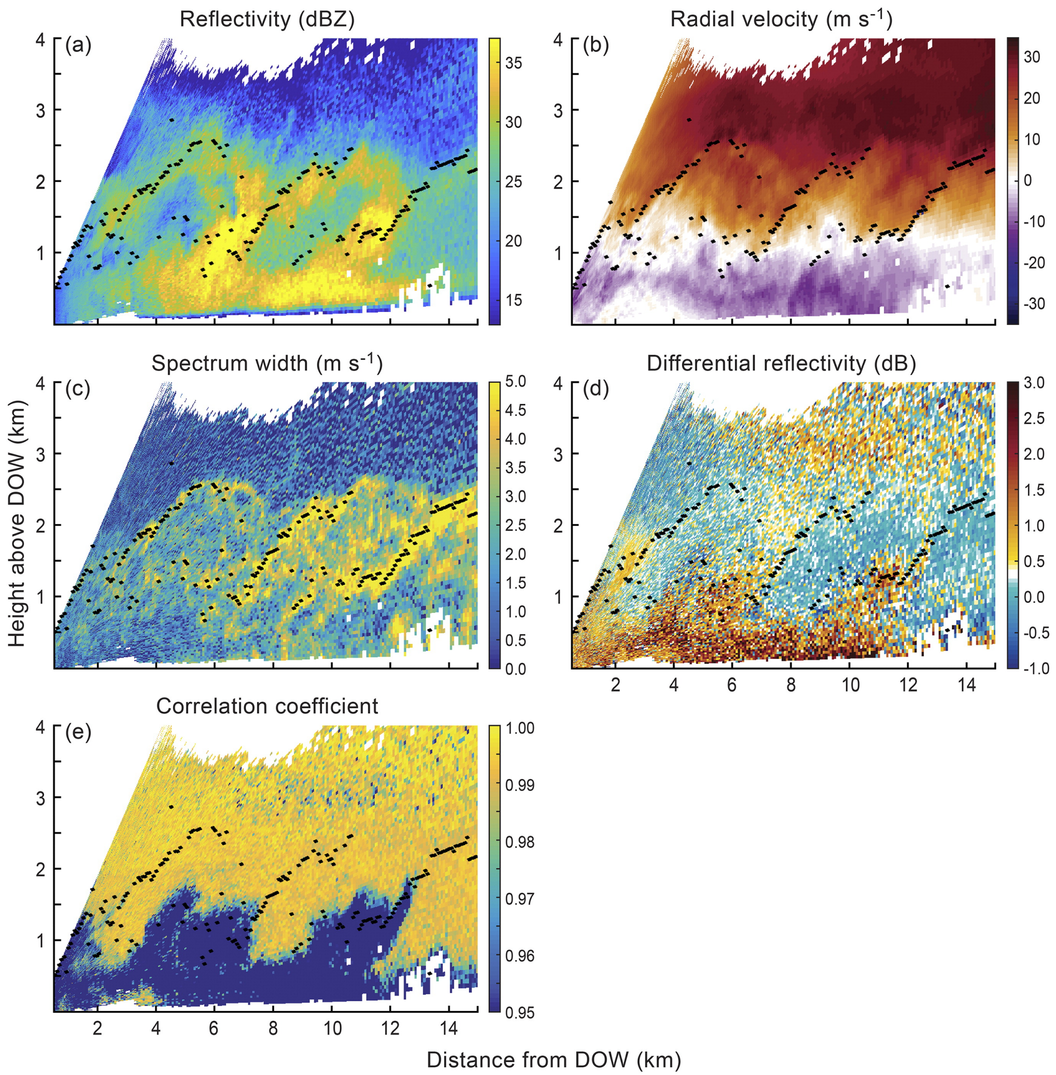
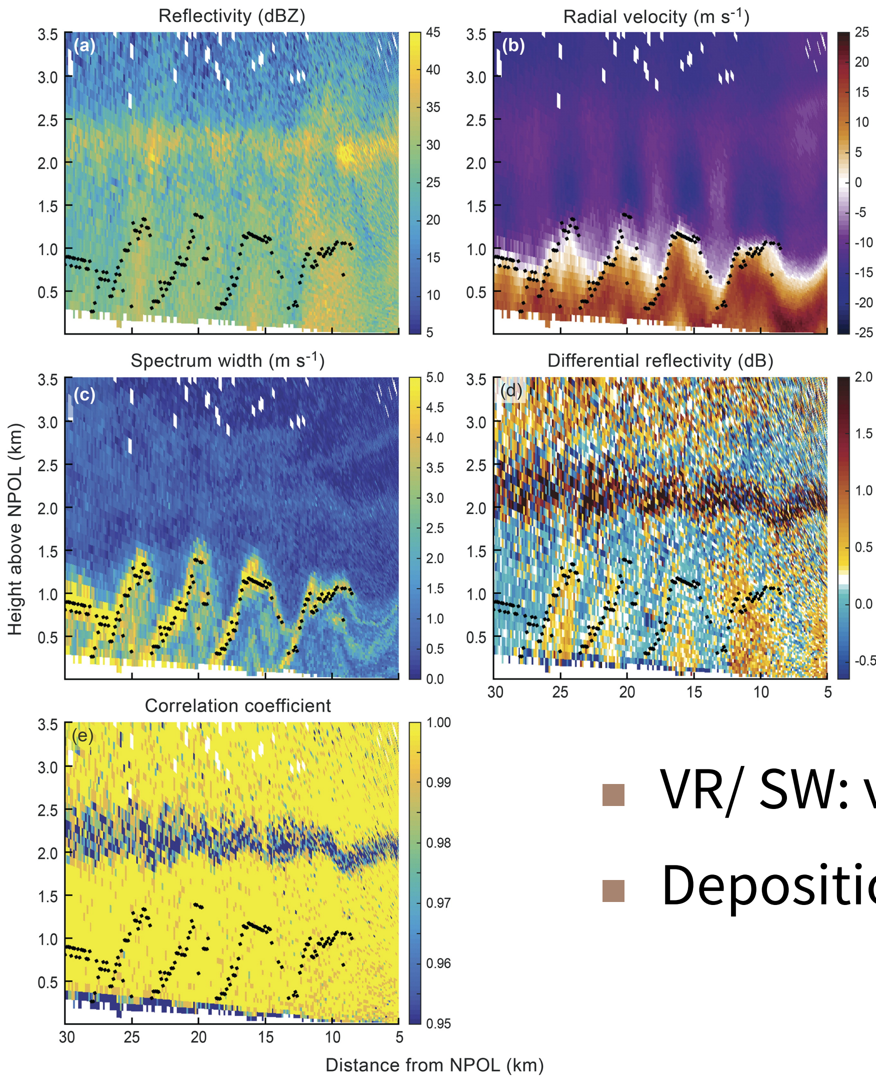


FIG. 10. As in Fig. 9, but for an RHI scan from the DOW radar at an azimuthal angle of 54° at 2110 UTC 12 Dec 2015. The black dots show the location of the maximum spectrum width in each vertical column.

- KH waves induce riming (surface ~ 1.5km AGL)
- KH waves induce aggregation (> 1.5km AGL)
- Compared to Houser and Bluestein (2011):
  - Similar Z_H Z_{DR} ρ_{hv}.
  - More expansive Z_H ρ_{hv} in OLYMPEX
  - Enhanced SW in OLYMPEX.

RHI scans: KH waves (below ML)



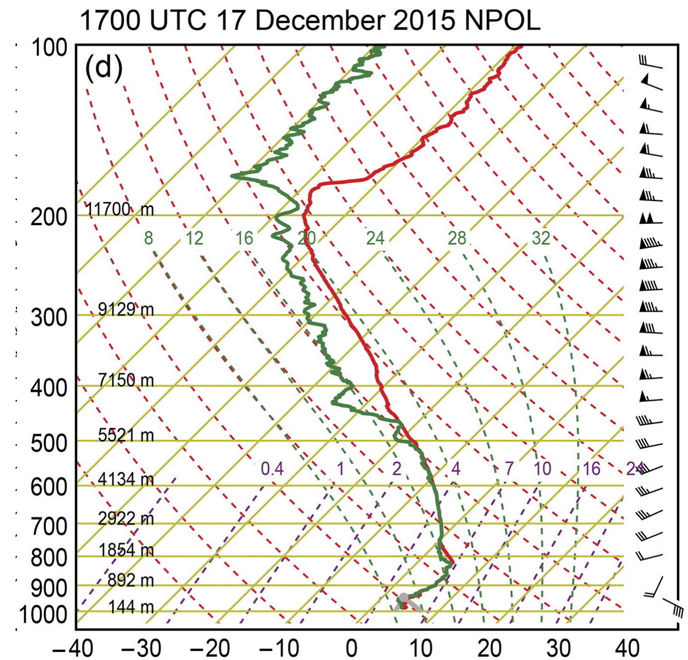
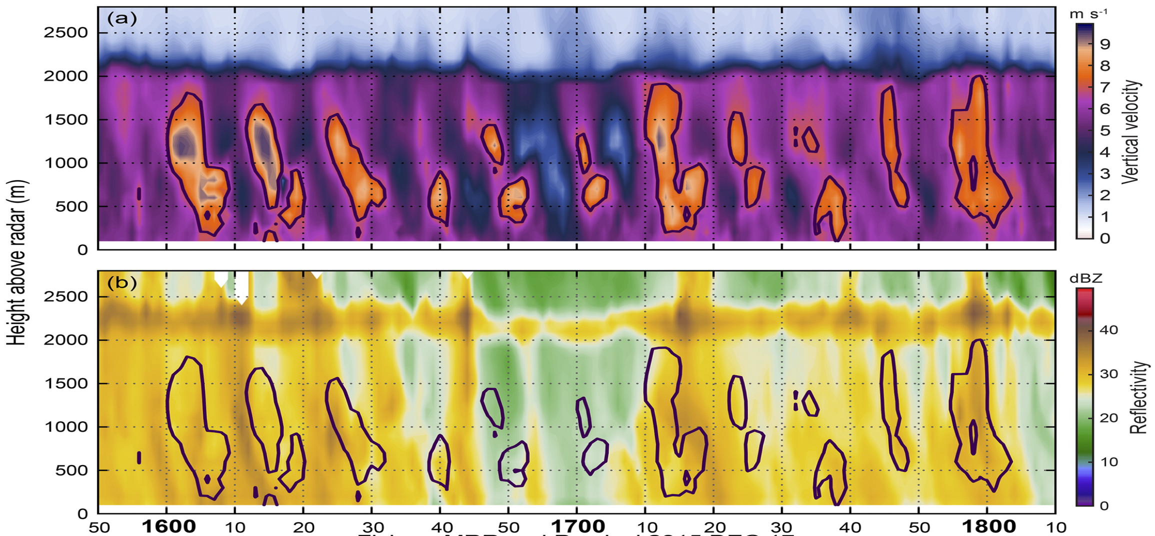


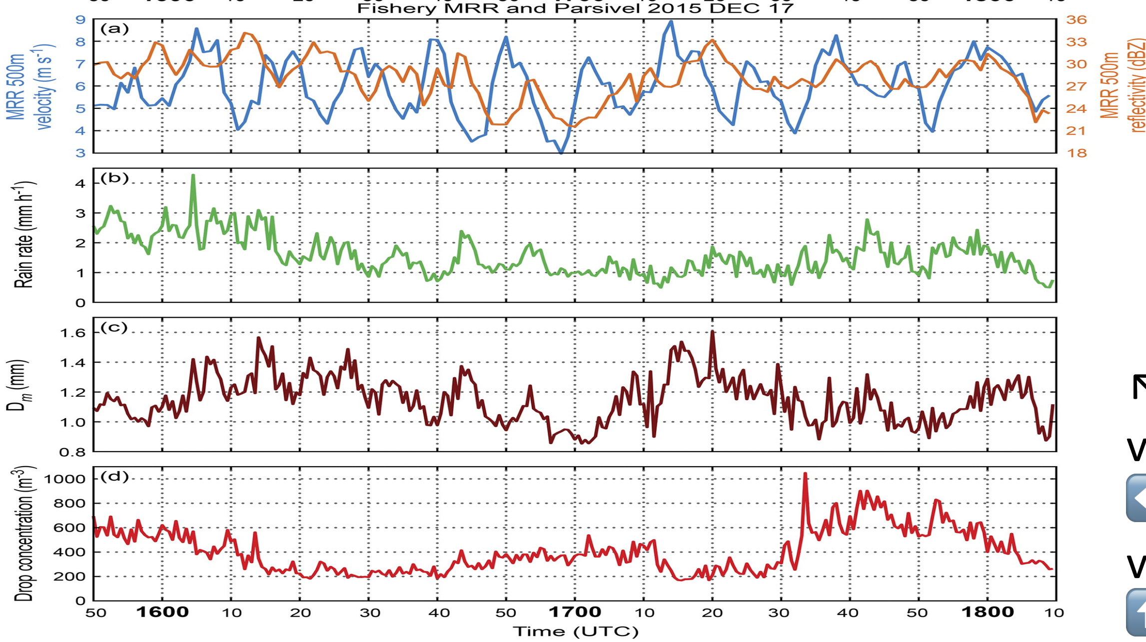
FIG. 11. As in Fig. 9, but for an RHI scan from the NPOL during OLYMPEX at an azimuthal angle of 254° at 1320 UTC 17 Dec 2015. The black dots show the location of the maximum spectrum width in each vertical column. Note that the x coordinate origin is on the right side of each panel. The x axis was flipped so that the orientation of the waves is consistent throughout the paper.

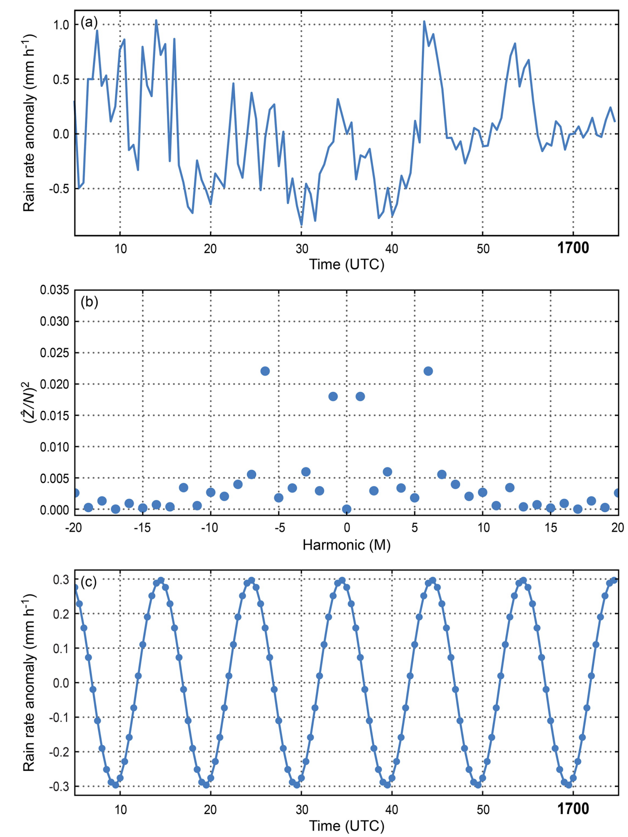
- VR/ SW: very clear signals
- Deposition / coalescence processes.

Ground observations



Fishery MRR and Parsivel 2015 DEC 17





↖ black contour: downward vertical velocity > 7m/s

⬅️ blue/orange (MRR) : 500m vertical velocity / ZH others: PARSIVEL-2

⬆️ PARSIVEL-2

Impact of topography

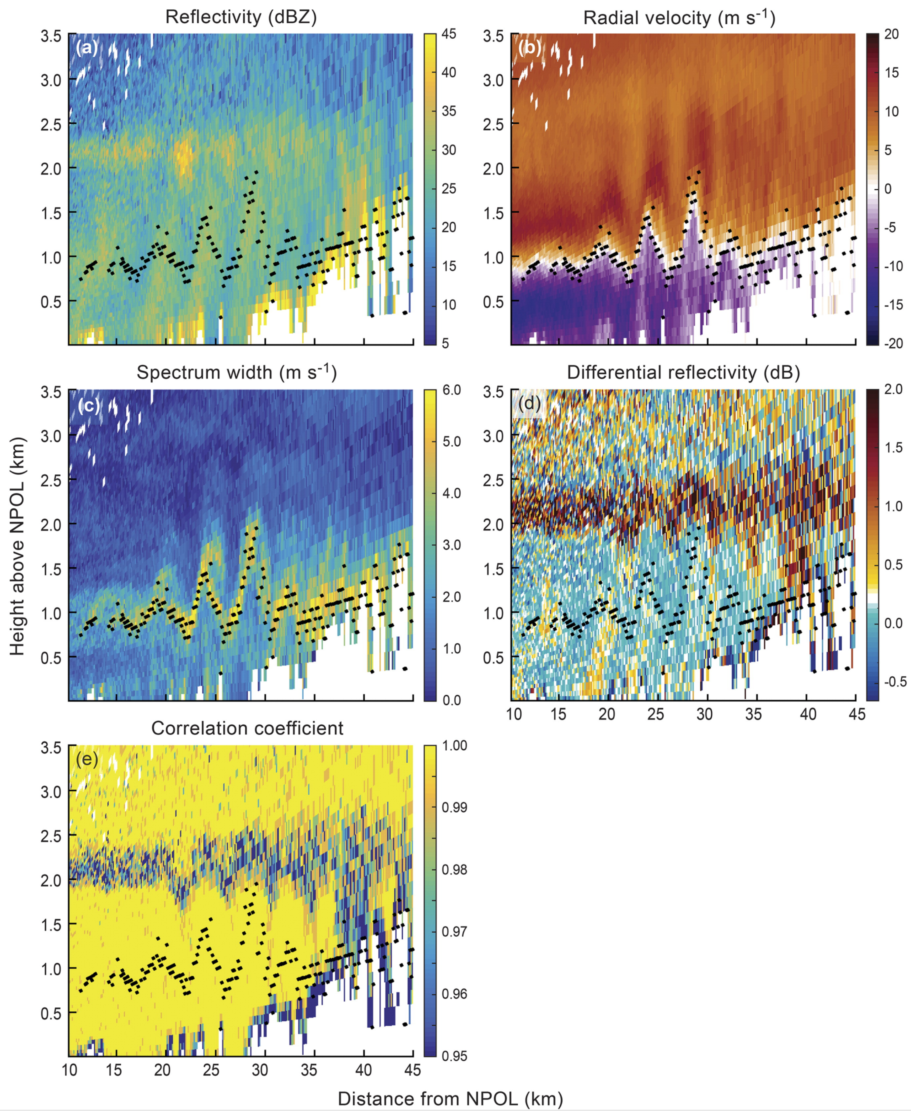


FIG. 15. As in Fig. 10, but for an RHI scan from the NPOL at an azimuthal angle of 54° at 1352 UTC 17 Dec 2015.

- Upward-sloping terrain can impact the amplitude of KH waves. (rapid jump of dots)
- Terrain
  - vertical wind shear ↑
  - Ri ↓
  - amplitude of the wave ↑
  - Force additional upward motion

Conclusions

- KH waves can occur at any altitude that has high static stability and strong vertical wind shear.
- KH waves can modify both the liquid- and ice-phase microphysics. The effects depend on the relative position to ML.
- KH waves enhance aggregation (above ML) , and riming (near ML)
- KH waves produced oscillatory behavior in the particle fall velocity, surface rain rate, and mass-weighted mean drop diameter.
- Complex terrain can make conditions more favorable to KH wave development