Scanning Doppler radar observations of a coastal orographic precipitation event in northern California during PACJET

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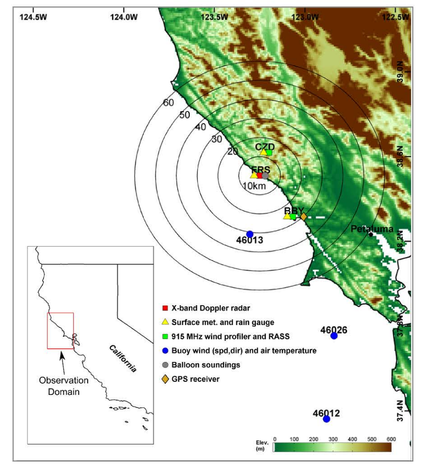
Motivation

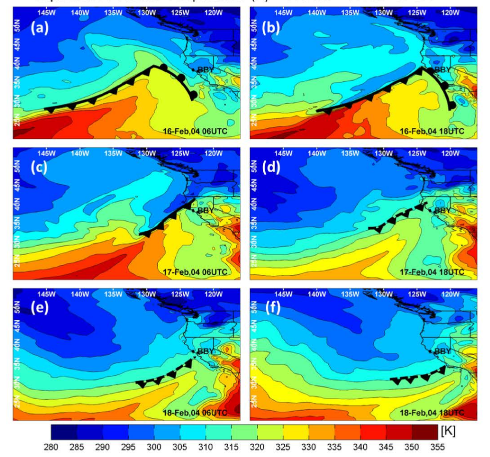
- The impact of moist pre-frontal low-level jets (i.e., atmospheric rivers, ARs) on the windward side of orographic barriers can lead to significant precipitation.
- Terrain-blocked airflows can lead to important changes in the intensity and spatial distribution of this precipitation by extending the physical width of the orographic barrier for impinging airflows and lifting ARs before they reach the windward side of the barrier.
- An AR that made landfall in northern California on 16-18 February 2004 produced copius orographic precipitation and a severe flood ranked number 2 among major flood events on California's Russian River between 1997 and 2006 even though the highest terrain in the area was below 1 km.
- Some of the questions that have not been addressed in previous studies are: how does the pre-cold frontal low-level jet (LLJ) interact with the blocked flow exactly? does the kinematic structure of blocked flows remain stationary as the storm progresses? If not, is there any relationship between its evolution and precipitation intensity?
- This reasearch documents the kinematic structure and evolution of the impinging moist low-level jet interacting with blocked flow associated with small-scale (<1 km) orography during the 16-18 February 2004 storm observed in PACJET.

Case of 16-18 February, 2004



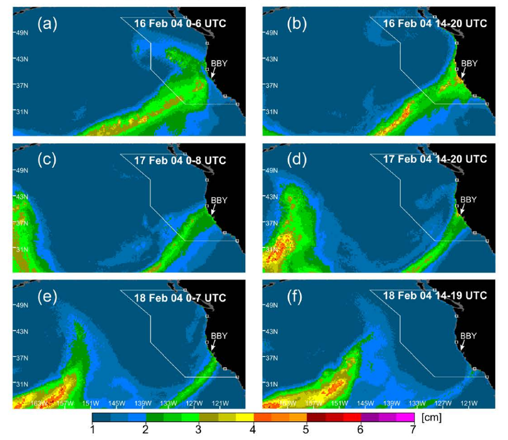
The present study is supported by data retrieved from the NOAA scanning ground-based dual polarization X-band Doppler radar (X-POL) located at Fort Ross (FRS). The observation domain and other instruments used in the present study are observed in the figure. The event was separated into **Episode 1** (06 UTC 16-Feb to 06 UTC 17-Feb) and **Episode 2** (06 UTC 17-Feb to 06 UTC 18-Feb).

Equivalent Potential Temperature (K) – 975 mb – NCEP-CFSR



In Episode 1, NCEP-CFSR data indicates a cold front advancing eastward and a warm front off the coast of California advancing northwestward and weakening (a-c). In Episode 2, the temperature gradient is weaker than Episode 1; however, surface meteorological, SSM/I-IWV, and Doppler radar observations indicate a cold front and its motion (dashed line, d-f).

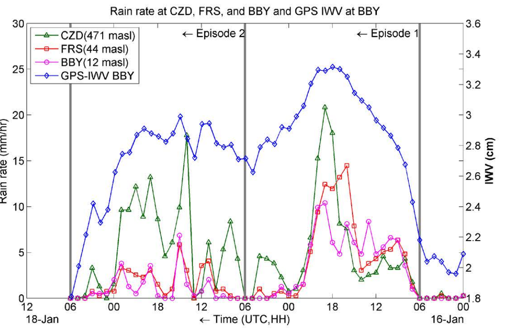
Composites of SSM/I Integrated Water Vapor



SSM/I observations of column-integrated water vapor (IWV) and CFSR data indicate the presence of an AR. Episode 1 is highlighted by the landfalling AR almost perpendicular to the coast (a-c). Then, in Episode 2 the AR moves southeastward to finally dissipating after the end of the episode (d-f).

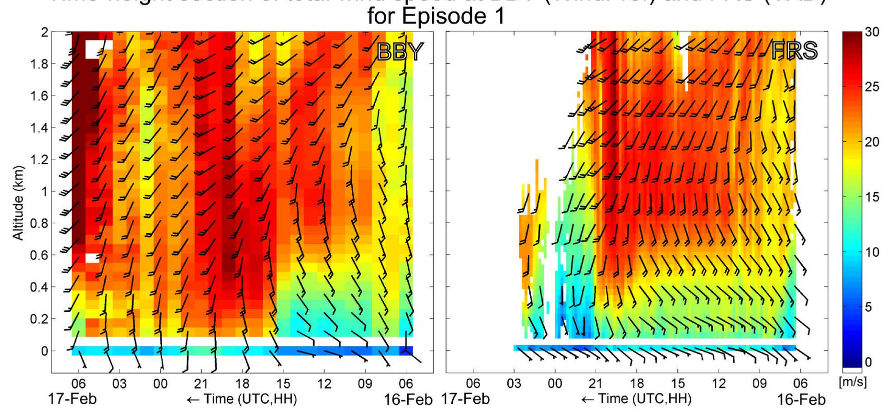
Episode 1 presents continuous rainfall over the coastal mountain (CZD) and along the coast (FRS and BBY). IWV stays above 2 cm with a rapid increase (landfalling AR). Episode 2 presents scattered rainfall with moments of virtually no precipitation. IWV shows a more steady-state behavior compared with Episode 1

Rain rate at CZD, FRS, and BBY and GPS IWV at BBY



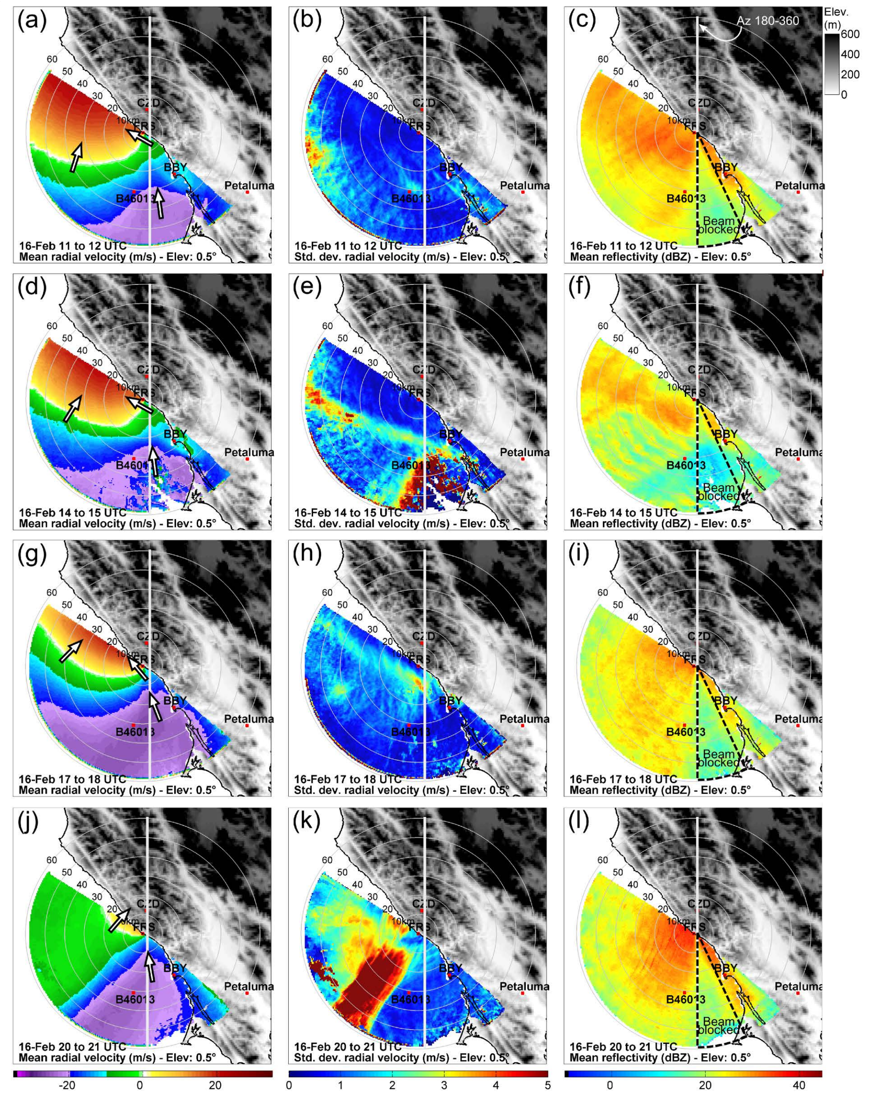
Episode 1

Time-height section of total wind speed at BBY (WindProf) and FRS (VAD) for Episode 1



- Strong vertical gradient in horizontal winds as a function of time.
- BBY shows an **intrusion of weaker winds** in a ~0-0.5 km ASL layer with an **east-southeasterly** component at the surface likely produced by a **gap flow** from Petaluma Gap.
- FRS presents the intrusion of weaker winds in the same layer but lasting until 18 UTC 16-Feb with a terrain-parallel southeasterly component.
- Above the weak winds intrusion, winds are about 25 m s^{-1} with a south-southeasterly to a southwesterly component.

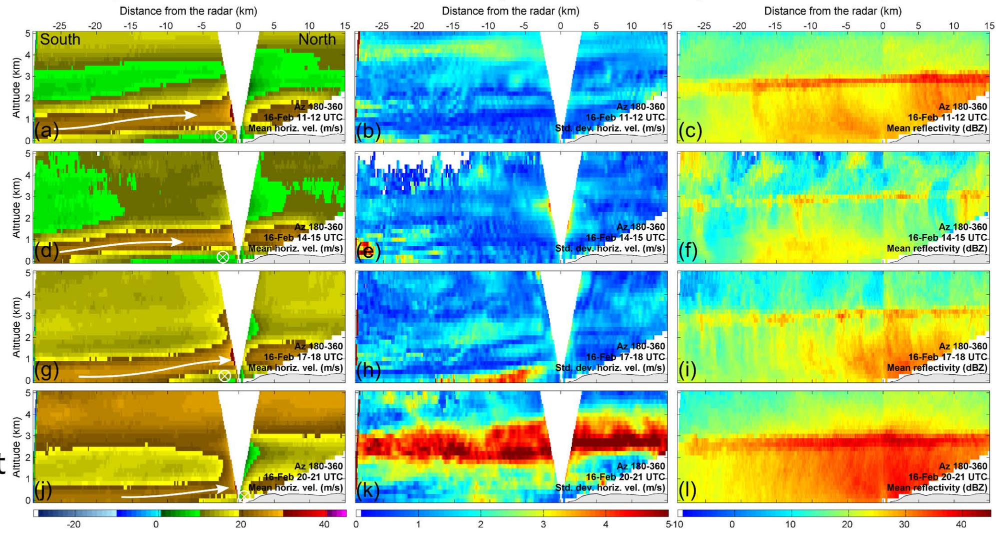
Hourly mean and std. dev. of radial velocity and mean reflectivity for PPI scans in Episode 1



- Hourly mean and standard deviation of radial velocity and mean reflectivity were calculated from PPI scans with an elevation angle of 0.5°.
- Hourly standard deviation of radial velocity measures variations in horizontal wind shear within the hour averaged associated with the LLJ/blocked flow interface motion.
- **Four stages** in the LLJ/blocked flow interaction were identified: **early** (a-c), **developed** (d-f), **weakening** (g-i), and **frontal passage** (j-l).
- **Early**: continuous horizontal wind shear in radial velocity, std. dev. with no particular structure, reflectivity with widespread echoes and somewhat enhanced reflectivity closer to the coast.
- **Developed**: strong horizontal wind shear in radial velocity, std. dev. with a band of large variability indicating LLJ/blocked flow interface motion, enhanced reflectivity band within 20 km range closest and near parallel to the coast.
- **Weakening**: smoother horizontal wind shear in radial velocity compared with developed stage, std. dev. with the band closer to the coast, narrow enhanced reflectivity band closer to the coast.
- **Frontal passage**: radial velocity, std. dev., and reflectivity display no structure as in previous stages. Large std. dev. band is associated with the frontal passage.

The vertical structure for the same stages is observed in composites of RHI scans (Azimuth 180° and 360°). Radial velocity was transformed into horizontal velocity.

Hourly mean and std. dev. of horizontal velocity and mean reflectivity for RHI scans in Episode 1



Early (a-c): LLJ riding over blocked flow, shallow enhanced std. dev. near surface, enhanced reflectivity below melting layer and close to the coast.

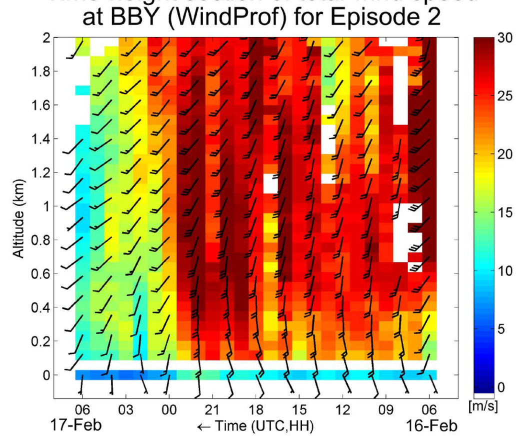
Developed (d-f): LLJ rides up and over blocked flow offshore, enhanced std. dev. near surface somewhat deeper, enhanced reflectivity below melting layer offshore at low levels and close to the coast.

Weakening (g-i): LLJ riding up and over blocked flow closer to the coast, deeper enhanced std. dev. closer to the coast, enhanced reflectivity below melting layer closer to the coast and over the mountains.

Frontal passage (j-l): LLJ riding up and over a remnant of blocked flow, enhanced std. dev. aloft due to frontal passage, widespread reflectivity below melting layer, somewhat enhanced near the coastline.

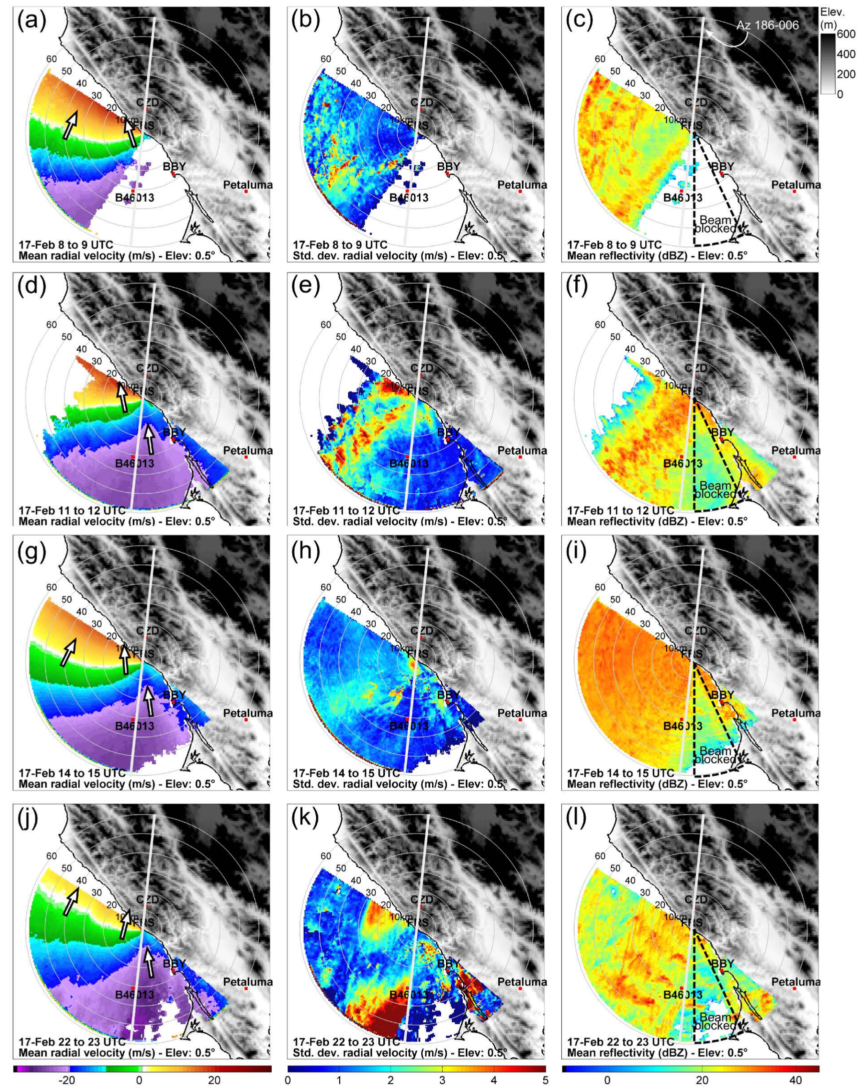
Episode 2

Time-height section of total wind speed at BBY (WindProf) for Episode 2



- Time-height section is only available at BBY.
- Vertical gradient in horizontal winds is weaker than in Episode 1 with **no evidence of a weak wind intrusion.**
- Wind shift after 23 UTC 17-Feb points out the arrival of the cold front.
- In general, winds are around ~20-30 m s^{-1} above the surface with a prominent southerly component.
- With the passage of the cold front, winds drop about 10 m s^{-1} keeping the southerly component at the surface and a more southwesterly component above.

Hourly mean and std. dev. of radial velocity and mean reflectivity for PPI scans in Episode 2

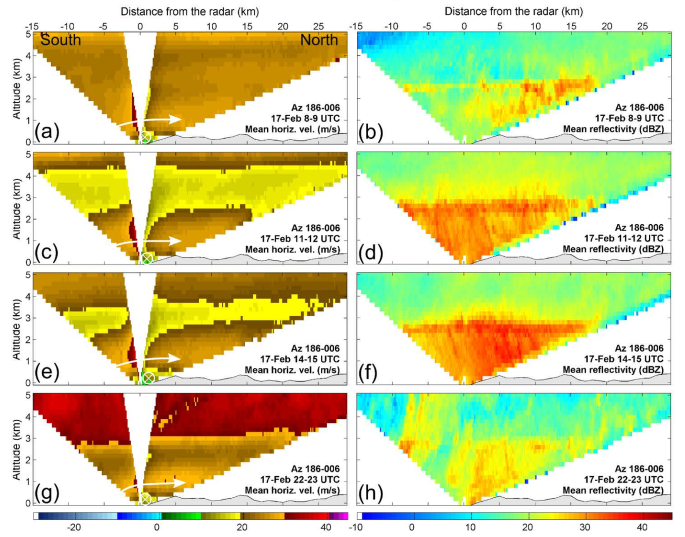


- Since the zero isodop and std. dev. of radial velocity show no evidence of LLJ/blocked flow interface motion, hours with **maximum precipitation at CZD** in Episode 2 where analyzed.
- Because more convective conditions are observed in Episode 2, hourly reflectivity averages present composites of enhanced reflectivity associated with cells and rainbands crossing the domain.
- **8-9 UTC (a-c)**: strong horizontal wind shear at a ~20 km range separating south-southeasterly and south-southwesterly winds, std. dev. with scattered maxima, reflectivity maxima associated with scattered cells crossing the domain.
- **11-12 UTC (d-f)**: south-southeasterly winds within a range of ~30 km, std. dev. with scattered maxima, reflectivity maxima associated with a narrow and deep rainband crossing the domain northeastward.
- **14-15 UTC (g-i)**: horizontal wind shear similar to 8-9 UTC but somewhat smoother, std. dev. with scattered maxima, widespread reflectivity with some cellularity structure.
- **22-23 UTC (j-l)**: southwesterly winds take over due to the passage of the cold front, std. dev. maxima associated with the frontal motion, reflectivity maxima associated with a rainband moving northeastward.

The vertical structure for the same hours is observed in RHI scans with 6° azimuth and max. elevation angle of 162°. Radial velocity was transformed into horizontal velocity.

Since LLJ/blocked flow interface motion is not evident, only horizontal velocity and reflectivity is presented.

Hourly mean horizontal velocity and mean reflectivity for RHI scans in Episode 2



8-9 UTC (a,b): small region of ~0.5 km depth with weak horizontal winds in the windward side indicates remnant of blocked flow lifting the LLJ, reflectivity suggest a melting layer at ~3 km ASL with scattered maxima below it.

11-12 UTC (c,d):remnant of blocked flow lifting LLJ in the windward side, widespread reflectivity below melting layer.

14-15 UTC (e,f): remnant of blocked flow lifting LLJ in the winward side, widespread reflectivity below melting layer somewhat enhanced over the coastal mountains.

22-23 UTC (g,h): remnant of blocked flow seems smaller but still lifting the LLJ, reflectivity exhibits scattered cellularity.

Summary

Episode 1 (06 UTC 16-February to 06 UTC 17-February) :

- Environment ahead of a warm front and landfalling atmospheric river (AR).
- A gap flow from Petaluma Gap likely contributed to the formation of a blocked flow that ultimately interacted with the LLJ .
- The interaction is evident as far as ~50 km from the coast and as deep as ~0.5 km from the sea surface.
- Four stages were identified in the LLJ/blocked flow interaction: early, developed, weakening, and frontal passage.
- Thermodynamic characteristics from RASS and ballong soundings (not shown) in the 100-500 m ASL layer are consistent with the landfall of an AR (dry neutral) and the presence of a gap flow (dry stable).

Episode 2 (06 UTC 17-February to 06 UTC 18-February):

- Environment ahead of the cold front and within the passage of the AR.
- There is no evidence of gap flow contributing to the formation of blocked flow and LLJ/blocked flow interface motion is not evident.
- Vertical examination of horizontal winds suggests that a remnant of the blocked flow is trapped in the windward side of the coastal mountains and lifting the LLJ probably ~5 km before reaching the windward side.
- Thermodynamic characteristics from RASS and balloon soundings (not shown) in the 100-500 m ASL layer are consistent with the observation of a remnant blocked flow (dry stable) and the environment pre (dry neutral/unstable) and post (dry stable) passage of the cold front.

Conclusions

1. The pre-cold frontal AR and LLJ is forced by blocked flow to ascend at least ~50 km before reaching the windward slope of the coastal mountain. The blocked flow is likely generated by a gap flow formed in Petaluma Gap.
2. The kinematic structure of the blocked flow indicates a roughly constant depth (~0.5 km ASL) but an evolving extension offshore associated with synoptic conditions.
3. Four stages were identified in the evolution of the blocked flow:early, developed, weakening, and frontal passage. The early stage was associated with a general decreasing rainfall.The developed stage was associated with a general increasing rainfall. The weakening stage was associated with increasing rainfall over the coastal mountains. The frontal passage stage was associated with decreasing rainfall and momentary weakening of the storm.
4. Further reasearch is needed to determine what mechanisms and sources are associated with the remnant blocked flow after the frontal passage stage. We hypothesize that a down valley flow created by evaporative cooling exiting trough the Russian River valley is sustaining the remnant blocked flow trapped in the windward slope of coastal mountains.

Acknowledgments

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