The Wind Forecast Improvement Project In Complex Terrain (WFIP2)

Jim McCaa, PhD
Vaisala, Inc.

…borrowing liberally from the entire WFIP2 team

VAISALA

WFIP2 Partners

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

Argonne NATIONAL LABORATORY

Lawrence Livermore National Laboratory

NREL
National Renewable Energy Laboratory

Pacific Northwest NATIONAL LABORATORY

VAISALA

Hay Canyon Wind Farm – with Mount Hood in the background – is among those in the study area. Photo courtesy of Iberdrola Renewables

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Earth System Research Laboratory

ARL Air Resources Laboratory

NATIONAL WEATHER SERVICE

Data Partners:

IBERDROLA RENEWABLES
SOUTHERN CALIFORNIA EDISON
PGE
Eurus Energy
SIEMENS

Team Members:

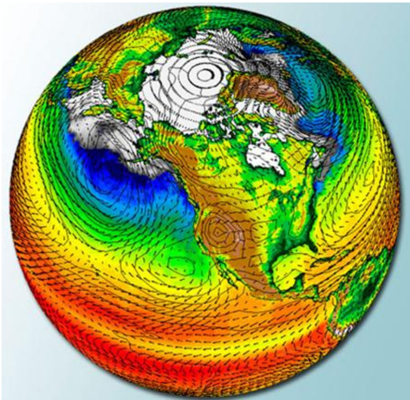
University of Colorado Boulder
TEXAS TECH UNIVERSITY College of Arts & Sciences
LOCKHEED MARTIN
UNIVERSITY OF NOTRE DAME
NCAR
Sharply Focused
BONNEVILLE POWER ADMINISTRATION

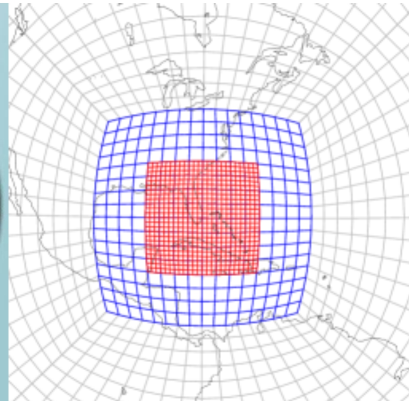
3TIER by Vaisala | VAISALA

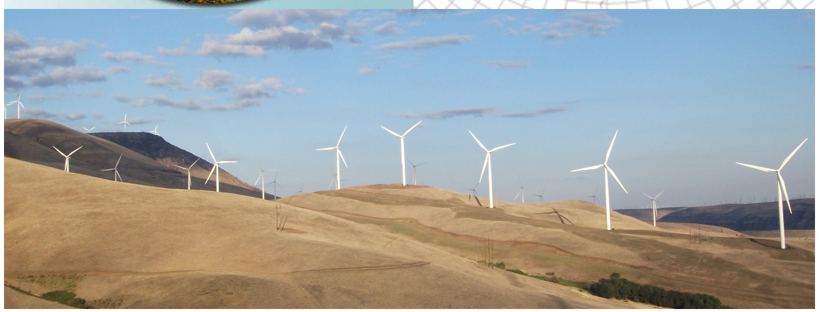
Outline

- Motivation for WFIP2
- Experimental design (field campaign)
- Analysis of observations
- Model development
- Transfer to industry
- Summary

Mesoscale Physics and NWP Models







Scientific Challenges for Wind Energy

- NWP models are excellent at forecasting general weather, optimized for temperature & precipitation
- Historically, errors tolerated for wind predictions at turbine heights result in significant errors in forecast power; $P \propto V^3$
- Mesoscale atmospheric structure drives the microscale wind plant inflow but turbulence processes, temporal and spatial scales are mismatched:
  - Mesoscale ≈ 3 km grid spacing, hour timescale variability
  - Microscale ≈ 1-10 m grid spacing, second timescale variability
- Conventional parameterizations not scale-independent or -aware
  - Not designed to capture heat flux or moisture variability on high-resolution grids or in complex terrain
  - For the mesoscale, often assumes stationarity and horizontal homogeneity of subgrid-scale processes
  - Sharp surface moisture and temperature gradients increase errors
- Improved NWP data assimilation methods are needed for state-of-the-art observations.

A2e's R&D Investments:

- Wind Forecast Improvement Project WFIP 1 -> WFIP 2

Vaisala, Inc. team; NOAA; DOE National Labs

- Experimental Planetary Boundary Layer Instrument Assessment (XPIA)

Dr. Julie Lundquist PI; (Univ. of Colorado)

- Providing the physics to bridge grid resolution gap from 3 km to 750 m
  - Examining the physics of the atmosphere at the scales needed for accurate wind characterization
  - Meso- to micro scale numerical coupling methods based on improved physics
  - First step in capturing large scale complex terrain variability
- Remote sensing instrument validation for state-of-the-art wind observations

WFIP Premise

- **Forecast Errors Expensive for Wind Industry**
- **Two Main Ways to Improve Short-Term (0-45 hr) Wind Forecasts**
  - **Improvement of Model Initialization**
    - Hypothesis: More accurate model initialization will provide a more accurate forecast
    - Current initialization data thin, particularly upper air
    - First field study (WFIP1): 2011-2012
      - Supplemented two areas with extensive observations
      - Demonstrated modest improvements in forecast accuracy
  - **Improvement of Model Physics**
    - Current parameterizations do not effectively account for complex terrain, where horizontal gradients are often important
    - Second field study (WFIP2): 2015-2016 with model analysis in 2017
      - Focus is to collect observations to evaluate and improve model physics, particularly for complex terrain, where much wind power is deployed

WFIP2 Implementation

- Funding Opportunity Announcement released by DOE in 2014
- **Vaisala, Inc.** selected as awardee
- Awardee works with larger, integrated WFIP 2 team:
  - NOAA-OAR
  - 4 DOE Laboratories:
    - Argonne National Laboratory
    - Lawrence Livermore National Laboratory
    - National Renewable Energy Laboratory
    - Pacific Northwest National Laboratory

Kyle Wade

Eric Grimit

Mark Stoelinga

- Experimental Design
- Instrument
- Model Development
- Data
- Verification & Validation
- Uncertainty Quantification
- Decision Support Tools

7 different teams report to Steering Committee

Jim Bickford

Steering Committee

- Steering Committee is composed of one representative from:
  - DOE HQ
  - NOAA
  - Vaisala
  - DOE Labs
  - DOE Contracting

GOALS

- Improve our understanding of atmospheric flows and processes that occur <u>in complex terrain</u> and impact wind forecasts at hub heights.
- Instrument the Columbia River Basin study area and carry out an 18 month field campaign (began October 2015).
- Develop physical parameterizations in WRF-ARW (with a focus on RAP & HRRR) to better represent physical processes and increase accuracy of wind forecasts in the 0-15 hour range, as well as day-ahead forecasts.
- Develop decision support tools, e.g., probabilistic forecast information, uncertainty quantification and forecast reliability for system operations.
- Transfer model improvements to NOAA/National Weather Service, other international forecast centers, and private industry.

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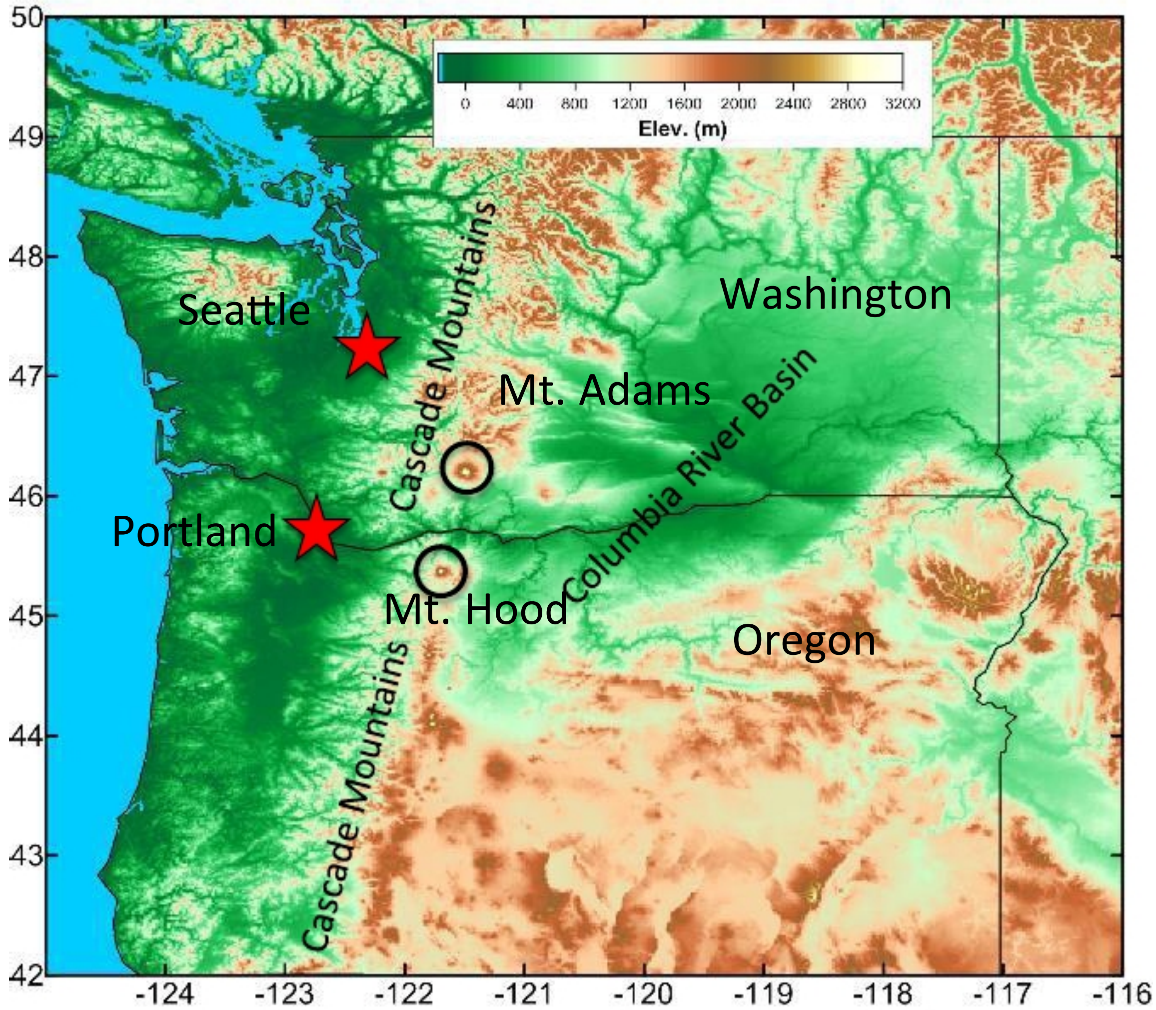
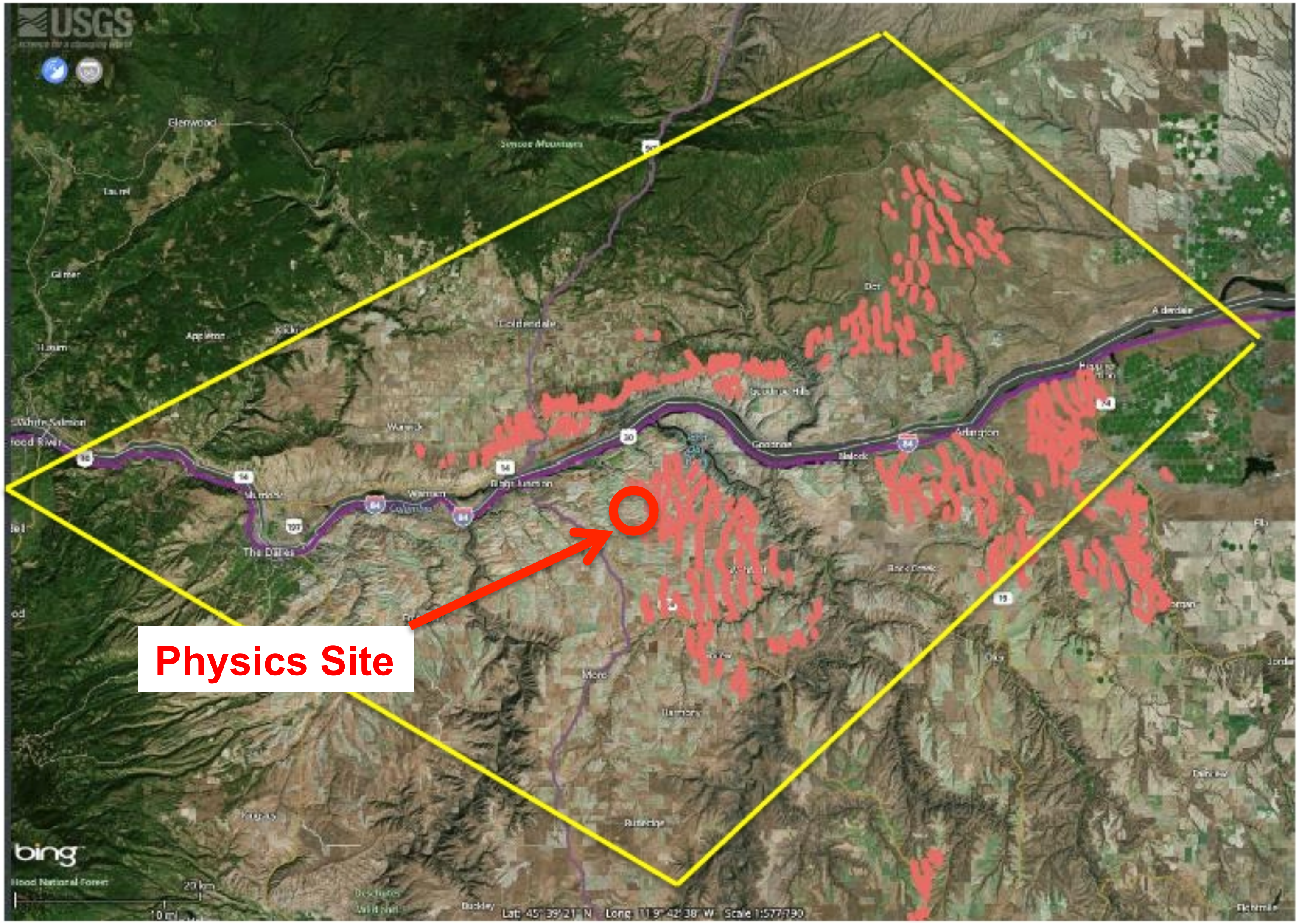
WFIP2 Study Area



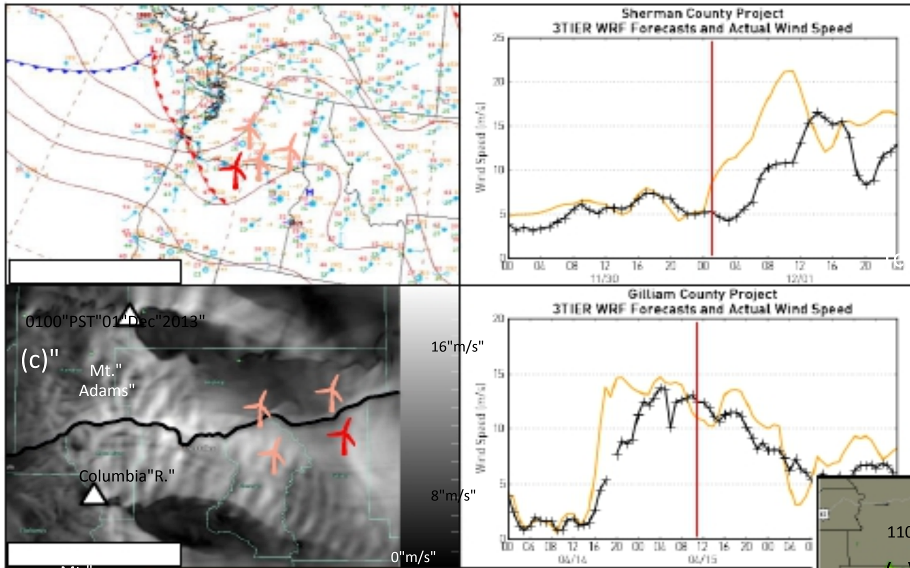
Columbia River Gorge

Columbia River Basin

Wind Turbine Locations



Key Phenomena in WFIP2 Region

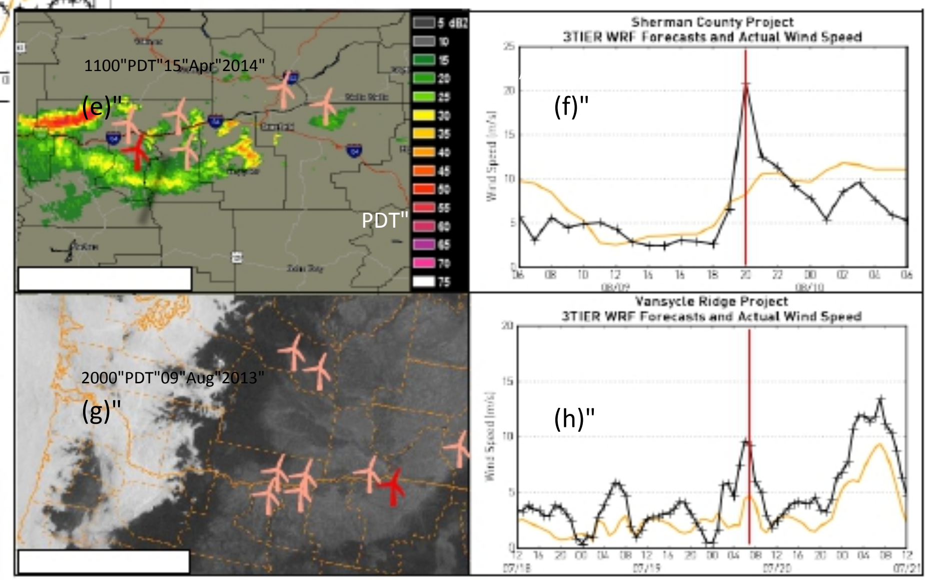


Timing and intensity of frontal passages

Orographic lee waves and wakes

Convective outflows

Marine layer /
regional thermal contrast /
gap flows



Ever-present challenge:
Build up and erosion of stable layers

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Colum

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Synoptic situations of primary concern for wind-energy forecasting in study area

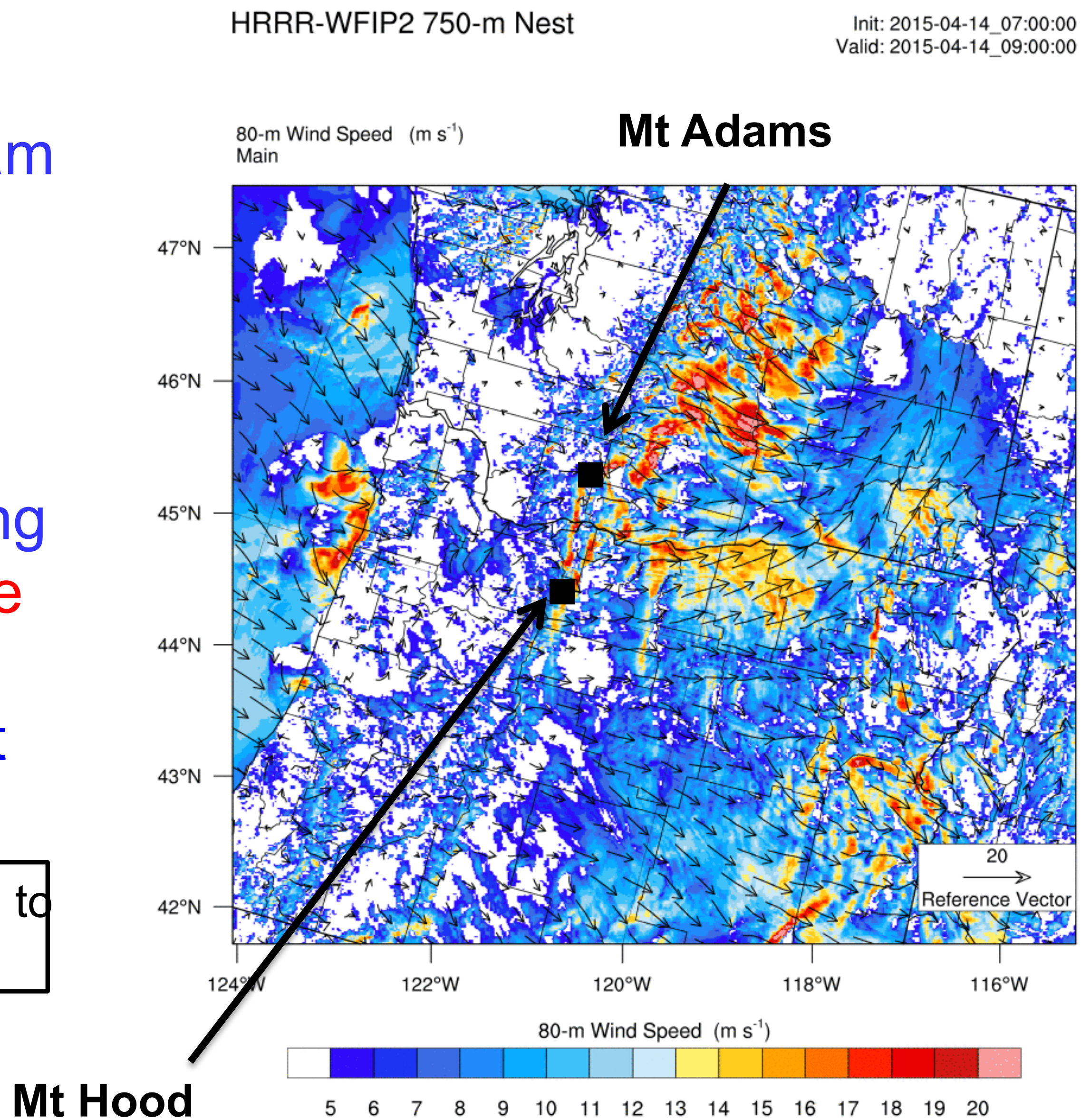
Description	Forecast issues	Model Challenges	Time of year
Low level cold air over Columbia Basin with approaching oceanic cyclone	Will warm strengthening flow aloft penetrate down to turbine level? Complications due to terrain modulation of flow	Stable PBL with strong vertical wind shear; representation of terrain-induced flow perturbations	Cold season
Mountain wave and wake flows in strong W-NW flow aloft	Will wave-induced winds reach down to turbine heights? Trapped lee wave-induced winds and wakes from the big mountains have strong horizontal, time-varying gradients in wind speed	Stable BL, resolution of terrain, WRF dynamics for vertically propagating and trapped-lee waves launched by complex terrain; horizontal mixing in sloping terrain. Accuracy of stratification and wind profiles in lateral boundary conditions	Mainly cold season
Marine pushes through Columbia Gorge other gaps in Cascades	Diurnal heating cycle is modulated by synoptic-scale flow; Timing and amplitude of ramp-up in wind speed	Modification of marine boundary layer west of Cascades, including effects of marine-layer clouds on surface heat budget Model dynamics for cross-barrier flows in difficult terrain; LBCs for offshore marine-layer structure	Primarily late spring and summer
Outflow winds associated with convection	Occurrence of convection sufficient to produce outflows; strength and propagation of outflows	Shallow Cu scheme and interaction with s/w radiation (initiation); Microphysics for evaporation and melting of pcpn (outflow generation); PBL for outflow propagation	Primarily summer

HRRR 750m Nest, 80m Wind Speeds

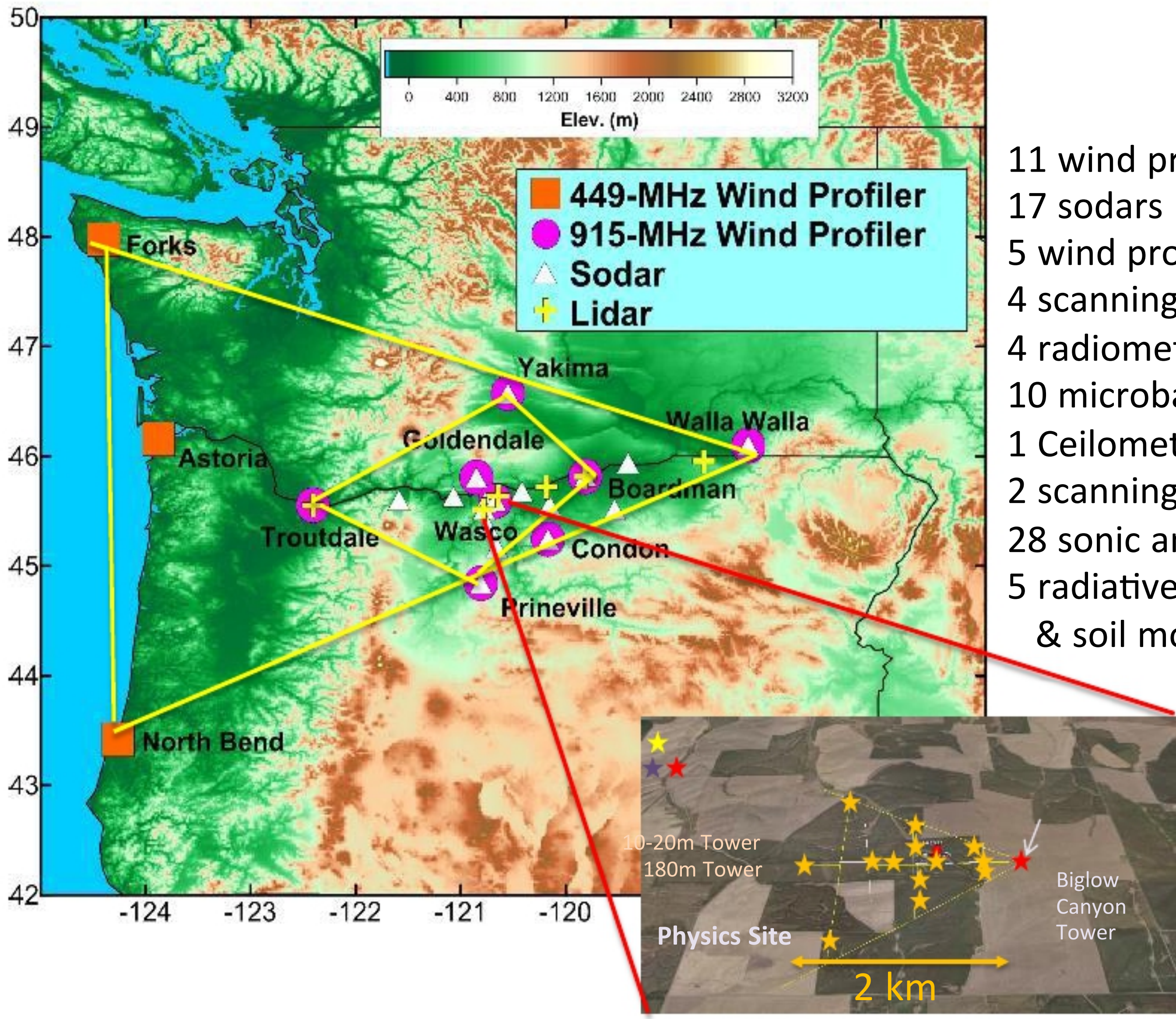
- Blocked flow upstream of Cascades

- Downstream of Cascades, locally persistent but evolving gap flows, downslope winds, and mountain wakes are prominent

9 hour loop from 3am to Noon local time.

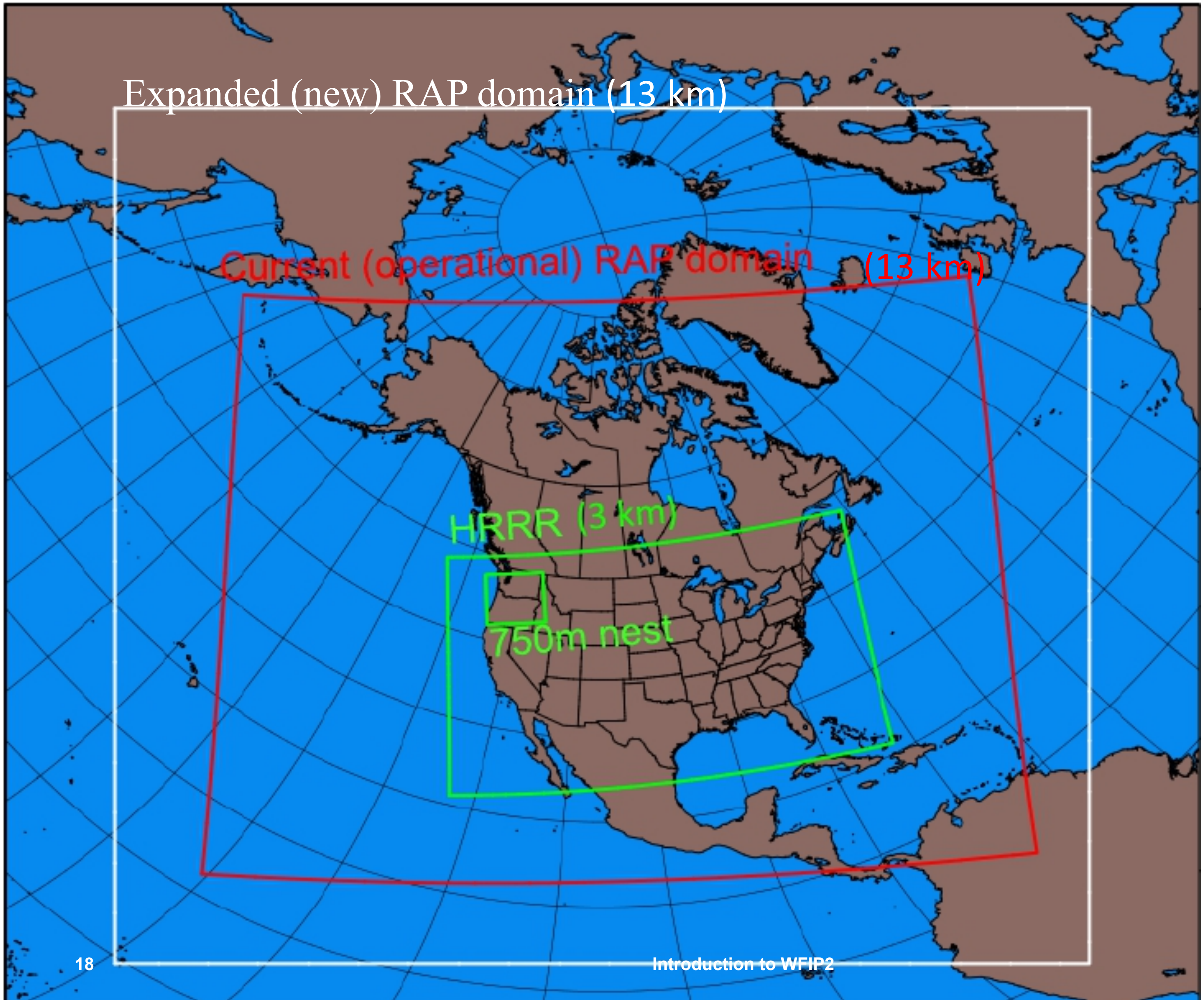


Multi-Scale Observations



11 wind profiling radars
17 sodars
5 wind profiling lidars
4 scanning lidars
4 radiometers
10 microbarographs
1 Ceilometer
2 scanning radars
28 sonic anemometers
5 radiative flux systems
& soil moisture

Primary Models (Hourly Updated)



RAP (13km)
Rapid Refresh

HRRR (3km)
High Resolution
Rapid Refresh

HRRR Nest (750m)

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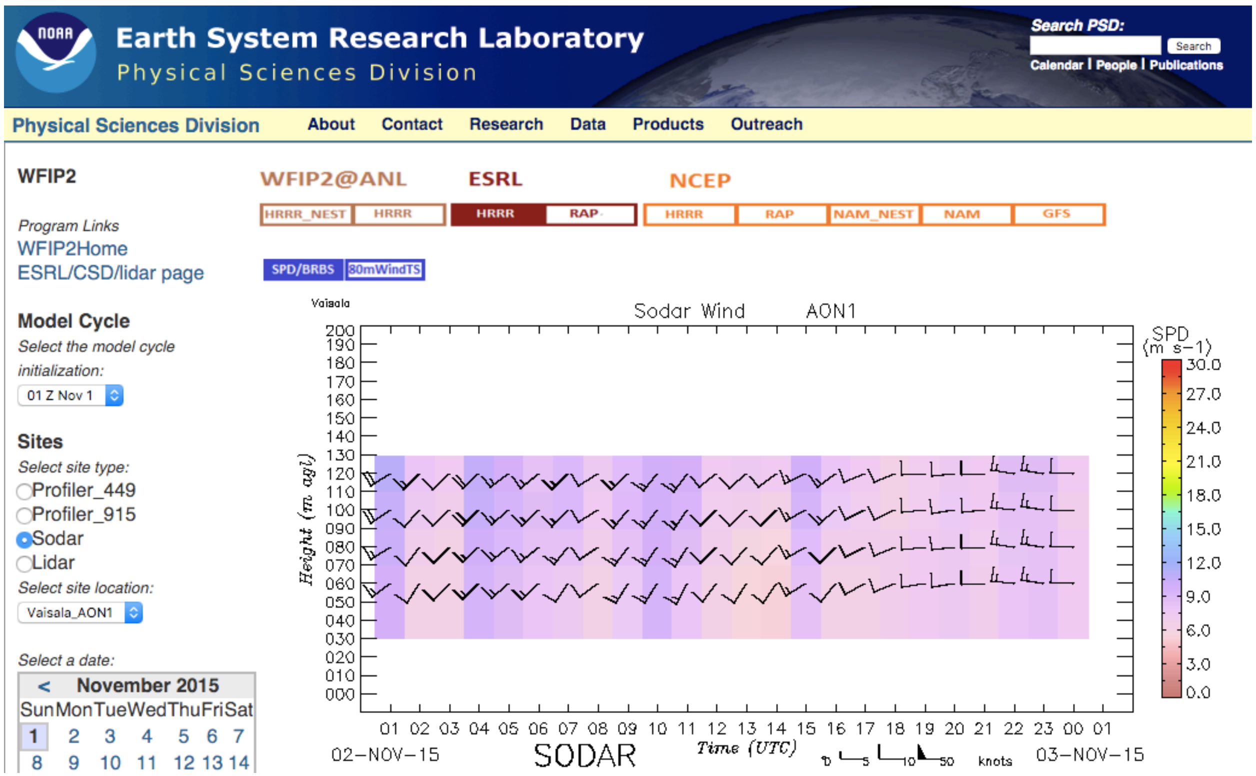
Model/obs evaluation web page

http://wfip.esrl.noaa.gov/psd/programs/wfip2/



- Observations from almost all instruments deployed for WFIP2
- Compares observations to model forecasts
- Web site is still evolving, but live now
- Likely that observations from industry data partners will need to be hosted elsewhere

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WFIP2@ANL | ESRL | NCEP

HRRR_NEST | HRRR | HRRR | RAP | HRRR | RAP | NAM_NEST | NAM | GFS

SNR/Winds | RASS/Winds | Surface | WSpeed LR | WSpeed HR

WFIP2

Program Links

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ESRL/CSD/lidar page

Model Cycle

Select the model cycle initialization:

06 Z Oct 25

Sites

Select site type:

- Profiler_449
- Profiler_915
- Sodar
- Lidar

Select site location:

Condon, OR

Select a date:

October 2015 >						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
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Contacts:

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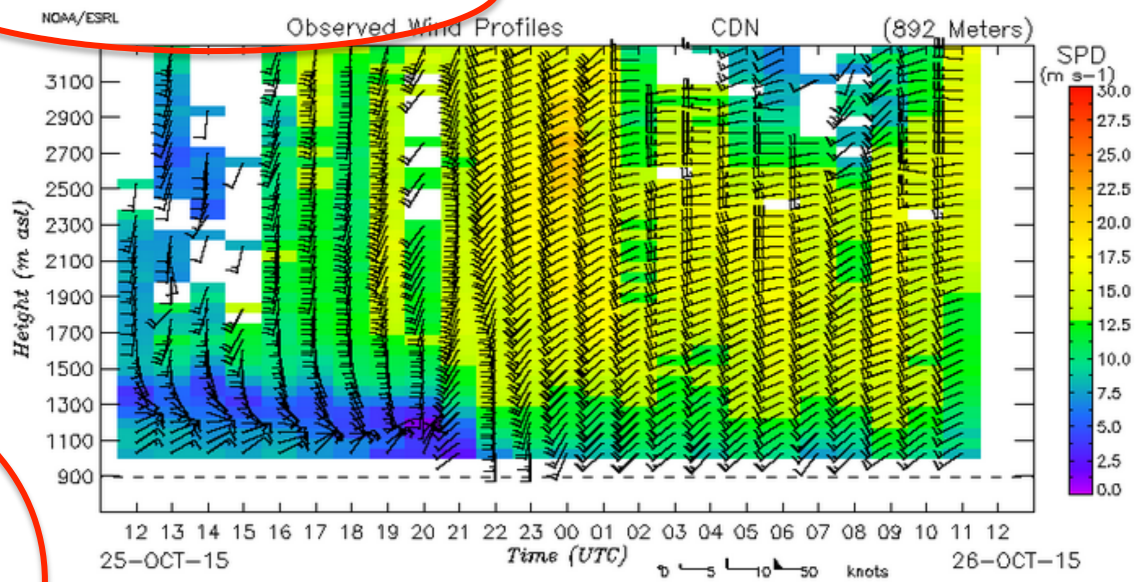
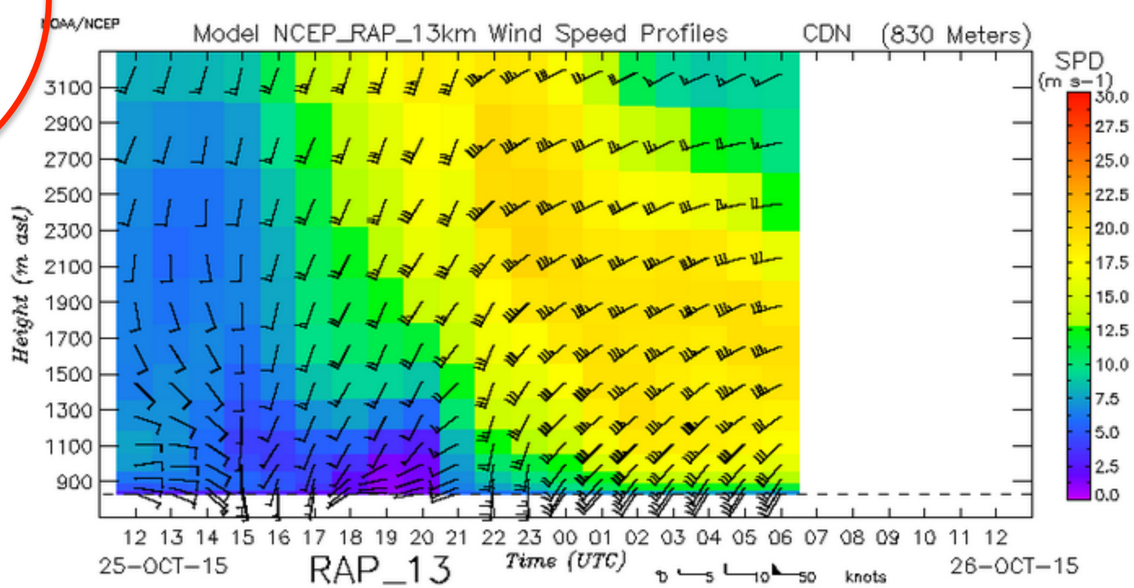
Irina Djalalova





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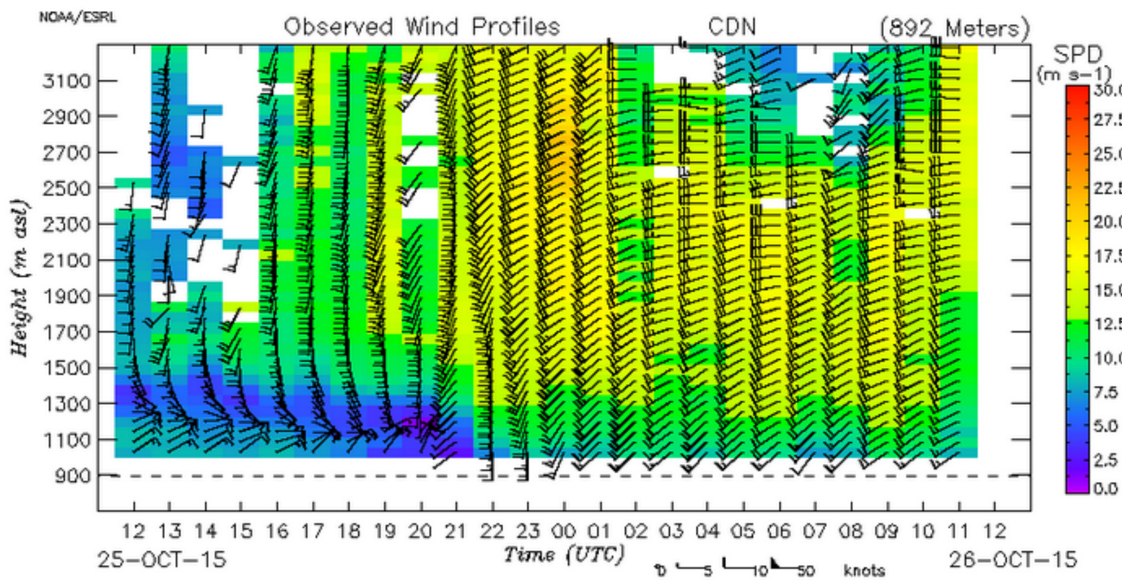
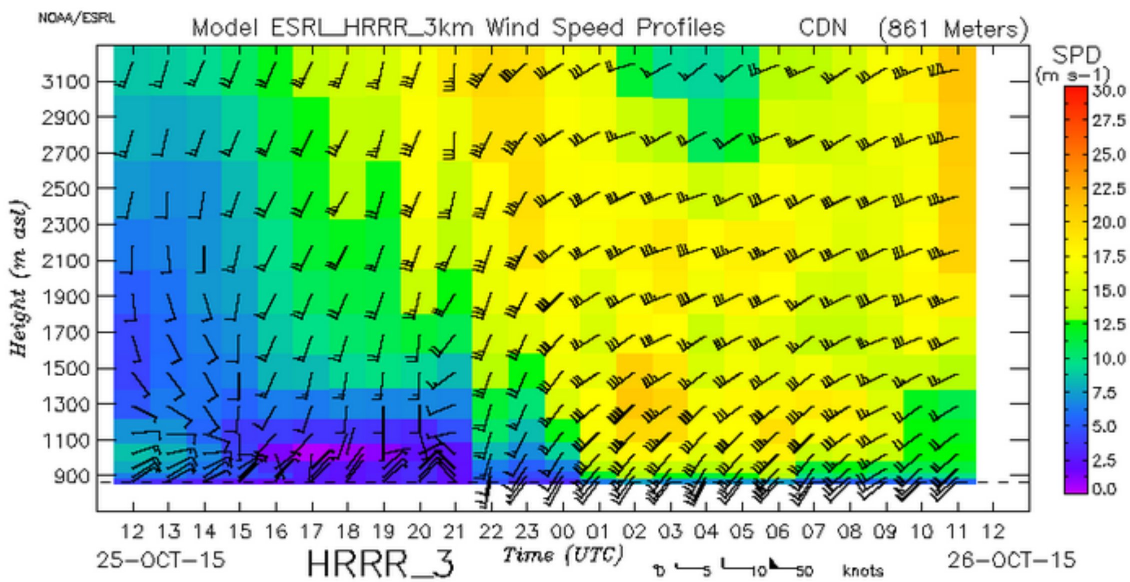
HRRR_NEST HRRR | HRRR RAP | HRRR RAP NAM_NEST NAM GFS

SNR/Winds RASS/Winds Surface WSpeed LR WSpeed HR





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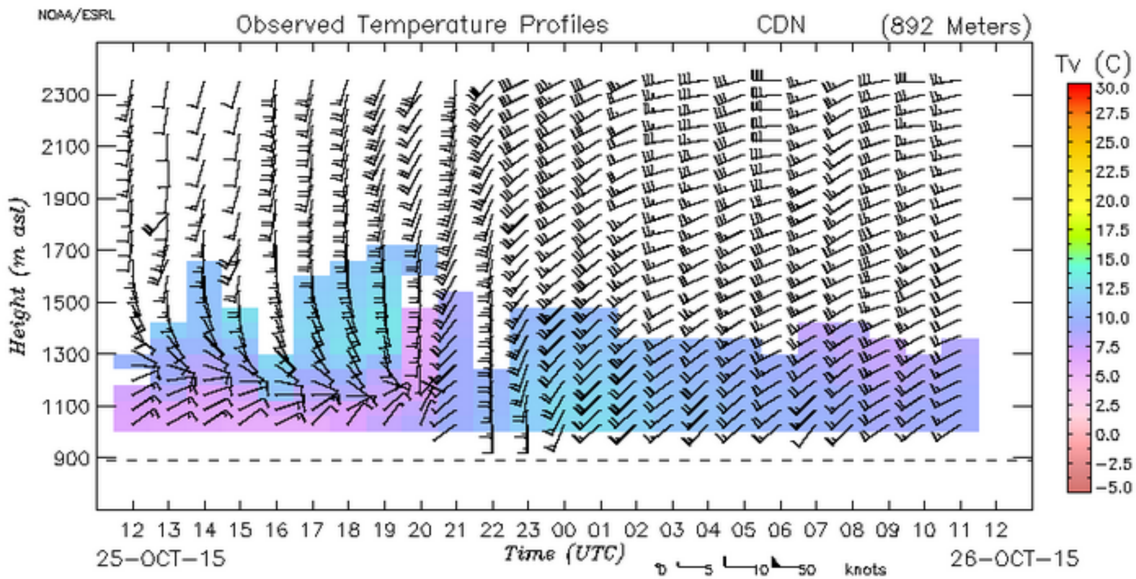
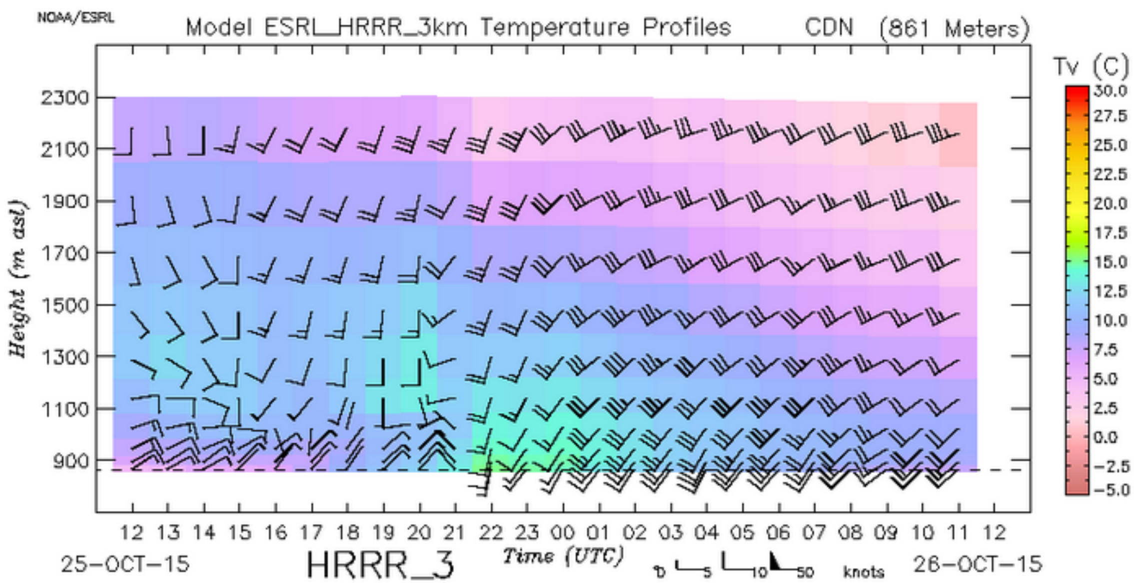
HRRR_NEST HRRR | HRRR RAP | HRRR RAP NAM_NEST NAM GFS

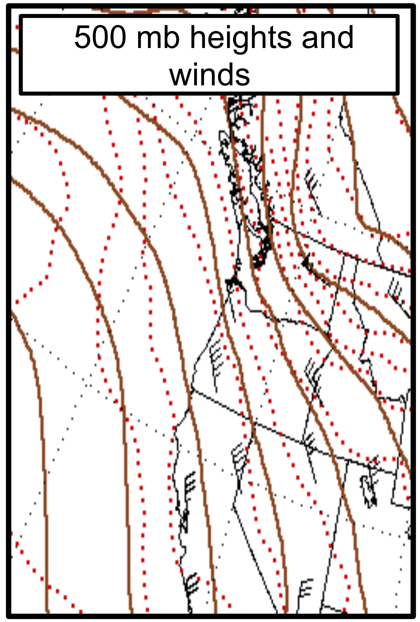
SNR/Winds RASS/Winds Surface WSpeed LR WSpeed HR

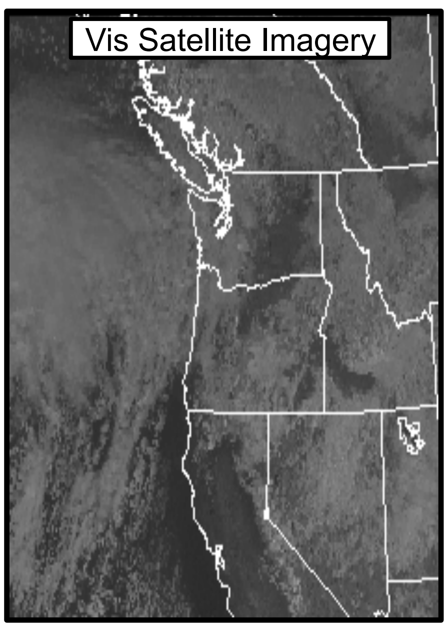


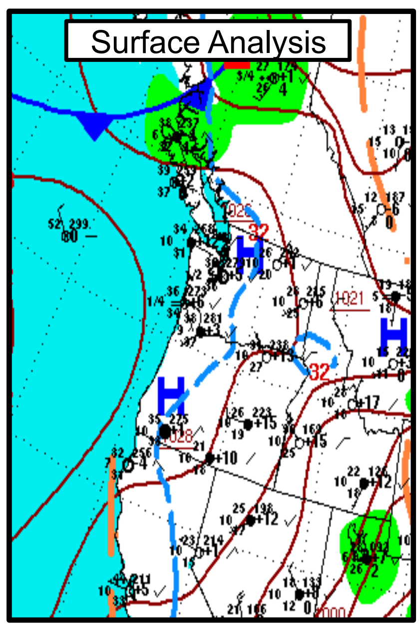


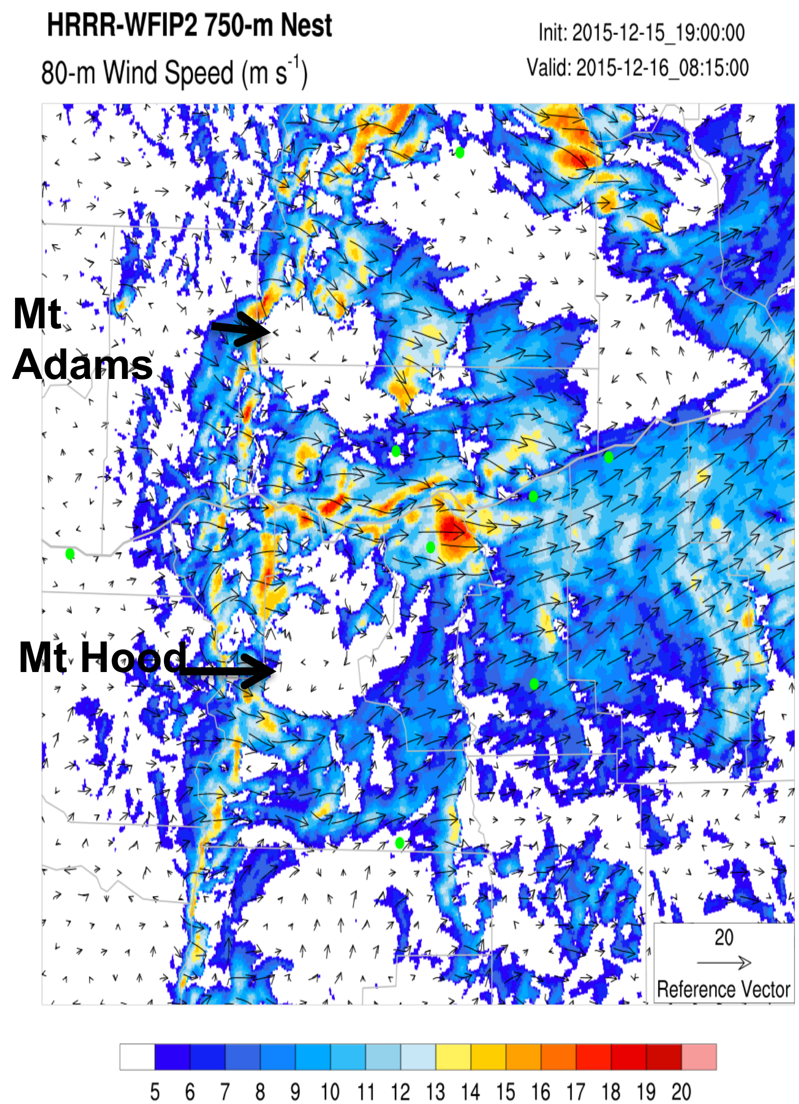
Case of 15-16 December 2015

- **Upper-level short-wave over WA**
- **Higher surface pressure offshore accelerates westerly flow through the Columbia River Gorge.**

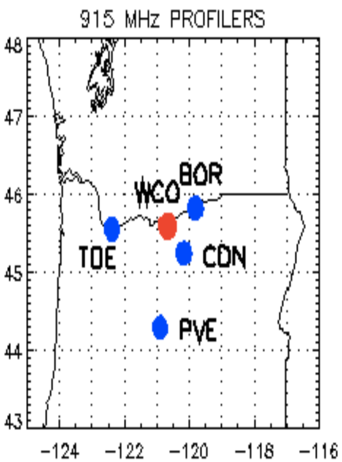


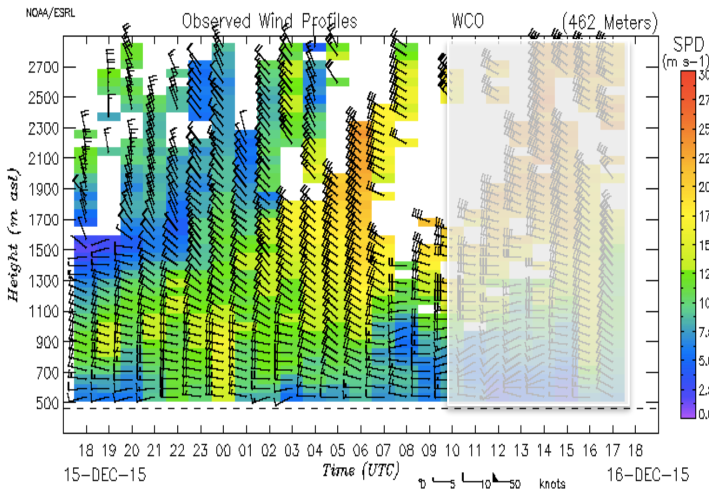


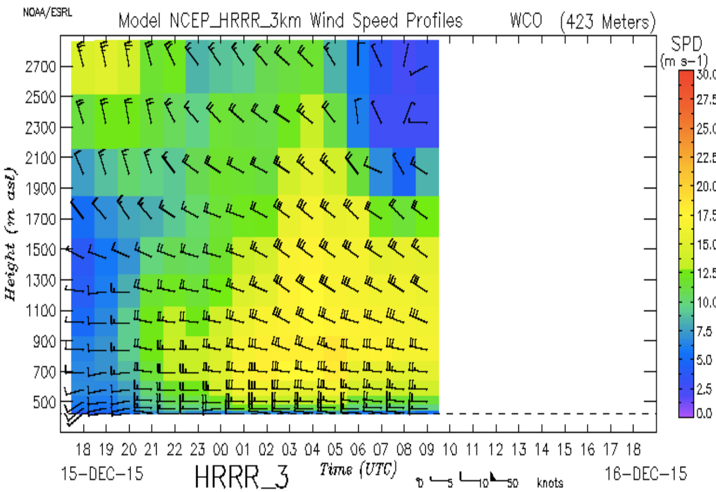




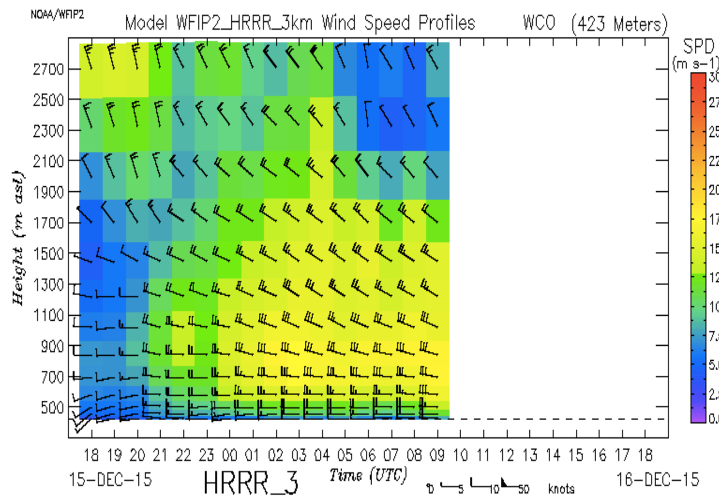
Comparison of CTL & EXP HRRR







- **Both HRRRs strengthen the gap flow too quickly and too much near the surface.**
- **HRRR-WFIP is slightly weaker (better match to obs) than the operational HRRR.**
- **Both HRRRs do poorly above 1500-m after 03 UTC, by advecting the Mt Adams wake too far south, over Wasco.**



Event Logging

- Classify weather events
- Document main features
- Compare model performance
- Weekly weather discussions
- Discuss results of RAP/HRRR testing
- Select case studies

Event Log

File Edit View Insert Format Data Tools Add-ons Help All changes saved in Drive

joseph.b.olson@noaa.gov

	A	B	C	D	E	F	G	H	I
1	Reminder: watch period spans 0000-235			Regime Types ->					
2	Consult "Event Logging Responsibilities"			(WF) Warm FROPA w/mix-out			(MP) Marine push		(SA) Surface anticyclone
3	documentation here.			(EG) Easterly gap flow			(IS) Inversion-level shear		(SW) Extended pre-frontal S/SWly flow
4				(CO) Convective outflows			(WG) Westerly gap flow		(OT) Other (free-form description)
5	HRRR-WFIP Configuration			(WS) Significant diurnal wind shift			(TW) Topographic wakes		
				(CF) Cold FROPA			(MW) mountain waves		
6				Regional Characterization: use model guidance to supplement observational evidence, as needed			Wasco-Area Measurements		Summary (This should be "tweet-length". Put more extensive write-up on "Remarks" sheet)
7				Subjective Regime Classification (enter "Type" ID)			PEAK RAMP (Wasco "Dalek2" Lidar, 100m)		
8	Date (UTC)	DOW	Event Logger	Dominant	Secondary	Tertiary	magnitude (m/s)	duration	
53	5-Dec-15	Sat	Qing Yang	CF	EG	IS	no ramps		mainly weak easteries/southlies associated with the weak frontal system
54	6-Dec-15	Sun	Qing Yang	WF	WG	IS	4 m s-1	2h	pick up in wind speed and shift to westeries at around 20 UTC
55	7-Dec-15	Mon	Eric Grimit	SW	WS	IS	9 m s-1	2h	Strong SW flow aloft, warm/wet, ramp down at 3 UTC with stable BL, then mixout large up ramp 21
56	8-Dec-15	Tue	Eric Grimit	SW			-9 m s-1	3h	Strong W flow aloft relaxes 7-13 UTC, increased low-level shear, then mixout w/ WSW flow 14-20 U
57	9-Dec-15	Wed	Eric Grimit	CF	MW		-4 m s-1	1h	Strong SW flow persists until cold frontal passage at 10-11 UTC, then W post-frontal flow with wave
58	10-Dec-15	Thu	Mark Stoelinga	CF	WF	EG	"+11 m s-1"	3h (twice)	Westerly postfrontal to easterly gap/warm advection aloft back to SW'ly postfrontal.
59	11-Dec-15	Fri	Mark Stoelinga	WG			-9 m s-1	3h	Downramping of postfrontal flow, then weak flow, then slight easterly upramp with approach of dyin
60	12-Dec-15	Sat	Mark Stoelinga				-7/+10/-10/+8 m/	3h/6h/4h/3h	
61	13-Dec-15	Sun	Jaymes Kenyon	TW	CF	MW	7	3 h	CFROPA at Wasco between 08-09Z, then pronounced afternoon waking from Mt Hood
62	14-Dec-15	Mon	Jaymes Kenyon	SA			no ramps		Fair weather; steadily weakeneing low-level WNW flow
63	15-Dec-15	Tue	Jaymes Kenyon	TW	WG		6	2.25 h	Development of modest westerly gap flow between Hood, Adams wakes
64	16-Dec-15	Wed	Joe Olson	WG	MW		4/-9	2/1.5h	Weak disturbance passes eastern edge of WFIP2 region; westerly GF with mountain wakes
65	17-Dec-15	Thu	Joe Olson	EG	IS	WF-non mix-out	3	2h	Warm front passes WFIP2 area later in the day. Easterly GF is not mixed out

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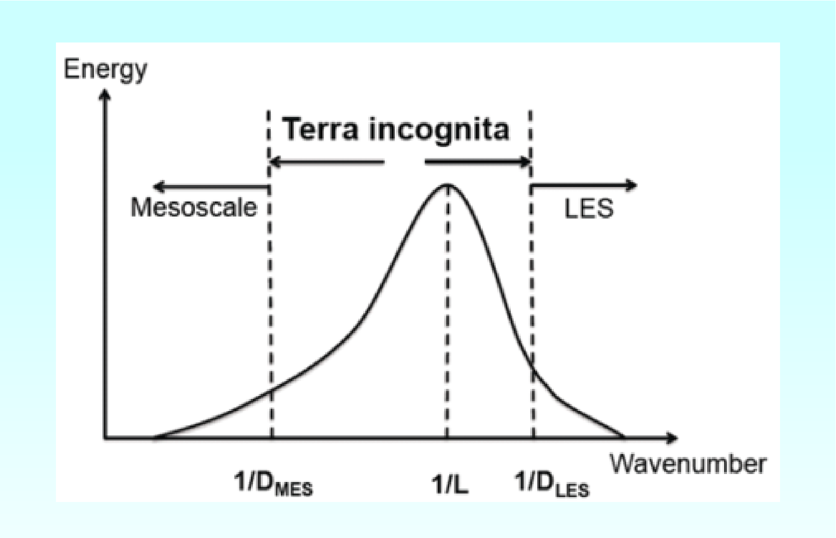
Model Development

- Scale-aware boundary layer physics - transition from 1D to 3D (Kosivić & Jimenez)

- Scale-aware cumulus mass-flux coupled to PBL scheme (NOAA)

- Scale-aware subgrid-scale clouds (NOAA)

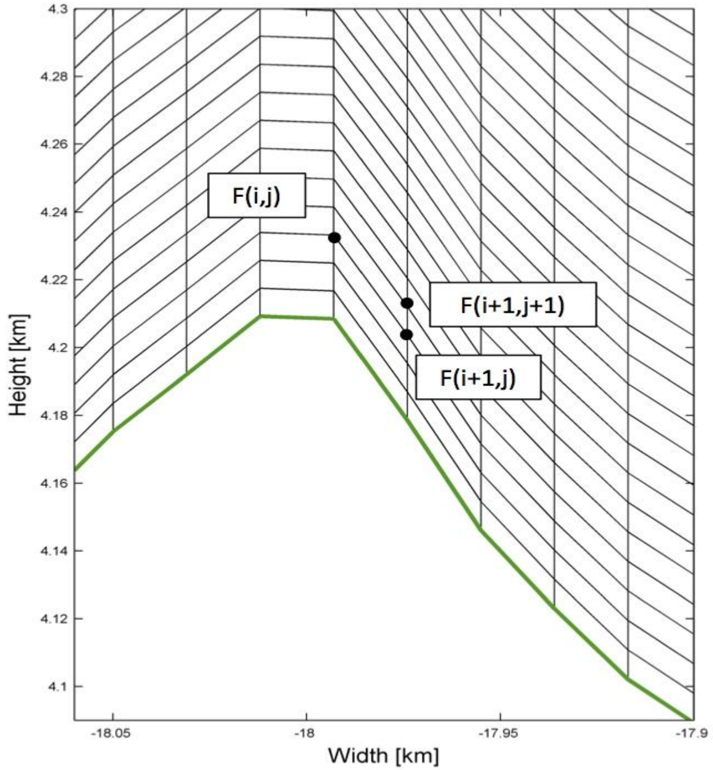
- Improved numerics in complex terrain
  - IBM - Immersed Boundary Method (K. Lundquist)

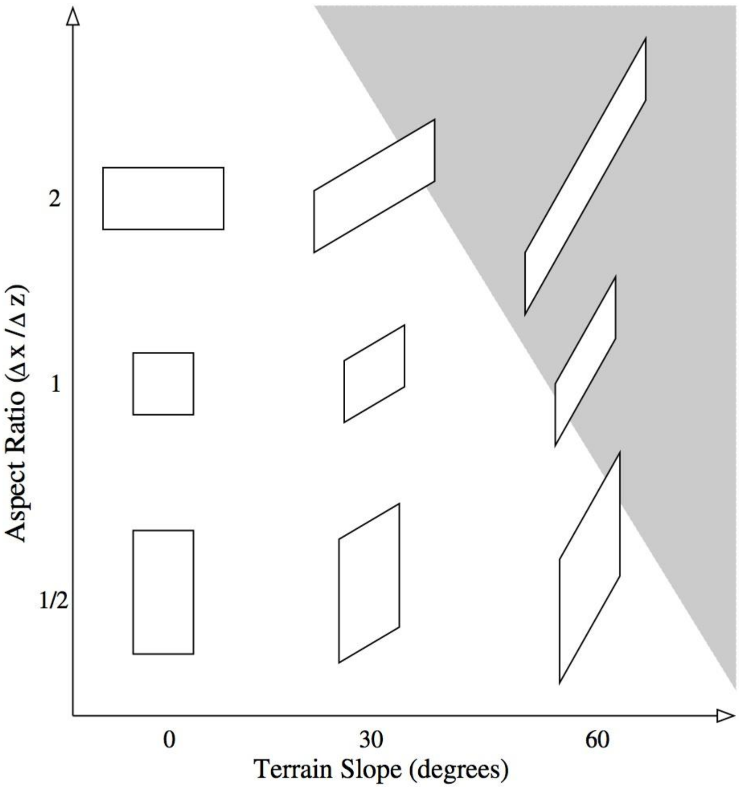


1-2 km 0.1 km

Note: New model physics not yet implemented in WRF-ARW

Errors from terrain-following coordinates





$$\frac{\partial F}{\partial x} = \frac{F(i+1,j) - F(i,j)}{\Delta x} + \frac{\partial z}{\partial x}\frac{F(i+1,j+1) - F(i+1,j)}{\Delta z}.$$

Development of a three-dimensional parameterization of turbulent mixing in PBL

Conservation equation for the horizontal wind components:

$$\frac{\partial U}{\partial t} + U_j \frac{\partial U}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - fV - \frac{\partial \langle uw \rangle}{\partial z}$$

$$\frac{\partial V}{\partial t} + U_j \frac{\partial V}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + fU - \frac{\partial \langle vw \rangle}{\partial z}$$

- The vertical turbulent fluxes are parameterized by the PBL scheme
- The horizontal turbulent fluxes are parameterized using Smagorinsky type (2D) diffusion scheme (Smagorinsky 1963)
- Different closure assumptions between PBL and diffusion schemes

Objective:

Incorporate a more consistent formulation of the turbulent fluxes based on first principles.

Development of a three-dimensional parameterization of turbulent mixing in PBL

Conservation equation for the zonal wind:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + 2\epsilon_{ijk}\Omega_j U_k - \frac{\partial \langle u_i u_j \rangle}{\partial x_j}$$

- 3D PBL scheme includes (diagnostic) parameterization of all six turbulent stress components and computation of stress divergence (Mellor and Yamada 1974,1982; Yamada and Mellor 1975)
- Consistent closure assumption for all stress components

Objective:

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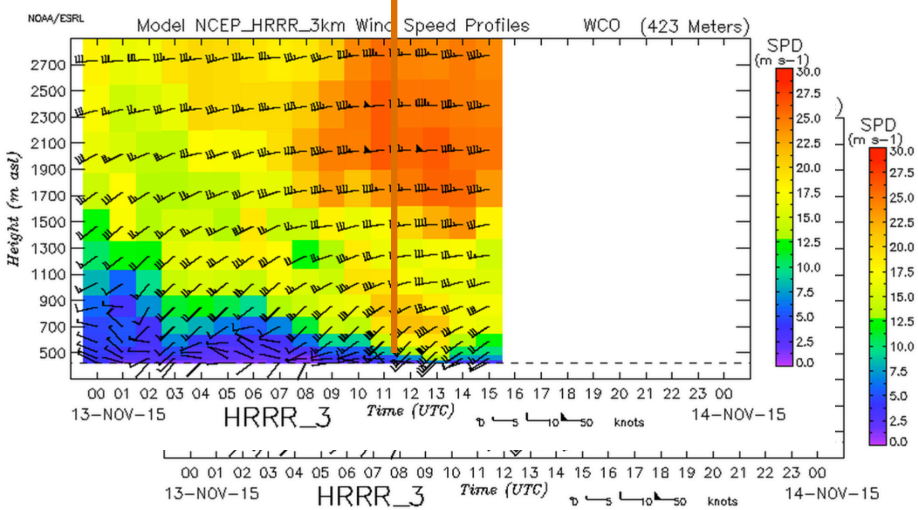
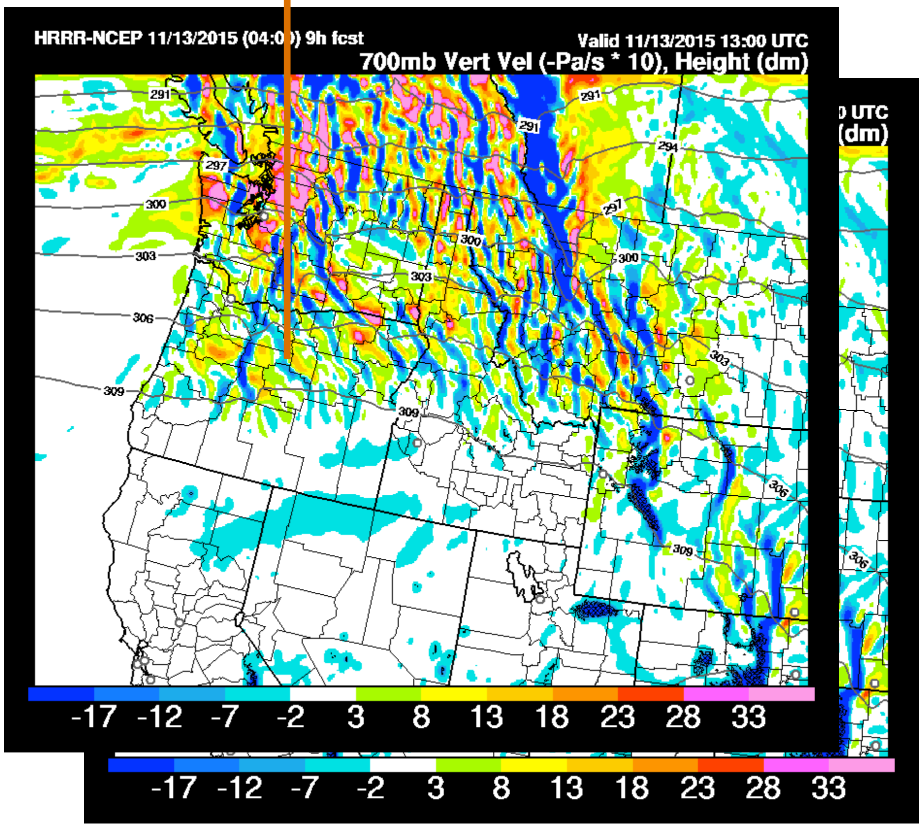
Delivering information to operators

Stable BL Mix-Out



Mountain Wave Volatility



Alert Design and Validation

- The alerts we design will be fully probabilistic
  - Whatever methods we choose will likely carry significant uncertainty, which must then be communicated to our users

Wind Project: Klondike

09:00 – 12:00

ALERT: 7 in 10 chance of stable cold pool mix-out leading to *power up-ramp*

12:00 – 15:00

ALERT: 3 in 10 chance of mountain wave induced *power volatility (up/down)*

- The evaluation will require standard methods for verification of probabilistic forecasts of binary and possibly multi-category event types
  - Contingency analysis (hit, miss, and false alarm rates)
  - Event-based summary metrics (equitable threat score)

Summary

WFIP2 provides a new opportunity to:

- Observe and understand flows & processes in complex terrain
  - Gap flows, marine pushes, mountain wakes, trapped lee-waves, cold pool erosion
- Improve NWP model physics in complex terrain
  - Data could be used to evaluate other models, especially global forecasts, and Improvements hopefully can be transferred to other models in other geographic regions
- Develop new probabilistic decision support tools

Most data will be available via DOE and NOAA archives

See: http://wfip.esrl.noaa.gov/psd/programs/wfip2/

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Thank you!   Questions?

