Surface radiation from observations and forecasts from the NOAA HRRR model for Renewable Energy Applications

Wind Forecasting Improvement Project (WFIP-2)

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NOAA

CIRES

NOAA Atmospheric Sciences for Renewable Energy (ASRE)

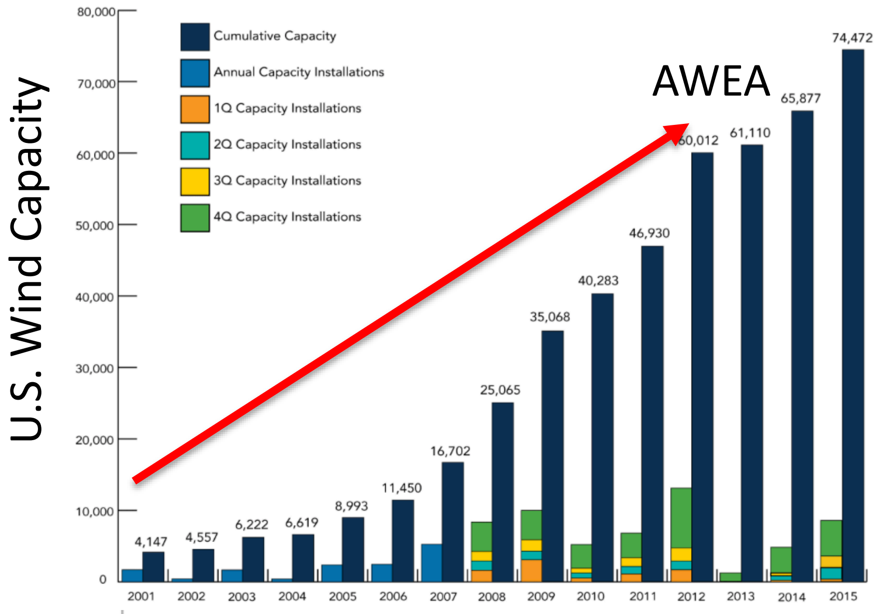
ASRE Mission

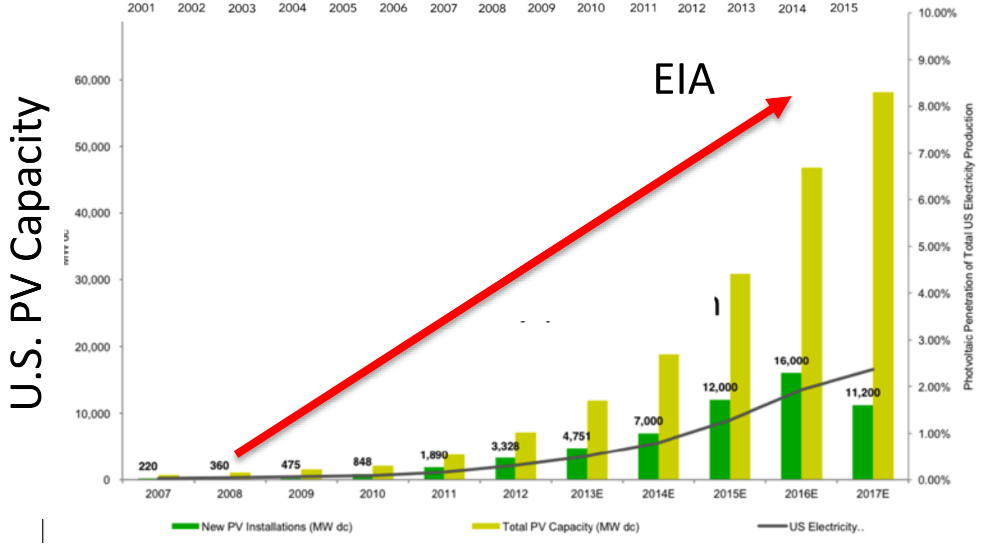
Developing improved forecasts, observations of wind and solar resources, and tools to improve the efficiency and sustainability of the energy system through better understanding and modeling

The ASRE Program addresses **NOAA's Next Generation Strategic Plan**

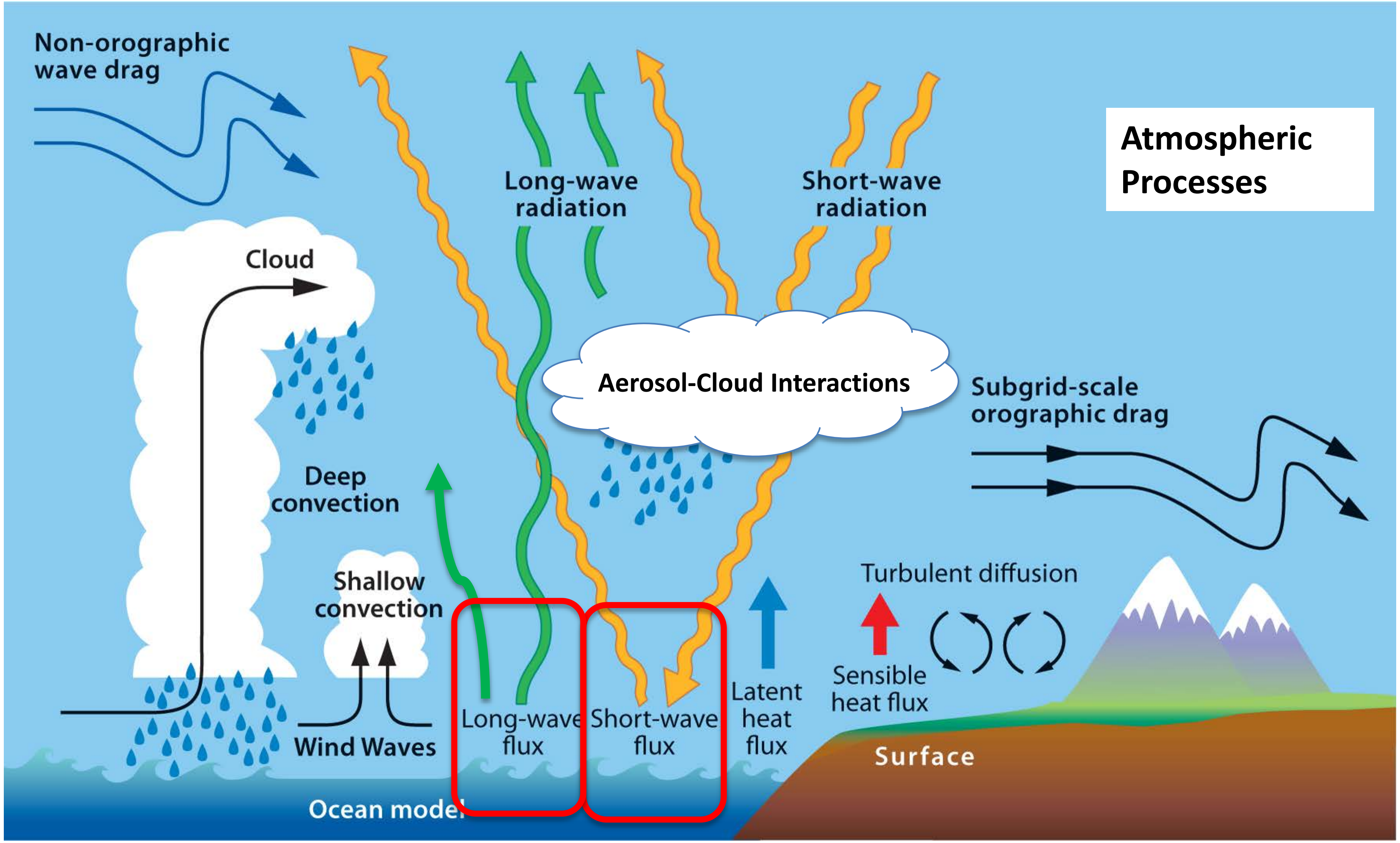
- Climate Adaptation & Mitigation
- Weather Ready Nation

The ASRE Program addresses the **Weather Ready Nation (WRN)** goal of improving sector-relevant information in support of economic productivity. The WRN Roadmap specifically calls for engaging in the renewable energy sector.





Why radiation for solar and wind forecasts?



There is an fundamental connection between solar radiation forecasts (both diffuse and direct) and low-level wind forecasts.

Surface Net Radiation

Energy available for SH, LH, and ground heat flux

Drives turbulent mixing, PBL formation, low-level winds, clouds

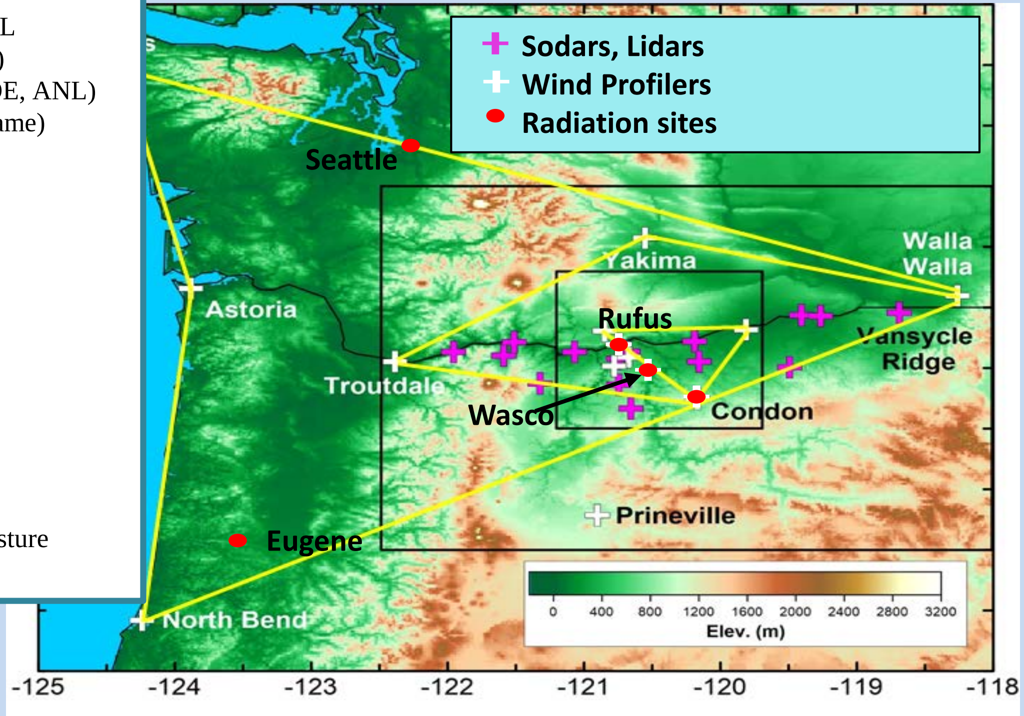
Wind Forecasting Improvement Project (WFIP-2)

Purpose: **DOE/NOAA** WFIP-2 has two overarching scientific goals:

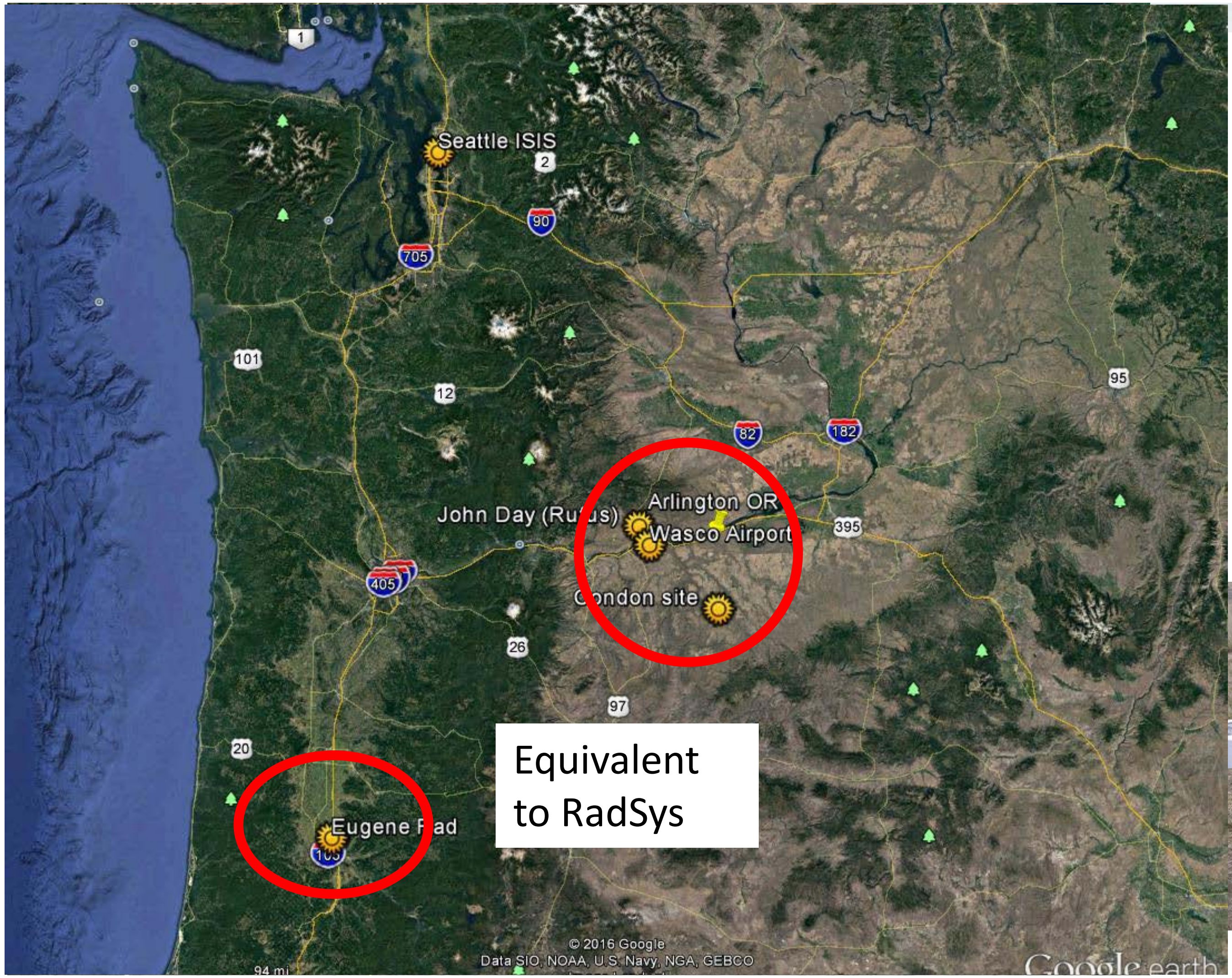
1. To improve the physical understanding of atmospheric processes that directly impact wind energy forecasts in areas of **complex terrain**
2. To incorporate the new understanding into a foundational weather forecasting model

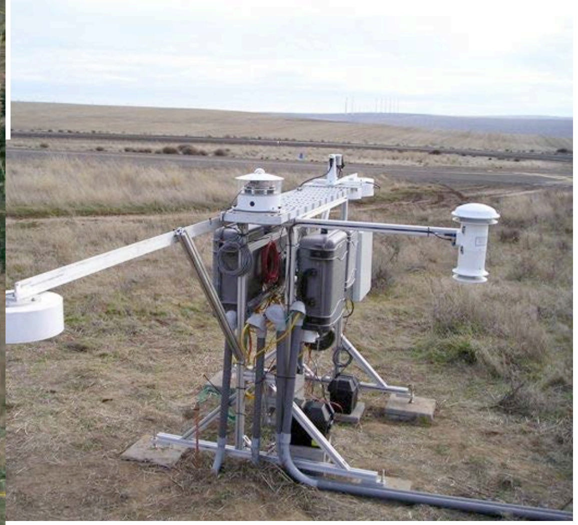
Multiple Partners
All divisions across NOAA/ESRL
Other NOAA laboratories (ARL)
Other Federal Agencies (e.g. DOE, ANL)
Universities (UC, U. of Notre Dame)
Private sector (e.g. Vaisala Inc)

Suite of Measurements
11 wind profiling radars
17 sodars
5 wind profiling lidars
4 scanning lidars
4 microwave radiometers
10 microbarographs
1 ceilometer
2 scanning radars
28 sonic anemometers
3 radiative flux systems/soil moisture
2 Radsys and 1 SURFRAD unit

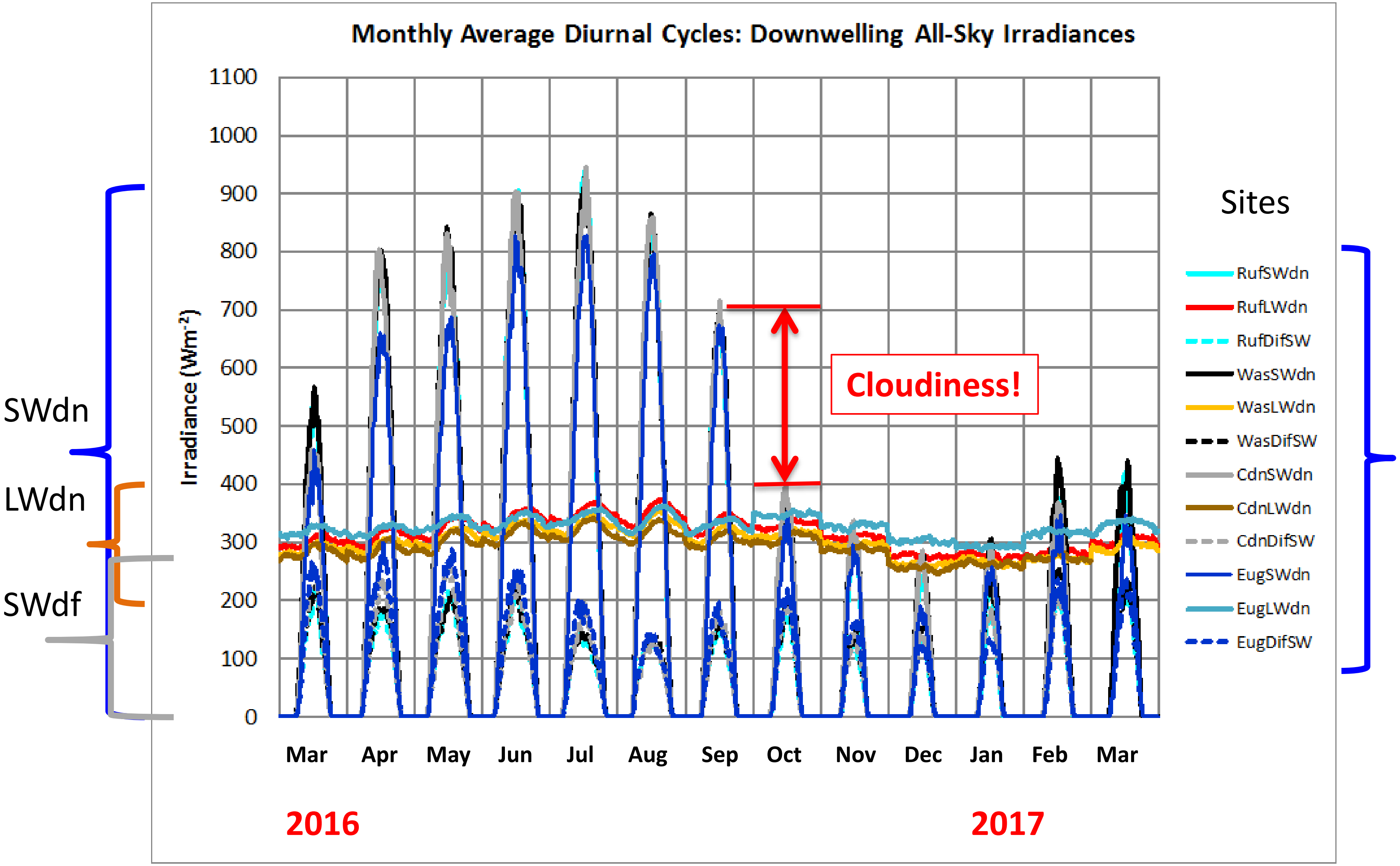


WFIP2: SURFRAD and RadSys Sites



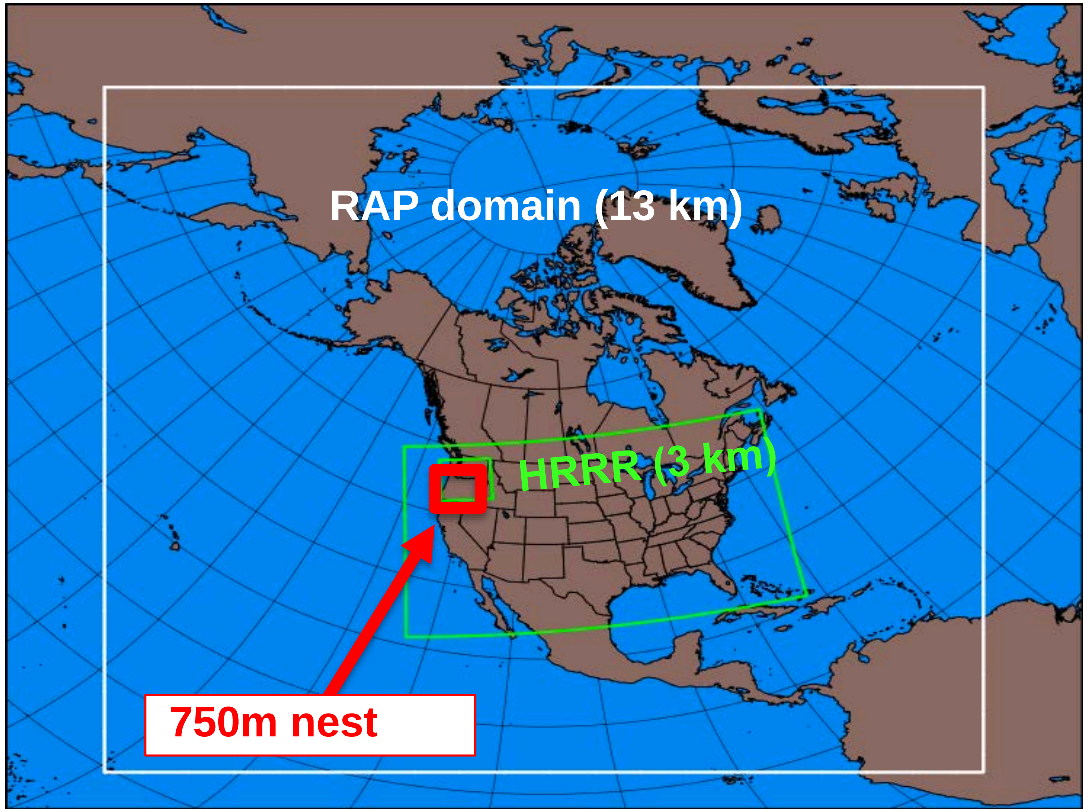


Average Monthly Diurnal Cycles



Rapid Refresh (RAP) and High Resolution Rapid Refresh (HRRR)
NOAA hourly updated models

Resolution: Conus (3km) and Nest (750m)



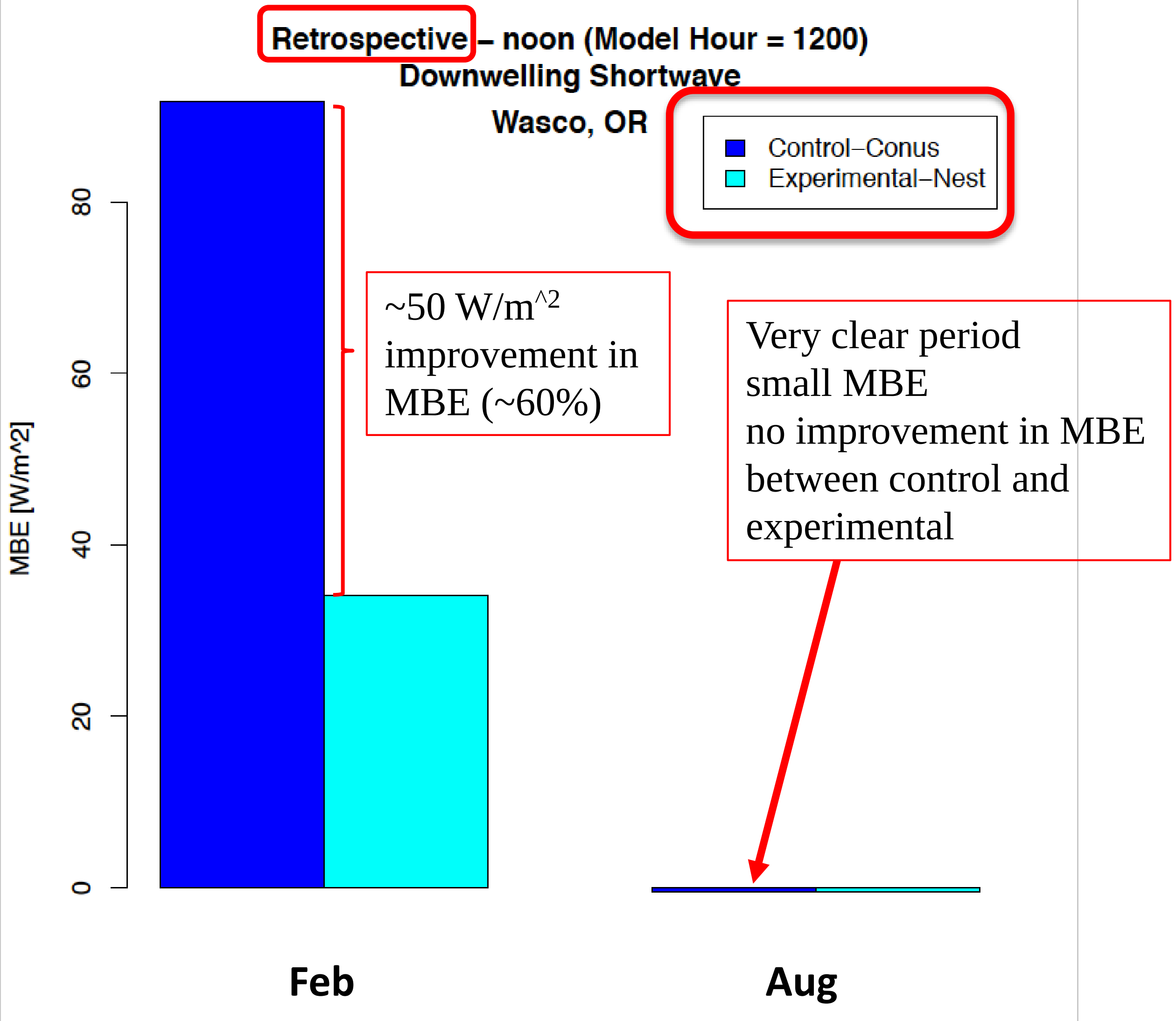
1. 10-day Retrospective

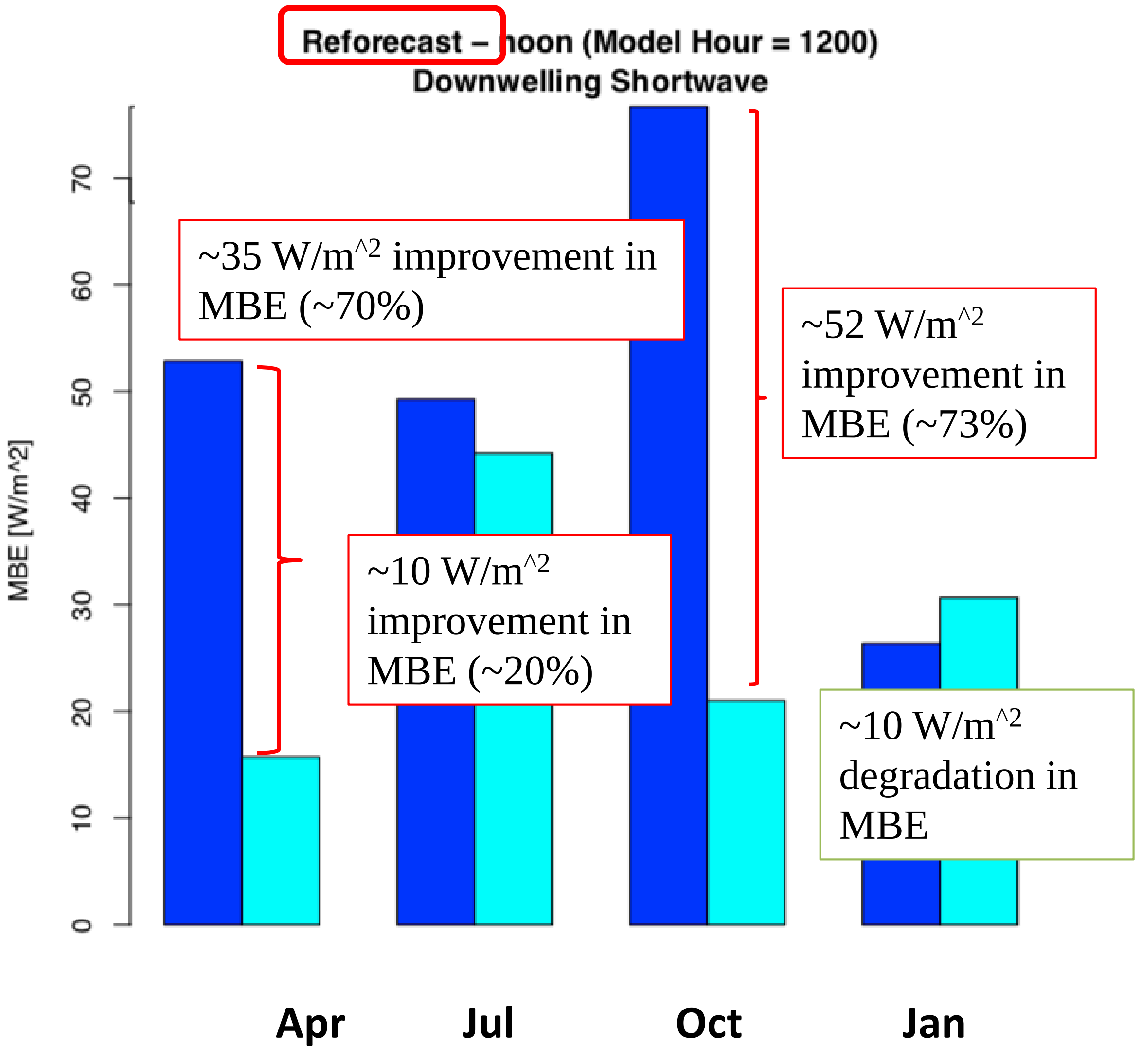
- Hourly updated forecasts
- Periods in **February** and **August**

2. Seasonal Reforecasts

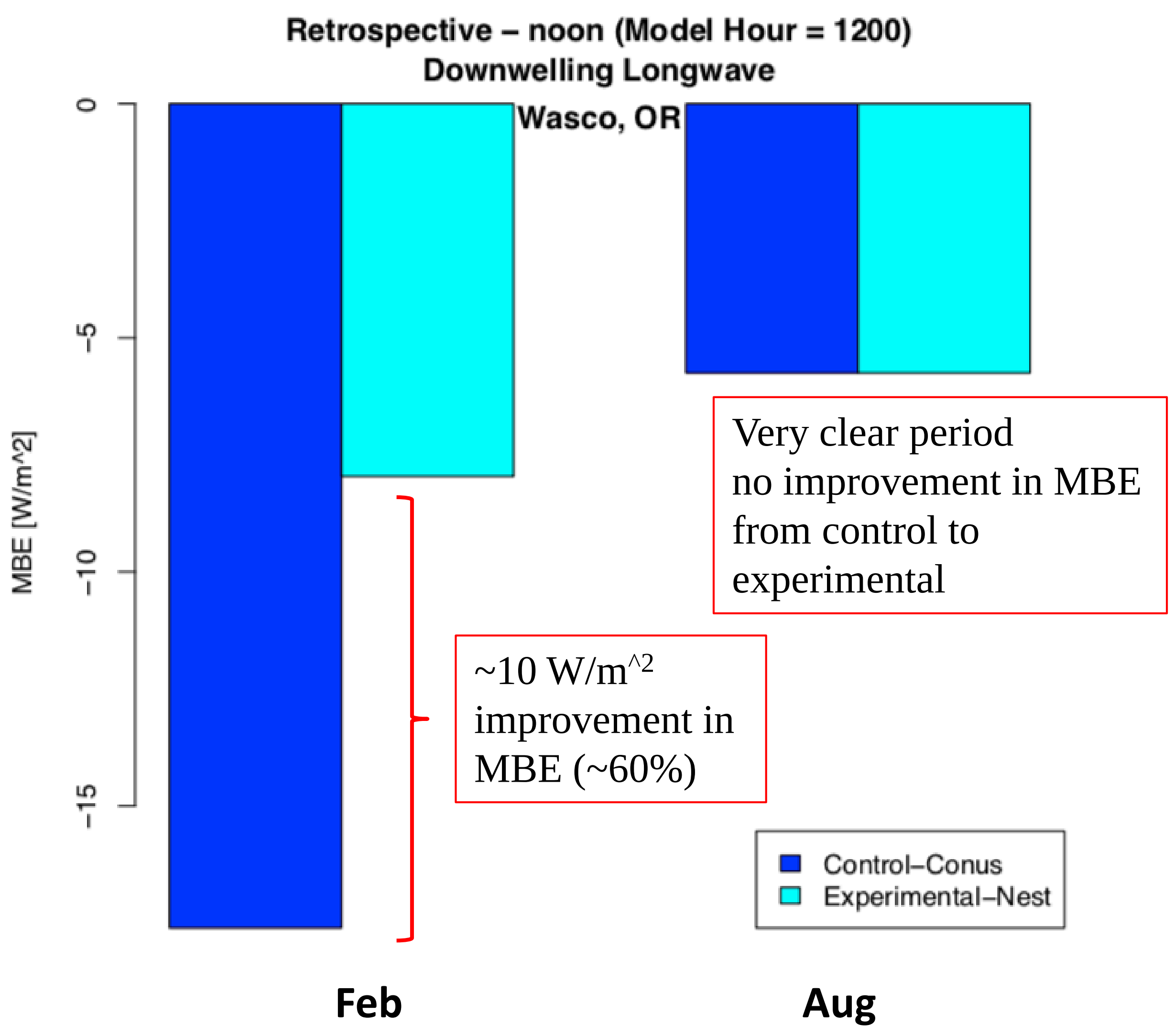
- Cold Start, no data assimilation or cycling
- Spanning 4 seasons in Apr, Jul, Oct 2016, and Jan 2017

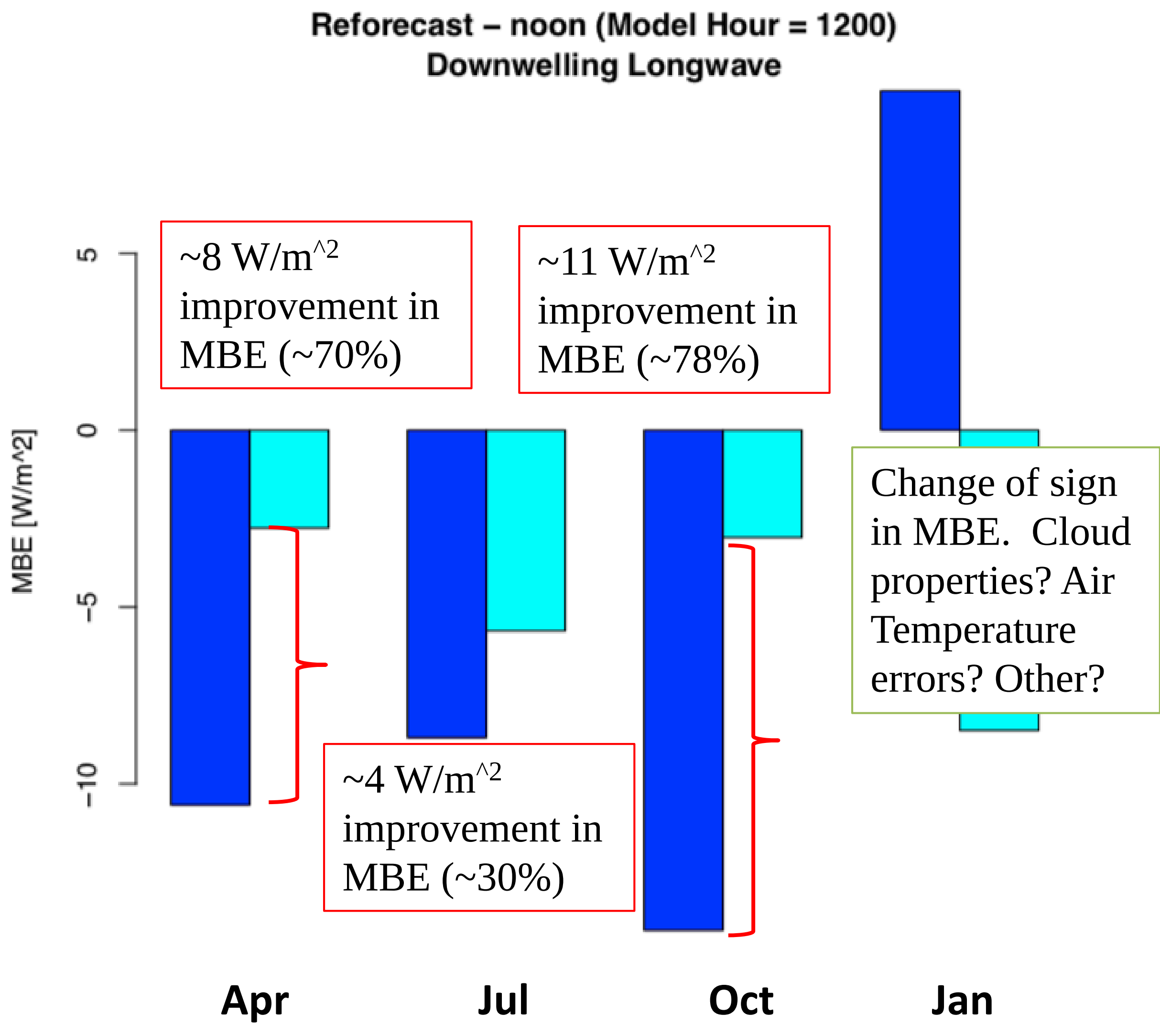
Downwelling Shortwave Radiation MBE
Wasco, OR



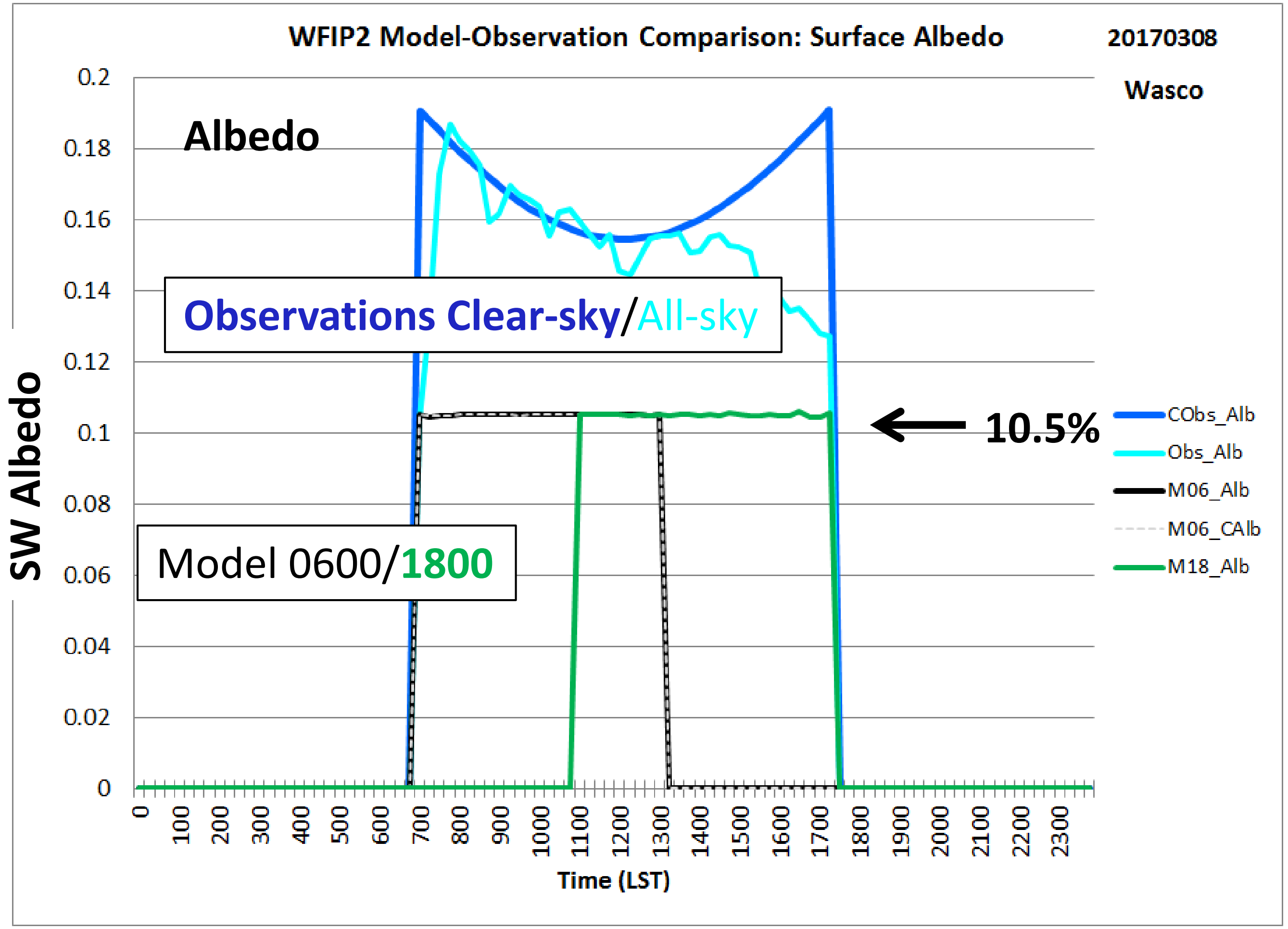


Downwelling Longwave Radiation MBE
Wasco, OR





SW Albedo – March 8
Wasco, OR

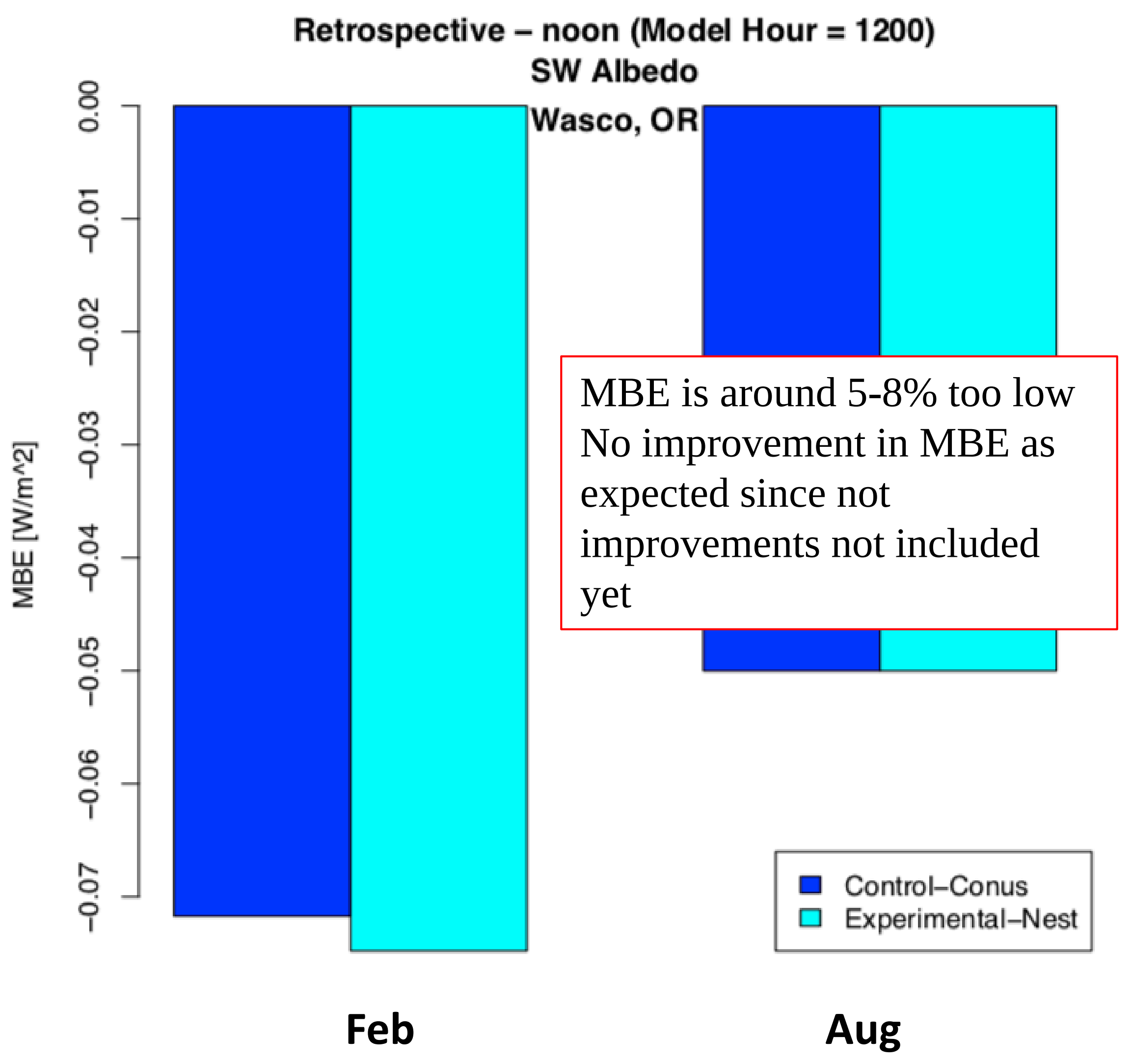


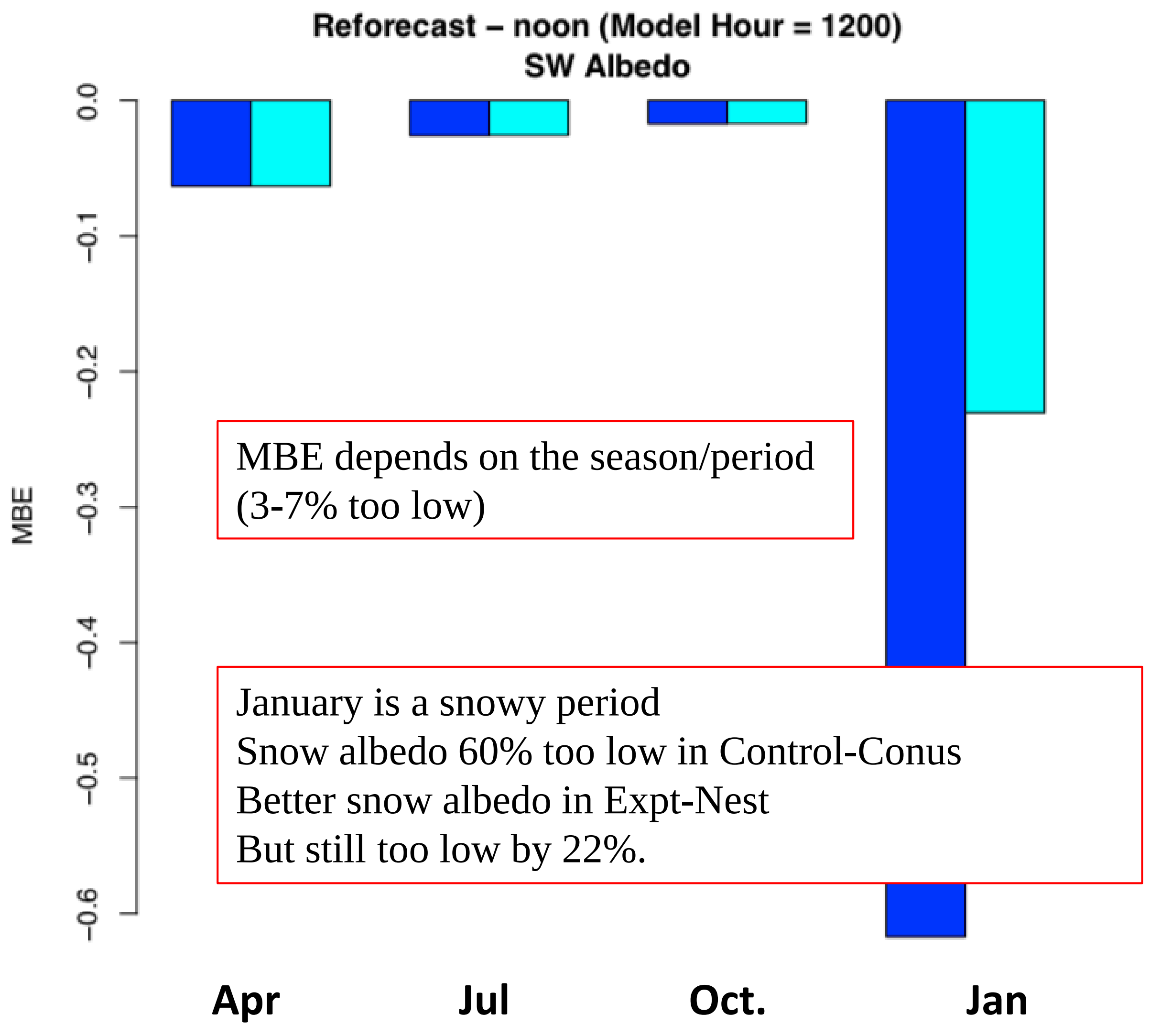
SW Albedo

- Model SW Albedo is too low at ~10.5% for March 8.
- This is unrealistic and much too low!
- The model does not reflect SZA dependence under clear skies.

- **Solution:** Improvements have been made in the model SW albedo using MODIS climatology that is more realistic.
- **Future:** Check new albedo against other surface types and across seasons (e.g SURFRAD sites).

Shortwave Albedo MBE
Wasco, OR

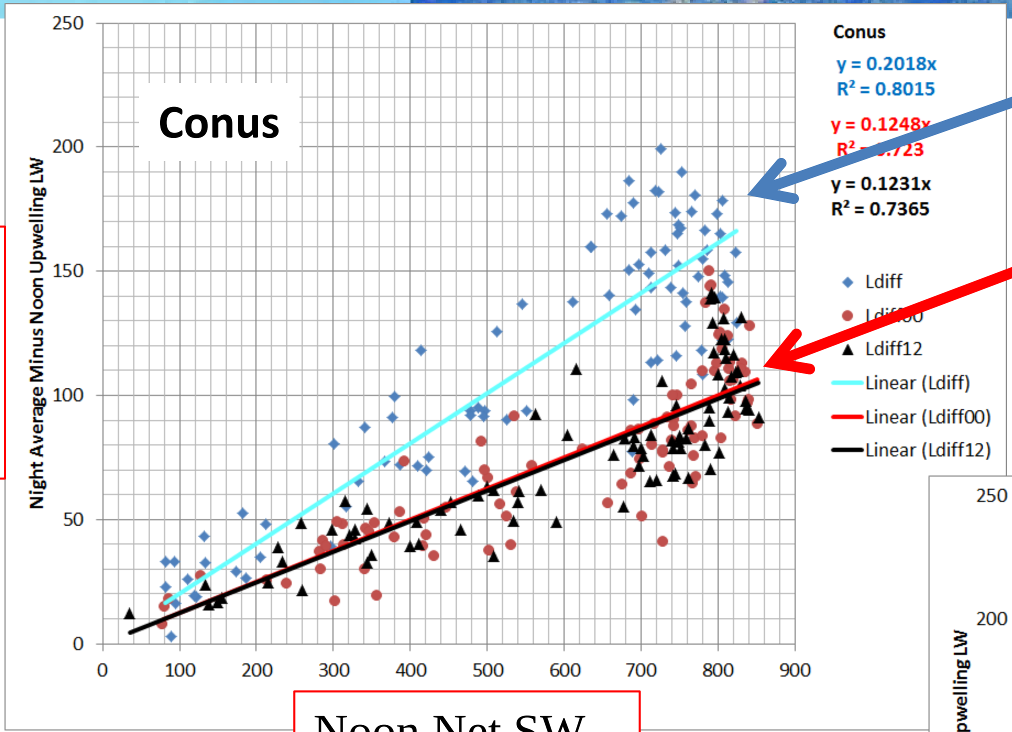




Response of LWup to SWnet Solar Enhancement

Reforecast periods Apr, July, October

Noon Upwelling LW minus night average

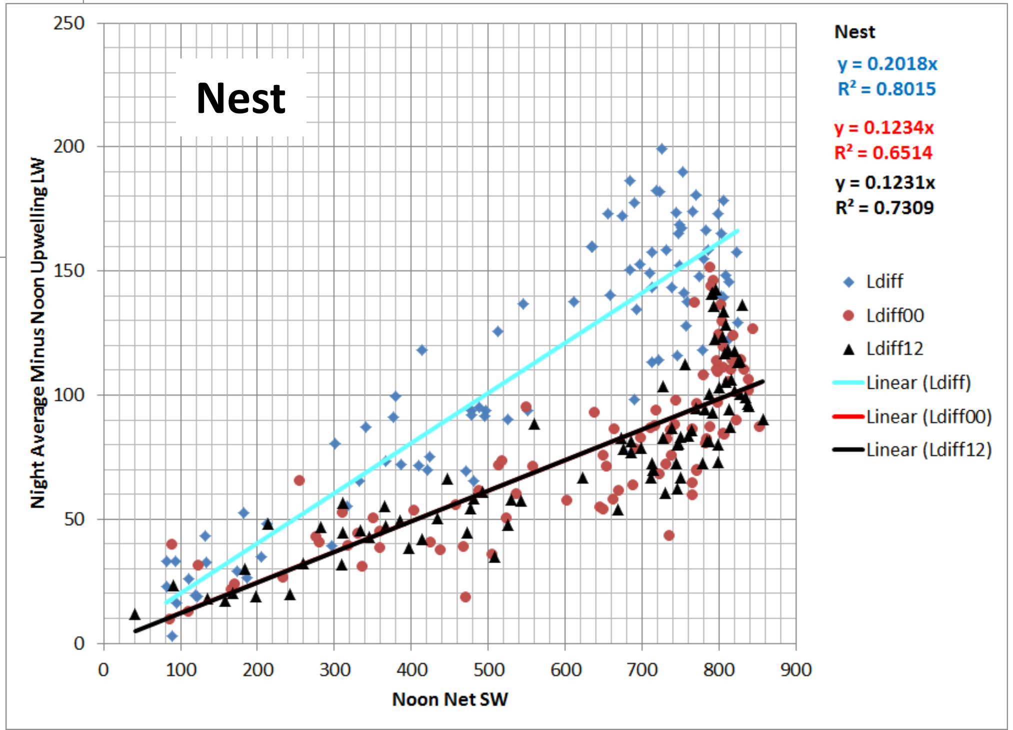


Noon Net SW

Observations: 20 Wm^{-2} enhancement per 100 Wm^{-2} SWnet

Models: 12 Wm^{-2} enhancement per 100 Wm^{-2} SWnet

40% less response to SWnet in models



Better LWup response in Retrospective runs
Retrospective is mode comparable to operational model

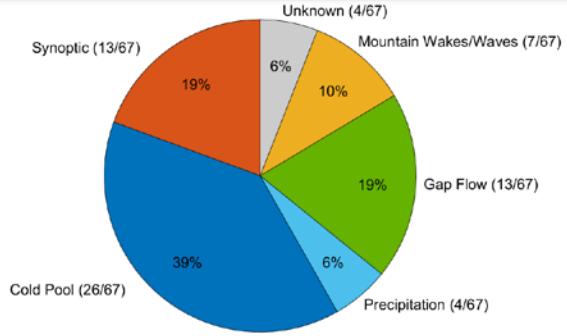
Summary for WFIP HRRR nest model versus radiation observations

- <u>Control-Conus to Experimental-Nest: </u> Significant improvement in downwelling shortwave radiation in retrospective (0 and 60%) in spring – fall reforecast periods (20-73%) and a degradation in winter (25%).
- <u>Control-Conus to Experimental-Nest: </u>Significant improvement in downwelling longwave radiation in retrospective (0-60%) and reforecast periods (0-78%) (especially cloudy months).
- Model all-sky SW radiation for reforecast period in April is in good agreement with observations, but direct is too high and diffuse is too low. Not getting partitioning correct, very important for Solar RE!
- Previous “peek” at the clear-sky variables showed clear-sky model components indicated model aerosol properties were unrealistic
- SW Albedo of ~10.5% is not realistic and too low. Bidirectional reflectance under clear-skies not captured. However, recent modeling work has improved the SW albedo and the SZA dependence.
- The *reforecast* model upwelling LW does not respond adequately to SW net surface heating as observations show. How is model radiation information coupled to the land surface model?

- **What about the winds!** Just getting started on this data-set, more to come. Improvements in windspeed are seen especially in cold season (cold pools), and second during gap flow and synoptic events.

Courtesy Jim Wilczak

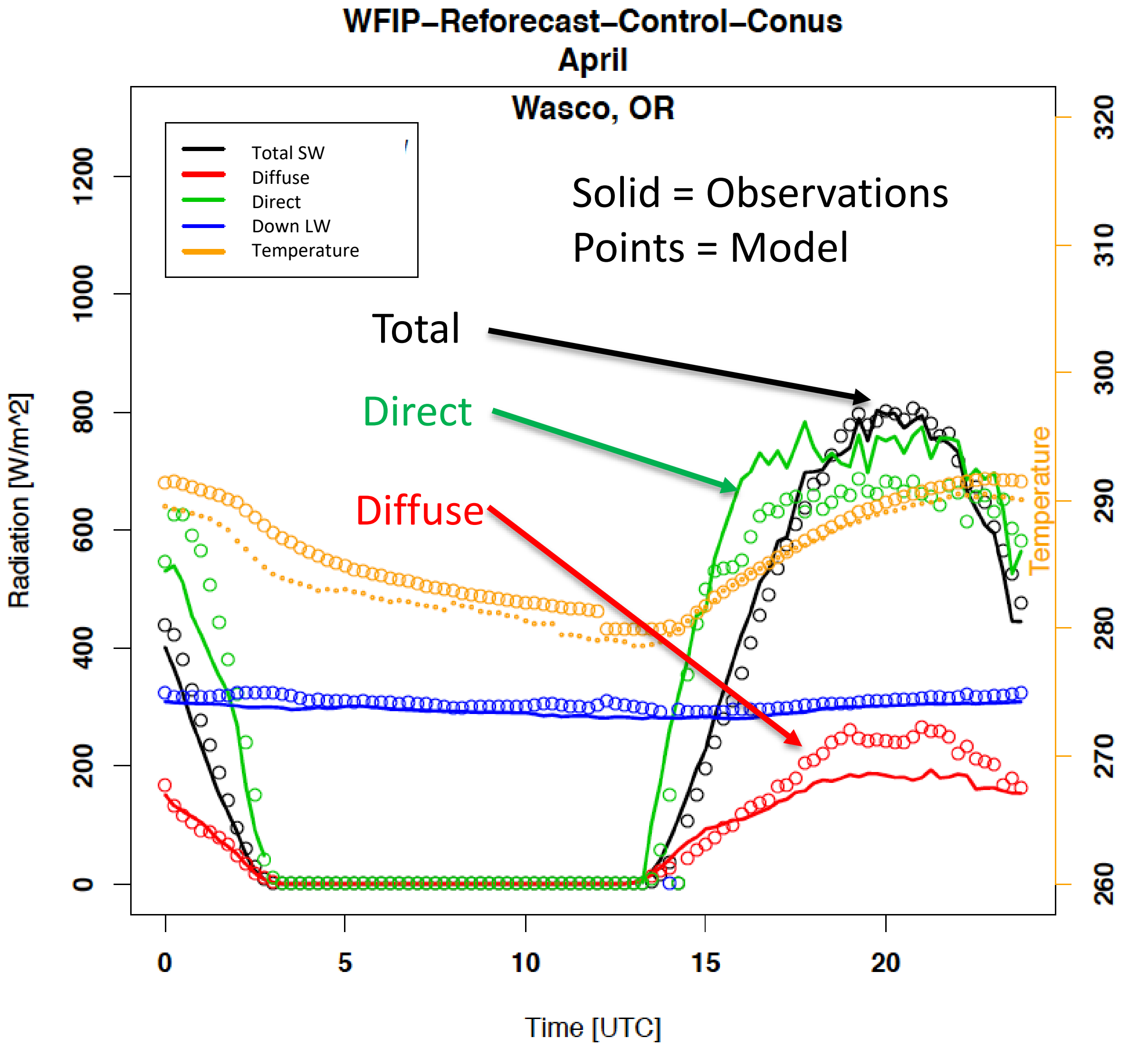
Large Forecast Busts by Meteorological Event



Thank you!

Extra slides

All-Sky Shortwave Components



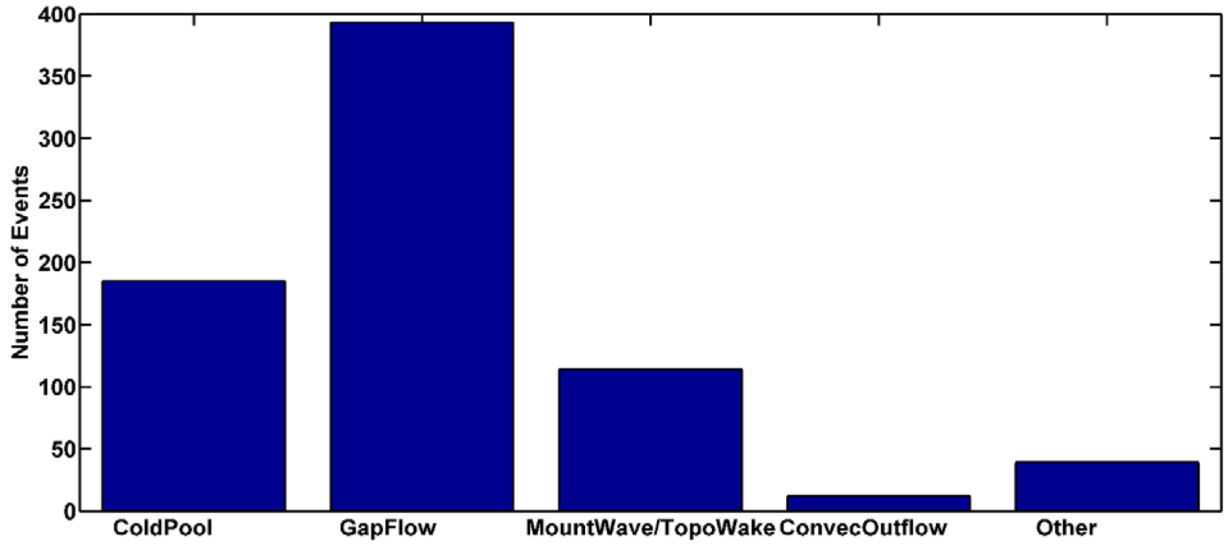
Reforecast – April – Wasco, OR

ALL-SKY mean values of Solar Components (Diffuse,Direct)

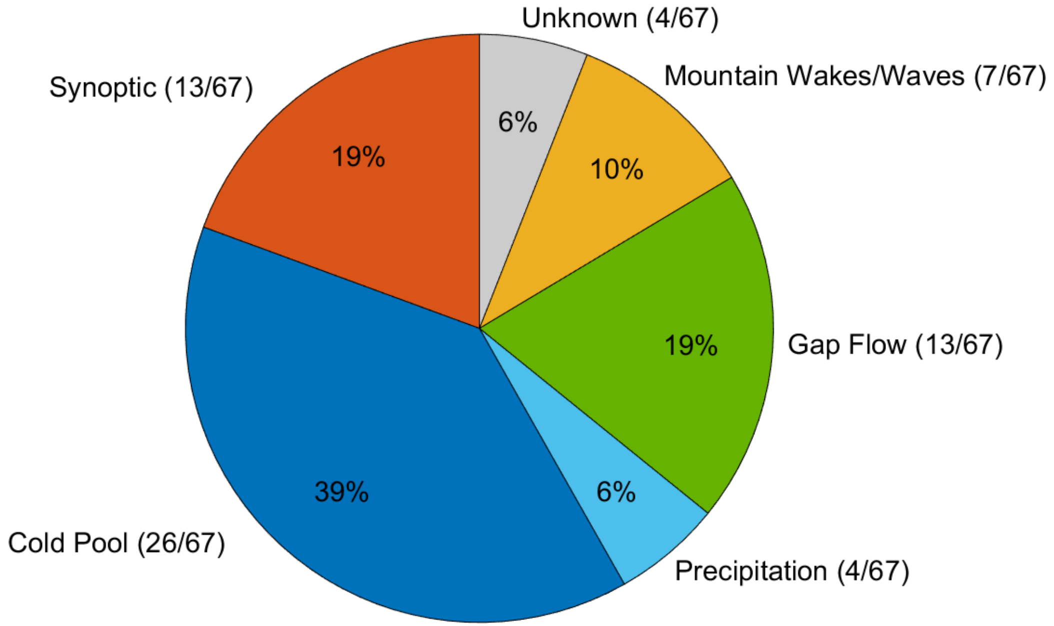
- Model Downwelling Shortwave Radiation is in good agreement with observations
- Model Direct normal irradiance (DNI) is too high
- Diffuse solar irradiance is too low
- Even though the downwelling SW is in agreement, the partitioning between the components is not correct.
- Note: Results are different by monthly means. Clear-sky components tell another story.
- **Future:** MBE for clear-sky solar components. Check reforecast versus retrospective because aerosols are handled differently.

Event Log: Meteorological Events

Event Log: Number of Cases Observed



Large Forecast Busts by Meteorological Event

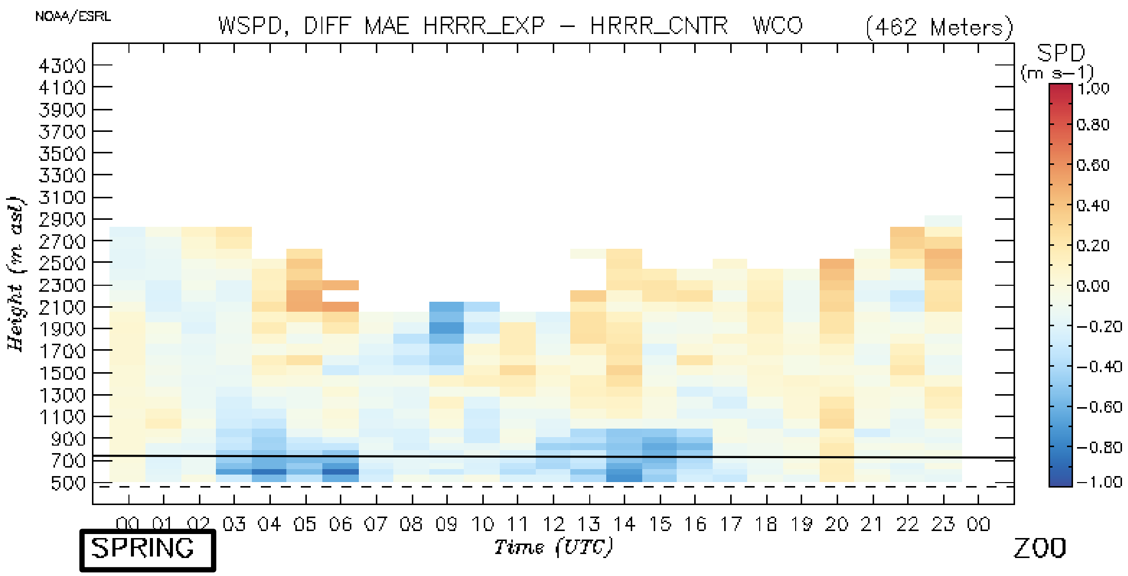


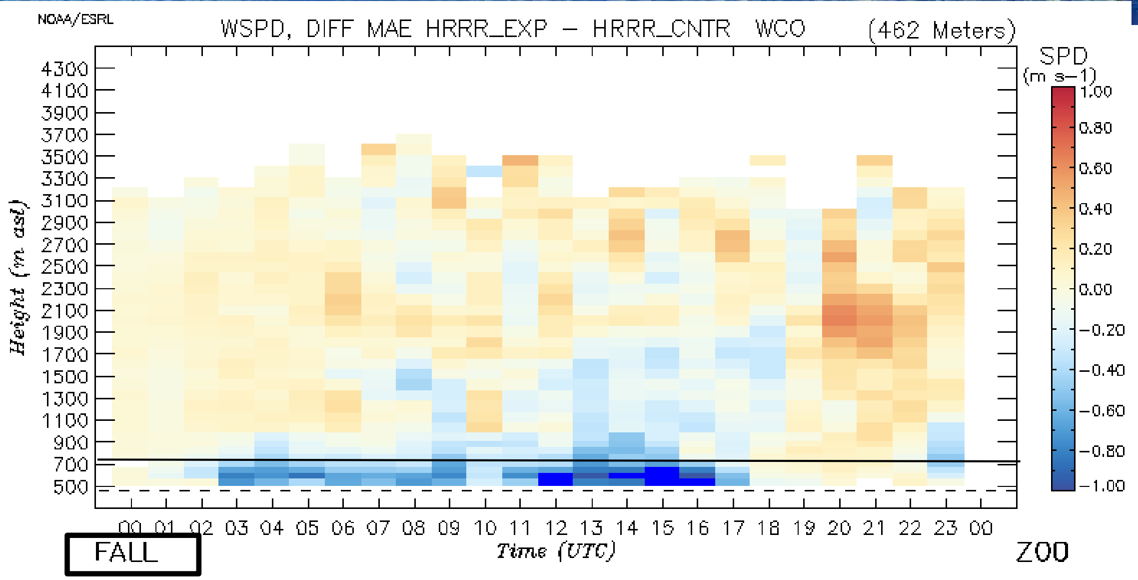
Courtesy of Aditya Choukulkar and Jim Wilczak

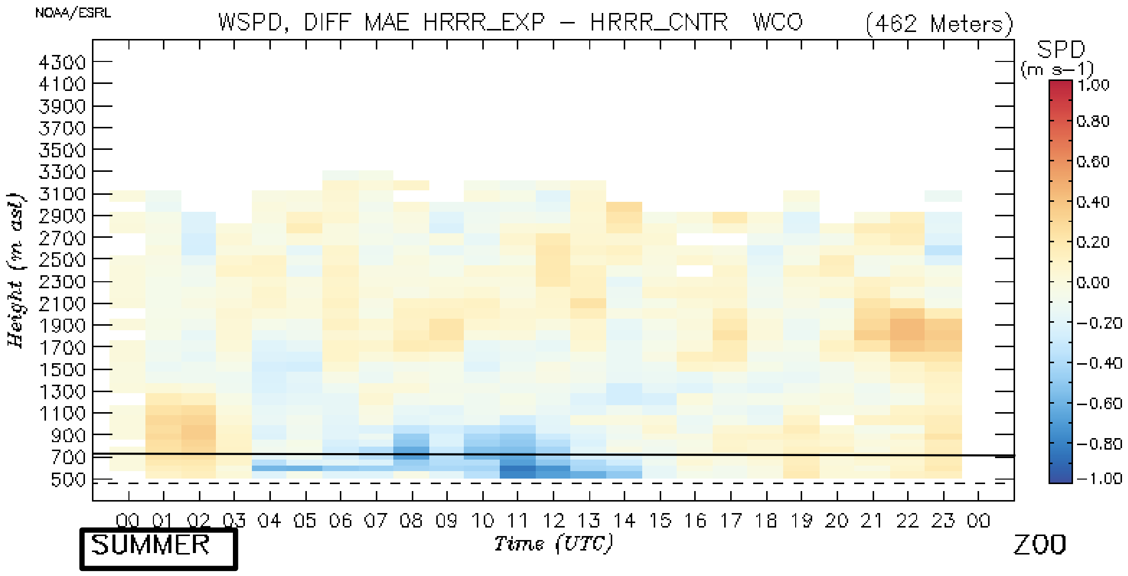
Physics: WCO, WINDSPEED MAE_HRRR_EXP – MAE_HRRR_CNTR (Reforecast periods)

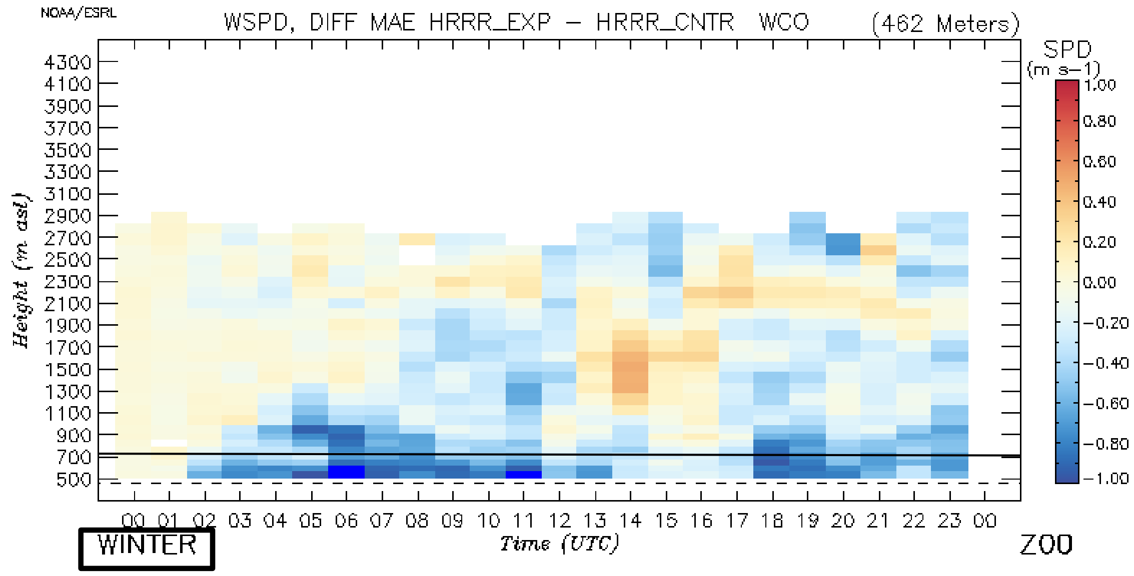
Courtesy of I. Djalalova (PSD)

00 UTC Runs only

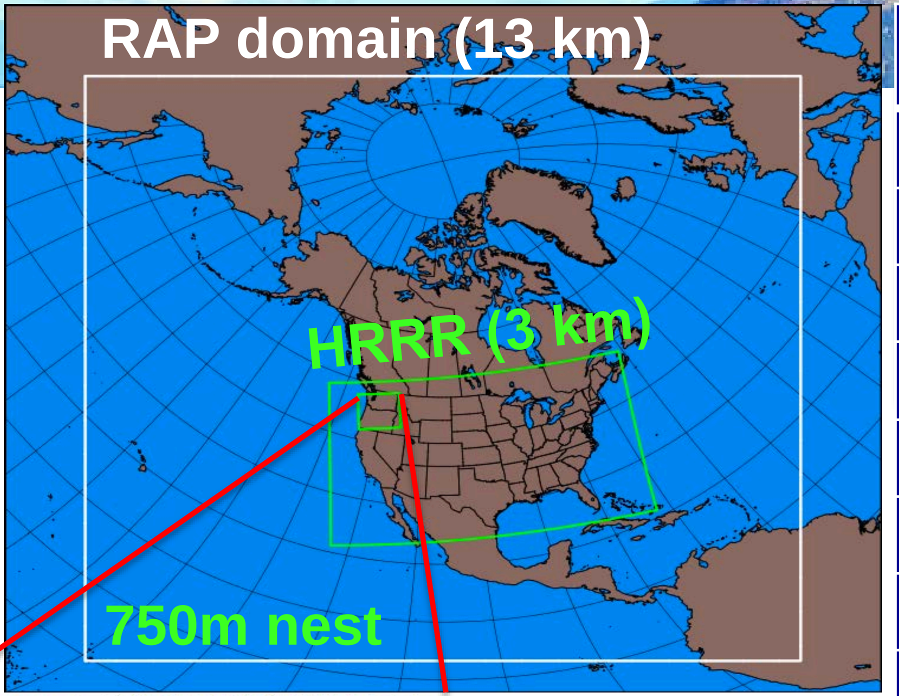


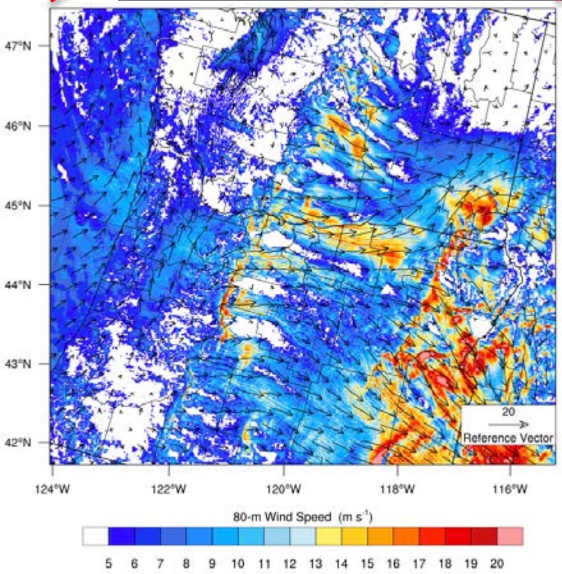






RAP/HRRR/nest Configuration





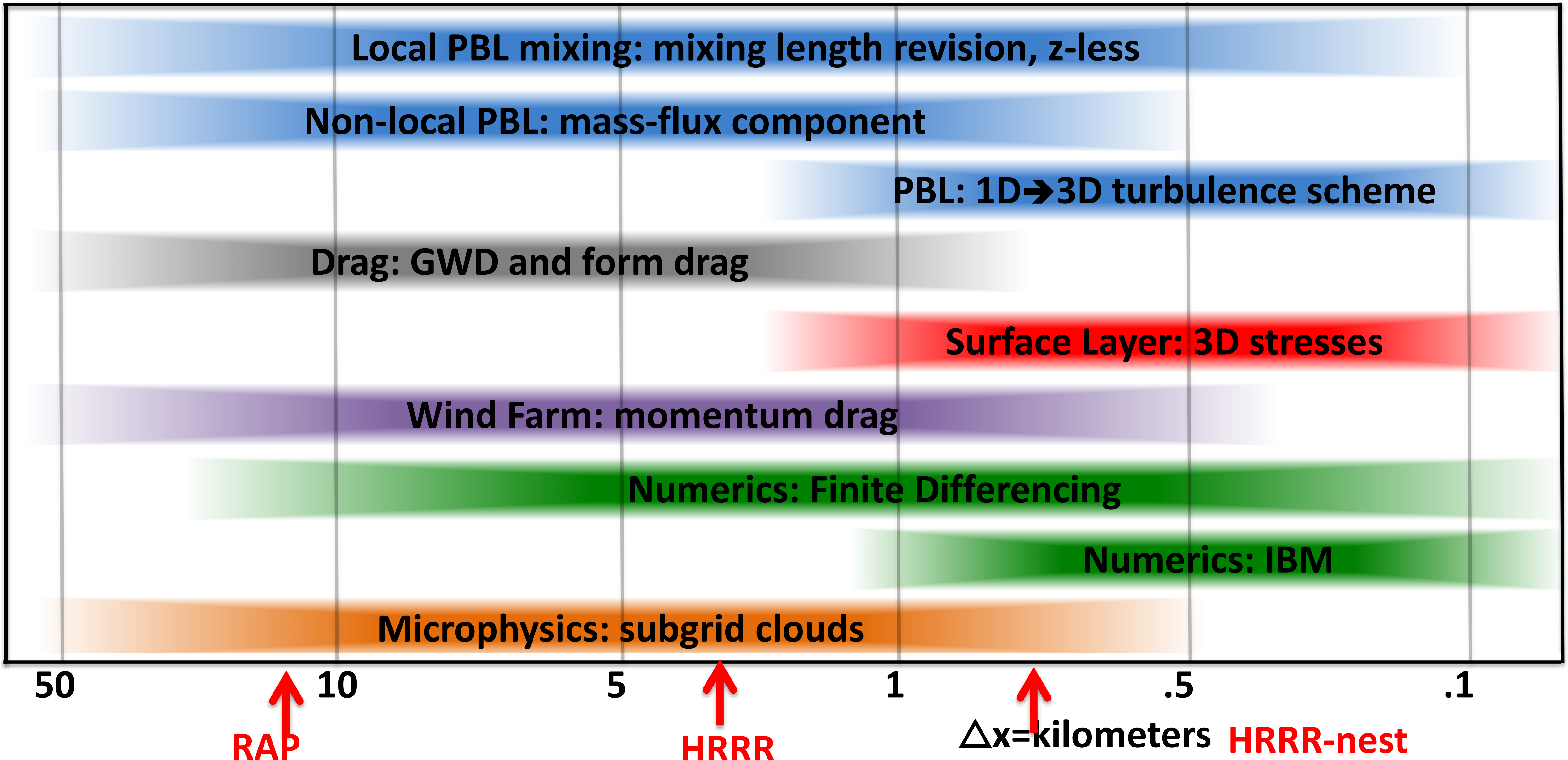
Terrain-specific modifications

Model Component	Control (Original)	Experimental (new)
LSM	RUC 9-level	RUC 9-level
Surface layer	MYNN	MYNN
PBL	MYNN level 2.5	MYNN-EDMF
SW Radiation	RRTMG	RRTMG
LW Radiation	RRTMG	RRTMG
Microphysics	Thompson Aero	Thompson Aero
Deep Convection	Grell-Freitas (RAP only)	Grell-Freitas (RAP only)
Shallow Convection	Grell-Freitas (RAP only)	MYNN-EDMF (all scales)
Horizontal Diffusion	Smag on sigma	Smag on X-Y-Z
Small-Scale GWD and Topographic Form Drag	---	Steeneveld et al. 2007 (JAMC) Beljaars et al. 2004 (QJRMS) (RAP and HRRR only)
Wind Farm Drag	---	Fitch et al. 2012 (MWR)
Vertical Coordinate	sigma	Hybrid sigma-P
Vertical levels	51 levels	51 levels

Physics	Aspect	Impact	Status
1D Turbulence Scheme (MYNN-EDMF)	Z-less mixing length (**improved**)	Improves maintenance of cold pools.	**Ready for code freeze 1** Implemented in RAP/HRRR
	Cloud PDFs/subgrid clouds (**improved**)	Modified form of Chaboureau and Bechtold (2002 and 2005). Improves representation of subgrid stratus, interfaces with mass-flux scheme. Small impact on low-level winds in most cases.	**Ready for code freeze 1** Implemented in RAP/HRRR
	Mass-flux scheme (**new**)	Improves coverage of shallow-cumulus and improves profiles of temperature and humidity compared to LES. Small impact on low-level winds.	**Ready for code freeze 1** Implemented in RAP/HRRR
3D Turbulence Scheme	Scale-aware 3D-TKE scheme (**new**)	Tests performed in real and idealized case studies. No non-local features yet integrated. Expected benefits at sub-kilometric scales.	Still under development
Subgrid-scale orographic drag	Small-scale gravity wave drag and form drag (**new**)	Small-scale gravity wave drag component is completed. Topographic form drag development in progress. Improves maintenance of cold pools and slightly reduces the high wind speed bias near the surface.	**Ready for code freeze 1** Implemented in RAP/HRRR
1D Surface Layer	Numerical procedure; transfer coefficients (**improved**)	Improves near-surface temperatures over snow and increased coupling help improve westerly gap flows associated with thermal troughs.	Still under development
3D Surface Layer	3D surface momentum fluxes (**new**)	Includes horizontal fluxes associated with steep topography. Expected benefits at sub-kilometric scales only.	Still under development
Wind Farm Parameterization	Elevated momentum drag and TKE source (**new addition**)	Integrating wind directional awareness and rotor-equivalent wind speed. Improves high wind speed biases within/near wind farms.	**Stock version used for code freeze 1**. Paper in progress.
Uncertainty Quantification	Understand sensitivity of hub-height winds to MYNN parameters	Some insight gained on certain parameters. This study can be useful for researchers new to the MYNN-EDMF scheme.	One paper published, another in review, third in progress.
Numerics	**Aspect**	**Impact**	**Status**
Finite Differencing	Pressure and diffusion gradient in x-y-z coordinates (**improved**)	Horizontal diffusion changes improve the maintenance of cold pools. Further numerical improvements in progress.	**Ready for code freeze 1** Implemented in RAP/HRRR
Hybrid Vertical Coordinate	Flatter vertical coordinate system over complex terrain (**new**)	Reduces noise aloft. Does not help much with low-level winds – most improvement is in the upper-troposphere.	**Ready for code freeze 1** Implemented in RAP/HRRR

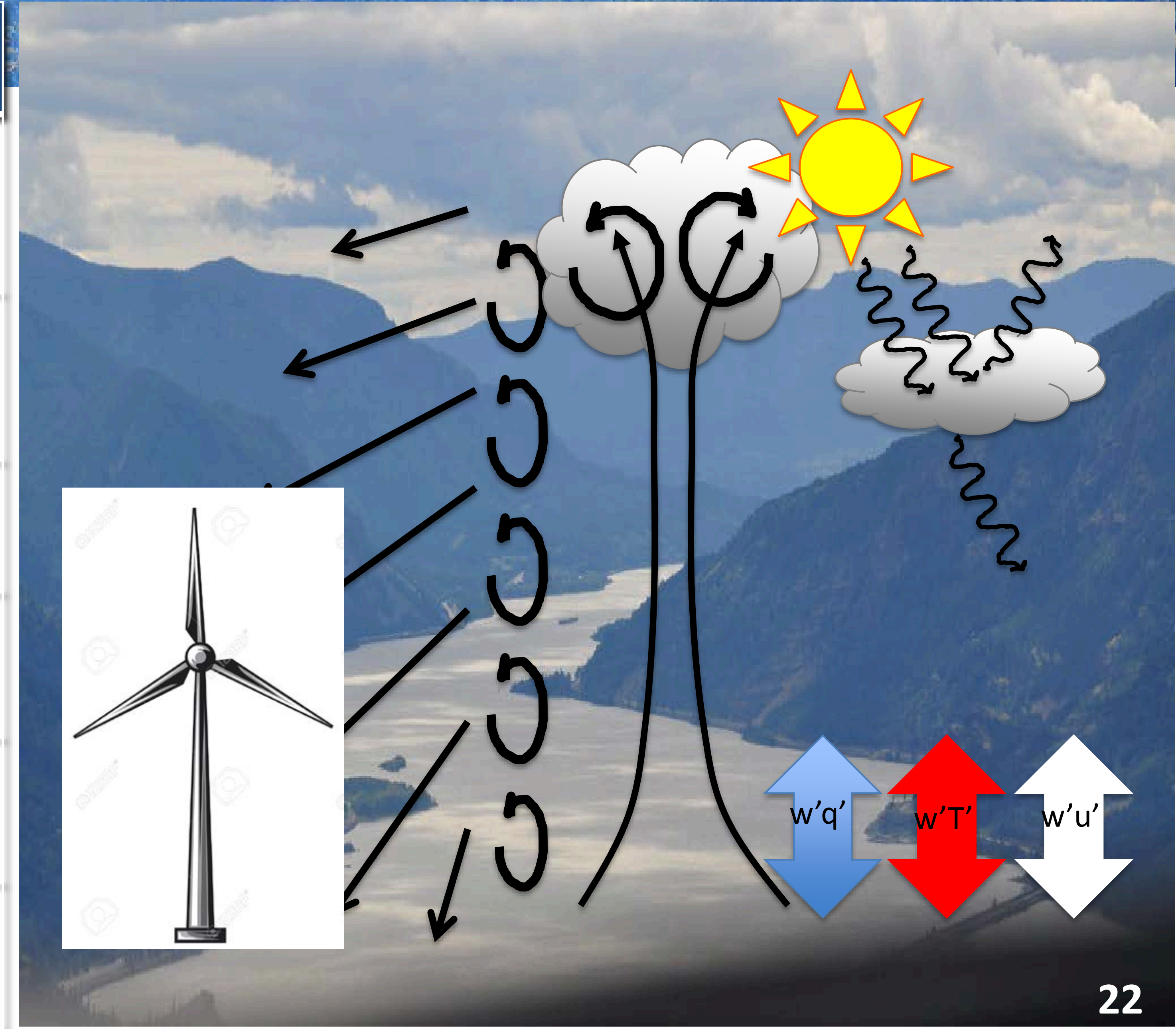
Model Revisions – Scales of Impact

Slide courtesy of Joe Olson

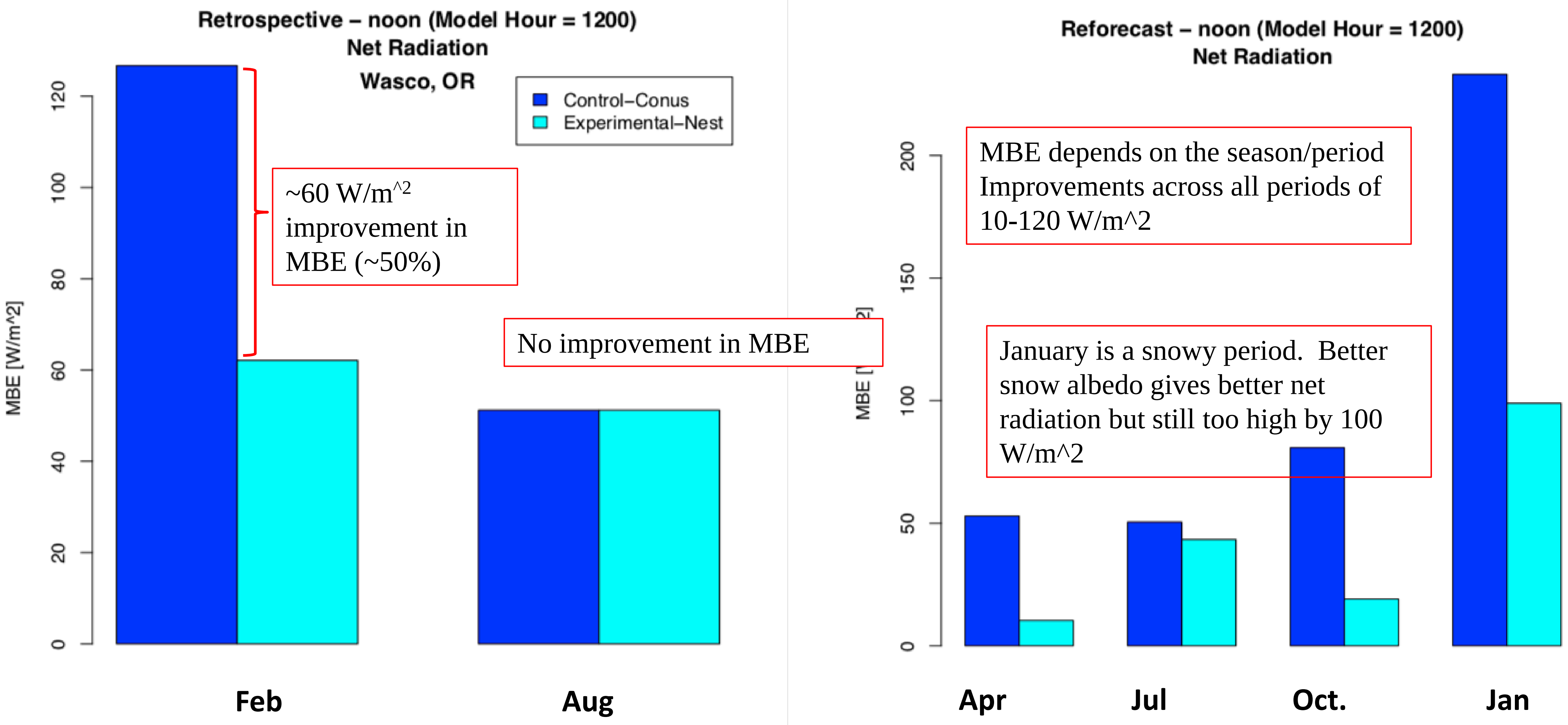


Physical Processes & their Representations in WRF

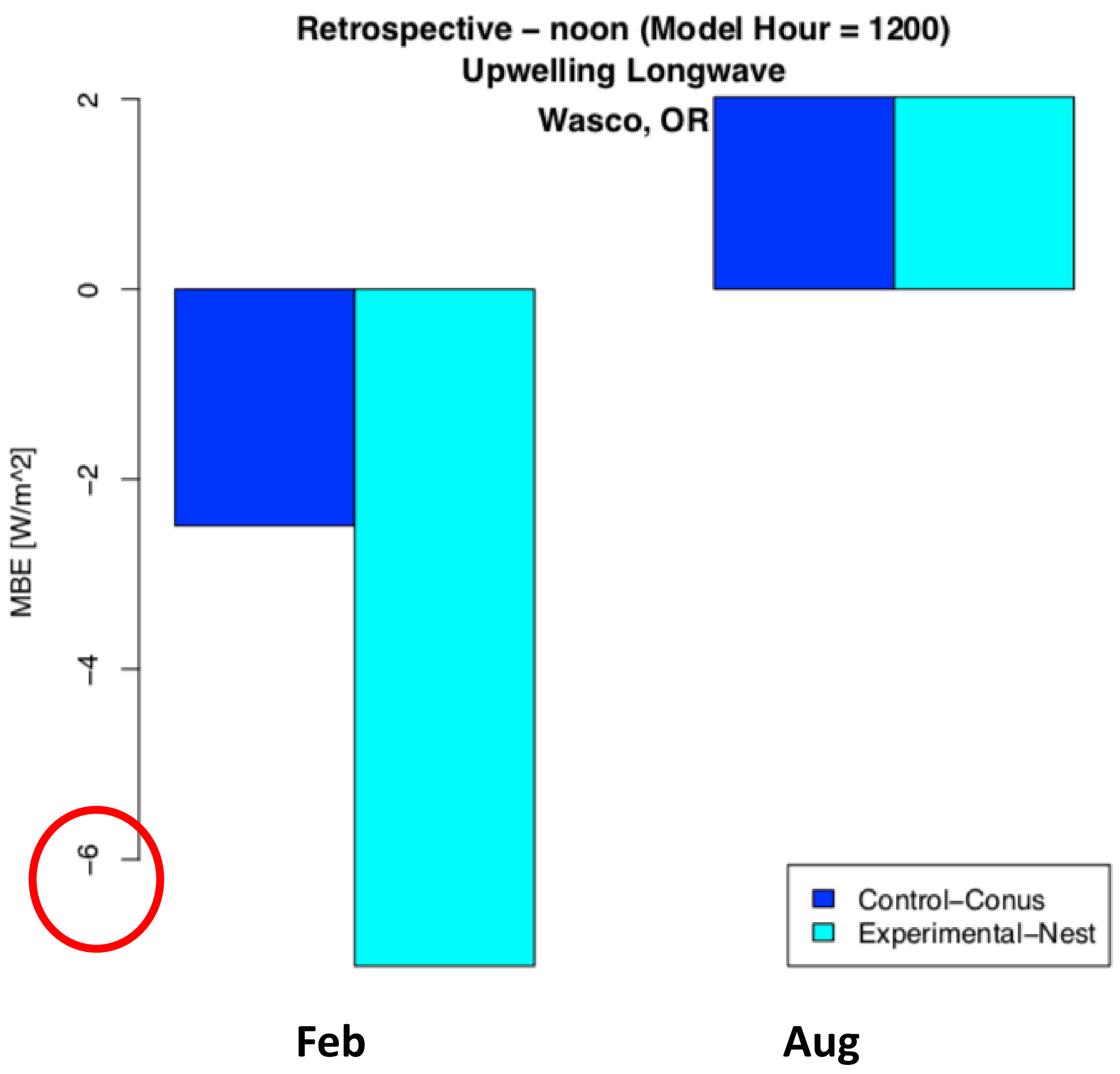
Process	Model Component	Change/Addition
Turbulent Diffusion	MYNN PBL/ 3d-Blended TKE	• Mixing length o Scale-adaptive o Z-less • 1D → 3D as Δx→0
Non-local Turbulent Transport	MYNN Mass-flux	• Multi-plume • TKE transport • Momentum transport • Scale-adaptive
Surface Fluxes	RUC LSM/ MYNN Sfc Layer	• Scalar roughness • M-O alternatives • 3D surface stress
Cloud-Radiation	Subgrid Scale Clouds	• Conv & Non-Conv • Coupled to radiation
Numerics	Vertical Coordinate, Advection	• Hyb σ-p Coordinate • Hor diffusion (x-y-z) • Finite differencing
Drag	Wind Farm, Orographic	• Momentum drag • TKE source (WFP only)

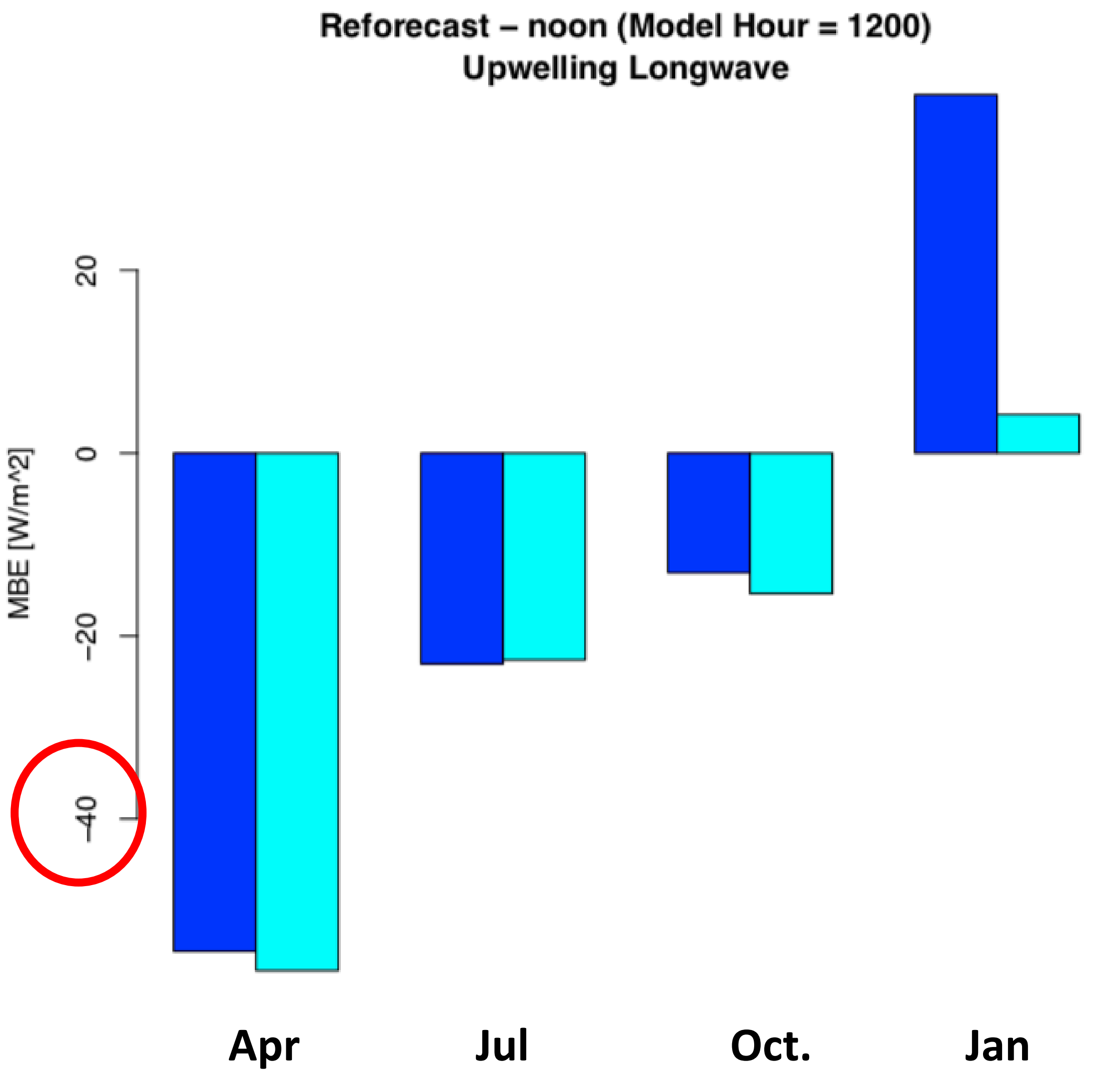


Net Radiation MBE
Wasco, OR



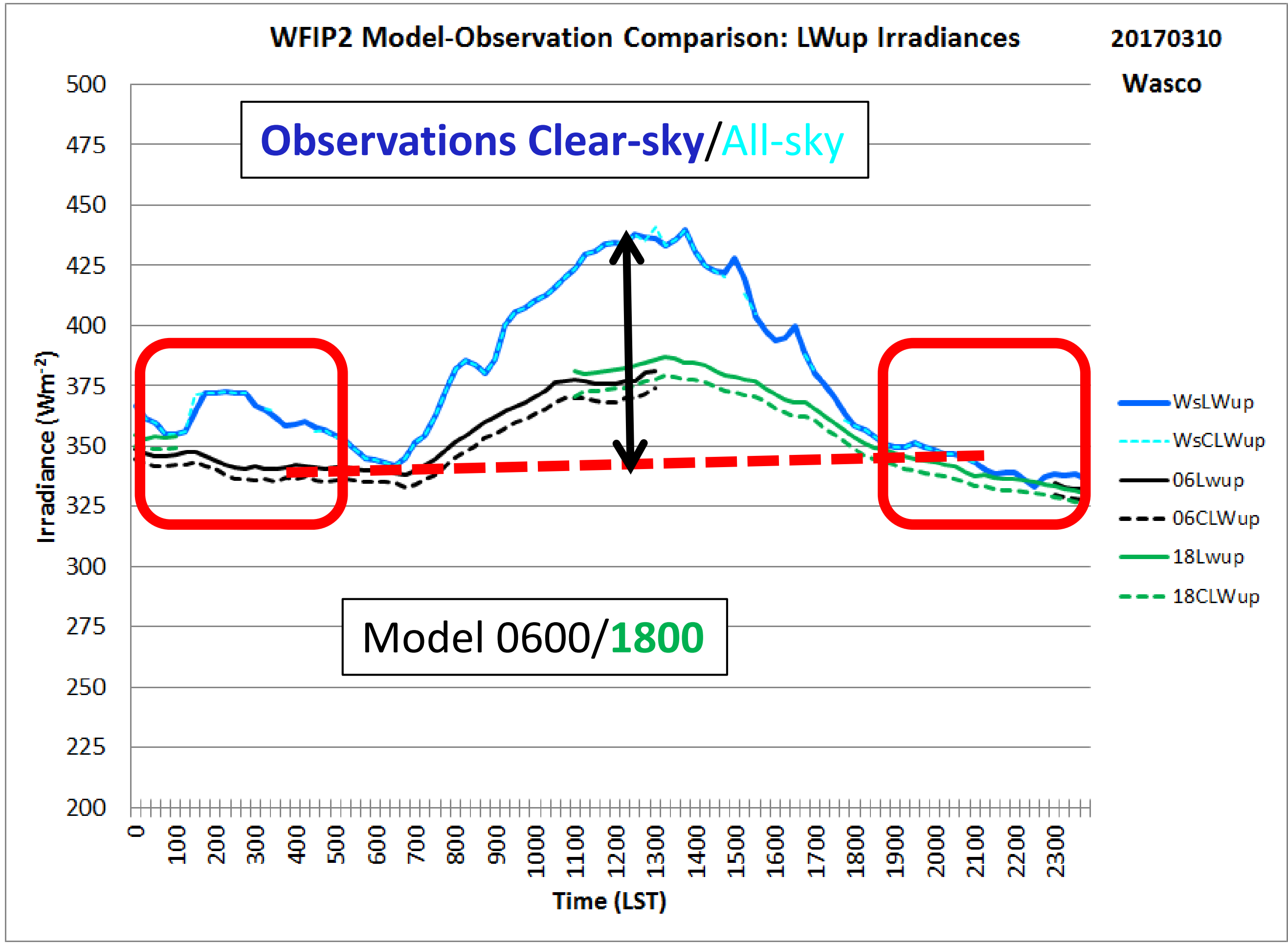
Upwelling Longwave MBE
Wasco, OR





LWup Analysis - Methodology

- March 10 Case: Model LWup is low compared to observations. This appeared to be the case on other days that are less cloudy.
- Use Reforecast April, July, October; Conus and Nest experimental run data
- Calculated the change in LWup from the average night value to noon
- Compared this to local noon SWnet



Radiative Flux Analysis

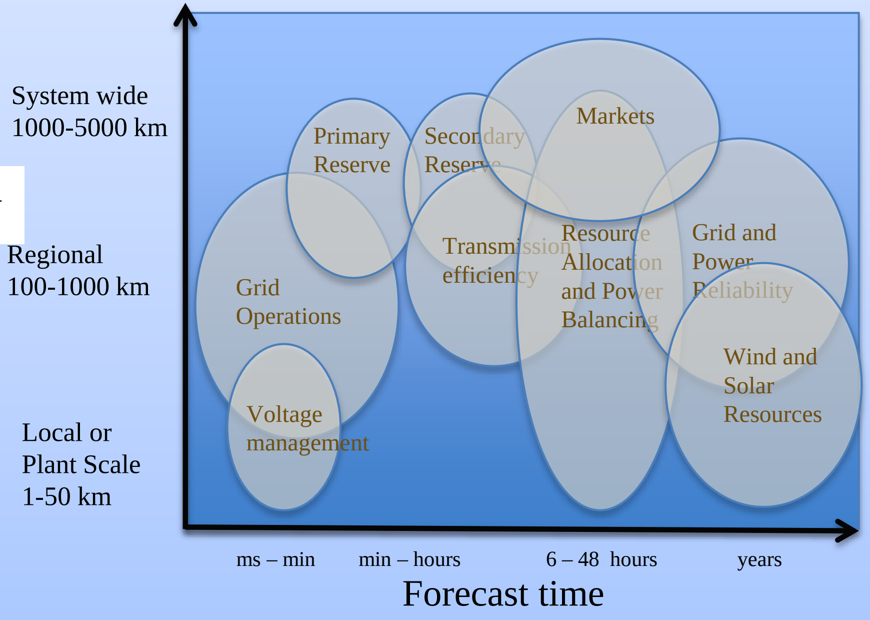
Parameter	Meas./Retr.	Comments
Downwelling Total SW	Measured	Unshaded Pyranometer
Clear-sky Total SW	Retrieved	Long and Ackerman, 2000, JGR
Diffuse SW	Measured	Shaded Pyranometer
Clear-sky diffuse SW	Retrieved	Long and Ackerman, 2000, JGR
Direct SW	Measured	Sun Tracking Perheliometer
Clear-sky direct SW	Retrieved	Long and Ackerman, 2000, JGR
Upwelling SW	Measured	Pyranometer
Clear-sky Upwelling SW	Retrieved	Long, 2005, ARM
Downwelling LW	Measured	Pyrgeometer
Clear-sky Downwelling LW	Retrieved	Long and Turner, 2008, JGR
Upwelling LW	Measured	Pyrgeometer
Clear-sky Upwelling LW	Retrieved	Long, 2005, ARM
Clear-sky periods	Retrieved	Long and Ackerman, 2000, JGR [daylight only]
LW Effective Clear-sky periods	Retrieved	Long and Turner, 2008, JGR [24-hour, may be high clouds present that do not affect LW]
Air Temperature	Measured	Temperature sensor
Relative Humidity	Measured	Humidity sensor
Total Sky Cover	Retrieved	Long et al., 2006, JGR [daylight only]
LW Effective Sky Cover	Retrieved	Long and Turner, 2008, JGR; Durr and Philipona, 2004, JGR [low/mid cloud only]
Cloud Vis optical depth	Retrieved	Barnard and Long, 2004, JAM; Barnard et al., 2008, TOASJ [Skycover>90% only]
Cloud SW transmissivity	Retrieved	Long and Ackerman, 2000, JGR [daylight only]
Sky brightness temperature	Retrieved	Long, 2004, ARM
Cloud radiating temperature	Retrieved	Long, 2004, ARM [LW Scv>50% only]
Clear-sky LW emissivity	Retrieved	Marty and Philipona, 2000, GRL; Long, 2004, ARM

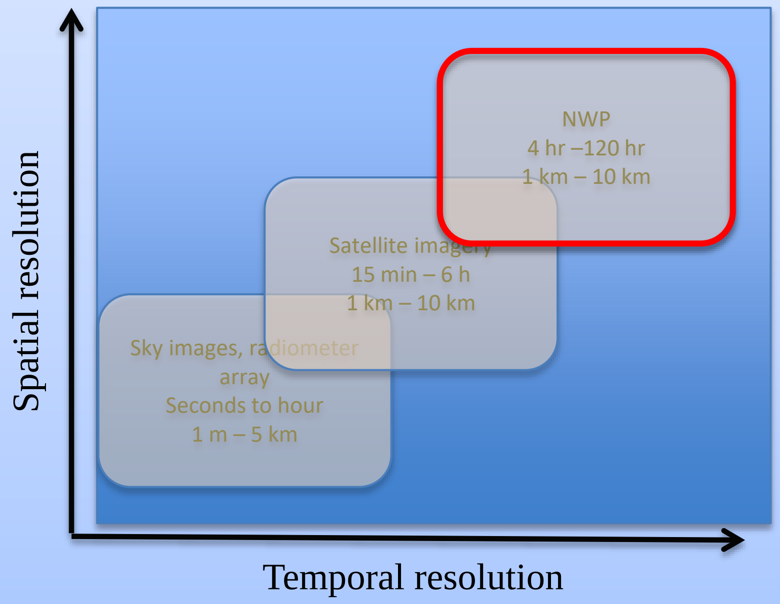
Complete net surface radiative cloud forcing and cloud macrophysical properties without using any measurements typically used as input for model calculations

Motivation for Solar and Wind Forecasting

- **Utility needs -**The utility industry needs reliable solar and wind power forecasts to facilitate integration into the nation's grid.
- **Why?** Accurate solar irradiance and wind forecasts will enable power grid operators, who must constantly balance power supply and demand, to make better scheduling decisions about the optimal mix of power generation sources, and to avoid excessive back-up reserves.

Utility industry



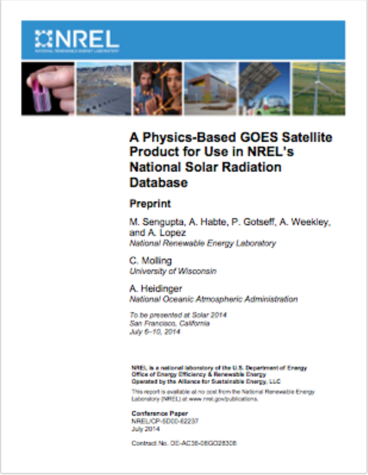


NOAA Information

Carlos Coimbra, Current Status and Needs of Solar Forecasting, presentation, 2015.

Impact of SURFRAD and SOLRAD Observations for Renewable Energy

- Solar resource is needed for siting of future solar farms (bankable solar resources)
- Ground-based solar observations are used in **Empirical methods** for solar resource estimates (e.g. NREL NSRDB Meteorological Statistical Models.
- NREL NSRDB **Physical Method**: Ground-based observations used for verification (e.g. Sengupta et al, 2014)
- **Semi-empirical Method**: statistical methods combining current satellite data, forecast data, with ground-observations for a current solar map which is then used in cost minimization studies, e.g. NEWS - Clack et al., 2015.
- NSRDB used in products such as PVWatts, SAM. SURFRAD used to validate commercial products (SolarAnywhere)
- Accurate solar observations and products for validation and diagnosing errors in NWP solar forecasts


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A Physics-Based GOES Satellite Product for Use in NREL's National Solar Radiation Database

Preprint

M. Sengupta, A. Habte, P. Gotseff, A. Weekley, and A. Lopez
National Renewable Energy Laboratory

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University of Wisconsin

A. Heidinger
National Oceanic Atmospheric Administration

To be presented at Solar 2014
San Francisco, California
July 6–10, 2014

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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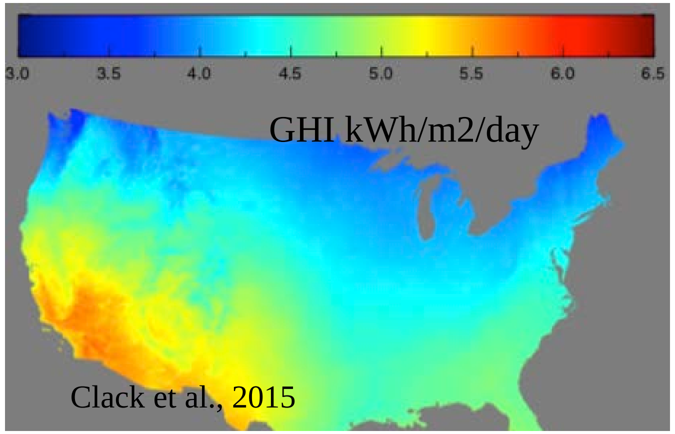

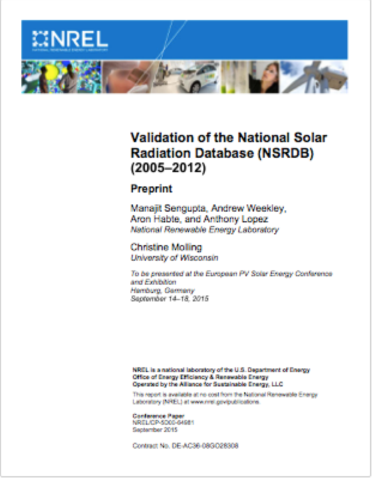
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Validation of the National Solar Radiation Database (NSRDB) (2005–2012)

Preprint

Manajit Sengupta, Andrew Weekley, Aron Habte, and Anthony Lopez
National Renewable Energy Laboratory

Christine Molling
University of Wisconsin

To be presented at the European PV Solar Energy Conference and Exhibition
Hamburg, Germany
September 14–18, 2015

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Office of Energy Efficiency & Renewable Energy
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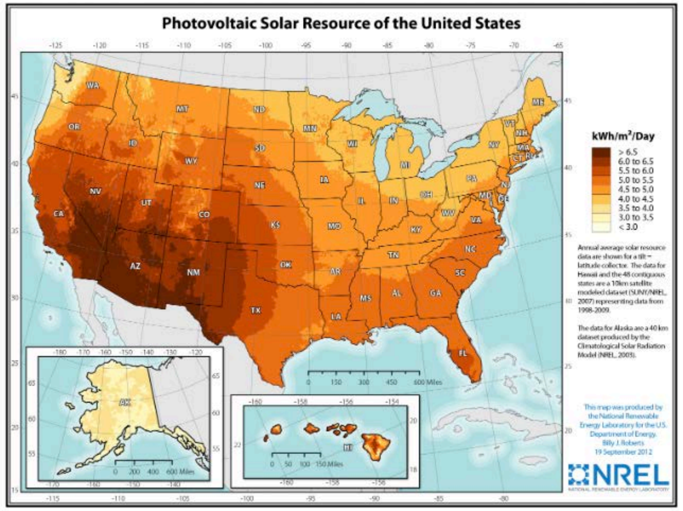
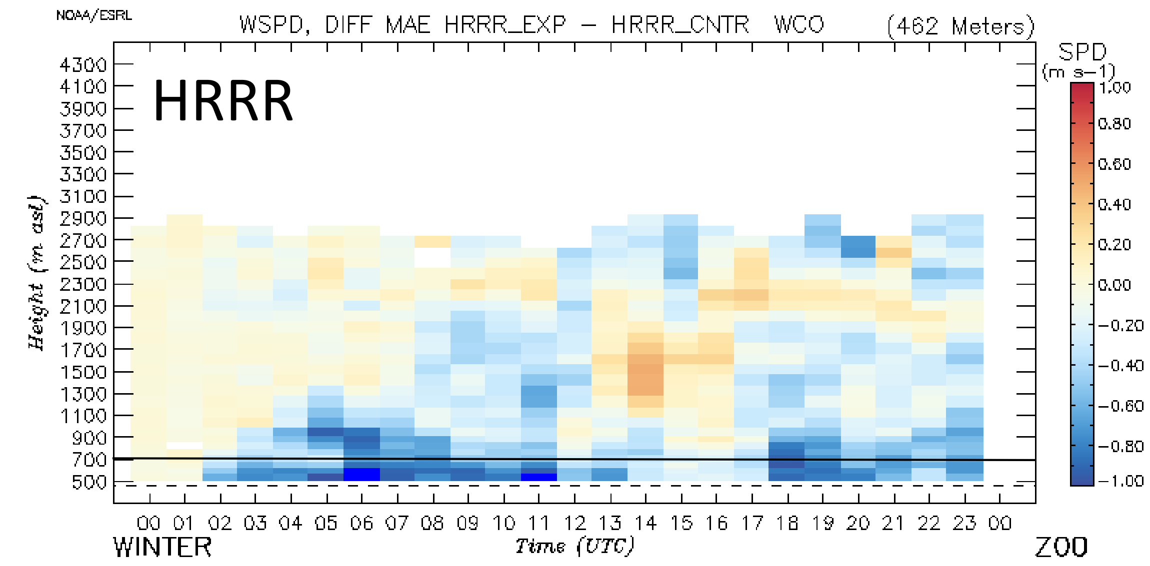
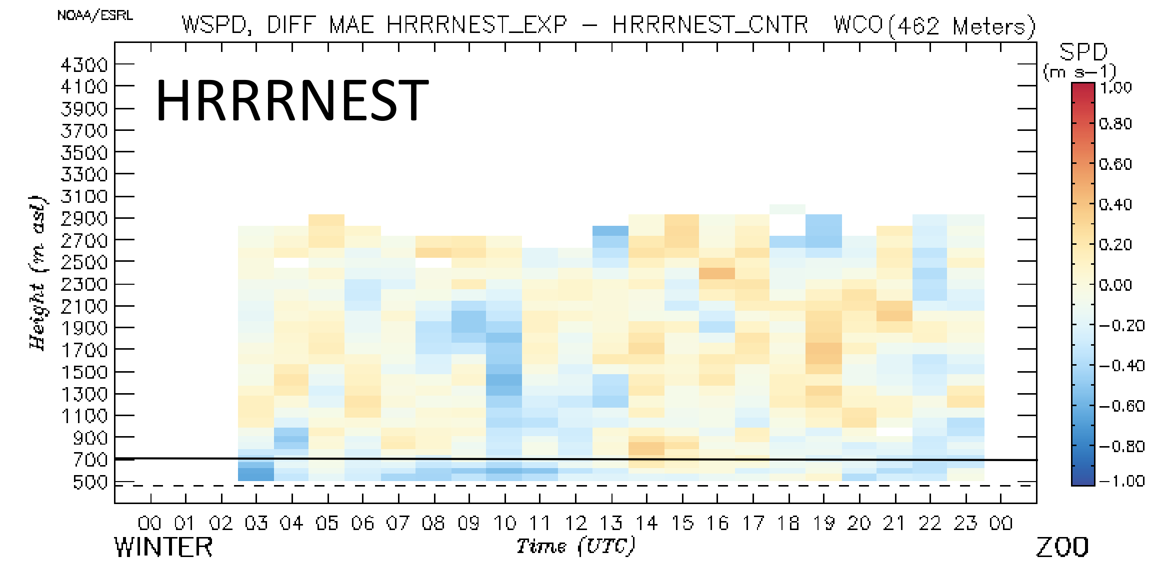


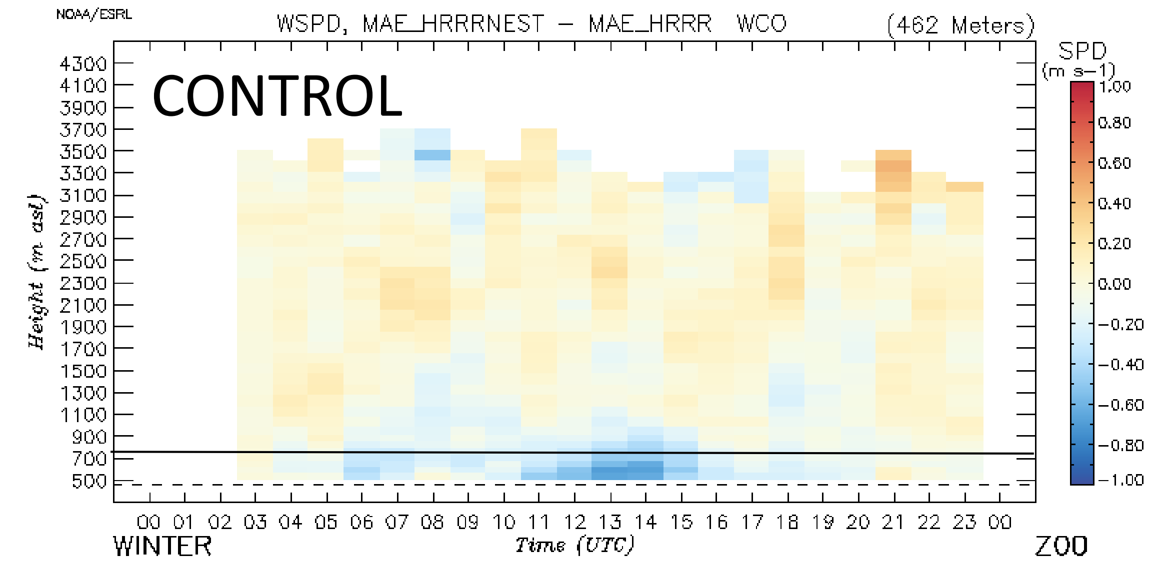
Courtesy of I. Djalalova (PSD)

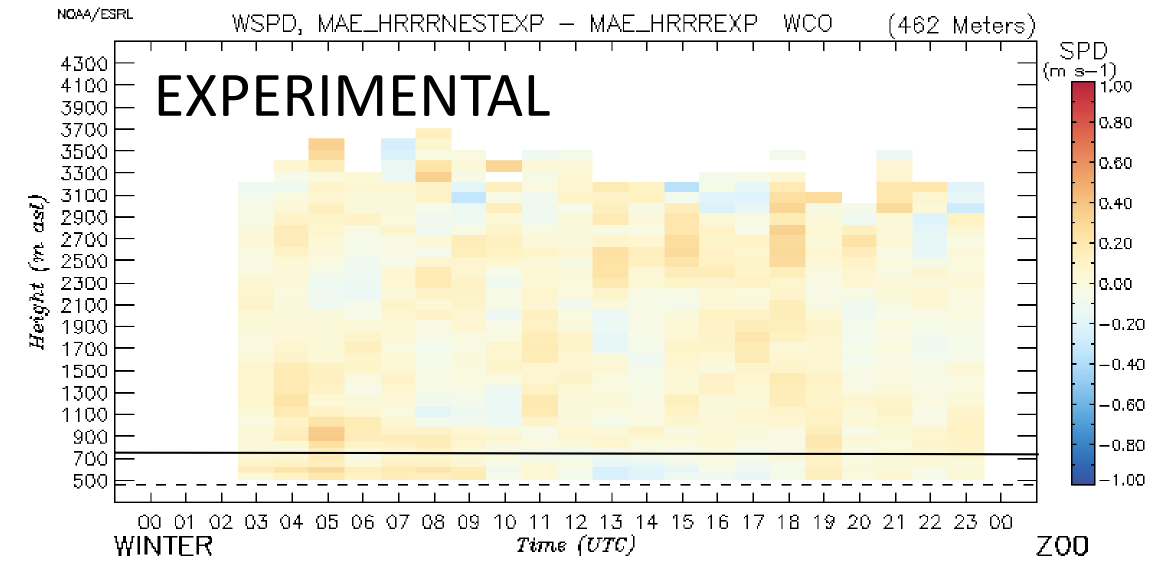
Wind Speed WCO improvement due to **physics**





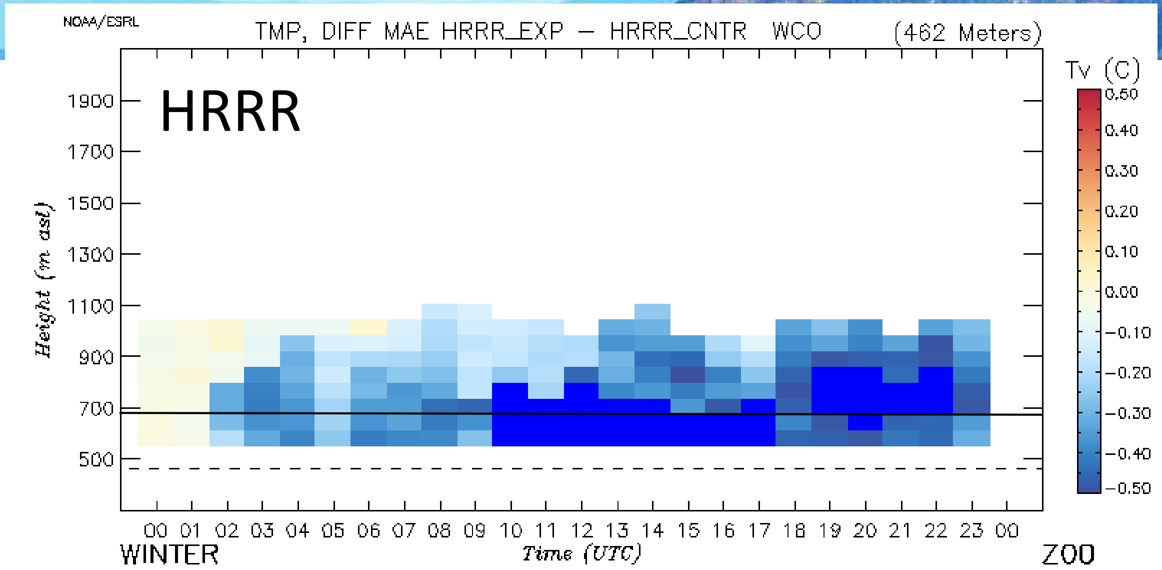
Wind Speed WCO improvement due to **resolution**

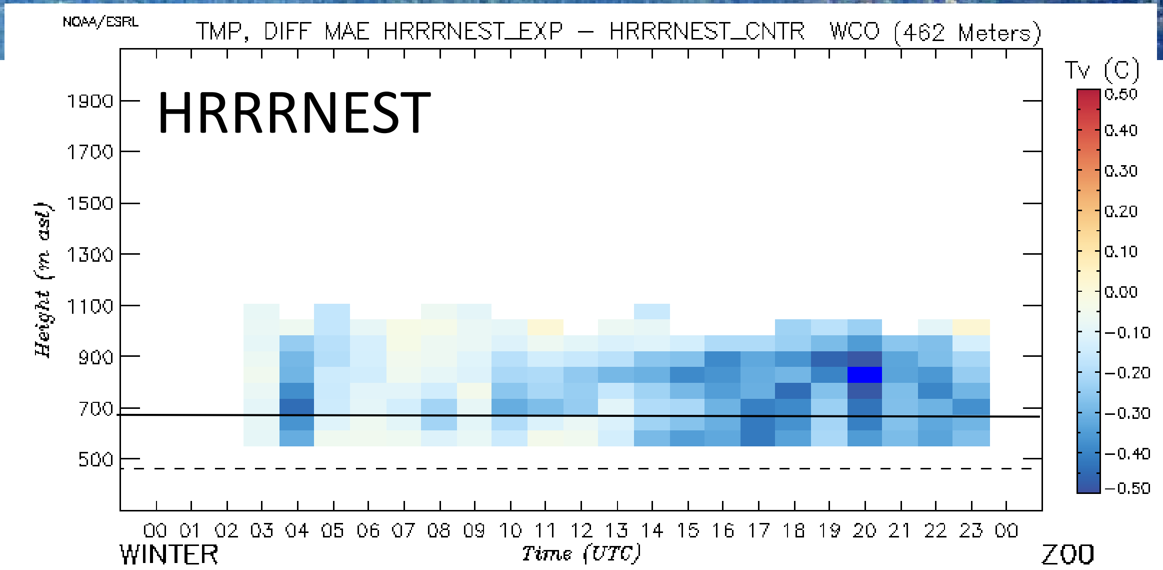




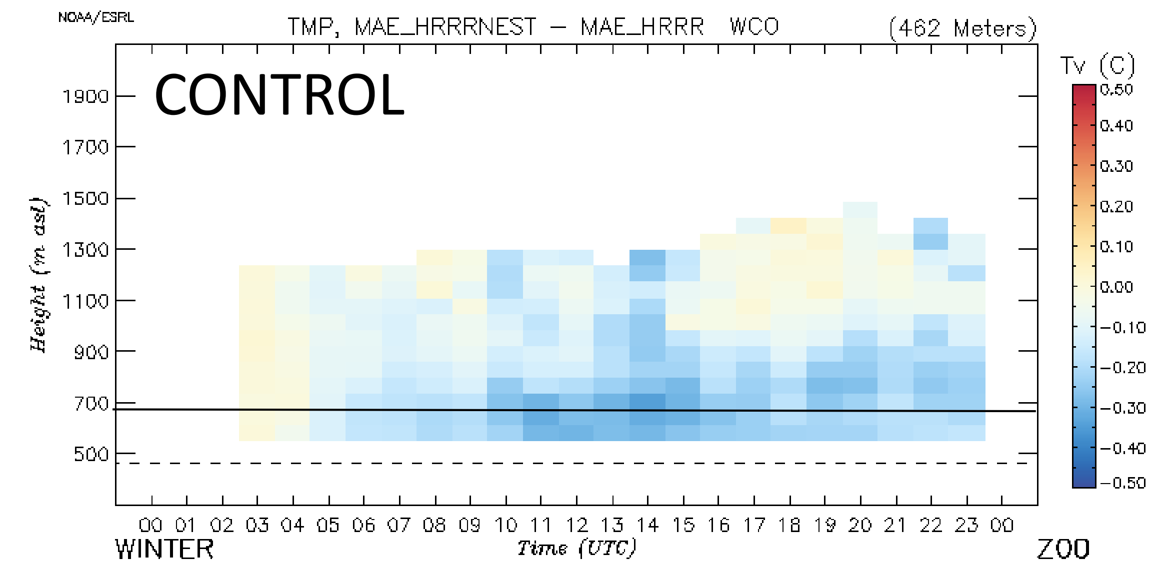
Courtesy of I. Djalalova (PSD)

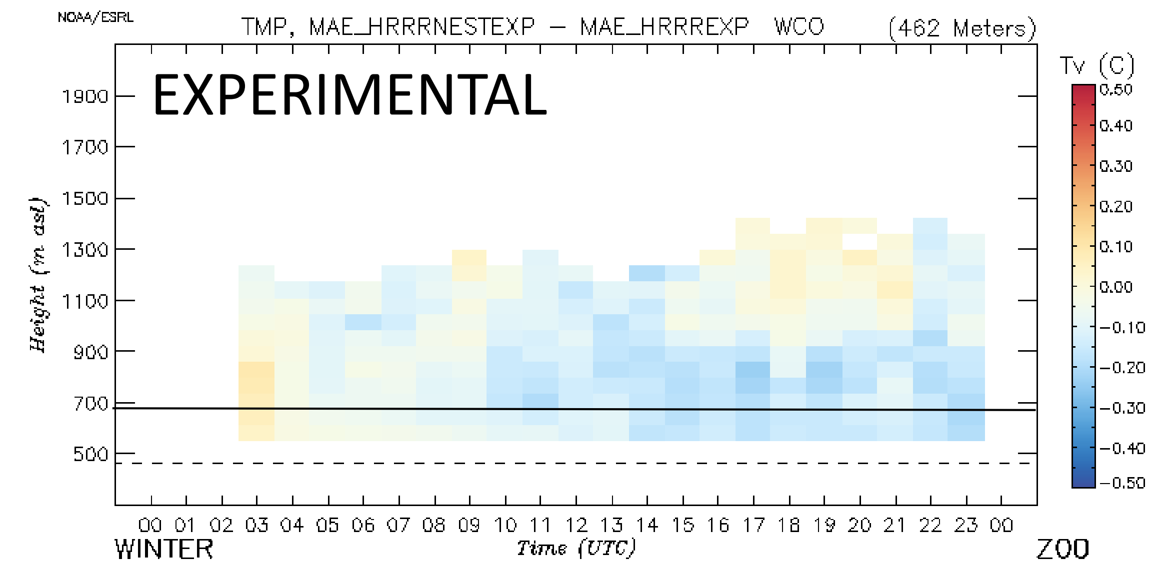
Temperature WCO improvement due to **physics**





Temperature WCO improvement due to **resolution**

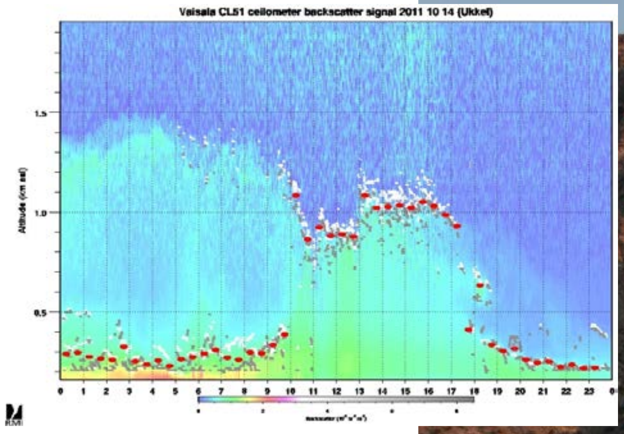


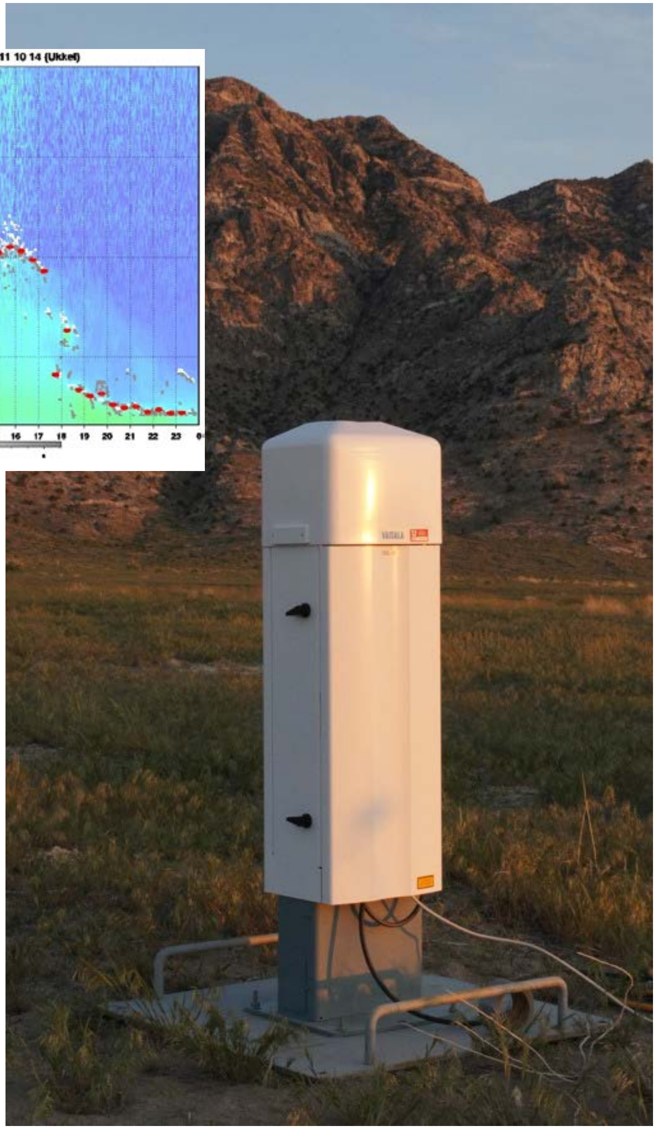


RadSys – Portable radiation system

- **Simple surface radiation and T/RH instrument system developed by <u>C. Long</u>**
  - Provides all needed quantities for the downwelling Radiative Flux Analysis methodology (Estimates of clear-sky downwelling and upwelling SW and LW, total fractional sky cover, LW effective sky cover, cloud optical depth, effective cloud transmissivity, clear-sky LW effective emissivity, cloud radiating temperature)
  - Robust, reliable, inexpensive
  - Low power
  - Compact, low environmental impact
- **Future research activities – These small easily deployed units can be used to answer the following science questions:**
  - What is the horizontal variability or SW and LW radiation within a model cell or satellite pixel?
  - What is the geographical representativeness around climate regions of SURFRAD sites?
  - Can a RadSys set deployed locally provide an accurate short term solar forecast of GHI and DNI? How many and at what spacing would be required?

Vaisala CL-51 High range ceilometer





- **Vaisala C-51 high range ceilometers**
  - Purchased CL-51 ceilometers in 2018 for 7 SURFRAD sites
  - Deploy during the annual SURFRAD site visits in summer/fall
- **Products**
  - Cloud base height (CBH) up to 13 km (CL-view software)
  - Detects 3 layers simultaneously
  - Boundary layer height (BL-view software)
- **Future research activities and science questions:**
  - Use CBH, cloud fraction, cloud optical depth for cloud regime classification.
  - What cloud regimes are the biggest challenge in wind and solar forecasting?
  - Can these cloud regimes be used to target parameterizations in NWP models?