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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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?

Atmospheric Processes

There is a 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
**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

### Columbia River Basin
- 18 month field study
WFIP2: SURFRAD and RadSys Sites

Rufus Wasco
Condon
Mobile SURFRAD Site
• SWdn, LWdn,
• Swup, LWup
• SW DIR, DIF, Met
• AOD
• Sky Images

RadSys Sites
• SWdn, LWdn,
• DIR, DIF, Met

Equivalent to RadSys
Average Monthly Diurnal Cycles

Monthly Average Diurnal Cycles: Downwelling All-Sky Irradiances

Sites

- RufSWdn
- RufLWdn
- RufDifSW
- WasSWdn
- WasLWdn
- WasDifSW
- CdnSWdn
- CdnLWdn
- CdnDifSW
- EugSWdn
- EugLWdn
- EugDifSW

Cloudiness!

SWdn, LWdn, SWdf
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

- **Retrospective** - noon (Model Hour = 1200)
  - Downwelling Shortwave
  - **Wasco, OR**

- **Very clear period**
  - Small MBE
  - No improvement in MBE between control and experimental
  - ~50 W/m² improvement in MBE (~60%)

- **Reforecast** - noon (Model Hour = 1200)
  - Downwelling Shortwave

- **~35 W/m² improvement in MBE (~70%)**
  - ~52 W/m² improvement in MBE (~73%)
  - ~10 W/m² improvement in MBE (~20%)
  - ~10 W/m² degradation in MBE
Downwelling Longwave Radiation MBE
Wasco, OR

Retrospective – noon (Model Hour = 1200)
Downwelling Longwave

Feb

Aug

~10 W/m$^2$
improvement in MBE (~60%)

Very clear period
no improvement in MBE from control to experimental

~8 W/m$^2$
improvement in MBE (~70%)

~11 W/m$^2$
improvement in MBE (~78%)

Change of sign in MBE. Cloud properties? Air Temperature errors? Other?

Reforecast – noon (Model Hour = 1200)
Downwelling Longwave

Apr
Jul
Oct
Jan

~4 W/m$^2$
improvement in MBE (~30%)
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).
MBE is around 5-8% too low
No improvement in MBE as expected since not improvements not included yet

MBE depends on the season/period
(3-7% too low)

January is a snowy period
Snow albedo 60% too low in Control-Conus
Better snow albedo in Expt-Nest
But still too low by 22%.
Response of LWup to SWnet Solar Enhancement

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

Reforecast periods Apr, July, October

Conus

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

Nest

Better LWup response in Retrospective runs
Retrospective is mode comparable to operational model
Summary for WFIP HRRR nest model versus radiation observations

- **Control-Conus to Experimental-Nest**: Significant improvement in downwelling shortwave radiation in retrospective (0 and 60%) in spring – fall reforecast periods (20-73%) and a degradation in winter (25%).

- **Control-Conus to Experimental-Nest**: 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.

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Courtesy Jim Wilczak

**Large Forecast Busts by Meteorological Event**

- Synoptic: 13/67 (19%)
- Mountain Waves/Waves: 7/67 (10%)
- Gap Flow: 13/67 (19%)
- Cold Pool: 26/67 (39%)
- Precipitation: 4/67 (6%)
- Unknown: 4/67 (6%)
Thank you!
Extra slides
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: Number of Cases Observed

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Pool</td>
<td>50</td>
</tr>
<tr>
<td>Gap Flow</td>
<td>400</td>
</tr>
<tr>
<td>Mount Wave/Topo Wake</td>
<td>150</td>
</tr>
<tr>
<td>Convect Outflow</td>
<td>30</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
</tr>
</tbody>
</table>

Large Forecast Busts by Meteorological Event

- **Cold Pool (26/67)**: 39%
- **Gap Flow (13/67)**: 19%
- **Synoptic (13/67)**: 19%
- **Mountain Waves/Waves (7/67)**: 6%
- **Unknown (4/67)**: 6%
- **Precipitation (4/67)**: 10%

Courtesy of Aditya Choukulkar and Jim Wilczak
Physics: WCO, WINDSPEED MAE_HRRR_EXP – MAE_HRRR_CNTR (Reforecast periods)

00 UTC Runs only

Courtesy of I. Djalalova (PSD)
### RAP/HRRR/nest Configuration

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

**Notes:**
- Terrain-specific modifications
- 13 km RAP domain
- 3 km HRRR domain
- 750m nest

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

Slide courtesy of Joe Olson

- Local PBL mixing: mixing length revision, z-less
- Non-local PBL: mass-flux component
- Drag: GWD and form drag
- PBL: 1D→3D turbulence scheme
- Surface Layer: 3D stresses
- Wind Farm: momentum drag
- Numerics: Finite Differencing
- Numerics: IBM
- Microphysics: subgrid clouds

RAP

HRRR

HRRR-nest

△x= kilometers
# Physical Processes & their Representations in WRF

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

**Diagram:**
- $w'q'$, $w'T'$, $w'u'$
No improvement in MBE

MBE depends on the season/period
Improvements across all periods of 10-120 W/m^2

January is a snowy period. Better snow albedo gives better net radiation but still too high by 100 W/m^2

~60 W/m^2 improvement in MBE (~50%)
Upwelling Longwave MBE
Wasco, OR

Retrospective – noon (Model Hour = 1200)
Upwelling Longwave
Wasco, OR

Retrace – noon (Model Hour = 1200)
Upwelling Longwave

MBE [W/m²]

Feb       Aug

Apr       Jul       Oct.       Jan

Control–Conus
Experimental–Nest
• 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
Complete net surface radiative cloud forcing and cloud macrophysical properties without using any measurements typically used as input for model calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meas/Retr.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downwelling Total SW</td>
<td>Measured</td>
<td>Unshaded Pyranometer</td>
</tr>
<tr>
<td>Clear-sky Total SW</td>
<td>Retrieved</td>
<td>Long and Ackerman, 2000, JGR</td>
</tr>
<tr>
<td>Diffuse SW</td>
<td>Measured</td>
<td>Shaded Pyranometer</td>
</tr>
<tr>
<td>Clear-sky diffuse SW</td>
<td>Retrieved</td>
<td>Long and Ackerman, 2000, JGR</td>
</tr>
<tr>
<td>Direct SW</td>
<td>Measured</td>
<td>Sun Tracking Pyrheliometer</td>
</tr>
<tr>
<td>Clear-sky direct SW</td>
<td>Retrieved</td>
<td>Long and Ackerman, 2000, JGR</td>
</tr>
<tr>
<td>Upwelling SW</td>
<td>Measured</td>
<td>Pyranometer</td>
</tr>
<tr>
<td>Clear-sky Upwelling SW</td>
<td>Retrieved</td>
<td>Long, 2005, ARM</td>
</tr>
<tr>
<td>Downwelling LW</td>
<td>Measured</td>
<td>Pyrgeometer</td>
</tr>
<tr>
<td>Upwelling LW</td>
<td>Measured</td>
<td>Pyrgeometer</td>
</tr>
<tr>
<td>Clear-sky Upwelling LW</td>
<td>Retrieved</td>
<td>Long, 2005, ARM</td>
</tr>
<tr>
<td>Clear-sky periods</td>
<td>Retrieved</td>
<td>Long and Ackerman, 2000, JGR [daylight only]</td>
</tr>
<tr>
<td>LW Effective Clear-sky periods</td>
<td>Retrieved</td>
<td>Long and Tumer, 2008, JGR [24-hour, may be high clouds present that do not affect LW]</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>Measured</td>
<td>Temperature sensor</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Measured</td>
<td>Humidity sensor</td>
</tr>
<tr>
<td>Total Sky Cover</td>
<td>Retrieved</td>
<td>Long et al., 2006, JGR [daylight only]</td>
</tr>
<tr>
<td>LW Effective Sky Cover</td>
<td>Retrieved</td>
<td>Long and Tumer, 2008, JGR [low/mid cloud only]</td>
</tr>
<tr>
<td>Cloud Vis optical depth</td>
<td>Retrieved</td>
<td>Barnard and Long, 2004, JAM; Barnard et al., 2008, TOASJ [Skycover&gt;90% only]</td>
</tr>
<tr>
<td>Cloud SW transmissivity</td>
<td>Retrieved</td>
<td>Long and Ackerman, 2000, JGR [daylight only]</td>
</tr>
<tr>
<td>Cloud radiating temperature</td>
<td>Retrieved</td>
<td>Long, 2004, ARM [LW Scv=50% only]</td>
</tr>
</tbody>
</table>
• **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.

• 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
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**

![HRRR Temperature Improvement](image1)

HRRR

![HRRRNEST Temperature Improvement](image2)

HRRRNEST

Temperature WCO improvement due to **resolution**

![CONTROL Temperature Improvement](image3)

CONTROL

![EXPERIMENTAL Temperature Improvement](image4)

EXPERIMENTAL

Courtesy of I. Djalalova (PSD)
RadSys – Portable radiation system

- Simple surface radiation and T/RH instrument system developed by C. Long
  - 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?