Advancing the WRF-Solar Model to Improve Solar Irradiance Forecast in Cloudy Environments

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Outline

• Recap of Key Project Elements
• Technical Accomplishments & Results
• Summary & Questions
Project Pyramid

❖ One Goal
Improve the state of art WRF-Solar model for forecasting solar irradiance in cloudy environments

❖ Four Objectives
• Improve cloud microphysics
• Improve radiative transfer
• Develop innovative analysis package
• Perform model evaluation

❖ Five Tasks
• Four objectives + Data integration

❖ BNL-NREL-SUNY Collaboration
Five Closely Related Tasks

- Improve Cloud Microphysics
- Improve Radiative Transfer
- Develop Innovative Analysis Package
- Perform Model Evaluation
- Data Integration

Model development/improvement calls for iterative cycle of development, evaluation, and further improvement; thus tasks are closely connected to one another.
Key Accomplishments

• Project has been progressing smoothly and as planned.
• Eight cloudy cases selected.
• Baseline simulations conducted and evaluated against measurements.
• Seven cloud microphysics schemes examined and difference quantified.
• Aerosol direct and indirect effects examined
• FARMS updated to consider circumsolar region & LUT generated for cloud transmittance
• WRF-Solar suite developed, along with various metrics
• Five presentations at AGU (3) and AMS (2); 3 primarily supported by this project; one paper submitted to Joule for publication; 3+ in writing
Summary of 8 Selected Cloudy Cases

Table 1.1. Selected cloudy cases at the ARF SGP site for the WRF-Solar baseline simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cloud Condition</th>
<th>Case Duration**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc20050325</td>
<td>Low-level and mid-level stratocumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Sc20090419</td>
<td>Low-level stratocumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Sc20090506</td>
<td>Low-level stratocumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Cu20090522</td>
<td>Shallow cumulus with high level ice clouds</td>
<td>60hr from 0522_6:00</td>
</tr>
<tr>
<td>Cu20160611</td>
<td>Shallow cumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Cu20160619</td>
<td>Shallow cumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Cu20160625</td>
<td>Shallow cumulus</td>
<td>15hr from 6:00</td>
</tr>
<tr>
<td>Cu20160818</td>
<td>Shallow cumulus with high level ice clouds</td>
<td>15hr from 6:00</td>
</tr>
</tbody>
</table>

* The case name consists of cloud type (Cu or Sc) and starting date of the case (yyyyymmdd).
** Case duration is the period used in the baseline simulation instead of exact duration of the clouds.
Task 1: Cloud Microphysics
Co-Evolution of Solar Radiation and Clouds in WRF-LES

- Cu20160619
- From sunrise to sunset
- White color for clouds; color scheme for total irradiance
- Strong effects of clouds
- Opposite effects on direct and diffuse radiation
Substantial Differences between Baseline Sim and Obs

- Substantial model errors, esp. for direct solar radiation
- Error compensation between direct and diffuse radiation
- Details are case-dependent
- Cases at DOE ARM supersite at Southern Great Plains (SGP)
- Parameterizations for cloud microphysics & radiative transfer are responsible for (part of) the model errors
Effect of Cloud Microphysics Schemes on WRF-Solar

- Seven microphysics schemes tested
- Significant microphysics-induced model difference
- Larger differences correspond generally to higher total water contents
- Support proposed improvement in cloud microphysics parameterization
Test of Microphysics Schemes: Role of Water Content

- Clouds with higher water amount have stronger microphysics sensitivity.
- Sc clouds tend to hold more water than cu clouds, and thus microphysics induces larger differences in cloud albedo, cloud fraction & solar radiation.
- Clearly demonstrate the essential role of cloud microphysics parameterizations
Influences of Aerosol Direct and Indirect Effects

• Direct aerosol effect with GEOS-5 aerosol outputs
• Indirect aerosol effect with Thompson aerosol aware scheme (ThomA)
• Considering aerosol effects improves solar irradiances significantly, esp. for cu clouds
• Critical to treat aerosol effects correctly!
Task 2: Radiative Transfer
How to Model DNI?

Lambert Law

Compute radiation in an infinite-narrow beam. **Does not consider angular extent of the solar disk.**

Empirical Model

Link between long-term GHI and DNI observations. **Depend on data availability at locations and time.**

Physical Model

Numerically solve the radiative transfer equation. **Time consuming.**
What Is FARMS?

**FARMS**, the **Fast All-sky Radiation Model for Solar** applications, is a physics-based radiative transfer model that efficiently (>500 times faster than the state-of-the-art models) computes **all-sky** solar radiation.

FARMS and the extension models have been used to support multiple DOE-sponsored projects on solar resource assessment and forecasting.

**FARMS-DNI** model is developed to provide an efficient physics-based solution of DNI that improves solar irradiance forecast in cloudy environment.
FARMS-DNI

Clear-sky Conditions
Directly use an empirical model to compute DNI.

Cloudy-sky Conditions
- Use Lambert Law to compute solar radiation in the infinite-narrow beam.
- Develop a pre-computed lookup table of cloud transmittance for solar radiation in the circumsolar region.
- Use FARMS to compute the scattered radiation between the cloud and land surface that reenter the beam or the angular extent of the solar disk.
32-stream DISORT is used to compute the lookup table.
- $9.1 \times 10^8$ calculations, each takes ~1-2 seconds.
- 30-120 years by a single CPU.
FARMS-DNI Outperforms FARMS and Empirical DISC

• Beer law underestimates DNI
• Empirical DISC overestimates DNI
• FARMS DNI improves DNI substantially

There are great potentials for using FARMS-DNI to improve solar energy forecast & beyond.
Task 3: Analysis Package
New Analysis Framework

• Relationship between clearness index $K_T$ & RCRF
  
  \[ K_T = \frac{F_{all}^{dn}}{F_{TOA}^{dn}} = \frac{F_{all}^{dn}}{F_{clr}^{dn} \cdot T_a^{-1}}; \quad \text{RCRF for total radiation } R_{tot} = \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn}} \]

  \[ R_{tot} = 1 - K_T \cdot T_a^{-1} \]

  \[ R_{tot} \sim \alpha_r f \text{ suggests that } K_T \text{ is affected by both cloud fraction } (f) \text{ and cloud albedo } (\alpha_r) \gg \text{Can we separate cloud fraction effect from cloud albedo effect?} \]

• New framework separating cloud fraction effect from albedo effect
  
  • Cloud albedo: \( a_r \sim B_1 / B_2 = B_3 \)
    
    \[ B_1 = \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn} - F_{all}^{up} r^2} \approx \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn}} = R_{tot} \]

  • Cloud fraction: \( f \sim B_2 \)
    
    \[ B_2 = \frac{F_{clr,d}^{dn} - F_{all,d}^{dn}}{F_{clr,d}^{dn}} = R_{dir} \text{ (RCRF for direct radiation)} \]

Applications next
Separation of Cloud Radiative Effects

- Simulated Irradiance vs simulated cloud properties.
- New measures allow separation of clearness index error into cloud fraction and albedo errors & are more informative.
- Underestimated cloud fraction/albedo leads to overestimated total and direct irradiances but underestimated diffuse irradiance.
- Diffuse and direct irradiances are more problematic.
- Similar results for other clouds.
New Framework for Nowcasting

\[ F_{\text{dn}}^i(t_f) = [1 - R_i(t)] \times F_{\text{clr},i}(t_f) \]

• “i” = total or direct irradiance

\[ F_{\text{dif}}^\text{dn}(t_f) = F_{\text{tot}}^\text{dn}(t_f) - F_{\text{dir}}^\text{dn}(t_f) \]

• New method outperforms simple persistence model for total, direct and diffuse irradiance beyond certain lead time;

• New method offers not only total, but also direct & diffuse irradiance

• Similarity & difference between percent error (or RMSE) and relative Euclidean distance

Great potentials & merit further study!
Regime Classification of Solar Radiation Variation

- Combination of new framework with K mean clustering
- Decade-long measurements at DOE ARM SGP site
- 12 different regimes with distinct combinations of variation patterns in total, direct and diffuse solar irradiances
- Potential use for regime-based solar forecast
- Potential additional role of aerosols
Task 4: Model Evaluation Framework

- **WRF-Solar Testbed Suite**
  - Adapt BNL Fast Physics Testbed:
    - WRF-Solar
    - WRF-Solar LES
    - Single Column WRF-Solar (SWRF-Solar)

- **Evaluation Metrics Suite**
  - Conventional metrics (e.g., RMSE)
  - Relative Euclidean distance
  - Taylor diagram
  - New analysis package

In addition to quantifying the model-observation differences, our evaluation framework is designed to detect physical causes underlying the model-observation differences and to test new parameterizations.
WRF-Solar Suite Performance

- Lest error in total irradiance; comparable for the rest
- DNI and DHI highly related to cloud parameterizations
- Different model configurations perform differently.
- D metric and percent error may convey different info (e.g., cloud fraction and cloud albedo for sc).

Different configurations and metrics help detect model deficiencies.

\[ D = \sqrt{\left(\frac{\bar{x} - \bar{y}}{y}\right)^2 + \left(\frac{\sigma_x - \sigma_y}{\sigma_y}\right)^2 + (c_{xy} - 1)^2}, \]
Summary and Questions?

- Project has been progressing smoothly and as planned.
- Encouraging results to summarize/polish for publication.
- Developing/testing cloud transmittance parameterizations.
- Implementing/testing/developing cloud microphysics scheme.
Technical Accomplishments (ST5.1)

- Several more observational data streams collected at the DOE ARF SGP site using different instruments have been examined to select the cloudy cases:
  - LASSO archive & RACORO Campaign: Cloud fraction vertical profiles
  - Radiative flux analysis (1min): Solar irradiances
  - ARM best estimation (hourly): LWP, atmospheric properties
  - VARANAL: Large scale forcing used to drive SWRF and WRF-LES
  - CLDTYPE: cloud type classification
  - MICROBASE: cloud microphysical properties including LWC
  - MWRRET: LWP from microwave radiometer retrievals
  - TSI: cloud fractions from totals sky imager
## WRF-Solar Suite Configurations

### Table 1.1. WRF-solar configurations for the baseline simulation (Nested), large eddy simulation (LES), and single column model (SCM)

<table>
<thead>
<tr>
<th></th>
<th>Nested</th>
<th>LES</th>
<th>SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary condition</td>
<td>NARR</td>
<td>VARANAL</td>
<td>VARANAL</td>
</tr>
<tr>
<td># of domains</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Size of (inner) domain</td>
<td>90km</td>
<td>14.4km</td>
<td>-</td>
</tr>
<tr>
<td>Horiz grid size (inner domain)</td>
<td>3km</td>
<td>100m</td>
<td>3km</td>
</tr>
<tr>
<td># of vertical levels</td>
<td>50</td>
<td>227</td>
<td>50</td>
</tr>
<tr>
<td>Model top</td>
<td>100mb (~16000m)</td>
<td>14800m</td>
<td>14800m</td>
</tr>
<tr>
<td>Microphysics</td>
<td>Thompson scheme</td>
<td>Thompson scheme</td>
<td>Thompson scheme</td>
</tr>
<tr>
<td>Radiation (SW / LW)</td>
<td>RRTMG / RRTMG</td>
<td>RRTMG / RRTMG</td>
<td>RRTMG / RRTMG</td>
</tr>
<tr>
<td>Boundary layer</td>
<td>MYNN</td>
<td>-</td>
<td>MYNN</td>
</tr>
<tr>
<td>Land surface model</td>
<td>RUC</td>
<td>VARANAL*</td>
<td>VARANAL*</td>
</tr>
<tr>
<td>Cumulus parameterization</td>
<td>GF shallow cumulus</td>
<td>-</td>
<td>GF shallow cumulus</td>
</tr>
</tbody>
</table>
Table 1.1. A summary of microphysics schemes examined in this quarter*

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Mass variable</th>
<th>Number variable</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morrison (DM)</td>
<td>Qc Qr Qi Qs Qg</td>
<td>Nr Ni Ns Ng</td>
<td>Morrison et al. 2009</td>
</tr>
<tr>
<td>Thompson (SM)</td>
<td>Qc Qr Qi Qs Qg</td>
<td>Ni Nr</td>
<td>Thompson et al. 2008</td>
</tr>
<tr>
<td>Lin (SM)</td>
<td>Qc Qr Qi Qs Qg</td>
<td></td>
<td>Lin et al. 1983</td>
</tr>
<tr>
<td>WDM6 (DM)</td>
<td>Qc Qr Qi Qs Qg</td>
<td>Nn Nc Nr</td>
<td>Lim and Hong 2010</td>
</tr>
<tr>
<td>WSM6 (DM)</td>
<td>Qc Qr Qi Qs Qg</td>
<td></td>
<td>Hong and Lim 2006</td>
</tr>
<tr>
<td>NSSL SM</td>
<td>Qc Qr Qi Qs Qg Qh</td>
<td>Vg</td>
<td></td>
</tr>
<tr>
<td>NSSL DM</td>
<td>Qc Qr Qi Qs Qg Qh</td>
<td>Nc Nr Ni Ns Ng Nh</td>
<td>Mansell, Ziegler and Bruning 2010</td>
</tr>
</tbody>
</table>

*Q and N denote mixing ratio and number concentration, respectively. The subscripts c, r, l, s, g, h, ip, ic, id, and n denote cloud, rain, ice, snow, graupel, hail, ice plates, ice columns, ice dendrites, cloud condensation nuclei (CCN), respectively. Vg is the graupel volume. For convenience of this report, a bulk microphysics scheme is regarded as double moment (DM) if more than half of the mass variables have corresponding number variables; otherwise it is categorized as single moment (SM).
Baseline Simulations: Solar Radiation

- Better total irradiance better than the direct and diffuse component
- Model errors in direct and diffuse irradiance cancel out
- Worse performance for Sc clouds
Test of Microphysics Schemes: Radiative Effects

- Better simulated total irradiance than components
- Error cancellation of direct and diffuse radiations
- Simulate cu better than sc generally
- Large sensitivity to cloud microphysics
# Summary of 8 Cases (5 Cu and 3 Sc)

<table>
<thead>
<tr>
<th></th>
<th>Cumulus Cases</th>
<th>Stratocumulus Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Cases</strong></td>
<td>• Larger errors cancel out in direct and diffuse irradiances leading to smaller error in total irradiance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Larger errors in simulated cloud properties than in irradiances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Large errors in irradiances during the transition of the clouds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Possible error compensation from incorrect cloud structures</td>
<td></td>
</tr>
<tr>
<td><strong>Regime</strong></td>
<td>• Small cloud fraction, Smaller sensitivity to microphysics than Sc</td>
<td>• Large cloud fraction, Larger sensitivity to microphysics than Cu</td>
</tr>
<tr>
<td>dependent</td>
<td>• Better simulated cloud structures (2D cloud fraction) in LES</td>
<td>• Better simulated cloud structures (2D cloud fraction) in nested WRF-Solar</td>
</tr>
<tr>
<td></td>
<td>• Overestimated direct irradiance and underestimated diffuse irradiance</td>
<td>• All simulations tend to underestimate the 2D cloud fraction (therefore the deeper clouds in LES results in better irradiances)</td>
</tr>
<tr>
<td></td>
<td>• Better simulated direct irradiance than diffuse irradiance</td>
<td>• Better simulated diffuse irradiance than direct irradiance</td>
</tr>
<tr>
<td><strong>Case</strong></td>
<td>• All short cases shows small sensitivity to microphysics, while the microphysics sensitivity start from the 2(^{nd}) day of simulation of the 60 h case.</td>
<td>• Performance of LES, Nested WRF-Solar and SCM varies from case to case</td>
</tr>
<tr>
<td>dependent</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cloud transmittances of water (left) and ice (right) clouds related to infinite narrow beam (Lambert Law) and scattered radiation within the circumsolar region (FARMS-DNI).
BP1 R&D lays the foundations for further R&D in BP2 and BP3.
We will perform similar analysis for corresponding observational data to facilitate model evaluation and shorter-range forecasting as well.
WRF-Solar Suite: Cu Case

- All but SCM capture Cu pattern
- Better Cu structure in LES
- In nested WRF-Solar, overestimated high-clouds compensates underestimated low clouds to produce more reasonable solar irradiance.

Comparison to using different microphysics schemes
WRF-Solar Suite: Sc Case

- Better Sc structure in nested WRF-solar
- Better simulated irradiances in LES (compensating errors?)

Comparison to using different microphysics schemes