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

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7-8 Oct 2019

SETO SF2 Workshop

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

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UNIVERSITY AT ALBANY State University of New York

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

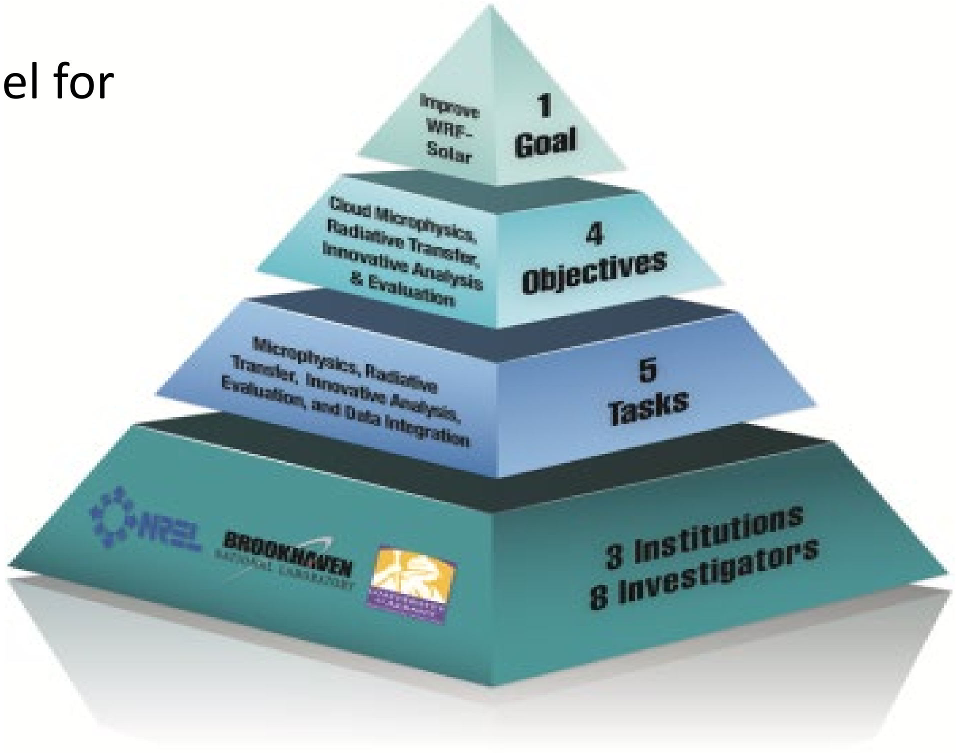
❖ Four Objectives

- Improve cloud microphysics
- Improve radiative transfer
- Develop innovative analysis package
- Perform model evaluation

❖ Five Tasks

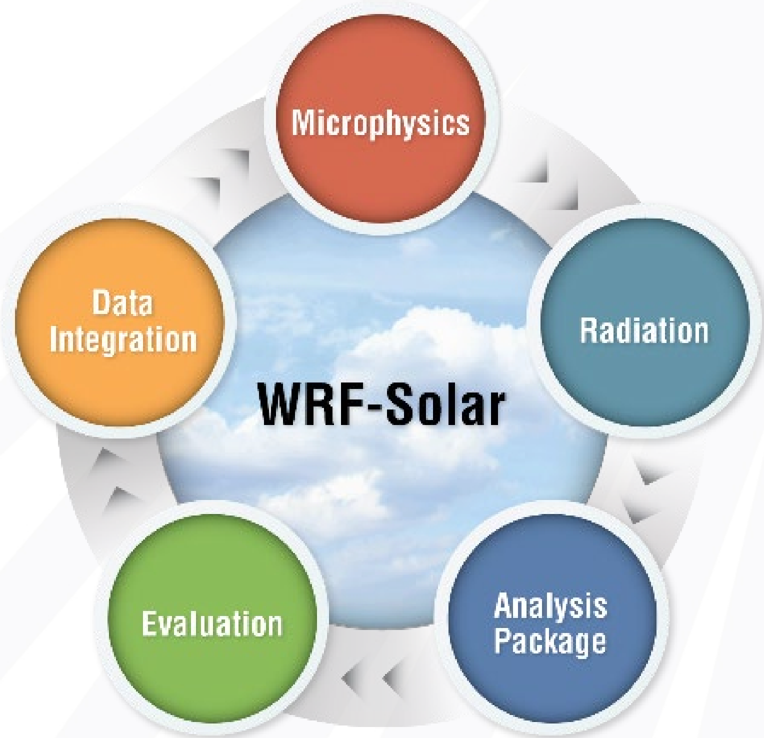
- Four objectives + Data integration

❖ 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.

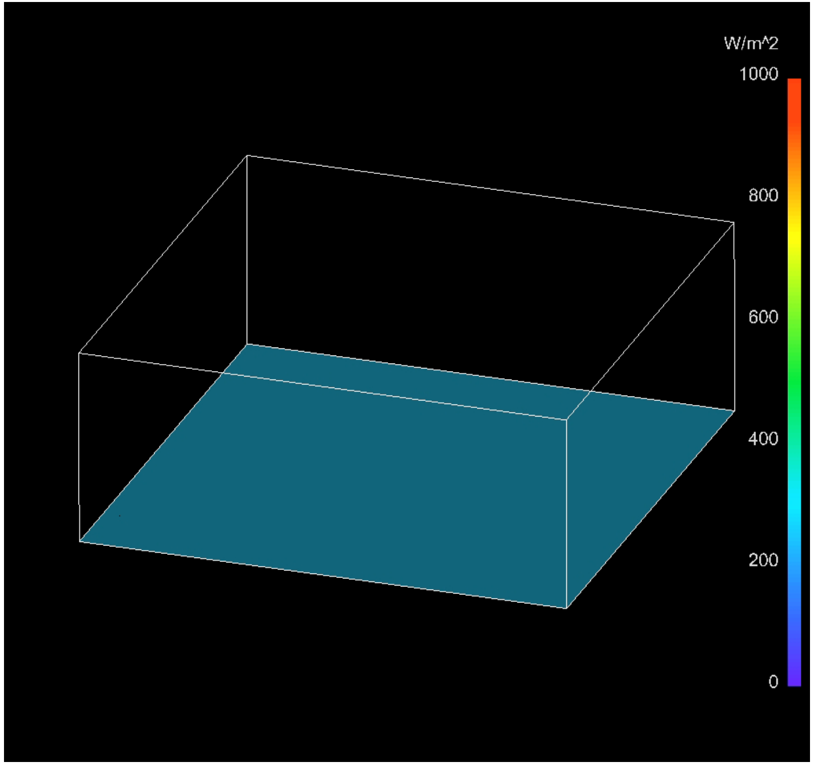
Case *	Cloud Condition	Case Duration**
Sc20050325	Low-level and mid-level stratocumulus	15hr from 6:00
Sc20090419	Low-level stratocumulus	15hr from 6:00
Sc20090506	Low-level stratocumulus	15hr from 6:00
Cu20090522	Shallow cumulus with high level ice clouds	60hr from 0522_6:00
Cu20160611	Shallow cumulus	15hr from 6:00
Cu20160619	Shallow cumulus	15hr from 6:00
Cu20160625	Shallow cumulus	15hr from 6:00
Cu20160818	Shallow cumulus with high level ice clouds	15hr from 6:00

* The case name consists of cloud type (Cu or Sc) and starting date of the case (yyyymmdd).
** Case duration is the period used in the baseline simulation instead of exact duration of the clouds.

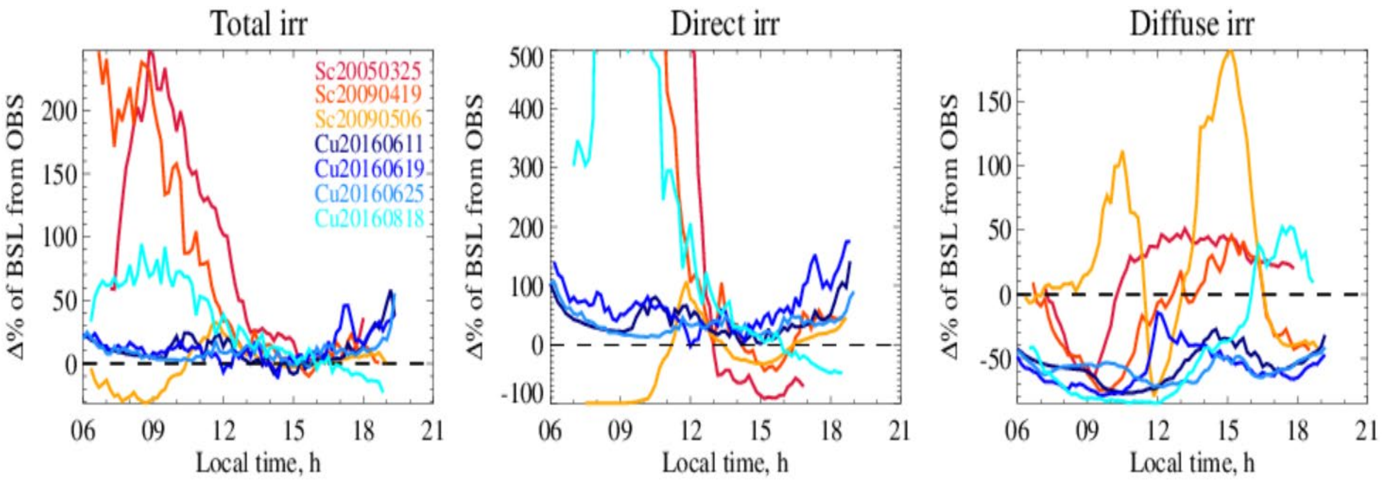
Task 1: Cloud Microphysics

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

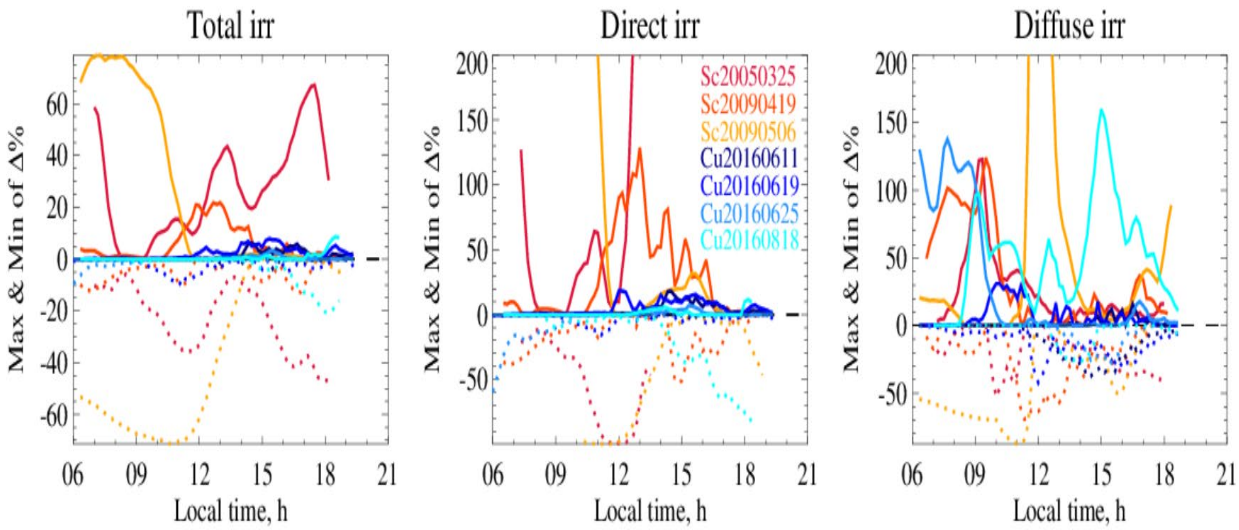


Substantial Differences between Baseline Sim and Obs



- 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

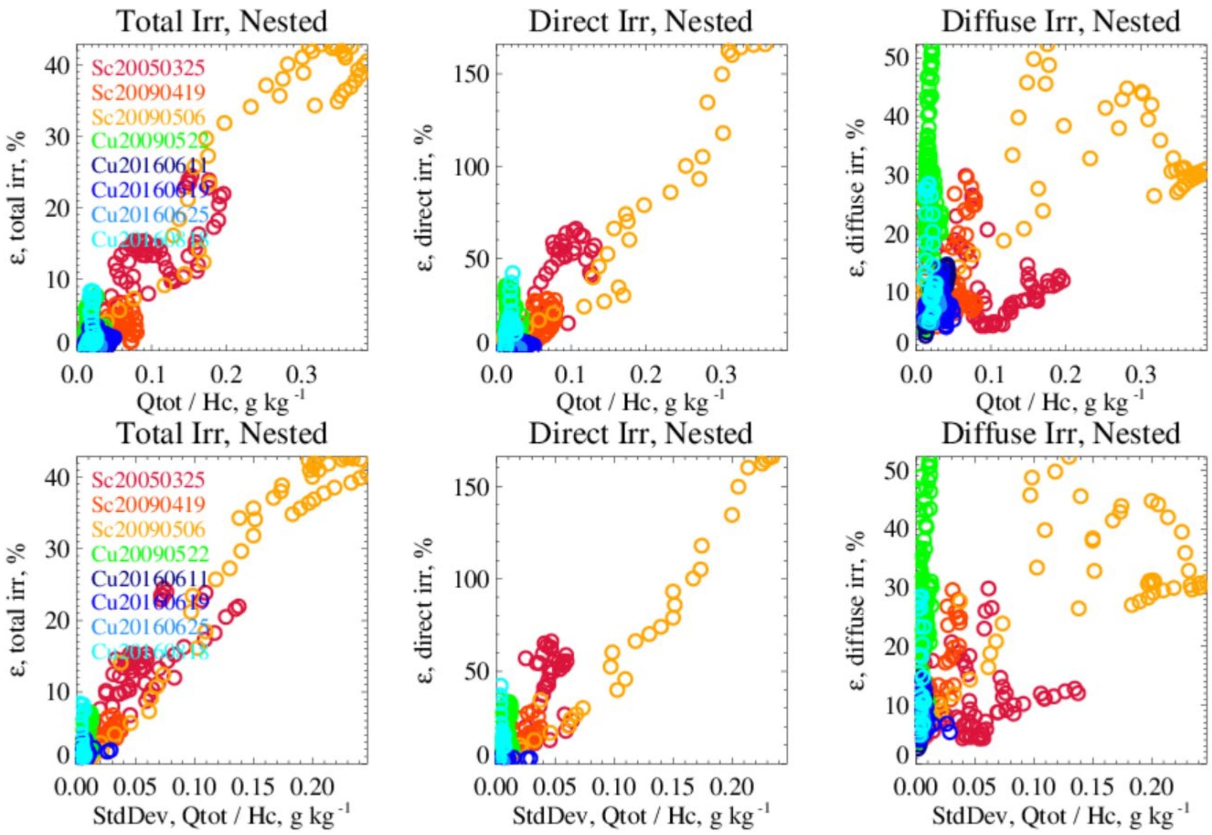
Effect of Cloud Microphysics Schemes on WRF-Solar



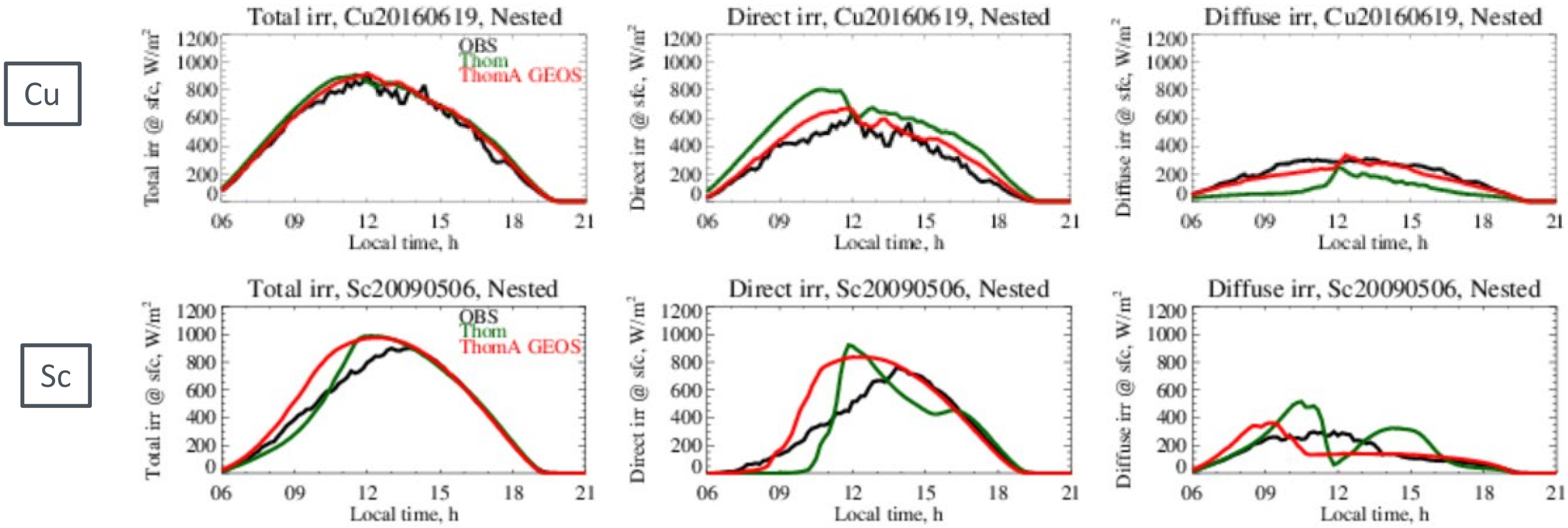
- Seven microphysics schemes tested
- Significant microphysics-induced model difference
- Larger differences correspond generally to higher total water contents
- Support proposed improvement in cloud microphysics parameterization

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



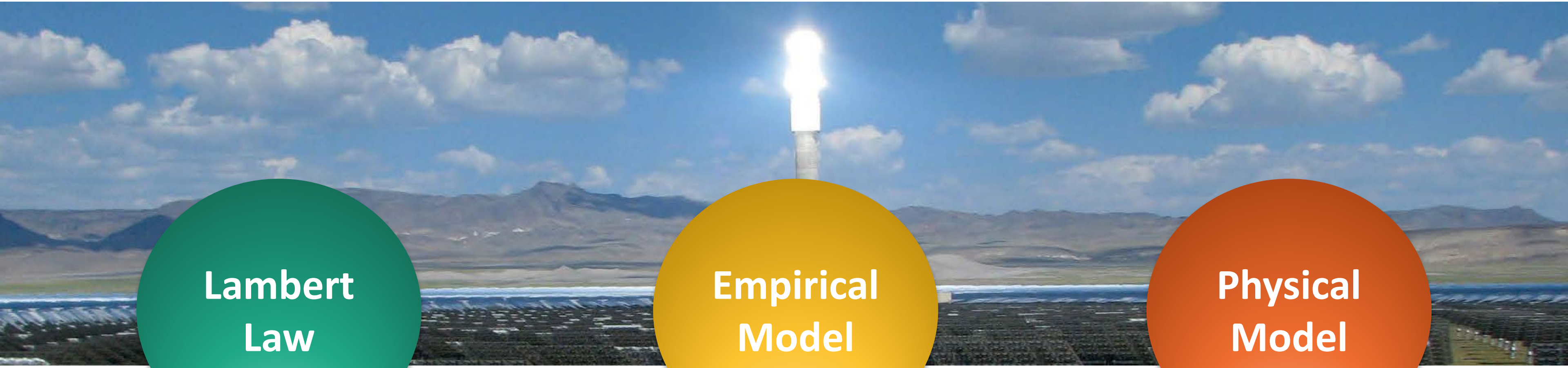
Influences of Aerosol Direct and Indirect Effects



- 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

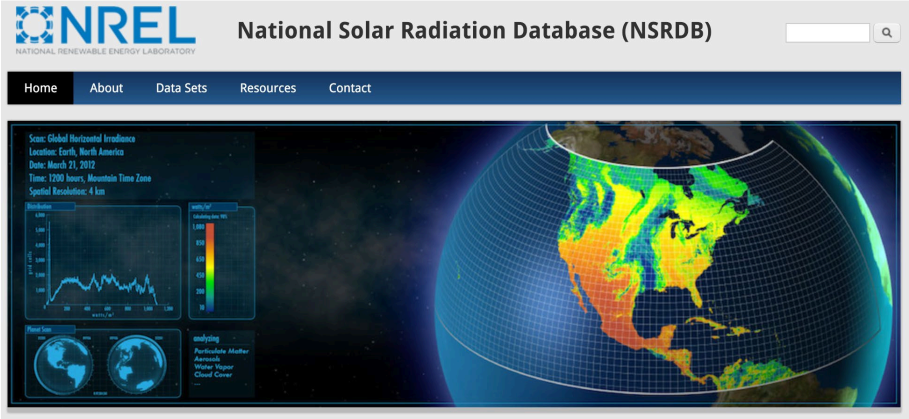
Numerically solve the radiative transfer equation. **Time consuming.**

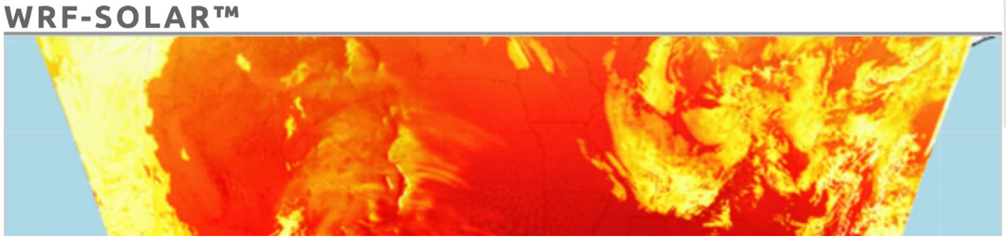
What Is FARMS?

FARMS, the **F**ast **A**ll-sky **R**adiation **M**odel for **S**olar 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.

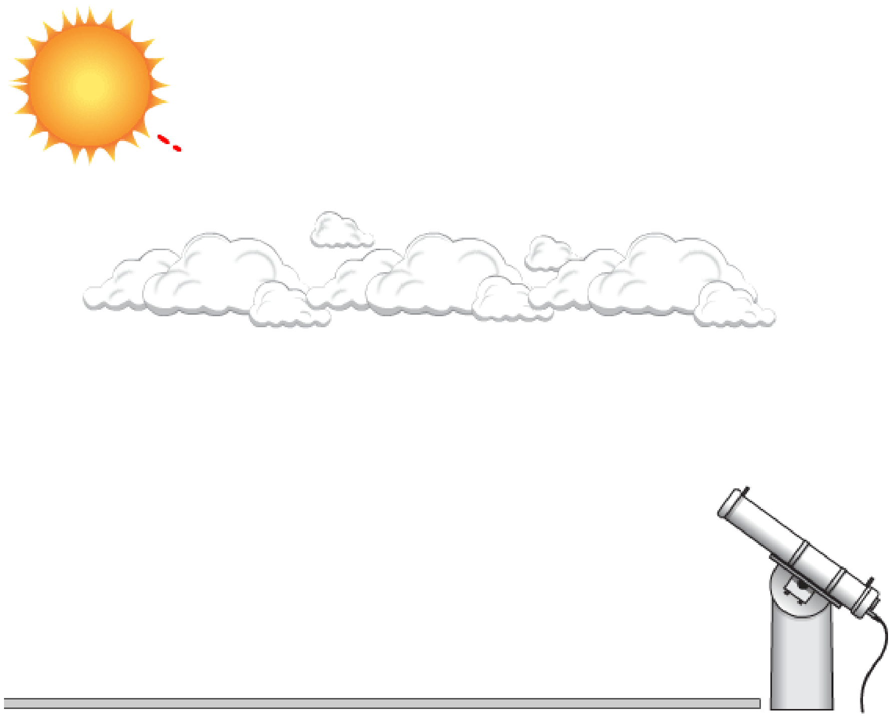
FARMS and the extension models have been used to support multiple DOE-sponsored projects on solar resource assessment and forecasting.

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.

Lookup Table of Cloud Transmittance

97
wavelength

2
Cloud phase

39
Cloud Optical Thickness

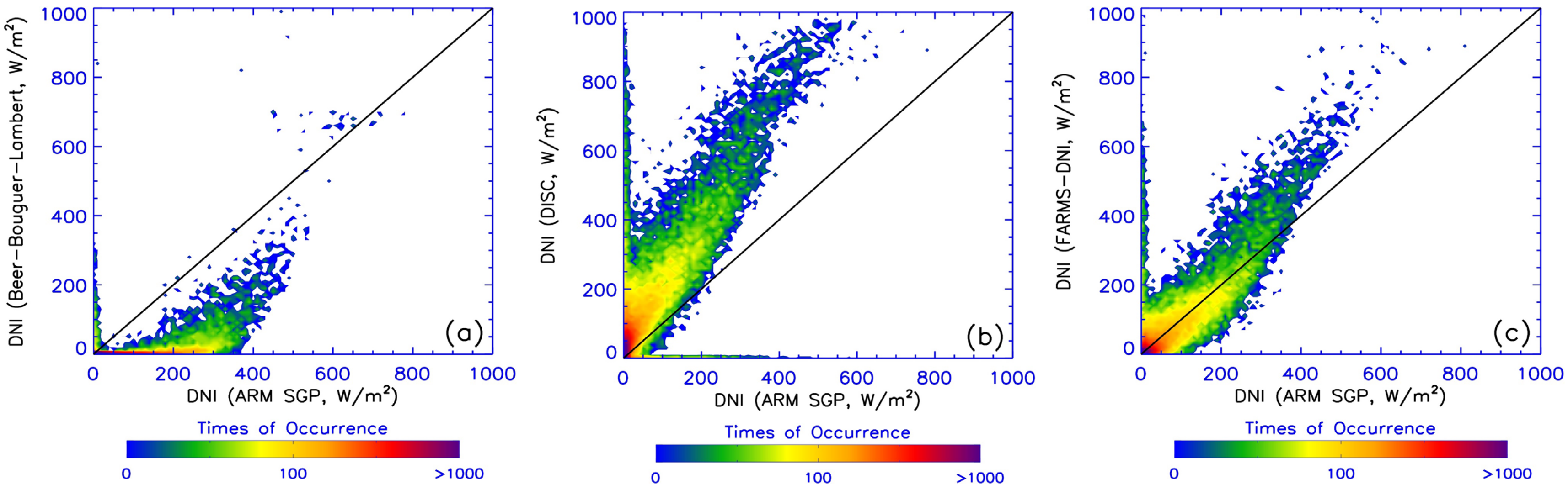
28
Cloud Particle Size

43
Solar Zenith Angle

100-200
Viewing Direction

- 32-stream DISORT is used to compute the lookup table.
- 9.1 X 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
  - $K_T = \frac{F_{all}^{dn}}{F_{TOA}^{dn}} = \frac{F_{all}^{dn}}{F_{clr}^{dn} \cdot T_a^{-1}}$; RCRF for total radiation $R_{tot} = \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn}}$
  - $R_{tol} = 1 - K_T \cdot T_a^{-1}$
  - $R_{tol} \sim \alpha_r f$ suggests that K_T is affected by both cloud fraction (f) and cloud albedo (α_r) >> Can we separate cloud fraction effect from cloud albedo effect?
- New framework separating cloud fraction effect from albedo effect
  - Cloud albedo: $a_r \sim B_1/B_2 = B_3$
  - Cloud fraction: $f \sim B_2$

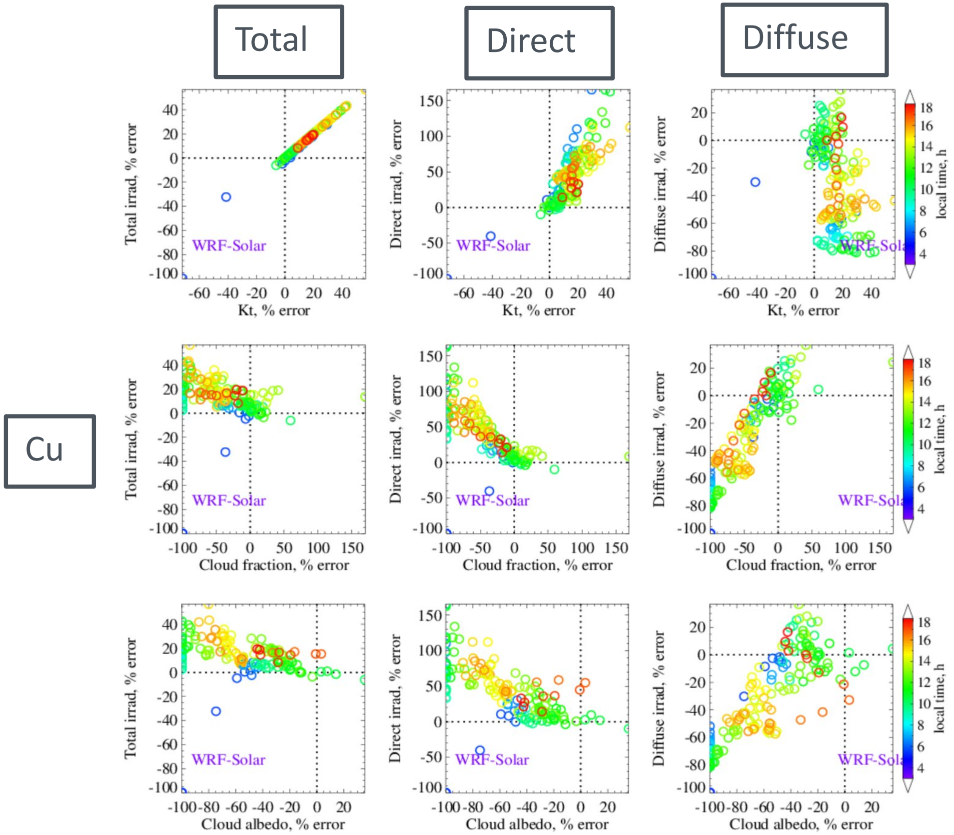
$$B_1 = \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn} - F_{all}^{up} T_a^2} \approx \frac{F_{clr}^{dn} - F_{all}^{dn}}{F_{clr}^{dn}} = R_{tot}$$

$$B_2 = \frac{F_{clr,d}^{dn} - F_{all,d}^{dn}}{F_{clr,d}^{dn}} = R_{dir} \ (RCRF\ for\ direct\ radiation)$$

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



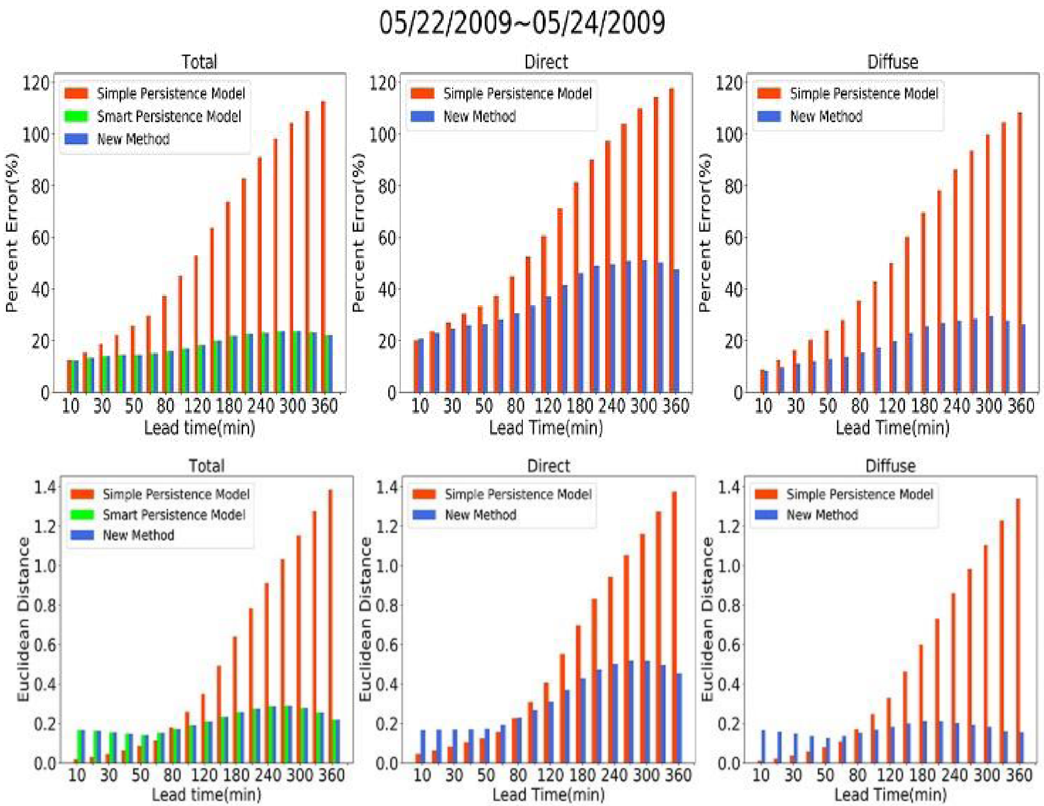
New Framework for Nowcasting

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

"i" = total or direct irradiance

$$F_{dif}^{dn}(t_f) = F_{tot}^{dn}(t_f) - F_{dir}^{dn}(t_f)$$

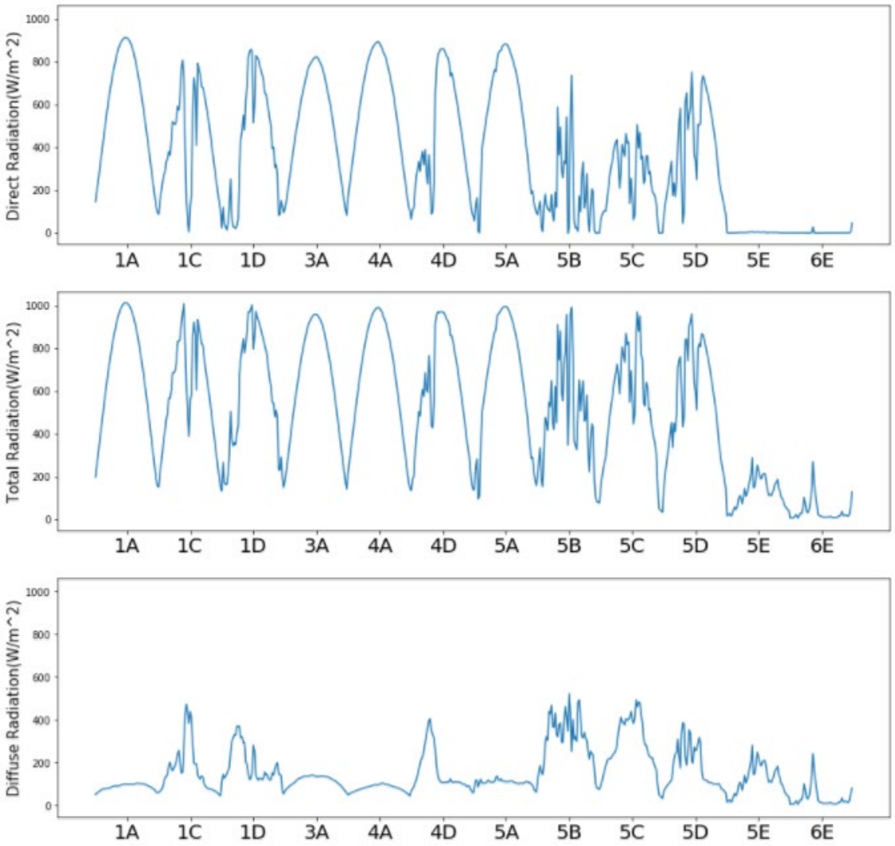
- New method outperforms simple persistence model for total, direct and diffuse irradiance beyond certain lead time;
- New method offers not only total, but also direct & diffuse irradiance
- Similarity & difference between percent error (or RMSE) and relative Euclidean distance



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

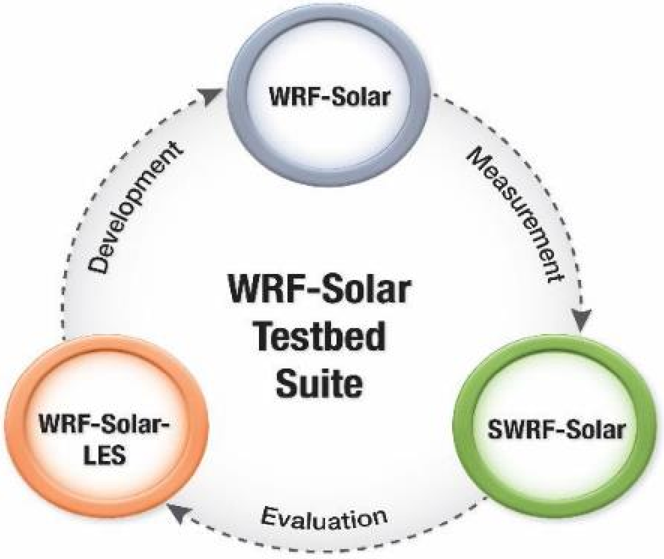
❖ WRF-Solar Testbed Suite

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

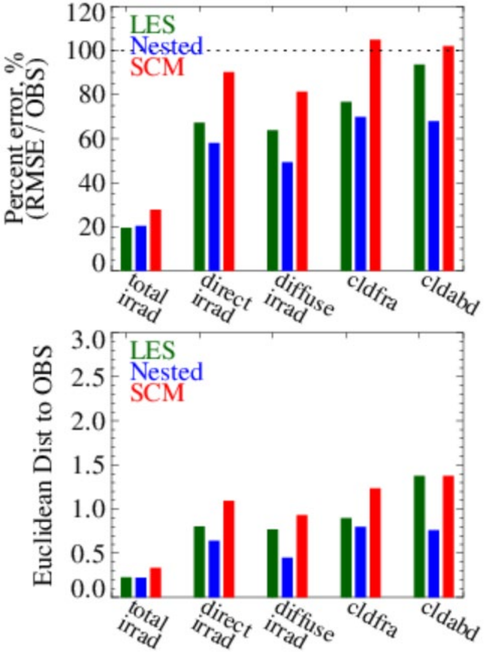


In addition to quantifying the model-observation differences, our evaluation framework is designed to detect physical causes underlying the model-observation differences and to test new parameterizations.

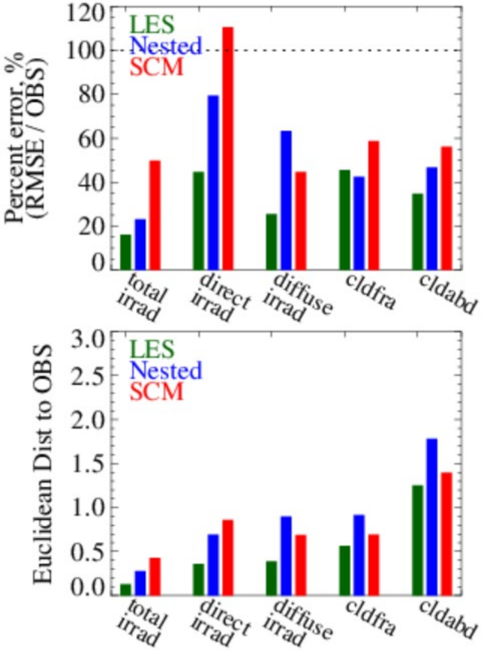
WRF-Solar Suite Performance

- 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).

Cu



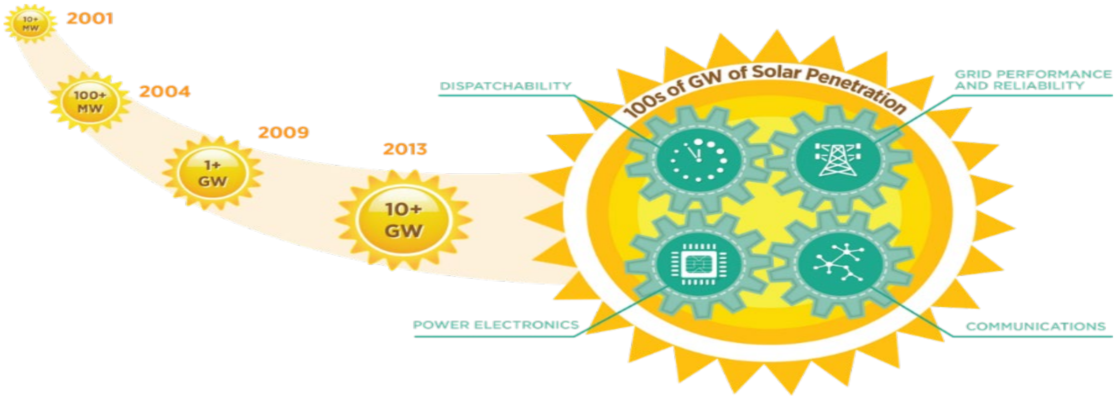
Sc



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)

	Nested	LES	SCM
Boundary condition	NARR	VARANAL	VARANAL
# of domains	2	1	1
Size of (inner) domain	90km	14.4km	-
Horiz grid size (inner domain)	3km	100m	3km
# of vertical levels	50	227	50
Model top	100mb (~16000m)	14800m	14800m
Microphysics	Thompson scheme	Thompson scheme	Thompson scheme
Radiation (SW / LW)	RRTMG / RRTMG	RRTMG / RRTMG	RRTMG / RRTMG
Boundary layer	MYNN	-	MYNN
Land surface model	RUC	VARANAL*	VARANAL*
Cumulus parameterization	GF shallow cumulus	-	GF shallow cumulus

Technical Accomplishments (T1)

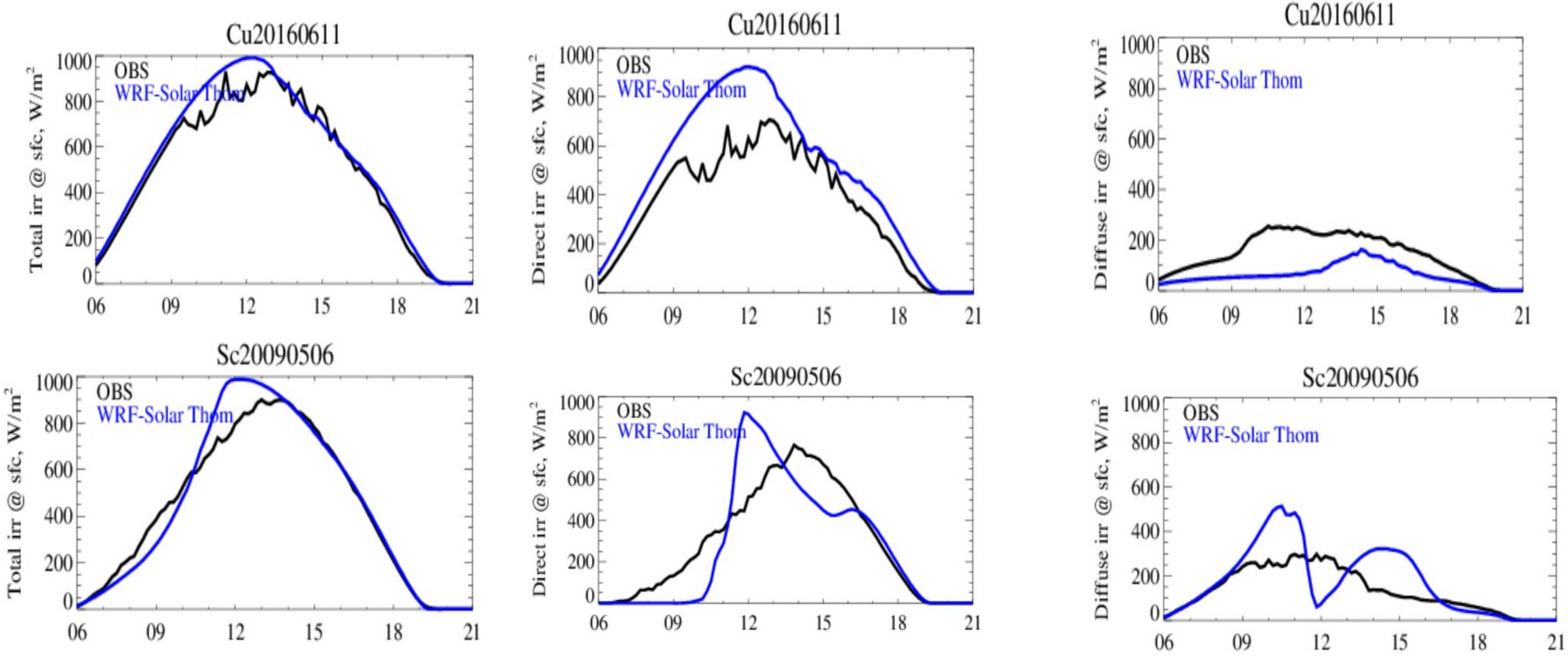
Table 1.1. A summary of microphysics schemes examined in this quarter*

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

*Q and N denote mixing ratio and number concentration, respectively. The subscripts c, r, I, 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

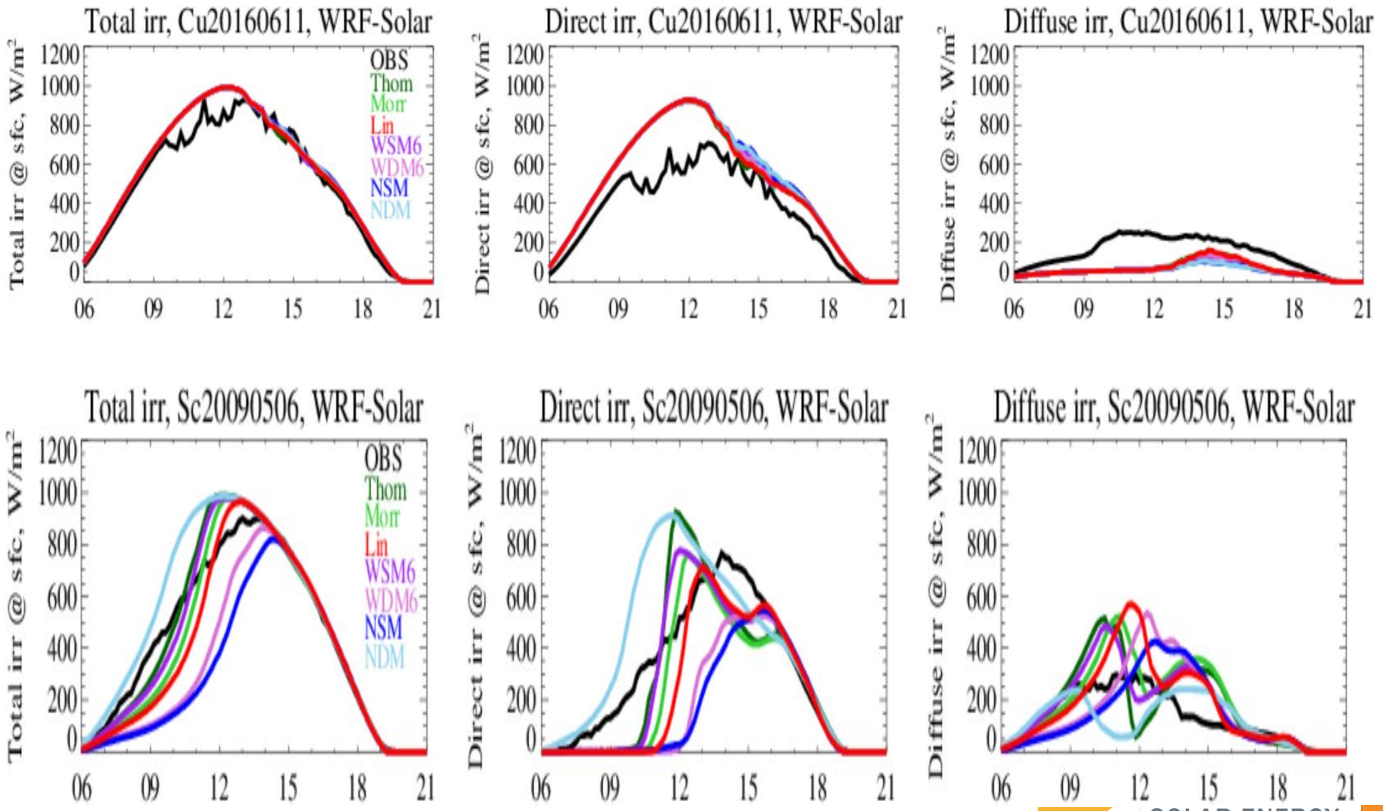
Total | Direct | Diffuse



- 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



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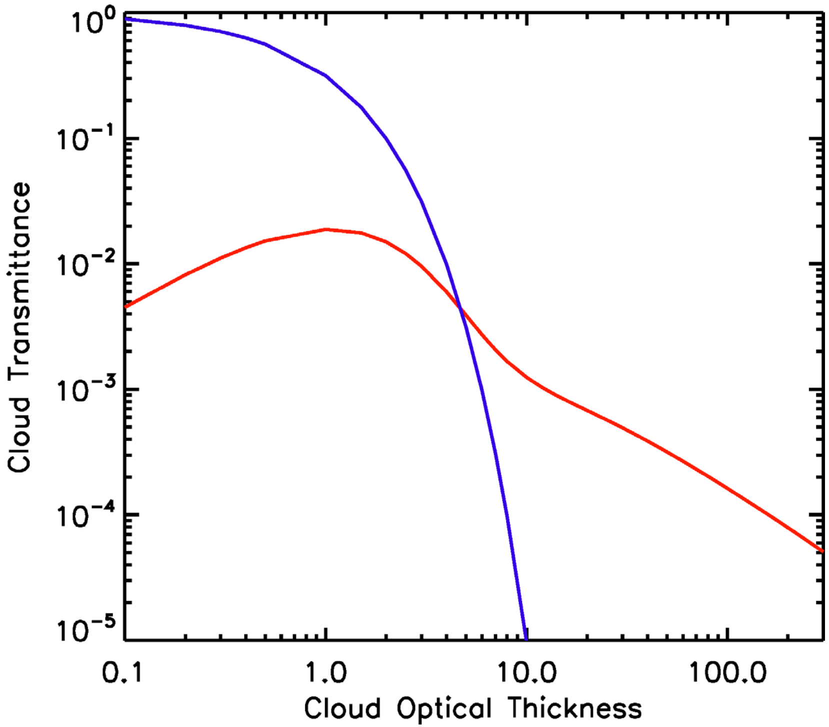
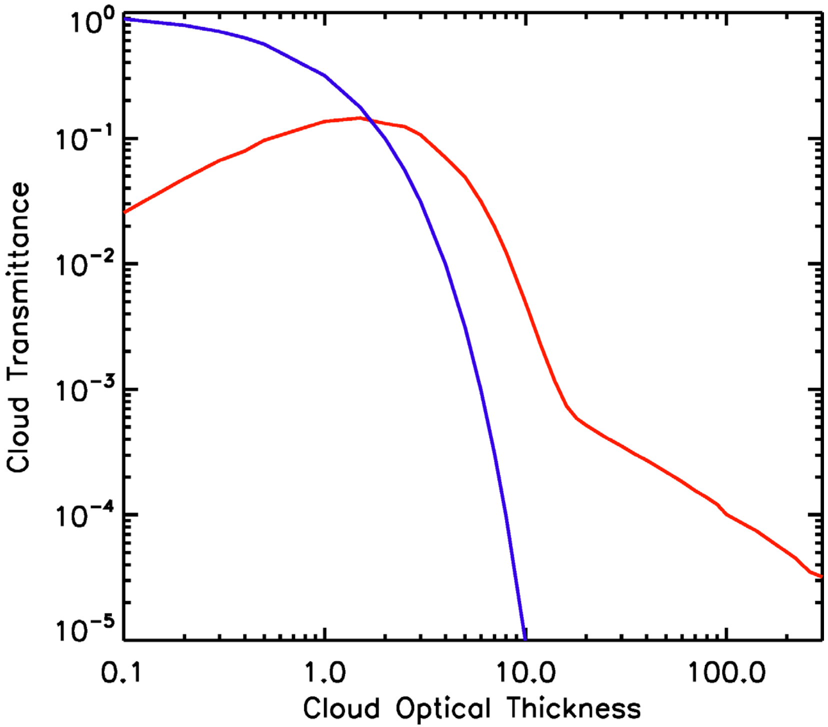
Summary of 8 Cases (5 Cu and 3 Sc)

	Cumulus Cases	Stratocumulus Cases
All Cases	• Larger errors cancel out in direct and diffuse irradiances leading to smaller error in total irradiance. • Larger errors in simulated cloud properties than in irradiances • Large errors in irradiances during the transition of the clouds • Possible error compensation from incorrect cloud structures	
Regime dependent	• Small cloud fraction, Smaller sensitivity to microphysics than Sc • Better simulated cloud structures (2D cloud fraction) in LES • Overestimated direct irradiance and underestimated diffuse irradiance • Better simulated direct irradiance than diffuse irradiance	• Large cloud fraction, Larger sensitivity to microphysics than Cu • Better simulated cloud structures (2D cloud fraction) in nested WRF-Solar • All simulations tend to underestimate the 2D cloud fraction (therefore the deeper clouds in LES results in better irradiances) • Better simulated diffuse irradiance than direct irradiance
Case dependent	• All short cases shows small sensitivity to microphysics, while the microphysics sensitivity start from the 2nd day of simulation of the 60 h case.	• Performance of LES, Nested WRF-Solar and SCM varies from case to case

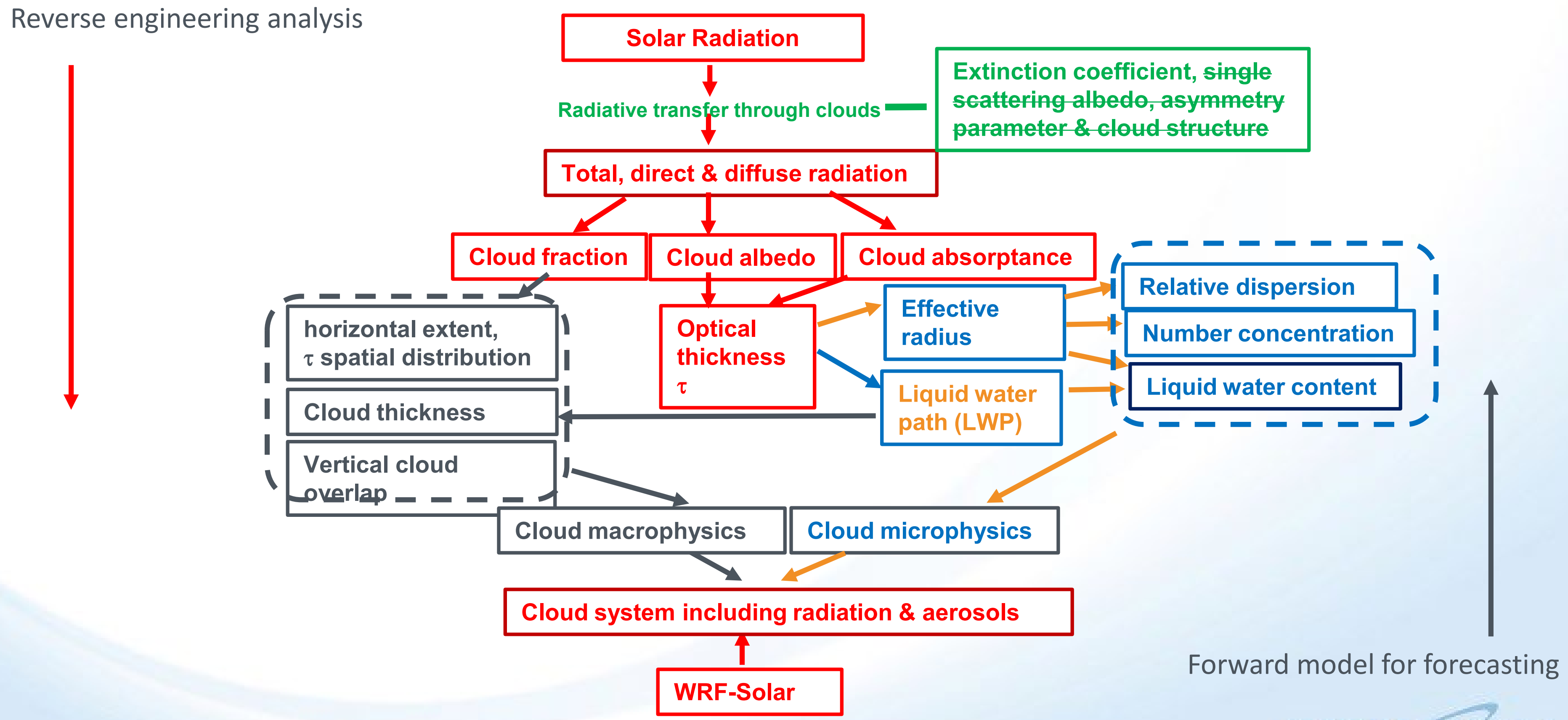
Cloud Transmittance vs Cloud Optical Depth





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**).

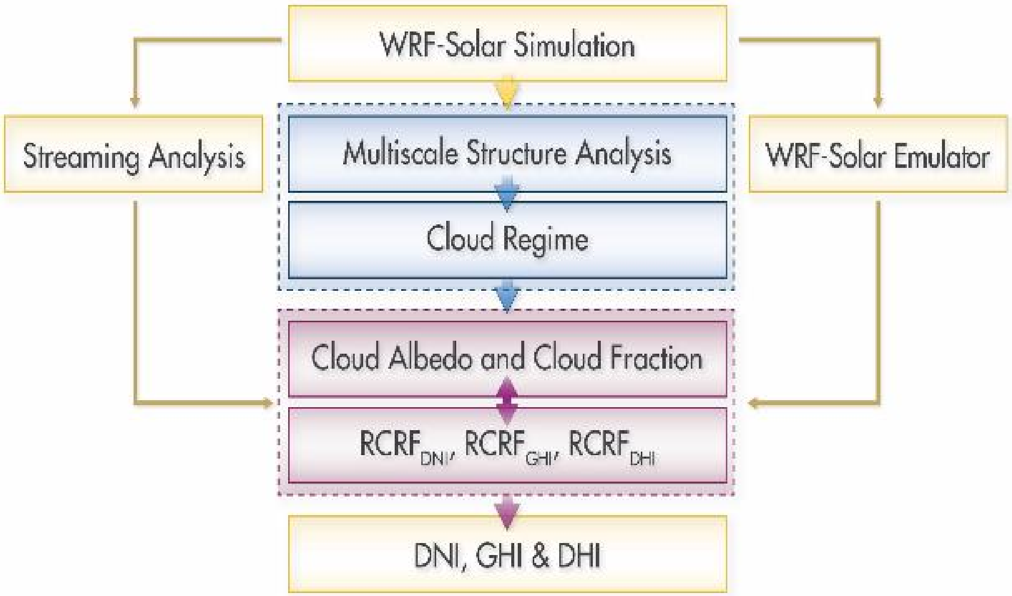
Radiation Tree for Studying Cloud Effects on Radiation



BP1 R&D lays the foundations for further R&D in BP2 and BP3.

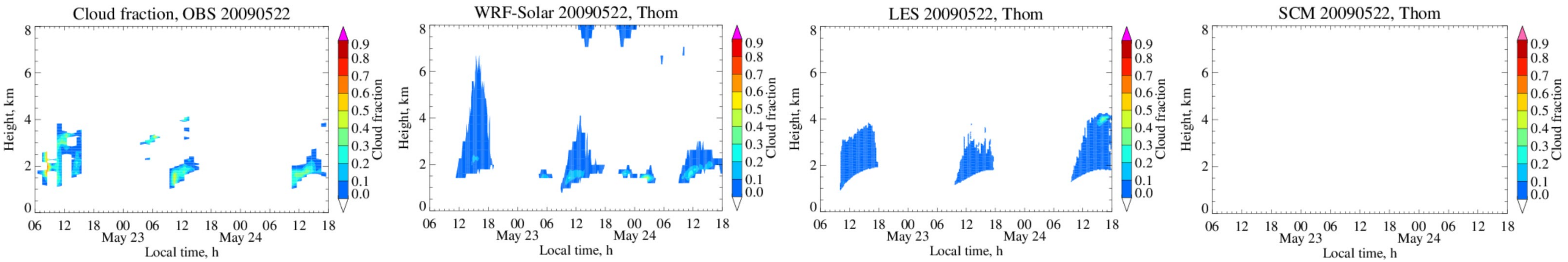
Task 3: Innovative Analysis Package

- Radiation-cloud relationships
- Cloud regimes
- Model/process emulator
- Streaming analysis

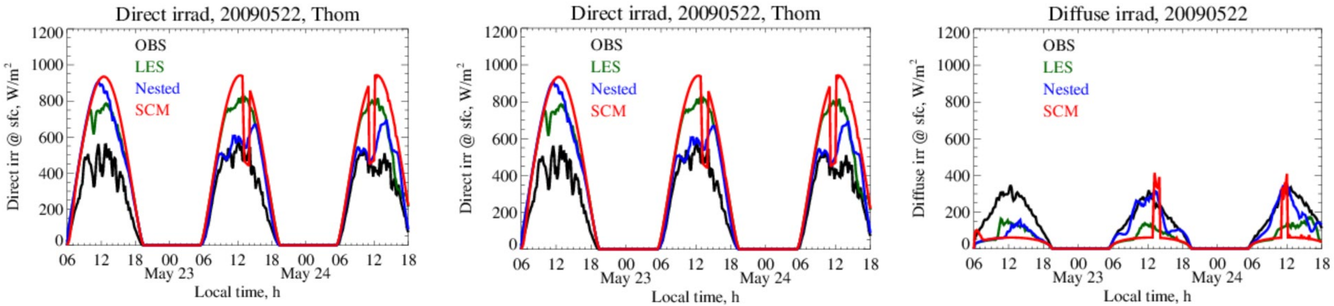


We will perform similar analysis for corresponding observational data to facilitate model evaluation and shorter-range forecasting as well.

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

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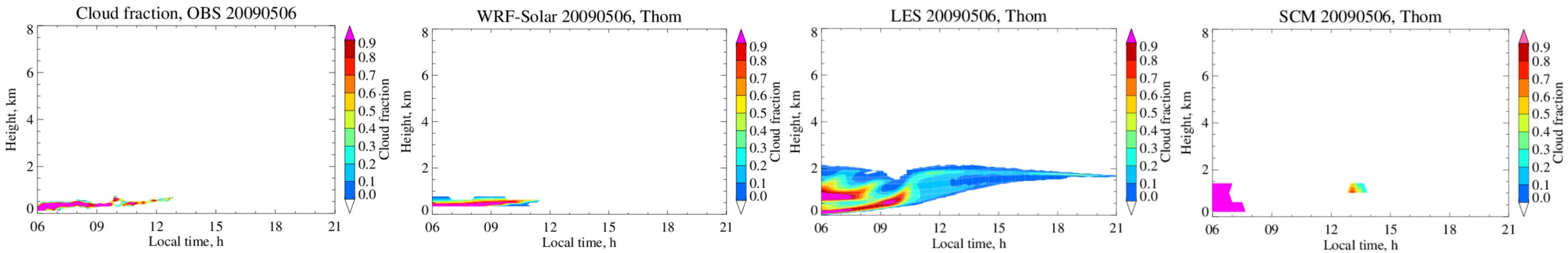
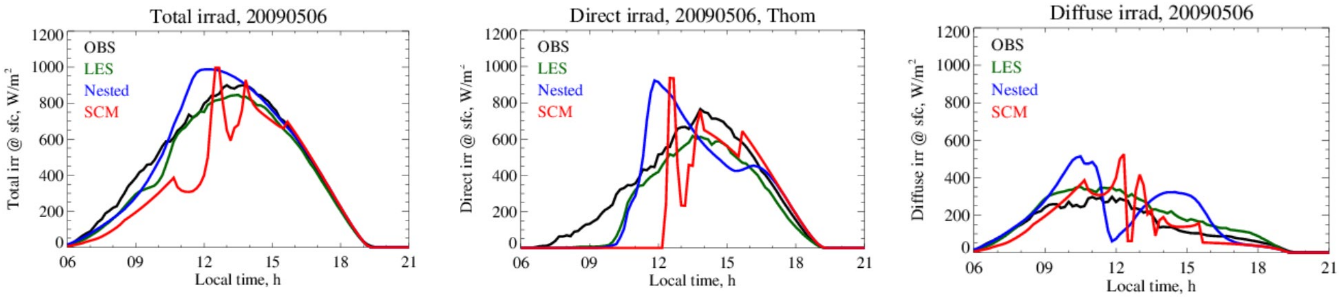
WRF-Solar Suite: Sc Case



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



Comparison to using different microphysics schemes