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

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Presented by Wuyin Lin (BNL)

Other team members:
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SUNY-Albany: Qilong Min
BNL: Shinjae Yoo & Satoshi Endo

SF2 Kickoff Meeting
July 12, 2018

Project Pyramid

❖ One Goal

Improve the state of art *WRF-Solar* model for forecasting solar irradiance in *cloudy* environment

❖ Four Objectives

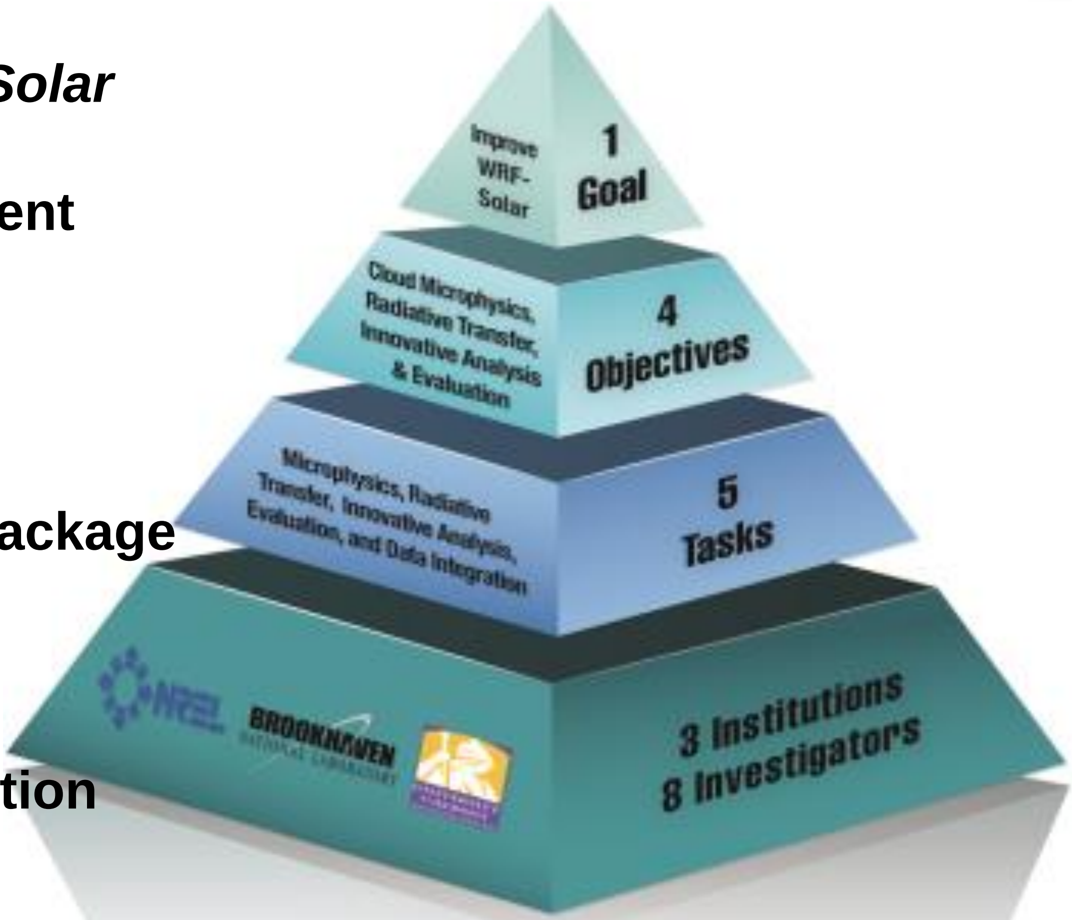
- **Improve cloud microphysics**
- **Improve radiative transfer**
- **Develop innovative analysis package**
- **Perform model evaluation**

❖ Five Tasks

- **Four objectives + Data integration**

❖ Collaborative Proposal

- **Three institutions (BNL, NREL, & SUNY-Albany)**
- **Eight investigators with unique combined expertise**

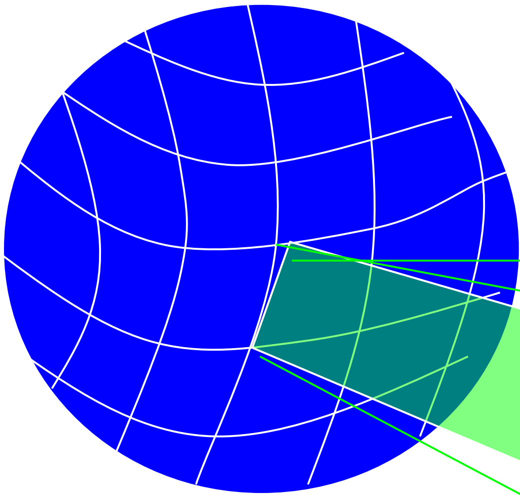


Five Closely Related Tasks

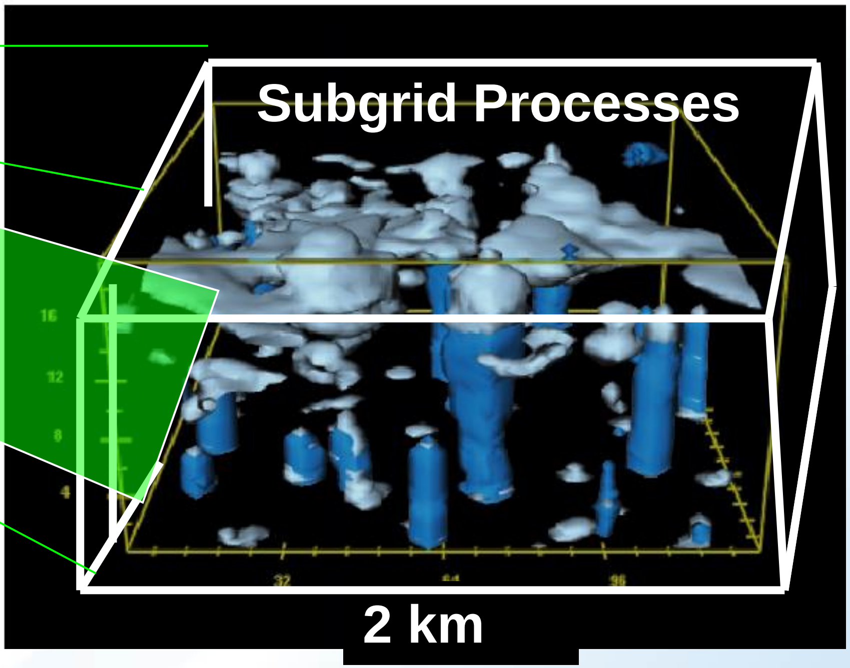
- Improve Cloud Microphysics
- Improve Radiative Transfer
- Develop Innovative Analysis Package
- Perform Model Evaluation
- Data Integration

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

Anatomy of WRF-Solar Model



$$\frac{dX}{dt} = \underset{\text{(Resolved/Grid)}}{\text{Dynamics}} + \underset{\text{(Unresolved/Subgrid)}}{\text{Fast Physics}}$$



Targeted Fast Physics:

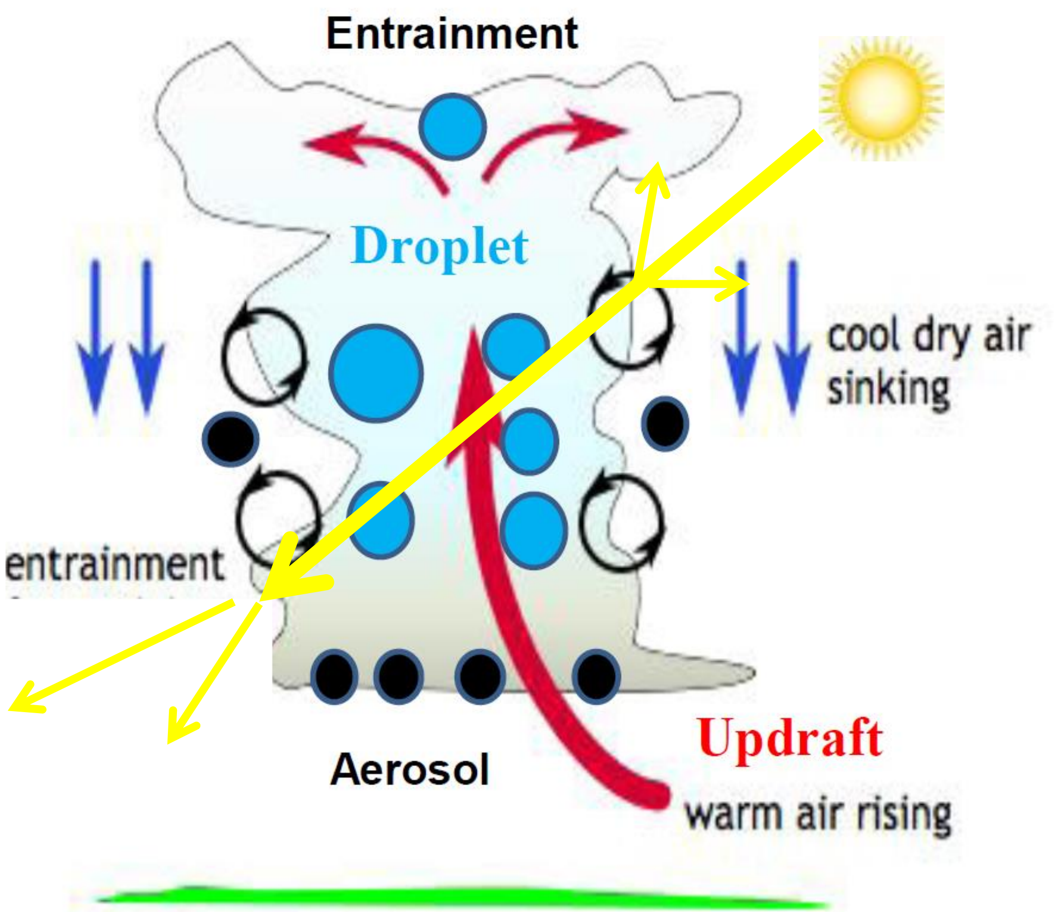
- **Microphysics**
- **Entrainment-mixing**
- **Radiation**
- **Cloud-radiation interaction**
- **Aerosol**

Fast physics is critical for Topic Area 2; its parameterization is largely responsible for model deficiencies.

Task 1: Improve Cloud Microphysics

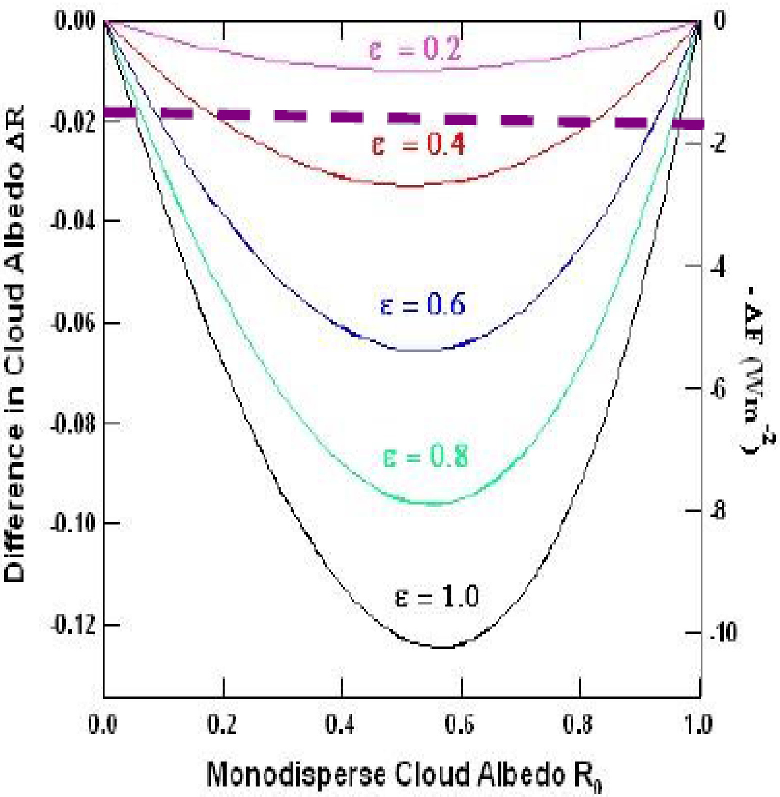
Processes critical, but not represented in current WRF-Solar:

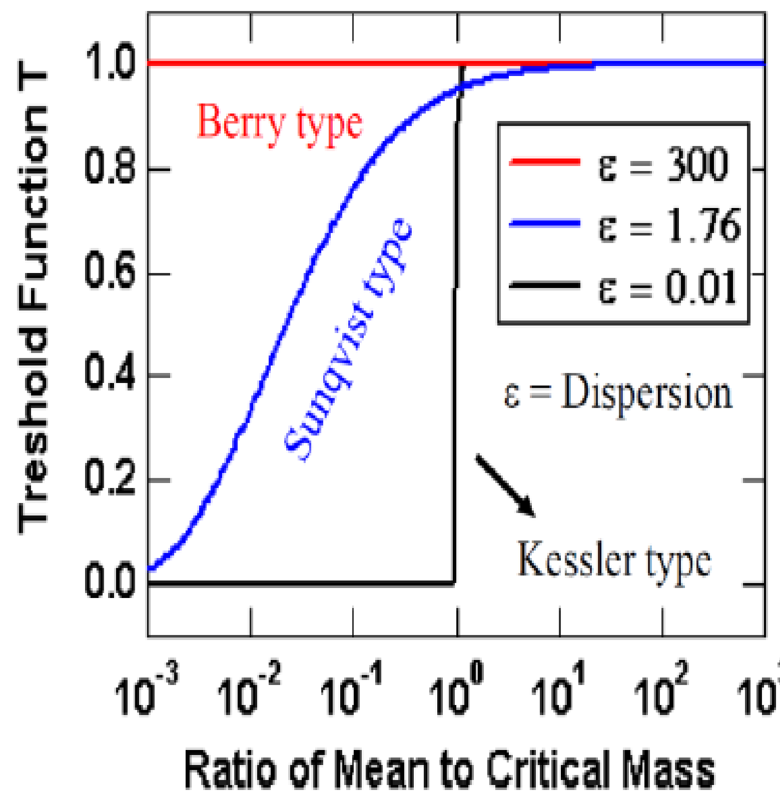
- **Evolution of spectral shape of cloud droplet size distribution**
- **Entrainment-mixing process**
- **Radiative effect on microphysics**



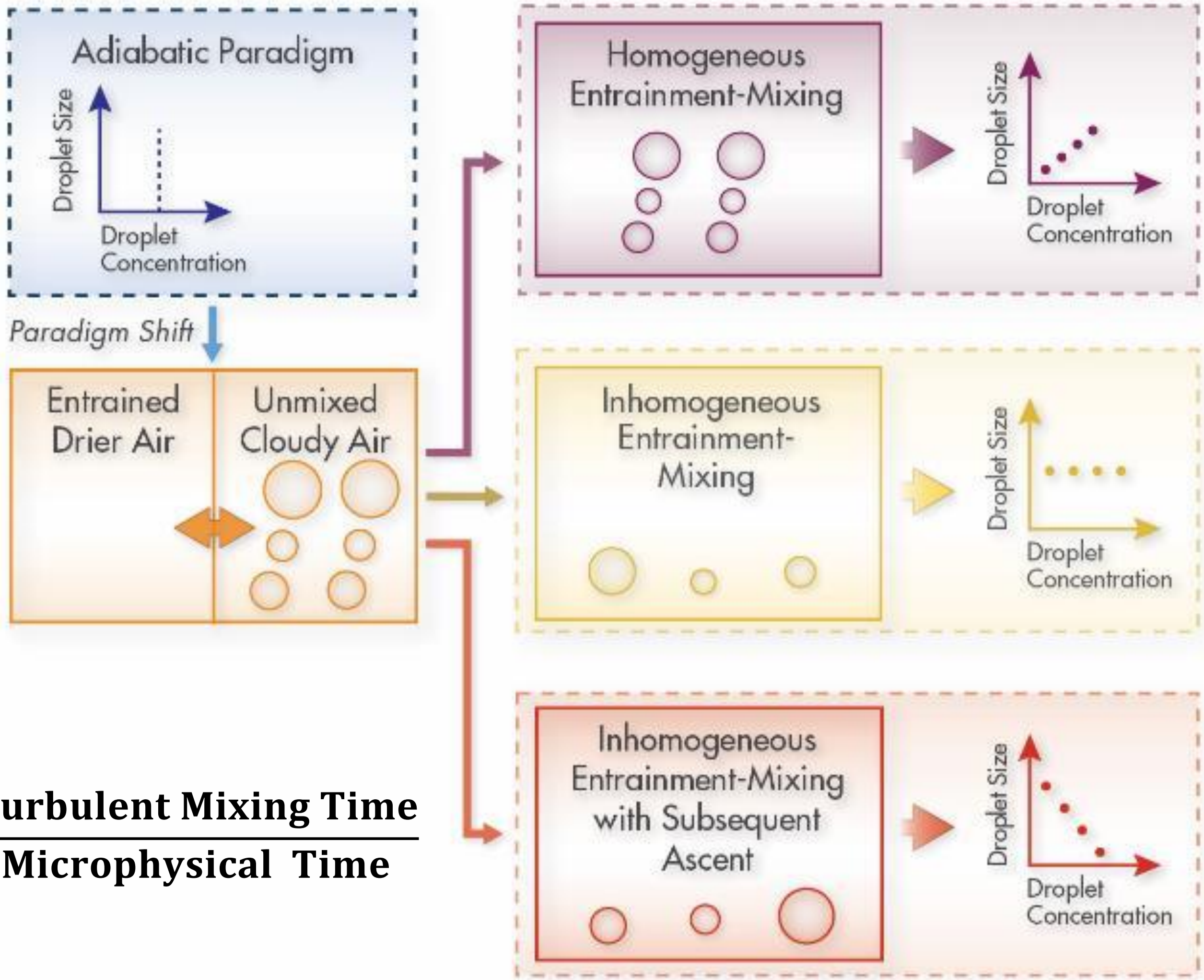
The proposed research is built on past accomplishments in related areas by BNL team members under DOE BER support.

Task 1a: Spectral shape affects cloud radiative and precipitation significantly.





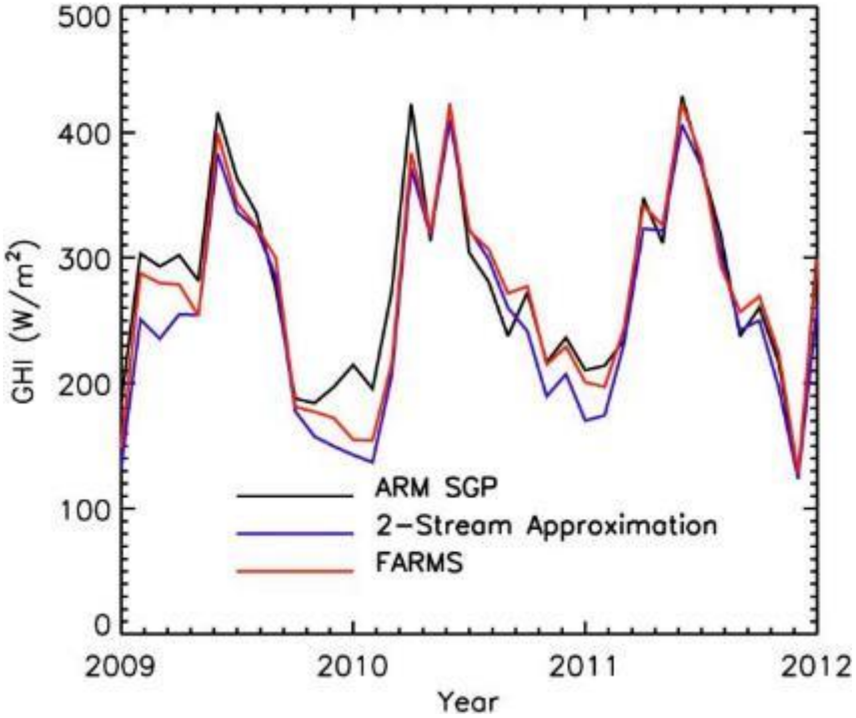
Task 1b: Entrainment-mixing processes alter cloud properties significantly



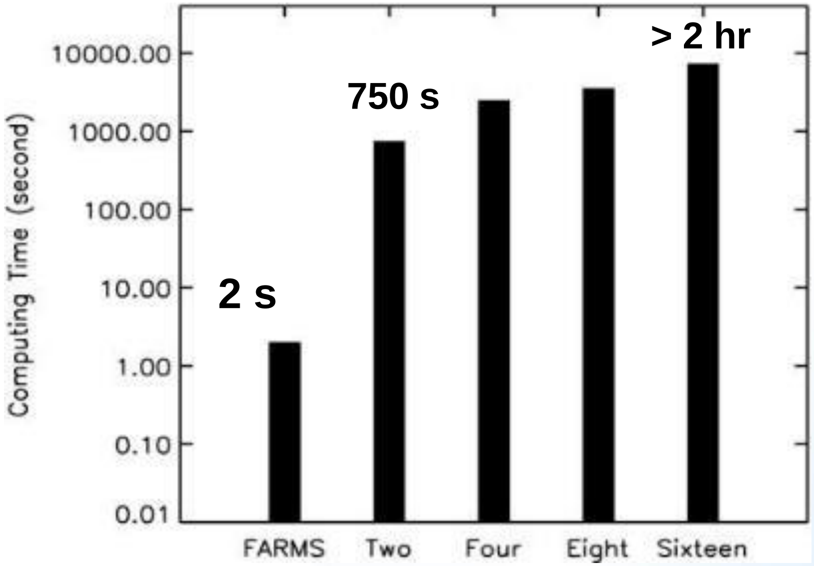
$$D_A = \frac{\text{Turbulent Mixing Time}}{\text{Microphysical Time}}$$

Task 2a: Accurate & Fast FARMS

Comparable or better accuracy



Order of magnitude faster



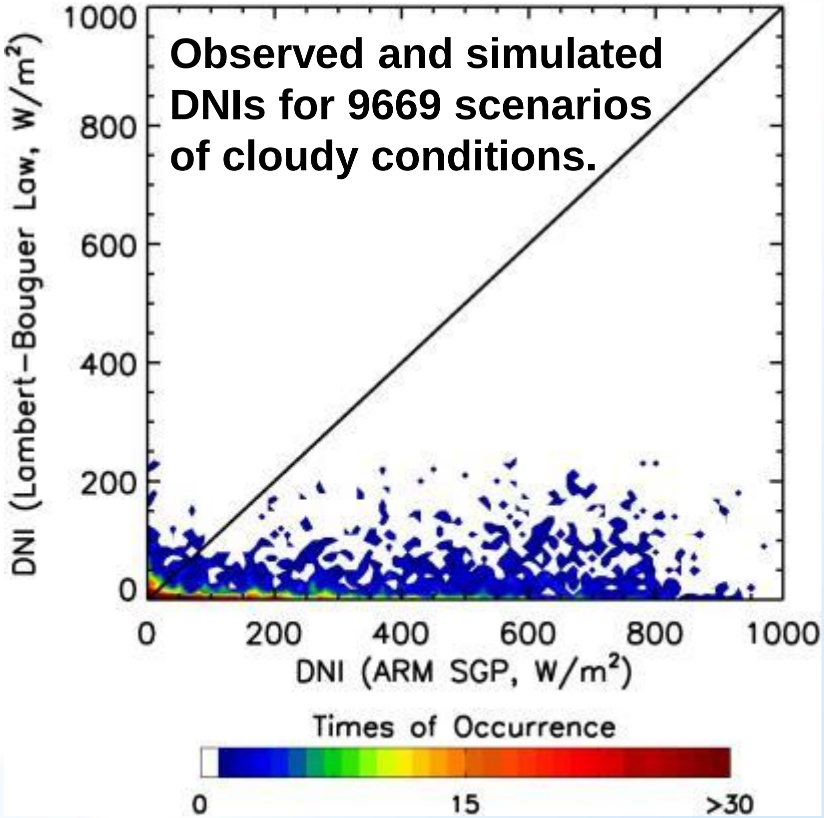
Computation of solar radiation for 9669 scenarios of cloudy sky conditions over ARM SGP.

FARMS represents Fast All-sky Radiation Model for Solar applications, is used in the current WRF-Solar, and developed by our NREL team members. But >>

Task 2b: Improve FARMS

❖Challenge:

- **Large DNI uncertainty in current FARMS in WRF-Solar**
- **Model-observation mismatch of circumsolar region**
- **Conventional regression functions not universally applicable**



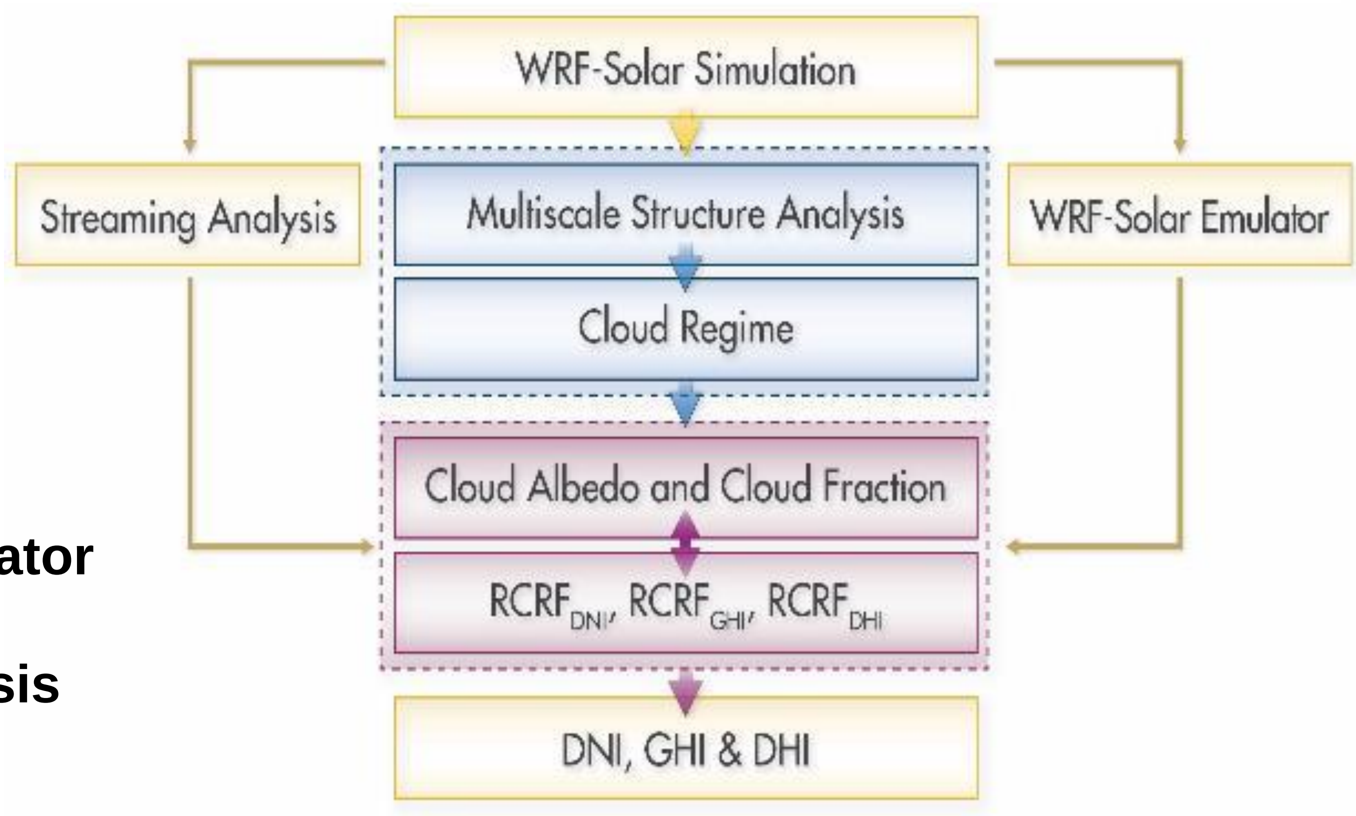
❖ Solution:

- **Upgrade FARMS to address the mismatch problem according to physics**

Similar problem exists for diffuse radiation as well, both of which are universal, not just limited to FARMS!

Task 3: Innovative Analysis Package

- Cloud regime
- Cloud structure
- Cloud-radiation relationship
- WRF-Solar Emulator
- Streaming analysis



We will perform the analysis for both simulation and observational data to facilitate model evaluation and shorter-range forecasting.

Task 4a: Model Evaluation

❖ **WRF-Solar Testbed Suite**

Adapt BNL Fast Physics Testbed:

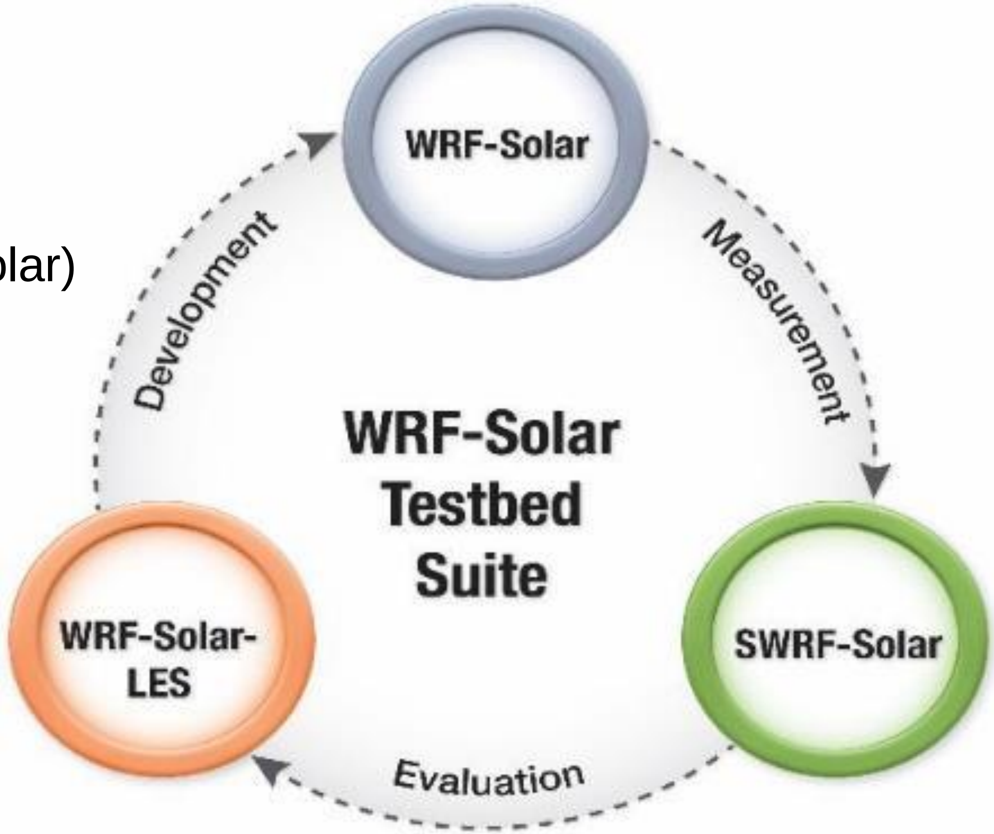
- WRF-Solar
- WRF-Solar LES
- Single Column WRF-Solar (SWRF-Solar)

❖ **Evaluation Metrics Suite**

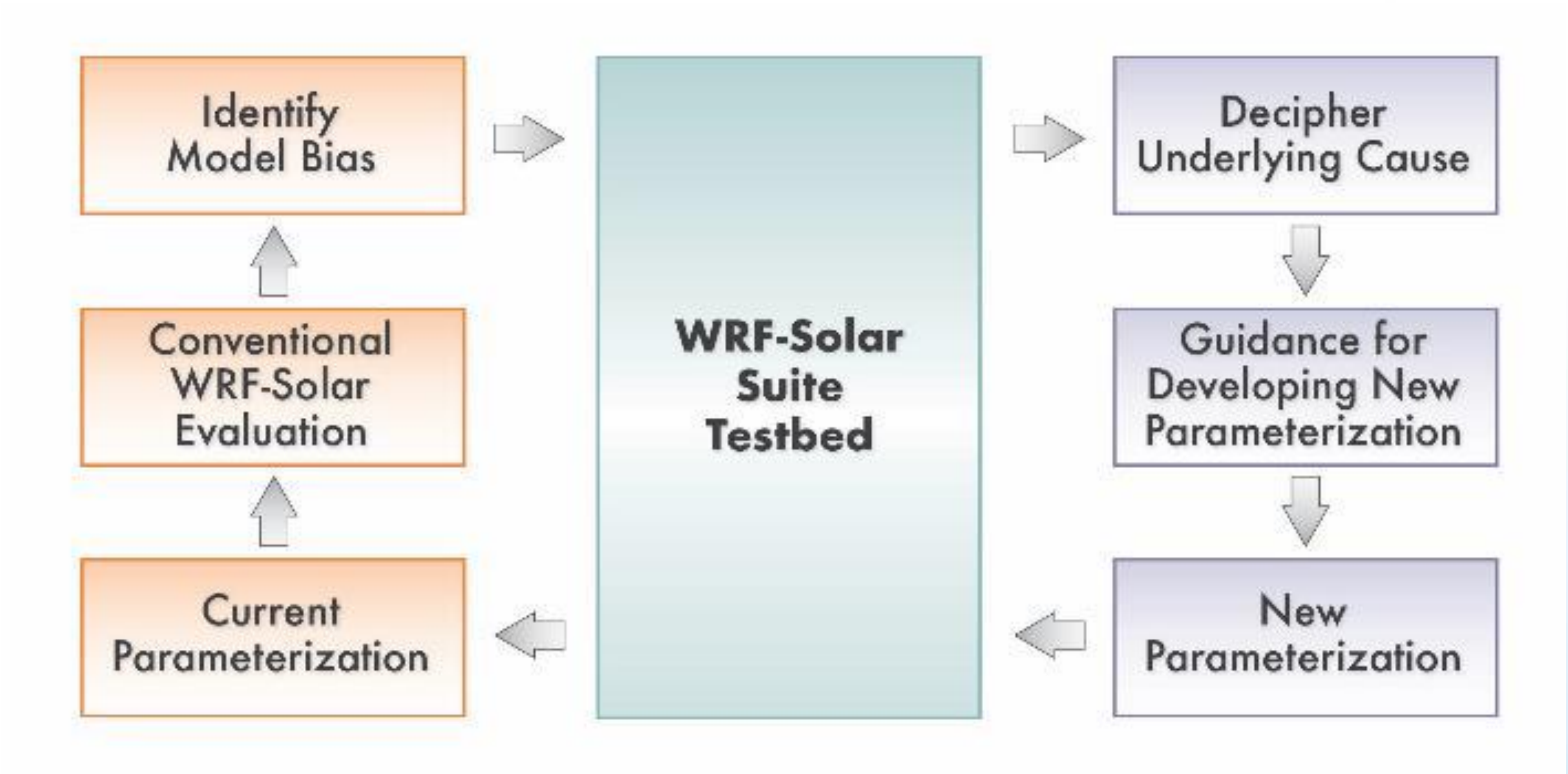
- Conventional metrics (e.g., MAE, RMSE, MAPE)
- Taylor plot
- Relative Euclidean distance
- New analysis package

❖ **TA-1 Test Framework**

❖ **State of Art Measurements (Task 5)**



Task 4b: Iterative Model Evaluation-Development Process



In addition to quantifying the model-observation differences, our evaluation framework is designed to detect underlying physical causes to guide further model development.

Task 5: Data Integration

Collect, analyze, and integrate the data from the following three existing programs/projects and tailor them for this project, especially for model evaluation:
DOE ARM SGP Site

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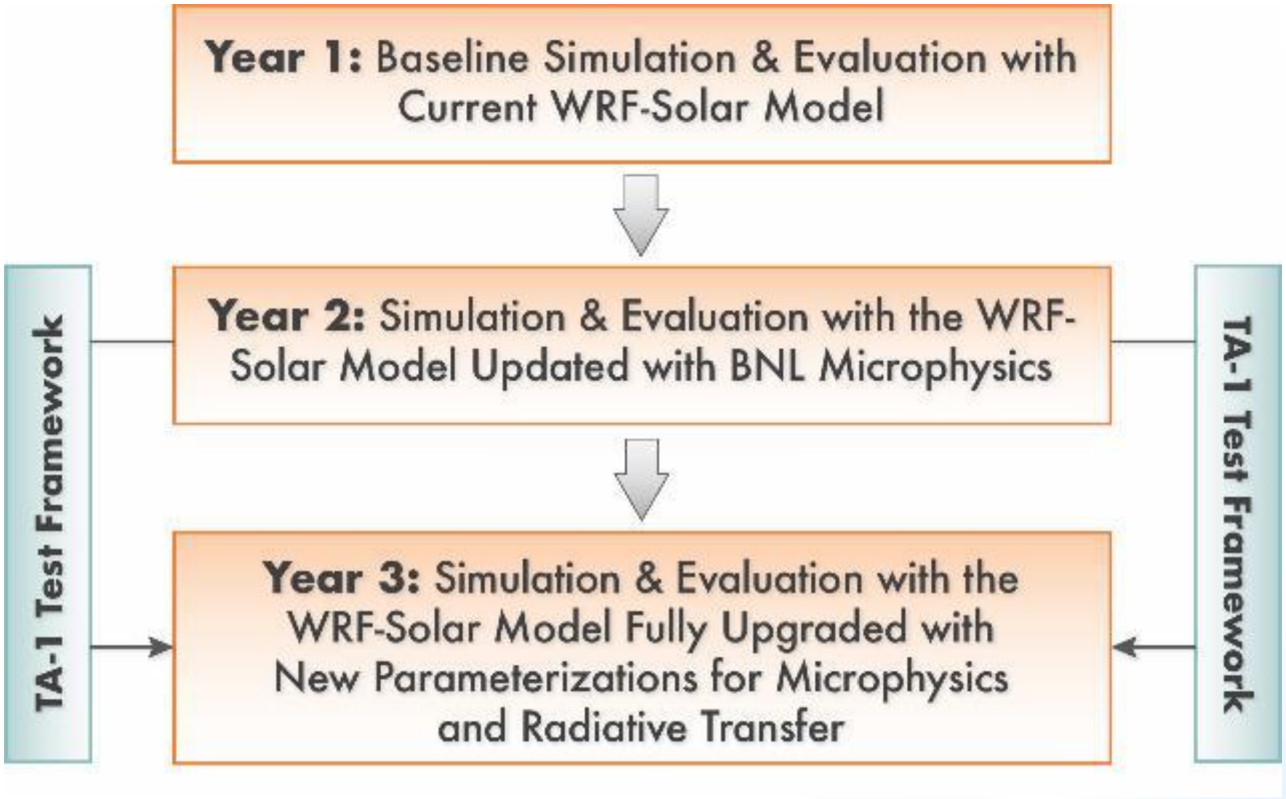
- **DOE ARM SGP Site**
- **NYS Mesonet**
- **NREL NSRDB**

The three programs maintain state of the art radiation and cloud measurements essential to the success of the project in particular, & Topic Area 2 in general.

Modeling Work Flow



We will carefully and timely monitor the progress of each task, communicate with program managers, and make necessary adjustments accordingly.

Main Outcomes and Impacts

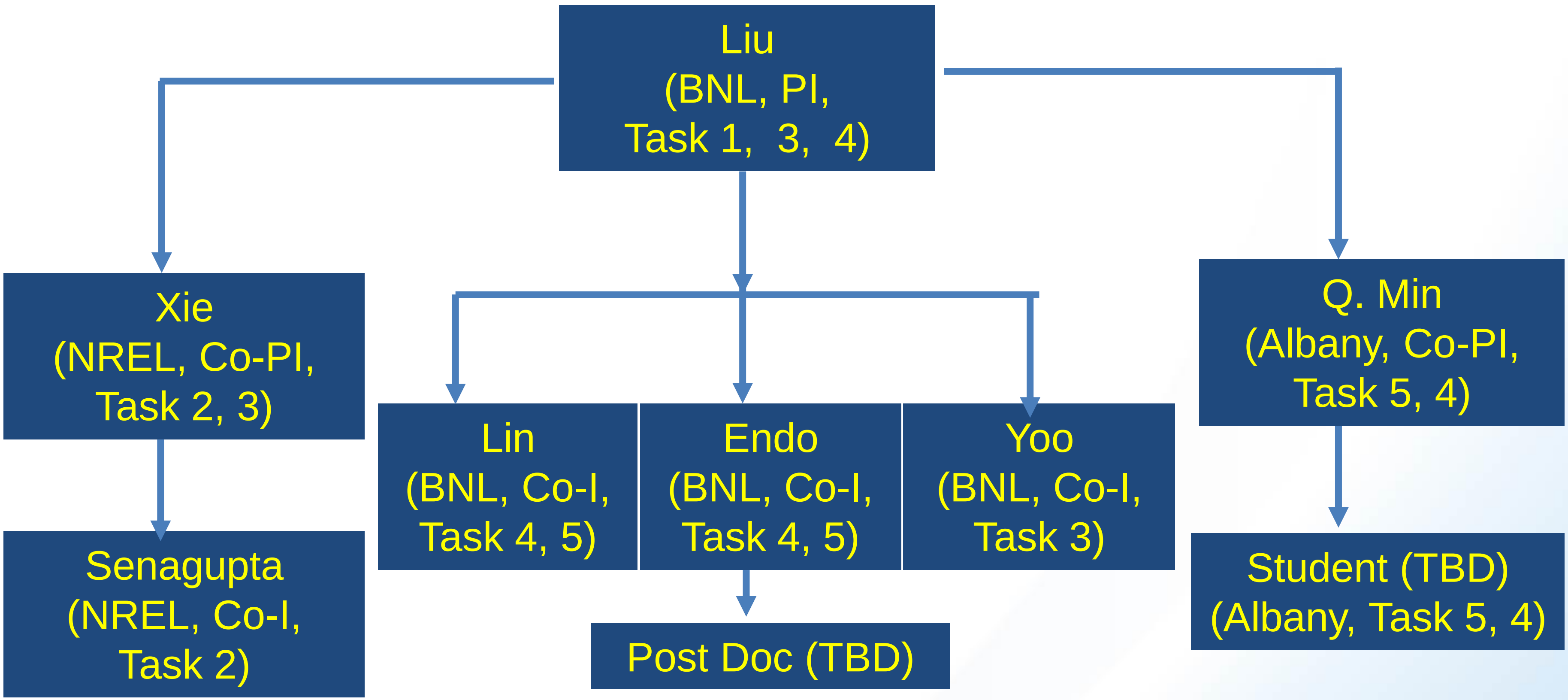
❖ Main Outcomes

- Upgraded WRF-Solar Model that improves solar irradiance forecast on the horizon of day-ahead (e.g., 24-48 hours) and intra-day (e.g., 1-6 hours)
- Innovative analysis package
- Improvement of ~15% DNI and 10 to 80% GHI
- Unique DNI treatment & gap-filling microphysics developments

❖ Expected Impacts

- Topic Area 2: Improvement in solar irradiance forecasting
- SETO program: Improve solar power forecasting and overall utility integration
- Broader impact: Improved parameterizations of radiation & microphysics, and innovative analysis package will affect other DOE programs and beyond.
- Even broader impact expected after the updated WRF-Solar released to public

Project Management



- Despite different foci, members will work closely with one another.
- Team coordination via biweekly conference calls, emails, and/or visits as needed.
- Regular communications with program managers
- Backup for Liu: Xie and Lin will take the overall and BNL leadership, respectively
- Outreach: Active coordination with awardees in TA1 and TA3

Backup Slides

Project Plan

- Baseline simulations with Current WRF-Solar
- Implement/test other two moment schemes
- Analyze cloud-radiation relationships
- Modify BNL testbed
- Examine/select ARM cases

Year 1

- Incorporate/test BNL parameterizations
- Develop DNI transmittance
- Streaming analysis
- Evaluate model results
- Continue ARM cases and extend to NYS Mesonet

Year 2

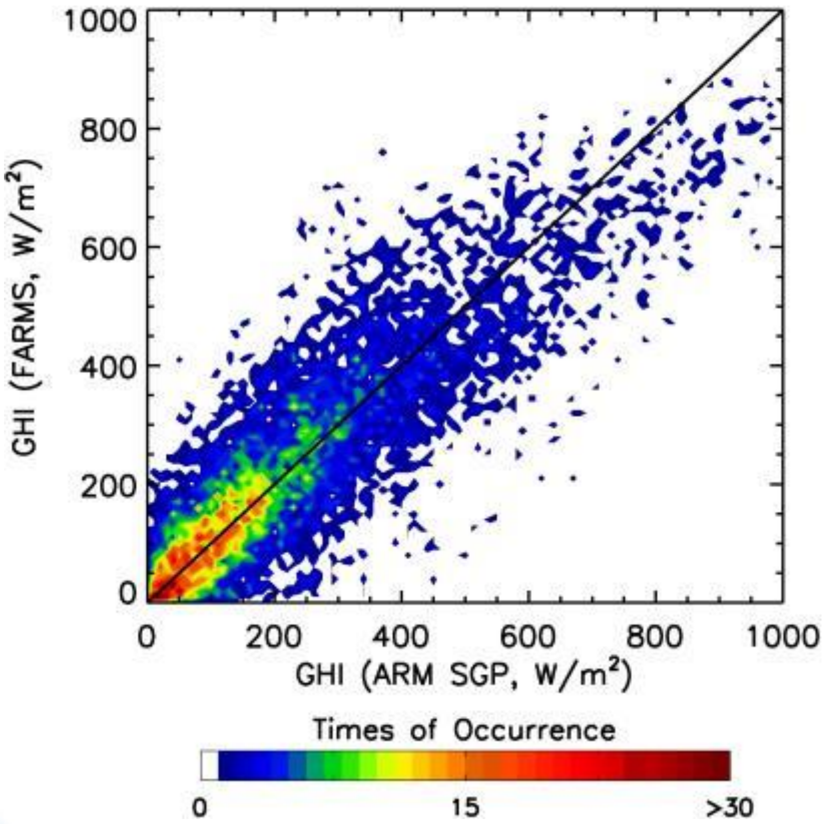
- Develop/test new parameterizations
- Upgrade/test FARMS
- Develop emulators
- Evaluate new simulations
- Integrate ARM/NYS Mesonet & extend to NSRDB as needed

Year 3

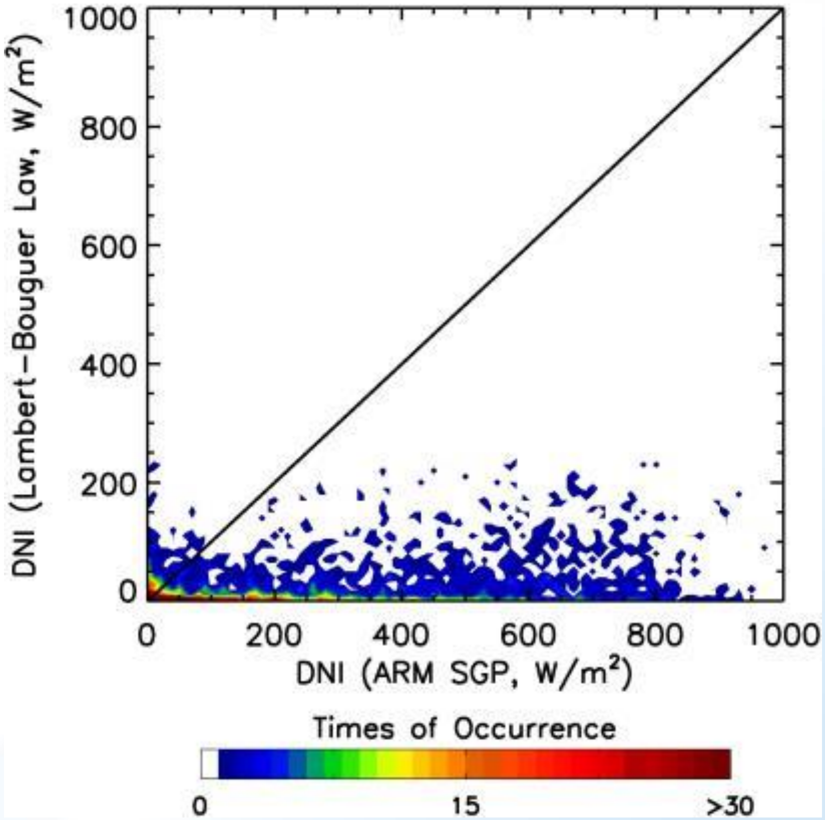
We will carefully and timely monitor the progress of each task, communicate with program managers, and make necessary adjustments accordingly.

Task 2: Improve Radiation Transfer (FARMS)

Large DNI Uncertainty in Current FARMS



Comparison of GHIs for 9669 scenarios of cloudy conditions.



Comparison of DNIs for 9669 scenarios of cloudy conditions.

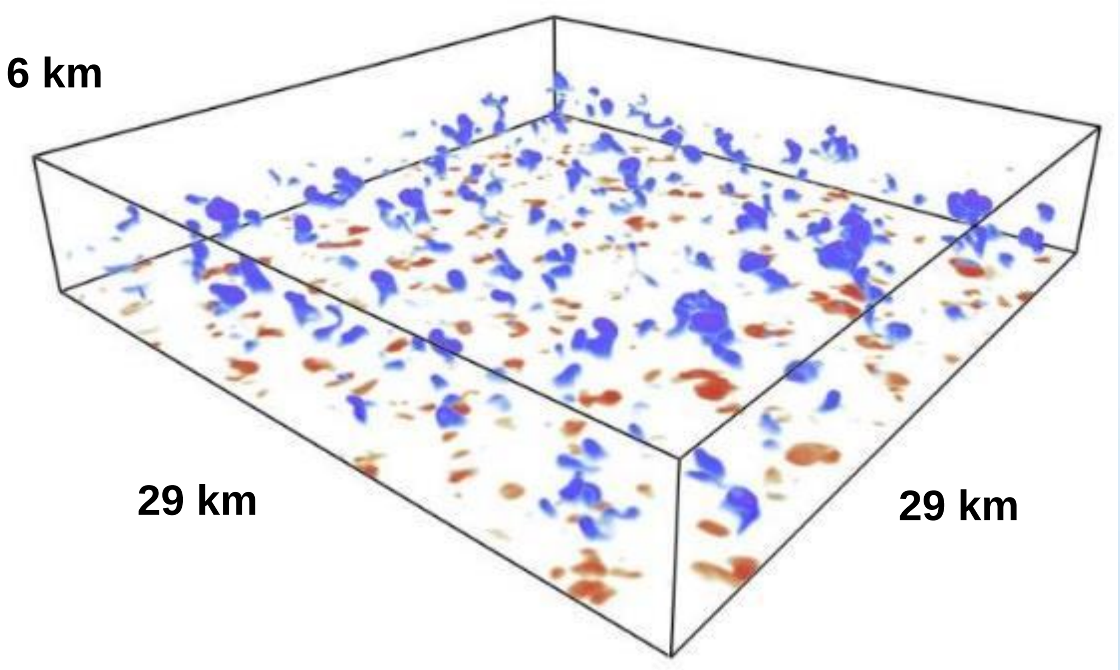
Improving the DNI simulation in FARMS

- **Relevant research focuses on reducing the overall uncertainties from the circumsolar region by developing regression functions.**
- **NREL's recent work showed that solar radiation representing certain spatial orientations can be precisely quantified by numerical models.**
- **Solar radiances will be integrated to compute DNI and parameterized as functions of atmospheric properties that can be forecasted by NWP models.**

Preliminary Results Support Proposed Research (1): BNL LES Simulations

- **Evident effects of cloud on solar radiation**
- **Ramp events in connection to cloud structure and edges**
- **Support the proposed improvements**
- **Details remain to explore with WRF-Solar**

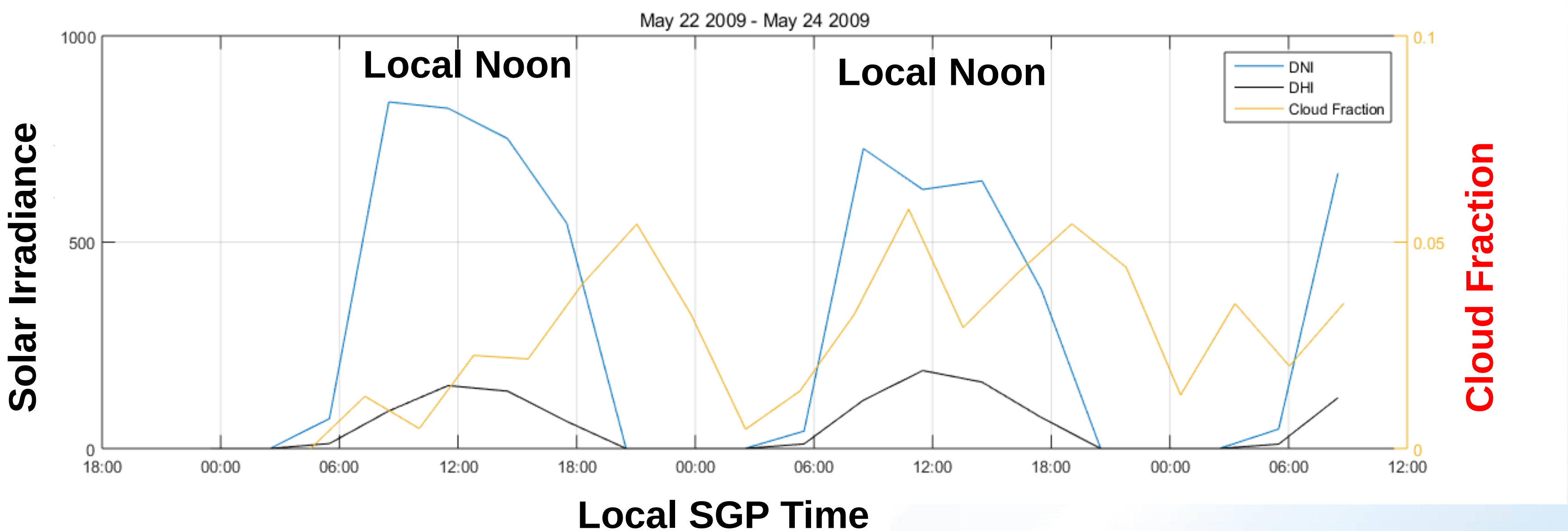
Spatial Distribution of Cumulus Clouds and Surface Solar Radiation over ARM SGP



Blue: 3D Cloud Water Content
Red: Surface SW_{down} "Void"

Preliminary Results Support Proposed Research (2): WRF-Solar Simulations

Temporal Evolution of Cloud Fraction and Solar Irradiance (DNI and DHI) Simulated by Current WRF-Solar



- **Notable but complex role of clouds in determining DNI and DHI**
- **Three-hour average smooths out large fluctuations (ramp events)**
- **More to be learned by comparison with measurements & different parameterizations, etc.**

Poorest performance in direct and diffuse radiation is likely more cloud-related.

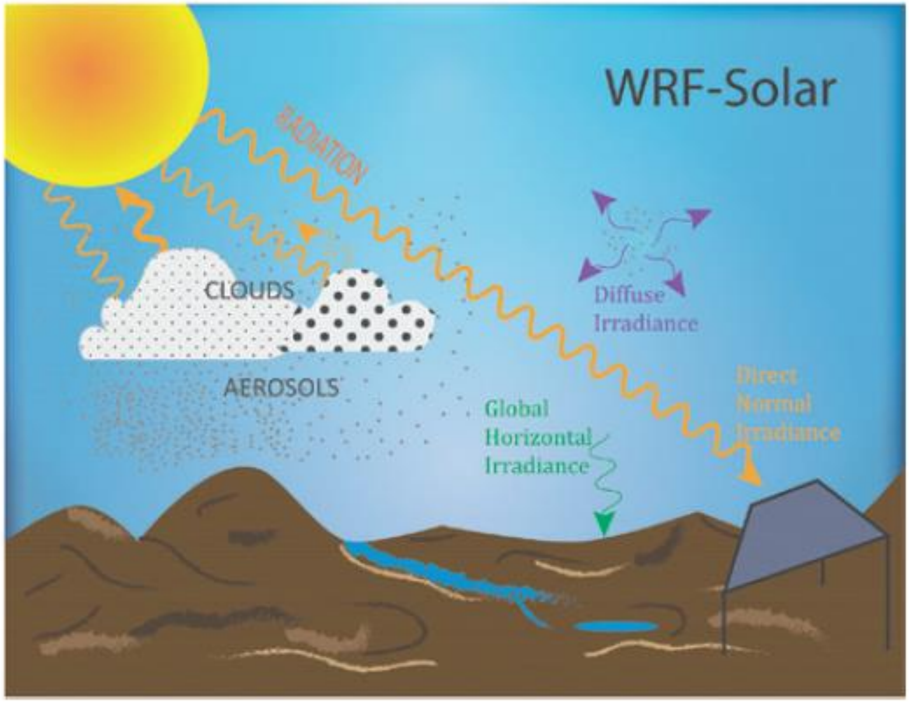


FIG. 1. Sketch representing the physical processes that WRF-Solar improves. The different components of the radiation are indicated.

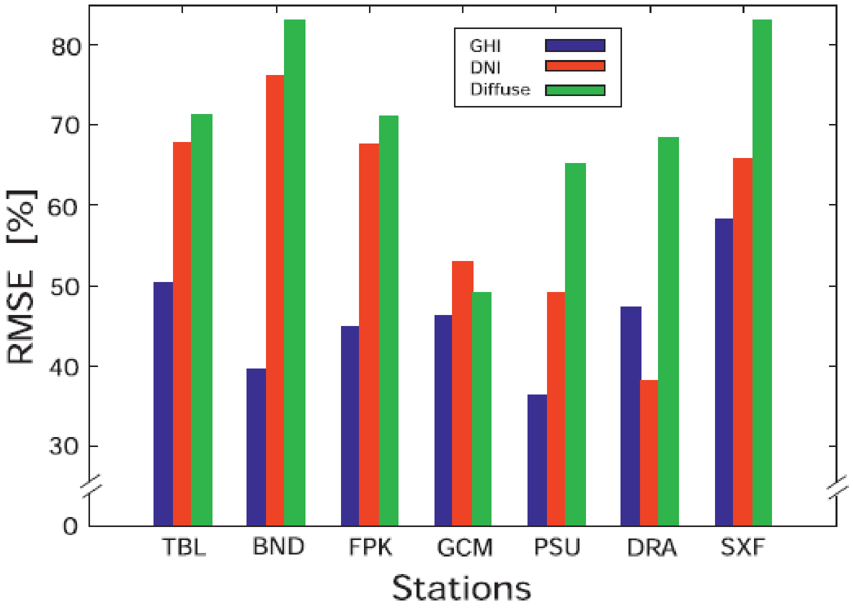
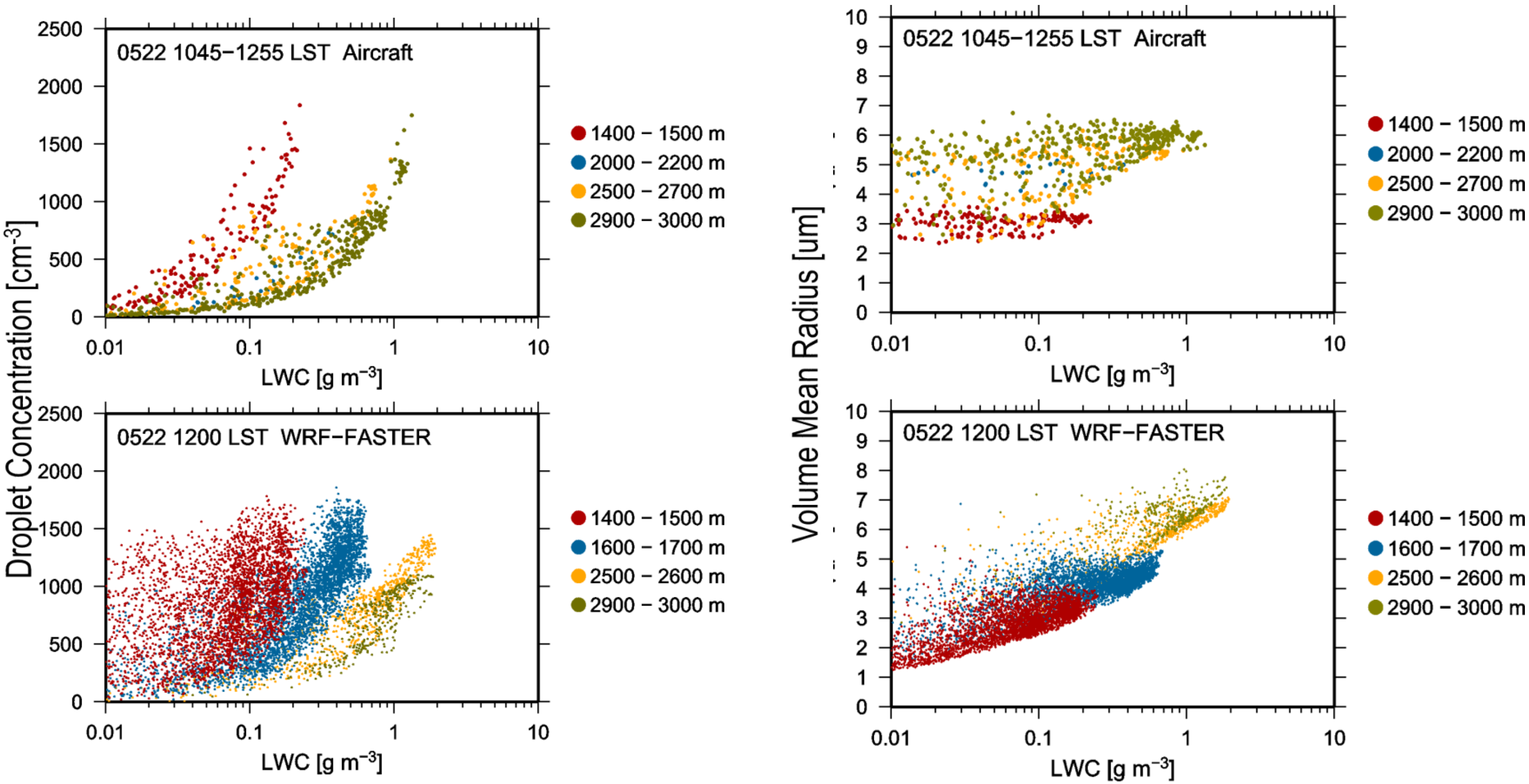


FIG. 10. Improvements introduced by WRF-Solar (experiment GEOS5-AOD) in the estimations of the clear-sky surface irradiance components at the SURFRAD sites. The standard WRF simulation is used as a baseline for comparison.

(Jimenez et al., BAMS, 2016)

LES vs. Observation: Microphysics



LES captures the general trend of co-variation of droplet concentration and LWC; *but the LES mixing type tend to be more homogeneous than observations (left panel).*

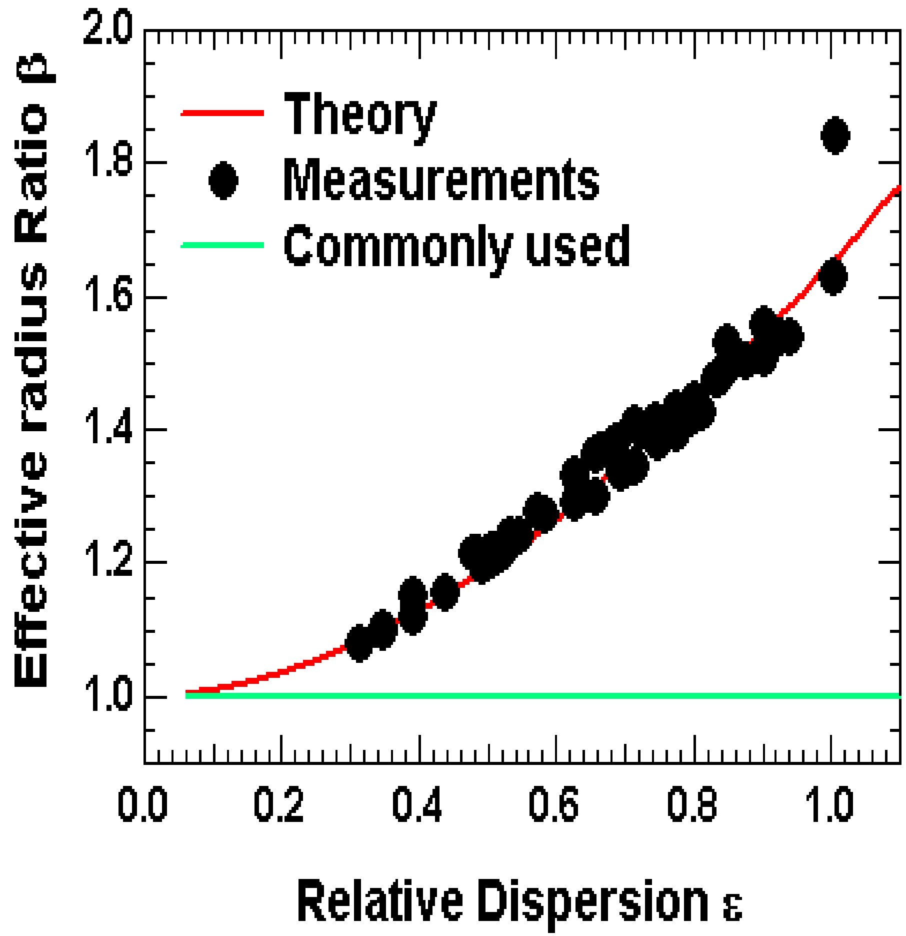
β in terms of Relative Dispersion

$$r_e = \beta\left(\frac{3}{4\pi\rho_w}\right)^{1/3}\left(\frac{L}{N}\right)^{1/3}$$

$$\beta = \frac{\left(1+2\varepsilon^2\right)^{2/3}}{\left(1+\varepsilon^2\right)^{1/3}}$$

$$\varepsilon = \frac{\sigma}{\bar{r}}$$

= Standard Deviation/Mean Radius

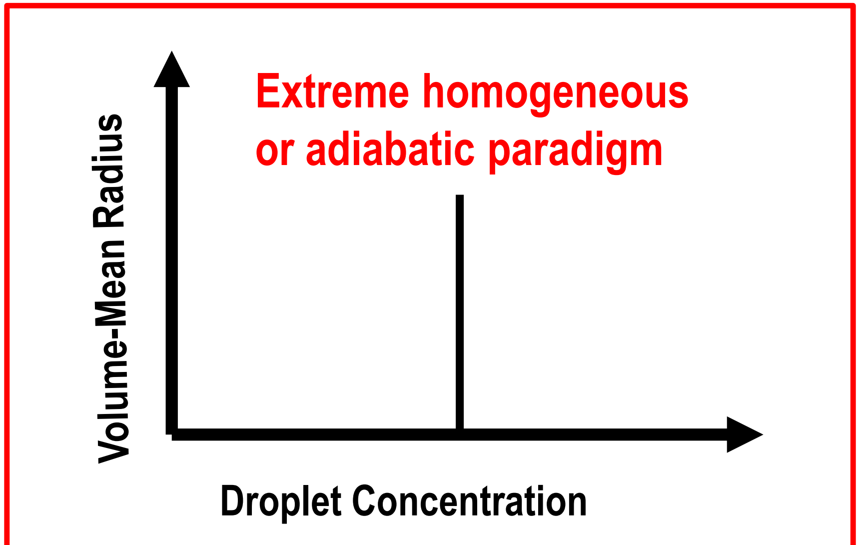


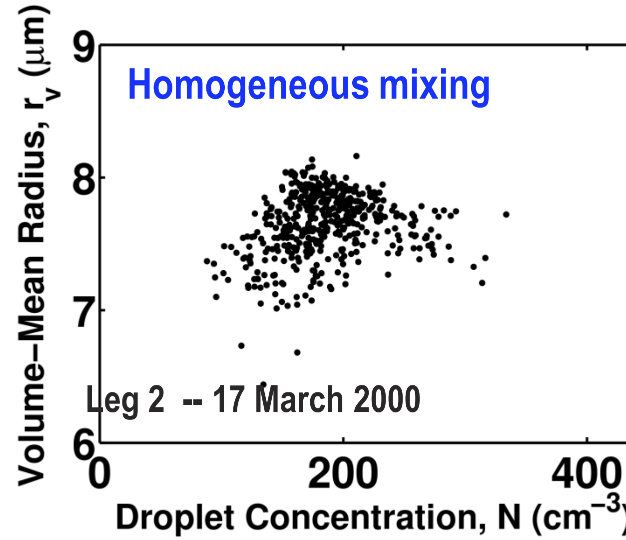
$$r_e = \frac{\int r^3 n(r)dr}{\int r^2 n(r)dr}$$

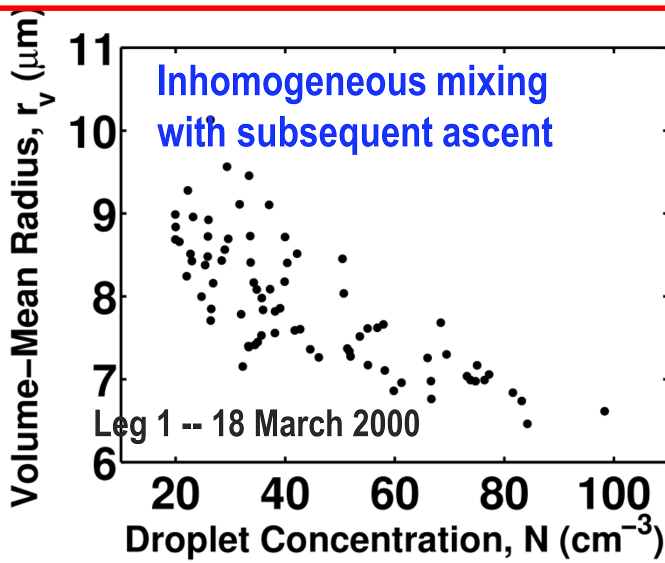
Effective radius ratio β is an increasing function of relative dispersion.

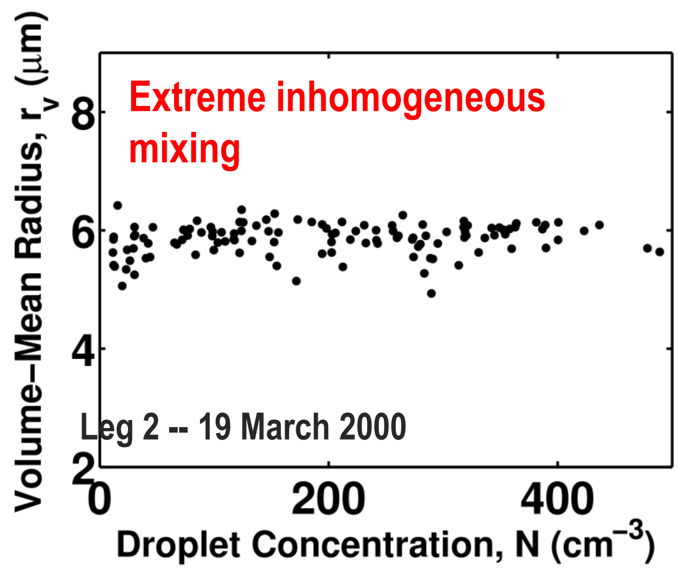
Why Do We Care and Why Paradigm Shift?

March 2000 Cloud IOP at SGP









(Lu et al 2011: J. Geophys. Res, 116, D2027)

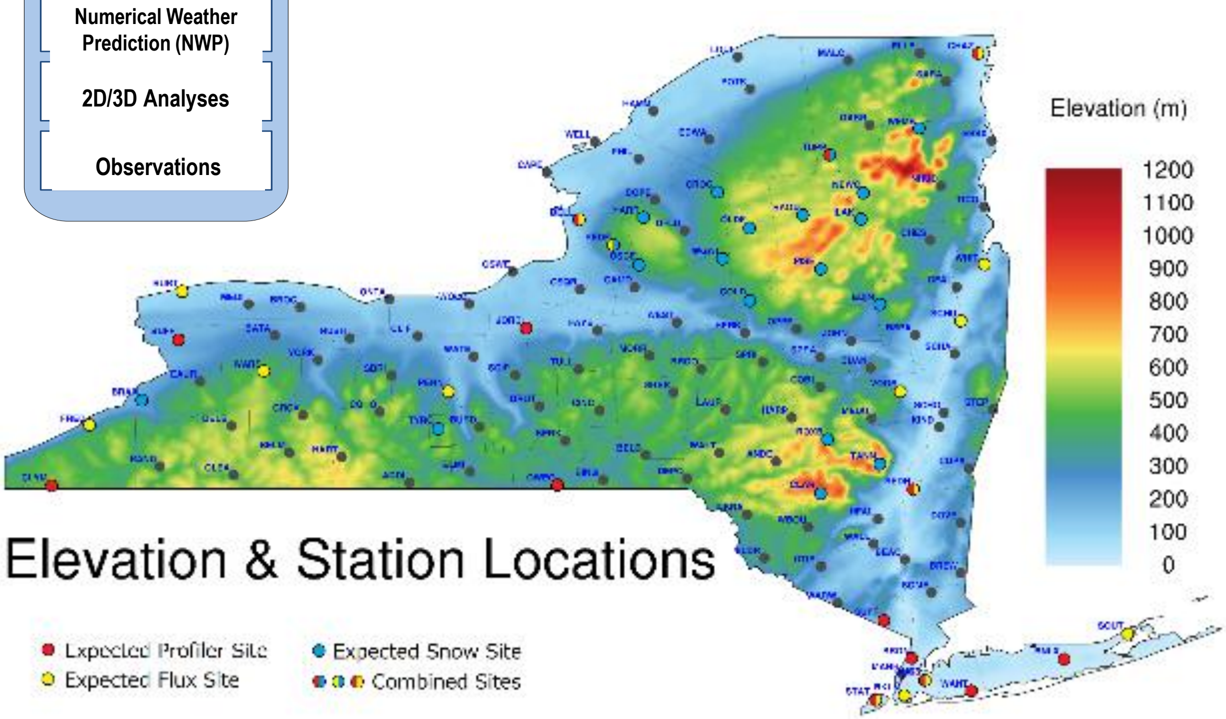
NYS Mesonet

The NYS Early Warning Weather Detection System: NYS Mesonet

- ✓ Monitoring and assimilation
- ✓ Large-scale forcing and forecasting
- ✓ Evaluation and validation

The Mesonet System

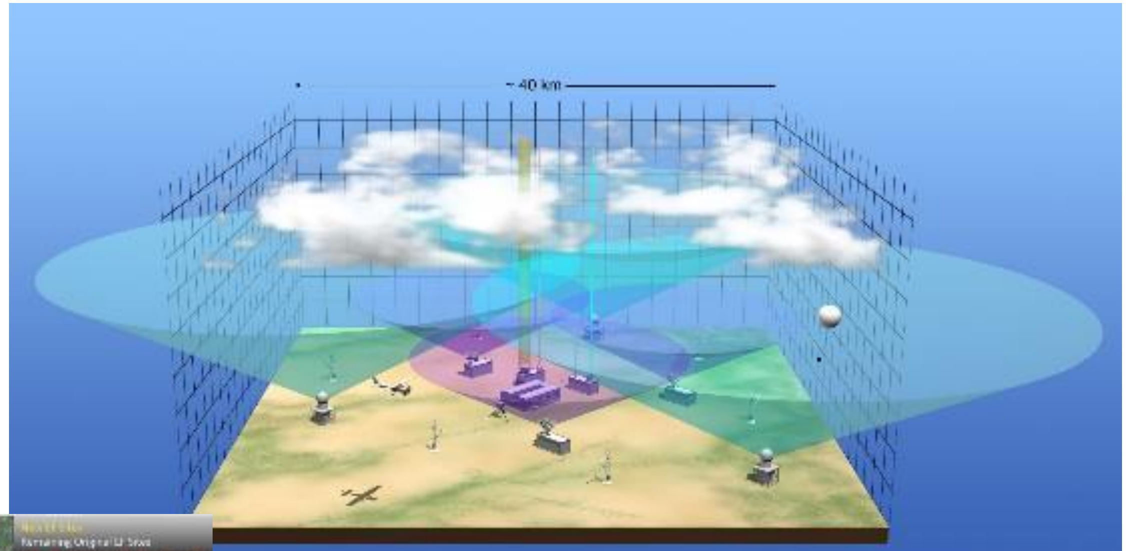
- Numerical Weather Prediction (NWP)
- 2D/3D Analyses
- Observations

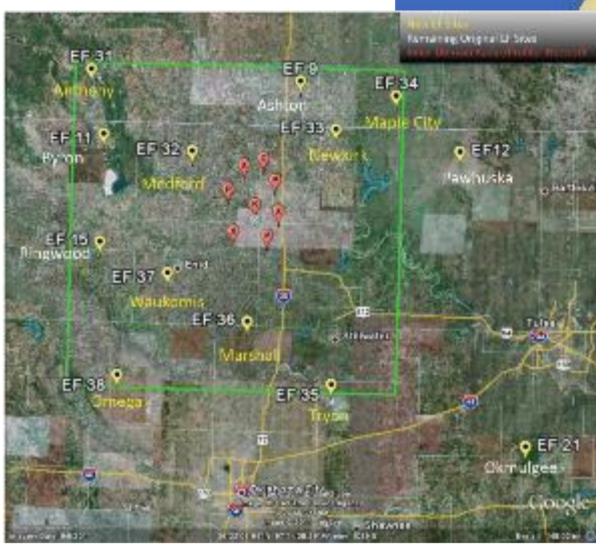


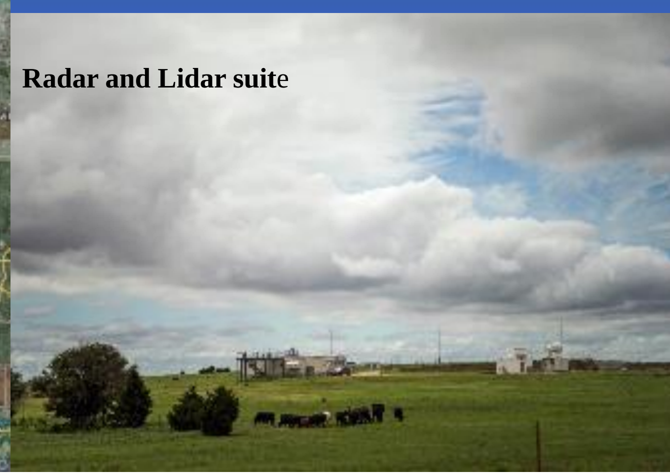
Sky Imager-Radiometer (eSIR)

Part of the analytic package are used by DOE ARM as operational algorithms

- Solar Radiation:
  - ✓ Accurate spectral and angular radiation
  - ✓ diffuse/direct
  - ✓ Synthesis: Solar Spectrum & PAR [Min 2005]
- Monitoring aerosols:
  - ✓ Aerosol optical depth [Min et al, 2004a]
  - ✓ Angstrom coefficients [Min et al, 2004a]
  - ✓ Single scattering albedo (SSA) [Yin et al., 2013]
  - ✓ Aerosol size information
  - ✓ PM2.5 [Li et al, 2015]
- Monitoring clouds:
  - ✓ Optical depth (5 and up) and effective radius from diffuse [Min and Harrison, 1996; Min et al, 2003]
  - ✓ Optical depths of aerosols and thin clouds (0 ~ 7) from direct beam [Min et al, 2004a; Min et al, 2004b]
  - ✓ Cloud phase for thin clouds [Wang and Min 2008]
  - ✓ Cloud fraction [Yang et al, 2014, 2015, 2017]
  - ✓ Cloud size (LWP)
  - ✓ Cloud motion & short term forecast [Du and Min, 2017, in preparation]

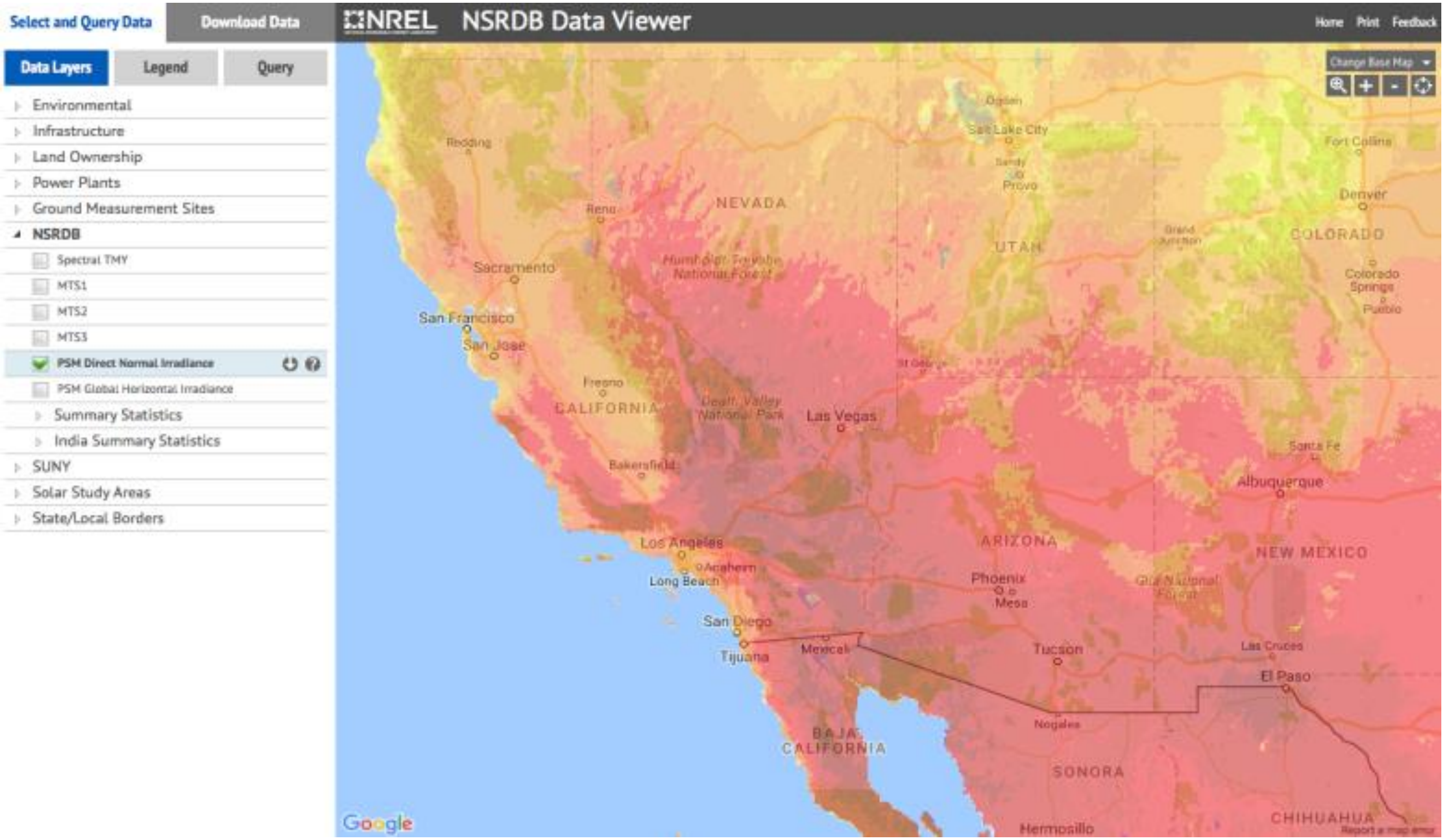






Aerosol-cloud-radiation:

Multi-Platform
Active and Passive
Observation Suites



The NSRDB is a serially complete collection of meteorological and solar irradiance data sets for the United States and a growing list of international locations.

Phase I: Hindcast

- Intra-day and inter-day
- Test model configuration, spin-up effect, baseline, new microphysics and radiation treatments
- IC: HRRR analysis
- LBC:
  intra-day: HRRR analysis
  inter-day: HRRR only, or
  RAP analysis after 18 hours, or
  NAM CONUS analysis 18+ hours
- Test hydrometeor initialization using HRRR analysis (not commonly used in WRF modeling, reduce spinup)
- Additional diabatic initialization (saturation where cloud lidar/radar profiling available (e.g., ARM))
- Update cycle: IC 1-3 hourly (intra-day), 6hrs (inter-day)

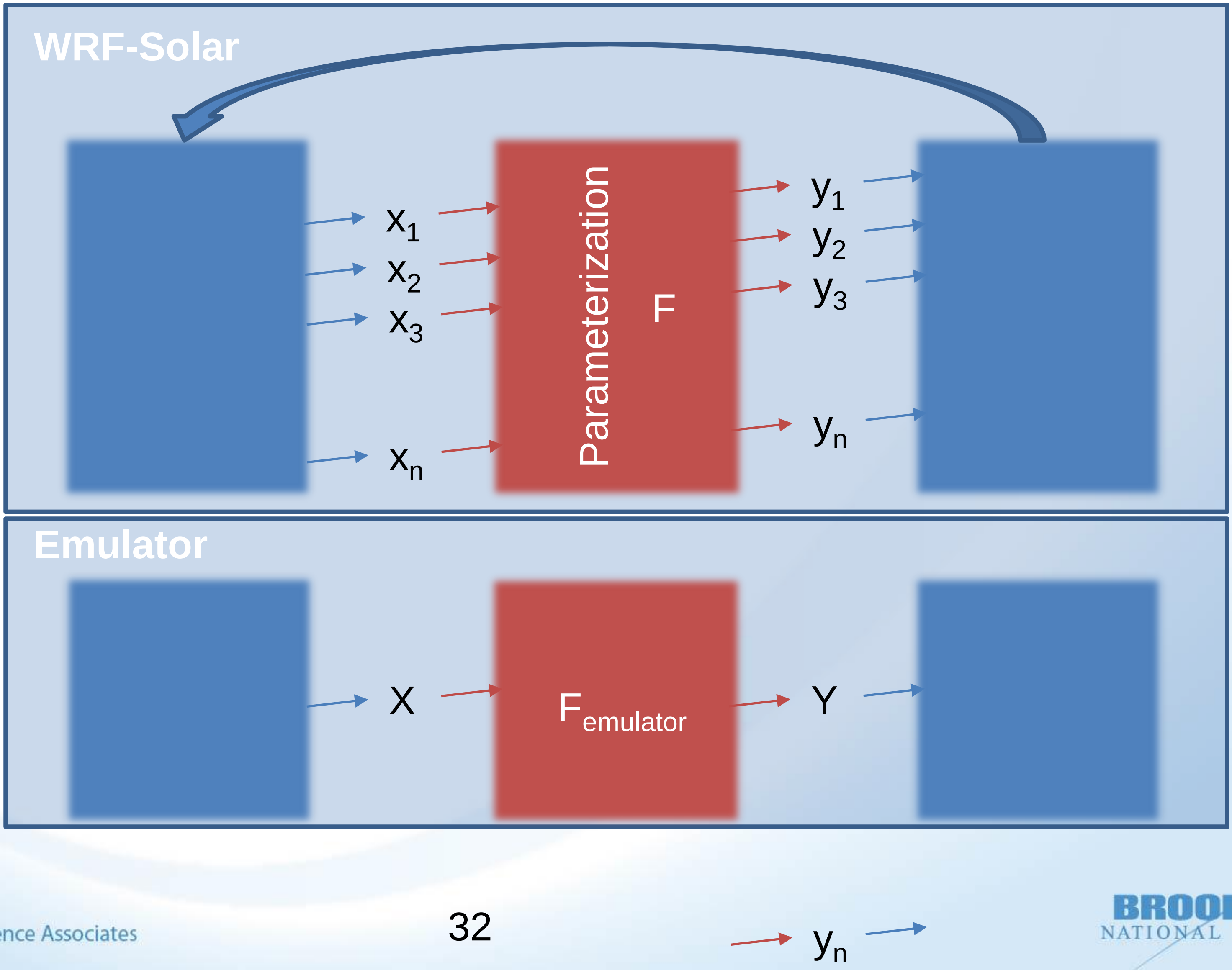
Phase II: Pilot Forecast

- Same as phase I in general
- Forecast and validation
- IC: historical HRRR analysis
- LBC:
  Intra-day: HRRR forecast (<= 18 hours)
  Inter-day: HRRR + NAM CONUS forecast
  (may also test other forecast, e.g., SREF mean)
- Same update cycle as Phase I

Phase III: Realtime Forecast

- Same as phase II except for real time
- Design workflow to automatically synchronize with HRRR analysis for realtime forecast

Parameterization of physics are mapping.



Gaussian Process (GP) Emulator

GP Emulator estimate interpolates data

GP Emulator uncertainty grows between data points

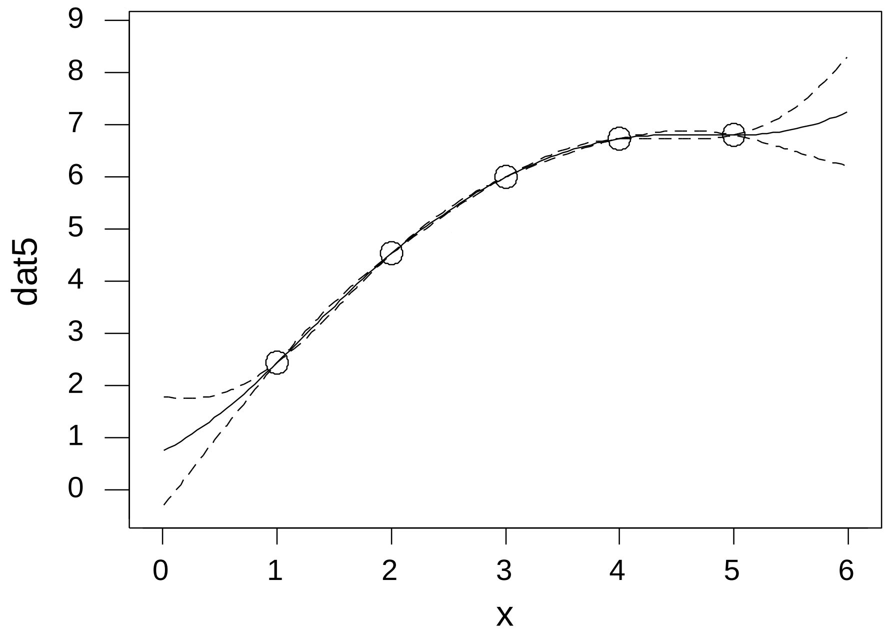
Adding another point changes estimate and reduces uncertainty

F(.) ~ GP(m(.), c(.,.))

m(.) is the mean function

c(.,.) is the covariance function

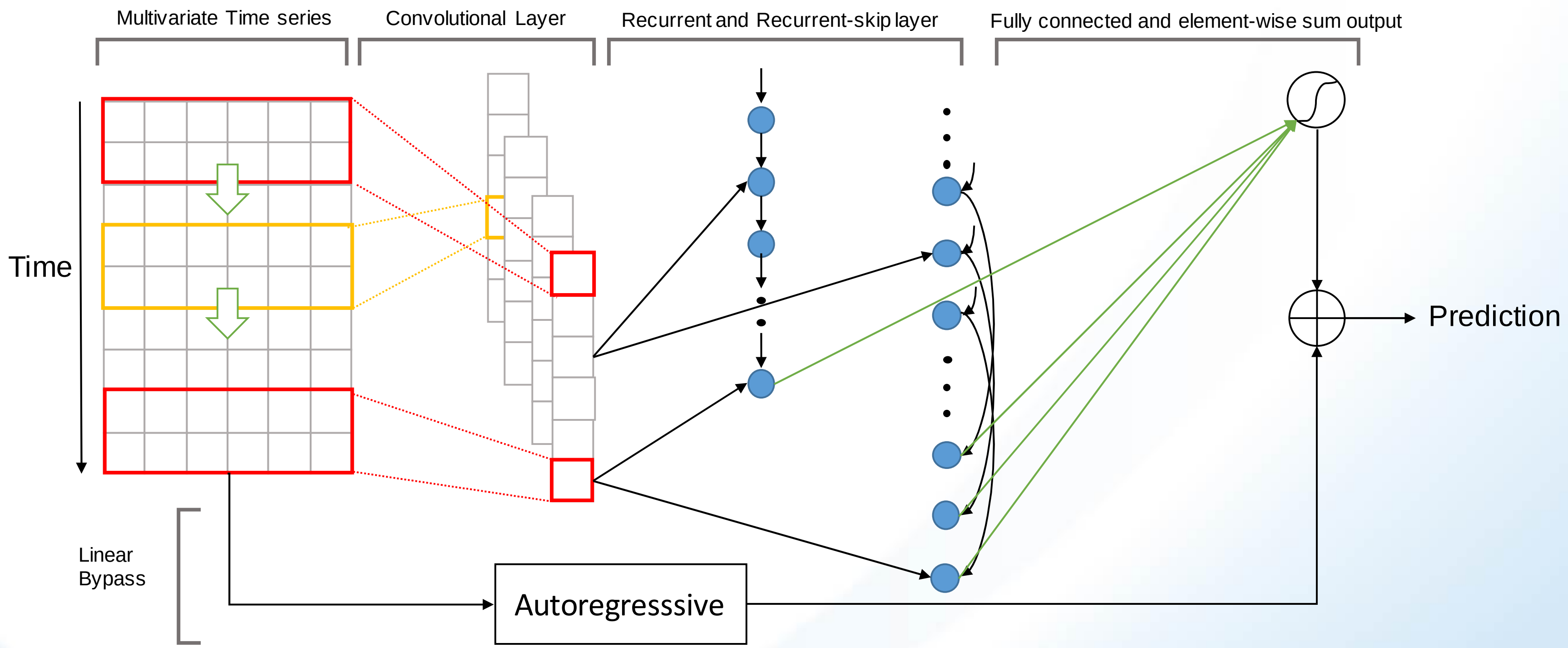
F(x) has a normal distribution with mean m(x) and variance c(x,x)



Dynamic Emulator

Many simulators produce time series output by iterating
Output y_t is function of state vector s_t at time t
Exogenous forcing inputs u_t, fixed inputs (parameters) p
Single time-step simulator F*
$s_{t+1} = F^*(s_t , u_{t+1} , p)$
Emulate F*
Correlation structure in time faithfully modelled
Need to emulate accurately
Not much happening in single time step but need to capture fine detail
Iteration of emulator not straightforward!
State vector may be very high-dimensional

Deep Learning based Emulator



Why Us (1): Unique Combination of Expertise & Experience

-- NREL members (Y. Xie & M. Sengupta): Radiation

-- BNL members (Y. Liu, W. Lin, S. Endo, S. Yoo): Cloud theory, modeling, machine-learning

-- UAlbany (Q. Min): Radiation, measurements

-- Track record of prior and on-going collaboration

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2014JD021705

Special Section:
Fast Physics in Climate Models: Parameterization, Evaluation, and Observation

Retrievals of cloud fraction and cloud albedo from surface-based shortwave radiation measurements: A comparison of 16 year measurements

Yu Xie[1,2], Yangang Liu[1], Charles N. Long[3], and Qilong Min[4]

Coauthored by PI & Co-PIs

Why Us (2): Available Capabilities/Data Readily Adapted for This Project

- **BNL Fast Physics Testbed and Leadership in DOE BER Programs (e.g., ASR and ARM)**

- **NREL NSRDB**

- **Existing Links to DOE BER Programs, ASCR program, and NYS Mesonet**

- **Past accomplishments on Which the Project Is Built:**

-- FARMS in current WRF-Solar
-- Widely used BNL parameterizations
-- State-of-art instruments developed at U Albany