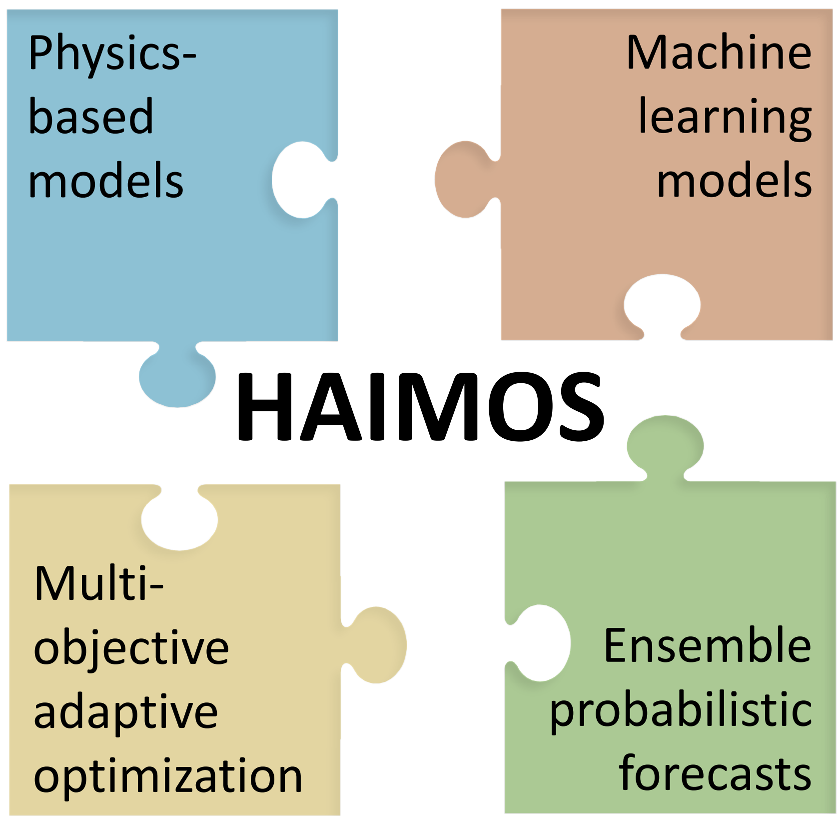
HAIMOS Ensemble Forecasts for Intra-day and Day-Ahead GHI, DNI and Ramps



HAIMOS Ensemble Forecasts for Intra-day and Day-Ahead GHI, DNI and Ramps

UC San Diego

Clean Power Research

Principal Investigator Prof. Carlos F. M. Coimbra, UC San Diego

Project Team Center for Energy Research/UCSD + Clean Power Research (CPR)

Requested EERE funds $ 1,316,203
Cost sharing amount $ 162,500

Summary

This project proposes a Hybrid Adaptive Input Model Objective Selection (HAIMOS) ensemble model to improve solar irradiance and cloud cover forecasts. Major HAIMOS components:

- Holistic optimization framework: all aspects of the model (data preprocessing, input selection, etc.) subject to an adaptive optimization to reduce bulk error metrics, predict ramp onset, produce accurate probabilistic forecasts for horizons ranging from 1 to 72 hours;
- Ingestion of new-generation cloud cover products (high-resolution rapid refresh satellite images, detailed atmosphere modeling using Large Eddy Simulation) to improve cloud optical depth forecast and irradiance forecasts in the 1 to 6 hours horizons.

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Impact

Simply put: Accurate irradiance probabilistic forecast reduce solar generation prediction error and enable wider use of forecasting tools by solar energy stakeholders.

Goals

Increase the state of the art forecast skill from their present values of 10 to 30%. Aim to achieve the 50% forecast skill level consistently for both GHI and DNI.

Key idea

HAIMOS blends state of the art machine learning methodologies with detailed physics-based models for cloud cover and cloud optical depth forecasts.

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Increase substantially the state of the art forecast skill from their present values of 10 to 30%.

Aim to achieve the 40-50% forecast skill level consistently for both GHI and DNI.

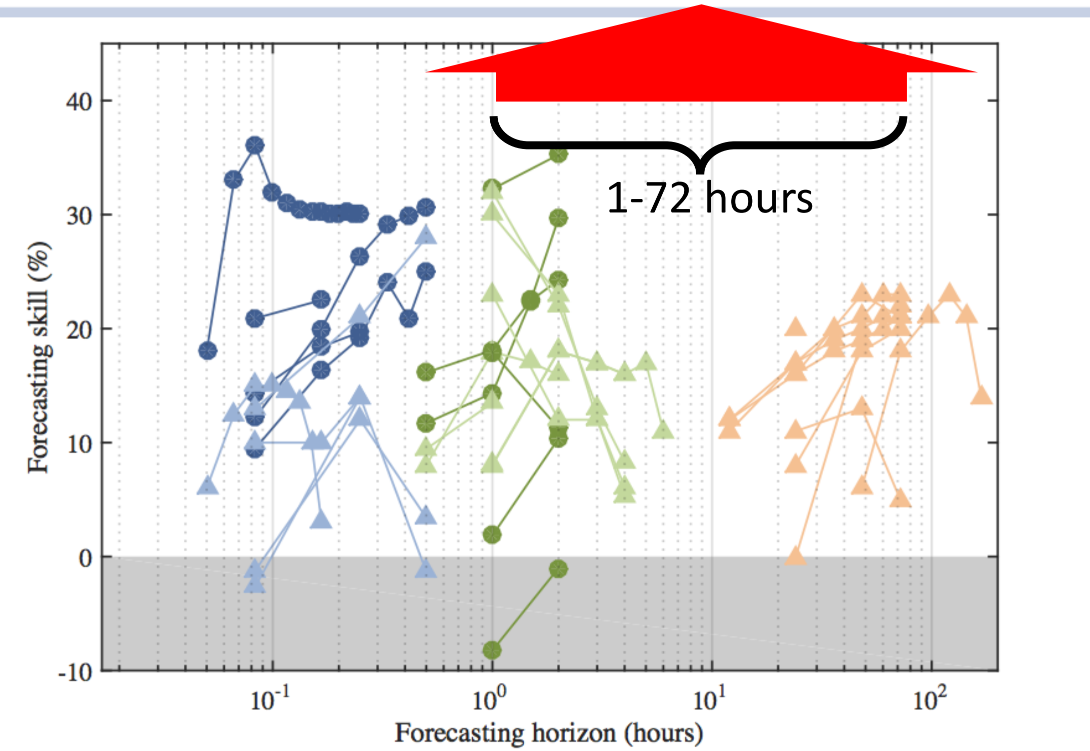

Figure 1: Comparison of forecasting skill of various peer-reviewed results. The comparison is limited to studies that list RMSE for the new proposed methods and persistence ($RMSE_p$). Forecasting skill is computed as $s = (1 - RMSE/RMSE_p) \times 100$. The colors indicate the different forecasting horizons: - 3 to 30 minutes, - 30 minutes to 6 hours, - 12 hours and longer. The symbol • indicates UCSD forecasts and the symbol ▲ indicates other authors. Figure adapted from Inman, Pedro & Coimbra (2013).

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Approach

- **HAIMOS** combines Numerical Weather Prediction (NWP) forecasts, determinist physics-based algorithms, and new-generation cloud information extracted from high-resolution satellite images and Large Eddy Simulations (LES).
- Key aspects of HAIMOS such as data preprocessing, input selection, error metrics, etc., will be optimized adaptively to find the best model for a specific goal (reduce DNI or GHI forecast error, improve the prediction of ramp onset, etc.).
- Focus on improving cloud identification and forecasting of cloud cover and cloud optical depth.

Innovations

- HAIMOS combines the latest innovations in machine learning algorithms (deep-learning, feature engineering, etc.) with detailed physics-based models for cloud cover and cloud optical depth forecasts.
- Integration of information derived from the new GOES satellites sensors and cloud cover simulations from LES. Both these technologies enable a spatial and temporal sensing/modeling of clouds at much higher resolutions than previously possible.

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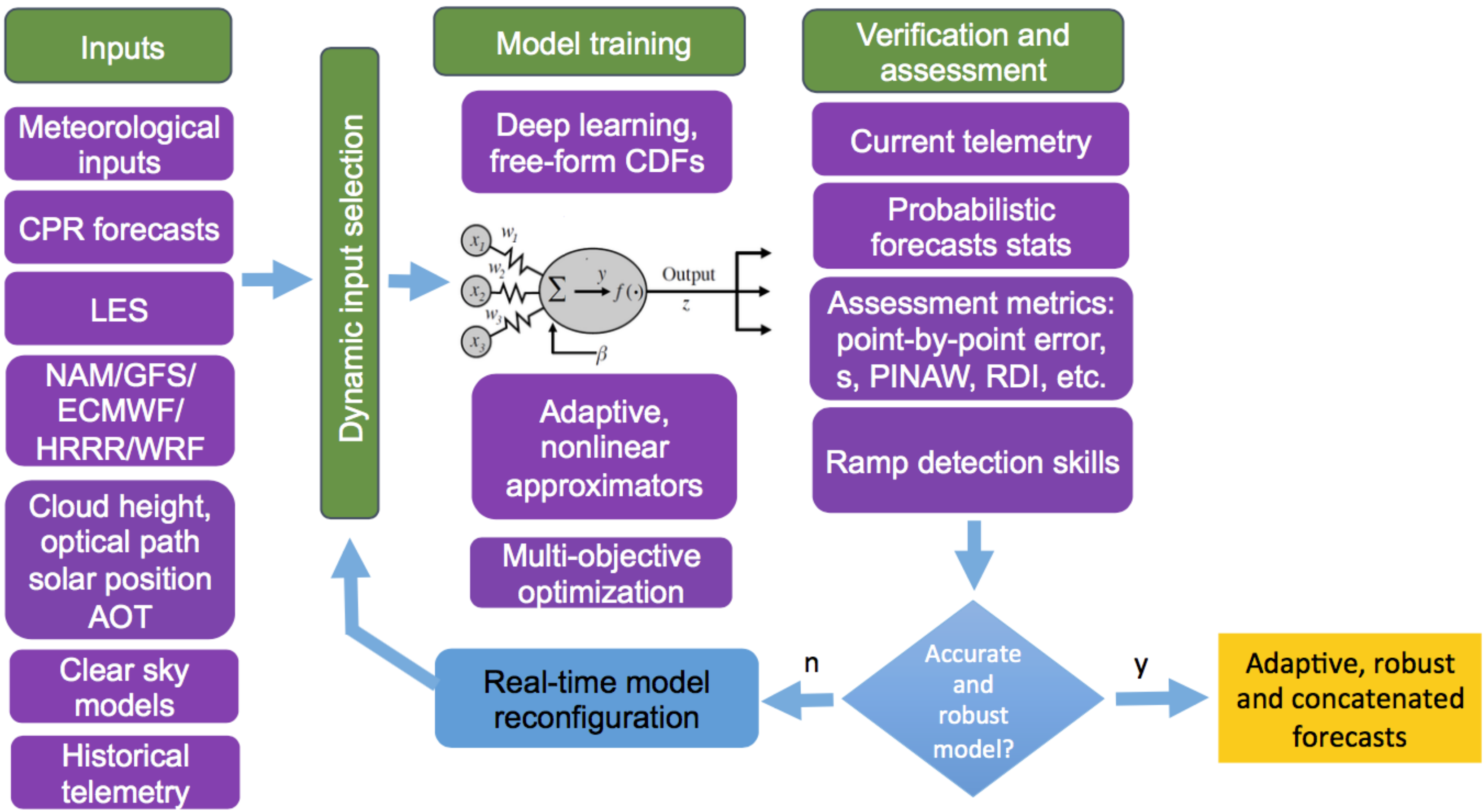
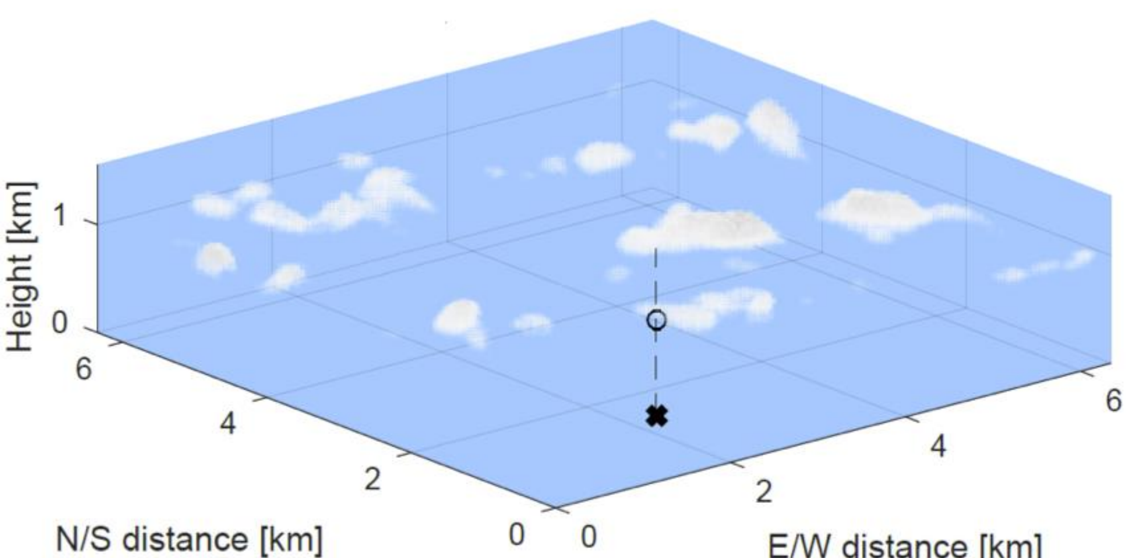
Technical Approach

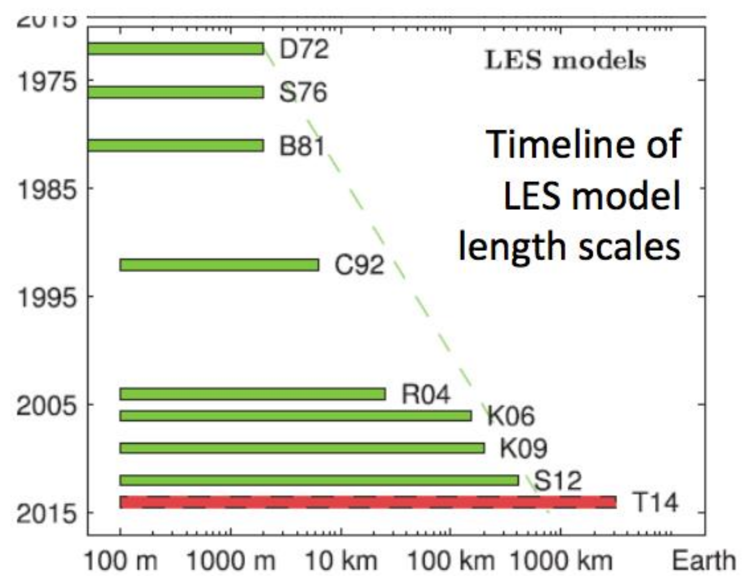
HAIMOS



Large-Eddy Simulations

- LES is the ultimate tool for weather forecasting
  - Directly resolves and simulates mixing in clouds
- Historically limited to ~10 mile domains
- Recent advances in GPU high performance computing allow domains of 1,000 miles to be simulated.





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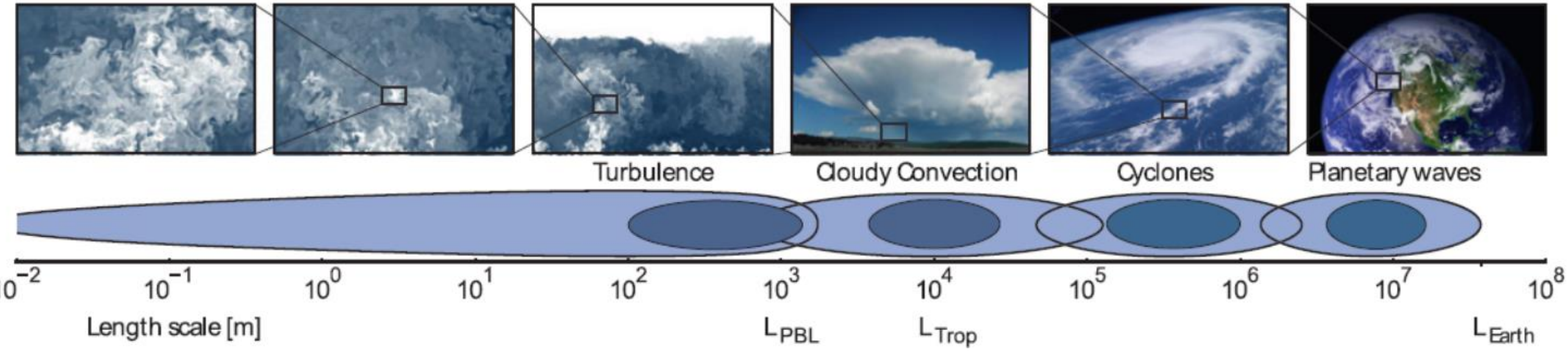
Schalkwijk et al. (BAMS, 2015)

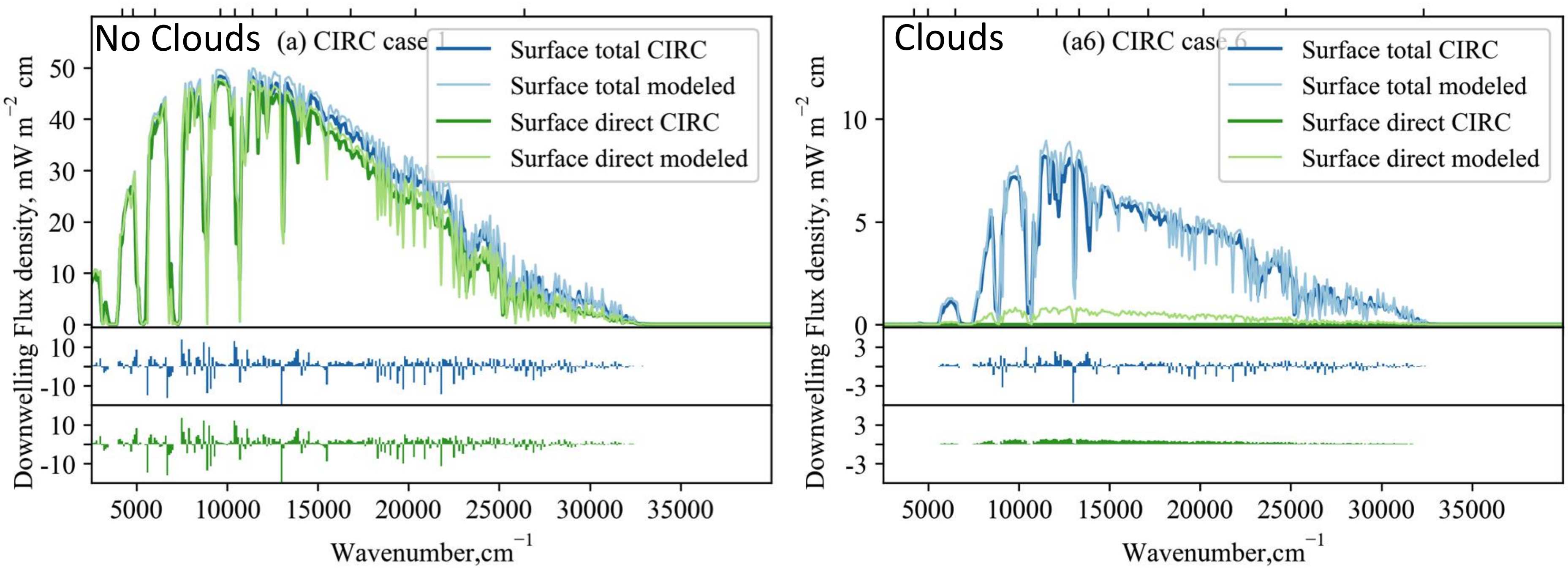
Cloud Resolving GPU-LES

- Proof-of-concept for weather forecasting in The Netherlands
- UC San Diego has proven expertise in LES of clouds
- Operationalization still requires significant speed-up
- Initialization with limited measurements



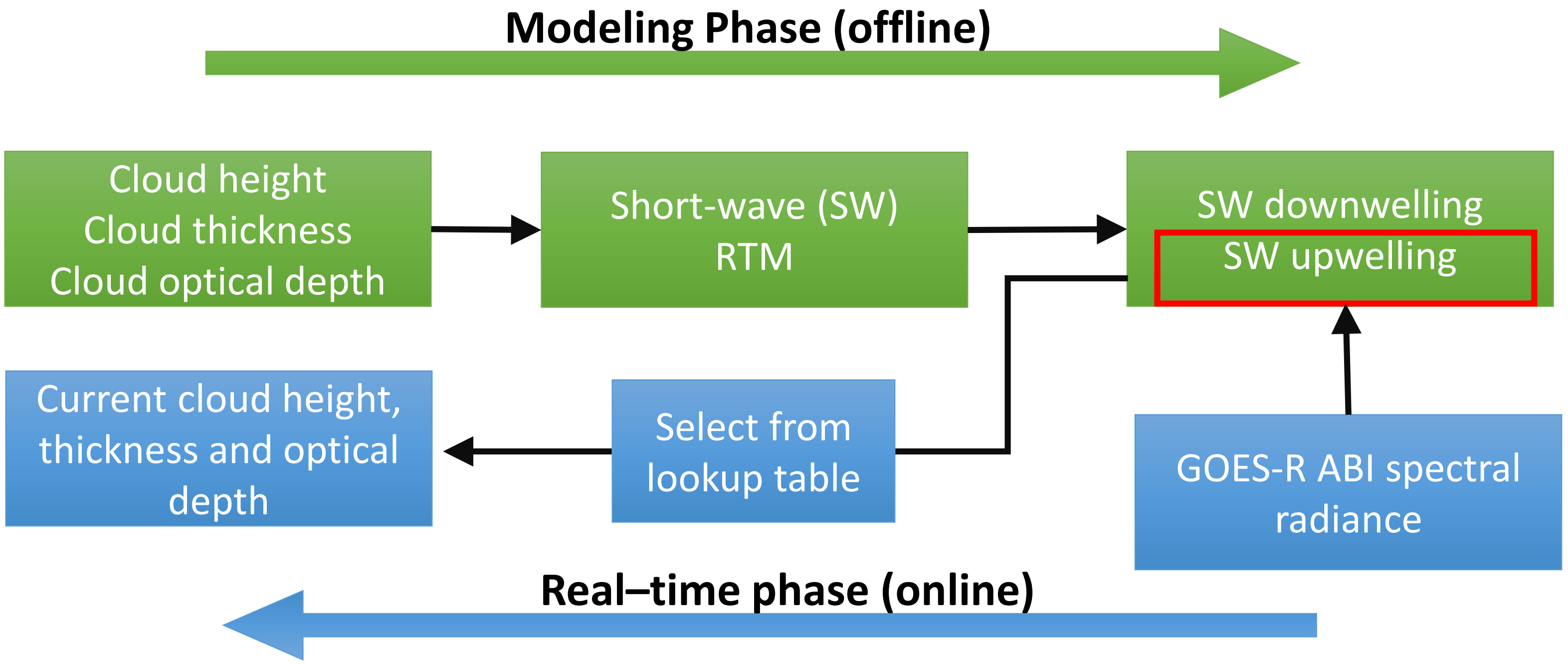
Physics-based cloud modeling

- Short-wave (SW) radiative transfer model (RTM) developed and validated **with and without** clouds.
- Computes **downwelling and upwelling** spectral radiation.
- Validated against NASA's CIRC data



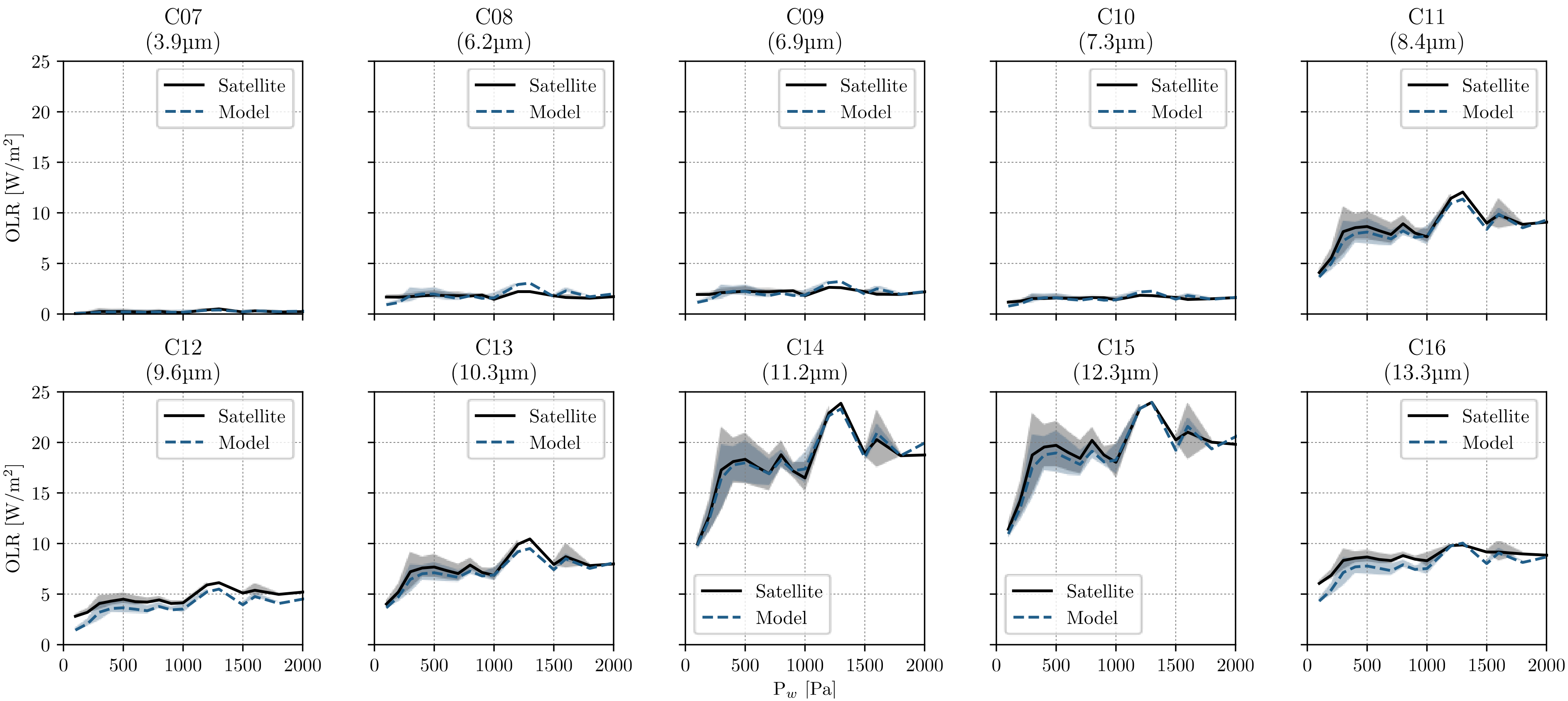
Left: RTM validation for clear-sky periods. *Right*: RTM validation for cloudy periods. Bottom plots show the error between UCSD's RTM and NASA's data.

- RTM output can be paired with GOES-R spectral data to characterize clouds (height, thickness and optical depth) for any given location of interest in real-time.



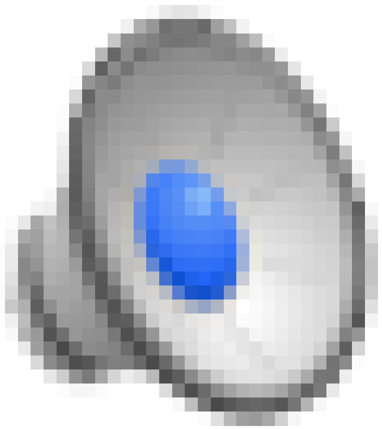
Preliminary results (RMT + GOES-R radiance data)

- Clear-sky periods at different relative humidity levels
- Ground data from SURFRAD (Bondville, Il)



GOES-R Cloud and Moisture Imagery Product (CMIP) is a good predictor for irradiance

- GHI (SURFRAD): measured ground data
- GHI (CMIP): modeled GHI from GOES-R data



Left: CMIP data over target location.

Right: Measured GHI and GHI modeled from CMIP data.

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The Research and Development Team

Leadership

Prof. Carlos F.M. Coimbra, UCSD (PI)
Dr. Hugo T.C. Pedro, UCSD (Co-PI)
Prof. Jan Kleissl, UCSD
Mr. Skip Dise (CPR)

Workforce development: graduate + undergraduate students; project scientists, post-doctoral scholars

Experience: Stochastic methods, machine learning (GA, ANN, SVR, SVM, kNN, DL, etc.), clear sky modeling, WRF/NAM/GFS/ECMWF/ HRRR/LES, cloud parameterization, remote sensing, sky imaging, image processing, ensemble numerical modeling, atmospheric radiation, aerosols transport and solar radiation.

Proven experience in all areas of solar forecasting, from deterministic models to PDF propagation of prediction intervals, ramp forecasts; including GHI/DNI/DHI and net load forecasts; covering resource prediction , central station and distributed generation.

UCSD and CPR have a history of successful projects with several IOUs and BAs/ISOs in California (PG&E, SCE, SDG&E, SMUD, CAISO) funded by the CEC, CPUC, DOE, DOD, and other private companies. UCSD manages solar resourcing and forecasting sites throughout the pacific rim (CA, WA, HI). The forecasting sites include over 650MWe of grid-connected solar power generation (CSP, CPV and tracking PV central station plants). UCSD and CPR have partnered before in DOE projects.

Impact, dissemination and workforce development: CER/UCSD in the past 5 years: 100+ journal papers on solar resourcing (30+) and solar forecasting (70+), and more than 100 conference/workshop public talks (UVIG, AMS, AGU, ASES, ISES, WREN, CEC/CPUC/DOE etc.); 15 PhDs and 5 post-docs trained in the solar forecasting area employed by a variety of national labs (SANDIA, NIST, etc.), private companies (Tesla, SolarCity, Northrop-Grumman, CPR, etc.), and consulting firms (GEI, DNV GL, Roland Berger, McKinsey and Co., etc.) mostly in the US, but also in Brazil, Spain, China and Germany.

Selection of training sites and data collection (BP1: Task 1)

- Collect endogenous (GHI and DNI) and exogenous data (NPW forecasts, satellite images, etc.) that will be used in the development of HAIMOS.
- Select data from 5 to 10 locations in the USA with potential for high solar penetration with the requirement that they are climatological distinct
  - collected at the UCSD solar laboratory
  - high-quality, publicly available data such as the one provided by NOAA's SURFRAD network.

Commercial Irradiance Forecasts (BP1: Task 2, BP2: Task 5, BP3: Task 8)

- Collaborate with a Commercial Irradiance Forecast Provider (CIFP), to obtain historical irradiance forecasts for the locations and time span selected in Task 1.
- CIFP forecasts will cover 1 to 72 hours horizons with a temporal resolution of 30 minutes and a spatial resolution of 1 km.
- Access to an application programming interface (API) for the purpose of obtaining on-demand DNI and GHI forecasts for the locations determined by the Area 1 test framework.

Improvement of cloud cover forecast (BP1: Task 3)

- Improve the accuracy of cloud detection models from satellite imagery.
    - Current models that rely on image segmentation show low accuracy in discriminating between thin and thick clouds, for instance.
- Explore image processing algorithms to identify and classify clouds from satellite imagery.
    - Use exogenous data such as detailed atmosphere data from NWP models (vertical humidity profiles, 1000-500mb thickness, etc.) to improve cloud classification.
- Physics-based models (i.e. Lagrangian cloud motion, convection-diffusion, WRF-Solar simulations) to improve the cloud cover forecast for time horizons ranging from 1 to 6 hours.

Set up HAIMOS framework (BP1: Task 4)

- Set up the HAIMOS framework for the different forecasting tasks:
    - accurate 1 to 72 hours DNI and GHI point forecasts,
    - accurate probabilistic forecasts, and prediction of large irradiance ramps.
- Develop adaptive training techniques that will be tested using data from the previous tasks.
- The goal is to obtain HAIMOS point forecasts for DNI and GHI 1 to 72 hours in the future with skill over the smart persistence model equal or above 30%.

Optimization of HAIMOS framework (BP2: Task 6)

- Detailed framework to optimize every component of the HAIMOS framework:
  - input preprocessing and selection,
  - machine-learning technique (regressive models, deep learning, nearest-neighbors, etc.),
  - objective function,
  - post-processing ensembling.
- The optimality of the resulting model will be assessed using data collected in Task 1

New-generation cloud forecasting tools (BP2: Task 7)

- Include new-generation exogenous data as inputs to HAIMOS.
    - Increase HAIMOS accuracy in the 1 to 6 hour horizon by using high-resolution imagery from the new GOES-R satellite and improve cloud cover forecasts obtained from LES run at UCSD.
- LES simulations will be nested over the areas of interest to simulate the local meteorology and solar forecasts up to a few hours ahead, at resolutions of seconds and 100 m.
    - The WRF-Solar runs from Task 3 will provide boundary conditions for LES.

Area 1 test framework validation (BP3: Task 9)

- Apply the HAIMOS forecast model to the test framework developed in Area 1.
- Collect the necessary exogenous data for the locations and time period determined by the test framework.
- Retrained HAIMOS using the endogenous data provided by the test framework and exogenous data produced by this project.
- Run retrained HAIMOS and provide the forecasts according the guidelines for model validation (variables, resolution, conditions, measurements, etc.) stipulated by Area 1 test framework.

Go/No-Go Decision Point 1 (end of BP1)

- The performance of the forecast models at this point in the project should show improvements higher than 30% relative to the baseline persistence model for all forecast horizons (1 to 72 hours) for periods of variable solar irradiance (i.e. excluding cloudless periods defined by a clear-sky index above 0.9).
- Deliver measured and forecasted data used in the validation of the forecast models developed until the end of budget period 1.

Go/No-Go Decision Point 2 (end of BP2)

- The performance of the forecast models at this point in the project should show improvements higher than 40% in the conditions used in the **Go/No-Go Decision Point 1**.
- For probabilistic forecasting two metrics will taken into account.
  - The Prediction Interval Normalized Averaged Width (PINAW)
  - The Probability Interval Coverage Probability (PICP).
- The forecasting performance should be **PICP > 90%** and **PINAW<20%** for all the forecast horizons and target locations.

Budget Summary

Section A - Budget Summary					
		Federal	Cost Share	Total Costs	Cost Share %
	Budget Period 1	$555,444	$82,500	$637,944	12.93%
	Budget Period 2	$305,964	$40,000	$345,964	11.56%
	Budget Period 3	$454,795	$40,000	$494,795	8.08%
	Total	$1,316,203	$162,500	$1,478,703	10.99%

Section B - Budget Categories					
CATEGORY	Budget Period 1	Budget Period 2	Budget Period 3	Total Costs	% of Project
a. Personnel	$216,215	$119,400	$192,502	$528,117	35.71%
b. Fringe Benefits	$81,636	$44,735	$79,231	$205,602	13.90%
c. Travel	$3,000	$3,343	$3,343	$9,686	0.66%
d. Equipment	$0	$0	$0	$0	0.00%
e. Supplies	$7,372	$0	$0	$7,372	0.50%
f. Contractual					
Sub-recipient	$120,000	$70,000	$50,000	$240,000	16.23%
Vendor	$0	$0	$0	$0	0.00%
FFRDC	$0	$0	$0	$0	0.00%
Total Contractual	$120,000	$70,000	$50,000	$240,000	16.23%
g. Construction	$0	$0	$0	$0	0.00%
h. Other Direct Costs	$24,870	$15,619	$17,349	$57,838	3.91%
Total Direct Costs	$453,093	$253,097	$342,425	$1,048,615	70.91%
i. Indirect Charges	$184,851	$92,867	$152,370	$430,088	29.09%
Total Costs	$637,944	$345,964	$494,795	$1,478,703	100.00%

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