Solar Energy Irradiance and Electric Generation Forecasting

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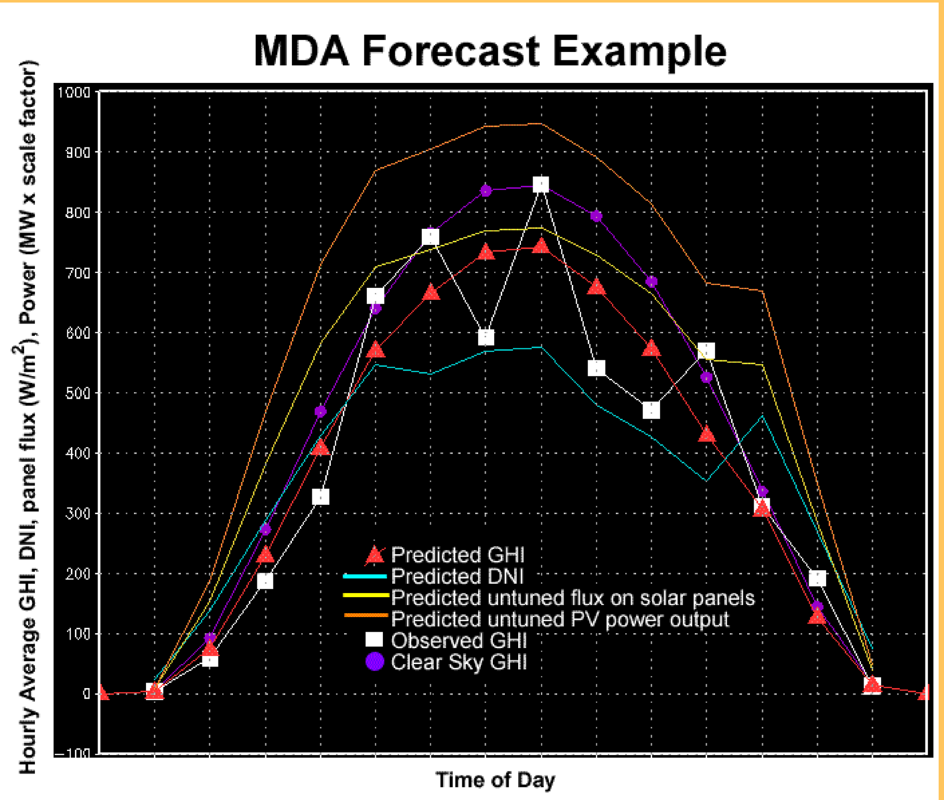
MDA Solar Energy and Solar Irradiance Forecasting

Enough solar energy has been installed in some regions that uncertainty associated with this variable power resource affects load balancing and electric system performance, adding cost to integrating this power into the electric grid. Forecasts of solar power output are needed, similar to those needed for wind energy.

Forecast lead times needed for the electric power industry:
- Next few minutes to next hour
- Next several hours
- 1 day ahead
- Several days to a week or more ahead

Installation types requiring forecasts include:
- Large solar concentrating plants (several technologies – PV, troughs, etc.)
- Utility-scale collections of photovoltaic (PV) on transmission grid
- Widespread small rooftop PV on distribution grid

MDA Information Systems, LLC has developed a solar forecasting system
- Individual sites or collections of sites now, distributed generation coming
- Focus now on day-ahead and beyond, short-term coming
- Panels of any tilt or sun-tracking
- Prediction of
  - Solar power generation
  - Global Horizontal Irradiance **(GHI)**
  - Direct Normal Irradiance **(DNI)** and Direct Horizontal Irradiance **(DHI)**
  - Irradiance incident on panels



Skill is dominated by prediction of clouds. Predicting evolution beyond the first few hours requires use of numerical weather prediction **(NWP)** models
- Cloud prediction is a weak point in NWP
- Time-averaged, not instantaneous, values of surface shortwave flux are needed
- Output frequency for most major NWP models is insufficient
- Surface shortwave fluxes from NWP models need complex bias correction (function of other variables)
- Most NWP models do not output direct beam irradiance (DNI or DHI) and those that do provide it have little skill independent of predicted GHI

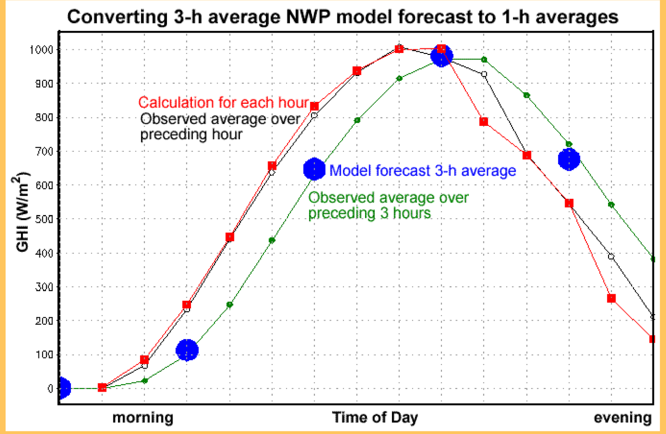
MDA Information Systems, LLC solar forecasting system meets these challenges through
- Leveraging the REST2 (Gueymard, 2008) clear sky model as a foundation for time interpolation, bias correction, and direct beam calculation
- Employing a variety of public data sets to obtain aerosol-related and other parameters needed for REST2 and for considering cloudy atmospheres
- NWP bias correction as a function of key variable combinations
- Skill-based blending of NWP models and time-lag ensembles

Reference: Gueymard, C. A., 2008: REST2: High-performance solar radiation model for cloudless-sky irradiance, illuminance, and photosynthetically active radiation – Validation with a benchmark dataset. *Solar Energy*, **82**, 272-285

Numerical Weather Prediction (NWP) models Time Interpolation using REST2

NWP model outputs 3-h average GHI
- Prorate to finer intervals using REST2 clear sky flux as basis
- When cloudiness is constant during the 3-h period and model has good 3-h average, averages over finer intervals match observations

Model may have little skill for 1-h average at forecast lead times beyond 1-day
- Small sample with NAM model showed output at 1-h intervals had same skill as calculations prorating 3-h averages to each hour

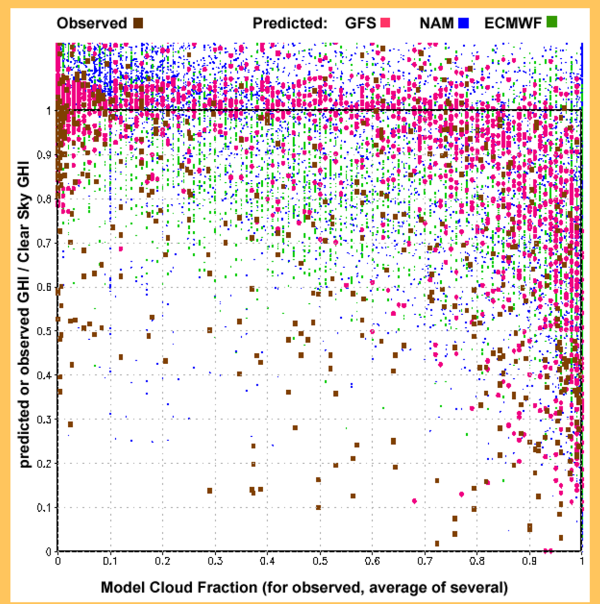


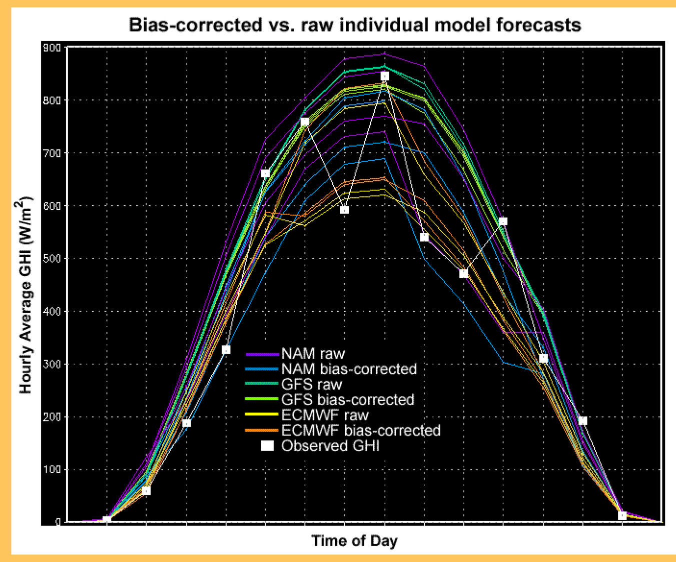
NWP Models: Bias Correction

Example of complex bias:
As cloud fraction increases, GHI decreases
- GFS model does not follow the curve, has same fluxes with 60% cloud cover as with 0%

(NAM values exceeding clear sky are due to overall high bias unrelated to cloud fraction)

Example of changes due to bias correction
(1 day, 1 site, 4 NAM runs, 4 GFS runs, 3 ECMWF runs)
- Bias-corrected values mostly closer to observed
- Different models/runs better at different times
- No single model run had right idea for all times

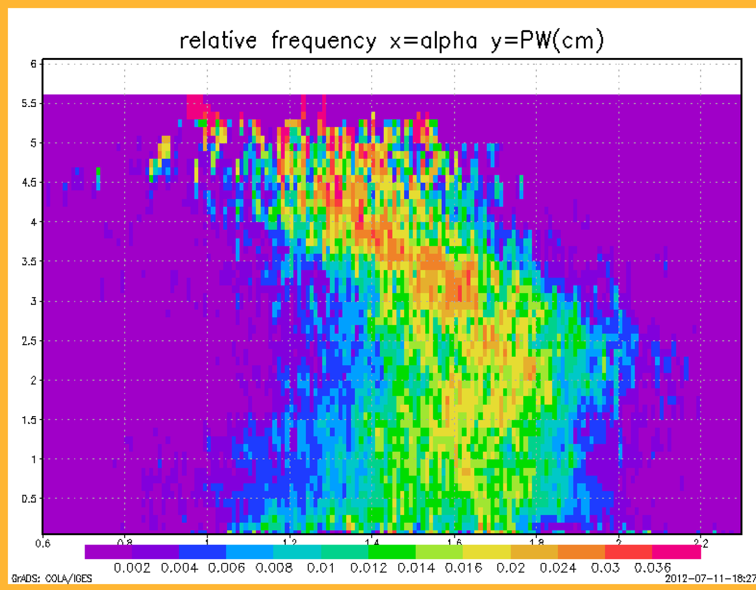


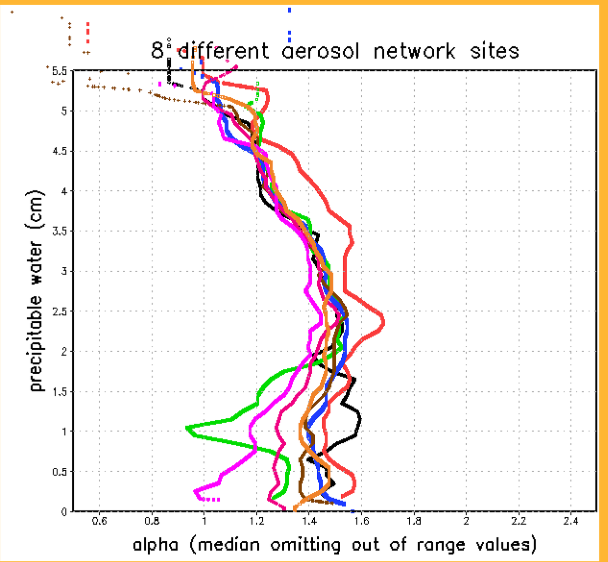


Using Public Scientific Datasets

The wealth of publicly available high-quality scientific data is a treasure heavily utilized in the MDA forecast system

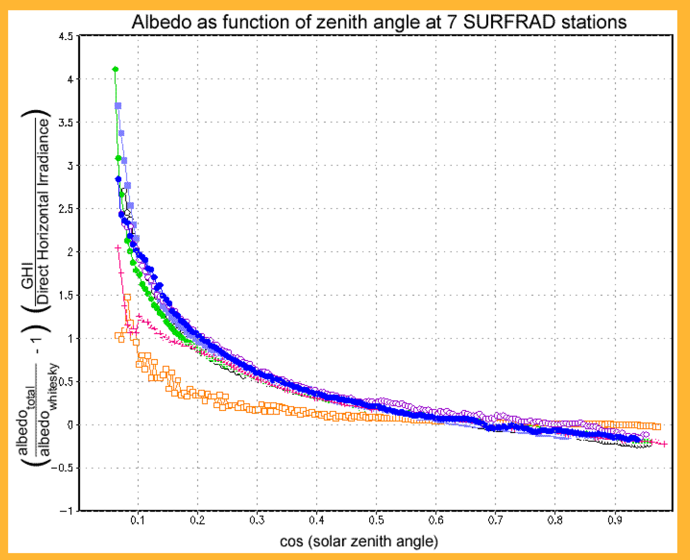
Example: Aerosol scattering
- REST2 requires wavelength-dependent (in 2 bands) Angstrom exponents and Angtrom turbidity coefficients
- These can be calculated from the photometer data in AERONET aerosol robotic network aeronet.gsfc.nasa.gov
- These parameters vary with column water vapor (PW) and 8 mid-Atlantic region sites showed the same relationship (shown here for one Angstrom exponent α. The β aerosol loading parameter is a stronger function of PW)
- These relationships can be used to estimate aerosol properties from NWP modelforecasts



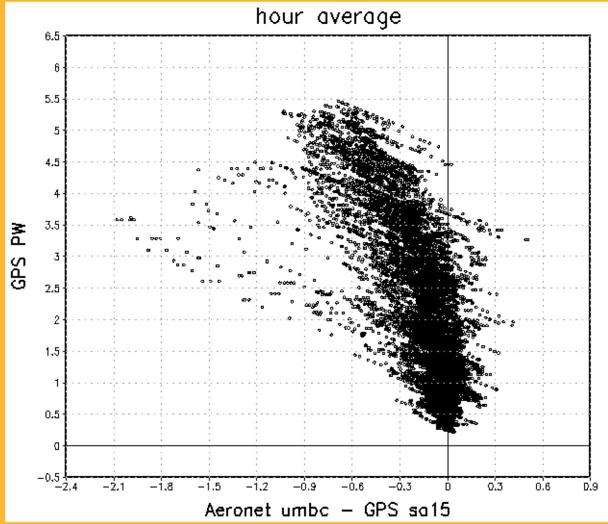


Example: GHI and DNI observations
- NREL Measurement and Instrumentation Data Center (MIDC) midcdmz.nrel.gov is used extensively to test and validate the forecasts and compare against private data

Example: 1-minute data, upwelling shortwave used for albedo relationships, and direct beam for cloudy sky relationships
- NOAA SURFRAD Surface Radiation Network www.esrl.noaa.gov/gmd/grad/surfrad/index.html
- 1-mnute data used to gauge frequency of extreme values due to scattering into the beam from sides
- REST2 and flux on tilted PV panels require surface albedo, varies by sun angle. Upwelling shortwave data (with no snow on ground) resulted in fit shown in plot to left – not medians or means – plot shows all scatter!
- Direct beam irradiance under cloudy skies is a crucial component in the forecast system and utilizes relationships developed from SURFRAD data

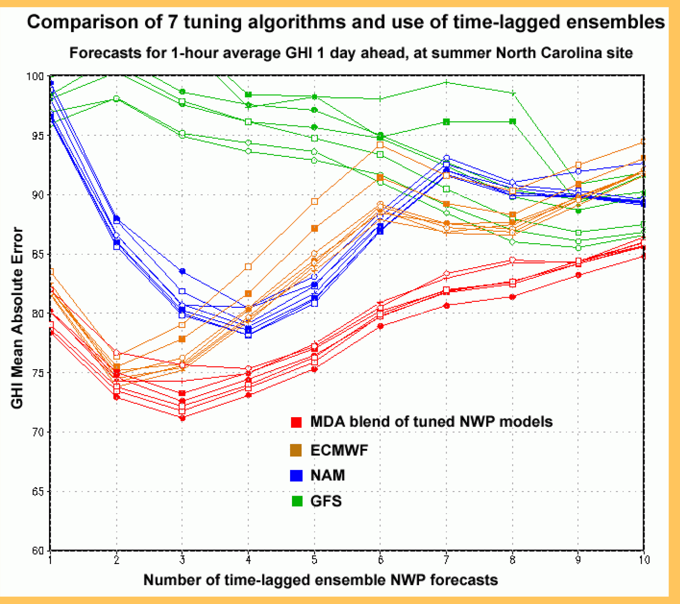


Example: Column water vapor is required to have clear sky reference values at MIDC and SURFRAD sites
This is available from NWP data but could be extracted much faster in much smaller file sizes for a long range of dates from Suominet GPS measurements www.suominet.ucar.edu/data/index.html
- However, Suominet and AERONET have systematic disagreements at several colocated sites including the one plotted here to the right



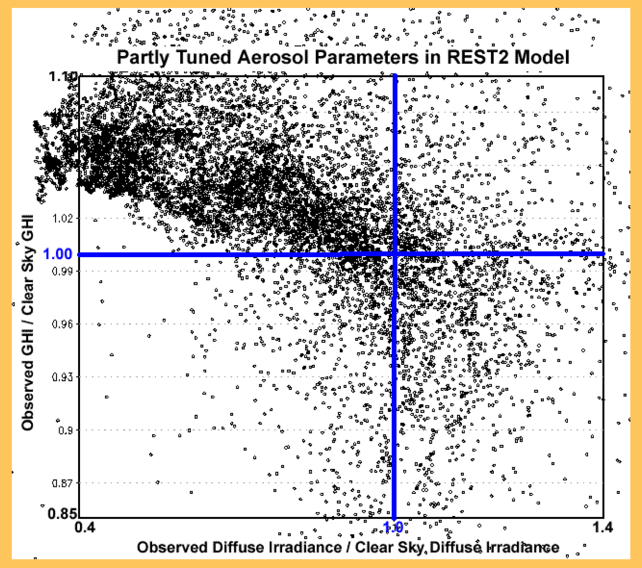
NWP Models: Ensembles

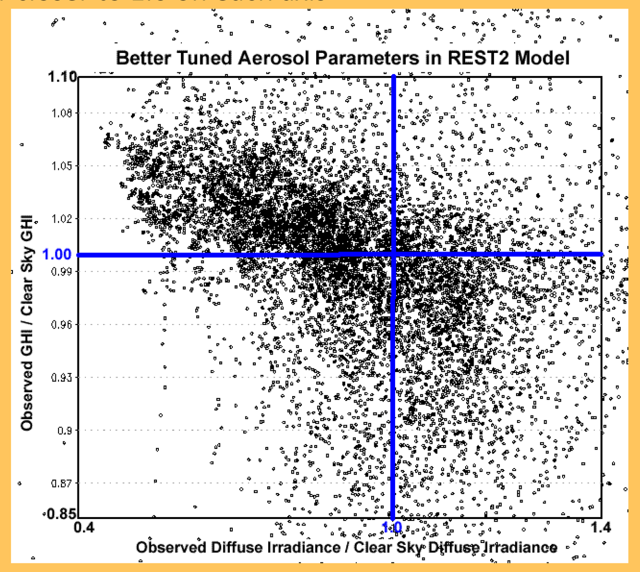
- Forecasts are improved by blending bias-corrected individual model runs
- Skill is sensitive to the number of individual runs included (balance between diversity of forecasts and skill of individual members – for example, in a time-lag ensemble, older members have longer lead time = less skill)
- Skill is slightly sensitive to details in bias correction
- Skill is slightly sensitive to weighting method in blend



Direct Beam Irradiance: Clear Sky using REST2

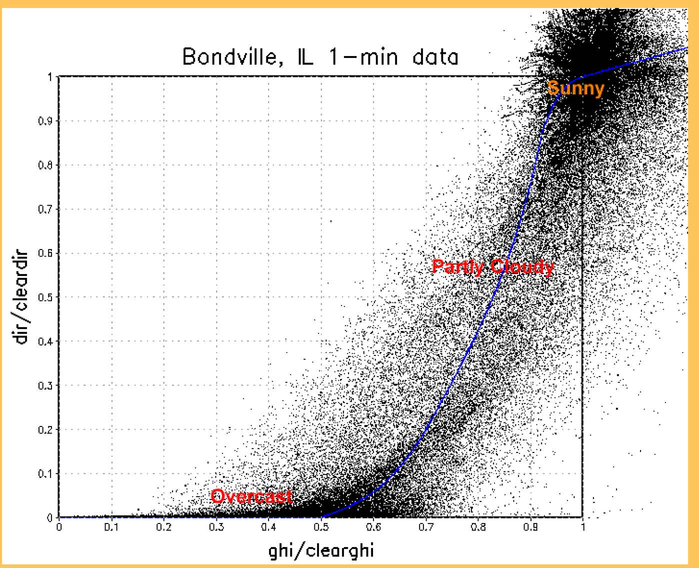
Clear sky direct beam irradiance calculated using REST2
Accuracy depends on estimation of aerosol parameters used by REST2
Plots show fit to hour-averaged observations (summer, North Carolina)
- Horizontal axis is for diffuse component, vertical axis is total (GHI)
- Dense cluster is mostly from clear-sky hours
- Well-tuned parameter estimates bring the cluster closer to 1.0 on each axis

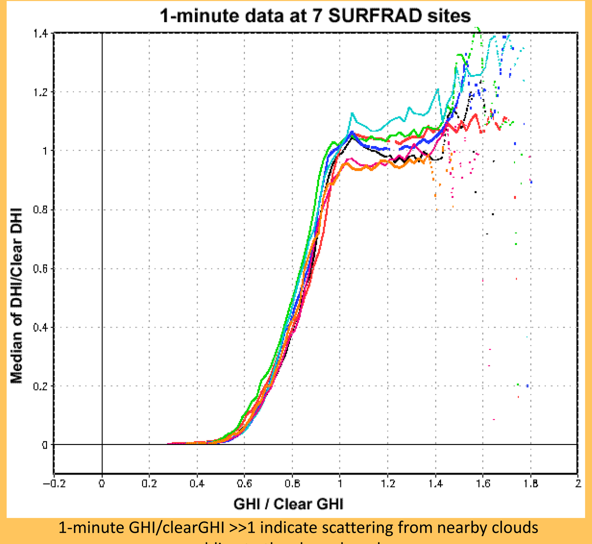




Direct Beam Irradiance: Cloudy Sky

Direct beam irradiance varies under cloudy skies more sharply than GHI
Example plot below shows the relationship with some scatter → can estimate DHI based on GHI
- Relationship appears same for 1-minute data, 1-hour averages, and 3-hour averages
- Relationship appears the same at diverse geographic locations
- Skill applying this relationship to ECMWF GHI is nearly same as for ECMWF DHI directly from the model (in limited sample – more testing needed to validate)





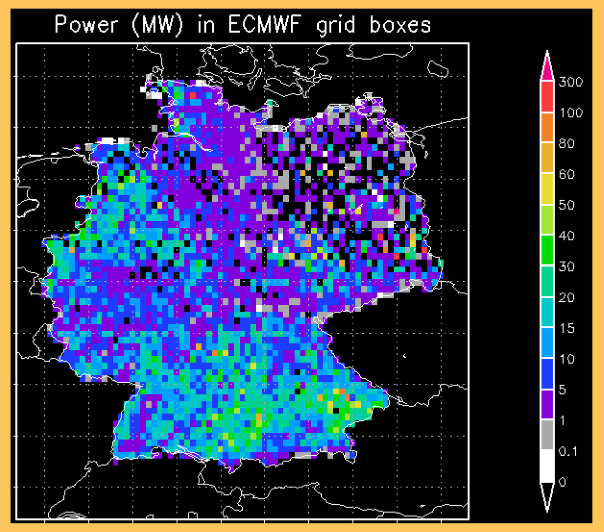
1-minute GHI/clearGHI >>1 indicate scattering from nearby clouds adding to the clear-sky values

Forecasting Distributed PV using Public Data

Example:
Germany has 28 GW of installed solar power capacity, mostly scattered on a million residential and commercial rooftops
- Site registry is public
- Aggregate estimated generation in each transmission region and some subregions is public
- Forecast skill can be compared to official forecast (publicly posted with delay)

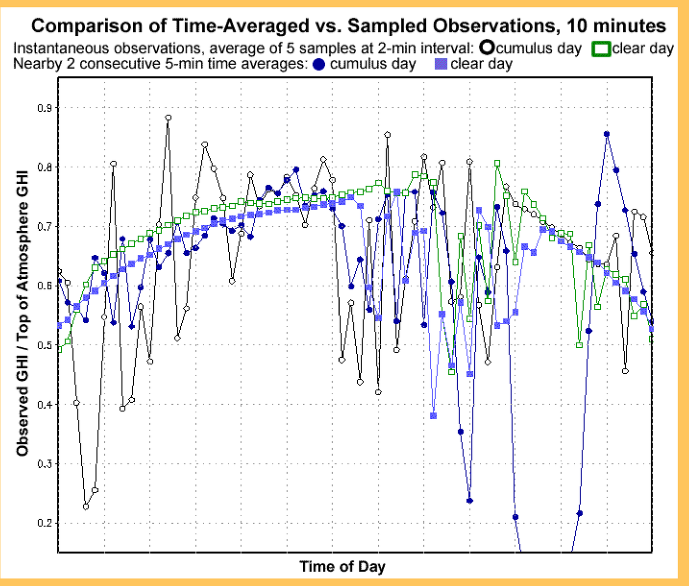
MDA will shortly be forecasting for distributed PV

Capacity in each ECMWF 1/8° output grid box
Map created by aggregating site data by zip code



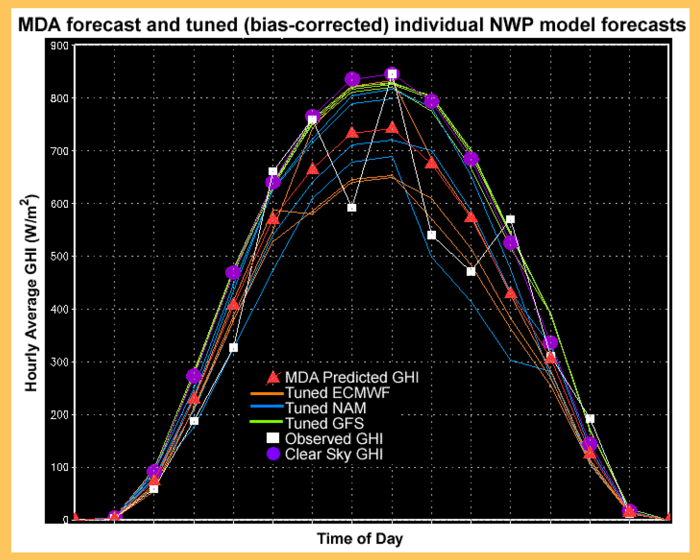
Noisy Data

Observations at high temporal frequency can be "noisy"
- Quality is better when data are time-averaged rather than instantaneous samples representing a few seconds



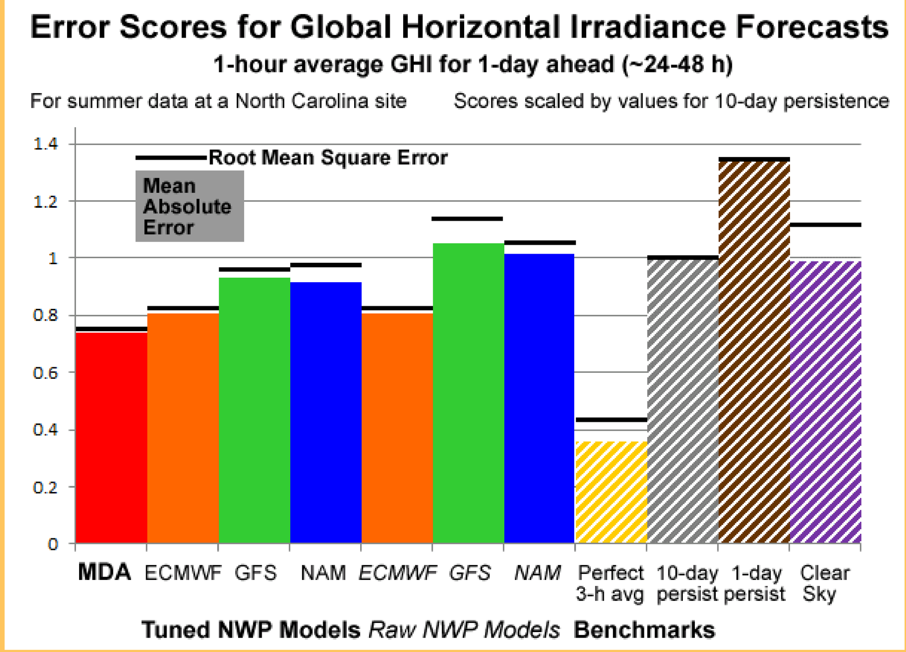
MDA Forecast Skill

Example of one forecast day:
- MDA forecast and 4 NAM, 4 GFS, 3 ECMWF runs
- Day had mixed sun/some clouds
- All GFS predicted sunny day, others varied
- Different model runs better at different times



Forecast Stats for MDA, NWP Models, and Benchmarks

Summer 2012 at a private site in mid-Atlantic region:
- MDA best overall, about halfway between a perfect 3-hour average forecast and 10-day persistence
- "Perfect 3-h average" scores measure variability in 1-hour GHI and a model with perfect predictions of 3-h averages would have these errors



The Way Forward

Irradiance forecast would benefit from improved NWP model cloud prediction (involves feedback among radiation, microphysics, boundary layer, etc.)
Power forecast would benefit from public hourly or finer data of power generated at individual sites or geographically compact collection of sites