

# Solar resource assessment and forecasting: Recent achievements, bankability pressures, and current challenges

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# Key issues in solar resource assessment

1. What are the most suitable areas?
2. Can we trust old/distant measured data? Can we trust modeled time series based on satellite data? Can we trust TMYs?
3. What technology to select? What is the resource for each technology?
  - PV (crystalline silicon or thin films)
    - Fixed flat-plate?
    - 1-axis or 2-axis tracking?
  - Concentrating solar power (CSP): thermal process
    - 1-axis or 2-axis tracking?
  - Concentrating PV (CPV): direct conversion to electricity
4. What are the uncertainty and the interannual variability in the resource?
5. How much energy can be produced the first year? During the worst years?
6. How reliable is the resource assessment prepared by Company X? Is a second opinion needed? Who are the real experts?
7. Where to install a weather station? How long are such measurements needed for bankability? What to do if the modeled and measured data disagree?

## *Renewed interest in solar resource fundamentals*

1. Obvious increase in number of journal papers and conference presentations (ASES, ISES, SolarPACES, CPV...)
2. Complexity of radiative transfer processes in the atmosphere: more science needed, more scientists attracted.
3. Major solar developers realize the solar resource cannot be modeled with perfect accuracy; some really bad experiences occurred (e.g., Abu Dhabi).
4. Uncertainties in solar resource data have been shown to be the largest source of error in CSP/CPV production estimates.
5. Banks become more suspicious, sometimes require second opinions.
6. More resource data providers because of new markets.
7. Increasing interest for nowcasting and forecasting from operators and utilities (electricity grid stability, reserve dispatching, spot market...)
8. Accelerated convergence between different scientific fields: atmospheric sciences, meteorology, climate, GIS, metrology, radiometry, solar engineering...

# Progress in Solar Resource Assessment (1)

## 1930–1980s:

- Ångström-type empirical correlations: daily GHI vs. daily **sunshine**.
- First world monthly distribution maps of GHI in 1965 (Löf et al.).
- *Hot topics*: Local vs. “universal” correlations; modeled GHI accuracy; interpolation/extrapolation; sub-daily data; value of sunshine data.



# Progress in Solar Resource Assessment (2)

## 1980–1990s:

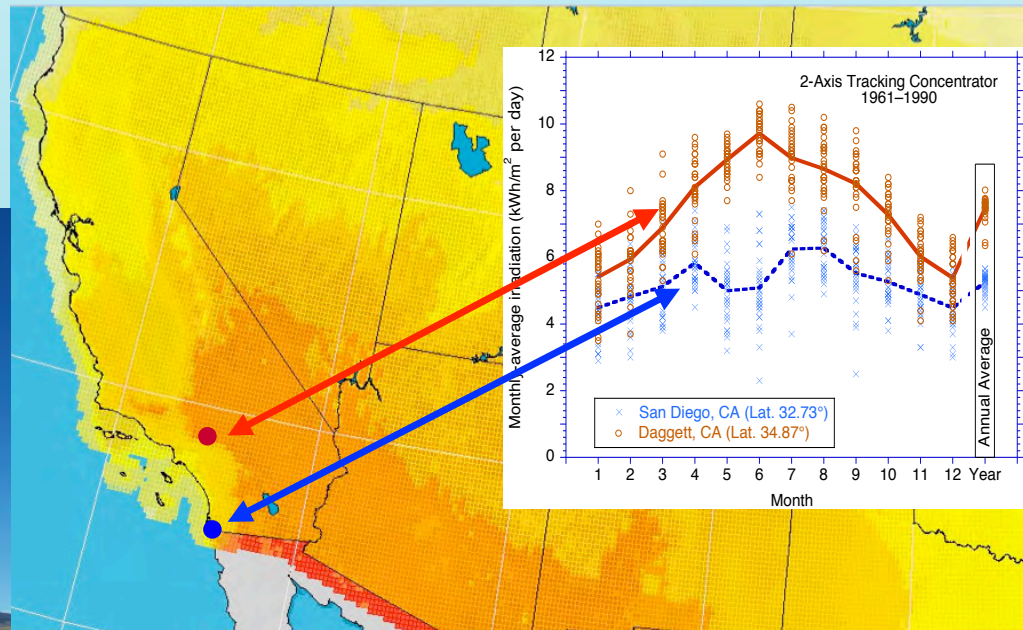
- Broadband radiation models used to predict hourly irradiances from meteorological information (cloud cover...) at specific sites (airports). Example: NREL's NSRDB 1961–1990.
- Development of TMYs for energy simulations (buildings & solar).
- *Hot topics*: How to obtain aerosol data?; spatial interpolation methods; combination of measured and modeled data; subjectivity of human cloud observations.



# Progress in Solar Resource Assessment (3)

## 1990s–2000s:

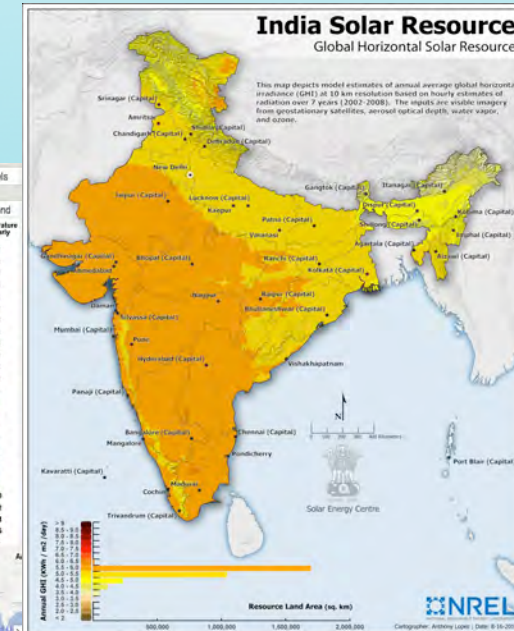
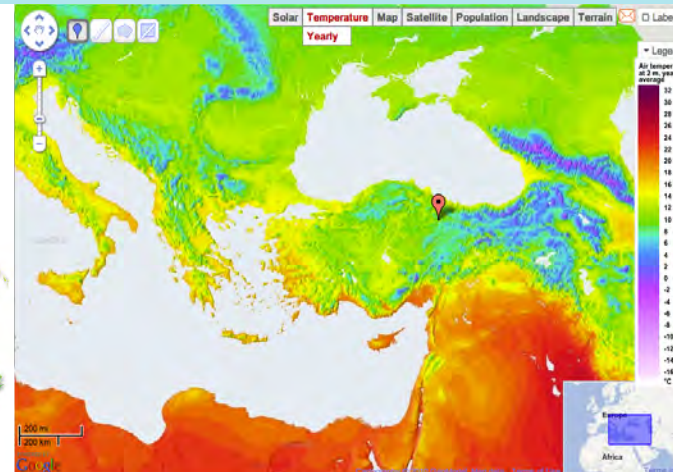
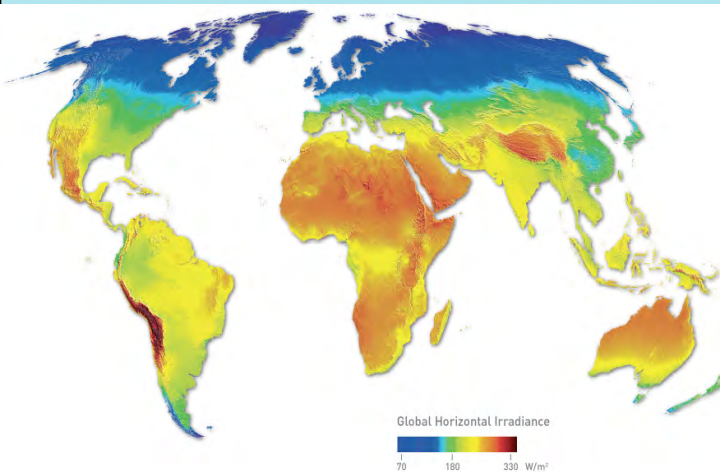
- Hourly irradiances predicted from spaceborne cloud observations and other data.
- Huge improvement in spatial resolution, time resolution, making continuous maps and GIS applications possible.
- Thermal imbalance issue discovered in many pyranometers; development of rotating shadowbands, spectral correction methods.
- *Hot topics*: Clouds vs. snow; sources of aerosol data; validation issues; derivation of DNI; value of stochastic models.



# Progress in Solar Resource Assessment (4)

## 2000s–now:

- Many data providers now offering long-term 15-min to 60-min irradiance time series and global datasets.
- Nominal spatial resolution typically  $\approx 3$  km, can be disaggregated down to  $\approx 90$  m, with shading analysis.
- Nowcasting/Forecasting now possible, but still in their infancy.
- **Hot topics:** Surface reflectance issues; daily vs. monthly aerosol data; DNI modeling; validation of modeled DNI (lack of HQ measurements); variability; bankability; value of TMYs; modeled/measured data combination; forecasting; which data should be used where or for what purpose?



# What is the fuel of solar systems?

## ◎ Incident irradiance:

- CSP/CPV plants use **DNI**: *Direct Normal Irradiance*
- Fixed flat-plate collectors use **GHI**: *Global Tilted Irradiance*
- 2-axis tracking flat-plate collectors use **GNI**: *Global Normal Irradiance*.

◎ **GHI** (*Global Horizontal Irradiance*) is mostly used in intermediate calculations and “first look”, rough solar resource visualization.

◎ **DNI** is what 2-axis tracking CSP/CPV concentrators can utilize fully; 1-axis trackers (e.g., parabolic troughs) get somewhat less.



# Solar Resource Enhancement Factor

FAQ: What type of collector should be used in any given area?



or

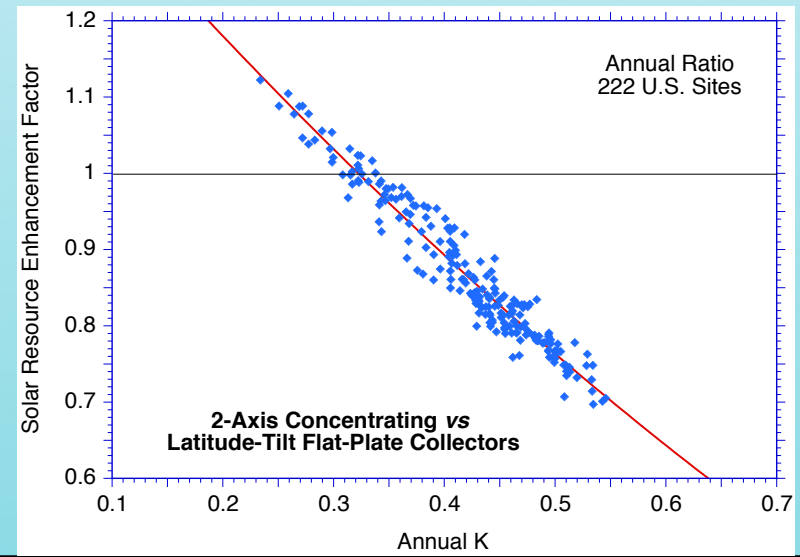
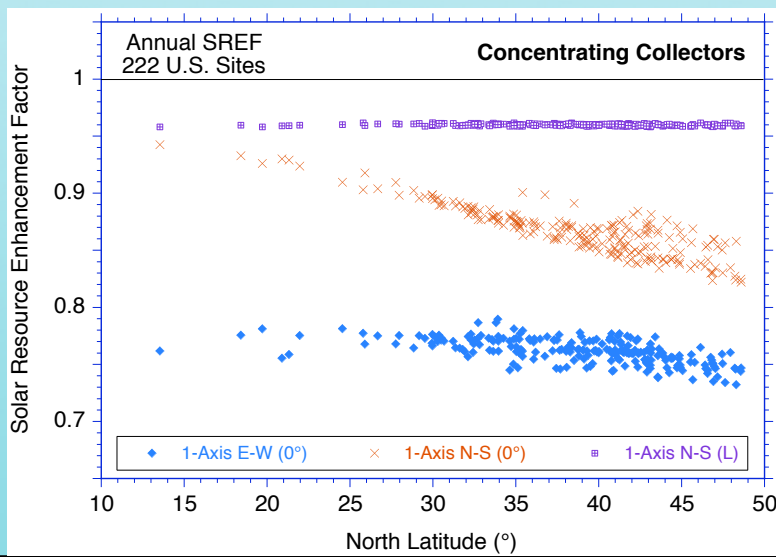


or



???

- For each type of concentrator, **SREF** compares the annual or seasonal resource in relative terms.
- 1-axis tracking can approach the resource of 2-axis tracking **only if** collectors are oriented N-S and tilted at latitude. 1-axis troughs oriented E-W have a much reduced resource.
- 2-axis tracking concentrators have a better resource than latitude-tilt flat-plates only in very sunny areas.

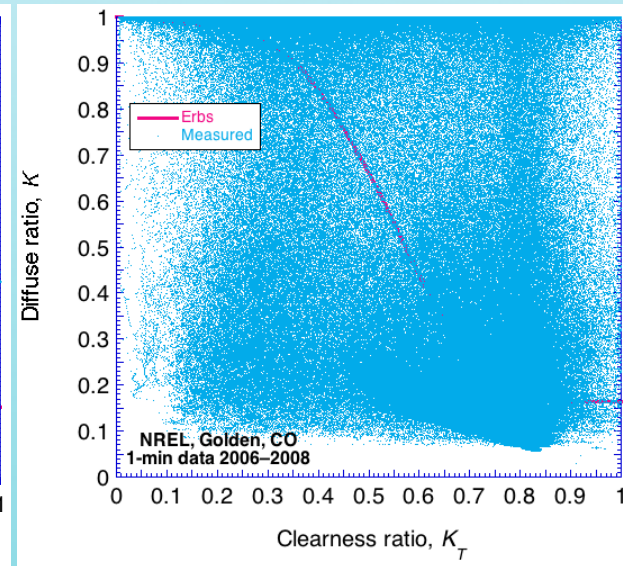
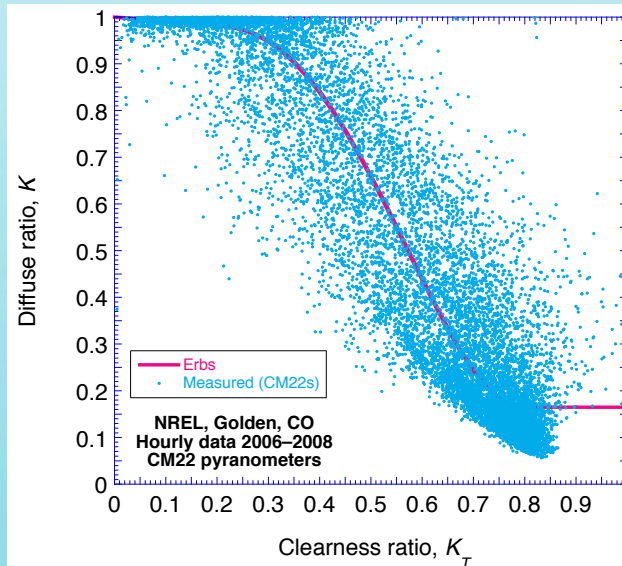
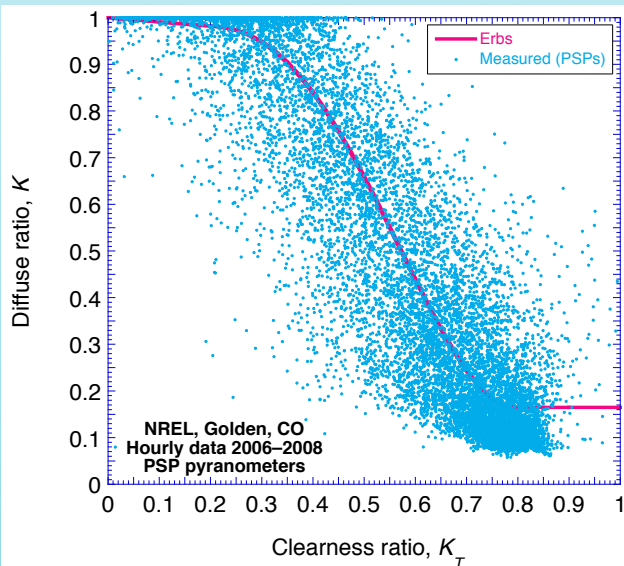
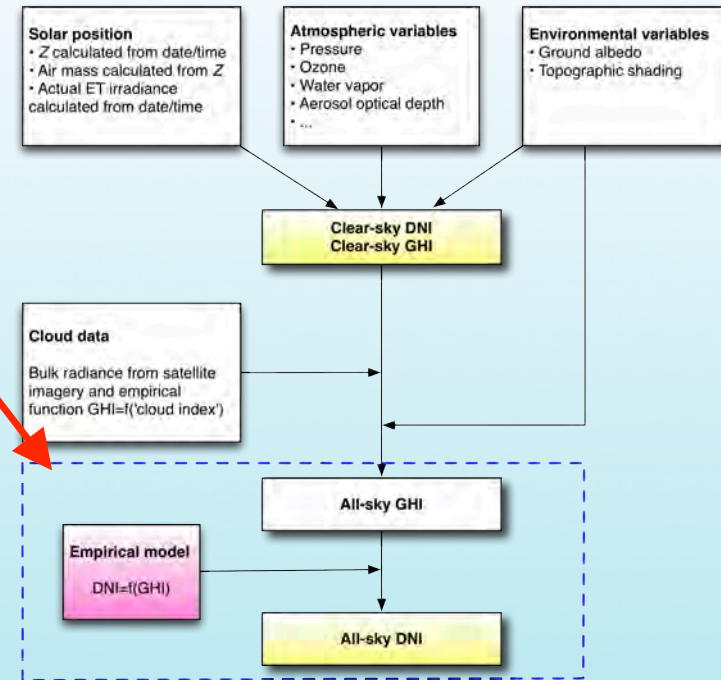


# Challenges

1. Improve DNI modeling: from *empirical* to *physical* derivation
2. Improve radiative transfer modeling through clouds: 3D, shading effects...
3. Improve aerosol data
4. Improve refresh frequency of surface reflectance data: Snow, ice...
5. Understand why solar resource datasets differ so much!
6. Evaluate future trends in solar resource, in relation with climate change (*dimming vs. brightening*)
7. Increase availability, spatial distribution, and quality of public-domain ground-truth measurements of aerosols and solar irradiance
8. Harmonize validation methods; standardize uncertainty reporting, TMY derivation
9. Validate, *validate*, **validate**! Aerosol data, modeled irradiance time series, TMYs, forecasts, ...
10. Standardize bankability requirements and methods
11. Improve awareness about desirable expertise and credentials  
Developers and banks tend to trust “big names” (engineering firms or consultants in solar technology), who may not know much about solar resource issues.
12. Accuracy is not always welcome: Beware of special interests!

# DNI Modeling

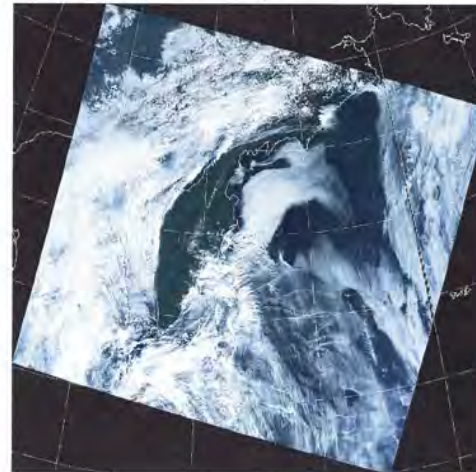
- Inaccurate empirical derivation of DNI from GHI
- Explains large random errors in hourly or sub-hourly DNI/GTI from current satellite-derived datasets
- Future solution: Use more sophisticated *physical* modeling



# Physical Radiative Modeling

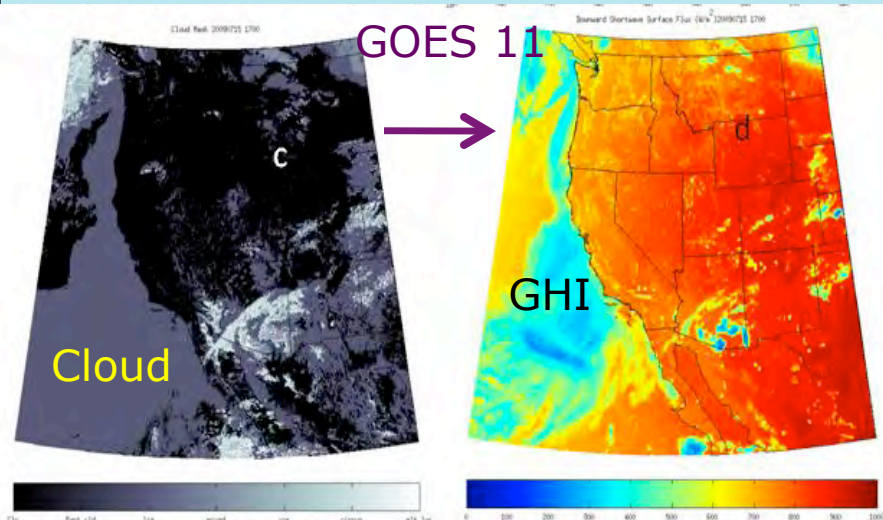
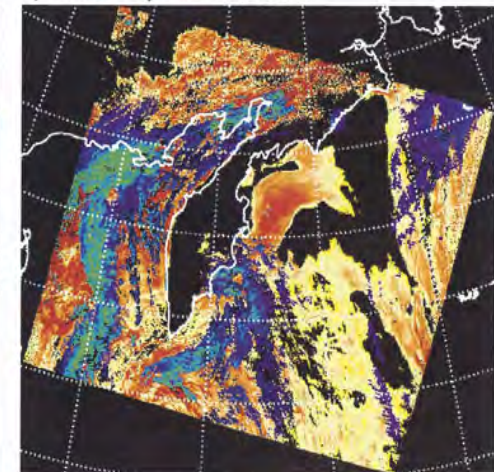
- Requires cloud retrieval information (layer cloud cover, ice/water cloud optical depths...) and surface optical properties (vegetation, temperature...) rather than visible radiance data: more complexity.
- Example: GSIP, based on GOES real-time data. Encouraging initial validation...
- Reanalysis data can provide historical time series of various atmospheric constituents.
- NWP and mesoscale models now used for cloud and solar radiation forecasts

a)  $R(0.645, 0.555, 0.469)$



MODIS view over Kamchatka

b) Cloud Optical Thickness

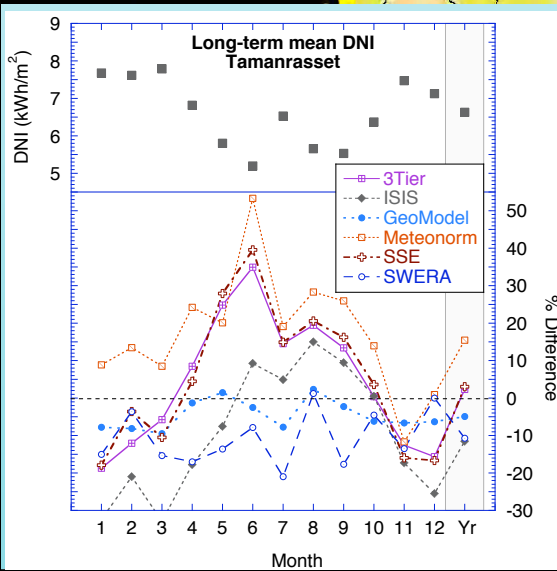
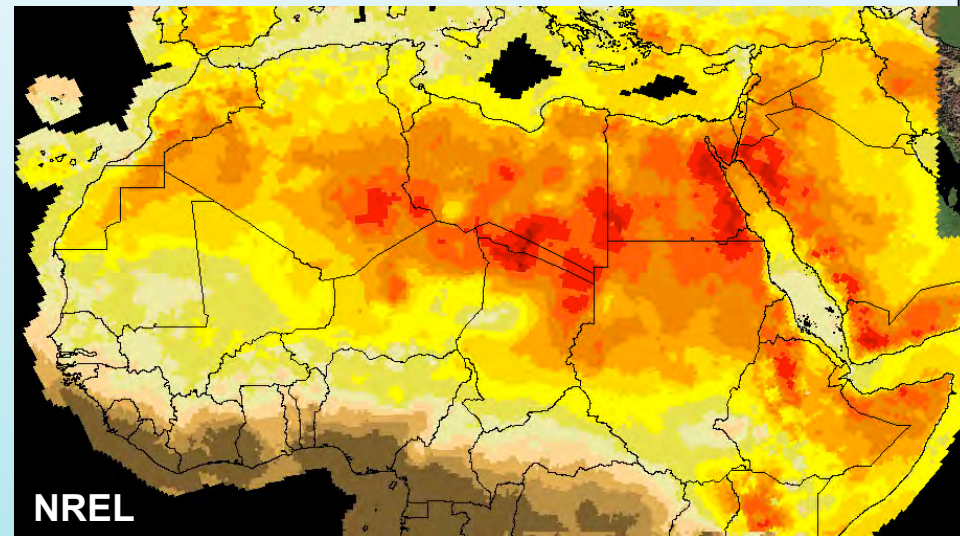
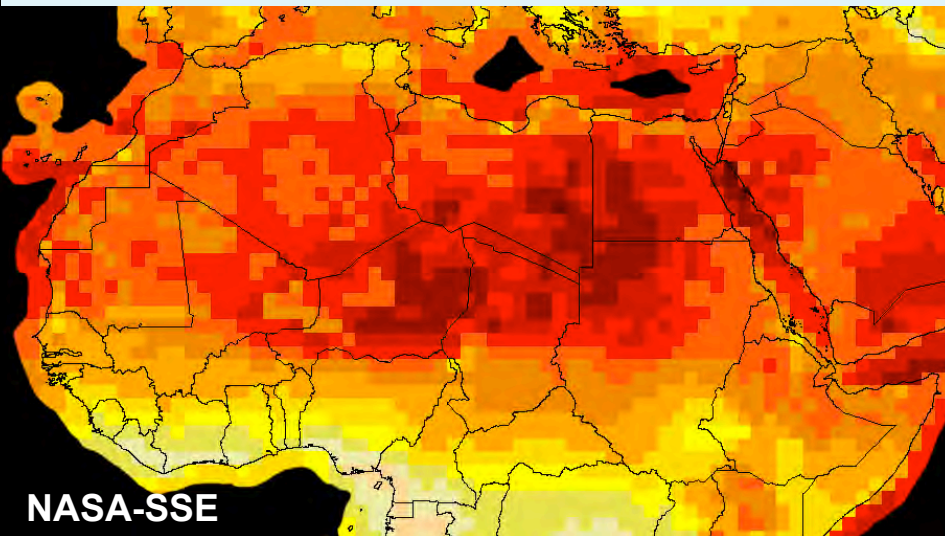


Convergence with meteorology/  
climate/atmospheric sciences



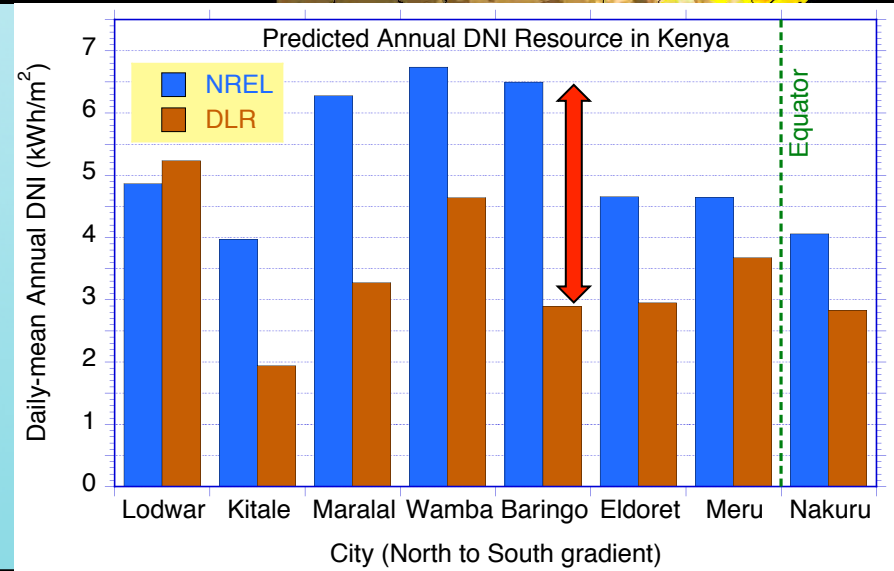
# Differences in Resource Maps (1)

Large differences between solar resource maps (particularly DNI), and between modeled and measured data, over many areas.



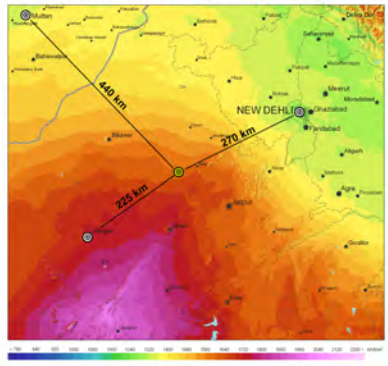
**Sahara**  
Large monthly and annual errors in all datasets: Inaccurate aerosol data, etc.

**Kenya**  
NREL vs. DLR:  
up to 50% differences

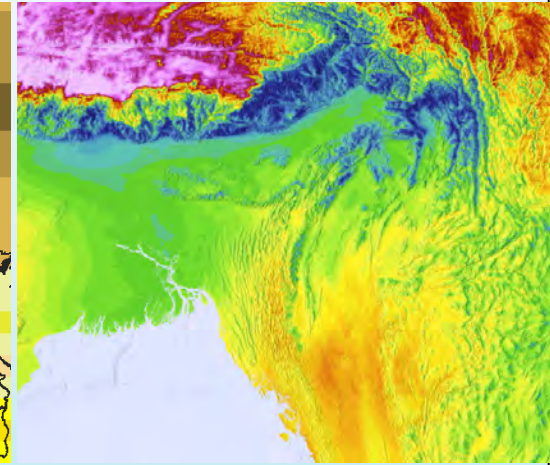
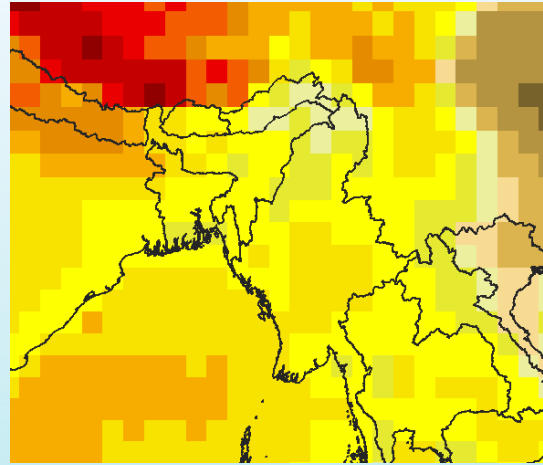


# Differences in Resource Maps (2)

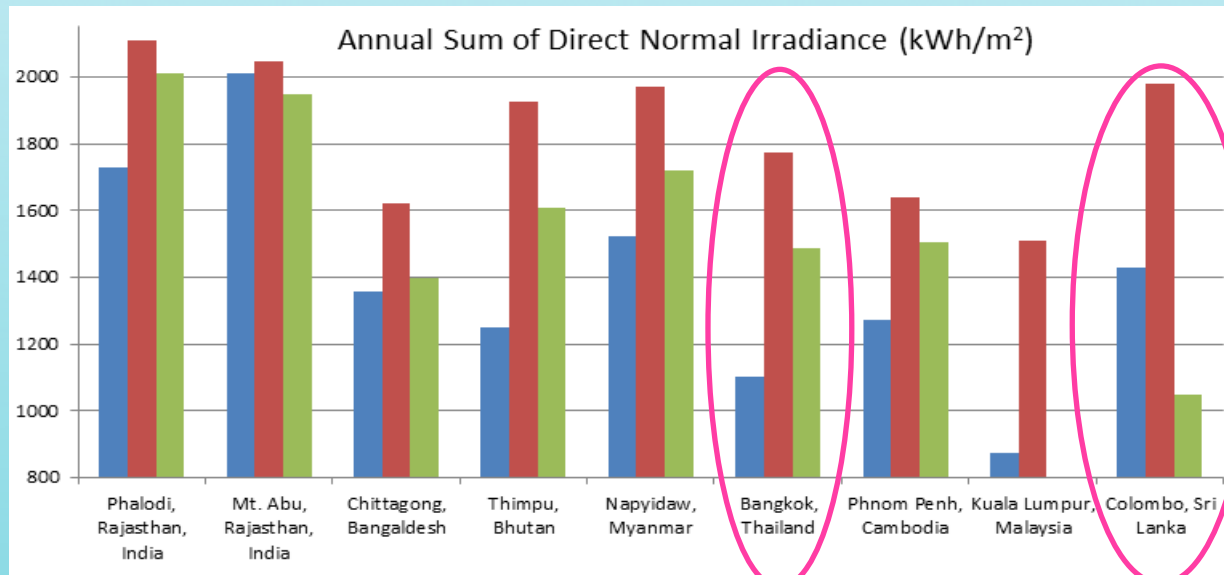
- Large differences in DNI resource maps in Asia
- Obvious effect of spatial resolution; interpolation methods too risky.



**Eastern India**  
Low- vs. high-  
resolution data



- No public-domain HQ radiation measurements there: Serious validation nearly impossible.
- Radiation climate changes rapidly: urbanization, pollution, dust, etc.
- Resource for CSP may not be as high as most developers expect (monsoon, dust, etc.).
- DNI's negative trend: 1–10% per decade (*dimming*).
- Resource often evaluated as simple average or interpolation of low-resolution (free) data.
- Gross performance mis-predictions can be expected in many cases!



# Uncertainty in Modeled Irradiance

- Typical **bias** achievable globally with the **best** satellite-based data sources:
  - < **±3%** for GHI (**±5% or more** over difficult areas)
  - < **±7%** for DNI (**±15% or more** over difficult areas)
- Typical hourly **RMSD** achievable in **semi-arid regions** with the **best** data sources:
  - < **14%** for GHI, < **25%** for DNI
- Only **experts** can tell which would be the best data source over a given area!
- Sources of uncertainty:
  1. Systematic features in simplified/empirical parts of the radiative model (lack of physics)
  2. Oversimplification of the cloud index method for some types of clouds, 3D effects, ...
  3. Local issues: complex terrain, costal zones, mountains, urban/industrial polluted areas
  4. High-albedo surfaces misinterpreted as clouds
  5. Satellite imagery: Spatial resolution, mislocation
  6. Ground (pinpoint) observations vs. area-averaged values from satellite cloud data
  7. Poor time and/or spatial description of local variability in atmospheric or cloud data
  8. Errors in measured data used for validation: miscalibration, no regular cleaning, inadvertent shading, instrument malfunction, data gaps, lack of QC...
- Highest uncertainty zones: temperate/cloudy climates, complex terrain, high-AOD (hazy/turbid) areas (particularly for DNI).

# Uncertainty in Modeled DNI

## Hourly DNI

Variable	Clear sky	Scattered clouds	Cloudy/overcast
Elevation, shading	very low	very low	very low
Clear-sky model	low	very low	very low
Aerosols	high	low	very low
Water vapor	low	very low	very low
Cloud index	low	moderate	very low

## Annual DNI

Variable	Humid tropics	Arid & semi-arid	Temperate climate	Steep terrain	Snow & ice	Costal zones	Polluted areas
Elevation, shading	very low	very low	very low	low		very low	very low
Clear-sky Model	very low	very low	very low	very low	low	very low	low
Aerosols	low	high	low	medium		low	high
Water vapor	very low	very low	very low	low		very low	very low
Cloud index	medium/high	low	medium	low	medium	low	low

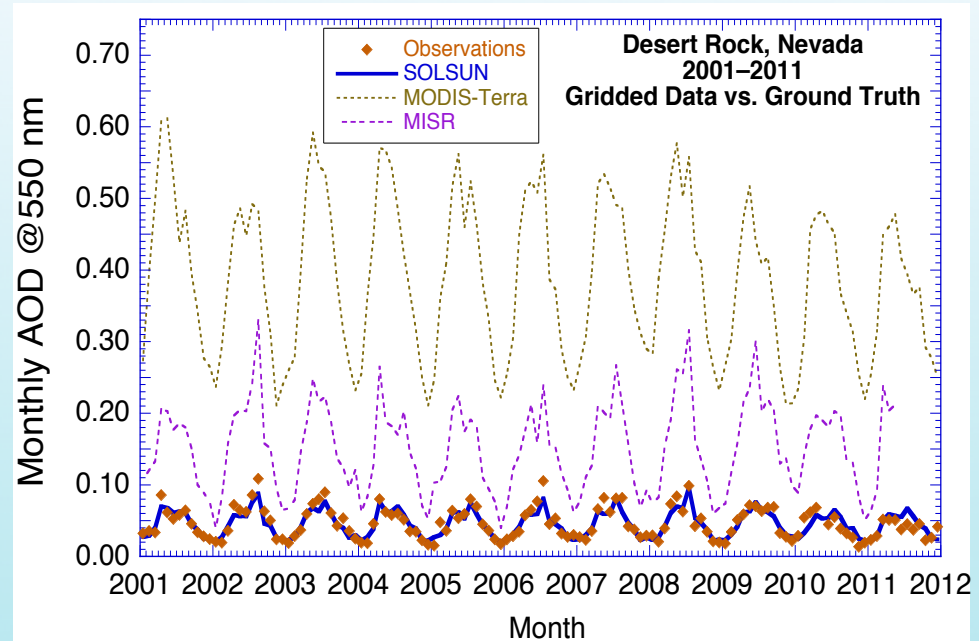
# Aerosol Issues

- Over arid areas, AOD largest source of uncertainty in DNI and GTI.
- Not enough HQ ground observations
- Satellite observations and chemical transport models still have significant biases
- Difficult quantification of AOD-to-DNI error propagation
- Need for improved data quality over many regions (sun belt)
- Need for higher spatial resolution
- Need for HQ daily AOD data, 1980–now
- Need for good AOD forecasts.

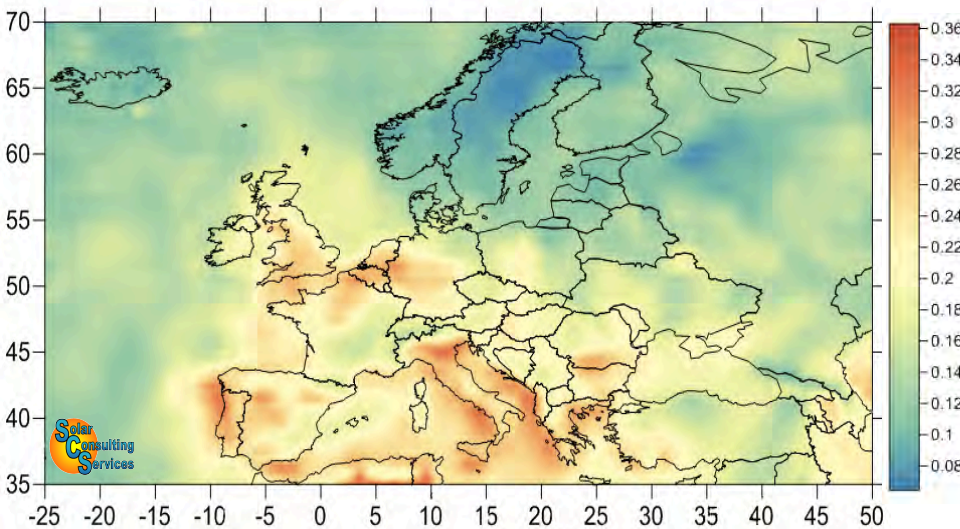


# SOLSUN AOD Database

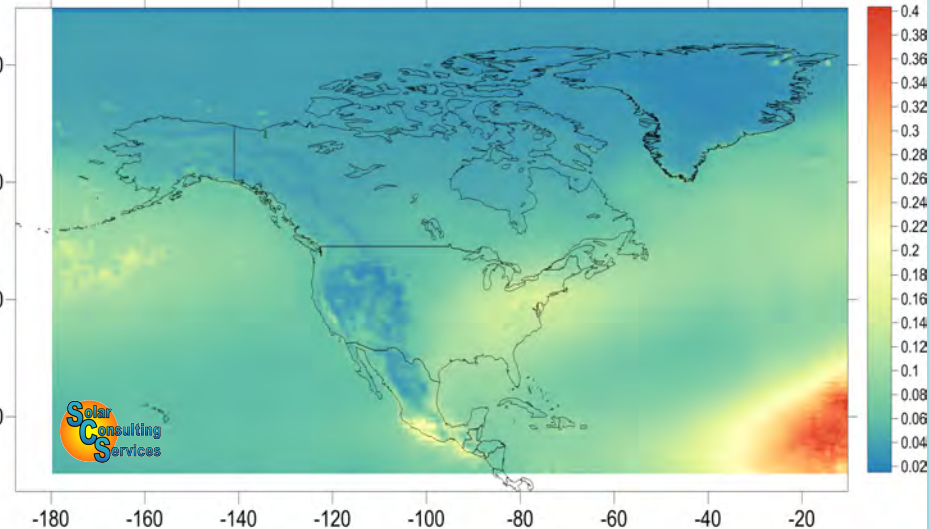
- Calibrated aerosol data (monthly, 2000–2011) for the world, 0.5x0.5° resolution
- Huge improvement over existing satellite data in many areas (SW USA...)
- Commercial product for solar resource data providers, climate research, etc.
- Available soon (*contact us*)



AOD550, Europe, Aug. 2003 (*heat wave, fires*)



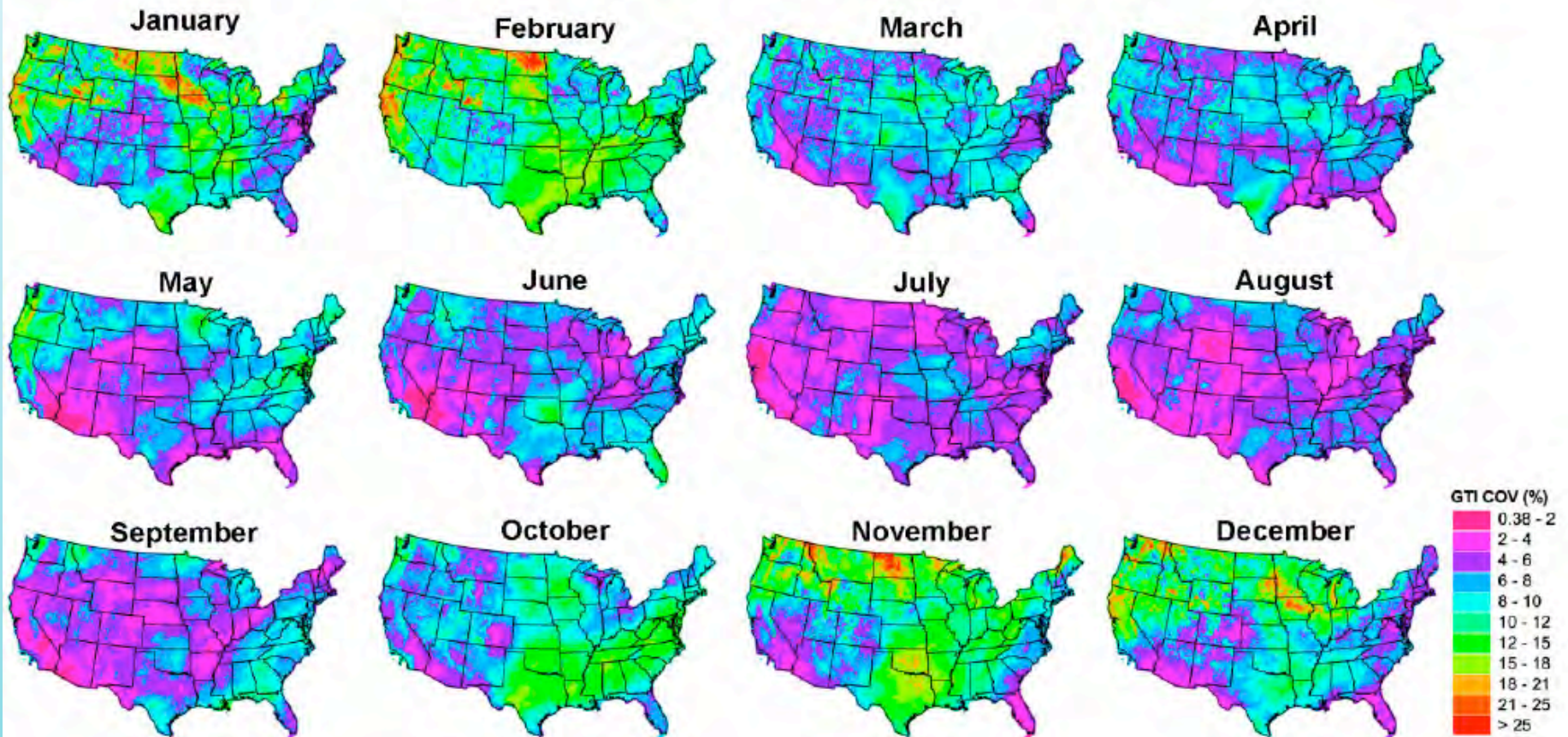
AOD550, North America, 2000–2011 Avg.



# Interannual Variability

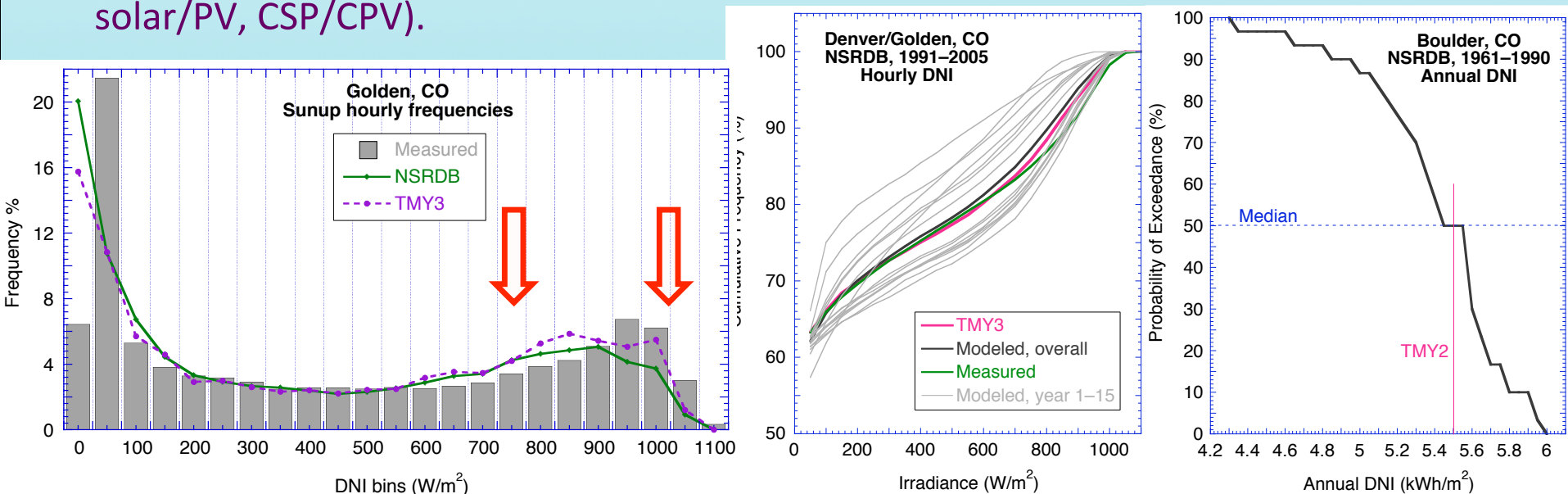
- Monthly variability can change from low (summer) to high (winter)
- Seasonal compensations over the year
- Interannual variability: DNI >> GTI >> GHI.

## Monthly GTI Interannual COV (%) 1998-2005



# TMY Issues

- TMYs are not a panacea!
- TMYs are usually based on  $\approx 100\%$  modeled data. At clear sites, TMY2/TMY3 hourly distributions show significant discrepancies above  $500 \text{ W/m}^2$ .
- Hourly values are used: Not ideal for non-linear systems with thresholds above  $200 \text{ W/m}^2$  (CSP). 1-min to 15-min data desirable, but not accurately modeled.
- TMYs are made to represent average conditions ( $\approx P50$ ); extreme months are *excluded* by design.
- Financial institutions are most interested in worst-case scenarios (P90, P95, P99), not in P50; bankable reports cannot be obtained from TMY data!
- Lack of standard TMY methodology; specialized TMYs may be needed (buildings, solar/PV, CSP/CPV).



# Local Measurements

- Critical part of solar resource assessment, necessary to sort out local variability effects at different time scales.
- Performance and prices vary...
- Adverse conditions frequently exist (dust, snow, frost, birds...): regular maintenance is essential!
- Minimum measurement period for bankability: 9–12 months.

Short-term observations should be used to correct long-term satellite-based modeled data with appropriate NWP and statistical methods.

⇒ **Only way to guarantee  $\pm 5\%$  accuracy and bankability for CSP/CPV or in “difficult” areas!**

For expert advice: <http://solarconsultingservices.com>

Configuration 1

Cellular Modem

Data Logger

Barometer  
(inside enclosure)

LI-COR Pyranometers  
Primary (shade/un-shade)  
Secondary (un-shaded)

PV Powered

Temp/RH

Wind Set on guyed tower  
and Tipping Bucket Rain  
Gauge (not shown)

