SUNPOWER

Clear sky irradiance and temperature models for mitigating sensor drift in PV system degradation analysis

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PV Performance Modeling and Monitoring Workshop
8th PVPMC, 2017-05-09

Agenda

1. **Introducing clear sky models for PV degradation analysis**
2. Examples of clear sky normalization
3. Static vs dynamic clear sky models

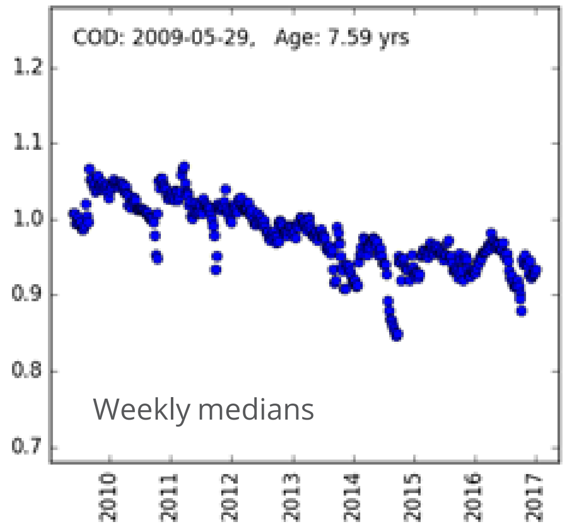
Degradation assessment, method PR_{STC}

- Normalize:
  - Use sensor irradiance and temperature to model expected performance

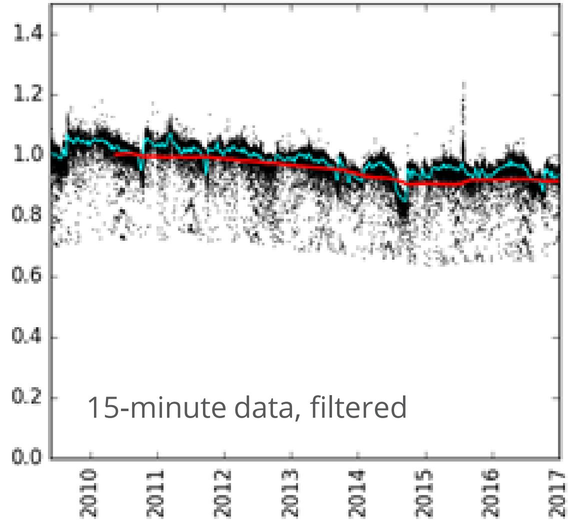
$$PR_{STC} = \frac{[P_{AC}\ (kW)]}{P_{STC,rated} * \frac{\left[Irradiance\ POA\ \left(\frac{W}{m2}\right)\right]}{1000\left(\frac{W}{m2}\right)} * (1 + \gamma_{tempco} * ([T_{cell}] - 25\ °C))}$$

PR_{STC} metric uses irradiance and temperature sensors to normalize power data

PR_{STC}



PR_{STC}

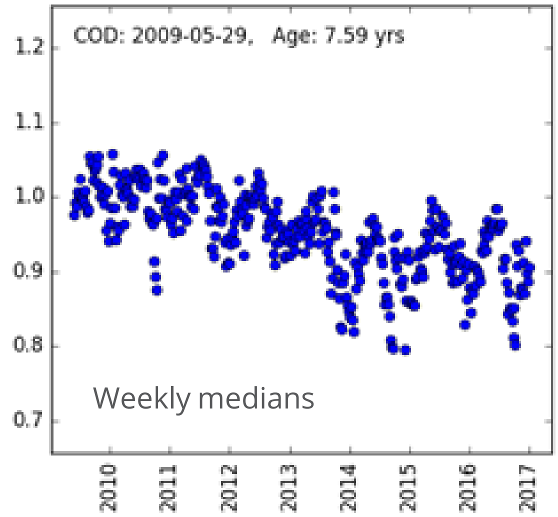


Degradation assessment, method PR_{CS}

- Normalize:
  - Use clear sky irradiance and temperature to model expected performance

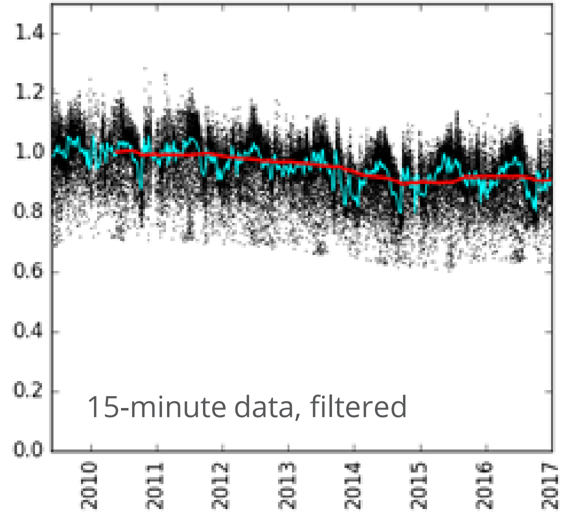
$$PR_{CS} = \frac{[P_{AC}\ (kW)]}{P_{STC,rated} * \frac{\left[Clear\ Sky\ Irradiance\ POA\ \left(\frac{W}{m2}\right)\right]}{1000\left(\frac{W}{m2}\right)} * (1 + \gamma_{tempco} * ([T_{clear\ sky\ cell}] - 25\ °C))}$$

PR_{CS}



PR_{CS} instead uses clear sky models to normalize power data

PR_{CS}

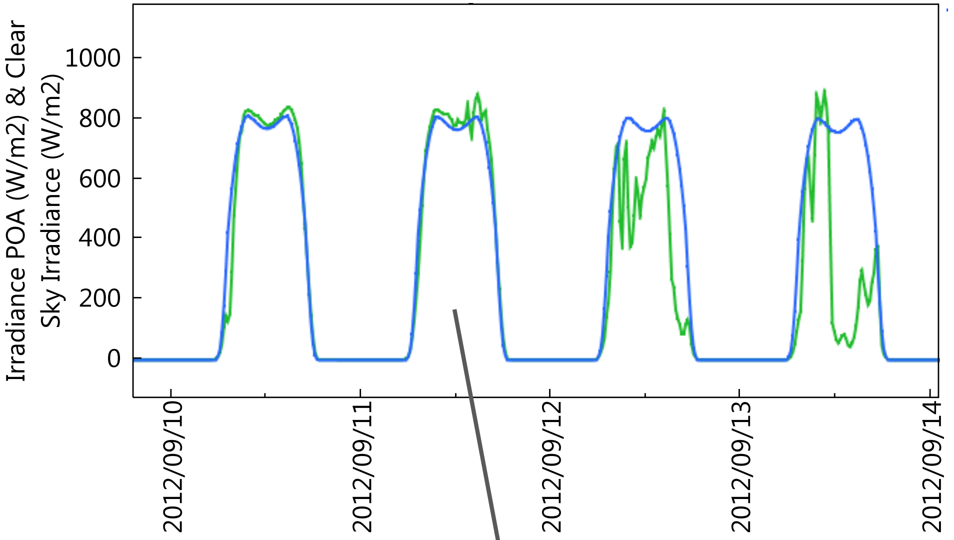


(Sensor data still used for clear sky filtering)

1. Dirk C. Jordan, Chris Deline, Sarah R. Kurtz, Gregory M. Kimball, Mike Anderson, "Robust PV Degradation Methodology and Application", *PVSC*, 2017.

Clear sky irradiance model

Modeled and measured irradiance

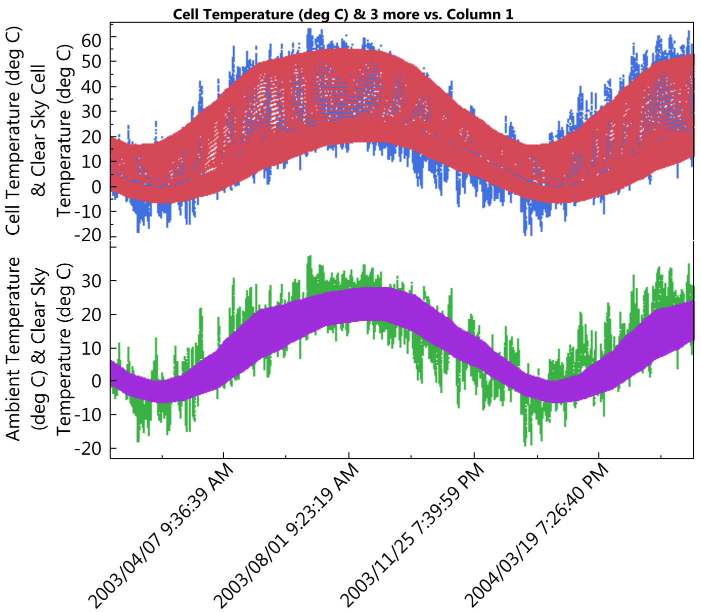


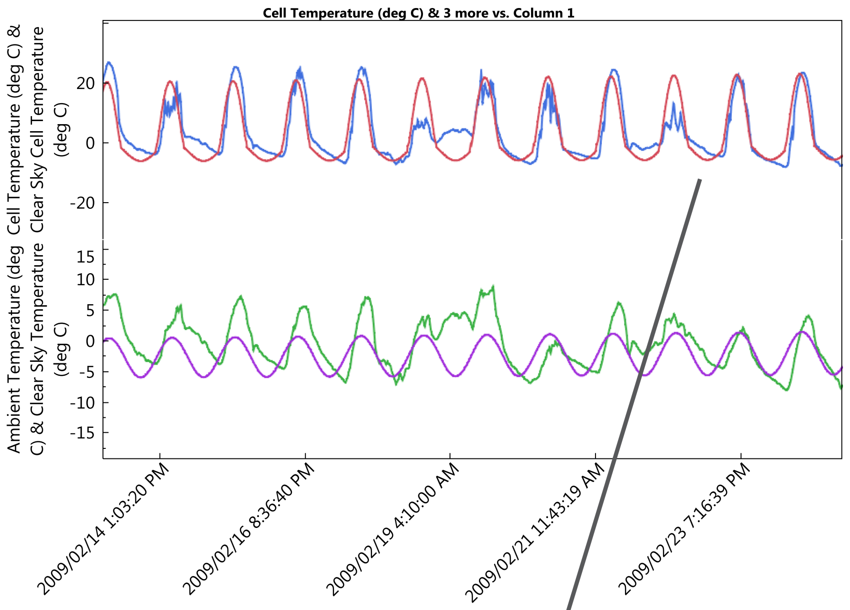
- Clear sky irradiance models report the expected solar resource under clear conditions
- Transposition of the data converts to plane-of-array (POA) irradiance
- PVLIB provides an open-source clear sky model

$$PR\_CS = \frac{[P_{AC}\ (kW)]}{P_{STC,rated} * \frac{\left[Clear\ Sky\ Irradiance\ POA\ \left(\frac{W}{m2}\right)\right]}{1000\left(\frac{W}{m2}\right)} * (1 + \gamma_{tempco} * ([T_{clear\ sky\ cell}] - 25\ °C))}$$

1. W. F. Holmgren, R. W. Andrews, A. Lorenzo, J. S. Stein. "PVLIB Python 2015". 42nd IEEE Photovoltaics Specialists Conference, 2015.
2. J. S. Stein, W. F. Holmgren, J. Forbes, C. W. Hansen. "PVLIB: Open Source Photovoltaic Performance Modeling Functions for Matlab and Python". 43rd IEEE Photovoltaics Specialists Conference, 2016.

Clear sky temperature model





$$PR\_CS = \frac{[P_{AC}\ (kW)]}{P_{STC,rated} * \frac{\left[Clear\ Sky\ Irradiance\ POA\ \left(\frac{W}{m2}\right)\right]}{1000\left(\frac{W}{m2}\right)} * (1 + \gamma_{tempco} * ([T_{clear\ sky\ cell}] - 25\ °C))}$$

- We introduce clear sky temperature models to report the expected solar cell temperature under clear conditions
- NEO provides average ambient day and night temperature based on climate models
- Cell temperature is a function of ambient temperature and irradiance

Source data from Nasa Earth Observatory, derived from MODIS
Available at: https://github.com/kwhanalytics/rdtools/tree/clearsky_temperature

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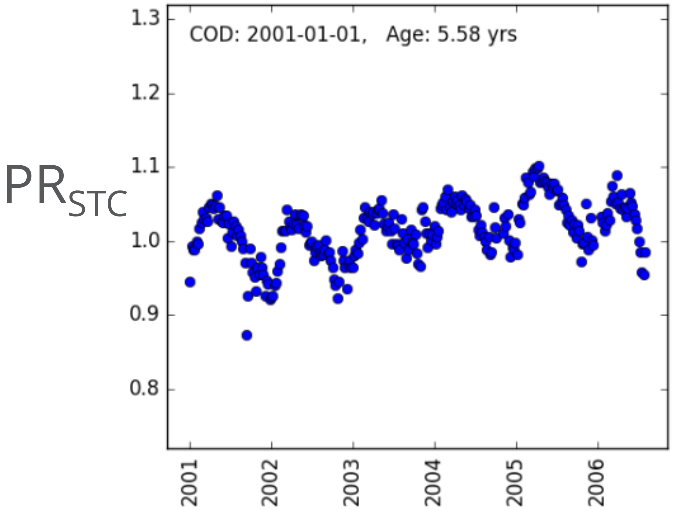
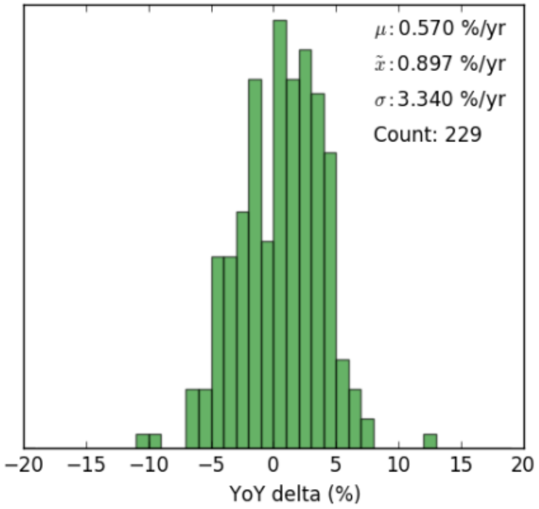
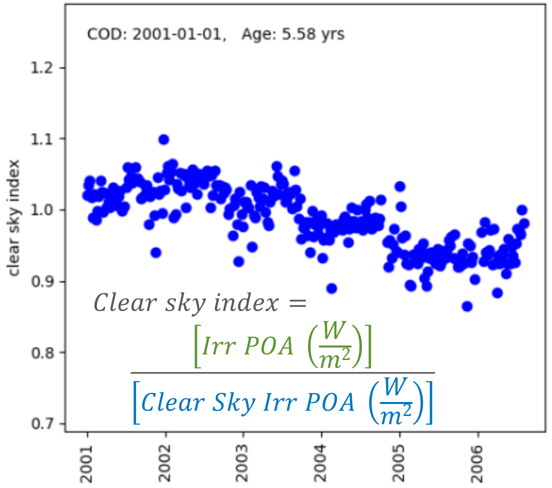
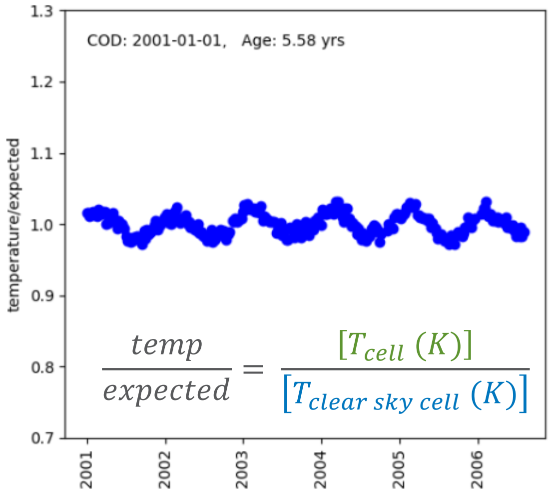
2. **Examples of clear sky normalization**
3. Static vs dynamic clear sky models

Sensor drift and shift, example 1









PR$_{STC}$ shows drift to more positive values

Clear sky index shows decreasing values. Temperature/Expected remains steady.

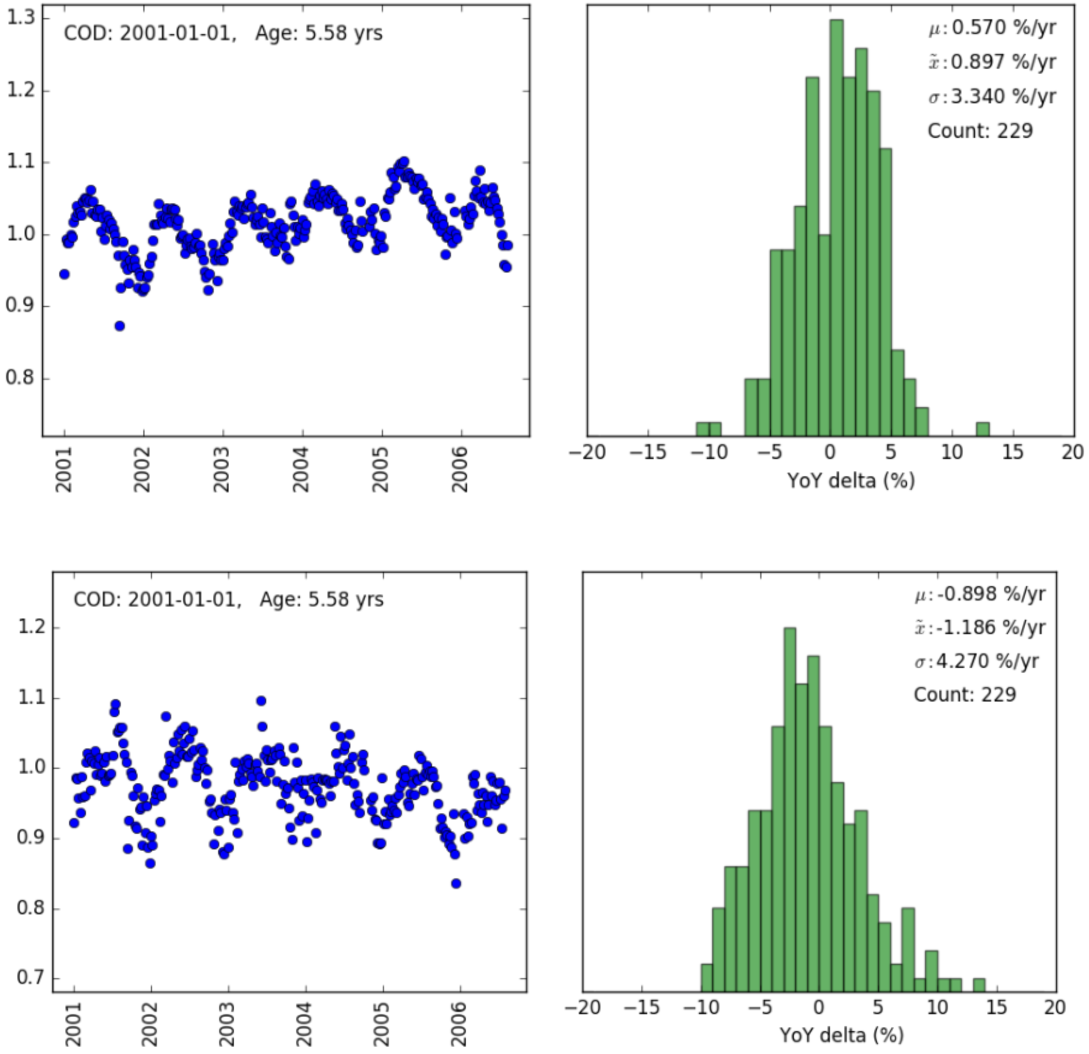
However, sensor drift compromises PR$_{STC}$!

1. Mike Anderson, Zoe Defreitas. "A SunPower Fleet-Wide System Degradation Study using Year-over-Year Performance Index Analysis", *SunPower white paper*, 2012.
2. Mike Anderson, Zoe Defreitas, et al., "A System Degradation Study of 445 Systems using Year-over-Year Performance Index Analysis", *PVMRW*, 2013.

Sensor drift and shift, example 1

PR_{STC}

PR_{CS}



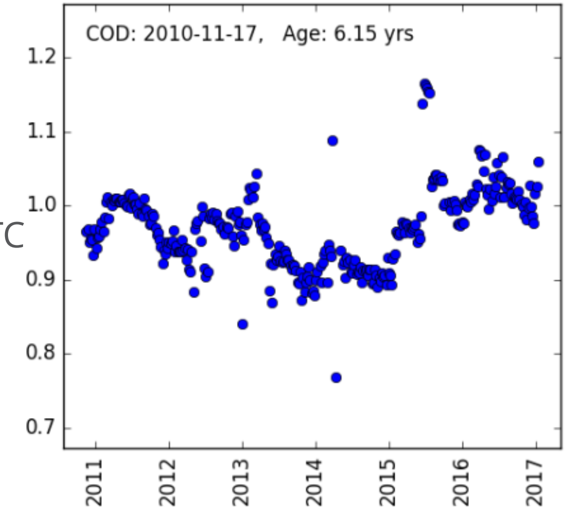
PR_{STC} shows median degradation rate of +0.6 %/yr

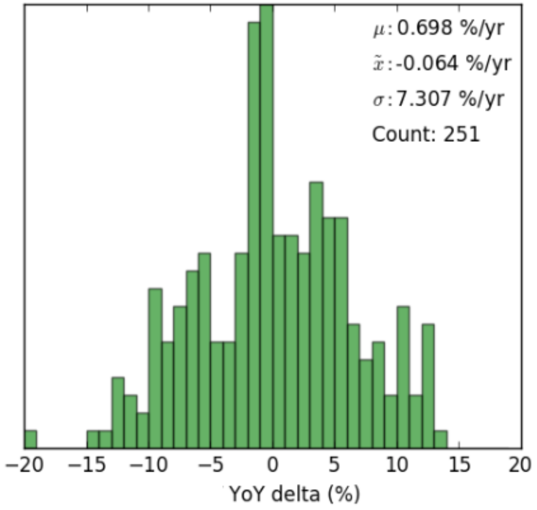
PR_{CS} shows median degradation rate of -0.9 %/yr

PR_{CS} trades precision for accuracy.

Sensor drift and shift, example 2

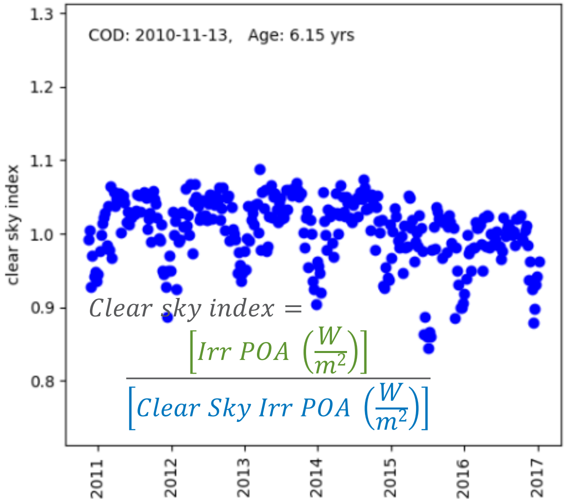
PR_{STC}

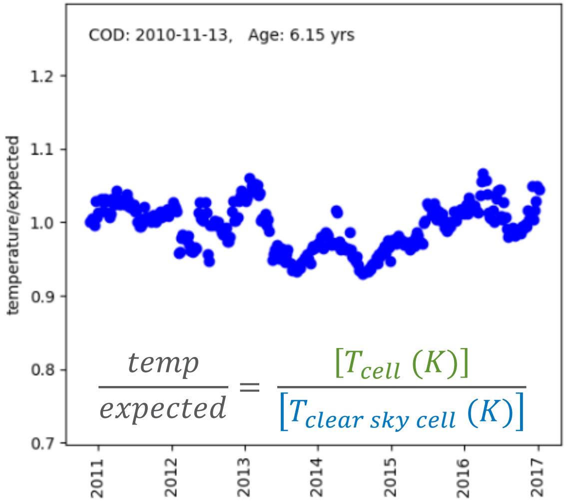




PR_{STC} shows shifts in 2013, 2015, with PR>1 in 2016

Clear sky index shows decreasing values in 2015-2016. Temperature/Expected shifts down in 2013-2015.



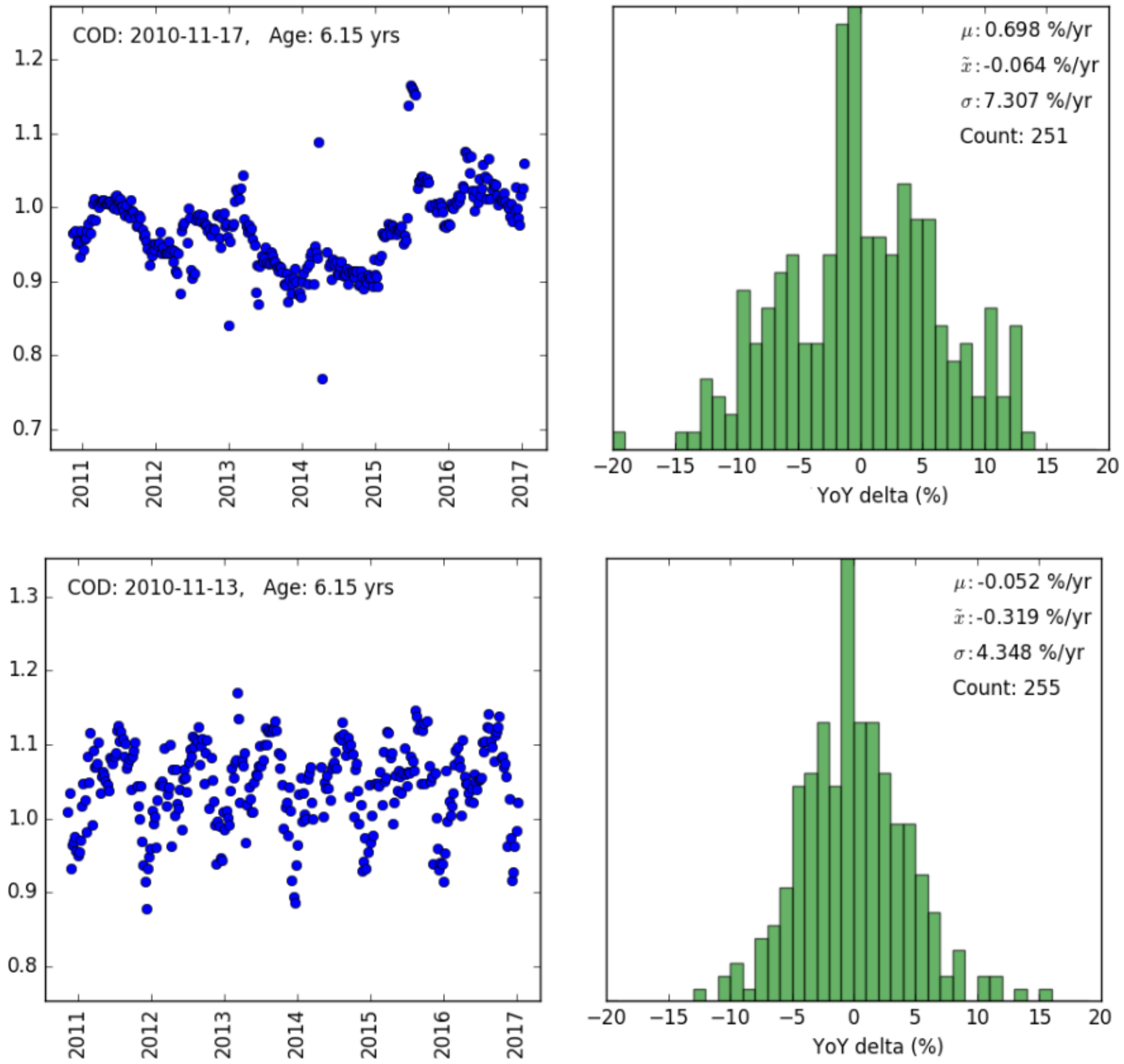


And sensor shifts are just as bad.

Sensor drift and shift, example 2

PR_{STC}

PR_{CS}



PR_{STC} shows shifts in 2013, 2015, with PR>1 in 2016

PR_{CS} shows consistent behavior throughout its history

PR_{CS} trades precision for stability.

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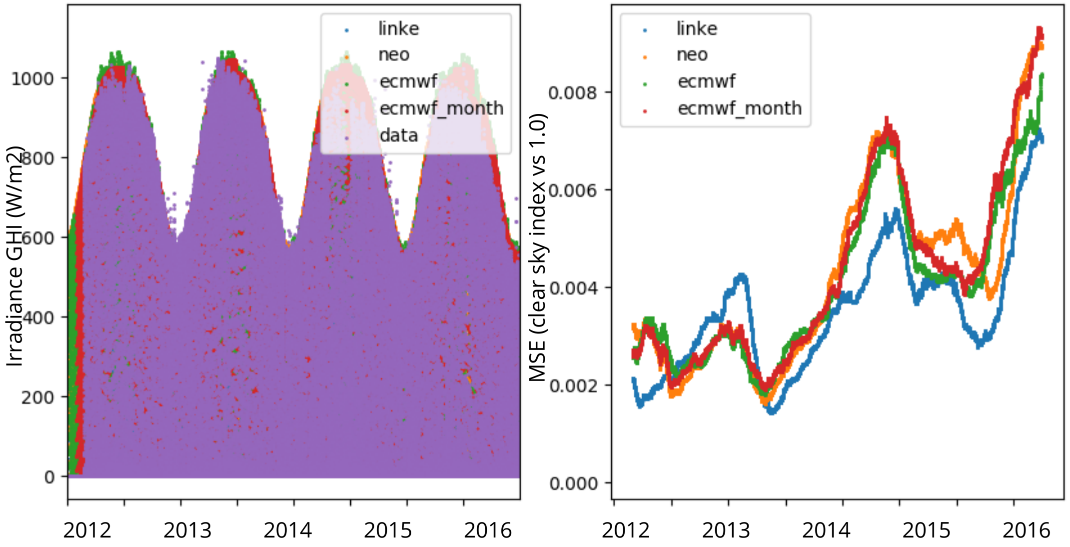
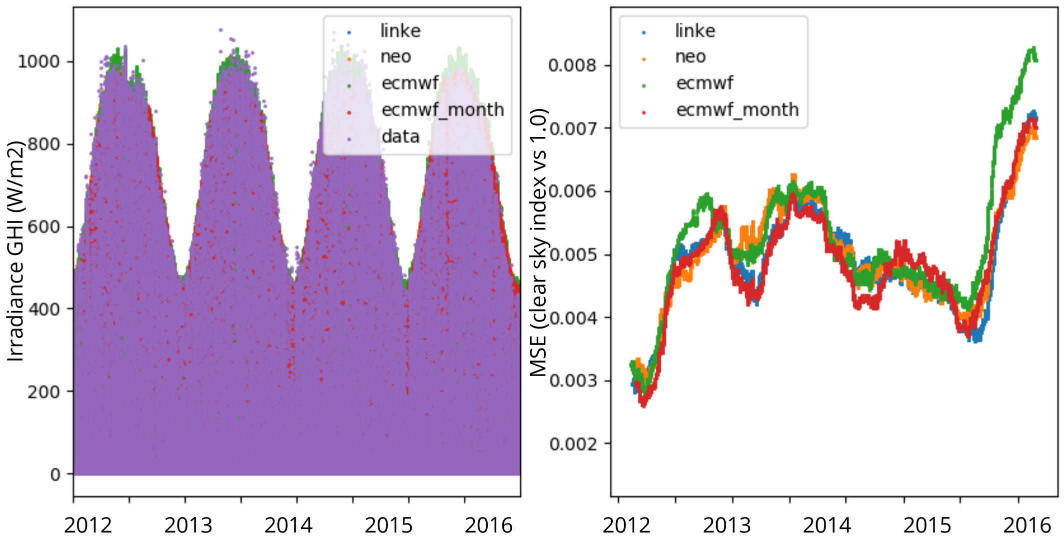
3. **Static vs dynamic clear sky models**

Clear sky irradiance models

Model name	Data source	Model type	Spatial resolution (°)	Temporal resolution	Size
Linke	SoDa, Ineichen	static	0.16	Monthly	20 MB
NEO	NEO/Modis, Solis	dynamic	0.05	Monthly	80 MB/yr
Ecmwf	ECMWF, Solis	dynamic	1	3 hr	130 MB/yr
Ecmwf month	ECMWF, Solic	dynamic	1	Monthly	3 MB/yr

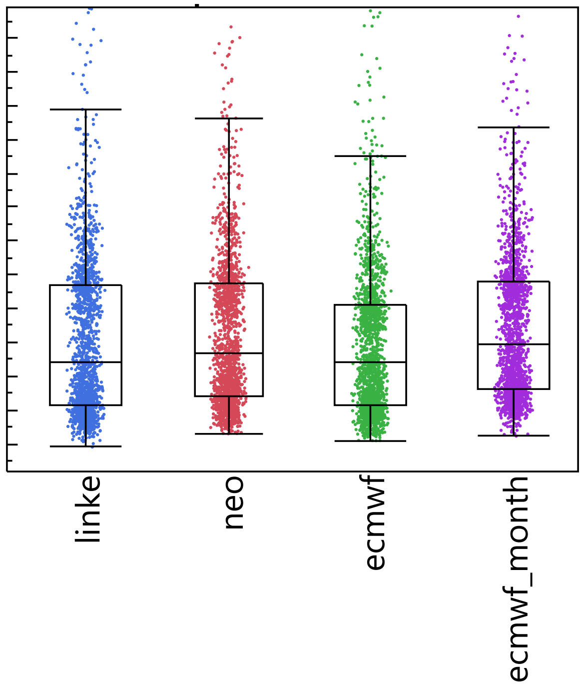


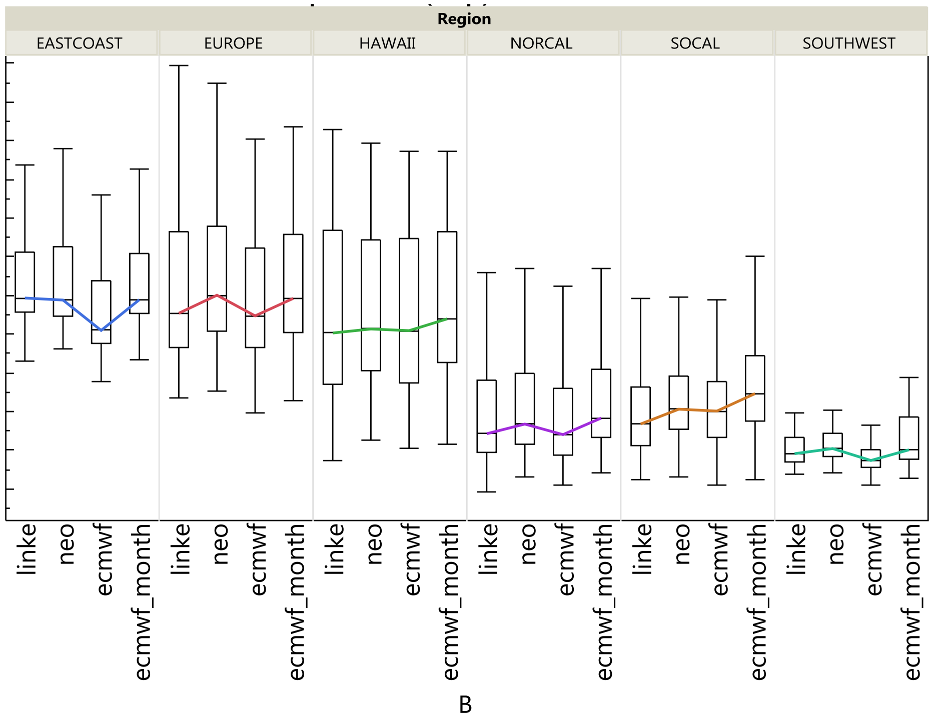


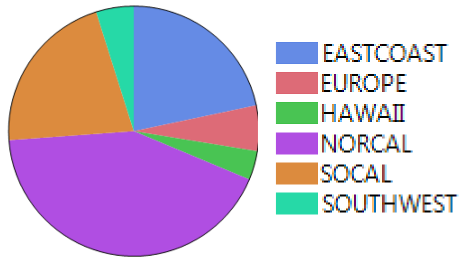
Irradiance model performance

irradiance

MSE (sensor vs model)





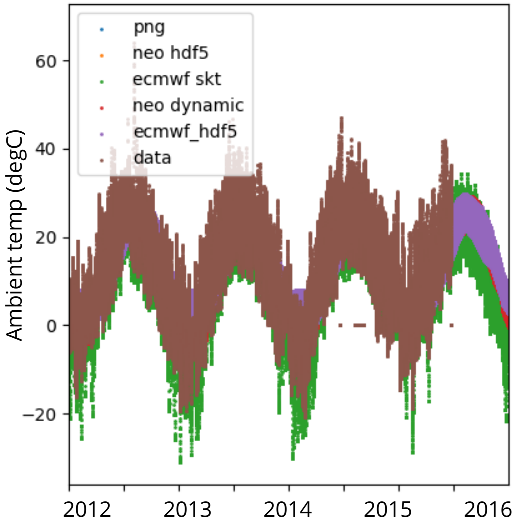


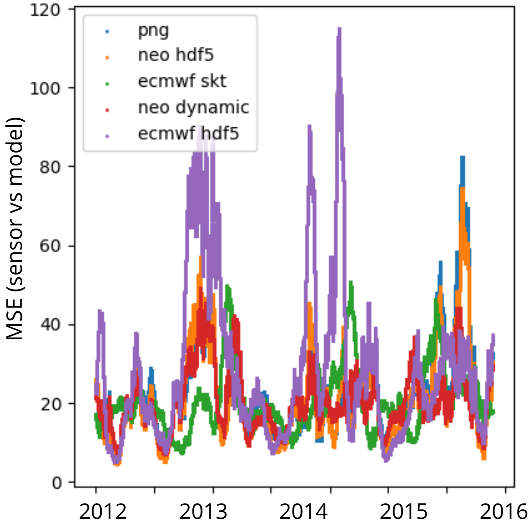
~480 sites evaluated
90% of sites in the US

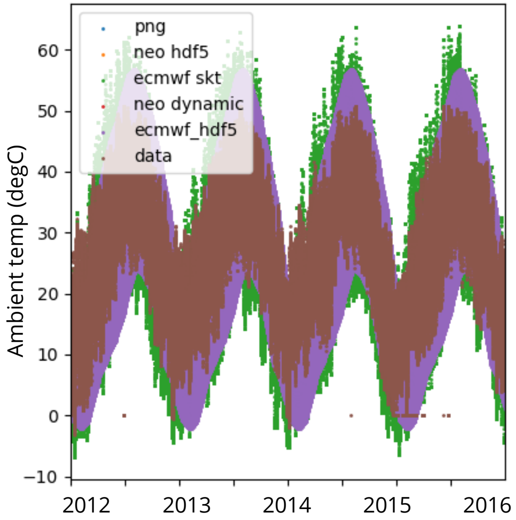
Static models and dynamic models show similar errors versus sensor data

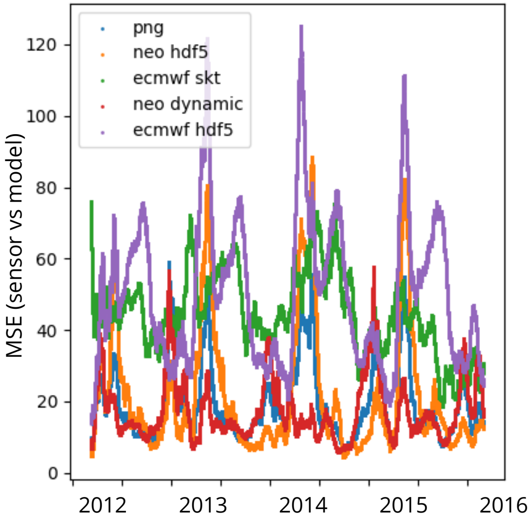
Clear sky temperature models

Model name	Data source	Model type	Spatial resolution (°)	Temporal resolution	Size
png	NEO/Modis	static	0.05	Monthly day/night	22 MB
neo hdf	NEO/Modis	static	0.5	Monthly day/night	6 MB
Ecmwf skt	ECMWF	dynamic	1	3 hr	90 MB/yr
Neo dynamic	NEO/Modis	dynamic	0.05, 1	Monthly day/night	22 MB + 0.2 MB/yr
Ecmwf hdf5	ECMWF	static	1	Monthly day/night	3 MB



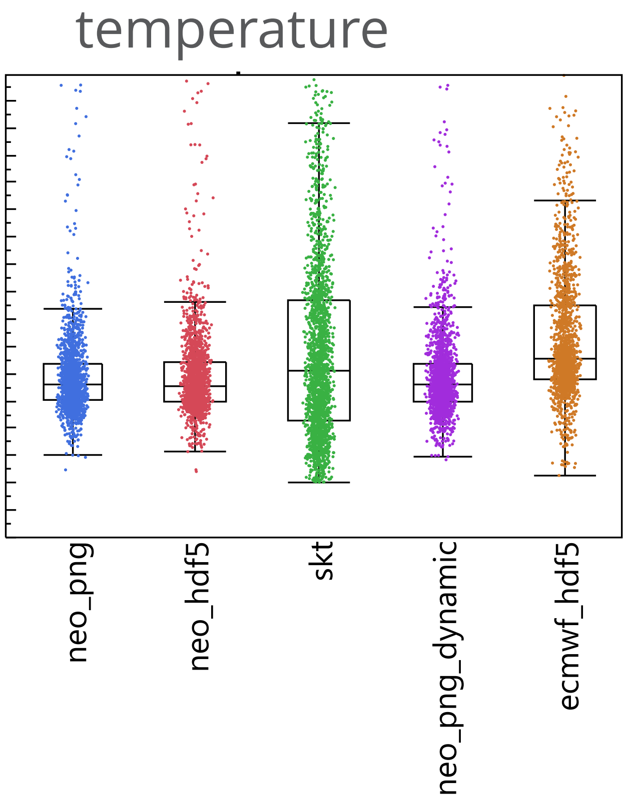


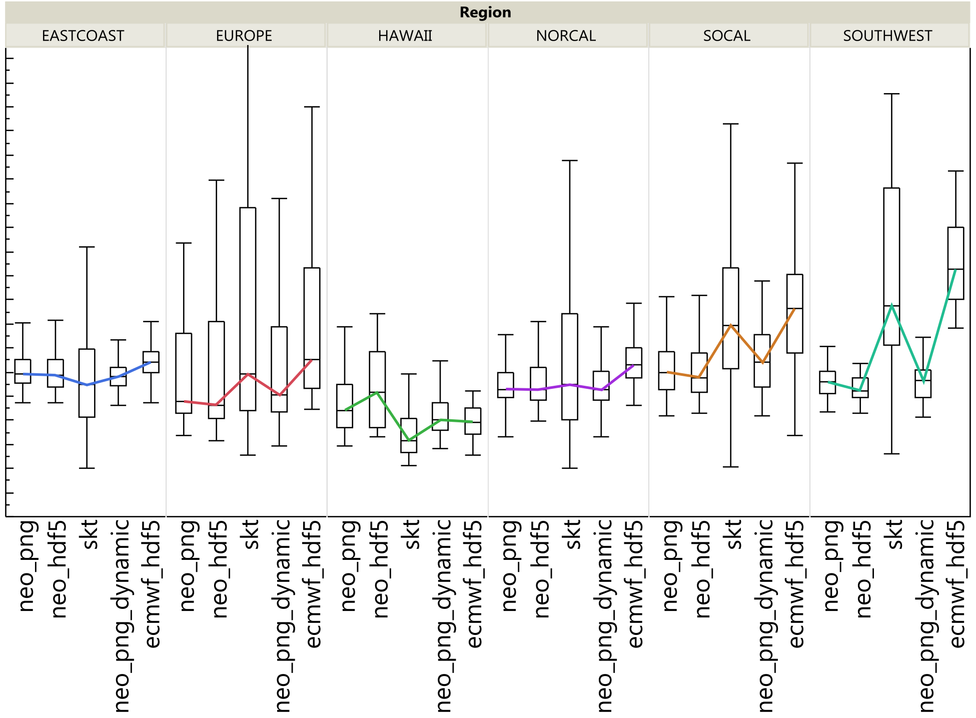


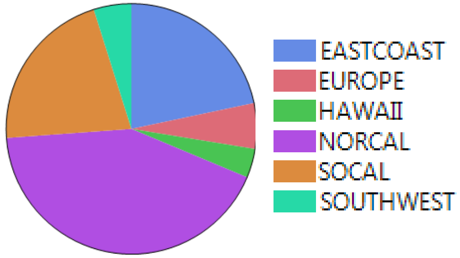


Temperature model performance

MSE (sensor vs model)







~480 sites evaluated
90% of sites in the US

Static models and dynamic models show similar errors versus sensor data

Conclusion

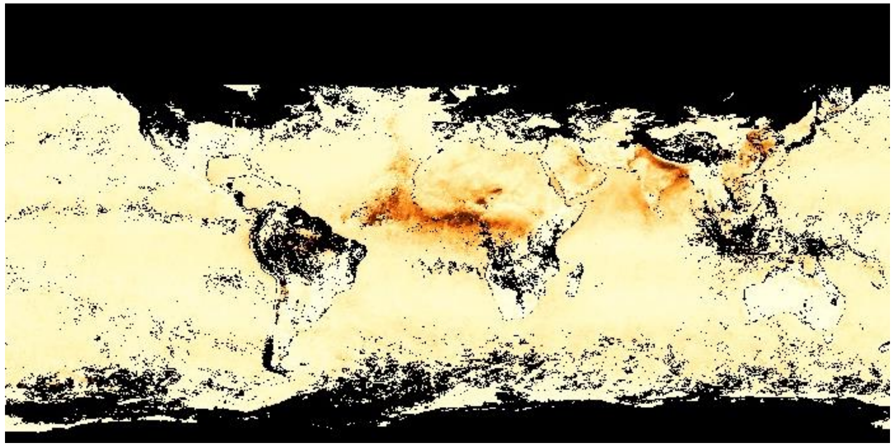
- High quality models are available for clear sky irradiance (thank you PVLIB). We introduce simple models of clear sky ambient temperature (thanks to Nasa, ECMWF).
- Using clear sky models, PV system performance can be analyzed without the effects of sensor drift and degradation.
- For degradation analysis, simple static models appear to perform as well as more complex dynamic models.

The PR_{CS} metric prevents poor sensors from looking like AMAZING performance.

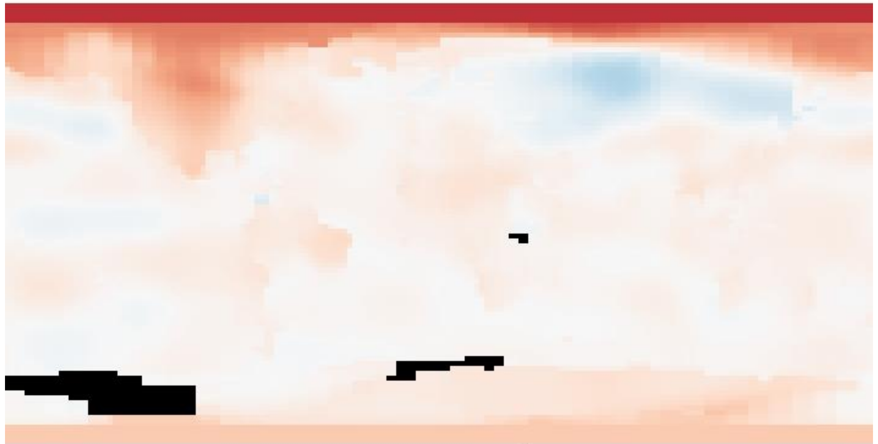
Thank you!

Dynamic clear sky model components

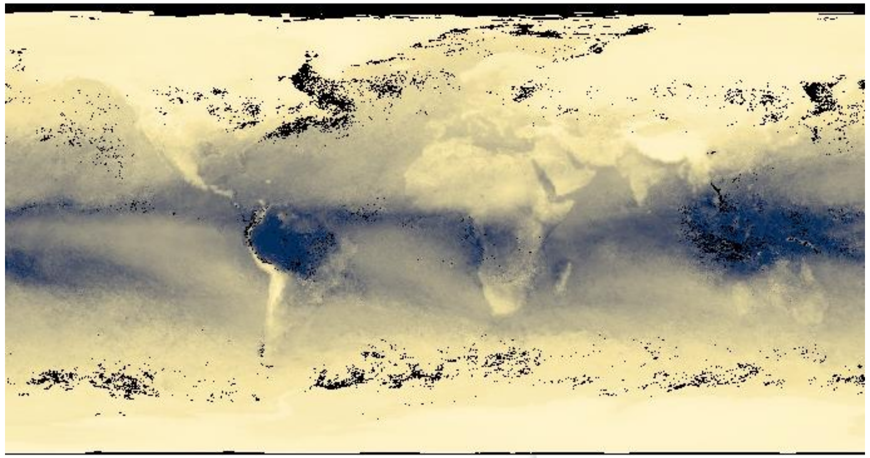
AEROSOL OPTICAL THICKNESS (1 MONTH - TERRA/MODIS)



GLOBAL TEMPERATURE ANOMALY (1 MONTH)



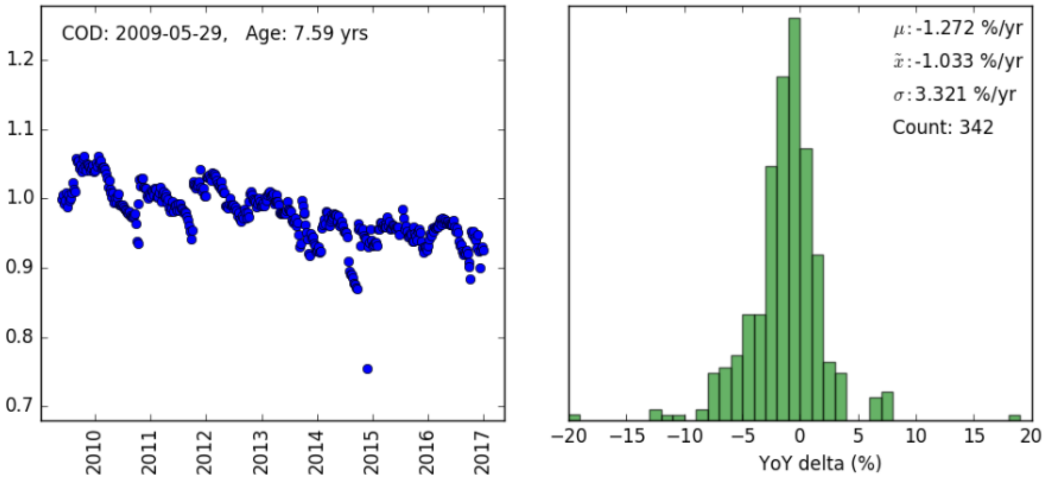
WATER VAPOR (1 MONTH - AQUA/MODIS)



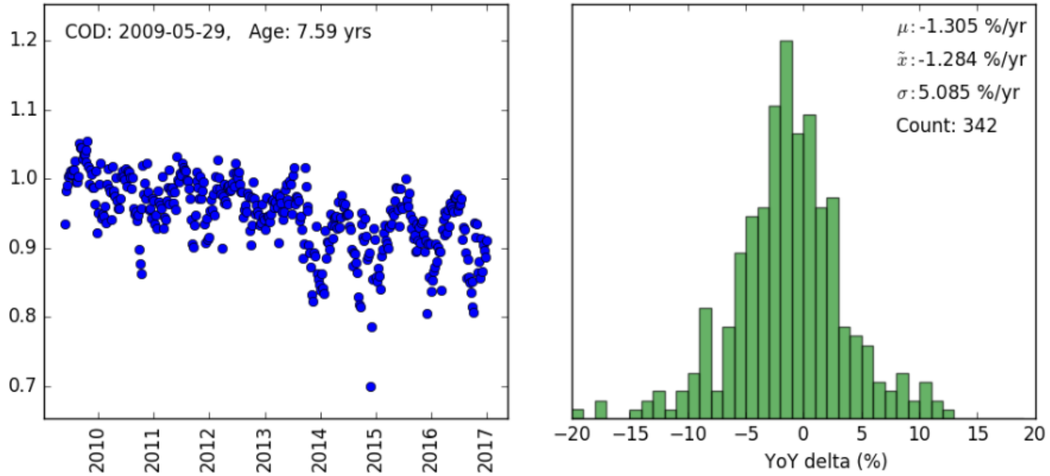
- The dynamic clear sky model uses monthly average data from satellite sources to account for the effect of aerosols, water vapor, and temperature anomaly.
- The model generates values for clear sky irradiance (W/m2) and clear sky temperature (°C) that vary from year-to-year.

Sensors with nominal behavior

PR_{STC}



PR_{CS}



PR_{STC} shows median degradation rate of -1.3 %/yr with σ_{YoY} of 3.3 %/yr

PR_{CS} shows median degradation rate of -1.3 %/yr with σ_{YoY} of 5.1 %/yr

PR_{CS} has lower precision but……