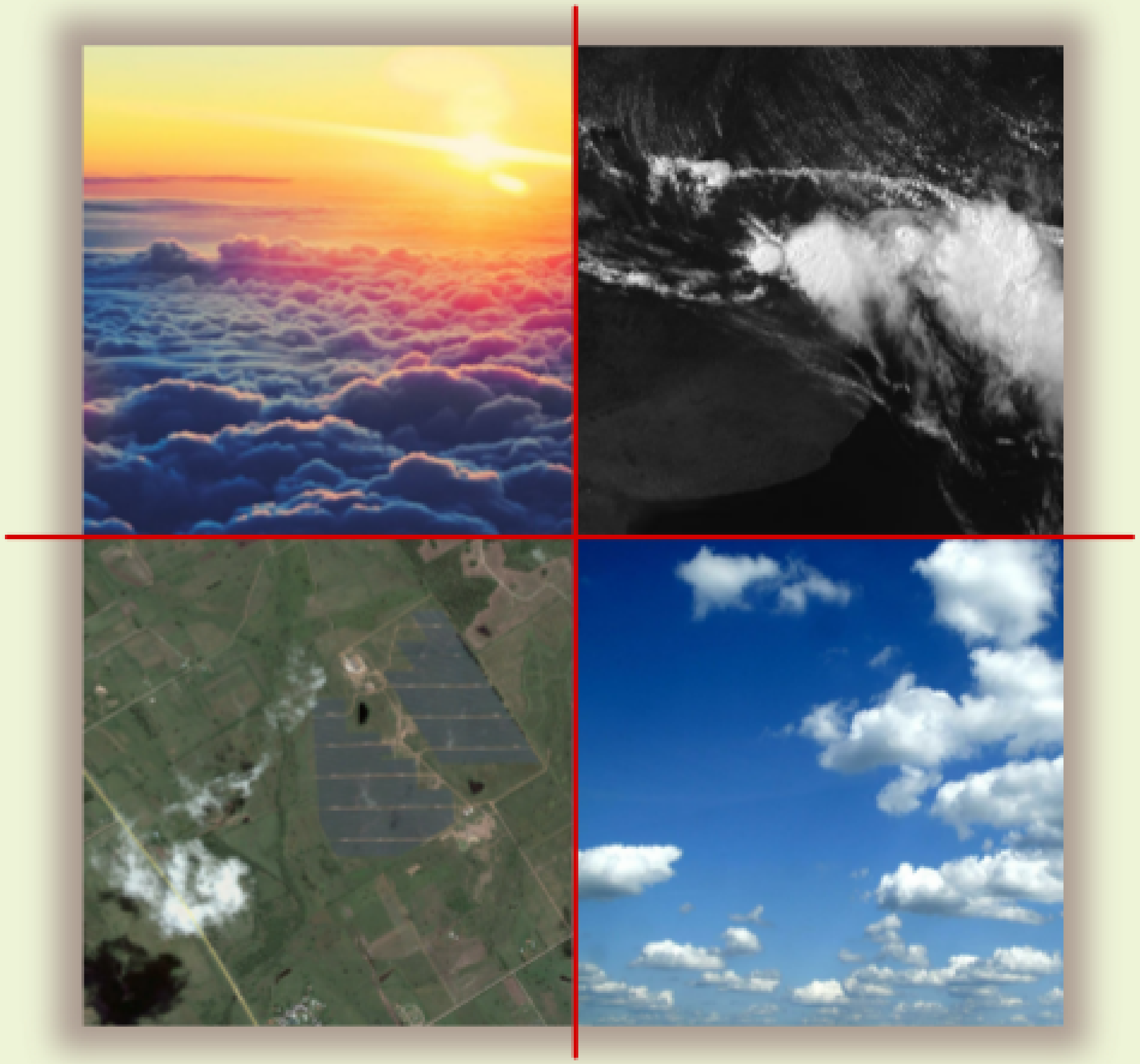
SATELLITE-BASED SOLAR RESOURCE ASSESSMENT



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LABORATORIO DE ENERGÍA SOLAR
UNIVERSIDAD DE LA REPÚBLICA

AGENDA

URUGUAY'S SOLAR ENERGY LAB

Uruguay's Background:

Some general information

~3.2 millon people (~5% of france)

176.000 km² (~ 1/3 of france)

Mostly plain, temperate climate

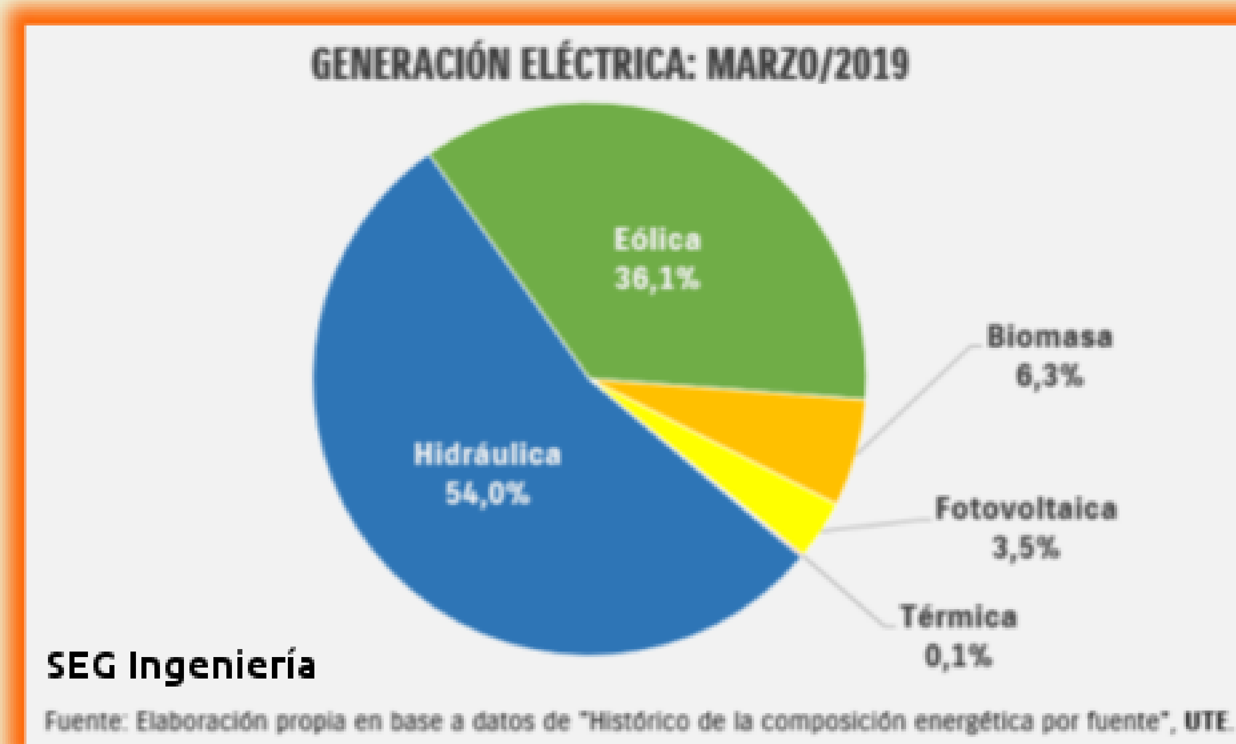
Uruguay's countryside landscape

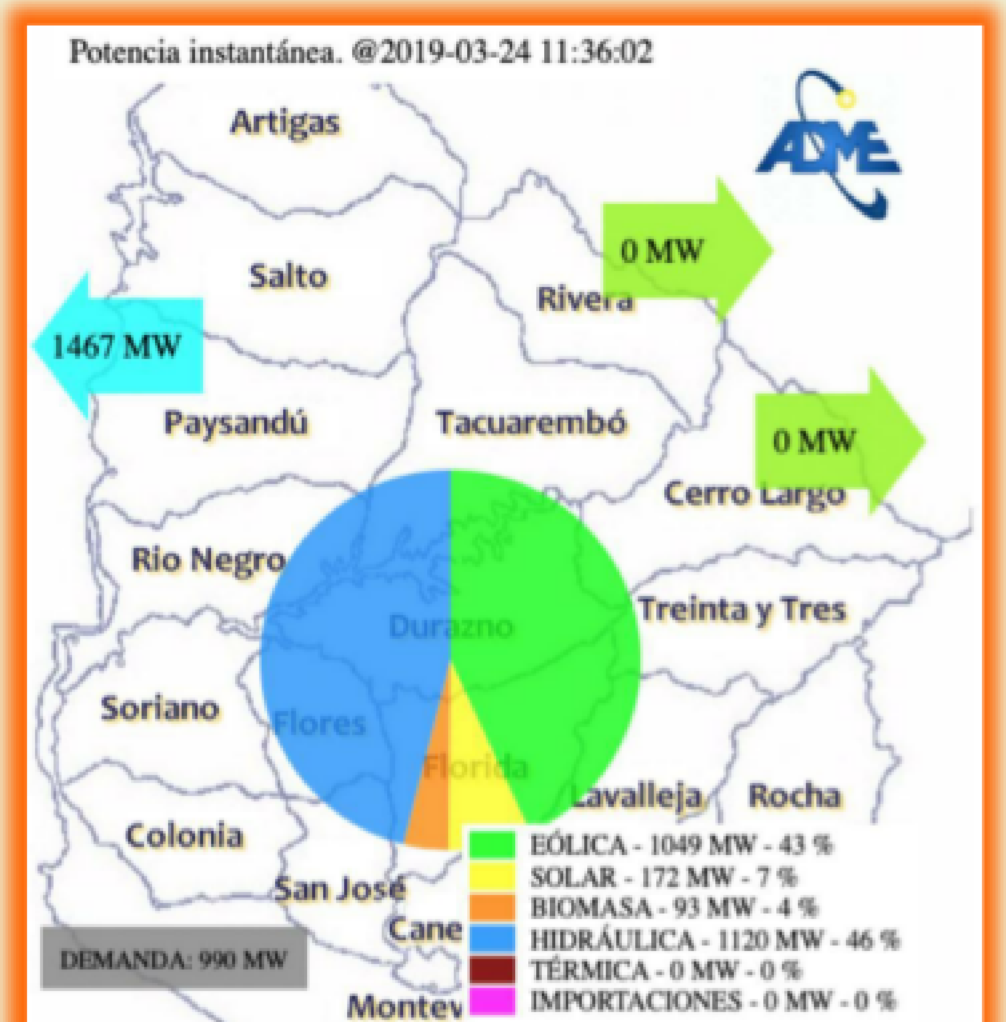
URUGUAY HAS VERY UNIQUE CAPACITIES CONCERNING RENEWABLES MANEGEMENT

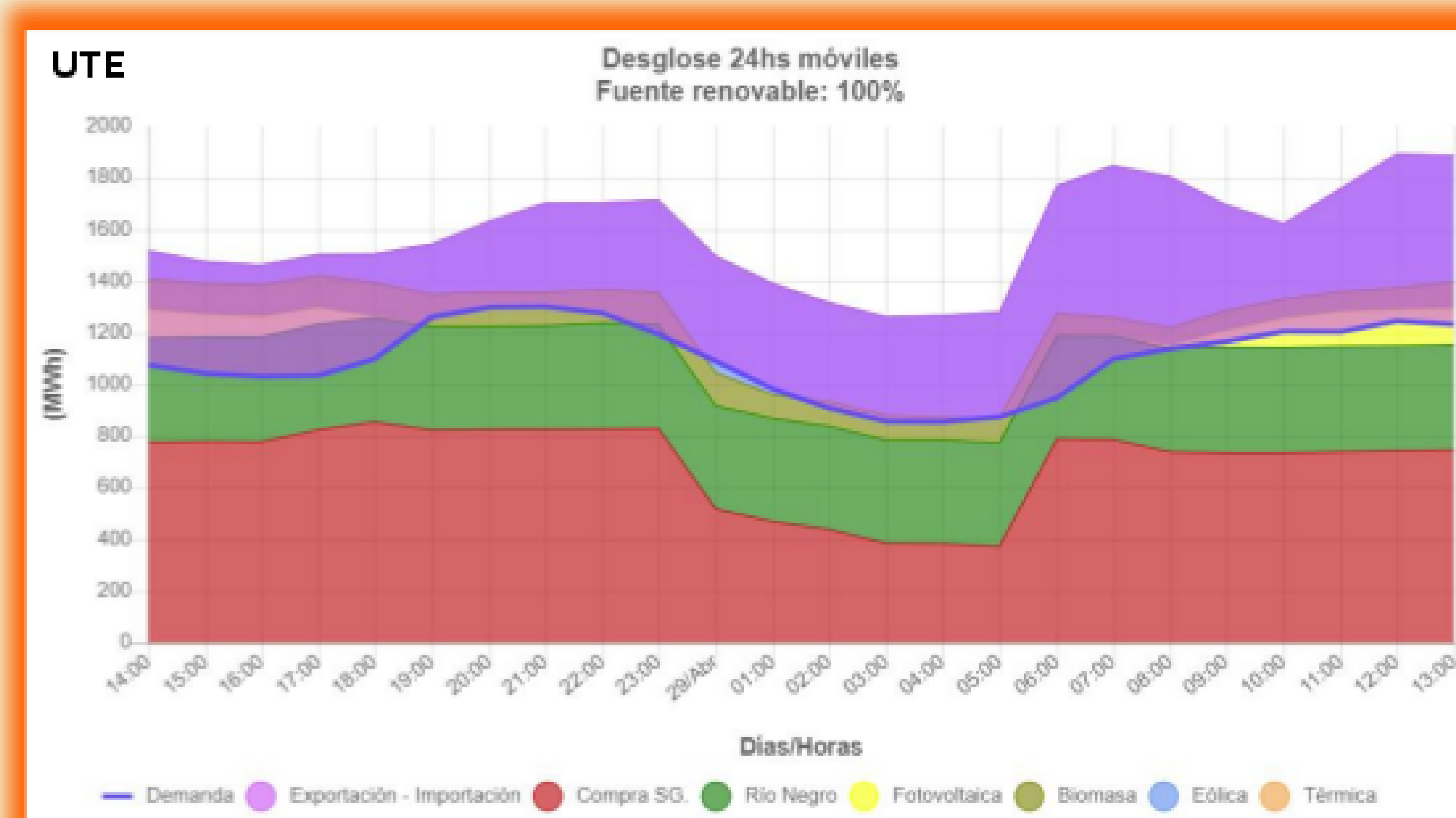
Can generate more than the double of its demand based on renewables

Can met a monthly demand with 99.9% renewable generation (0.1% thermal backup)

Can run for more than 24hs only with renewables (demand + exports)







BACKGROUND

BACKGROUND

UNIVERSIDAD DE LA REPÚBLICA
(~85 000 stud., 6500 grad stud., 6000 teachers)

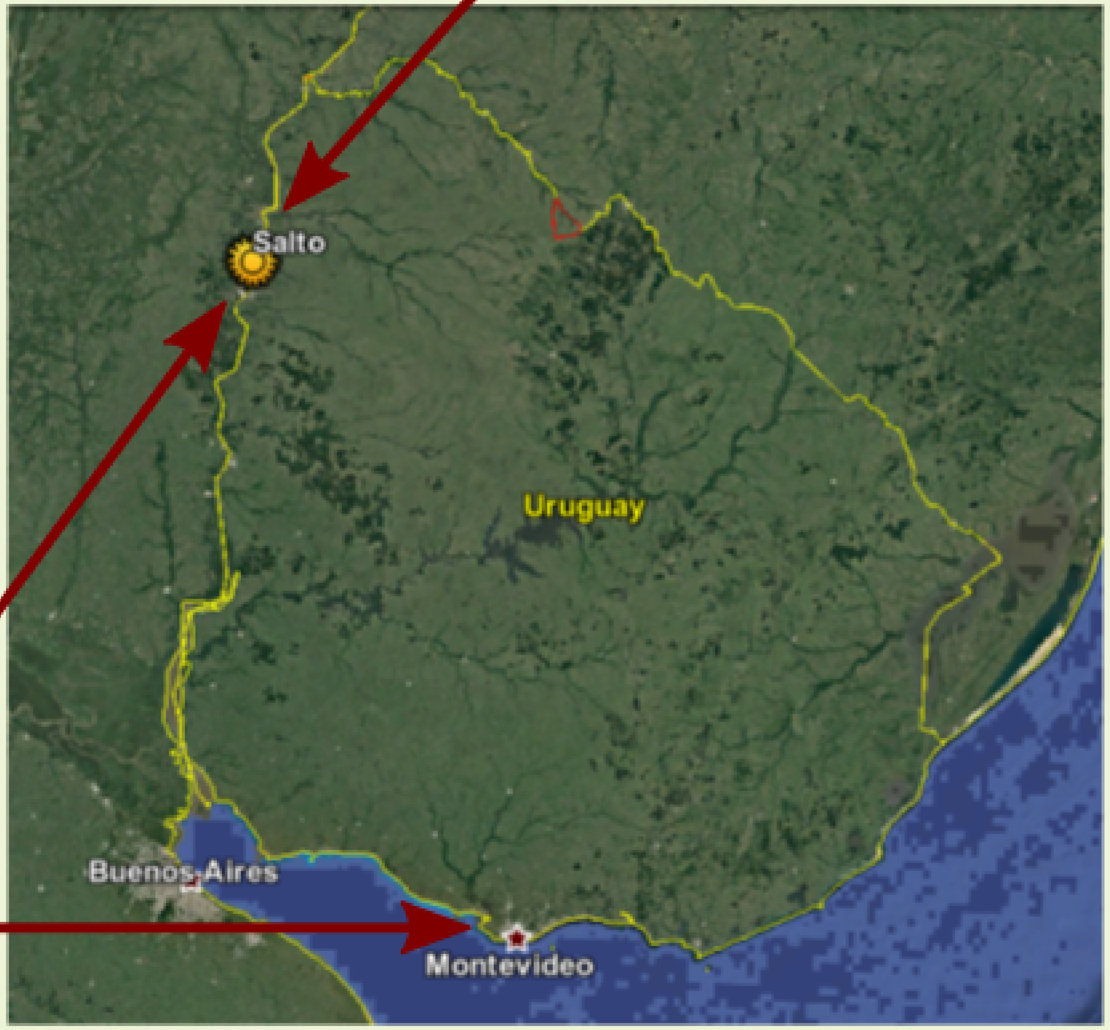
FACULTY OF ENGINERING
7500 students (1300/year)
350 grad students
850 teachers

REGIONAL SALTO
3800 students
300 teachers

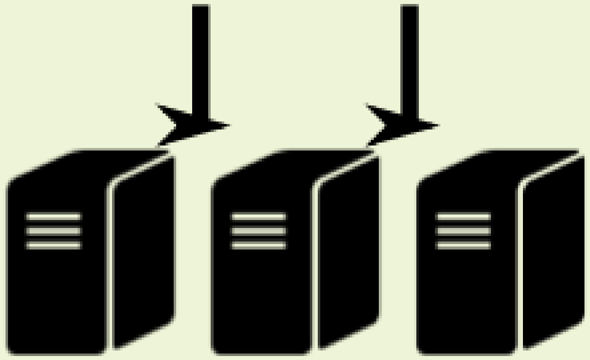
PHYSICS INSTITUTE
60 teachers
25 professors

PHYSICS DEPARTMENT
10 teachers
3 professors

SOLAR ENERGY LABORATORY
(15 members, 4 professors, 5 grad stud.)



MEASUREMENT'S NETWORK



Global Horizontal Irradiance
(Kipp & Zonen +first class)

Diffuse horizontal Irradiance
(SPN1 DeltaT radiometer)

Temperature, others

OTHER MEASUREMENTS

SOLYS2 station (GHI, DHI, DNI)

DHI with shadow band

Vaisala Weather Station

Rotating Shadow Radiometer

Outdoor calibration facility
Secondary Standart K&Z CMP22

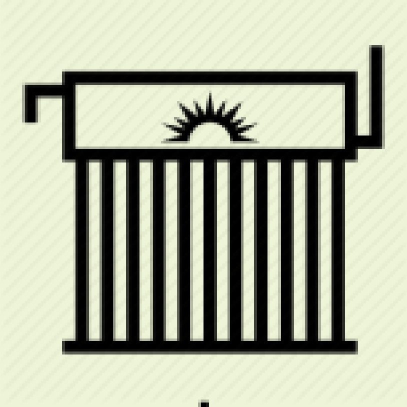
BACKGROUND

Solar passive arquitecture

Heat transfer in buildings

Experimental facility for testing walls (Trombe Wall)

Solar Heating



Low cost solar water heaters for low temp.

CSP prototype (low-medium temp.)

Solar testing facility for solar water heaters (ISO standars)

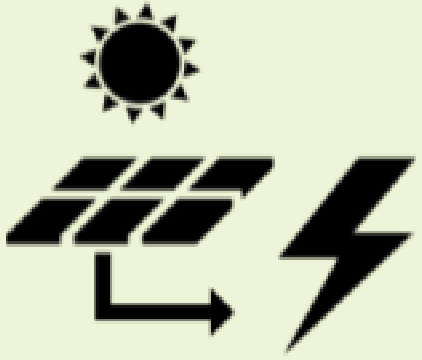
Solar Resource Assessment

Measurements Network (RMCIS)

Special high-quality measurements

Satellite resource assessment

Solar Resource Forecasting



Numerical Weather Predict (GFS+WRF)

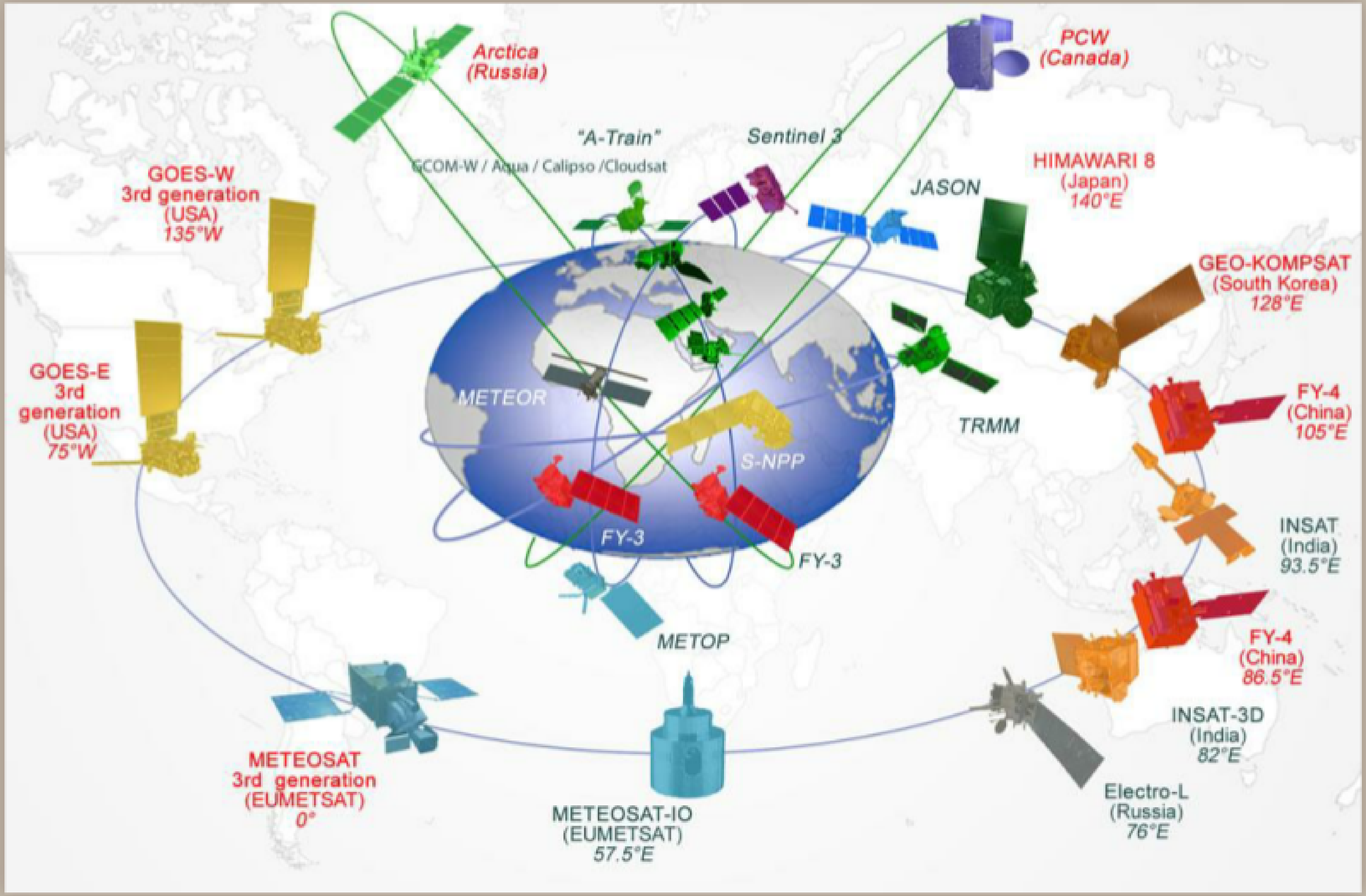
Satellite Forecast

All-Sky camera short-term forecast

Time series analysis

SATELLITE IMAGES

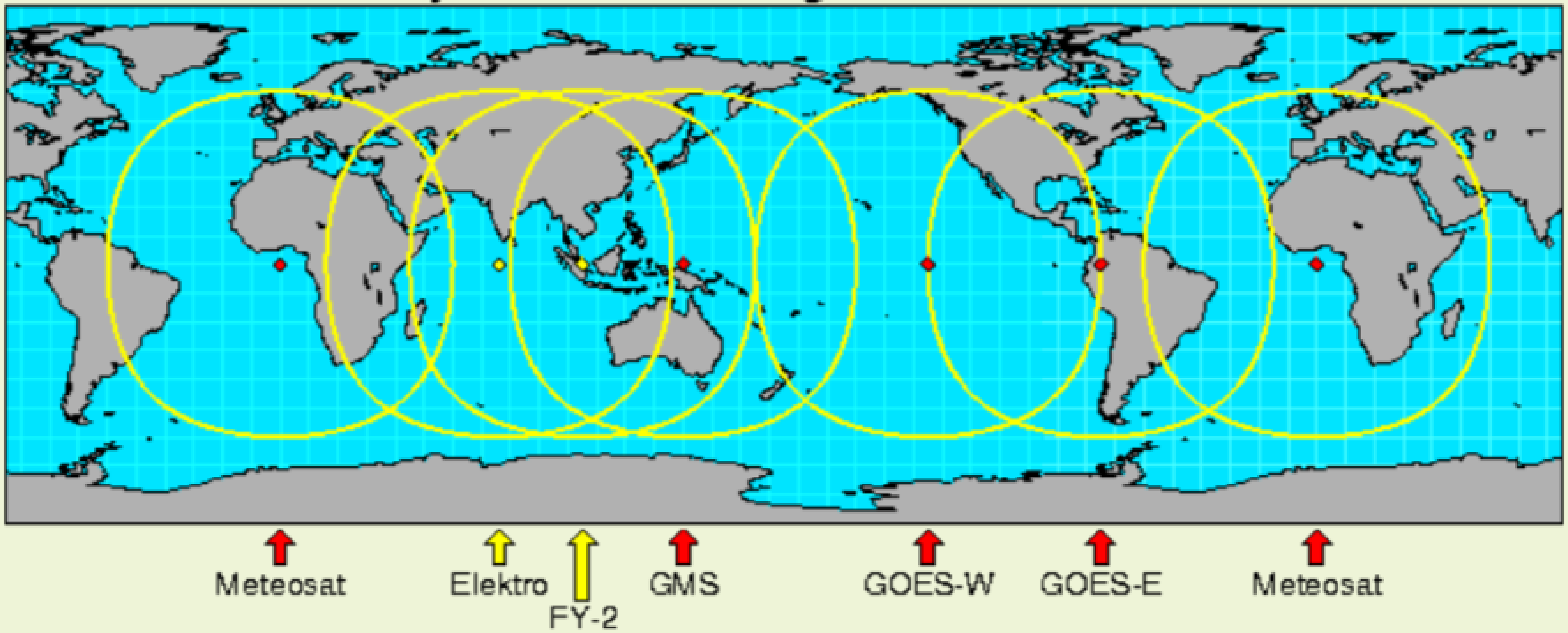
Different satellite orbits: trade-off between space and time resolutions



GEOSTATIONARY SATELLITES

- In geostationary orbit: always in the same position with respect to Earth
- Global coverage via a WMO network (under the operation of different countries)
- High time resolution (10-15-30 minutes schedules / 3 hourly images)
- Moderate space resolution (500m to 1-4 km, depending on the spectral band)

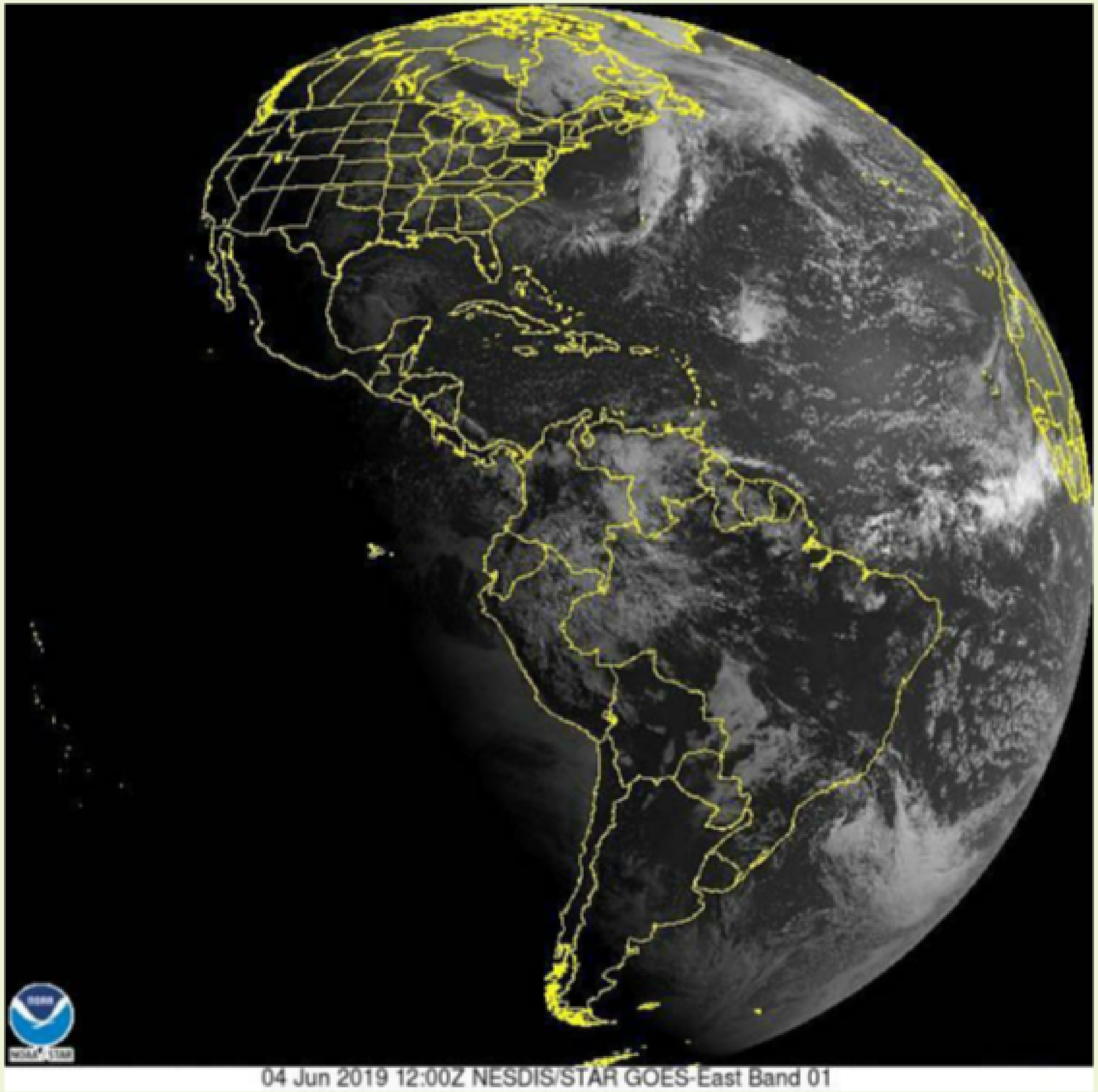
Global Geostationary Satellite Coverage



FULL-DISK VISIBLE CHANNEL IMAGE (0.47 um)

GOES-EAST
POS: -75º

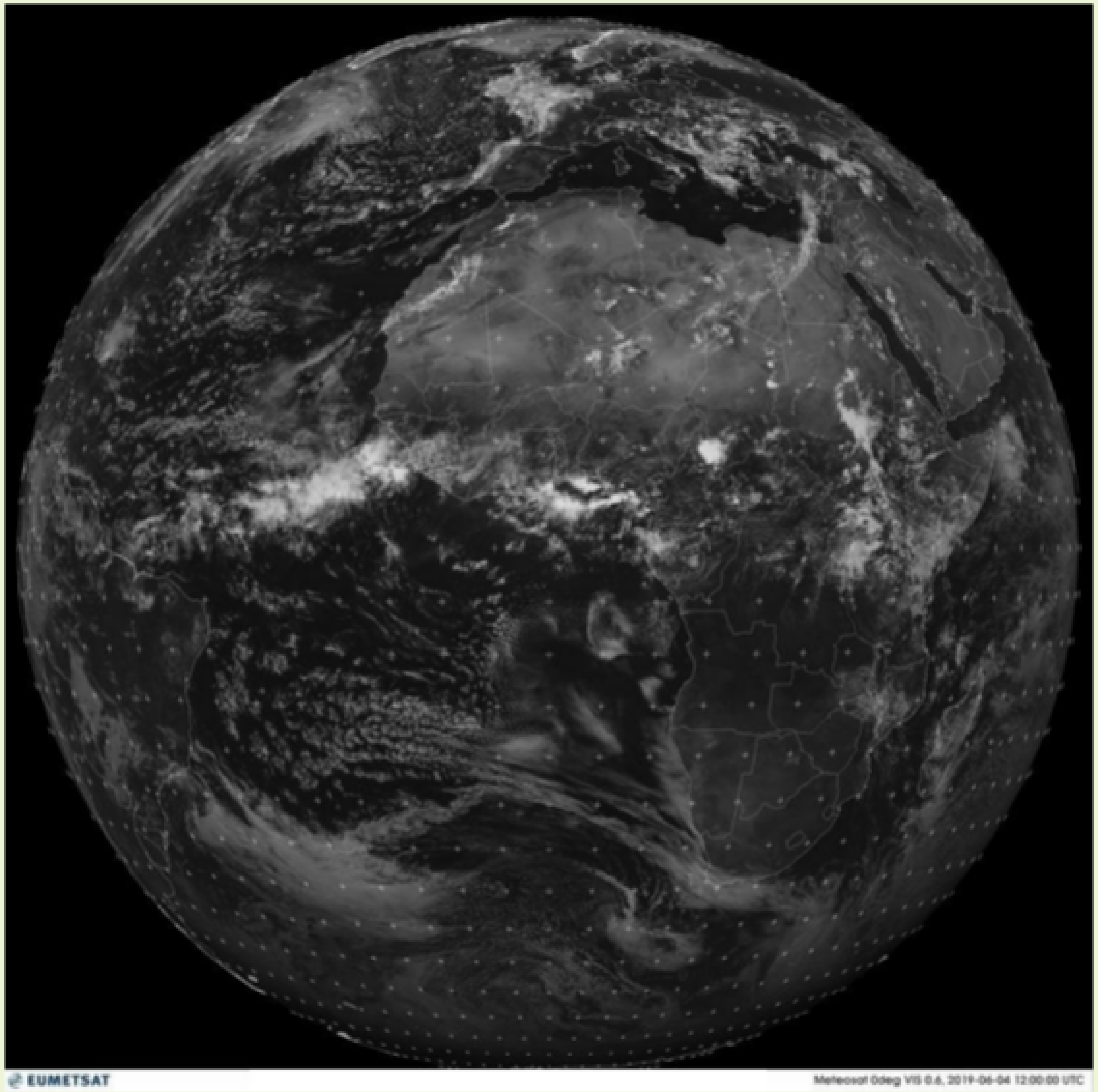
4TH JUNE
12:00 UTC



FULL-DISK VISIBLE CHANNEL IMAGE (0.60 um)

Meteosat
POS: 0º

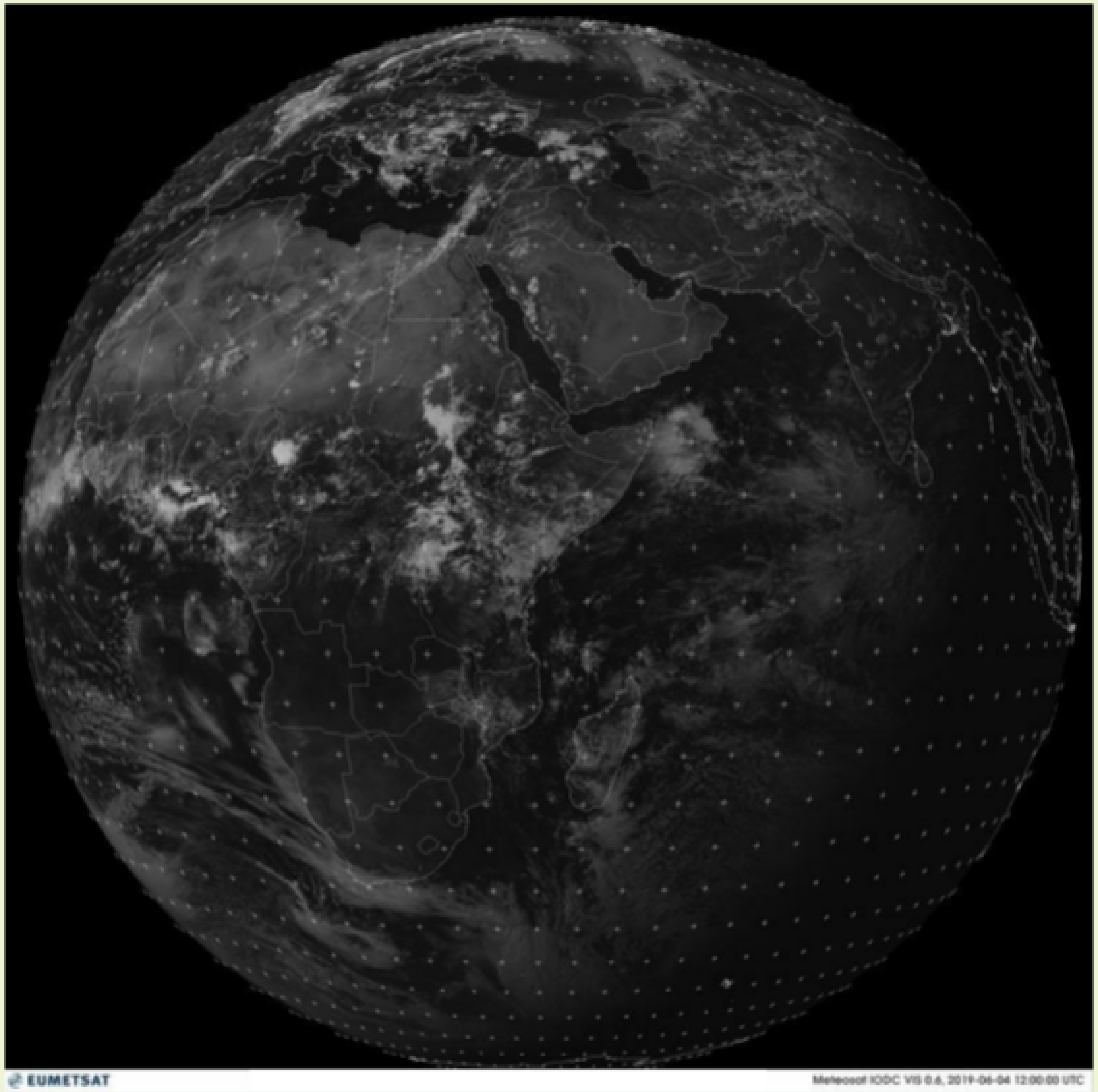
4TH JUNE
12:00 UTC



FULL-DISK VISIBLE CHANNEL IMAGE (0.60 um)

Msat IODC
POS: +41.5º

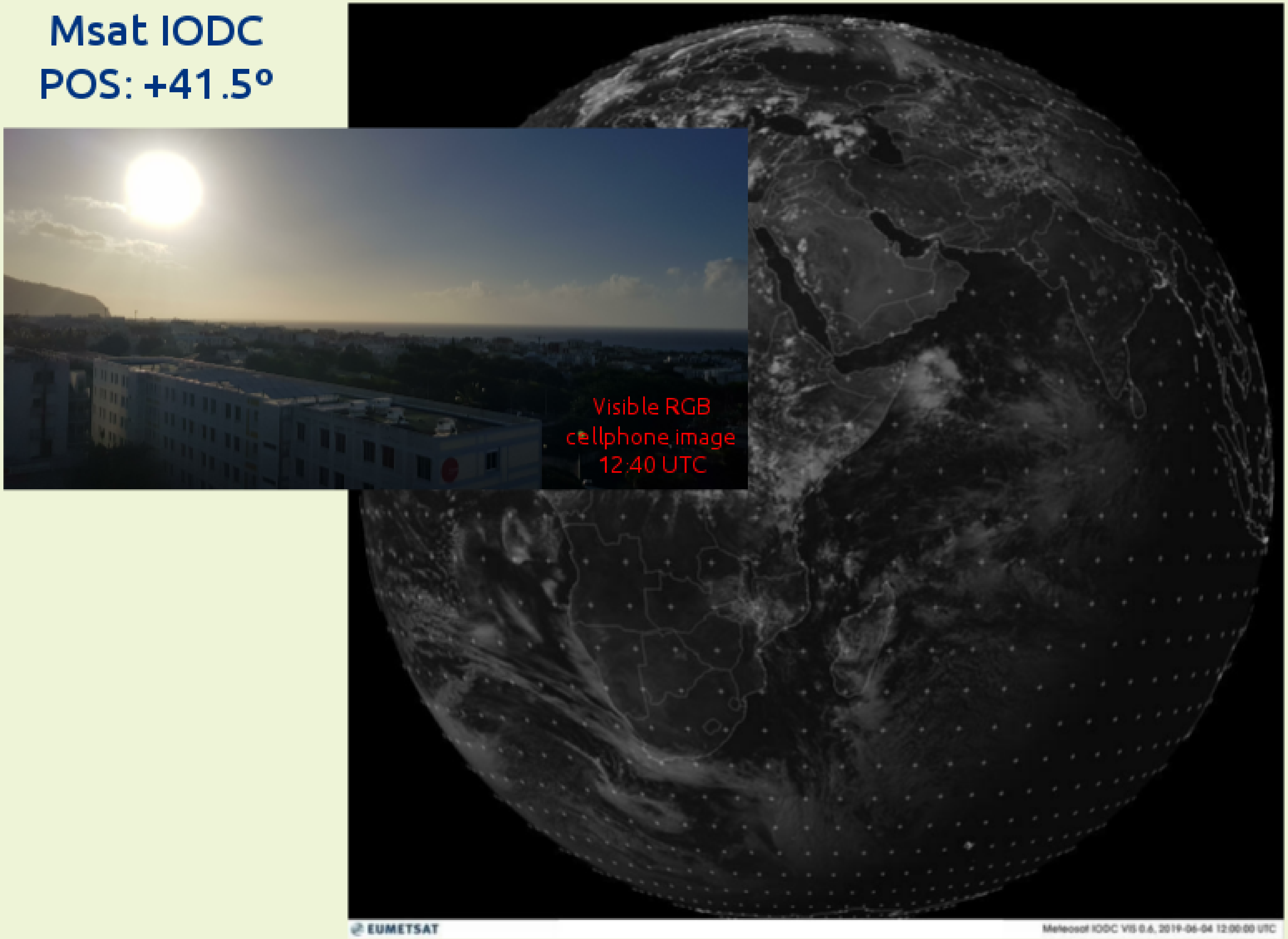
4TH JUNE
12:00 UTC



FULL-DISK VISIBLE CHANNEL IMAGE (0.60 um)

Msat IODC
POS: +41.5º

4TH JUNE
12:00 UTC



What is a satellite measuring?

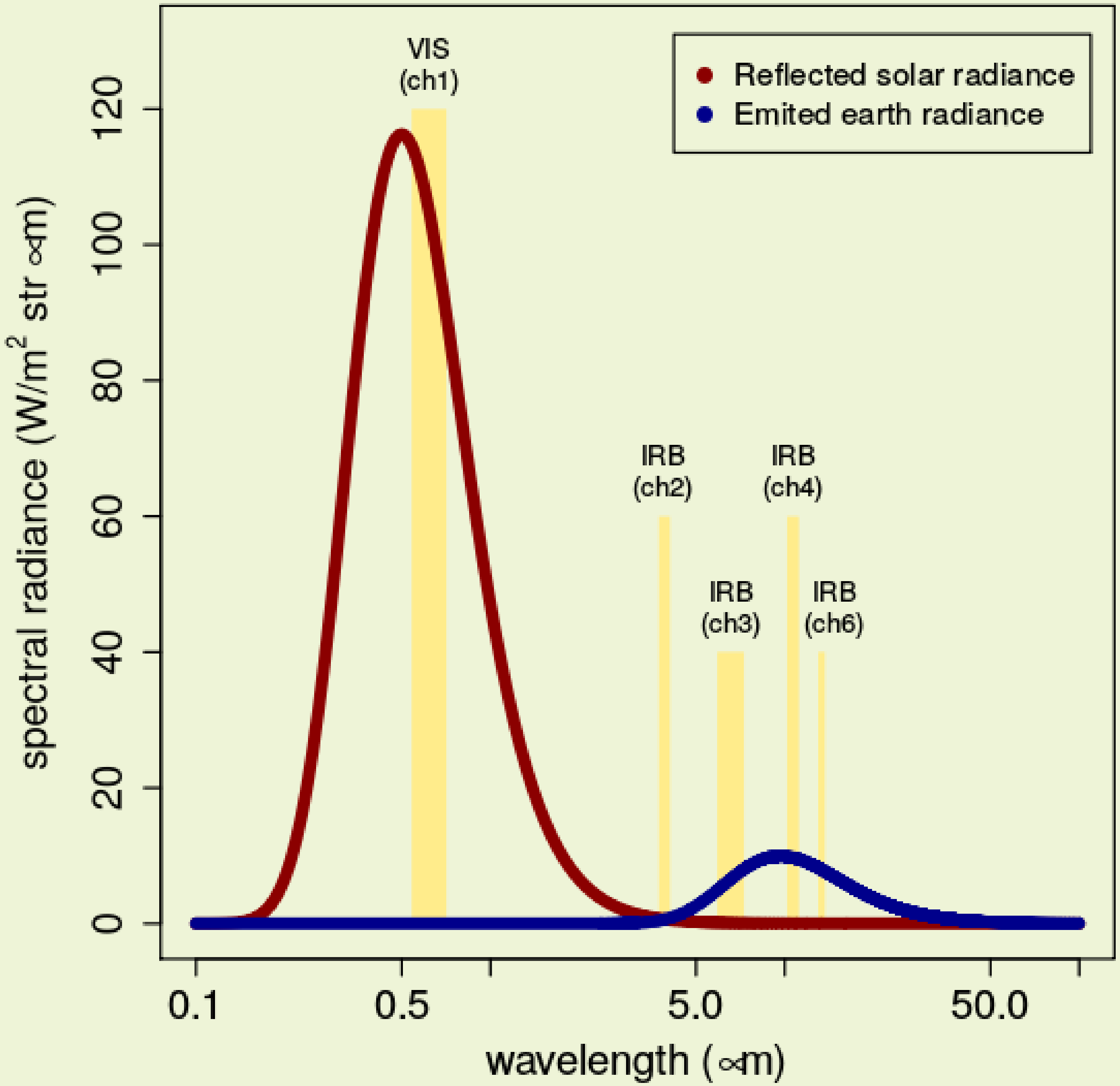
A SATELLITE MEASURES
OUTGOING RADIANCE
REFLECTED AND/OR EMITTED BY THE EARTH

VISIBLE CHANNELS
MEASURE SOLAR RADIANCE
REFLECTED AT THE EARTH

INFRARED CHANNELS (>4.0 um)
MEASURE EMITTED
RADIANCE BY THE EARTH

IN-MIDDLE BANDS LIKE FORMER
CHANNEL 2 REQUIRE DAYLIGHT
PROCESSING TO REMOVE SOLAR
REFLECTED CONTRIBUTION

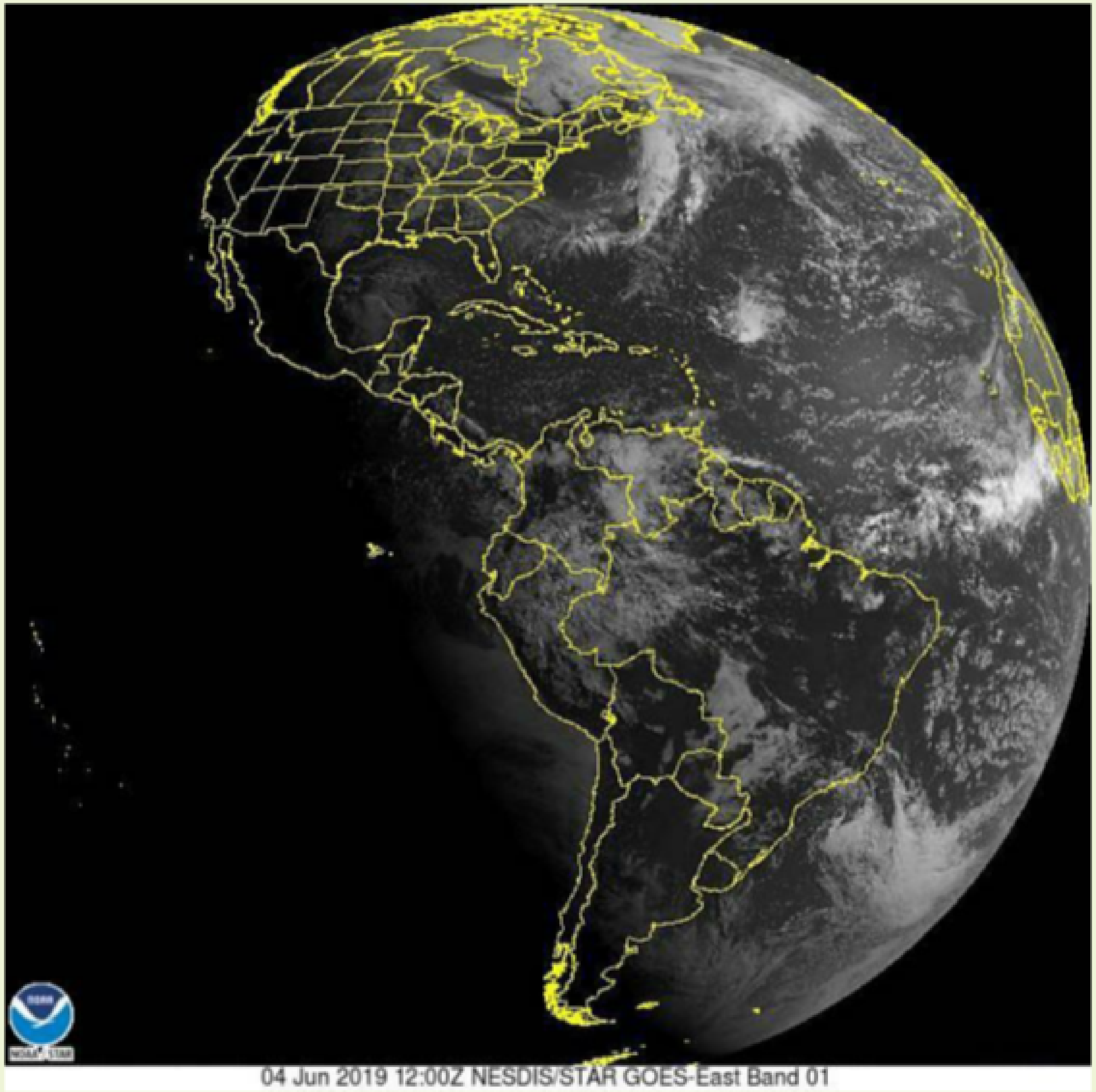
PAST GOES-EAST SATELLITE (1997-2017)



FULL-DISK VISIBLE CHANNEL IMAGE (0.47 um)

GOES-EAST
POS: -75º

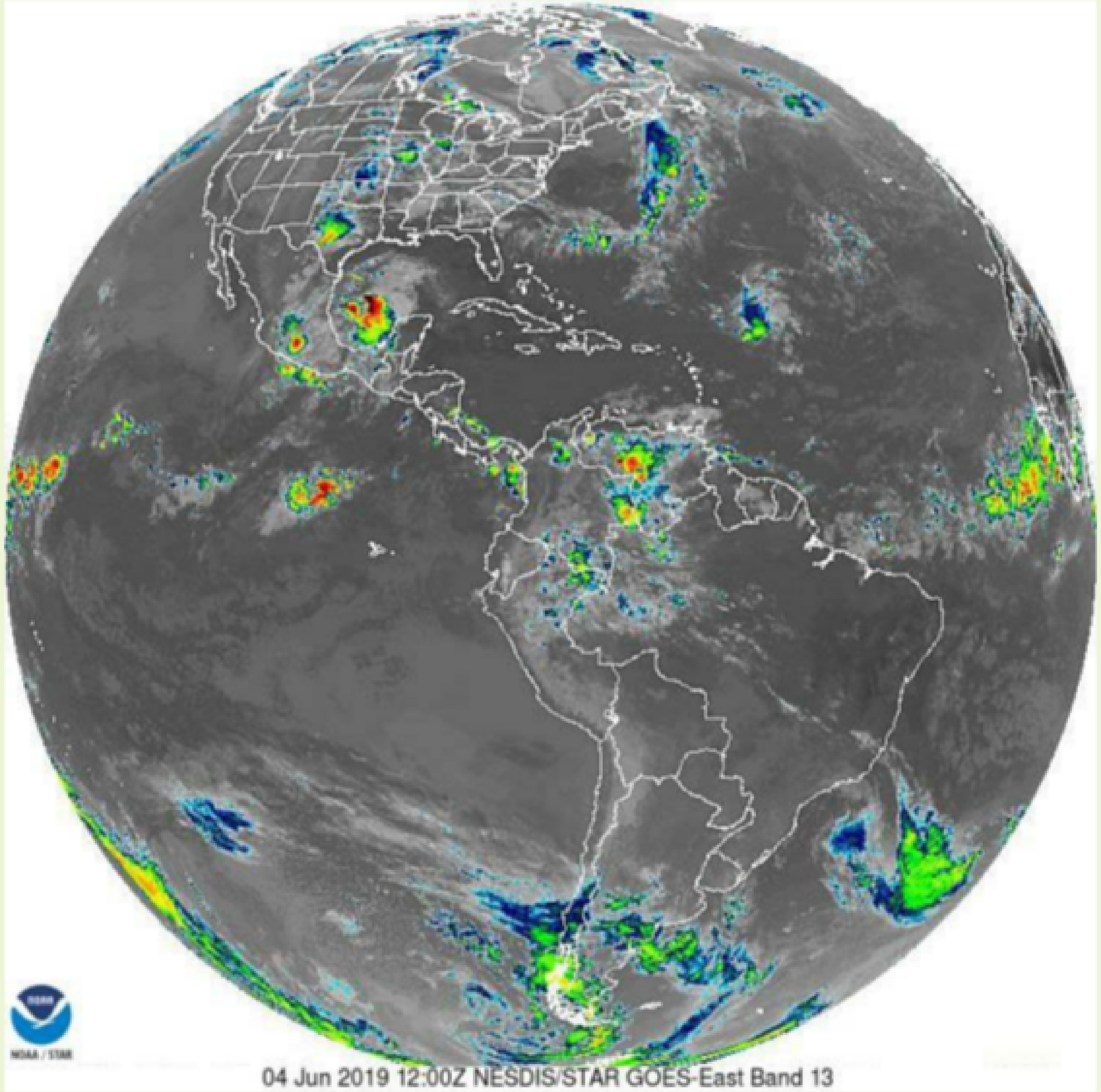
4TH JUNE
12:00 UTC



FULL-DISK INFRARED CHANNEL IMAGE (10.3 um)

GOES-EAST
POS: -75º

4TH JUNE
12:00 UTC



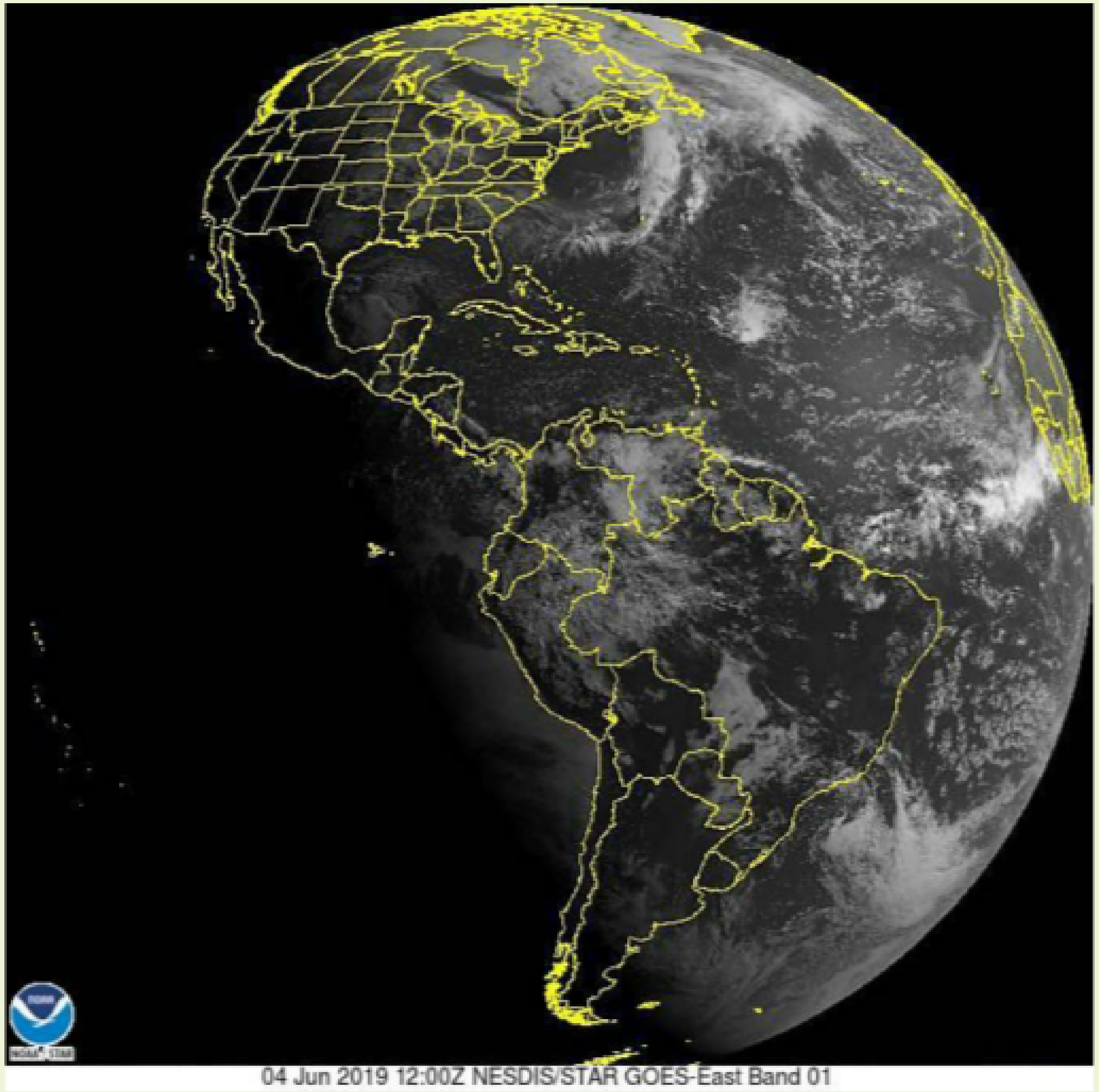
FOR SNOW-FREE AREAS WITHOUT HIGH ALBEDO (i.e. salars), VISIBLE CHANNEL IMAGES CAN BE USED TO IDENTIFY CLOUDS

REFLECTANCE FACTOR:

$$F_R = \frac{\pi \; L_s^{\text{vis}}}{G_\Delta^{\text{sc}} \; F_n}$$

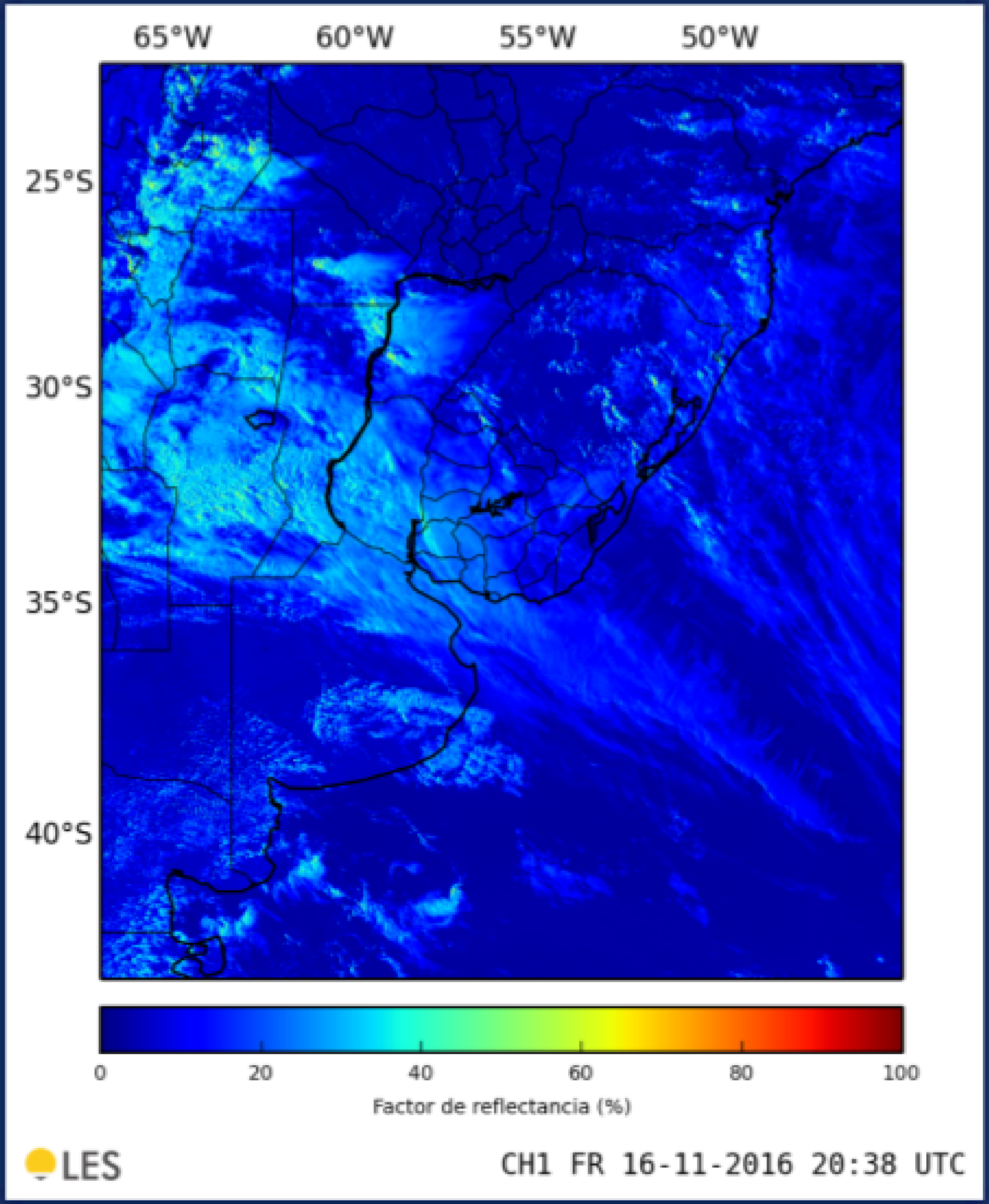
REFLECTANCE OR ALBEDO:

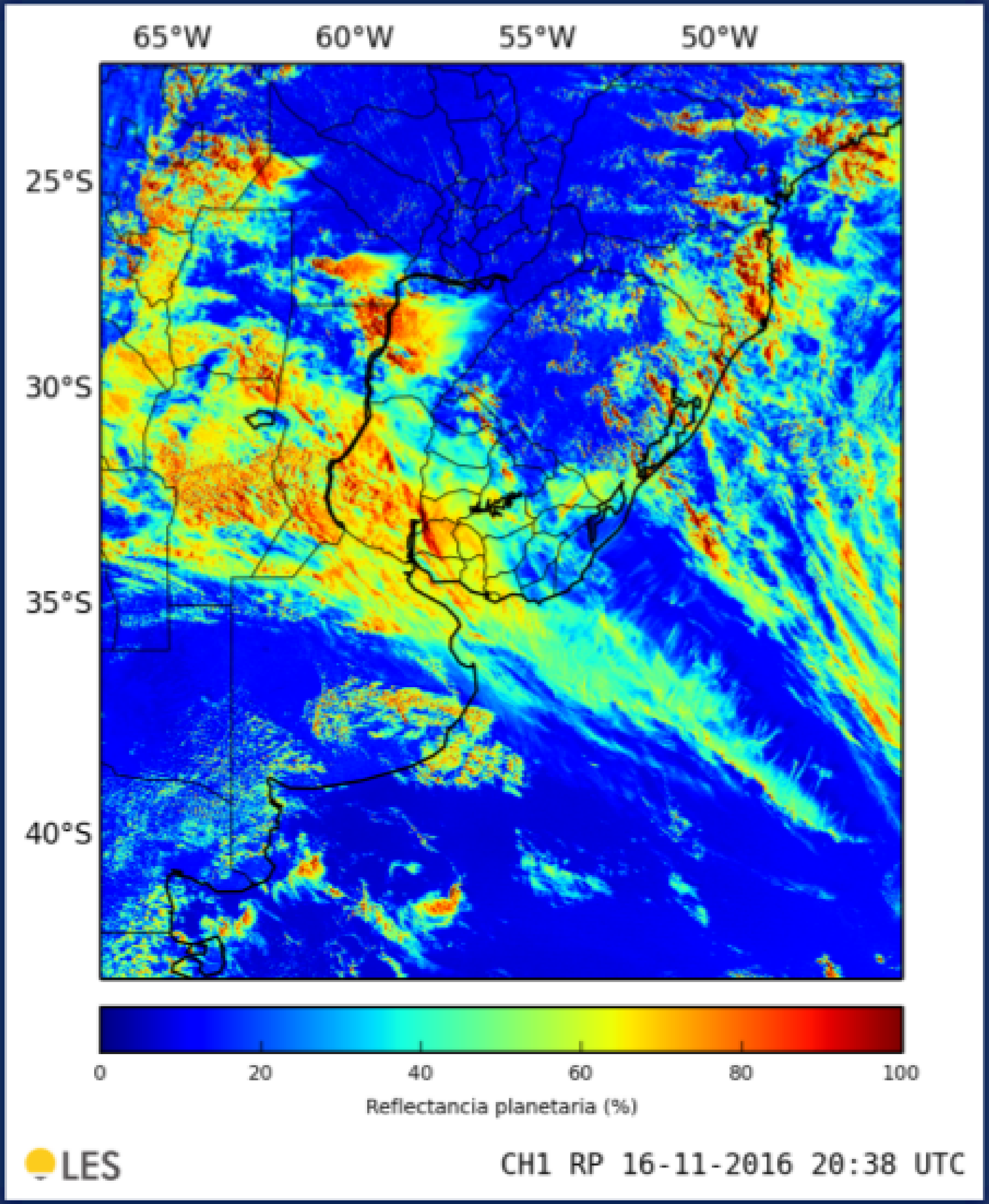
$$\rho_p = \frac{\pi \; L_s^{\text{vis}}}{G_\Delta^{\text{sc}} \; F_n \; \cos\theta_z} = \frac{F_R}{\cos\theta_z}$$



LES

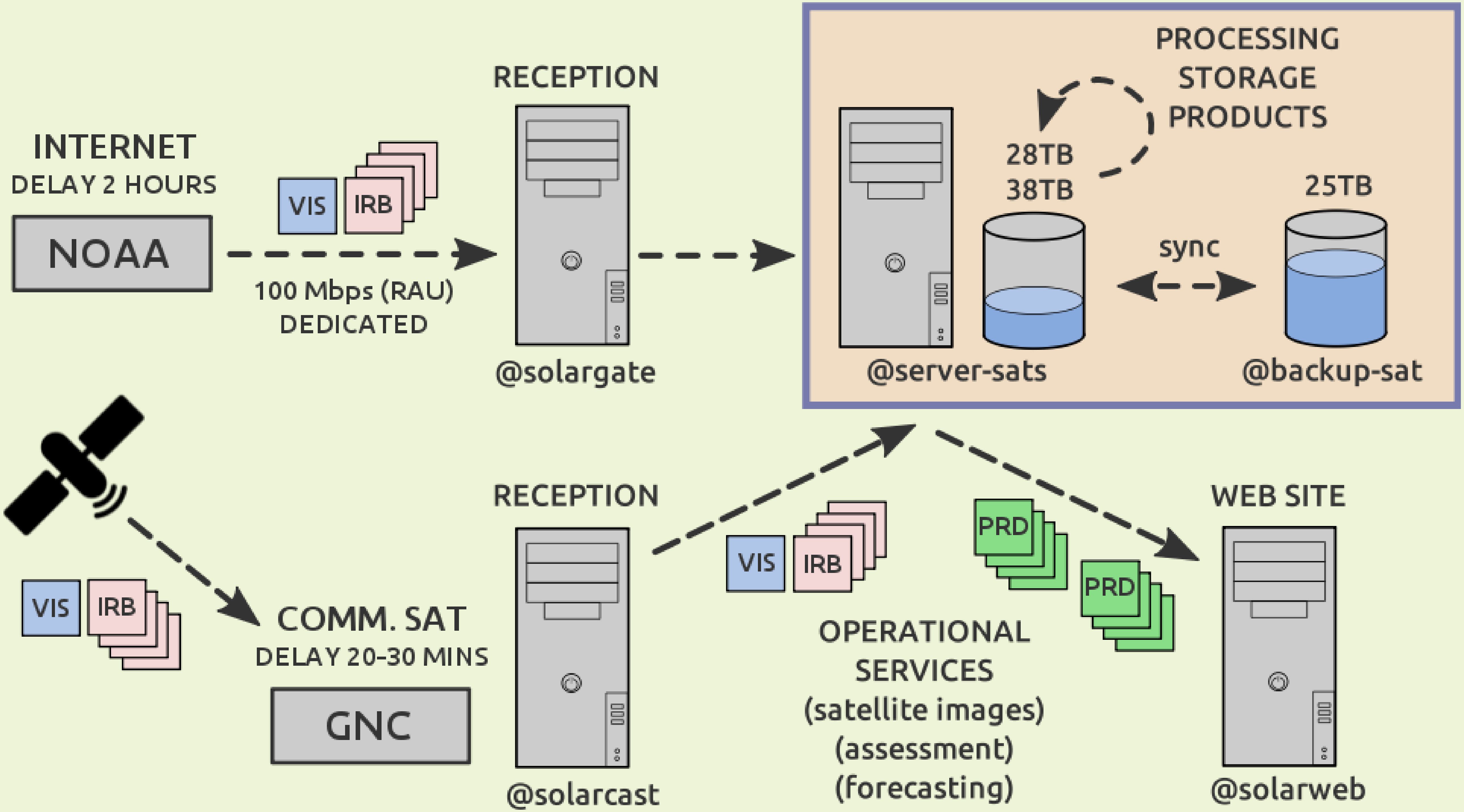
SATELLITE





(some videos now!)

LES-LAB INFRASTRUCTURE:



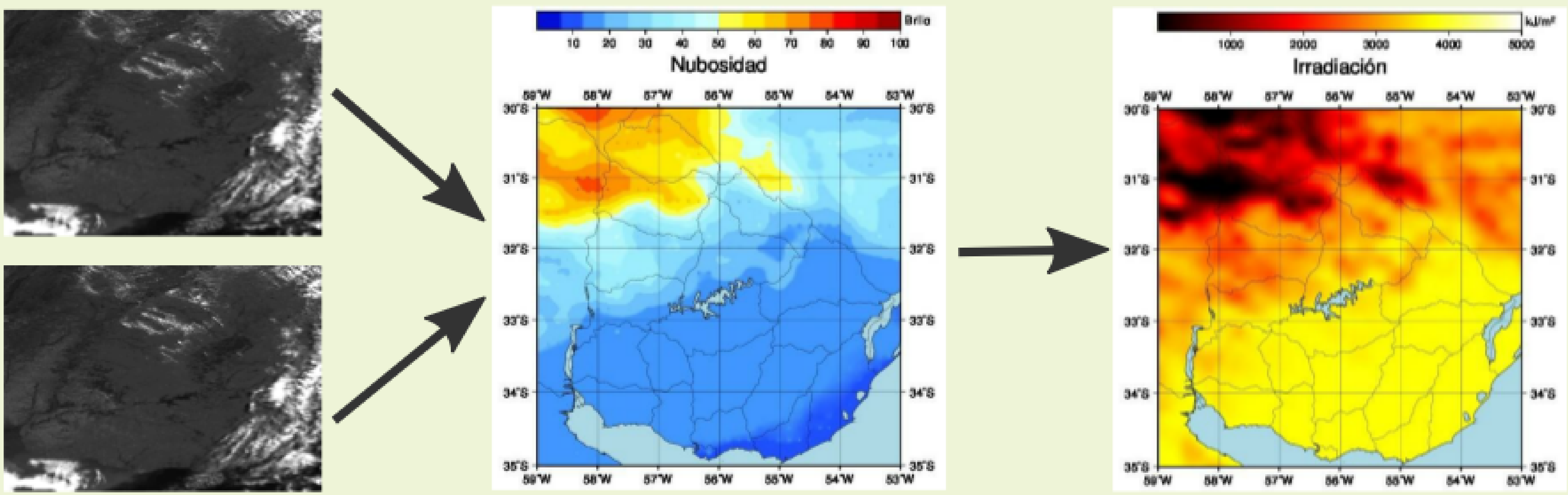
ALL-SKY SOLAR IRRADIATION MODELS

Satellite-based solar resource assessment?

satellite images

cloudiness

solar irradiation



Why geostationary satellite images?

1. Solar irradiance is highly variable in space and time. Spatial coverage.
2. Satellite images provide information for intra-hour estimation.
3. Interpolation of ground measurements presents high uncertainty.
4. Extense satellite datasets: ~20 years since GOES8.

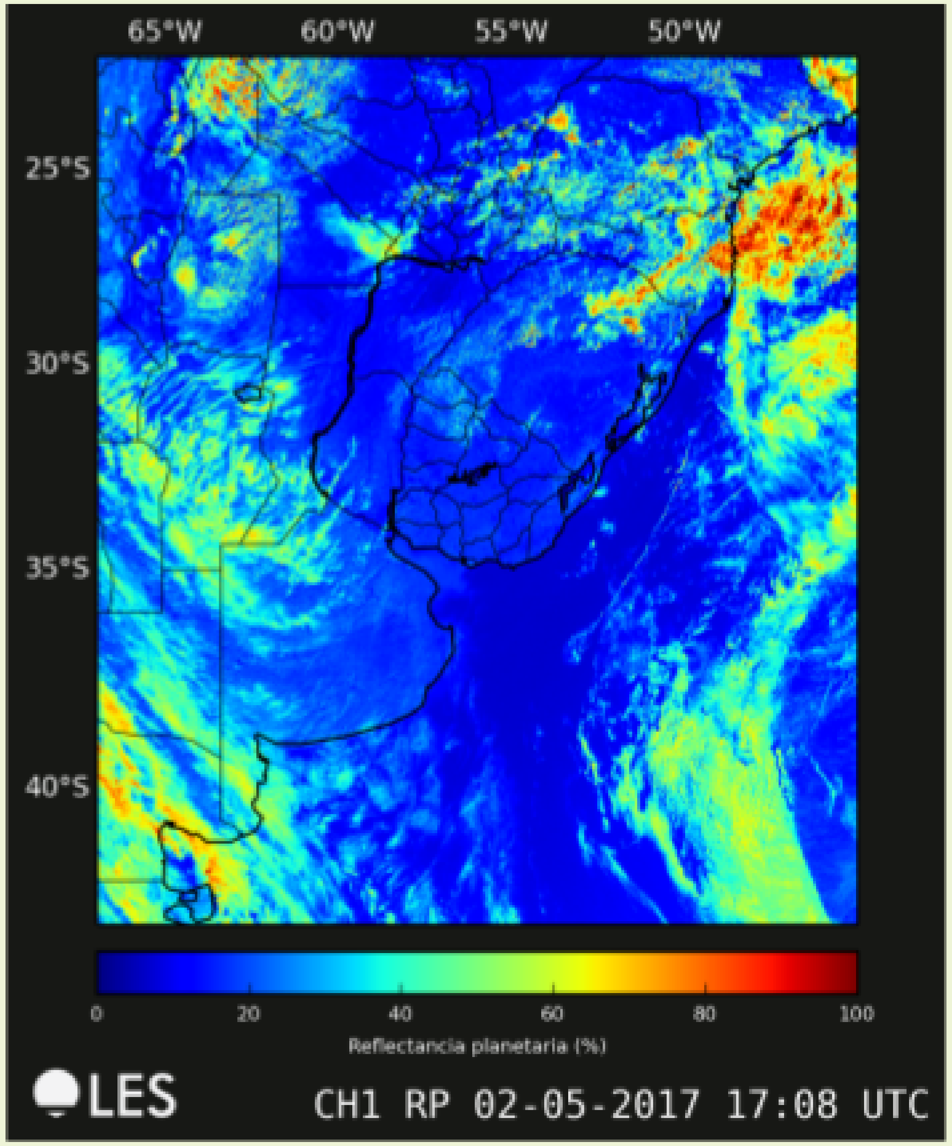
LES

SATELLITE MODELS

Measurements

tradeoff between uncertainty and space resolution

Satellite



Low uncertainty in the measurement site.

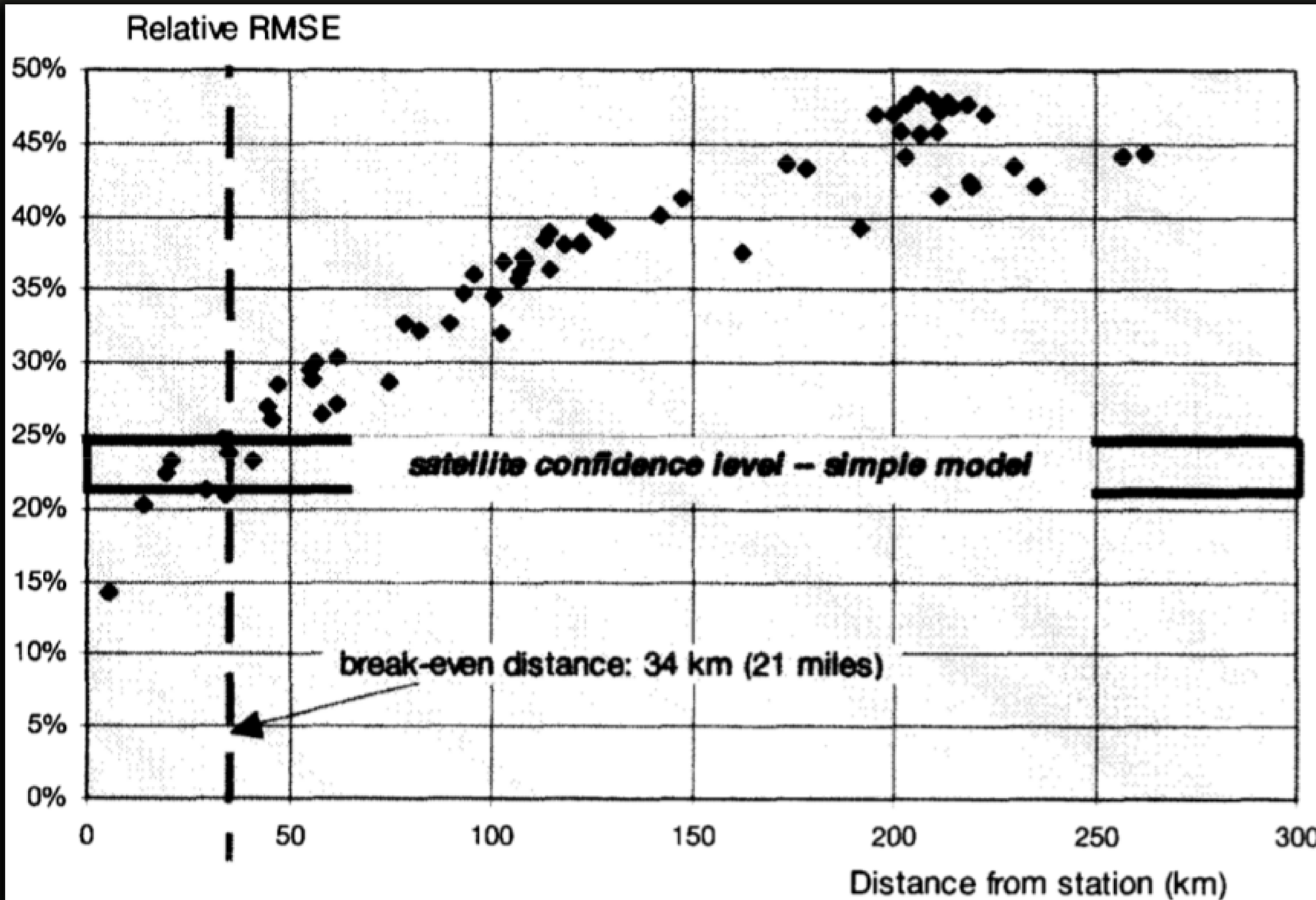
It is not possible to measure in all the points.

In soma cases: short measurements time span.

"Measures" in all points at the same time ~1km

There is more than 20 years satellite images.

SATELLITE MODELS



SOLAR IRRADIATION SATELLITE-BASED MODELS

EMPIRICAL MODELS

Tarpley et al. model
Cano et al. model
Machine Learning models

Rely in a set of parameters that have to be adjusted for the region

High-dependence in the availability of high quality measurements

Simple but not extrapolable (to other regions) models

PHYSICAL MODELS

Heliosat-4
NASA/SSE
Brasil-SR / Chile-SR
GL model (Brasil)

Attemp to model in detail the radiative transfer in the atmosphere

Require a high-detail/quality knowledge of the atmosphere state

More feasible to extrapolate to regions that lack of measurements

SEMI-EMPIRICAL MODELS

SUNY model
Heliosat-1/2 models
SolarGIS model

Have a physical basis but rely in some adjustable parameters

Trade-off: simplicity, measurements availability and extrapolation

Commonly used in commercial platforms (Geomodel, SolarAnywhere)

UPDATED TARPLEY MODEL (statistical)

$$I_h = I_{sc}\ F_n\ \cos\theta_z \left(a + b\ \cos\theta_z + c\ \cos^2\theta_z\right) + d\left(F_{Rm} - F_{Ro}\right)$$

A SIMPLE PARAMETRIZATION OF THE HOURLY SOLAR IRRADIATION

reflectance factor

I_{sc} Solar constant hourly value

F_n Excentricity factor (Earth-Sun distance)

F_{Rm} Hourly mean "brigthness" in a cell. Cell size is tuned to represent an hourly value.

F_{Ro} Background mean "brightness" for the pixel position and time

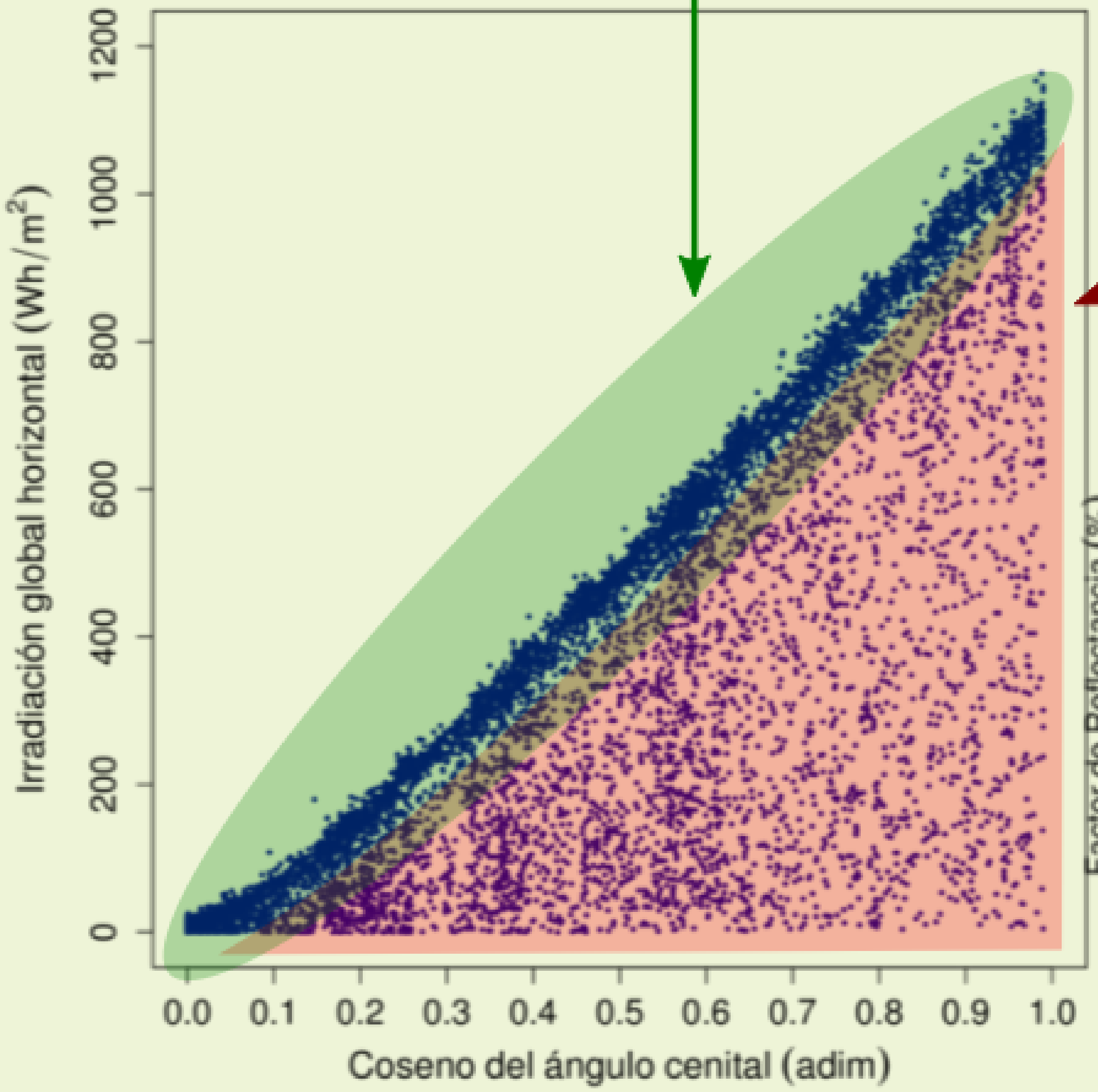
a, b, c and d are empirical coeficients to be tuned with ground measurements

SATELLITE MODELS

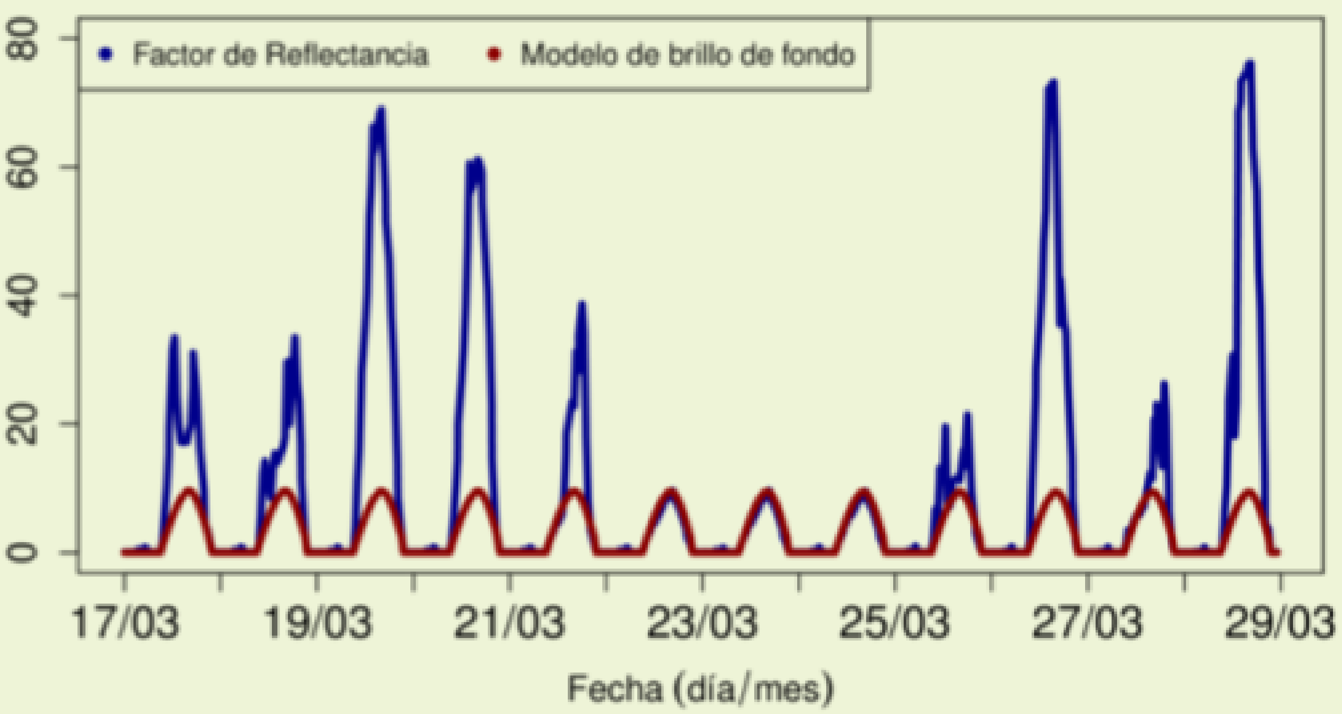
Clear-sky part of the model

Effect of cloudiness

$$I_h = I_{sc}\, F_n\, \cos\theta_z \left(a + b\, \cos\theta_z + c\, \cos^2\theta_z\right) + d\left(F_{Rm} - F_{Ro}\right)$$



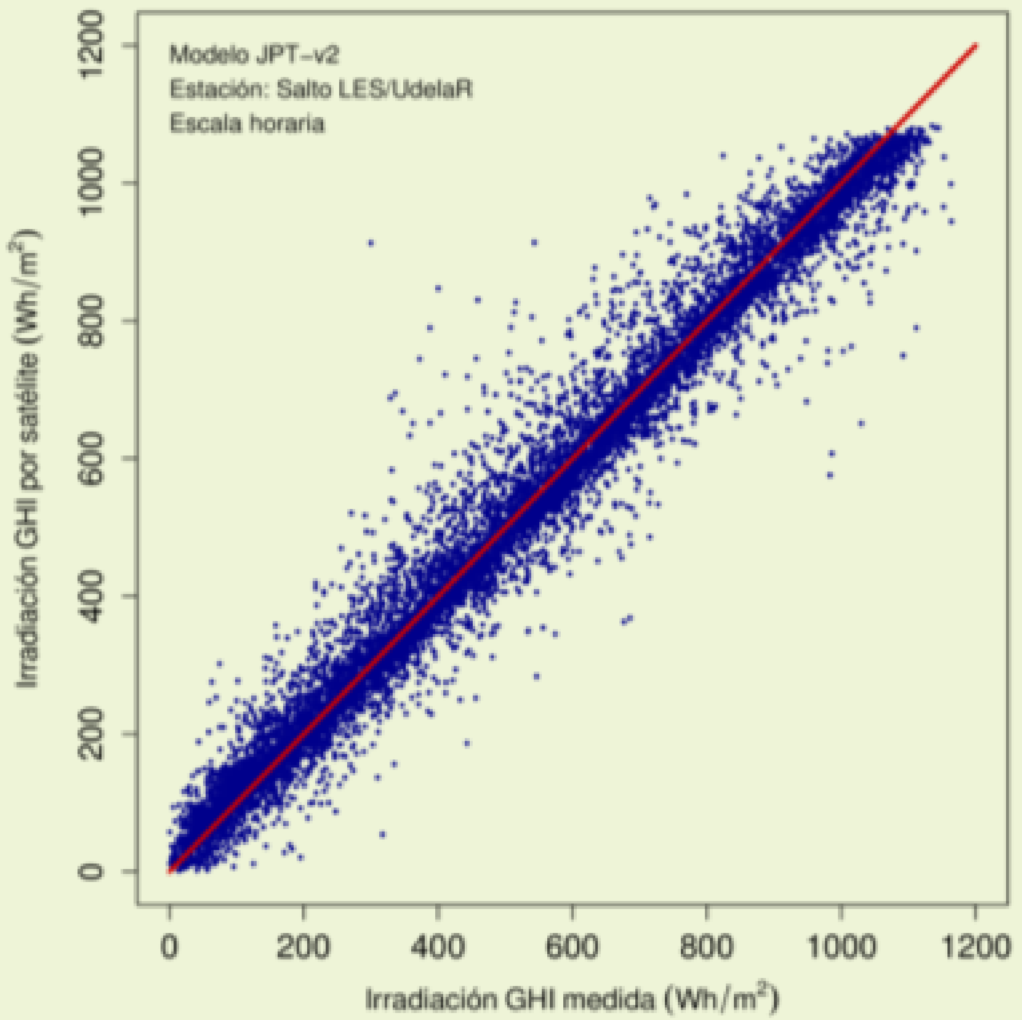
Background "brightness" estimation

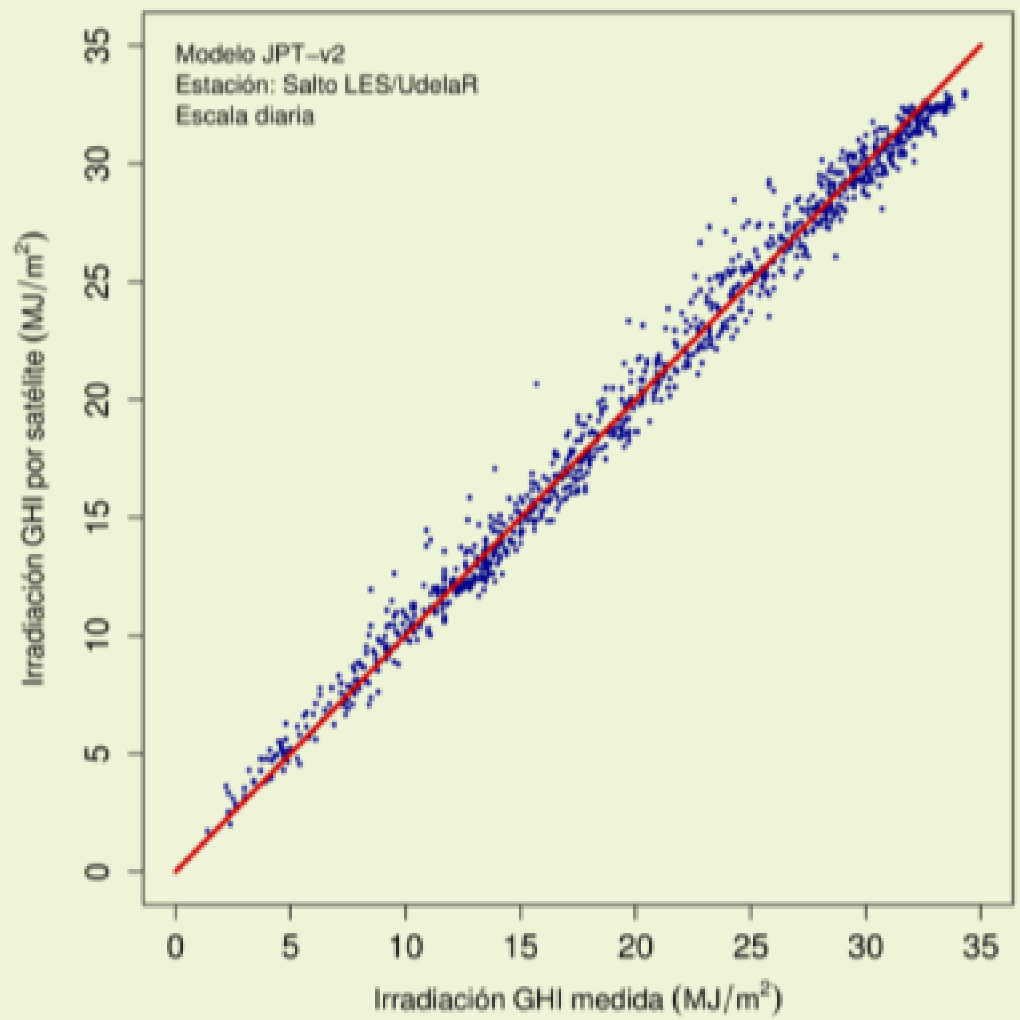


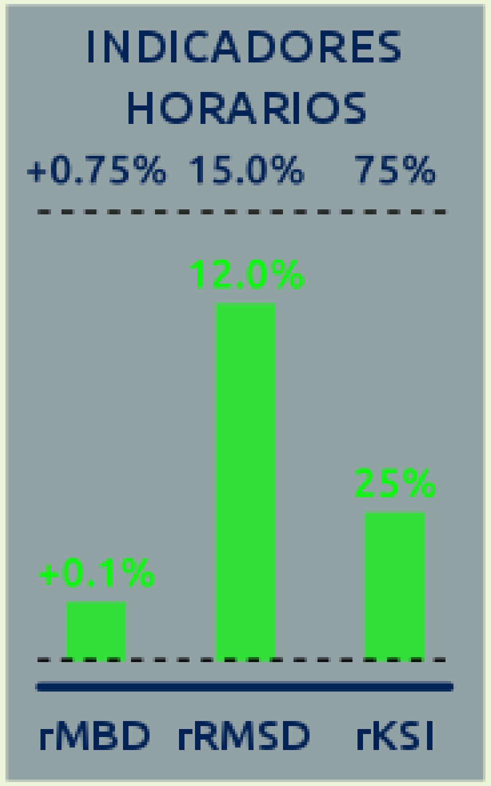
SATELLITE MODELS

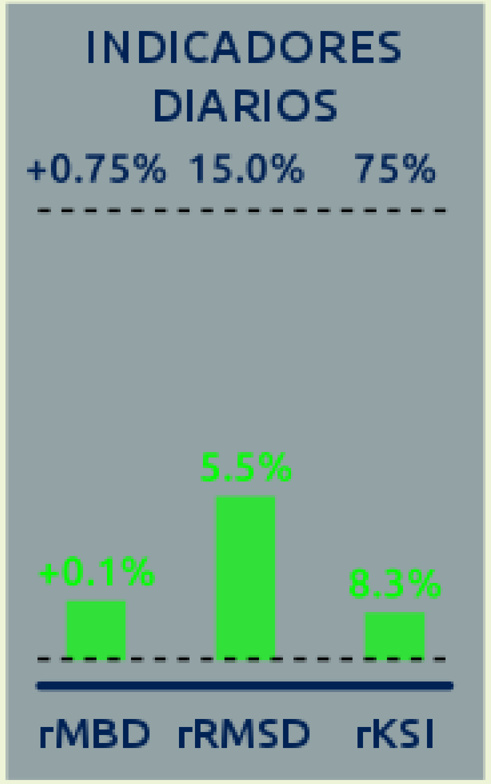
PERFORMANCE

Hourly and daily evaluation









CLOUD INDEX MODELS (CIMs - hybrid)

Clear-sky model

$$G_h = G_h^{csk} \times F(\eta)$$

Cloudiness attenuation

CLEAR SKY MODELS (some of them)

* ESRA: Rigollier et al., 2000.

* Simplified SOLIS: Ineichen & Perez, 2002.

* REST2: Gueymard, 2008.

*McClear Model: Lefevre, 2013.

THE CLOUD INDEX IS DEFINED FROM THE SATELLITE ALBEDO

$$\eta = \frac{\rho_p - \rho_{min}}{\rho_{max} - \rho_{min}}$$

DIFFERENT IMPLEMENTATIONS

WE USE THE BACKGROUND MODEL FOR MIN AND A FIXED ALBEDO VALUE FOR MAX

CLEAR SKY MODELS

Gueymard, 2012

A comparison of 18 clear-sky models performance over 5 stations that account for a wide range of climates.

The inputs variables considered for each model are different
(from 0 to 8 input variables, REST2)

Table 1. Requested atmospheric inputs (besides date, zenith angle and solar constant) for all models considered here. Possible inputs are: h, site elevation (m); ρ_g, surface albedo; p, barometric pressure (mb); T, temperature (°C); RH, relative humidity; u_o, total ozone abundance (atm-cm); u_n, total nitrogen dioxide abundance (atm-cm); w, precipitable water (cm); V, horizontal visibility (km); k, atmospheric transparency; T_L, Linke turbidity coefficient; τ_a, broadband aerosol optical depth; τ_{a700}, aerosol optical depth at 700 nm; α, Ångström's wavelength exponent; β, Ångström's turbidity coefficient; ω_a, aerosol single-scattering albedo. The total number of inputs appears in the last column.

#	Model Name	Year	h	ρ_g	p	T	RH	u_o	u_n	w	V	k	T_L	τ_a	τ_{a700}	α	β	ω_a	Total
1	ASHRAE	1972																	0
2	HLJ	1976	•																1
3	Kumar	1997			•														1
4	Fu-Rich	1999	•																1
5	Heliosat-1	1996			•								•						2
6	ESRA	2000			•								•						2
7	Heliosat-2	2004	•										•						2
8	Ineichen	2008			•					•					•				3
9	Yang	2001			•			•		•							•		4
10	NRCC	2005			•		•			•	•								4
11	Hoyt	1978		•	•			•		•							•		5
12	MAC	1988		•	•	•				•		•							5
13	METSTAT	1998		•	•			•		•				•					5
14	CSR	1998		•	•			•		•				•					5
15	MRM-5	2008		•	•			•		•							•		5
16	Bird	1981		•	•			•		•						•	•		6
17	Iqbal-C	1983	•	•				•		•						•	•		6
18	REST2	2008		•	•			•	•	•						•	•	•	8

CLEAR SKY MODELS

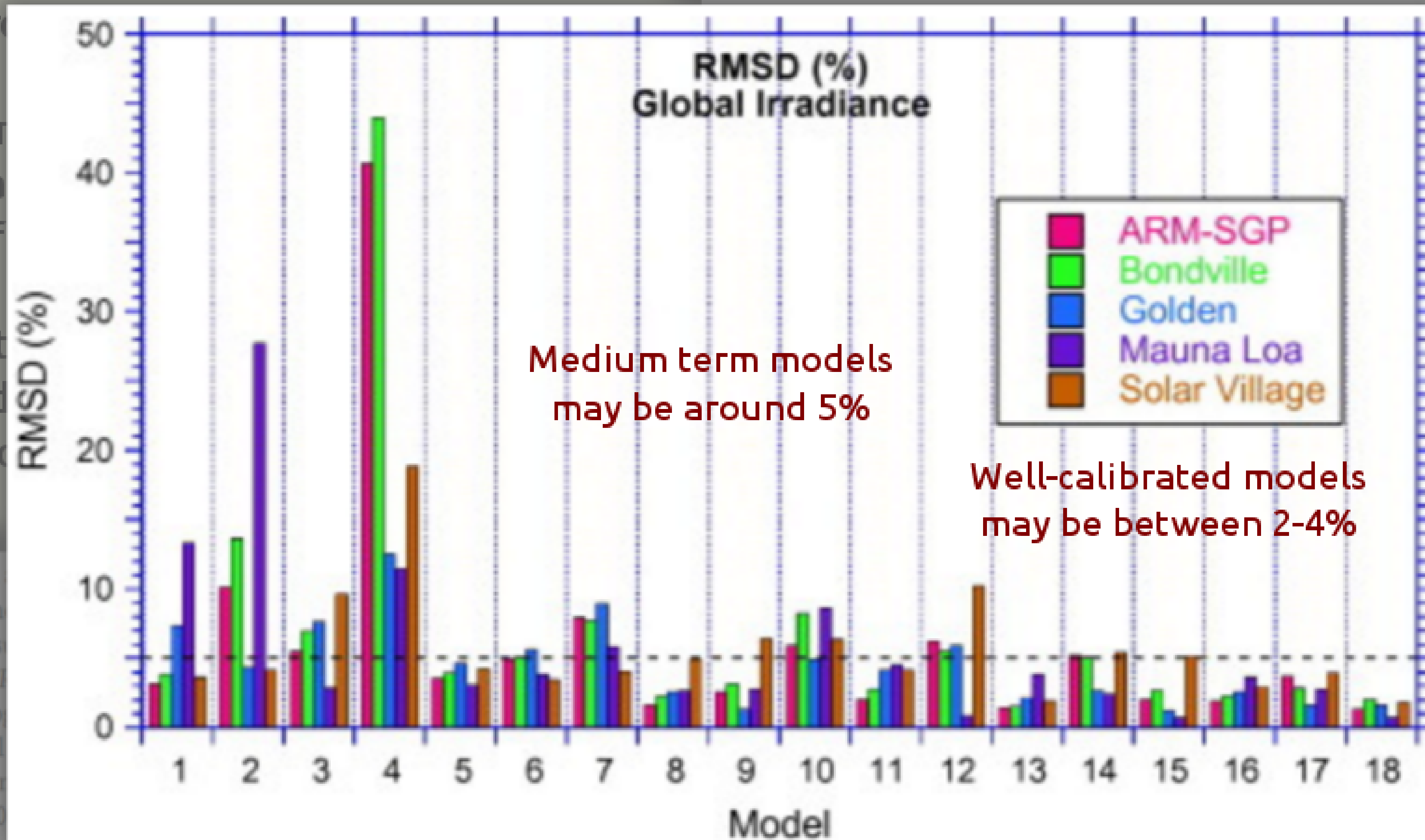
Gueymar

A compar
performa
account f

The input
each mod
(from 0 t

Table 1. Requested
constant) for all m
elevation (m); ρ_g, s
temperature (°C);
cm); u_n, total nitro
(cm); V, horizontal
turbidity coefficie
optical depth at 70
turbidity coefficient; ω_a, aerosol single-scattering albedo. The total number
of inputs appears in the last column.

#	Model Name	Year	h	ρ_g	p	T	RH	u_o	u_n	w	V	k	T_L	τ_a	τ_{a700}	α	β	ω_a	Total
1	ASHRAE	1972																	0
																			1
																			1
																			1
																			2
																			2
																			2
																			3
																	•		4
																			4
																	•		5
																			5
																			5
																			5
																	•		5
																•	•		6
17	Iqbal-C	1983	•	•				•		•						•	•		6
18	REST2	2008		•	•			•	•	•						•	•	•	8

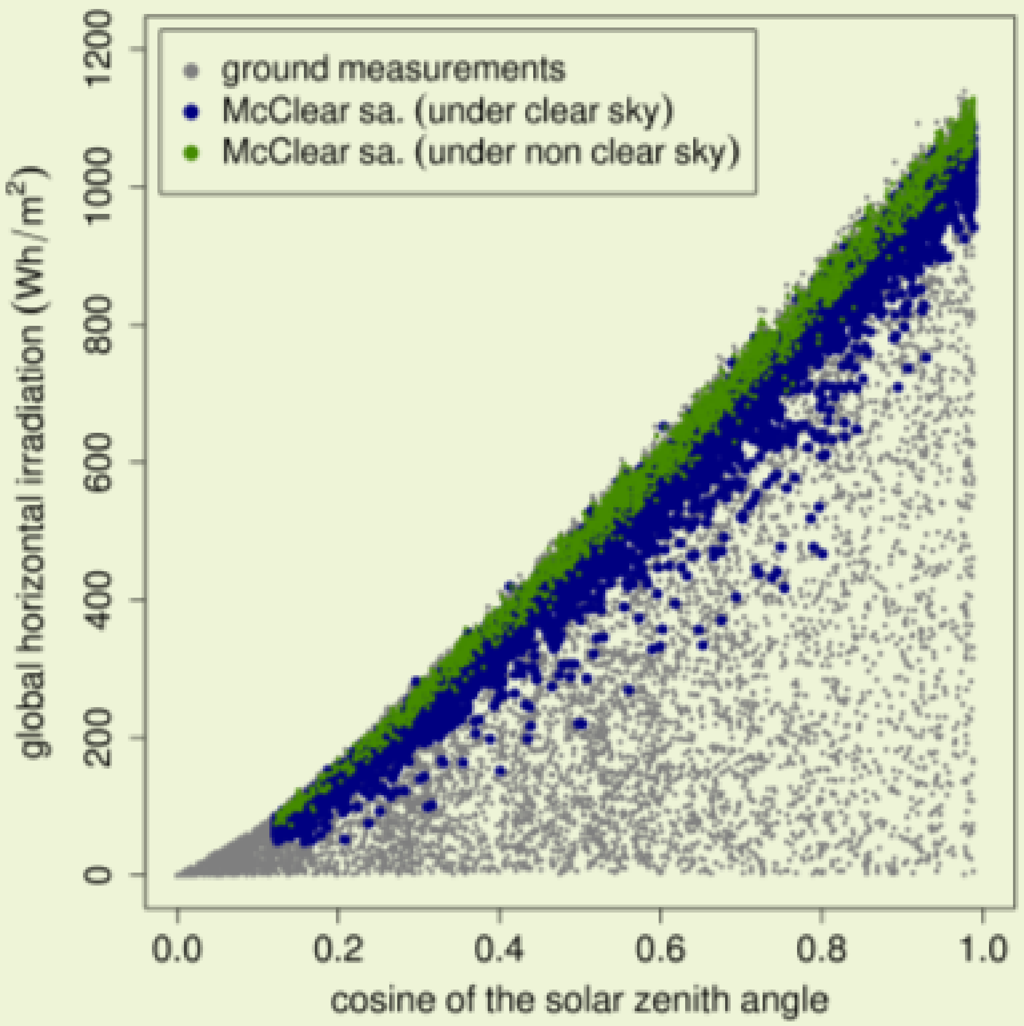


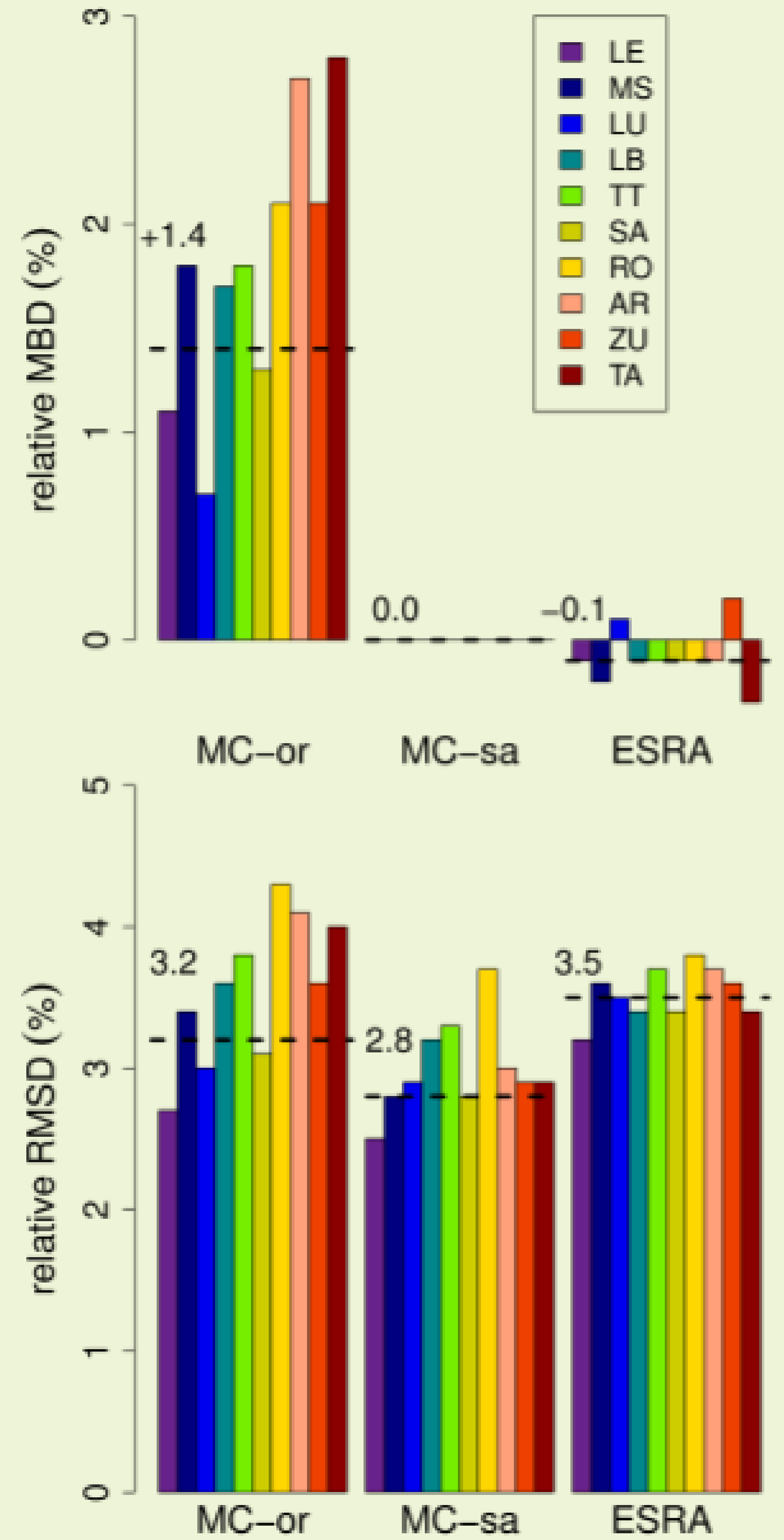
CLEAR SKY MODELS - our evaluation

McClear model is a succesful RTM model that use atmospheric inf. (MACC) and is operational via LUT

Comparison between McClear and ESRA with local average seasonal TL values (Pampa Humeda evaluation)

Special behavior of McClear model





CLOUD INDEX MODELS (CIMs - hybrid)

SUNY-v2 model:

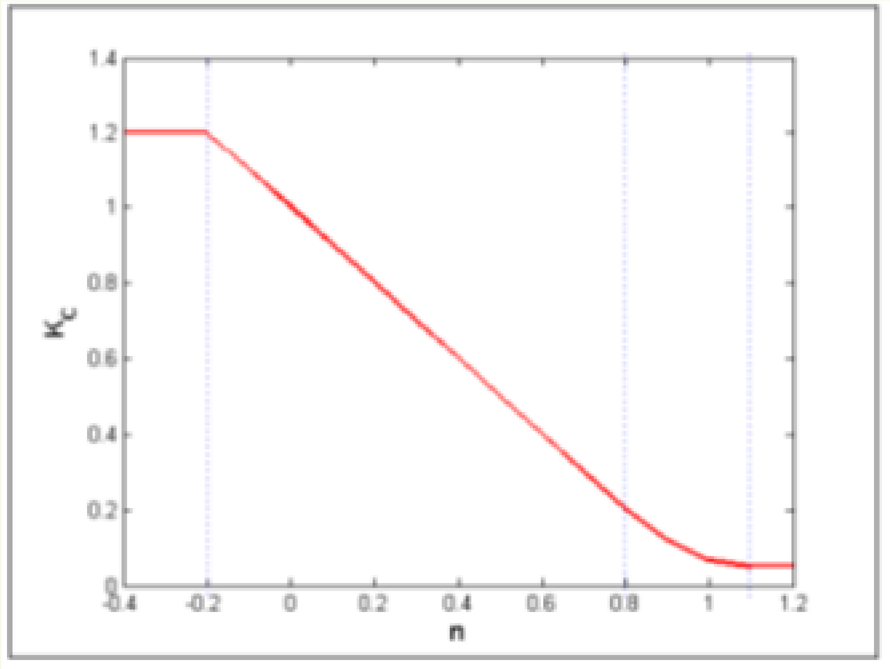
SOLYS

$$G_h = G_{csk} \times f(\eta) = G_{csk} \times [a + b(1 - \eta)]$$

Heliosat-2 model:

ESRA

$$G_h = G_{csk} \times f(\eta)$$



THE CLOUD INDEX ARE COMPUTED DIFFERENTLY IN BOTH MODELS

CLOUD INDEX MODELS (CIMs - hybrid)

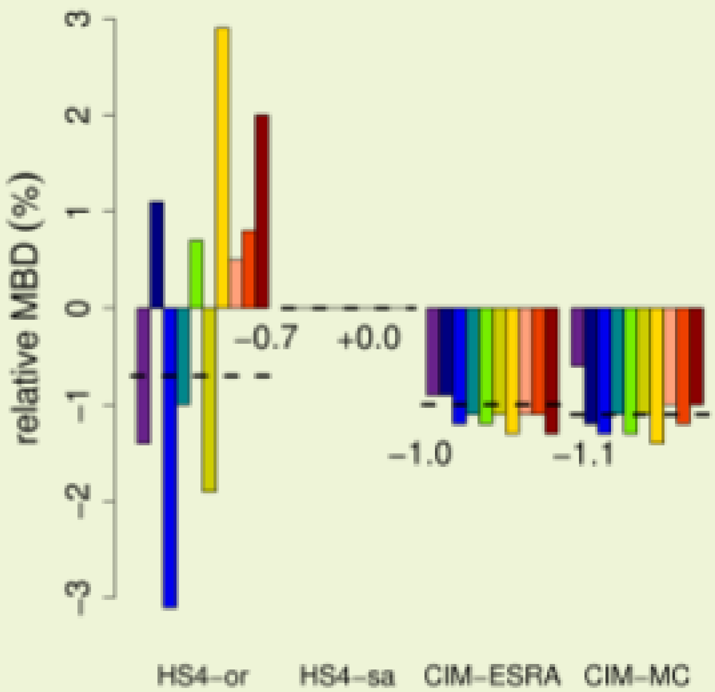
Ineichen, 2014 - evaluates several models in 18 measurements sites in Europe.
- standard deviations between 17-24% for GHI and 34-49% DNI.

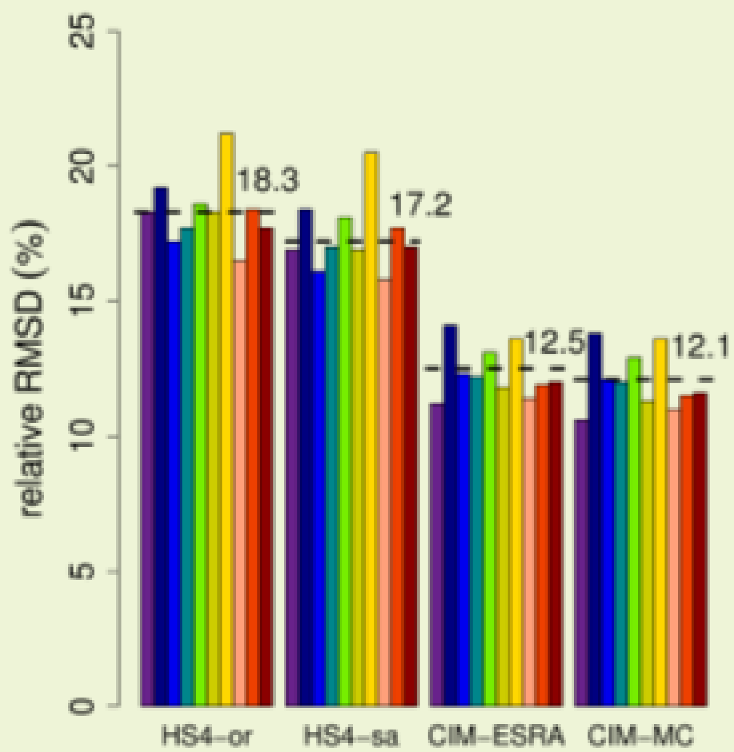
Perez et al. 2013 - typical GHI uncert.: 7-20% arid/semi-arid and 15-30% for complex sites.

	SolarGis						Helioclim 3						Solemi					
	Gh		Bn		Dh		Gh		Bn		Dh		Gh		Bn		Dh	
	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd
hourly [Wh/m2h]	341		351		134		345		354		134		349		361		134	
	0	57	-6	119	7	47	5	70	21	166	-13	60	8	71	-34	160	31	78
	0%	17%	2%	34%	5%	35%	1%	20%	6%	47%	-10%	45%	2%	20%	-9%	44%	23%	58%
Daily [kWh/m2]	[illegible]		[illegible]		[illegible]		3.81		3.91		1.49		3.82		3.95		1.47	
	0.00	0.31	[illegible]	0.79	0.05	0.34	[illegible]	0.43	0.18	1.23	-0.12	0.46	0.06	0.58	-0.34	1.37	0.28	0.60
	0%	8%	-1%	21%	4%	23%	1%	[illegible]	5%	32%	-8%	31%	2%	15%	-9%	35%	19%	41%
Monthly [kWh/m2]	107.7		110.2		42.6		109.2		112.0		42.8		111.0		114.6		42.6	
	-0.1	3.9	-1.4	10.7	1.8	4.6	1.1	7.1	5.3	[illegible]	-3.6	6.1	1.8	6.8	-10.8	17.0	9.0	9.0
	0%	4%	-1%	10%	4%	11%	1%	6%	5%	16%	[illegible]	14%	2%	6%	-9%	15%	21%	21%

	Heliomont						62m Solutions						IrSOLaV					
	Gh		Bn		Dh		Gh		Bn		Dh		Gh		Bn		Dh	
	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd	mbd	sd
hourly [Wh/m2h]	320		325		132		443		465		[illegible]		340		352		134	
	2	64	9	133	0	50	11	86	58	196	-22	77	2	81	-2	174	5	62
	1%	20%	3%	41%	0%	38%	2%	19%	12%	42%	-16%	58%	1%	24%	1%	49%	4%	46%
Daily [kWh/m2]	3.53		3.58		1.46		4.40		4.62		1.49		[illegible]		[illegible]		1.41	
	0.06	0.34	0.17	0.85	-0.01	0.34	0.12	0.46	0.53	1.27	-0.19	0.56	0.02	0.44	0.00	1.19	0.04	0.42
	2%	10%	5%	24%	-1%	24%	3%	11%	11%	28%	-13%	37%	0%	12%	0%	32%	3%	30%
Monthly [kWh/m2]	100.7		102.2		41.7		126.2		132.4		42.8		105.0		108.4		40.9	
	1.9	4.7	5.1	12.2	-0.1	4.5	3.5	6.1	16.2	15.2	-5.9	6.9	0.6	6.4	-0.5	15.9	1.6	5.4
	2%	5%	5%	12%	0%	11%	3%	5%	12%	11%	-14%	16%	1%	6%	0%	15%	4%	13%

CLOUD INDEX MODELS - our evaluation





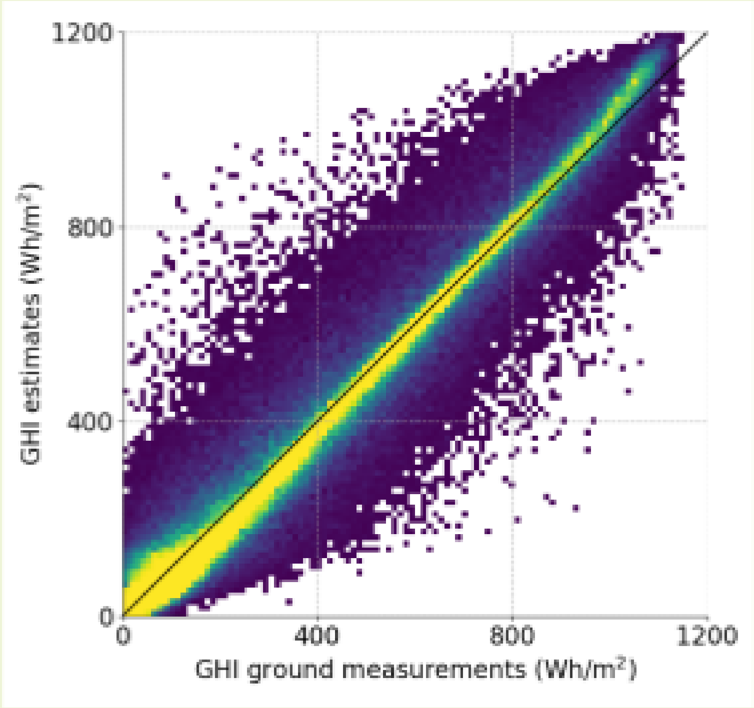
Heliosat-4 (CAMS)

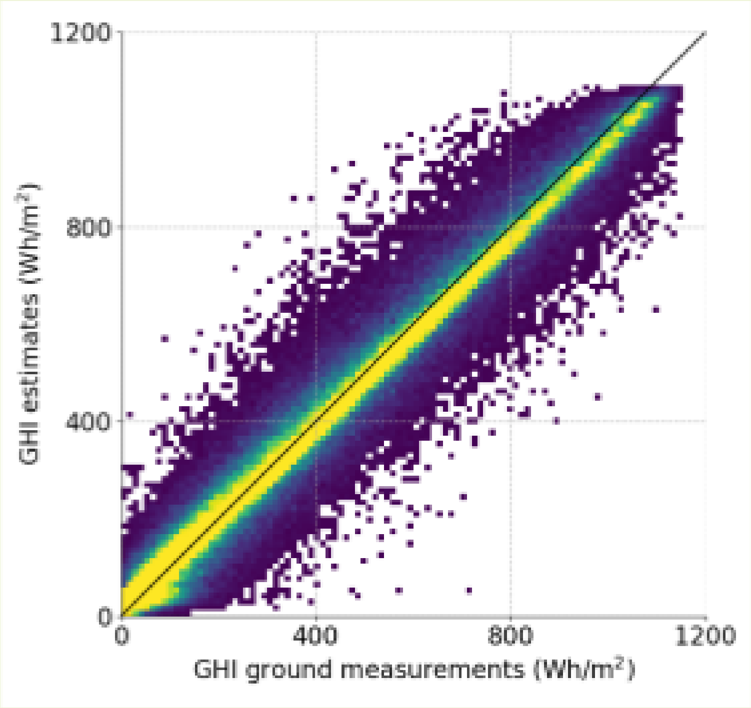
CIM-McClear

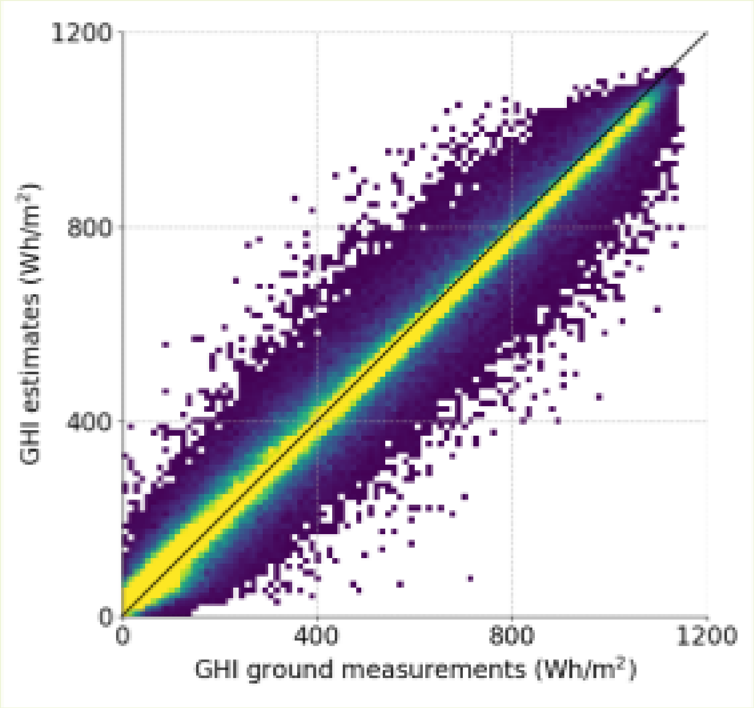
CIM-ESRA

Different satellite inputs

Heliosat-4 -> MSG
CIMs -> GOES-East



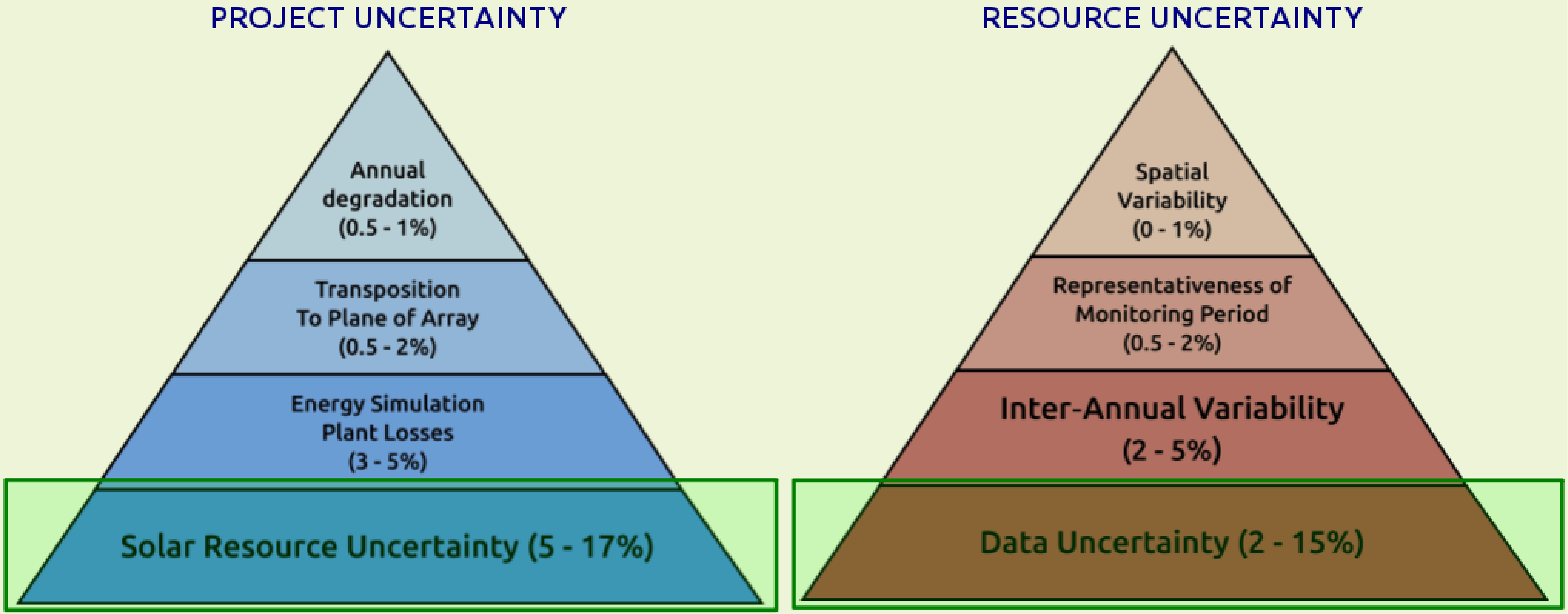




SOLAR RESOURCE ASSESSMENT

APPLICATION OF SATELLITE MODELS

UNCERTAINTY = FINANTIAL RISK



THE SOLAR RESOURCE UNCERTAINTY AT THE SPECIFIC PROJECT SITE IS THE HIGHER

THE DATA UNCERTAINTY IS THE HIGHER

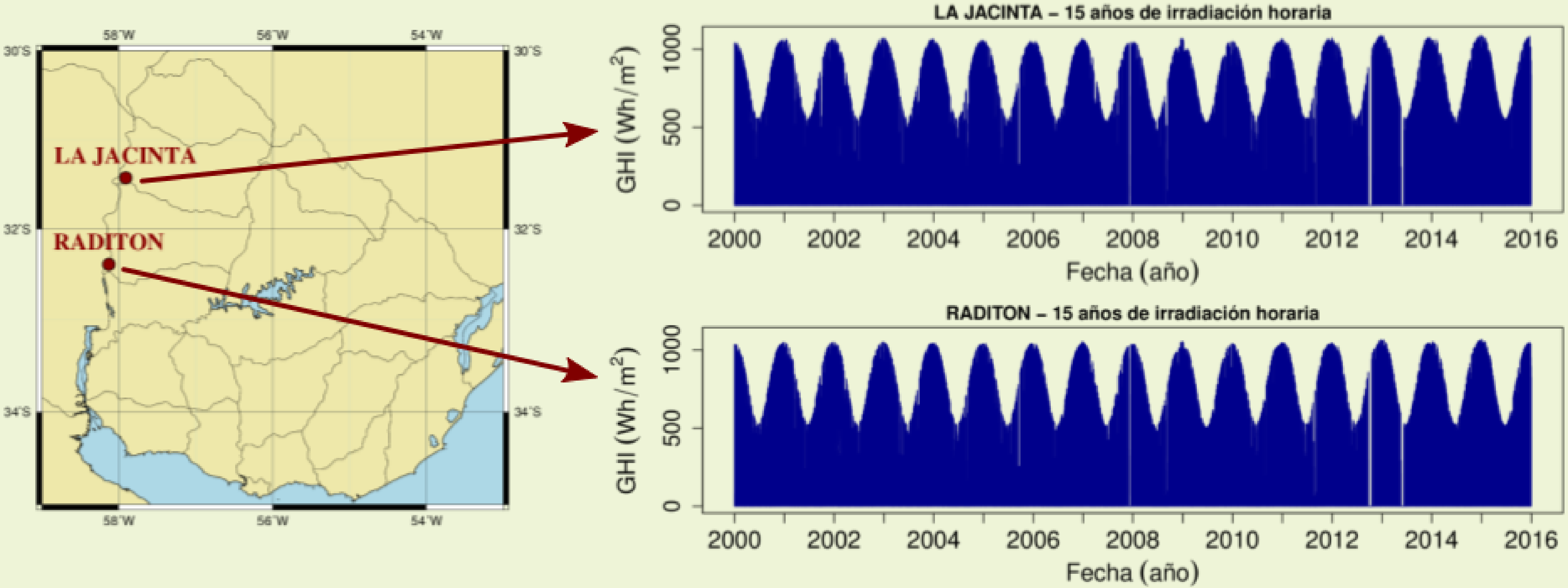
Schnitzer et al., 2012

APPLICATION OF SATELLITE MODELS

THE MODELS CAN BE USED TO ESTIMATE SOLAR IRRADIATION TIME-SERIES AT SPECIFIC SITES

THE IRRADIATION SERIES ARE ESSENTIAL FOR SOLAR APPLICATIONS DESIGN AND SIMULATION

USING LONG-TERM SATELLITE IMAGES IT IS POSSIBLE TO ESTIMATE THE SOLAR IRRADIATION IN ANY SITE (~2 km resolution) AT AN INTRA-HOUR TIME BASIS ENABLING THE ASSESSMENT



URUGUAY'S SOLAR MAP
(second version, 2017)

First long-term characterization

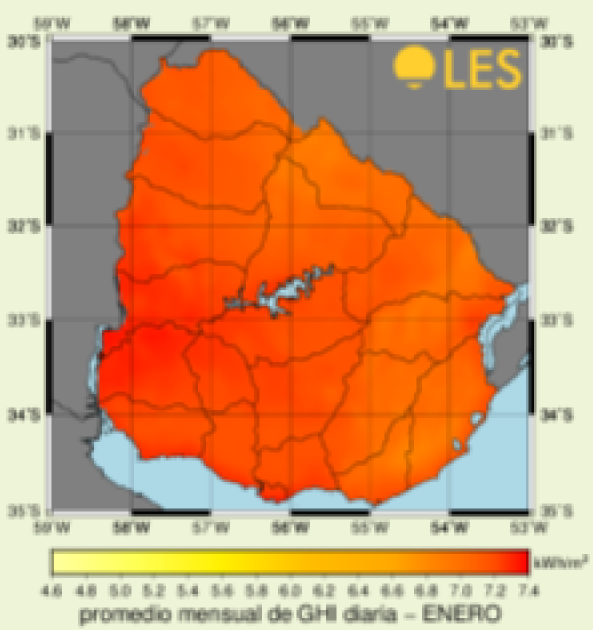
Spatial resolutionl: ~2 km

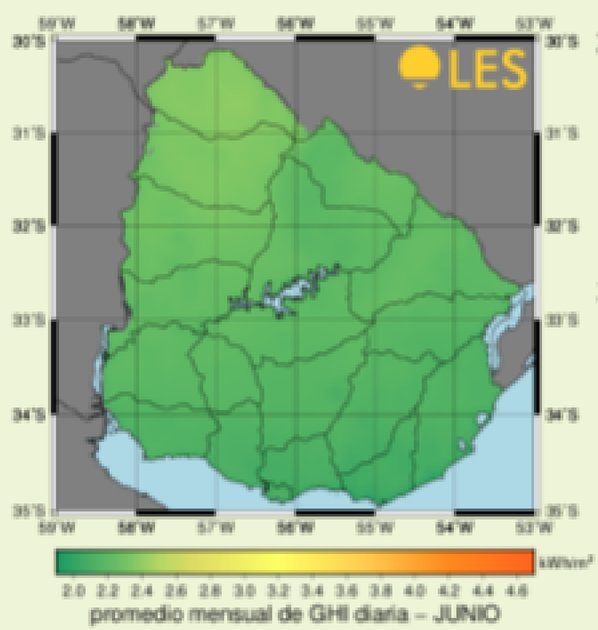
Input information:

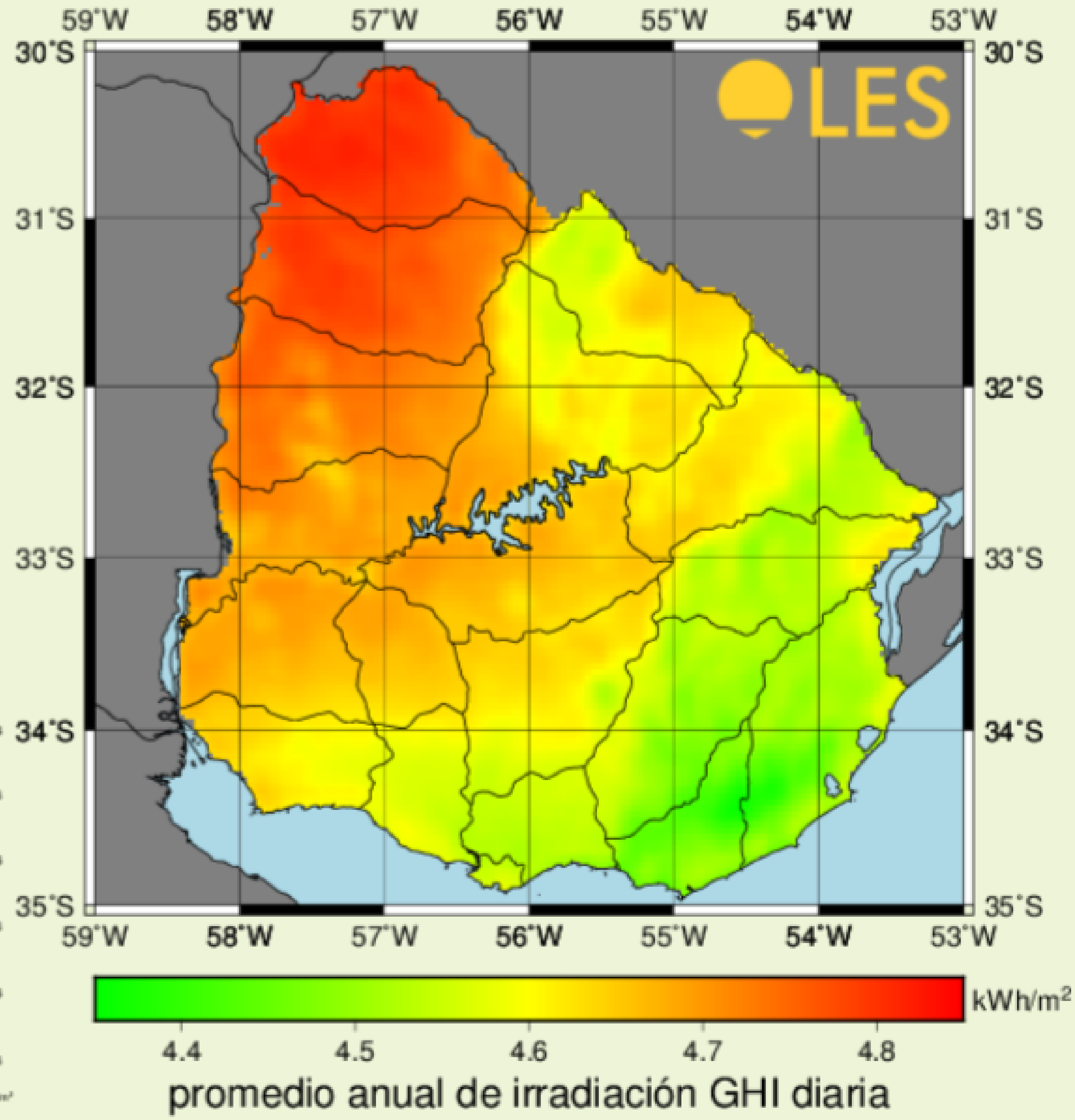
- ~16 years of satellite information
- ~5 years of ground measurements

Uncertainty:

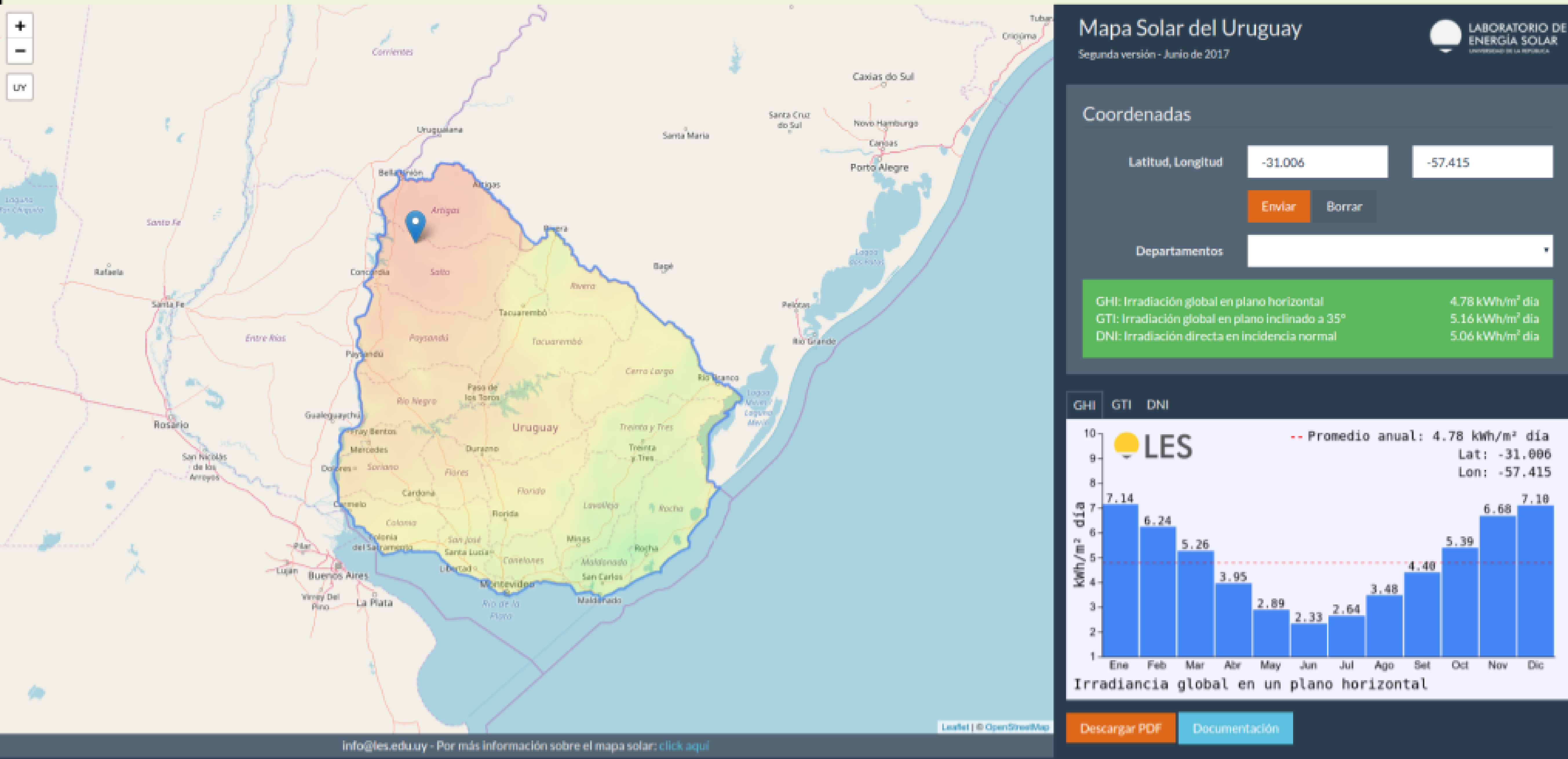
- 2% for monthly an annual maps
- 4% for month-to-month estimates
- 6% for daily estimates
- 13% for hourly estimates







ONLINE SOLAR MAP TOOL

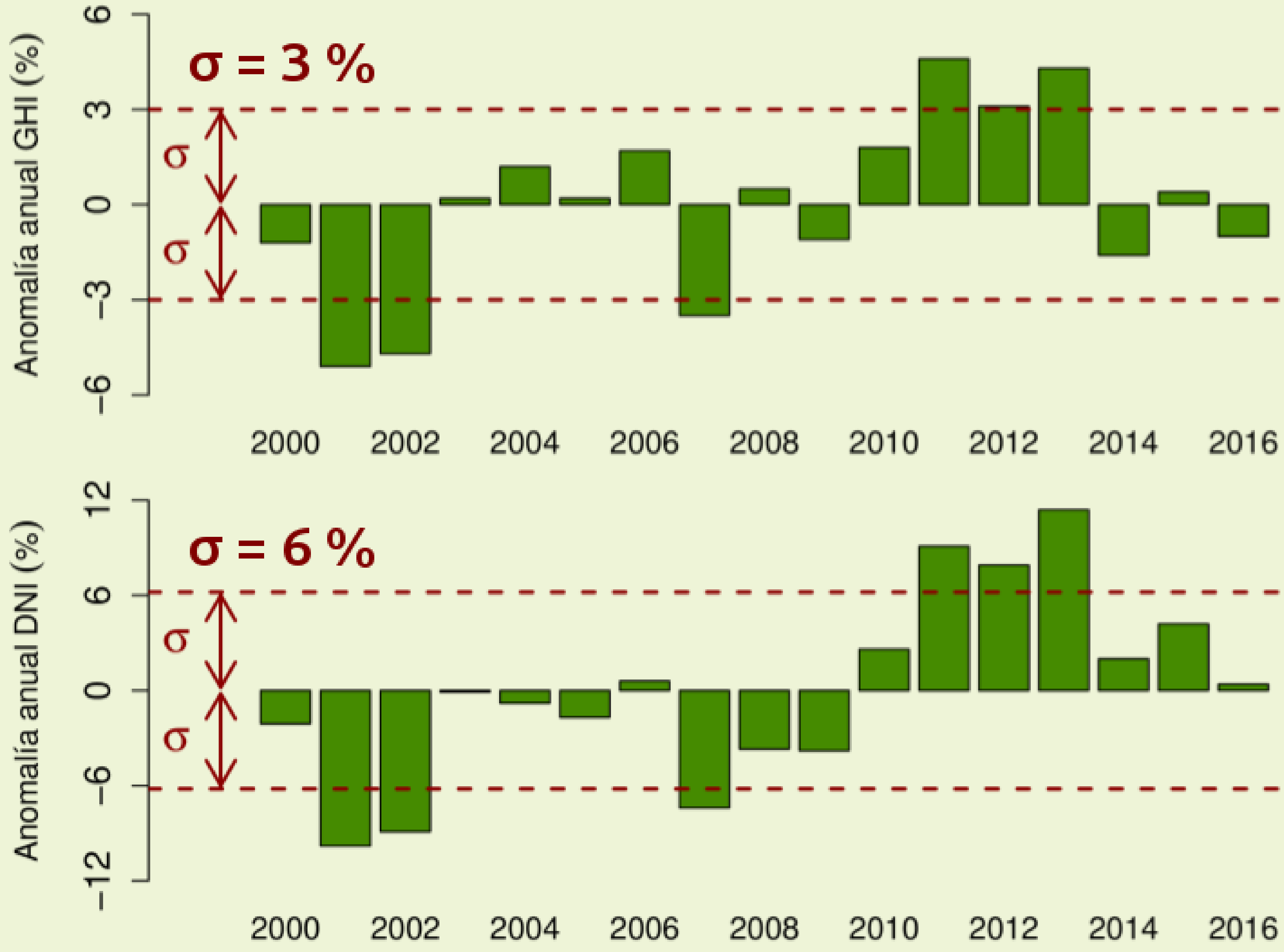


http://les.edu.uy/online/msuv2/

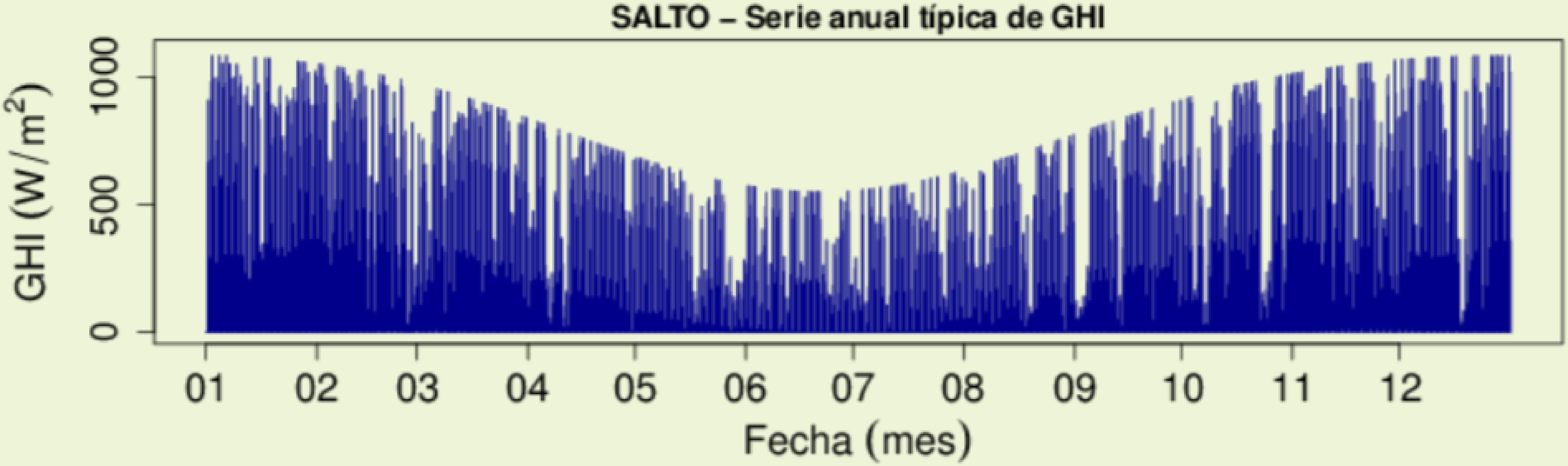
INTER-ANNUAL VARIABILITY

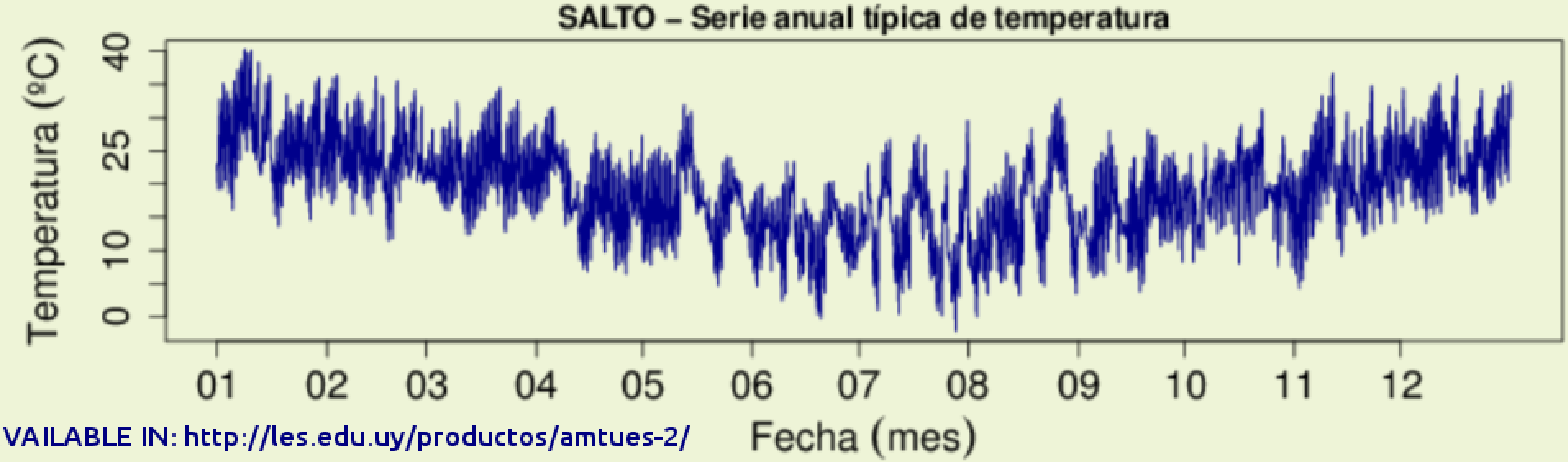
95% of the yearly sums are between ± 6% (P95)

95% of the yearly sums are between ± 12% (P95)



TYPICAL METEOROLOGICAL YEAR - SOLAR APPLICATIONS





AVAILABLE IN: http://les.edu.uy/productos/amtues-2/

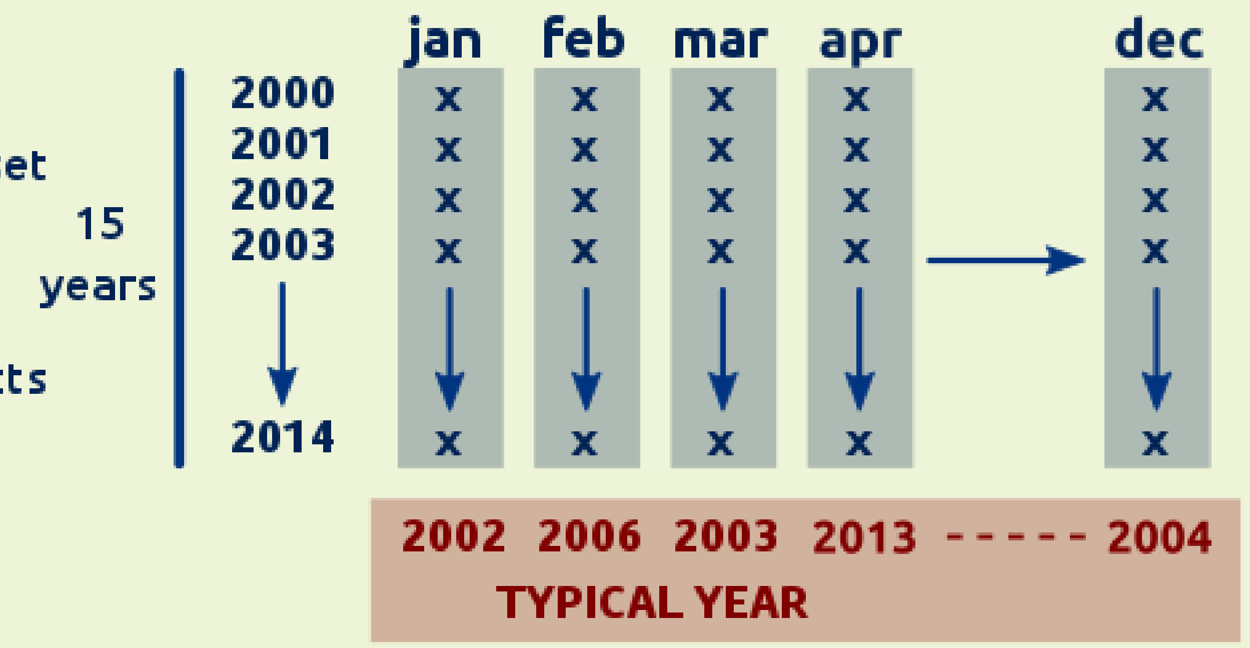
TYPICAL METEOROLOGICAL YEAR FOR SOLAR ENERGY APPLICATIONS

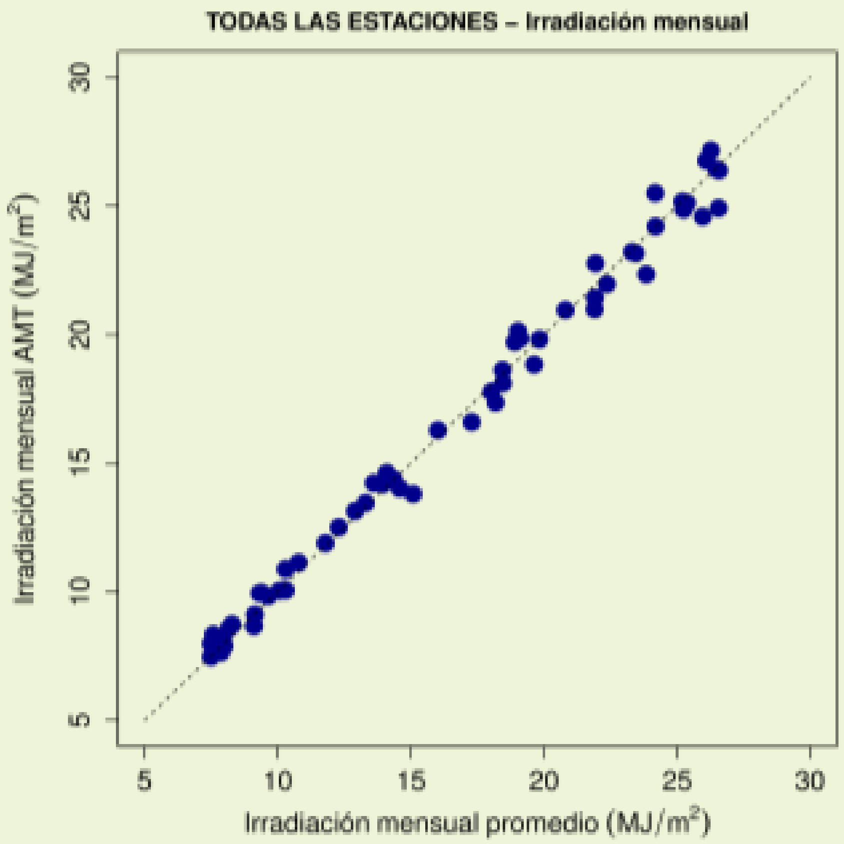
SANDIA-NREL METHODOLOGY (TMY3, EEUU)

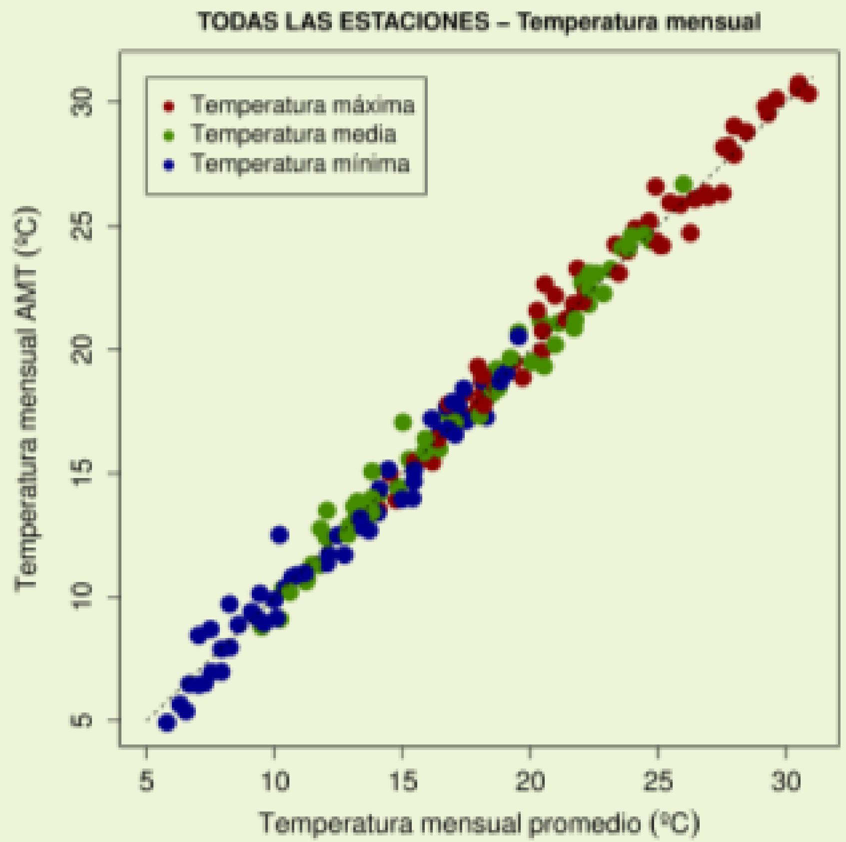
The typical characteristics of each year-month data set is quantified by comparing with the long-term CDF

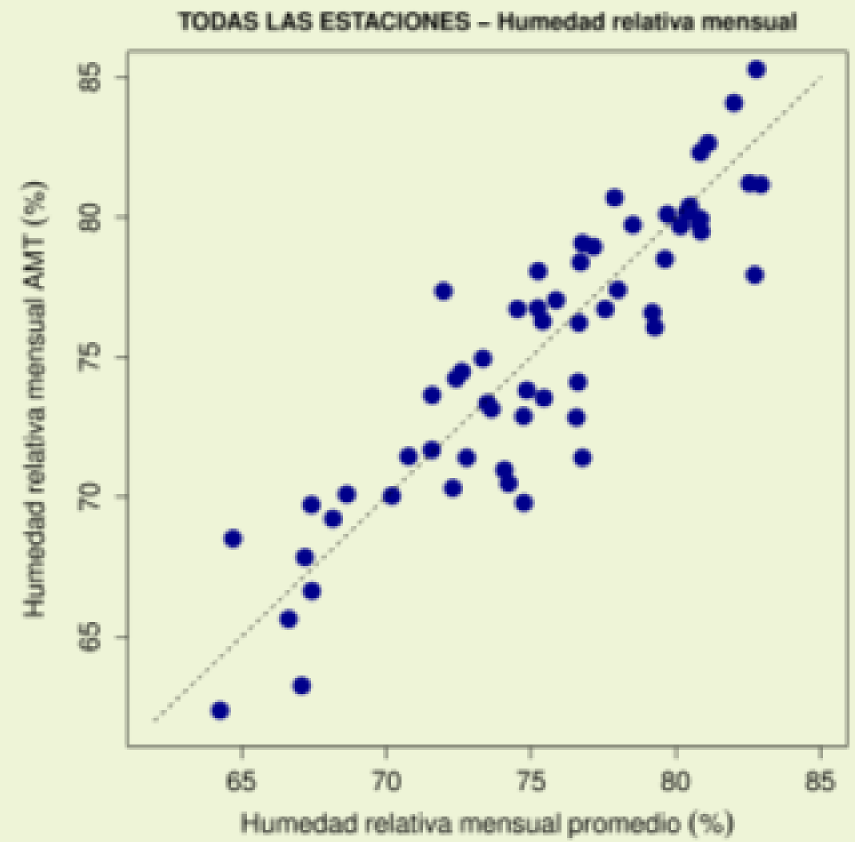
The typical measure of each variable is weighted in accordance to its importance for solar energy projects

A special smoothing procedure is required in each month interface for the non-solar variables









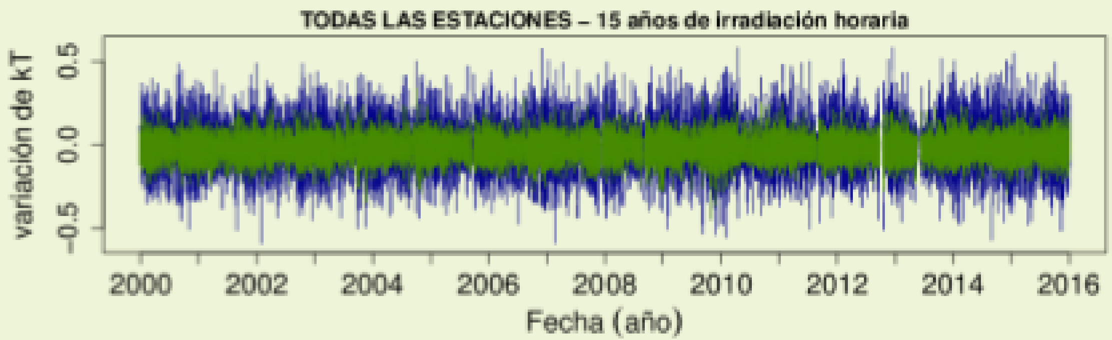
OUR CURRENT WORK

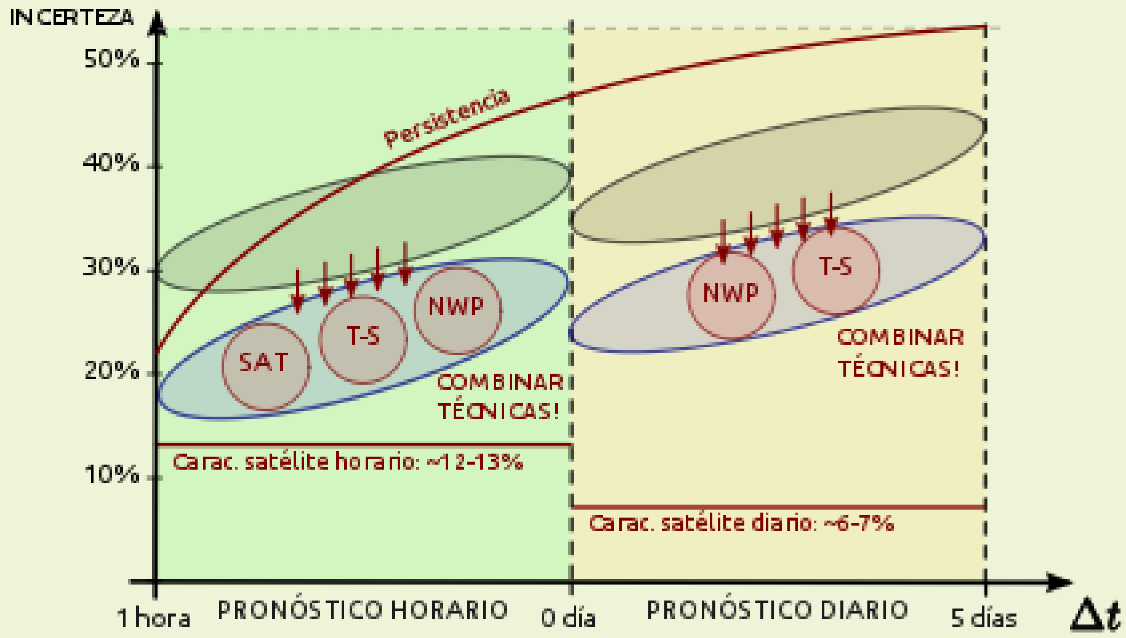
CURRENT WORK

RELATED TO SOLAR PV POWER PLANTS LOCATED IN URUGUAY

UNDERSTAND SHORT-TERM VARIABILITY IN URUGUAY
(minutal, 10-minutal, hourly)

REDUCE THE UNCERTAINTY OF SOLAR FORECASTING
hourly satellite forecast
some days-ahead NWP forecast





IMPROVE SATELLITE MODELS (GHI, DNI and GTI): semi-empirical and physical models.

ALL TECHNIQUES FOR POINT FORECAST: NWP, satellite, all-sky cameras, time-series analysis.

PROBABILISTIC FORECAST: with Philippe and Mathieu (in collaboration with PIMENT).

ENHANCE SATELLITE INFORMATION USE IN URUGUAY: cloud classification, fog, rain estimates, etc.

NOW: accessing satellite data for other parts of the world

Thank you for your attention!

LABORATORIO DE ENERGÍA SOLAR
UNIVERSIDAD DE LA REPÚBLICA

http://les.edu.uy/
http://les.edu.uy/online/

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