3rd SFERA Summer School

Solar resource forecasting

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B. Kraas, CSPServices (former Solar Millennium AG)

J. Remund, Meteotest

Outline

- Forecast requirements
- Basic meteorological terminology and forecast methodolgies
- Numerical weather prediction – verification measures, spatial error correlation
- Do we need aerosol forecasts?
- Possibilities of ground measurements?
- Satellite-based nowcasting
- Some thoughts on the economic value of forecasts (only market participation case)

- Credits to
  - EC – Global Monitoring for Environment and Security (GMES)
    MACC Atmosphere core service preparations project
    ENDORSE (Energy downstream services) project
  - ESA – Integrated Application Program – CSP-FoSyS project
  - EC DG ENV – EnerGEO project

This talk concentrates on

- Direct normal irradiance forecasting
- Focus on hourly resolution
- Less than hourly resolved forecasting

- No solar power output forecast
  = fct (power plant state, plant technology)
- No other meteo parameters
(wind gust, temperature, wind)

- This overview concentrates on principles
- It does not provide many information on
typical accuracies (look into the additional slides)

Use cases in grid integration studies

Transmission System operator (TSO) point of view

- grid stabilisation
- 15 minutes interval
- up to 1-2 hour forecast needed

Power plant operator point of view
(especially for CSP)

Market participation

Participation on the Spanish electricity market (OMEL):

→ Day ahead market (obligatory)
→ 6 intraday market sessions
→ False programming results in penalties

Grid access license

To be considered as a predictable power source ("procución gestionable"):

→ 10% accuracy for 24 hour forecast needed
→ 5% accuracy for 6 hour forecast needed
→ Predictability test ("prueba de gestionabilidad")

Plant operation

Optimization of plant operation using forecast systems:

→ Power Block Control and security warnings (15-180 minutes)
→ Plant operation planning (24-48 hours)
→ Maintenance planning (1-7 days)

Forecast parameters

Importance of meteorological parameters that have to be forecasted for a CSP Power Production prevision

Parameter:

→ Direct solar radiation

→ Wind gust

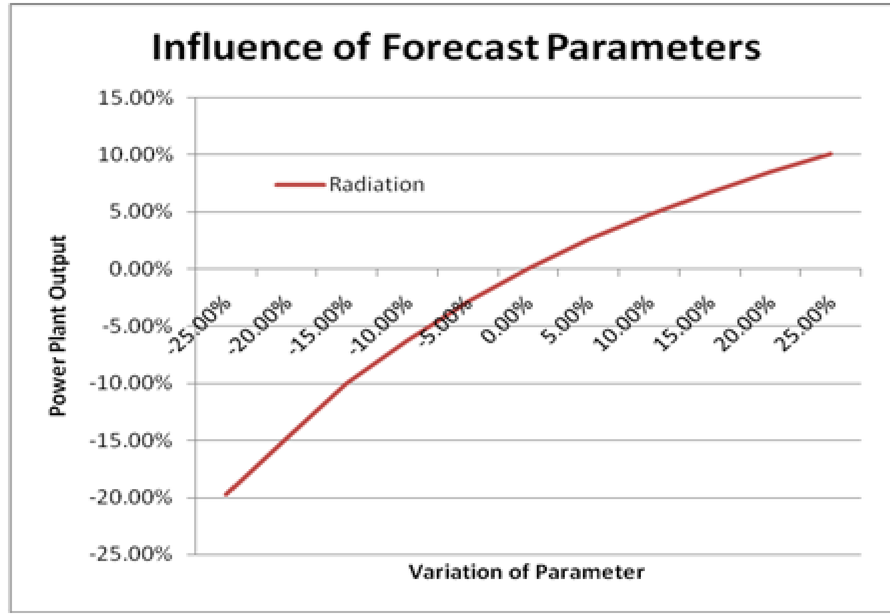
→ Temperature

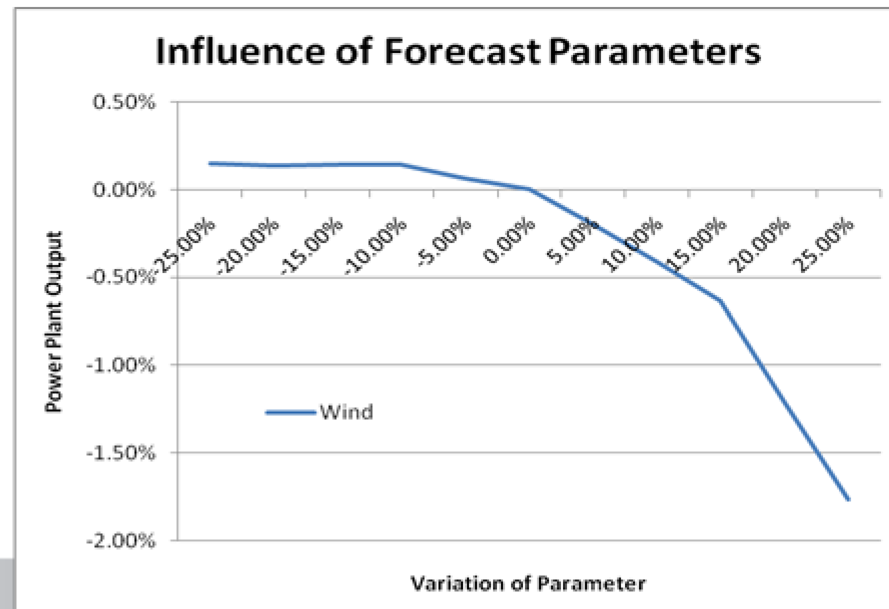
→ Wind speed

Importance:

Based on 1 year measurements at the Andasol site

Solar Millennium



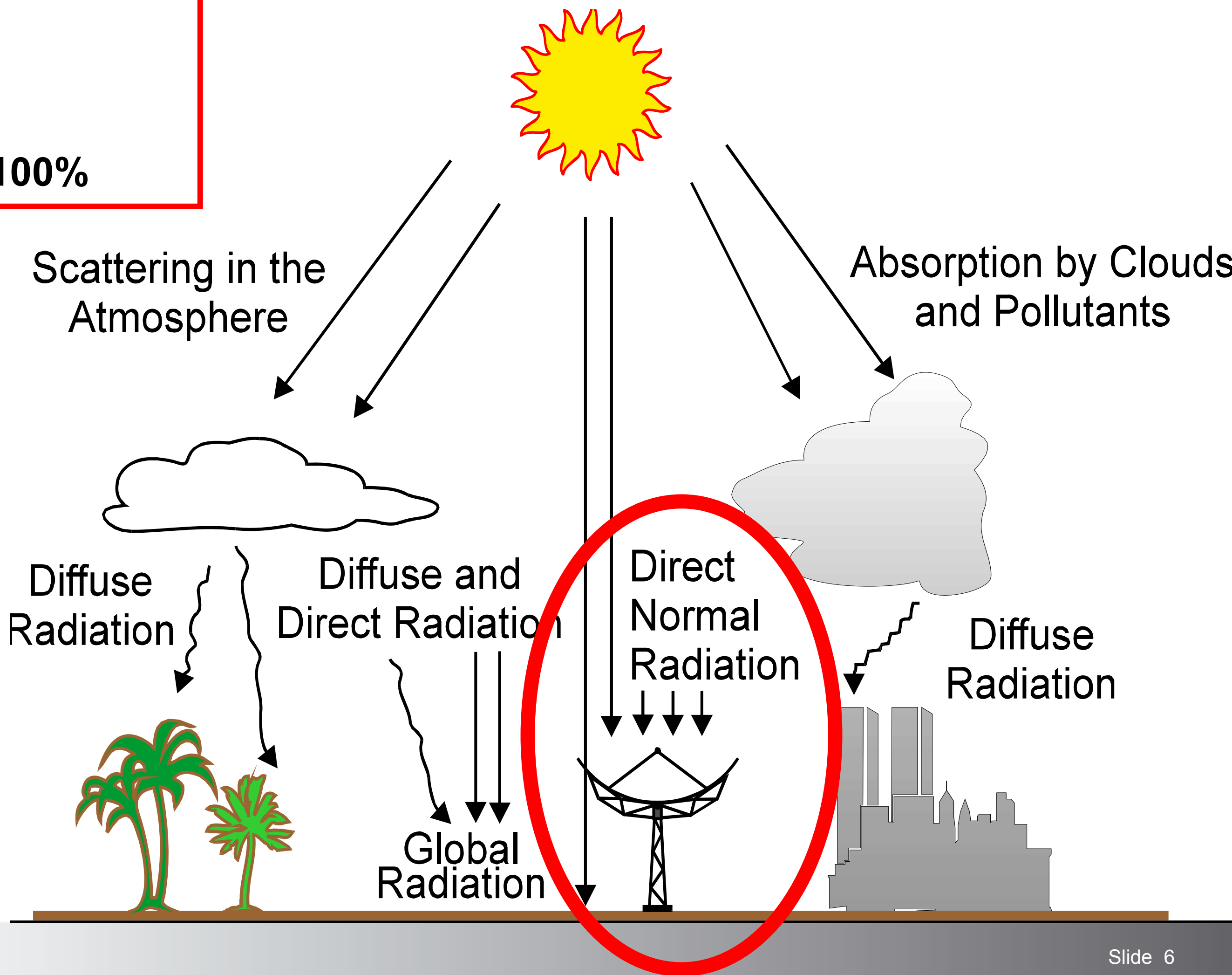


Reduction of direct irradiance

Clouds up to 100%

Water vapour 10-15%

aerosols 20-25%, up to 100%

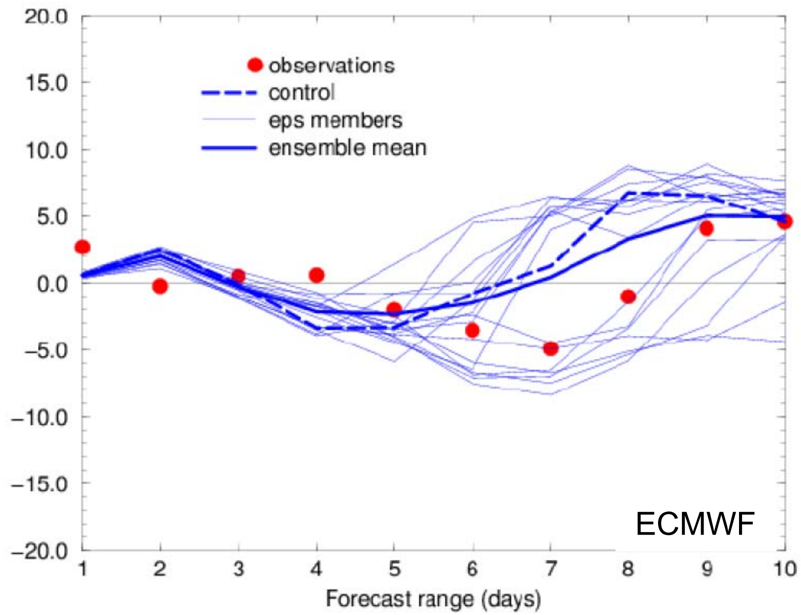


Hindcast — historical forecasts
good for assessments/development

Nowcast = up to 3 hours
Shortterm forecast = up to 6 hours
Day ahead forecast = up to 48 hours
Medium range forecast = up to 10 days

Climate scenarios — NOT a foreca
a scenario de
e.g. 2050 or 2

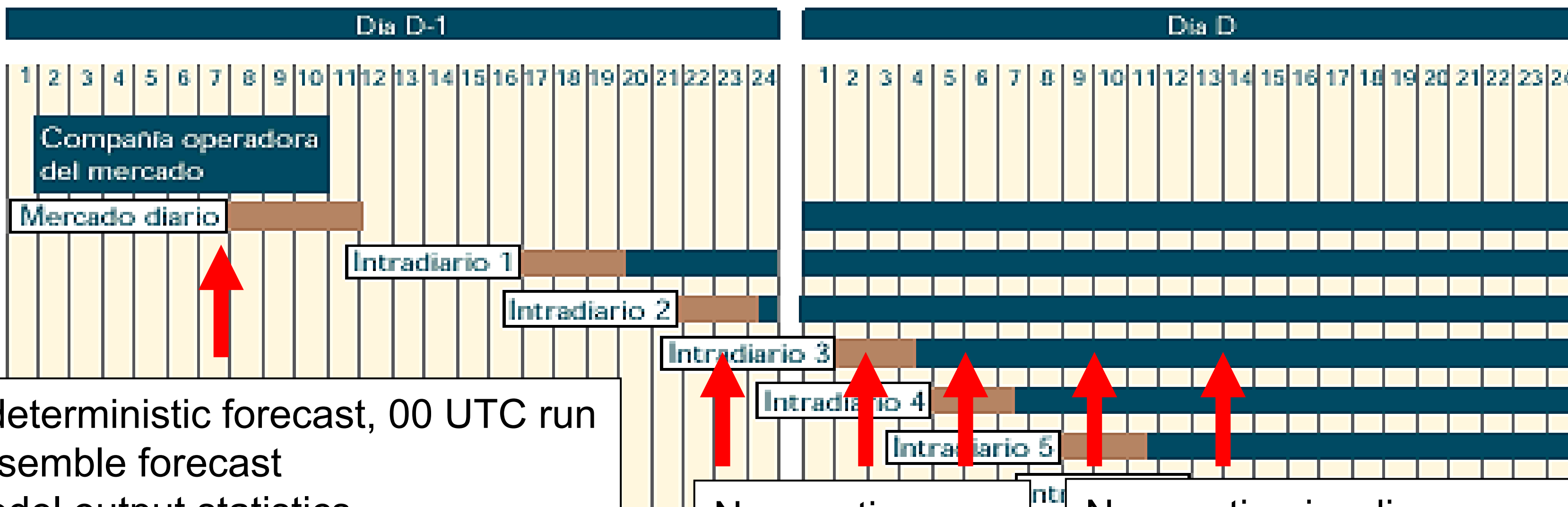
Deterministic forecast — a single weat
Ensemble forecast — 30 or 50 wea
probabilistic e



CSP operator point of view – example case Spain

Day ahead

Intra-day



48h deterministic forecast, 00 UTC run
+ ensemble forecast
+ model output statistics
Aerosol forecasts (chemical transport model)

Nowcasting clouds
(IR satellite)

Nowcasting irradiance,
cloud movement vectors
aerosol monitoring
Stochastic methods

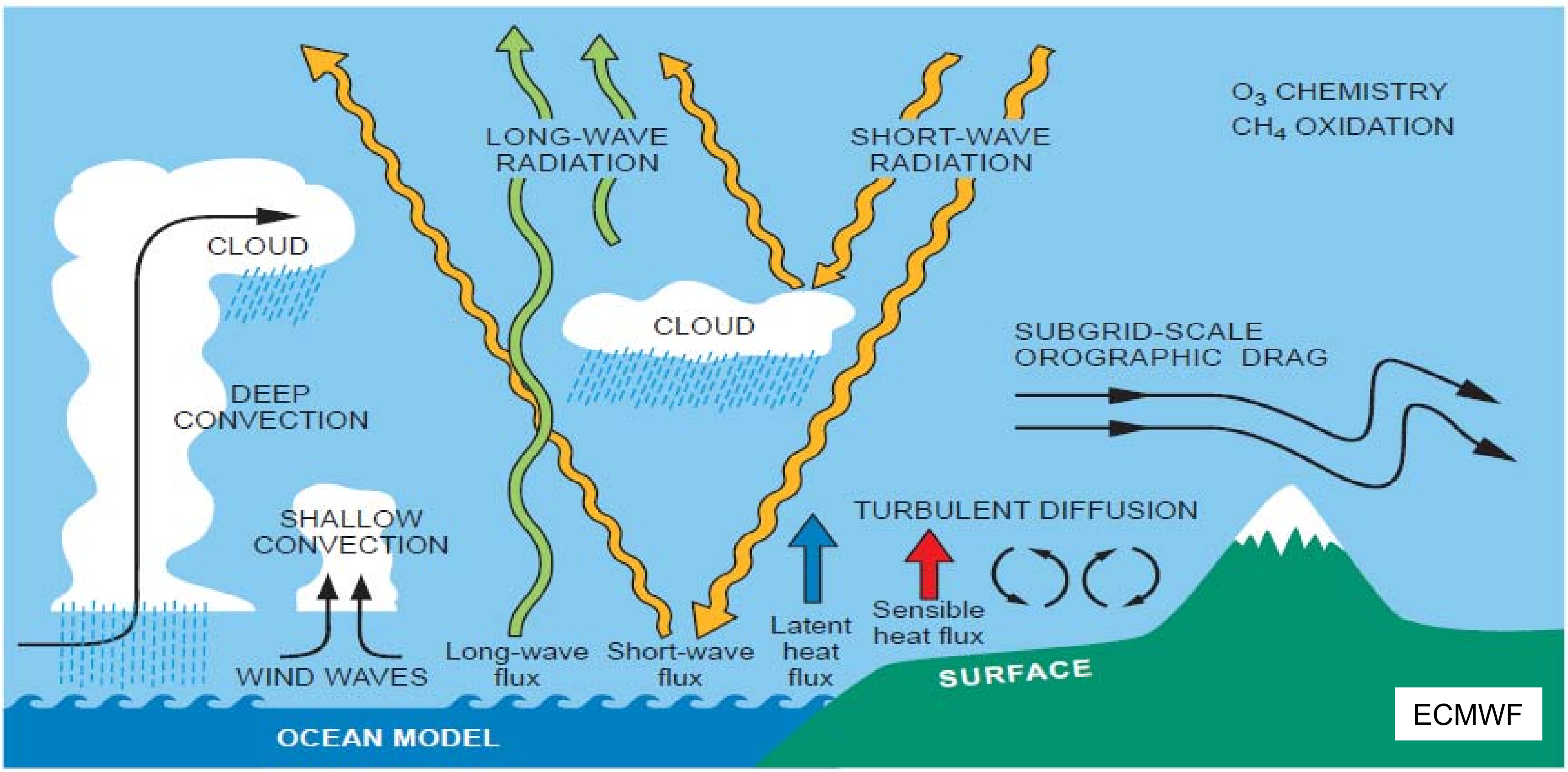
Large open question:
Use and value of forecasts in plant operations besides day ahead and intraday markets …. Not treated so far…

Methods and results

Physical methods

Apply physical principles (atmospheric dynamics, thermodynamics, radiative transfer, optical properties)

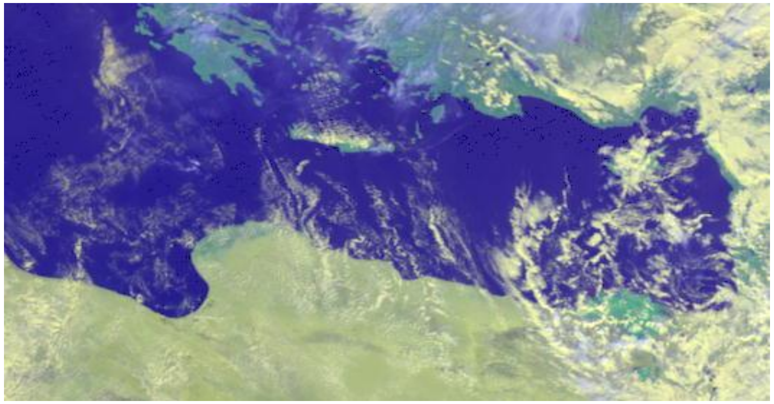
Numerical weather prediction



Physical methods

Satellites

optical measurements in visible and infrared spectrum
optical properties like refractive indices
radiative transfer modeling -> radiation



Forecast based on either NWP through data assimilation
or on stastical procedures (next slide)

Stochastic learning techniques

Characteristics:

- rely on past data to train models, no/little physical assumptions
- assumption that future irradiation can be predicted
  based on historical patterns
- assume persistence in opacity, direction and velocity of clouds

Methods

- persistence approach ‚yesterday == tomorrow‘ (2 day sometimes needed)
- auto-regressive models
- artificial intelligence/neural network
- cloud motion vectors (cloud camera/satellites)

Advantages

- Good for intra-hour or nowcasting
- cheap

Characteristics of solar forecasting techniques

Technique	Sampling rate	Spatial resolution	Spatial extent	Maximum Suitable Forecast horizon	Application
Persistence	High	One point	One Point	Minutes	Baseline
Whole Sky Imagery	30 sec	10 to 100 meters	3-8 km radius	10s of minutes	Ramps, regulation
Geostationary satellite imagery	15 min	1 km	65°S – 65°N	5 hours	Load following
Numerical weather prediction (NWP)	1 hour	2 - 50 km	Worlwide	10 days	Unit commitment regional power prediction

Source: Remund, 2012

Circum-solar taken into account?

- Typical textbook definition:

  the radiant flux collected by a surface normal to the direction of the Sun, within the extent of the solar disk only (half-angle δ = 0.266°)

- Three "worlds" : three definitions of DNI!
  - World of Radiative Models (e.g. 6S, libRadtran): Solar source is a Dirac

    NWP, some SAT

  - World of Physical Measurements: definition of DNI by the corresponding measurement device. From WMO CIMO Guide (2008):
    "*Direct solar radiation is measured by means of pyrheliometers, the receiving surfaces of which are arranged to be normal to the solar direction. By means of apertures, only the radiation from the sun and a narrow annulus of sky is measured, the latter radiation component is*
    - *sometimes referred to as circumsolar radiation or aureole radiation*"

    Some stochastic methods

  - World of Solar Energy Conversion: definition of DNI by the corresponding concentrating solar system (0.9 to 5°)

Numerical weather prediction

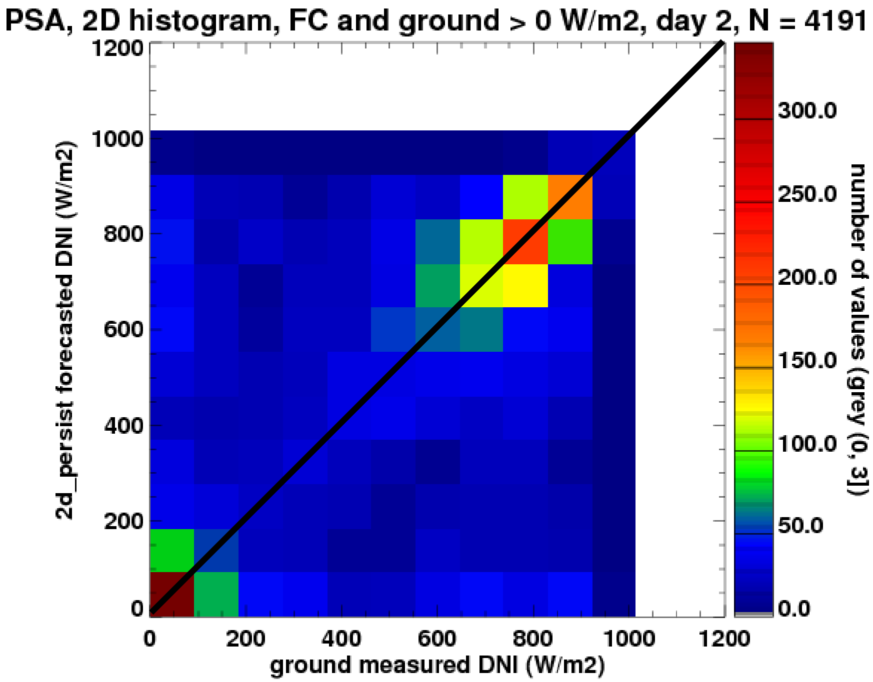
- Model runs initiated two to four times per day (e.g. 0, 6, 12 and 18 UTC)
- initial conditions from satellite, in-situ, ground observations
- Pre-processed and interpolated to the 3D grid
- resolution of global NWP models is coarse (15 to 90 km)
- mesoscale or limited area models: limited geographical area with higher resolution (up to few km)

- Trouble with mesoscale models: Place clouds still at the wrong place and have RMSE worse than global ECMWF model.

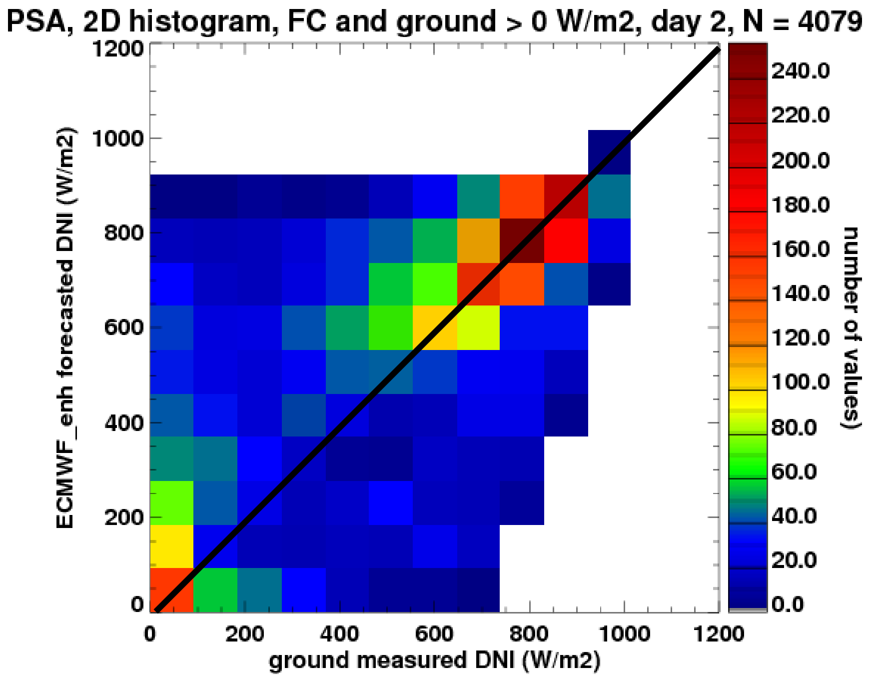
- ECMWF = European Centre for Middle-Range Forecasts

- Since 2011 ECMWF provides also direct irradiance forecasts
- Most models provide only global -> statistical global to direct conversion needed

Verification ECMWF/DLR : Scatterplots for hourly values



2 day persistence,
2005

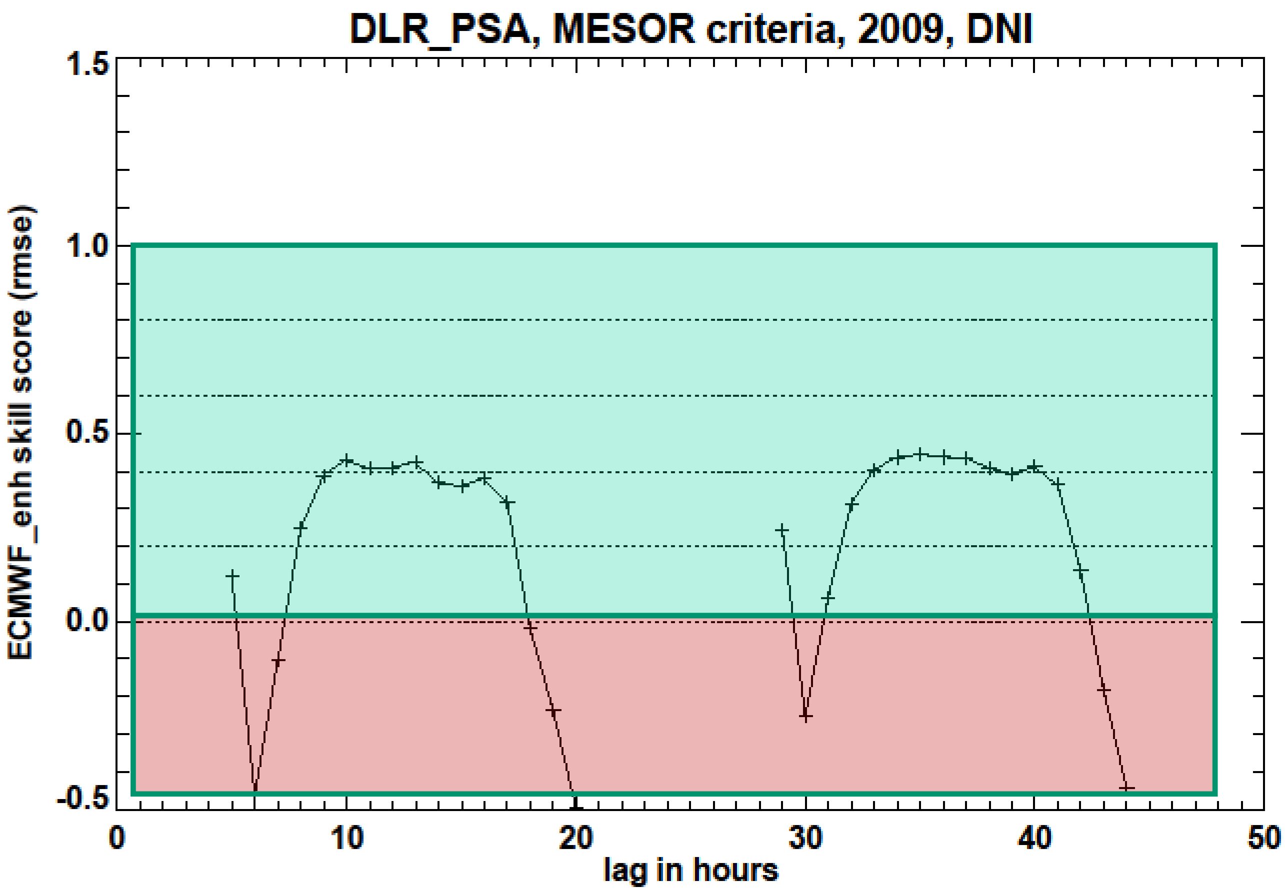


ECMWF/DLR,
2005

Verification ECMWF/DLR

$$skill\ score = \frac{Metric_{reference} - Metric_{forecast}}{Metric_{reference} - Metric_{perfect\ forecast}}$$

Skill score = $(RMSE_{fc} - RMSE_{pers})/RMSE_{pers}$



Bad morning due to 3-hourly forecast

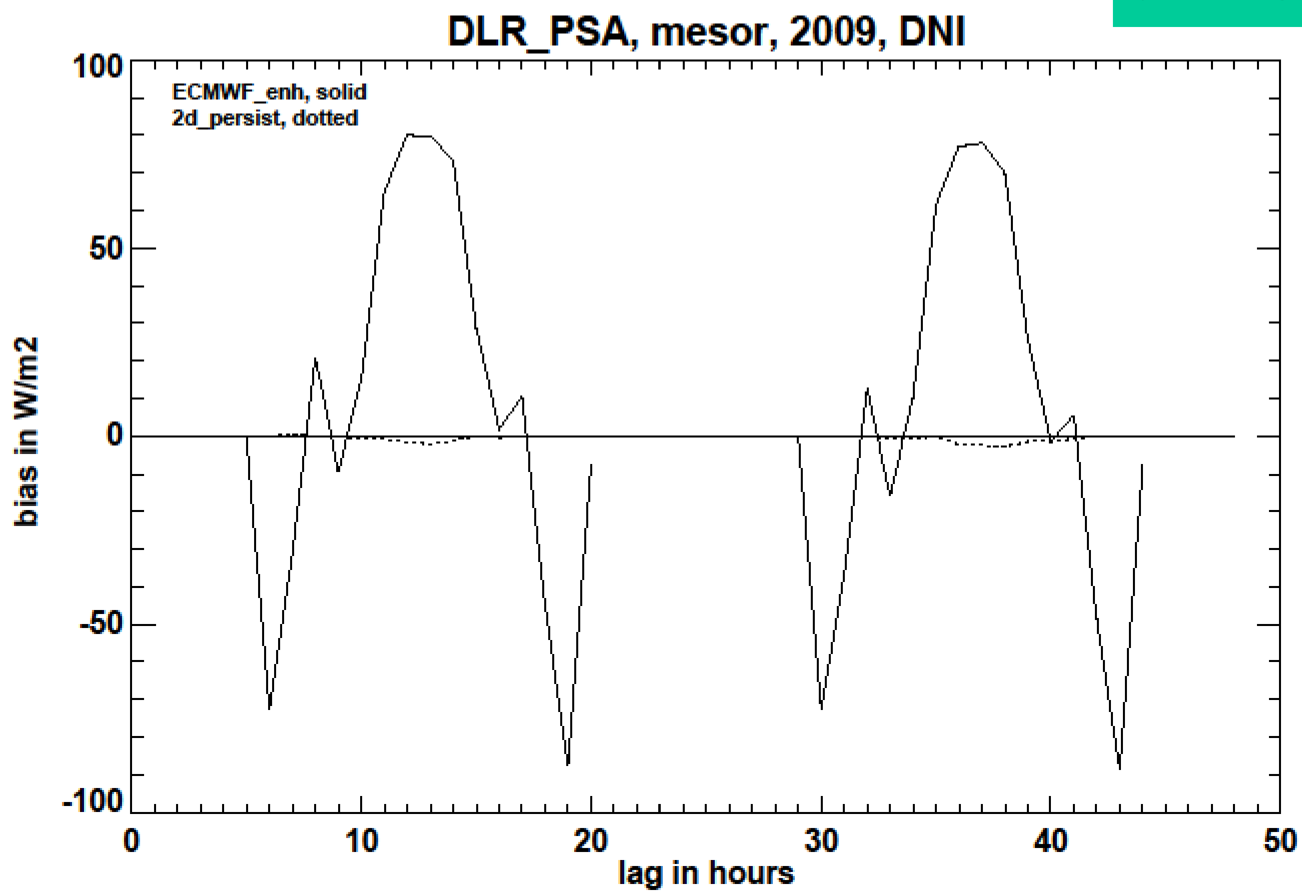
Better than persistence

worse

Verification ECMWF/DLR

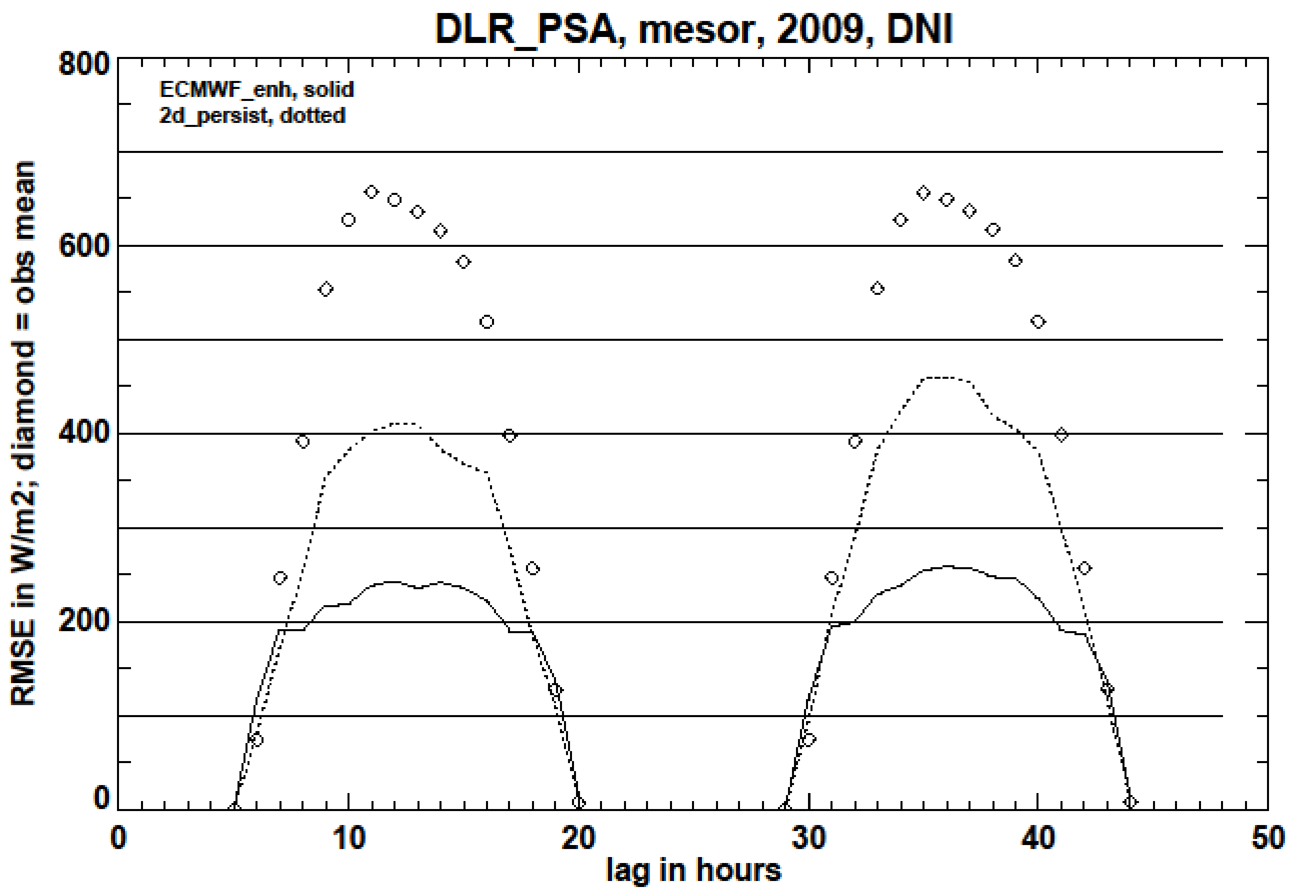
under-estimation thin ice clouds

biases = fct (time of day)



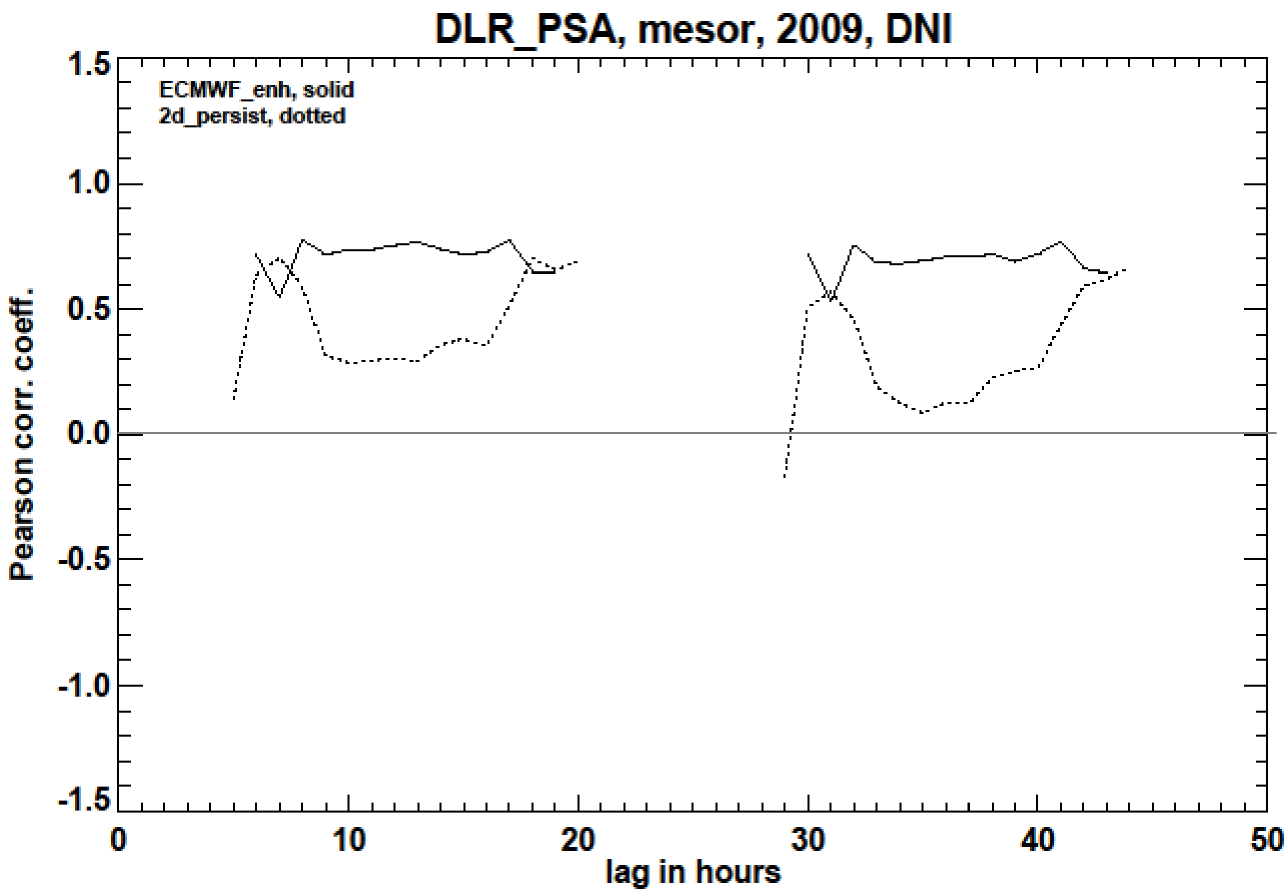
Verification ECMWF/DLR

RMSE = fct (time of day)



Verification ECMWF/DLR

Local correlation coeff. = fct (time of day)



Verification ECMWF/DLR

Same parameters:
Biases, RMSE, rel RMSE, local correlation coeff.,
skill scores
= fct (month of year)
Temporal lag errors (if any)

Perfect forecast capability for a renewable resouce

↓

No reserve power needed to cope with forecasting errors

↓

Reduced costs from the grid operator point of view

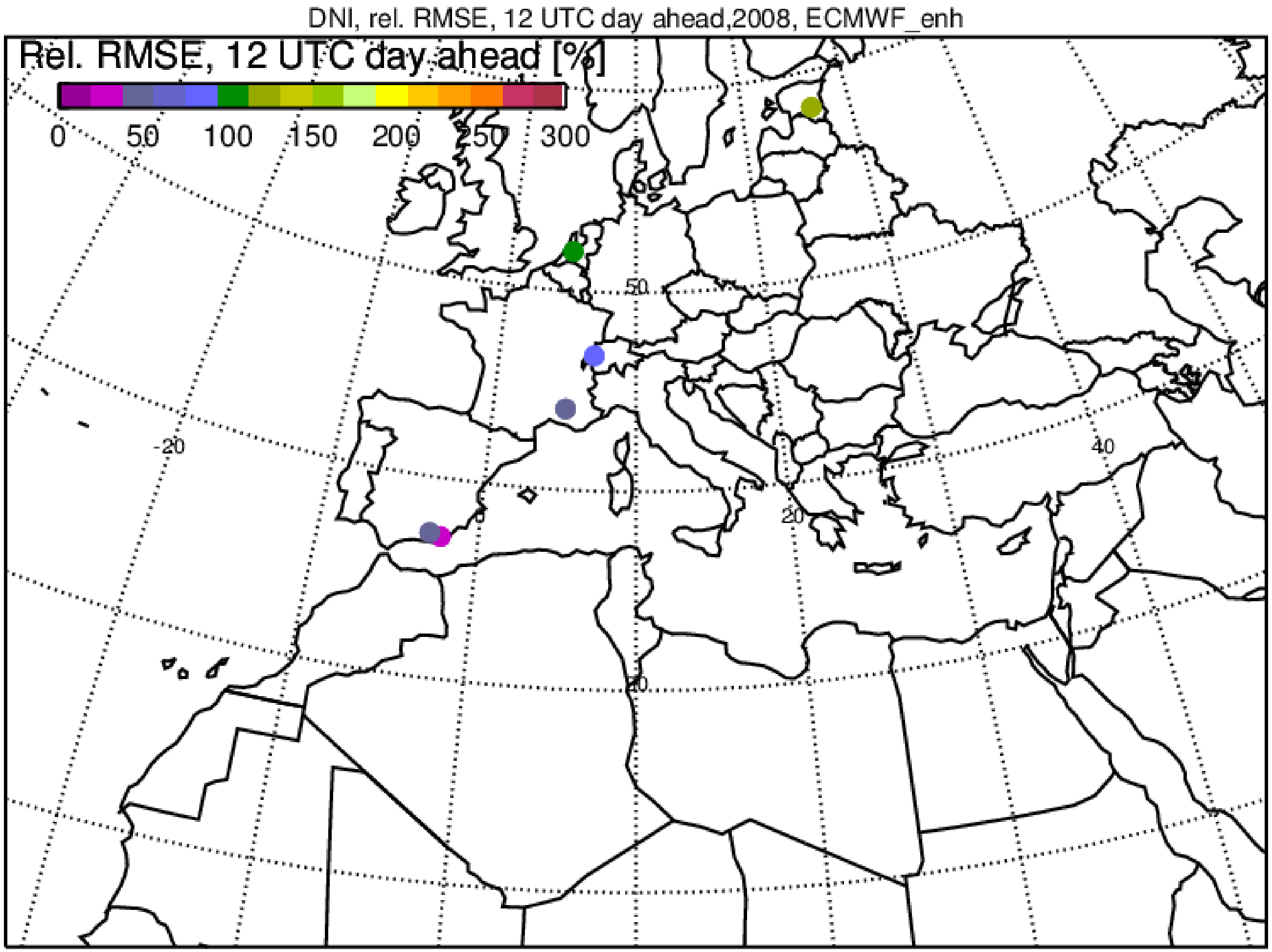
Perfect forecast capability for a renewable resouce – not the case for solar

reserve power needed to cope with forecasting errors

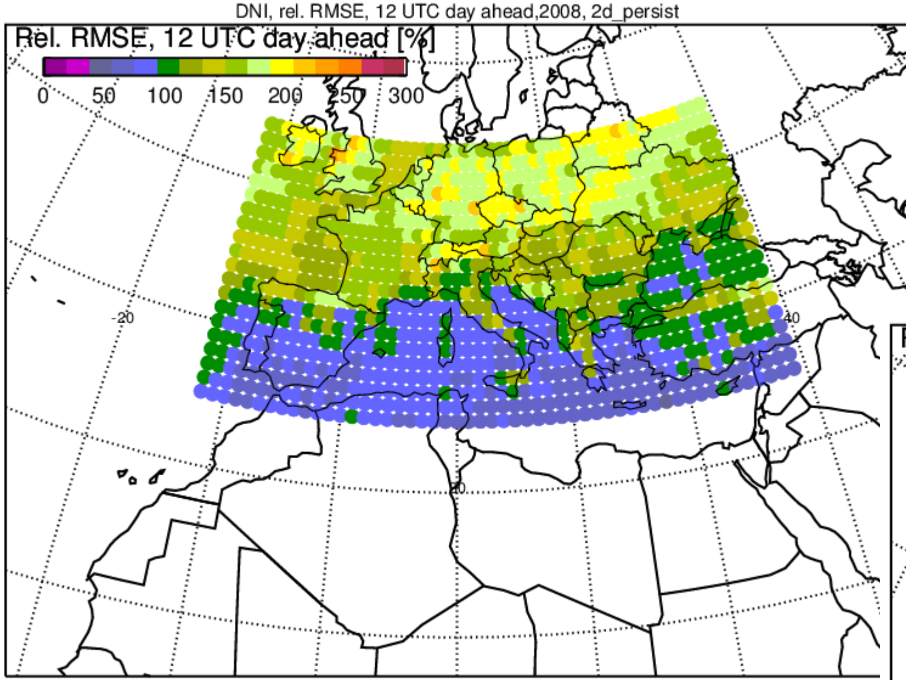
Costs need to be taken into account from the grid operator point of view

Is there any spatial variability in these costs?

Go from a single location to a list of validation sites – European BSRN sites

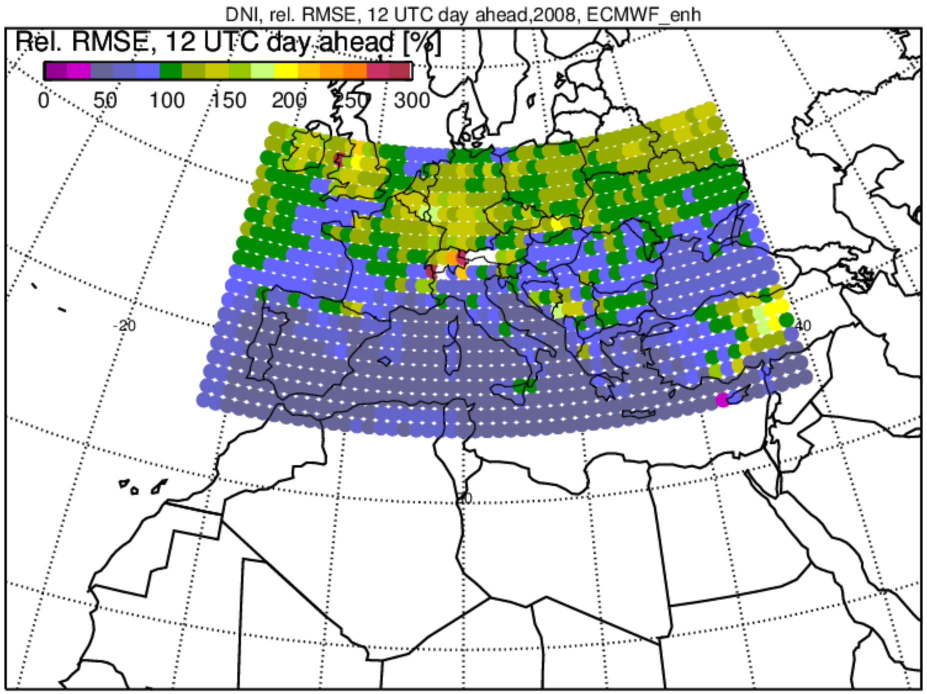


Assessment based on satellite measurements as ground truth

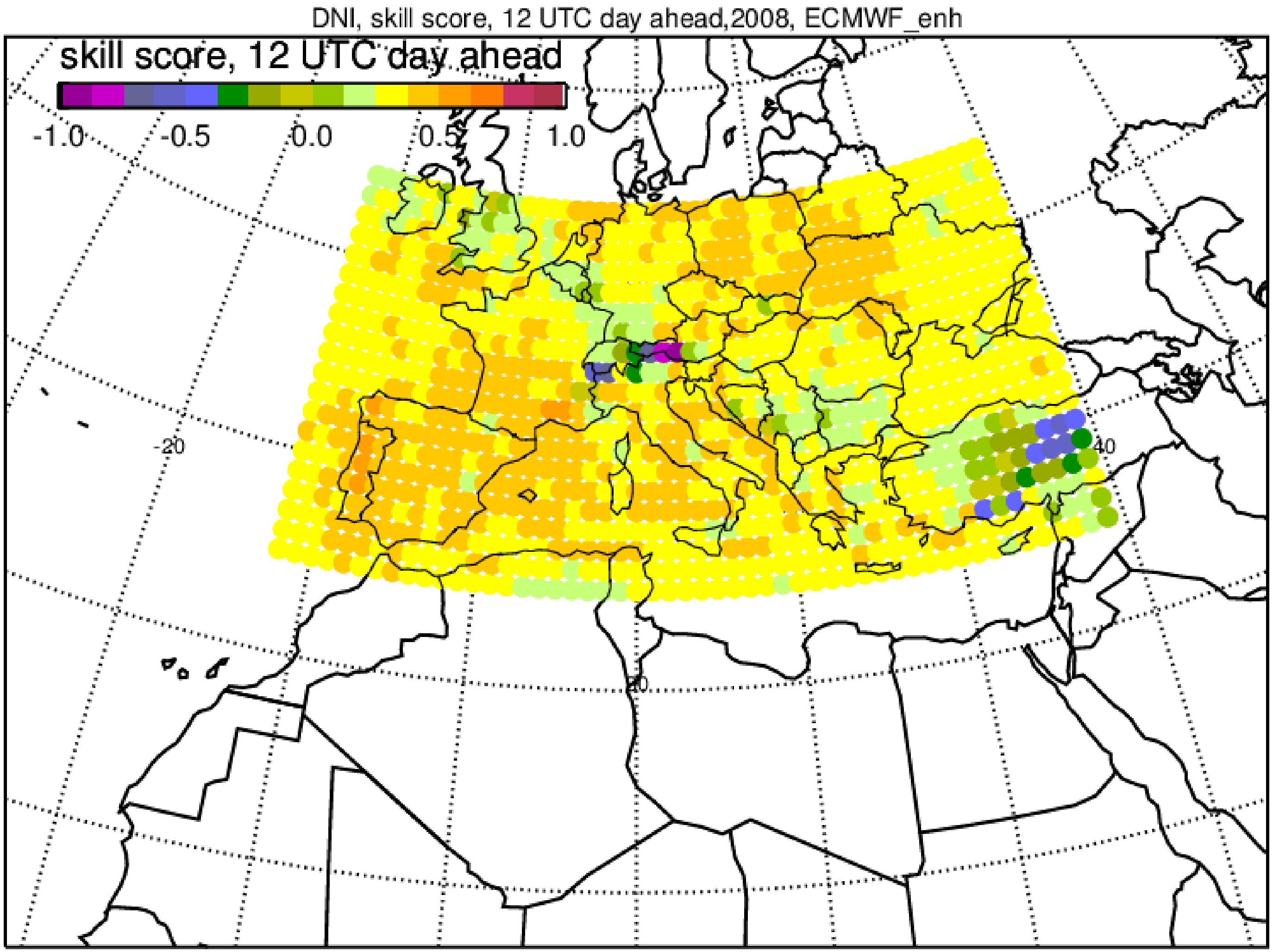


2 day persistance
Rel. RMSE, 2008

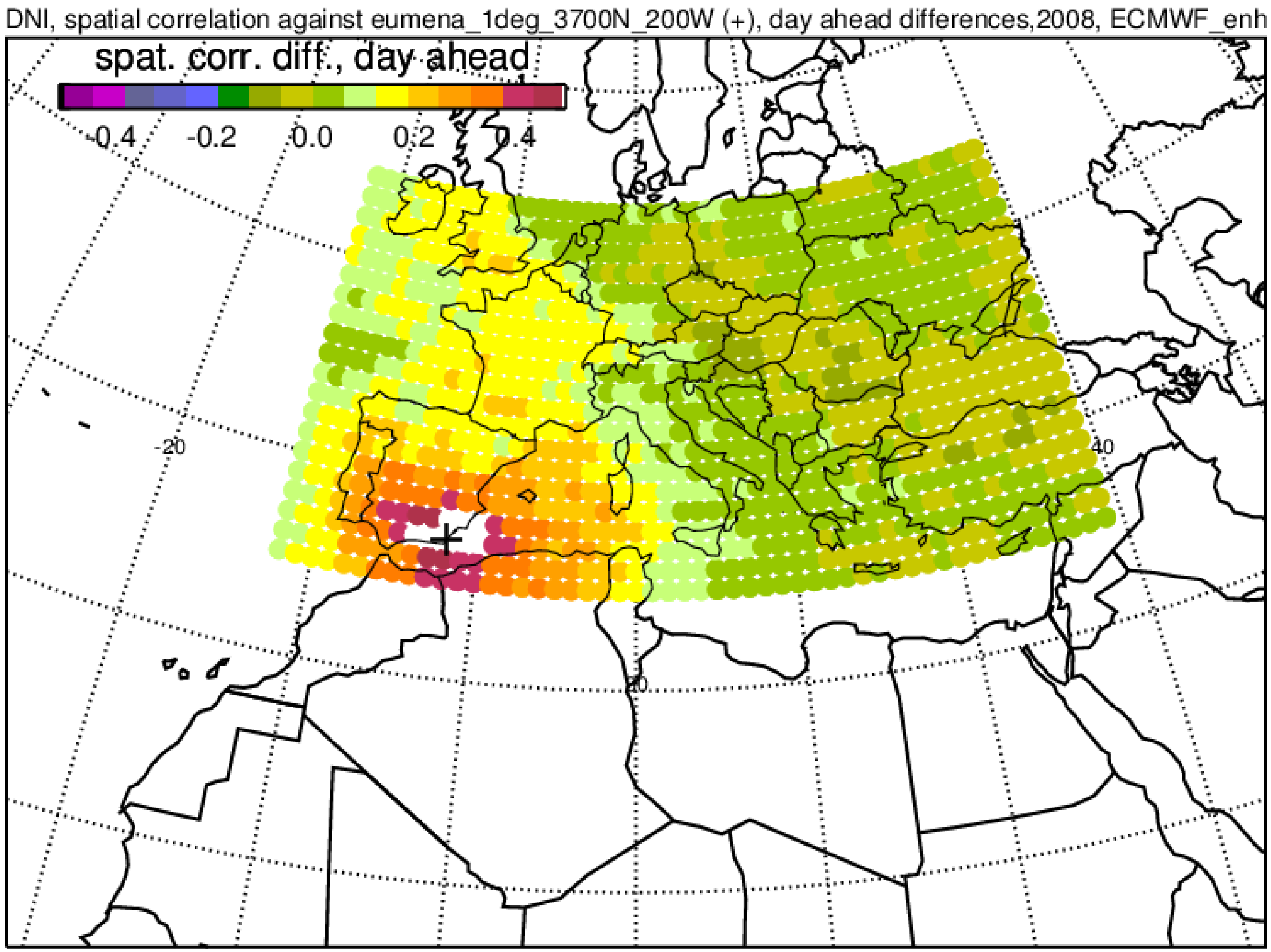
ECMWF



ECMWF skill score, 12 UTC, 2008



ECMWF, error spatial correlation vs. cross, 2008



Model output statics (MOS)

- It does:
  - Spatio-temporal interpolation and smoothing (from grid)
  - Local adaptation + bias correction
  - Multi-NWP-model combination

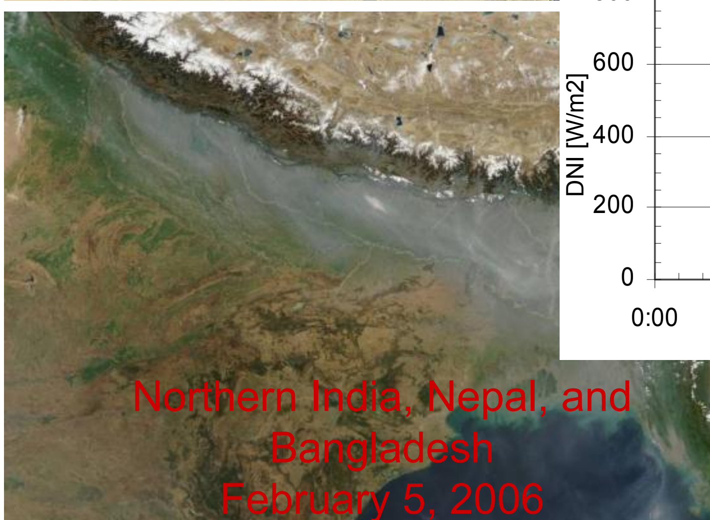
- General problems
  - Update for each NWP model change
    (happens frequently, monitoring needed)
  - Update for each location needed

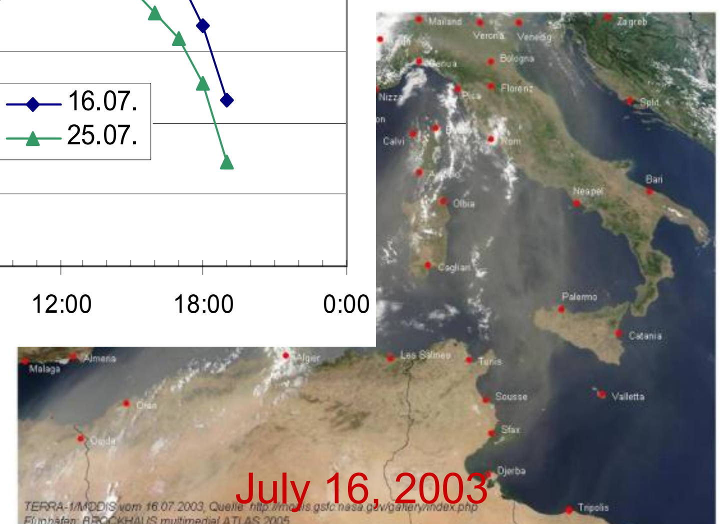
- Specific problems for DNI
  - Generate DNI out of cloud coverage, global irradiance, other parameters
  - Most input models provide no information about aerosols
  - Temporal interpolation from global 3-hourly to hourly

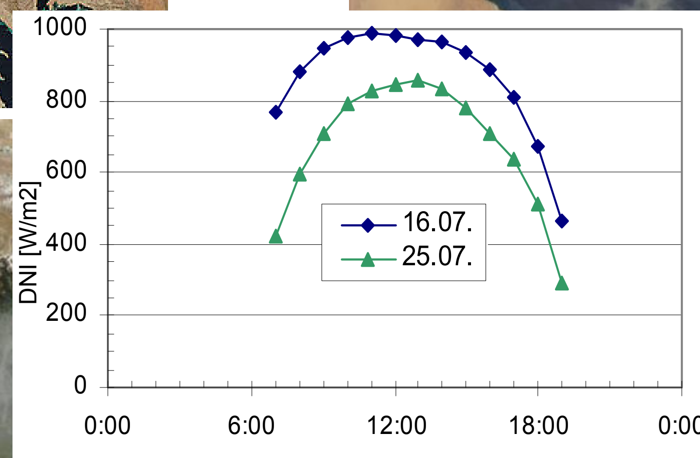
  - Finding for Spain: ECMWF is still performing better than existing commercial MOS systems

Aerosole

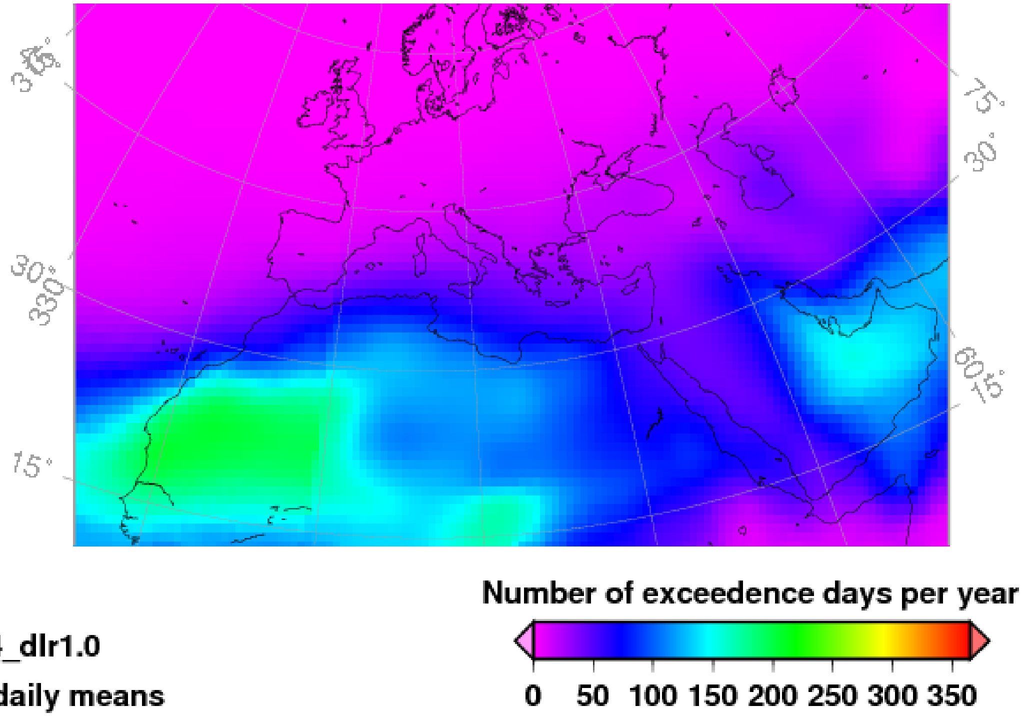
typical: - 25% direct irradiance
- 5% global irradiance





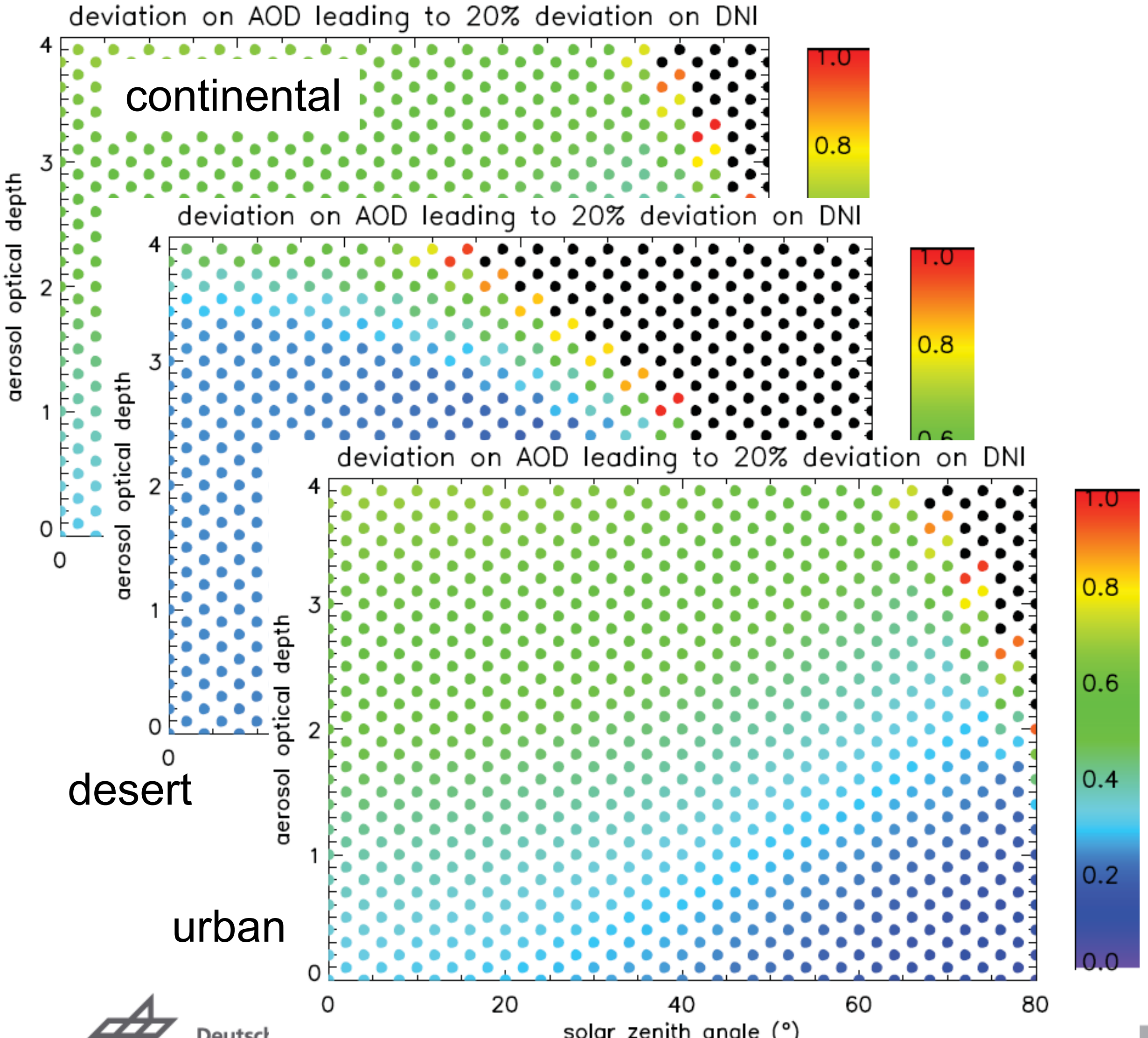


Exceedance days per year – direct irradiance – desert dust only



Number of days with a direct irradiance extinction due to dust above 30% based on a 1983 -2007 DLR/MATCH aerosol model for the EUMENA region

User requirements for aerosol accuracy



Basic input for CSP:

DNI (Direct Normal Irradiance)

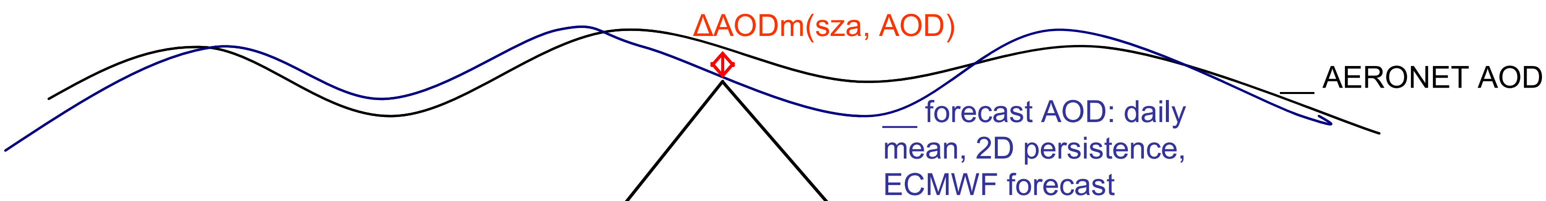
each AOD and each SZA,

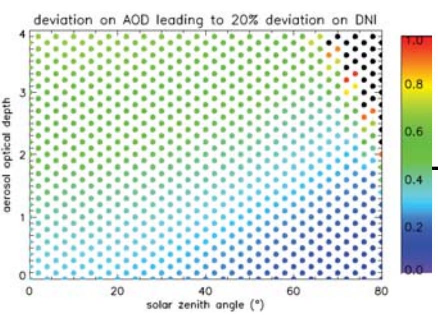
minimum deviation on AOD leading to **x% deviation on DNI**

done for **5%, 10%, 20%**

Minimum DNI : 10 W/m2

User specific validation approach





Check for each hour
If ΔAOD > ΔAOD_{crit}

ΔDNI =
fct (sza, AOD, Δ AOD)

Libradtran forward LUT

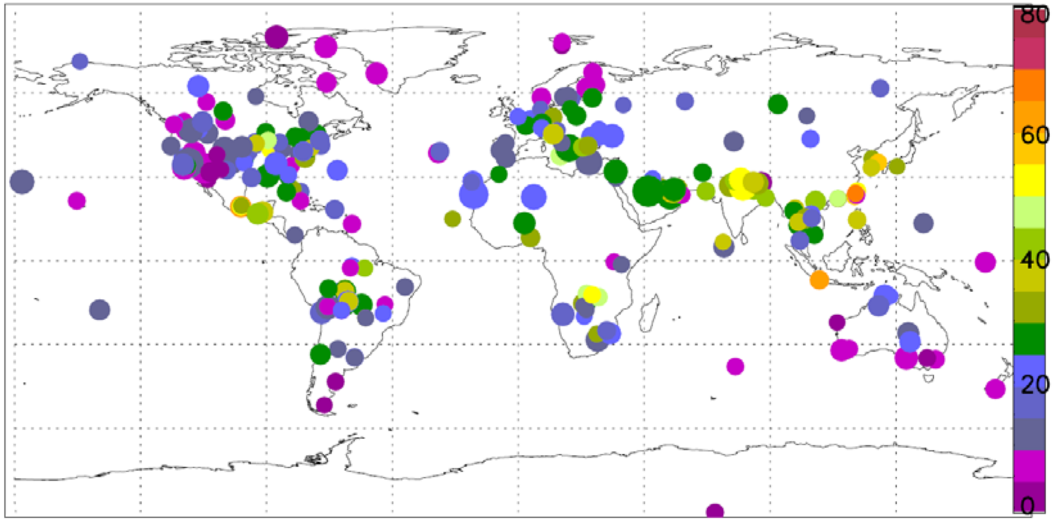
For all timeseries, at each station

% of hours where ΔAODm leads to x% ΔDNI

relative bias and relative RMS on DNI

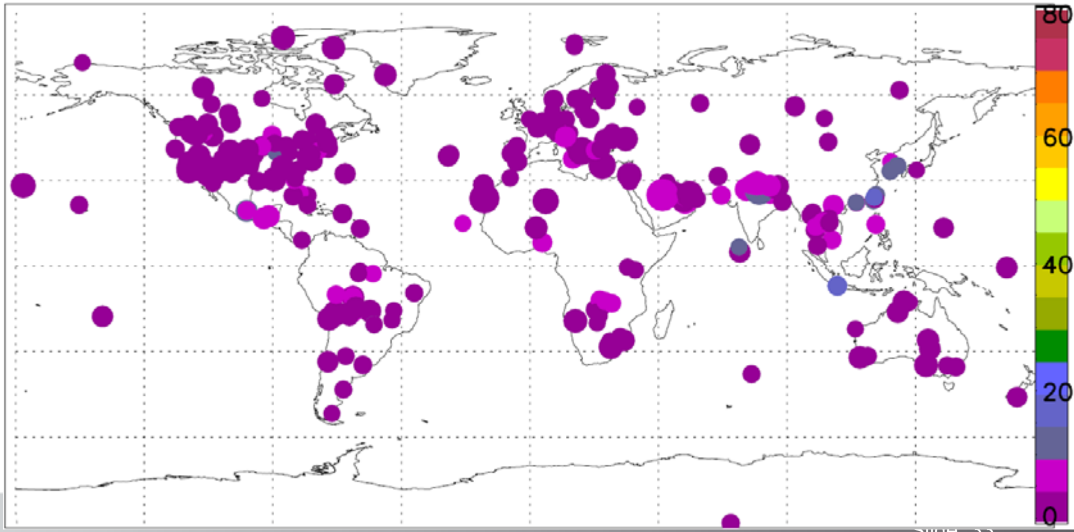
DNI =
Direct normal irradiance

Does intra-day variation matter in our case?

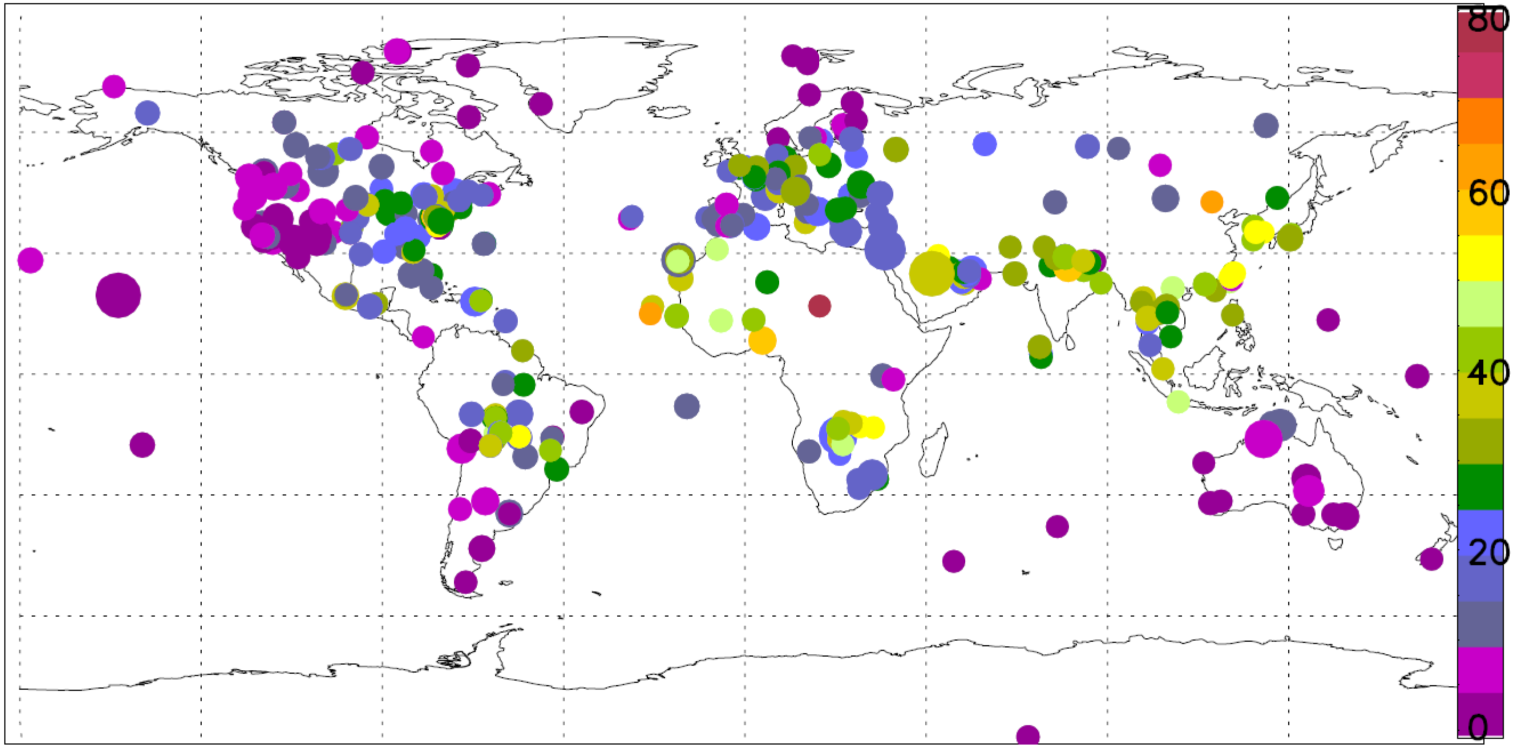


% of hours where the deviation on DNI due **to intra-day variability** is higher than **5%**

% of hours where the deviation on DNI due **to intra-day variability** is higher than **20%**



Is a 2 day persistence forecast sufficient?



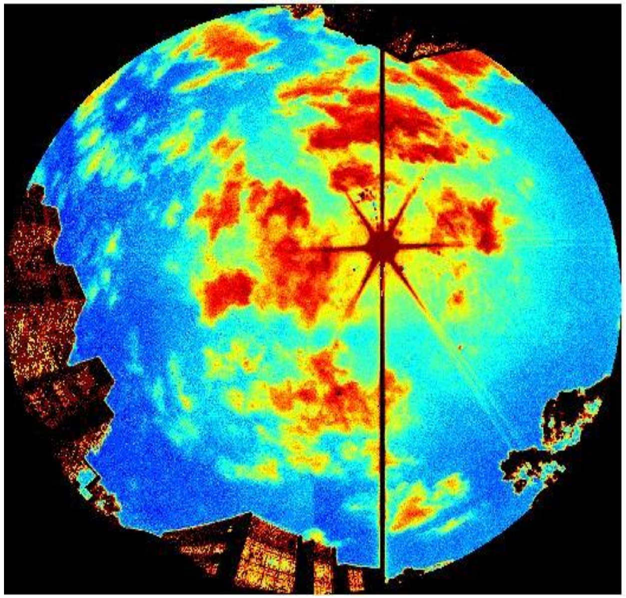
% of hours where the deviation on DNI due **2 day persistence forecasting** is higher than **20%**

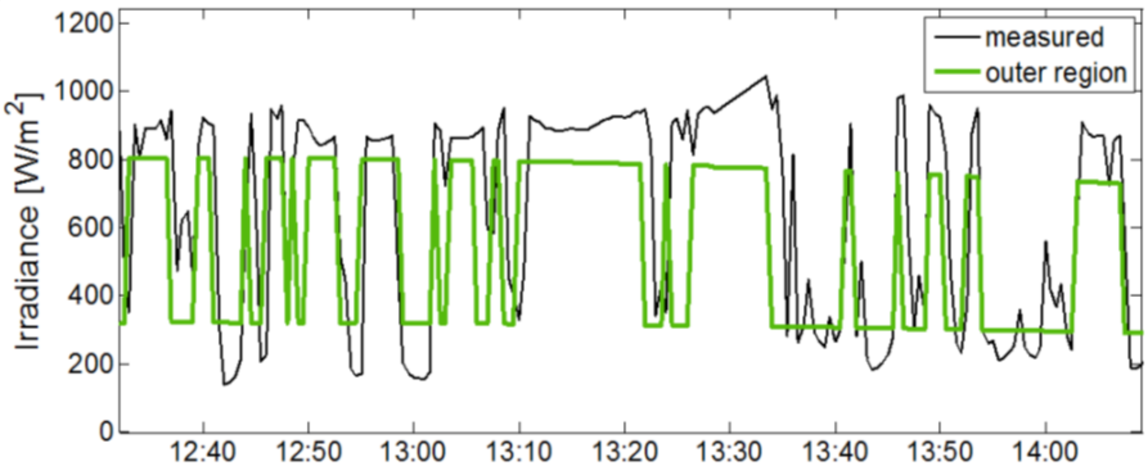
Cloud camera, total sky imagery

- very short-term (minutes ahead) predictions of future cloud patterns
- does not account for cloud development and dissipation

- limited to the field of view of the sky imager
- may use multiple imagers at different locations
- actual look-ahead time depends upon the cloud velocity and cloud height
  - low and fast clouds the forecast horizon may only be 3 minutes
  - high and slow clouds it may be over 30 minutes
  - generally horizons between 5 to 20 minutes are typical.

- multiple height cloud layers have different motion vectors
  - extremely important for DNI





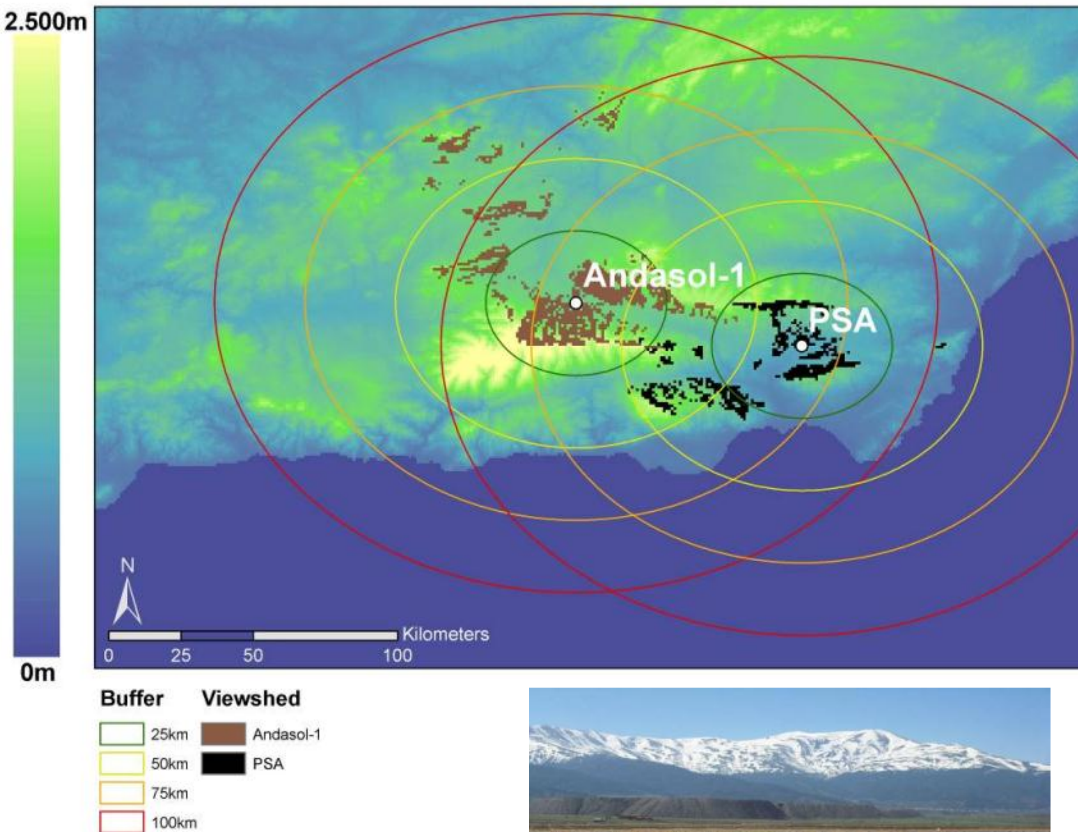
- 30 second GHI ramp forecast
- against 1 sec GHI measurements
- day with cumulus clouds

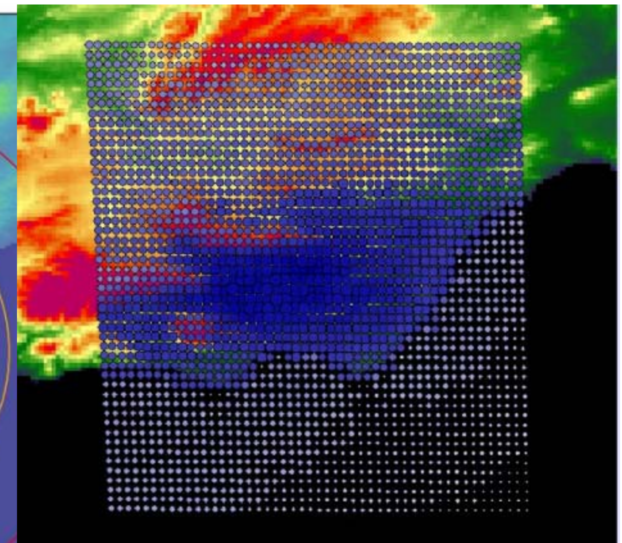
•Ratio of red and blue channel intensity
•a partly cloudy day
•UC San Diego solar forecasting sky imager
•high RBR are classified as cloudy

Mathiesen, Kleissl, 2012

No experience with DNI available so far…

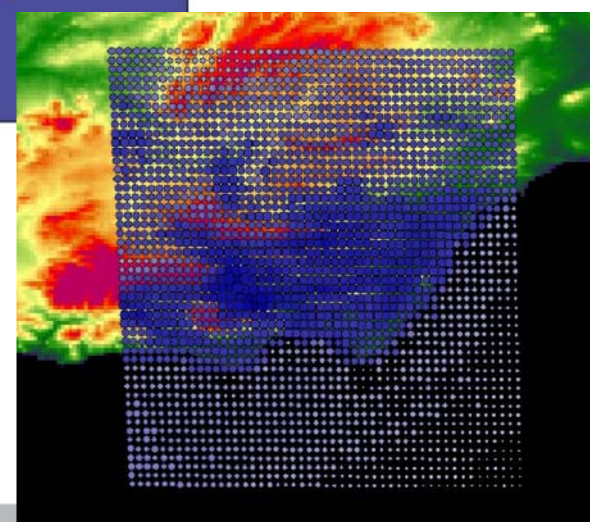
Representativeness of nearby pixels





PSA
-1 hours lag

scale from
0.65
to 0.73
(42-53% explained)



PSA
-2 hours lag

scale from
0.48
to 0.55
(23-30% explained)

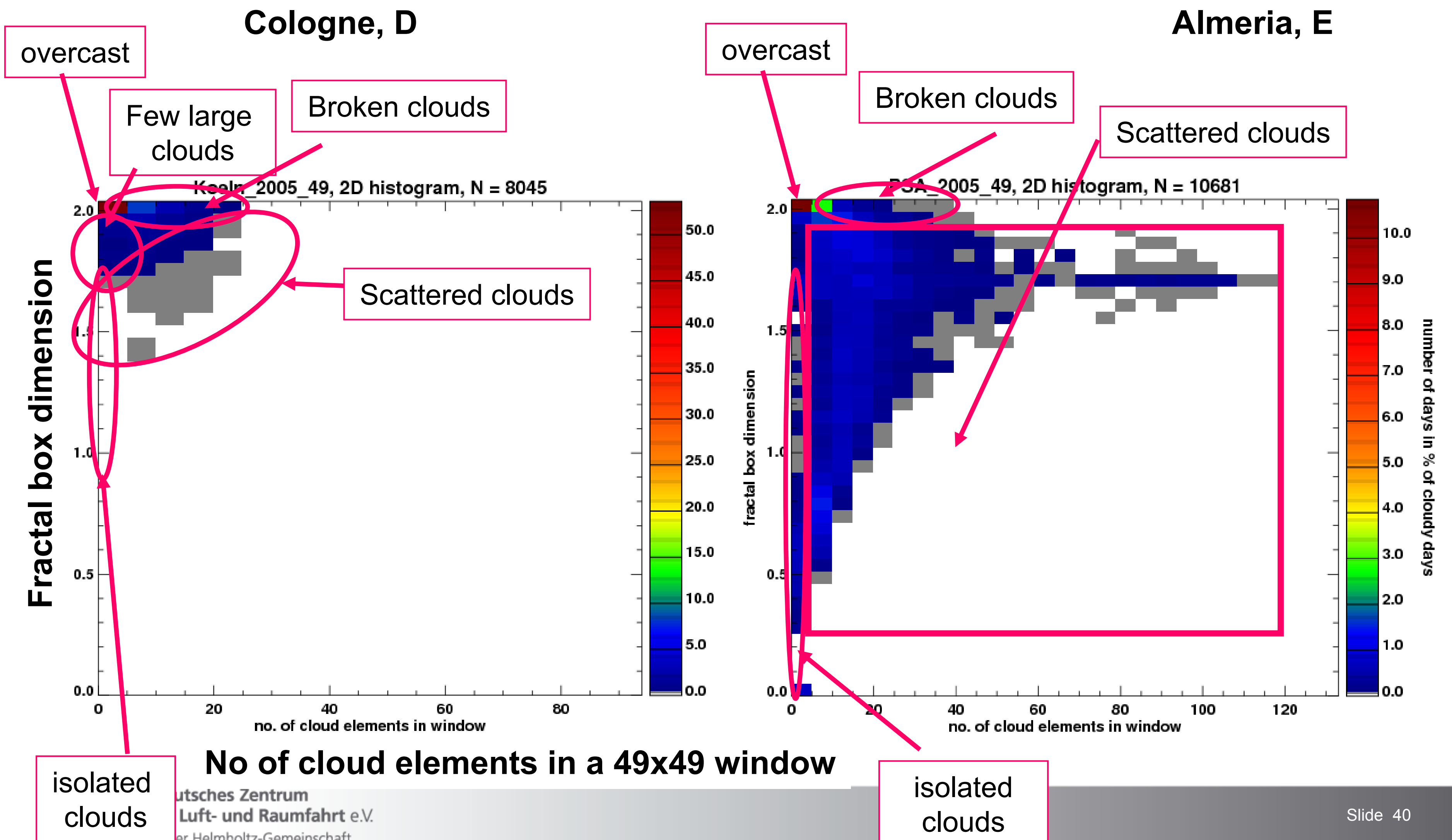
Sun
point
information

cloud camera
20 min forecast horizon
high resolution

satellite
several hours
forecast
type of cloud
less spatial resolution

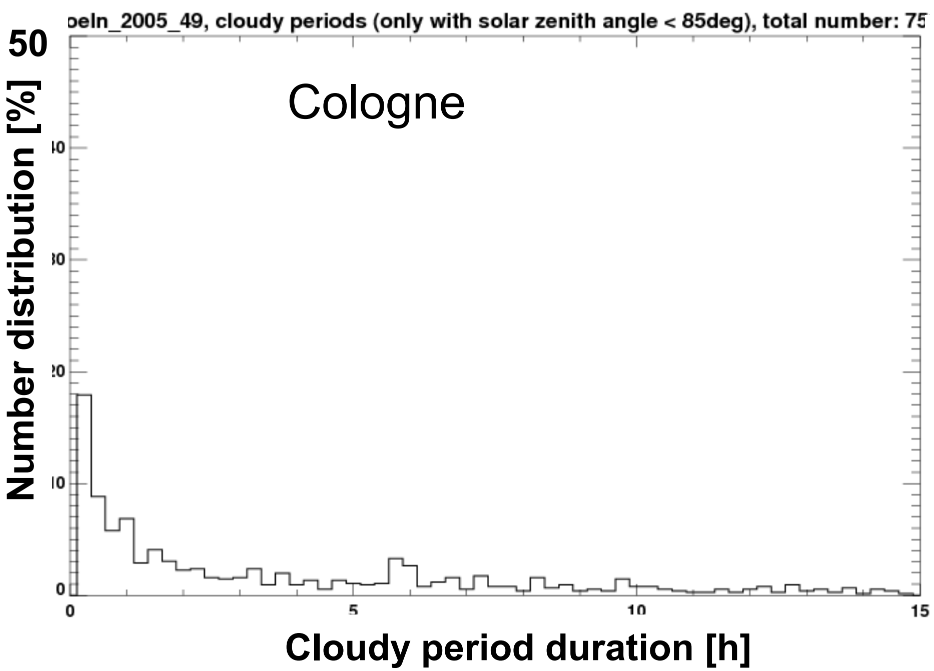
Satellite based information about typical weather conditions at the power plant site

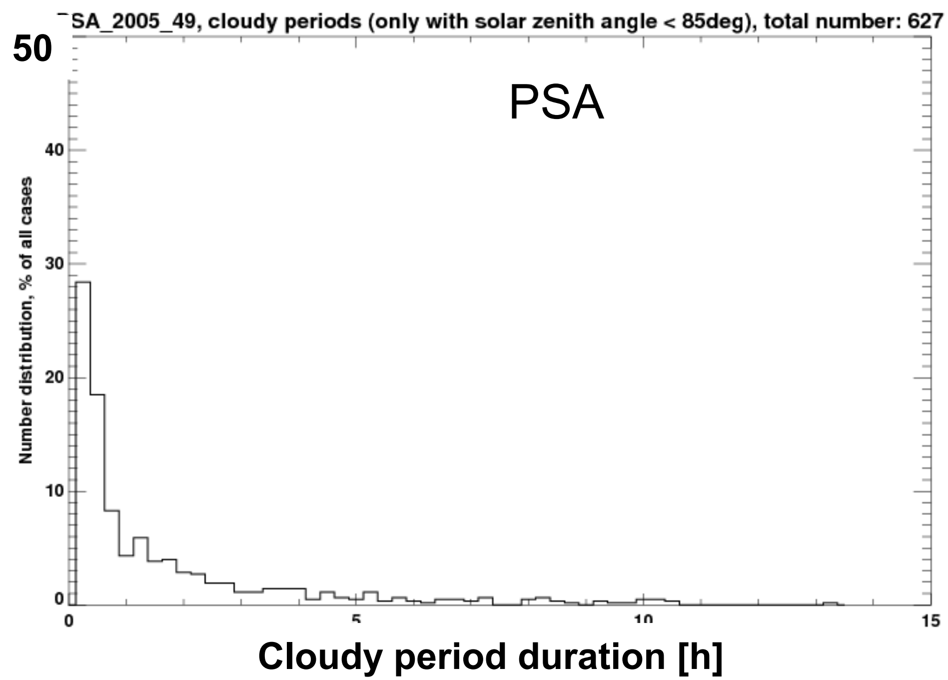
Cloud compactness indicators



utsches Zentrum
Luft- und Raumfahrt e.V.
der Helmholtz-Gemeinschaft

Cloud period duration statistics





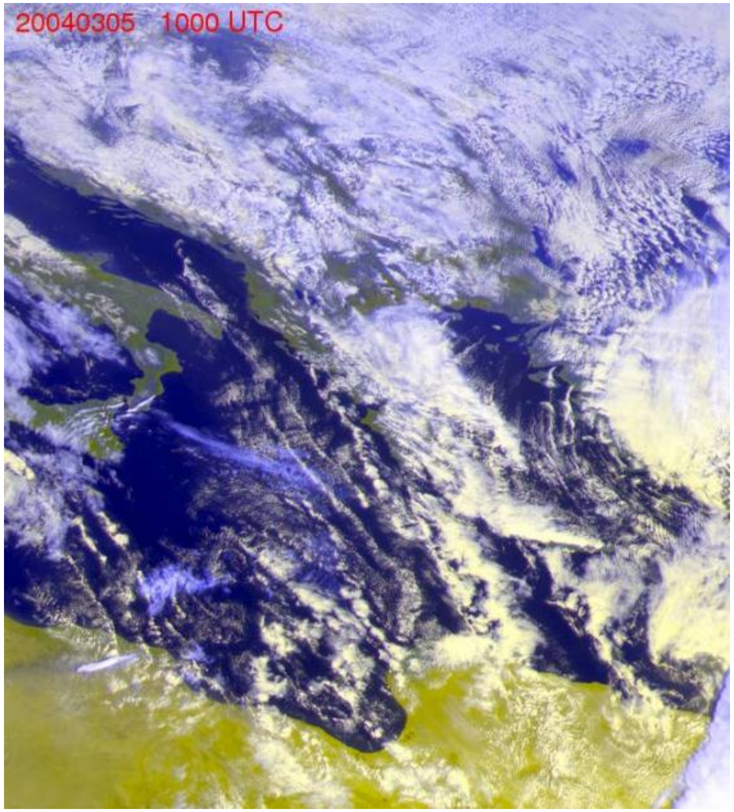
18% <= 15 min
39% < 1 h
90% < 9.75 h
98% < 13.5 h

28% <= 15 min
59% < 1 h
90% < 4.5 h
98% < 9.25 h

Nowcasting based on satellite measurements

Nowcasting and short-term forecasting based on EO

Example: cloud fields from Meteosat Second Generation
HRV channel for Greece (source DLR-IPA), basis for short-term forecasts



cloud motion vectors

1/8

Nowcasting and short-term forecasting based on EO

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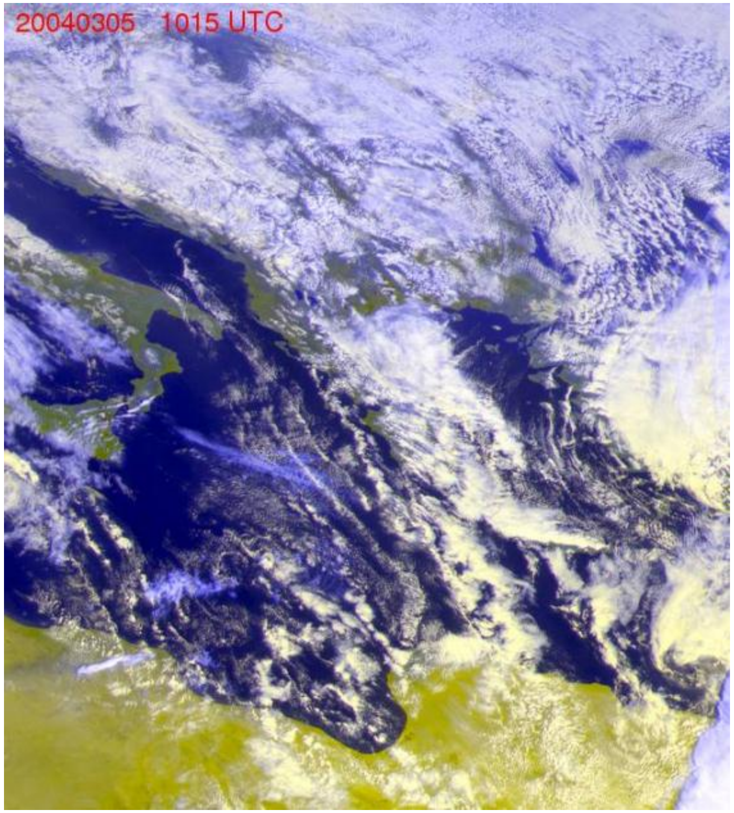

cloud motion vectors

2/8

Nowcasting and short-term forecasting based on EO

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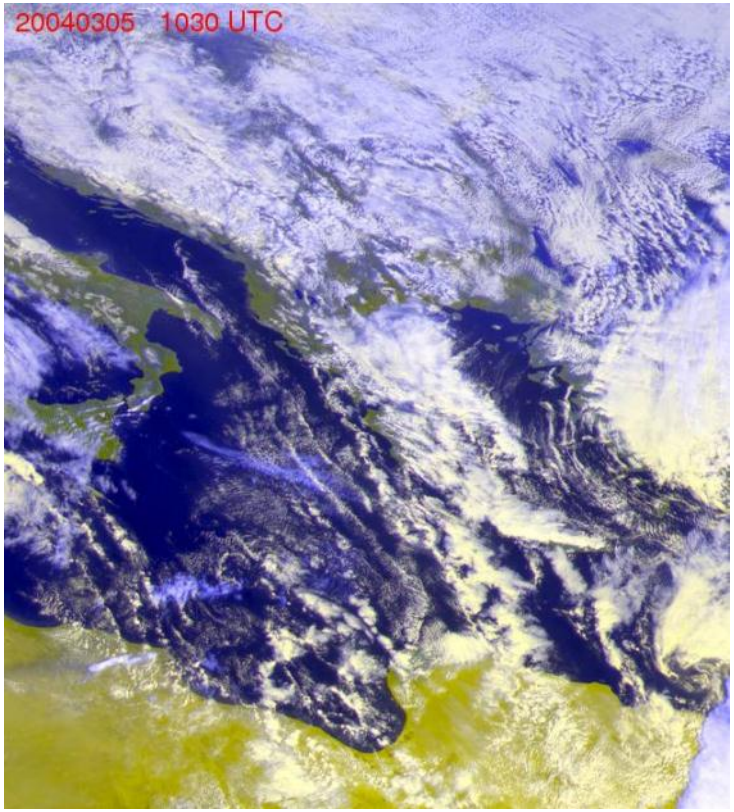

cloud motion vectors

3/8

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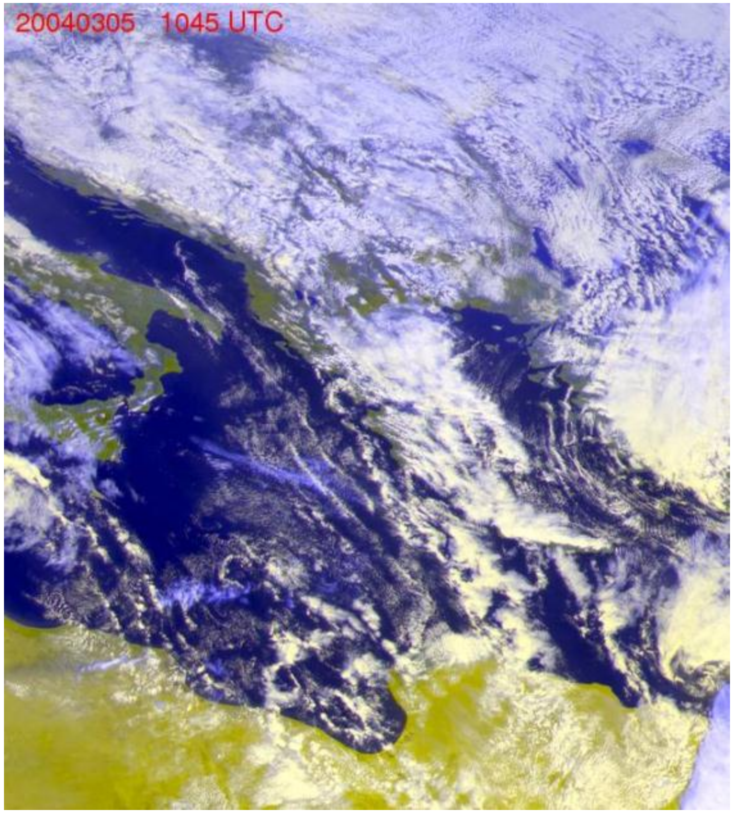

cloud motion vectors

4/8

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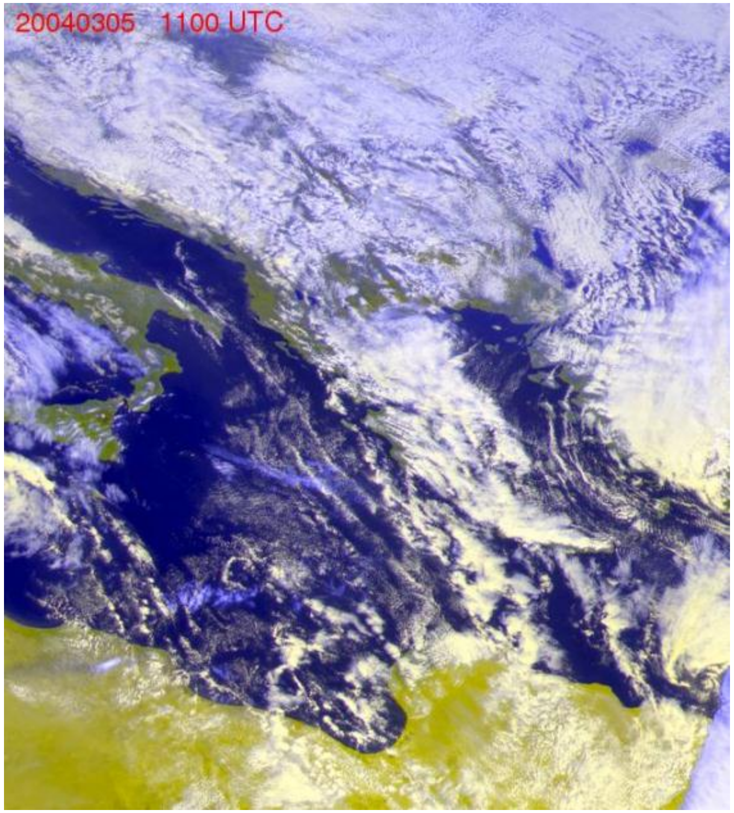

cloud motion vectors

5/8

Nowcasting and short-term forecasting based on EO

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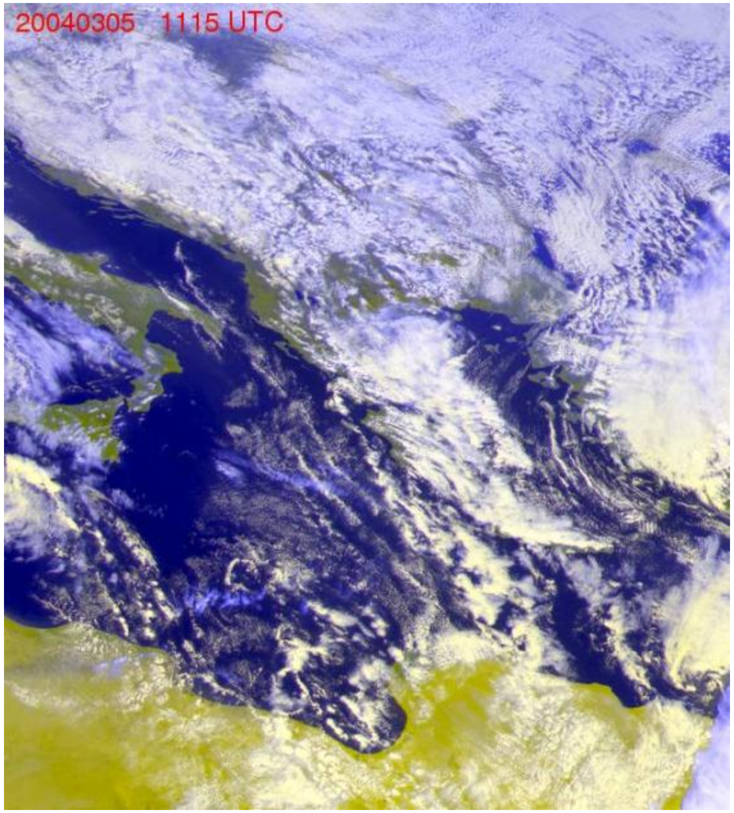

cloud motion vectors

6/8

Nowcasting and short-term forecasting based on EO

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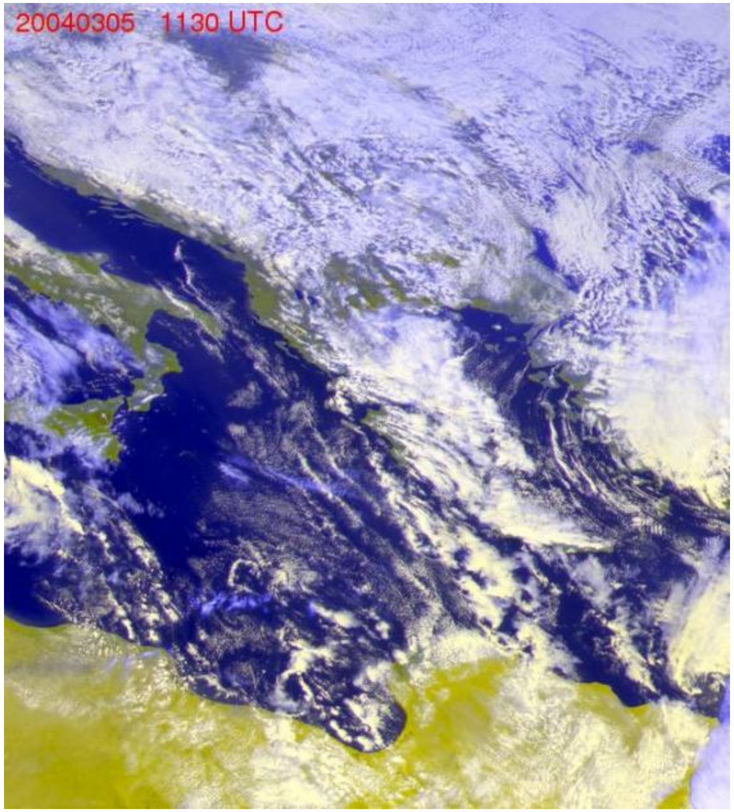

cloud motion vectors

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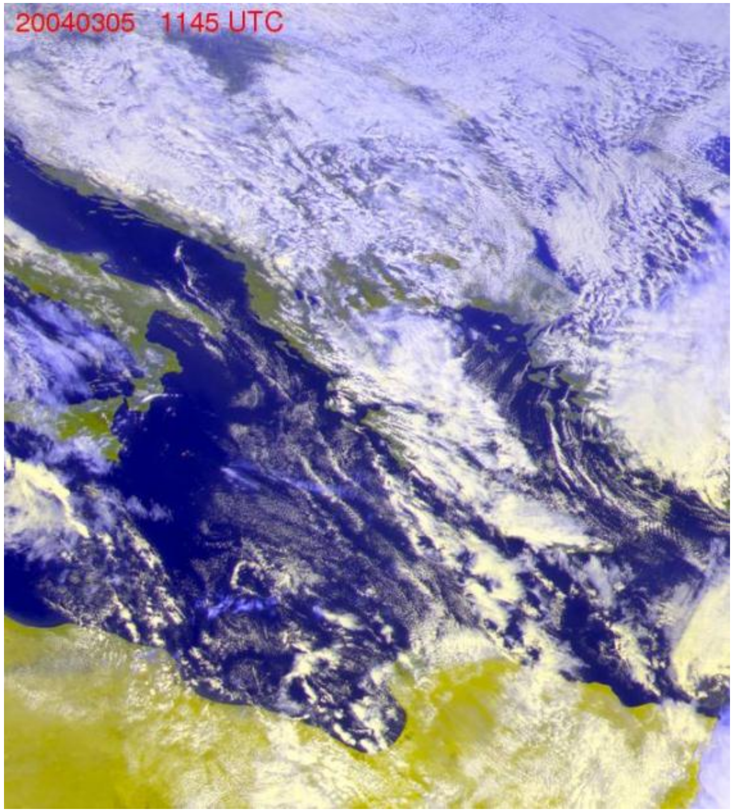
Nowcasting and short-term forecasting based on EO

Example: cloud fields from Meteosat Second Generation
HRV channel for Greece (source DLR-IPA), basis for short-term forecasts



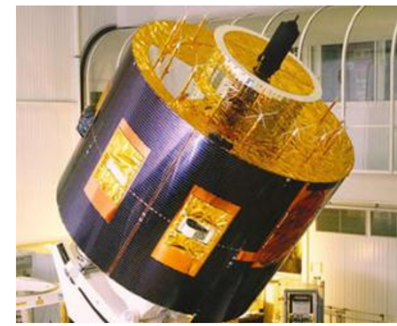
cloud motion vectors

8/8

METEOSAT SECOND GENERATION – What can be seen more?

- More spectral information allows assessment of physical cloud parameters
- 15 min resolution instead of 30 minutes
- Pixel size 3 km at nadir;
  4x5 or 5x6 km in Europe

Channel no.		Characteristics of spectral band (μm)		
		λ_{cen}	λ_{min}	λ_{max}
1	VIS0.6	0.635	0.56	0.71
2	VIS0.8	0.81	0.74	0.88
3	NIR1.6	1.64	1.50	1.78
4	IR3.9	3.90	3.48	4.36
5	WV6.2	6.25	5.35	7.15
6	WV7.3	7.35	6.85	7.85
7	IR8.7	8.70	8.30	9.10
8	IR9.7	9.66	9.38	9.94
9	IR10.8	10.80	9.80	11.80
10	IR12.0	12.00	11.00	13.00
11	IR13.4	13.40	12.40	14.40
12	HRV	Broadband (about 0.4 – 1.1)		



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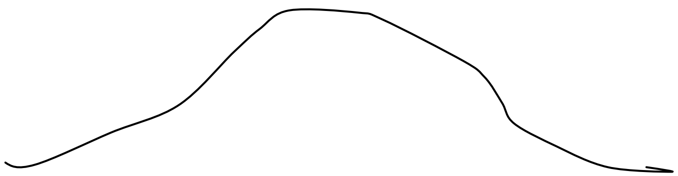
Upcoming Key Questions:

- How do I choose technical features of the power plant ? (Engineering)
- How do I operate my power plant? (Operation & Maintenance)

Strategy to use nowcasting at the power plant

Type A



48 h forecast made by **weather service** yesterday

Type B

Satellte images

Now – 45 Min	Now – 30 Min	Now – 15 Min	now

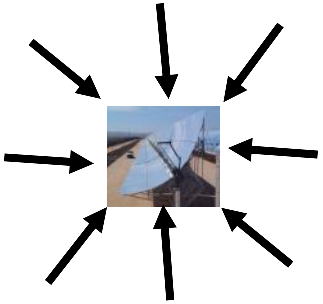
Human forecast with knowledge about upcoming cloud fields

Type C

Satellte images

Now – 45 Min	Now – 30 Min	Now – 15 Min	now

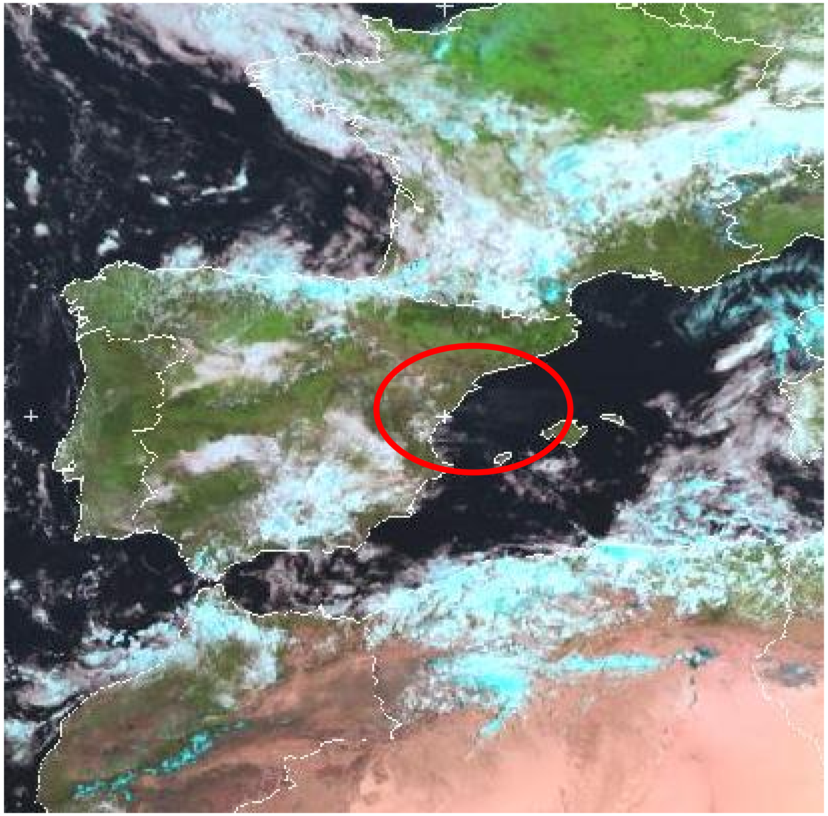
now



Automatic 8h-nowcast of upcoming **cloud** fields

Automatic 8h-nowcast of upcoming **DNI** values

Photo-like quick look
Low clouds white, high clouds turquoise blue



Looks ‚natural'

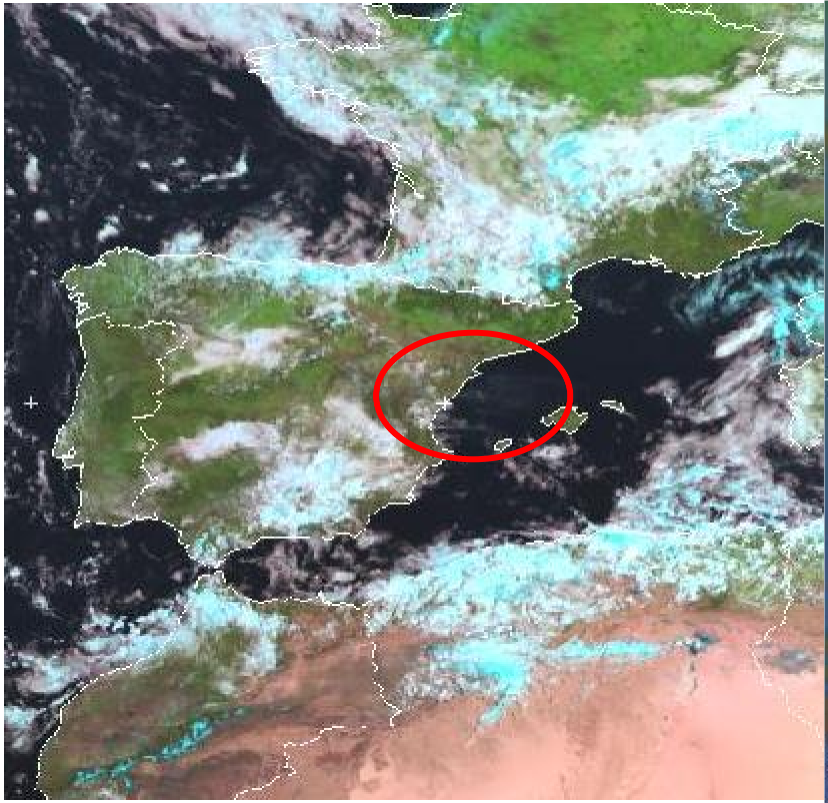
Looks ‚known' to the operator

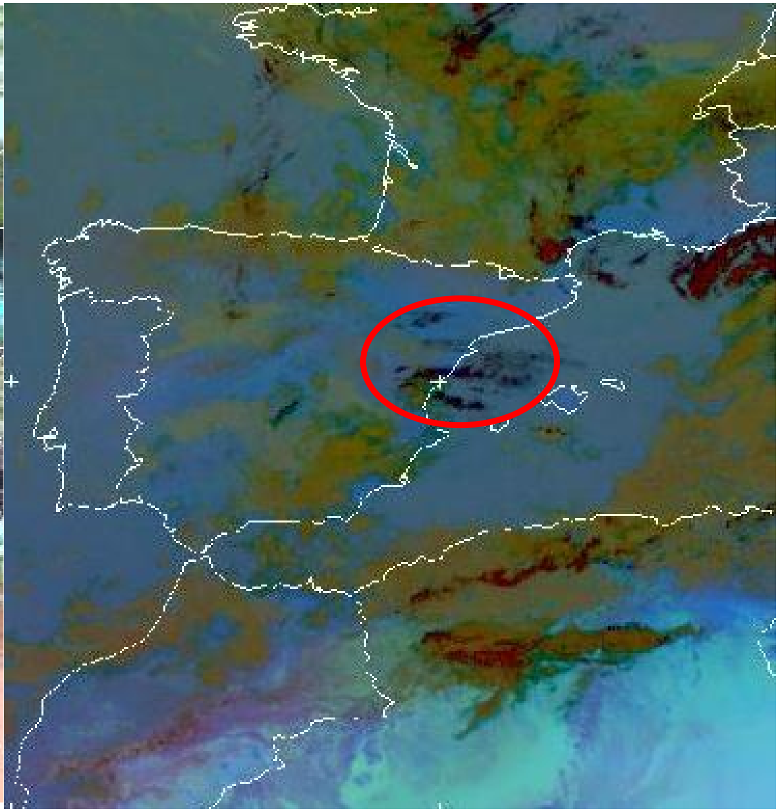
We just see iced tops of clouds.
We can't distinguish
thick ice clouds (e.g. 10% DNI)
from thin ice clouds (e.g. 50% DNI)

Can't see dust over land

Dust and cirrus – special colors

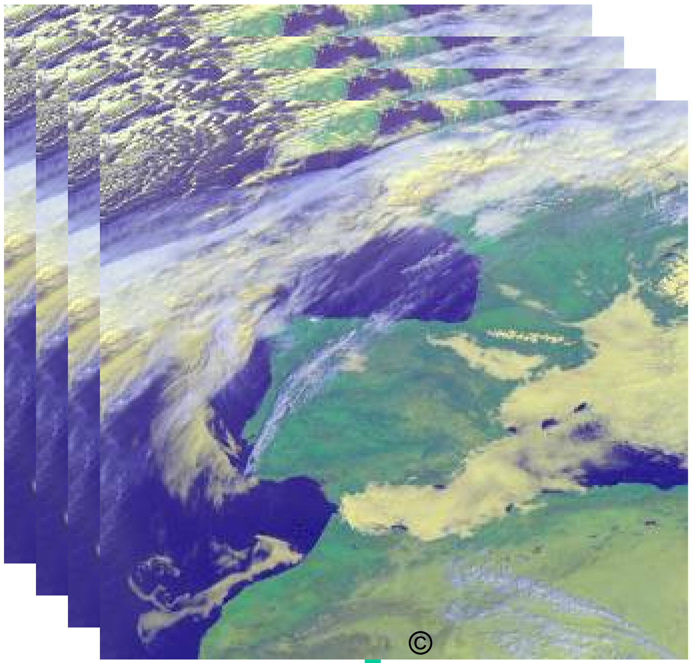
Dust pink, thin cirrus black, available at night time !!!





3th May 2011, 0900 UTC

Automatic nowcasting – which DNI to expect?



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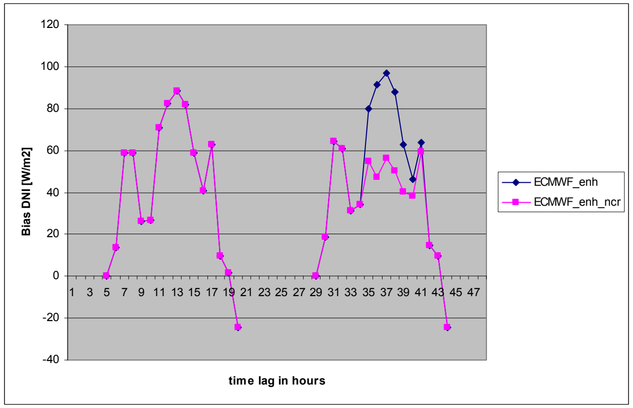
APOLLO cloud retrieval for MSG

Cloud mask
- water clouds
- thin cirrus clouds
- 15 min update

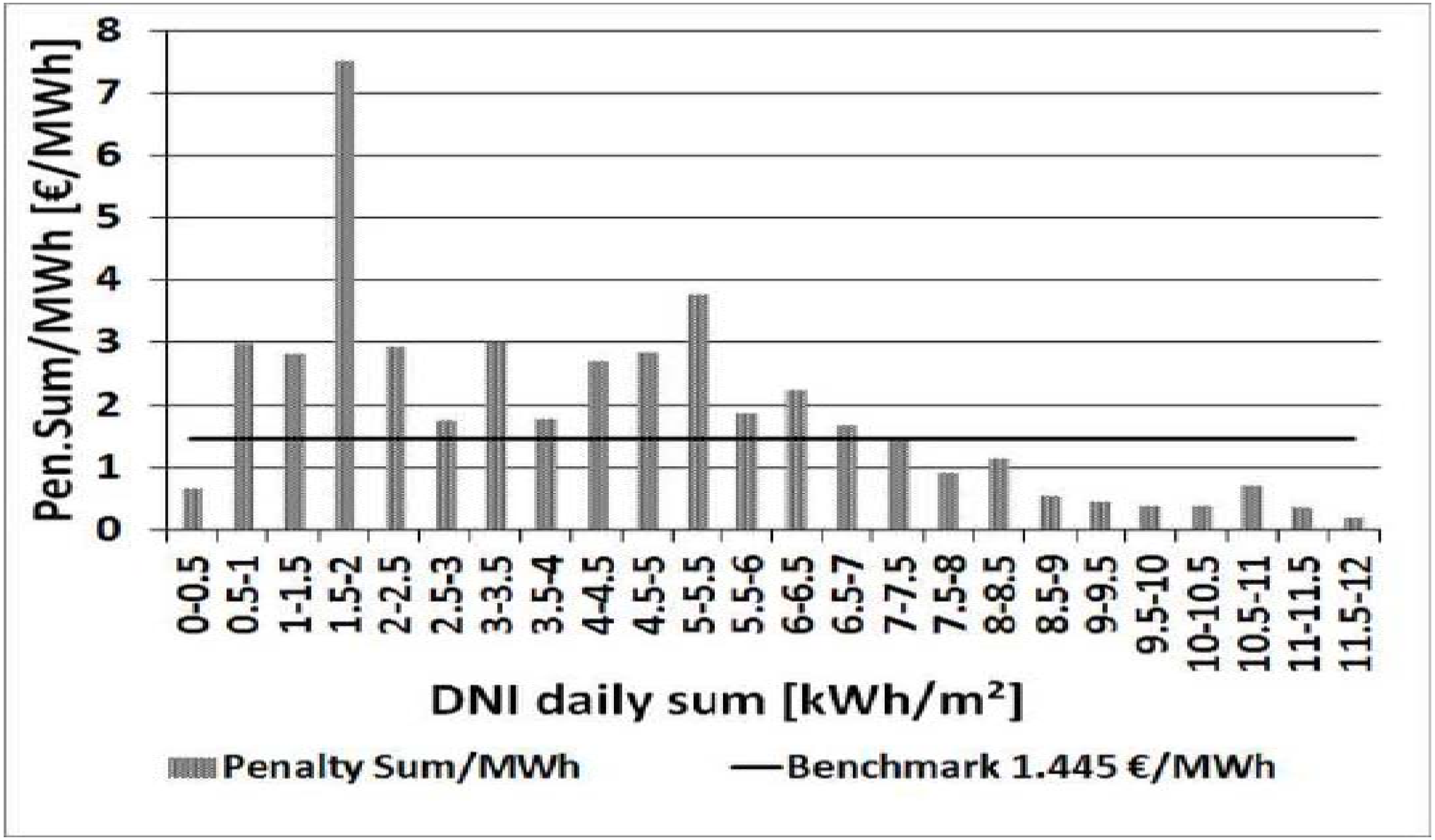
DNI forecast



Receptor model cloud mask forecast

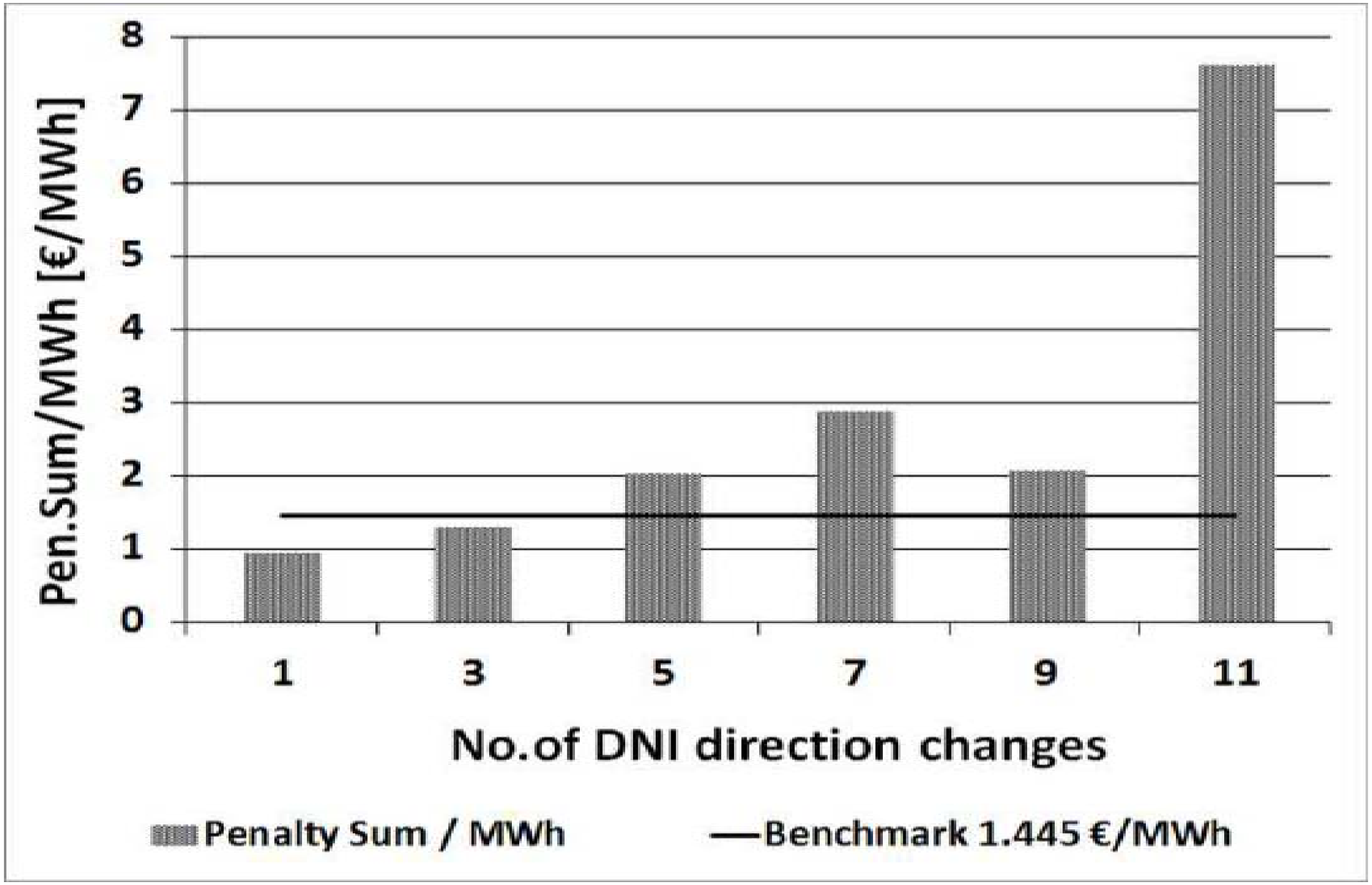
Day and night !!

Some comments on the economic value of forecasts….

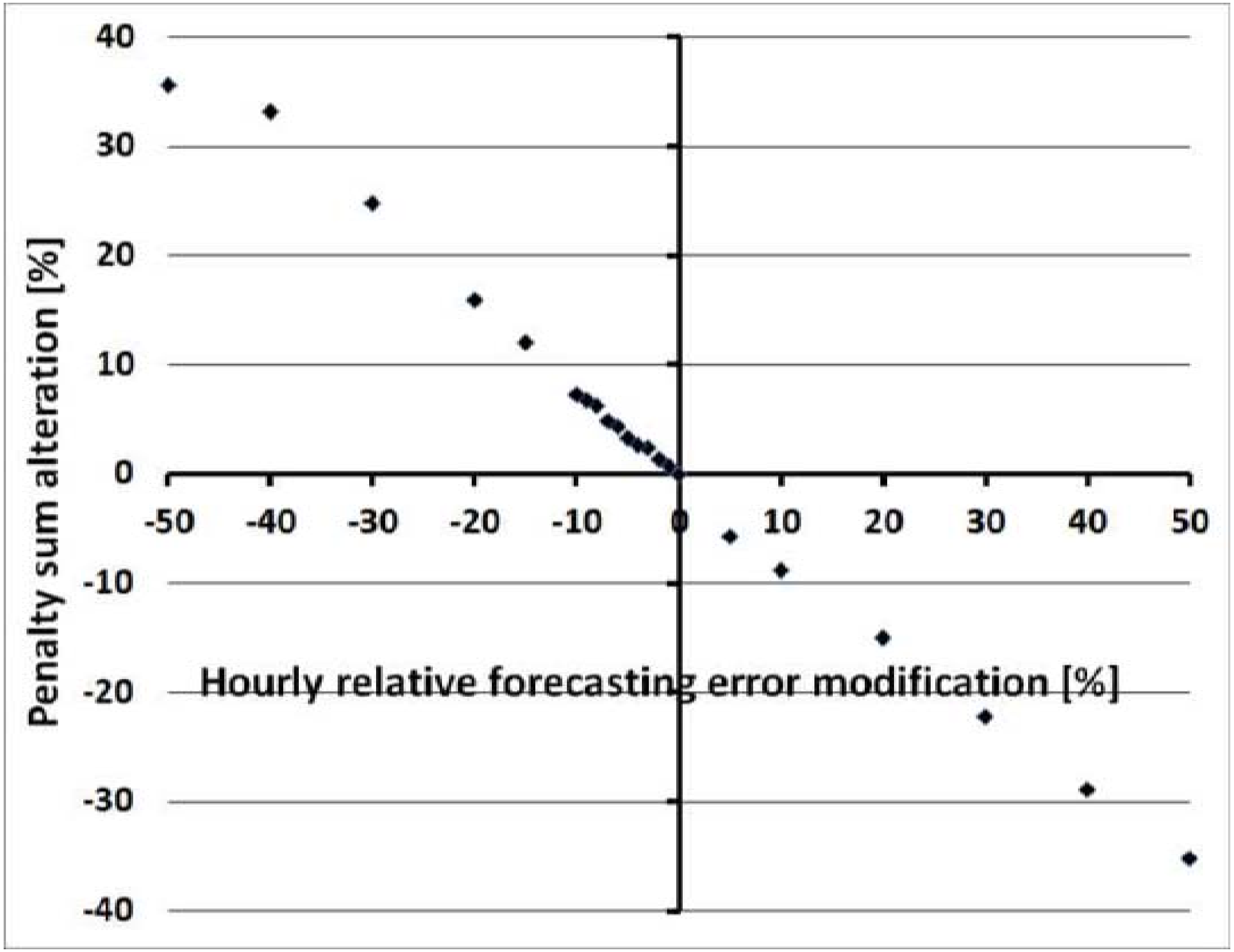


Kraas et al., SolarPaces 2010;
submitted to Solar Energy

Based on Meteologica MOS
July 2007 to December 2009
Benchmark = average penalty



Benchmark = average penalty



Penalty sum alteration [%]
40
30
20
10
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
50
Hourly relative forecasting error modification [%]

Conclusions

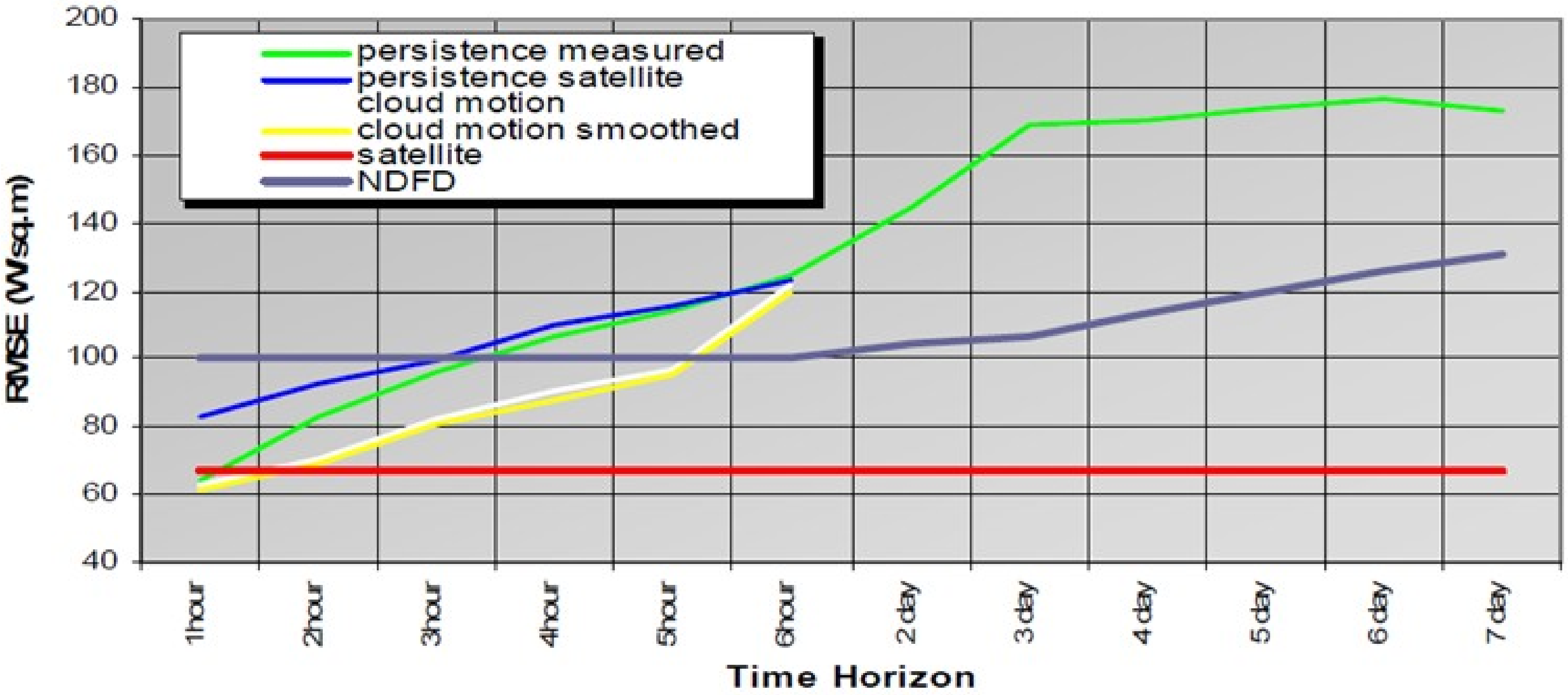
- User requirements and meteorological basics
- Numerical weather prediction – verification measures have been explained – NWP can be used, potential for improvements is also large
- First results on spatial correlation of forecast errors
- Global maps – need of hourly aerosol forecasts, need of aerosol forecasts at all – regionally different
- Ground measurements are difficult to use in the multi-hour forecast horizon
- Satellites help to characterize any location in advance with respect to typical cloud behaviour
- Satellite-based nowcasting provides decision support to the plant operator – both visual and quantitatively
- Value of forecasts quantified for the market participation case
- Value of forecast improvments is a nearly linear effect – also if taking a non-linear market into acount – not obvious

References

- **Beyer, H.G., Martinez, J.P., Suri, M.** et al., 2009. MESOR Report on Benchmarking of Radiation Products. Deliverable 1.1.3, Management and Exploitation of Solar Resource Knowledge (MESOR), European Commission 6th framework programme, Contract Number 038665.
- **Breitkreuz, H., Schroedter-Homscheidt, M., Holzer-Popp, T., Dech, S**., 2009. Short Range Direct and Diffuse Irradiance Forecasts for Solar Energy Applications Based on Aerosol Chemical Transport and Numerical Weather Modeling. Journal of Applied Meteorology and Climatology, 48 (9), pp. 1766-1779. DOI: 10.1175/2009JAMC2090.1.
- **Beyer HG, Polo Martinez J, Suri M, Torres JL, Lorenz E, Müller SC, Hoyer-Klick C and Ineichen P.** D 1.1.3 *"Report on Benchmarking of Radiation Products"*. Report under contract no. 038665 of MESoR, 2009. Available for download at http://www.mesor.net/deliverables.html, (January 12, 2012).

- **Lara-Fanego, V., Ruiz-Arias, J.A., Pozo-Vázquez, D., Santos-Alamillos, F.J., Tovar-Pescador, J**., Evaluation of the WRF model solar irradiance forecasts in Andalusia (southern Spain). Solar Energy, 2012
- **Mathiesen P, Kleissl J.** *“Evaluation of numerical weather prediction for intra-day solar forecasting in the continental united states”*. Solar Energy. 2011;85(5):967-77.
- **Perez R, S Kivalov, J Schlemmer, K Hemker Jr., D Renne, TE Hoff,** *“Validation of short and medium term operational solar radiation forecasts in the US”*, Solar Energy, 2010
- **Remund, J.,** Photovoltaic and solar forecasting – state of the art, IEA PVPS report, section 3.4, 2012 (in edit stage at the moment)
- **Wittmann, M., Breitkreuz, H., Schroedter-Homscheidt, M., Eck, M**., Case Studies on the Use of Solar Irradiance Forecast for Optimized Operation Strategies of Solar Thermal Power Plants, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 1, 1, 2008

Additional slides – dealing with accuracies



Source Perez et al, 2010:
RMSE for GLOBAL IRRADIANCE forecasts
US SURFRad stations
Similar results for DNI are not available so far

Example on forecast metrics

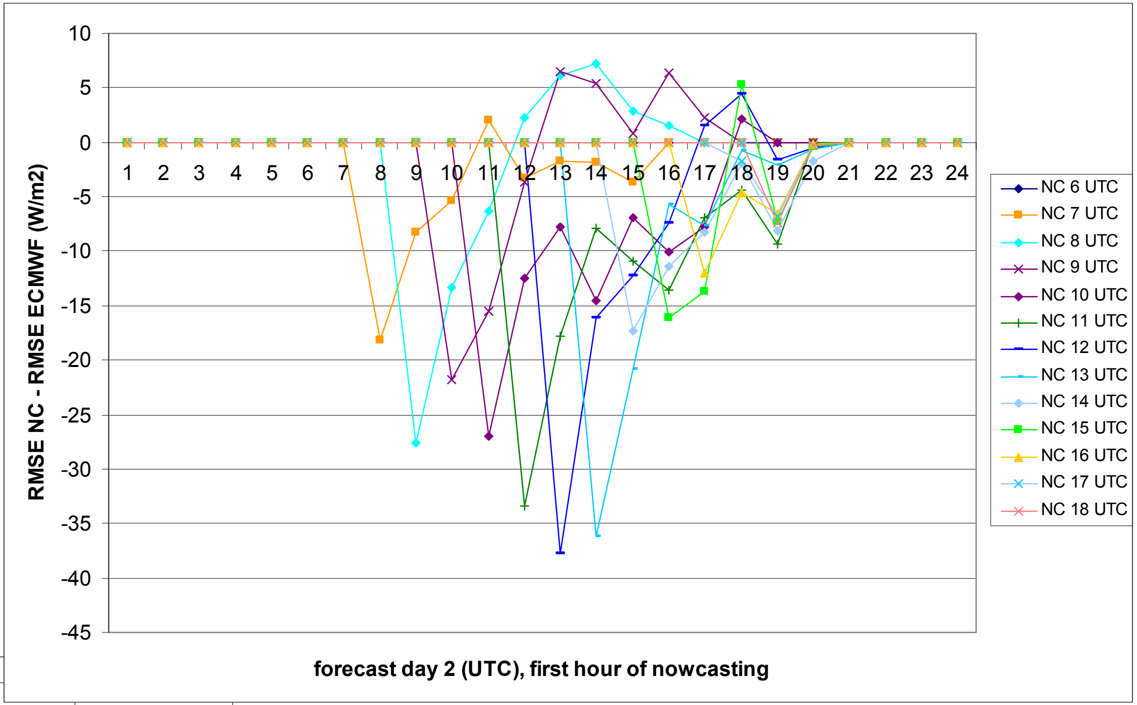
- ECMWF global irradiance forecasts
  - 0.25 degree spatial resolution
  - Day 2 forecast to deal with day ahead market
  - 1 hourly resolution generated from 3 hourly ECMWF output for day ahead/intra day markets
  - GHI2DNI conversion scheme for concentrating solar power
- BSRN, PSA and Andasol-3 surface radiation ground measurements
- MSG SOLEMI irradiance retrievals

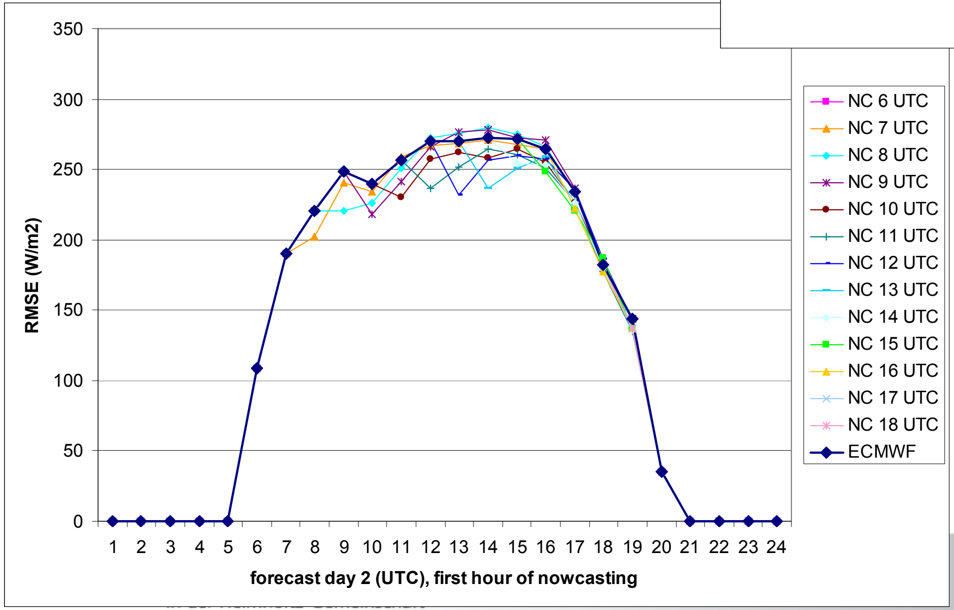
- MESOR QC/Benchmarking standards (see references)

Verification of ECMWF-based direct irradiance forecasts, PSA, 2005

Day 2, PSA, 2005 GHI_g>0	2 day Persistence **Daily sum**	ECMWF/DLR **Daily sum**	Persistence **hourly**	ECMWF/DLR **hourly**
Obs. DNI mean [Wh/m²] or [W/m²]	**6278**	**6278**	**485**	**485**
Bias [Wh/m²] or [W/m²]	**24**	**556**	**0.4**	**42**
RMSD [Wh/m²] or [W/m²]	**3380**	**2194**	**344**	**241**
Rel. RMSD [%]	**54**	**35**	**71**	**50**
Corr.	**0.33**	**0.71**	**0.52**	**0.76**

Quantification sat-based nowcast impact vs. latest deterministic ECMWF forecast (case of Southern Spain)

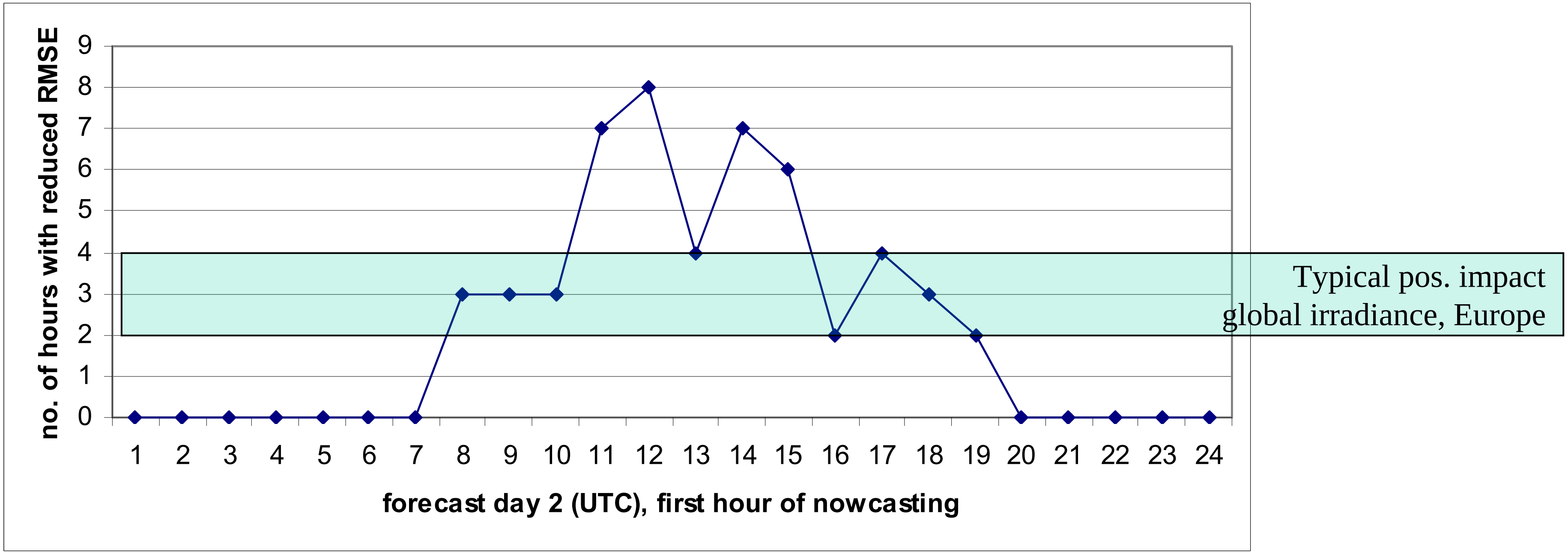




2007, all days
Nowcasting only if discrepancy between ground measurement and forecast is observed

Mainly bias reduction !!!

Duration of positive impact of satellite nowcasting
Case of Southern Spain



Typical values in Europe
for direct irradiance
-> we don‘t know ….