Basic model and concepts, NWP and satellite-based solar forecasting

Elke Lorenz

10.07.2023

www.ise.fraunhofer.de

Agenda

Agenda

Agenda

1. Basic models and concepts

    i. Clear sky models
    ii. Clear sky index

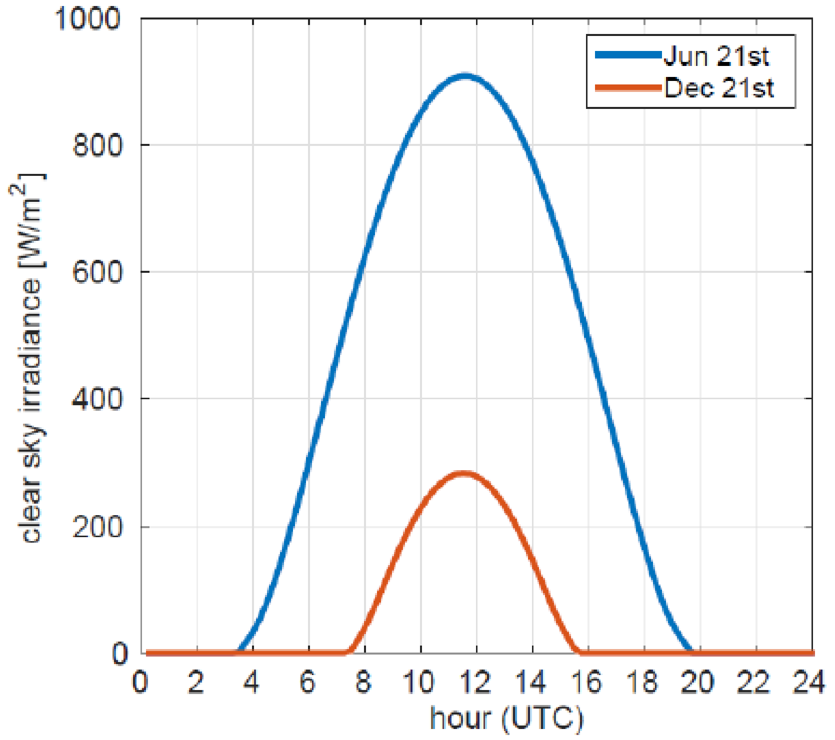
Clear sky models

Definition "clear sky irradiance: irradiance for a cloudless sky at a given site, time and atmospheric conditions

Describe daily and seasonal course of irradiance

Used in many radiation models

Used for normalization of irradiance



Source: Kühnert, 2015

Clear sky models

Definition “clear sky irradiance” irradiance for a cloudless sky at a given site, time and atmospheric conditions

- used in many radiation models
- used for normalization of irradiance

Source: Pierre Ineichen

What do you see?
What effect on GHI do you expect?

Clear sky models

Atmospheric transmission depends on:

- Geometry
- NO2, CO2, O2, N, etc.
  constant effect
- O3
  slight dependence
- water vapor (WV), aerosols (AOD)
  strong dependence

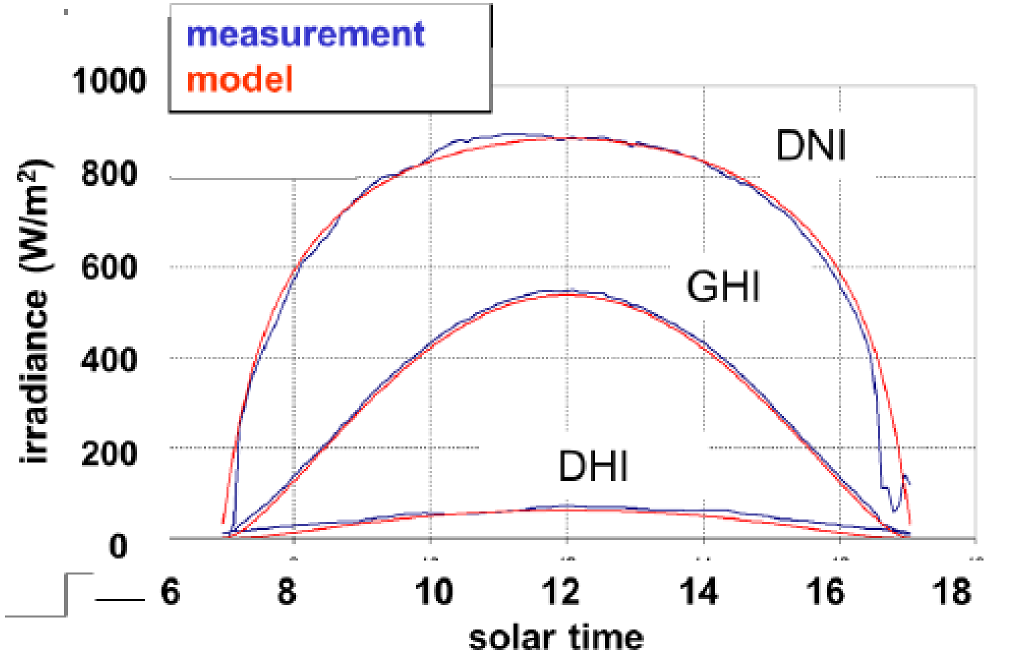
Source: Pierre Ineichen

I_{clear} = f(geometry, air molecules, ozone, aerosols, water vapor)

Clear sky models

Available models:

- Parametric models
- Radiative transfer models



Source: Pierre Ineichen

Quality of clear sky calculations strongly depends on atmospheric input parameters

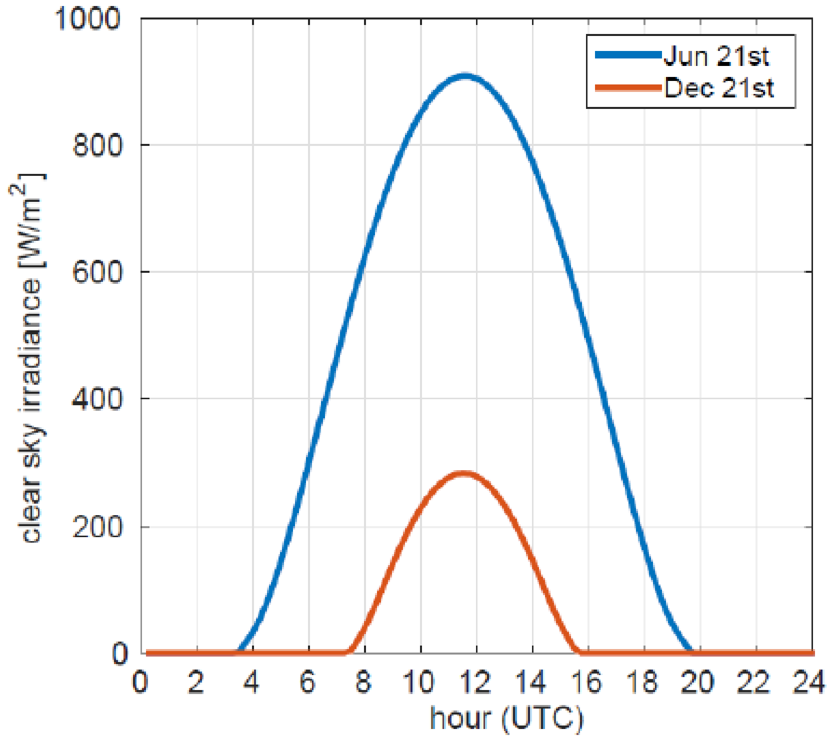
"Good" accuracy of available models, for "good" input parameters

Clear sky index

Clear sky index

Relation of irradiance incident on the horizontal earth's surface GHI to clear sky irradiance GHI_clear

$$k^*=GHI/GHI_{clear}$$



Source: Kühnert, 2015

Clear sky index

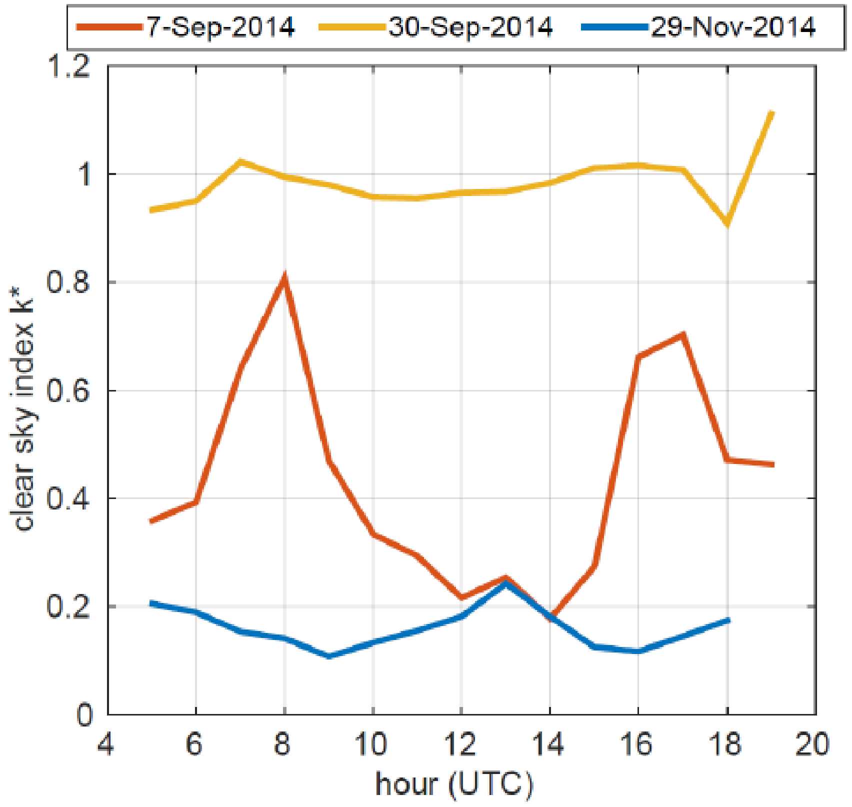
Clear sky index

relation of irradiance incident on the horizontal earth's surface GHI to clear sky irradiance GHI_clear

$$k^*=GHI/GHI_{clear}$$

measure of cloud transmissivity

trend-free for a perfect clear sky model



Source: Kühnert, 2015

Forecast Evaluation

RMSE

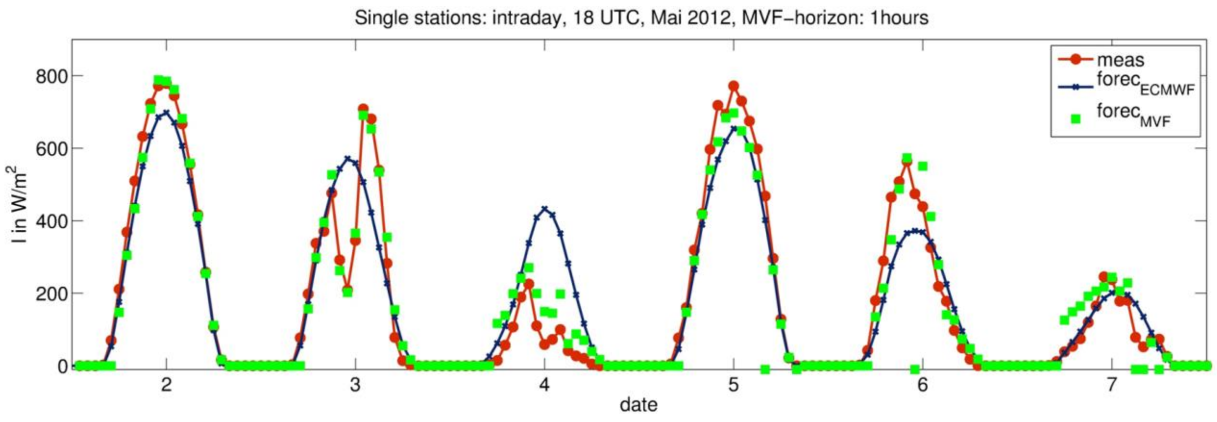
Foreasts are evaluated by comparison to ground measurements

Different scores are used for forecast evaluation

Frequently used: Root mean square error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_p(i) - x_m(i))^2}$$

n: number of data pairs
$x_p(i)$: predicted value
$x_m(i)$: measured value



Agenda

Numerical Weather Prediction NWP

Description of atmospheric processes with differential equations (prognostic equations) and parametrizations

Momentum

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u - \frac{uv}{a} \tan\varphi = fv - \frac{1}{\rho\, a \cos\varphi} \left(\frac{\partial p'}{\partial \lambda} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial \lambda} \frac{\partial p'}{\partial \sigma} \right) - \left(\frac{\nabla \cdot \underline{\mathbf{F}}}{\rho} \right) \cdot \mathbf{e}_\lambda$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \frac{u^2}{a} \tan\varphi = -fu - \frac{1}{\rho\, a} \left(\frac{\partial p'}{\partial \varphi} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial \varphi} \frac{\partial p'}{\partial \sigma} \right) - \left(\frac{\nabla \cdot \underline{\mathbf{F}}}{\rho} \right) \cdot \mathbf{e}_\varphi$$

$$\frac{\partial w}{\partial t} + \mathbf{v} \cdot \nabla w = \frac{g\, \rho_0}{\rho\, p^*} \frac{\partial p'}{\partial \sigma} + g \frac{\rho_0}{\rho} B - \left(\frac{\nabla \cdot \underline{\mathbf{F}}}{\rho} \right) \cdot \mathbf{e}_z$$

Pressure

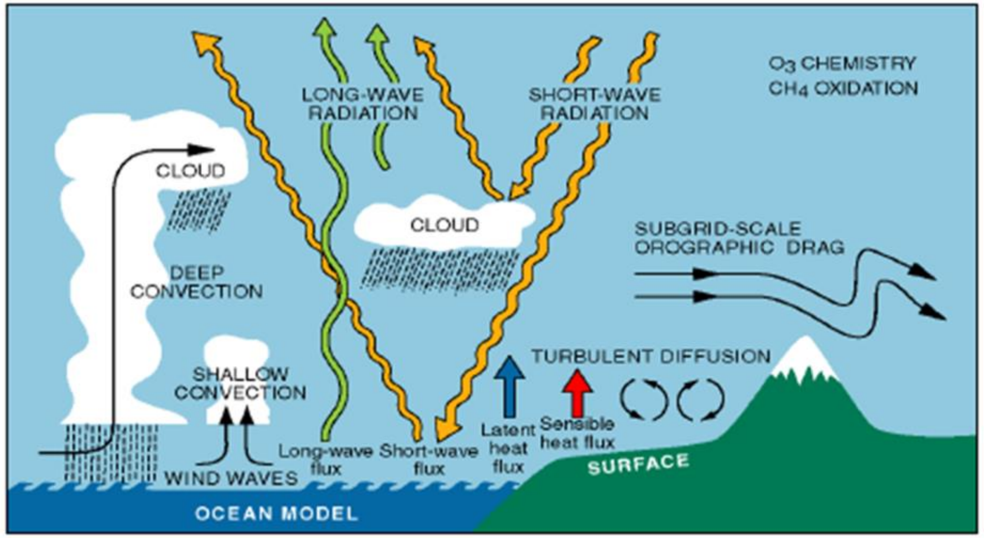
$$\frac{\partial p'}{\partial t} + \mathbf{v} \cdot \nabla p' - g\, \rho_0\, w = -\gamma\, p\, D + \frac{\gamma\, p}{T} \left\{ \frac{Q}{c_p} + T \frac{d\alpha}{dt} \right\}$$

Temperature

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \frac{1}{\rho\, c_p} \left(\frac{\partial p'}{\partial t} + \mathbf{v} \cdot \nabla p' - g\, \rho_0\, w \right) + \frac{Q}{c_p},$$

Humidity

$$\frac{\partial q^k}{\partial t} + \mathbf{v} \cdot \nabla q^k = -\frac{1}{\rho} \left(\nabla \cdot \mathbf{J}^k + \nabla \cdot \mathbf{F}^k \right) - \frac{1}{\rho} I^k$$



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Numerical Weather Prediction NWP

Solving equations numerically on a grid

- Horizontal discretization
- Vertical levels
- Temporal discretization
- Limited by computation costs

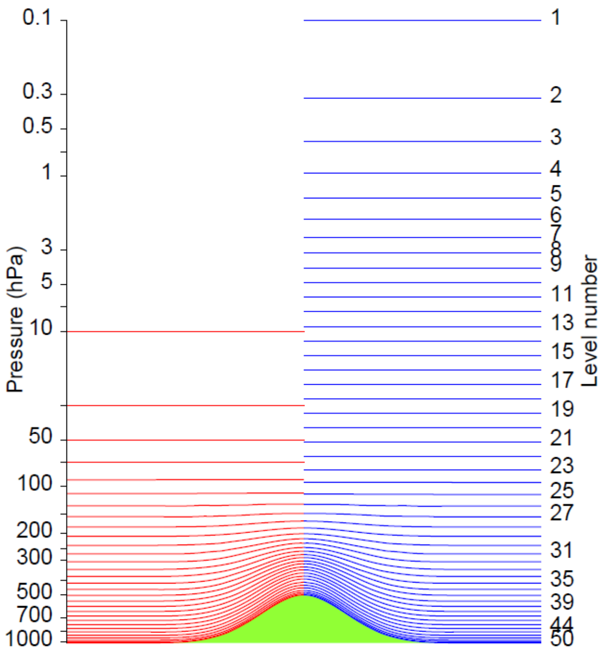
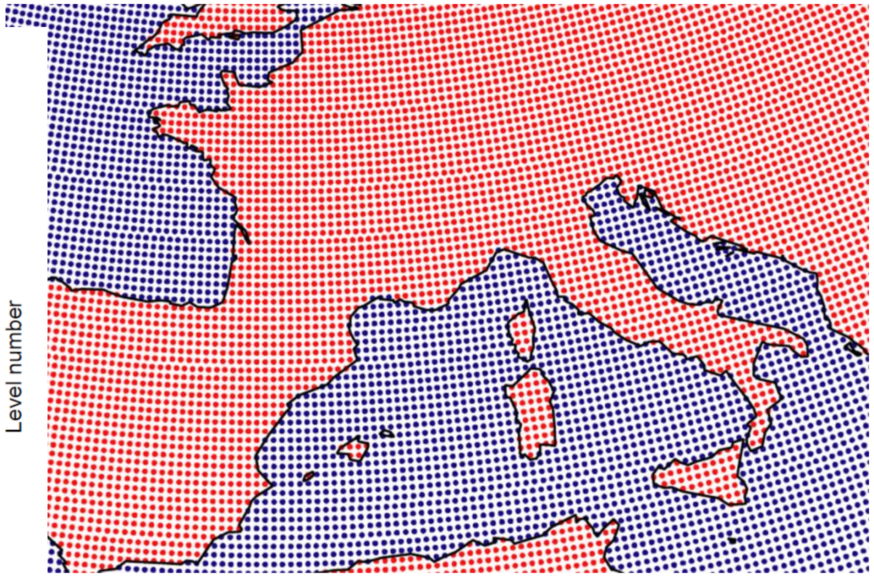


Figure 6. Vertical levels of the ECMWF model.



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Numerical Weather Prediction NWP

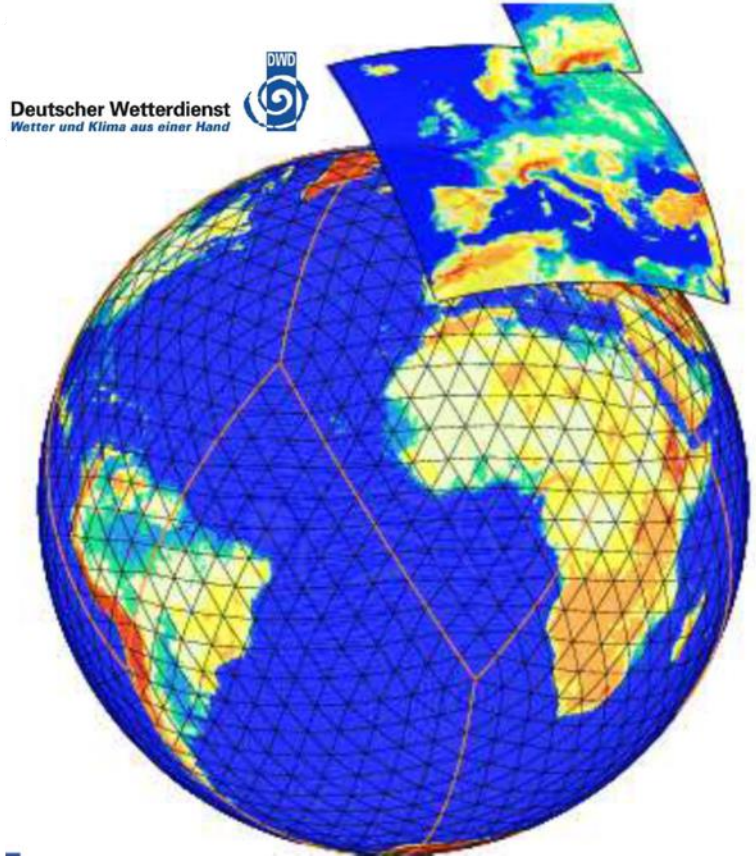
Global and meso-scale models

Global models cover the complete Earth

- spatial resolution ~12-100 km
- temporal resolution, 1-6 hours

Meso-scale/local/regional models allow for higher resolution

- spatial resolution ~1-7 km
- temporal resolution, hourly
- boundary conditions from global model
- multiple nests



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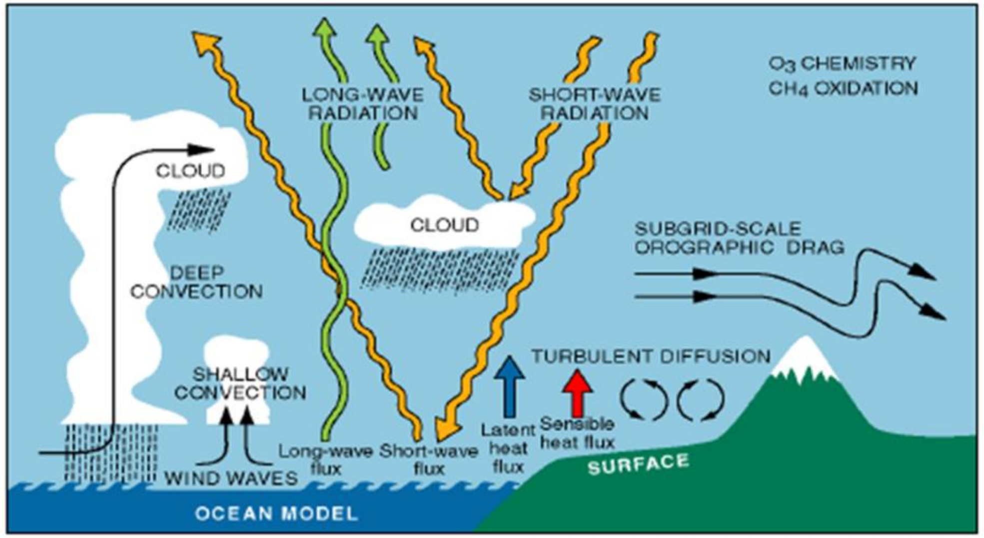
Numerical Weather Prediction NWP

Physics parametrizations

Modelling of processes not explicitly resolved by the grid

- Radiation
- Condensation
- Convection
- Turbulence
- Land Surface Processes



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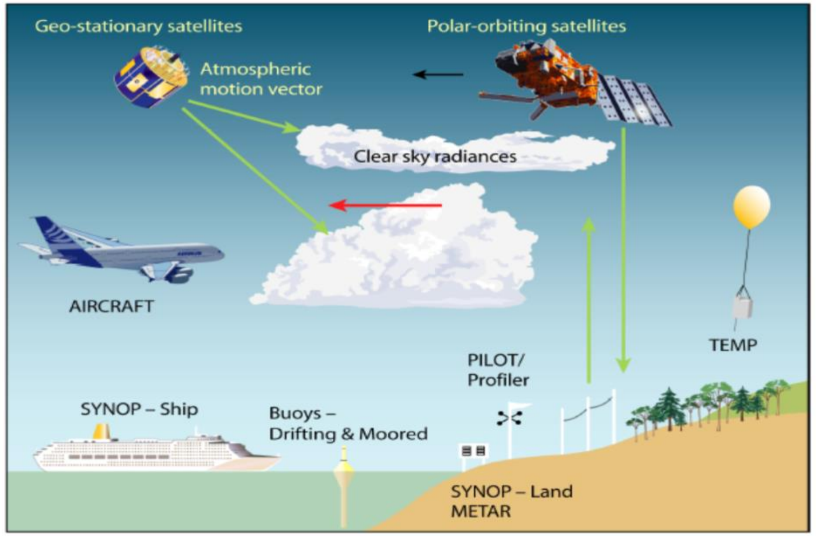
Numerical Weather Prediction NWP

Initial conditions and data assimilation

Assimilation of worldwide meteorological observations:

- Satellite data
- Ground based sensors
- Sondes,…

Observations and short-range forecasts are combined by calculating a weighted average for all grid points where the weights depend on the respective characteristic errors.



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Numerical Weather Prediction NWP

Provided by weather services

Examples:

- **Global models**

Integrated forecast systems (IFS) of the European Centre for Medium-Range Weather Forecasts (ECWMF)

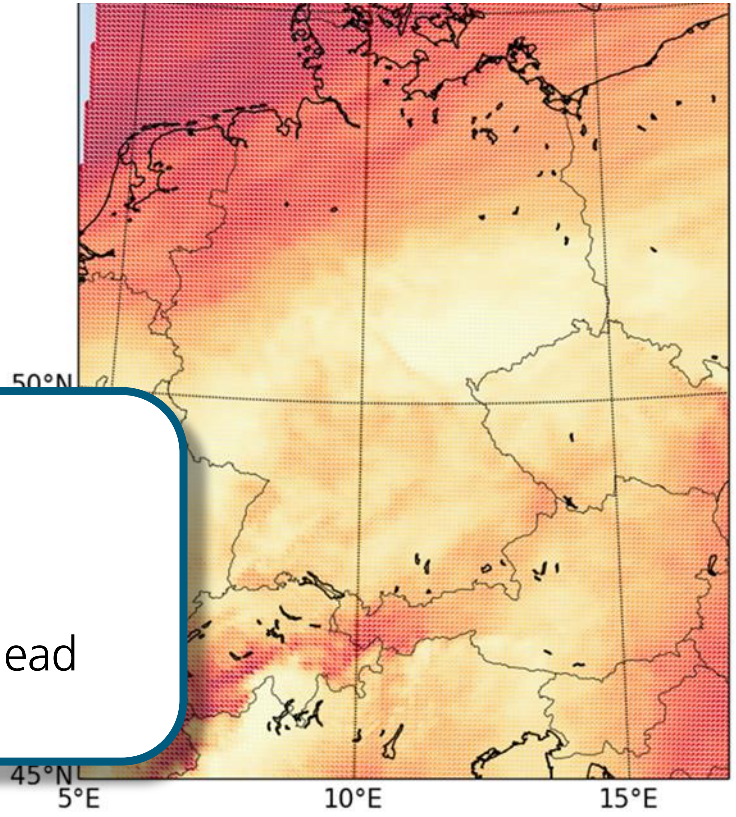
Global forecast system GFS a National Centers for Environmental Prediction (NCEP) U

- **Regional models**

German Meteorological service (D

Meteo France: AROME

COSMO EU, dir. irradiance
2004-05-02, 12:00



NWP irradiance forecasting

resolution: 1-3 hours, 3- 20 km

forecast horizon: 3 to 15 days ahead

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NWP Ensembles

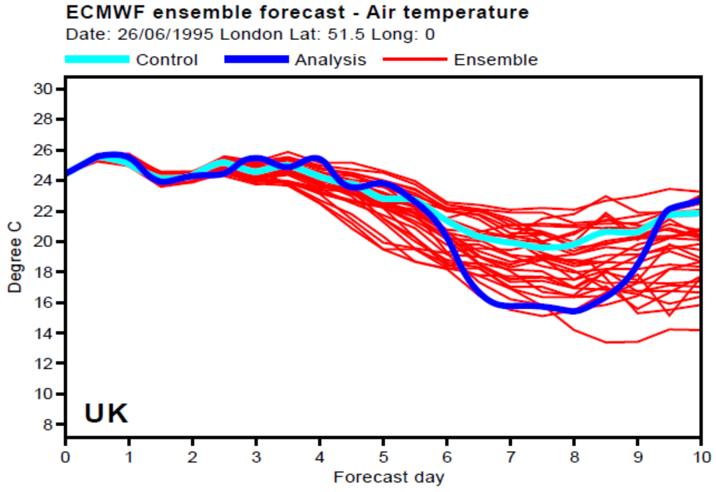
Several runs of a weather prediction model

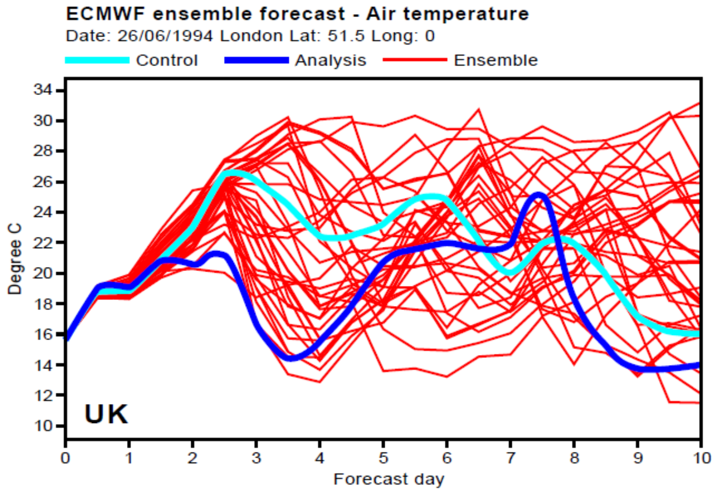
variation in initial conditions

variation in model physics

Distribution of forecast results describes forecast uncertainty

Forecast uncertainty depends on weather conditions!





Agenda
Subtitel

1. **Basic models and concepts**
2. **NWP forecasts**
3. **Satellite based forecasts**

Agenda

3. Satellite based forecasts

- Satellite-based irradiance retrieval
- Satellite-based irradiance forecasting

Solar radiation data from satellite images

Availability

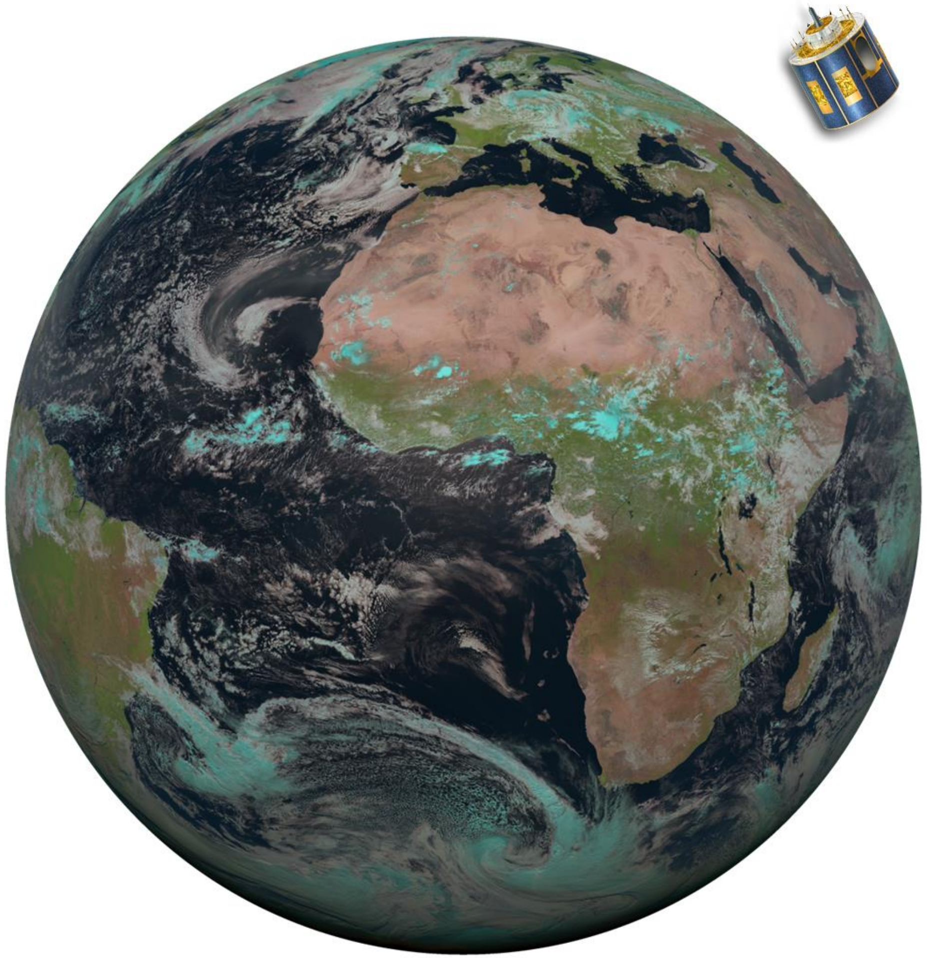
Europe and La Reunion:
Meteosat Second Generation Satellites

High spatial and temporal resolution

- 1 km / 3 km at sub-satellite point
- 15 minutes

Services

- MSG 0 Degrees



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Solar radiation data from satellite images

Availability

Europe and La Reunion:
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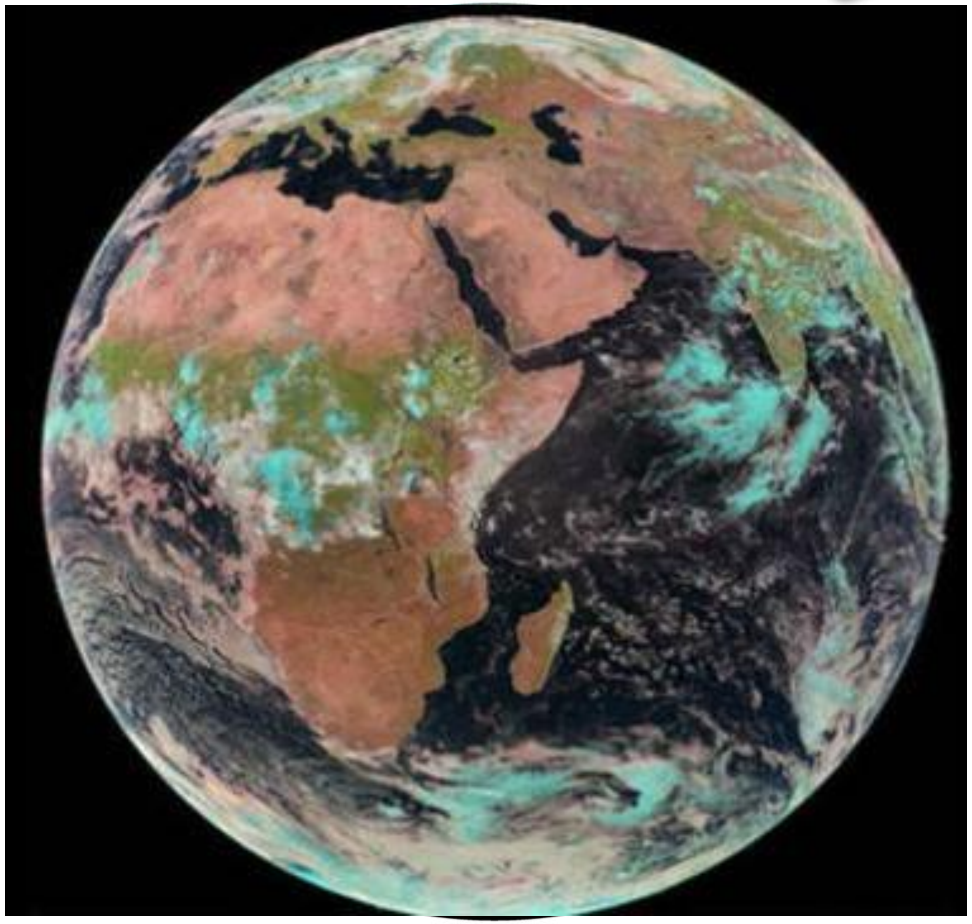
- MSG- IODC



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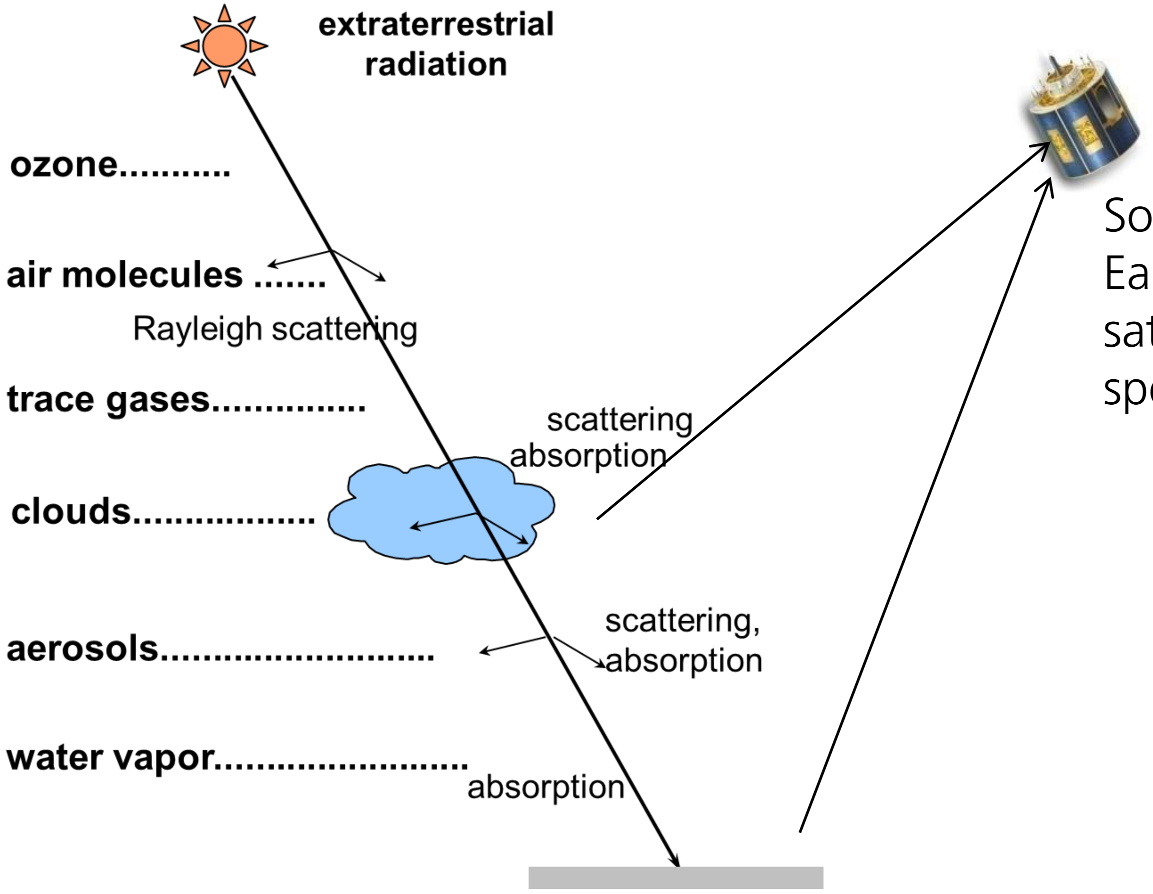
Satellite-based irradiance models

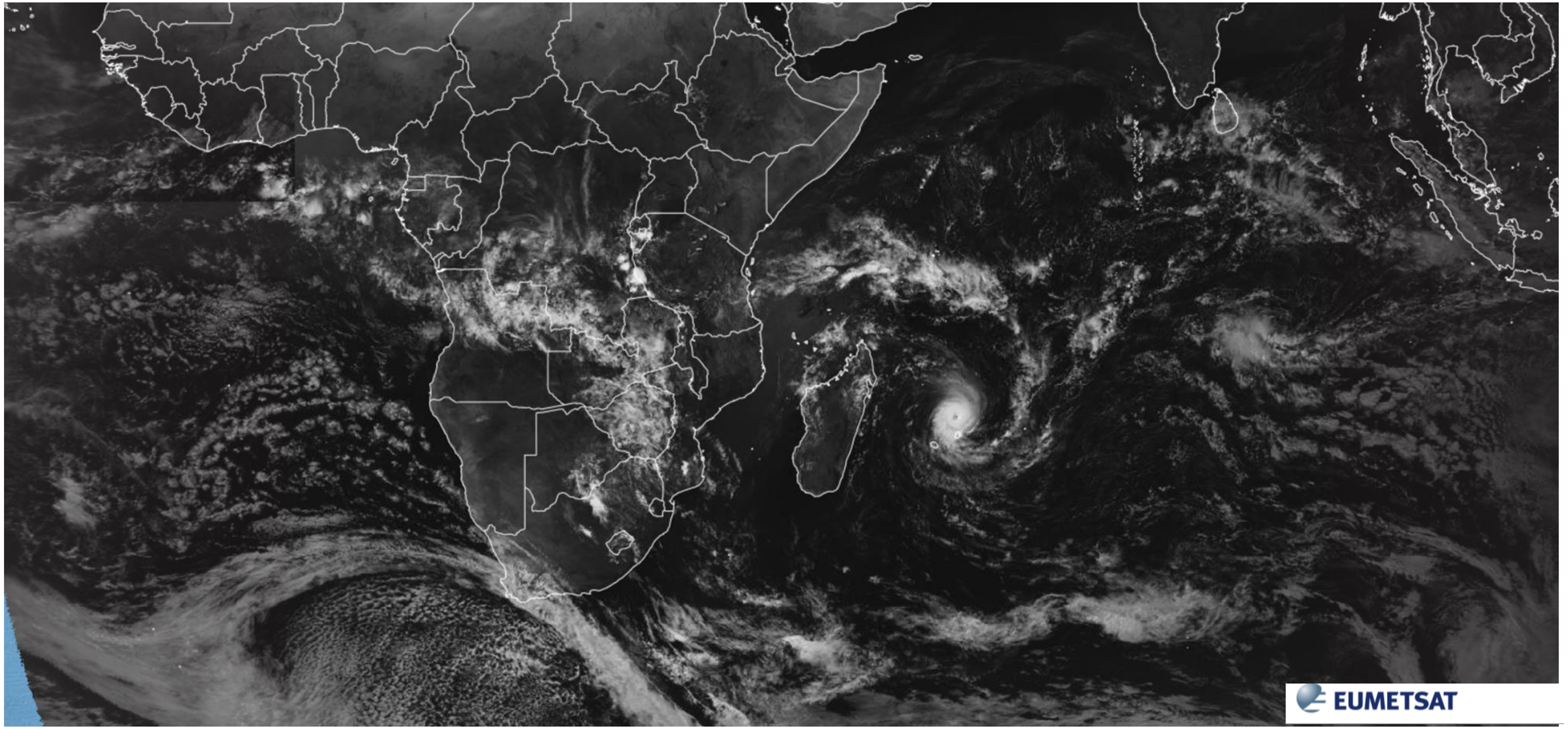
Surface solar irradiance and atmospheric processes



Solar radiation scattered back by the Earth/Atmosphere is measured with satellite instruments in the visible spectral range

MSG IODC

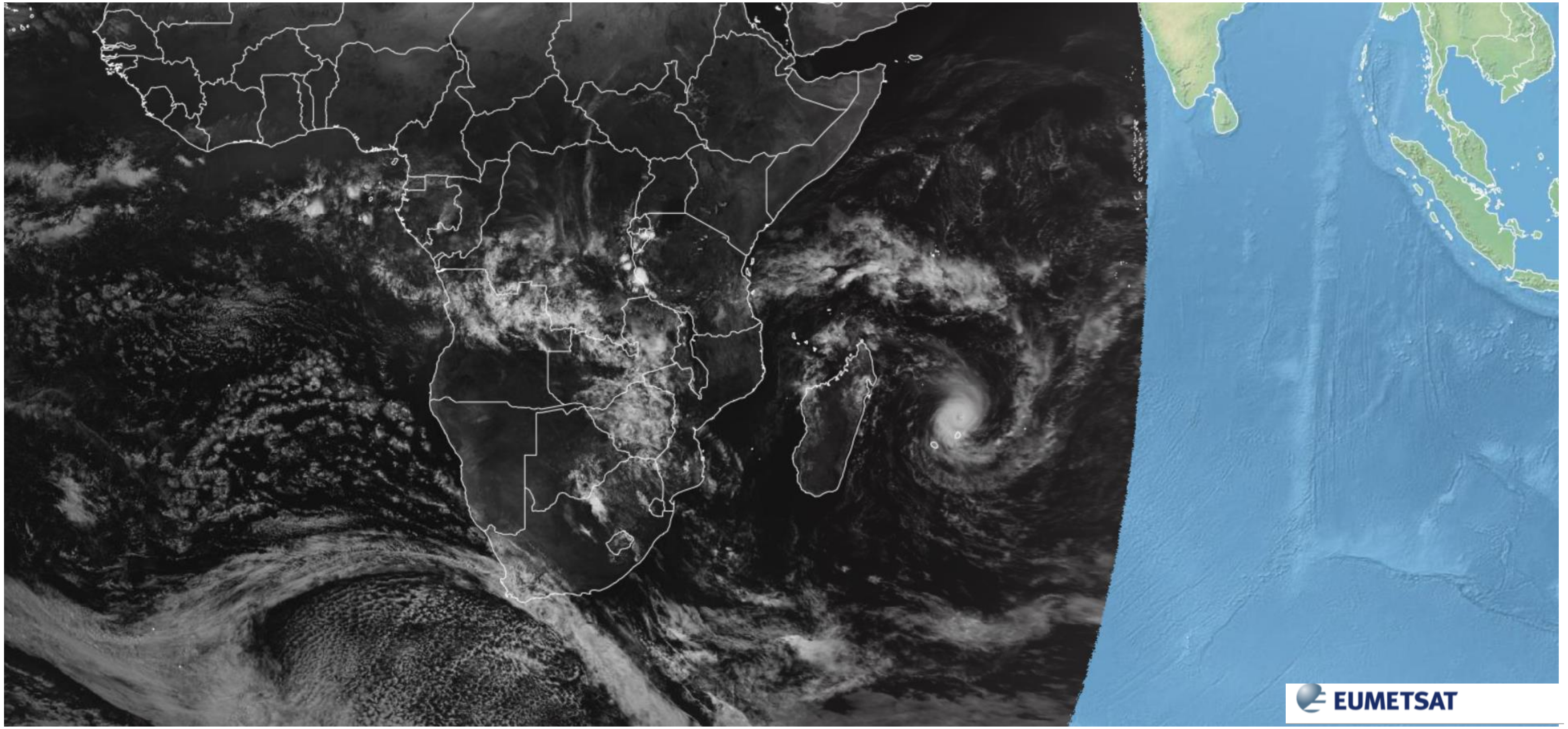
Visible range, 20.02.2023



Source: https://view.eumetsat.int/productviewer?v=default

MSG 0°

Visible range, 20.02.2023



Source: https://view.eumetsat.int/productviewer?v=default

Satellite images

Meteosat Second Generation (MSG)

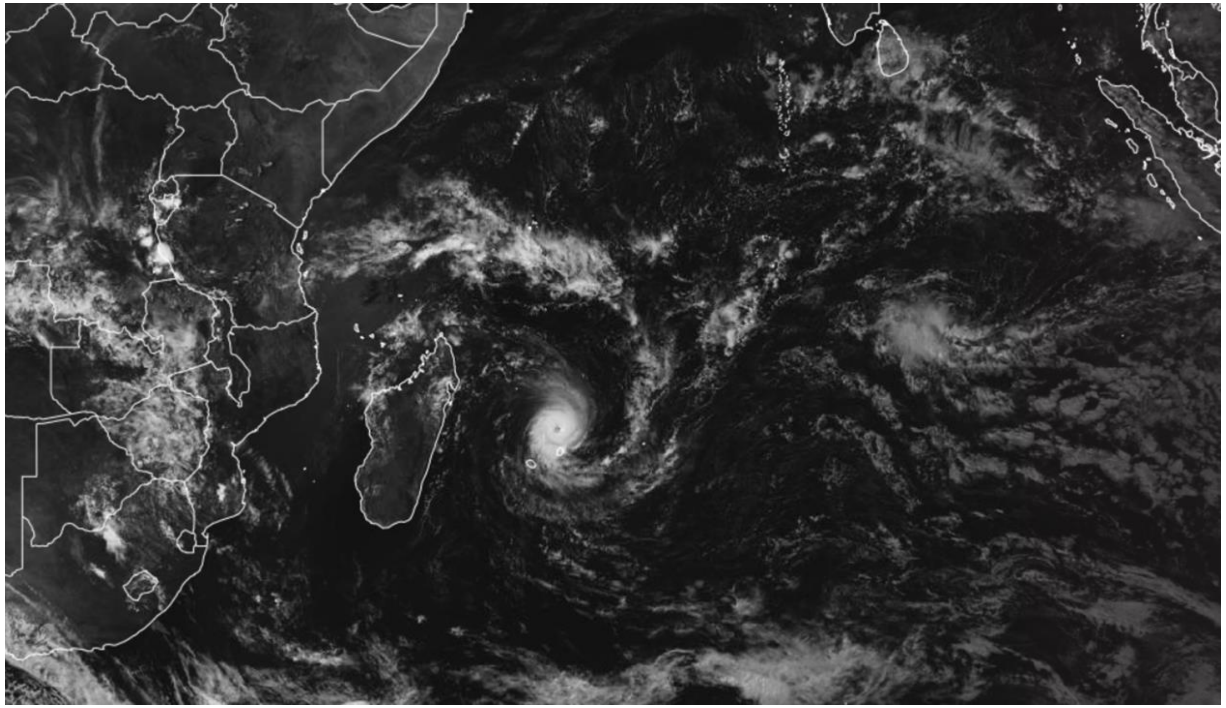
High resolution visible (HR-VIS) channel: 600-900nm

Resolution at sub-satellite point

- 1 km x 1 km
- 15 minutes

cloud detection based on
reflected radiation

- bright clouds (high Albedo)
- dark surface
  - very dark water (very low Albedo)
  - dark ground (low Albedo)

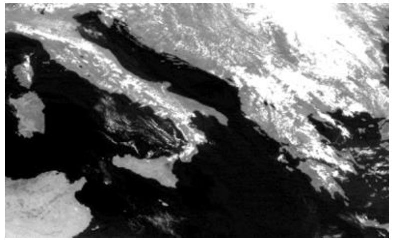


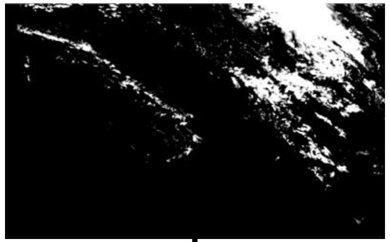
EUMETSAT

Source: https://view.eumetsat.int/productviewer?v=default

Solar surface irradiance from satellite data

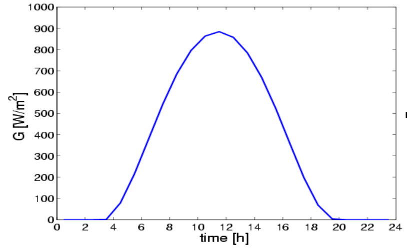
Heliosat method

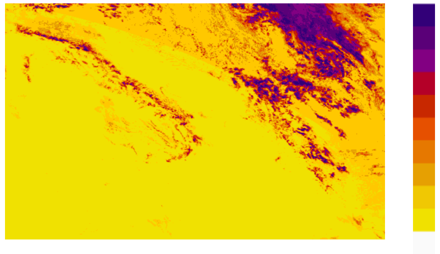




cloud index images:
measure of cloudiness

clear sky model





100 W/m^2

500 W/m^2

1000 W/m^2

maps of
global irradiance

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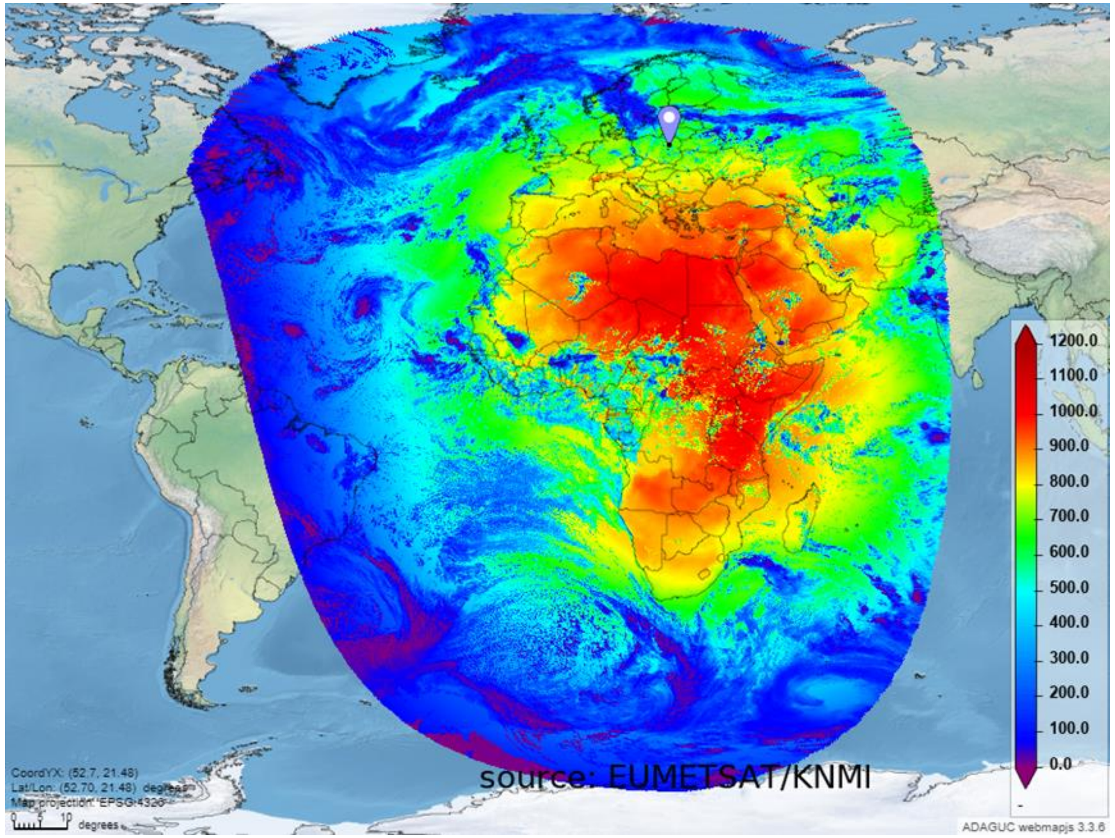
Solar surface irradiance from satellite data

Data Products

High resolution maps of current irradiance conditions

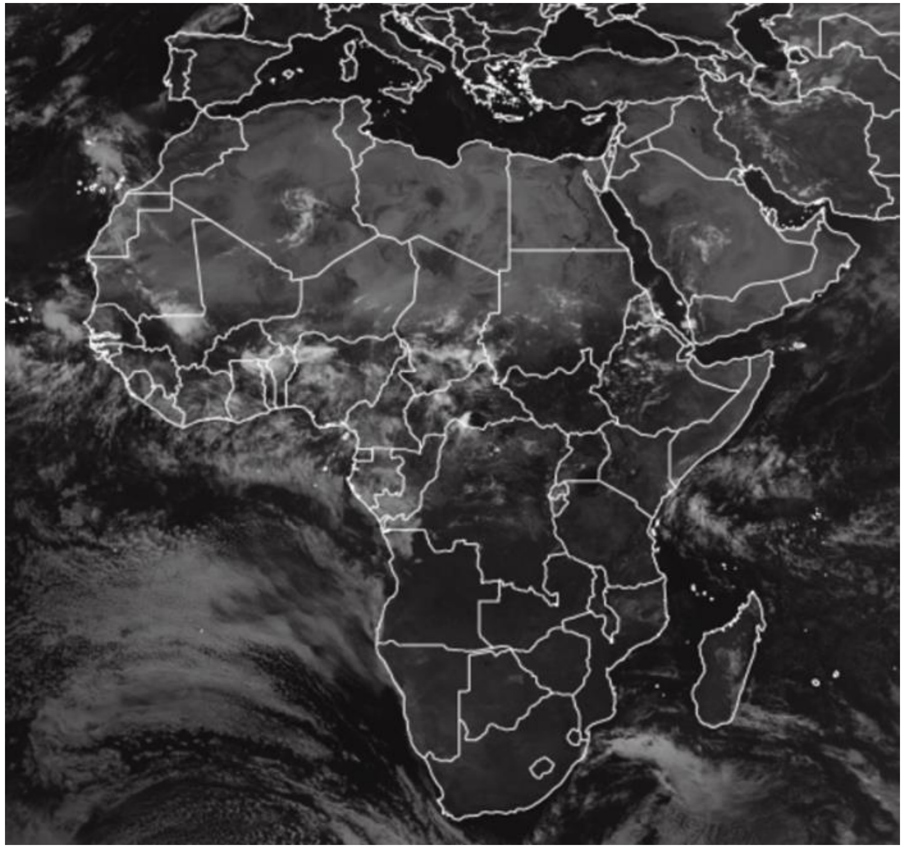
- Update very 15 minutes
- Spatial resolution 1 or 3 km at sub satellite point



Solar surface irradiance from satellite data

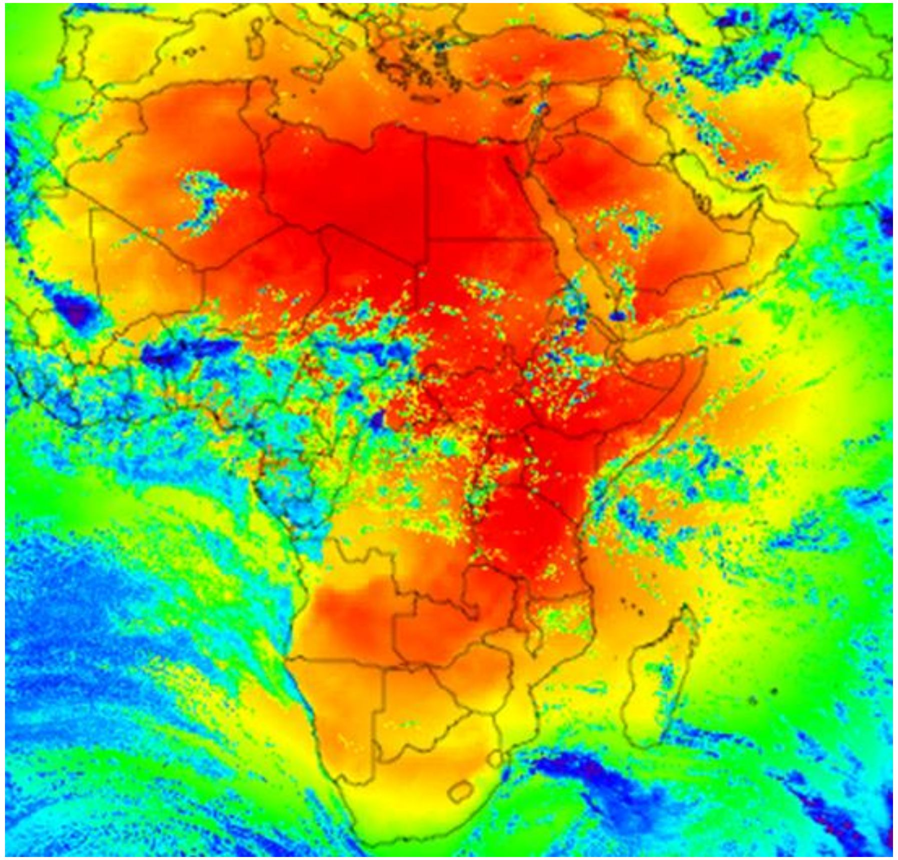
20.08.2023 10:15

EUMETSAT



Source: https://view.eumetsat.int/productviewer?v=default

SOURCE: EMETSAT/KNMI
https://msgcpp.knmi.nl/adaguc-viewer/index.html



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Solar surface irradiance from satellite data

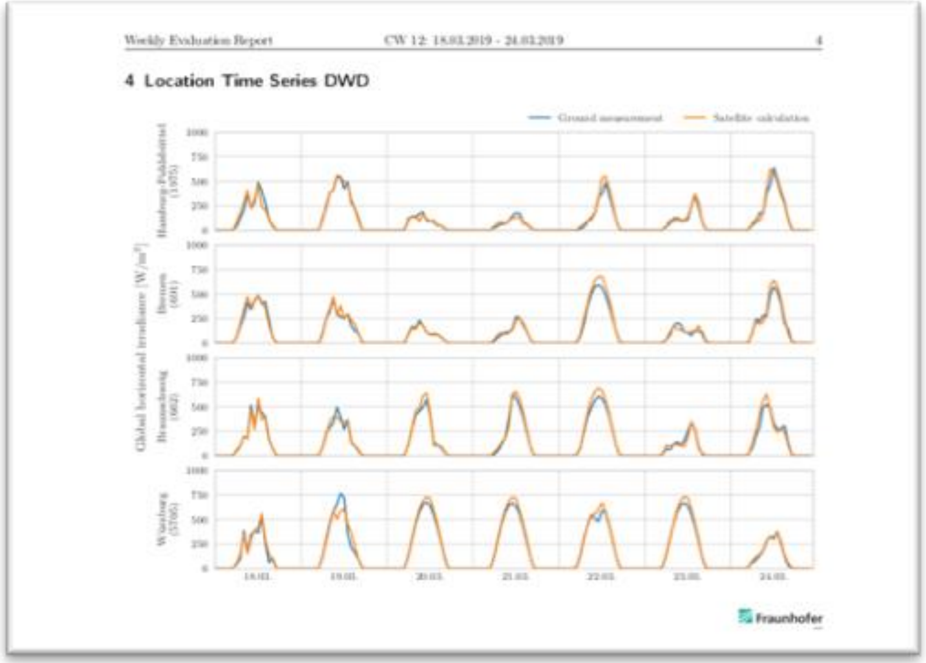
Data Products

High resolutions maps of current irradiance conditions

- Update very 15 minutes
- Spatial resolution 1 or 3 km at sub satellite point

Time-series of GHI/DNI

- 15 minute resolution



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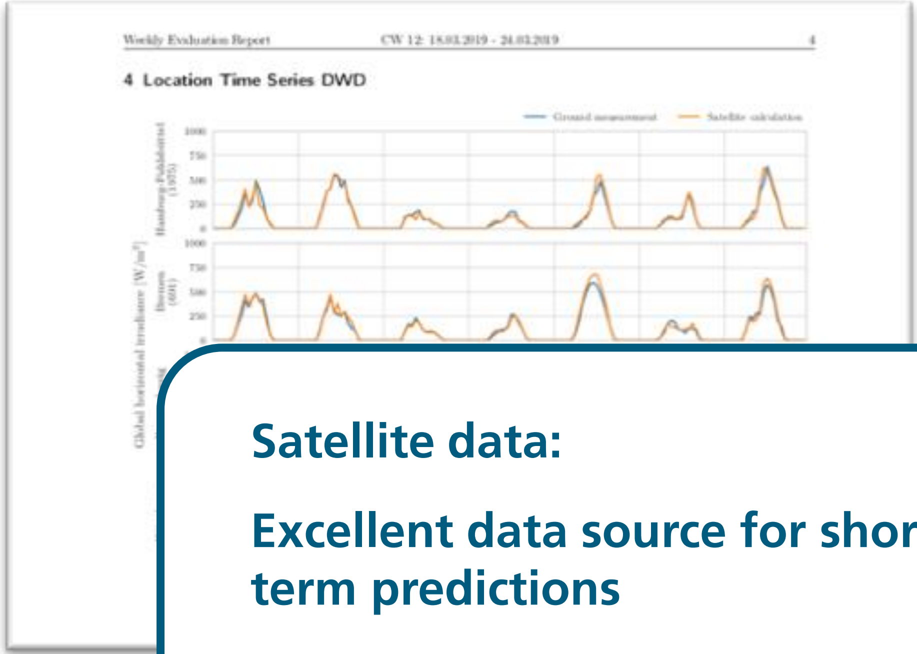
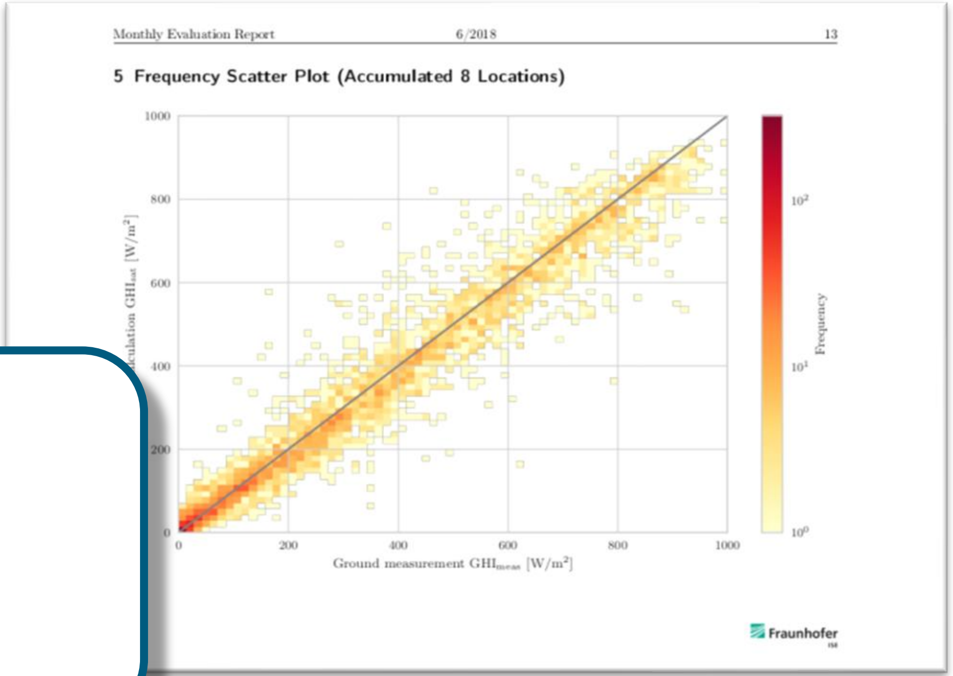
Solar surface irradiance from satellite data

Comparison to ground-measured irradiance

Visual assessment

- Time-series
- Scatterplots





Satellite data:

Excellent data source for short term predictions

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Satellite based irradiance prediction

Detection and extrapolation of cloud motion

CMV – Cloud Motion Vectors

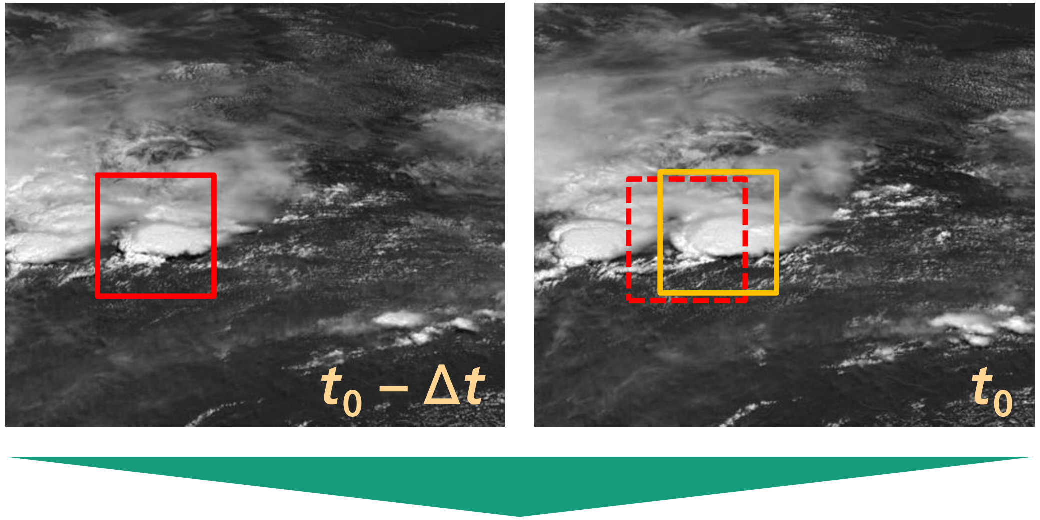
Computation of optical flow from subsequent cloud index images

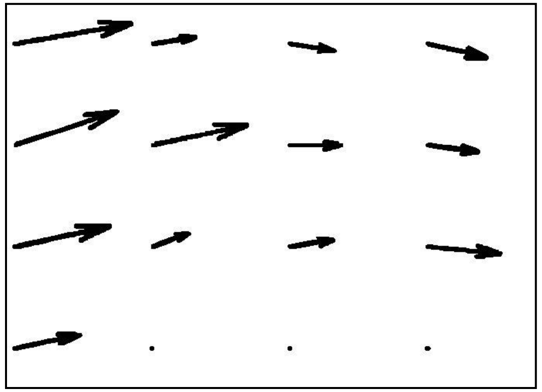
Basic assuption: Cloud structures remain constant during motion

Basic identification of similar patterns in consecutive images

Methods:

- Block Matching
- Based on Machine Learning





cloud motion vector field

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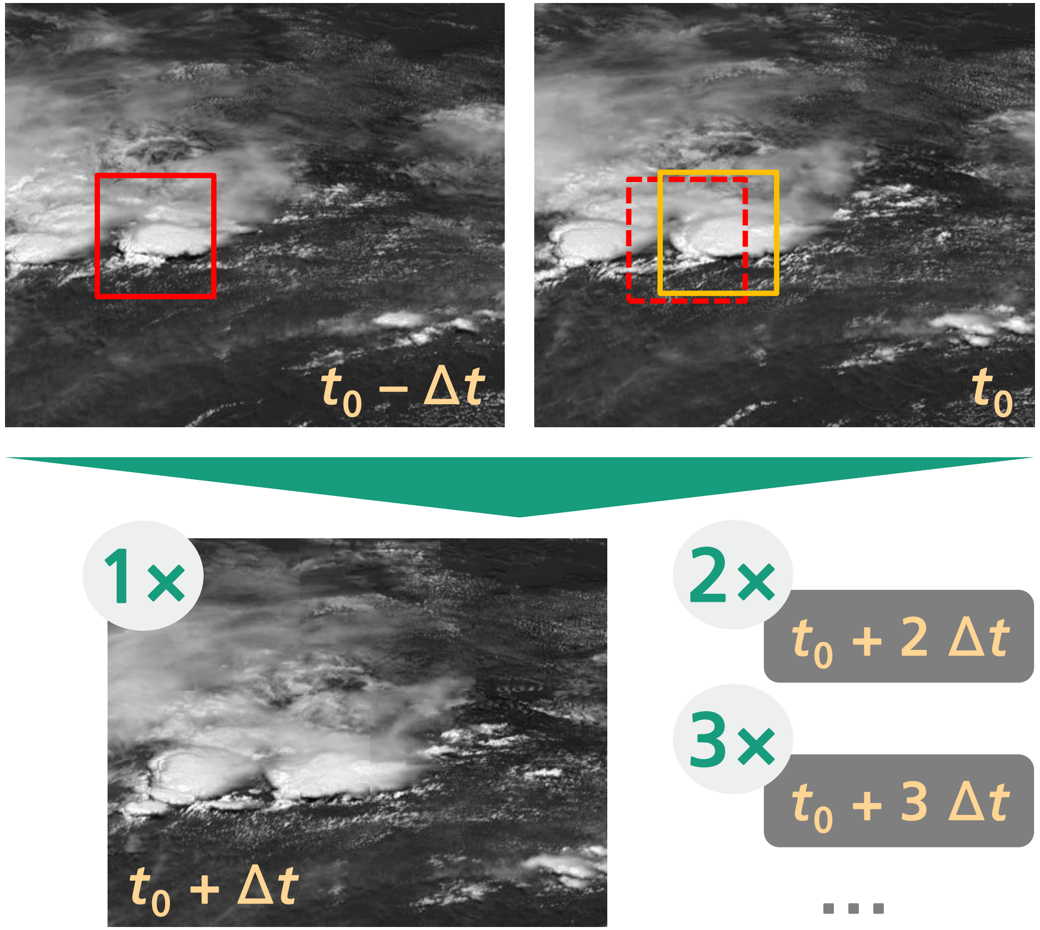
Satellite based irradiance prediction

CMV – Cloud Motion Vectors

Computation of predicted flow from subsequent cloud index images

Prediction of cloud motion

Application of cloud motion vectors to current image to predict future cloud index images



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Satellite based irradiance prediction

CMV – Cloud Motion Vectors

Computation of predictable flow from subsequent cloud index images

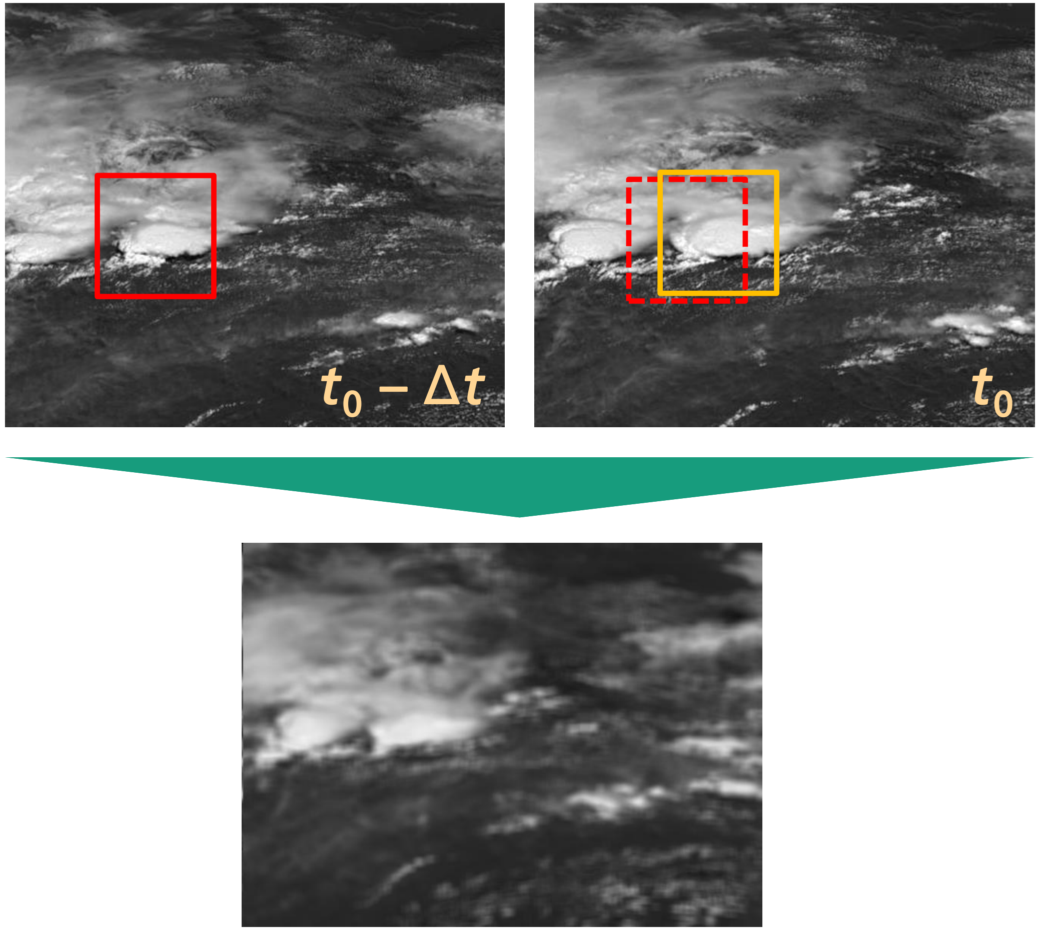
Prediction of cloud motion

Application of cloud motion vectors to current image to predcit future cloud index images

Smoothing

Irradiance prediction

Infer irradiance from predicted cloud index images (Heliosat Method)



Comparison of satellite-based and NWP predictions

CMV – Cloud Motion Vectors

Computation of predictable flow from subsequent cloud index images

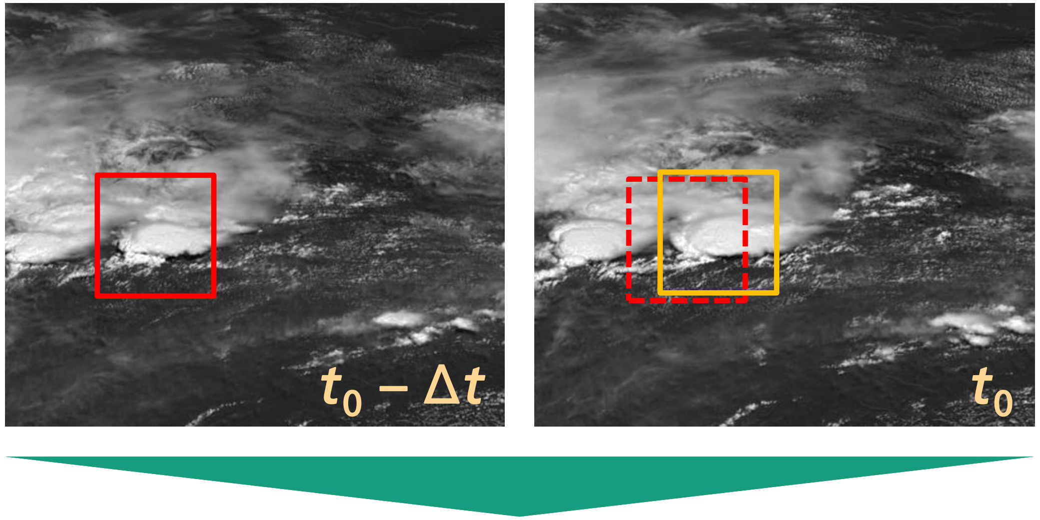
Prediction of cloud motion

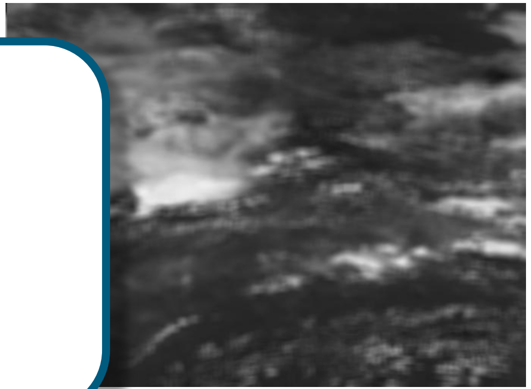
Application of cloud motion vectors to current image to predict future cloud index images

Smoothing

Irradiance prediction

Infer irradiance from predicted coud
Method)





NWP irradiance forecasting

resolution: 15 minutes, 1-3 km

forecast horizon: several hours ahead

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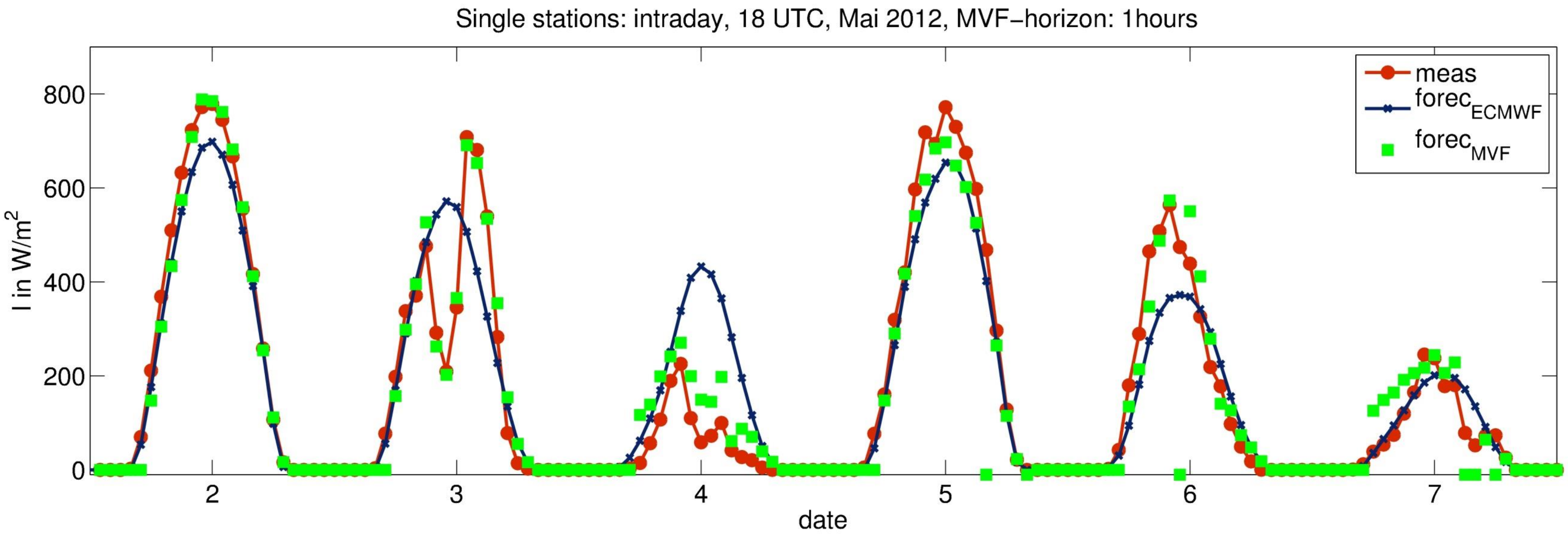
Evaluation of satellite-based and NWP predictions

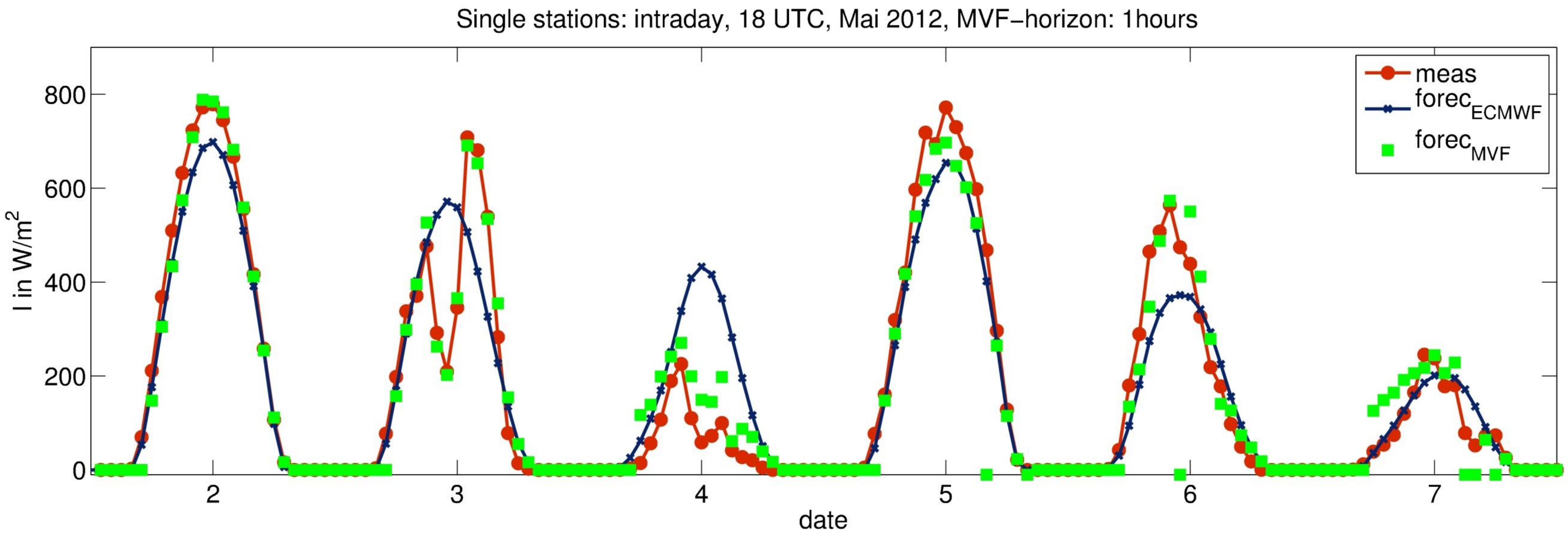
Comparison to ground measured irradiance



What can you see when comparing NWP forecasts (ECMWF) and satellite based forecasts MVF to measurements?

Evaluation of satellite-based and NWP predictions

Comparison to ground measured irradiance



Good agreement with measurements for clear sky day for both NWP and satellite-based

Satellite-based forecasts capture fluctuations in variable cloud conditions for an hour ahead

Evaluation of satellite-based and NWP predictions

RMSE in dependence of forecast horizon

DWD-Standort Hamburg-Fuhlsbüttel, Mai-June 2019

Different scores are used for forecast evaluation

Frequently used: Root mean square error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_p(i) - x_m(i))^2}$$

n: number of data pairs
$x_p(i)$: predicted value
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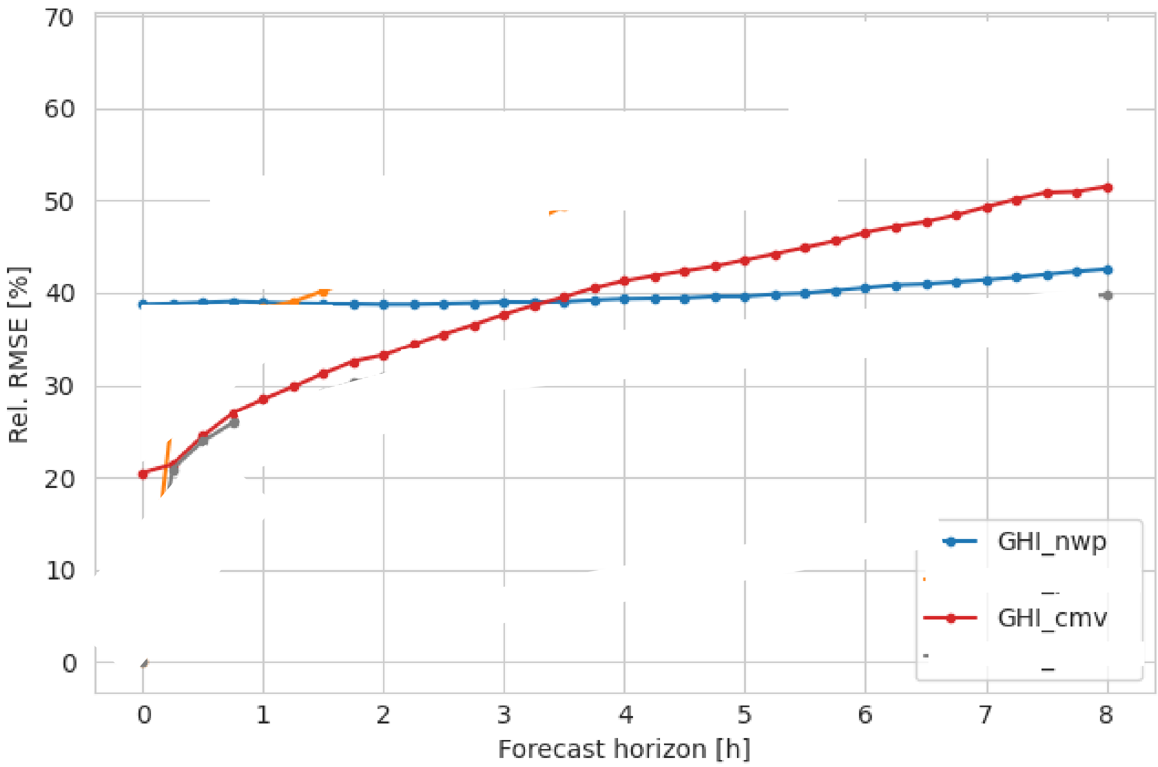

Evaluation of satellite-based and NWP predictions

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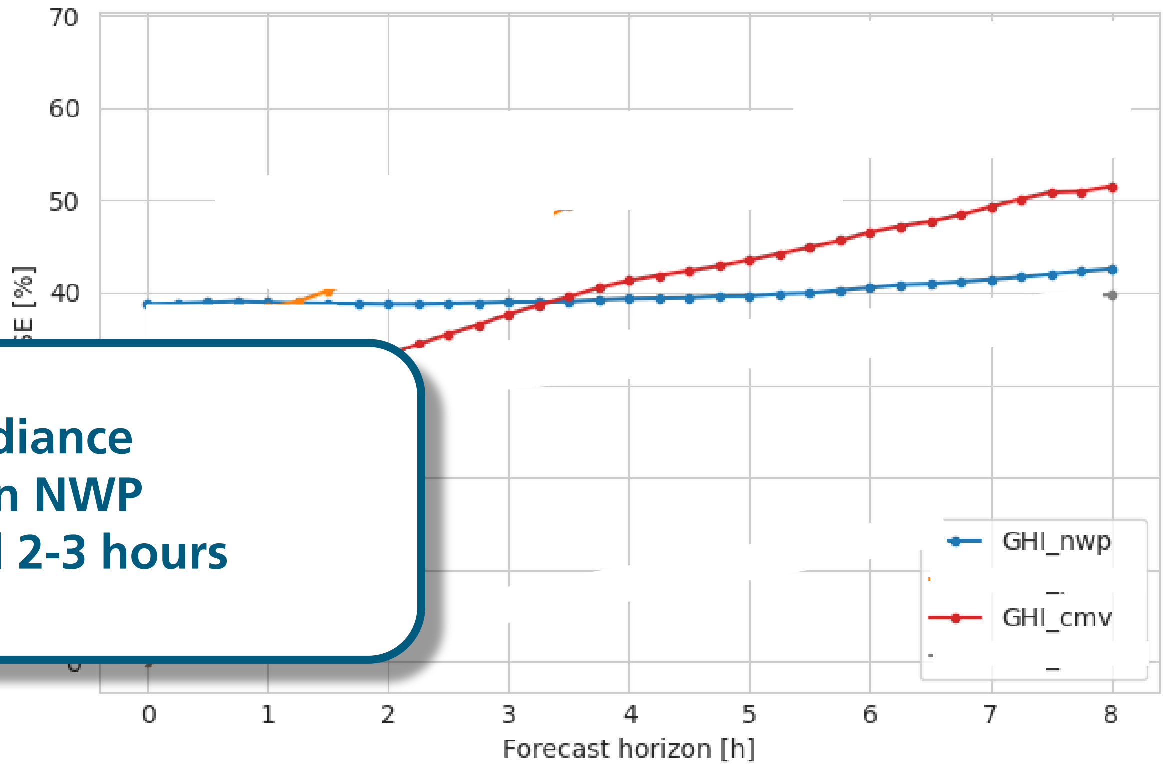
DWD-Standort Hamburg-Fuhlsbüttel, Mai-June 2019



Satellite-based irradiance forecasts better than NWP forecasts for several 2-3 hours ahead

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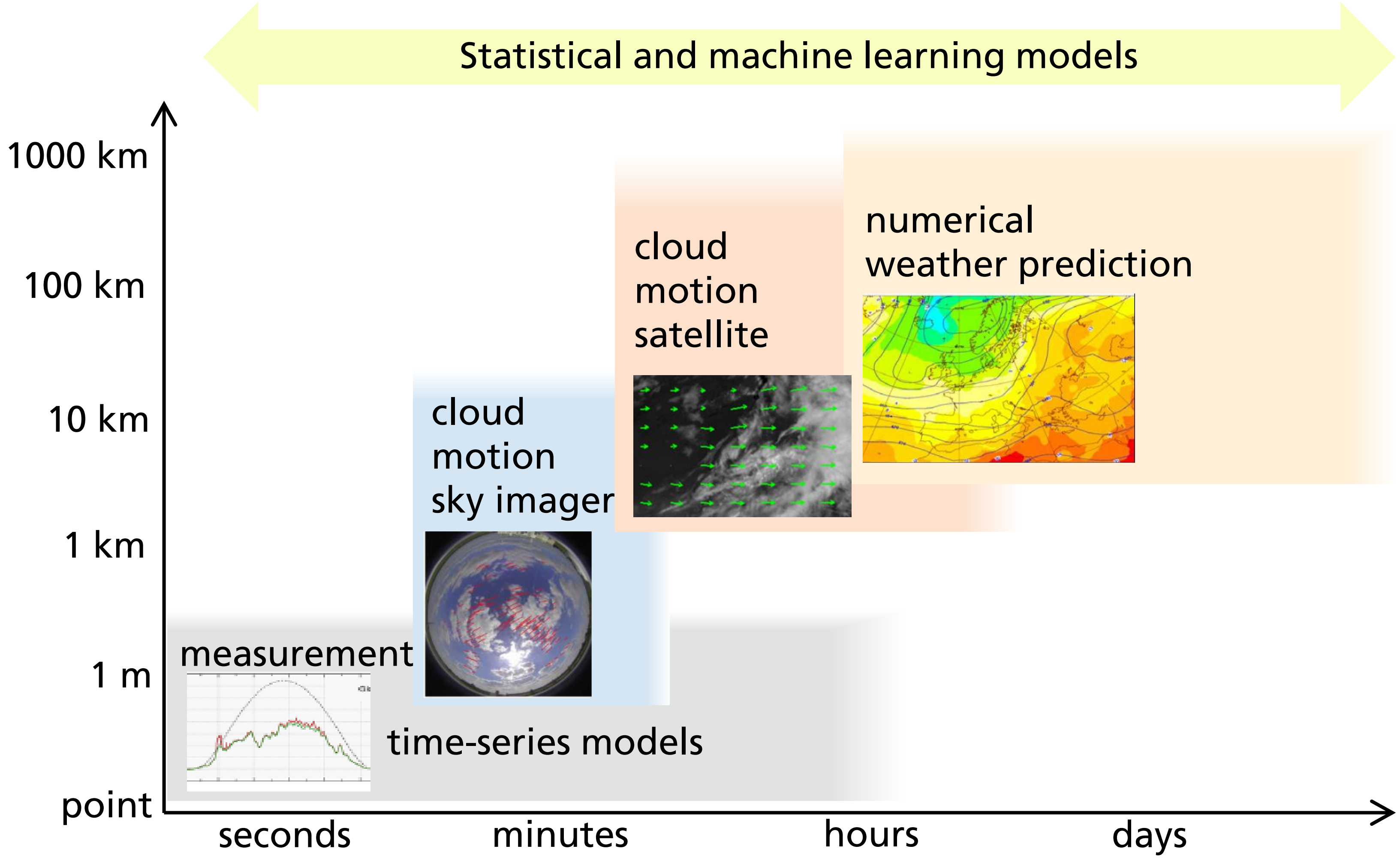
Overview of irradiance prediction models



Thank you for your attention!

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79110 Freiburg
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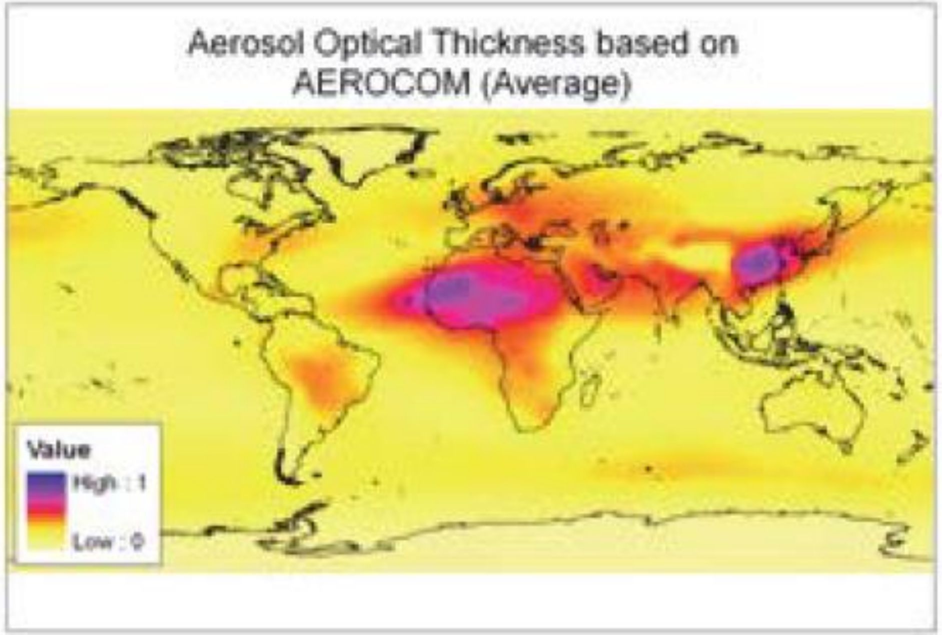
Clear sky models
Atmospheric input parameters

Climatological monthly mean values of AOD / Link Turbidity derived from

- satellite data
- ground measurements
- numerical weather prediction models



Source: User's Guide to the CAMS Radiation Service, Schroedter-Homscheidt 2016

Clear sky models

Atmospheric input parameters

Climatological monthly mean values of AOD / Link Turbidity derived from:

- satellite data
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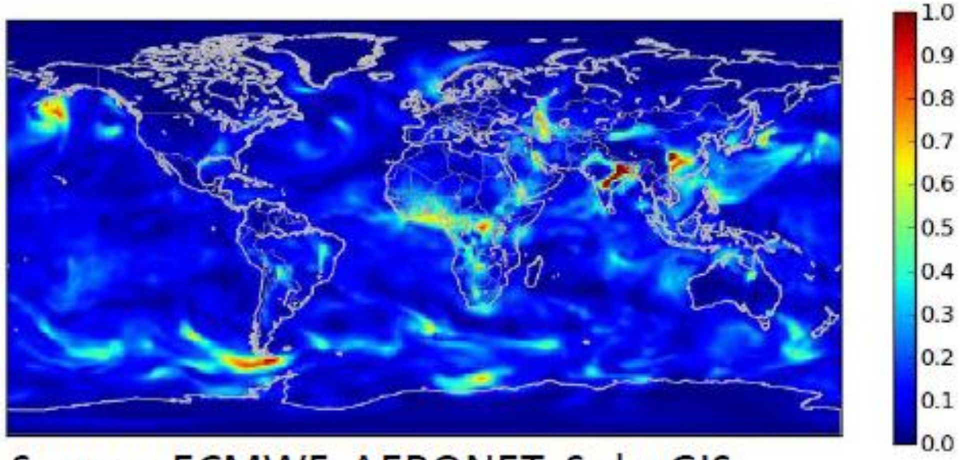


Source: ECMWF, AERONET, SolarGIS

Daily/three-hourly values of AOD derived with numerical weather prediction models:

e.g. CAMS

Clearness index

Clearness index

relation of irradiance incident on the horizontal earth's surface GHI to the horizontal extraterrestrial irradiance G_0

$$k_t = GHI/I_{TOA}$$

measure of atmospheric transmissivity

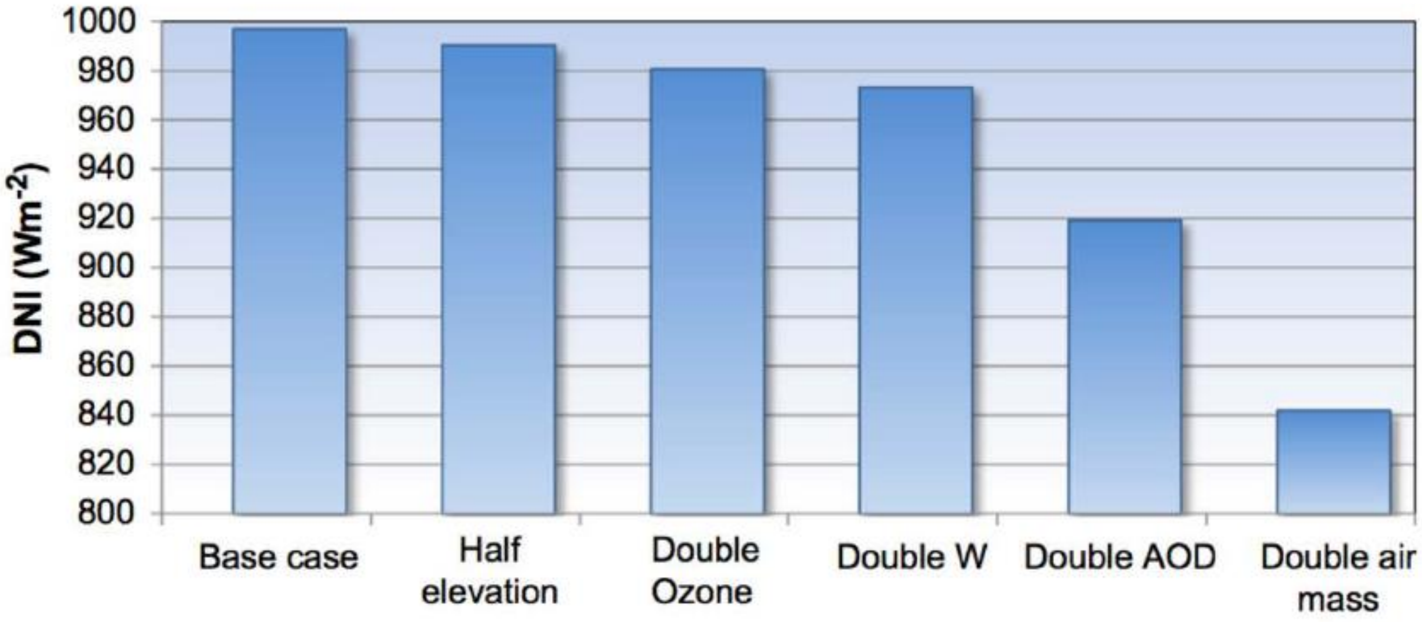
independent of solar geometry

still influenced by path length through atmosphere

$$I_{TOA} = TSI * \varepsilon * \cos\theta_{zenith}$$

- TSI: Total solar irradiance or solar constant
- ε: eccentricity factor

Factors influencing clear sky irradiance



starting from the base-case: AM 1.5, 1100 m elevation, broadband AOD = 0.03, w = 0.75 cm, and ozone = 320 dobson units (DU).

Source: Solar Energy Forecasting and Resource Assessment (Kleissl, 2013)

AM1.5: $\Theta_z = 48.2°$

AM 3: $\Theta_z = 70.5°$

Solar radiation data from satellite images

Availability

world-wide coverage

long term data: > 20 years