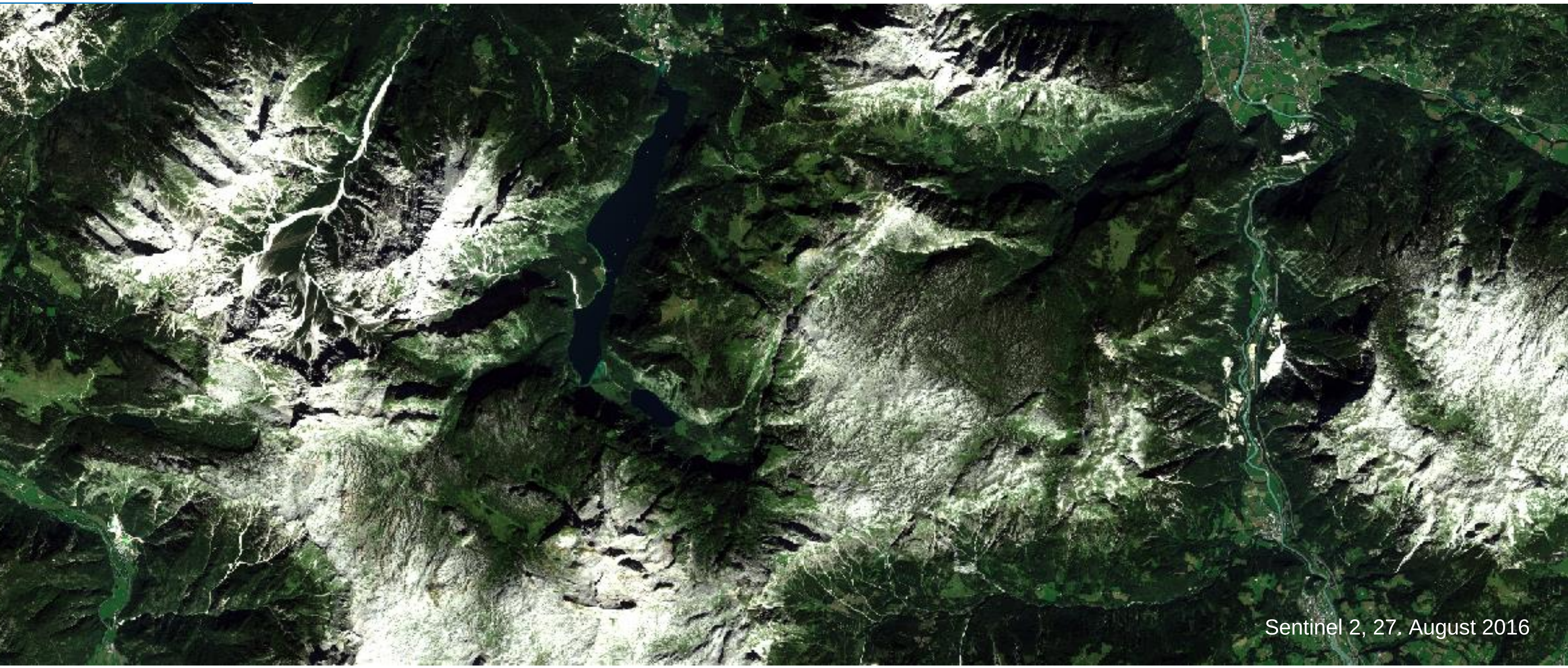
Deutscher Wetterdienst
Wetter und Klima aus einer Hand


Sentinel 2, 27. August 2016

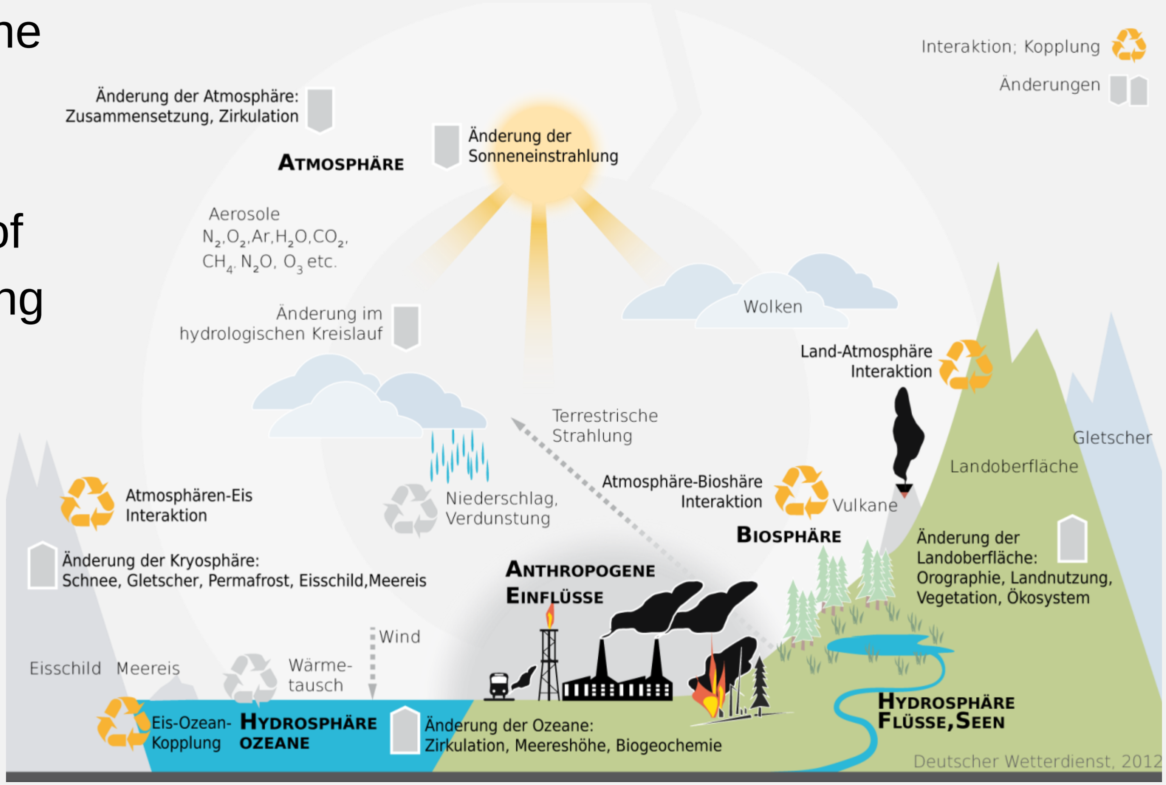
Satellite-based High Resolution Climate Data Records

Jörg Trentmann
Deutscher Wetterdienst

Overview

Why are we collecting climate data?

- To document the status of the climate system.
- To clasify the current state of the climate system in the long term climatology
- Climate Observations are coordinated by the Global Climate Observing System (GCOS).



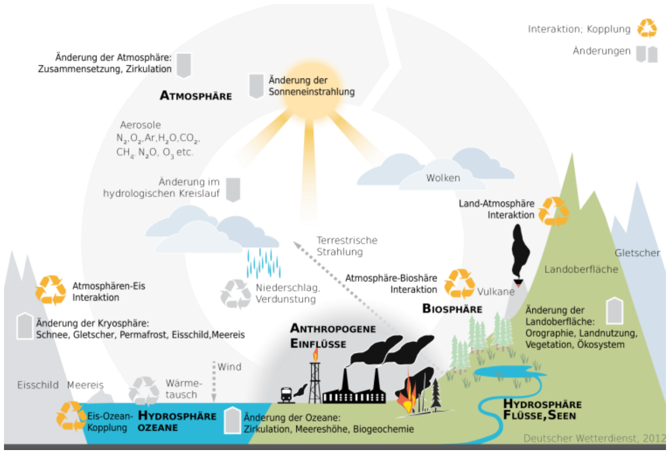
What are the requirements for climate monitoring?

- The climate can be characterized using long-term observations (> 30 years).
- Our observing sytem has to be able to monitor the variability / extremes of the climate system.
- Climate Monitoring requires homogeneous, climatological reference data and consistent, current measurements

Climate Monitoring: historic climate data + consistent, current measurements

Which parameters do we need to measure?

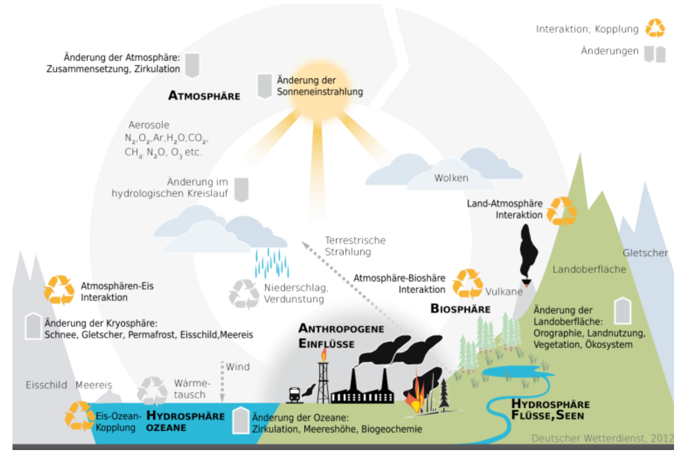
Measurement Domain	Essential Climate Variables (ECVs)
Atmospheric	Surface: Air temperature, Wind speed and direction, Water vapour, Pressure, Precipitation, Surface radiation budget. Upper-air: Temperature, Wind speed and direction, Water vapour, Cloud properties, Earth radiation budget, Lightning. Composition: Carbon Dioxide (CO_2), Methane (CH_4), Other long-lived greenhouse gases (GHGs), Ozone, Aerosol, Precursors for aerosol and ozone.
Oceanic	Physics: Temperature, Sea Surface Temperature, Salinity, Sea Surface Salinity, Currents, Surface Currents, Sea Level, Sea State, Sea Ice, Ocean Surface Stress , Ocean Surface heat Flux Biogeochemistry: Inorganic Carbon, Oxygen, Nutrients, Transient Tracers, Nitrous Oxide (N_2O), Ocean Colour Biology/ecosystems: Plankton, Marine habitat properties
Terrestrial	Hydrology: River discharge, Groundwater, Lakes, Soil Moisture Cryosphere: Snow, Glaciers, Ice sheets and Ice shelves, Permafrost Biosphere: Albedo, Land cover, Fraction of absorbed photosynthetically active radiation, Leaf area index, Above-ground biomass, Soil carbon, Fire, Land Surface Temperature Human use of natural resources: Water use, GHG fluxes



Essential Climate Variables (ECV) have been identified for the monitoring of the climate system (coordinated with GCOS).

Which parameters do we need to measure?

Measurement Domain	Essential Climate Variables (ECVs)
Atmospheric	incl. Temperature, Precipitation, Radiation, Wind, Clouds, Water Vapor, CO_2, CH_4 Composition: Carbon Dioxide (CO_2), Methane (CH_4), Other long-lived greenhouse gases (GHGs), Ozone, Aerosol, Precursors for aerosol and ozone.
Oceanic	Physics: Temperature, Sea Surface Temperature, Salinity, Sea Surface Salinity, … tress , … acers, incl. SST, Sea Level, Salinity, Ocean Currents, Carbon Biology/ecosystems: Plankton, Marine habitat properties
Terrestrial	incl. Soil Moisture, River Discharge, Snow, Glaciers, Albedo, Land Cover, LST, Fire … active … urface Human use of natural resources: Water use, GHG fluxes



Essential Climate Variables (ECV) have been identified for the monitoring of the climate system (coordinated with GCOS).

Which parameters can be observed from satellite?

➔ Some ECVs can be derived from satellite measurements

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	Precipitation, Earth radiation budget (including solar irradiance), Upper-air temperature, Wind speed and direction, Water vapour, Cloud properties, Carbon dioxide, Ozone, Aerosol properties.
Oceanic	Sea-surface temperature, Sea level, Sea ice, Ocean colour (for biological activity), Sea state*, Ocean salinity*.
Terrestrial	Lakes*, Snow cover, Glaciers and ice caps, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI)*, Biomass*, Fire disturbance, Soil moisture*.

Which parameters can be observed from satellite?

➔ Some ECVs can be derived from satellite measurements

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	Precipit… …e), Upper-air temperature, Wind s… …bon dioxide, Ozone, Aerosol propert…
Oceanic	Sea-surface temperature, Sea… …activity), Sea state*, Ocean salinity*.
Terrestrial	Lakes*, Snow cover, Glaciers … …getation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI)*, Biomas…

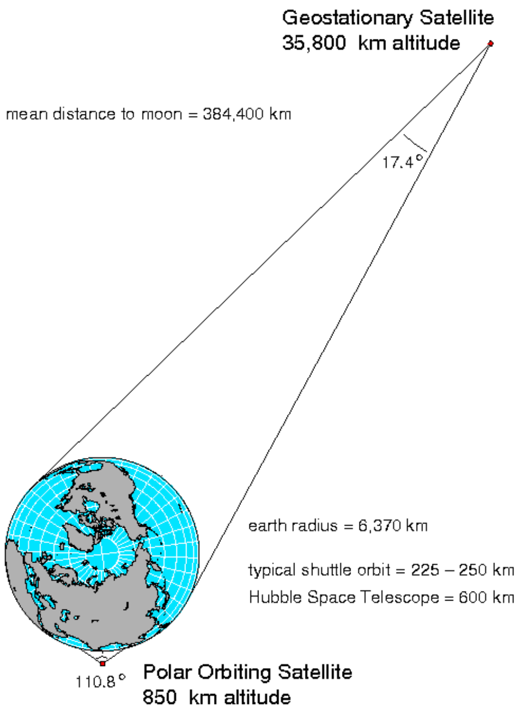
incl. ~~Temperature~~, (Precipitation), Radiation, (Wind), Clouds, Water Vapor CO_2, CH_4

incl. SST, Sea Level, Salinity, ~~Ocean Currents, Carbon~~

incl. Soil Moisture, ~~River Discharge,~~ Snow, Glaciers, Albedo, Land Cover, LST, Fire

Satellite Meteorology 101

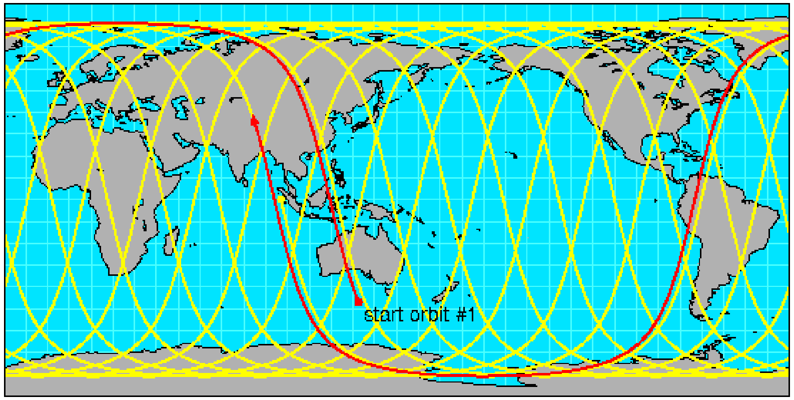
- **Geostationary Satellites**
  - Orbit: 36.900 km altitude; located at the equator
  - Examples: Meteosat First / Second Generation (MFG / MSG) / GOES / Himawari etc
  - Instruments: MVIRI / SEVIRI / GERB
  - Always observe the same part of the Earth surface (sometimes called ‚Disc‘); cannot observe polar region
  - Spatial resolution in the range of 1 km to 10 km
  - Sampling frequency between 5 min and 30 min



https://www.rap.ucar.edu/~djohnson/satellite/coverage.html

Satellite Meteorology 101

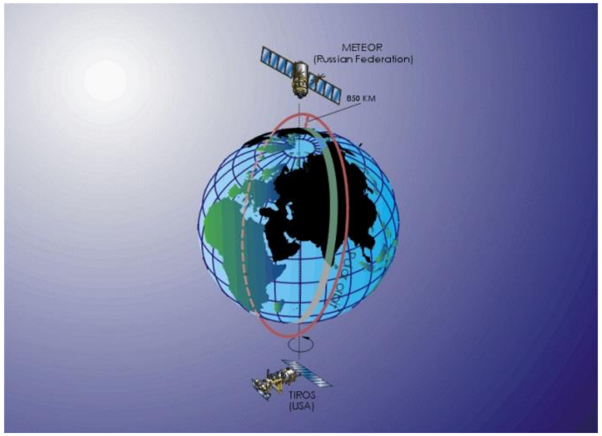
- **Polar-Orbiting Satellites**
  - Orbit: ca. 850 km
  - Cycle the Earth in about 1 day
  - Examples: Metop-A/B, NOAA-16, Terra / Aqua, DMSP, Sentinel-1/-2/-3
  - Instruments: AVHRR, SSM/I, CERES, MODIS
  - Spatial resolution in the range of 10 m to 50 km
  - Sampling frequency: 12-h up to weekly / monthly



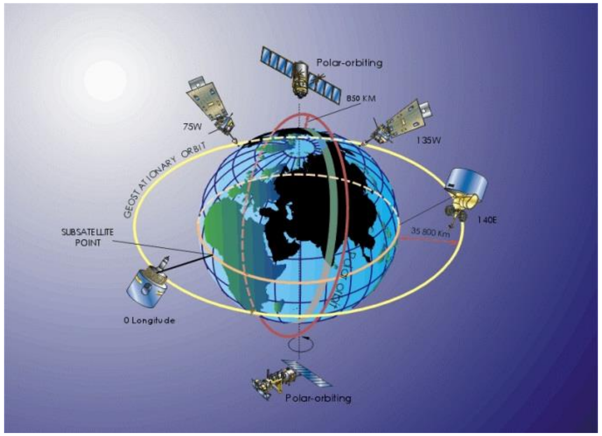
https://www.rap.ucar.edu/~djohnson/satellite/coverage.html

Evolution of the Earth-observing satellite system

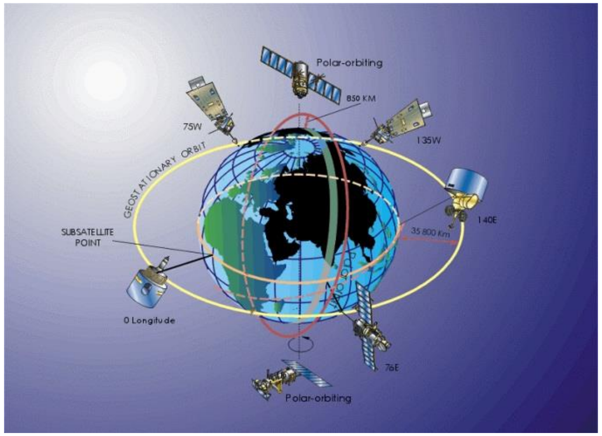
1961



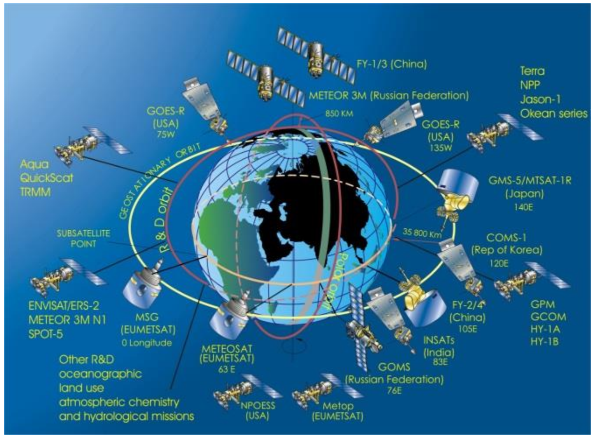
1978



1990



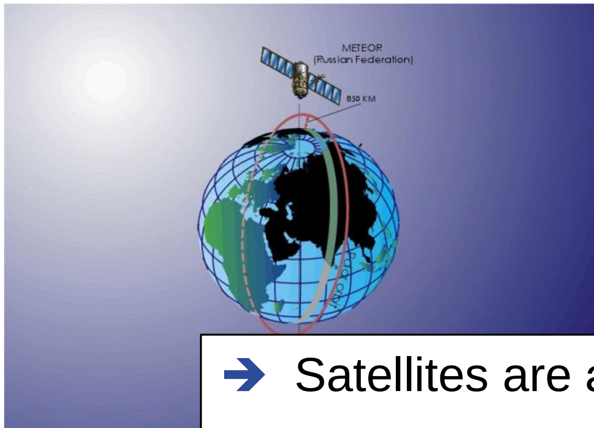
2009



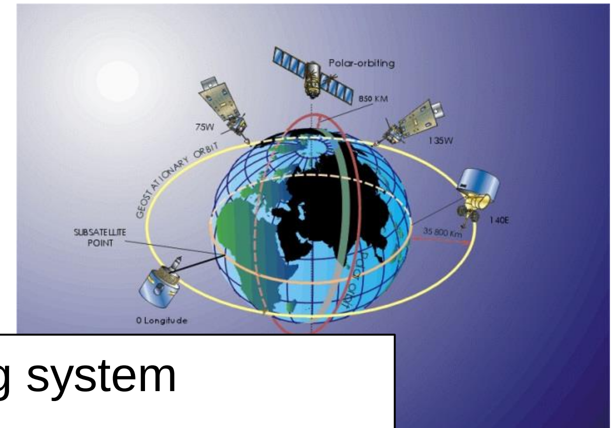
Courtesy WMO, B. Ryan

Evolution of the Earth-observing satellite system

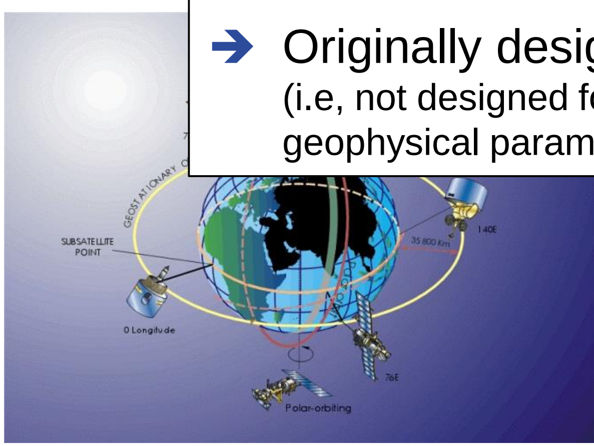
1961

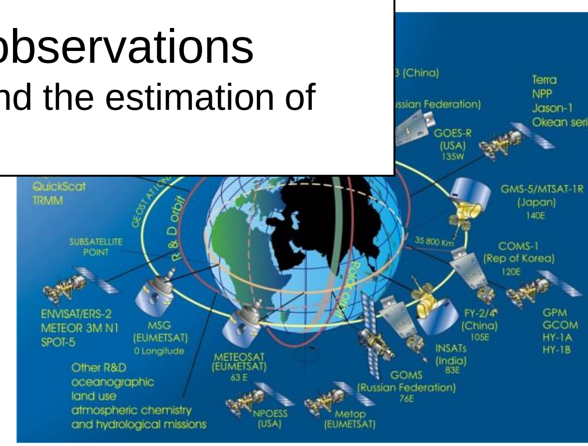


1978



1990



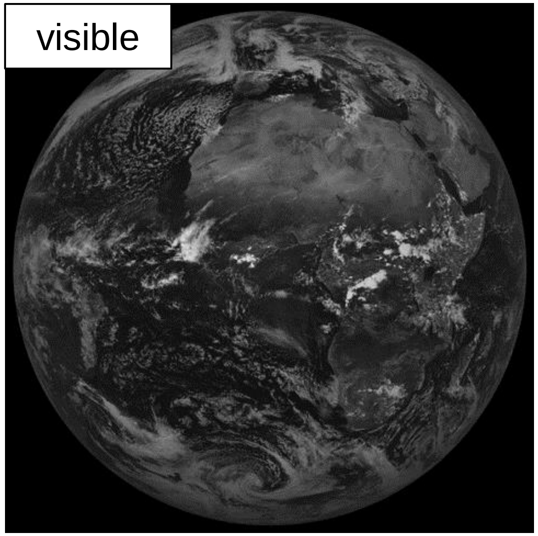


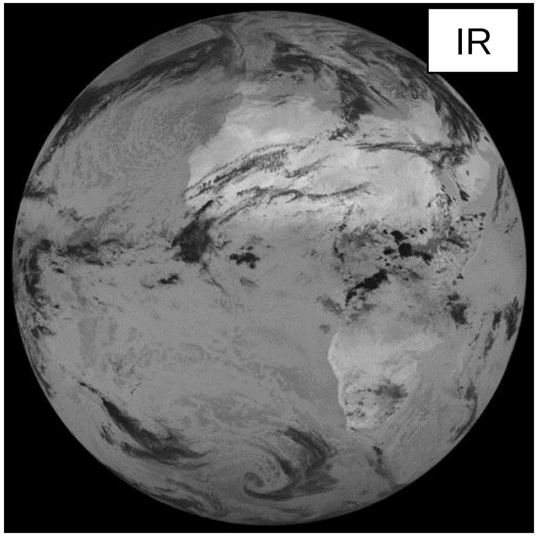
- ➔ Satellites are a ‚young‘ observing system
- ➔ Data available since early 1980s
- ➔ Originally designed for weather observations
  (i.e, not designed for climate monitoring and the estimation of geophysical parameters)

Courtesy WMO, B. Ryan

Satellite Meteorology 101

- Earth-observing satellite instruments measure the radiation reflected (solar) / emitted (thermal) from the Earth-Atmosphere System
- Typically the radiation is measured separately for certain wavelengths (spectrally resolved)
- If the measured radiation contains information on geophysical quantities, these can be derived from the satellite measurement using a „retrieval algorithm‘





Satellite Meteorology 101

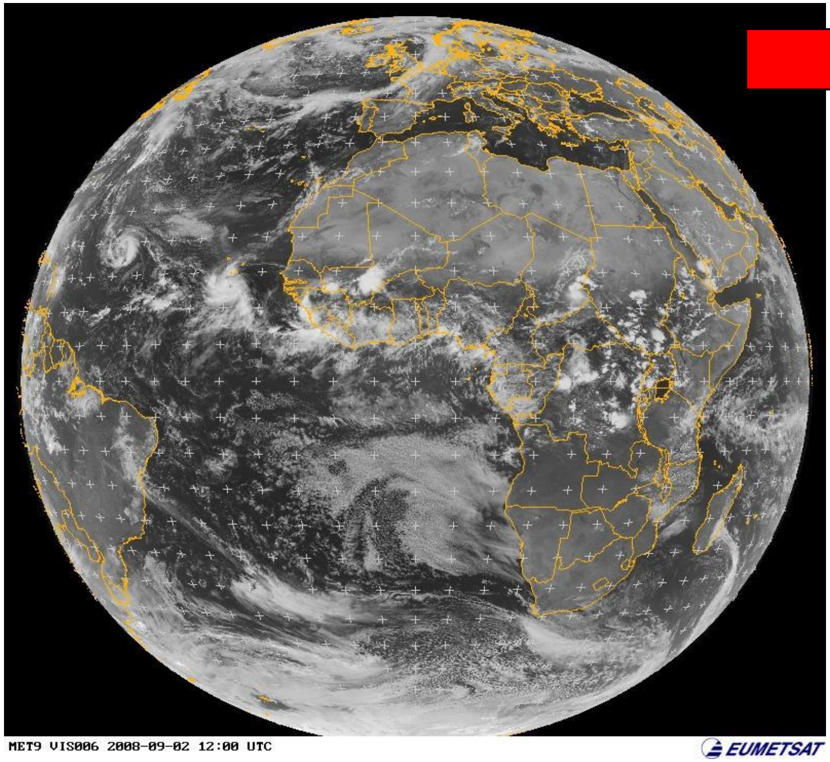
Different retrieval algorithms exist for each geophysical parameter

Example: **Surface Solar Incoming Radiation** (aka. global radiation, irradiance)

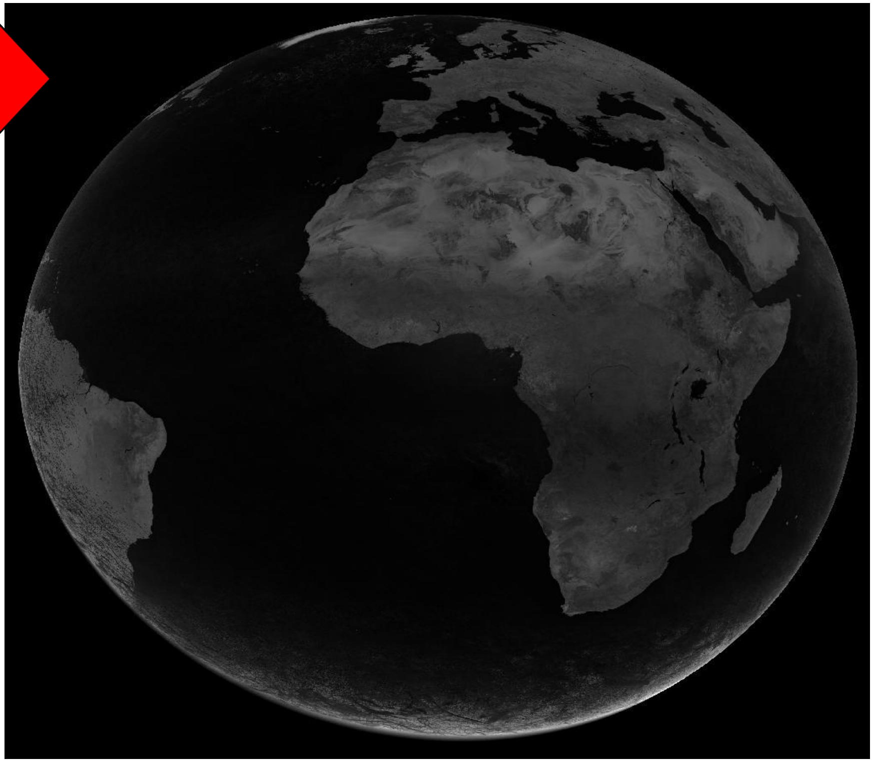
- ➔ ‚Physical‘:
  - ➔ Use derived cloud properties in radiative transfer model
- ➔ Statistical:
  - ➔ Relate „brightness“ of clouds to cloud optical thickness
- ➔ Look-up tables:
  - ➔ Relate measured upward fluxes to downward fluxes
- ➔ Optimal Estimation:
  - ➔ Determine the state of the atmosphere that matches best the (spectral) satellite measurement

The „Heliosat“ algorithm

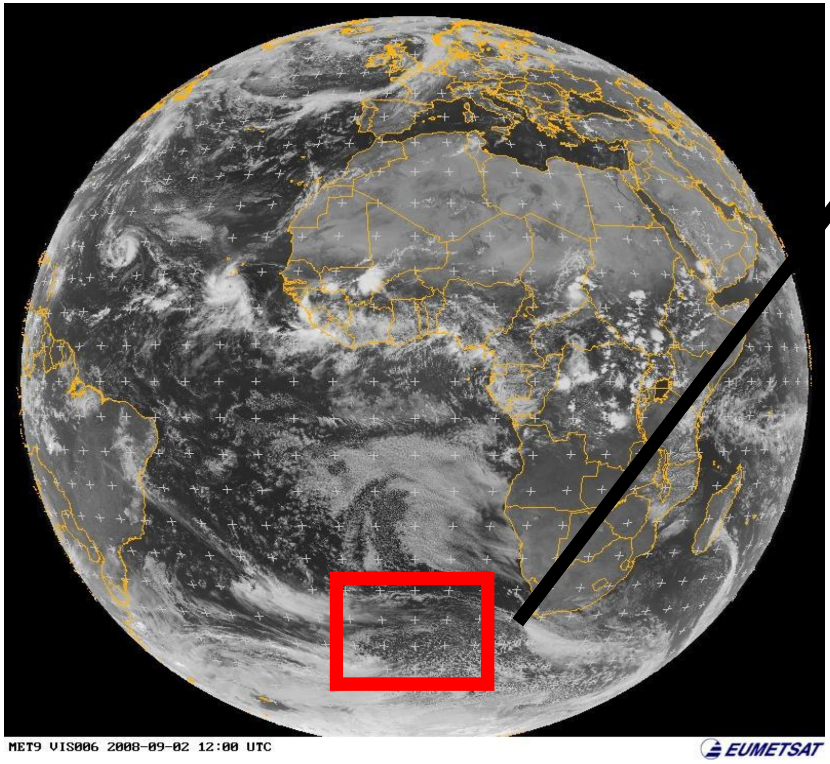
Reflectivity, 12 UTC, 2 Sept 2008



Min. Reflectivity, R_{min}, 12 UTC, Sept 2008

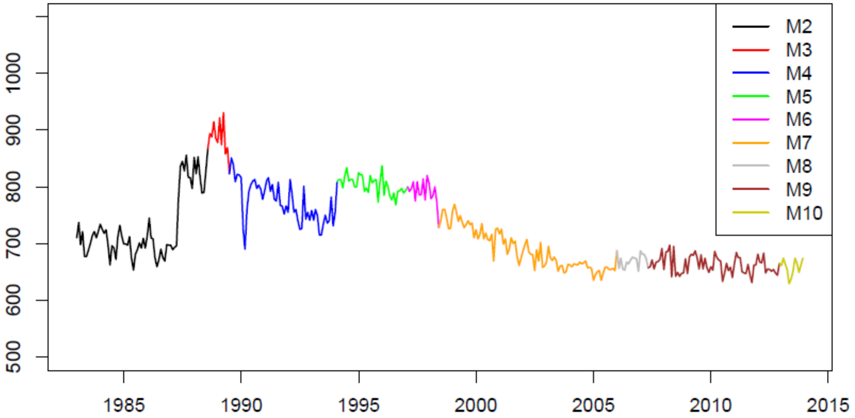


Reflectivity, 12 UTC, 2 Sept 2008



Max. reflectance, R_{max}:
95 % percentile of counts during one month in the reference region

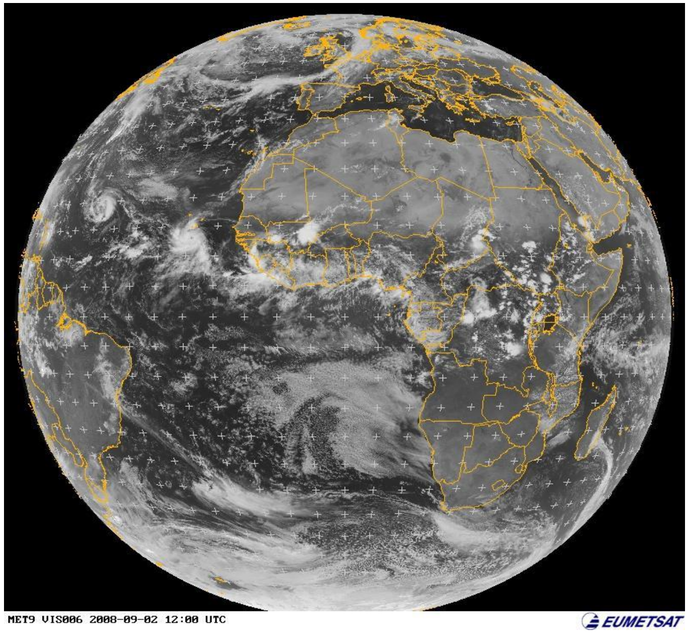
Temporal evolution of R_{max}



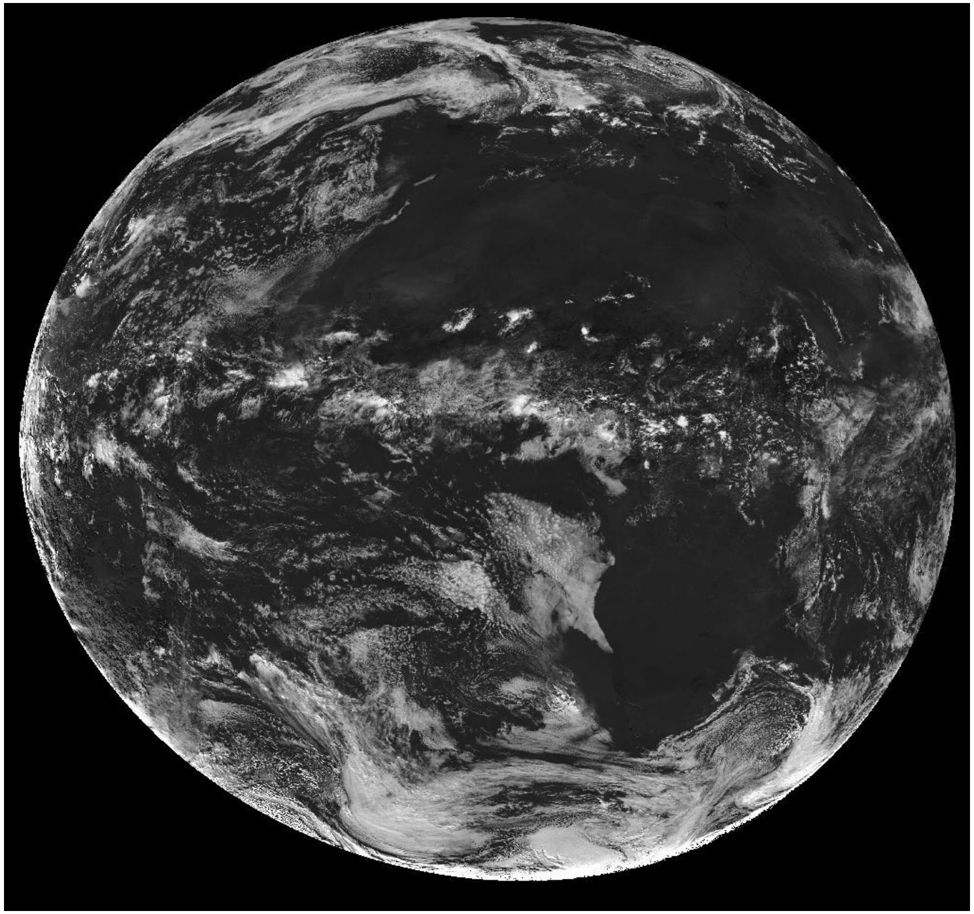
Self-calibration method, no intercalibration of different instruments required!

The Cloud Index n:

$$n = \frac{R - R_{min}}{R_{max} - R_{min}}$$



Cloud Index, 11 UTC, 1 July 2005



The Heliosat method

- The cloud index, n, is related to the clear-sky index, k:

$$k = 1 - n$$

- The clear-sky index, k, is the ratio between the all-sky surface irradiance, G, and the clear-sky surface irradiance, G_{clear}:

$$G = k * G_{clear}$$

- G_{clear} can be calculated by radiation transfer calculations assuming water vapor column, surface albedo, aerosol information

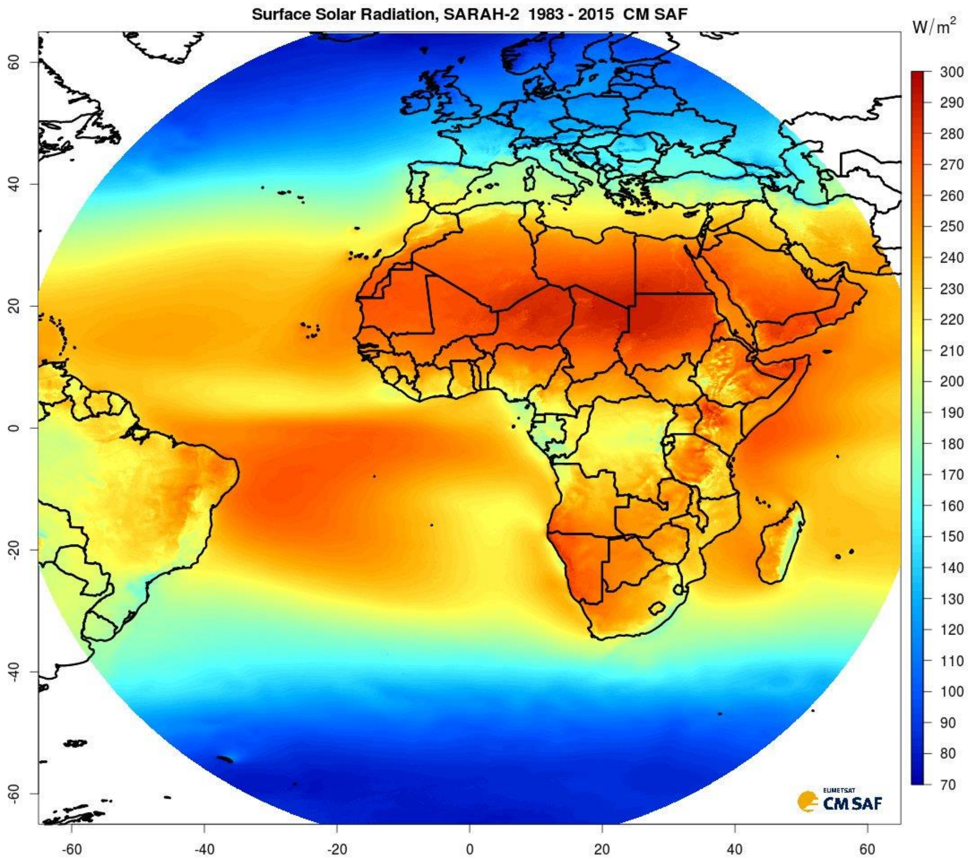
Temporal averaging

- Temporal averages (daily / monthly) are required for climatological analysis
- Additional uncertainty (in addition to the retrieval uncertainty) is introduced in the generation of the temporal average, due to the limited number of observations
- Higher uncertainty for data derived from polar-orbiting satellites; sometimes compensated by spatial averaging
- Example: **Surface Solar Incoming Radiation**
  - Clear-sky daily mean can be accurately derived from RTM calculations
  - Daily mean can be accurately estimated with:

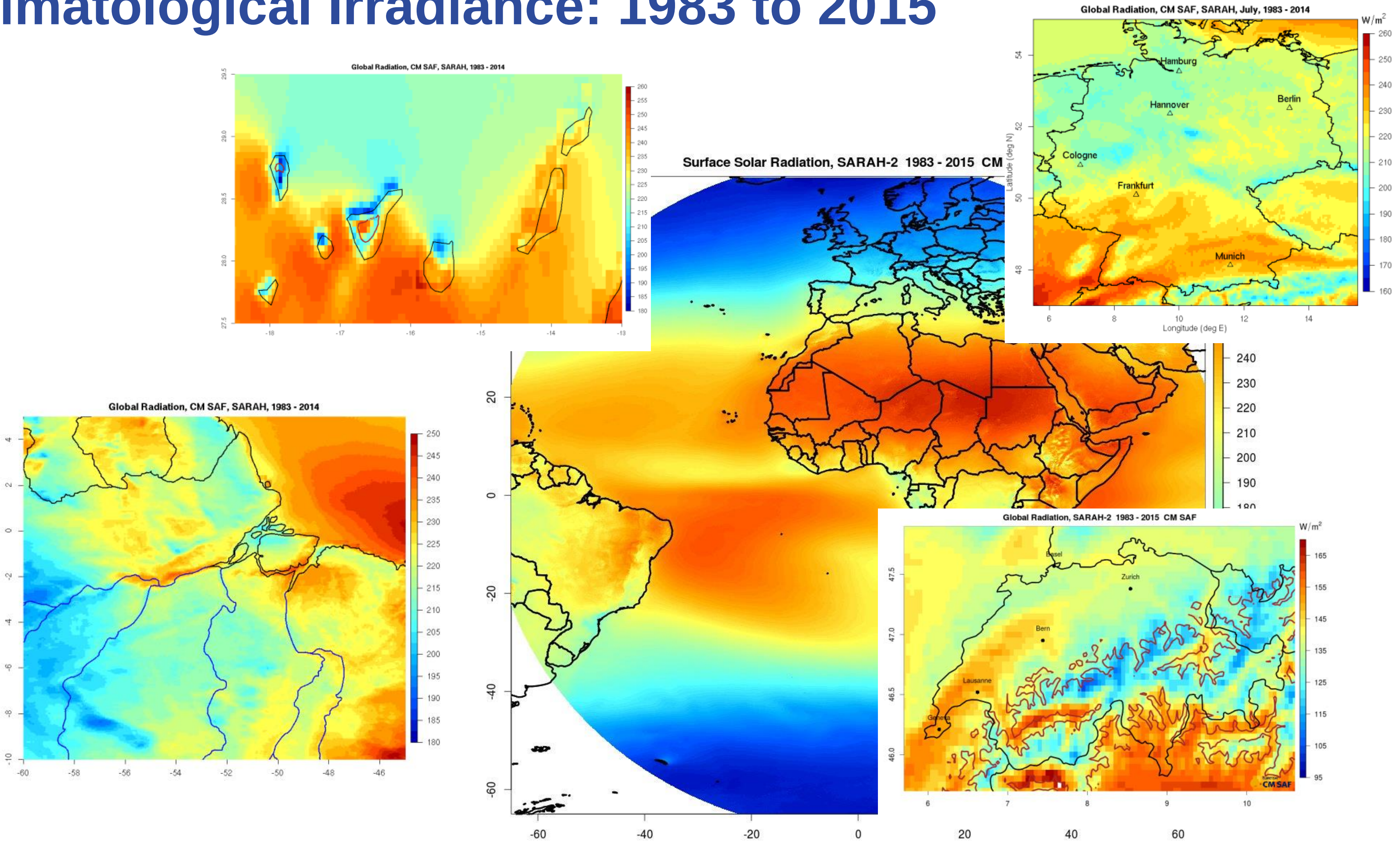
$$SIS_{DA} = SIS_{CLSDA} \frac{\sum_{i=1}^{n} SIS_i}{\sum_{i=1}^{n} SIS_{CLS\,i}}$$

  - Monthly means based on daily means

Climatological Irradiance: 1983 to 2015



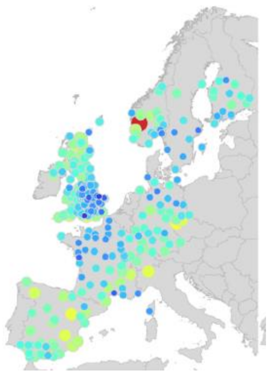
Climatological Irradiance: 1983 to 2015

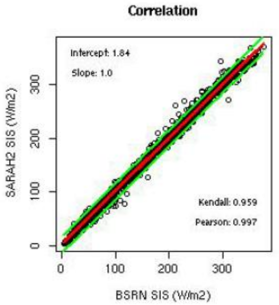


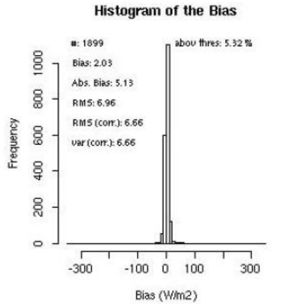
Validation of satellite-derived climate data

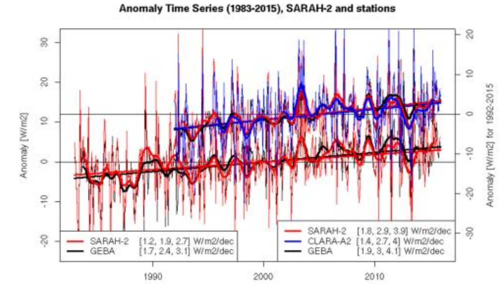
Reference data records required for the validation of the satellite-derived data

- ➔ Need to fulfill stronger requirements than the satellite data, i.e, in terms of accuracy, stability etc
- ➔ Should be available globally
- ➔ Often satellite data can only be compared to other satellite-based data: ‚Data evaluation'
- ➔ Example: **Surface Solar Incoming Radiation**
  - ➔ BSRN, GEBA data from global networks freely available
  - ➔ Data from national networks also exists, but not always available, and no common standard

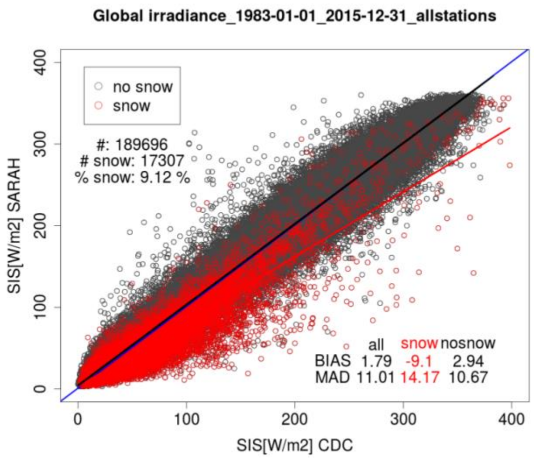








Reduced performance over snow

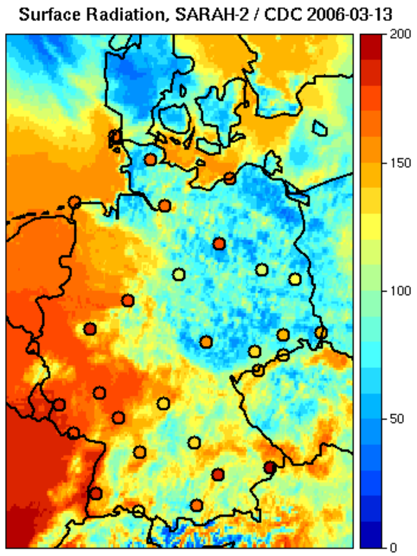


- Daily surface radiation:

  Very good comparison with surface measurements

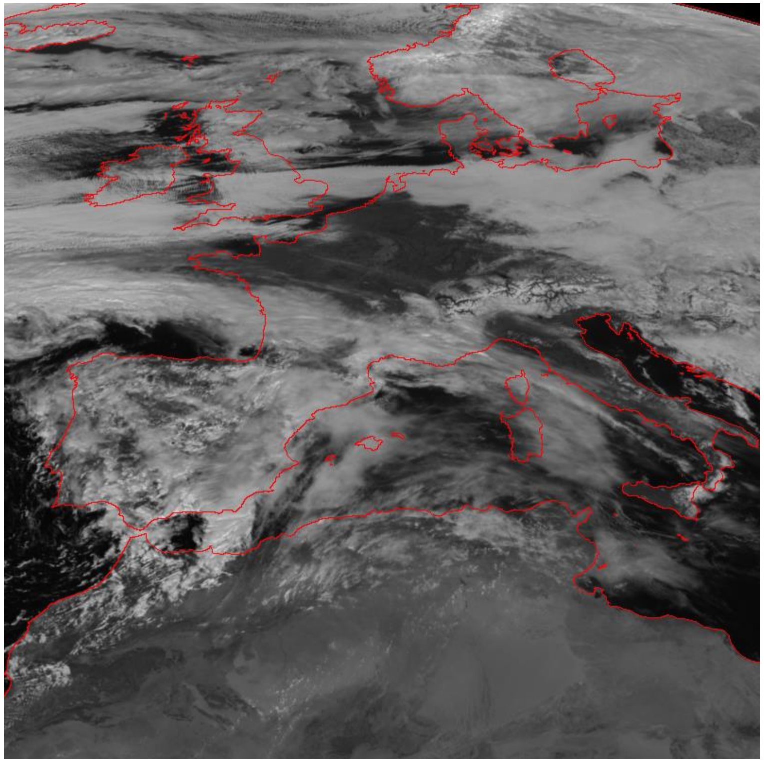
- Degraded performance over snow-covered surfaces

- Snow coverage appears as thick clouds, resulting in an under-estimation of surface radiation



Improved retrieval over snow

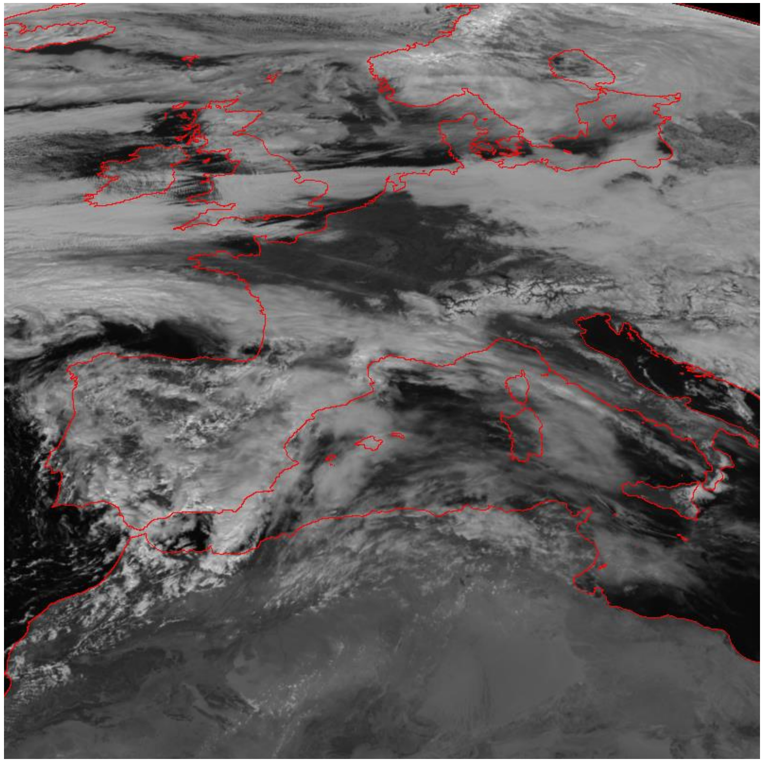
- Difficult separation between cloud and snow for the historic data: only 3 spectral channels available
- Concept:
  Separation between Cloud and Snow based on ‚motion'
- Modern programming tools (OpenCV: ‚optical flow') allow the processing of long time series
- Identification of snow coverage allows to adjust the cloud index



18 March 2006, 1200 UTC

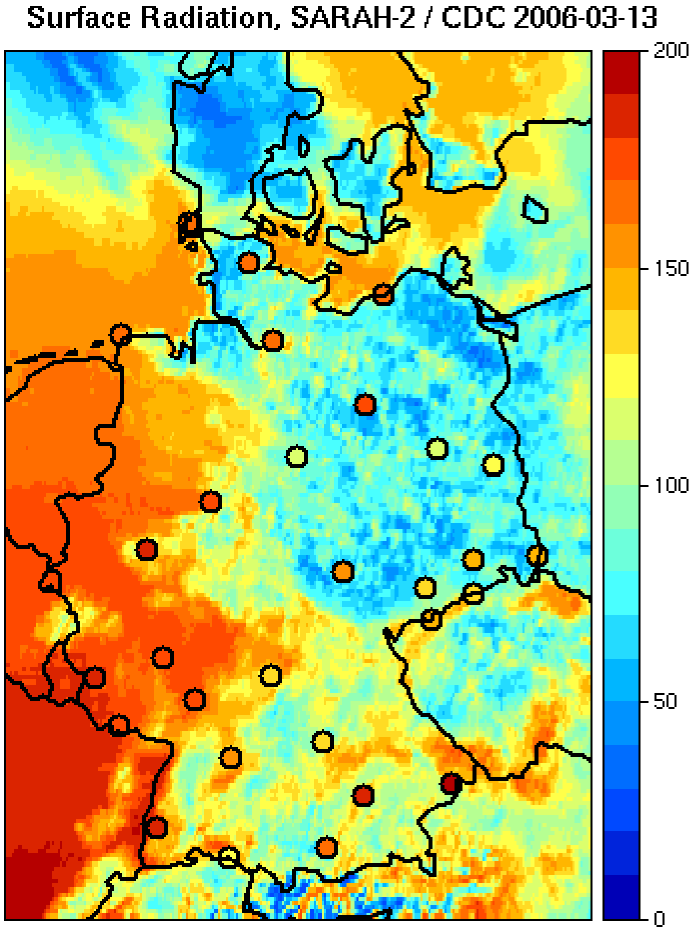
Improved retrieval over snow

- Difficult separation between cloud and snow for the historic data: only 3 spectral channels available
- Concept:
  Separation between Cloud and Snow based on ‚motion'
- Modern programming tools (OpenCV: ‚optical flow') allow the processing of long time series
- Identification of snow coverage allows to adjust the cloud index

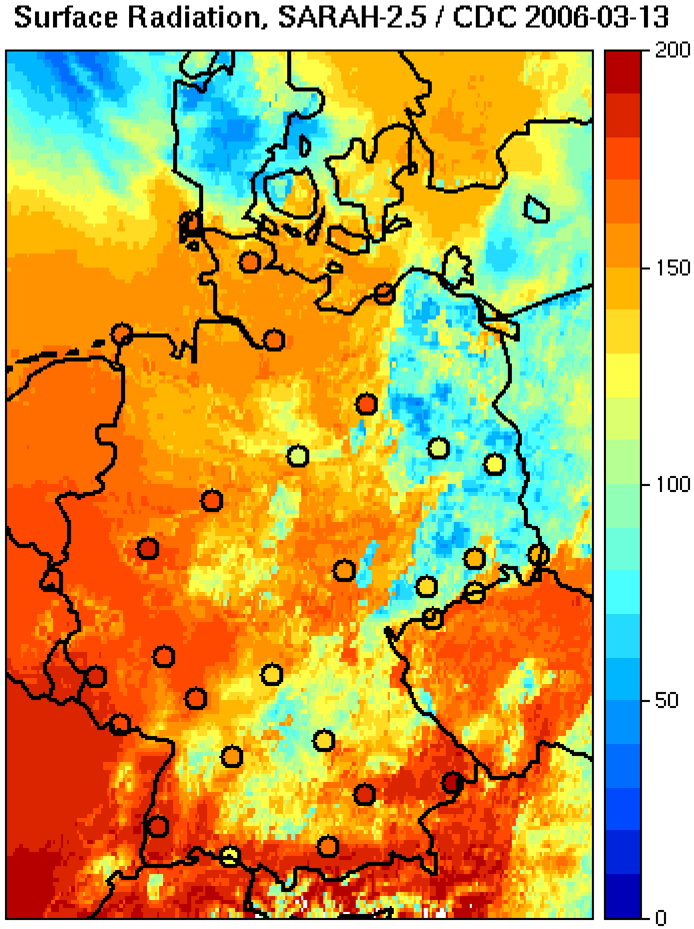


18 March 2006, 1230 UTC

Original

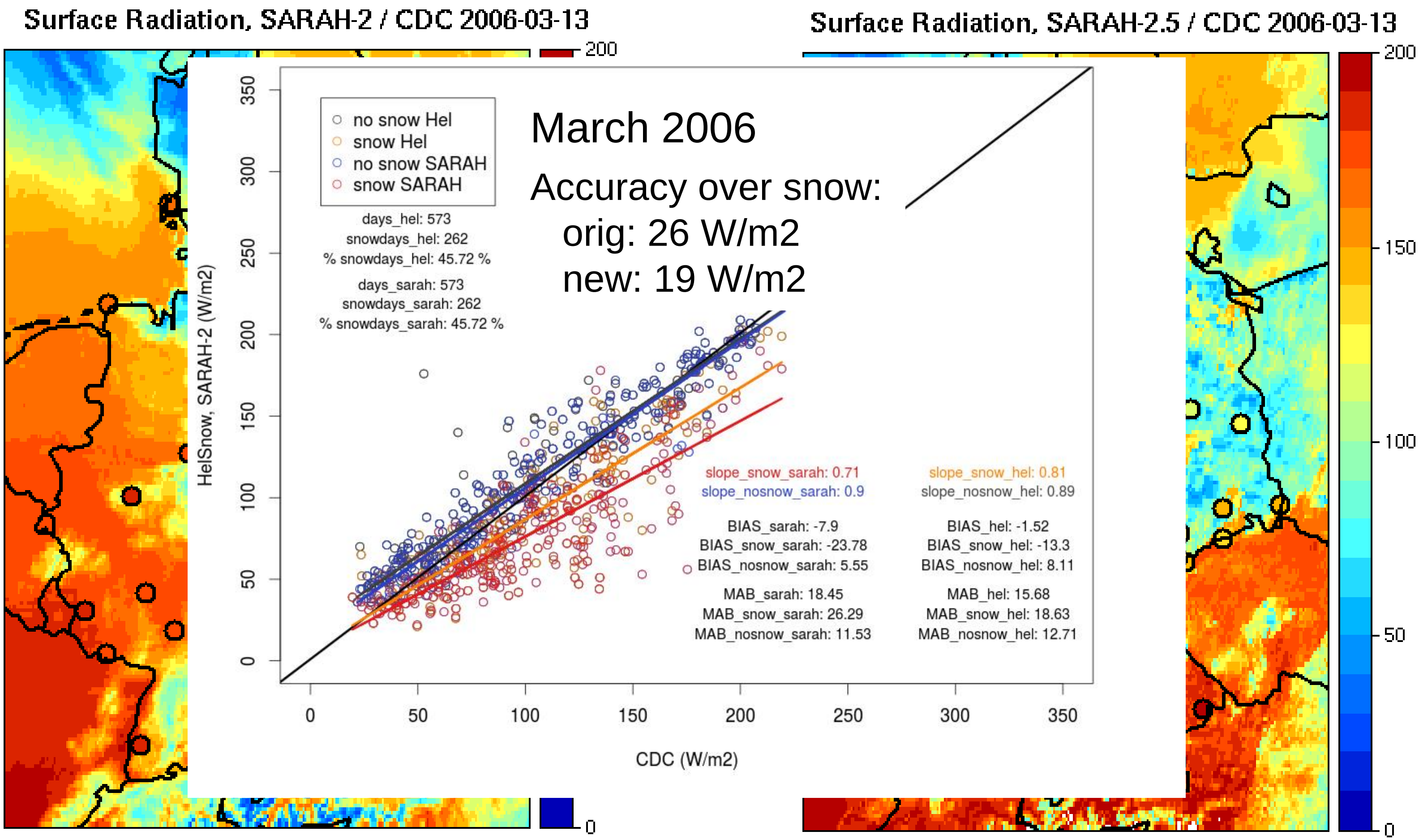


New



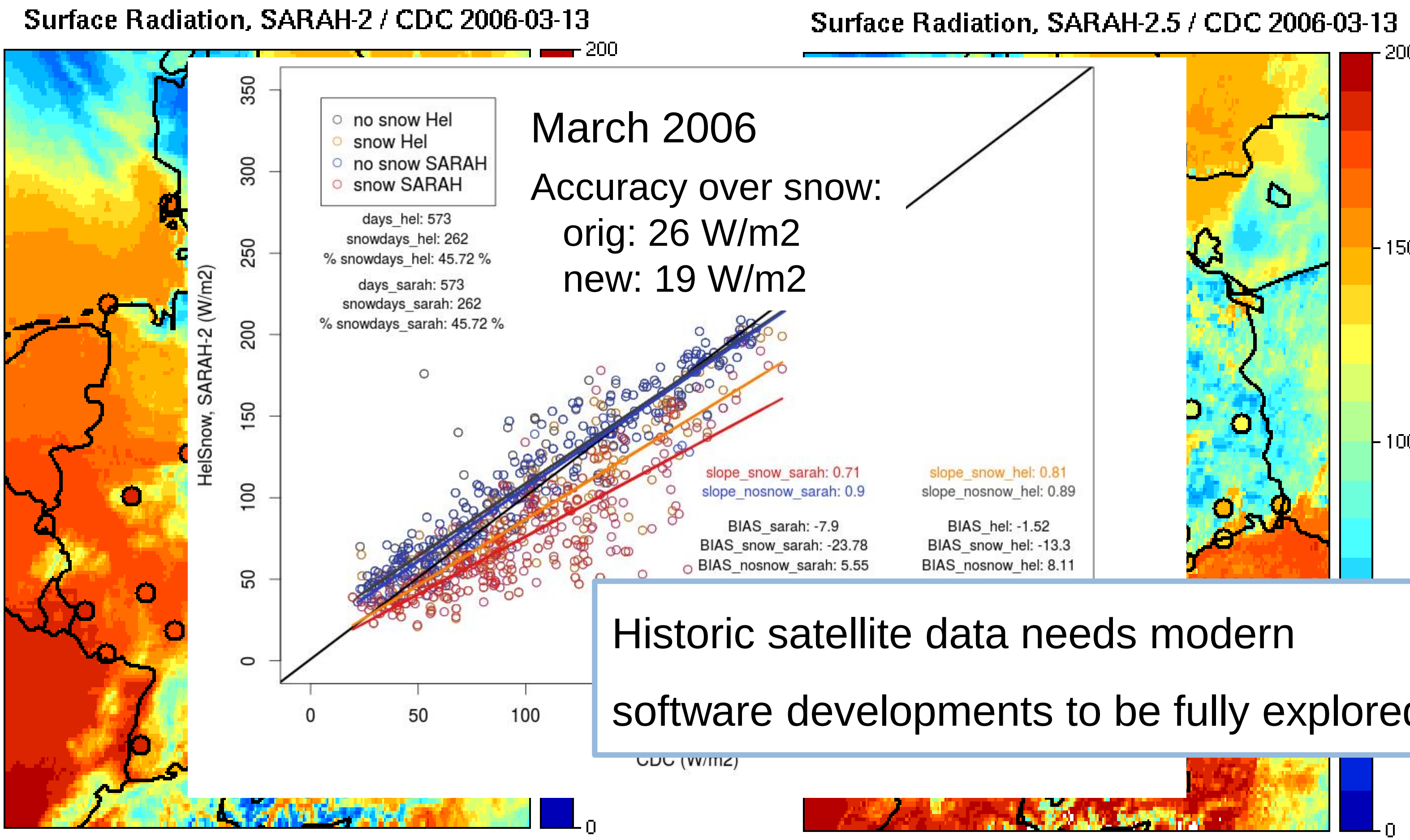
Original

New



Original

New



March 2006

Accuracy over snow:
orig: 26 W/m2
new: 19 W/m2

Historic satellite data needs modern software developments to be fully explored!

Where can you get satellite-based climate data?

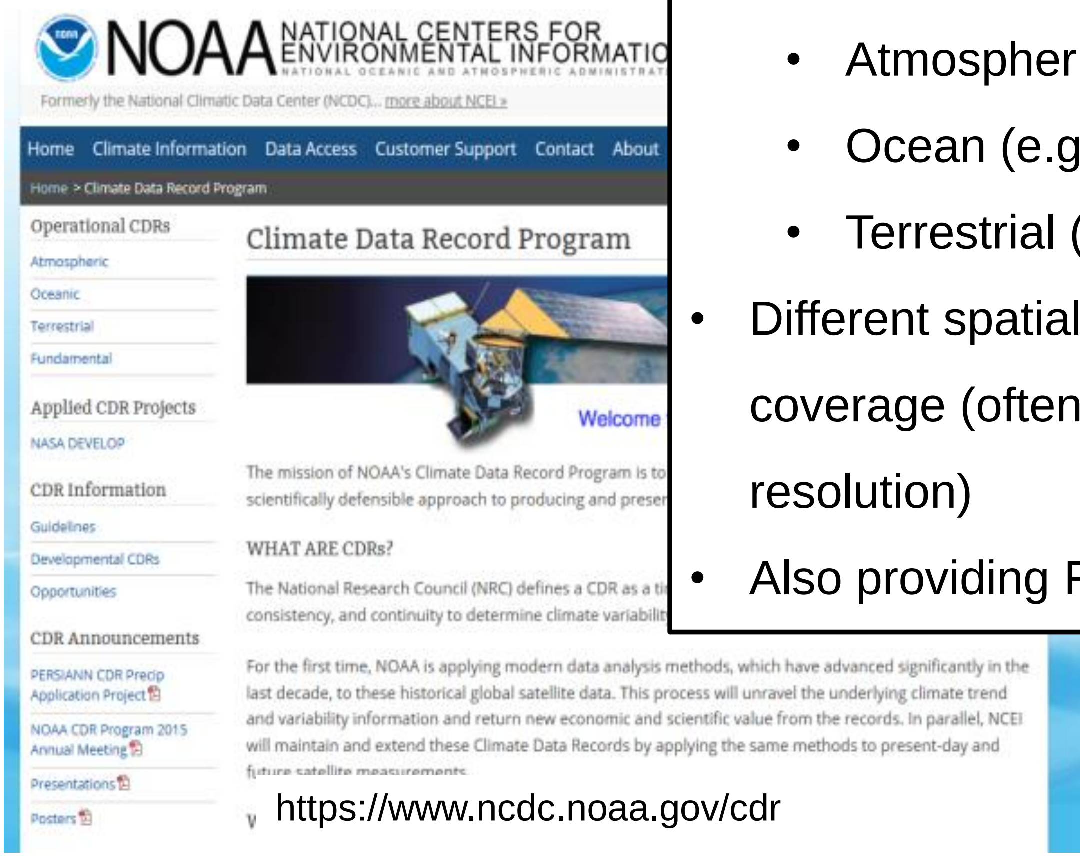
https://www.ncdc.noaa.gov/cdr

http://www.cmsaf.eu

http://cci.esa.int/

- All data are available at no charge
- Mostly in netcdf-format following the CF-standard

NOAA NCDC



https://www.ncdc.noaa.gov/cdr

- Focus on GCOS ECVs:
  - Atmospheric (e.g., ISCCP, GPCP)
  - Ocean (e.g., SST, Sea Ice)
  - Terrestrial (e.g., snow coverage)
- Different spatial / temporal resolutions + coverage (often global coverage, moderate resolution)
- Also providing FCDRs (e.g., AVHRR)

ESA Climate Change Initiative (CCI)

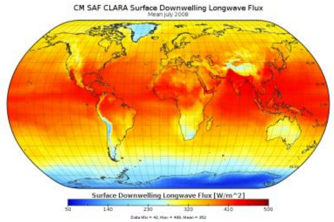
- Organized in 14 different projects, e.g., clouds, glaciers, land use, aerosol etc.
- Focus on historic climate data records
- New projects (ECVs) are about to be starting, no continuation of the current projects

EUMETSAT CM SAF

CM SAF
Climate Monitoring

- ➔ EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF)
  - ➔ Focusing on Energy and Water cycle
  - ➔ Long-term data records > 30 years
  - ➔ Operational data (timeliness about 1 week)
  - ➔ Radiation, clouds and their properties, albedo, land surface temperature, water vapor, precipitation
  - ➔ Sustained funding via EUMETSAT satellite program

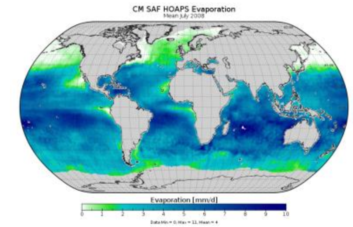
CLARA



- **Variables**
  - Cloud properties
  - Surface albedo
  - Radiation
- **Resolution**
  - 0.25° × 0.25°
  - daily-, pentad-, monthly
- **Coverage**
  - global
  - 1982 to 2015

DOI:10.5676/EUM_SAF_CM/CLARA_AVHRR/V002

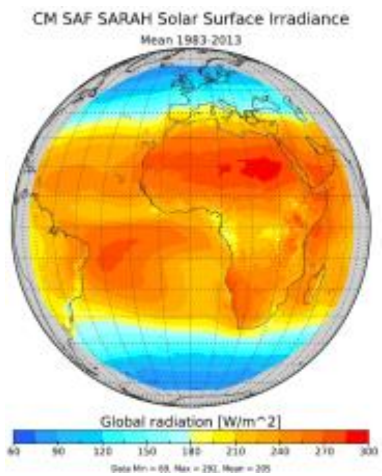
HOAPS



- **Variables**
  - Water Vapor
  - Precipitation, evaporation
  - Latent heat flux
  - Fresh water flux
- **Resolution**
  - 0.5° × 0.5°
  - 6-hourly-, monthly means
- **Coverage**
  - global ice free ocean
  - 1987 to 2015

DOI:10.5676/EUM_SAF_CM/HOAPS/V002

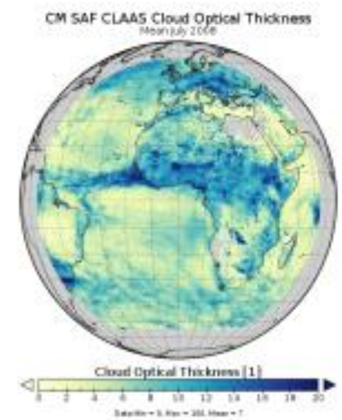
SARAH



- **Variables**
  - Global radiation
  - Surface direct irradiance
  - Sunshine duration
- **Resolution**
  - 0.05° × 0.05°
  - 30 min instantaneous, daily-, monthly means
- **Coverage**
  - Meteosat disk
  - 1983 to 2015

DOI:10.5676/EUM_SAF_CM/SARAH/V002

CLAAS

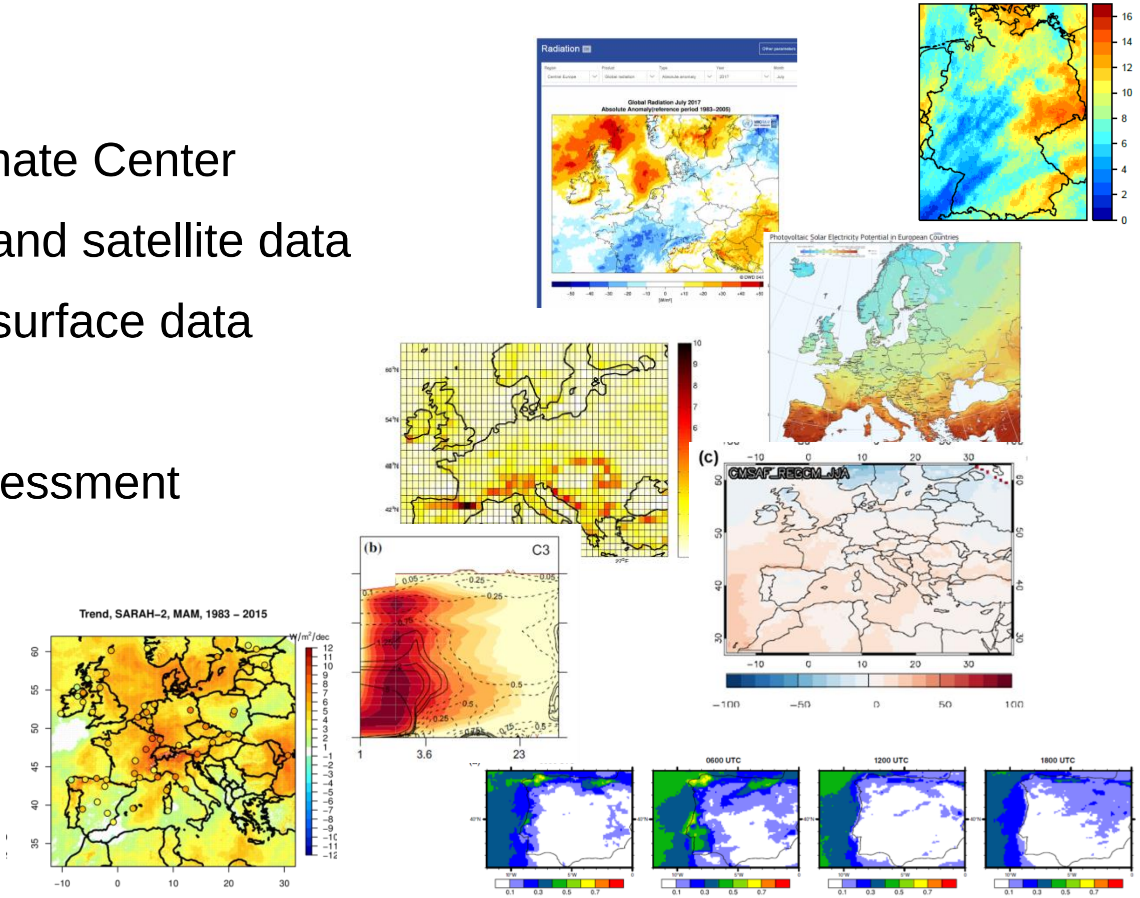


- **Variables**
  - Cloud coverage
  - Cloud properties
- **Resolution**
  - up to 0.05° × 0.05°
  - 30 min instantaneous, daily-, monthly means
- **Coverage**
  - Meteosat disk
  - 2004 to 2015

DOI:10.5676/EUM_SAF_CM/CLAAS/V002

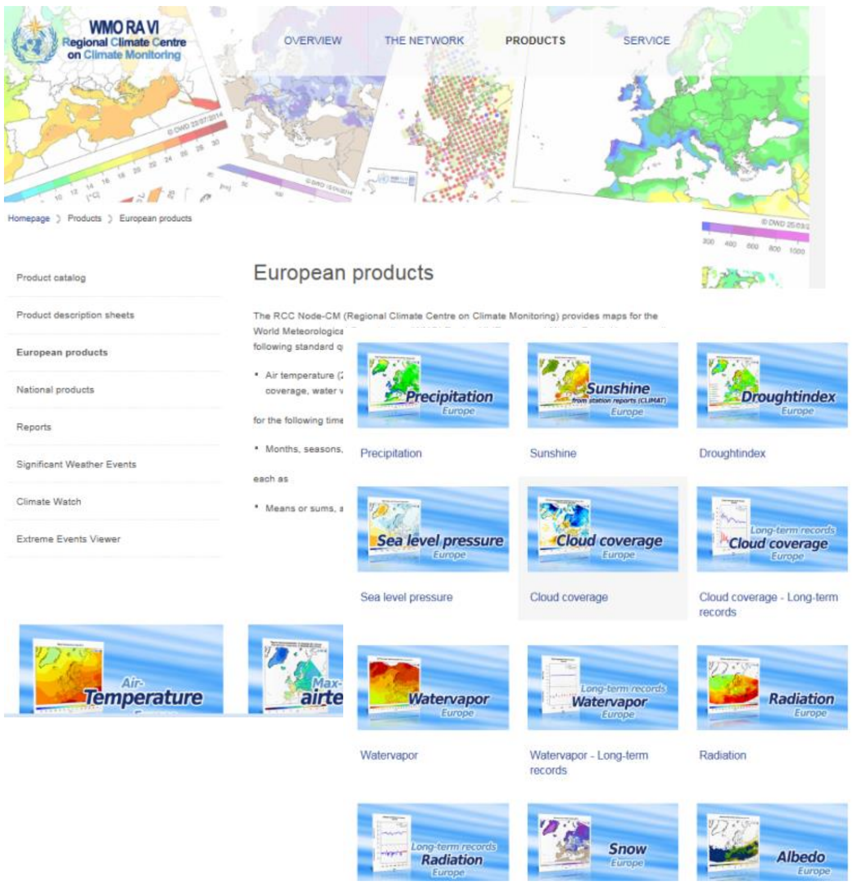
Selected Applications
High-Resolution Satellite Climate Data

- Climate Monitoring
  - WMO Regional Climate Center
  - Merging of surface and satellite data
  - Representativity of surface data
- Model Evaluation
  - Regional Model assessment
  - Process studies
- Climate Analysis
  - Trend Analysis



WMO Regional Climate Centre (RCC)

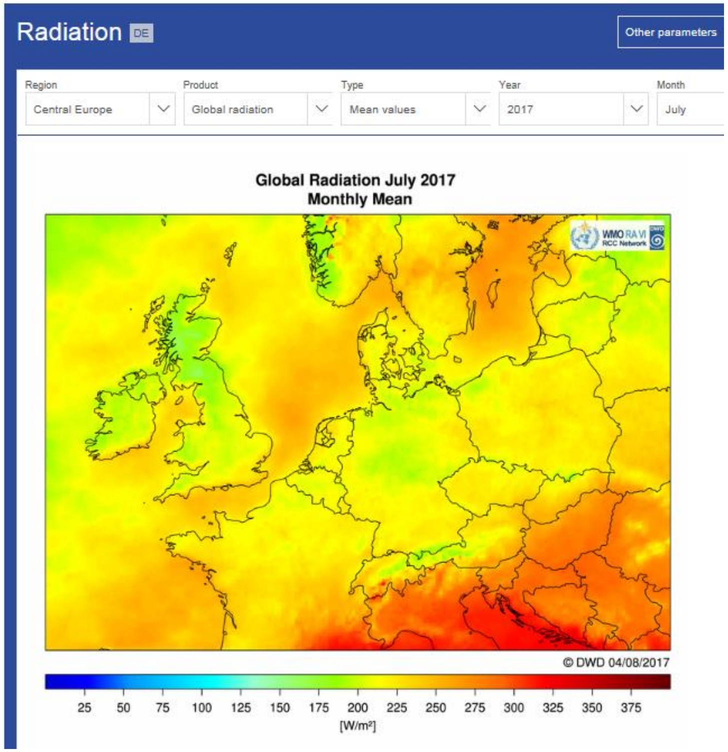
http://rcccm.dwd.de

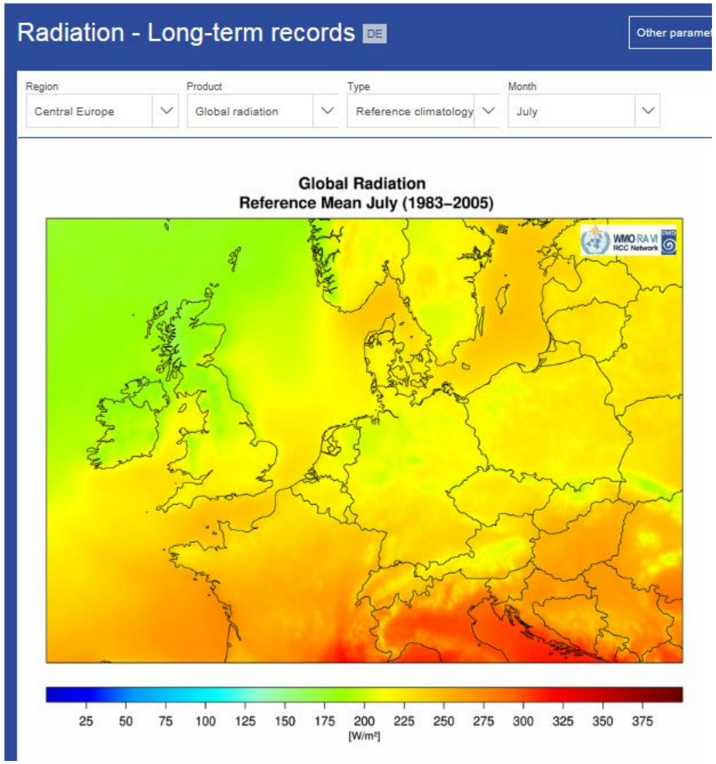


- ➔ Provides maps of climatological relevant parameters for the WMO Region VI
- ➔ Many products based on surface-based records
  - ➔ Data quality / availability of surface data is different between countries
- ➔ Satellite data offer spatially consistent data

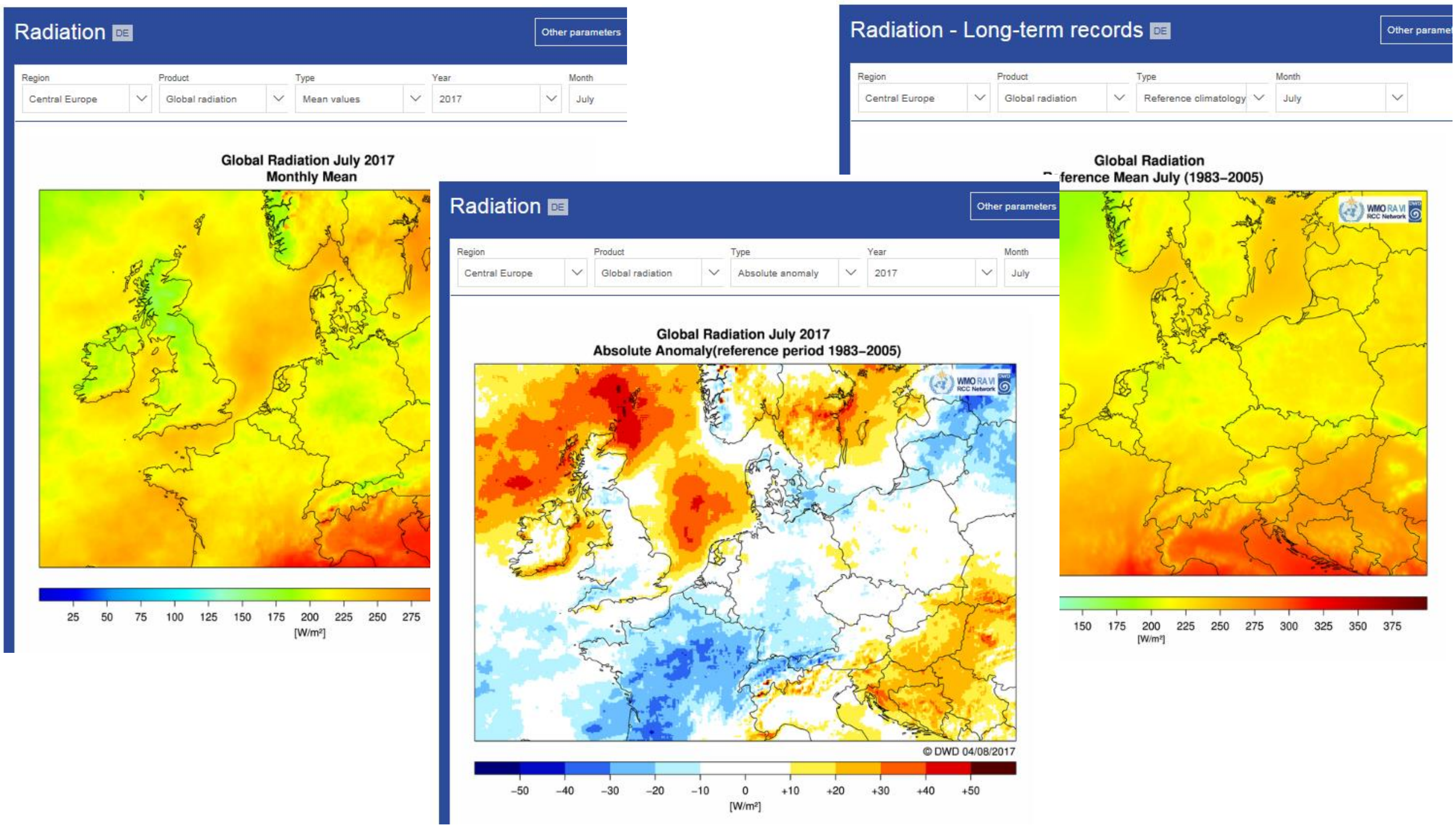
Obregón, A. et al., (2014), *Advances in Science and Research*, *11*, 25-33

Example: Surface Radiation, July 2017

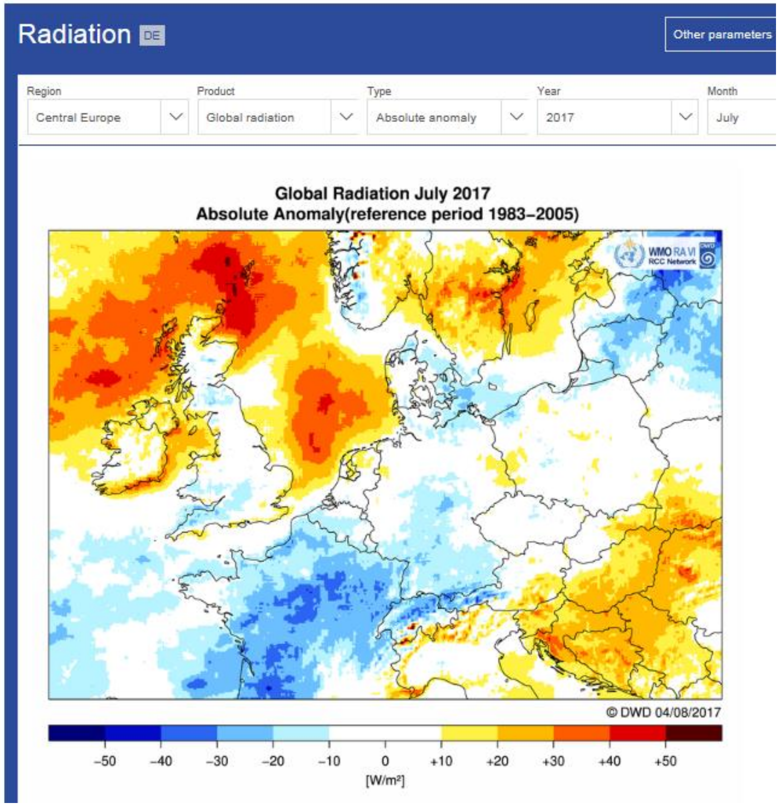


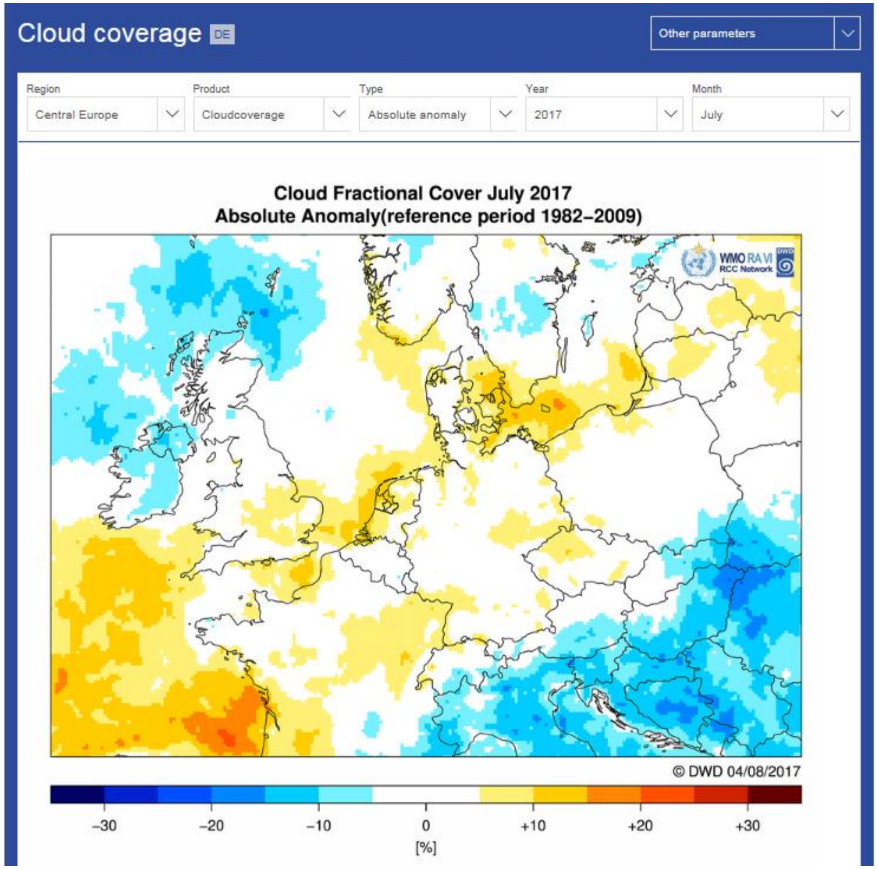


Example: Surface Radiation, July 2017

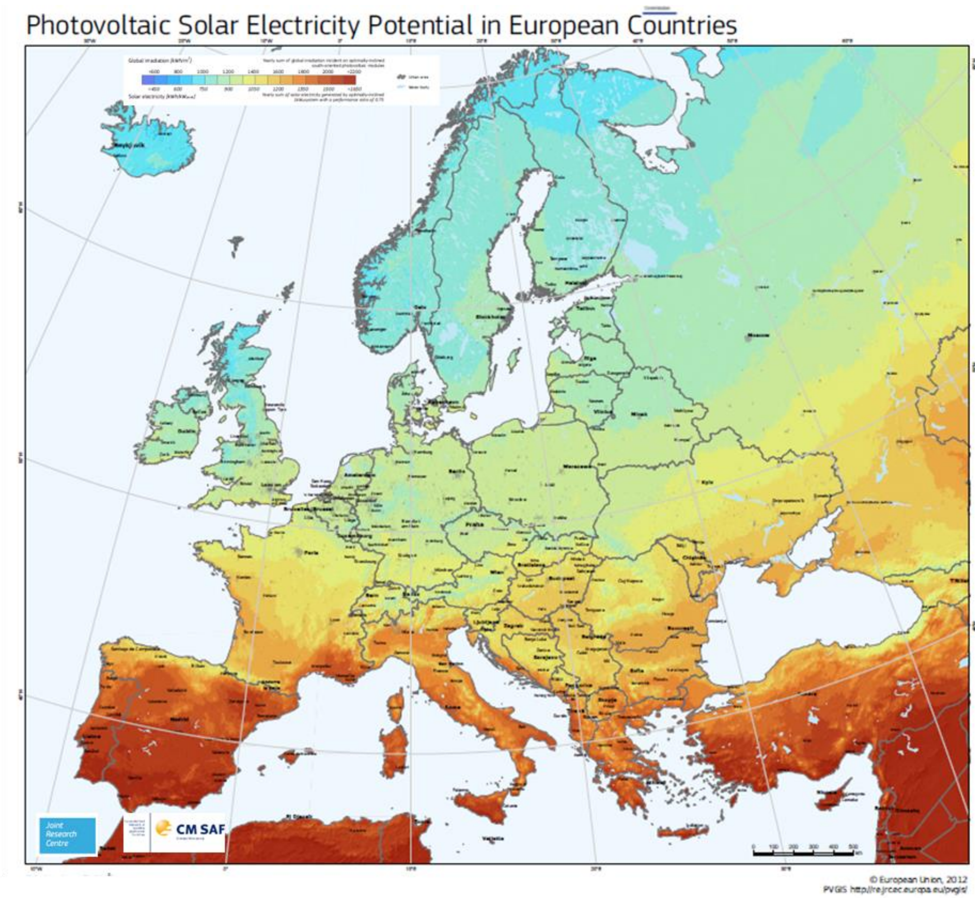


Example: July 2017





Solar Energy Potential: JRC PV GIS



- ➔ European photovoltaic potential estimated based on hourly satellite-based climatological surface radiation.
- ➔ Similarly the current power production can be monitored.

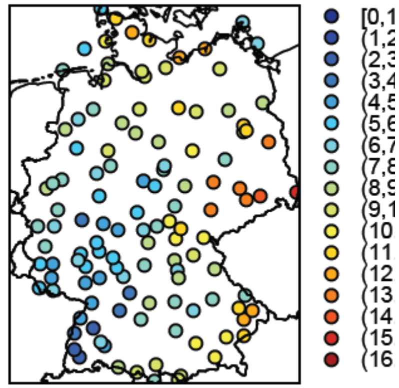
Huld, T. et al., (2012), Solar Energy, 86(6), 1803-1815

Merging of satellite- and surface-based data

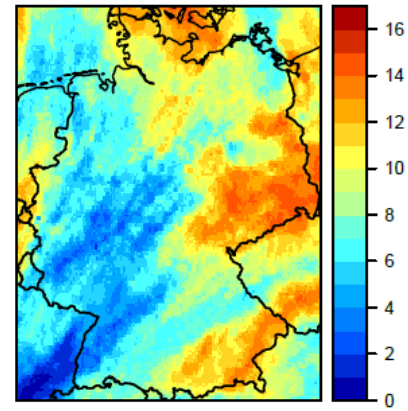
- The combination of high-resolution satellite data (spatial information) and surface measurements (accuracy) provides excellent means to determine climate parameters

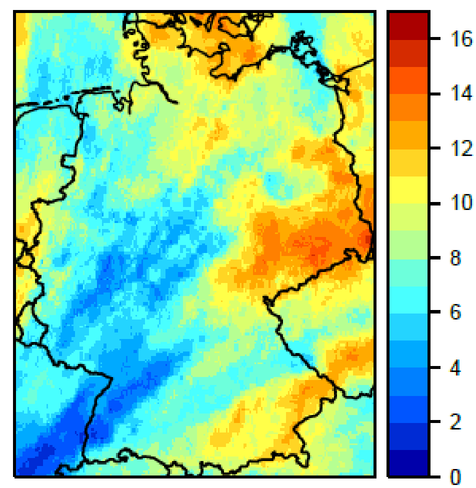
- Different methods for the merging have been applied / further research needed.

Surface data



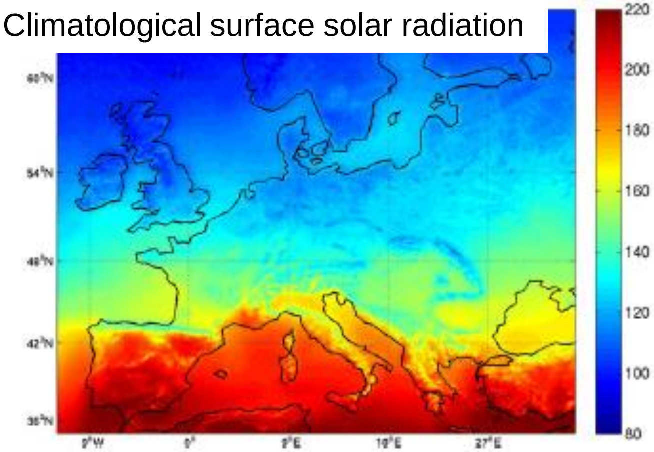
Satellite data



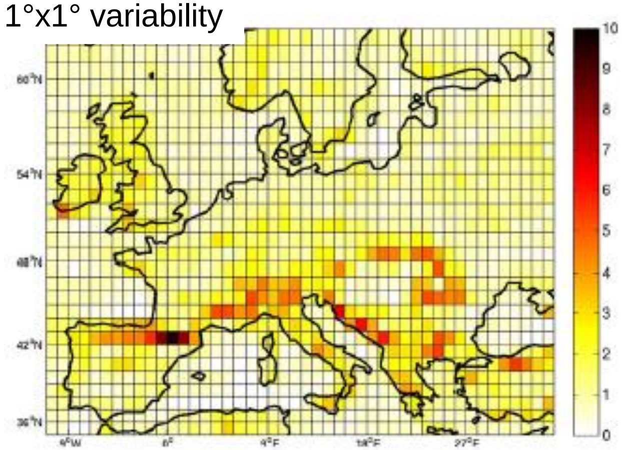


Representativity of locations / surface data

Climatological surface solar radiation



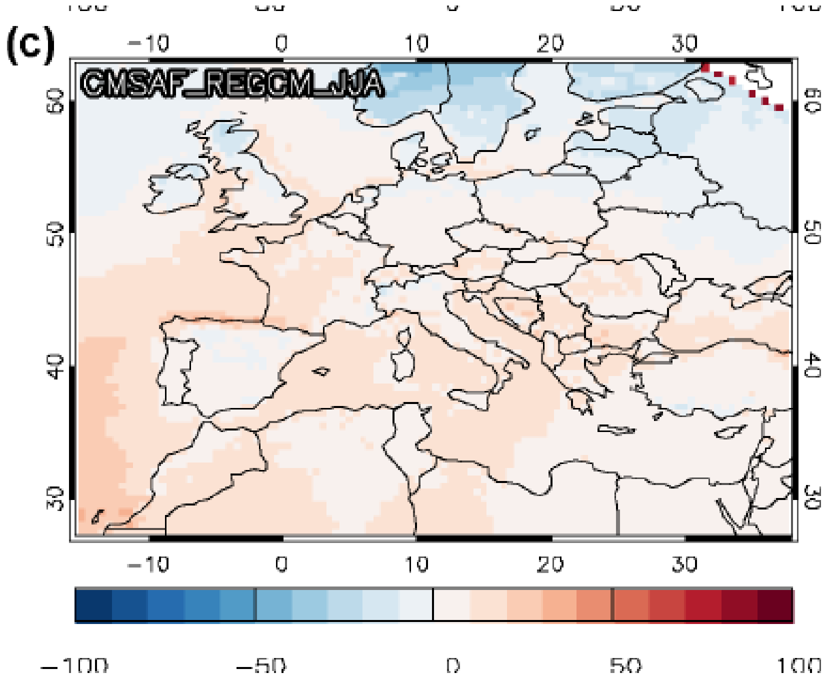
1°x1° variability



- ➔ High resolution satellite-based climate data can be used to estimate the spatial variability on the coarser scale
- ➔ Information relevant for station deployment, model evaluation etc.
- ➔ Also useful for quality control of surface data

Hakuba, M. Z. et al., (2013), *Journal of Geophysical Research*, *118*(15), 8585-8597

Regional Climate Model Evaluation



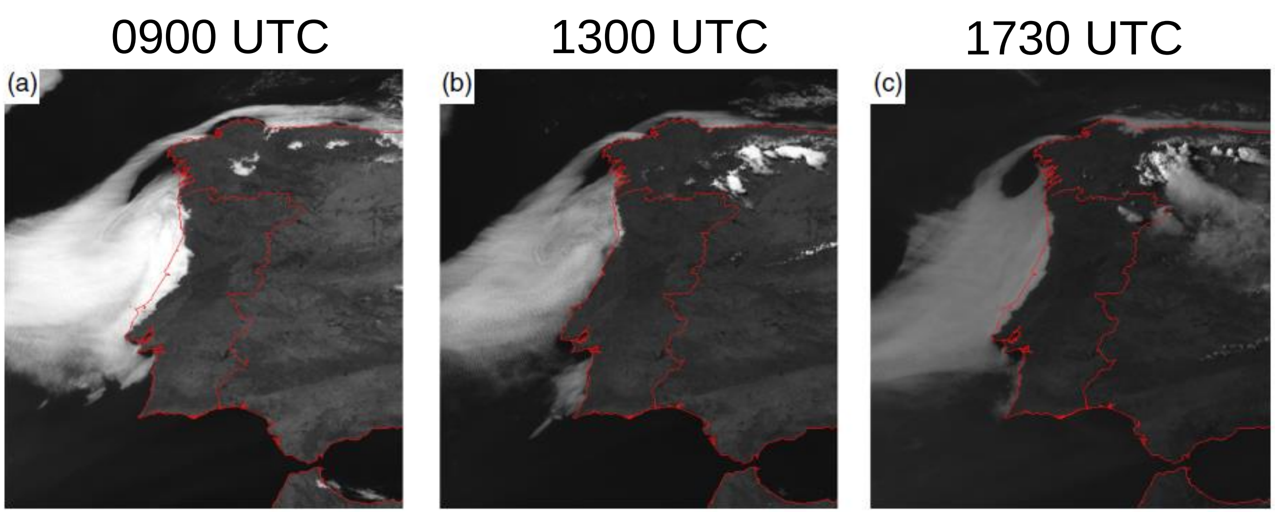
- Difference between climatological values from model vs satellite
- Classical‘ evaluation of high-resolution climate model simulation, e.g., from CORDEX

Alexandri, G., et al., (2015), *Atmospheric Chemistry and Physics*, *15*(22), 13195-13216

Regional Climate Model Evaluation

➔ High resolution (time and space) satellite climate data allow process-based evaluation of climate models

a) Diurnal cycle of low clouds



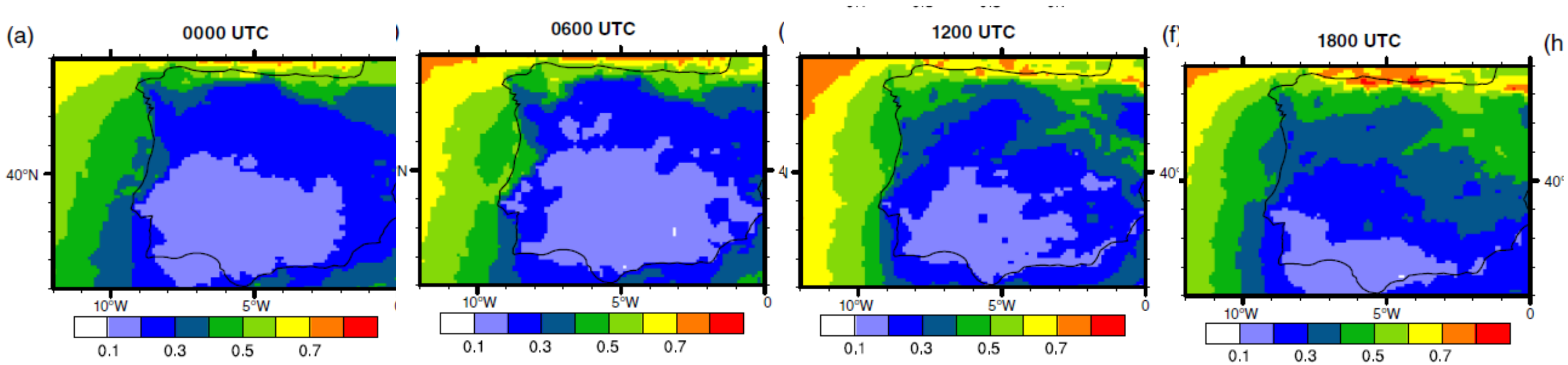
A typical summer day in the Iberia west coast cloudiness, as seen from MSG-SEVIRI high resolution visible channel (HRV). Images were taken on 10 July 2013. (a) 0900 UTC, (b) 1300 UTC, (c) 1730 UTC.

Martins, J. P. A., et al., (2016), *International Journal of Climatology*, *36*(4), 1755-1772

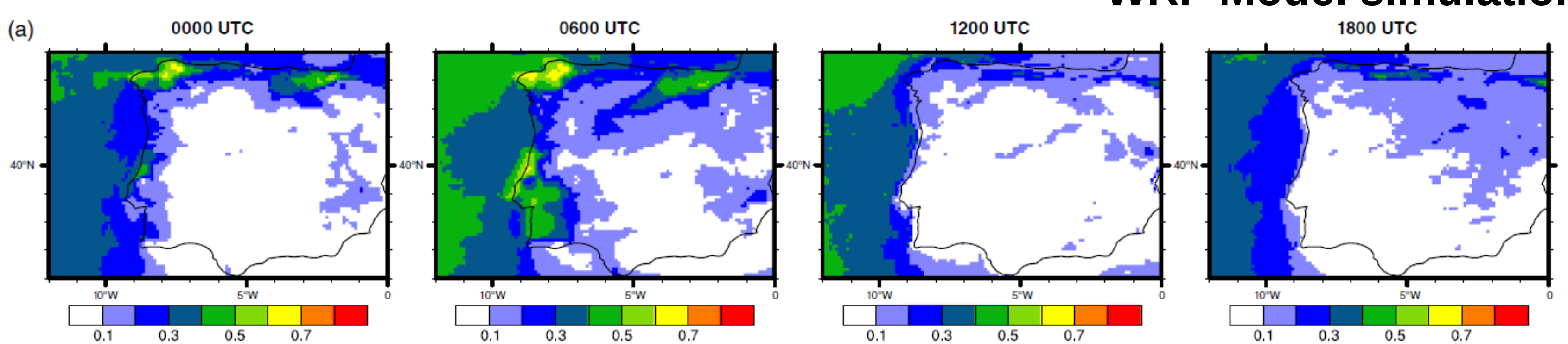
Regional Climate Model Evaluation

Climatological diurnal cycle of cloud coverage, JJA

CM SAF CLAAS



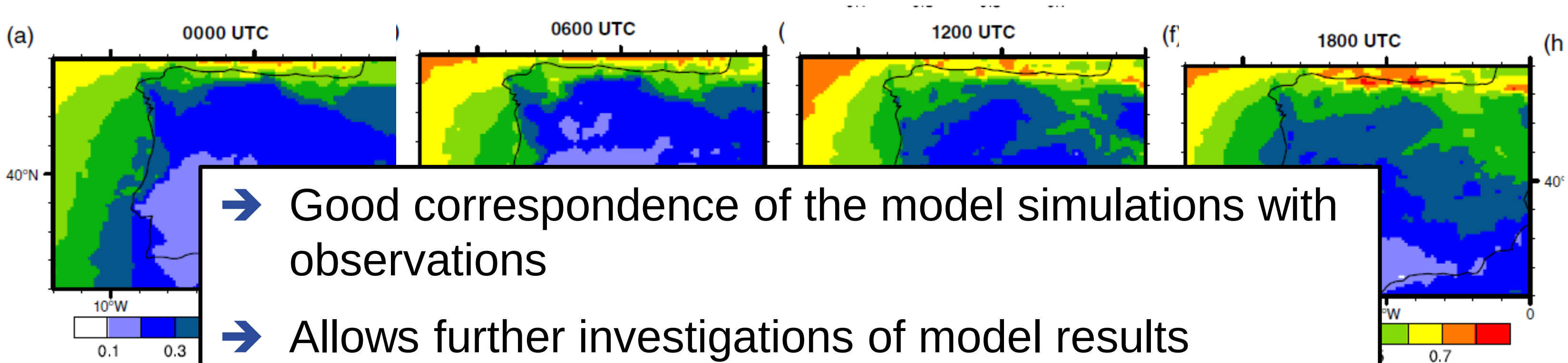
WRF Model simulations



Regional Climate Model Evaluation

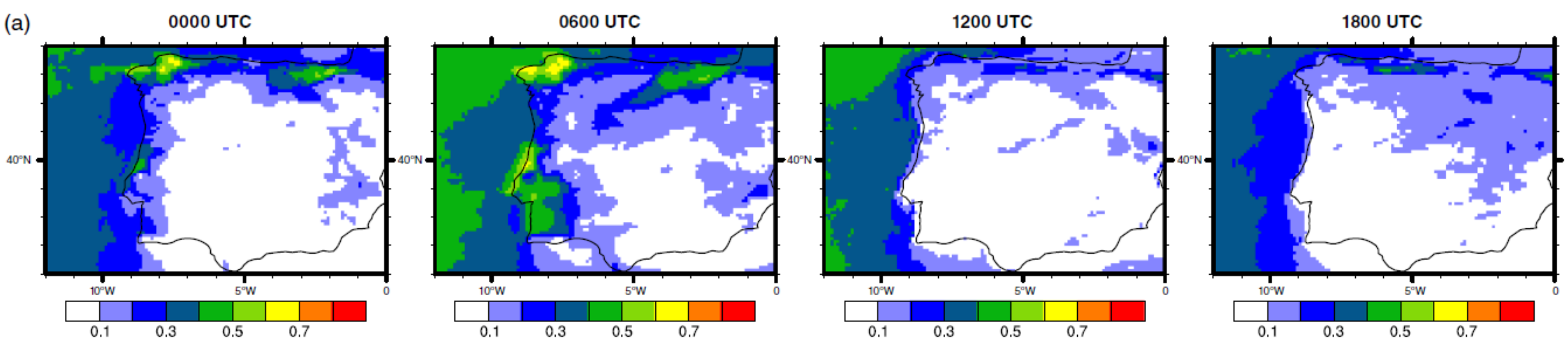
Climatological diurnal cycle of cloud coverage, JJA

CM SAF CLAAS



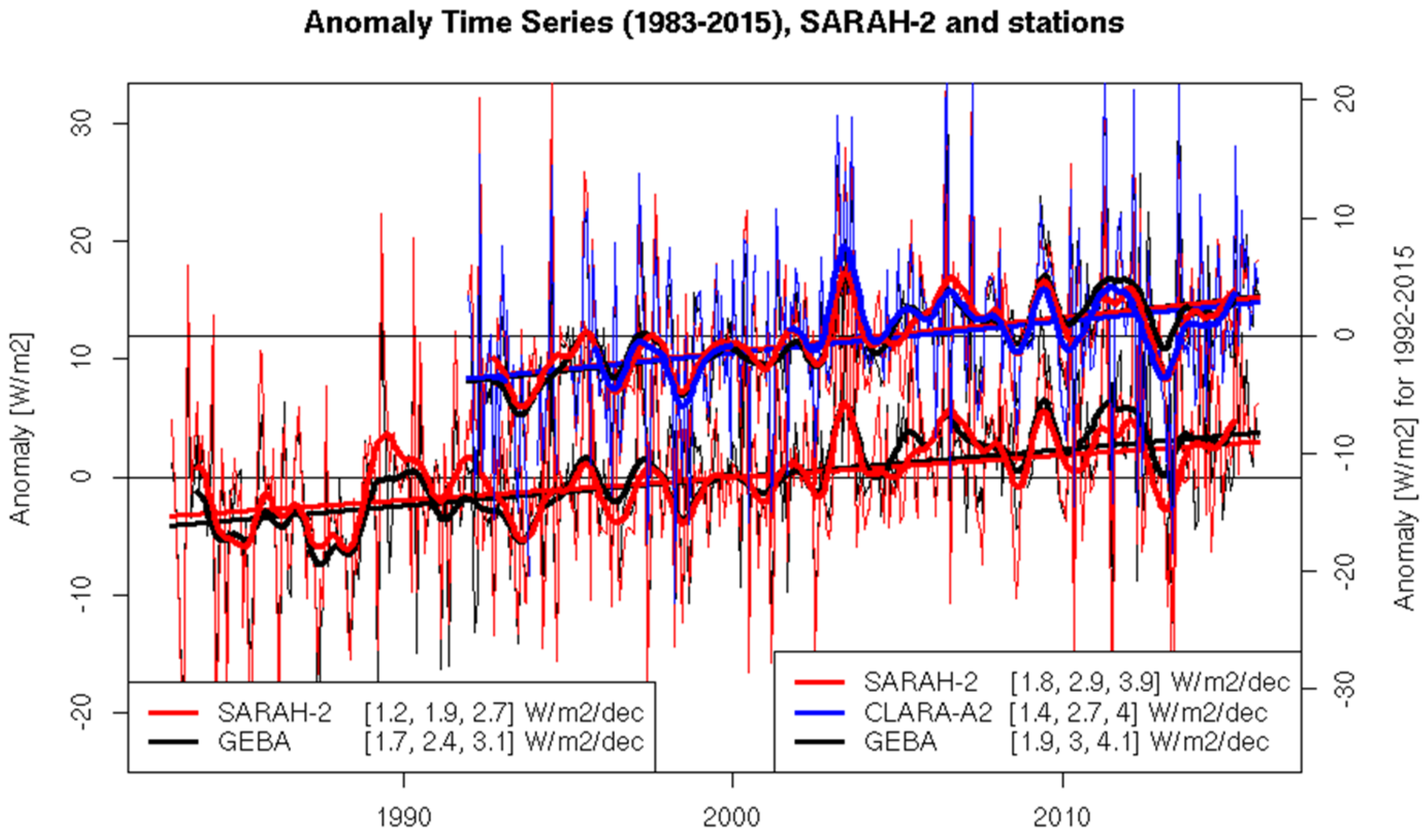
- ➔ Good correspondence of the model simulations with observations
- ➔ Allows further investigations of model results

WRF Model simulations



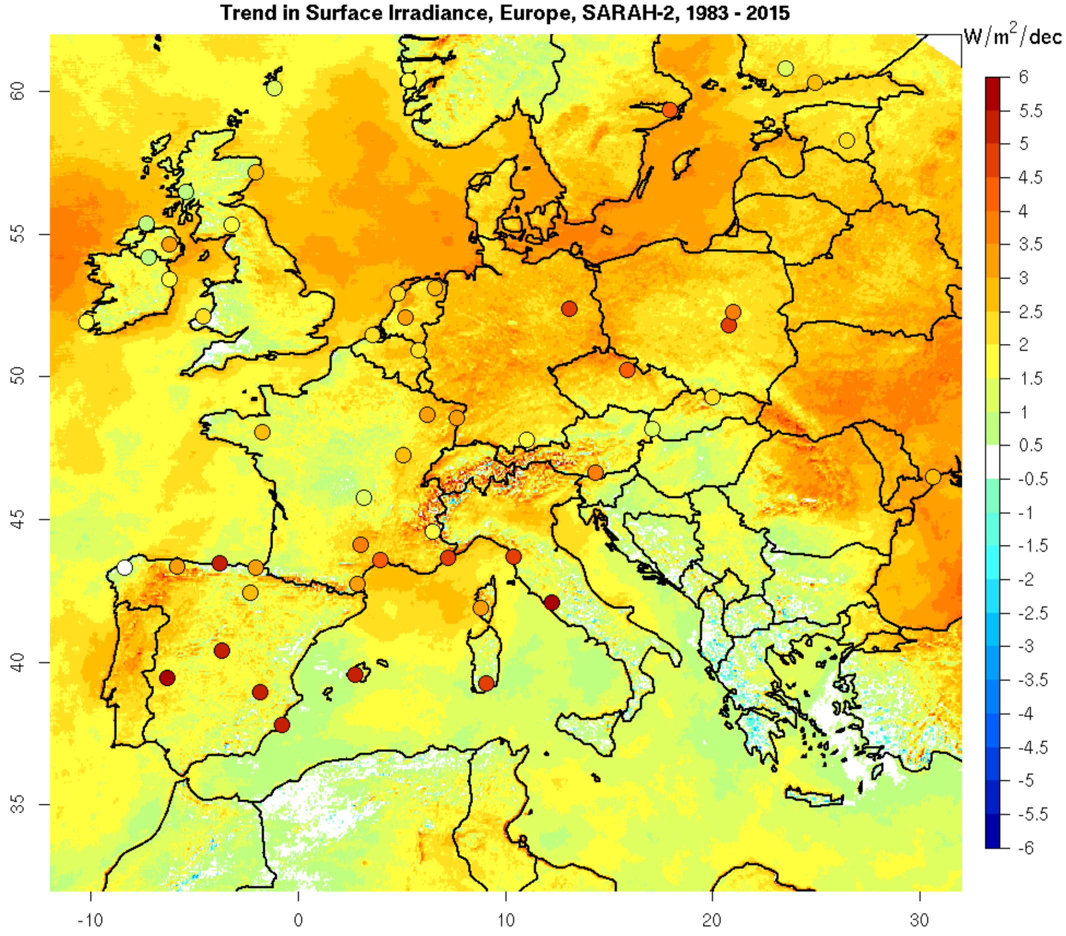
Climate Analysis: Trend in Surface Solar Radiation

Validation of satellite data



Trend: SARAH / Surface

SARAH: 1983 - 2015

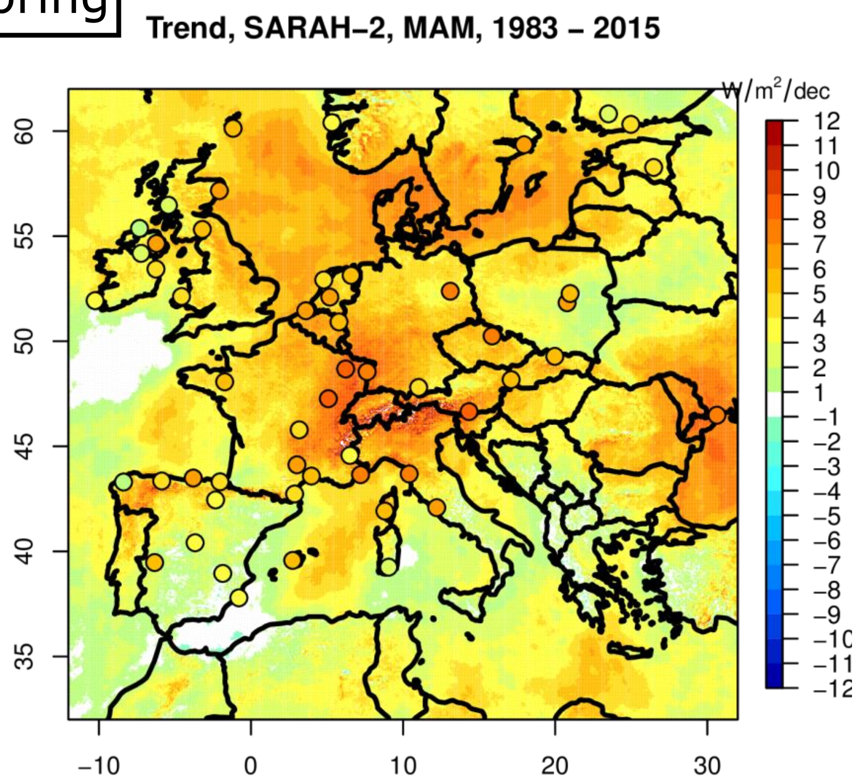


- Spatial variability of the trend in surface radiation
- Good correspondence of the spatial variability of the trends between satellite and surface data.

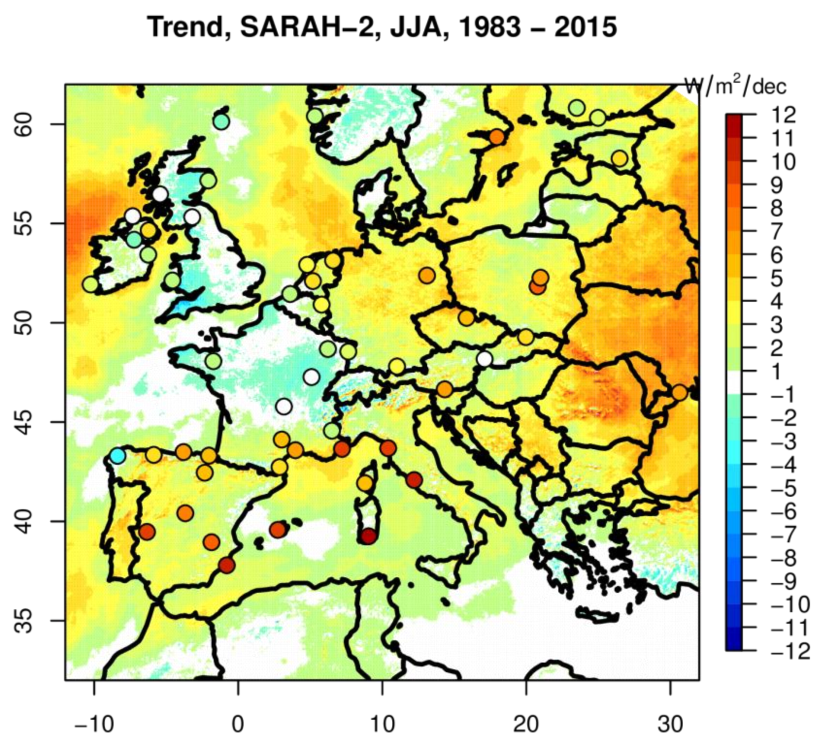
Seasonal Trends: Surface / SARAH

- Large scale 'brightening' in spring
- Spatially diverse trends in summer

Spring



Summer



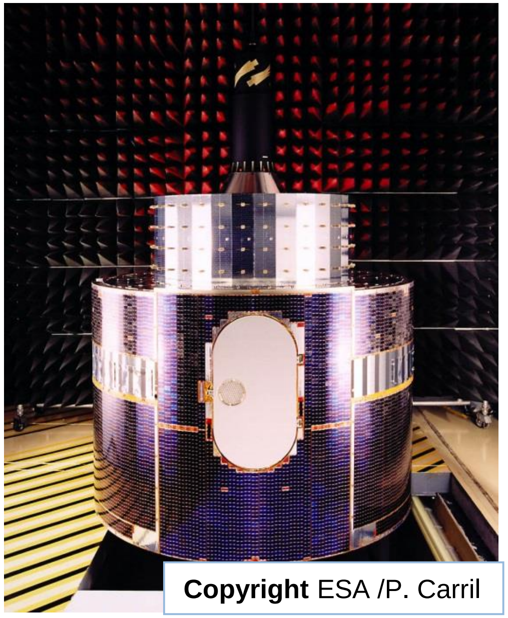
Status and Outlook: EUMETSAT Meteosat Satelliten

1. Generation (MVIRI)
(1982 - 2006)

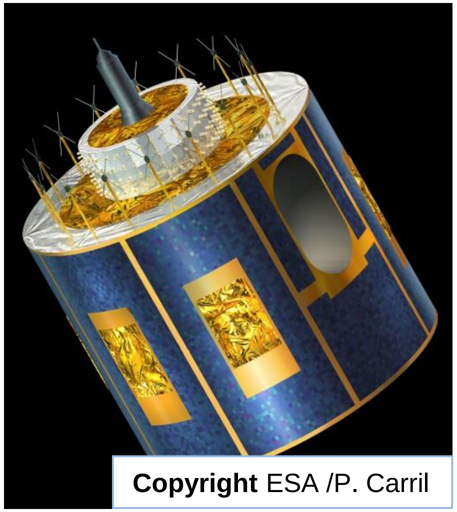
➔ 3 spektrale Kanäle

➔ Zeit: 30 min

➔ Raum: 5 km



Status and Outlook: EUMETSAT Meteosat Satelliten

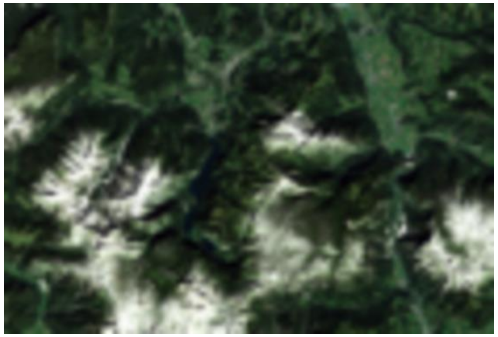


1. Generation (MVIRI)
(1982 - 2006)

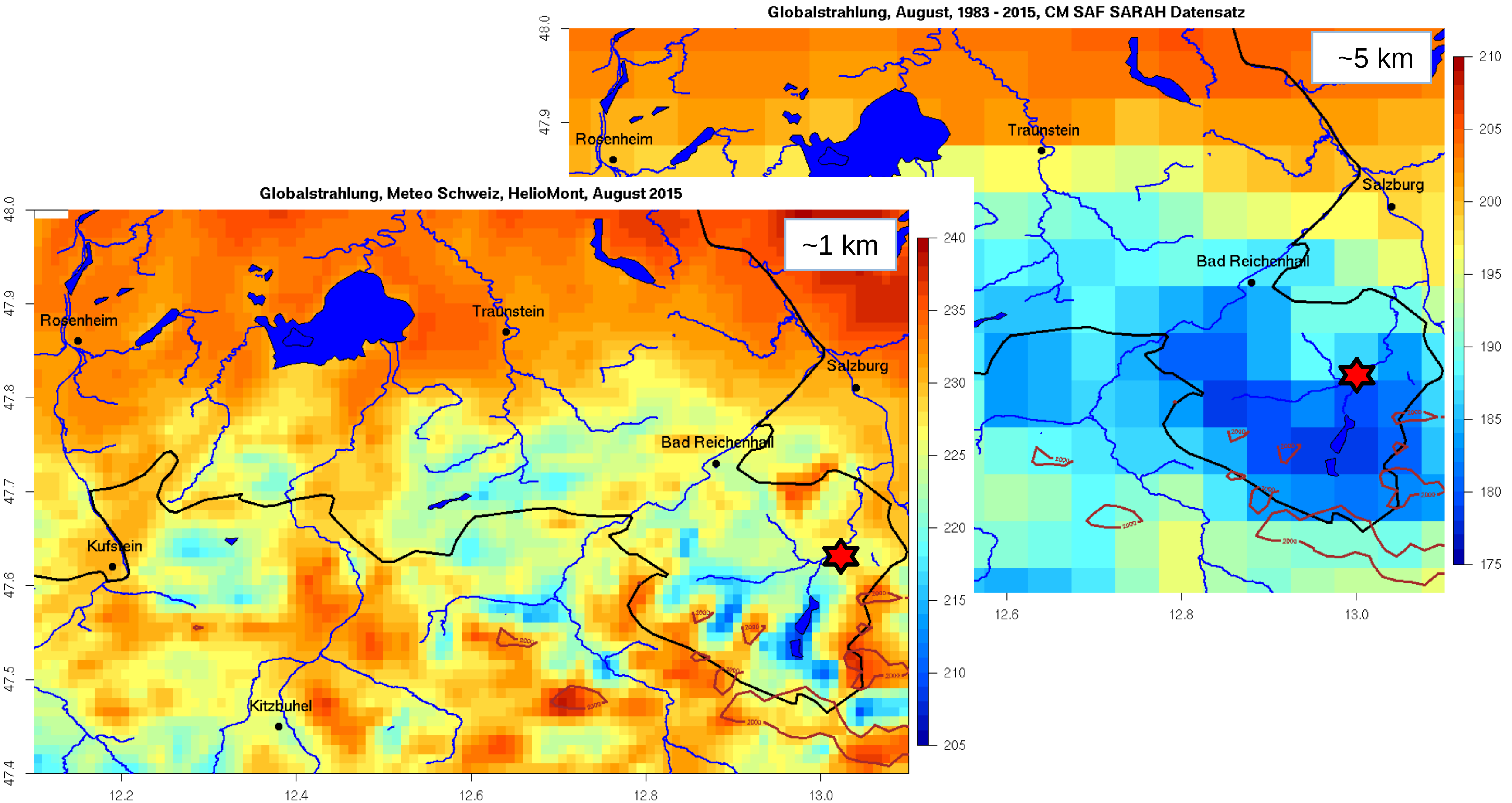
- 3 spektrale Kanäle
- Zeit: 30 min
- Raum: 5 km

2. Generation (SEVIRI)
(2004 - ~2020)

- 11 spektrale Kanäle
- 5 min bis 15 min
- 5 km / 1 km (HRV)



Example: Surface Radiation, August 2015



Surface Radiation August 2015
R. Stöckli, Meteo Schweiz

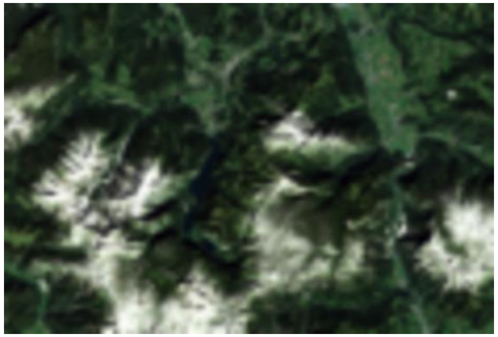
Status and Outlook: EUMETSAT Meteosat Satelliten

1. Generation (MVIRI)
(1982- 2006)

- 3 spektrale Kanäle
- Zeit: 30 min
- Raum: 5 km

2. Generation (SEVIRI)
(2004 - ~ 2020)

- 11 spektrale Kanäle
- 5 min bis 15 min
- 5 km / 1 km



3. Generation (FCI)
(ab ~ 2020)

- 16 spektrale Kanäle
- 2.5 min bis 10 min
- 500 m / 1 km / 2 km

Summary

- Collecting climate data is a core element to monitor climate
- Satellite-based high resolution climate data are readily available
- Data availability / quality depends on the parameter + maturity of retrieval algorithm
- High-resolution satellite-based climate data is extending the information available from surface observations
- High-resolution satellite data provide new possibilities to address the quality of regional climate models