Satellite-based High Resolution Climate Data Records

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Overview

- Motivation: Climate Data for Climate Monitoring
- Satellite-based climate data
  - Introduction to satellite meteorology
  - Available climate data from satellite
- Selected Applications
  - Climate Monitoring
  - Climate Modeling
  - Climate Analysis
- Summary and Outlook
Why are we collecting climate data?

1. To document the status of the climate system.
2. To classify the current state of the climate system in the long term climatology.
3. 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 system has to be able to monitor the variability / extremes of the climate system.

- Climate Monitoring requires homogeneous, climatological reference data and consistent, current measurements.
Which parameters do we need to measure?

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<td>Oceanic</td>
<td>incl. SST, Sea Level, Salinity, Ocean Currents, Carbon</td>
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<td>incl. Soil Moisture, River Discharge, Snow, Glaciers, Albedo, Land Cover, LST, Fire</td>
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Which parameters can be observed from satellite?

Some ECVs can be derived from satellite measurements

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<td>Precipitation, Earth radiation budget (including solar irradiance), Upper-air temperature, Wind speed and direction, Water vapour, Cloud properties, Carbon dioxide, Ozone, Aerosol properties.</td>
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<td><strong>Oceanic</strong></td>
<td>Sea-surface temperature, Sea level, Sea ice, Ocean colour (for biological activity), Sea state*, Ocean salinity*.</td>
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<td><strong>Terrestrial</strong></td>
<td>Lakes*, Snow cover, Glaciers and ice caps, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI)<em>, Biomass</em>, Fire disturbance, Soil moisture*.</td>
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* denotes variables that are not yet fully operational.
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

Satellites are a 'young' observing system

1978

Data available since early 1980s

1990

Originally designed for weather observations (i.e., not designed for climate monitoring and the estimation of geophysical parameters)

Courtesy WMO, B. Ryan
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“.

![Visible and IR images of Earth](image-url)
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, $R_{\text{min}}$, 12 UTC, Sept 2008
Reflectivity, 12 UTC, 2 Sept 2008

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

Temporal evolution of $R_{\text{max}}$

Self-calibration method, no intercalibration of different instruments required!
The Cloud Index $n:\n\ \ \ \ \ \ n = \frac{R - R_{\text{min}}}{R_{\text{max}} - R_{\text{min}}}\n\ \ \ \ \ \ 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, \( G_{\text{clear}} \):
  \[
  G = k \times G_{\text{clear}}
  \]
- \( G_{\text{clear}} \) 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 underestimation 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
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18 March 2006, 1230 UTC
March 2006 Accuracy over snow:

orig: 26 W/m²
new: 19 W/m²
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](https://www.ncdc.noaa.gov/cdr)
- [http://cci.esa.int/](http://cci.esa.int/)
- [http://www.cmsaf.eu](http://www.cmsaf.eu)

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

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

- 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

http://www.cmsaf.eu
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**
  - $0.05^\circ \times 0.05^\circ$
  - 30 min instantaneous, daily-, monthly means

- **Coverage**
  - Meteosat disk
  - 1983 to 2015

**CLAAS**

- **Variables**
  - Cloud coverage
  - Cloud properties

- **Resolution**
  - up to $0.05^\circ \times 0.05^\circ$
  - 30 min instantaneous, daily-, monthly means

- **Coverage**
  - Meteosat disk
  - 2004 to 2015

DOI:10.5676/EUM_SAF_CM/SARAH/V002

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
  - Representatitivity 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

Example: Surface Radiation, July 2017

Global Radiation July 2017
Monthly Mean


© DWD 04/09/2017
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.
Representativeness of locations / surface data

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

Regional Climate Model Evaluation

Difference between climatological values from model vs satellite

Classical' evaluation of high-resolution climate model simulation, e.g., from CORDEX

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.

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

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

CM SAF CLAAS

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

**Spring**
Trend, SARAH–2, MAM, 1983 – 2015

- Large scale ‘brightening’ in spring
- Spatially diverse trends in summer

**Summer**
Trend, SARAH–2, JJA, 1983 – 2015
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

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2. Generation (SEVIRI)
   (2004 - ~2020)
   ➔ 11 spektrale Kanäle
   ➔ 5 min bis 15 min
   ➔ 5 km / 1 km (HRV)

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Example: Surface Radiation, August 2015

Globalstrahlung, August, 1983 - 2015, CM SAF SARAH Datensatz
~5 km

Globalstrahlung, Meteo Schweiz, HelioMont, August 2015
~1 km

Surface Radiation August 2015
R. Stöckli, Meteo Schweiz
## Status and Outlook: EUMETSAT Meteosat Satelliten

### 1. Generation (MVIRI)
(1982 - 2006)
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### 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.