# SOIL MOISTURE REMOTE SENSING

Bernhard Raml and Wouter Dorigo

26.09.2023

# Topics

Physical basis

Retrieval methods

Satellite data sources

Climate Data Records

Validation and Quality Assurance

Applications

# Physical basis and retrieval methods

# Approaches to Remote Sensing of Soil Moisture

Visible to shortwave infrared (0.4 – 3 μm)

Change of "colour"

Water absorption bands at 1.4, 1.9 and 2.7 μm

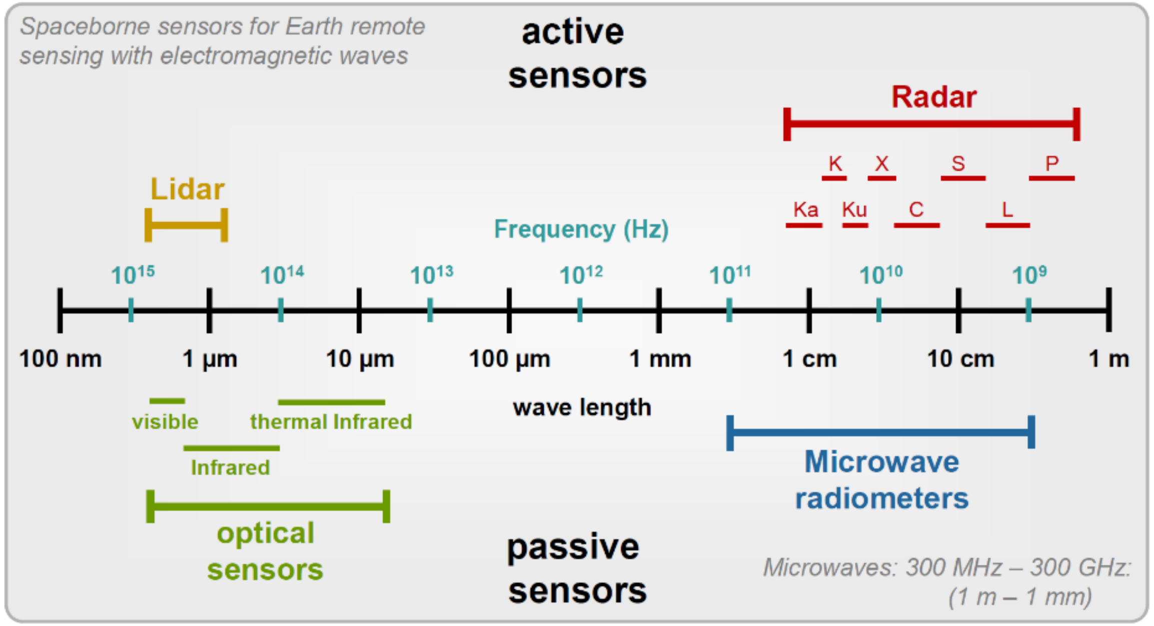
Thermal Infrared (7-15 μm)

Indirect assessment of soil moisture through its effect on the surface energy balance (temperature, thermal inertia, etc.)

**Microwaves (1 mm – 1 m)**

Change of dielectric properties

https://earth.esa.int/documents/10174/642943/6-LTC2013-SAR-Moreira.pdf



# Active Microwave Sensors

Create their own electromagnetic energy

**Observable**: Backscattering coefficient $\sigma^0$

a measure of the reflectivity of the Earth surface

Sensors

- Altimeters
- Side-looking
- Real aperture radar
- Scatterometer (SCAT)
- Synthetic Aperture Radar (SAR)

Sensitive to roughness and vegetation

High spatial resolution possibility through SAR

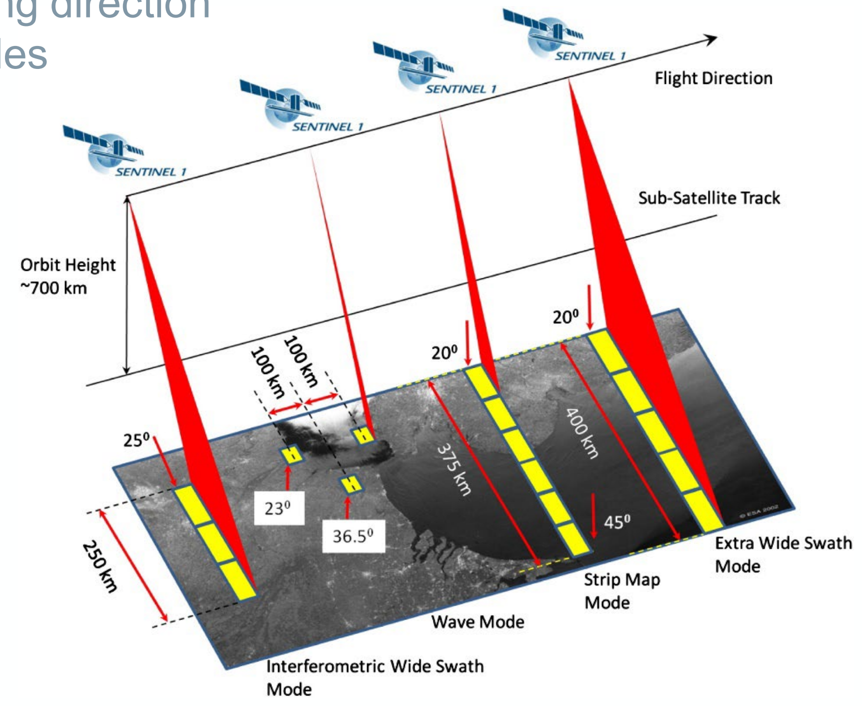
**Sentinel-1 CSAR**

Synthetic aperture radar

Fine resolution 20-80m

Single-viewing direction

Several modes



# Passive Microwave Sensors

Record emitted energy from the Earth surface

**Observable**: Brightness temperature

$T_B = eT_s$, where e is the emissivity and $T_s$ is the surface temperature

Sensors

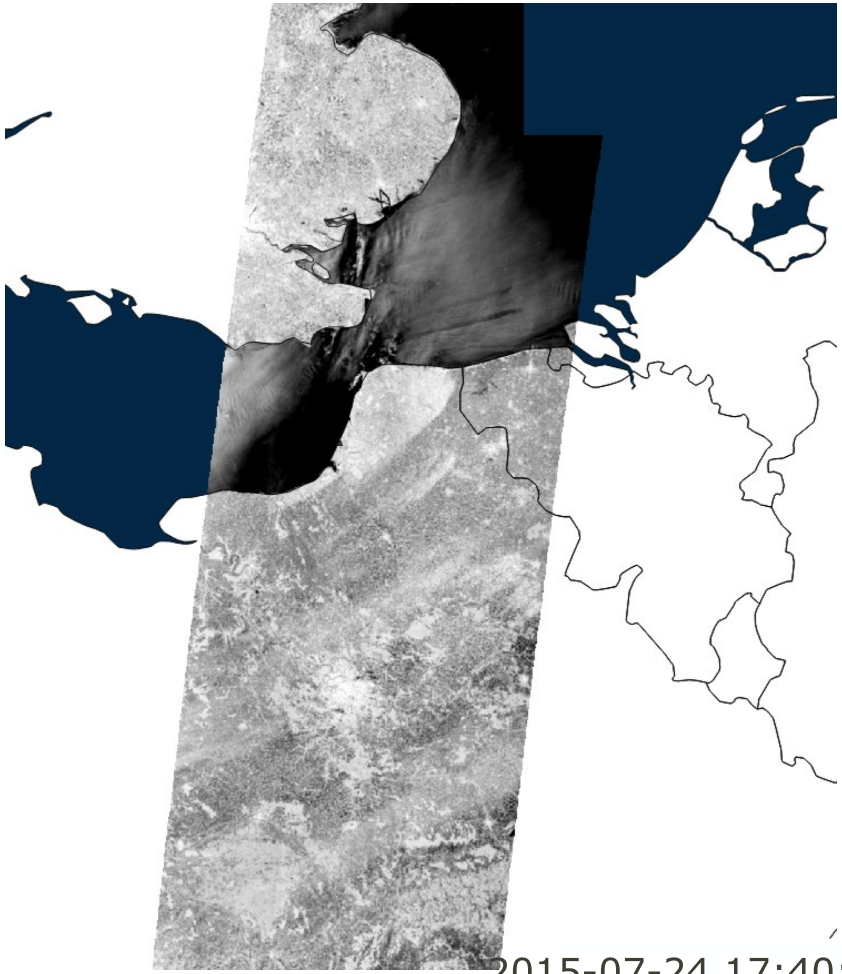
Microwave radiometers

Dependent on land surface temperature

Less sensitive to structural effects

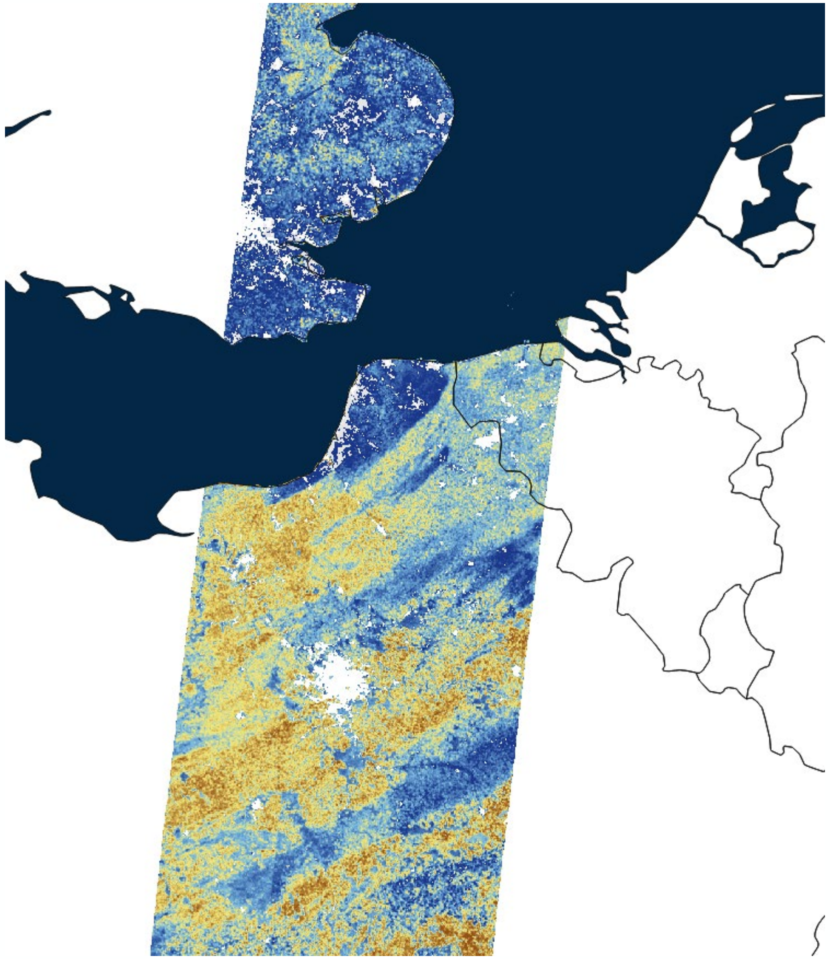
# Linear relation for soil moisture?

**Satellite Radar Backscatter in dB**



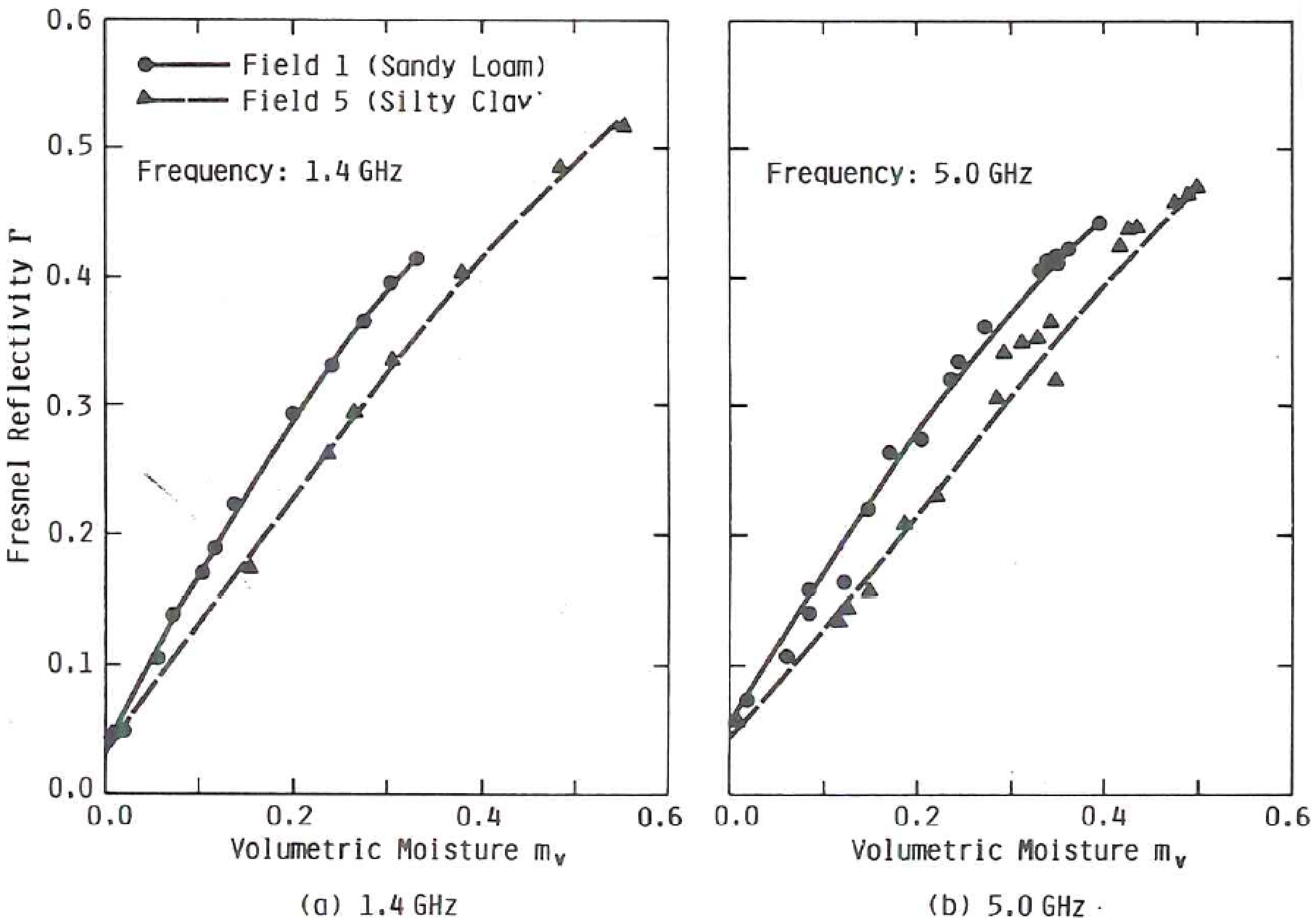
2015-07-24 17:40:08

**Soil Moisture in %**



# Active and Passive Sensing of Soil Moisture

Kirchhoff's law: $e = 1 - r$ where $r$ is the reflectivity

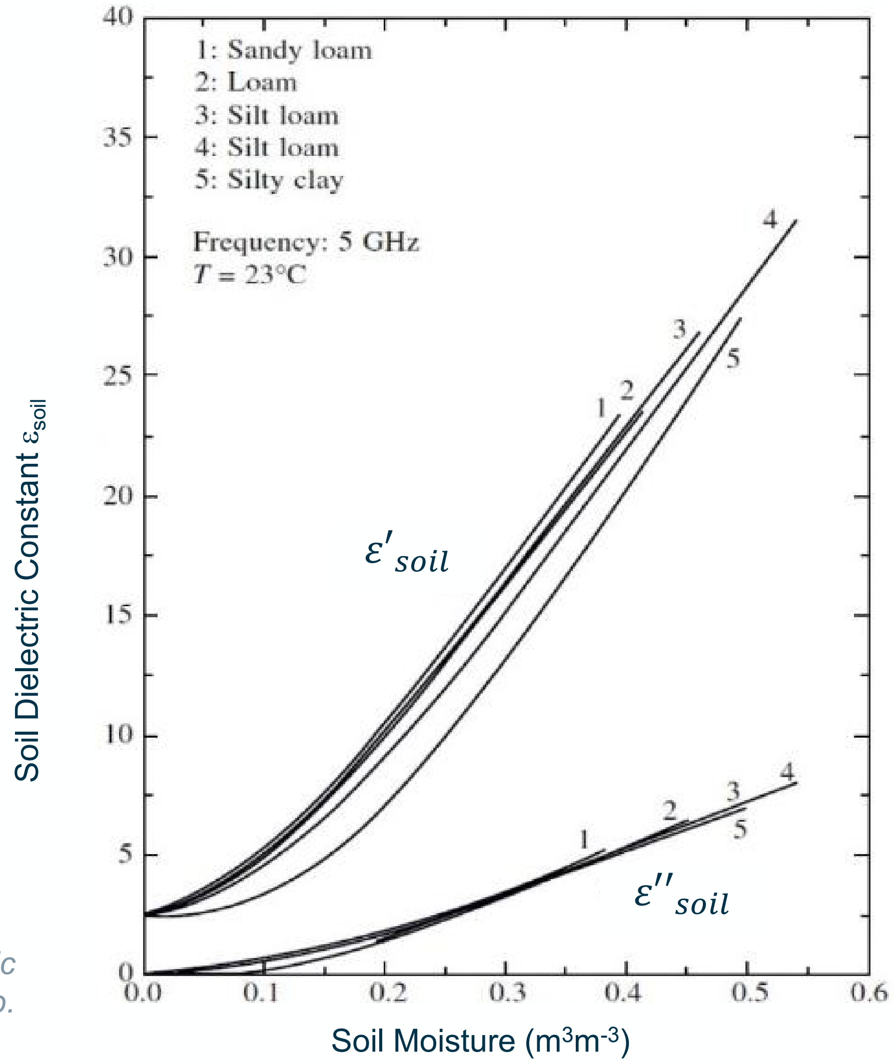



From F.T.Ulaby, R.K.Moore, A.K.Fung: *Microwave Remote Sensing: Active and Passive Vol.1,* Artech House (1981)

# Soil Contribution

Soil scattering and emission is principally driven by

- Soil dielectric constant
  - Soil moisture
  - Texture




*Behari (2005) Microwave dielectric behaviour of wet soils, Springer, 164 p.*

# Linear relation for soil moisture?

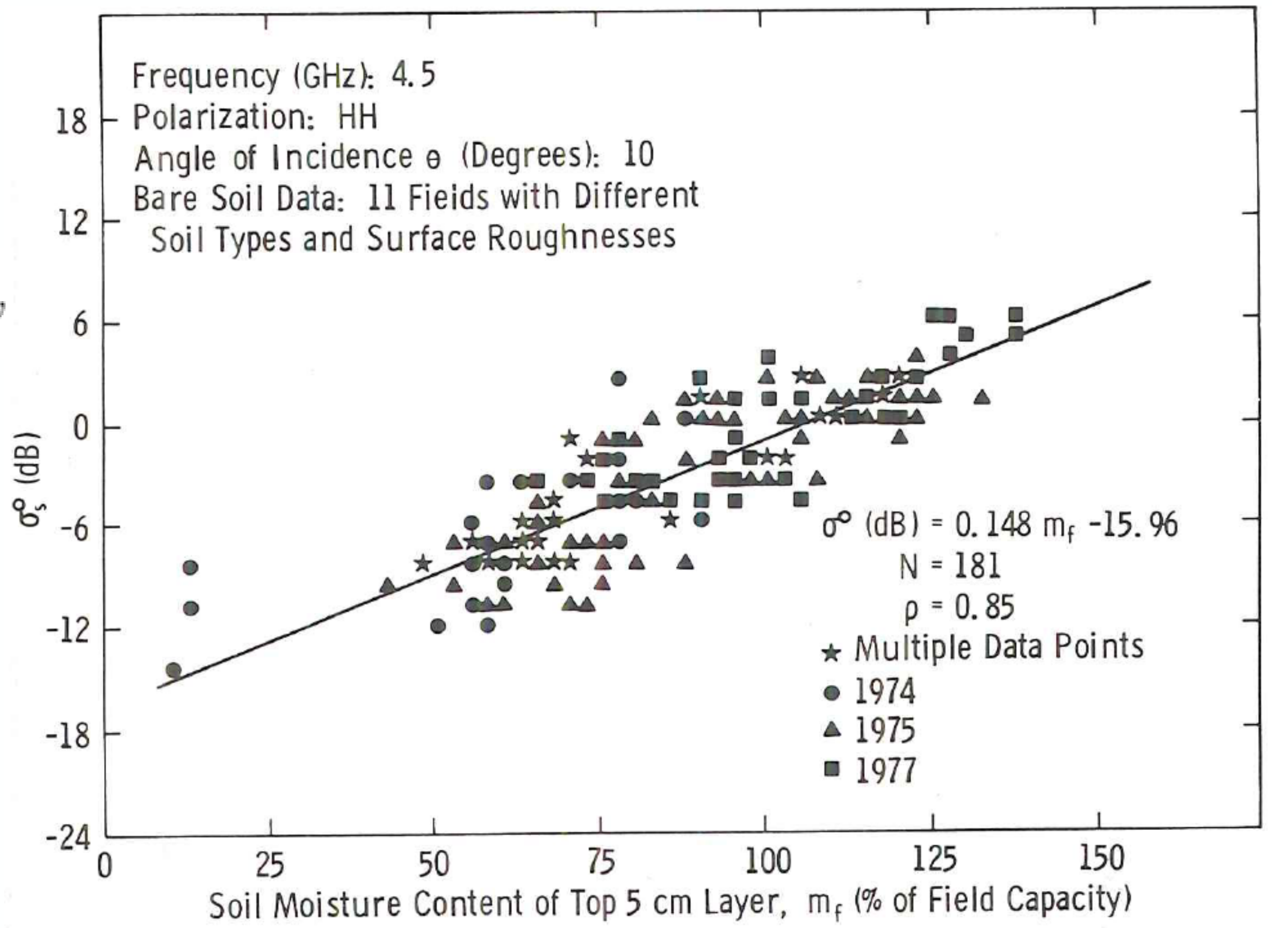
$$\sigma^0_{soil}[dB] = A + Bm_v$$

$$\sigma^0_{soil}[m^2m^{-2}] = 10^{\frac{A+Bm_v}{10}} = e^{\frac{ln10(A+Bm_v)}{10}} = ae^{bm_v}$$

$m_v$ = soil moisture

A = dry soil backscatter

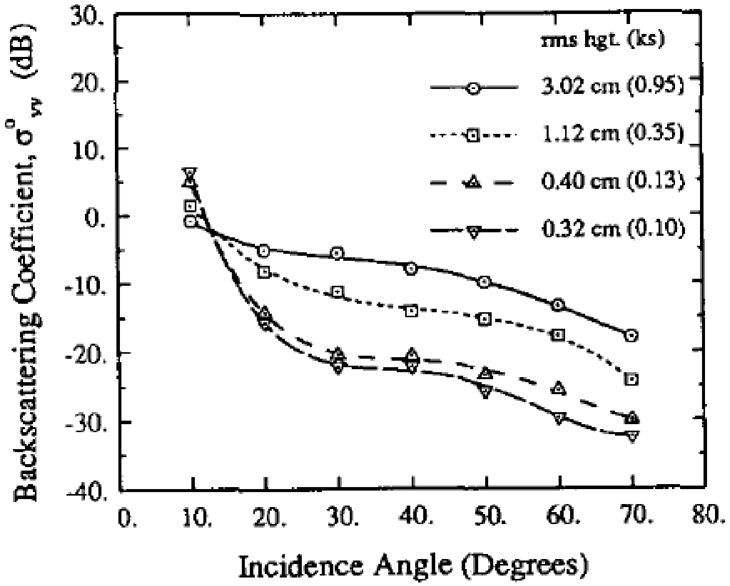
B = sensitivity

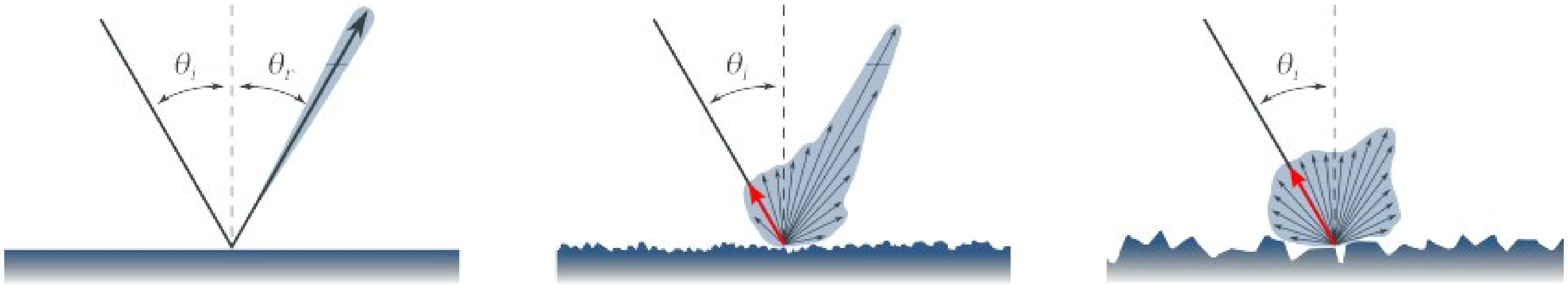


# Soil Contribution

Soil scattering and emission is principally driven by

- Soil dielectric constant
  - Soil moisture
  - Texture
- Soil surface “roughness”
  - Relative to wavelength
  - Dependent on soil moisture

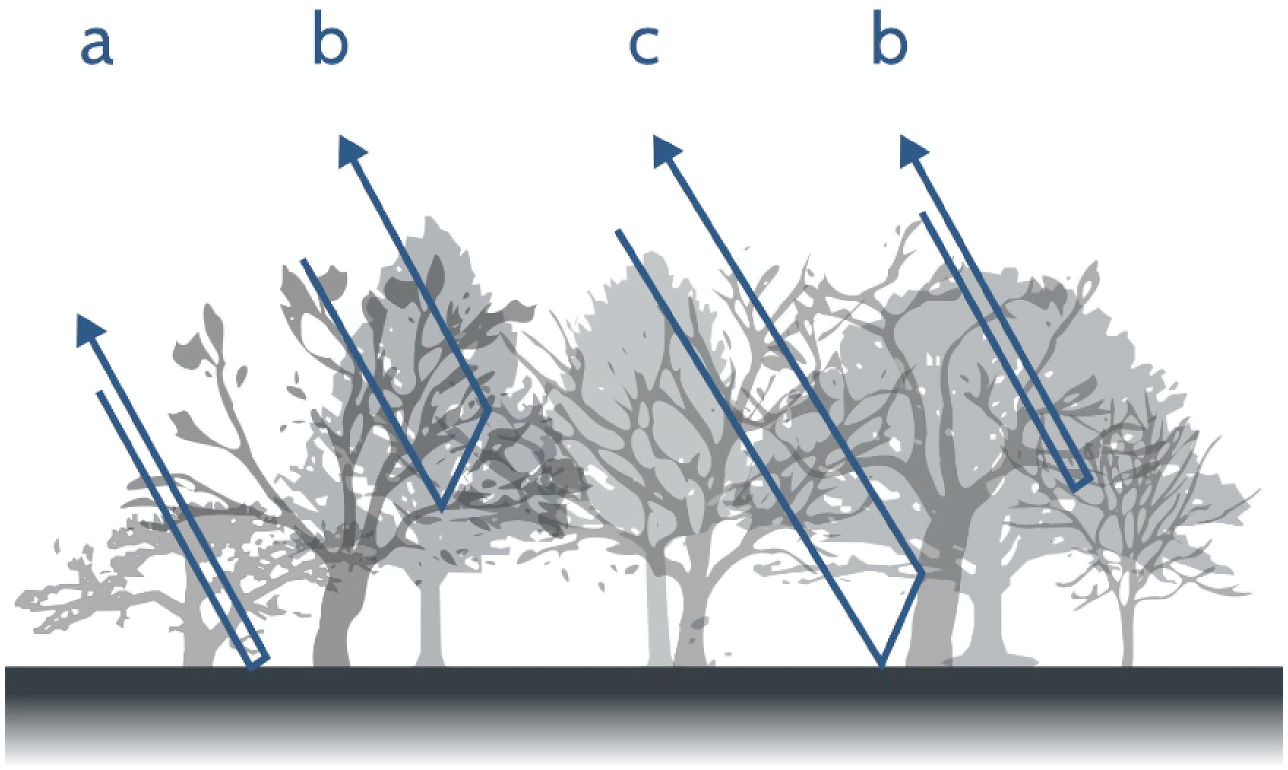



*Graphic by M. Vreugdenhil, TU Wien*

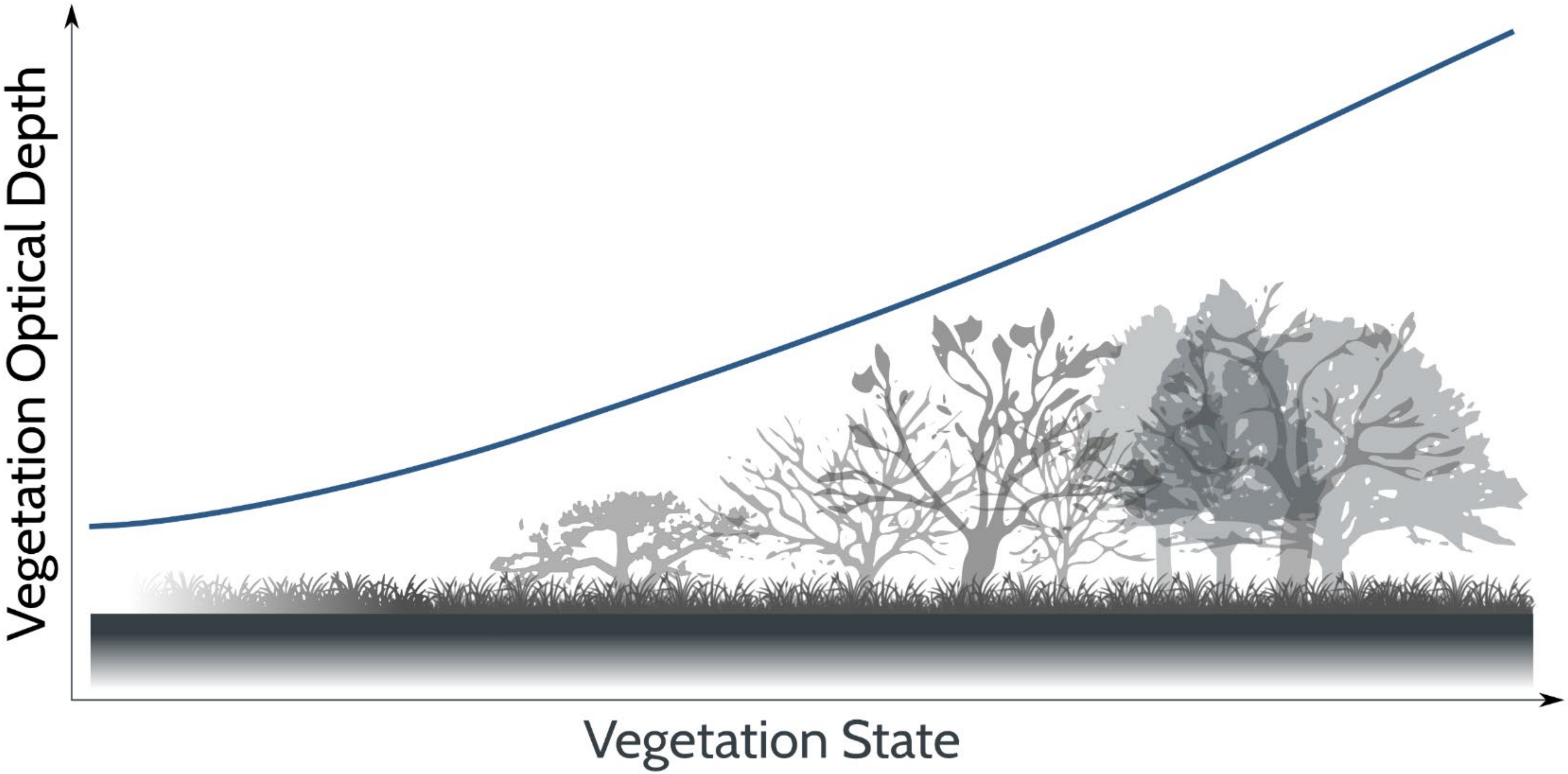
# Example for a Vegetated Surface

$$\sigma° = \sigma°_{Surface} + \sigma°_{Volume} + \sigma°_{Interaction}$$




Graphic by M. Vreugdenhil, TU Wien

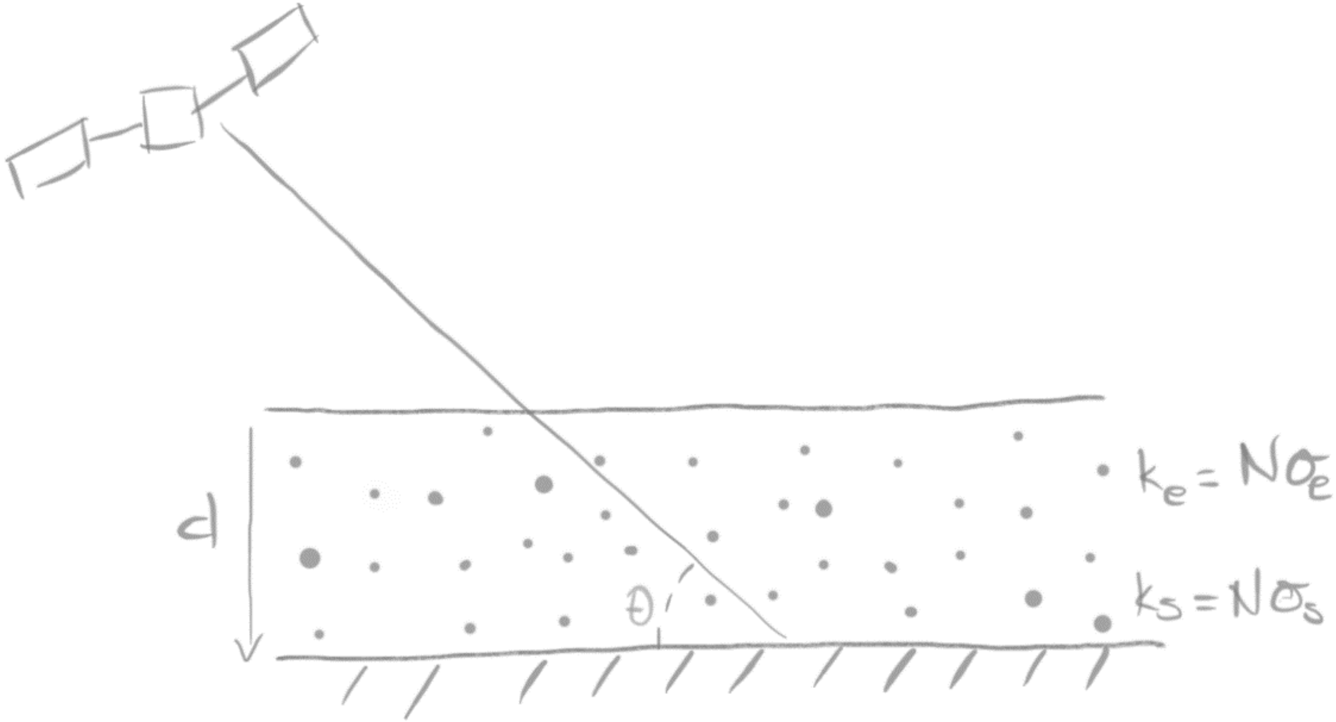
# Vegetation Optical Depth



# Parsimonious Models - Water Cloud Model

## Water cloud model ($\omega - \tau$ model)

$$\sigma°(\theta) = \sigma°_s(\theta)e^{\frac{-2\tau}{cos\theta}} + \omega cos\theta \left(1 - e^{\frac{-2\tau}{cos\theta}}\right)$$




$k_s = N\sigma_s$

$k_e = N\sigma_e$

$\omega = \frac{k_s}{k_e}$ Single Scattering Albedo

$\tau = ked$ Vegetation Optical Depth

*Graphic by M. Vreugdenhil, TU Wien*

# Parsimonious Models - Water Cloud Model

$$\sigma°(\theta) = \sigma°_s(\theta) e^{\frac{-2\tau}{cos\theta}} + \omega cos\theta \left(1 - e^{\frac{-2\tau}{cos\theta}}\right)$$

$$\sigma°(\theta) = \left(\frac{k_s}{2ke}\right)\left[1 - e^{-\frac{2ked}{cos\theta}}\right] cos\theta + \sigma°_s(\theta) e^{-\frac{2ked}{cos\theta}}$$

$$\sigma°_s = a e^{bm_v}$$

$$\sigma°(\theta) = \left(\frac{k_s}{2ke}\right)\left[1 - e^{-\frac{2ked}{cos\theta}}\right] cos\theta + a cos\theta e^{bm_v - \frac{2ked}{cos\theta}}$$

# Land Parameter Retrieval Method

Nonlinear iterative forward modelling procedure

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 39, NO. 8, AUGUST 2001 1643

A Methodology for Surface Soil Moisture and Vegetation Optical Depth Retrieval Using the Microwave Polarization Difference Index

Manfred Owe, Richard de Jeu, and Jeffrey Walker

$$T_b = (e_r T_s)e^{\frac{-\tau}{\cos\theta}} + (1-\omega)T_c\left(1 - e^{\frac{-\tau}{\cos\theta}}\right) + (1-\omega)T_c\left(1 - e^{\frac{-\tau}{\cos\theta}}\right)(1-er)e^{\frac{-\tau}{\cos\theta}}$$

Single scattering albedo and temperature are known

**Optimizing transmissivity** $\Gamma = \text{transmissivity} = e^{-\tau/cosu}$ **and emissivity** $e_r$

Dielectric mixing model to obtain **soil moisture** from emissivity

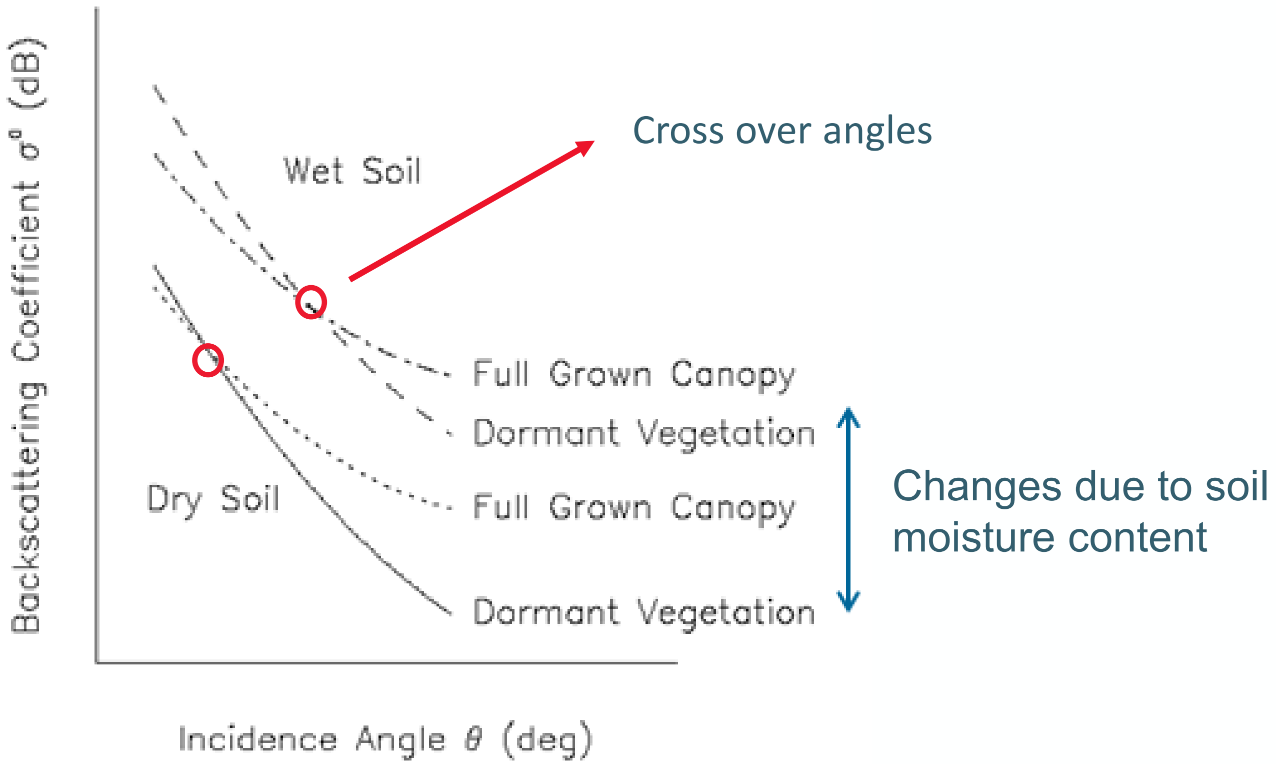
# Retrieval Algorithms

Changes in soil moisture shift curve

Changes in vegetation change slope

Vegetation attenuation and contribution are dependent on incident angle

At certain cross-over angles vegetation attenuation and contribution balance out



## Change detection method – Active systems

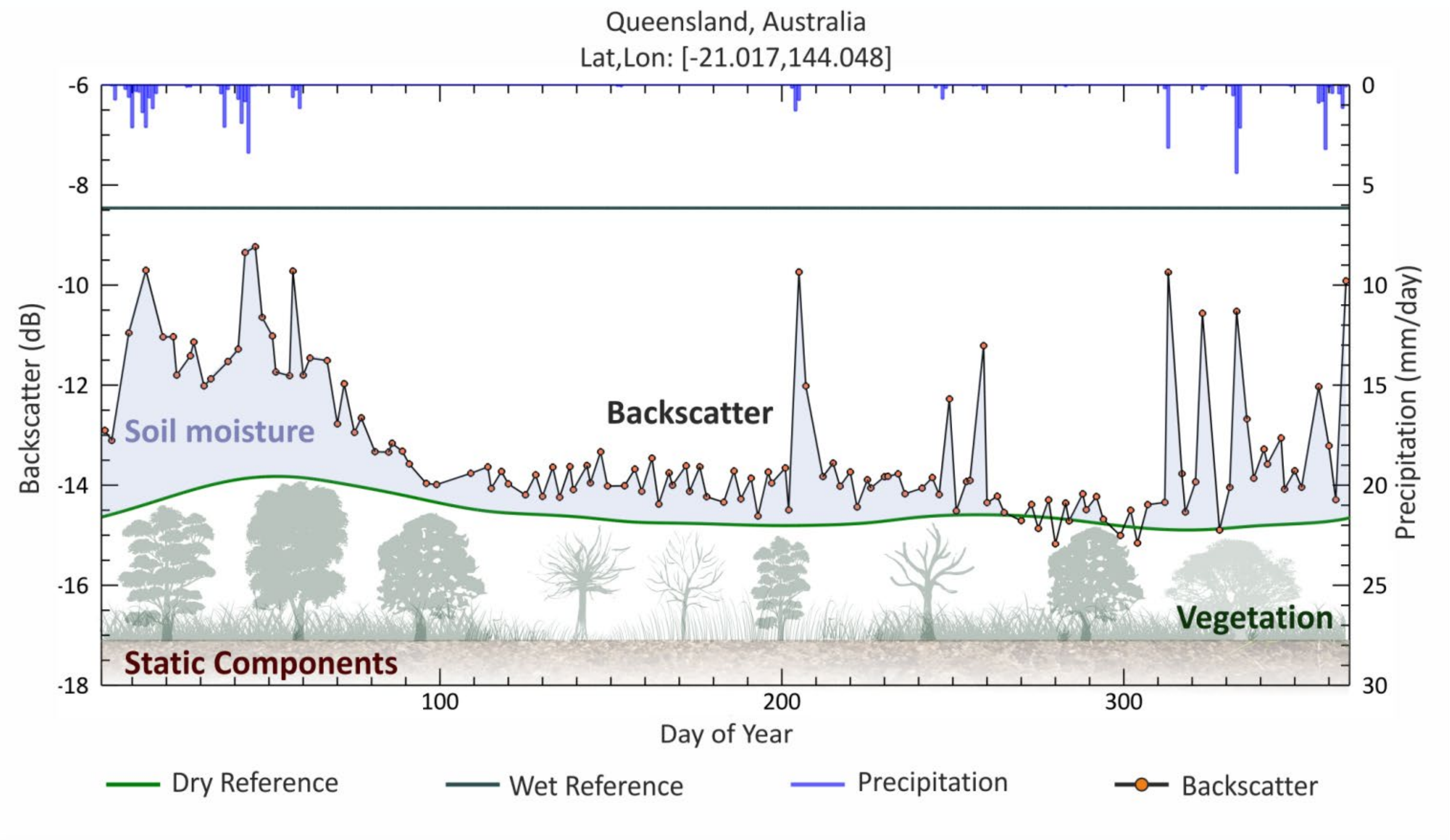
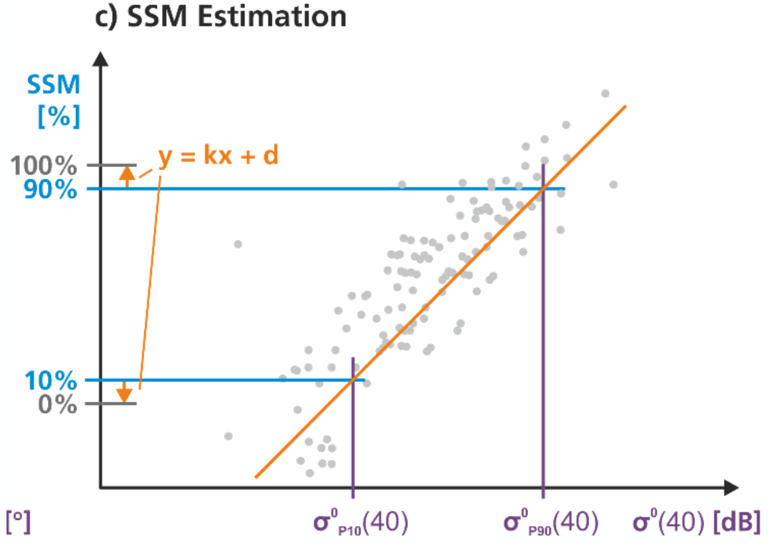



Figure: Vreugdenhil et al., 2016

$$m_s(t) = \frac{\sigma^0(t) - \sigma^0_{dry}(t)}{\sigma^0_{wet}(t) - \sigma^0_{dry}(t)}$$



# Where do retrievals go wrong?

Low signal-to-noise ratio (known from error propagation)

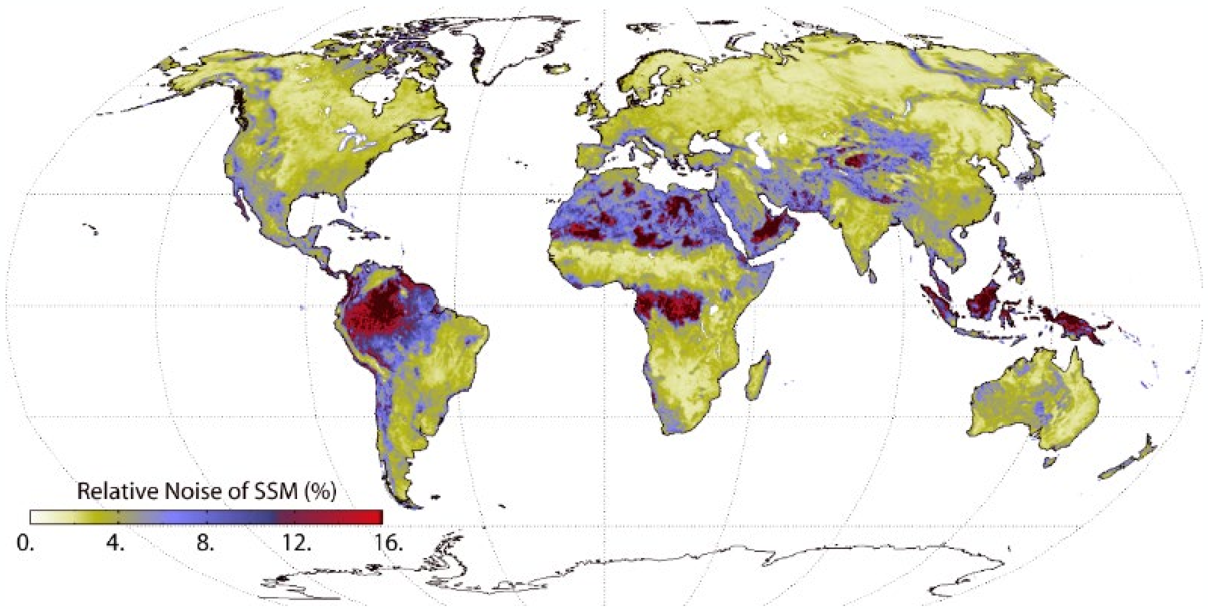
- Vegetation
- Mountainous regions
- Urban areas

Where does the model fail?

- Frozen ground
- Snow cover
- Water surfaces

Known issues

- Changes in land cover (urban sprawl, deforestation, etc.)
- Radio frequency interference
- Sub-surface soil scattering




*Graphics by S. Hahn, TU Wien*

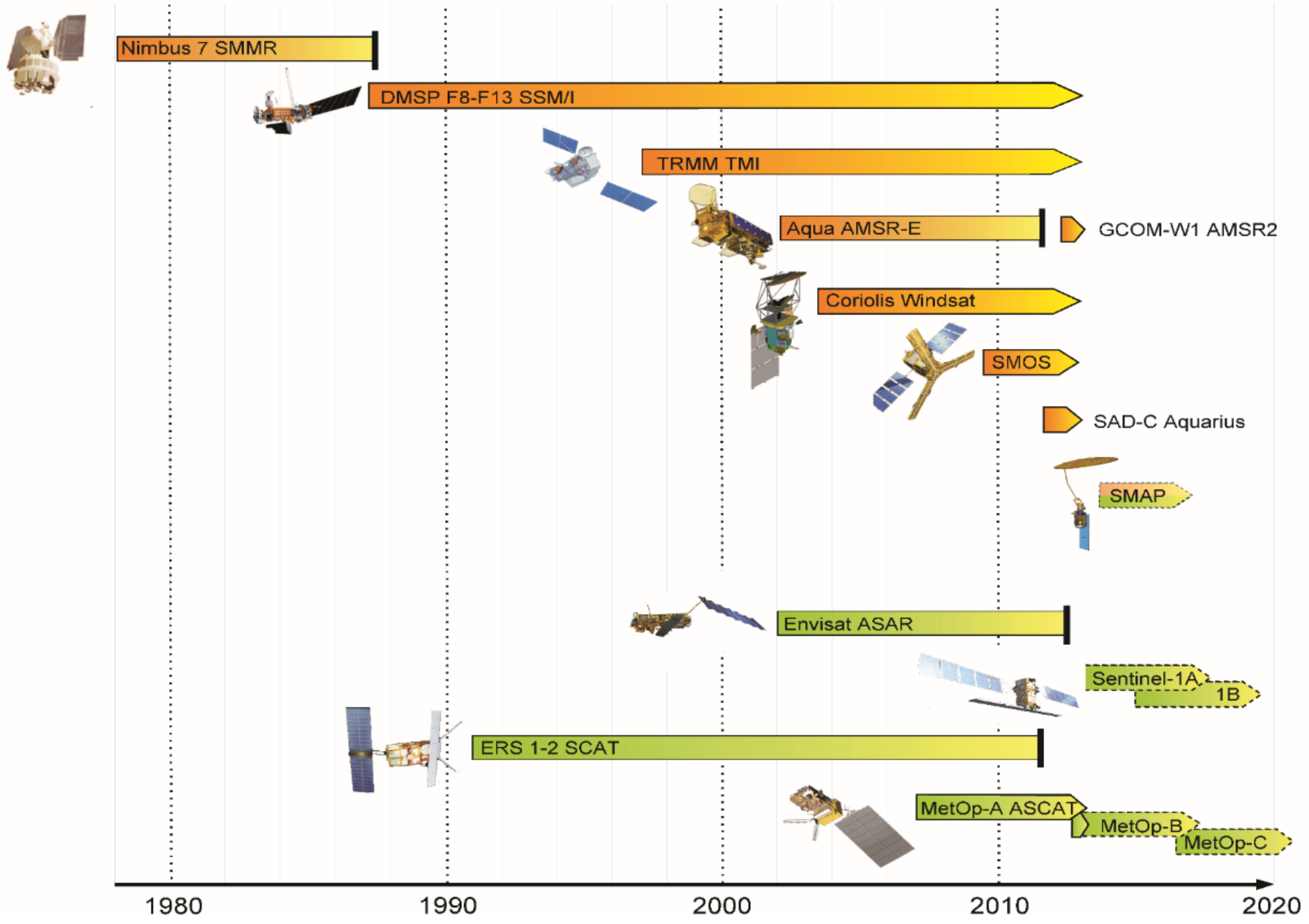
# Satellite Data Sources

# Microwave Remote Sensing Satellites






# Active and Passive Microwave Missions



# Operational Soil Moisture Products

| Satellite / Product | Temp. Cov. | Temp. res. | Latency | Spatial sampling | Spatial coverage | Organisation | Access |
|---|---|---|---|---|---|---|---|
| ESA CCI SSM | 1978- | 1-2 d | Year | 0.25° | Global | ESA | Free |
| C3S SSM | 1978 | 10 d | 10d | 0.25° | Global | Copernicus | Free |
| H SAF ASCAT SSM CDR | 2007- | 1-2 d | Year | 12.5 km | Global | EUMETSAT H SAF | Free |
| H SAF ASCAT SSM NRT | 2007- | 1-2 d | 1 d | 12.5 km | Global | EUMETSAT H SAF | Free |
| CGLS ASCAT SWI | 2007- | Daily | 3 d | 0.1° | Global | CGLS | Free |
| SMOS L2 SSM | 2010- | 1-2 d | 1 d | 36 km | Global | ESA | Free |
| SMAP L3 SSM | 2015- | 1-2 d | 1 d | 36 km | Global | NASA | Free |
| SMAP L4 RZSM | 2015- | Daily | 7 d | 9 km | Global | NASA | Free |
| CGLS S-1 SSM | 2015- | 3-24 d | 1 d | 0.5 km | Europe | CGLS | Free |
| CGLS SCATSAR SWI | 2015- | 1-2 d | 3 d | 0.5 km | Europe | CGLS | Free |
| VanderSat | 2002- | Daily | | 100m | request | Planet | Paid |

# European C-Band Scatterometer Series

**AMI Scatterometer**

Frequency: 5.3 GHz
Polarisation: VV

Resolution: 50 km
Daily coverage: <40%

**Satellites**
ERS-1: 1991-2000
ERS-2: 1995-2011

**METOP ASCAT**

Frequency: 5.255 GHz
Polarisation: VV

Resolution: 25 km
Daily coverage: 82%

**Satellites**
METOP-A: 2006
METOP-B: 2012
METOP-C: 2018

**METOP-SG SCA**

Frequency: 5.355 GHz
Polarisation: VV + VH + HH

Resolution: ~12.5 km
Daily coverage: ~88%

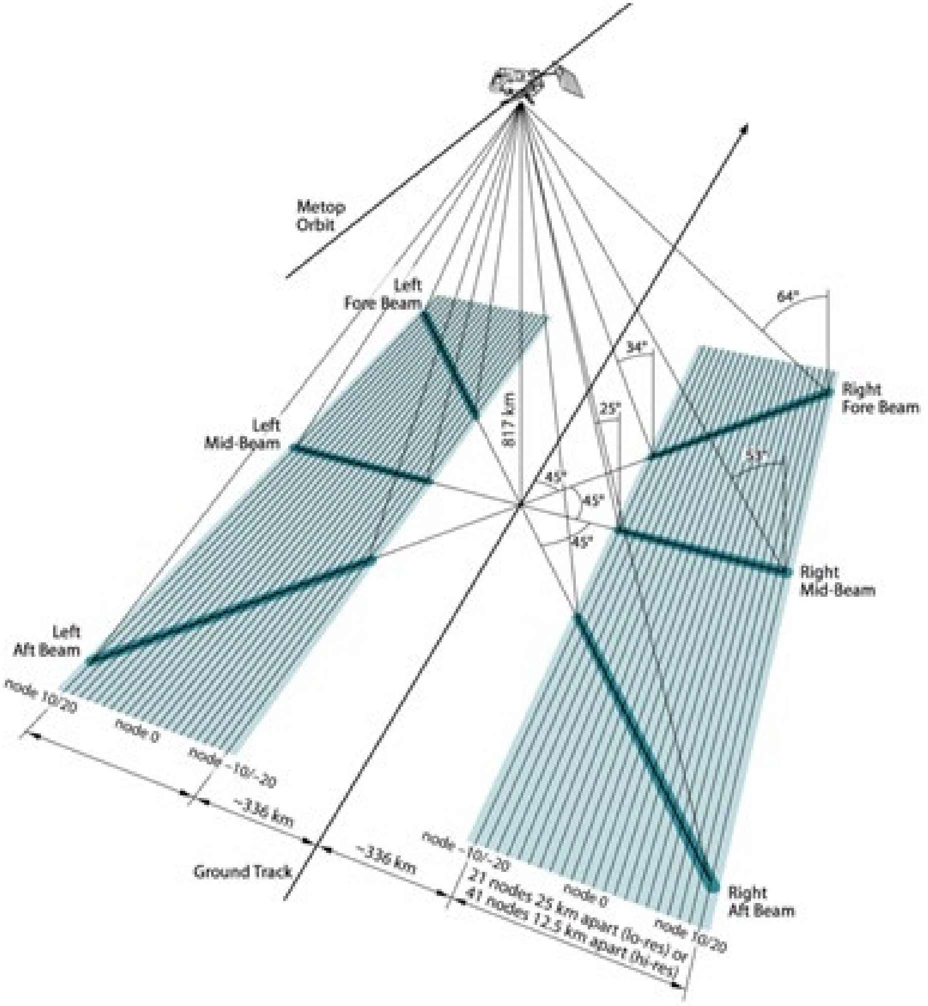
**Satellites**
METOP-SG-B1: 2022
METOP-SG-B2: 2030

# ASCAT Measurement Concept

Multiple-viewing directions through aft- mid- and fore-beam

Advantageous for slope estimation, because many more observations from different angles

Can also estimate curvature, resulting in more accurate incident angle normalisation



# ASCAT NRT Surface Soil Moisture

NRT

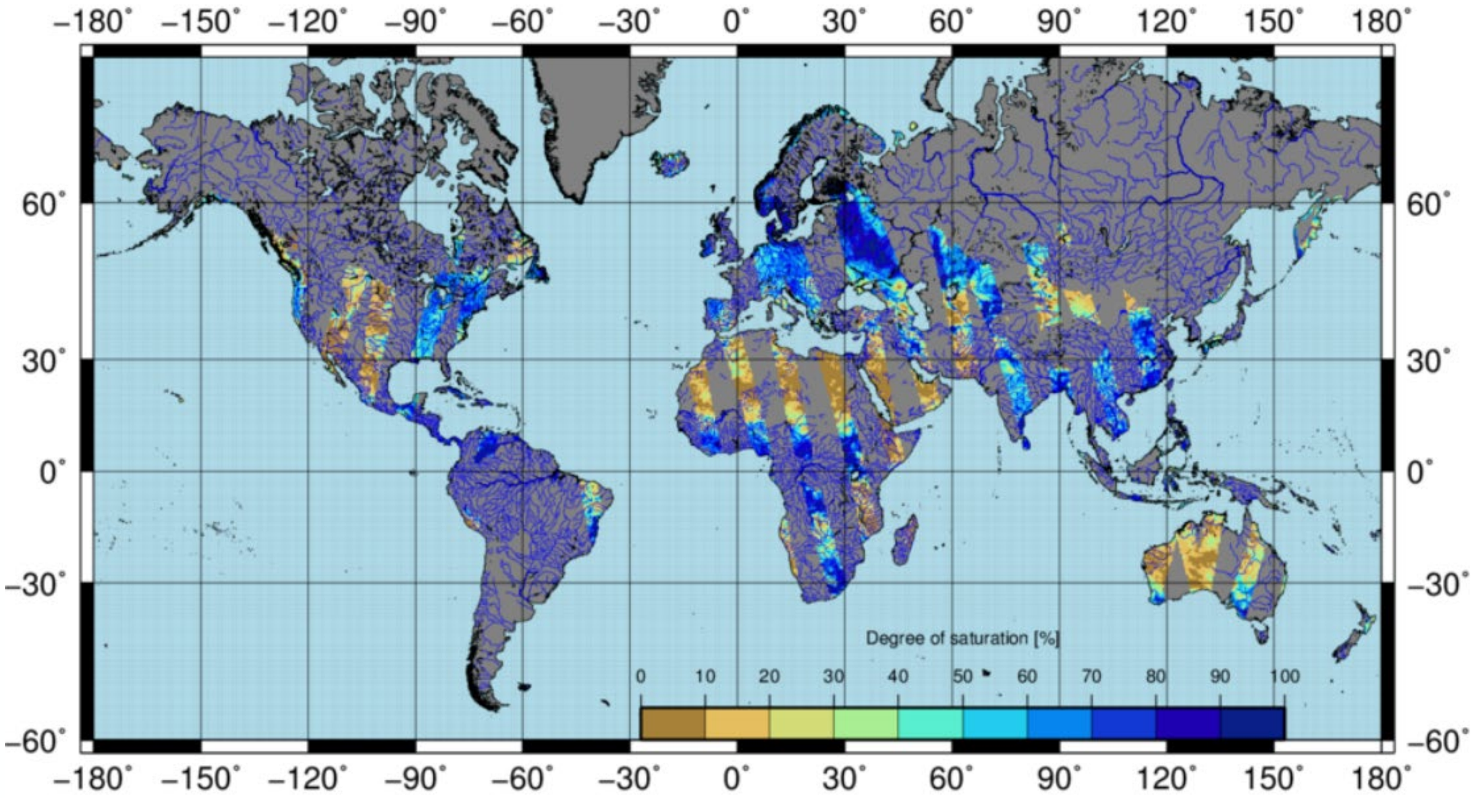
**Latency 2 hours**

2007 – now

12.5km

Sub-daily

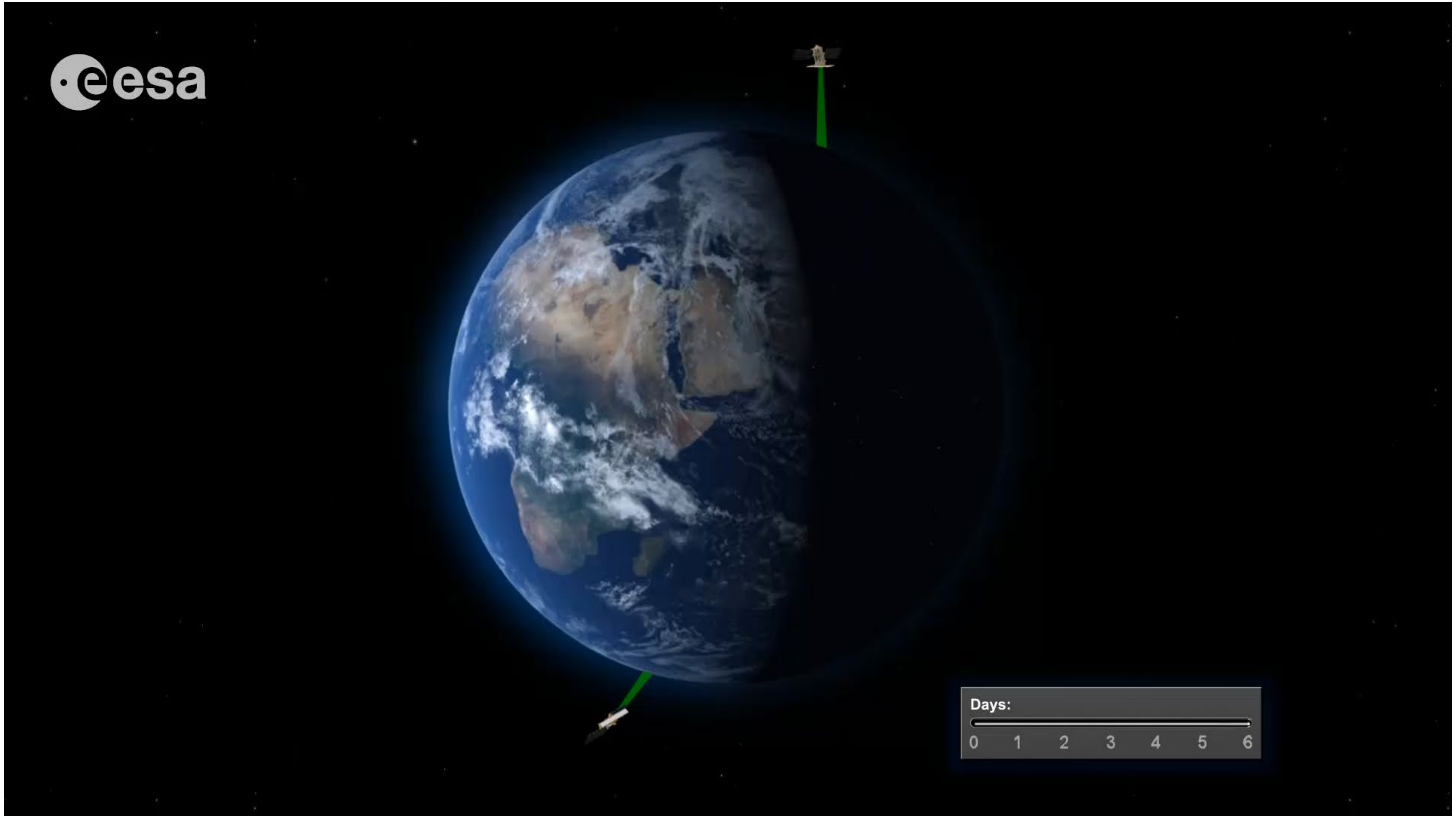
ASCAT soil moisture 20221103_0210, Metop–B, 125




https://hsaf.meteoam.it/Products/ProductsList?type=soil_moisture

EUMETSAT H SAF

# Sentinel-1 – A Game Changer

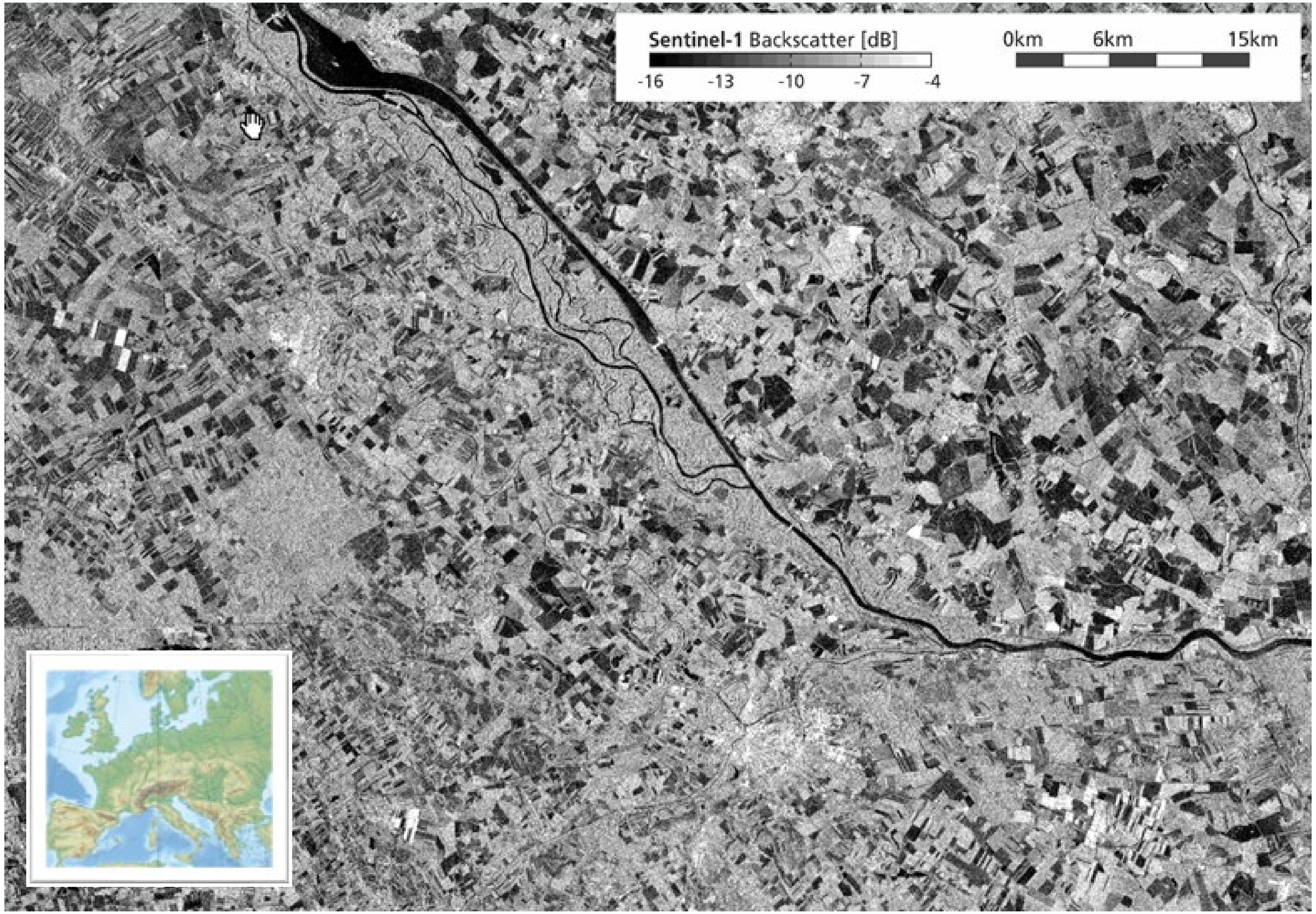


# Sentinel-1 – A Game Changer

C-band SAR satellite

High spatio-temporal coverage

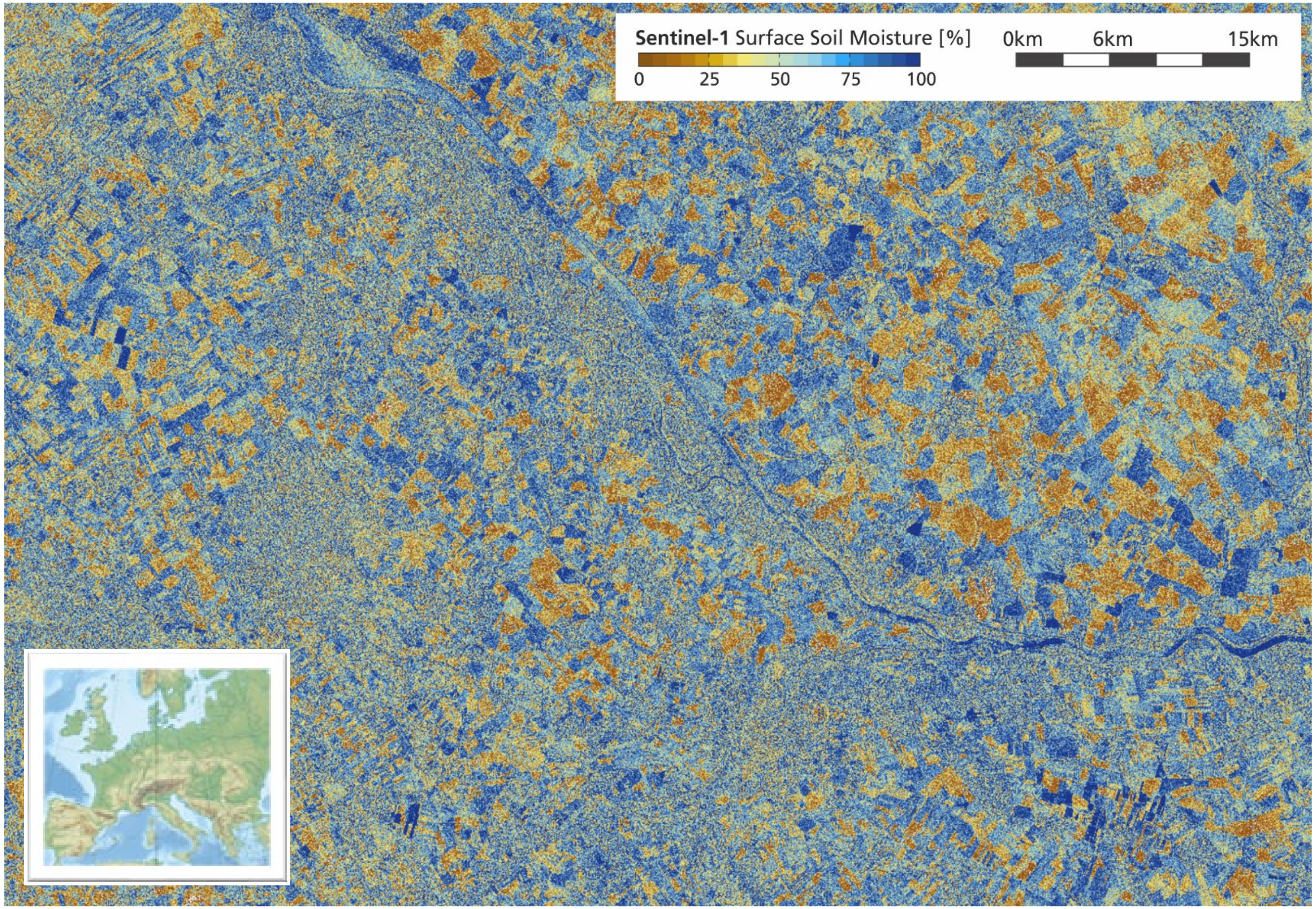
- Spatial resolution 20-80 m
- Temporal resolution < 3 days over Europe and Canada with 2 satellites




Copernicus
The European Earth Observation Programme

# Field Scale SSM

- Field scale SSM very complex
- Mostly driven by land cover
- Many assumptions of change detection or other models fail
- Failure becomes more prominent at higher resolution



# Retrieval Algorithm – Change Detection Method

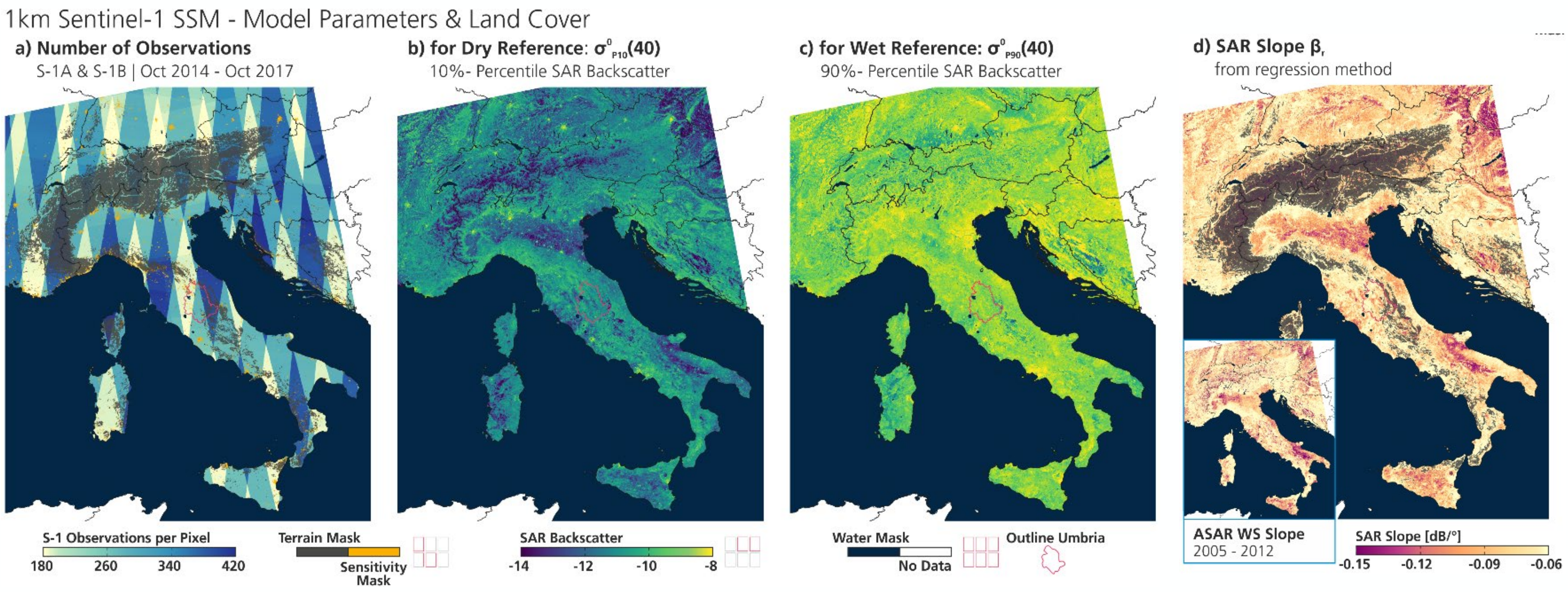



*Figure: Bauer-Marschallinger et al., 2018*

# Copernicus Global Land Service

Copernicus Global Land

1 km Sentinel-1 SSM for Europe

1 km ASCAT/Sentinel-1 SWI data for Europe

NRT

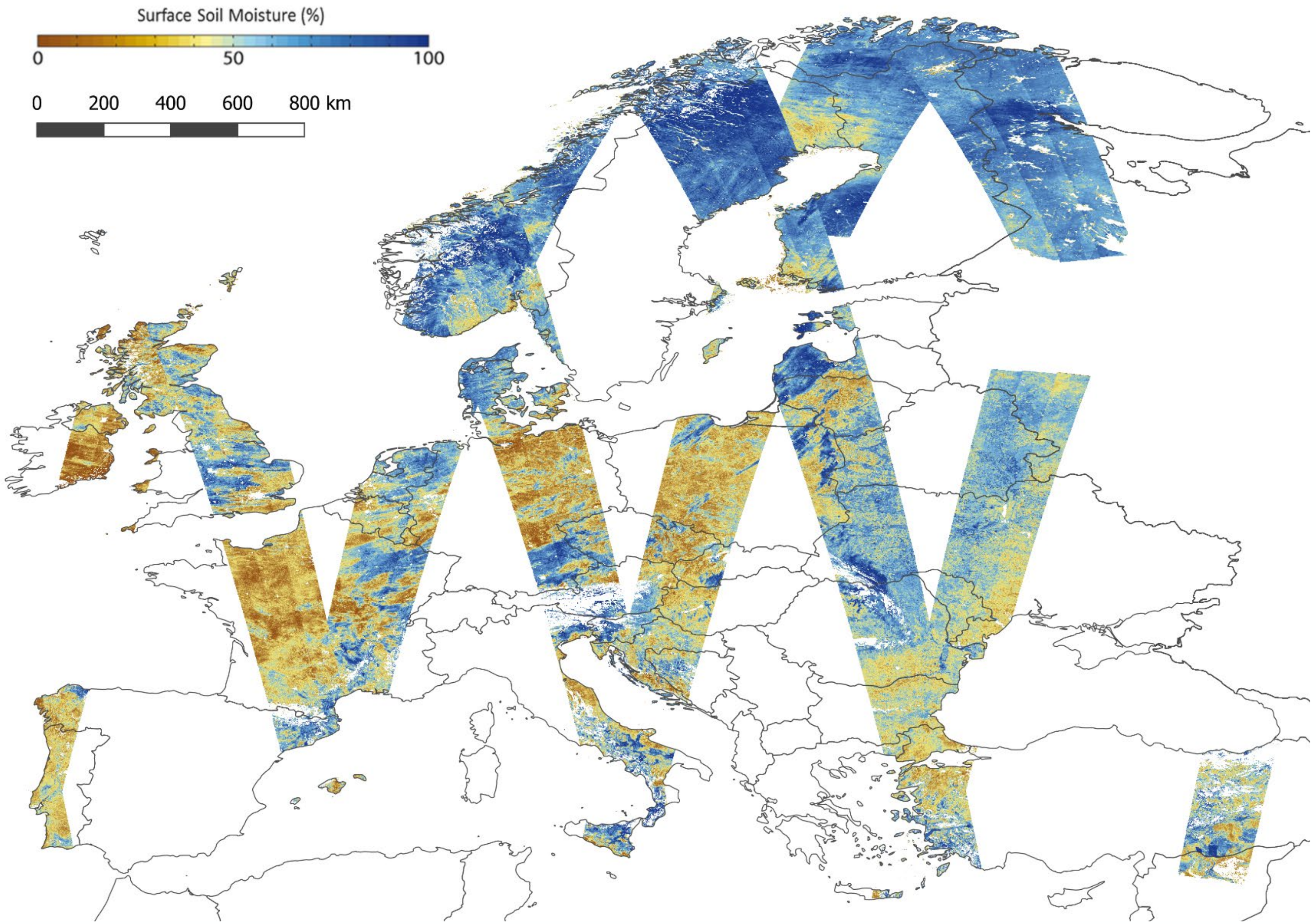
**Daily**

**Latency 24-48 hours**

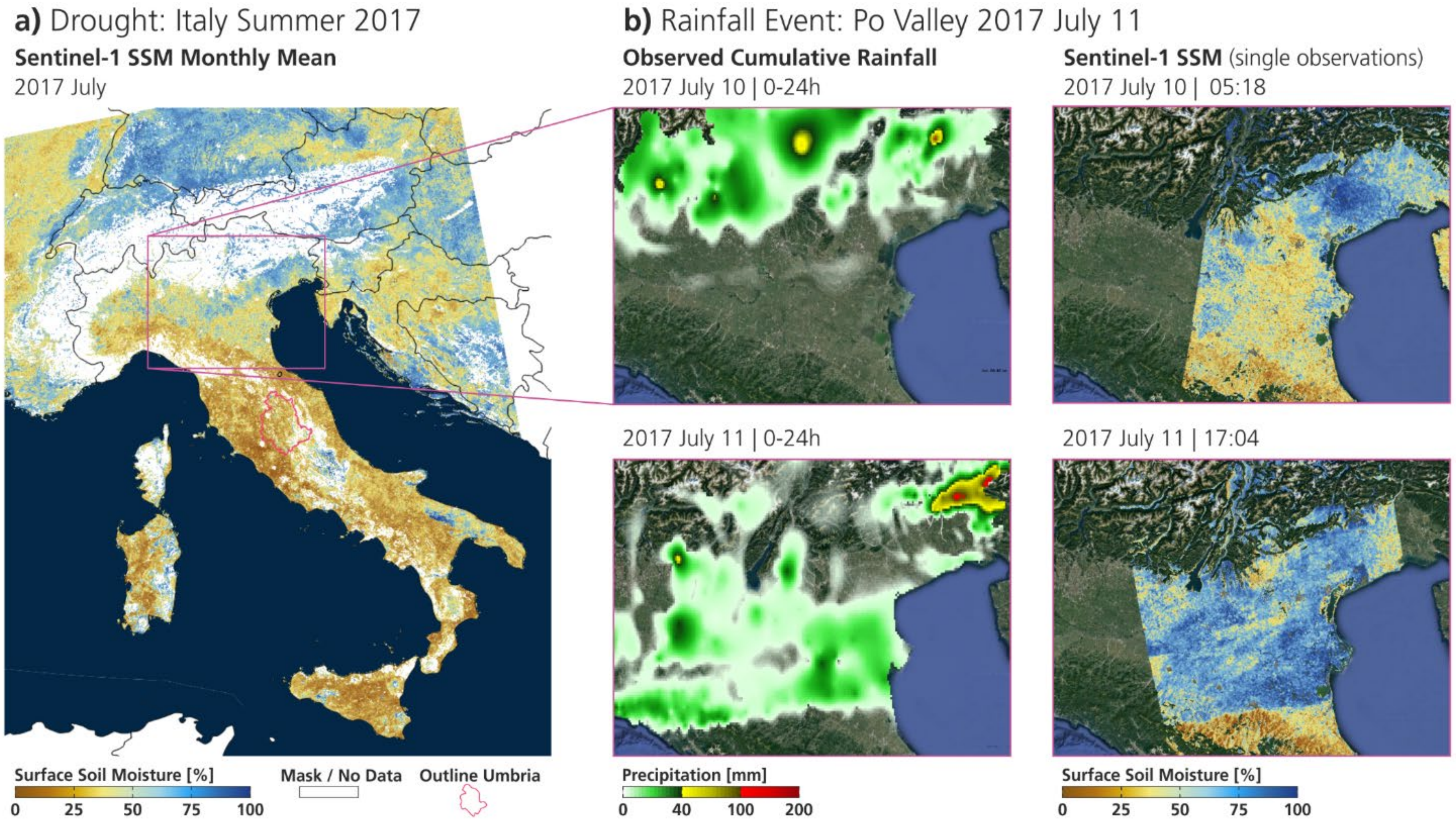
2015 – now

**500m**

1-4 days

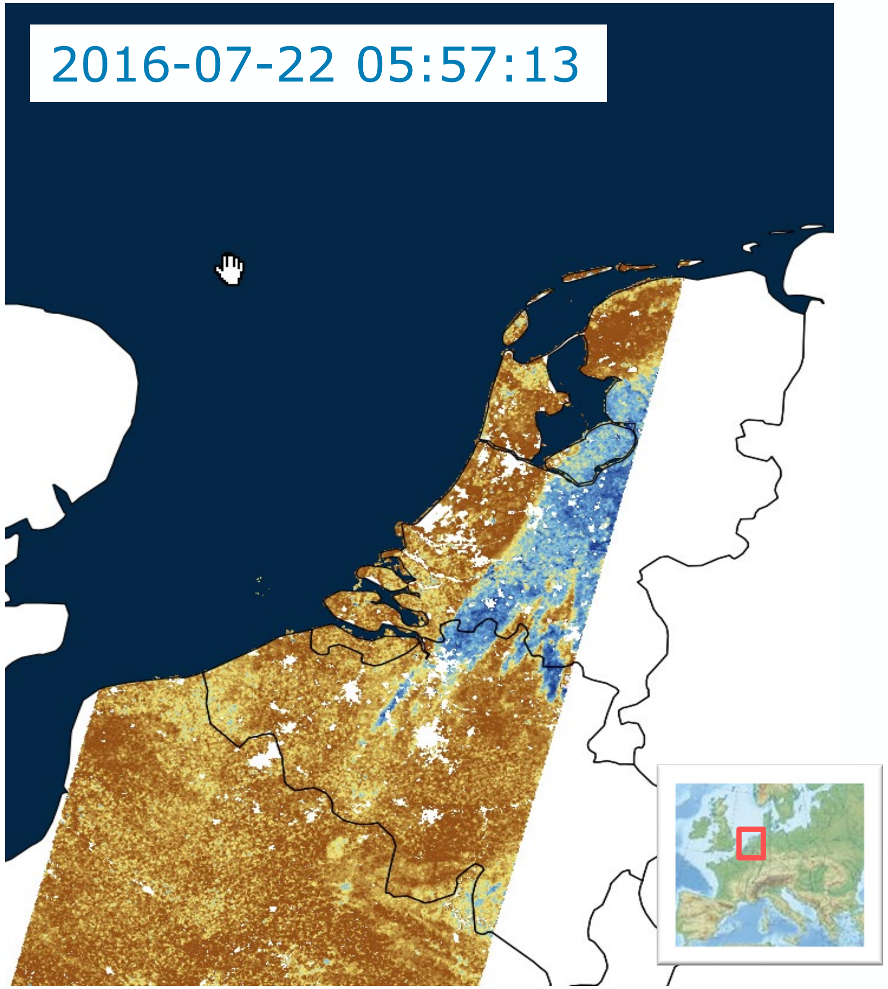


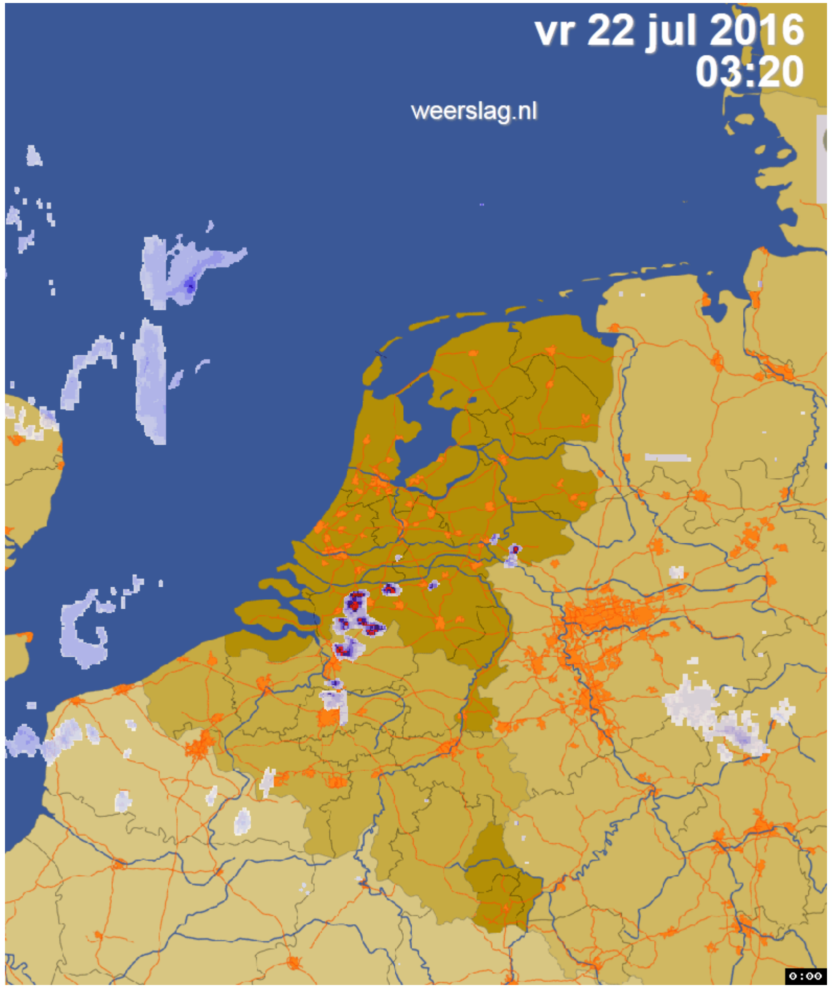
# Sentinel-1 Soil Moisture




*Bauer-Marschallinger et al., 2018, Towards Global Soil Moisture Monitoring with Sentinel-1: Harnessing Assets and Overcoming Obstacles", in* IEEE Transactions on Geoscience and Remote Sensing

# Sentinel-1 Soil Moisture & Precipitation Radar




*Graphic by B. Bauer-Marschallinger, TU Wien*

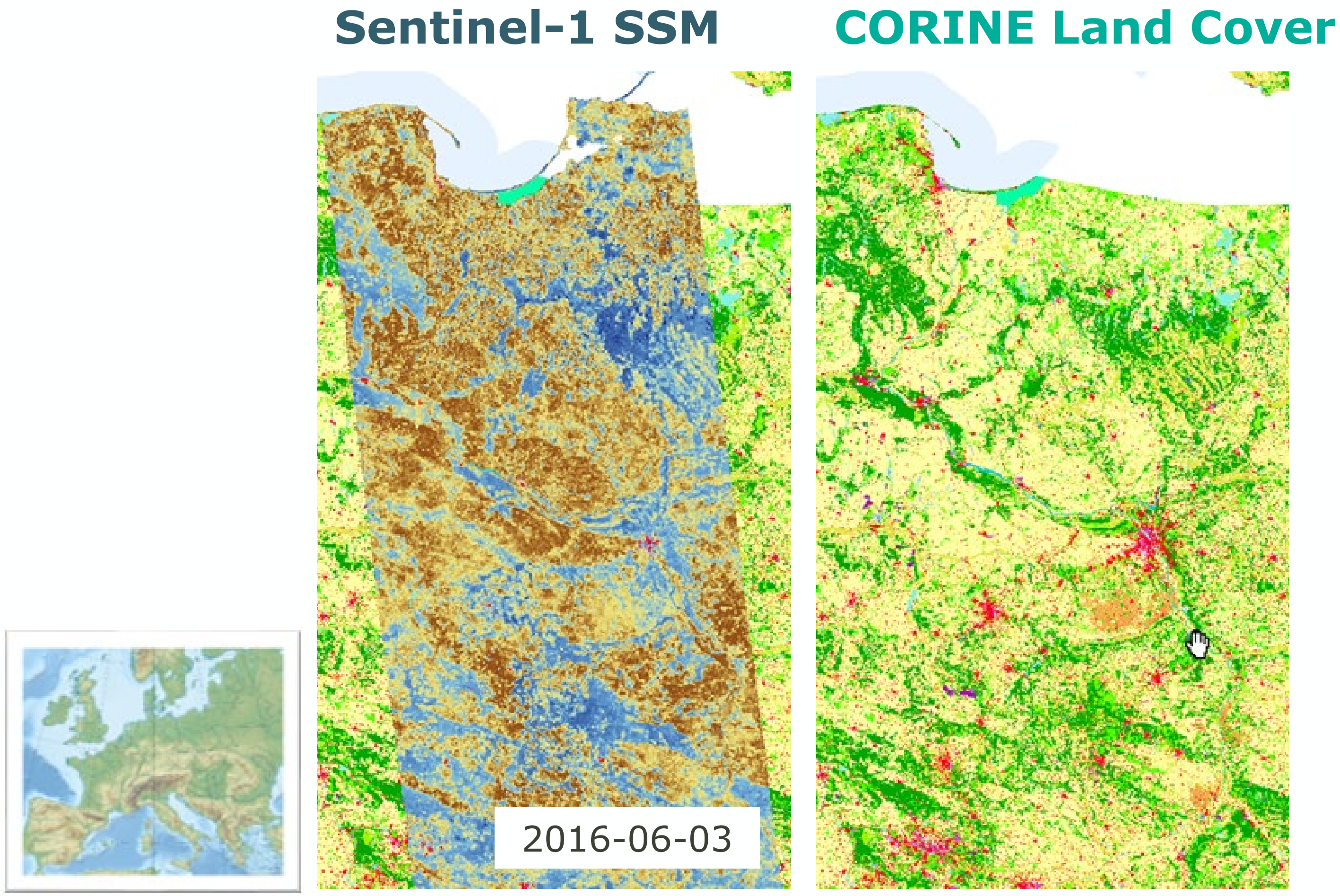
# Limitations & Improvements – Vegetation Biases

Retrieval algorithm currently does not take vegetation dynamics into account.

Vegetation density and water content unknown.

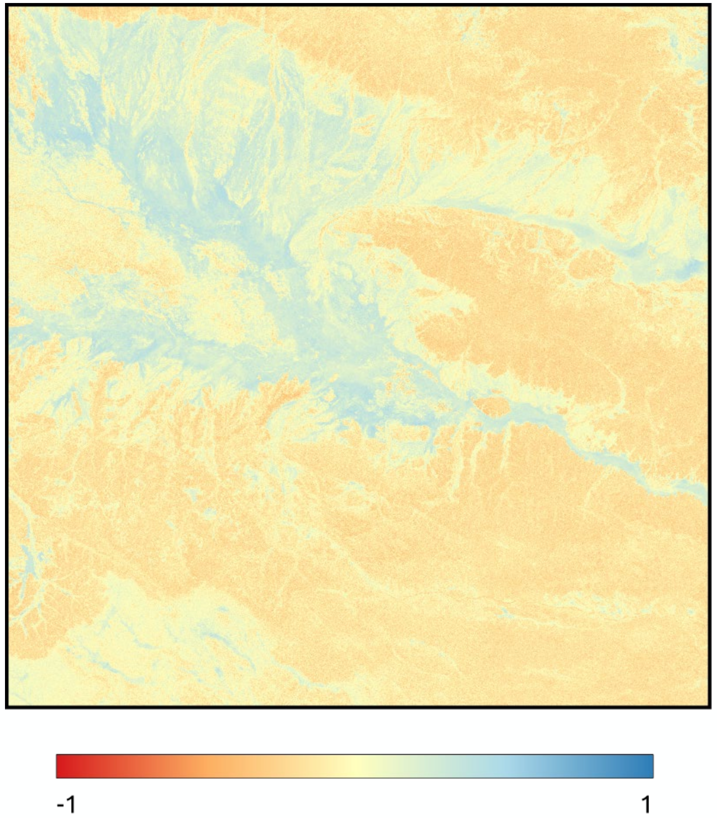
Potential improvements?

- Model vegetation attenuation using radiative transfer models such as RT1 (see R. Quast et al., 2023).
- Integrate VH-polarised data.
- Separate seasonal calibration parameters.

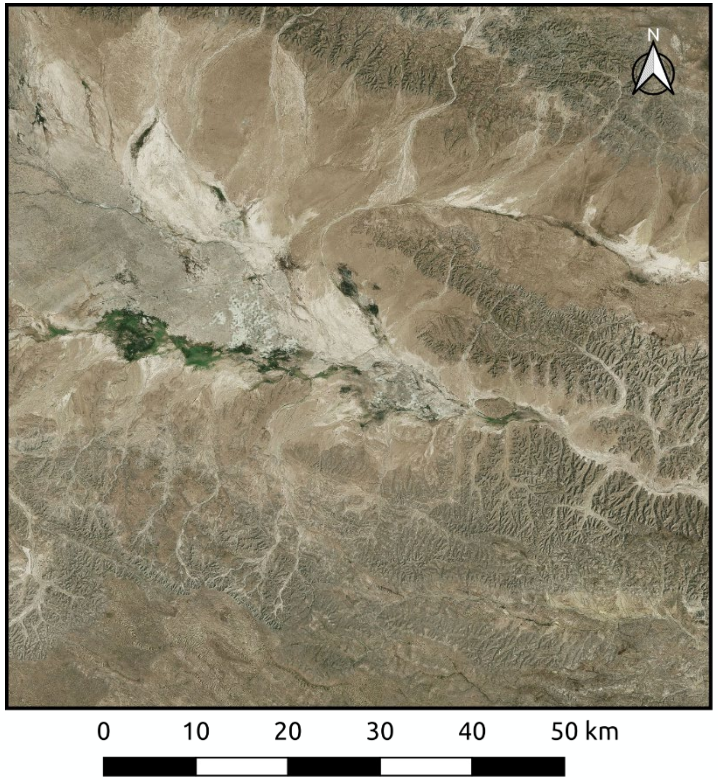



*Graphic by B. Bauer-Marschallinger, TU Wien*

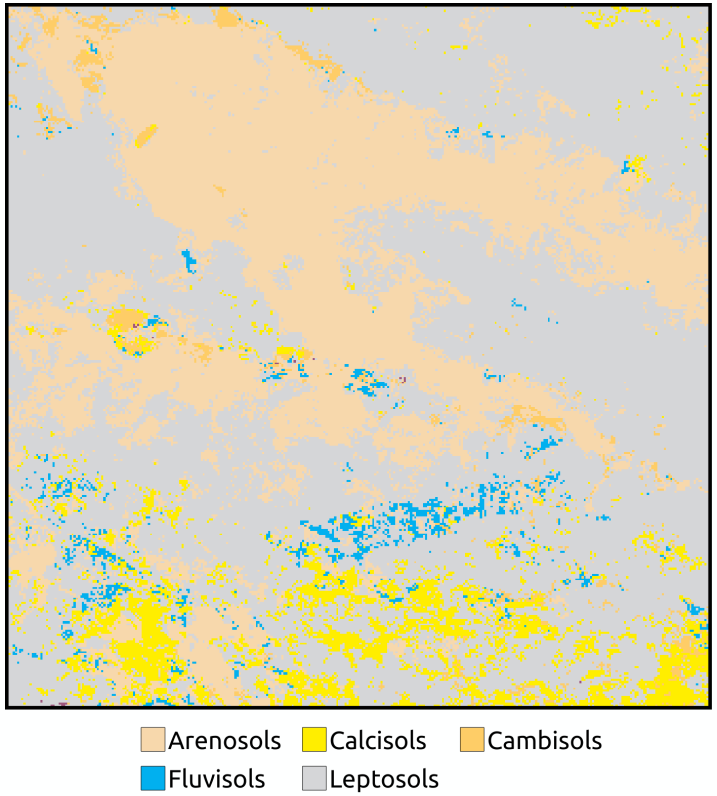
## Backscatter correlation to ERA5-Land Soil Moisture – Horn of Africa




Pearson r $\sigma°$ to ERA5-Land swvl1




Optical image Bing Aireal




SoilGrids soil groups

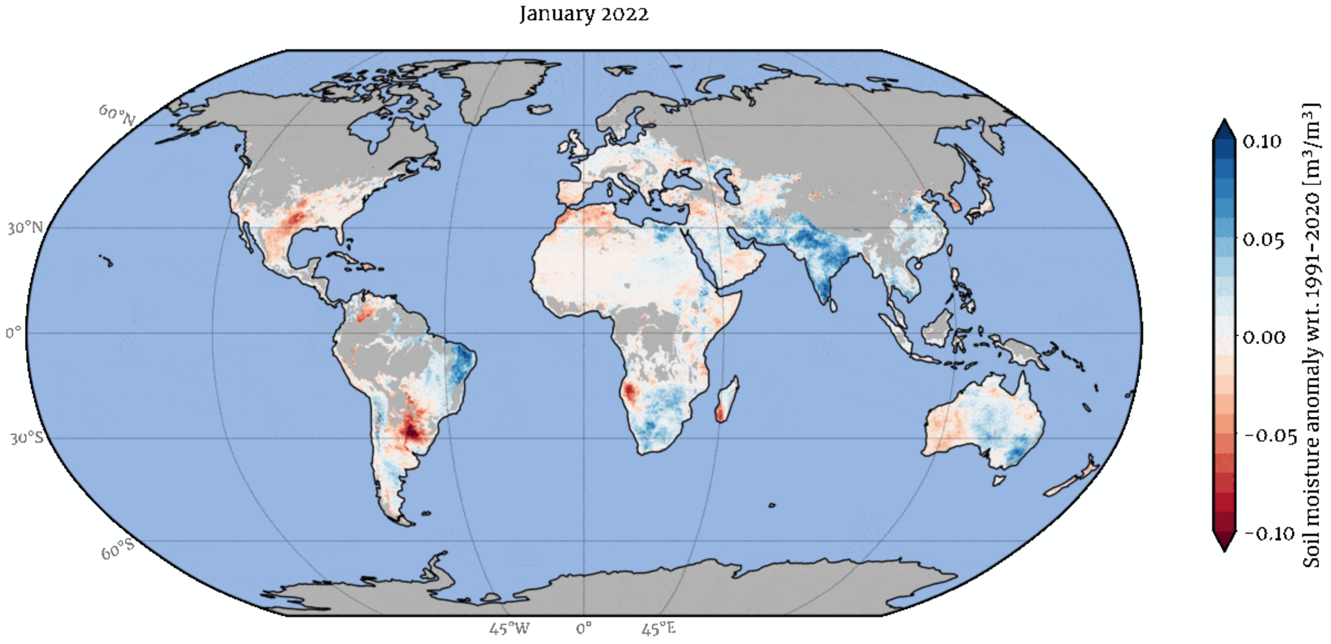
*Graphics by B. Raml, TU Wien*

# Climate Data Record

# ESA CCI Soil Moisture

**ESA CCI Soil Moisture** as a successful response to the need for independent, consistent, observation-based and multi-decadal climate data records, having:

- 12000+ registered users
- 100+ publications per year
- Benchmark dataset in BAMS State of the Climate

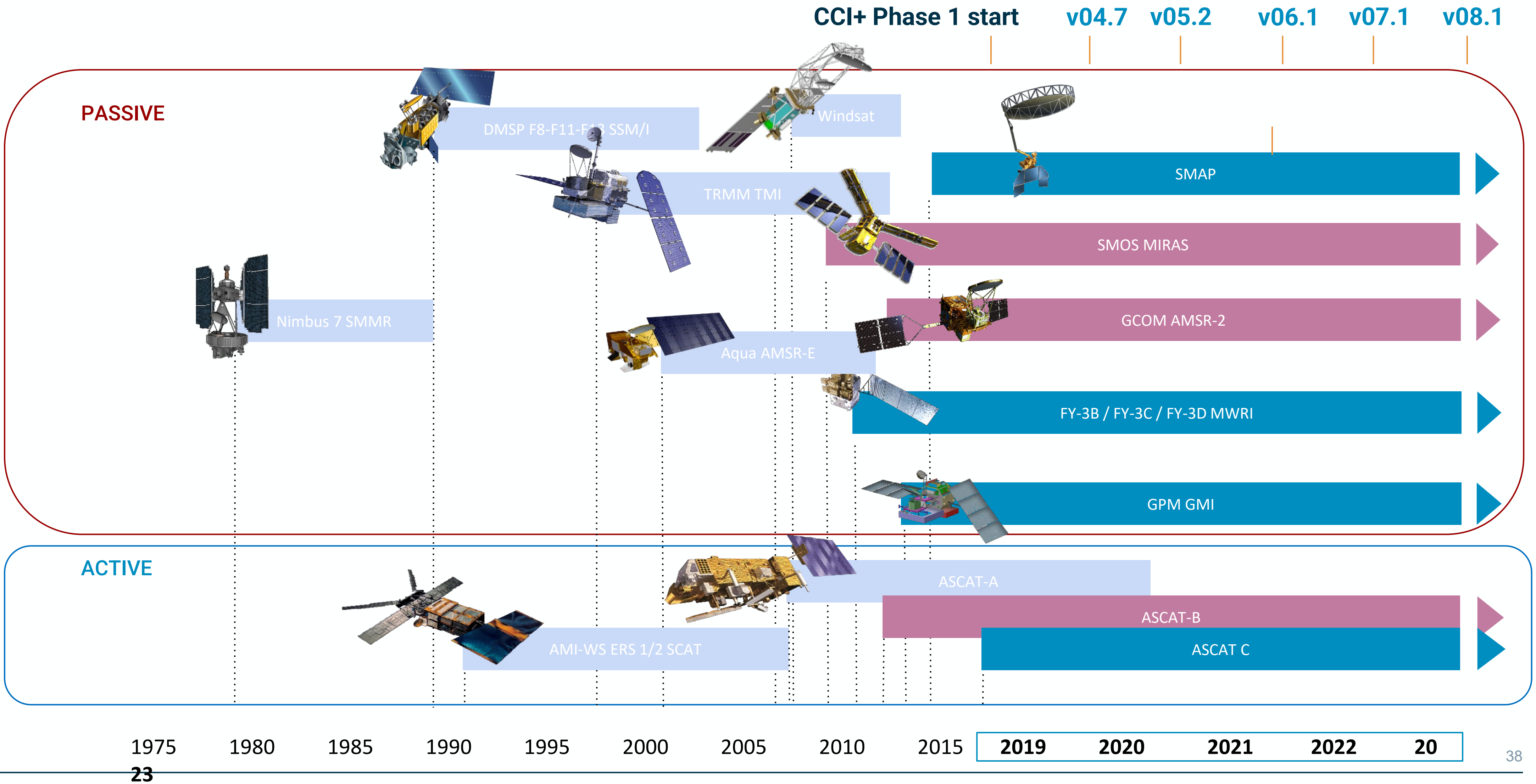



soil moisture cci

A collaboration between

TU WIEN, GEO, planet., eodc, ETH zürich, INRAE, KU LEUVEN, CESBIO, METEO FRANCE, VanderSat

# Development of the Climate Data Record




Operational, updated

Before CCI+ Phase 1

Added with CCI+ Phase 1

**Version 8.1 (1978-2022) is now available!**

# Scientific Evolution – general objectives

**Extension**, increase robustness by adding and updating satellites

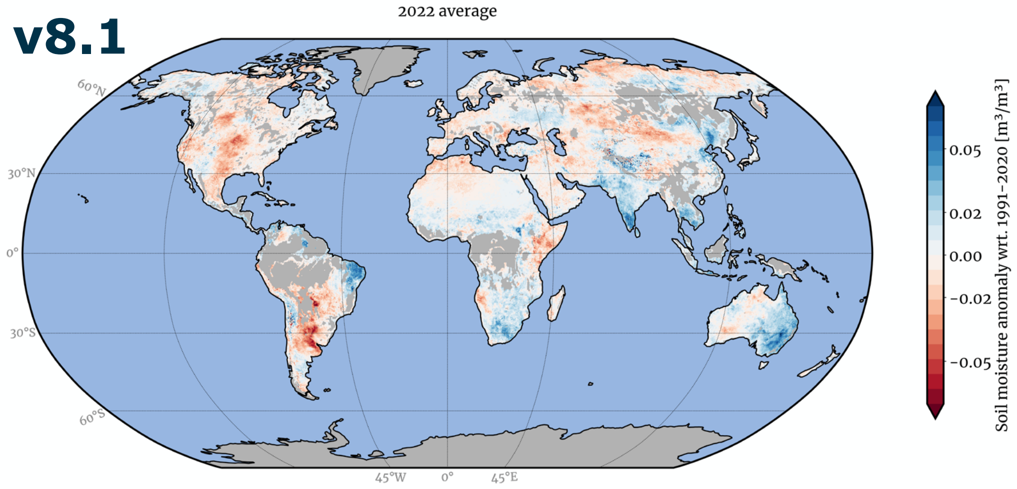
**Consistency**, improve merging and calibration on all levels

**Model independency**, remove impact from LSM where possible

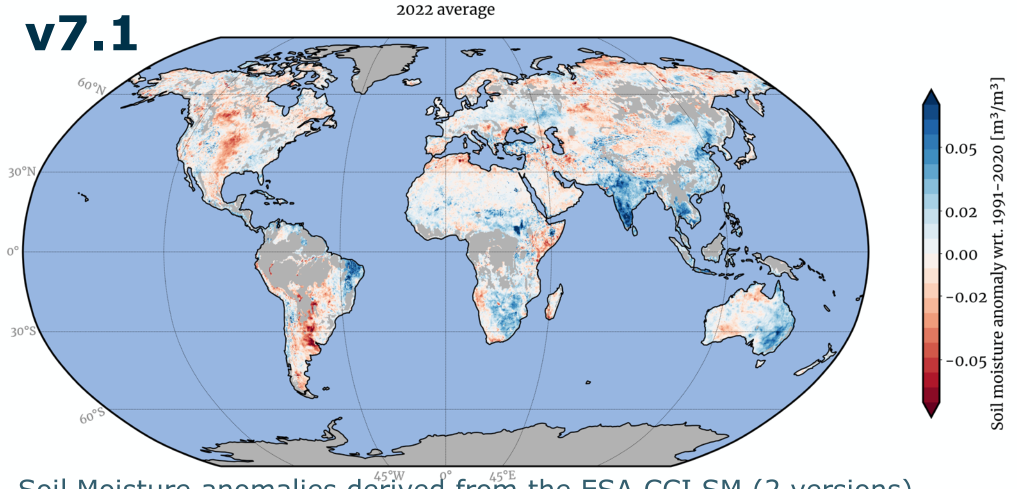
**Skill**, best reflect actual conditions by improving retrieval algorithms

**Understand**, both the strengths and weaknesses of the datasets

**v8.1**




**v7.1**

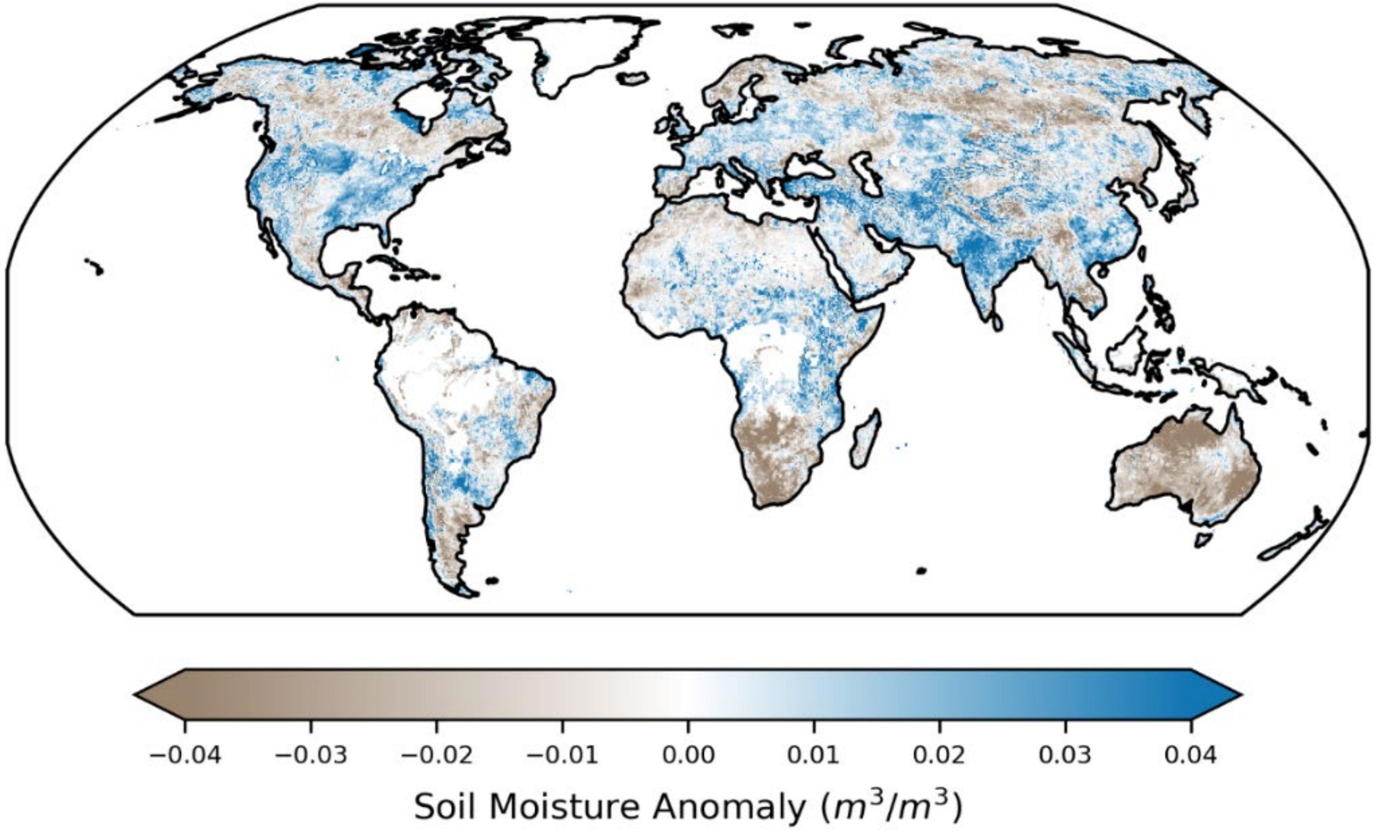



Soil Moisture anomalies derived from the ESA CCI SM (2 versions) using the 1991-2020 reference period

# C3S Soil Moisture (C3S)

- NRT implementation of CCI methodology
- **updated every 10 days**
- Latency 10 days
- 1978 – now
- 0.25°
- daily, dekadal, monthly

Annual 2019 COMBINED SM Anomalies (v201812, 1991-2010 climatology)




http://climate.copernicus.eu/

Climate Change Service

# Validation and Quality Assurance

# Quality Assurance of EO SM Products

Estimating **systematic** and **random** errors through analytical comparison to reference data

Validation (or better: Evaluation) can be done using:

- Field campaigns
- In situ networks
- Model data
- Satellite products

Common metrics:

- Pearson correlation coefficient
- Unbiased Root Mean Square Difference

Remote Sensing of Environment 244 (2020) 111806

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

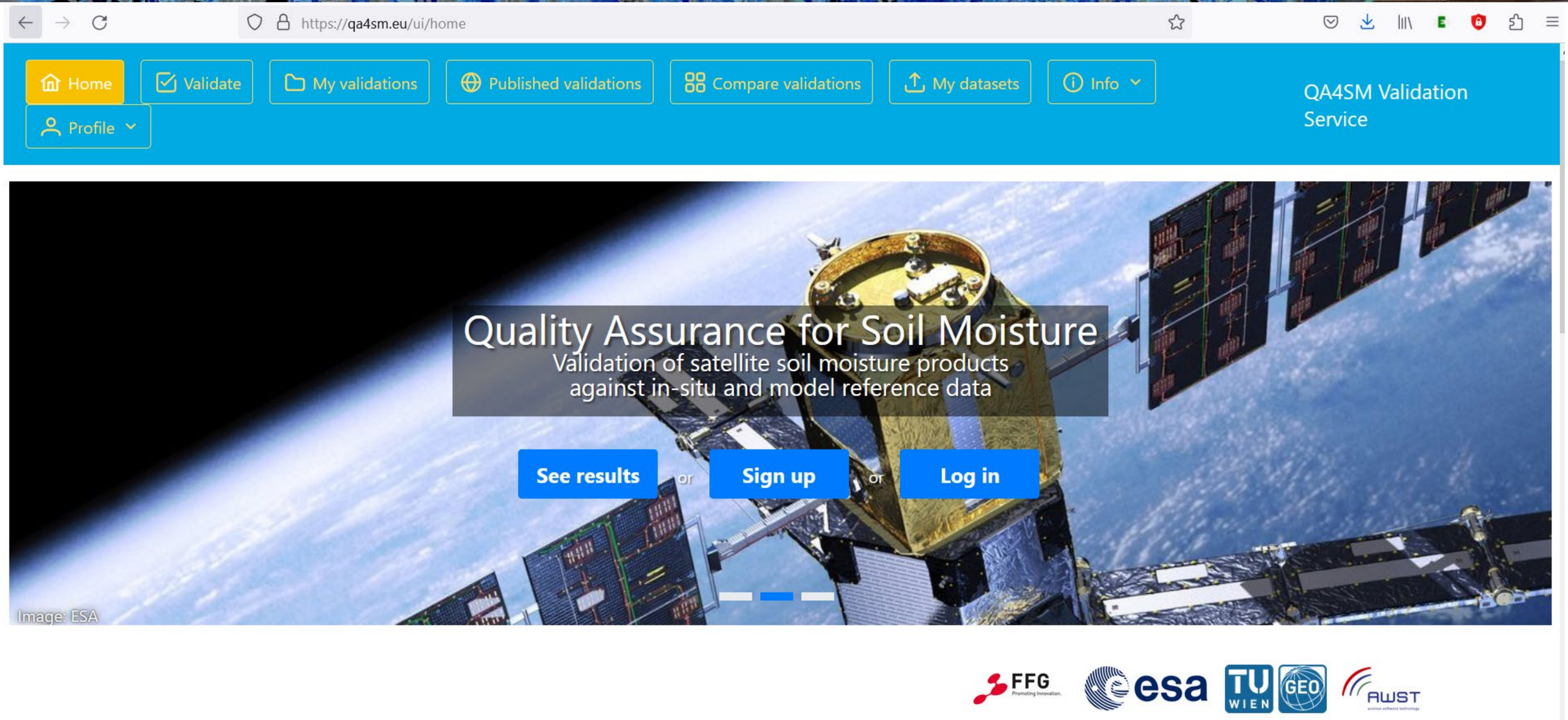
ELSEVIER

Review

Validation practices for satellite soil moisture retrievals: What are (the) errors?

A. Gruber[a,*], G. De Lannoy[a], C. Albergel[b], A. Al-Yaari[c], L. Brocca[d], J.-C. Calvet[b], A. Colliander[e], M. Cosh[f], W. Crow[f], W. Dorigo[g], C. Draper[h], M. Hirschi[i], Y. Kerr[j], A. Konings[k], W. Lahoz[l], K. McColl[m], C. Montzka[n], J. Muñoz-Sabater[o], J. Peng[p], R. Reichle[q], P. Richaume[j], C. Rüdiger[r], T. Scanlon[g], R. van der Schalie[s], J.-P. Wigneron[t], W. Wagner[g]

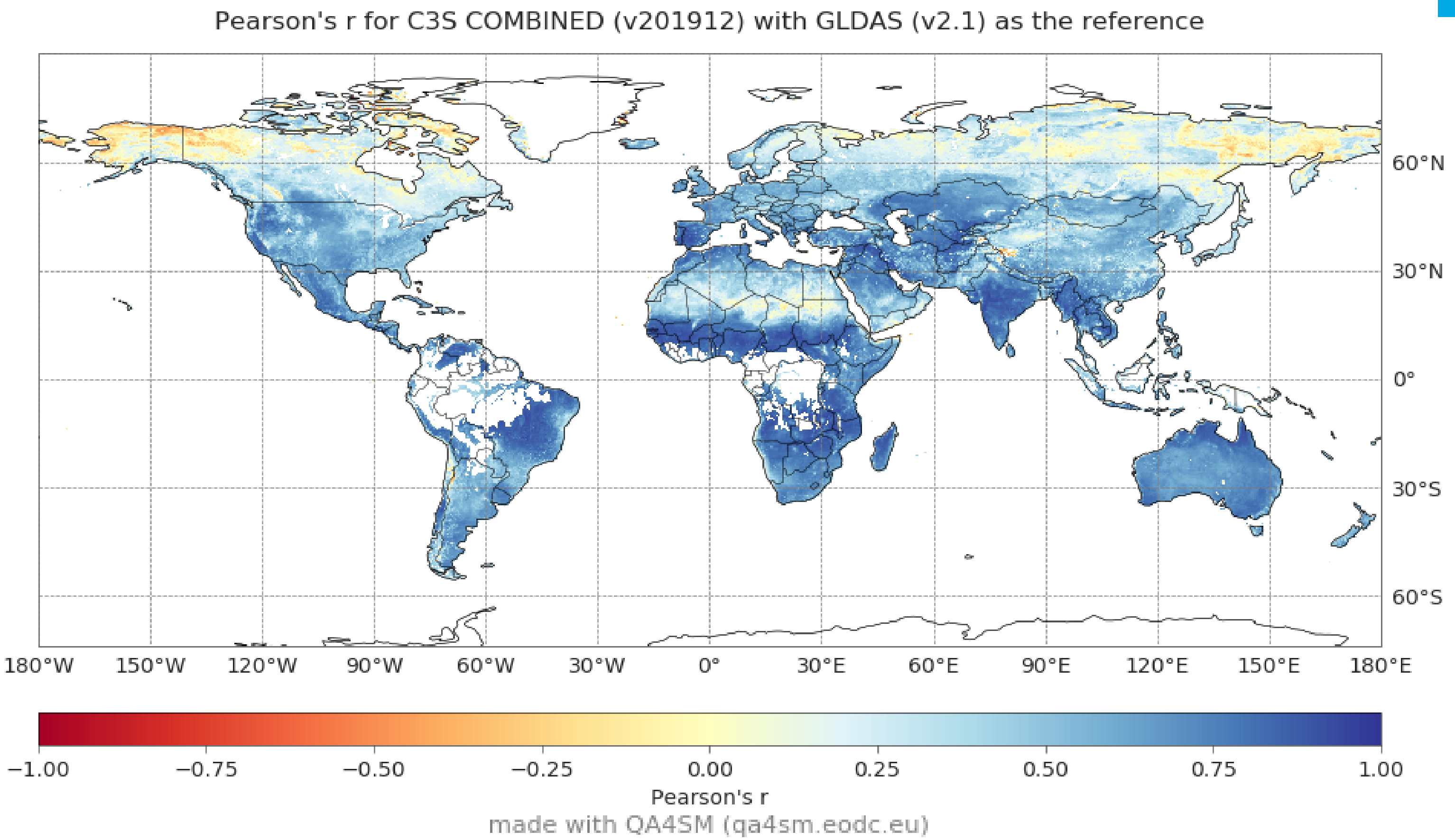
# Quality Assurance for Soil Moisture (QA4SM)



# Quality Assurance for Soil Moisture (QA4SM)

## Using http://qa4sm.eu

QA4SM Validation Service



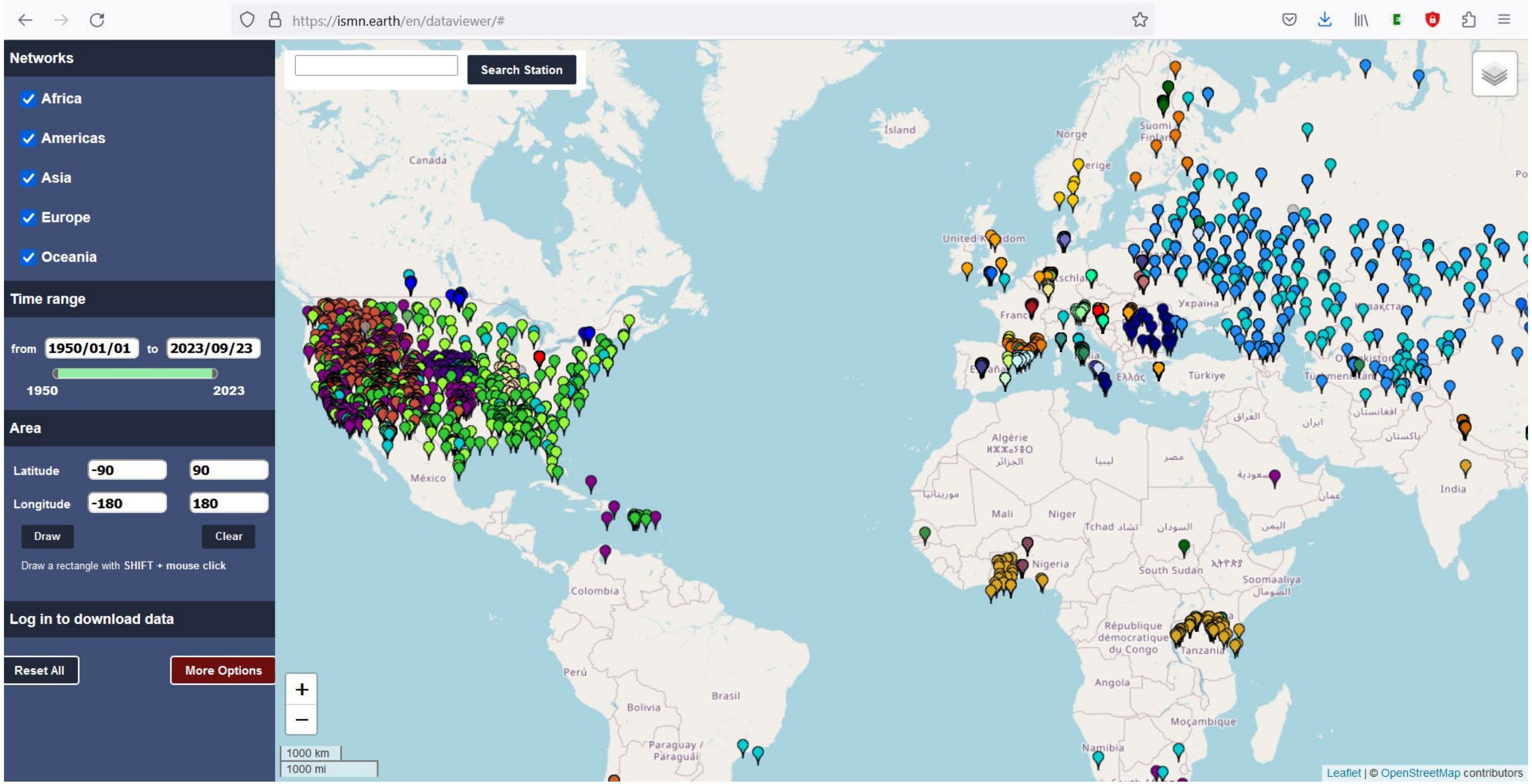

Correlation (Pearson) of the C3S v201912 COMBINED product with GLDAS v2.1 (covering the time period 2000-01-01 to 2019-12-31)

**pytesmo a Python Toolbox for the Evaluation of Soil Moisture Observations**

# International Soil Moisture Network

>75 networks

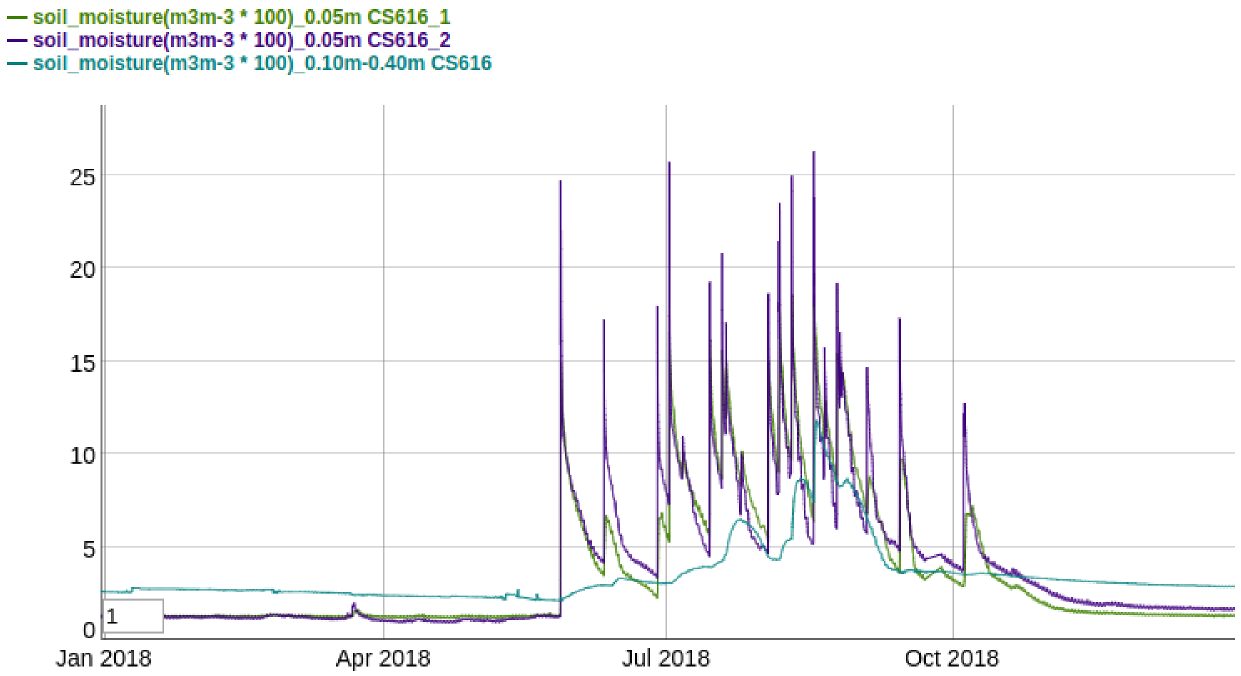
>3000 stations




https://ismn.earth

# International Soil Moisture Network

Dataviewer Station: Tondikiboro from: 2017/12/31 to: 2018/12/31




Drag an area vertical or horizontal to zoom in. Double click to zoom to whole date range.

**Select variables to show in graph**

soil_moisture(m3m-3 * 100)_0.05m CS616_1
soil_moisture(m3m-3 * 100)_0.05m CS616_2
soil_moisture(m3m-3 * 100)_0.10m-0.40m CS616

To see more data change the time interval on the left an press refresh.

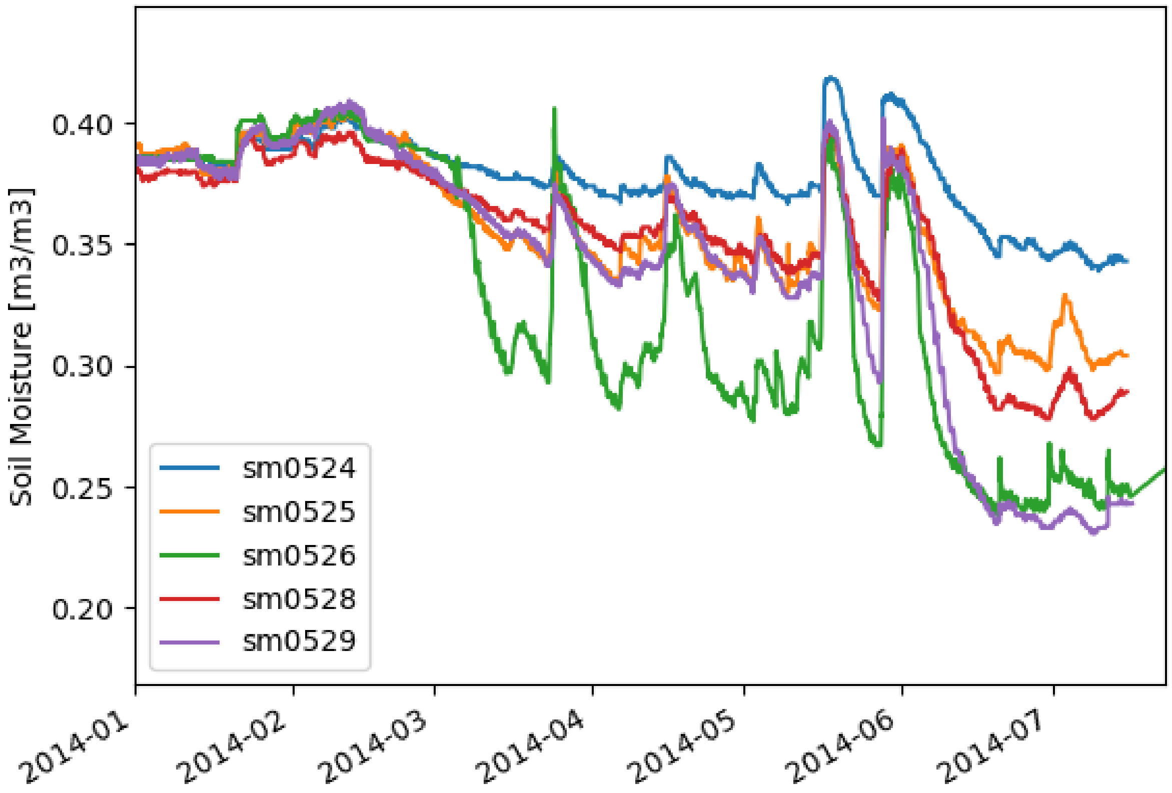
Refresh Close

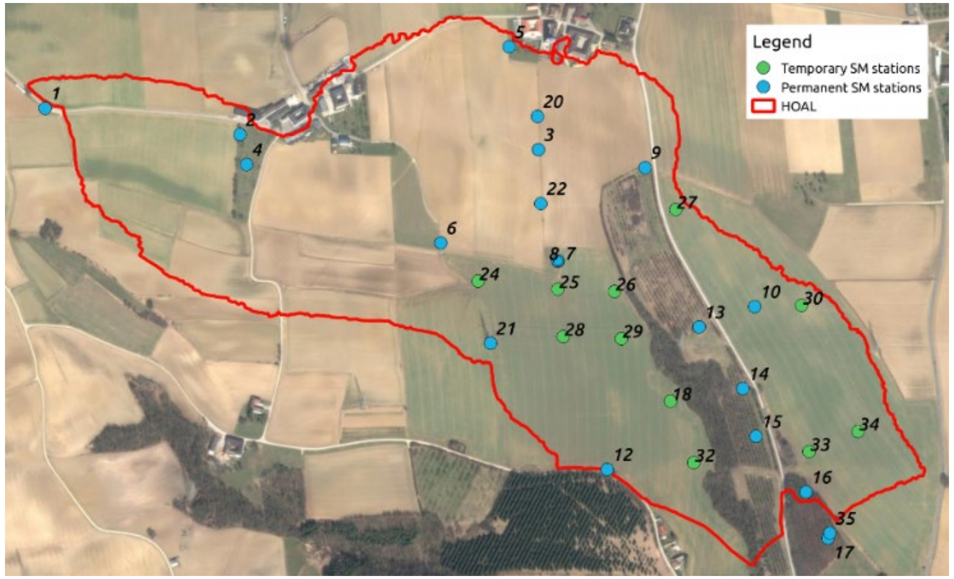
**https://ismn.earth**

# Representativeness of In Situ Data?

Soil moisture can vary within one field with the same land cover

Temporal stability concept




HOAL Soil Moisture Network, Petzenkirchen, Austria

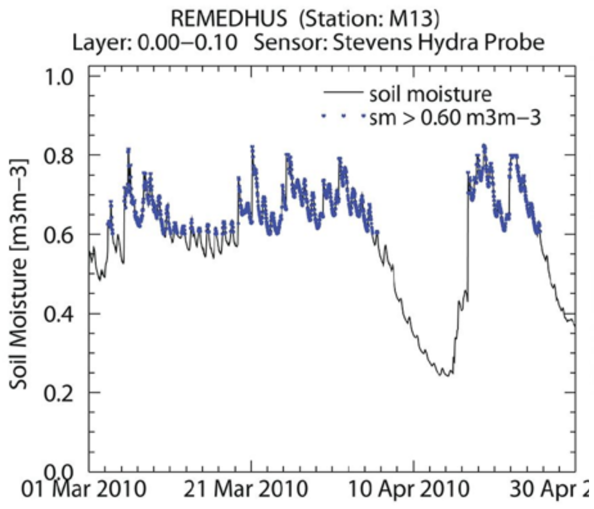
Vienna Doctoral Programme on Water Resource Systems

# International Soil Moisture Network

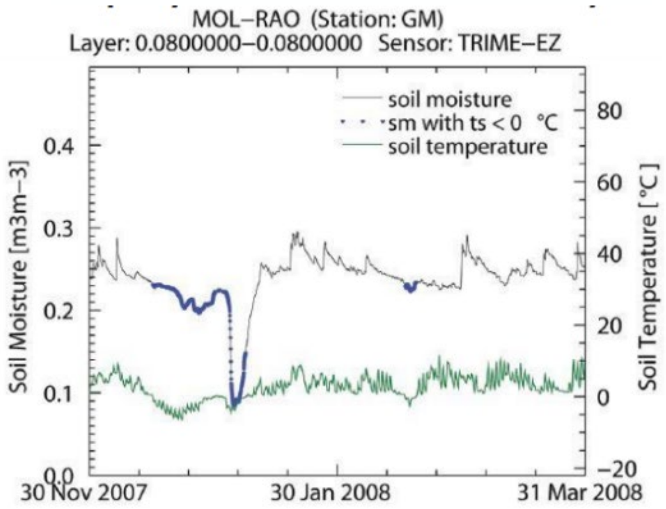
- Keeping flags from provider (rarely provided)
- quality flag added to each measurement (CEOP standards)

| Flag category | Flag values | Definition |
|---|---|---|
| C | C01 - C03 | Threshold based flags for all variables used in the ISMN (soil moisture, soil temperature, temperature air, etc.) |
| D | D01 - D10 | Questionable /dubious |
| M | | Parameter value missing OR derived parameter can not be computed |
| G | | Good |

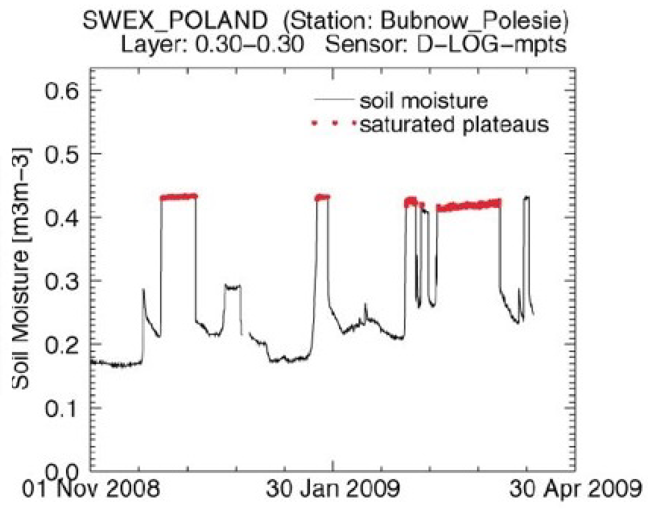
**1) Geophysical Dynamic Range**



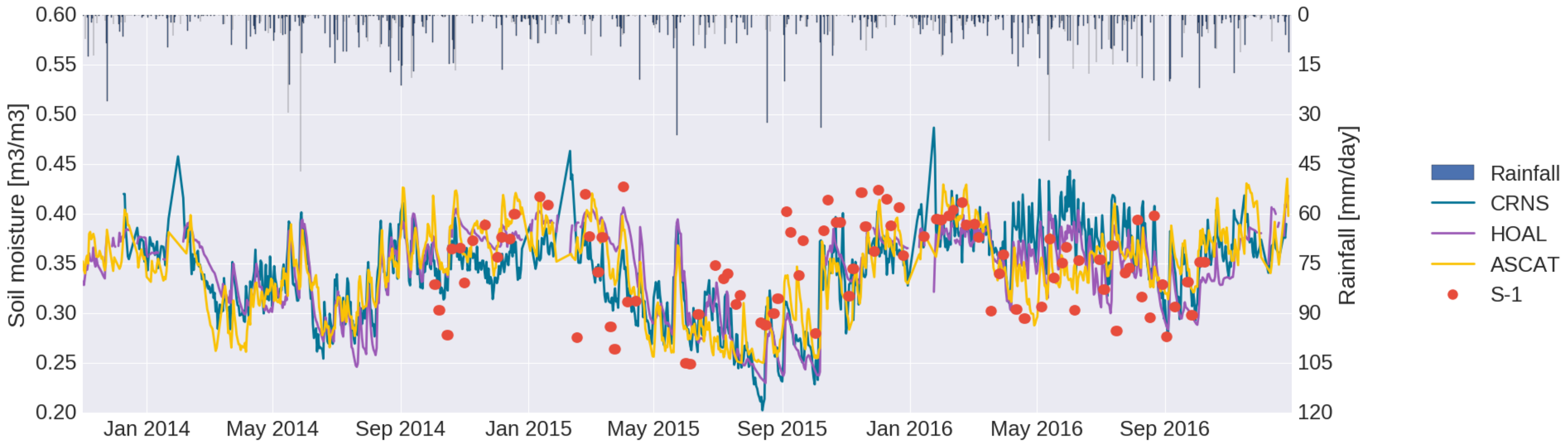

**2) Geophysical Consistency**




**3) Spectrum Based**



# Validation with In Situ Soil Moisture Data over HOAL



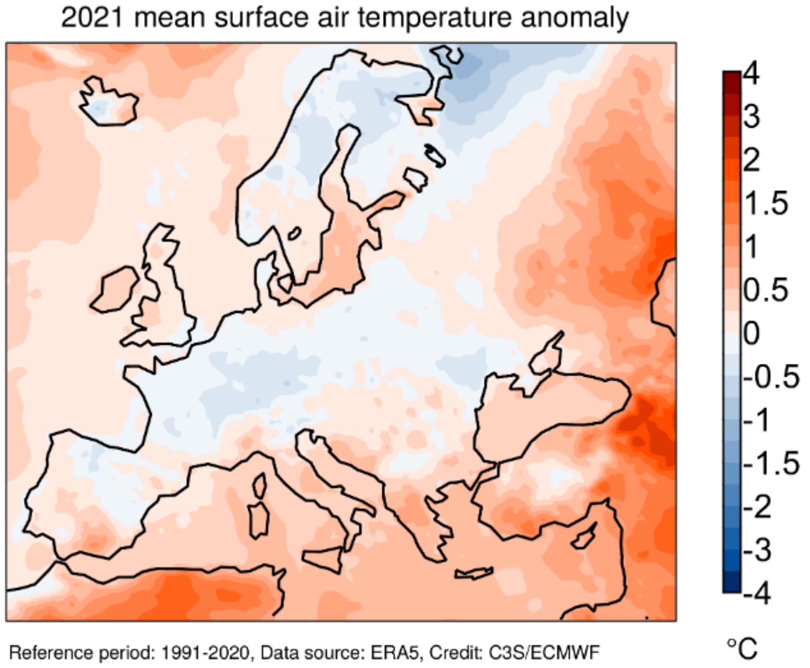

CRNS: Cosmic Ray Neutron Sensor
HOAL: Catchment average of 31 TDT measurements
ASCAT: 25 km ASCAT soil moisture retrievals (yellow)
S-1: 1 km Sentinel-1 soil moisture retrievals

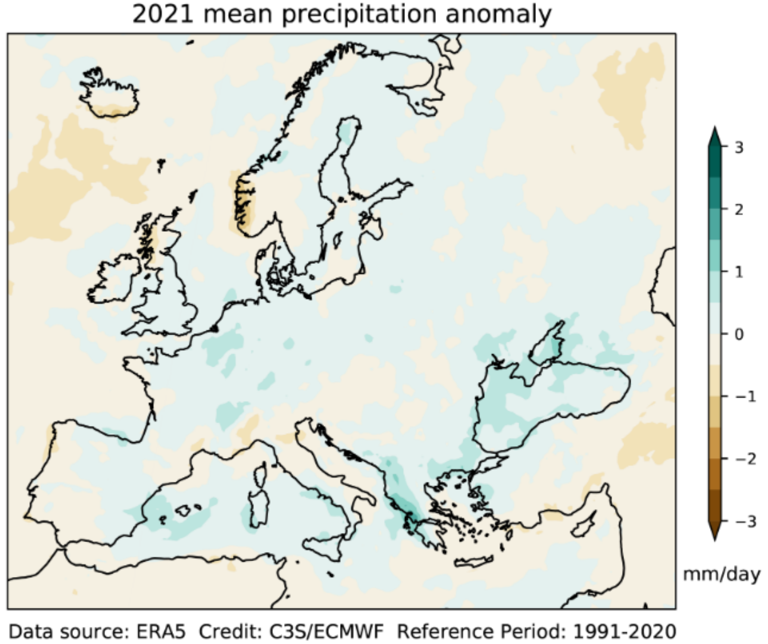
Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

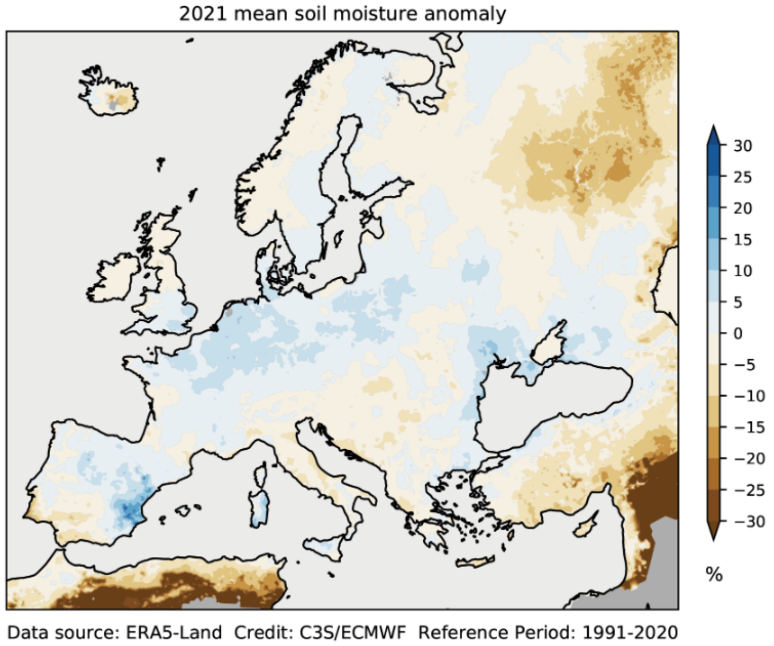
Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Austria

Vienna Doctoral Programme on Water Resource Systems

# Examples and Applications



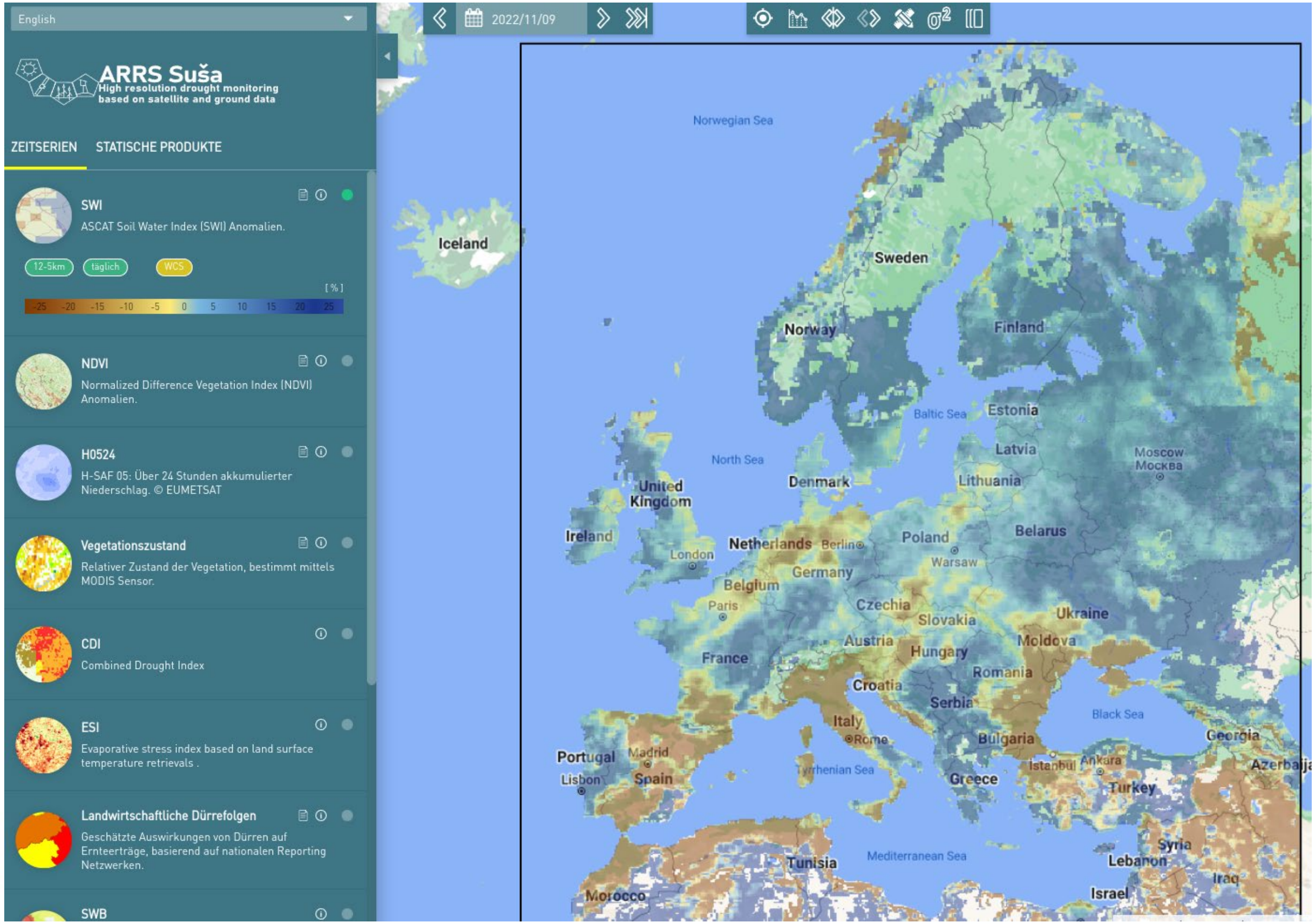

Anomalies of modelled temperature and precipitation, and satellite soil moisture anomalies for 2021.

http://climate.copernicus.eu/

Climate Change Service

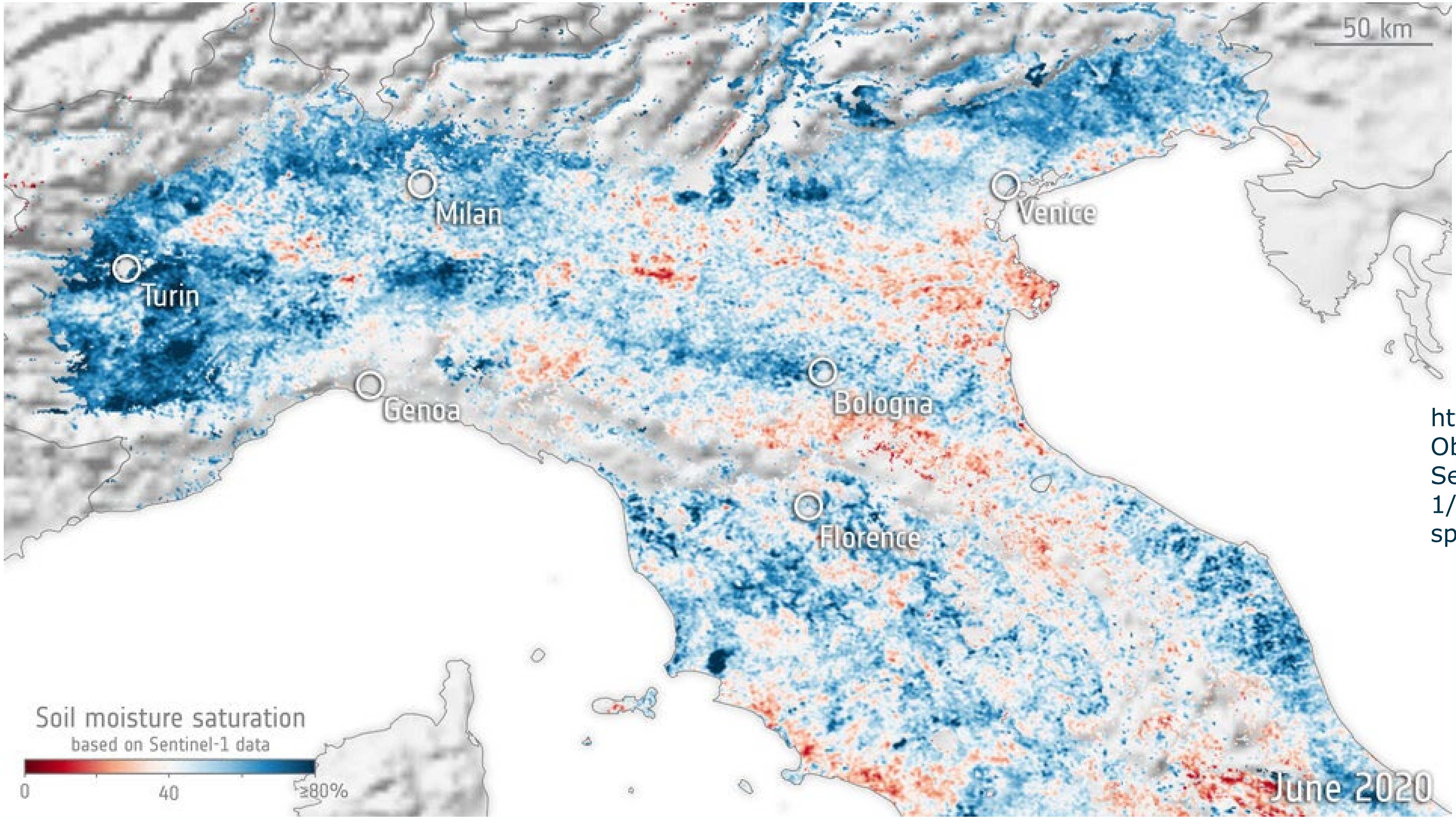
# Drought Monitoring

droughtwatch.eu



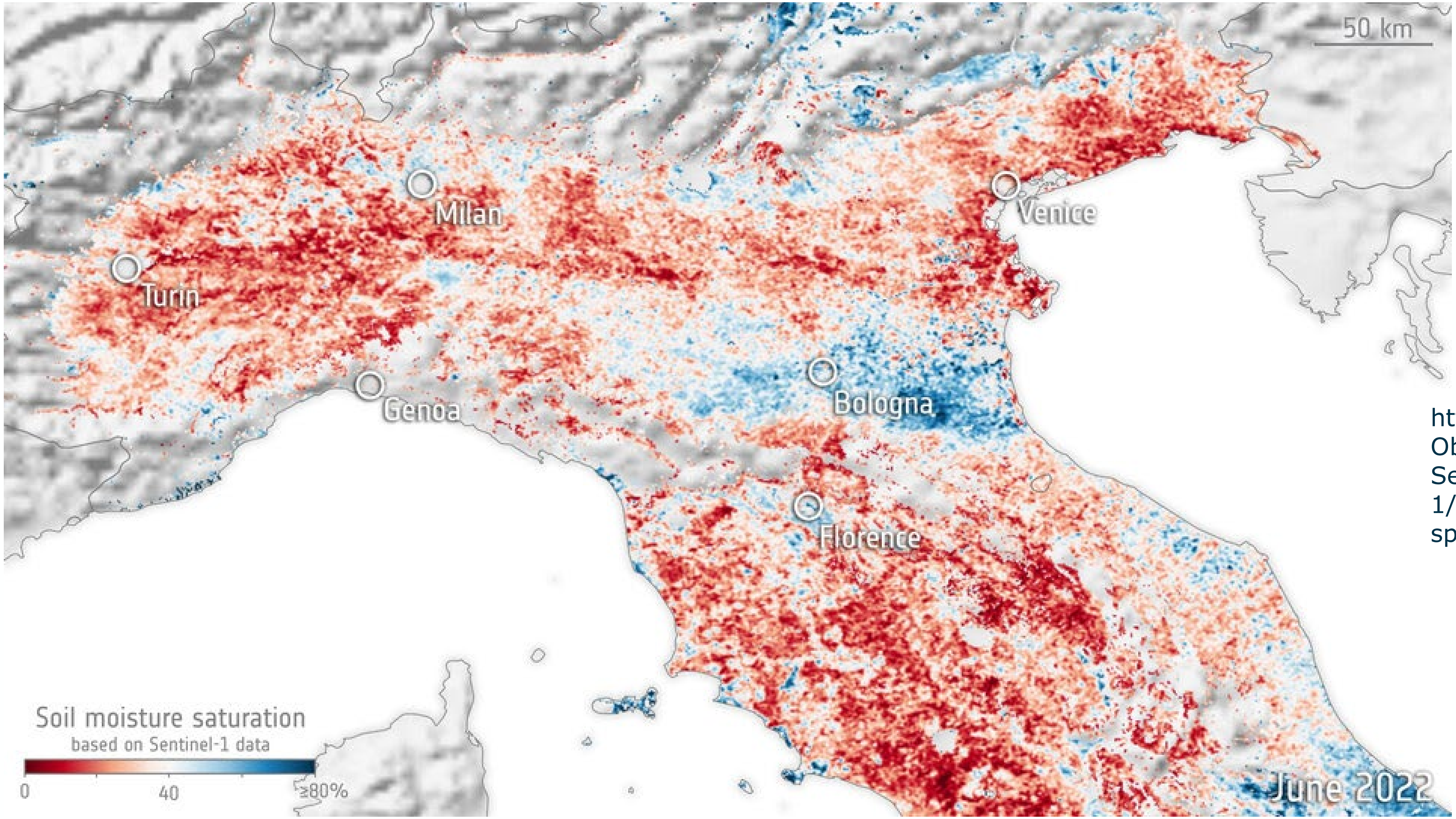

Interreg
Danube Transnational Programme
DriDanube

# Drought Monitoring




https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Zooming_in_on_drought_from_space

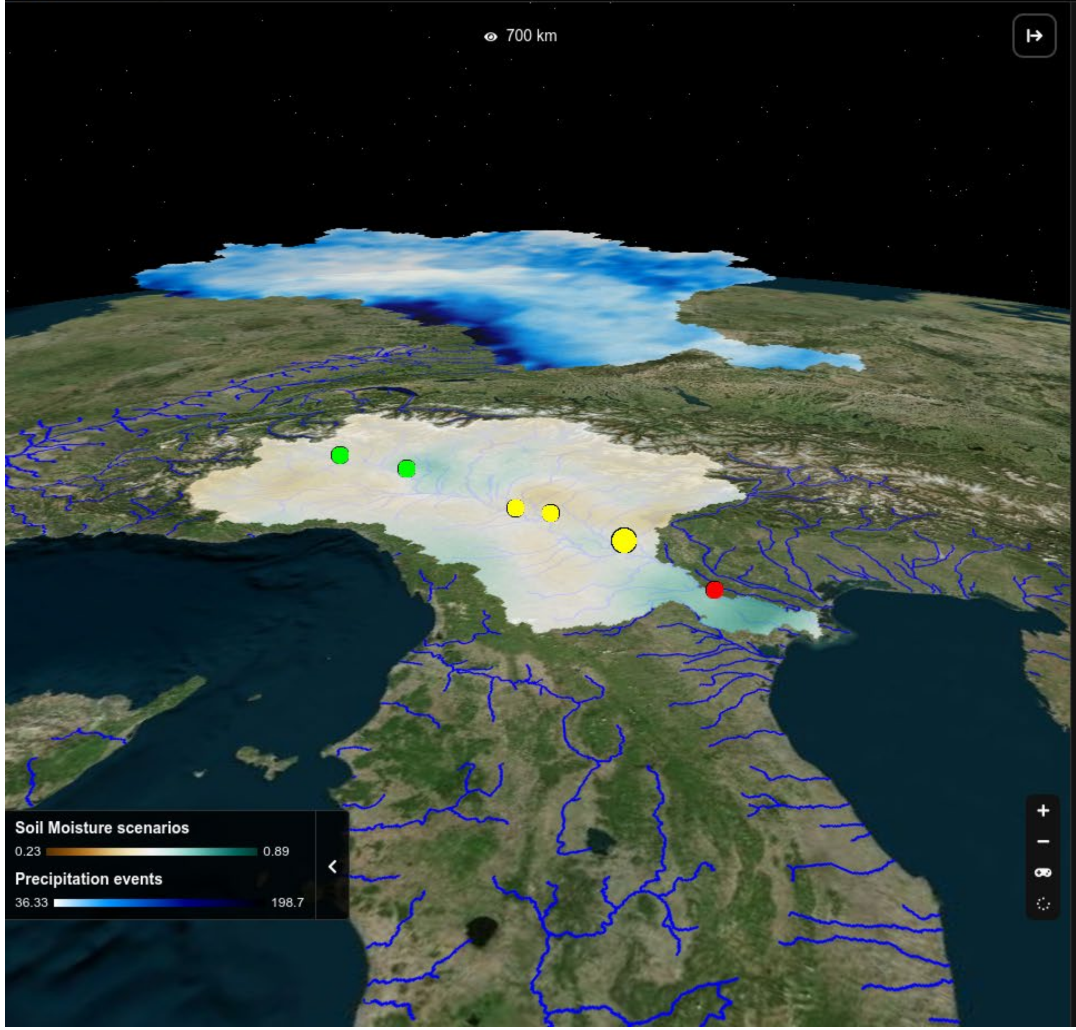
# Drought Monitoring




https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Zooming_in_on_drought_from_space

# Digital Twin Earth

DTE HYDROLOGY




## What-if scenario for flood risk assessment

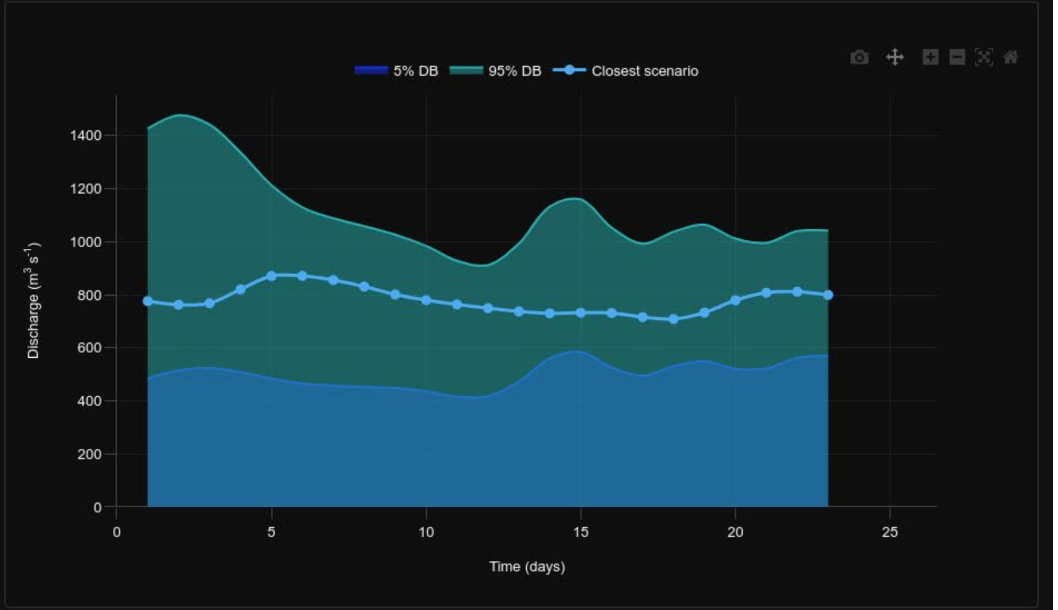
The "what-if scenario for flood risk assessment" provides the data over the **Po river**'s basin for 25 initial soil moisture conditions and 29 cumulated precipitation events. The map shows the selected initial conditions (soil moisture at the surface, precipitation at the top level) and respective alerts for 6 stations. The green markers represent low alert *(0—500)*, the yellow ones represent medium alert *(501—1000)* and the red ones represent high alert *(1001+)*.

The hydrograph displays the ensemble of river discharge on the station of **Borgoforte**.
To switch between stations click on the markers on the map.
To change the initial conditions edit the values in the "Soil moisture mean" and/or the "Precipitation mean" fields.

**Soil moisture mean**: 0.5

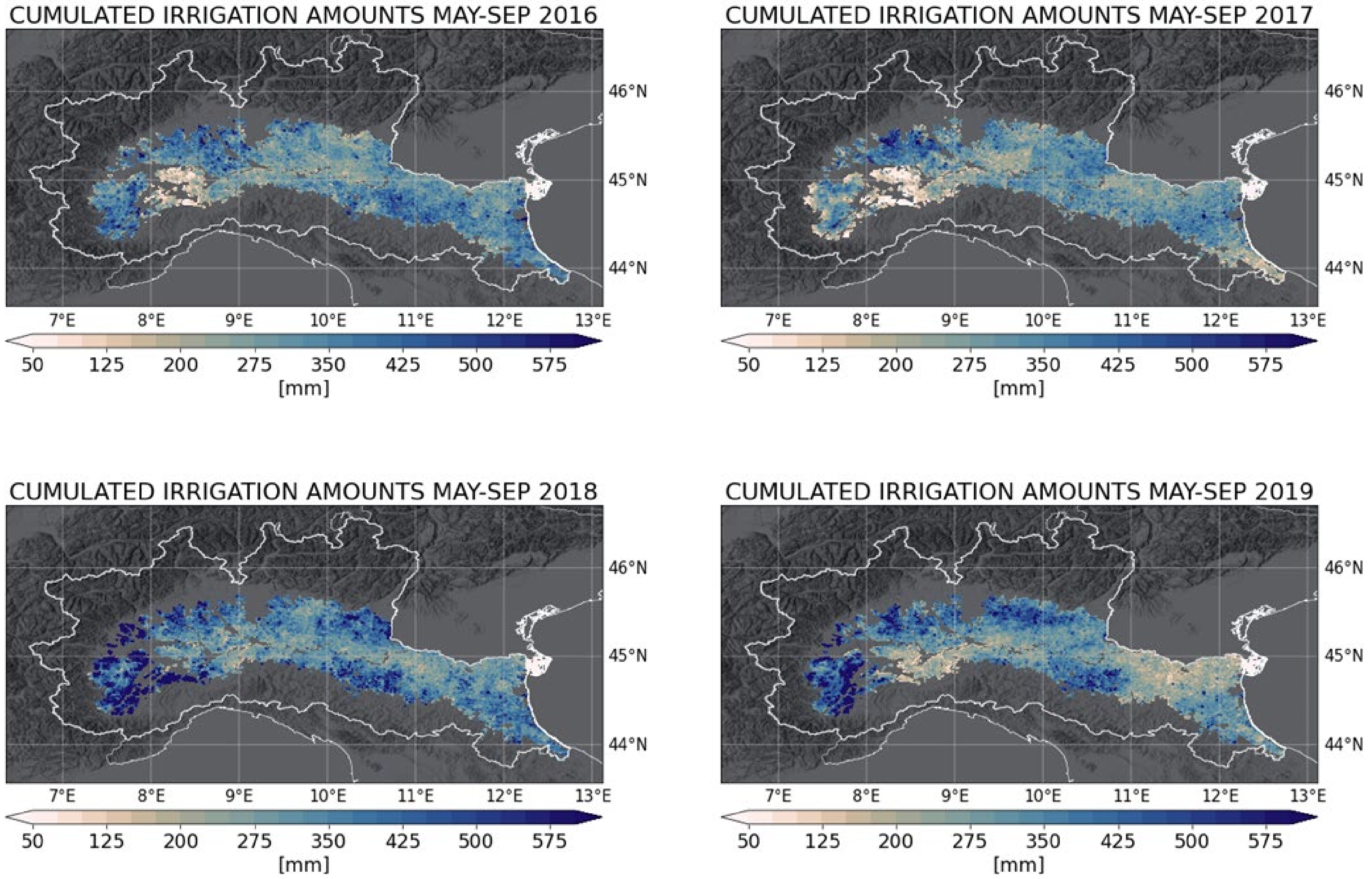
**Precipitation mean**: 36.33

**Show/hide precipitation layer**



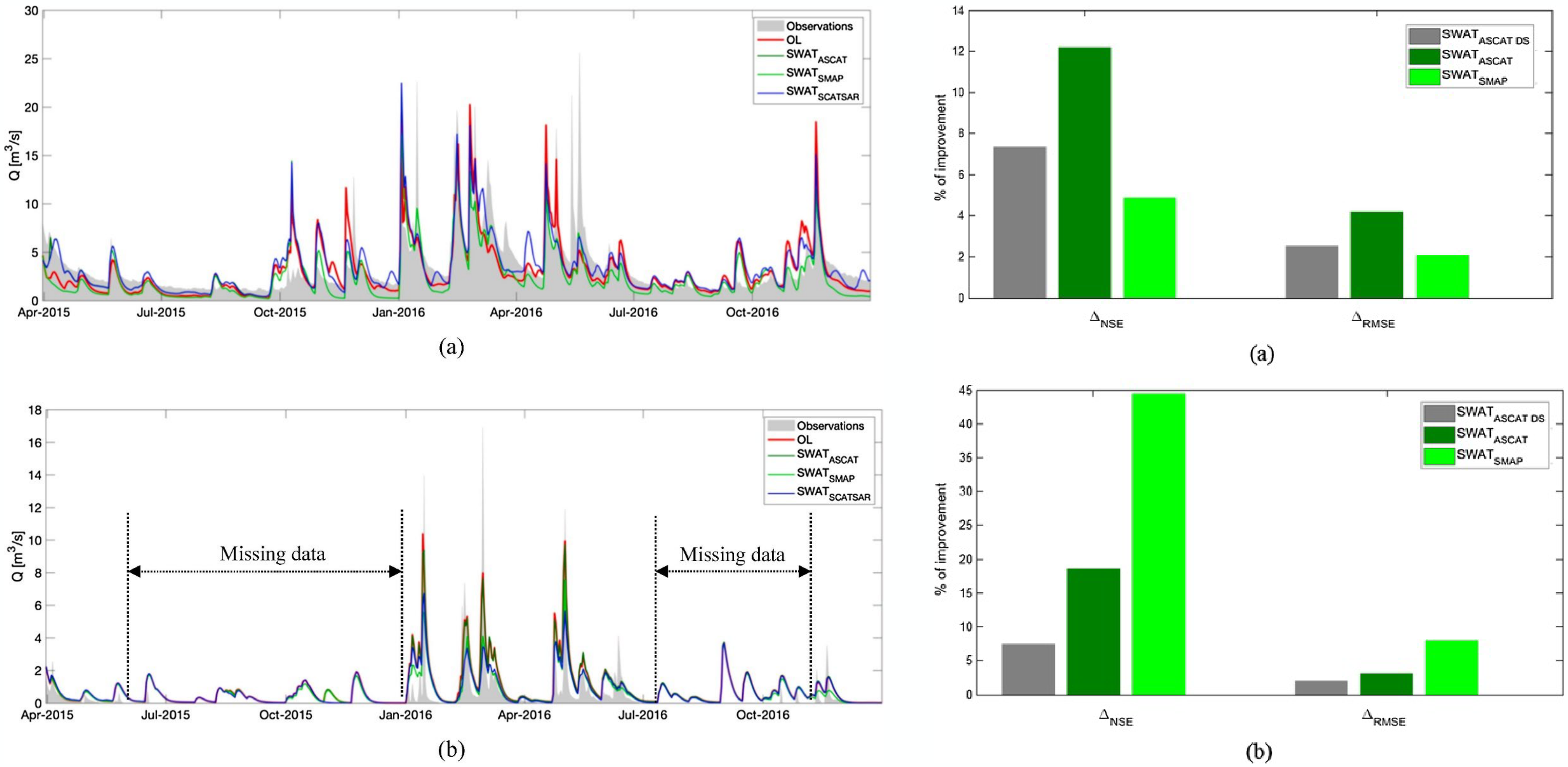
# Sentinel-1 for Irrigation Monitoring

Jacopo Dari – tomorrow




Istituto di Ricerca per la Protezione Idrogeologica

# Assimilation into discharge model
# Importance of temporal sampling

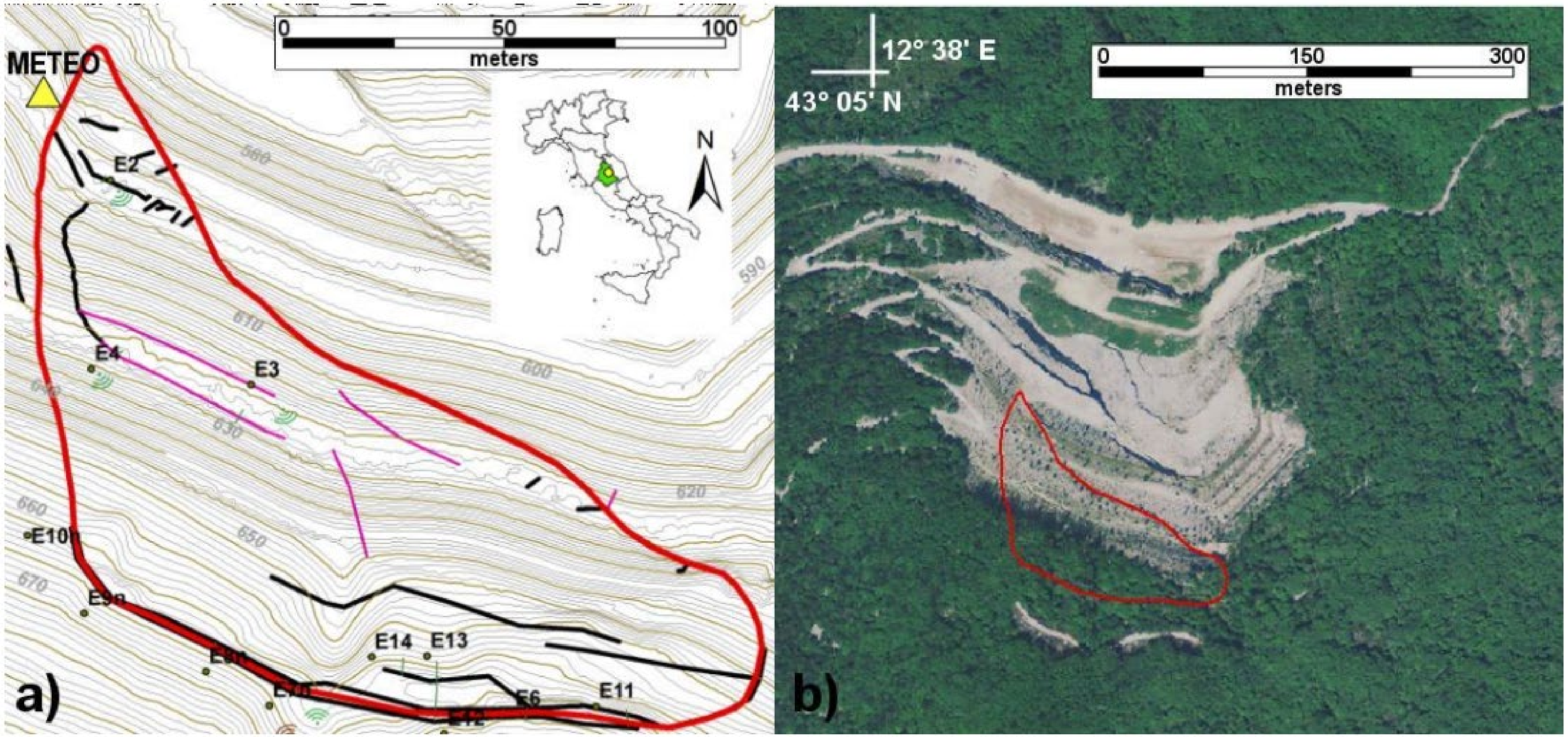



Discharge and improvements of statistics for two catchments in Umbria, Italy. Azimi et al., 2020 JoH.

# Landslide Monitoring

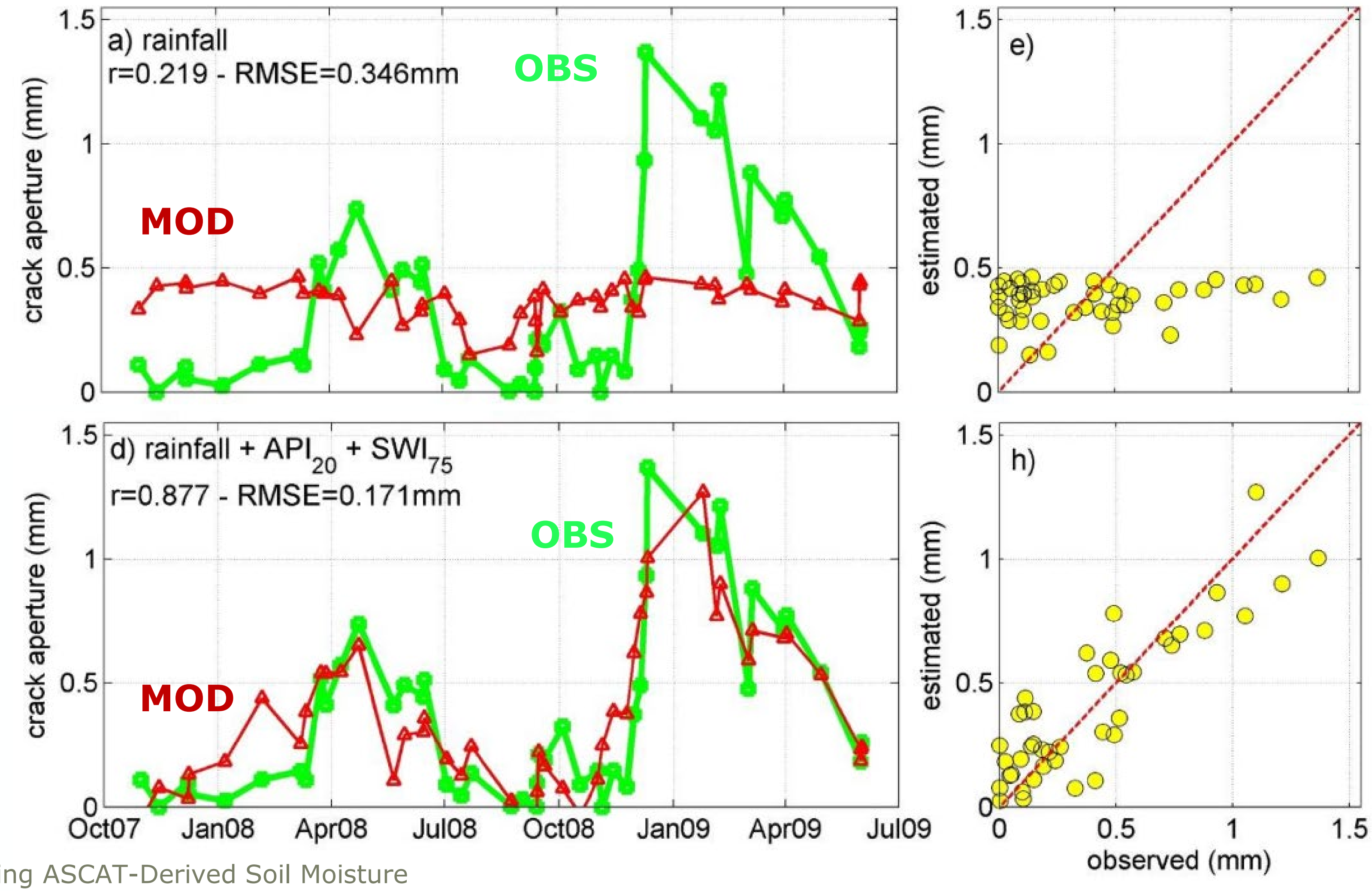
Torgiovannetto Landslide in Central Italy

Jacopo Dari – Thursday



# Landslide Monitoring

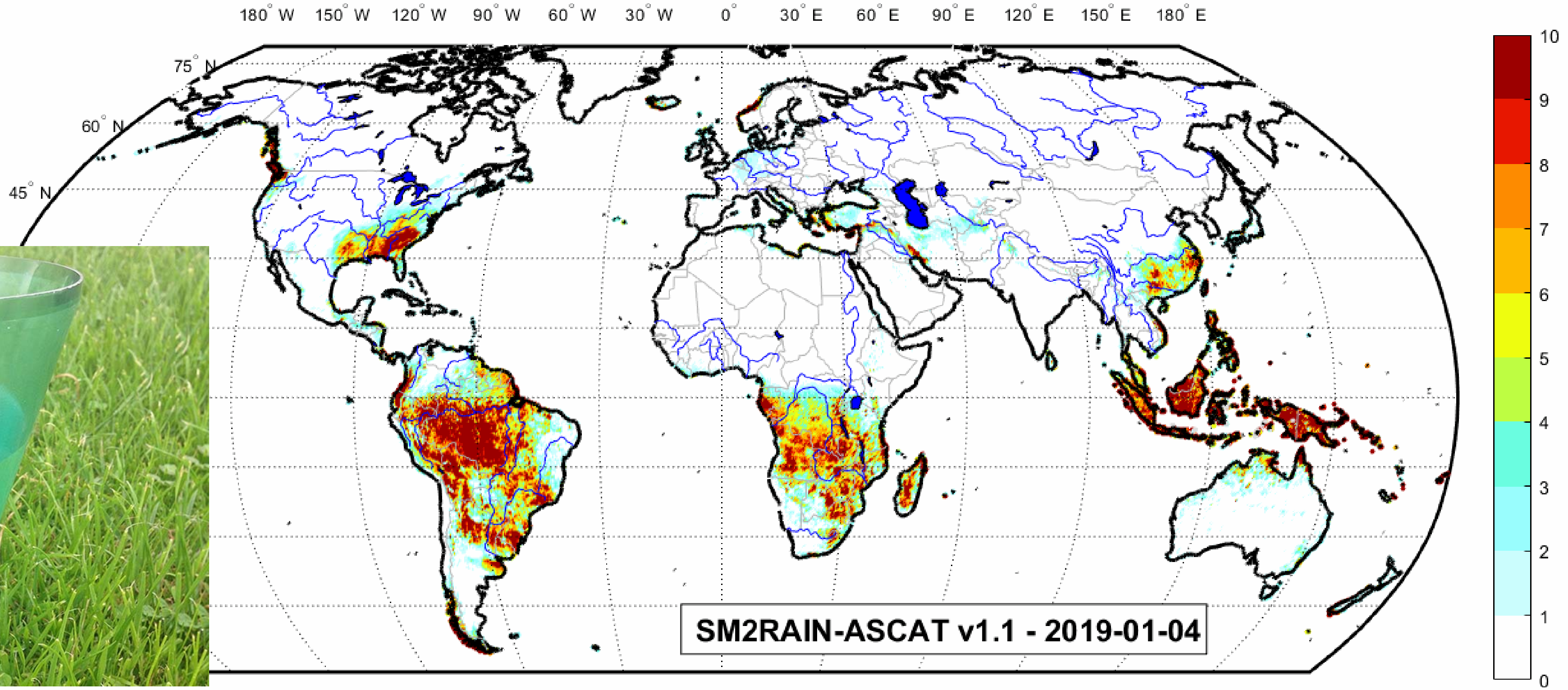
Comparison between observed (circles) and estimated (triangles) crack aperture of the Torgiovannetto Landslide in Central Italy from the beginning to the end of the selected rainfall events.




Brocca et al. (2012) Improving Landslide Forecasting Using ASCAT-Derived Soil Moisture Data: A Case Study of the Torgiovannetto Landslide in Central Italy, Remote Sensing, 4(5), 1232-1244.

# SM2RAIN ASCAT Daily Rainfall Data

Freely available @ Zenodo
https://zenodo.org/record/2591215

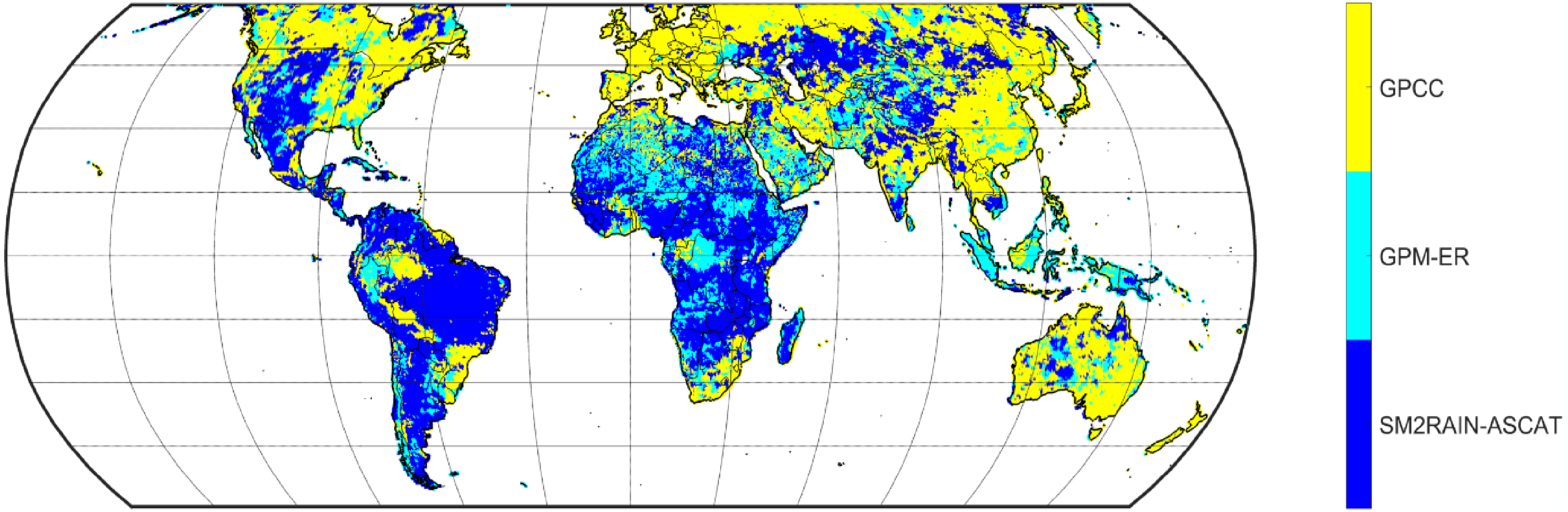




DOI 10.5281/zenodo.2591215

Brocca et al. (2019) SM2RAIN-ASCAT (2007–2018): global daily satellite rainfall from ASCAT soil moisture, Earth Syst. Sci. Data, 2019

irpi
Istituto di Ricerca per la Protezione Idrogeologica

# SM2Rain ASCAT vs GPM vs GPCC




Best performing rainfall product based on the results of a triple collocation (random error) analysis according to Brocca et al. (2019).

- GPCC = gauge-based Global Precipitation Climatology Centre data set
- GPM = Integrated Multi-Satellite Retrievals for Global Precipitation Measurement

irpi
Istituto di Ricerca per la Protezione Idrogeologica

# Exercise

**Mybinder:**

https://mybinder.org/v2/gh/pstradio/esa_ltc_materials/ltc_2023?labpath=lecture1_soil_moisture.ipynb

- Read and analyze CGLS Sentinel-1 and C3S soil moisture data
- Trend analysis
- ISMN comparison and validation

Thank you for your attention!