Operational Monitoring of Hydrological Land Surface Variables using Satellite Constellations

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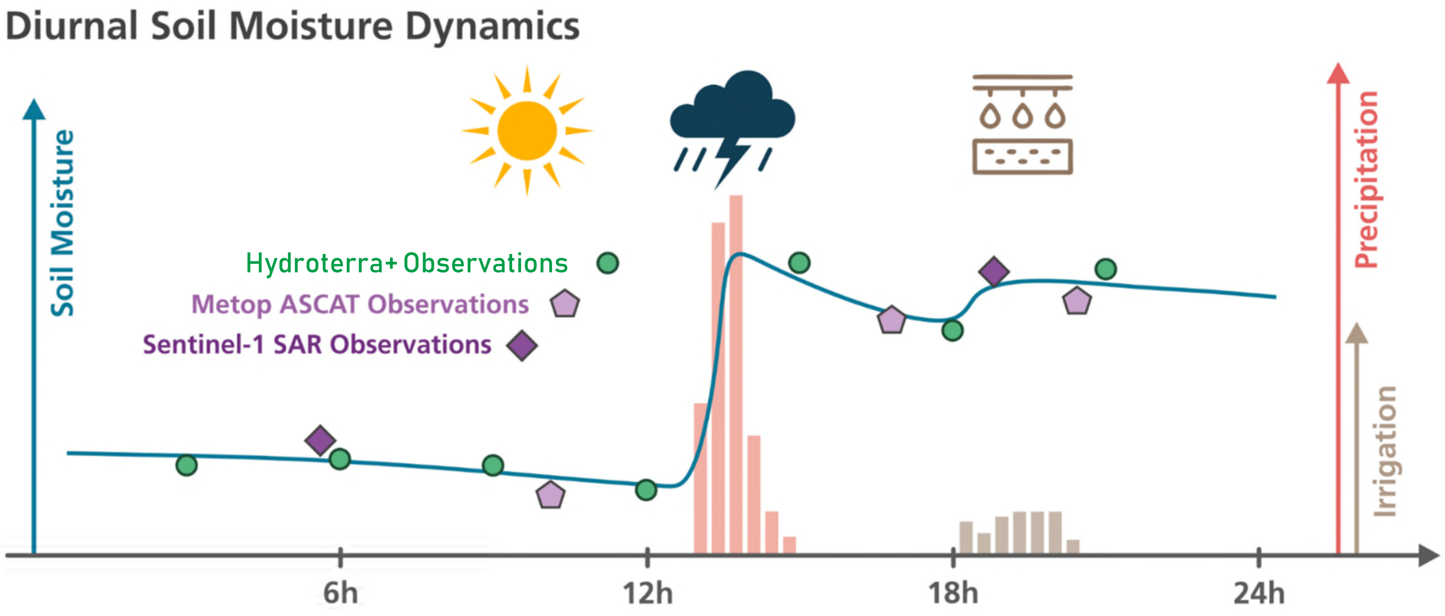
Earth Observation Data Centre for
Water Resources Monitoring

Hydrological Monitoring

- There is an urgent need for improving hydrological monitoring capabilities
  - Climate change pushes the water cycle into unknown territory
  - The terrestrial water cycle is not natural anymore
- Hydrological monitoring is challenging because
  - Hydrological processes are very dynamic → a short revisit time is essential
  - Anthropogenic activities take place at small space scales → a high spatial resolution is needed
  - Extremes need to be put in context → long and consistent time series are needed



Earth Observation

- Proliferation of sensing platforms
- Huge benefits for hydrology and water resources management expected but …

> *"The extent to which today's hydrologic models can usefully ingest such massive data volumes is unclear. Nor is it clear whether this deluge of data will be usefully exploited, either because the measurements are superfluous, inconsistent, not accurate enough, or simply because we lack the capacity to process and analyse them."*

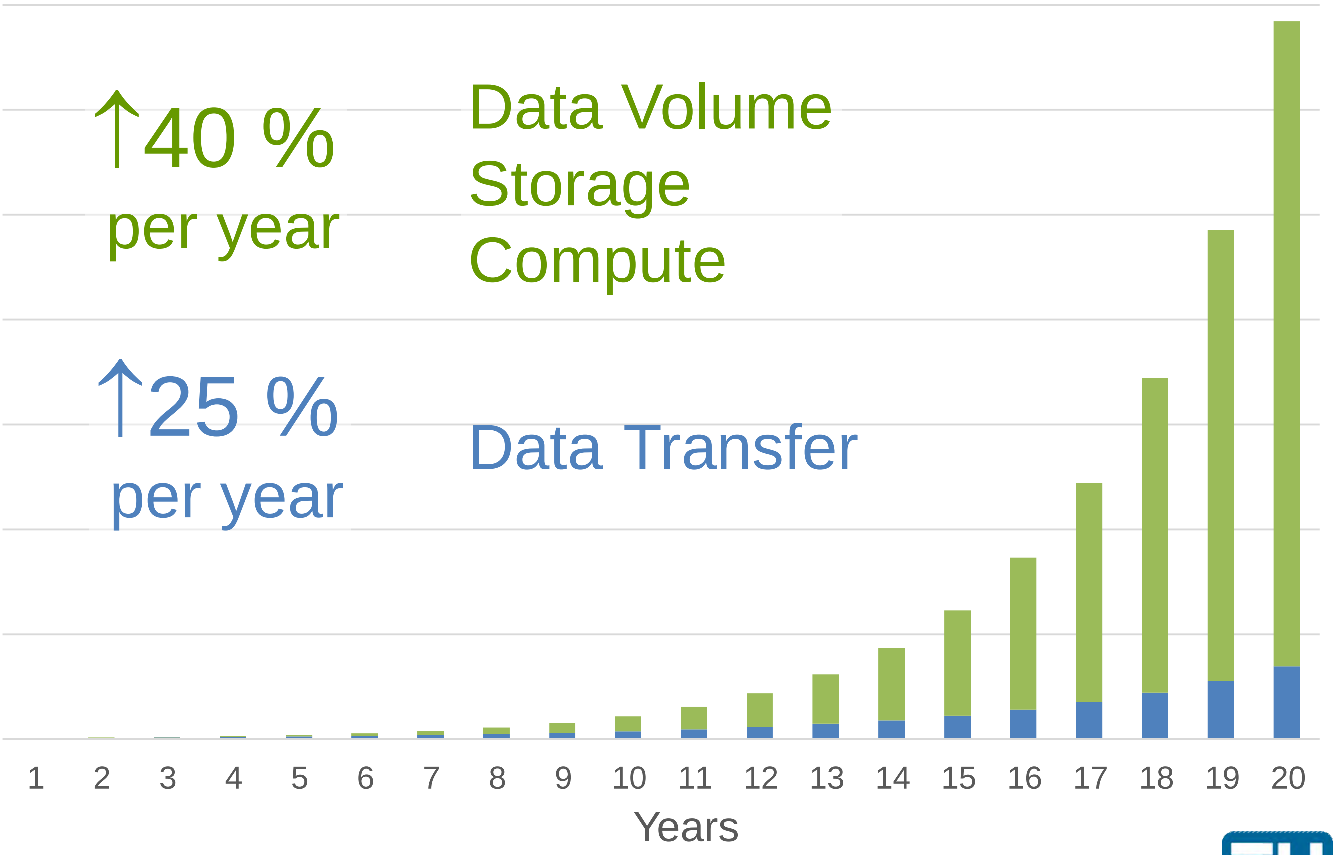
McCabe et al. (2017) The future of earth observation in hydrology, Hydrology and Earth System Sciences, 21, 3879-3914.

Why are Big Data Platforms & Cloud Solutions needed?

- Rapid growth in the quantity and quality of observations and model simulations
  - Some satellite missions produce > 10PB per year

- Data transfer capabilities have not grown as fast as data storage and compute capabilities
- We often do the same things – but just a little bit different
  - Energy savings and CO_2 reduction (EU Green Deal...)

“Bring the Software to the Data”



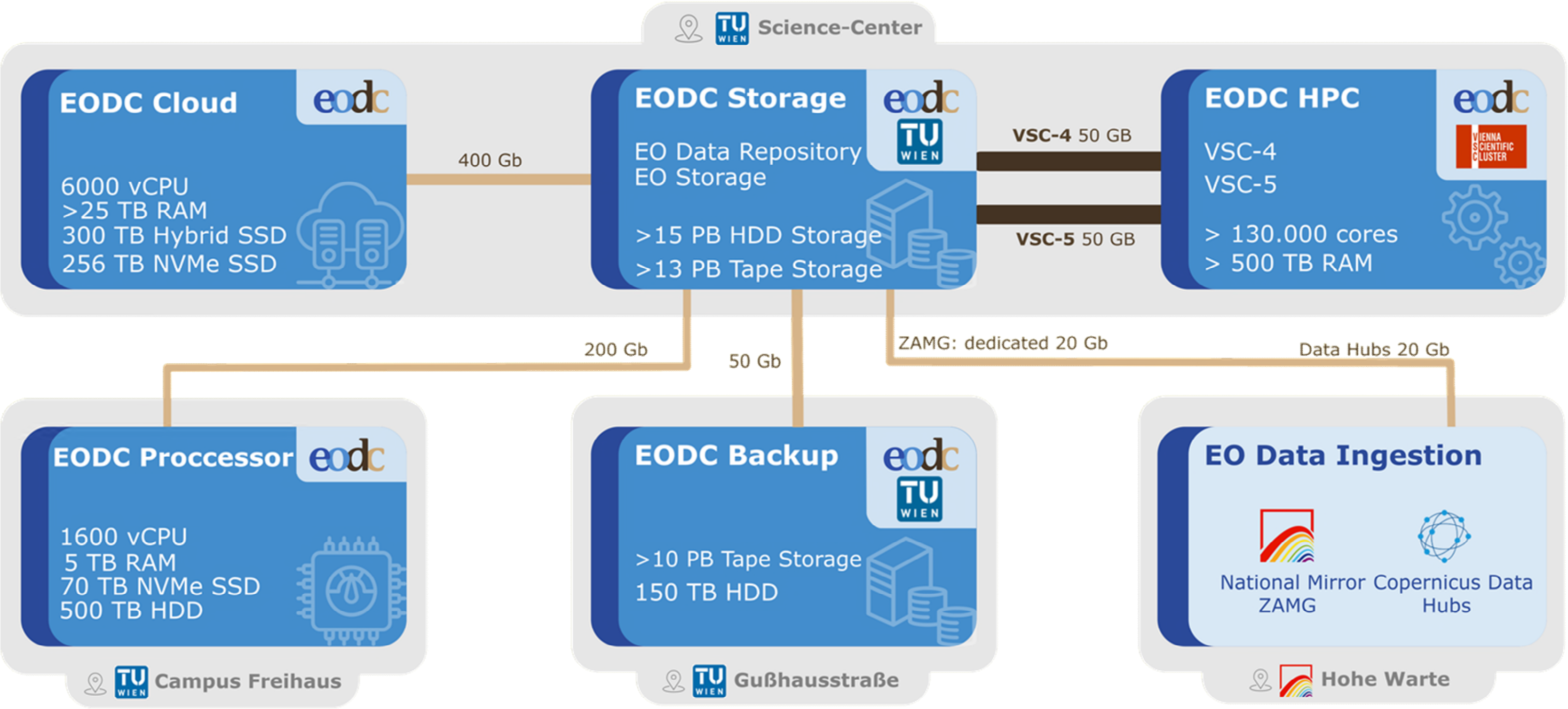
Earth Observation Data Centre

Collaboration for Earth Observation

Petabyte Storage

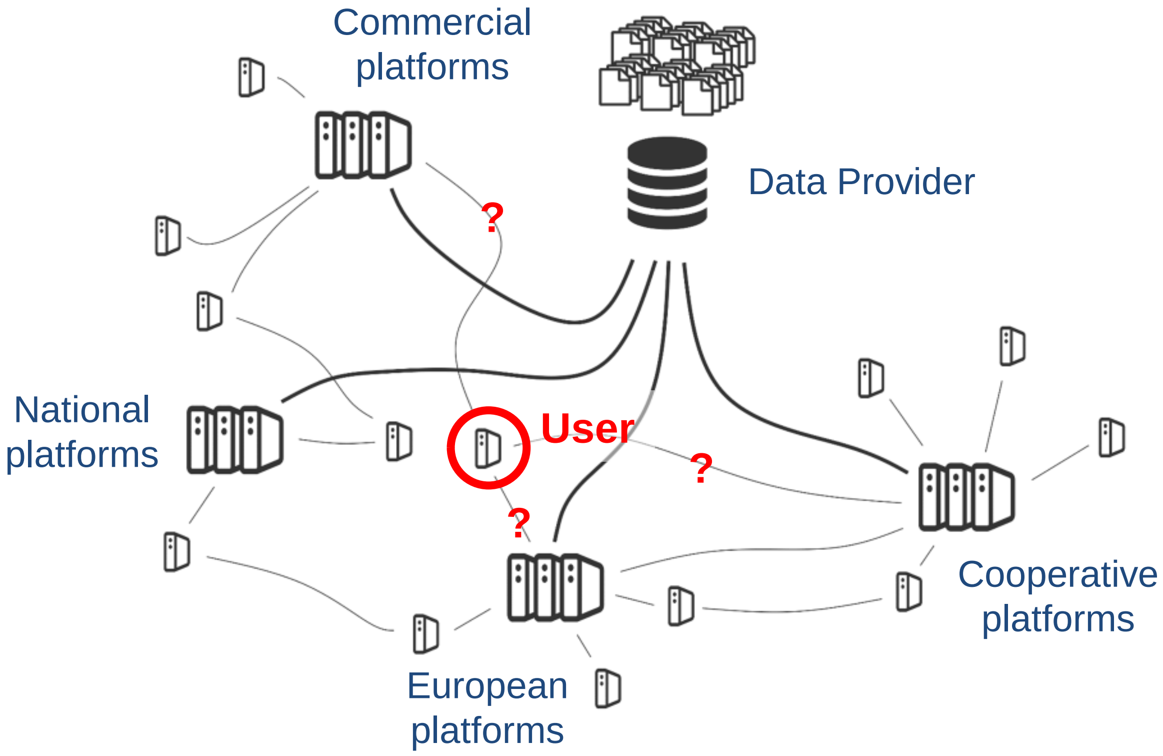
Supercomputing

Cloud Platform



Wagner et al. (2014) Addressing grand challenges in earth observation science: The Earth Observation Data Centre for Water Resources Monitoring, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Annals), Volume II-7, 81-88.

The Proliferation of Non-Interoperable Big Data Platforms



- Many different types of non-interoperable Earth observation platforms have emerged
  - Some thrived – others failed
- Bigger is not always better
  - Big data collections are nice to have but more important is to offer the best data
  - The diversity and complexity of scientific algorithms calls for very flexible solutions
  - Most users works with only small data volumes, i.e. data transfer is usually not the bottleneck
- There is no monolithic solution that can do it all

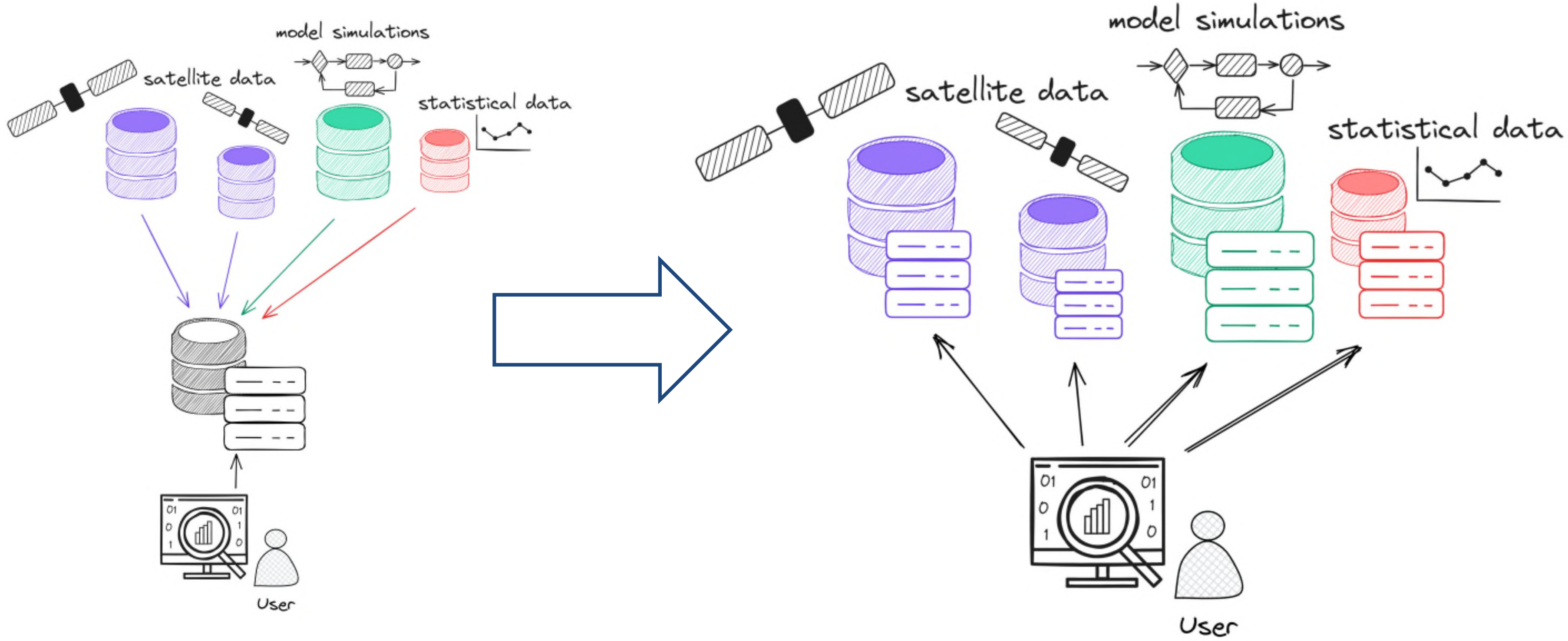
- Science has started to tackle these problems, e.g.
  - Schramm et al. (2021) The openEO API - Harmonising use of Earth Observation cloud services using virtual Data Cube functionalities, Remote Sensing, 13, 1125, 21p.
  - Backeberg et al. (2022) An open compute and data federation as an alternative to monolithic infrastructures for big Earth data analytics. Big Earth Data, 7(3), 1–19.

Towards a Web of FAIR Data and Services

- Powerful open source solutions has become available that will help turning the vision of the European Open Science Cloud into reality

Traditional Approach

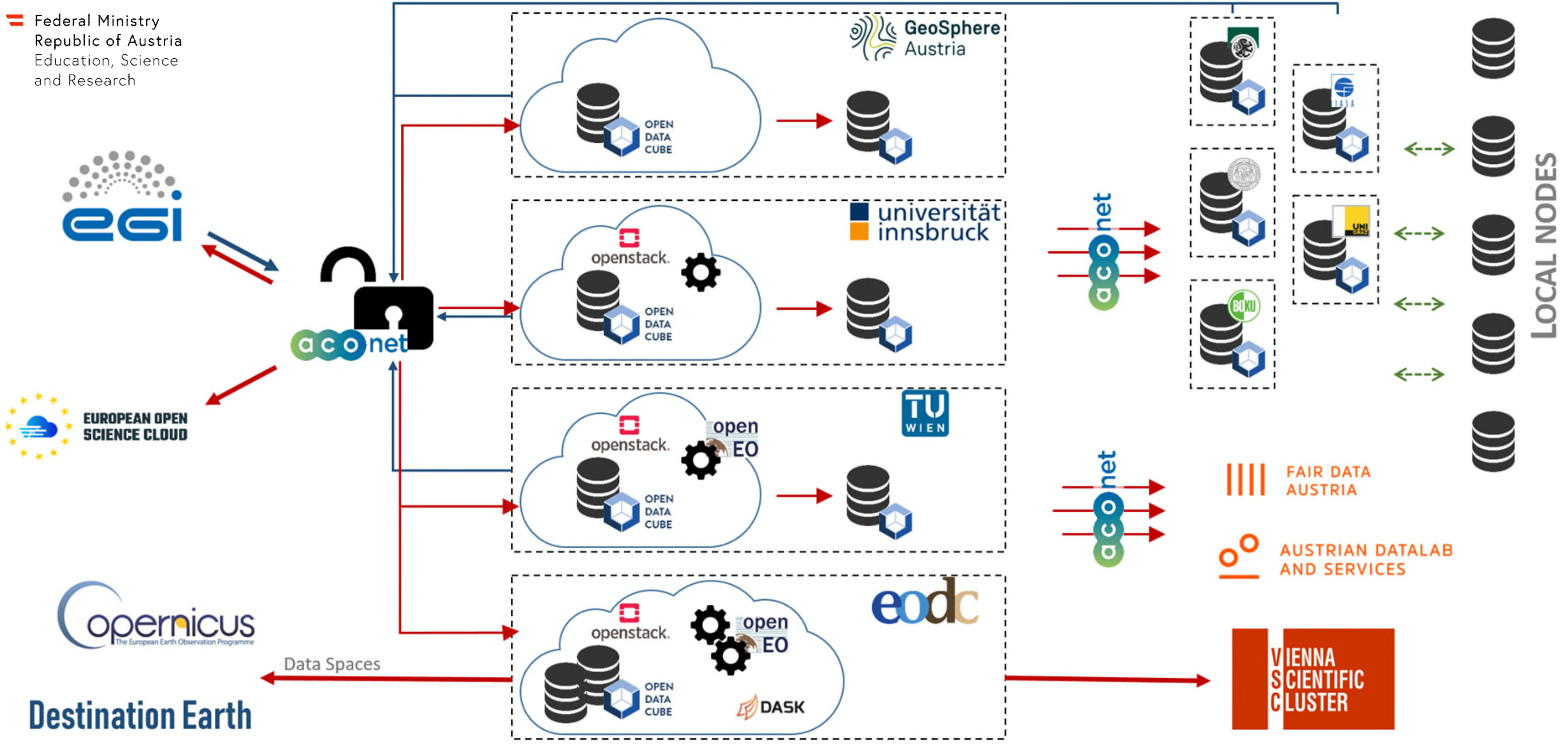
Data Proximate Computation



Reimer et al. (2023) Multi-cloud processing with Dask: Demonstrating the capabilities of DestinE Data Lake (DEDL), Proceedings of the 2023 Conference on Big Data from Space (BiDS'23), 161-164.

Cloud4GEO

Federal Ministry
Republic of Austria
Education, Science
and Research



Wagner, Schramm et al. (2023) Federating scientific infrastructure and services for cross-domain applications of Earth observation and climate data, Proceedings of the 2023 Conference on Big Data from Space (BiDS'23), 93-96.

TU WIEN GEO

ESA-DEVELOPED EARTH OBSERVATION MISSIONS
2010
2015
2020
2025
2030
ERS-1
ERS-2
Envisat
MetOp-A
Proba-1
SMOS
GOCE
CryoSat
Swarm
Proba-V
Meteosat 10 (MSG)
MetOp-B
Meteosat 11 (MSG)
Sentinel-1A
Sentinel-1B
Sentinel-2A
Sentinel-2B
Sentinel-3A
Sentinel-3B
Sentinel-5P
MetOp-C
Sentinel-6 Michael Freilich
MTG-I1
Sentinel-4A MTG-S1
Arctic Weather Satellite
Sentinel-1C
Sentinel-2C
Sentinel-3C
Aeolus
EarthCARE
Sentinel-1D
CO2M-A
CO2M-B
CO2M-C
Sentinel-5A MetOp-SG-A1
MTG-I2
MetOp-SG-B1
Biomass
Phisat-2
Sentinel-2D
Sentinel-3D
HydroGNSS
FLEX
ALTIUS
Sentinel-6B
CRISTAL-A
CIMR-A
ROSE-L-A
CHIME-A
LSTM-A
CRISTAL-B
CIMR-B
ROSE-L-B
FORUM
Harmony
CHIME-B
LSTM-B
TRUTHS
MAGIC
Earth Explorer-11
Earth Explorer-12
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-6
Sentinel Next Generation Missions
MTG-I3
Aeolus-2A
Sentinel-4B MTG-S2
Sentinel-5B MetOp-SG-A2
MetOp-SG-B2
Science
esa
Copernicus
European Union
Meteorology
EUMETSAT

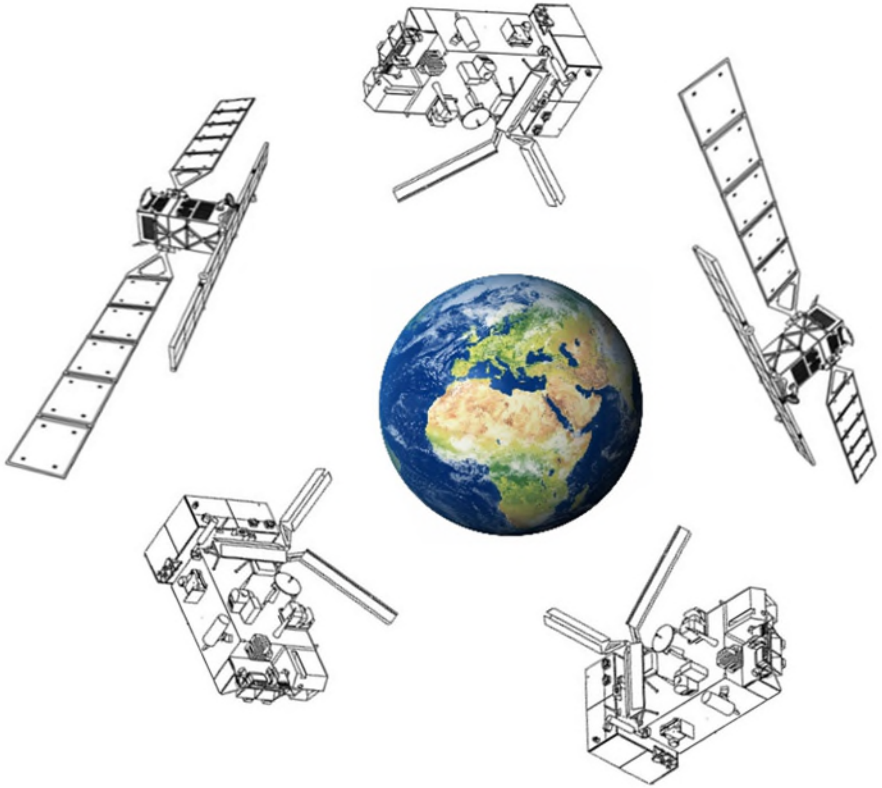
Scatterometer and SAR Satellite Constellations

Metop ASCAT

Frequency: 5.255 GHz
Polarisation: VV

Sampling: 6.25 km
Daily coverage: 82%

Satellites
Metop-A: 2006-2021
Metop-B: 2012 ongoing
Metop-C: 2018 ongoing
Metop-SG B1: foreseen 2026



Sentinel-1 SAR IW

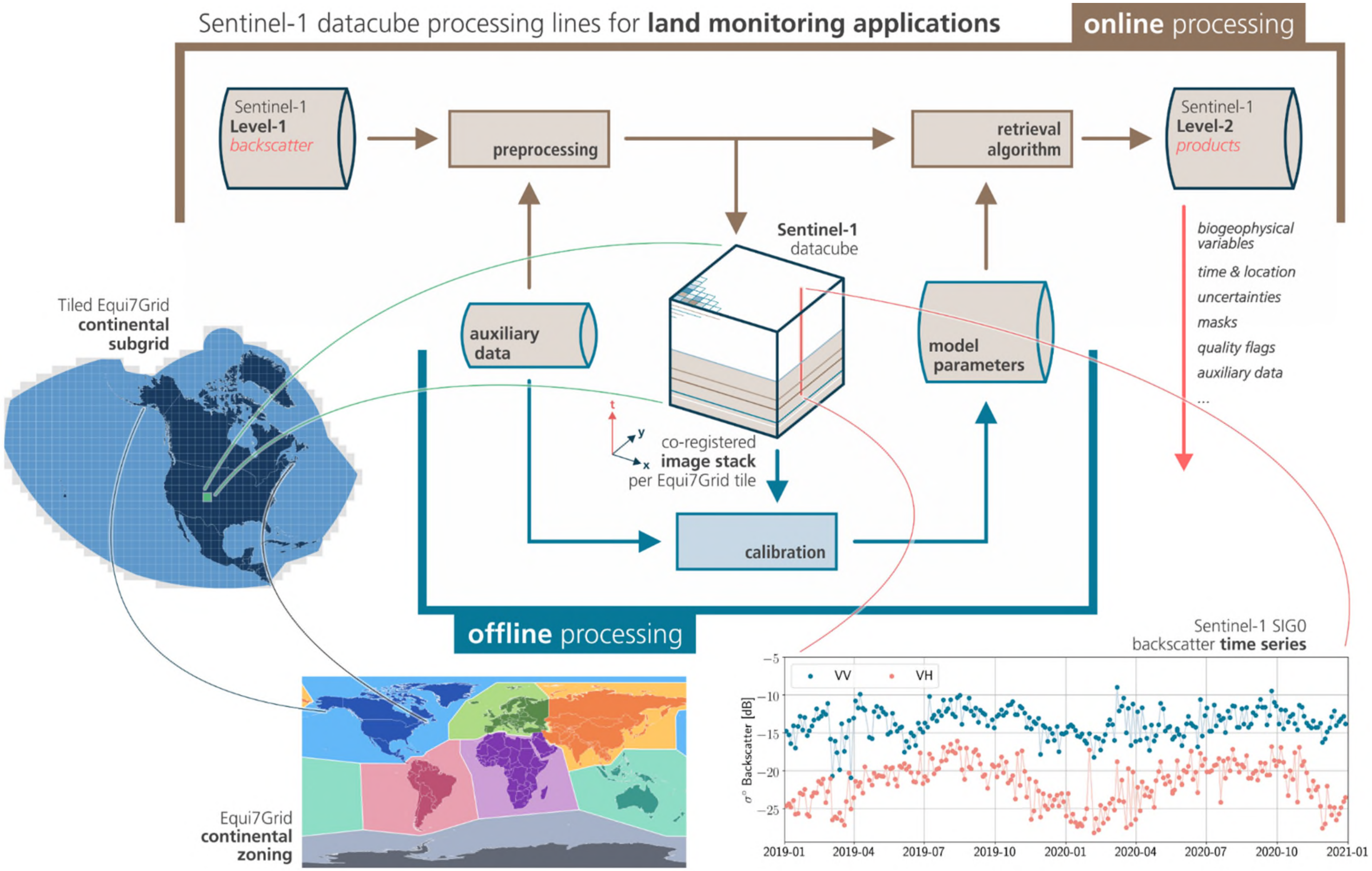
Frequency: 5.405 GHz
Polarisation: VV+VH

Sampling: 20 m
Repeat coverage: 3 – 12 days

Satellites
Sentinel-1A: 2014 ongoing
Sentinel-1B: 2016-2021
Sentinel-1C: foreseen 2024
Sentinel-1D: foreseen 2025

Achieve process understanding by combining the high temporal sampling capabilities of ASCAT and the high spatial resolution of Sentinel-1

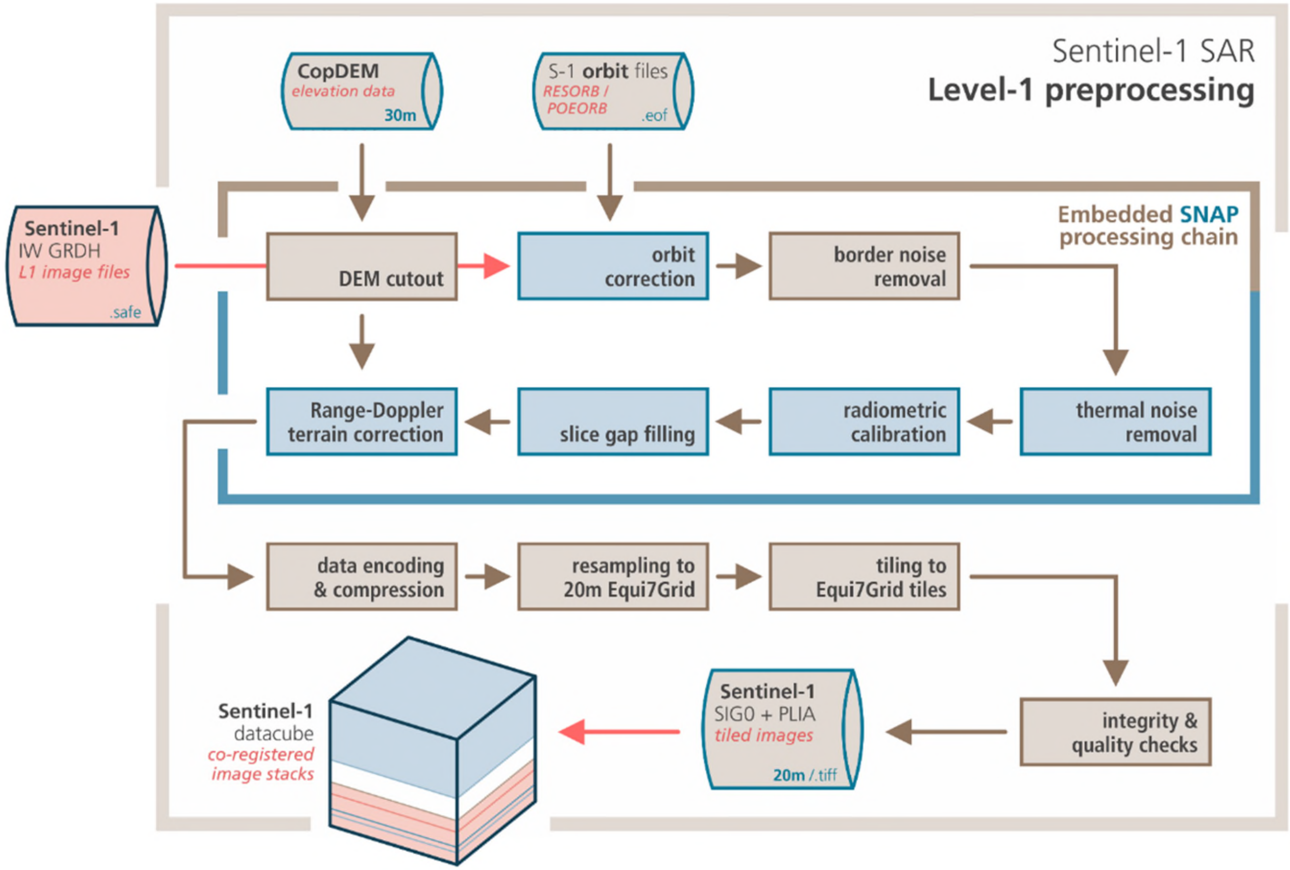
A Datacube for Dynamic Land Monitoring Applications



- Exploits the strengths of dense satellite time series
- Combines online and offline workflows
- Suited for training complex models
  - Physical models
  - AI models
  - Hybrid models

Wagner et al. (2021) A Sentinel-1 backscatter datacube for global land monitoring applications, Remote Sensing, 13, 4622.

Global Sentinel-1 Backscatter Datacube



Data Volume in TB

Level-1 Sentinel-1 IW GRD data

Year	Africa	Asia	Europe	NA	Oceania	SA	Total
2015	12.7	15.1	22.0	6.2	4.9	5.3	66.2
2016	20.6	19.2	31.9	11.5	6.6	9.0	98.8
2017	45.0	53.9	71.8	31.4	18.4	23.1	243.6
2018	48.0	58.1	70.3	35.3	20.2	24.7	256.6
2019	94.4	61.1	119.9	38.5	21.1	26.9	361.9
2020	97.3	63.3	130.7	41.4	21.3	28.6	382.6
Total	318.0	270.7	446.6	164.3	92.5	117.6	1409.7

20 m Sentinel-1 datacube

Year	Africa	Asia	Europe	NA	Oceania	SA	Total
2015	2.5	2.9	4.3	1.2	1.1	1.0	13.0
2016	4.4	4.0	6.4	2.5	1.5	1.9	20.7
2017	9.8	11.9	14.6	6.9	4.3	4.9	52.4
2018	10.3	12.8	12.8	7.6	4.7	5.2	53.4
2019	16.9	19.4	23.5	13.4	7.6	8.6	89.4
2020	17.3	20.1	25.0	14.6	7.7	9.4	94.1
Total	61.2	71.1	86.6	46.1	26.9	31.0	323.0

Wagner et al. (2021) A Sentinel-1 Backscatter Datacube for Global Land Monitoring Applications, Remote Sensing, 13, 4622.

CEMS Global Flood Monitoring (GFM) product

- **Sentinel-1** Synthetic Aperture Radar (SAR)
  - Systematic coverage
  - Currently only one satellite
- **Fully automatic processing** of all incoming Sentinel-1 scenes within 8 hours
- **Ensemble** of 3 flood mapping algorithms
  - LIST, DLR, TU Wien
- **Context** through 11 output layers incl.
  - Flood extent
  - Likelihood
  - Exclusion mask
  - Advisory flags

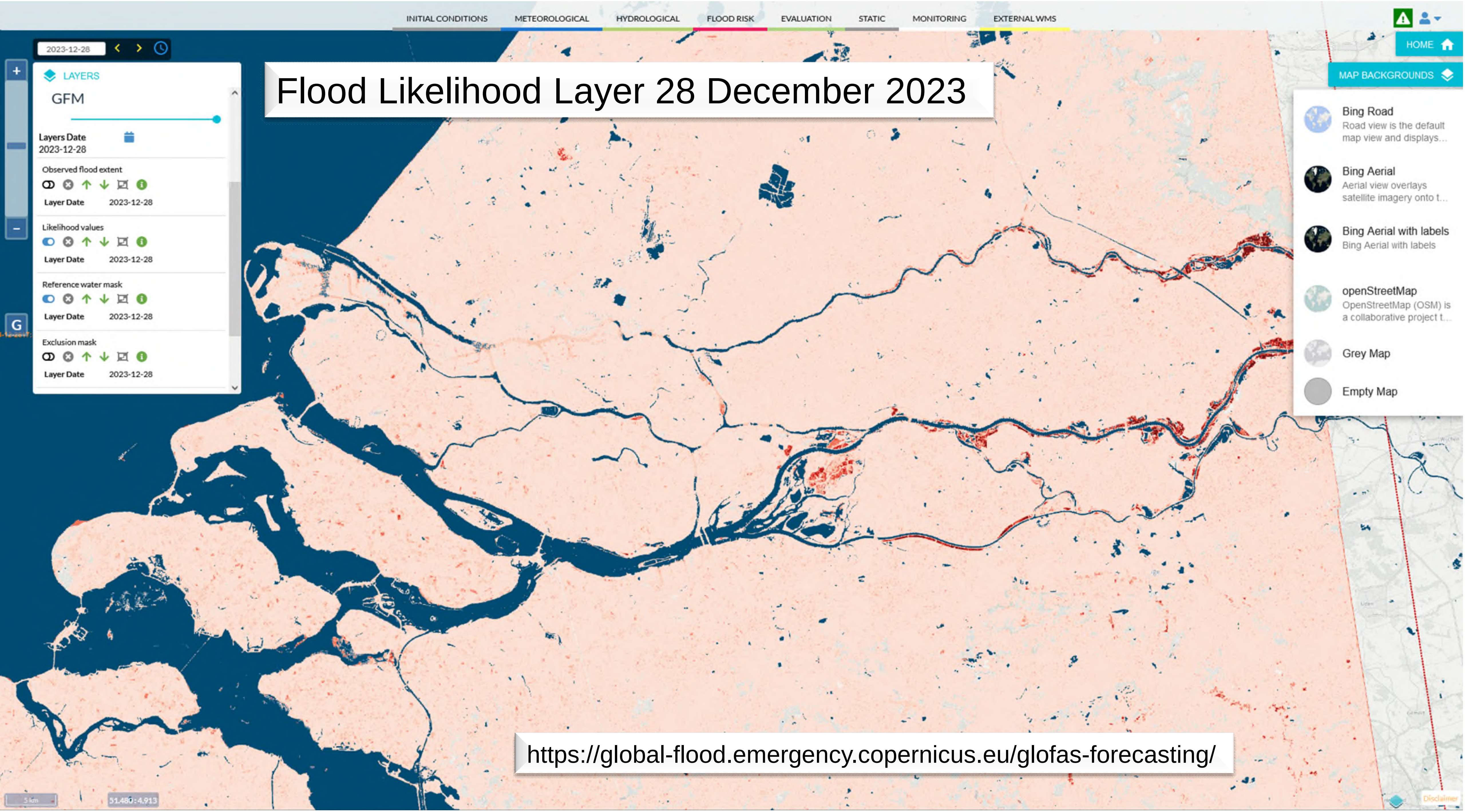
→ **Advantages**
- No time is lost due to human intervention
- Discover unreported events

→ **Disadvantages**
- False alarms
- Processing overhead

→ **Challenges**
- Accuracy
- Timeliness

Wagner et al. (2020) Data processing architectures for monitoring floods using Sentinel-1, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., V-3-2020, 641–648.

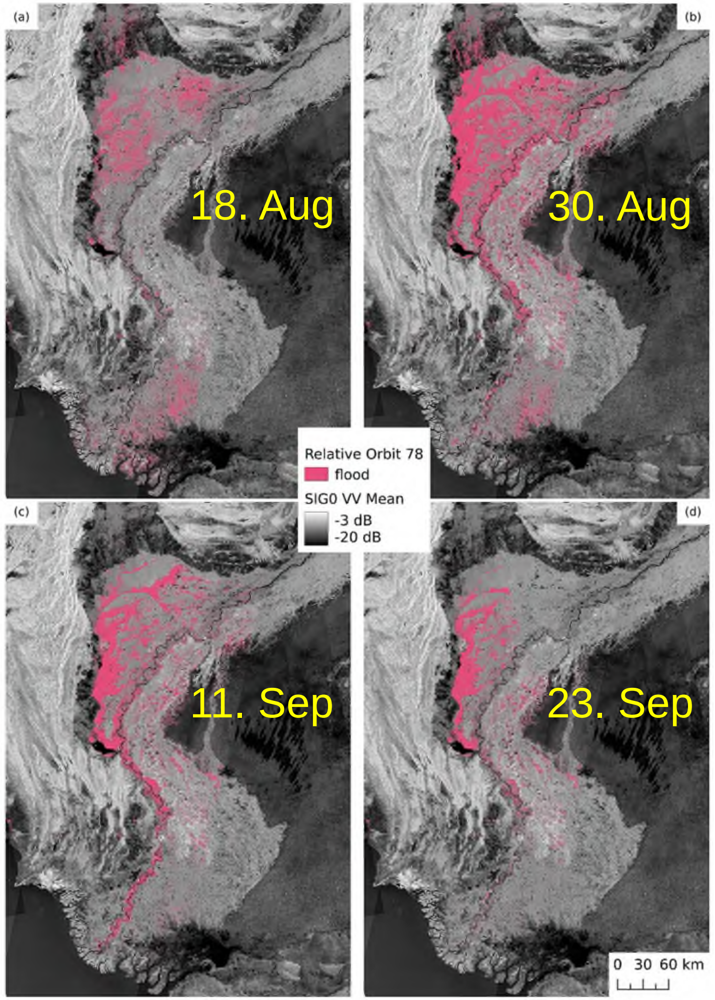
Flood Likelihood Layer 28 December 2023



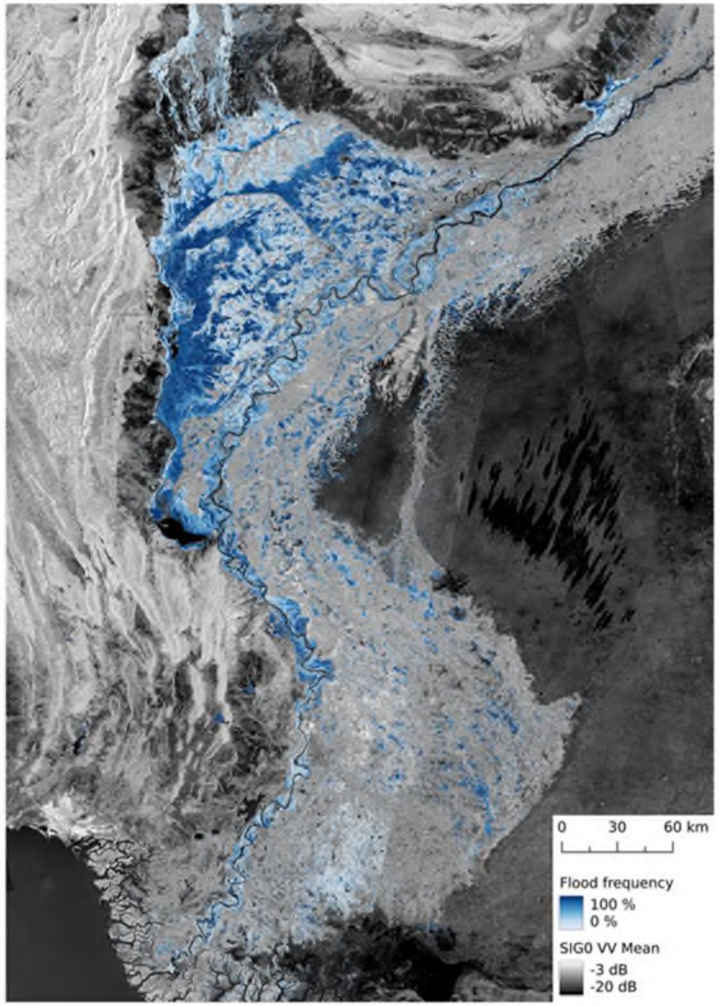
https://global-flood.emergency.copernicus.eu/glofas-forecasting/

Monitoring of the Flood in Pakistan in 2022

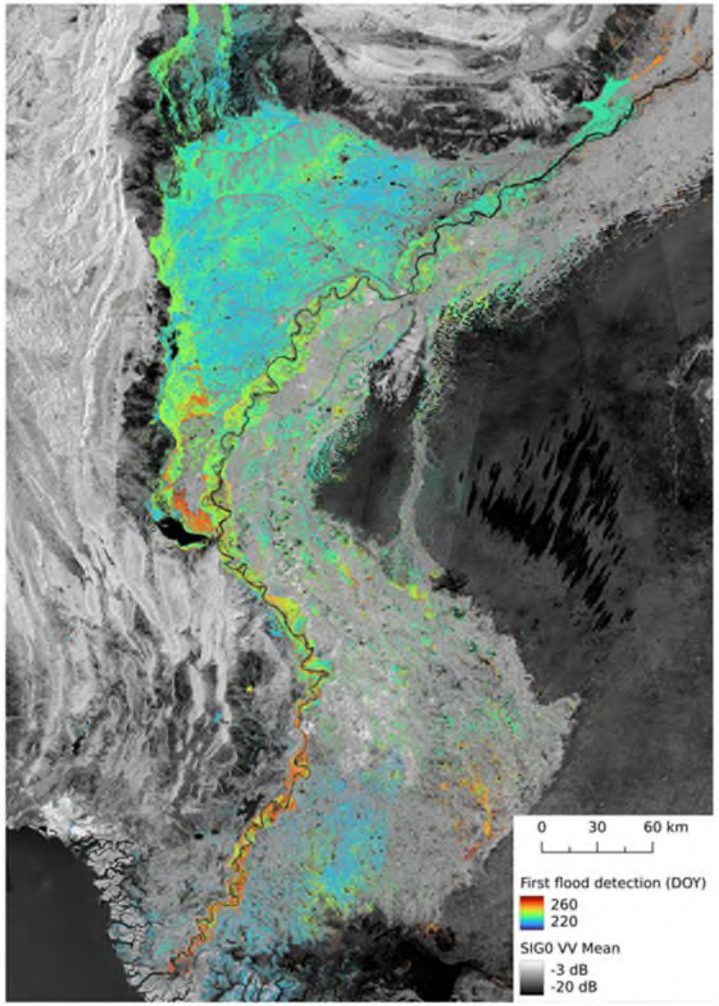
Individual Flood Scenes



Flood Frequencies

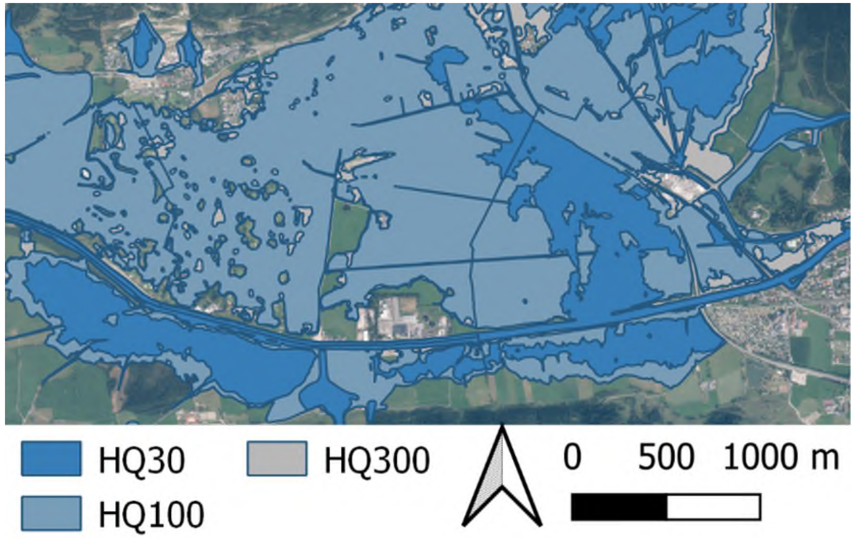


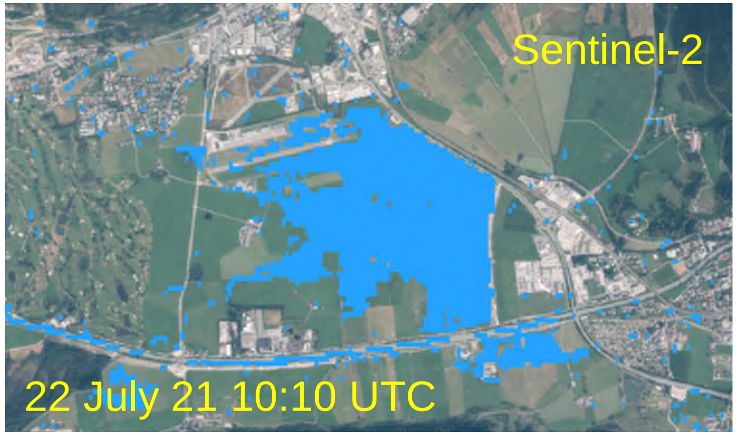
Day of First Flood Detection



Roth et al. (2023) Sentinel-1-based analysis of the severe flood over Pakistan 2022, Natural Hazards and Earth System Sciences, 23, 3305–3317.

Flooding Salzach July 2021





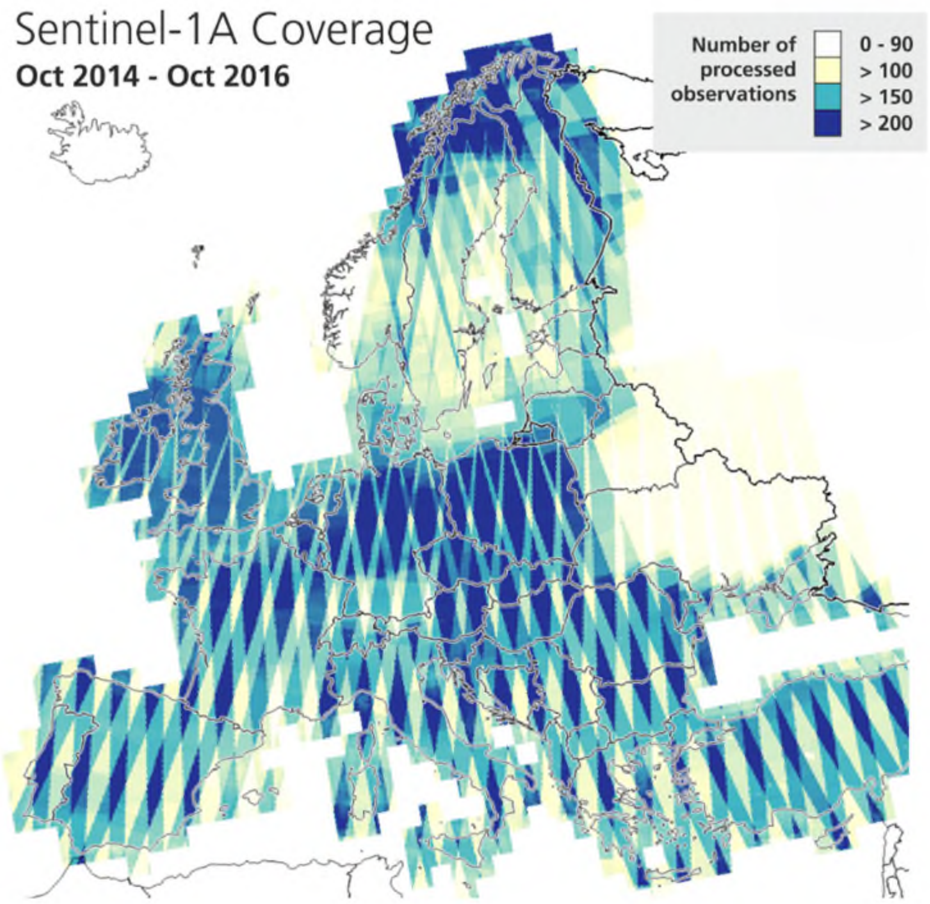
Scenario-based simulations of flood inundation areas for 30, 100 and 300 years return periods
(HQ = „Hoch“ und Abfluss-Kennzahl Q)

Federal Ministry
Republic of Austria
Agriculture, Regions
and Tourism

CLMS 1km Sentinel-1 Surface Soil Moisture

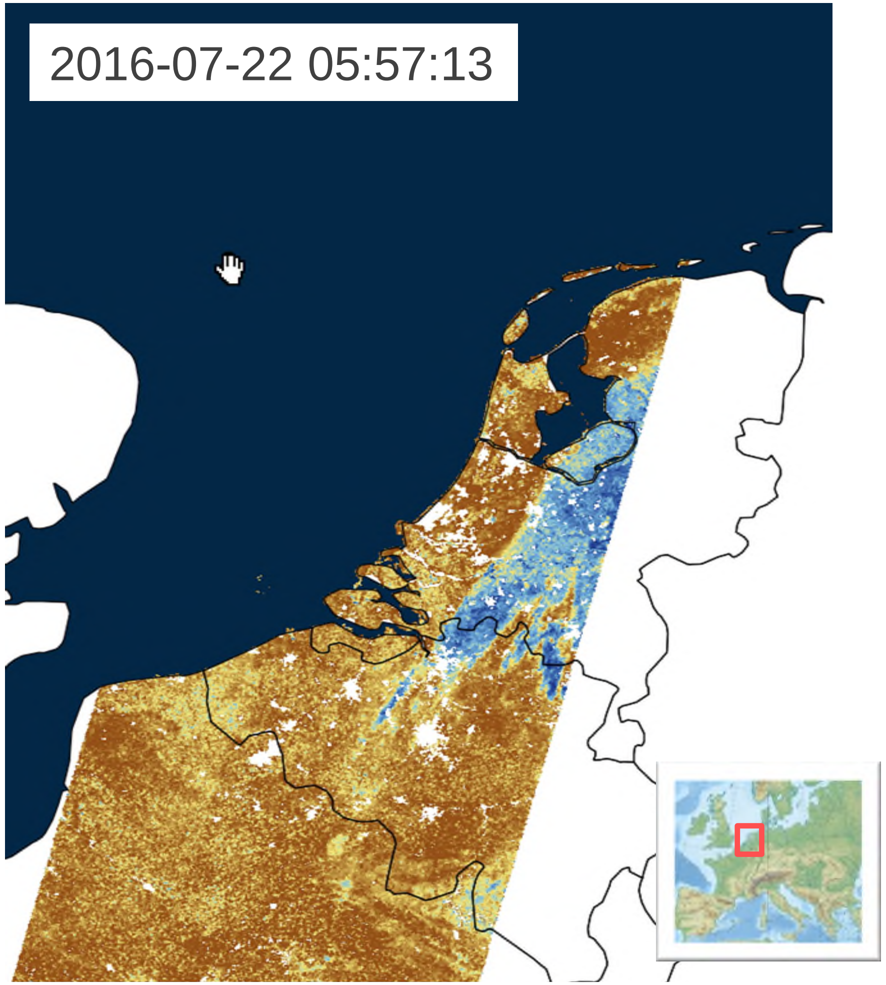
Global Land Operations

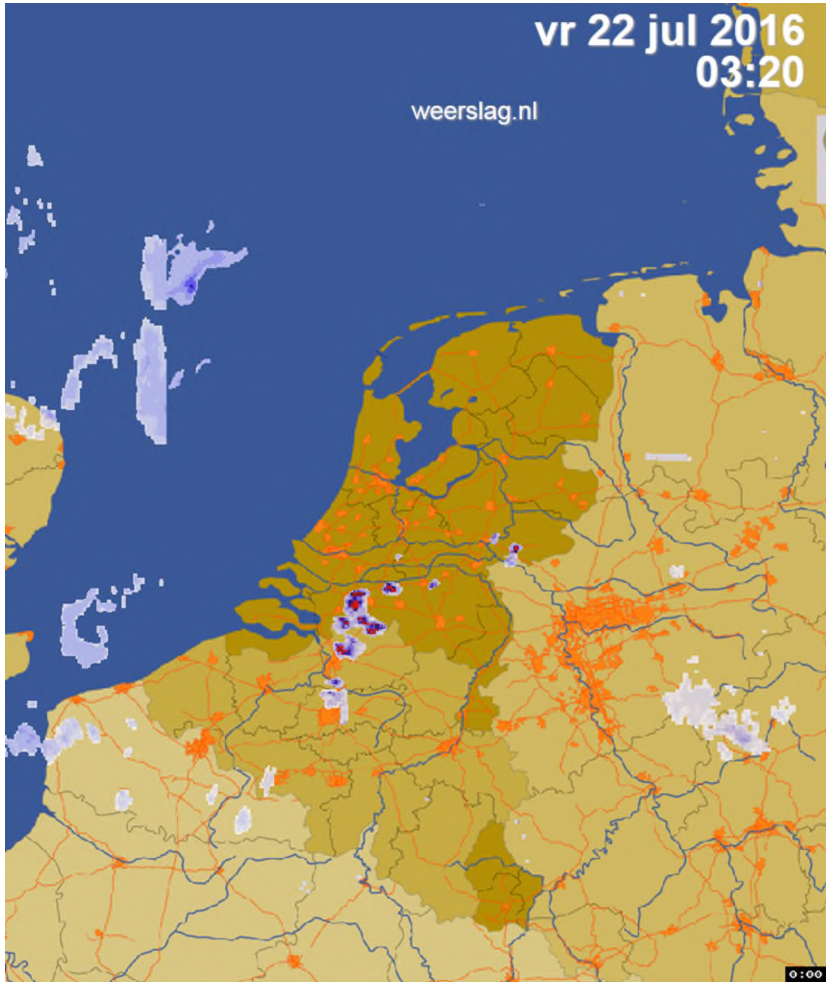
- **Fully automatic processing** of all incoming Sentinel-1 scenes over Europe
  - Daily updated
- **Change detection** model of TU Wien
  - Backscatter is aggregated to 1km before soil moisture retrieval
- **Context** through additional layers incl.
  - Uncertainty estimate
  - Exclusion mask
- There will be a major **update in 2025**
  - Global coverage
  - Seasonal vegetation correction
  - Removal of non-soil-moisture-sensitive 20m pixels
  - Better masking of snow and frost
  - Masking of flood affected areas

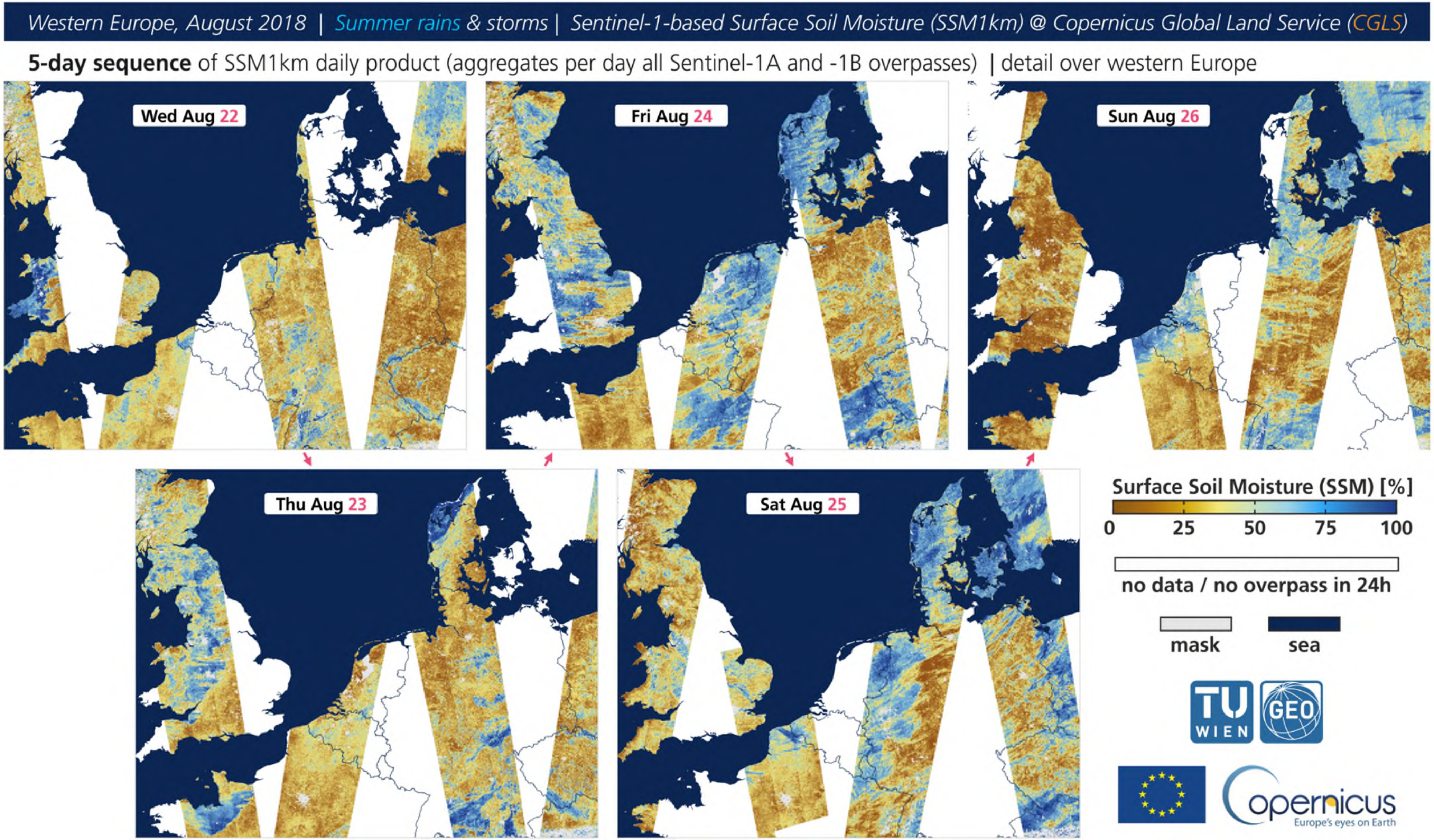


Bauer-Marschallinger et al. (2019) Towards global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles, IEEE Transactions on Geoscience and Remote Sensing, 57(1), 520-539.

Sentinel-1 Soil Moisture & Precipitation Radar

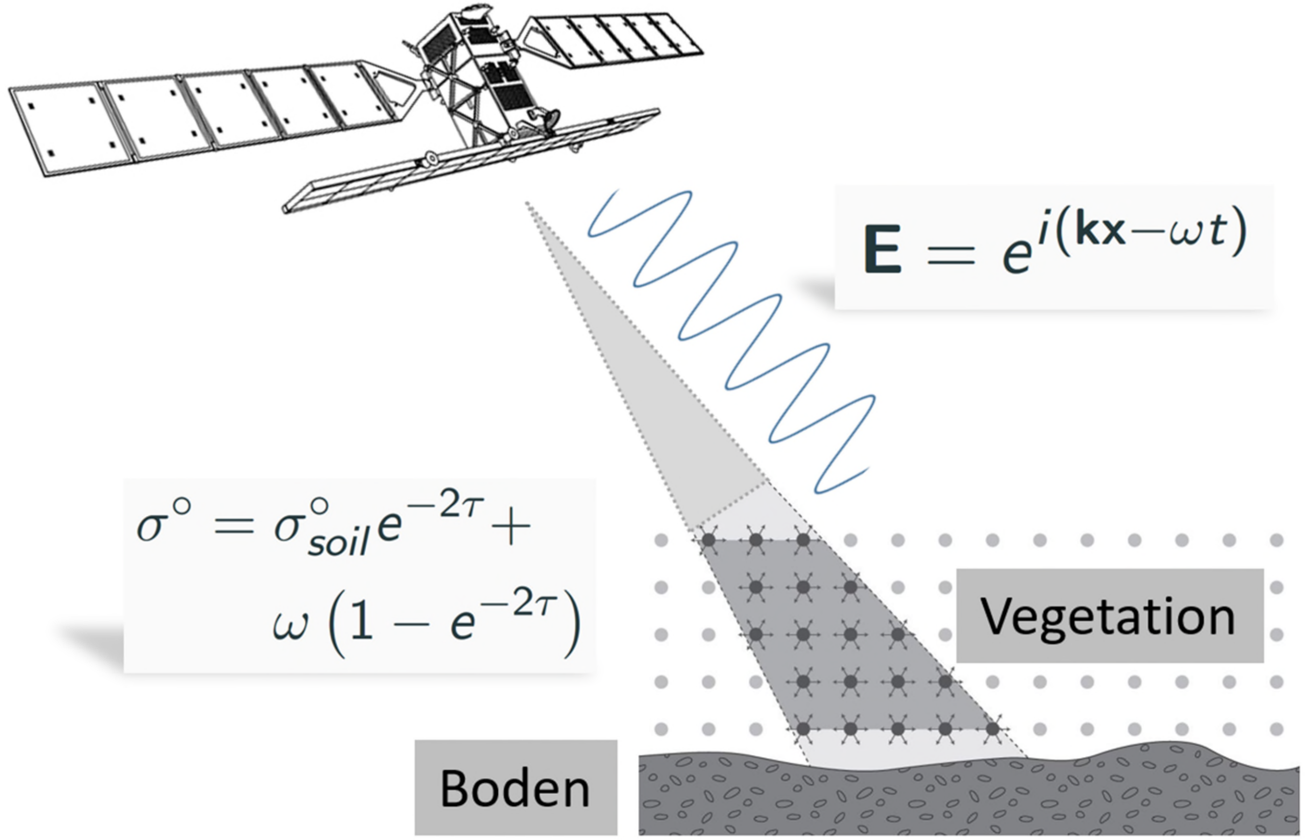






Wagner et al. (2024) Requirements from the Copernicus soil moisture and flood monitoring services for Sentinel-1 and ROSE-L mission operations, Proceedings EUSAR 2024, VDE Verlag, 114-118.

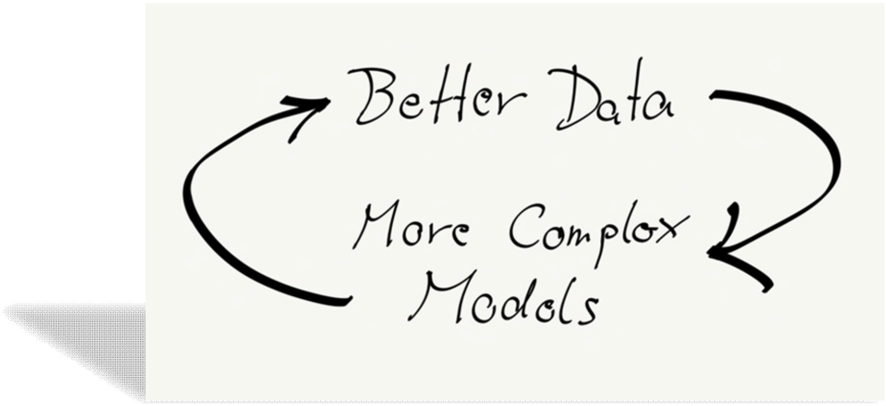
Modelling Radar Measurements



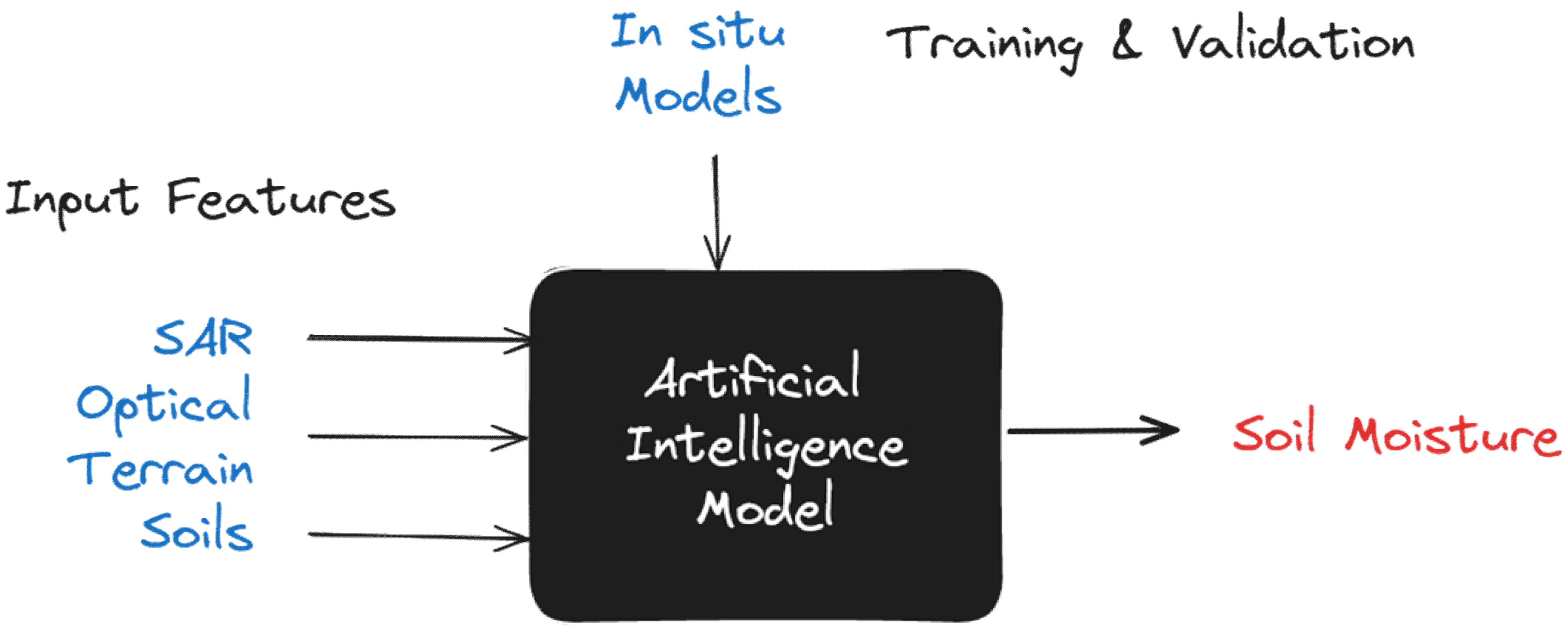
- The interaction between cm to dm waves with complex real-world objects can only be understood through
  - Physical modelling
  - Empirical evidence

AI & Machine Learning

Big Data

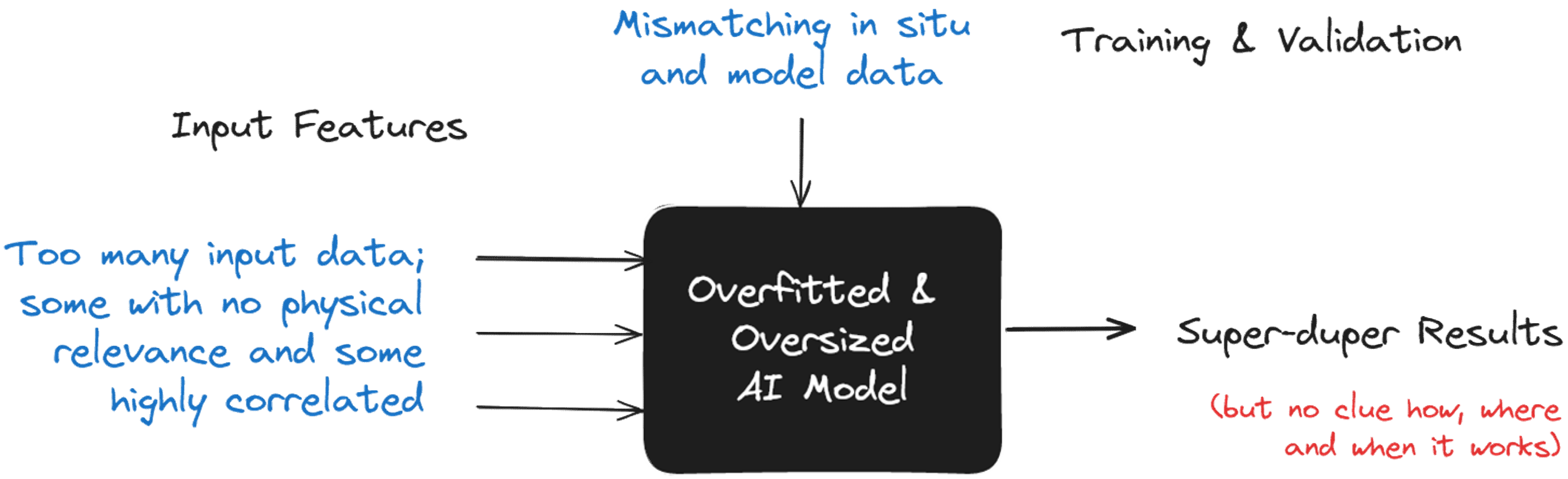


Use of AI for Soil Moisture Estimation



„What are benefits and dangers when using artificial intelligence for monitoring of soil moisture from Earth observation data?", Presentation at the HYDROSPACE 2023 Workshop, organised by ESA, GEWEX and CNES, Lisbon, Portugal, 30 November 2023.

What Can Go Wrong?



„What are benefits and dangers when using artificial intelligence for monitoring of soil moisture from Earth observation data?", Presentation at the HYDROSPACE 2023 Workshop, organised by ESA, GEWEX and CNES, Lisbon, Portugal, 30 November 2023.

Soil Moisture Retrieval using Hybrid Approaches

- Hybrid models
  - Physical models serve to constraint the solution space
  - AI techniques essential for data exploration, estimation of model parameters, approximating unknown processes, extrapolation, etc. etc.

- We use three backscatter models of increasing complexity
  - Change detection backscatter model
    - Developed for ENIVSAT ASAR and adopted for Sentinel-1

Bauer-Marschallinger et al. (2019) Towards global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles, IEEE Transactions on Geoscience and Remote Sensing, 57(1).

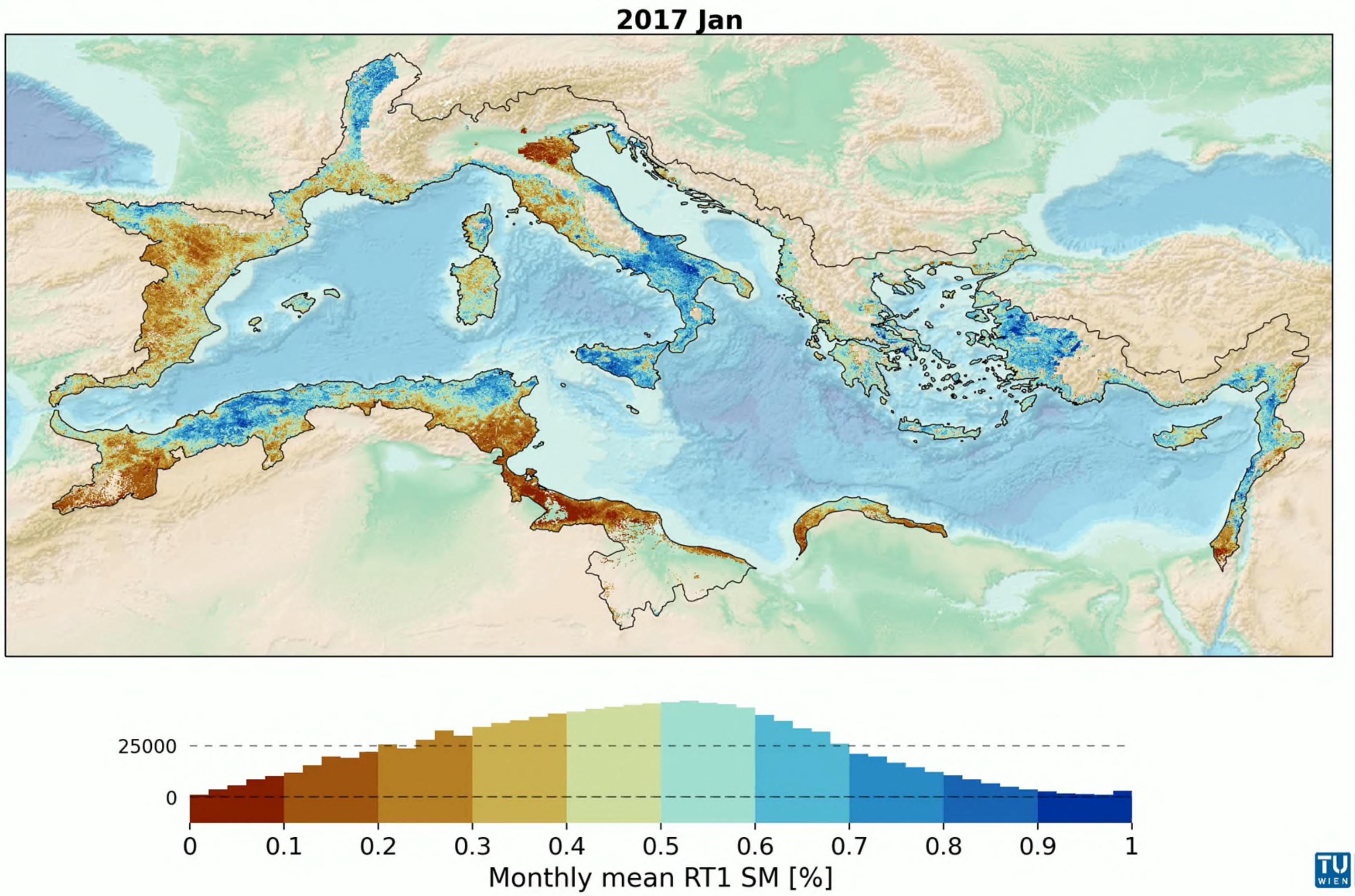
  - Zero-order radiative transfer model RT0
    - Modified water cloud model developed for studying subsurface scattering

Wagner et al. (2022) Widespread occurence of anomalous C-band backscatter signals in arid environments by subsurface scattering, Remote Sensing of Environment, 276, 113025.

  - First-order radiative transfer model RT1
    - Developed to describe soil-vegetation interaction mechanisms and a new way of modelling soil scattering

Quast et al. (2023) Soil moisture retrieval from Sentinel-1 using a first-order radiative transfer model - a case-study over the Po-Valley, Remote Sensing of Environment, 295, 113651.

Improved 1km Sentinel-1 Surface Soil Moisture Retrievals



Digital Twin Earth (DTE) Hydrology Project

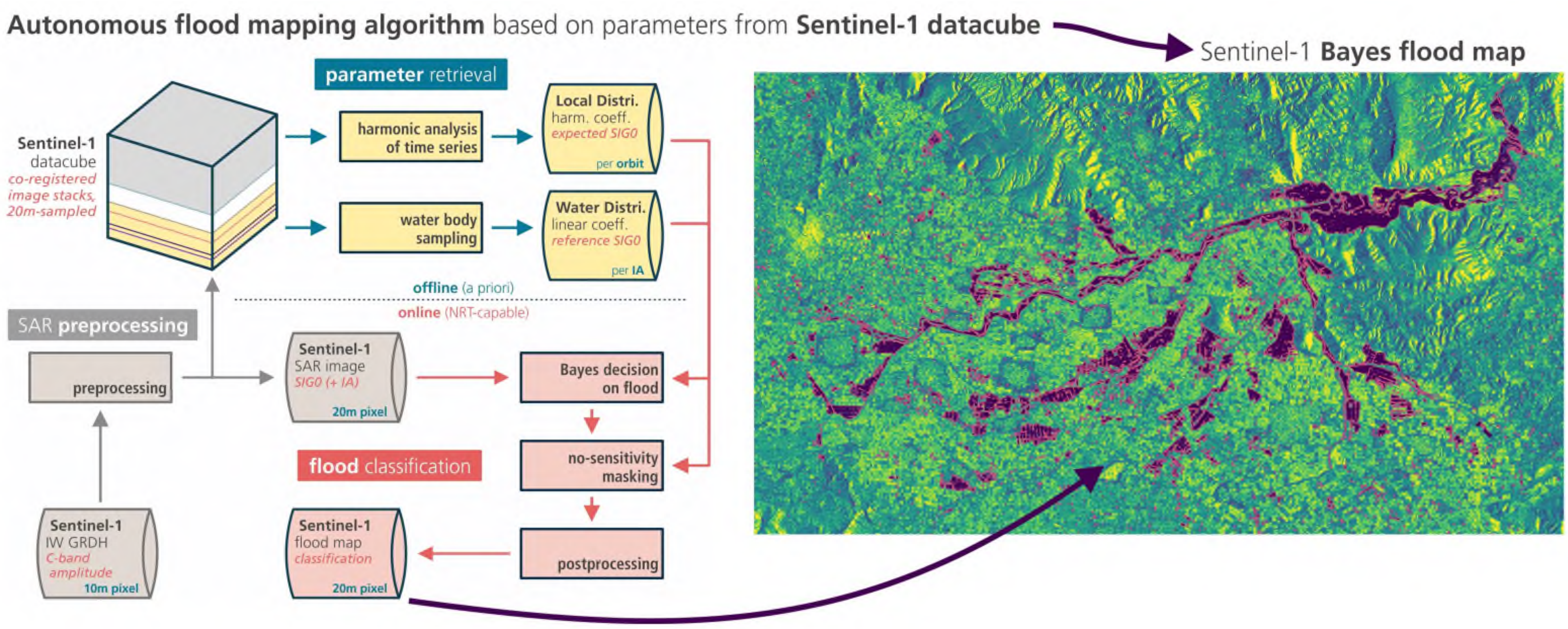
Mean-monthly Sentinel-1 surface soil moisture retrievals for the Mediterranean region from 2017 to 2021.

Quast et al. (2023) Soil moisture retrieval from Sentinel-1 using a first-order radiative transfer model - a case-study over the Po-Valley, Remote Sensing of Environment, 295, 113651.

TU Wien's Bayesian Flood Mapping Algorithm

- Sentinel-1 data cube needed to
  - parameterize the model
  - derive exclusion layers

$$P(F|\sigma^0) = \frac{p(\sigma^0|F)P(F)}{p(\sigma^0|F)P(F) + p(\sigma^0|NF)P(NF)}$$



Bauer-Marschallinger et al. (2022) Satellite-based flood mapping through Bayesian inference from Sentinel-1 SAR datacube, Remote Sensing, 14, 3673, 28p.

Conclusions & Outlook

- There has been rapid progress in our capability for monitoring hydrological processes
  - Bridging the gap from science to operations is much more demanding than most would expect

- The Web of FAIR data and services is becoming a reality
  - There is no need to enforce monolithic Big Data platform solutions

- More and more extremely powerful satellite missions are becoming available
  - Lack of resources for the proper care and exploitation of the data is a big concern

Acknowledgements
Copernicus: Land Monitoring Service, Emergency Management Service | ESA: DTE Hydrology and 4DMED |
FFG: DWC-Radar, S1Floods.AT, ScaleFloods | BMBWF: Cloud4GEO | Vienna Business Agency: FAIR2Earth