Climate
Change Service

climate.copernicus.eu

Leveraging C3S ECV Datasets for Earth System Modeling: insights and applications

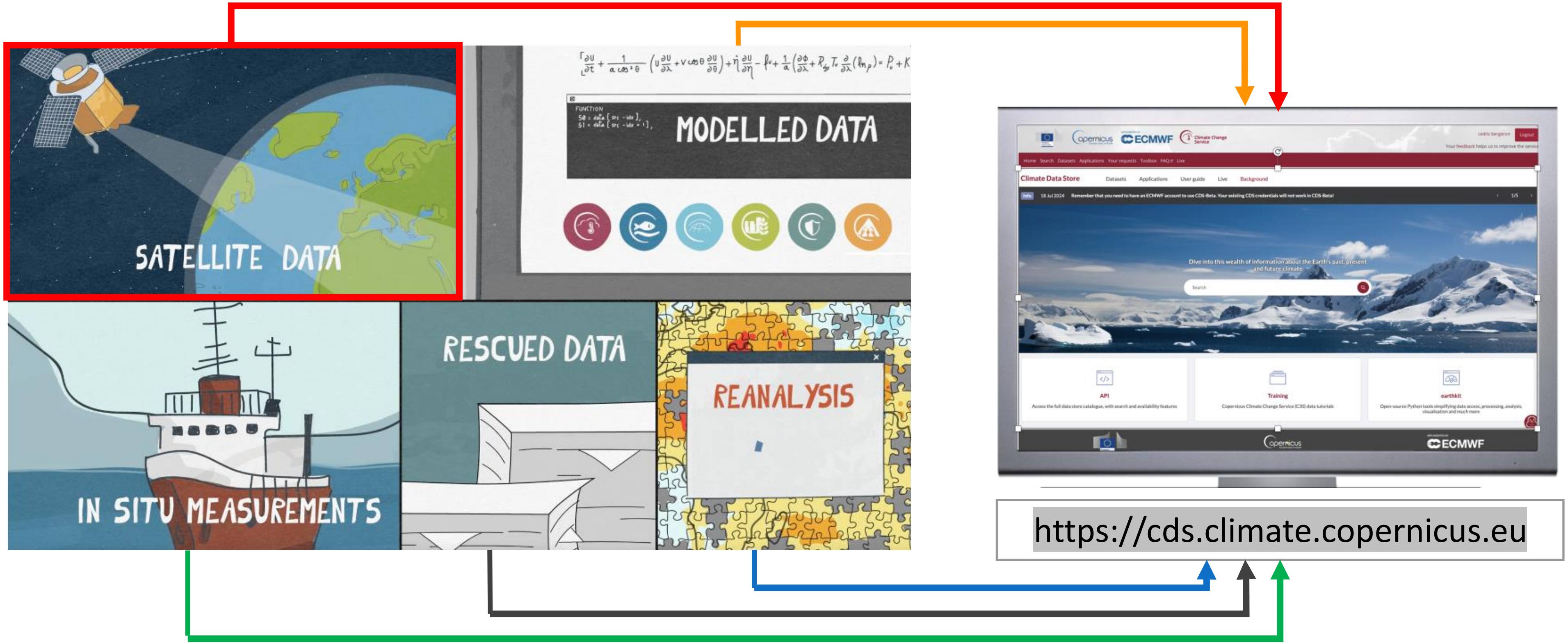
Workshop on ancillary data for land surface and Earth system modelling – 09-10 April 2025, Bonn

Joaquín Muñoz Sabater

C3S team and contractors

Open and free

Data to monitor climate



The starting point: the Global Climate Observing System (GCOS)

GCOS is the **authoritative global source of information** and advice for planning and development of the Global Climate Observing System, its networks and data management. It is the authoritative source reference for formulating **requirements for space and in situ climate observations**.

→ GCOS does not directly make observations nor generation of data products

<u>ECVs provide a comprehensive view of the climate system & are critical for understanding and predicting climate change</u>

- ECVs are crucial for implementing international agreements like the Paris Agreement
- Required to support the work of the UNFCCC and the IPCC (they use ECVs in assessment reports)
- Group on Earth Observations (GEO): promote use of ECVs in EO strategies

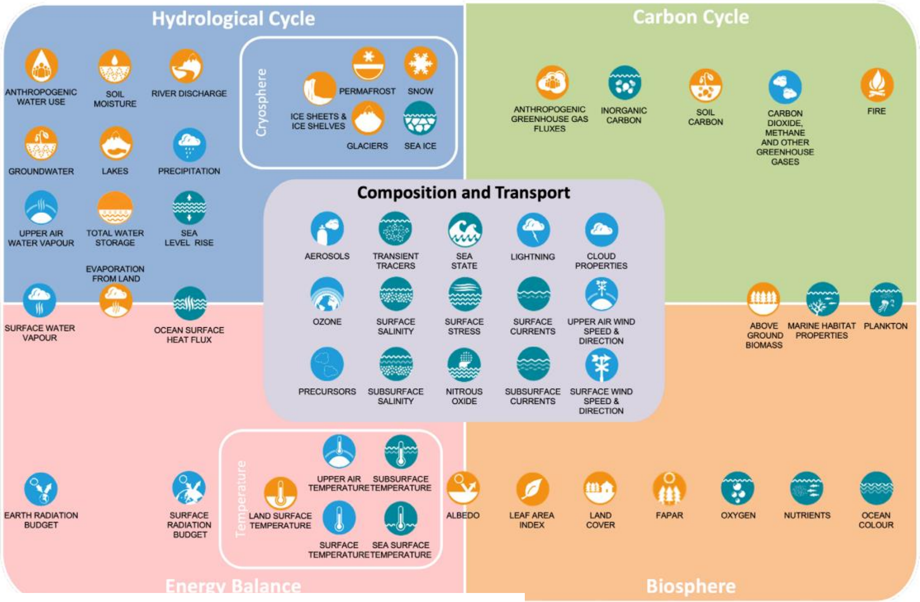
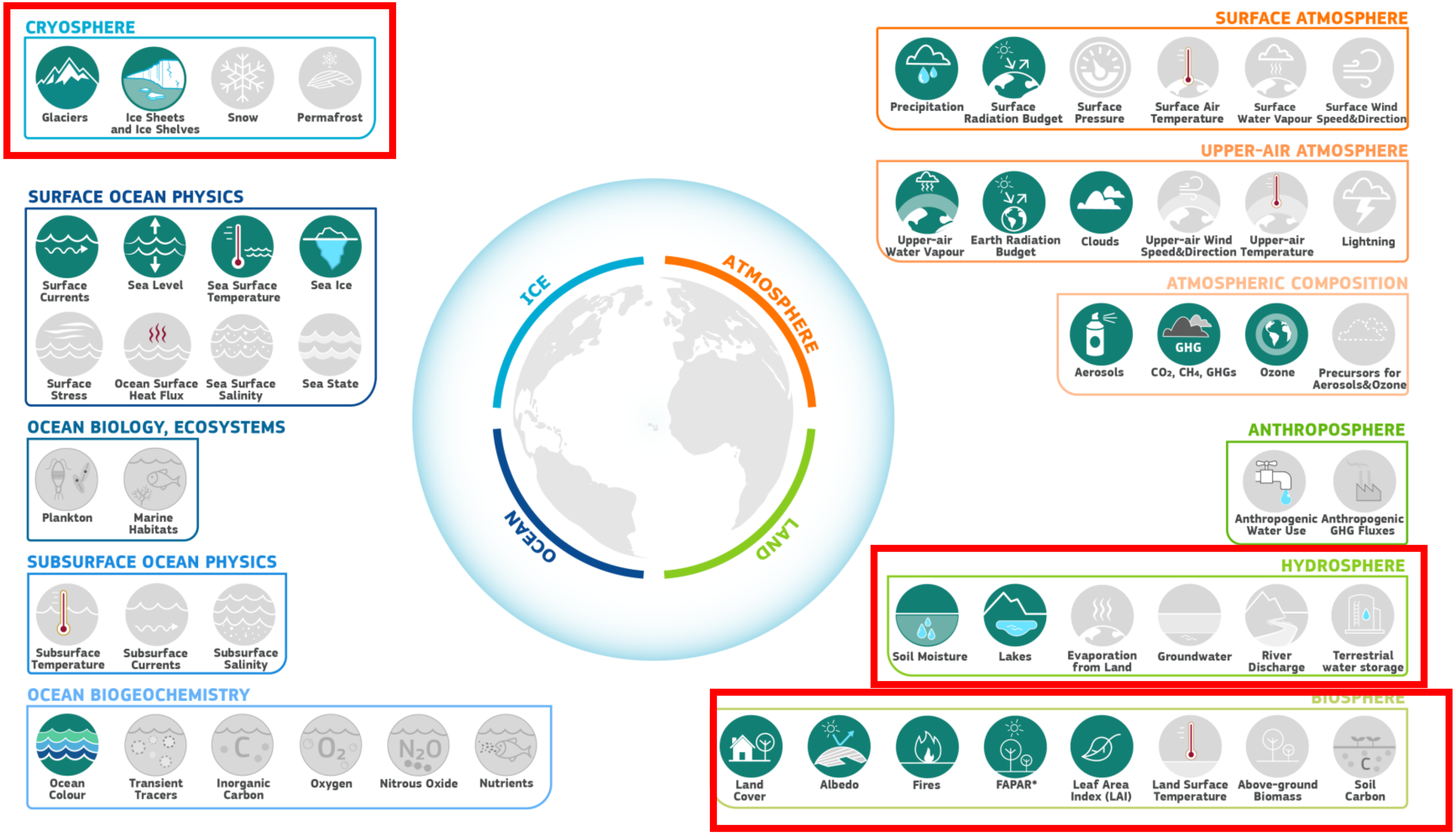


Fig.2 from GCOS IP-2022

The C3S ECV programme



In total GCOS defines 55 ECVs (GCOS 2022 Implementation Plan)

Three main domains:

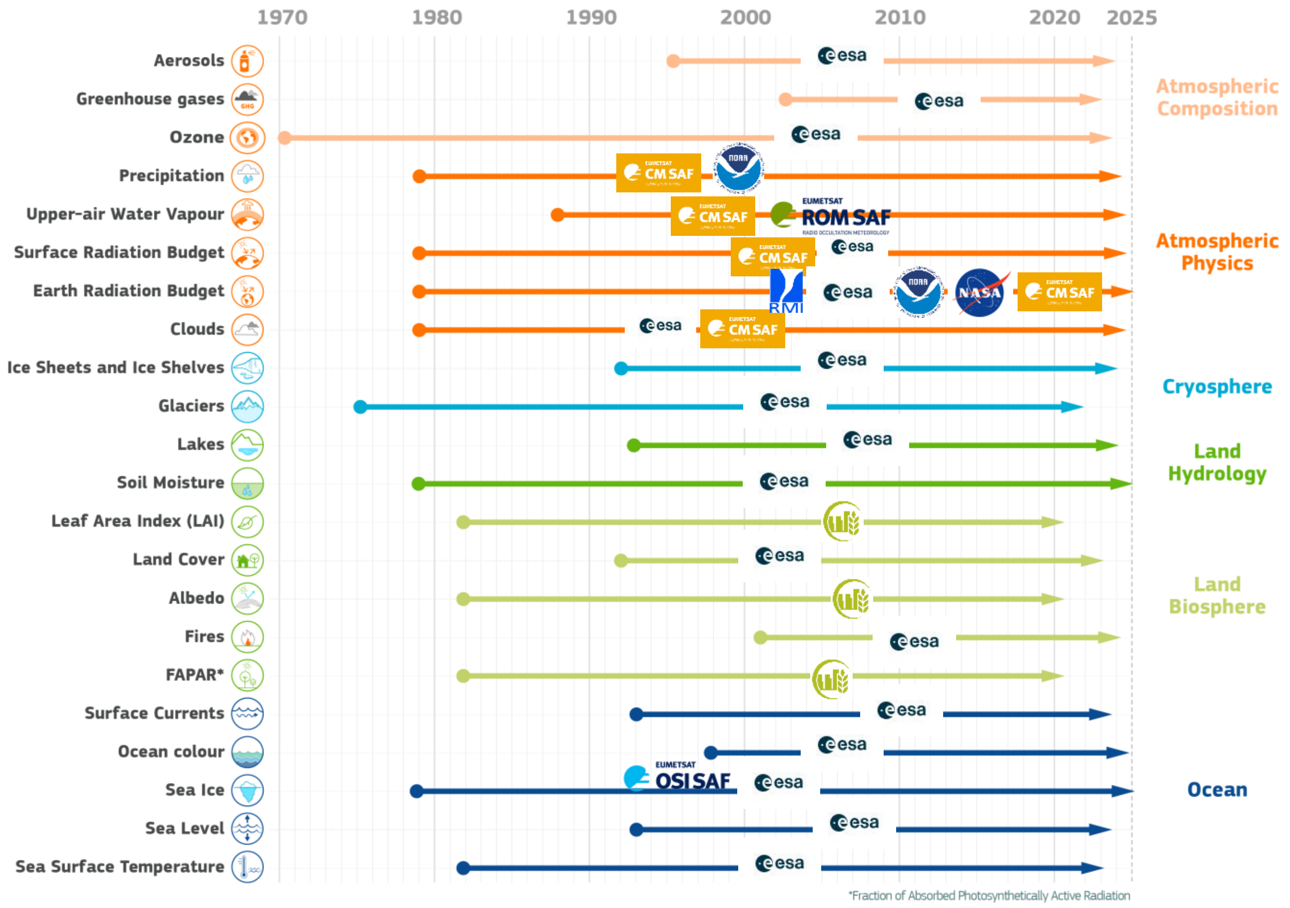
- Atmospheric
- Oceanic
- Terrestrial

Climate Data Records of Essential Climate Variables – current offer

Based on satellite data, they monitor trends and variability

Involve close coordination and collaboration with major providers (ESA, EUMETSAT) and Copernicus Services

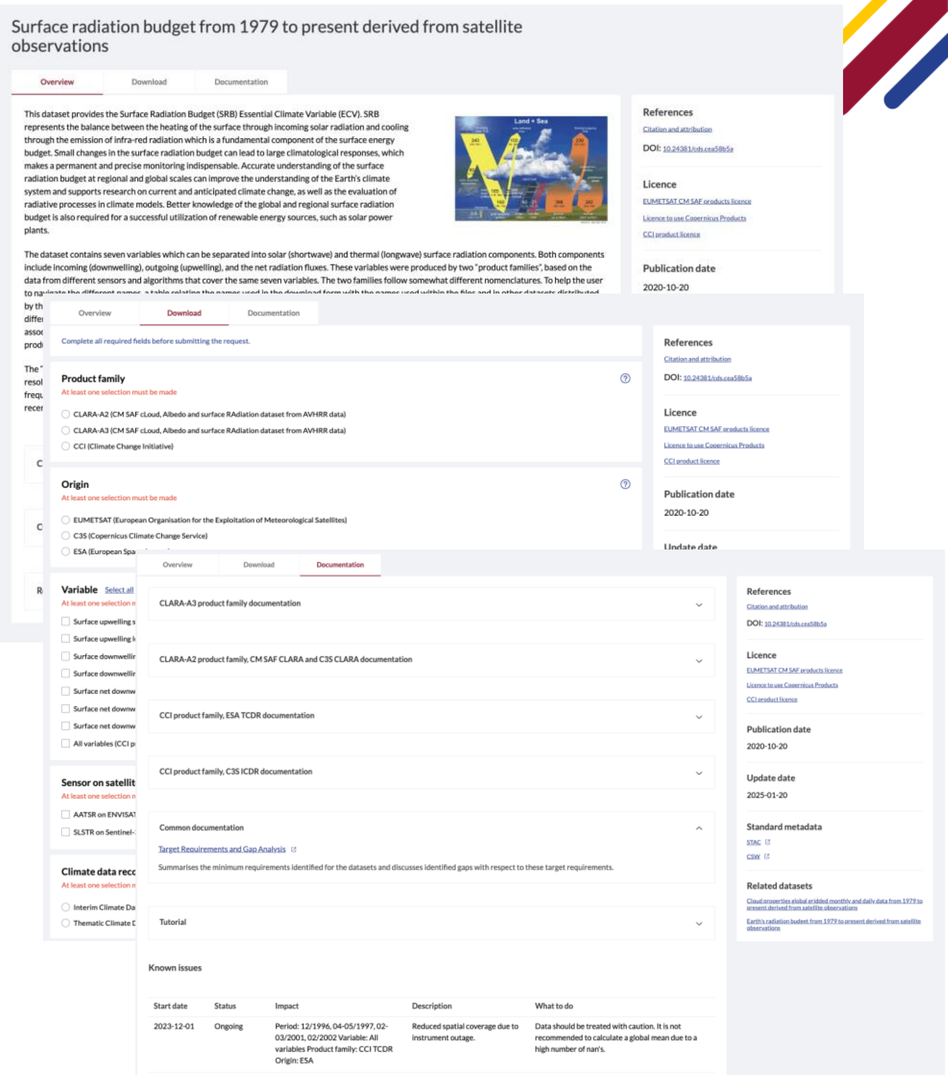
Their production require the expertise of many public and private entities in Europe



C3S ECV services

Access to ECV products through a harmonized look-and-feel interface (CDS), which are:

- State of the art (coordination with ESA, EUMETSAT, Copernicus Services)
- Long-term, consistent, complete (CDR) [multi-sensor approach]
- Regularly extended in time (ICDR)
- Gridded, aggregated (meeting climate requirements)
- Accessible & Traceable
    - Access through the Climate Data Store
    - Comprehensive documentation



C3S ECV services

Independent **Evaluation and Quality Control**

Specialised **User Support**

Training material

Use cases

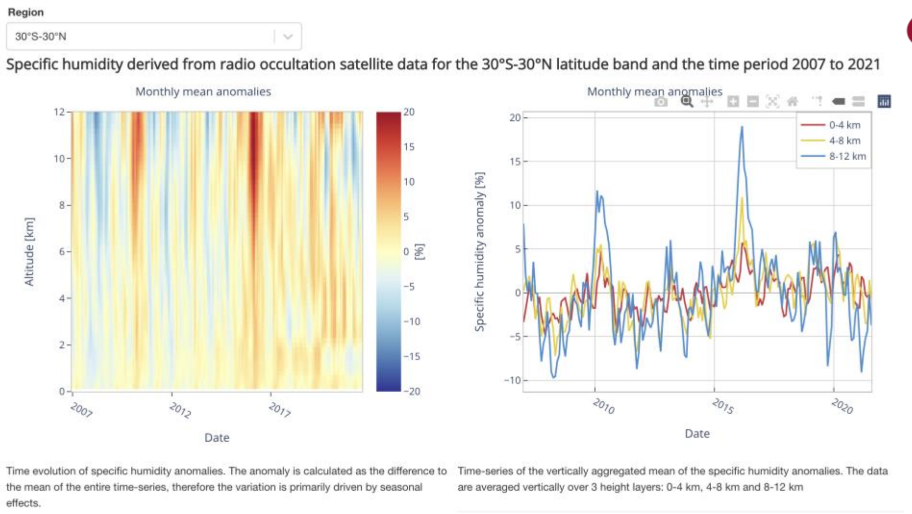
Data **visualisation**

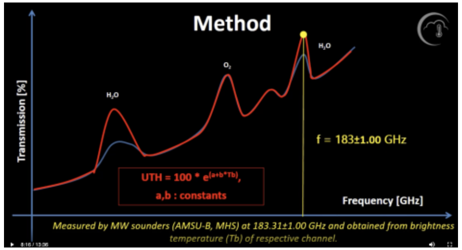
Licenses, references, doi

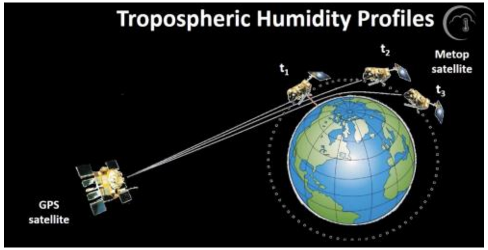
Applications tailored to different sectors

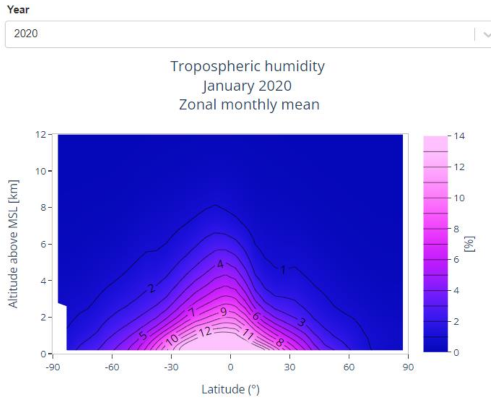
Climate Intelligence derived **products**

...







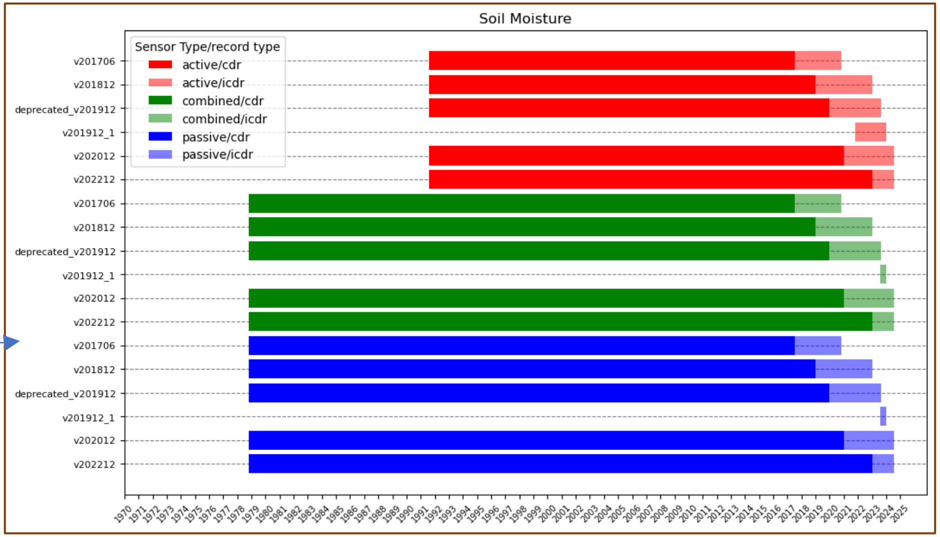


Land hydrology domain – satellite-based ECVs

Consortium led by the Earth Observation Data Centre (EODC).

ECVs: Soil Moisture, Lakes, *Groundwater and Terrestrial Water Storage*

Soil moisture



Soil moisture as a key data source for land hydrology

Adapted from the ESA CCI SM Climate Assessment Report (2024)

[*Thanks to Johanna Lems, UW*]

Main Purpose	References	Motivation for Using ESA CCI SM
Evaluating model states in hydrological models and LSMs	Loew et al. (2013); Fang et al. (2016); Du et al. (2016); Spennemann et al. (2015); Schellekens et al. (2016); Szczypta et al. (2014); Lauer et al. (2017); Mao et al. (2017); Lai et al. (2016); Rakovec et al. (2016); etc.	Robust statistics based on long comparison period
Evaluating model processes in hydrological models and LSMs	Chen et al. (2016); Raoult et al. (2021); Ghajarnia et al. (2021); Baker et al. (2021); Raoult et al. (2022); etc.	Realistic dry down characteristics
Assimilated to constrain coupled LSM and hydrological simulations	Albergel et al. (2017); Liu et al. (2018b); Pinnington et al. (2018); Raoult et al. (2018); Yan et al. (2018); etc.	Long-term availability
Error covariance matrix estimation in LSM simulations	Crow et al. (2015)	Long data record length essential for reducing sampling errors
Persistence and prediction of soil moisture anomalies	Nicolai-Shaw et al. (2016); Allen and Anderson (2018); Klingmuller and Lelieveld (2021); Piles et al. (2022); etc.	Long-term dataset required for robust statistics
Improving runoff predictions and flood (risk) analysis	Tramblay et al. (2014); Massari et al. (2015); Kim et al. (2018); Massari et al. (2018); El Khalki et al. (2018); Zhong et al. (2019); Ganguli et al. (2020); etc.	Not specified
Calibrating hydrological models	Kundu et al. (2017); Demirel et al. (2019); Koppa et al. (2019); etc.	Not specified
Improved water budget modeling	Allam et al. (2016); Abera et al. (2017); de Figueiredo et al. (2021); Mehrnegar et al. (2021); etc.	Long-term availability for more robust statistics
Computing changes in groundwater storage	Asoka et al. (2017)	Long-term availability for trends assessment
Modeling and understanding surface water dynamics	Heimhuber et al. (2017); Gu et al. (2019a); Khazaei et al. (2019); etc.	Long-term availability for more robust statistics
Assessing irrigation	Qiu et al. (2016); Kumar et al. (2015); Zhang et al. (2018b); Paciolla et al. (2020); Zhang et al. (2022a); Zappa et al. (2022); Fan et al. (2022)	Long-term data required for trend-based method of Qiu et al. (2015)
Assessing the impact of agricultural intensification on soil moisture	Liu et al. (2015)	Long-term data coverage needed for long-term impacts
Trigger of landslides	Dahigamuwa et al. (2016); Dahigamuwa et al. (2018); Zhuo et al. (2019); etc.	Long-term availability
Improving satellite rainfall retrievals	Bhuiyan et al. (2017a); Bhuiyan et al. (2017b); Qiu et al. (2016); Kumar et al. (2015)	Data record spans multiple satellite precipitation missions
Computing cumulative precipitation amounts	Ciabatta et al. (2016); Liu et al. (2015); Ciabatta et al. (2018); Massari et al. (2019); Miao et al. (2023); He et al. (2023)	Long data record needed for generation of long-term precipitation dataset
Validating soil moisture products derived from precipitation	Das and Maity (2015); Dahigamuwa et al. (2016); Ramsauer et al. (2021)	Long-term availability for robust statistics
Evaluating soil moisture products derived from other satellite platforms	Leng et al. (2017); De Zan and Gomba (2018); Pablos et al. (2018); Zhou et al. (2018); Cui et al. (2020b); Fan et al. (2020); etc.	Long-term availability for robust statistics
Evaluating in-situ networks	Ford et al. (2020)	Long-term availability

- **Multi-decadal**
- **Stability**
- **Consistency**

Application areas:
- *Data assimilation*
- *Hydrological modeling*
- *Model Calibration*
- *Hydrological assessment & validation*

Validating SSM fields in Land Surface Models

- Wang et al., 2022, Evaluated CMIP6 multimodel simulation with long-term SM dataset

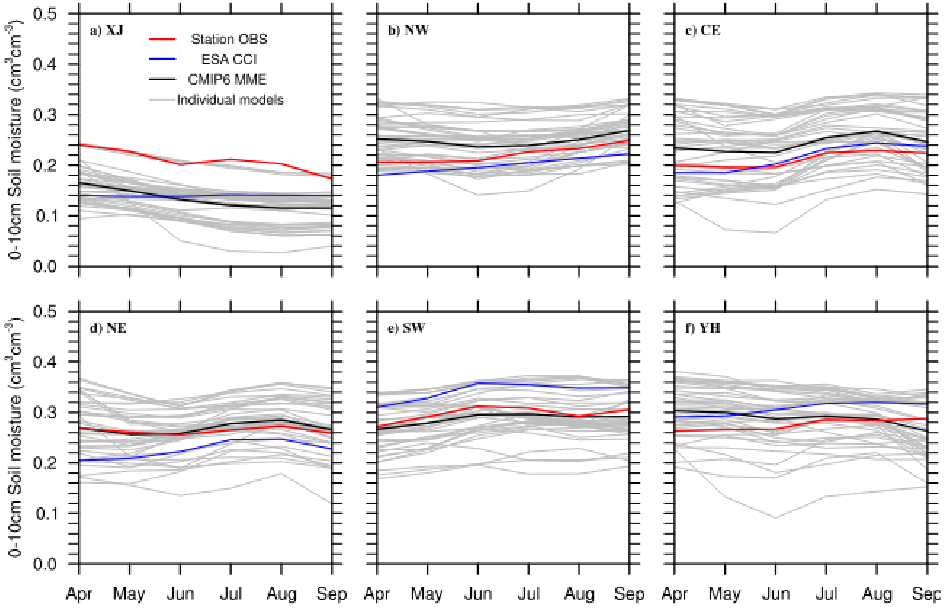


Figure 5. Seasonal cycles of regional mean surface (0–10 cm) soil moisture (SM) for station observation (WS2019, red curve), European Space Agency Climate Change Initiative (ESA CCI) data set (blue curve) individual CMIP6 model simulation (thin black curve), and multimodel ensemble mean (MME) (bold black curve) from the average SM of growing seasons (April to September) from 1992 to 2013. Regional divisions are indicated in Figure 1a.

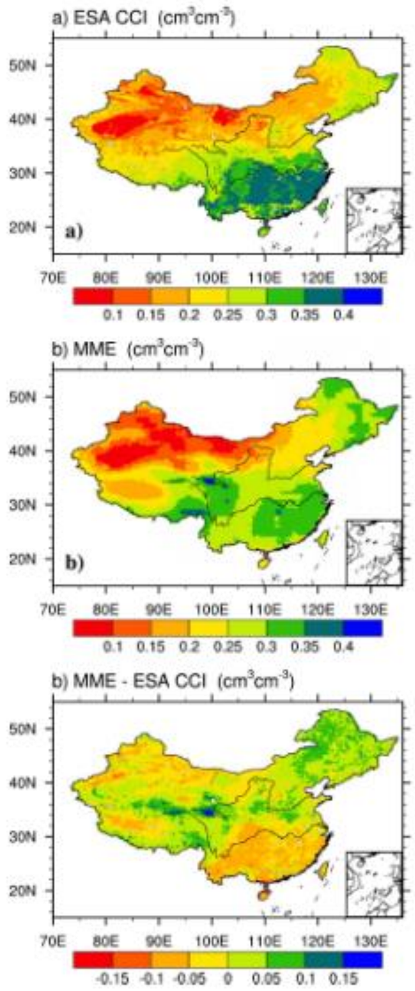


Figure 3. The mean soil moisture (SM) averaged over the growing season (April–September) for the period of 1992–2013 for (a) European Space Agency Climate Change Initiative (ESA CCI) data set; (b) 0–10 cm CMIP6 multimodel ensemble mean (MME), and (c) the differences between MME and ESA CCI. The area-weighted mean SM over China is 0.27 cm^3 cm^{-3} from both MME and ESA CCI.

Wang, A., Kong, X., Chen, Y., and Ma, X.: Evaluation of Soil Moisture in CMIP6 Multimodel Simulations Over Conterminous China, Journal of Geophysical Research: Atmospheres, 127, 10.1029/2022JD037072, 2022.

Use of Lake Water Level data to Lake modelling

IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 7, NO. 2, FEBRUARY 2014 609

Numerical Simulation and Forecasting of Water Level for Qinghai Lake Using Multi-Altimeter Data Between 2002 and 2012

Jingjuan Liao, Le Gao, and Xiaoming Wang

DOI: 10.1109/JSTARS.2013.2291516

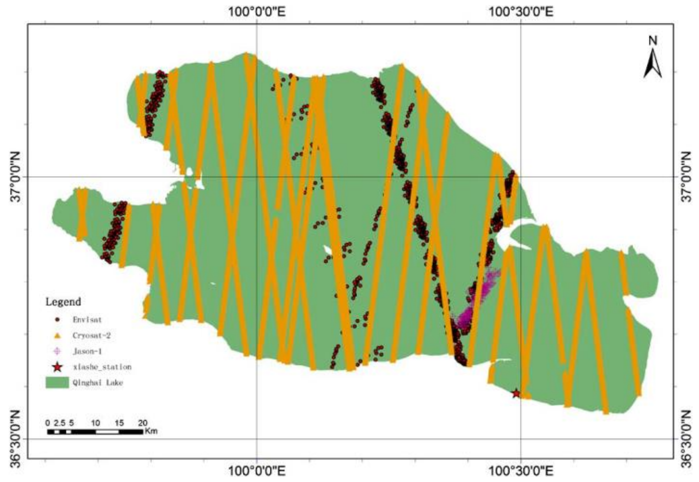
In this study, a combined linear periodic-residual model was established based on the SSA-extracted fluctuation signal from the lake-level time series of multi-altimeter data;

Least Square method and system bias correction algorithms → abnormal water levels and the system bias were eliminated, and an accurate lake-level time series was obtained

SSA → eliminated white noise & the accuracy of the altimeter data reached the decimeter level in inland lake monitoring

The water level changes over lake Qinghai (Kokonor) were predicted until two years

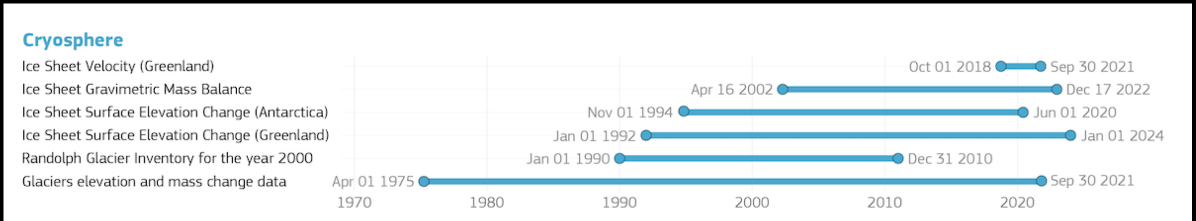
SSA : Singular Spectrum Analysis



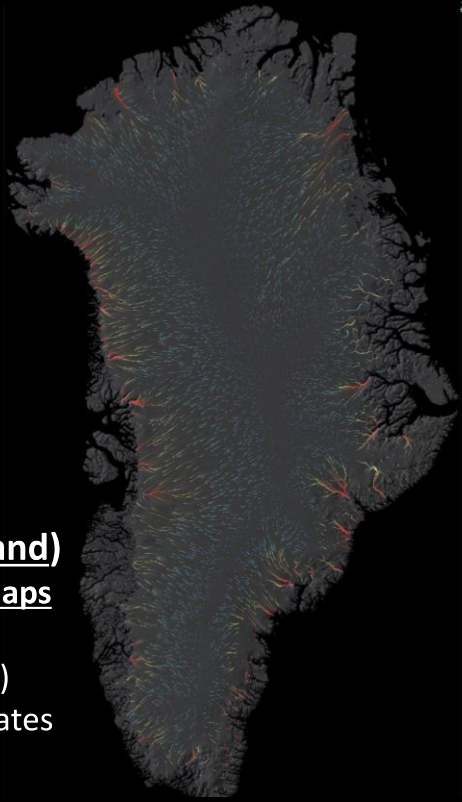
Lake Water Level of lake Qinghai, also known as Kokonor, is available in the C3S Climate Data Store

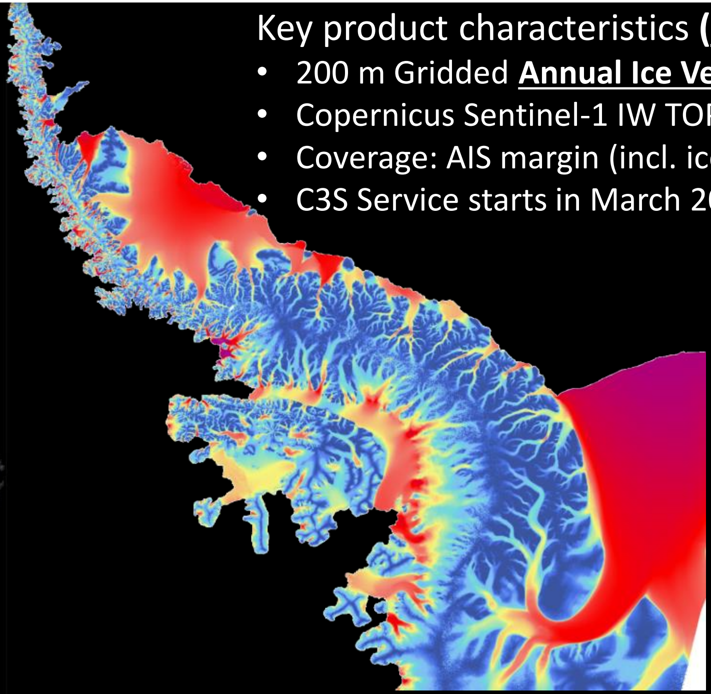
[*Thanks to Beatrize Calmettes, CLS*]

Land cryosphere domain



Consortium led by Environmental Observation Information Technology (ENVEO)
ECVs: Glaciers, Ice Sheets and Ice Shelves and *Snow*





Key product characteristics **(<u>Antarctica</u>)**

- 200 m Gridded **<u>Annual Ice Velocity Maps</u>**
- Copernicus Sentinel-1 IW TOPS SAR
- Coverage: AIS margin (incl. iceshelves)
- C3S Service starts in March 2023 - Yearly updates

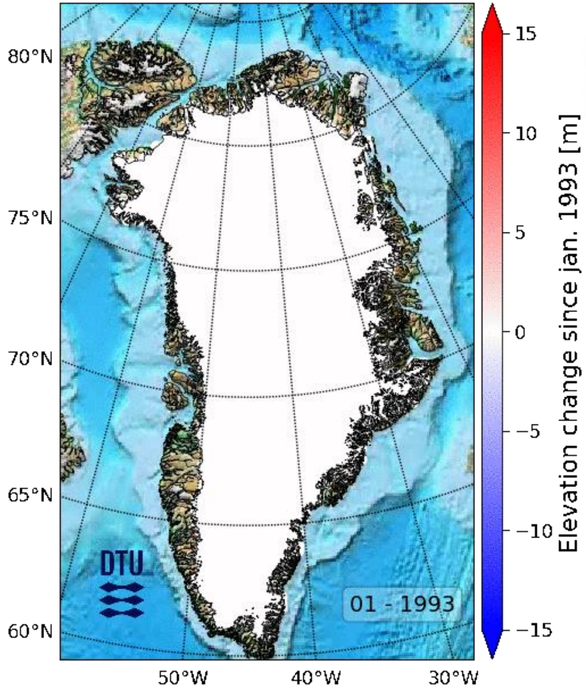
Key product characteristics **(<u>Greenland</u>)**

- 250 m Gridded **<u>Annual Ice Velocity Maps</u>**
- Copernicus Sentinel-1 IW TOPS SAR
- Coverage: GIS margin (incl. iceshelves)
- Timeseries starts in 2014 - Yearly updates

Surface Elevation Change

Paper: https://doi.org/10.1002/2020GL091216

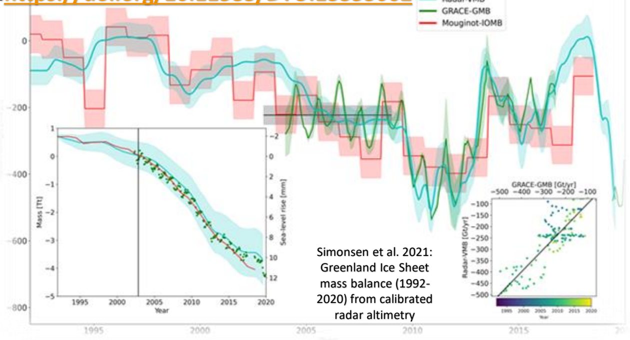
Data: :https://doi.org/10.11583/DTU.13353062

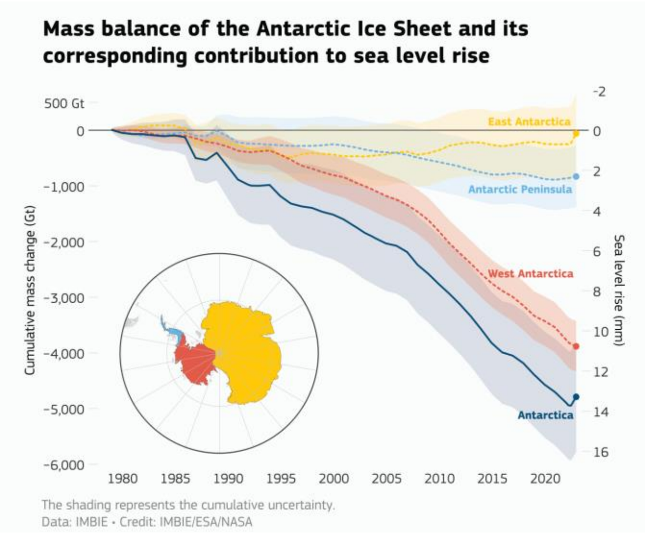


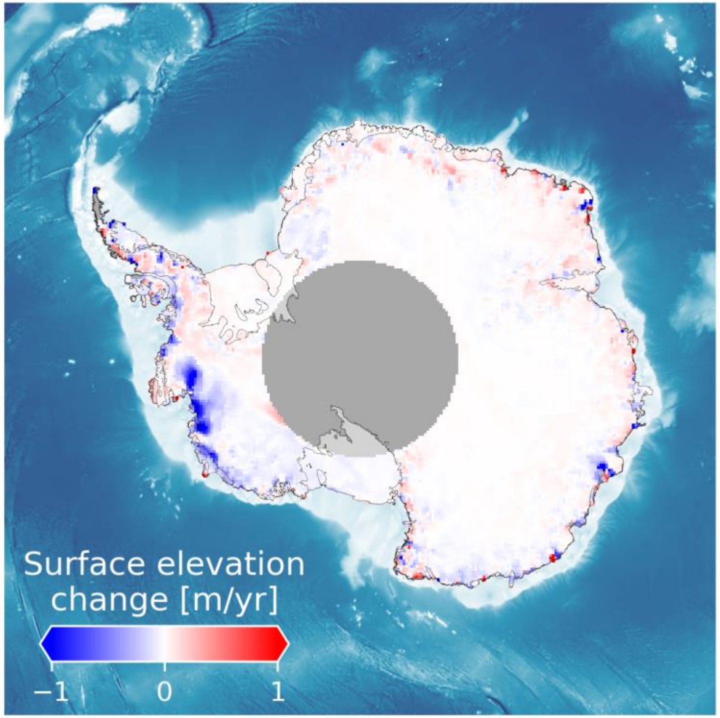
Greenland ice sheet mass balance from 1992- 2020:

12.1±2.3 mm s.l.e

More than 80% of this contribution occurs after 2003

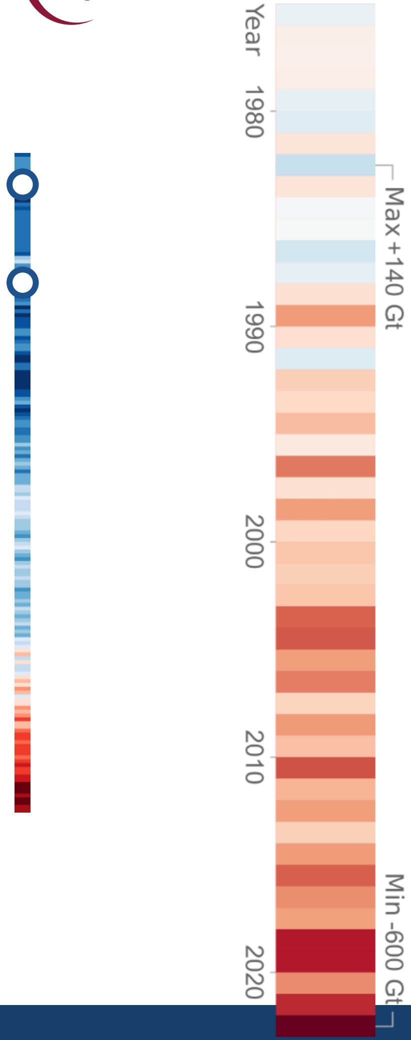


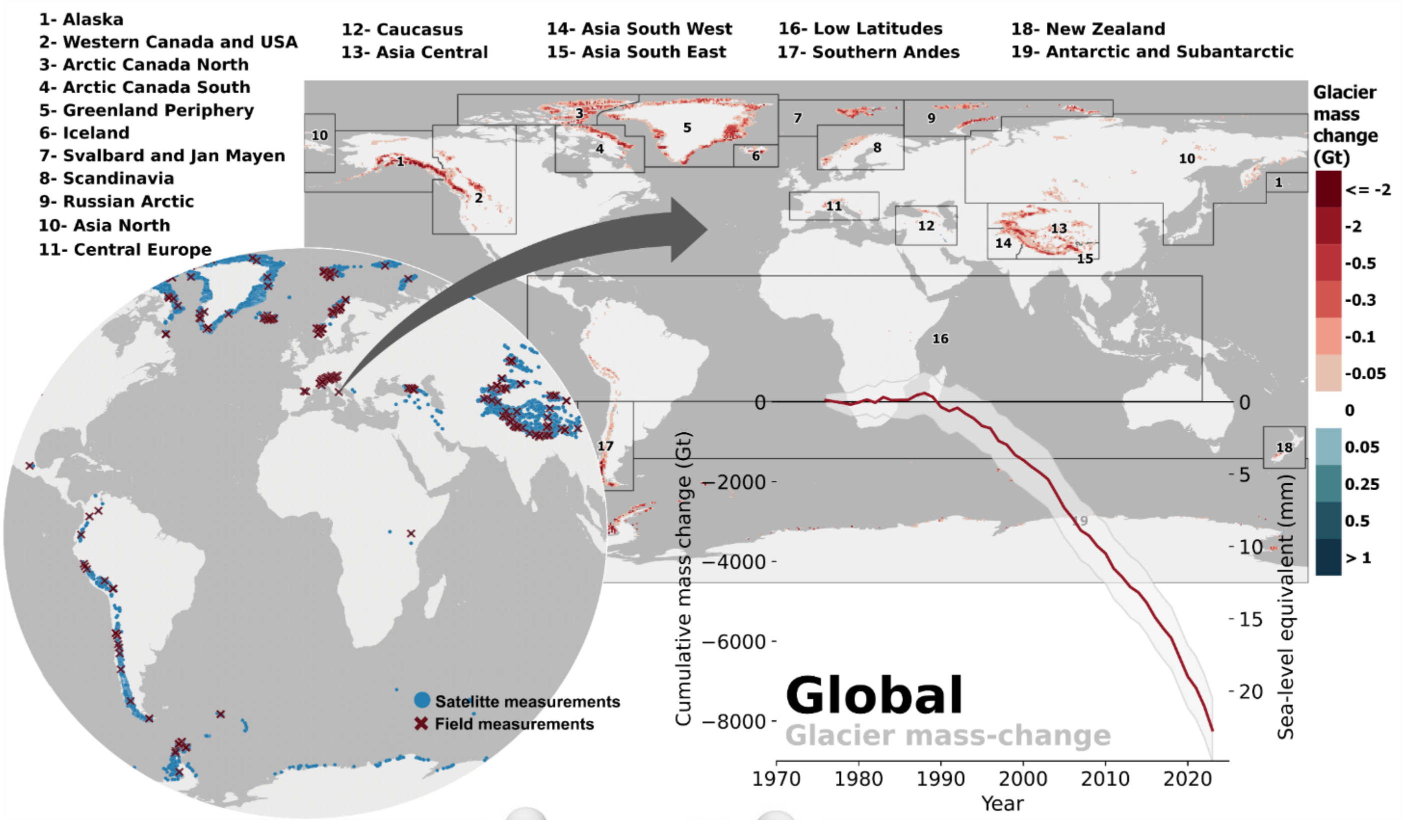




[Thanks to ENVEO]

Glacier Mass Change



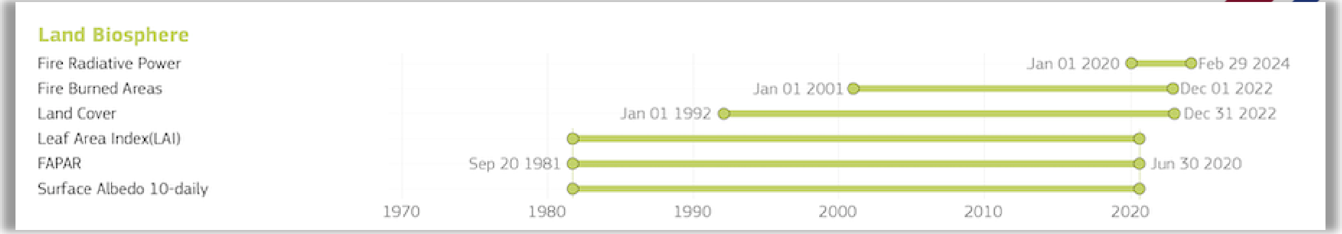


I. Dussaillant et al. (accepted)

Land Biosphere domain

Consortium led by Brockmann Consult (BC).

ECVs: Fire, Land Cover, *Land Surface Temperature*



CCI Land Cover concept revisited

LC + land surface seasonality + LC change

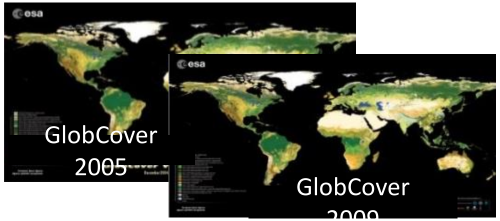
GlobCover: 2005 & 2009

CCI-LC 3 x 5-y epochs

CCI-LC: annual series

C3S: operational

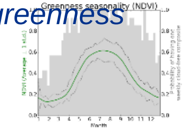
2008 — 2010 — 2014 — 2016 — 2017 — 2018



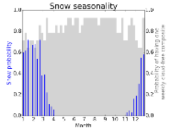
Automated processing chain
Gobal LC mapping at 300m
From MERIS FRS
22 FAO-LCCS LC classes

5-y consistency
2000, 2005 and 2010
only forest change

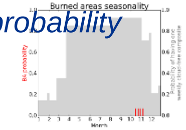
Vegetation greenness

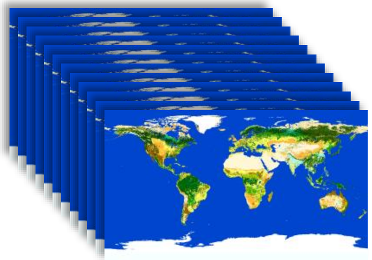


Snow probability



Burned areas probability

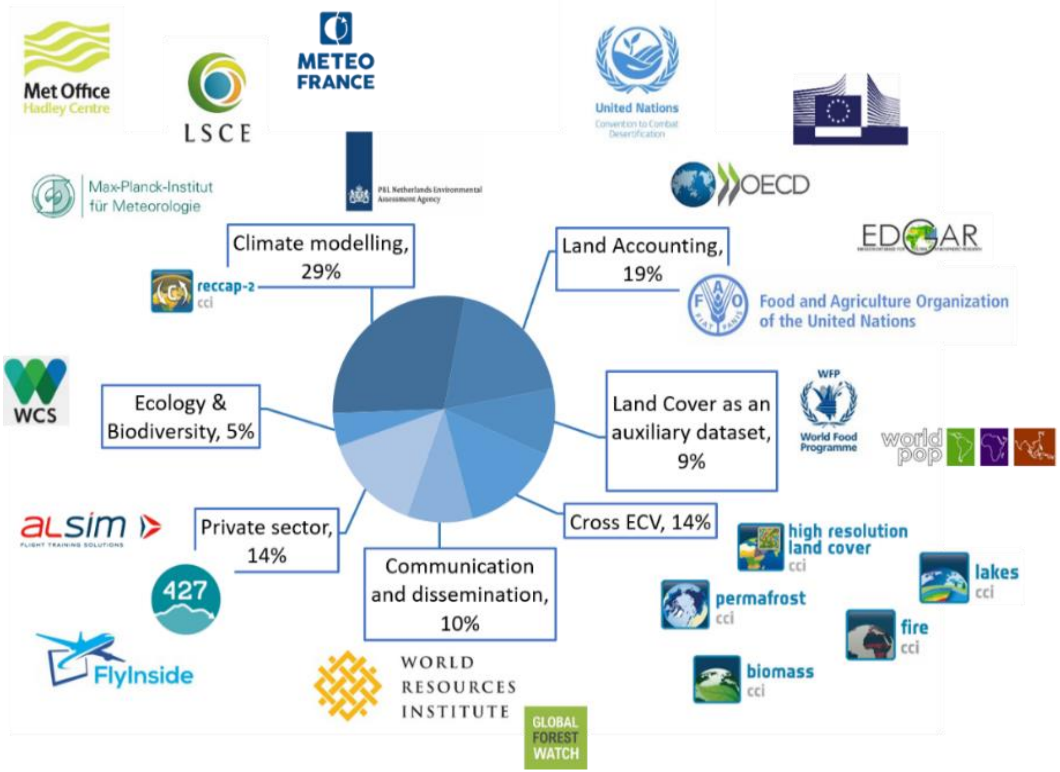




Annual consistency
1992-2015
13 changes

Operational Production 2016-2022

Land Cover



Land Accounting & Climate Policy

-**UNFCCC:** Sustainable Development Goals (SDG) Indicator 15.3.1 Land degradation tracking

-**FAOSTAT & OECD**:
Agri-environmental and green growth indicators

-**JRC EDGAR**:
LULUCF parameters for GHG emissions/removals estimation

-LC maps integrated into **CMIP6** experiments, **HYDE**, and **HURTT** historical reconstructions of LULC for Earth system modelling.

Ecology & Biodiversity

-**GEO BON** (GEO Biodiversity Observation Network):
Habitat distribution, fragmentation, biodiversity monitoring

-**LifeWatch**:
Remote sensing applications in biodiversity research

-**Wildlife Conservation Society (WCS)**:
Global deforestation, fragmentation, human footprint via geoportals

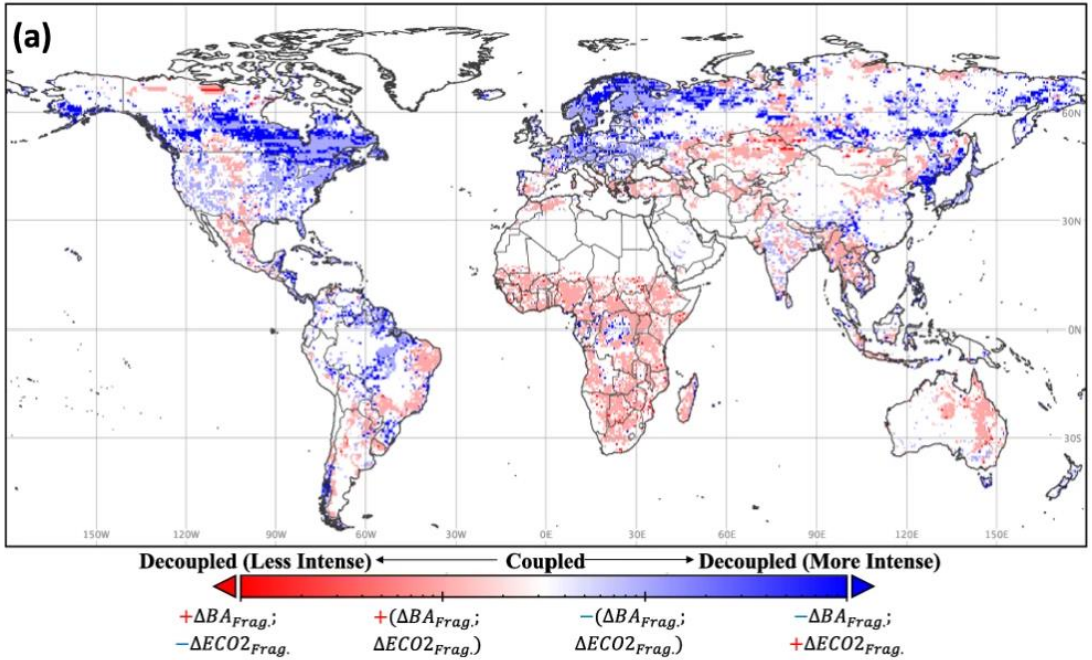
-**Biodiversity modellers & field ecologists**:
Foundational input for habitat and ecological mapping

[*Thanks to Celine Lamarche, UL*]

Fire Burned Area

The FireCCI51 dataset (converted to fire patches using the FRY2.0 dataset) has been used to analyse the relationship between land fragmentation and burned area (BA) occurrence, using the ORCHIDEE-SPITFIRE model.

On average, more fragmentation decreased net BA globally (−1.5%). However, in recently-deforested tropical areas, fragmentation drove observationally-consistent BA increases of over 20%.



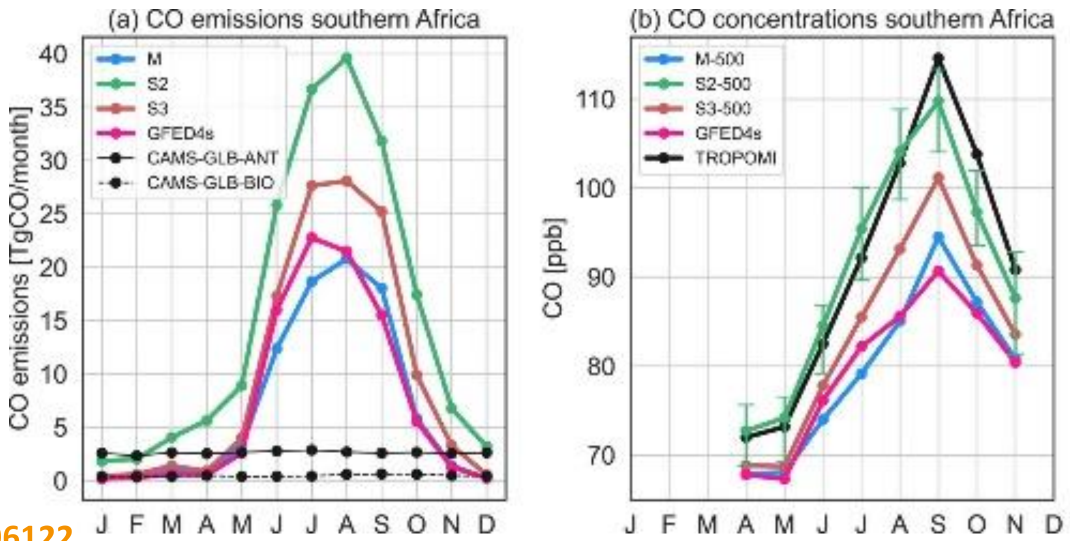
https://doi.org/10.1038/s41467-024-53460-6

[*Thanks to Lucrecia Pettinari, UAH*]

Fire Burned Area

The FireCCIS311 product has been used to calculate Carbon Monoxide (CO) emissions in Southern Hemisphere Africa for 2019, and compared to TROPOMI observations.

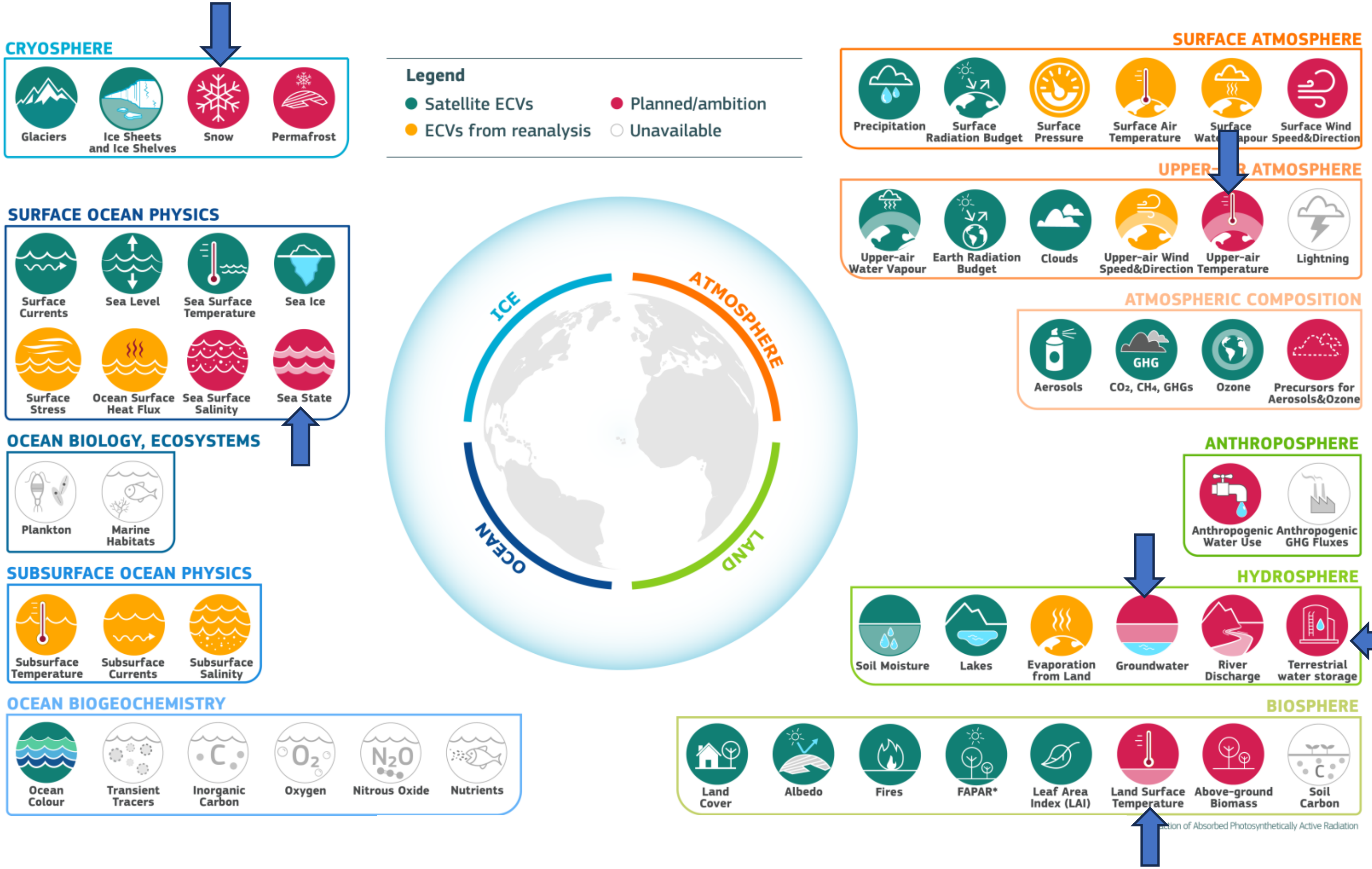
From the different medium-resolution products available, FireCCIS311 (denoted in the graph as S3-500) shows the highest agreement with observations.



https://doi.org/10.1029/2023GL106122

[*Thanks to Lucrecia Pettinari, UAH*]

Enhancing the ECV offering

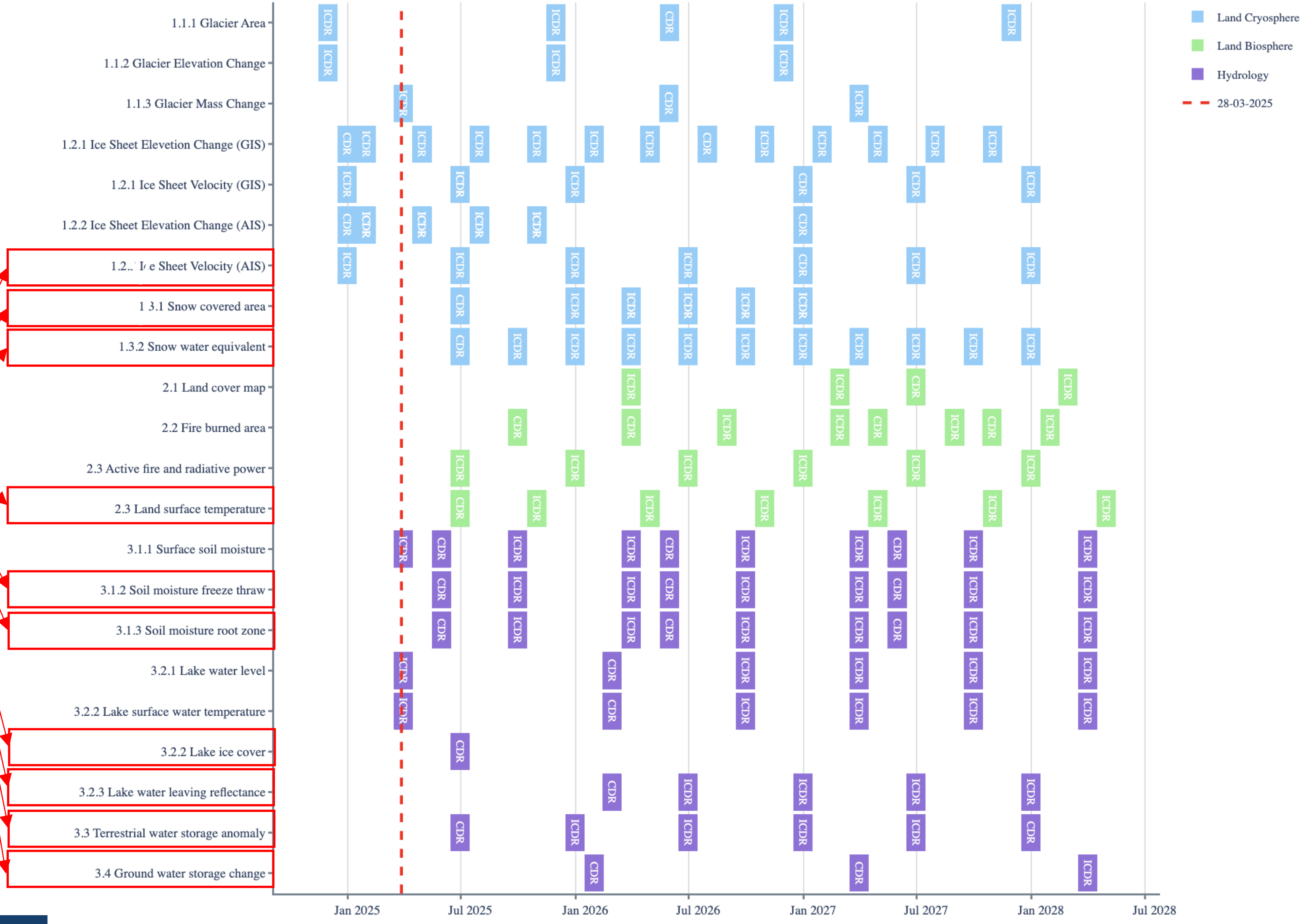


Crucial to understand changes in our climate.

C3S responds to GCOS and UNFCCC implementation needs.

Enhancing the ECV offer

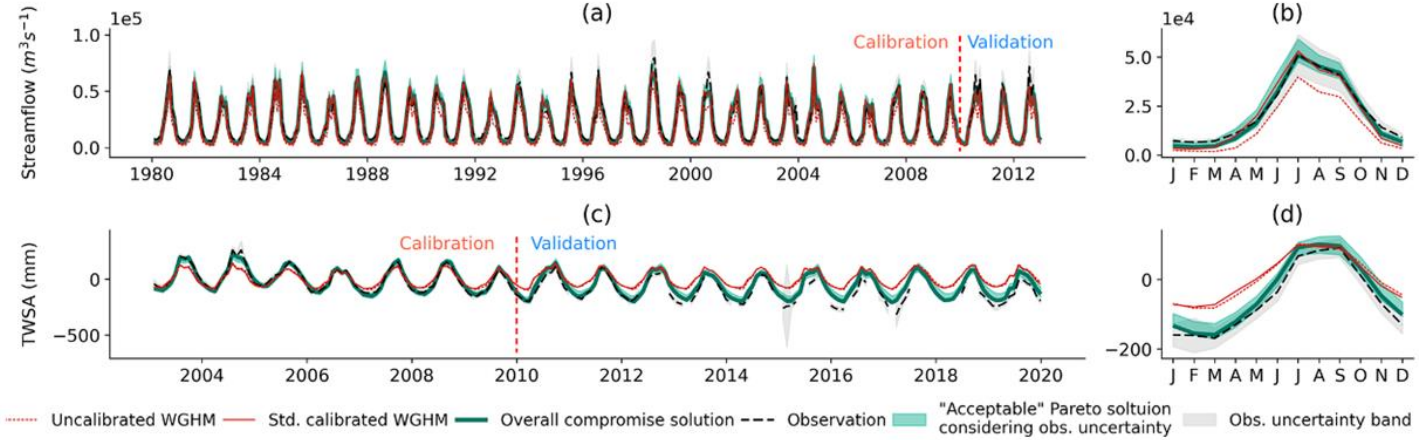
Schedule of major data deliverables, including new ECVs and ECV products

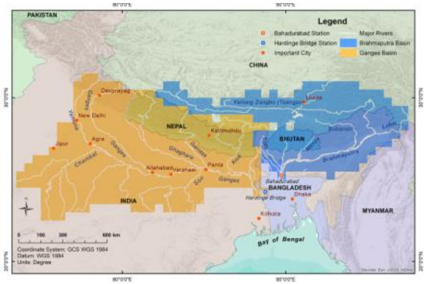


[Thanks to Erik Loebel]

Terrestrial Water Storage for improving hydrological models

Use of terrestrial water storage anomalies (TWSA) for the multi-variable calibration of the WaterGAP Global Hydrological Model (WGHM)





Example for the Brahmaputra basin (Hasan et al. 2025)

→ Constraining the model with GRACE-based TWSA leads to a more consistent simulation of the water cycle of the river basins with respect to, e.g., TWS, streamflow or evapotranspiration

Hasan, M., Döll, P., Hosseini-Moghari, M., Papa, F., Güntner, A. (2025): The benefits and trade-offs of multi-variable calibration of the WaterGAP global hydrological model (WGHM) in the Ganges and Brahmaputra basins. *Hhydrology and Eaarth System Sciences, doi:10.5194/hess-29-567-2025.*

[*Thanks to Andreas Güntner, GFZ*]

Summary

- C3S runs a sustained programme of satellite-based Essential Climate Variables for climate monitoring.

- A core component of the service is the provision of long-term, consistent, and quality-controlled data records of ECVs, fundamental for directly observing and understanding climate variability and change.

- The C3S ECV programme operates as an ongoing, operational service, with a key objective being the regular extension of ECV datasets as close to real time as possible.

- These datasets are highly valuable for the land surface modelling community, supporting a wide range of applications including data assimilation, model calibration, evaluation and validation.

- In addition to satellite-derived products, C3S also provides access to land surface variables based on reanalysis (ERA5-Land) and in-situ networks, offering complementary sources of ancillary data for Earth system modeling.

Back up slides

ESA CCI SM as supportive data

- Alberger et al., (2017): Model: Assimilation of satellite derived SSM and LAI

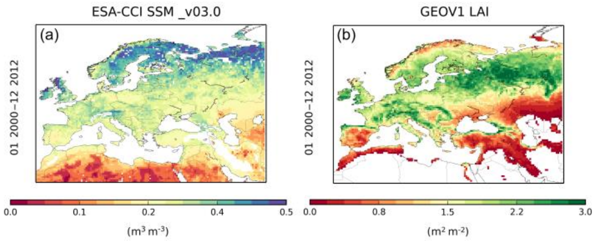


Figure 1. Averaged **(a)** surface soil moisture from the Climate Change Initiative project of ESA. **(b)** GEOV1 leaf area index from the Copernicus Global Land Service project (for pixels covered by more than 90 % of vegetation) over 2000–2012.

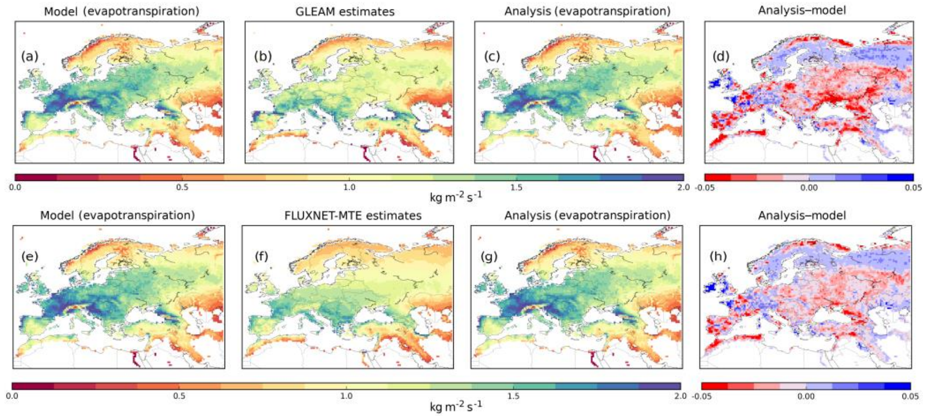


Figure 12. Top row: maps of averaged evapotranspiration taken over 2000–2012 from **(a)** the model (i.e open loop), **(b)** the GLEAM estimates, **(c)** the analysis and **(d)** differences between the analysis and model. Bottom row: maps of averaged evapotranspiration taken over 2000–2011 from **(a)** the model (i.e open loop), **(b)** FLUXNET-MTE estimates, **(c)** the analysis and **(d)** differences between the analysis and model.

Albergel, C., Munier, S., Leroux, D. J., Dewaele, H., Fairbairn, D., Barbu, A. L., Gelati, E., Dorigo, W., Faroux, S., Meurey, C., Le Moigne, P., Decharme, B., Mahfouf, J.-F., and Calvet, J.-C.: Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX_v8.0: LDAS-Monde assessment over the Euro-Mediterranean area, Geosci. Model Dev., 10, 3889–3912, https://doi.org/10.5194/gmd-10-3889-2017, 2017.

Validating SSM fields in LSM with ESA CCI SM

- Szczypta et al., 2014: compared ESA-CCI SM and ISBA-A-gs land surface model

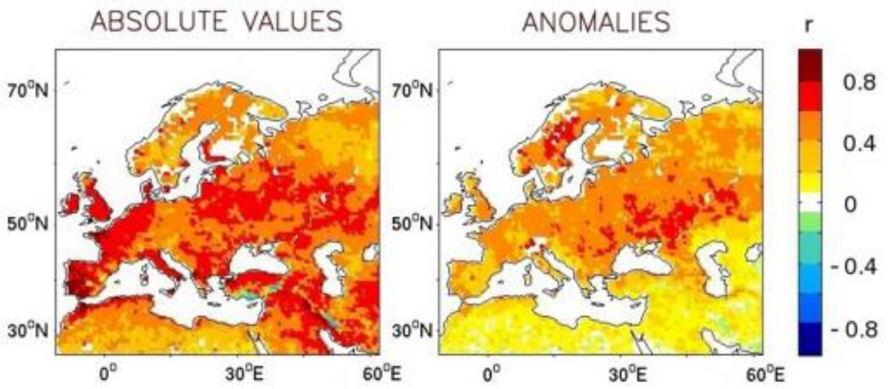


Figure 3. Comparison between the detrended ESA-CCI SSM and the detrended SSM simulated by ISBA-A-gs over the 1991–2008 period: Pearson correlation coefficient for (left) absolute values, (right) scaled anomalies (Eq. 1). White areas over land correspond to r values lower (higher) than 0.1 (−0.1).

Szczypta, C., Calvet, J. C., Maignan, F., Dorigo, W., Baret, F., and Ciais, P.: Suitability of modelled and remotely sensed essential climate variables for monitoring Euro-Mediterranean droughts, Geoscientific Model Development, 7, 931-946, 10.5194/gmd-7-931-2014, 2014.

Example 1: Use of LWL to calibrate and validate model Lake Turkana

Hydrol. Earth Syst. Sci., 16, 1–18, 2012
www.hydrol-earth-syst-sci.net/16/1/2012/
doi:10.5194/hess-16-1-2012

Hydrology and Earth System Sciences

A multi-source satellite data approach for modelling Lake Turkana water level: calibration and validation using satellite altimetry data

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[3]Climatus LLC, 800 W El Camino 180, Mountain View, CA, USA

This study demonstrates that satellite altimetry data can be used for model calibration and validation.

“From this study, we suggest that globally available satellite altimetry data provide a unique opportunity for calibration and validationof hydrologic models in ungauged basins.”

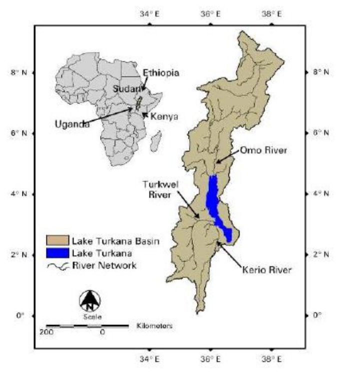
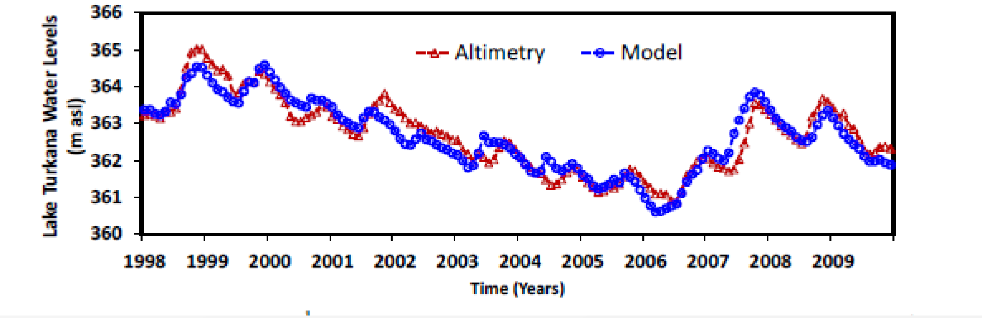


Fig. 1. Map of the study area showing spatial extent of the Lake Turkana basin in East Africa.



Lake Water Level of lake Turkana is available in C3S

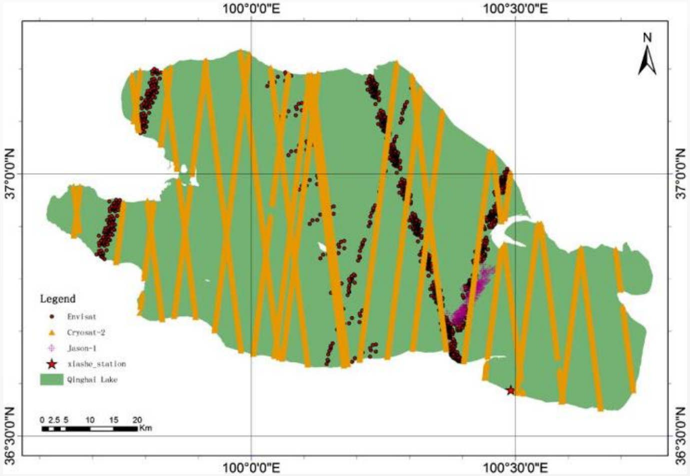
CLS
COLLECTE LOCALISATION SATELLITES

Example 2: Use of LWL to model Lake Quinghai (Kokonor)


IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 7, NO. 2, FEBRUARY 2014 609

Numerical Simulation and Forecasting of Water Level for Qinghai Lake Using Multi-Altimeter Data Between 2002 and 2012

Jingjuan Liao, Le Gao, and Xiaoming Wang



In this study, a combined linear periodic-residual model was established based on the SSA-extracted fluctuation signal from the lake-level time series of multi-altimeter data. The water level changes over lake Qinghai (Kokonor) were predicted until two years

Lake Water Level of lake Qinghai, also known as Kokonor, is available in C3S

SSA : Singular Spectrum Analysis
DOI: 10.1109/JSTARS.2013.2291516

Example 3: Use of LWL on water balance analysis

Lake Tanganyika basin water storage variations from 2003–2021 for water balance and flood monitoring

Paul Gérard Gbetkom[a,*], Jean-François Crétaux[a], Sylvain Biancamaria[a], Alejandro Blazquez[a], Adrien Paris[c,a], Michel Tchilibou[a,1], Laetitia Gal[c,a], Benjamin Kitambo[a], Rômulo Augusto Jucá Oliveira[c,a], Marielle Gosset[b]

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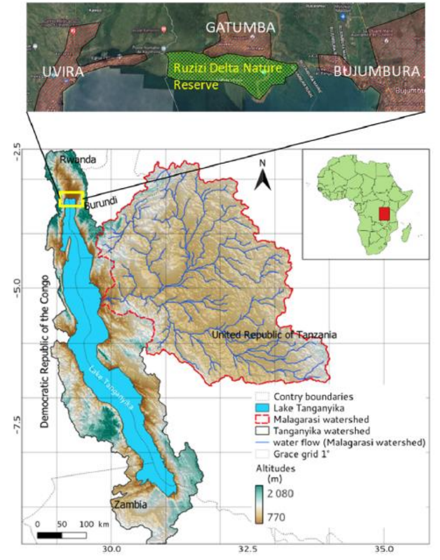
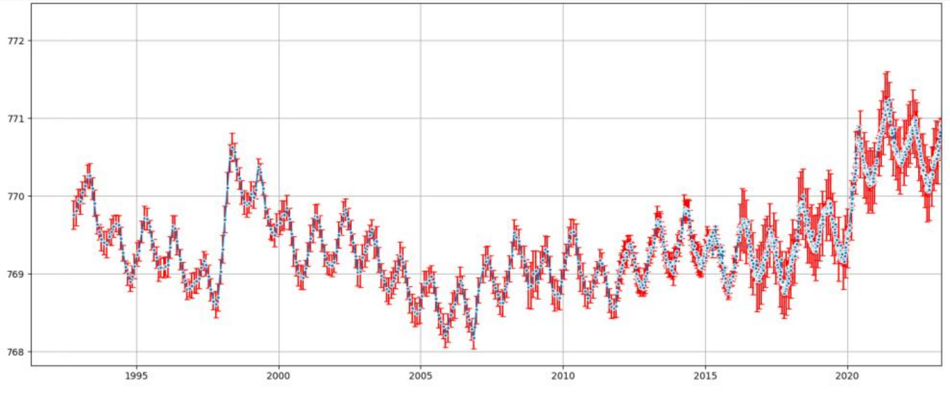
[c] Hydro Matters, 1 Chemin de la Pousaraque, 31460, Le Faget, France

Use of the lake water level on the Lake Tanganyika basin water balance between 2003 and 2021 to assess the influence of recent climate variability

The Hydroweb database was used to obtain Lake Tanganyika surface water storage (SWS) fluctuations





Lake Water Level of lake Tanganyika (Tanganika) is available in C3S

https://doi.org/10.1016/j.rsase.2024.101182