Progress and prospects on coupled data assimilation for exploitation of interface observations and in support of climate monitoring and weather prediction

Patricia de Rosnay, Phil Browne, Eric de Boisséson, Margarita Choulga, Stephen English, David Fairbairn, Sébastien Garrigues, Zdenko Heyvaert, Christoph Herbert, Eleni Kalogeraki, Tsz Yan Leung, Tony McNally, Kenta Ochi, Ewan Pinnington, Kirsti Salonen, Pete Weston, Hao Zuo

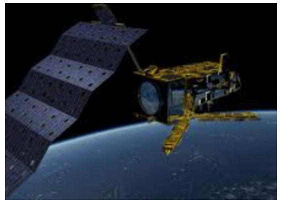
and many others

ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Coupled data assimilation: Why?

- ECMWF forecasts are based on an Earth system model → need Earth system data assimilation
- Provide balanced initial conditions across the coupled forecast model components
- Improve exploitation of satellite data sensitive to several Earth system components towards an “all surface” approach → <u>Interface observations</u>

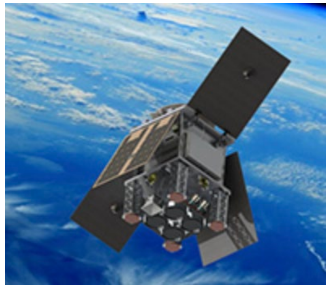
ASCAT



SMOS

Sentinel-1

HydroGNSS



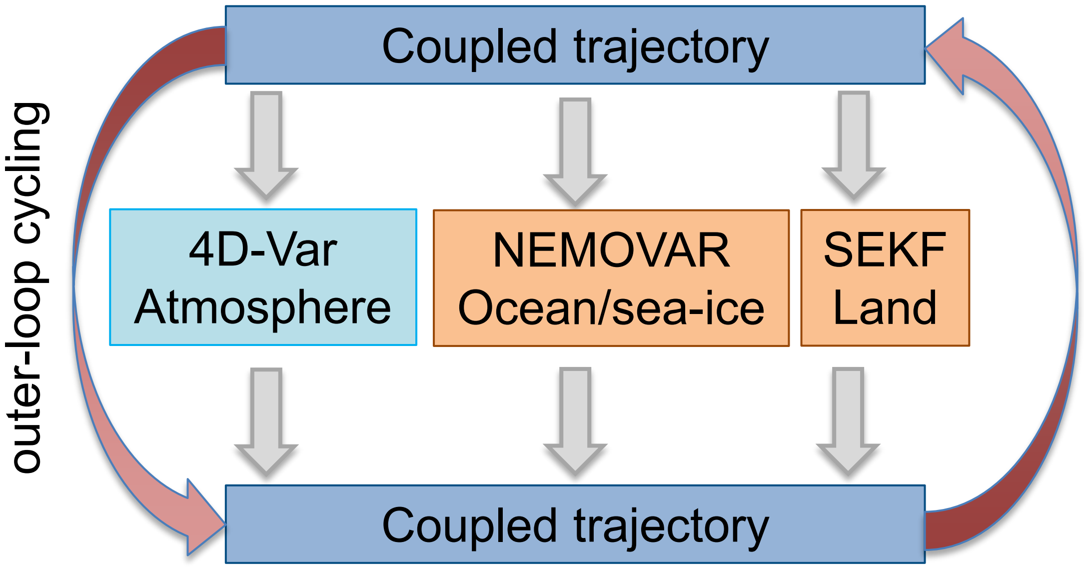
CRISTAL

LSTM

CIMR

Coupled data assimilation research at ECMWF

Outer loop coupling based on incremental 4D-Var cycling



Browne et al. in prep 2025 → ocean-atmosphere coupling

Herbert et al. in prep 2025 → land-atmosphere outer loop coupling

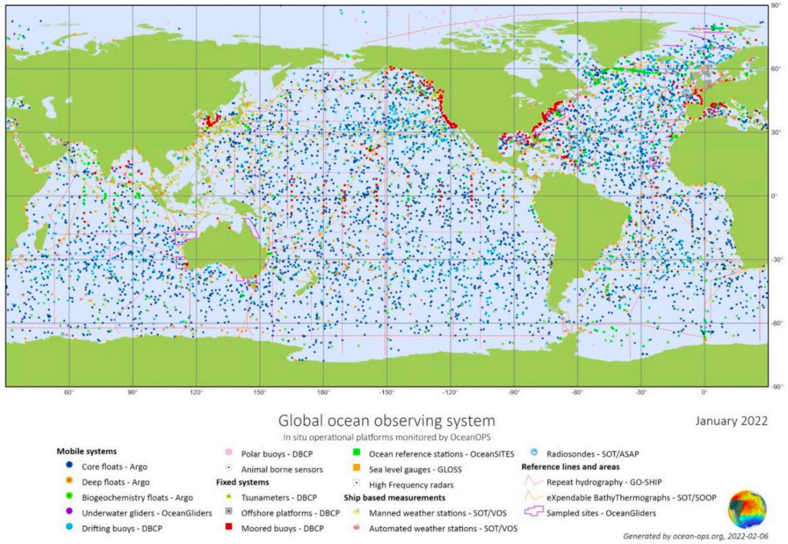
de Rosnay P. et al QJRMS 2022 → Coupled DA strategy

(SEKF: Simplified Extended Kalman Filter)

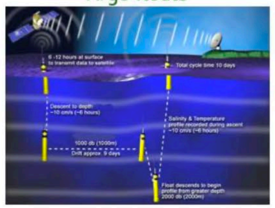
ECMWF

Assimilation of ocean observations

New observations types are emerging: ALAMO, gliders, Deep Argo, BioArgo, drifter, saildrone …

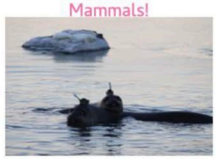


Argo floats



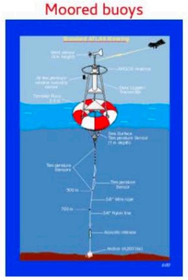
Argo operational cycle. [Argo 2018]

Mammals!



[MEOP et al. 2015]

Moored buoys

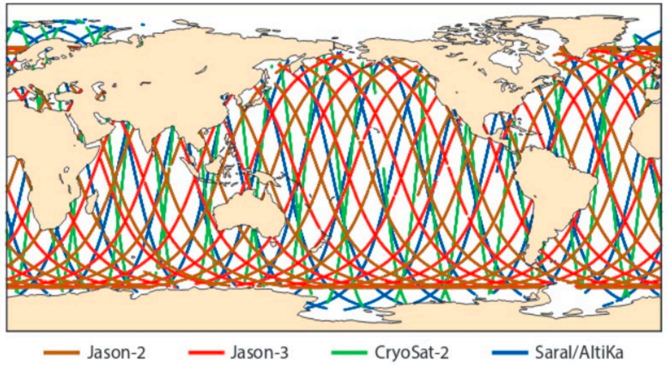


[PMEL 2018]

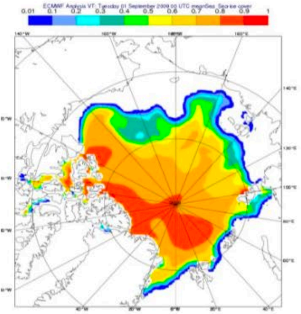
Ship based observations

[CSIRO 2001]

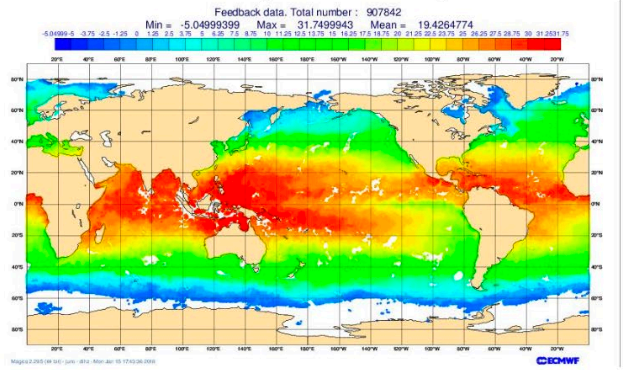
Sea-Level Anomaly (Altimeter)



Sea-ice concentration



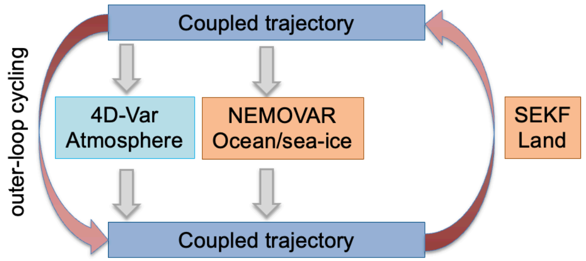
SST (IR, PMW)



ORAS6 data assimilation and monitoring
→ **Hao Zuo (today at 16:00)**, Eric de Boisséson et al.

Coupled observation operators in the ocean-sea-ice-atmosphere system

From IFS cycle 50r1 in Q4 2025



- Coupled nonlinear trajectories
  - Consistent physics and surface processes
  - Access to 3D ocean and sea ice model variables to build more complex observation operators

- Traditional ocean observations now have much less lag to NWP impact

- Constrain the system with existing L1 satellite data by approximating coupled observation operators, by extending the atmospheric control vector and adding a penalty term in the ocean/sea-ice cost function

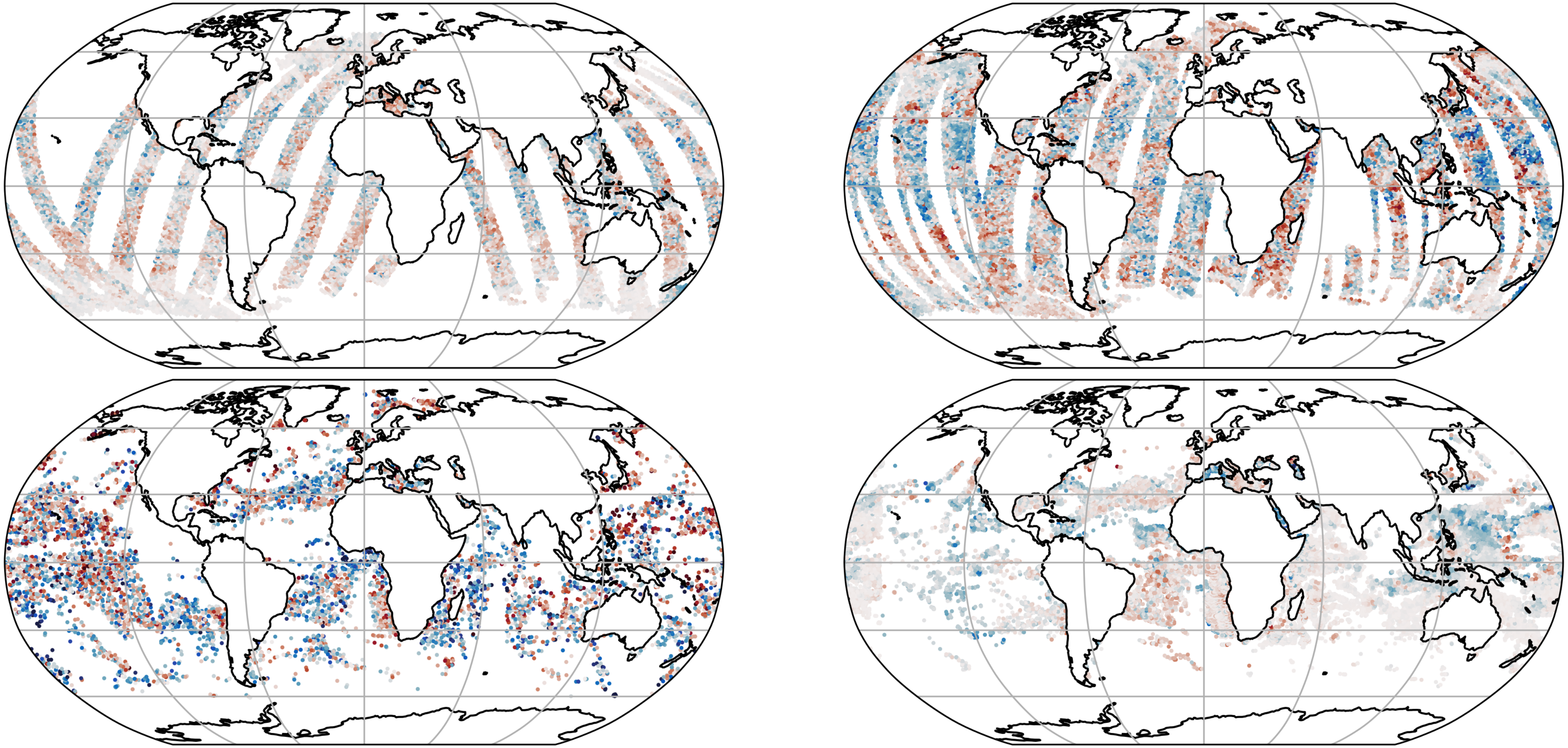
In this implementation, the ocean component is anchored to the thoroughly tested ORAS6 reanalysis preventing long-term drift of slow modes.

Coupled observation operators in the ocean-sea-ice-atmosphere system

Skin temperature XCV

GMI: MW LEO

AMSR2: MW LEO



CrIS: Hyperspectral IR LEO

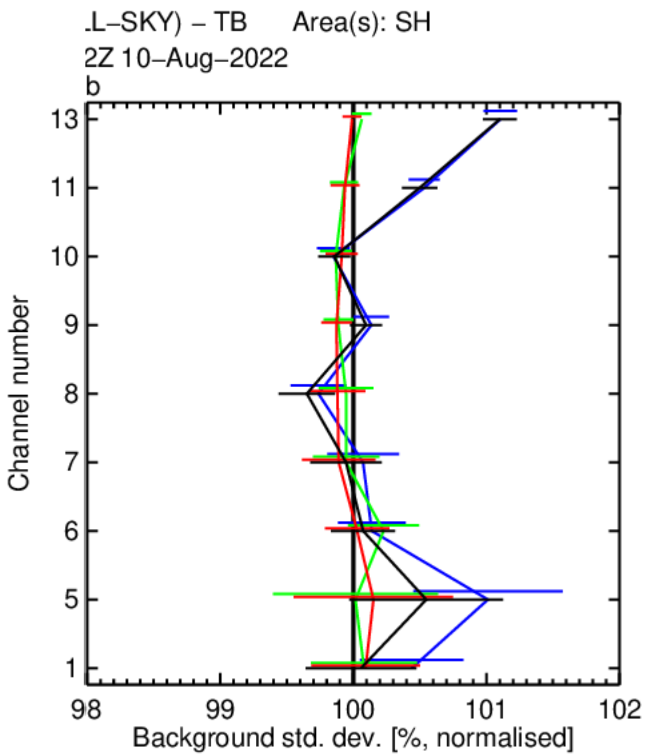
IR: GEOS
Meteosat/GOES/Himawari

Phil Browne

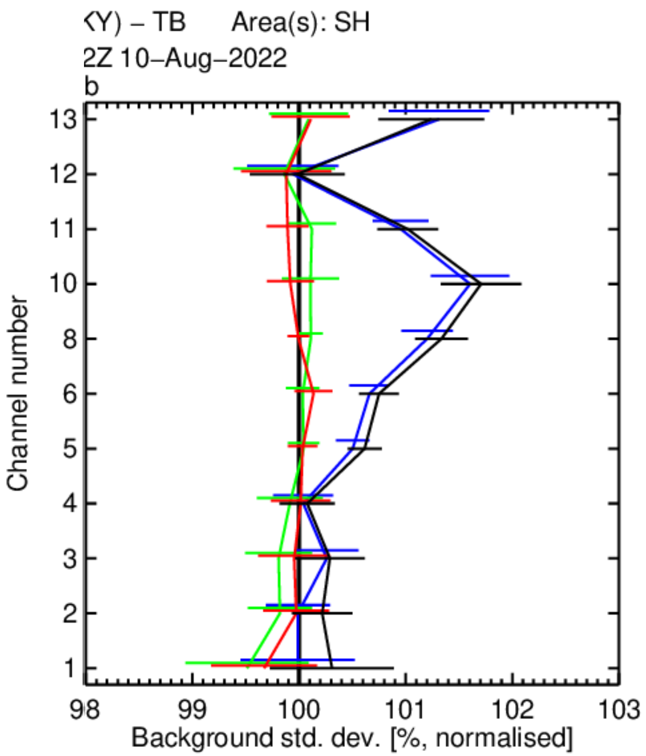
Coupled observation operators in the ocean-sea-ice-atmosphere system

Impact of coupled observation operators on satellite data usage – SH winter case

AMSR2



GMI

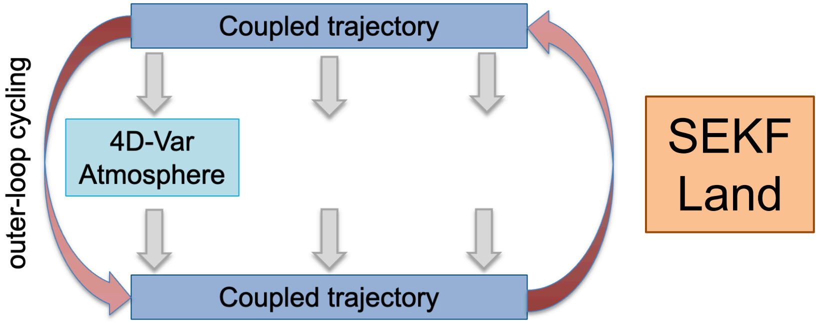


Blue = removal of all coupled observation operators
Black = removal of all sea ice coupled observation operator

Phil Browne

ECMWF

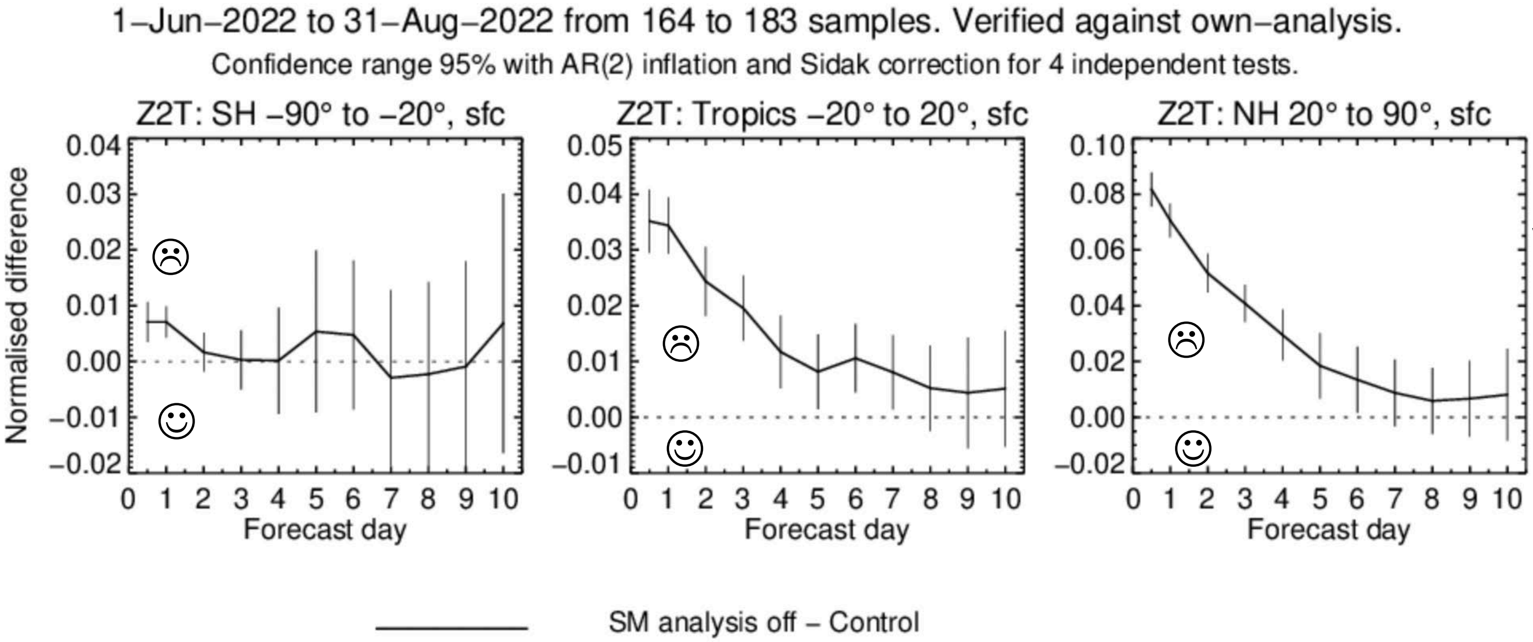
Soil analysis: impact on the atmospheric forecast



Current system:
Atmospheric and land data assimilation (DA) run in parallel to initialise the forecasts and the next 12h model background
→ Weakly coupled DA

T2m RMSE

JJA 2022
IFS cycle 49r1



Degradation when no SM DA

Zdenko Heyvaert

→ **Significant positive impact of soil moisture (SM) DA on low level atmospheric temperature forecasts**

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Soil moisture satellite observations used for NWP along with T2m, RH2m screen level observations

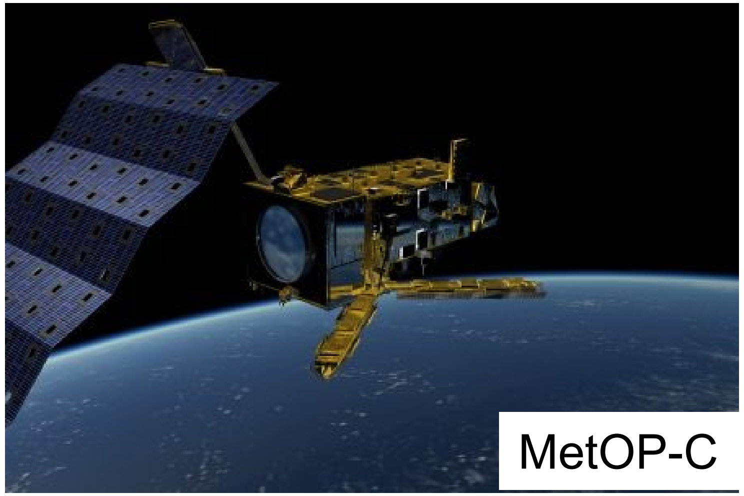
Active microwave data:

ASCAT: Advanced Scatterometer

MetOP-B (2012-), MetOP-C (2018-)

C-band (5.6GHz) backscattering coefficient

EUMETSAT Operational mission



Passive microwave data:

SMOS: Soil Moisture & Ocean Salinity (2009-)

L-band (1.4 GHz) Brightness Temperature

ESA Earth Explorer, dedicated soil moisture mission

(Kerr et al., 2016)

SMAP (monitoring)

L-band TB 2015-

NASA Dedicated soil moisture mission

Scatterometer soil moisture used in ERA5 (ERS-SCAT, Metop/ASCAT)

and SMOS in ERA6

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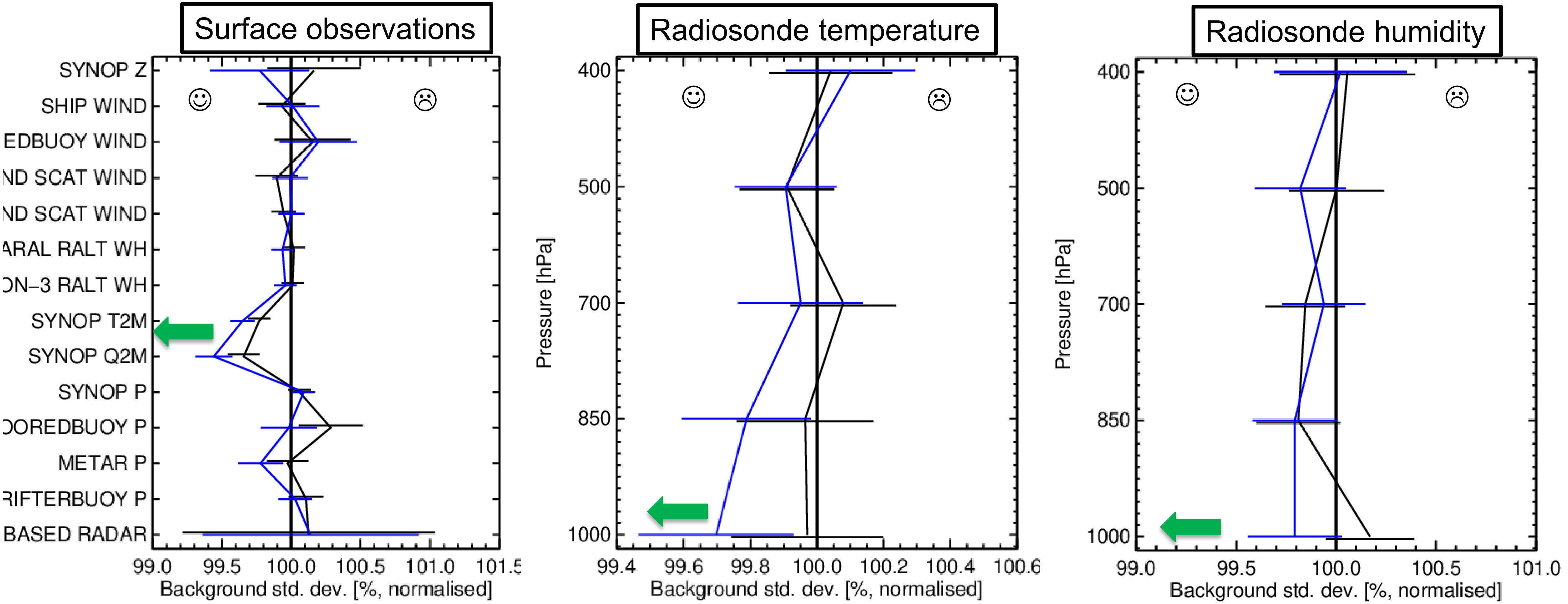
SMOS data assimilation impact

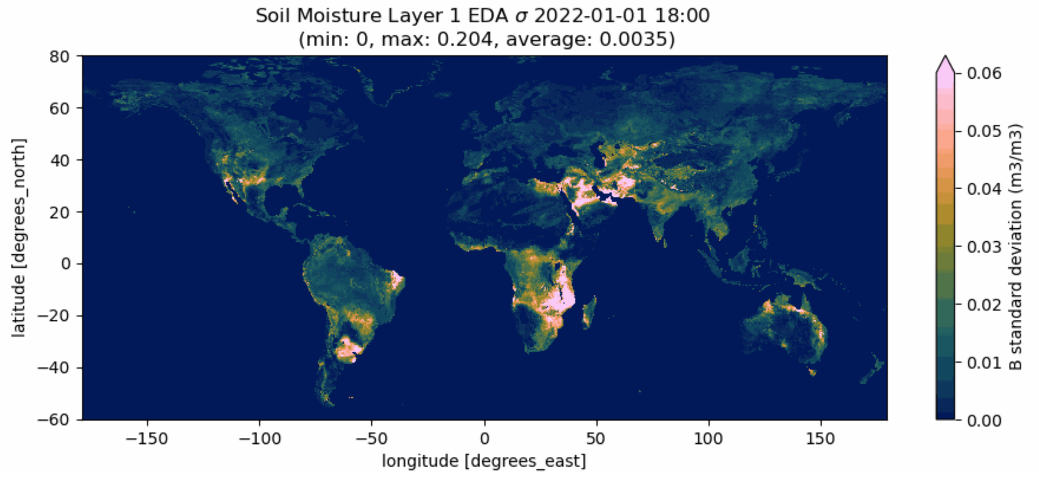
Kirsti Salonen

- Comparing random forest (XGBoost) and Neural Network SMOS data assimilation
- **Assimilation of SMOS soil moisture has positive impact near surface when compared to no SMOS experiment (100% line).**
- The positive impact of assimilation of **XB** based soil moisture is stronger than of **NN** in 49r1.

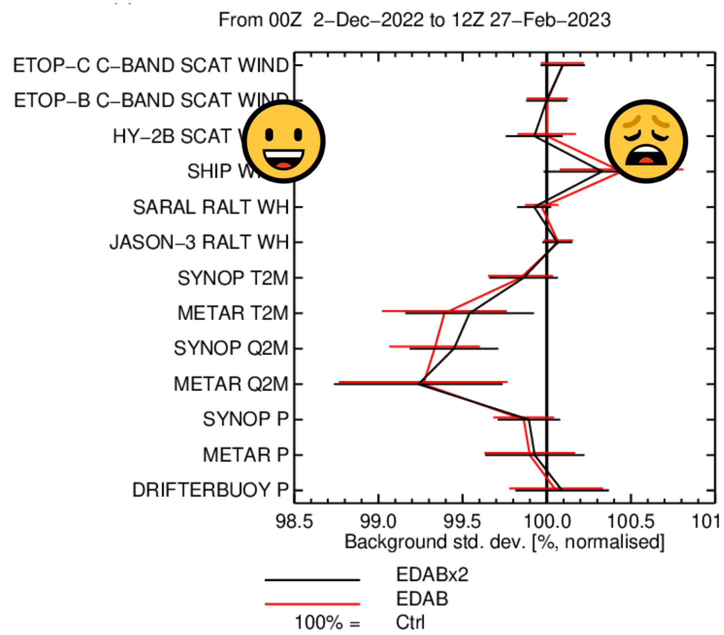


Ensembles for the Land Surface

- Background errors are static in the current land DA
- Spread in Ensemble of Data Assimilations (EDA) soil moisture highly variable in space and time
- Find improvement in surface temperature and humidity scores against observations when using flow-dependent **B**



→ Flow dependent B matrix in land DA from IFS cycle 50r1 (Q4 2025)



Ewan Pinnington
→ poster, Land ancillary data workshop 9-10 April

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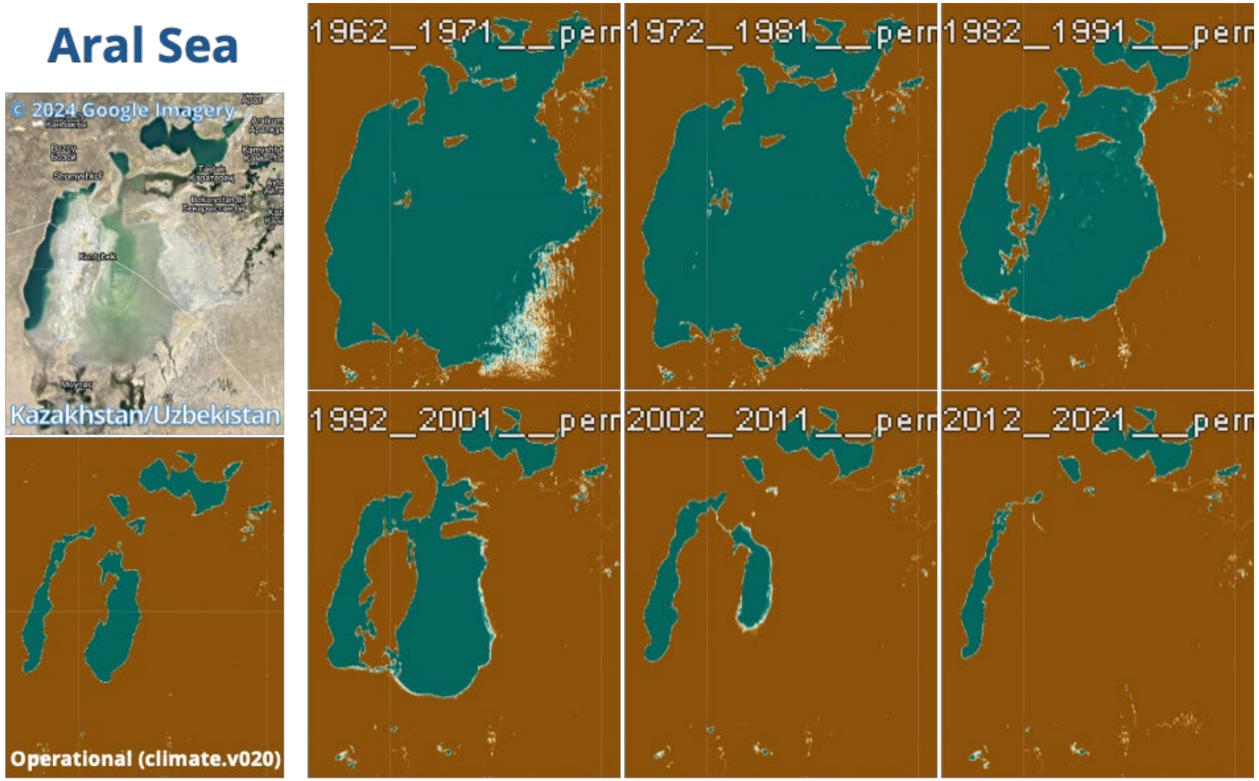
Time varying lake cover for land reanalysis

Time varying vegetation and lakes for next generation of C3S reanalysis

Aral sea **comparisons** between experiment results and **satellite composite data CCI LAKES improvement**

Impact on T_s – Aral Sea Region (Bias reduction)

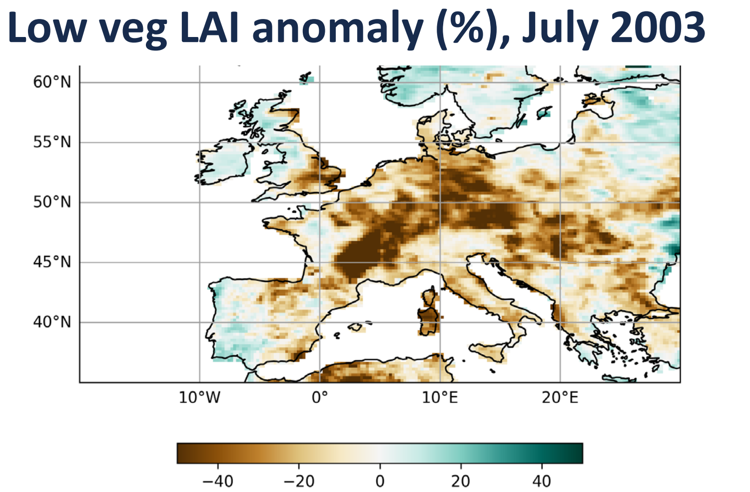
2012-2019:	1.5 K
2002-2011:	4 K
1995-2001:	6 K

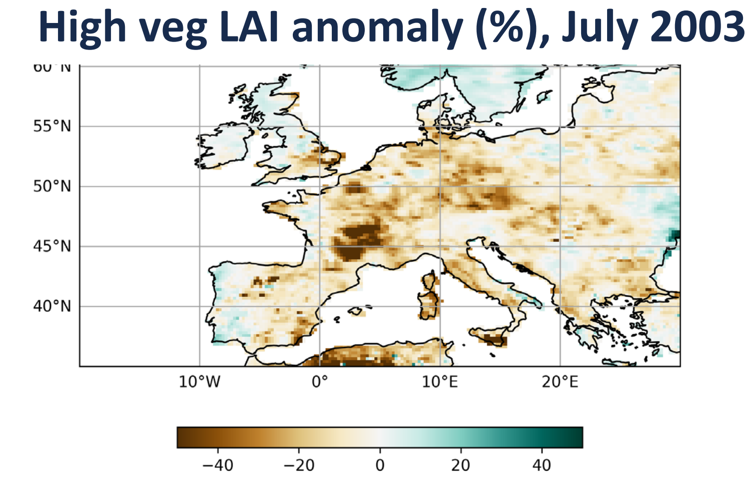


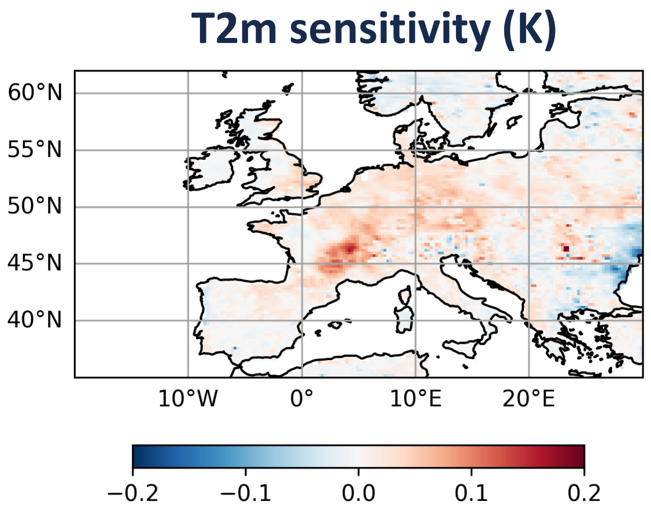
Margarita Choulga
→ poster, Land ancillary data workshop 9-10 April

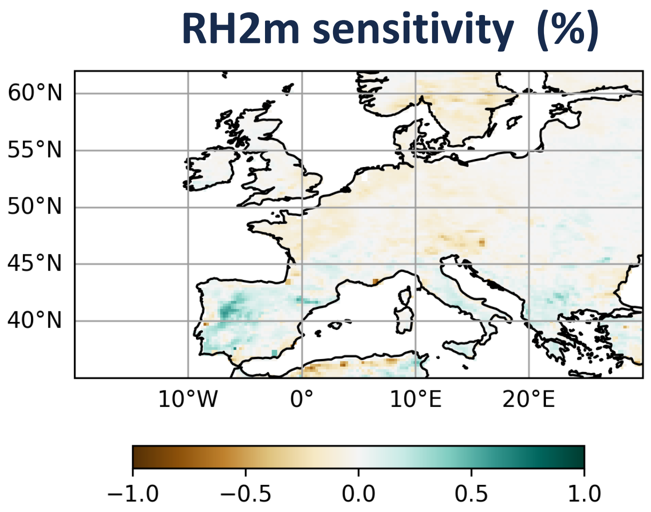
Time varying vegetation for land reanalysis

European 2003 heatwave – LAI/Land Cover impact









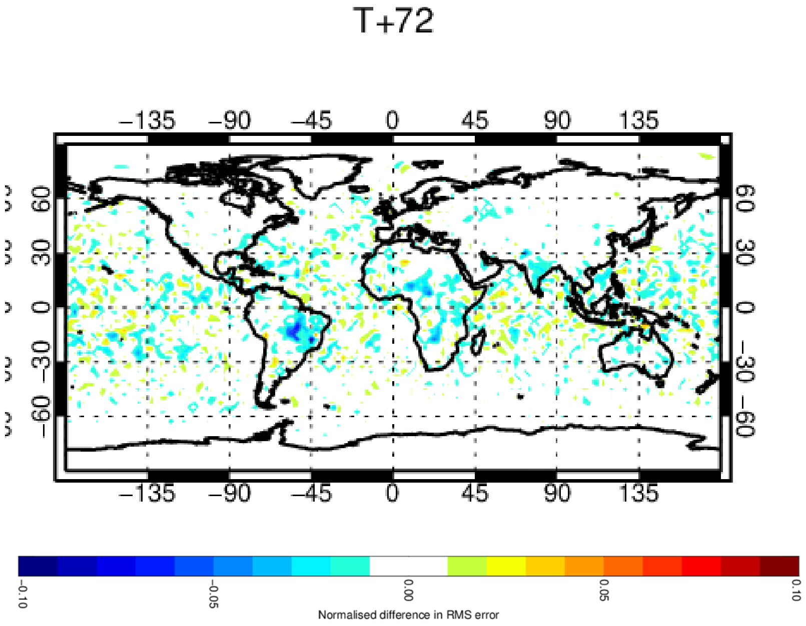
- **Left**: Negative LAI anomaly (~-40%) relative to static maps over central/western Europe due to anomalously dry conditions during July 2003
- **Right:** July 2003 average diff in 12 UTC T2m/RH2m for ecLand with time-varying vegetation vs control (static climatological vegetation)
- ecLand with time-varying vegetation demonstrates warmer conditions in places with negative LAI anomalies

David Fairbairn

SMOS Vegetation Optical depth (VOD) assimilation

Assimilation of VOD from passive microwave sensors to constrain vegetation water and carbon cycle variables.

- L-band VOD (1.41GHz) from SMOS
- C-band VOD (6.9GHz) and X-band VOD (10.65GHz) from AMSR2



T2m RMSE reduction (blue) 2018-2021

→ Positive impact of VOD assimilation on NWP
→ Challenges in terms of GPP impact

Pete Weston et al

CoCO2
Prototype system for a Copernicus CO_2 service

Funded by the European Union

Calvet et al.: Demonstrator systems for using remote sensing data (LAI, VOD, SIF) in online global prior fluxes for the CO2MVS prototype", CoCO2 H2020 project D3.4, June 2023, https://coco2-project.eu/sites/default/files/2023-11/CoCO2-D3-4-V2-1.pdf

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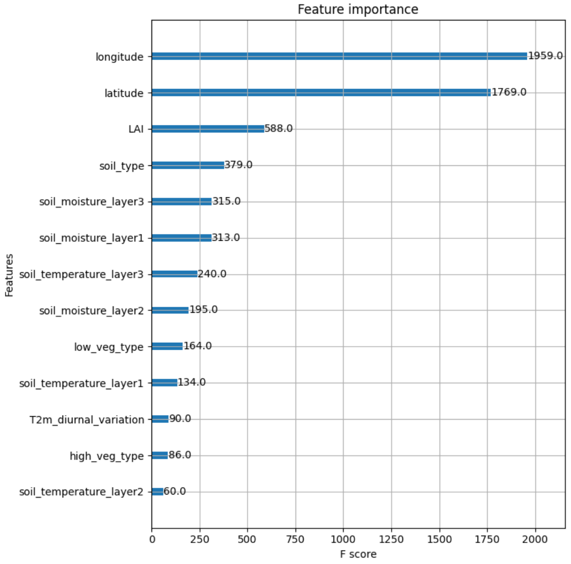
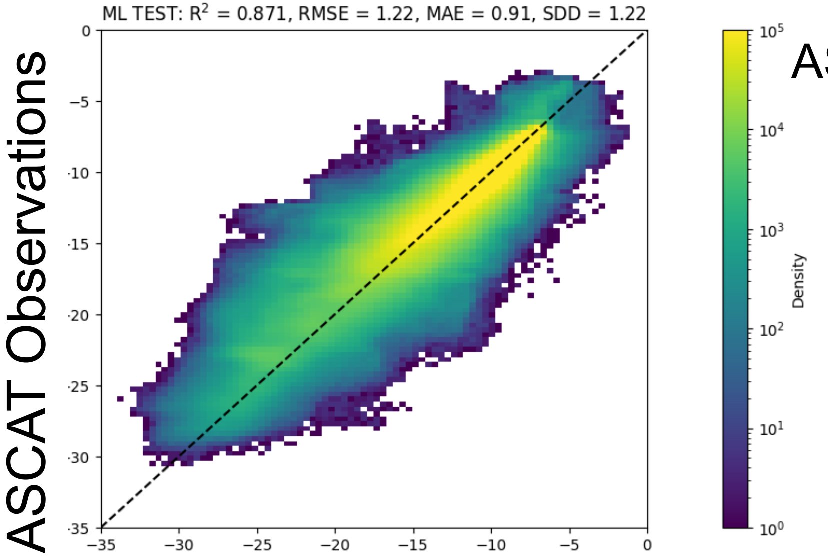
Passive and MW observation operators

Enhance the exploitation of satellite observations in coupled land-atmosphere assimilation to constrain vegetation water and carbon cycle variables.
→ Development of ML-based observation operators for MW and SIF observations

Information content analysis





ASCAT backscatter over land

Sébastien Garrigues et al.

→ Ongoing implementation in the IFS

→ Prepares for future observations assimilation such as Metop-SG/SCA, Copernicus Expansion CO2 and CIMR missions, which are all relevant to consistently constrain vegetation and carbon fluxes in CO2MVS

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The CORSO project (grant agreement No101082194) is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Commission. Neither the European Union nor the granting authority can be held responsible for them.

CORSO CO2MVS Research on Supplementary Observations
Funded by the European Union

LAI analysis using Solar Induced Fluorescence (SIF)

CORSO
CO2MVS Research on Supplementary Observations

https://doi.org/10.5194/essd-13-5423-2021

Data description paper |

The TROPOSIF glob
dataset from the S

Luis Guanter, Cédric Bacour, Andre
Christian Retscher, Philipp Köhler, Chr

Article | Assets | Peer review | Metrics | Related articles

nature › scientific data › data descriptors › article

Data Descriptor | Open access | Published: 20 July 2022

A long-term reconstructed TROPOMI solar-induced fluorescence dataset using machine learning algorithms

Xingan Chen, Yuefei Huang, Chong Nie, Shuo Zhang, Guangqian Wang, Shiliu Chen & Zhichao Chen

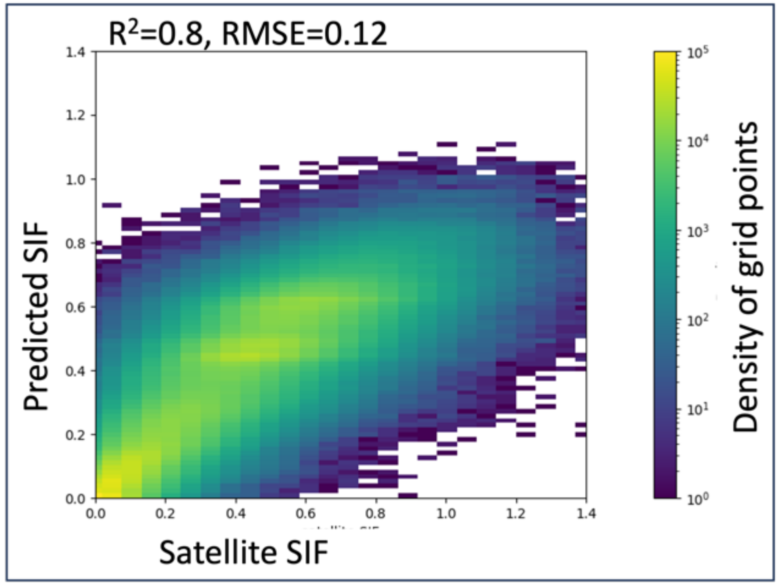
Funded by the European Union

SIF: electromagnetic signal emitted by the chlorophyll of assimilating plants

→ part of the energy absorbed by chlorophyll a is not used for photosynthesis but emitted at longer wavelengths as a two-peak spectrum roughly covering the 650–850 nm spectral range.

→ Relevant to analyse vegetation LAI and Gross Primary Production

Exploratory work to use SIF at ECMWF.
Observation operator development



Sébastien Garrigues

ECMWF

LAI analysis using Solar Induced Fluorescence (SIF)

CORSO
CO2MVS Research on Supplementary Observations

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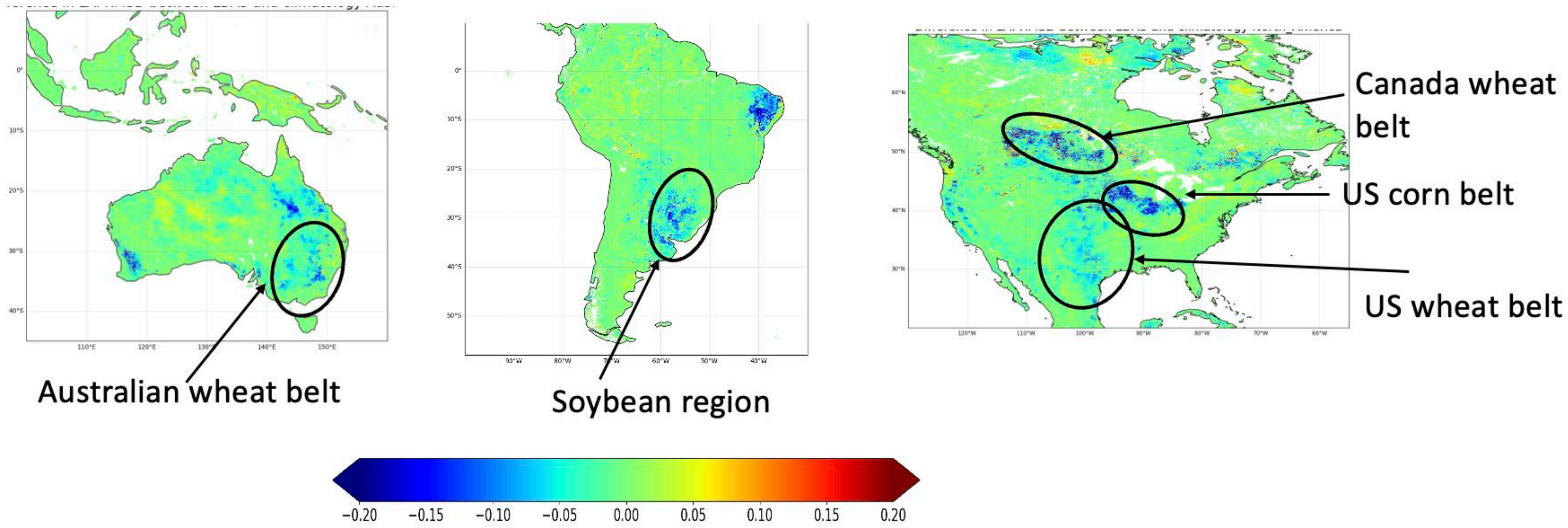
Impact of SIF DA shown as LAI RMSD differences with vs without SIF data assimilation against satellite (Copernicus Land) LAI for 2022

Improvement for cropland



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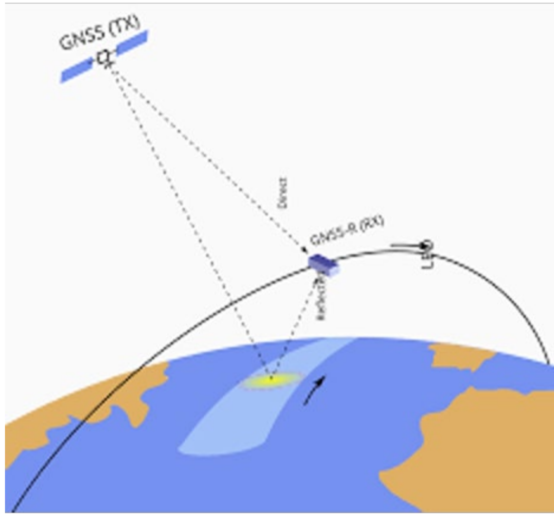
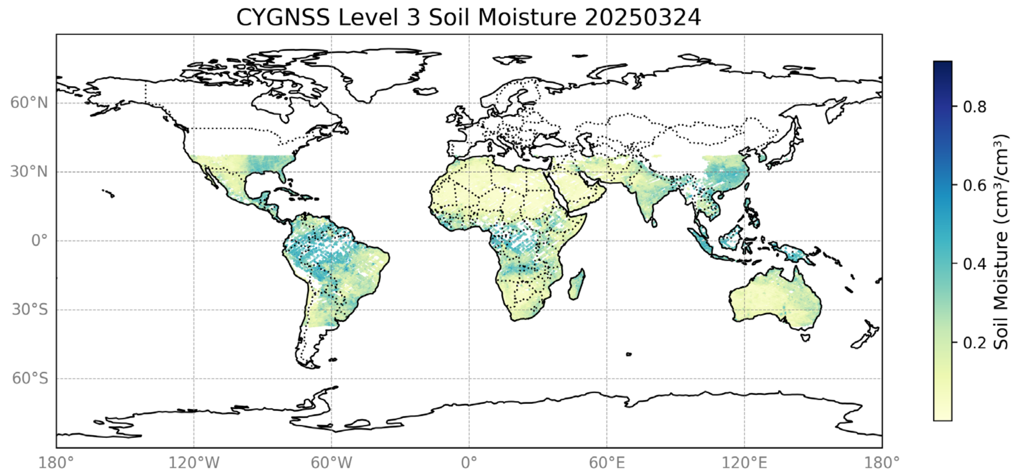
Investigate GNSS-R observation usage over land surface

- GNSS (Global Navigation Satellite System) systems include GPS (Global Positioning System), Galileo (European GNSS system, GLONASS (Russian system), BeiDou (Chinese system)

- GNSS-R (Reflectometry) gets information from the signal reflected at the surface, e.g from the CYGNSS constellation and future HydroGNSS ESA scout mission





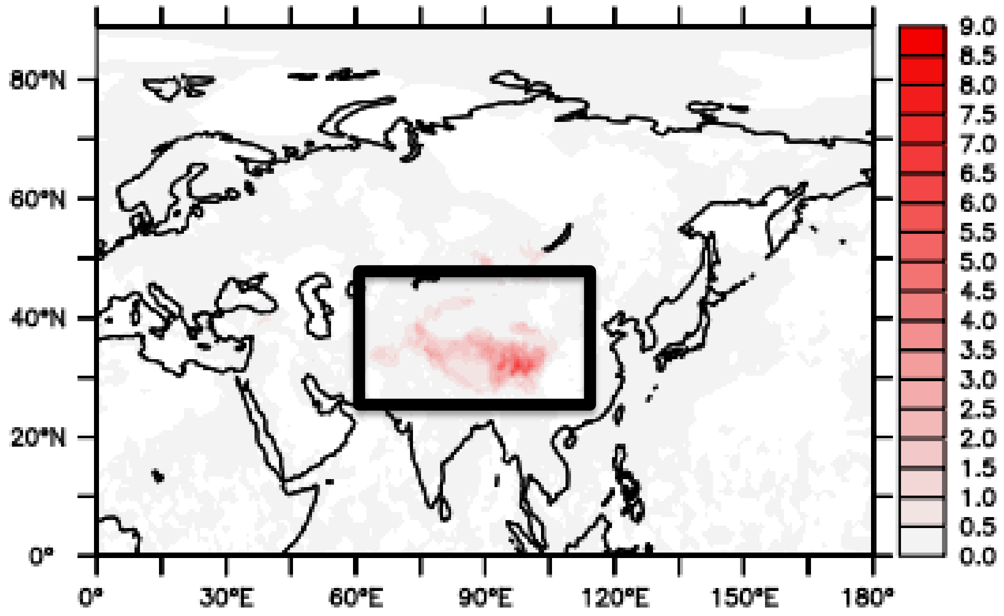
→ Potential of GNSS-R DA over land for NWP and reanalysis

Eleni Kalogeraki et al.

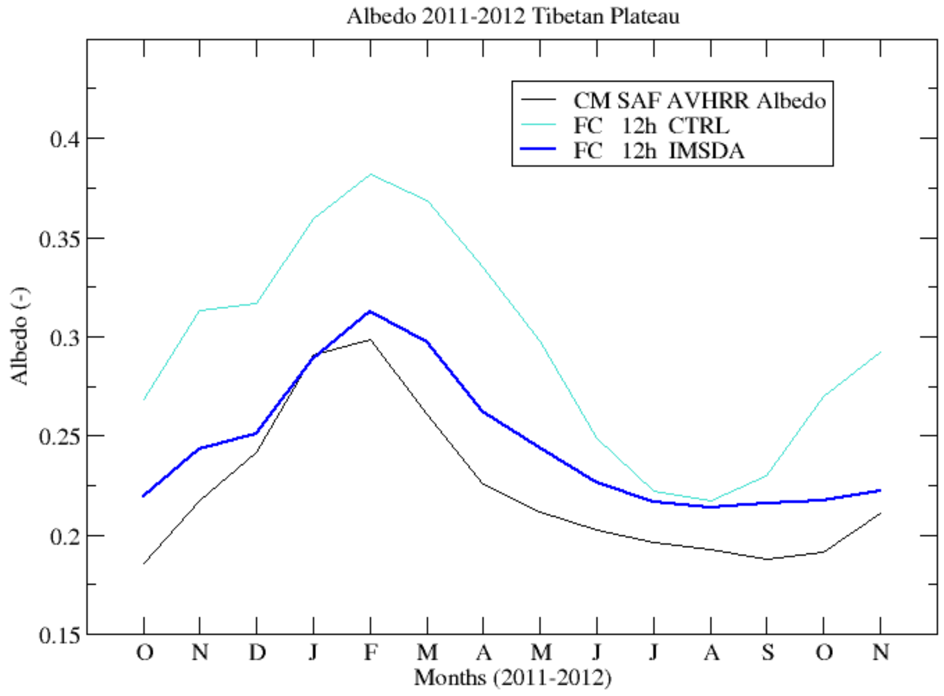
Impact of snow cover assimilation on two-meter temperature / on surface albedo

Snow cover assimilation removes snow
→ Warmer surface conditions than CTRL

Snow cover assimilation removes snow
→ Lower surface albedo



T2m diff (IMSDA-CTRL) (K)
Forecast day-10
Oct 2011-Sept 2012



Use Climate Monitoring SAF CLARA-2 albedo product (Karlsson et al. 2017)

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Snow reanalysis from ERA5 to ERA6

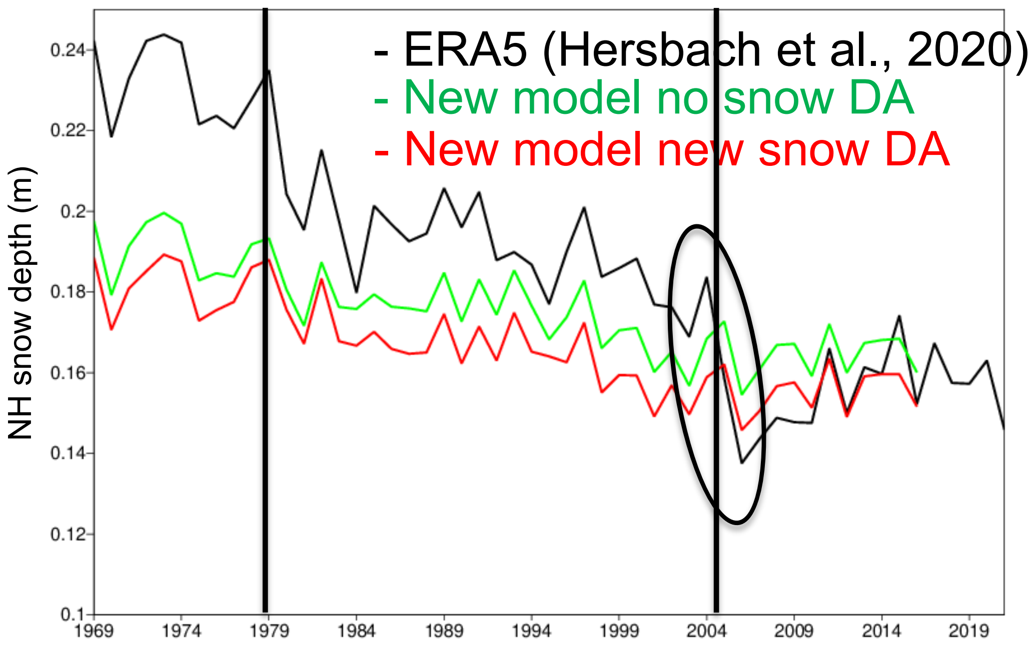
Funded by the European Union

- Step change in the ERA5 snow mass from 2004 (IMS snow cover started to be assimilated)
- Snow DA reduced the positive snow cover bias, but it amplified the snow mass negative trend

ERA6-Land 1st prototype (1939-2022)

ERA6:

- Snow model and a set of snow data assimilation improvements (Arduini et al., 2020)
- Snow cover DA: ESA CCI Cryoclim (1987-2010) + NOAA/NESDIS IMS (2010-NRT)



Kenta Ochi et al., in prep 2025

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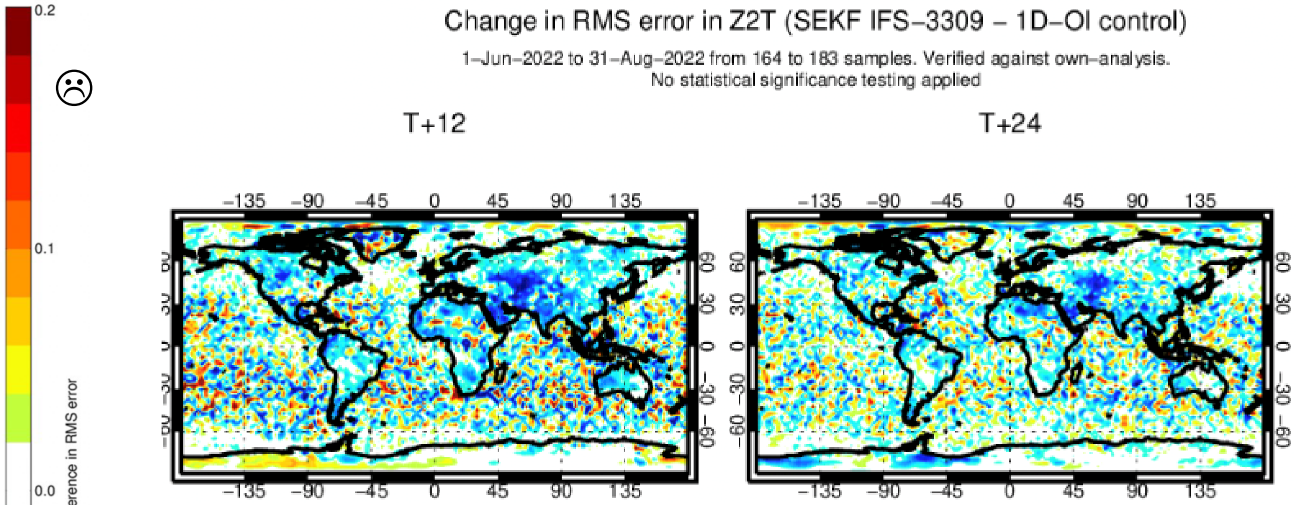
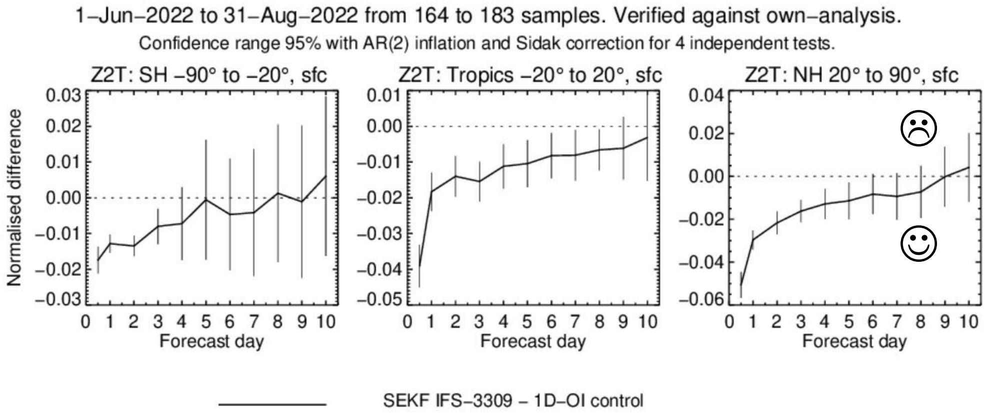
Unified soil & snow temperature analysis

Integration of the soil and snow temperature analysis in the SEKF, instead of using a 1D-OI approach

control variables $x_i = [swvl1, swvl2, swvl3, stl1, stl2, stl3, \mathbf{tsn}]$





Implemented in:
- 49r2 (ERA6)
- 50r1 (NWP Q4 2025)

- Significant improvement in T2m forecasts

Christoph Herbert et al. QJRMS 2024

Funded by the European Union

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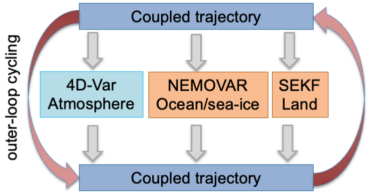
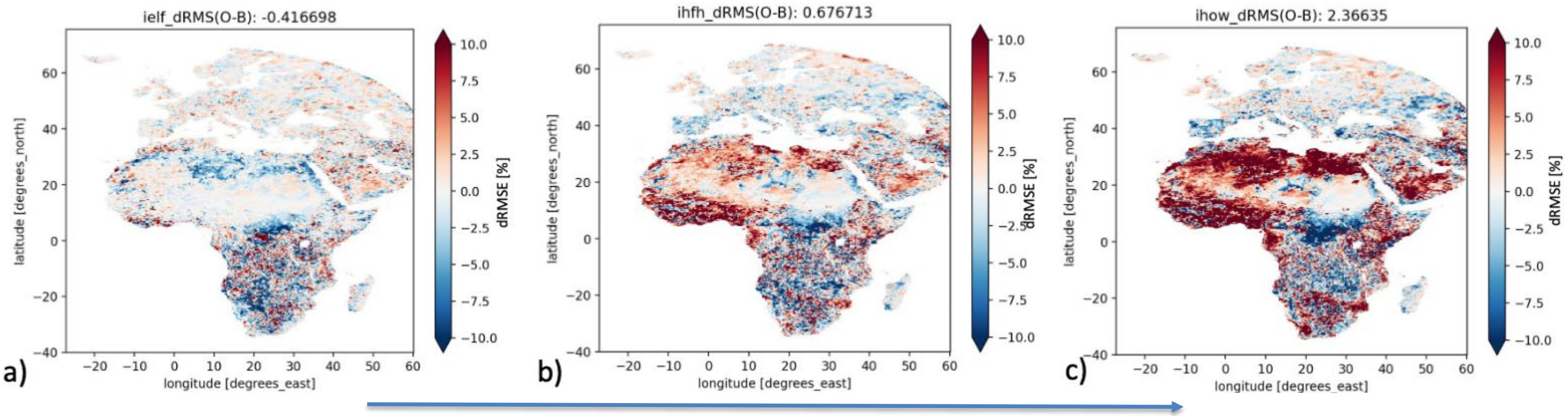
Strength of coupled land-atmosphere data assimilation



RMSE vs SEVIRI LSA SAF MSG LST (DJF 2022-2023)



- Optimal strength of coupling differs for atmosphere and land skills in the current system
- Ongoing thermal skin conductivity optimisation
- Potential of land surface temperature data assimilation in coupled land-atmosphere DA system

Funded by the European Union

Christoph Herbert

ECMWF

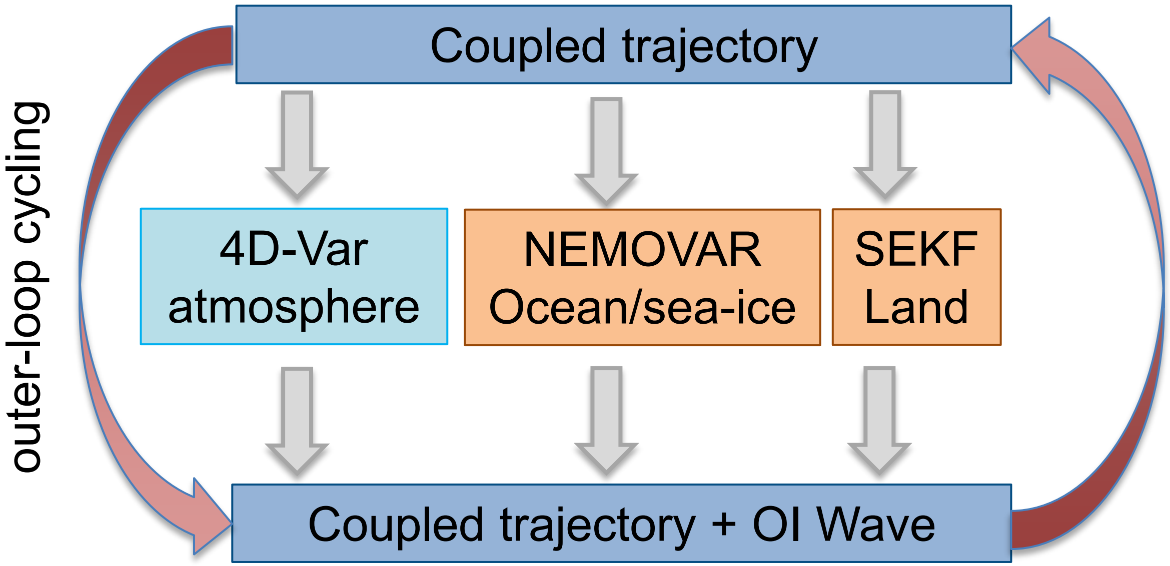
ECMWF-ESA project DANTEX 2024-2027

DANTEX: Data Assimilation and Numerical Testing for Copernicus Expansion Missions

- Preparation of coupled data assimilation of CIMR, CRISTAL and LSTM, and exploitation of Sentinel-1 wave spectra data
- For LSTM: Explore the potential of LST observations for coupled land-atmosphere assimilation in Earth system predictions systems.

Bring surface sensitive satellite information in the coupled DA cycling
→ DANTEX:
CIMR L1
CRISTAL L2/L1
LSTM L1/L2
Sentinel 1 L1

Christoforos Tsamalis
Tsz Yan Leung
Zdenko Heyvaert
James Steer



Using existing sensors:
SMAP, AMSR2
Cryosat-2, Altika,
SEVIRI

Summary and future plans

- Progressive implementation of coupled data assimilation (DA) for ocean-land-atmosphere for NWP, CO2MVS, and climate reanalysis, further develop DA in each component. More Earth system components on the way (e.g. fire, hydrology)

- Enhance exploitation of existing interface observations using level 1 in the coupled data assimilation system over land, ocean, sea-ice, snow, and account for time varying land surface characteristics for climate reanalysis. Key role of ML/AI in these developments

- Explore new observations types (e.g. SIF, GNSS-R) and prepare for coupled level 1 data assimilation of the upcoming Copernicus Sentinel missions

Thank you !