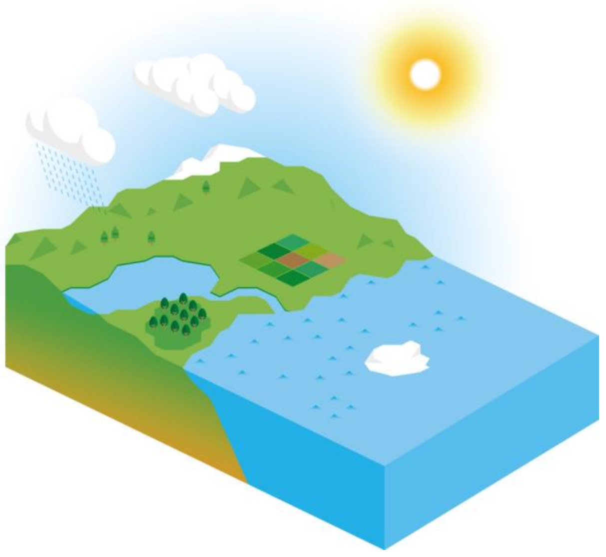
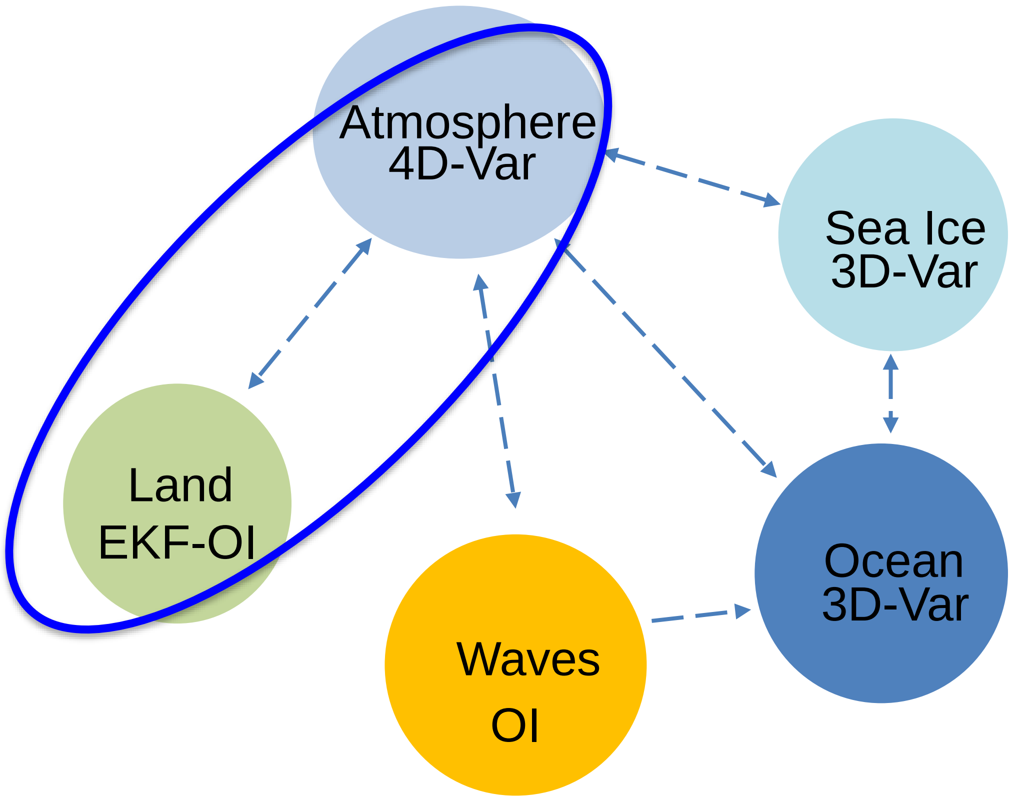
ECMWF/EUMETSAT NWP-SAF
Satellite data assimilation
Training course, 14 March 2024

Satellite data for land surface analysis in NWP systems

Patricia de Rosnay

Earth system approach

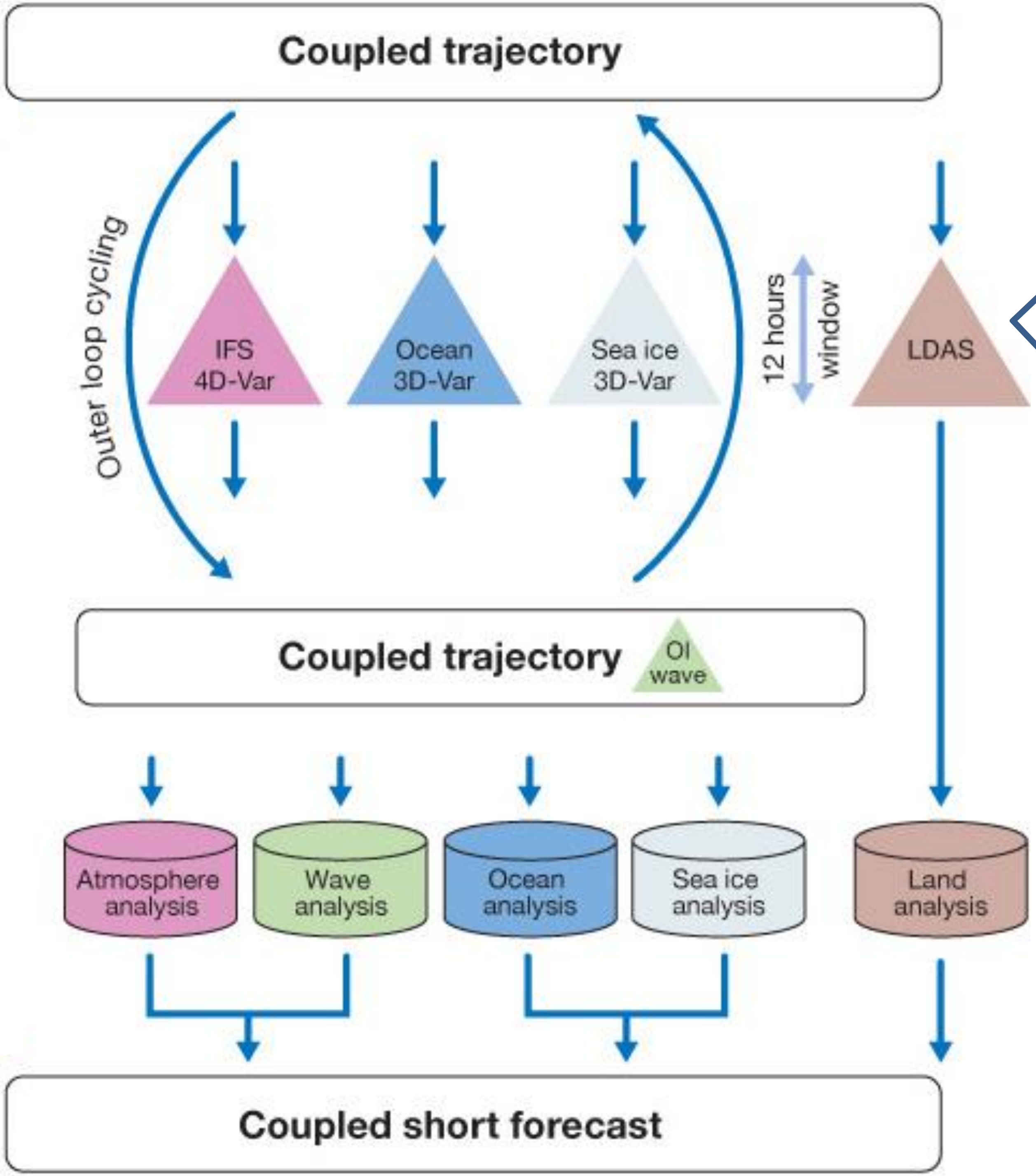




- Coupled assimilation developments for NWP and reanalyses

  Importance of interface observations such as snow, soil moisture over land

Coupled land-atmosphere assimilation



- T2m, RH2m 2D-Optimal Interpolation
- Snow 2D-Optimal Interploation
- Soil moisture SEKF (simplified Ext. Kalman Filter)
- Tsoil, Tsnow 1D-OI

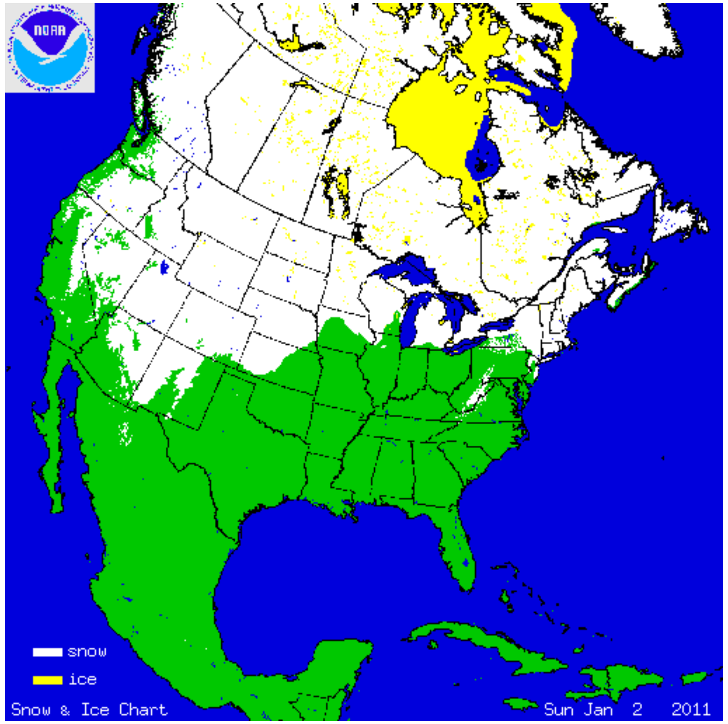
Further reading on coupled assimilation (de Rosnay et al QJRMS 2022): https://doi.org/10.1002/qj.4330

Snow in the ECMWF IFS for NWP

Snow Model: Component of the ECMWF land surface model H-TESSEL (Balsamo et al, JHM 2009)

- Single layer snowpack until 2023 (Dutra et al, JHM 2010,
- Multi-layer snowpack from June 2023 (Arduini et al., James 2019)

Observations: **de Rosnay et al ECMWF Newsletter 2015**
- Snow depth in situ data: SYNOP and National networks
- Snow cover extent: NOAA NESDIS/IMS daily product (4km)
  (Used only at altitude lower than 1500m)



http://nsidc.org/data/g02156.html

Data Assimilation: **de Rosnay et al SG 2014**

- **Optimal Interpolation (OI) →** optimally combine the model and obs
- The result of the data assimilation is the analysis

→ used to initialize NWP

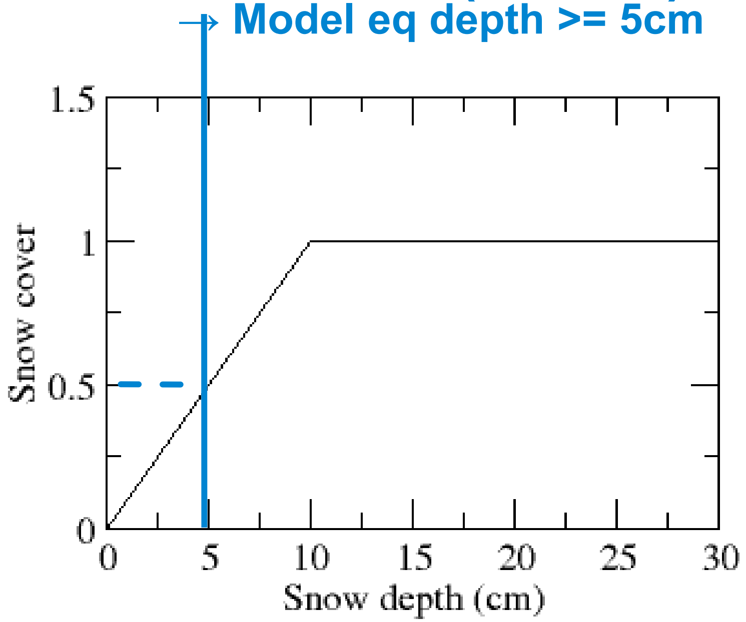
Use of NESDIS/IMS snow cover data for NWP

- IMS snow cover (SC) means SC>50%
- But no quantitative information on snow depth
- Relation snow cover (SC)/Snow Depth (SD): SC=50% corresponds to SD=5cm
- Quality Control: reject in mountainous areas above 1500m altitude

Fisrt Guess / NESDIS IMS	Snow	No Snow
Snow	x	**DA** 5cm
No Snow	DA	DA

Use of IMS at ECMWF

IMS has snow(SC>=50%)
→ Model eq depth >= 5cm



Model relation between Snow Cover (SC) and Snow Depth (SD)

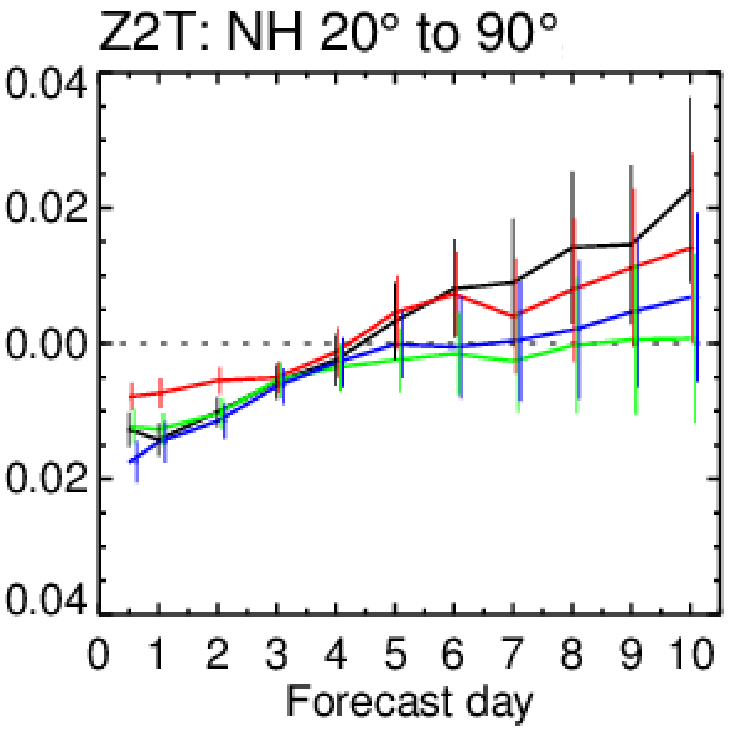
Error specifications:

BG:	σ_b	= 3cm
SYNOP	σ_{SYNOP}	= 4cm
IMS	σ_{ims}	= 8cm

Snow data assimilation Observing System Experiments

Winter 2014-2015 (December to April) - Assess the impact of the snow observing system

Expts	SYNOP	National Data	IMS snow cover
0- OL (no snow data assimilation)			
1- Snow DA: SYNOP+IMS	✓		✓
2- Snow DA: SYNOP+Nat (all in situ)	✓	✓	
3- Snow DA SYNOP+Nat+IMS (all)	✓	✓	✓

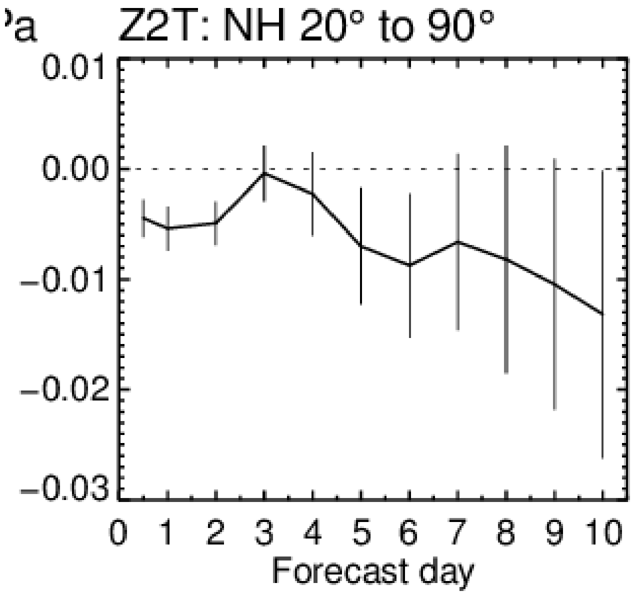


Impact on T2m Forecasts:
Normalized RMSE for T2m FC difference compared to the reference (OL)

SYNOP+IMS (1-0)
SYNOP+Nat (2-0)
SYNOP+Nat+IMS (3-0) -> oper

Best T2m Forecast when all observations, combining in situ and IMS, are assimilated.

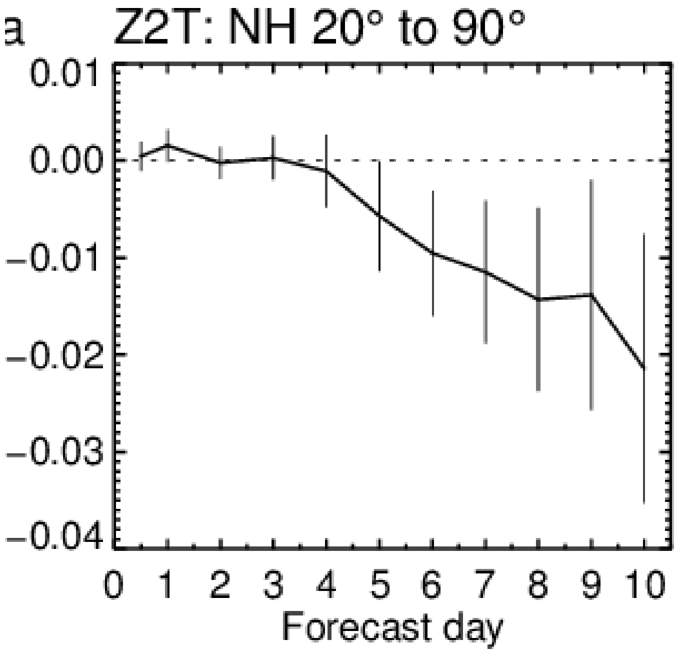
Impact of <u>IMS</u> snow cover assimilation (case 3-2)



All data assimilated (Synop+Nat+IMS)
compared to all in situ data assimilated (SYNOP+Nat)
-> Further T2m forecasts error reduction,
significant at short range

Impact of <u>National data</u> (case 3-1)

All data assimilated (SYNOP+Nat+IMS)
compared to SYNOP+IMS assimilation
-> Further T2m forecasts error reduction at medium range



Contribution & complementarities of each observation types to improve T2m forecasts at short and medium ranges

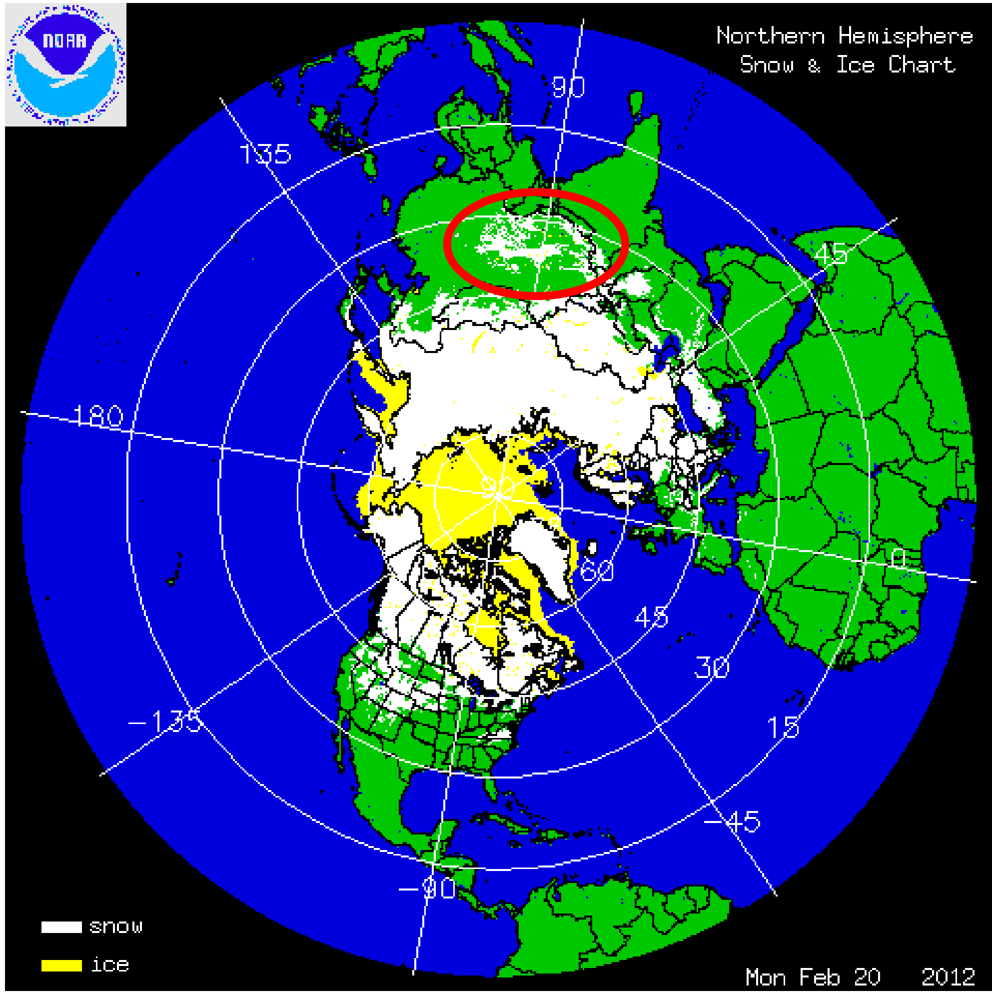
Impact of Tibetan Plateau snow cover assimilation on NWP

Overestimation of snow in the Himalayas (Orsolini et al. 2019)
→ Re-assess the potential benefit of IMS snow cover assimilation over the Tibetan Plateau

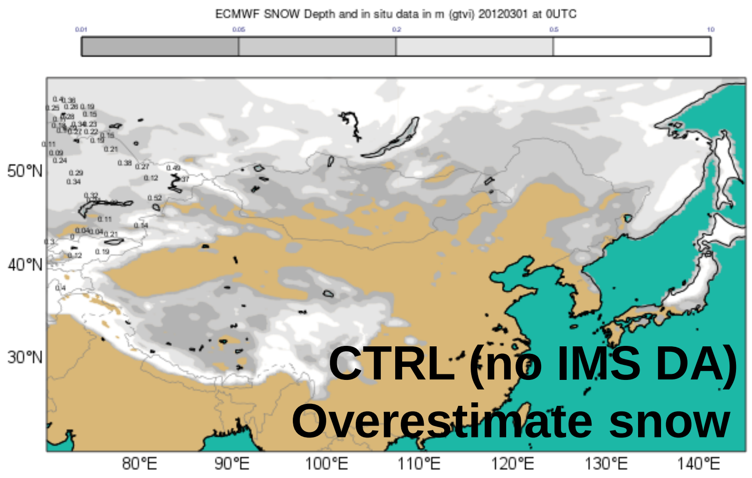
- NWP experiments, Sept 2011 – Dec 2012
- Two 10-day FC per day (488 days, 976 forecasts)
- Resolution: Tco399 (~25 km)
- IFS cycle: 43r3

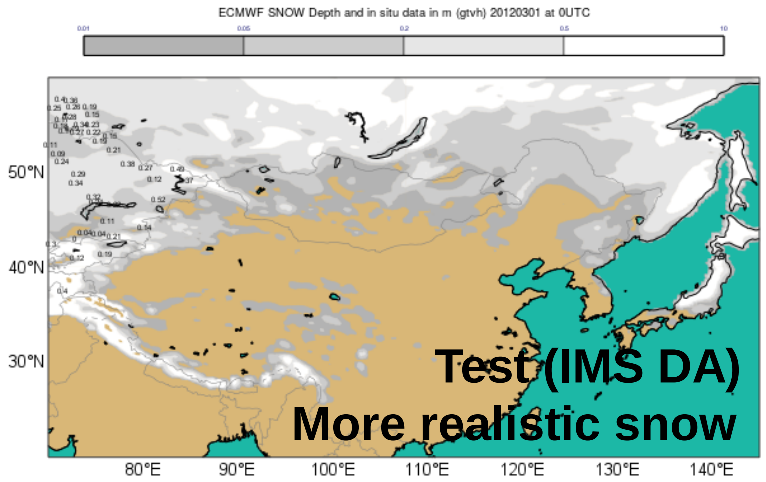
CTRL : QC rejects IMS above1500m altitude, as for operational NWP and ERA5

IMSDA : use IMS everywhere

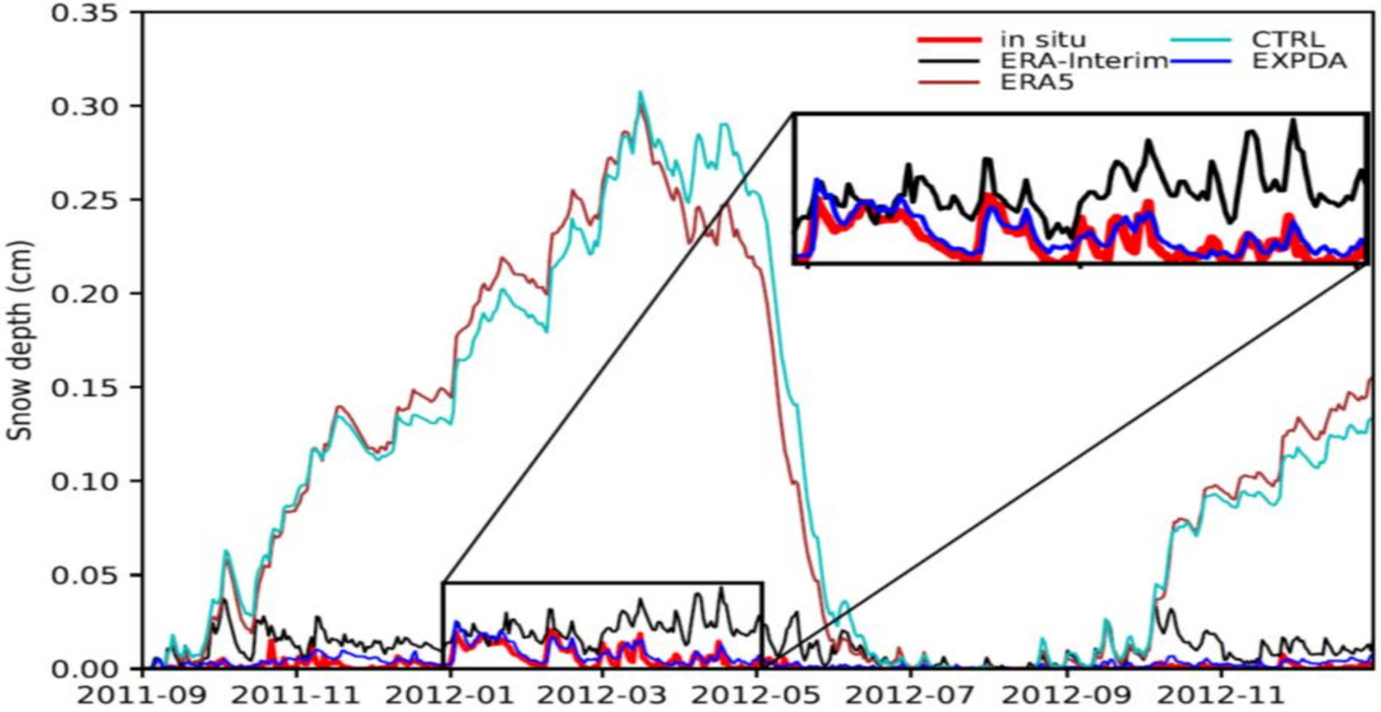


Snow cover coupled data assimilation impact over the Tibetan Plateau



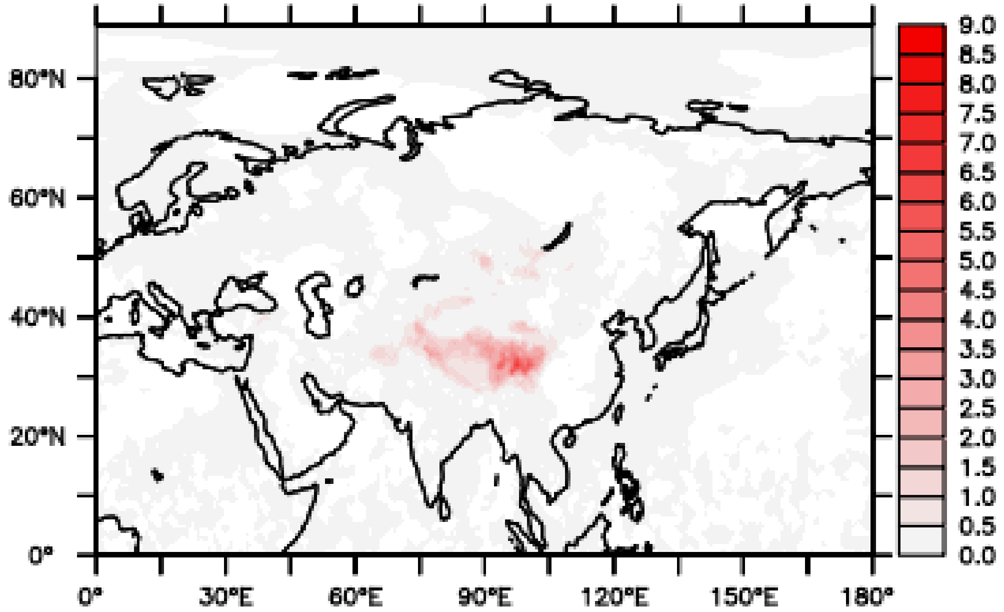


Snow cover DA removes snow and improves snow depth



Impact of snow cover assimilation on two-meter temperature

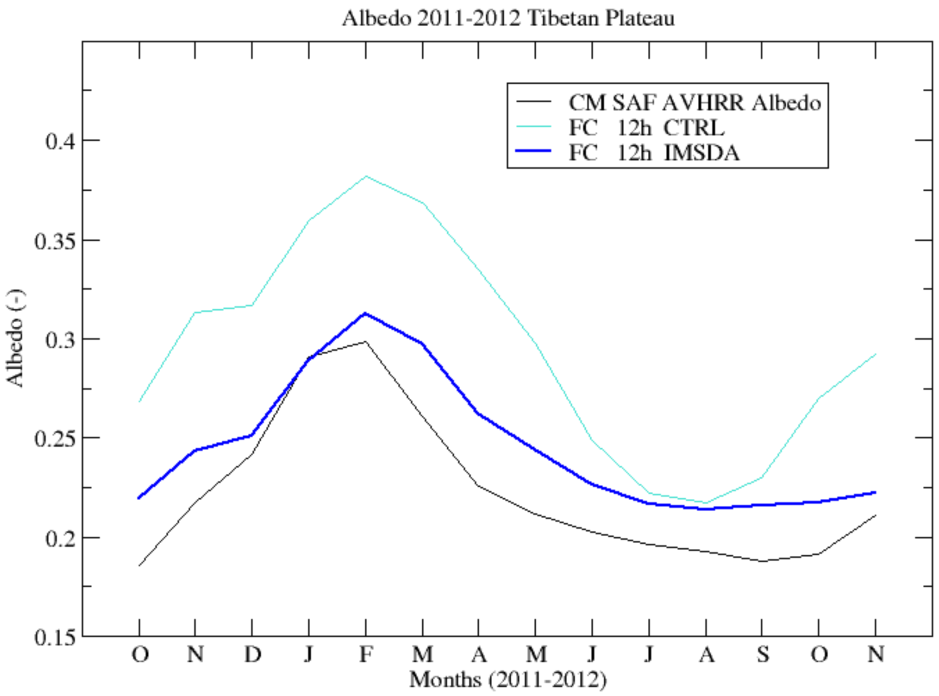
IMS assimilation removes snow
→ Warmer surface conditions than CTRL



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

Surface albedo verification

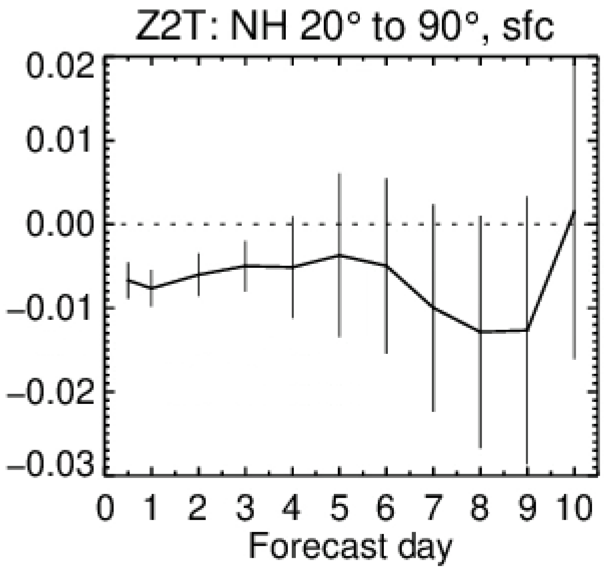
IMS assimilation removes snow
→ Lower surface albedo



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

Recent updates and plans for future implementation

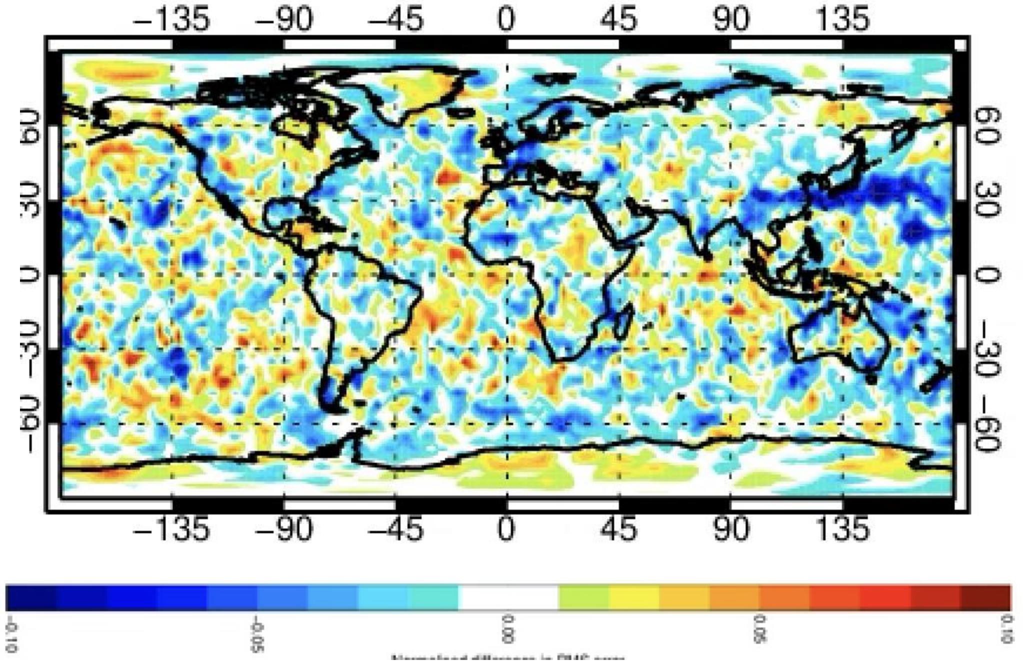
Future improvements (e.g. multi-layer snow model) lead to enhanced consistency between snow and boundary layer processes.
→ Impact of IMS snow cover assimilation in mountainous areas using improved system give promising results



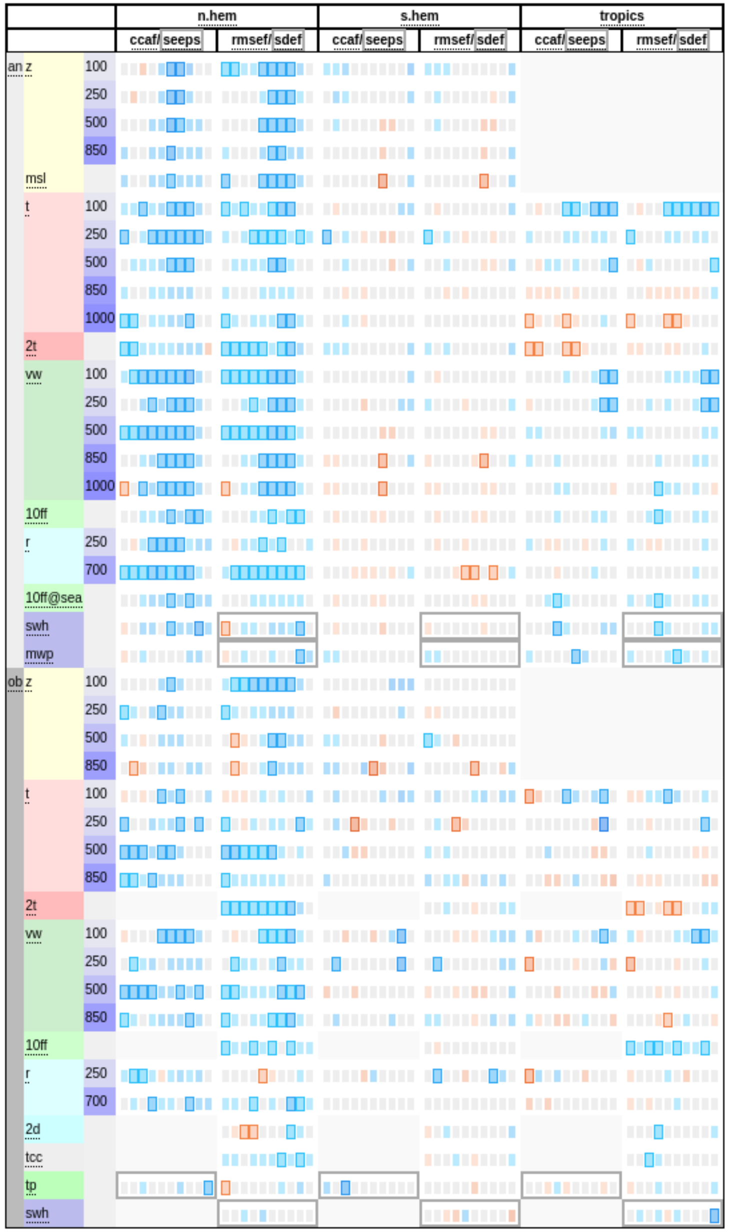
Surface air temperature improvement

T+72; 500hPa

Vector wind error reduction



Scorecard →
(blue= improved
red=degraded)



Kenta Ochi et al.

Snow reanalysis from ERA5 to ERA6

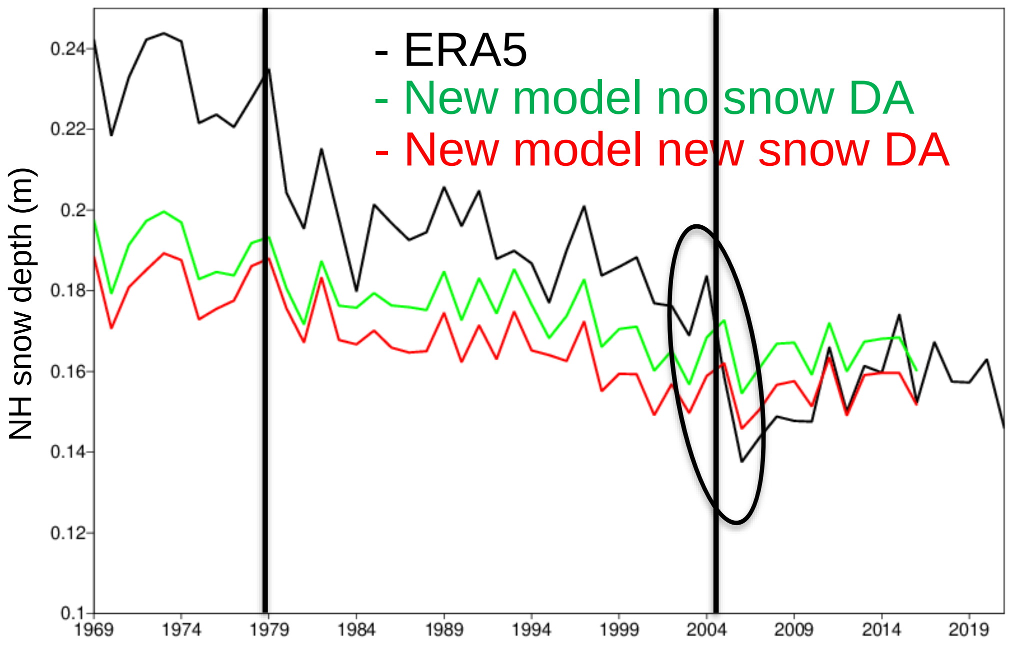
- Step change in the ERA5 (Hersbach et al 2020) snow mass from 2004 (IMS snow cover started to be assimilated)
- Snow DA reduced the positive snow cover bias, but it amplified the snow mass negative trend

Funded by the European Union

ERA6-Land 1st prototype (1939-2022)

ERA6:

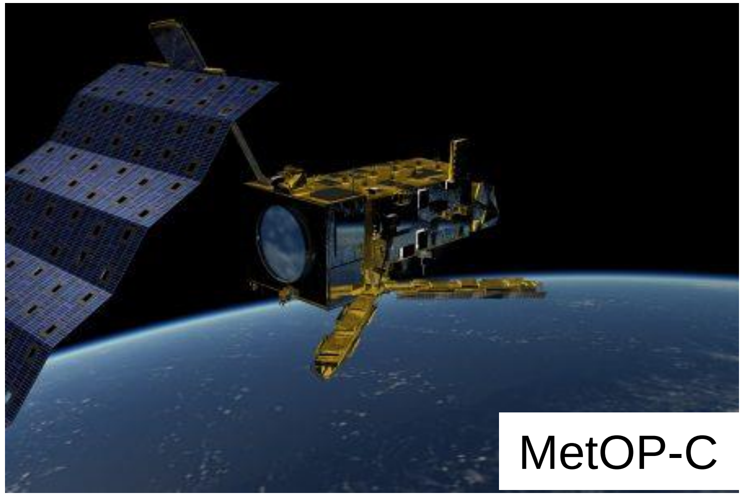
- Snow model and a set of snow data assimilation improvements
- ESA CCI Cryoclim (1987-2010) + NOAA/NESDIS IMS (2010-NRT)



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

Active microwave data:

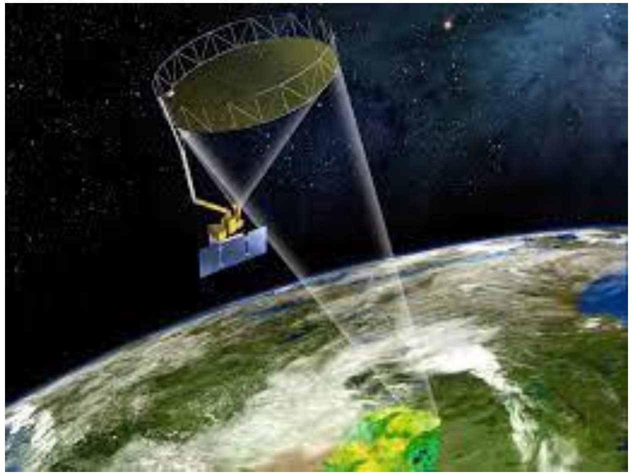
ASCAT: Advanced Scatterometer
MetOP-B (2012-), MetOP-C (2018-)
C-band (5.6GHz) backscattering coefficient
EUMETSAT Operational mission



Passive microwave data:

SMOS: Soil Moisture & Ocean Salinity (2009-)
L-band (1.4 GHz) Brightness Temperature
ESA Earth Explorer, dedicated soil moisture mission
(Munoz-Sabater et al., GRSL, 2012)

SMAP
L-band TB 2015-
NASA Dedicated
soil moisture mission

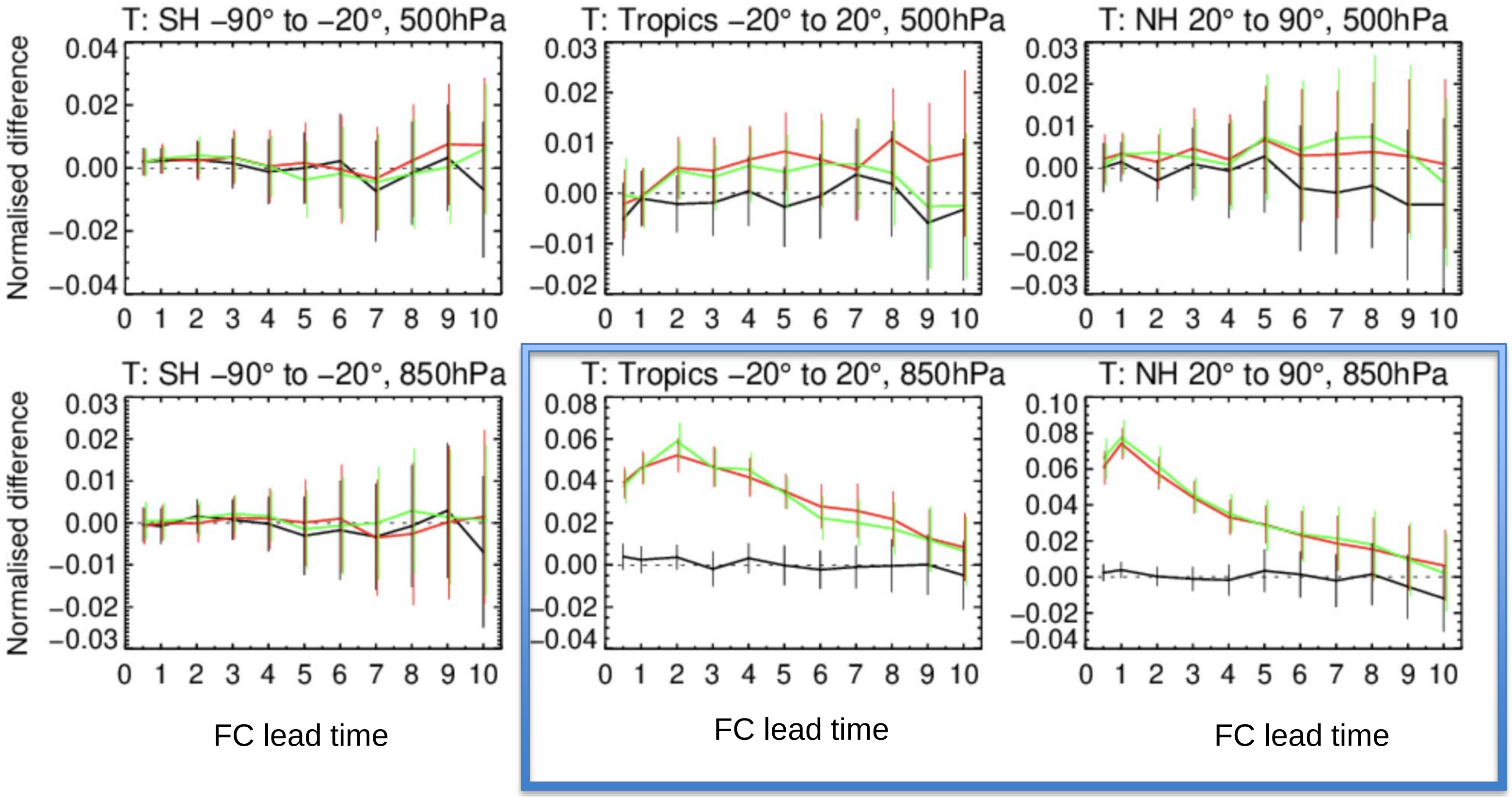


Scatterometer soil moisture also used in ERA5
(ERS-SCAT, Metop/ASCAT)

Soil analysis: impact on NWP

Temperature RMSE

JJA 2020
IFS cycle 48r1



Soil. Moisture DA:
Without without

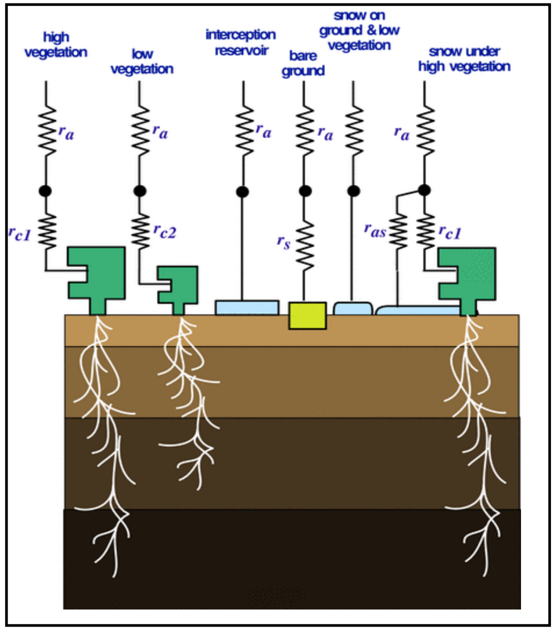
With

No soil moisture DA → increase forecast errors

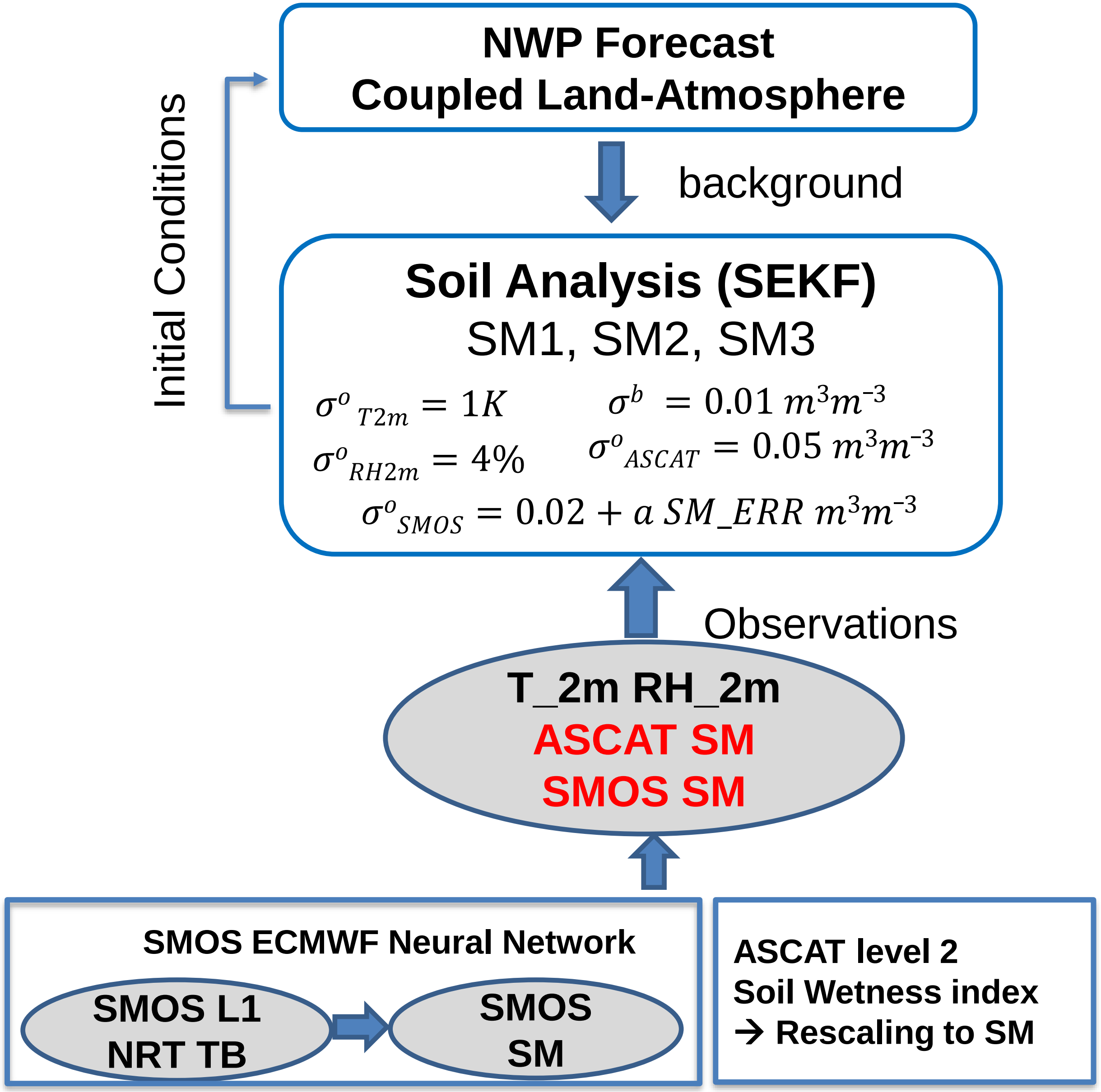
Sébastien Garrigues

Soil moisture (SM) data assimilation in the IFS

A **Simplified Extended Kalman Filter (SEKF)** is used to corrects the soil moisture trajectory of the Land Surface Model



SEKF: de Rosnay et al QJRMS 2013, Fairbairn et al JHM 2019



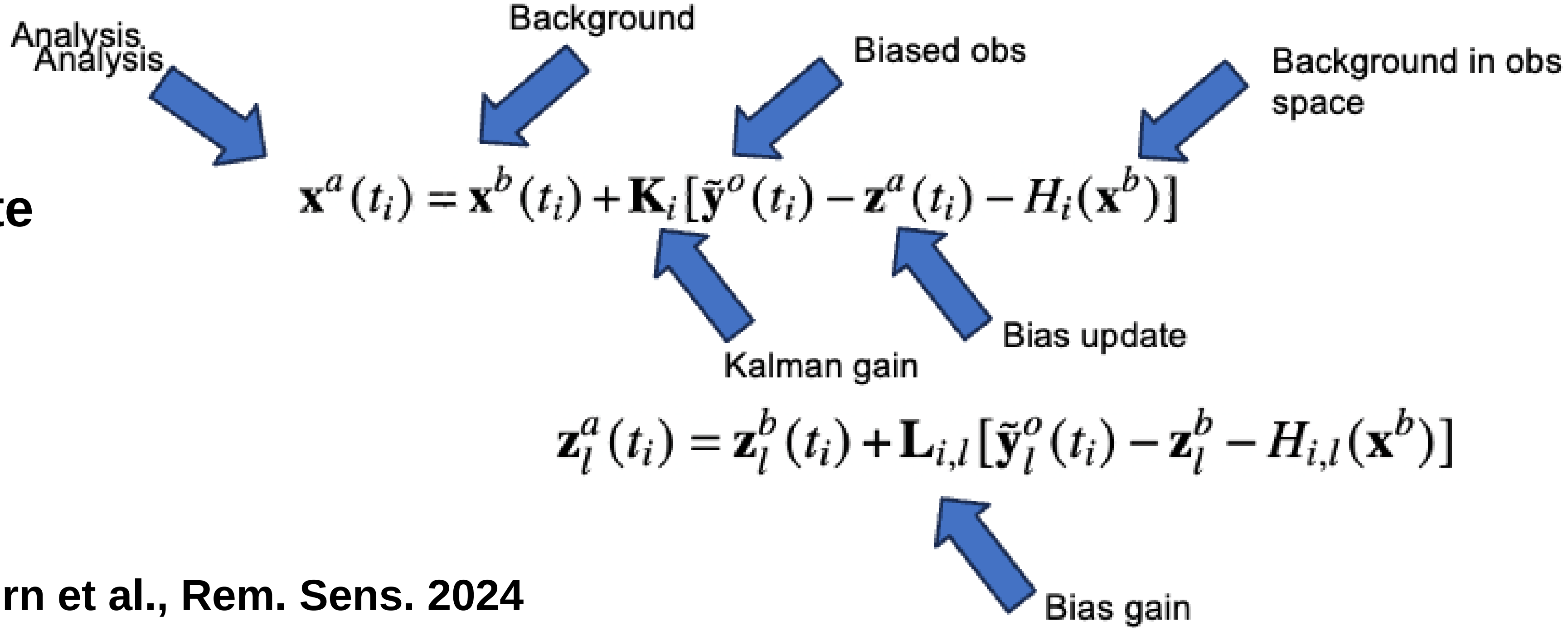
Soil moisture bias-correction

- **Current soil Moisture bias-correction** (BC) based on seasonal CDF (Cumulative Distribution Function) matching (de Rosnay et. al. 2020, Fairbairn et al., 2019)

  Observations rescaled with fixed seasonal parameters such that mean and std match model climatology
- **Adaptive bias correction developments**

  Two-stage filter adapted from Draper et al., (2015):

  Bias-correction ($\mathbf{z}^a$) of observations ($\mathbf{y}^o$) performed independently for ASCAT and SMOS level 2 soil moisture



(1) SEKF analysis update

$$\mathbf{x}^a(t_i) = \mathbf{x}^b(t_i) + \mathbf{K}_i[\tilde{\mathbf{y}}^o(t_i) - \mathbf{z}^a(t_i) - H_i(\mathbf{x}^b)]$$

(2) Bias update

$$\mathbf{z}_l^a(t_i) = \mathbf{z}_l^b(t_i) + \mathbf{L}_{i,l}[\tilde{\mathbf{y}}_l^o(t_i) - \mathbf{z}_l^b - H_{i,l}(\mathbf{x}^b)]$$

ECMWF

Fairbairn et al., Rem. Sens. 2024

From satellite to root zone soil moisture

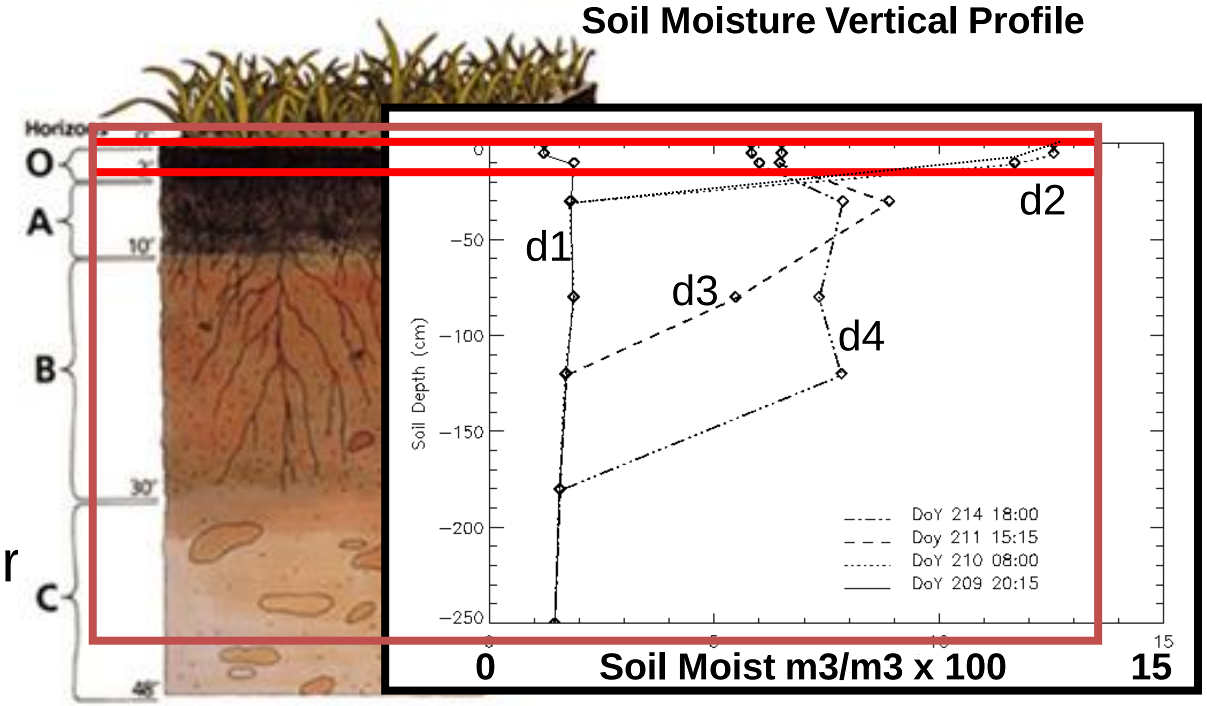
Satellite data → Surface information

Top soil moisture sampling depth: 0-2cm ASCAT, 0-5cm SMOS

Root Zone SM Profile

Variable of interest for Soil-Veg-Atm interaction, Climate, NWP and hydrological applications

Accurate retrieval requires to account for physical processes



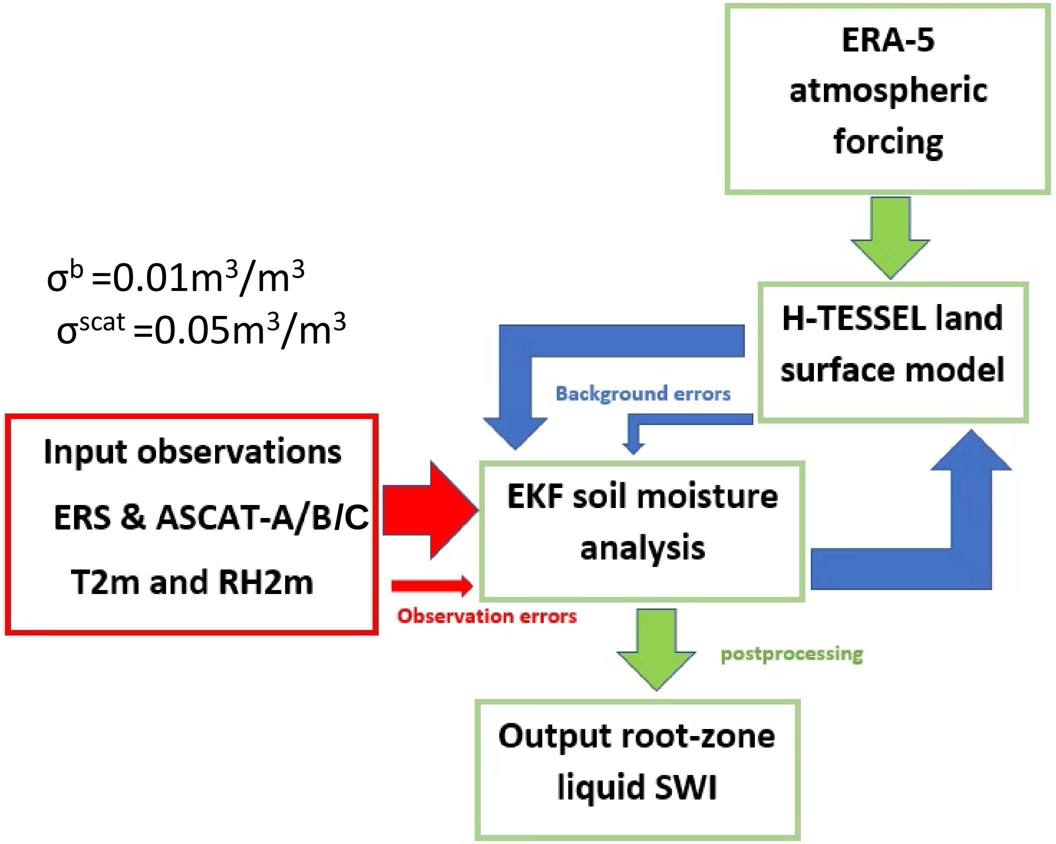
→ Retrieval of root zone soil moisture using satellite data relies on data assimilation

H SAF scatterometer root zone soil wetness products

SSM derived from change-detection approach (Wagner et al., 1999)

$\sigma^{b} = 0.01 m^3/m^3$

$\sigma^{scat} = 0.05 m^3/m^3$

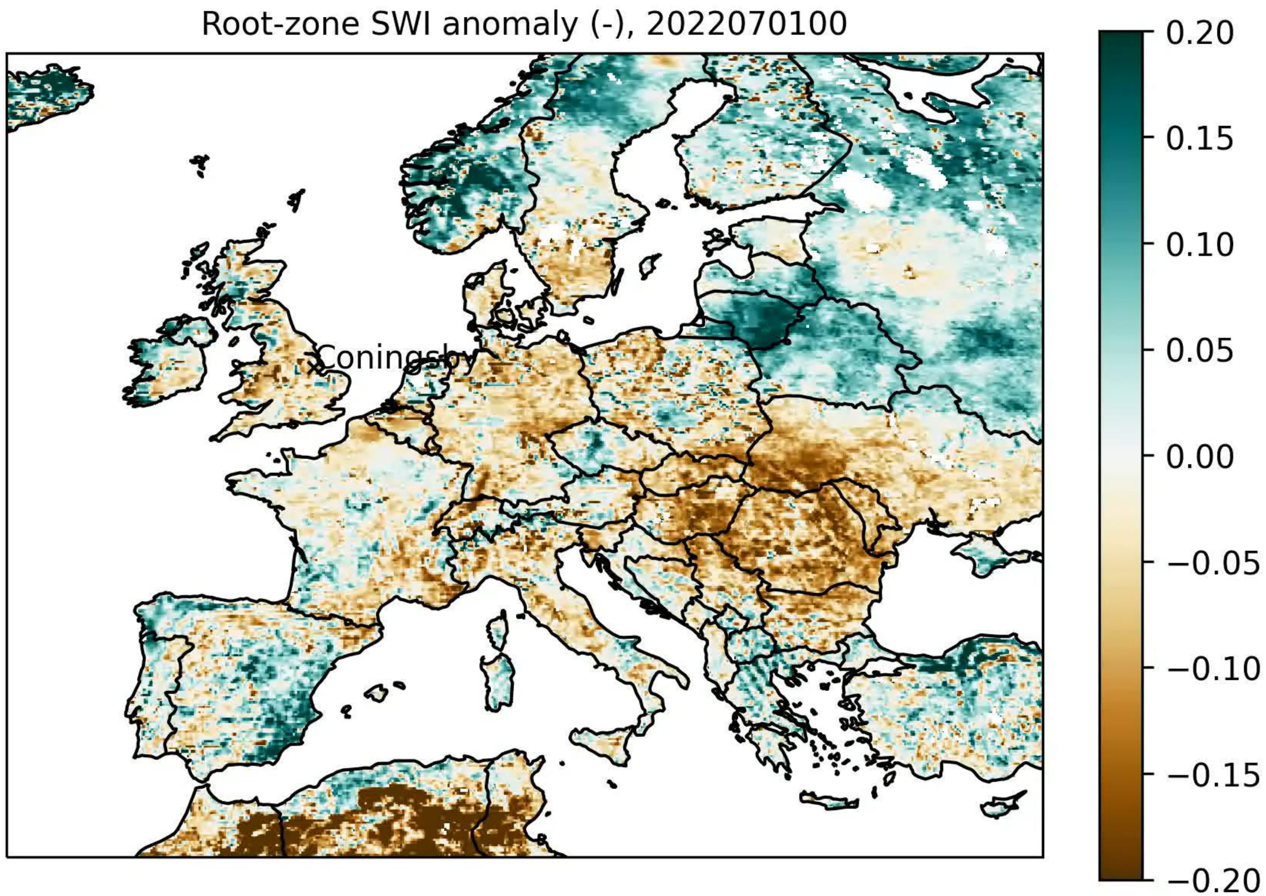


H SAF Root zone soil moisture suite

- Daily (00 UTC) global root-zone liquid soil wetness index
- Data record product (H SAF identifier): RZSM-DR2019-10km (H141) covers 1992-2018
- Data record extension product (identifier): RZSM-DR-EXT-10km (H142) covers 2019-2021
- NRT products H14 (25km from 2012) and H26 (10km from 2022)

Case study: Soil moisture anomalies during July 2022 drought

H26 anomaly (28-100 cm depth)
with respect to 1992-2021 H141/H142 July mean



Data assimilation used to propagate in space and time the ASCAT surface swath soil moisture information

- Fractional soil wetness index anomaly
- Extremely dry anomalies develop over most of Europe (<-15%)

H SAF: hsafcdop@meteoam.it

David Fairbairn

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

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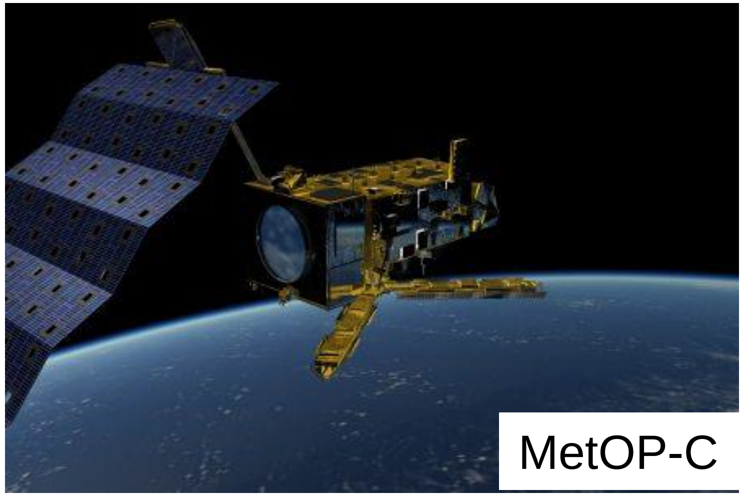

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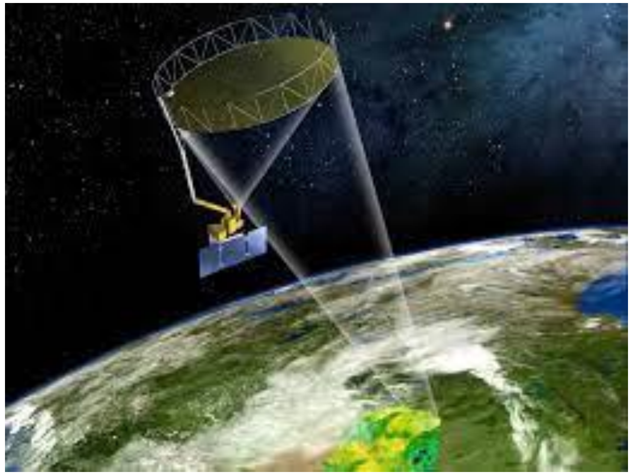
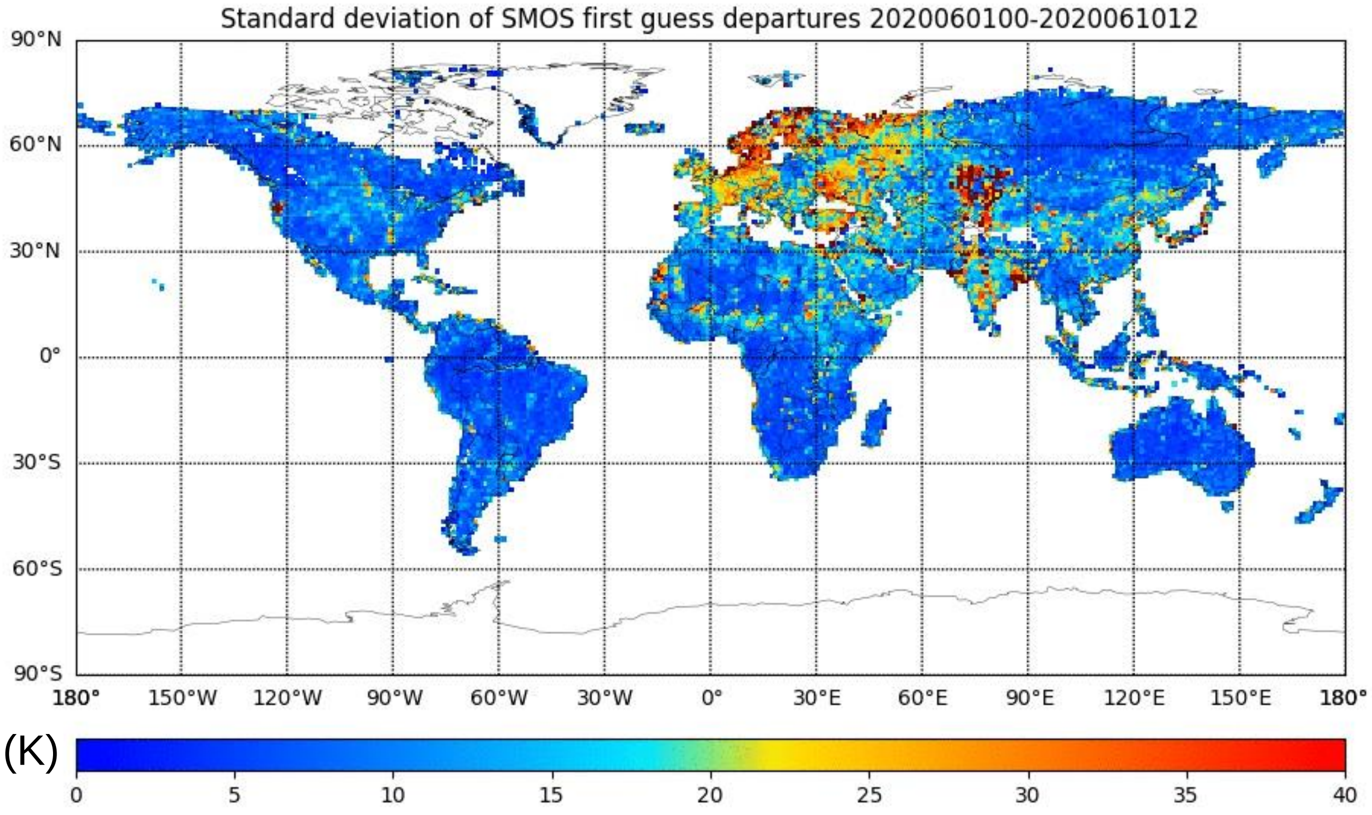


SMOS near real time brightness temperature monitoring

Some areas are affected by RFI (Radio Frequency Interference) contamination

→ Shown with large StDev of first guess departure (observation minus model)

→ RFI detection and filtering importance for data assimilation



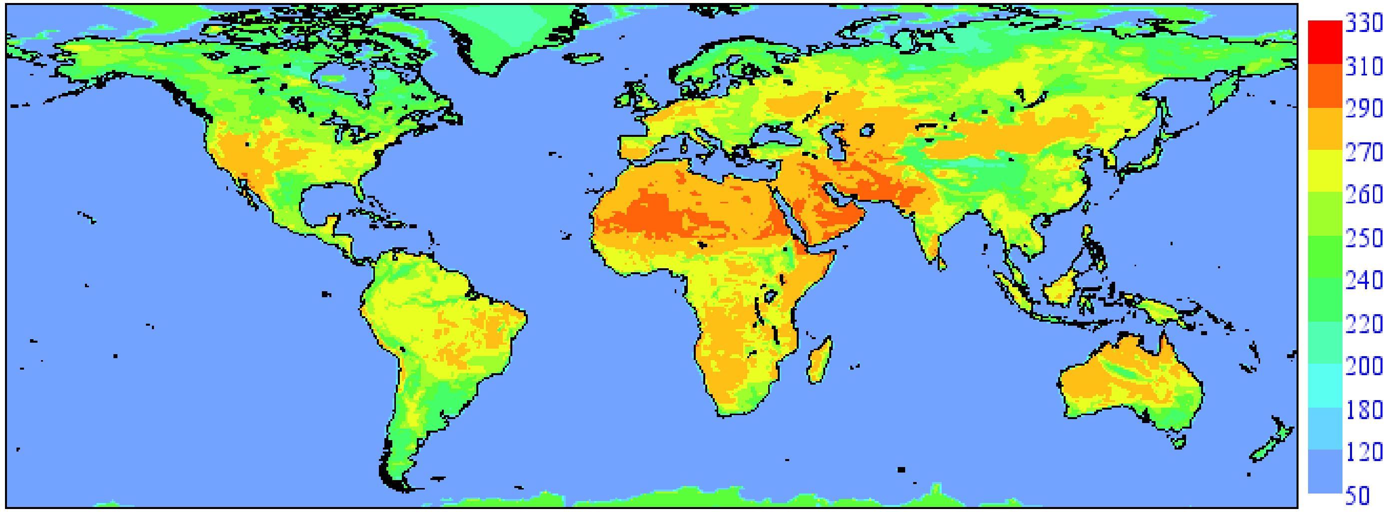
More on SMOS monitoring in Weston et al., RS 2021

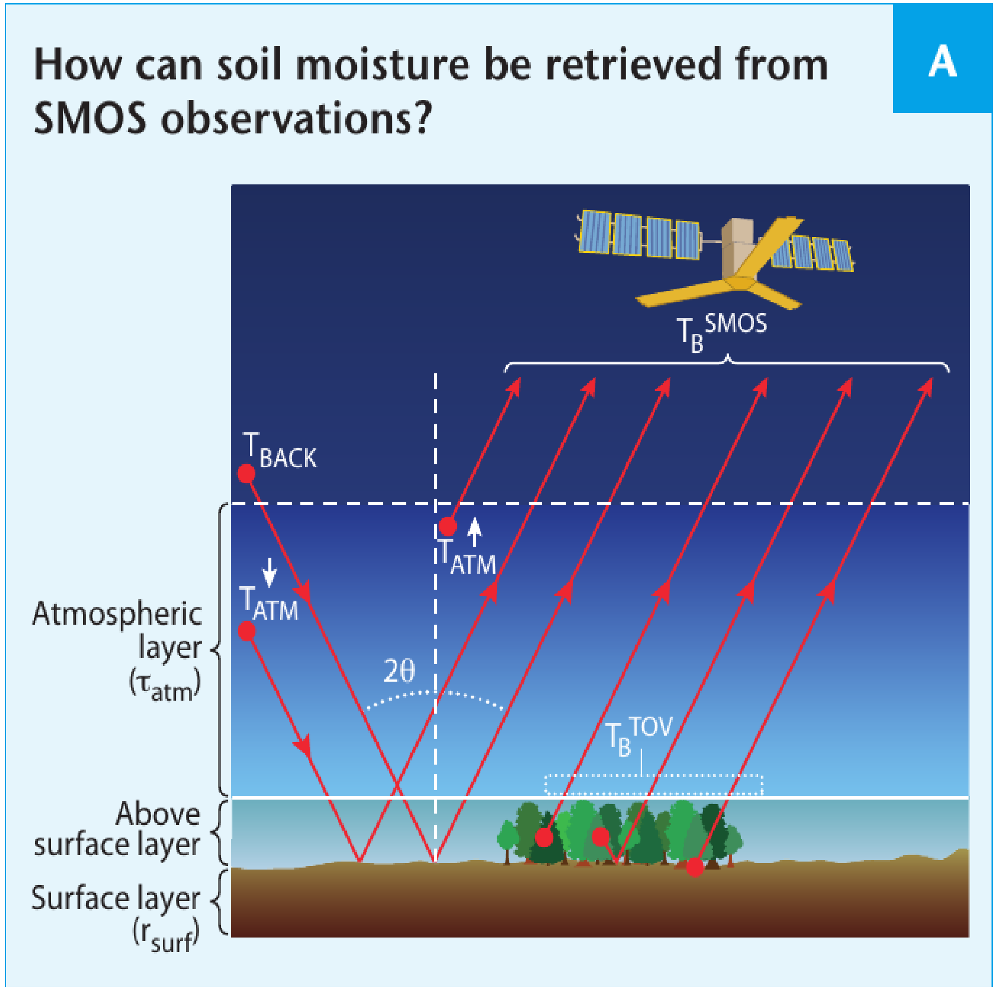
CMEM Simulations of L-Band Brightness Temperature (TB)

Forward operator: Community Microwave Emission Modelling Platform (CMEM)

de Rosnay et al. RSE 2020
Hirahara et all. Rem Sens. 2020

SMOS TB (K) ori WaWsWi_TOA H 2010070106 at angle 30

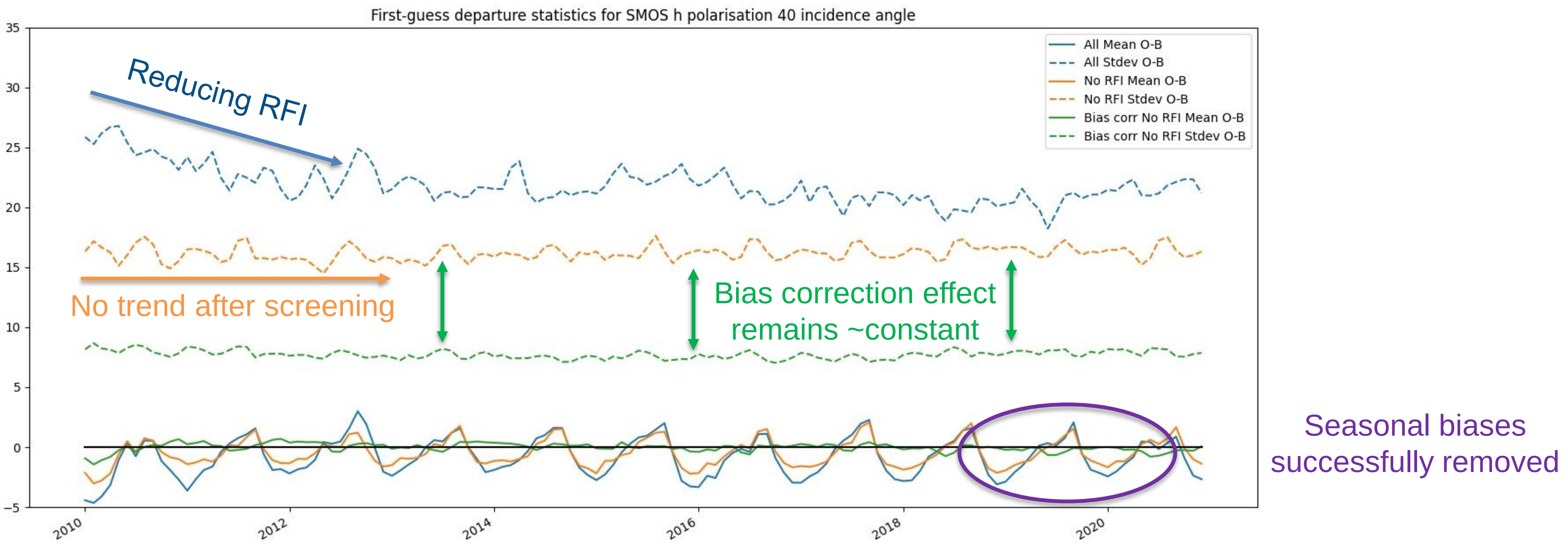




Muñoz Sabater et al, 2011
Muñoz Sabater et al, 2019

SMOS multi-year monitoring

- Monitor latest re-processed v724 SMOS L1C Tbs against stable ERA5 reference from 2010 to 2021



- Key take aways:
  - Improved RFI screening (orange v blue)
  - Newly developed bias correction performs consistently (green v orange)
  - Data quality is consistent over entire lifetime (after screening) – potential assimilation into future reanalyses

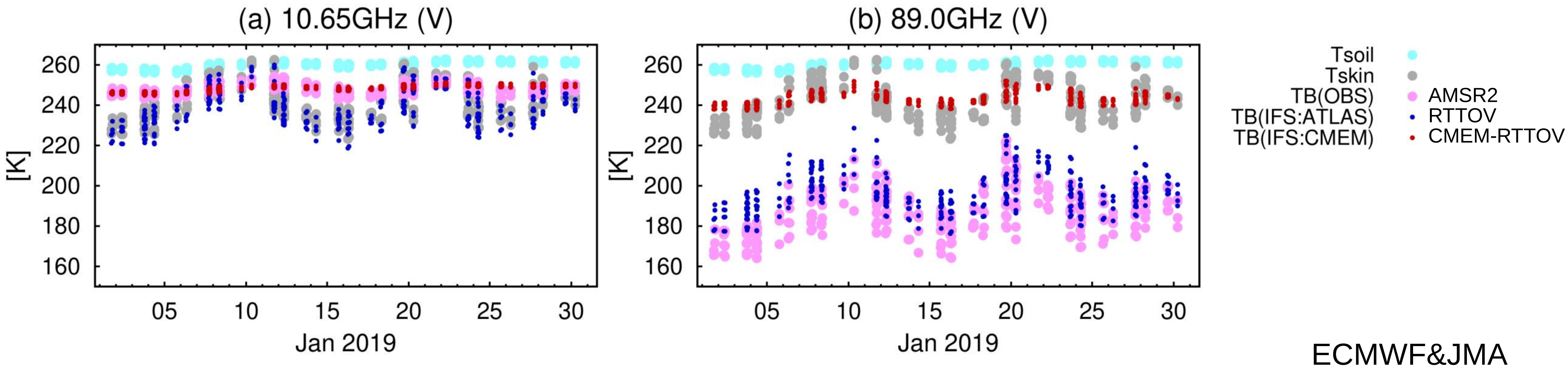
Pete Weston

CMEM over snow-covered areas

- Towards assimilation of surface-sensitive satellite data over land

- New interface between CMEM and RTTOV, processing of surface sensitive observations

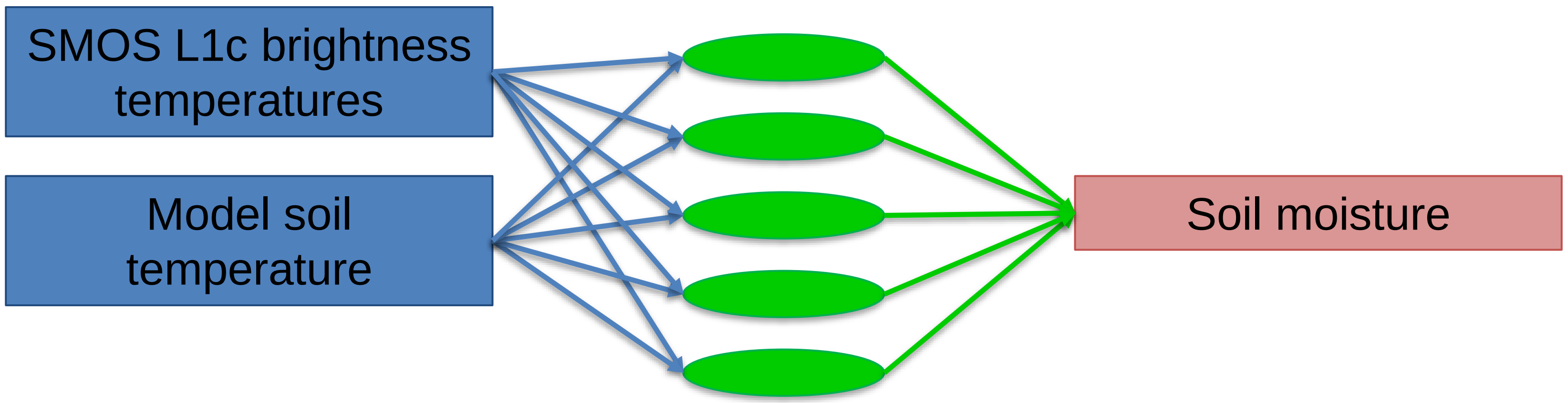
- Implementation of multi-layer snow radiative transfer scheme in CMEM



ECMWF&JMA

Hirahara et al., RS, 2020

SMOS Neural network: ESA level 2 SMOS NRT Soil Moisture product

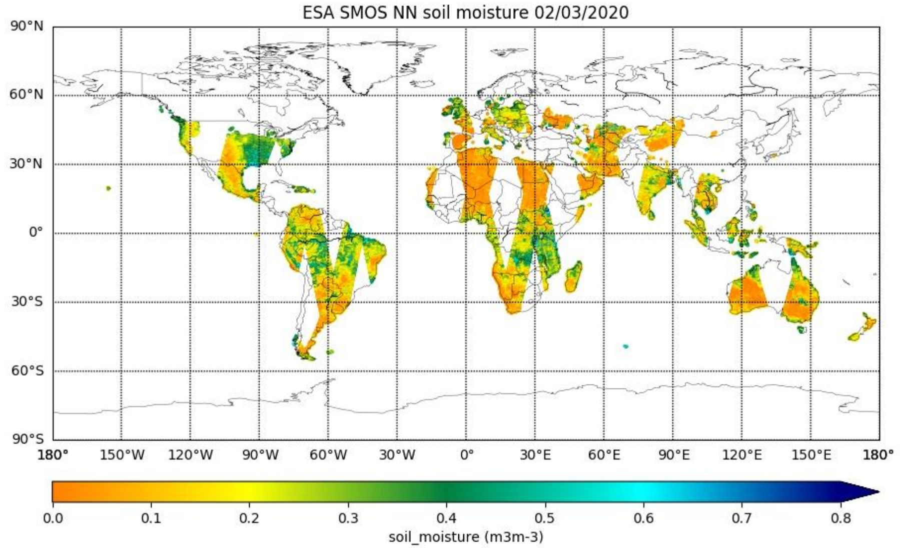


Designed by CESBIO/Estellus, Implemented by ECMWF

Rodriguez-Fernandez et al, HESS 2017

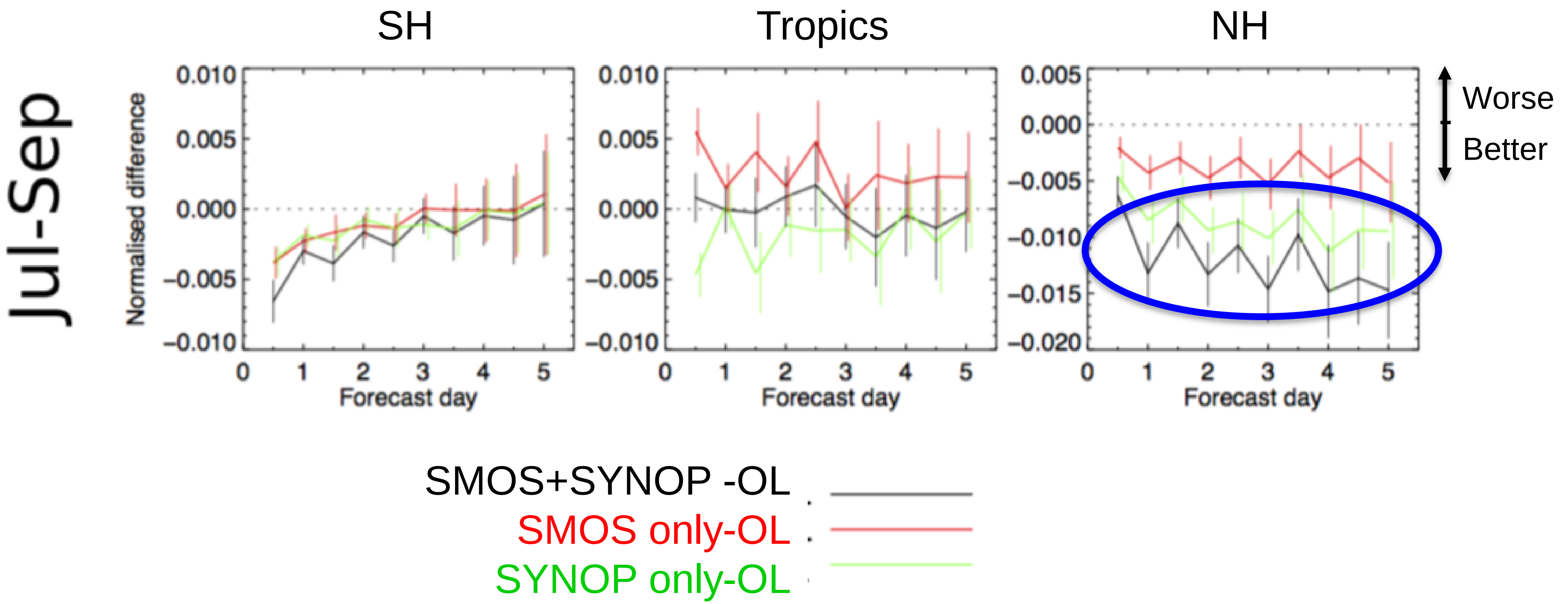
- Neural Network used to retrieve SMOS L2 SM:
  - Trained on SMOS L2 soil moisture
  - Single hidden layer, 5 neurons
- Product available within 4 hours of sensing time
- Available in NetCDF, since March 2016 on ESA SMOS Online Dissemination service

https://smos-ds-02.eo.esa.int/oads/access



SMOS Neural Network SM assimilation in the offline H-TESSEL

- Second parallel NN trained on ECMWF soil moisture
- Experiments assimilating a SMOS neutral network product
  - Offline assimilation in H-TESSEL and initialisation of stand-alone atmospheric forecasts (2012)
  - Reference H-TESSEL with no assimilation: Open Loop (OL)
- Impact on two-meter air temperature forecasts (July to September 2012)

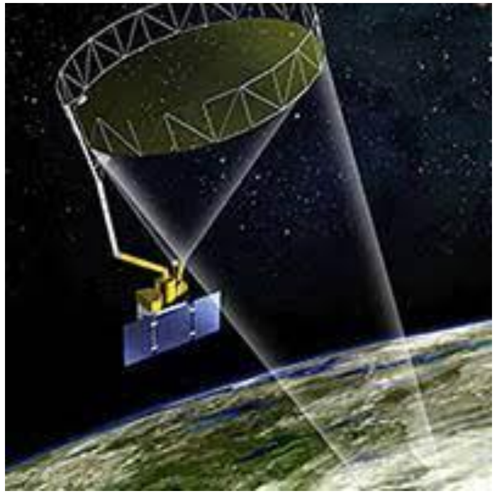


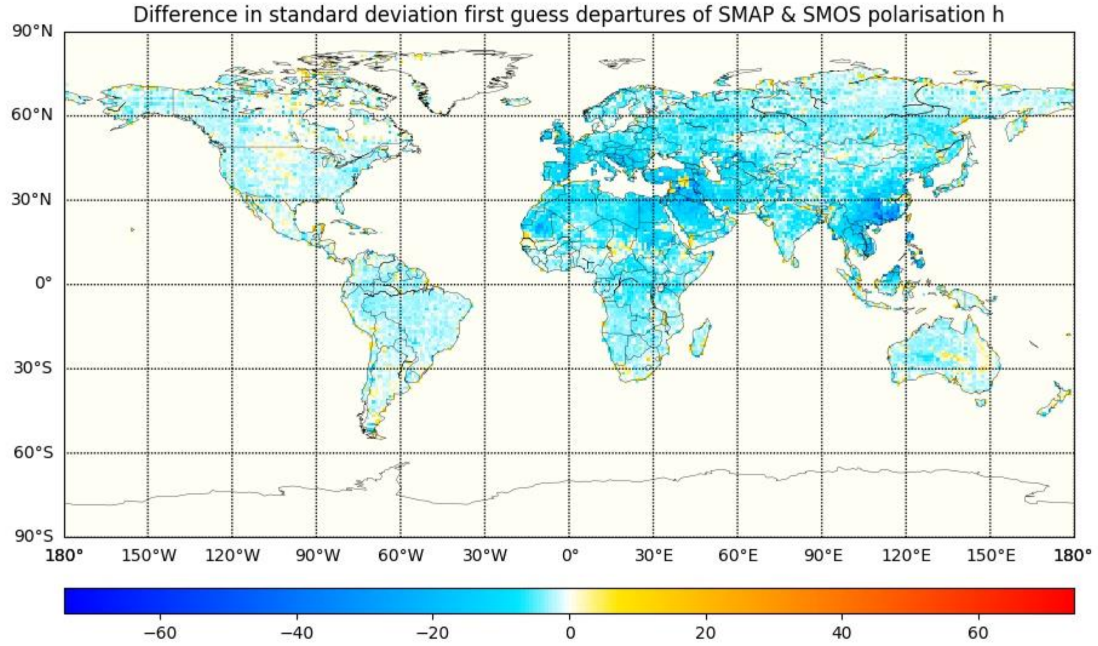
→ Proof of concept of offline SMOS NN assimilation for NWP initialisation

Rodriguez-Fernandez et al, Remote sensing, 2019

SMAP monitoring

- SMAP is a NASA satellite with an instrument measuring at 1.4GHz (Entekhabi et al 2010)
- Monitoring of SMAP Tbs will be implemented alongside existing SMOS Tb monitoring
- Data quality looks good:
  - Smaller std dev of first-guess departures
  - Less affected by RFI thanks to onboard filtering
  - Slightly larger biases (before bias correction)





- **Monitoring implemented with 47r2 on 11 May 2021**
- Next steps:
  - Assimilate SMAP Tbs directly into SEKF
  - Revisit CDF-matching bias correction scheme

Pete Weston et al., 2021

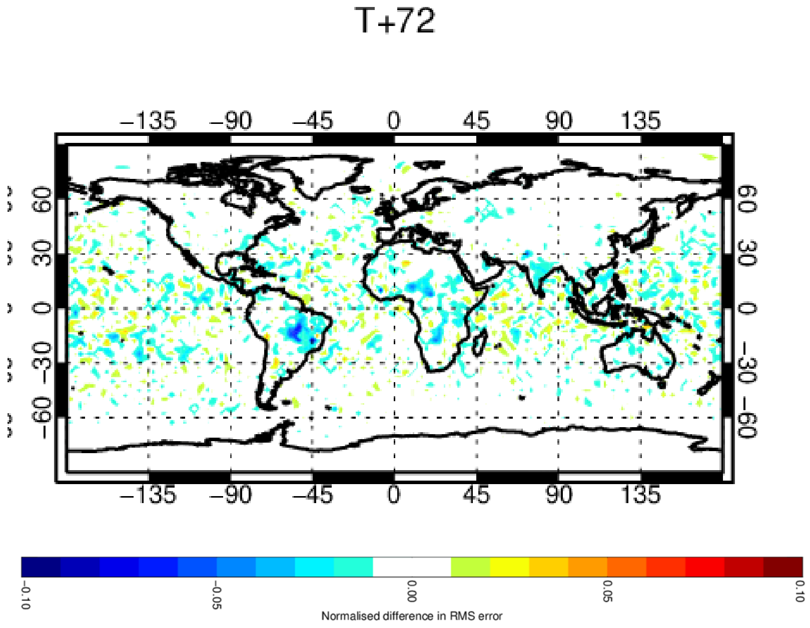
VOD assimilation→CoCO2 project

CoCO2
Prototype system for a Copernicus CO_2 service

Assimilation of **Vegetation Optical Depth (VOD)** from passive microwave sensors to analyse vegetation leaf area index (LAI) and constrain 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

Funded by the European Union



T2m RMSE reduction (blue) 2018-2021

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

Build-up on Calvet et al., 2019, Boussetta et al., 2013 showing the importance of LAI analysis

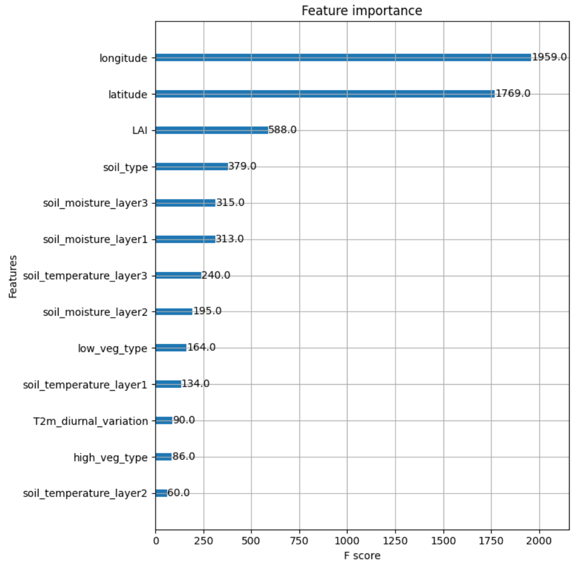
Pete Weston

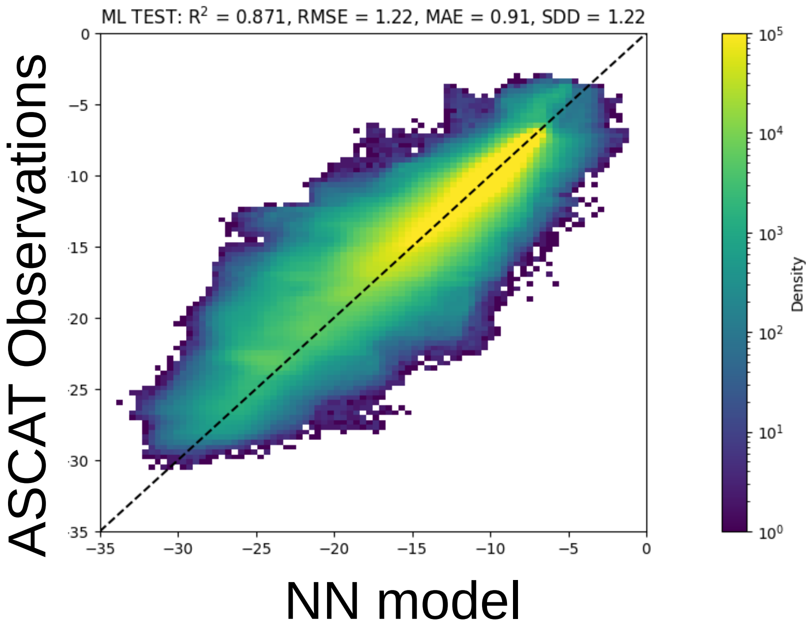
MW information on Leaf area index (LAI)

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





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→ 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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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

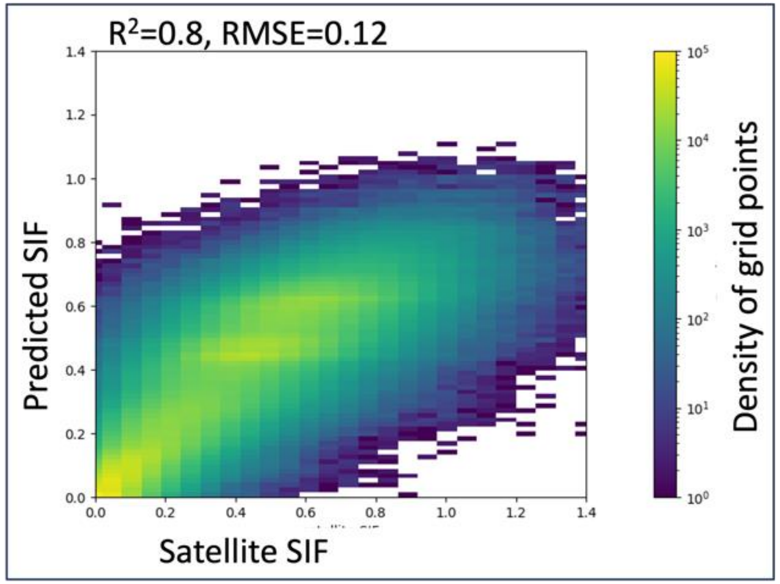
Funded by the European Union

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

Summary

- ECMWF soil moisture and snow based on data assimilation of in situ observations and satellite data (ASCAT, SMOS, snow cover), for NWP and reanalysis ERA5
- Strong impact of snow assimilation on NWP
- ECMWF SMOS neural network soil moisture assimilated for NWP since 2019
- EUMETSAT H SAF ASCAT root zone products: NRT and Climate data record, based on ASCAT-B/C surface soil moisture assimilation
- Impact of LAI analysis ton constrain water and carbon cycle variables
- Ongoing developments to explore multi-layer snow and soil approaches and to MW and Solar-Induced Fluorescence data to analyse vegetation characteristics
- Longer term: Assimilation of integrated hydrological variables such as river discharge

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