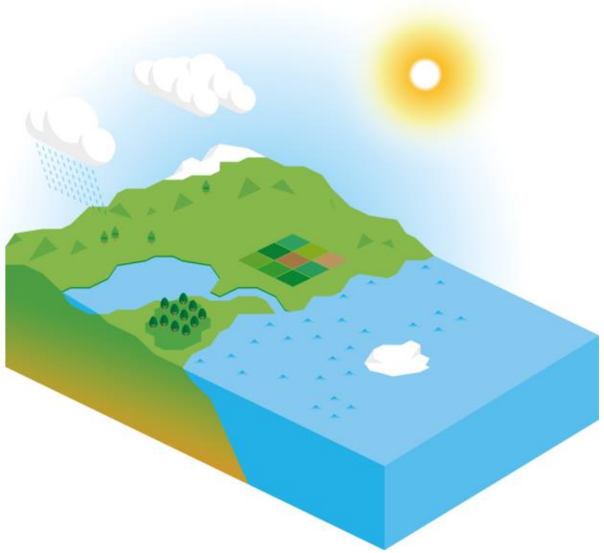
ECMWF/EUMETSAT NWP-SAF
Satellite data assimilation
Training course, 16 May 2023

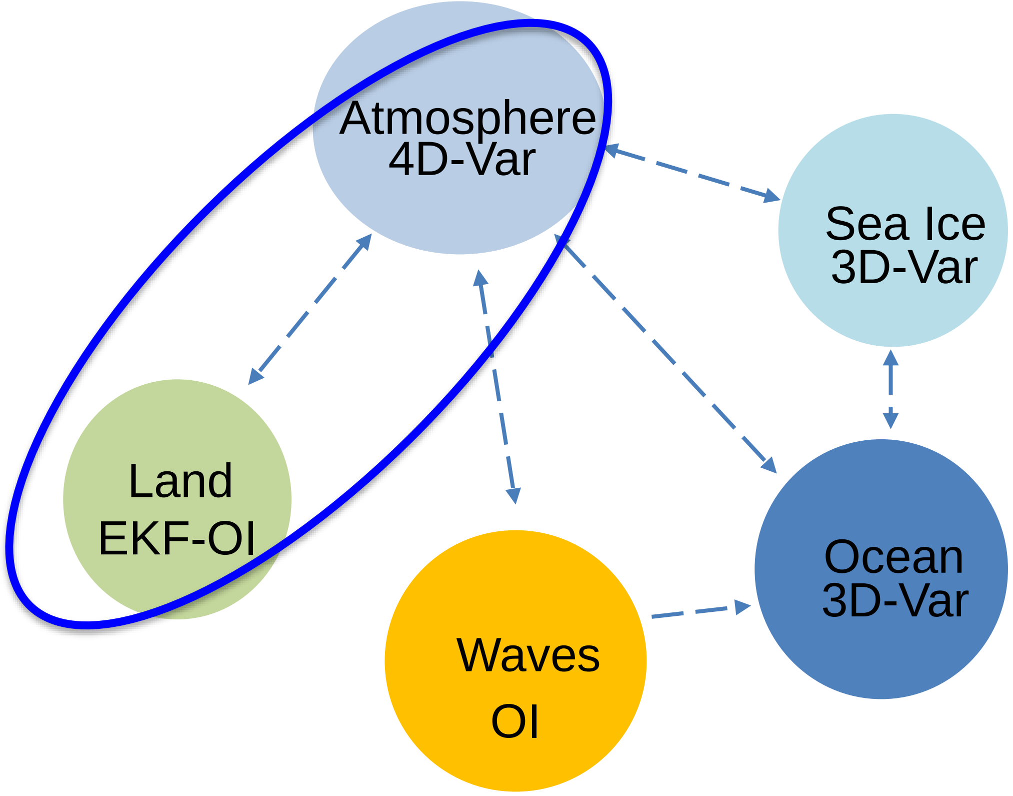
Satellite data for land surface analysis in NWP systems

Patricia de Rosnay

Earth system approach



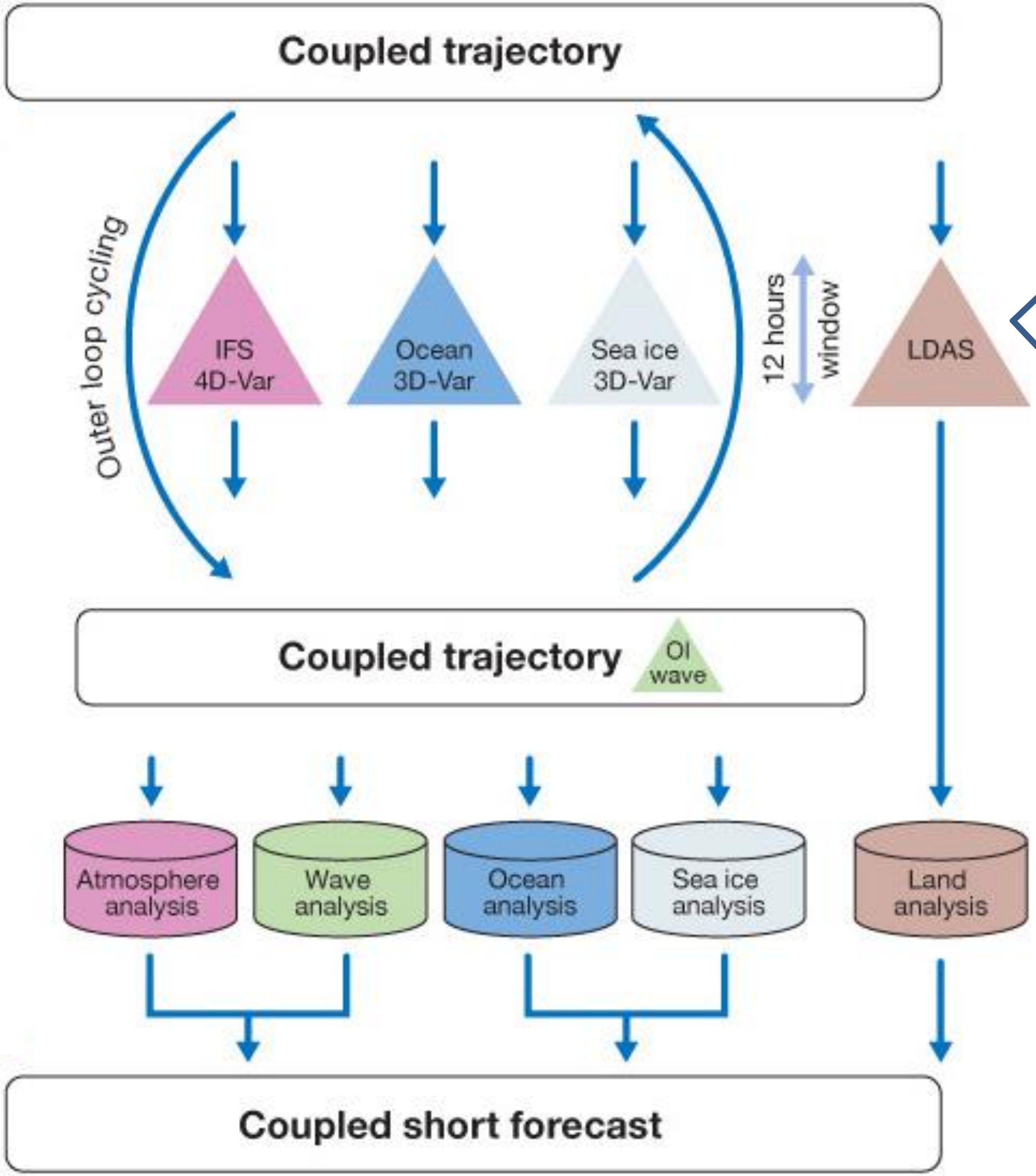
Integrated Forecasting System (IFS)



- 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

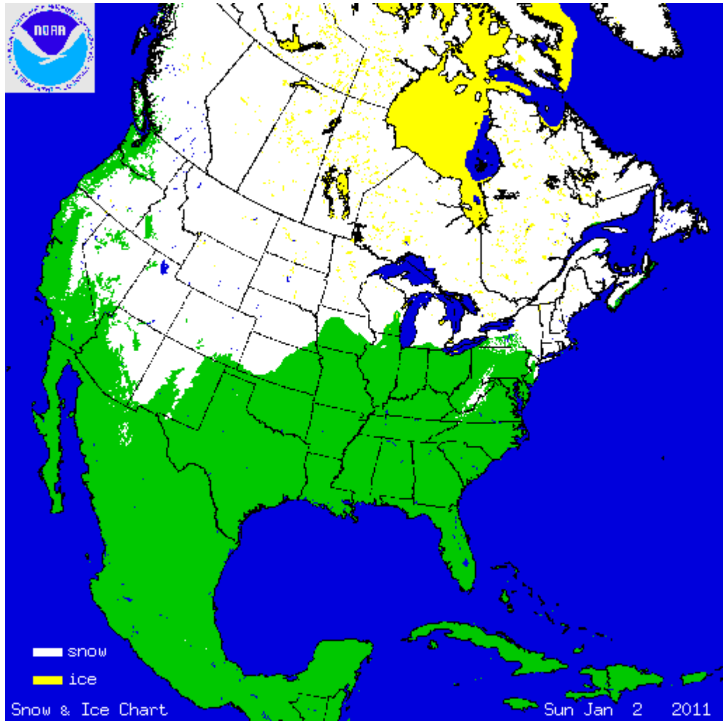
Further reading on coupled assimilation (de Rosnay et al QJRMS 2022): https://doi.org/10.1002/qj.4330

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**

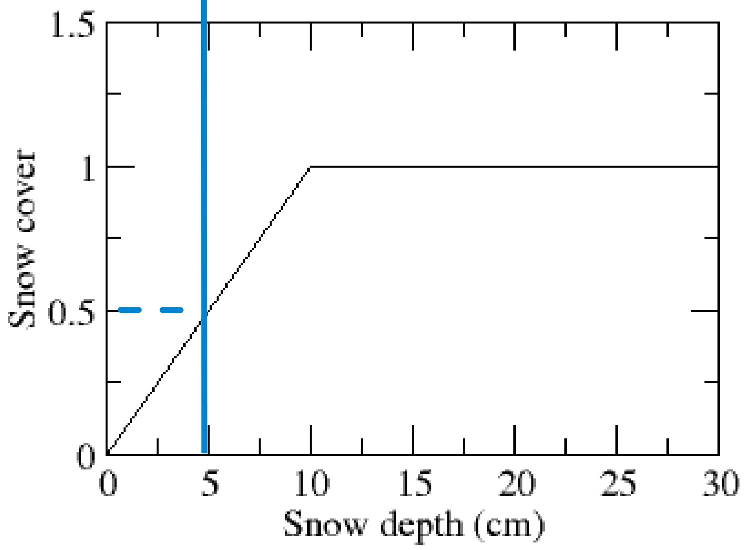
- **Optimal Interpolation (OI) →** optimally combine the model and obs
- The result of the data assimilation is the analysis

→ 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

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



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

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

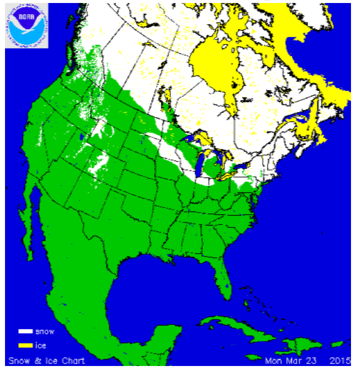
Use of IMS at ECMWF

Error specifications:

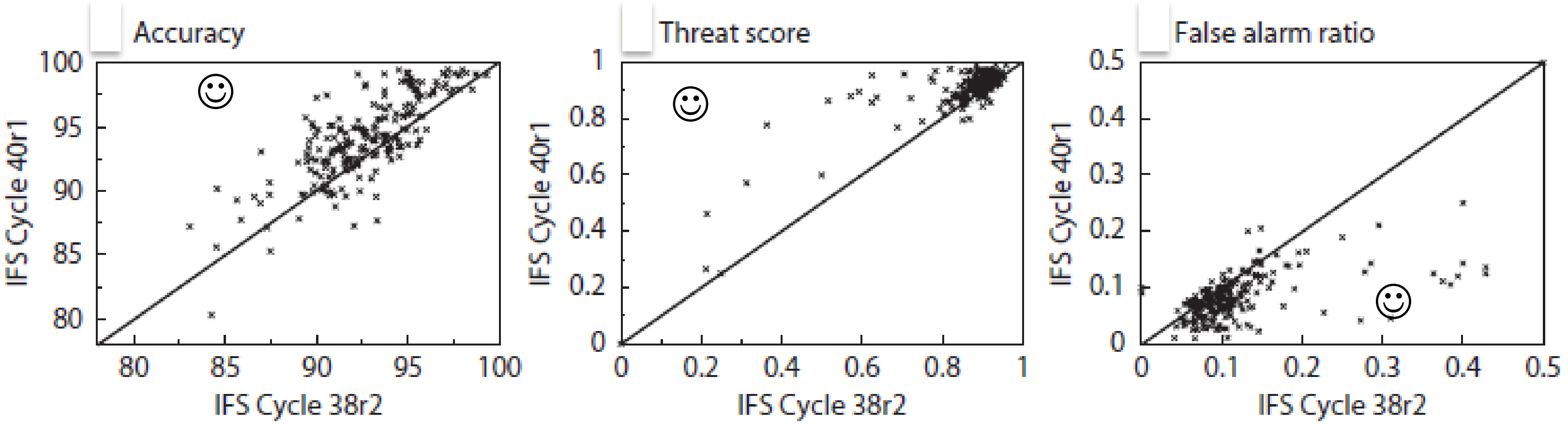
BG:	σ_b	= 3cm
SYNOP	σ_{SYNOP}	= 4cm
IMS	σ_{ims}	= 8cm

Snow assimilation: Forecast impact

Revised IMS snow cover data assimilation (2013)



Impact on snow October 2012 to April 2013 (251 independent *in situ* observations)



	Snow observed	No snow observed
Snow in analysis	a Hits	b False alarm
No snow in analysis	c Misses	d Correct no snow

The following scores are used for the evaluation:

- Accuracy = a+d / (a+b+c+d)
- False alarm ratio = b / (a+b)
- Threat score = a / (a+b+c)

Snow assimilation: Forecast impact

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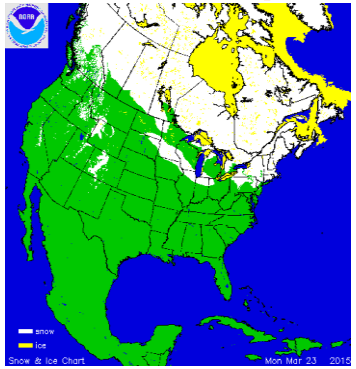

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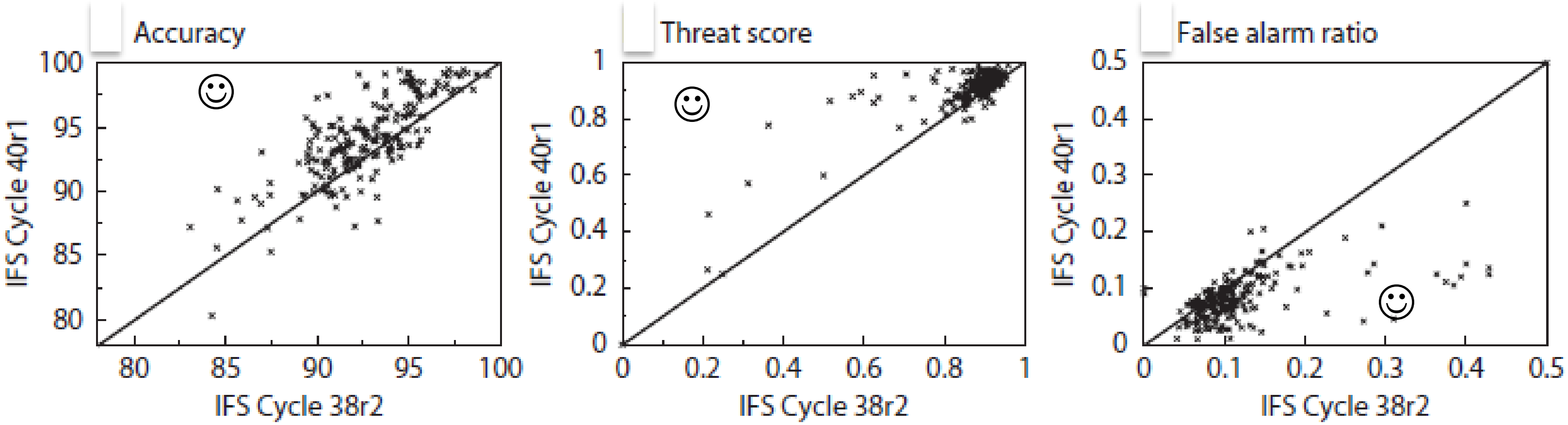
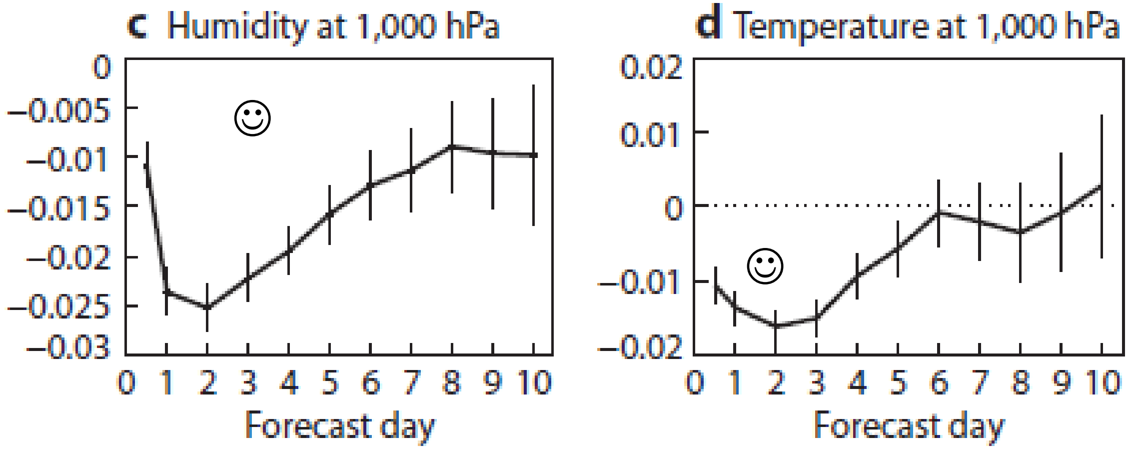


Impact on atmospheric forecasts

October 2012 to April 2013 (RMSE new-old)



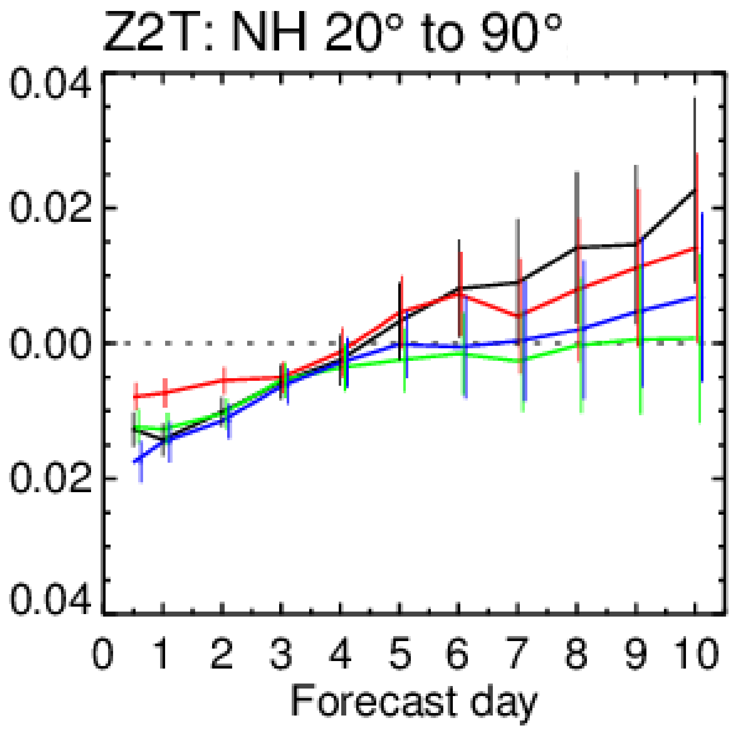
→ Consistent improvement of snow and atmospheric forecasts

de Rosnay et al., ECMWF Newsletter 143, Spring 2015

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)	✓	✓	✓

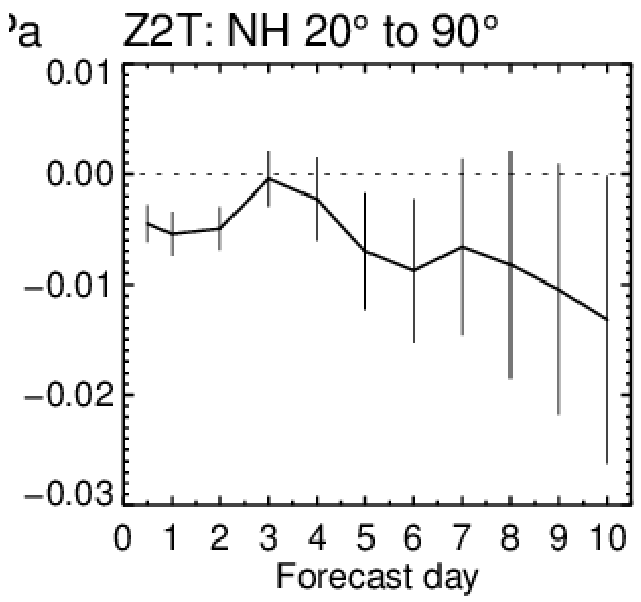


Impact on T2m Forecasts:
Normalized RMSE for T2m FC difference compared to the reference (OL)

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.

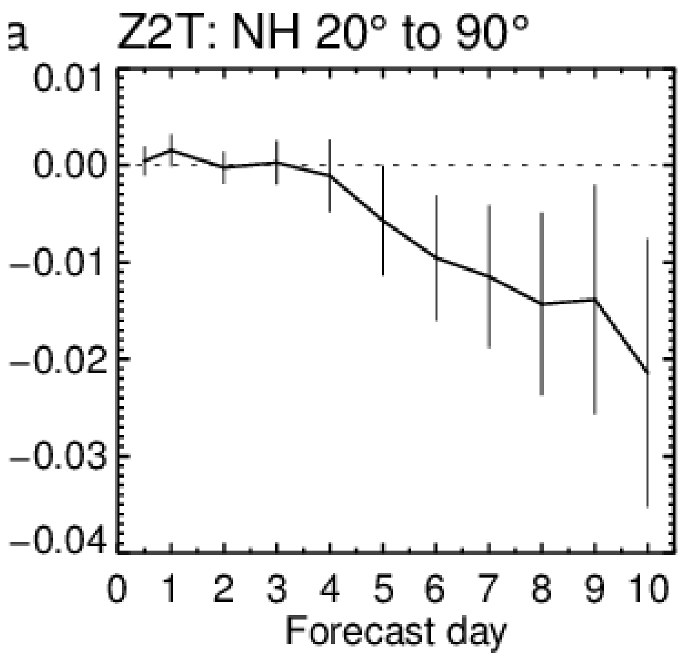
Impact of IMS snow cover assimilation (case 3-2)



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 National data (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

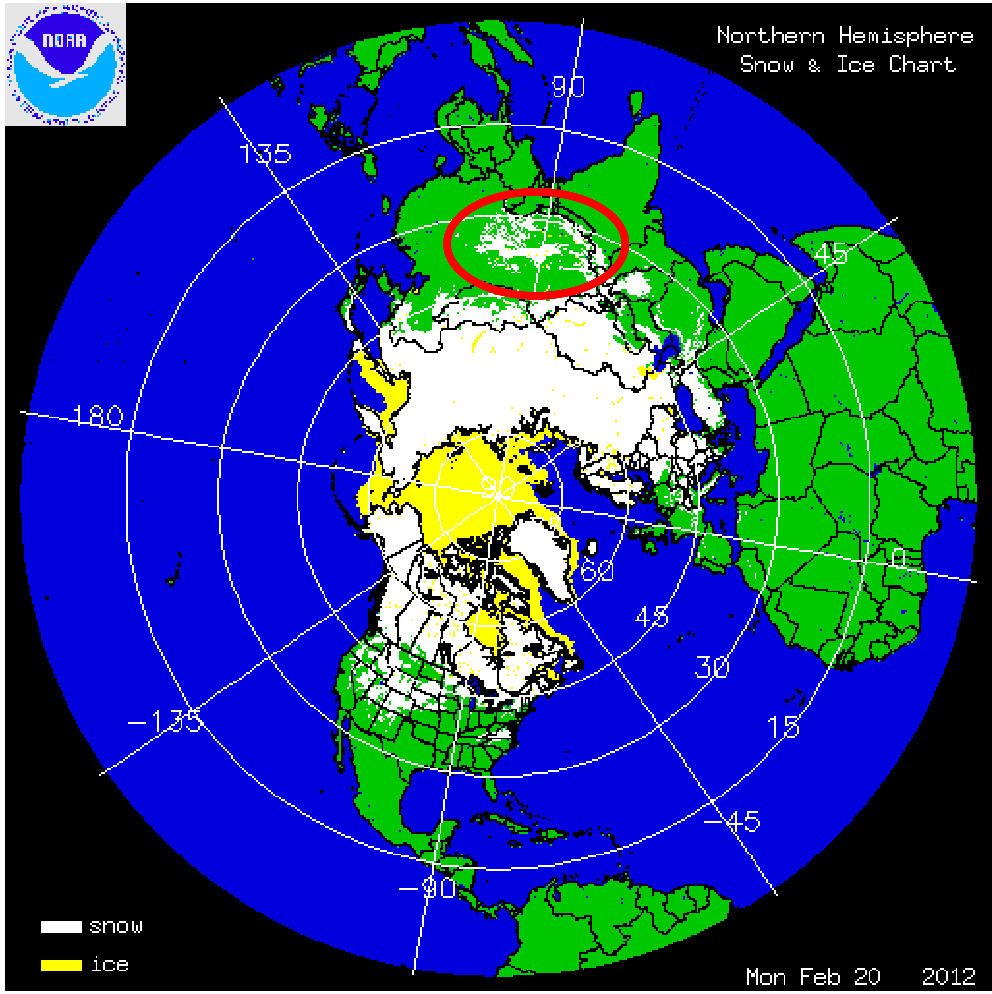
Impact of Tibetan Plateau snow cover assimilation on NWP

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

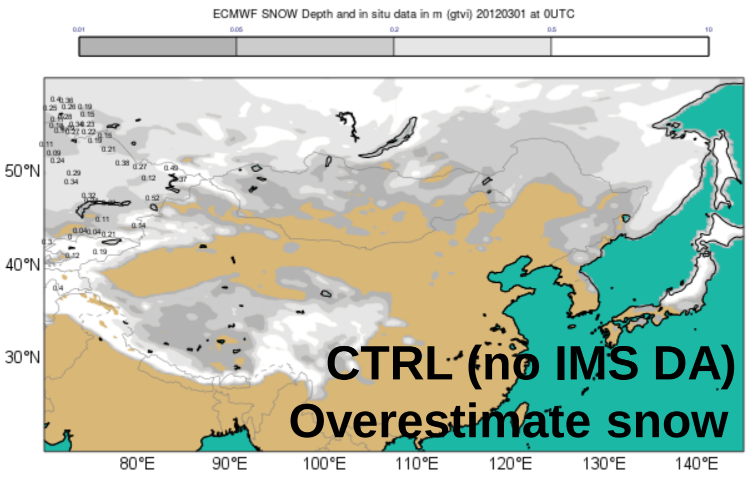
- NWP experiments, Sept 2011 – Dec 2012
- Two 10-day FC per day (488 days, 976 forecasts)
- Resolution: Tco399 (~25 km)
- IFS cycle: 43r3

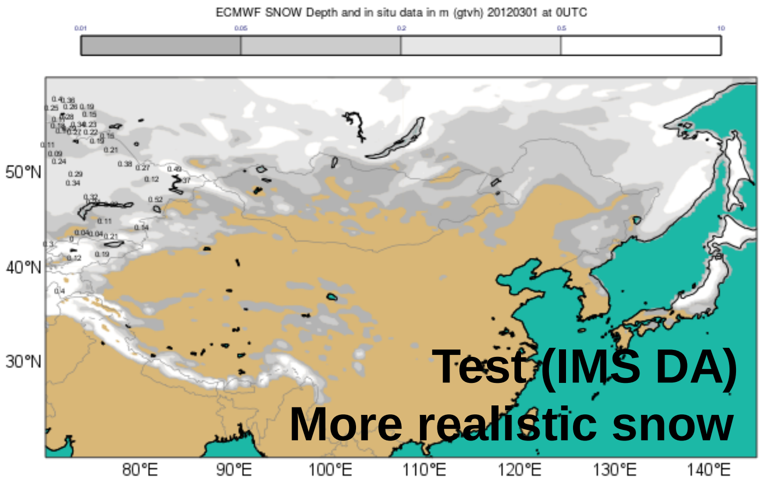
CTRL : QC rejects IMS above1500m altitude, as for operational NWP and ERA5

IMSDA : use IMS everywhere

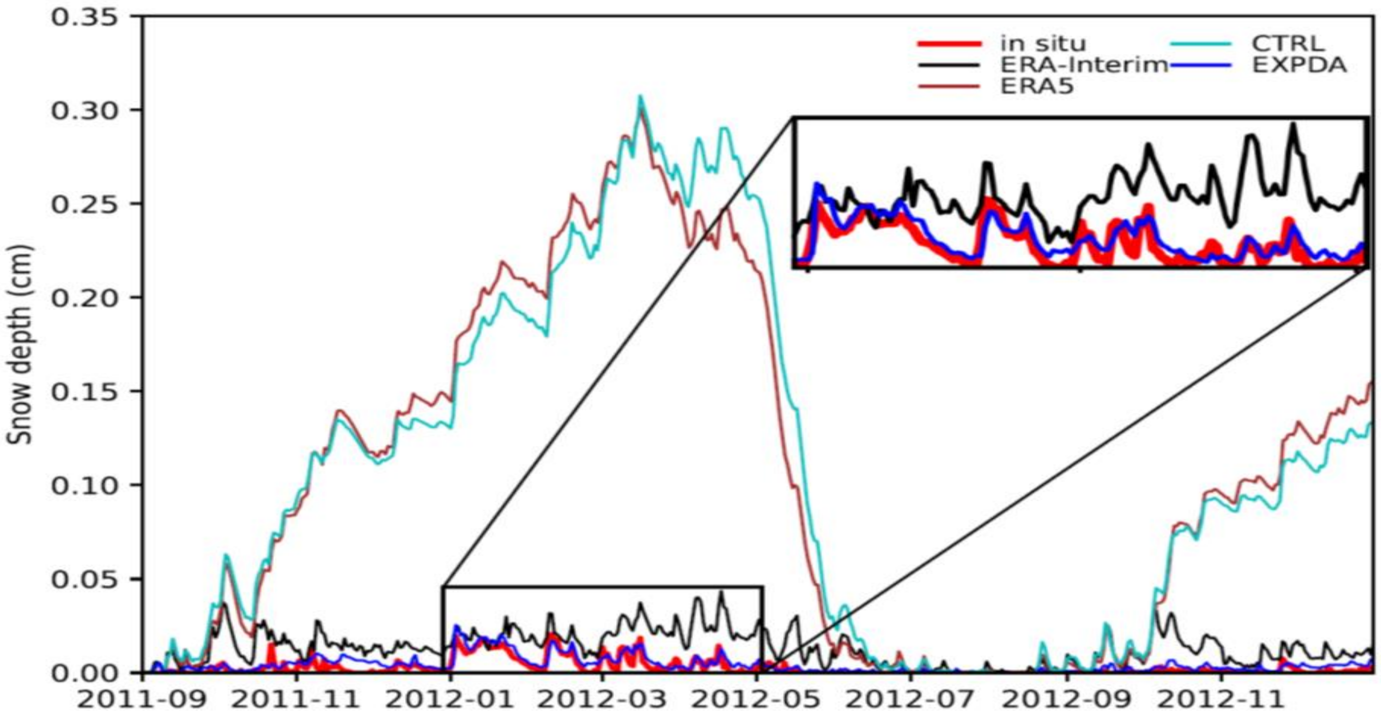


Snow cover coupled data assimilation impact over the Tibetan Plateau





Snow cover DA removes snow and improves snow depth

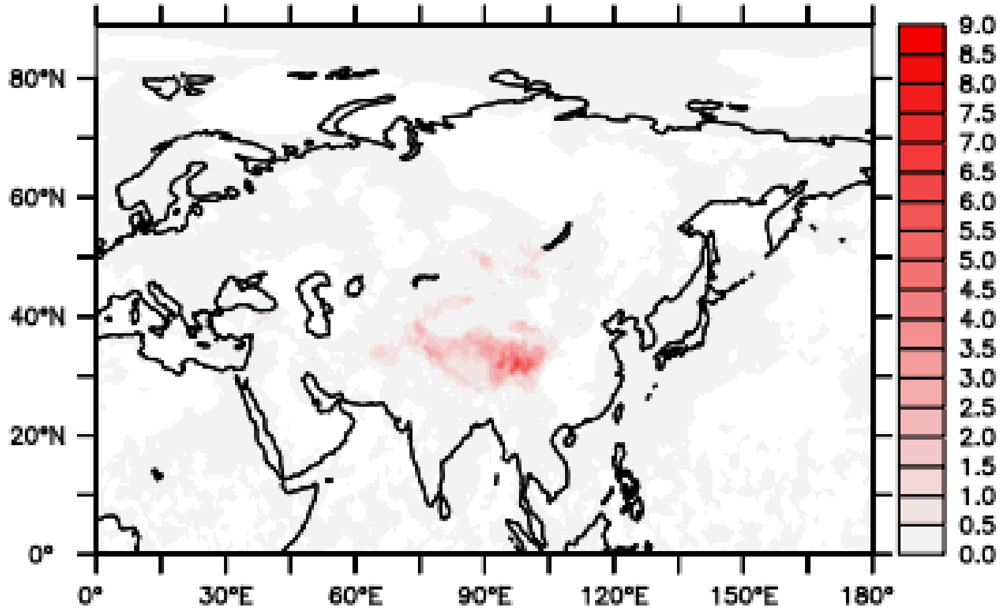


Impact of snow cover assimilation on two-meter temperature

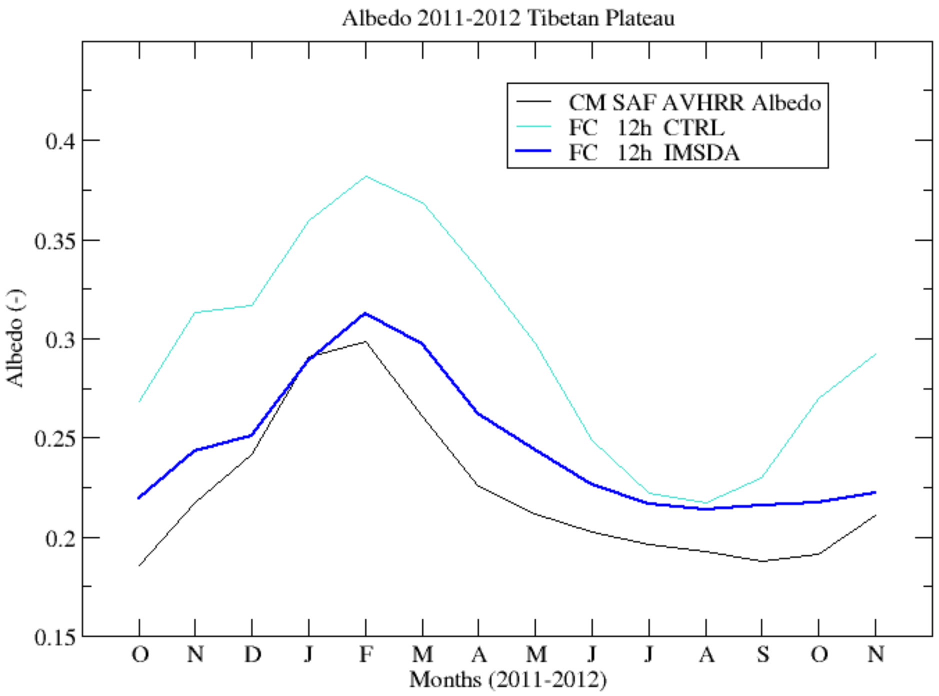
Surface albedo verification

IMS assimilation removes snow
→ Warmer surface conditions than CTRL

IMS assimilation removes snow
→ Lower surface albedo

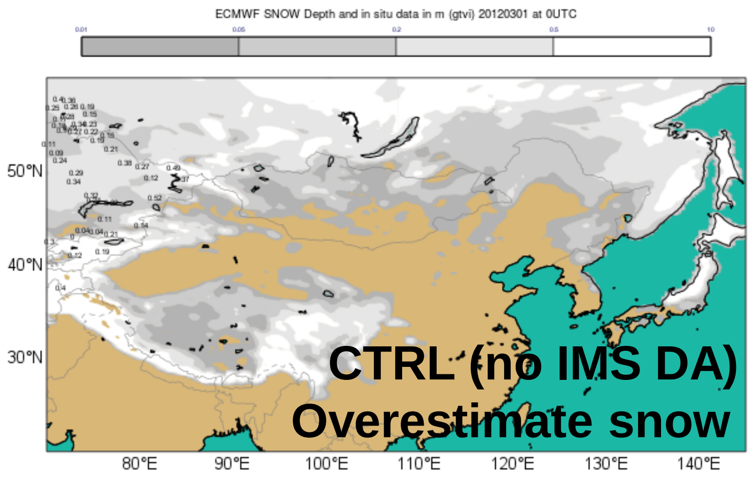


T2m diff (IMSDA-CTRL) (K)
Forecast day-10
Oct 2011-Sept 2012

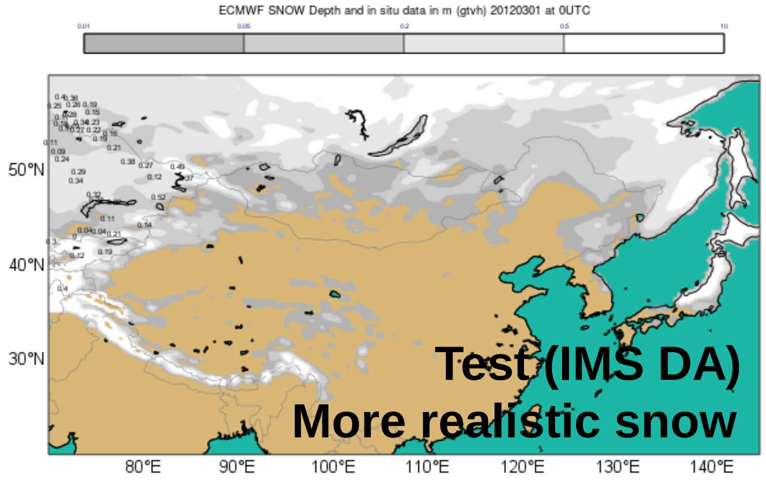


Use Climate Monitoring SAF CLARA-2 albedo product (Karlson et al. 2017)

Snow cover coupled data assimilation impact over the Tibetan Plateau



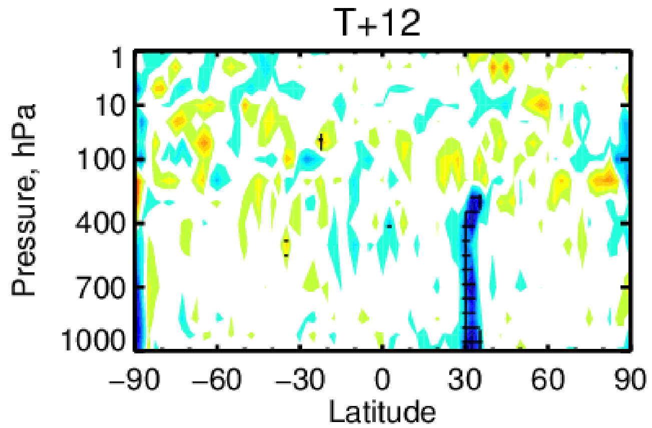
CTRL (no IMS DA)
Overestimate snow

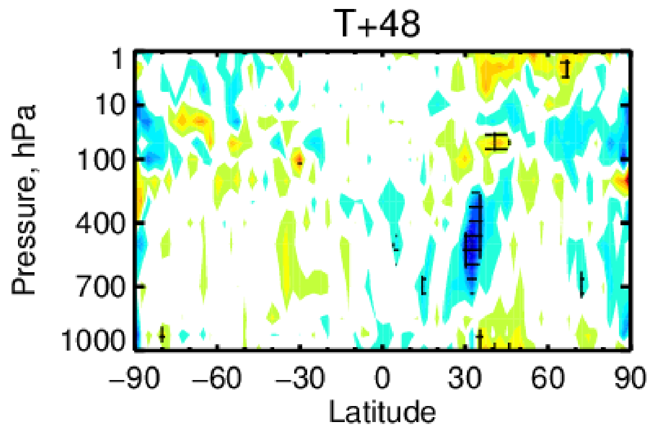


Test (IMS DA)
More realistic snow

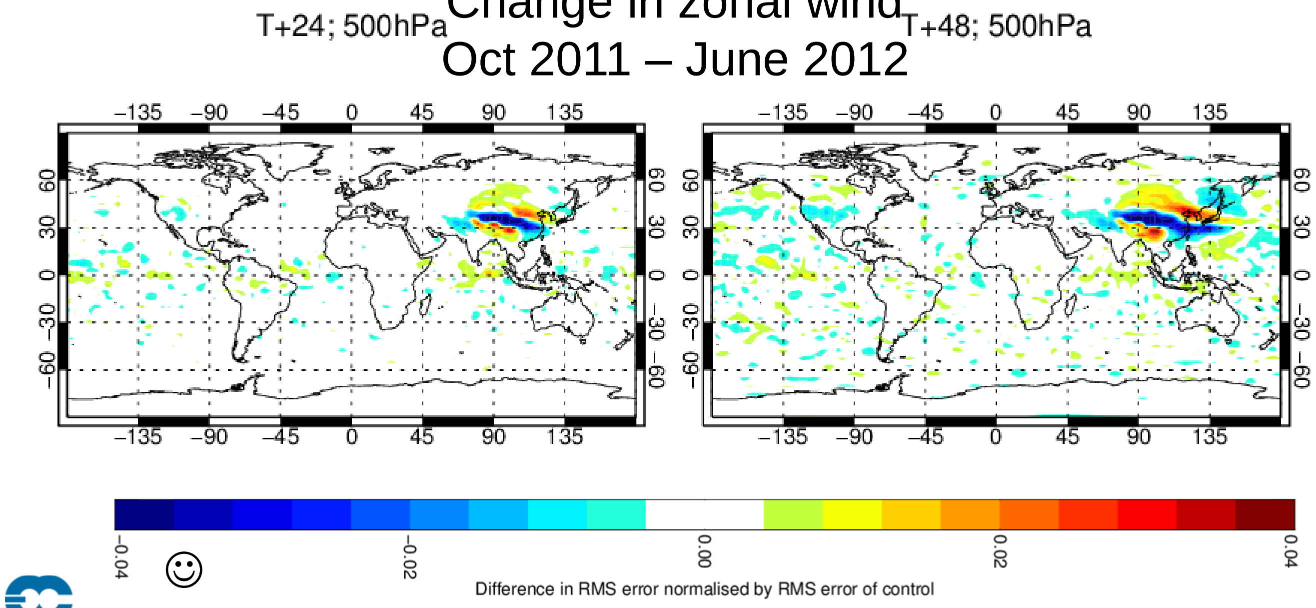
Impact on albedo and momentum
→ Modifies the jet circulation

Change in humidity FC error
Oct 2011 – June 2012





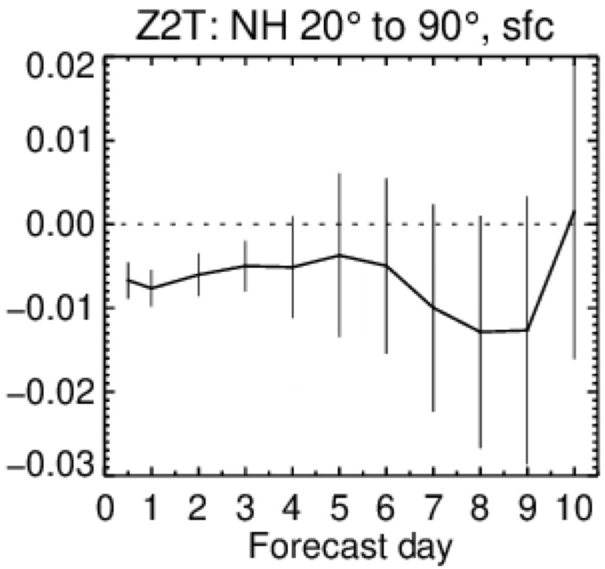
Change in zonal wind
Oct 2011 – June 2012



☺

Recent updates and plans for future implementation

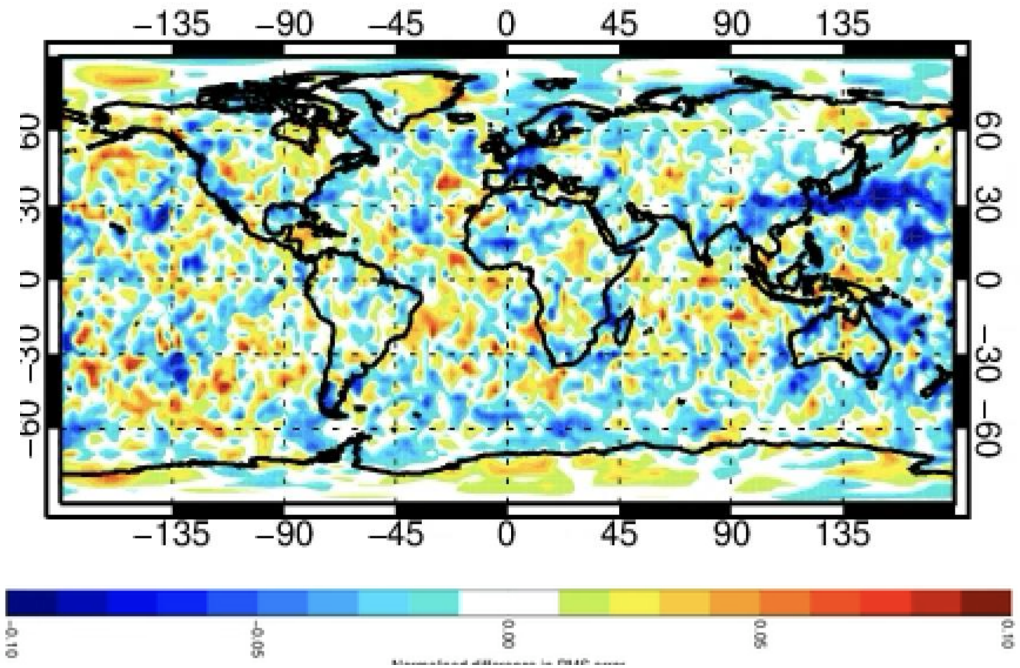
Future improvements (e.g. multi-layer snow model) lead to enhanced consistency between snow and boundary layer processes.
→ Impact of IMS snow cover assimilation in mountainous areas using improved system give promising results



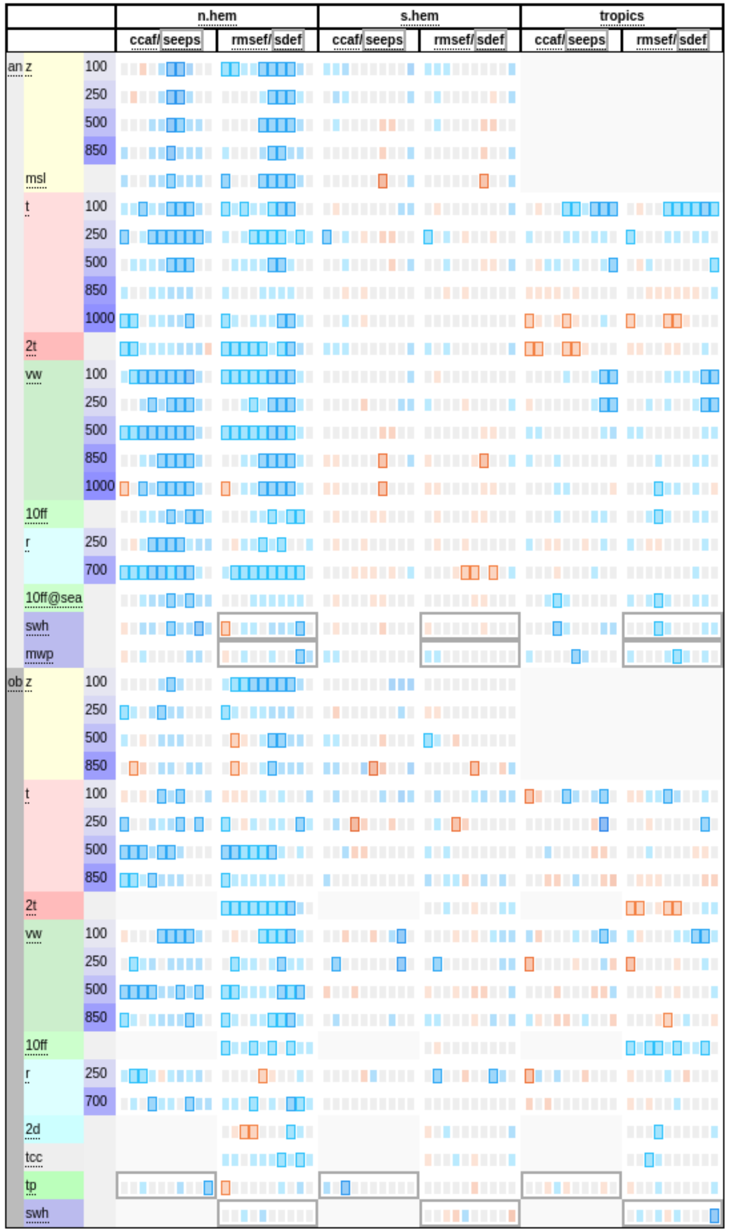
Surface air temperature improvement

T+72; 500hPa

Vector wind error reduction



Scorecard →
(blue= improved
red=degraded)



Kenta Ochi et al.

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

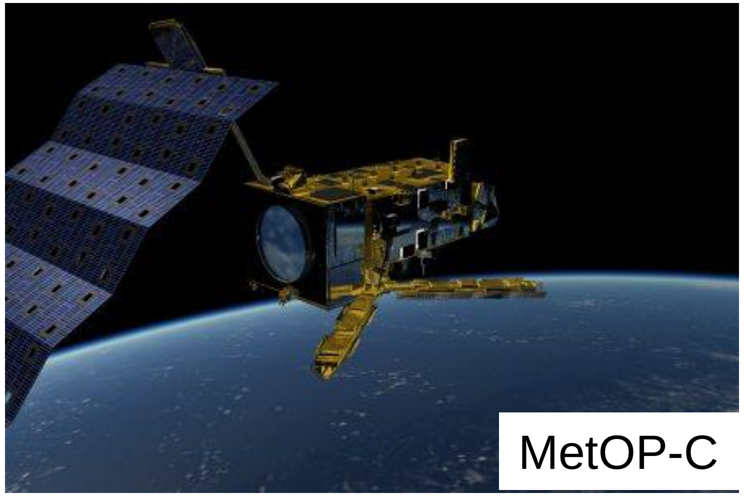
Active microwave data:

ASCAT: Advanced Scatterometer

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

C-band (5.6GHz) backscattering coefficient

EUMETSAT Operational mission



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

Passive microwave data:

SMOS: Soil Moisture & Ocean Salinity (2009-)

L-band (1.4 GHz) Brightness Temperature

ESA Earth Explorer, dedicated soil moisture mission

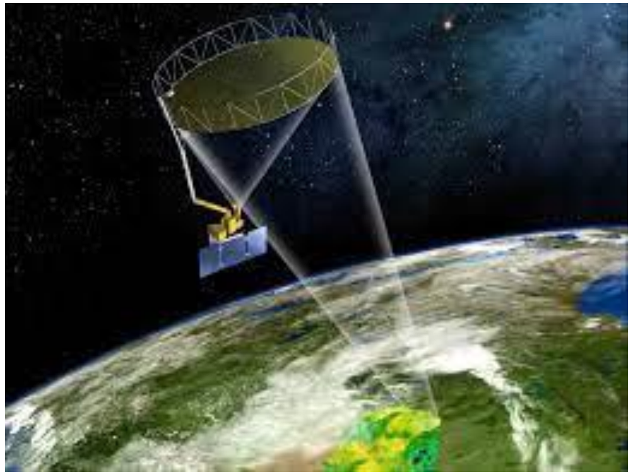
(Munoz-Sabater et al., GRSL, 2012)

SMAP

L-band TB 2015-

NASA Dedicated

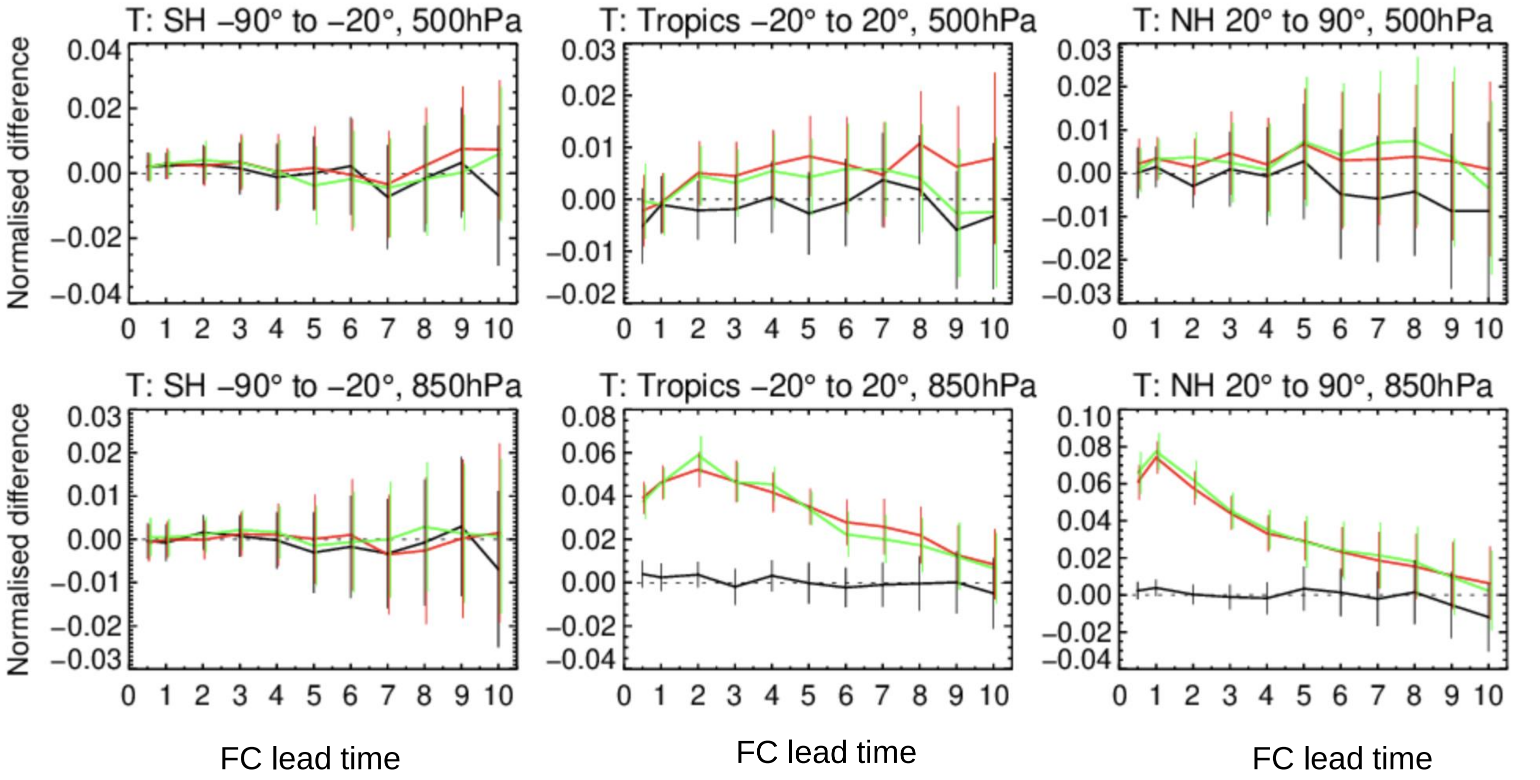
soil moisture mission



Soil analysis for NWP: impact on the atmospheric forecast

Temperature RMSE

JJA 2020
IFS cycle 48r1



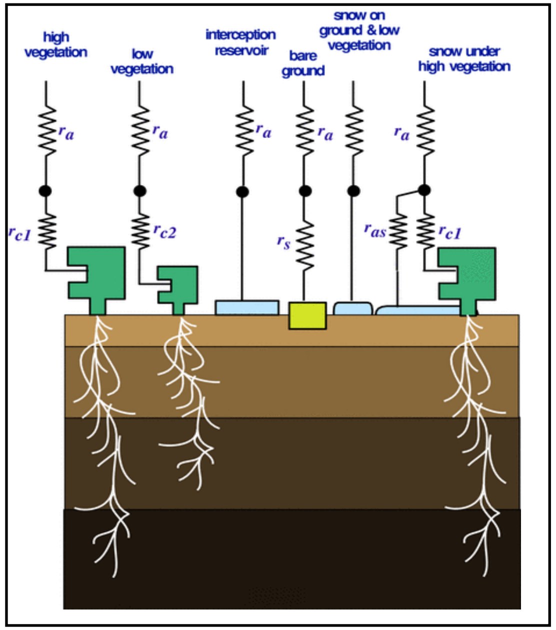
Soil. Moisture DA:
Without without

With

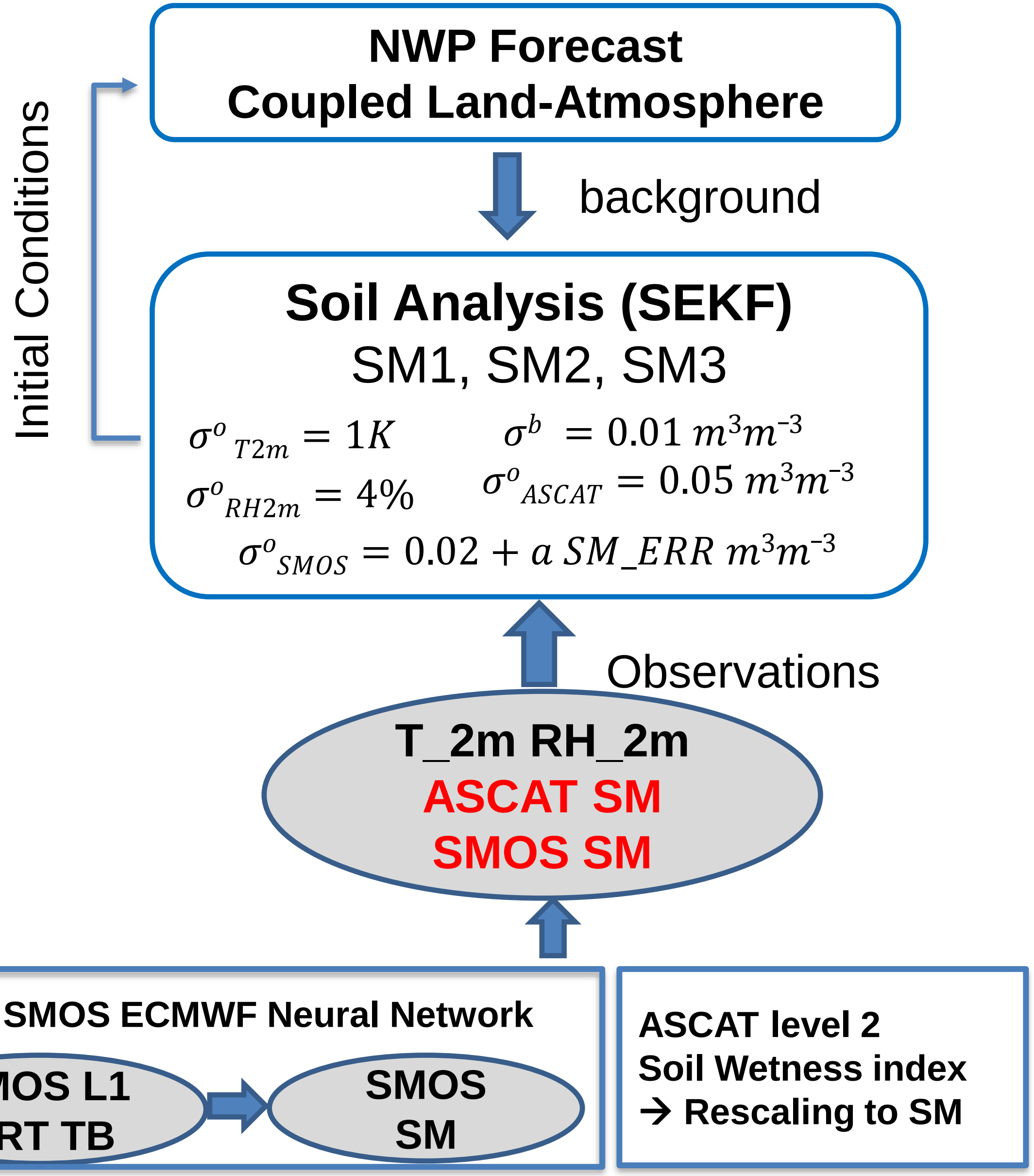
Sébastien Garrigues

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



From satellite to root zone soil moisture

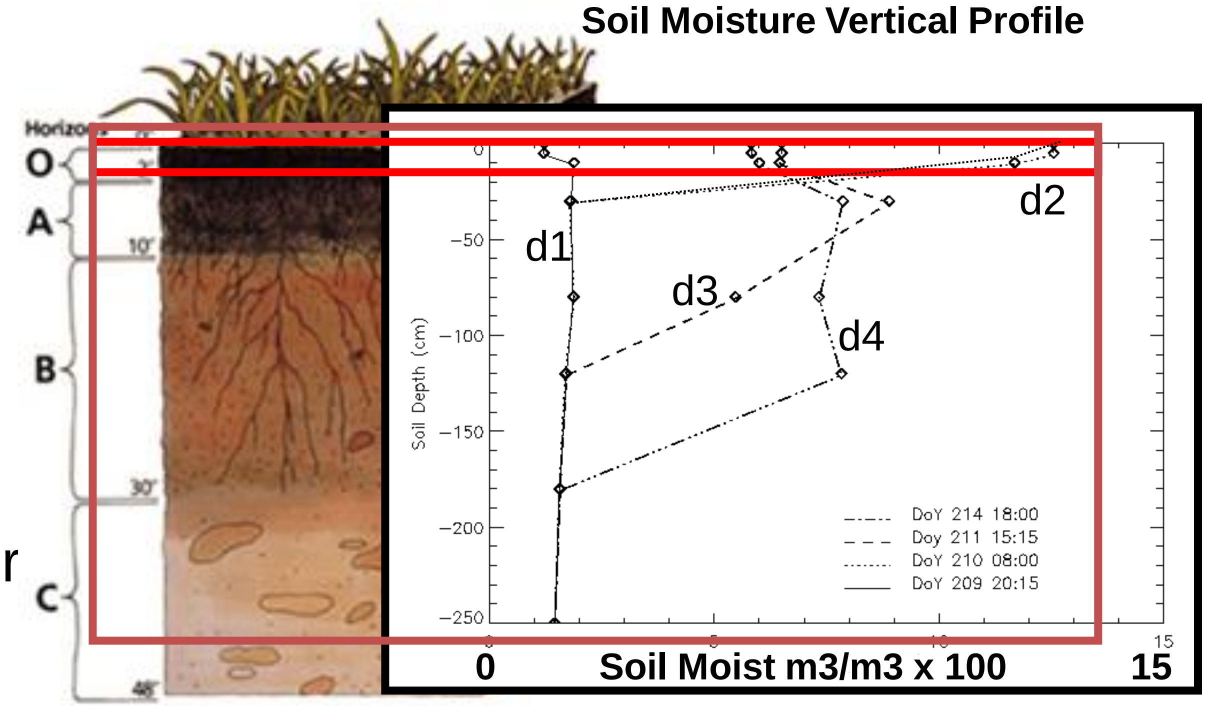
Satellite data → Surface information

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

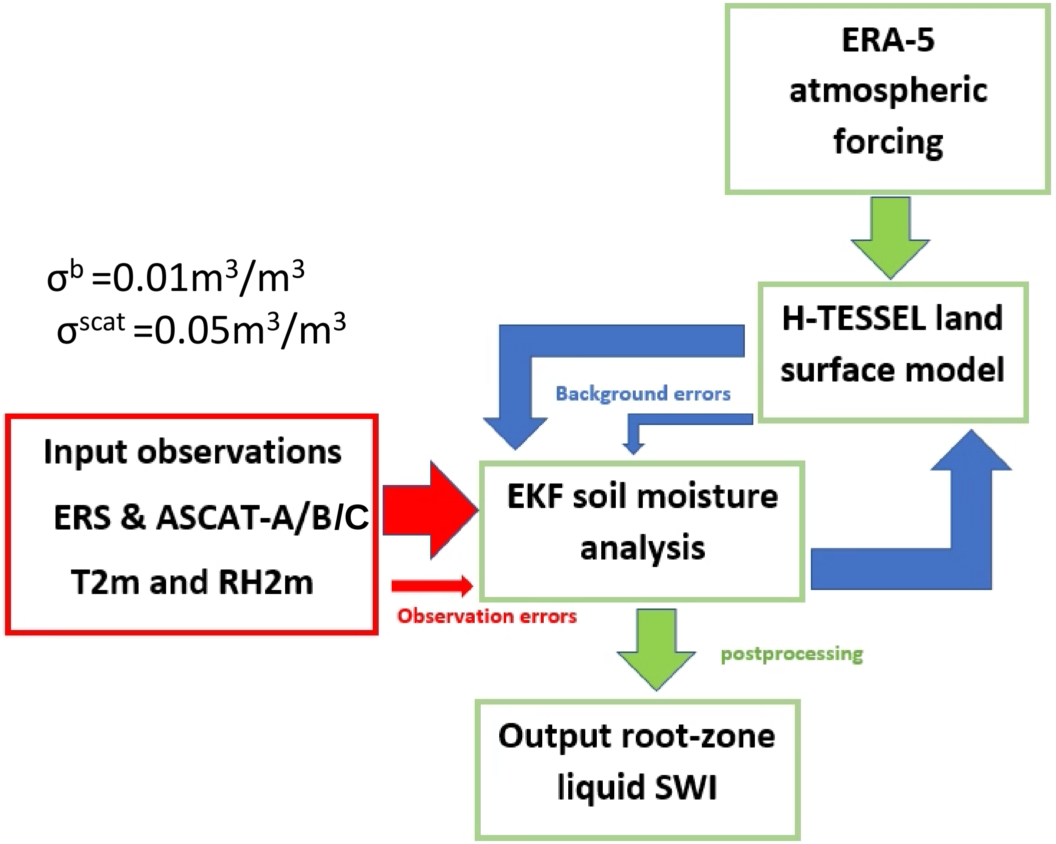


→ Retrieval of root zone soil moisture using satellite data relies on data assimilation

H SAF scatterometer root zone soil wetness products

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

$\sigma^b = 0.01 m^3/m^3$
$\sigma^{scat} = 0.05 m^3/m^3$

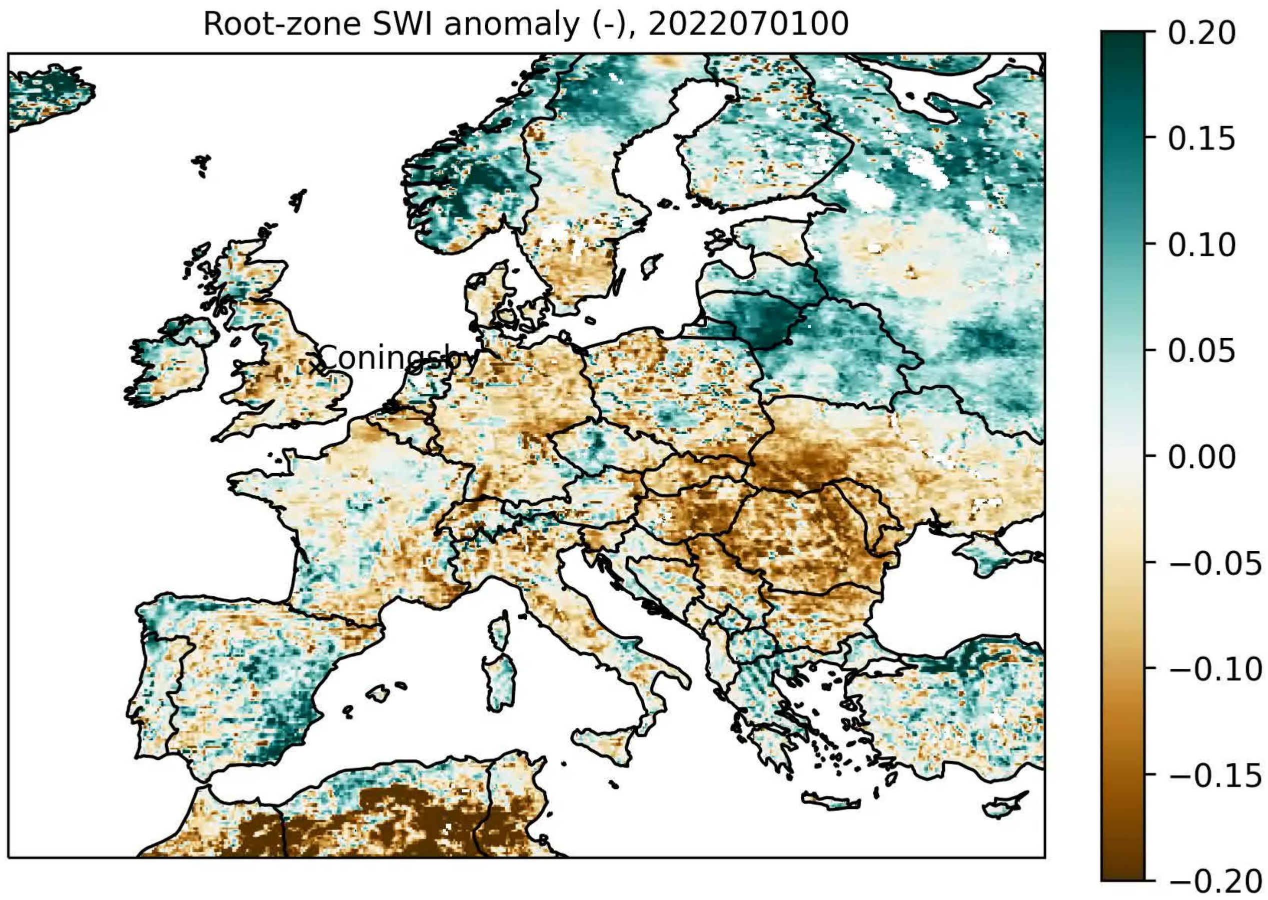


H SAF Root zone soil moisture suite

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

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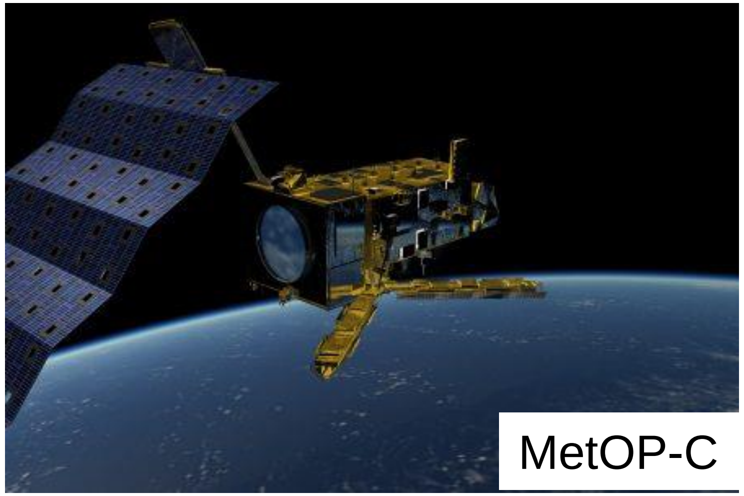

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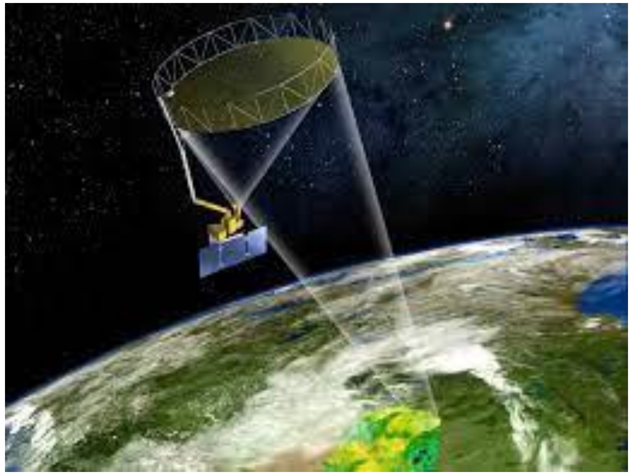
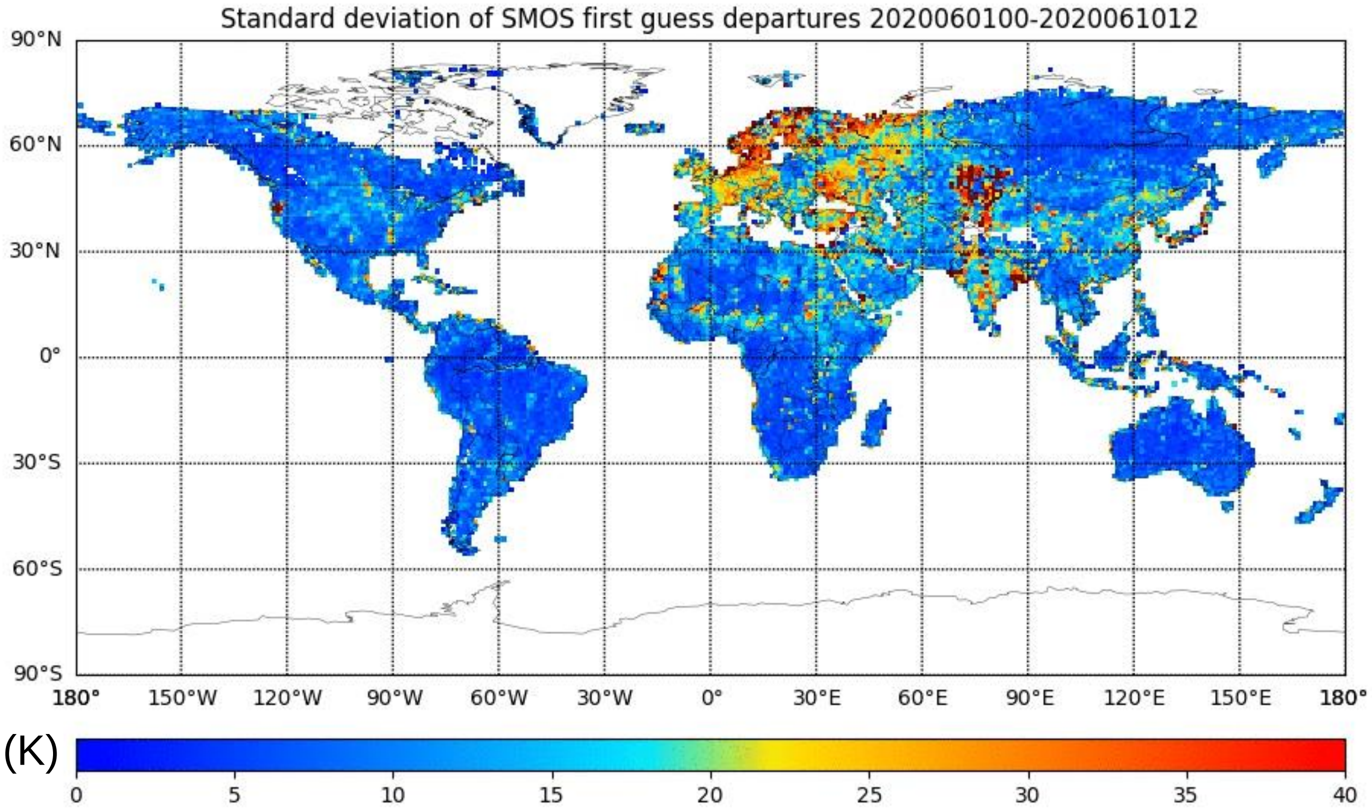


SMOS near real time brightness temperature monitoring

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

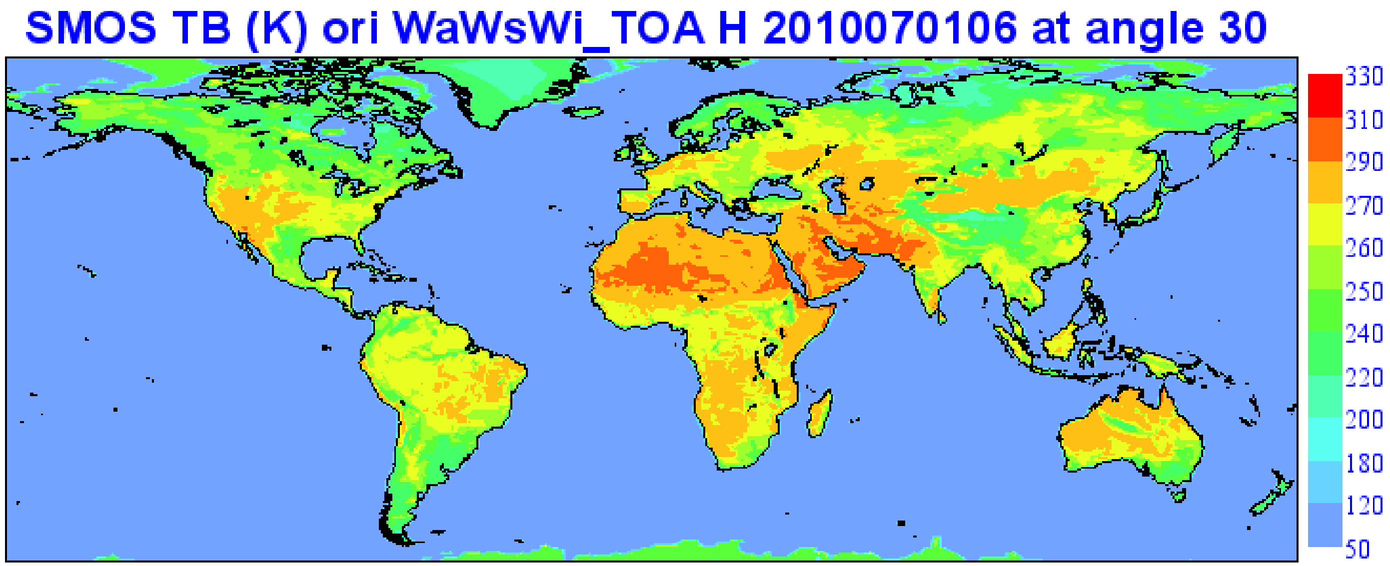


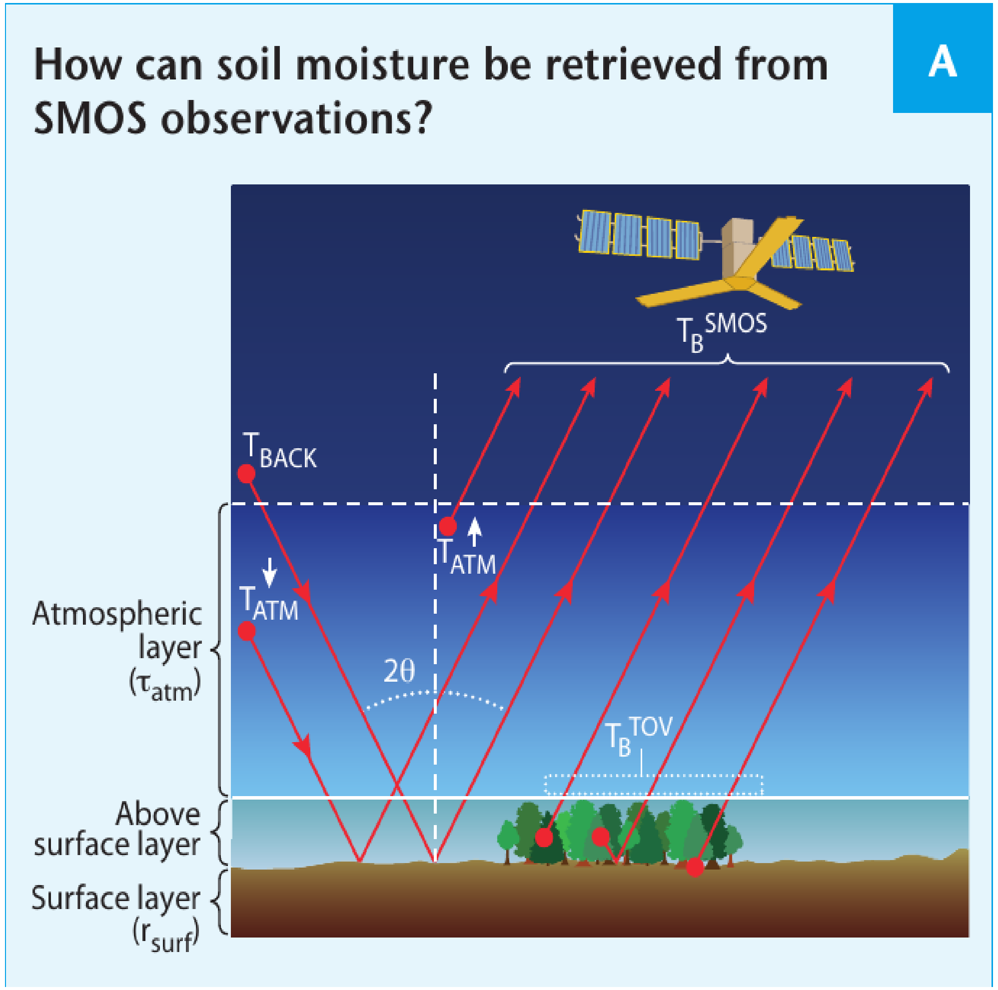
More on SMOS monitoring in Weston et al., RS 2021

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





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

SMOS Bias correction (BC)

- Data assimilation aims at correcting for the model random errors
- Bias correction method is necessary to match the observations and model climatologies
- Cumulative Distribution Function (CDF) matching → matches mean and variance of two distributions.

Matching parameters (a,b) at each grid point for each month:

$$TB_{SMOS\_bc} = a + b\, TB_{SMOS\_obs}$$

$$\text{with} \quad a = \overline{TB}_{ECMWF} - \overline{TB}_{SMOS\_obs} \left(\sigma_{ECMWF} / \sigma_{SMOS\_obs}\right)$$

$$b = \sigma_{ECMWF} / \sigma_{SMOS\_obs}$$

- Based on ECMWF reanalysis CMEM forward TB
- Data sets: 2010-2013, at 3 incidence angles 30°, 40°, 50°
- Computed at 40km resolution (SMOS resolution)
- Monthly CDF: 3-month moving window, similar to Draper et al., 2009
- Multi-angular (3 incidence angles 30°, 40°, 50°) and dual polarisation

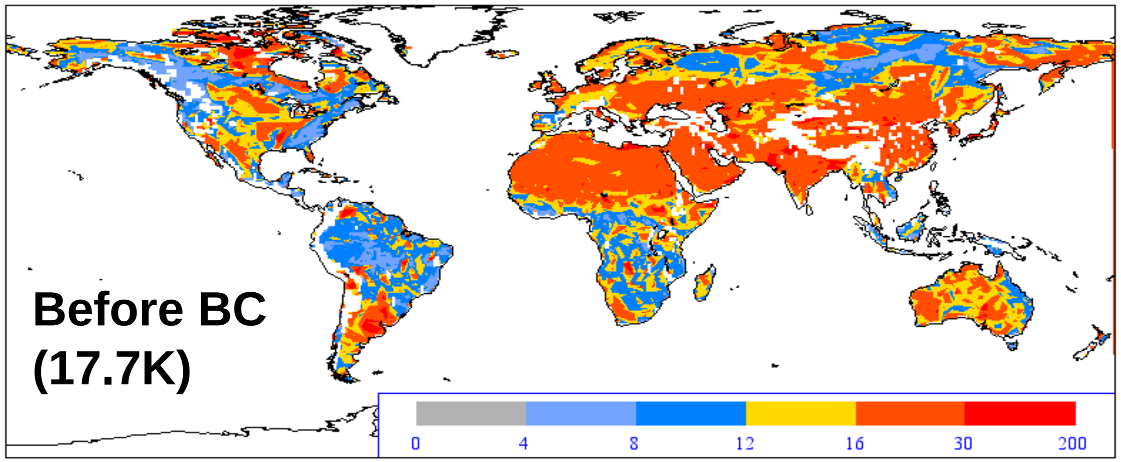
de Rosnay et al, RSE 2020

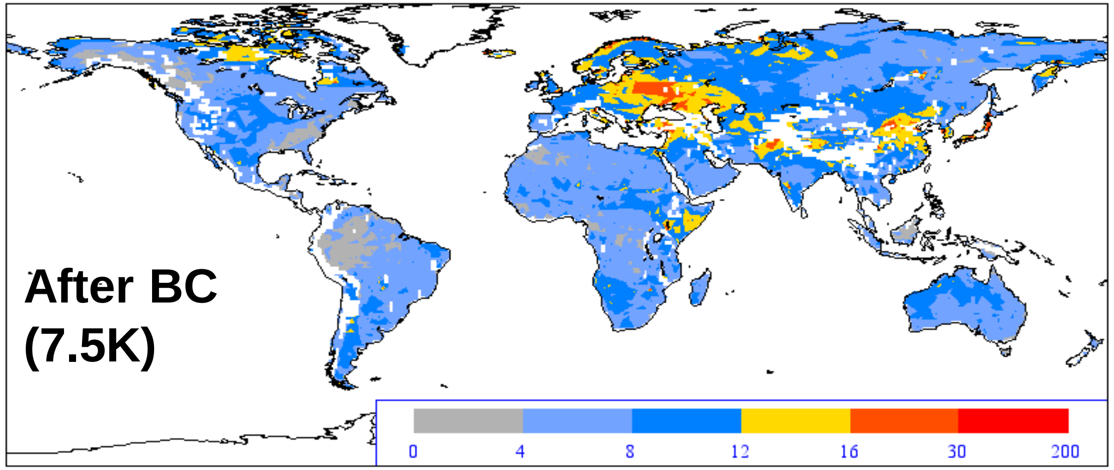
ECMWF L-band TB Bias correction

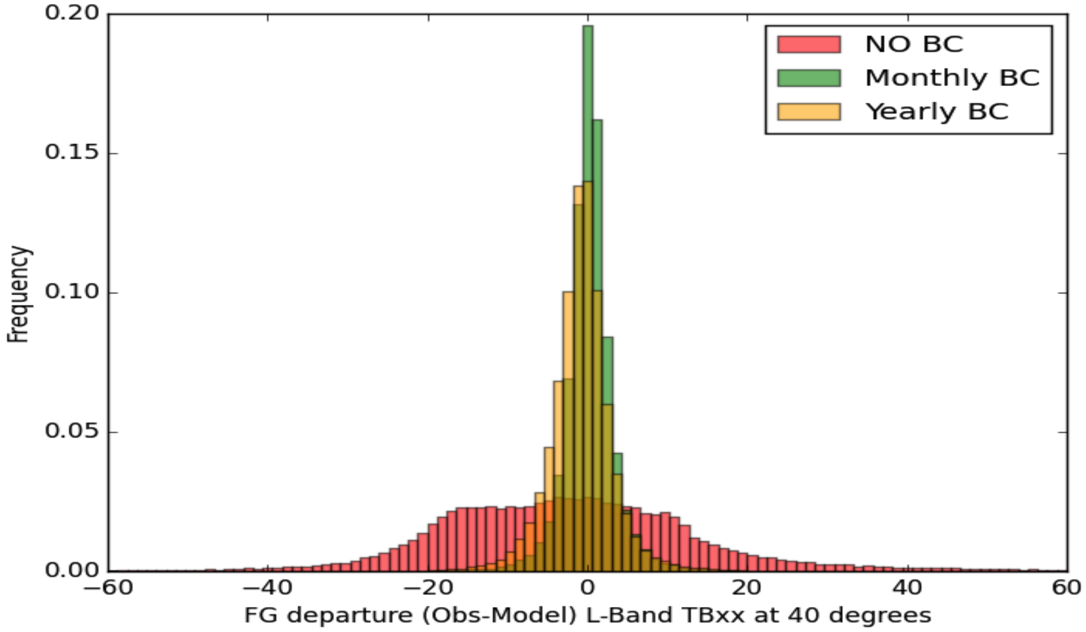
RMSD between SMOS Obs and ECMWF TBxx, 40 degrees

2012

RMSD (K)

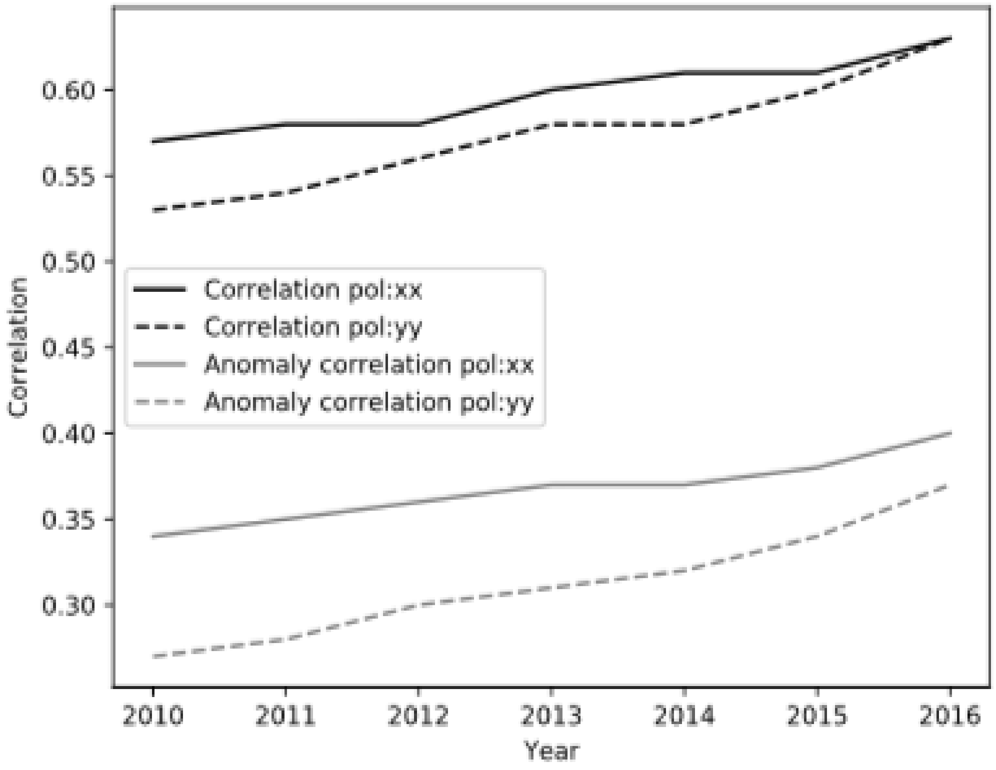




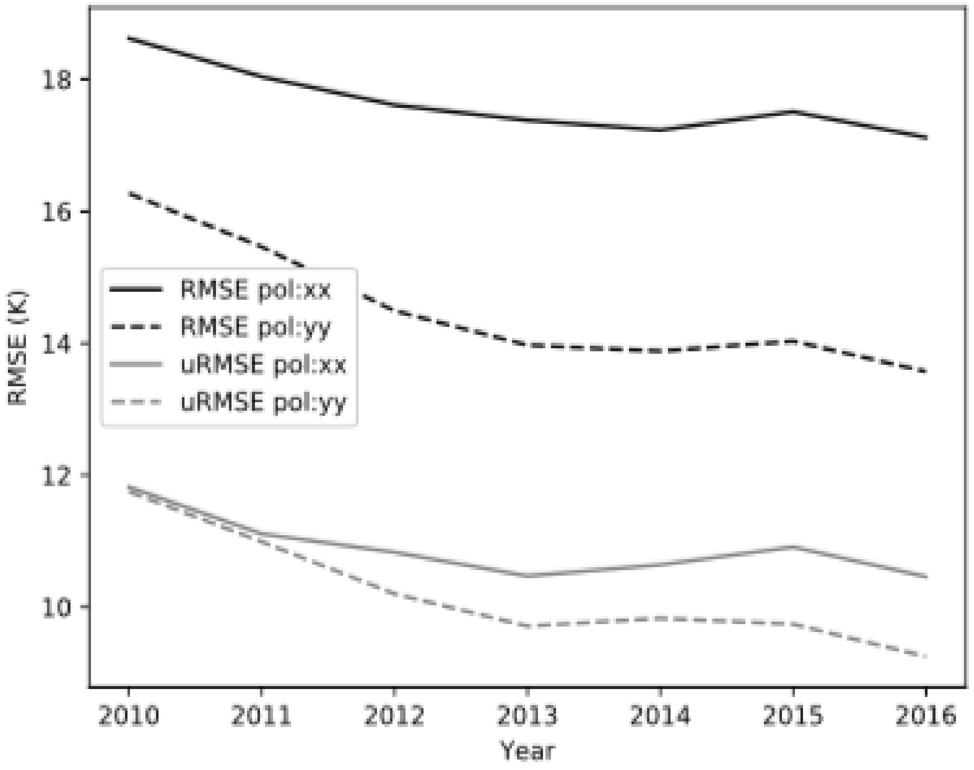


Low residual RMSD, except in areas affected by RFI (Radio Frequency Interferences)

Comparison between SMOS and ECMWF forward TB for 2010-2016



(a) Correlation

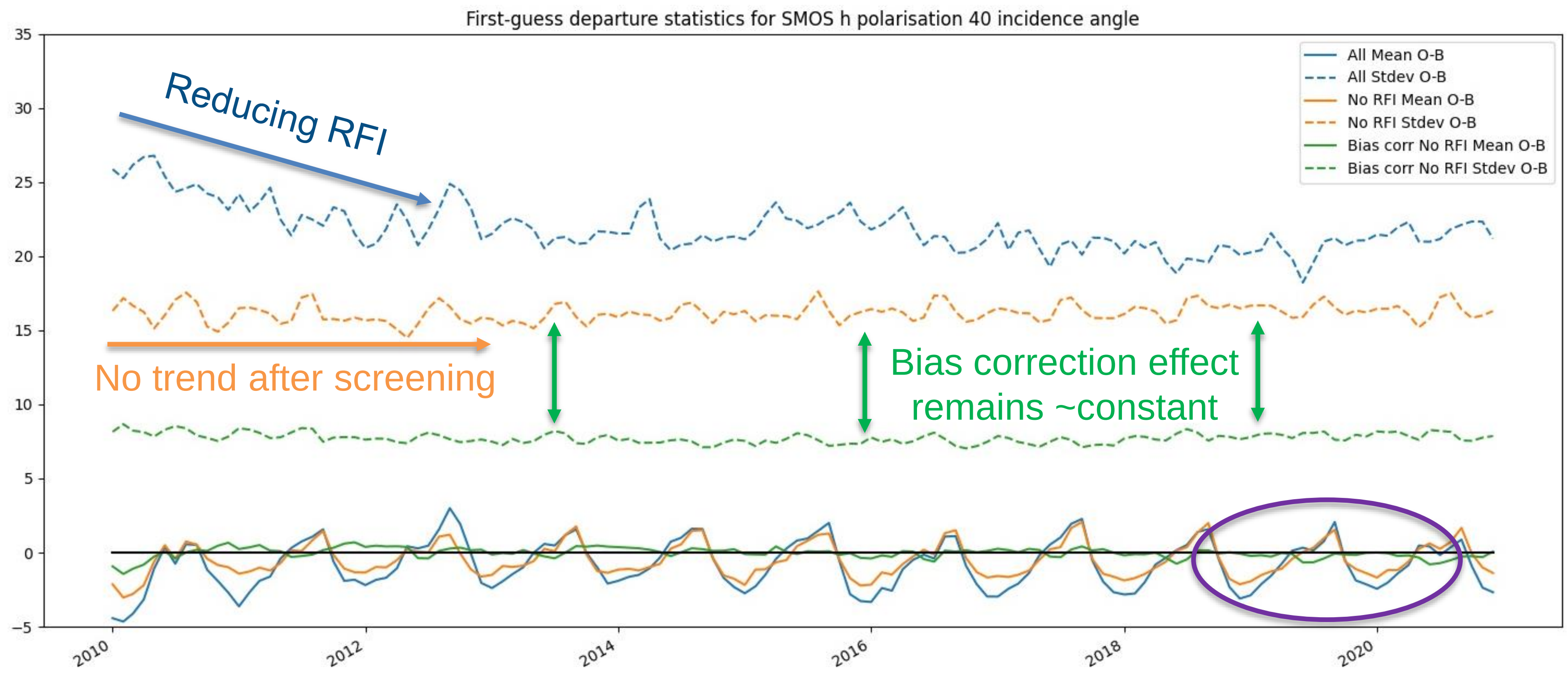


(b) Root mean square error

Consistent improvement of agreement between SMOS and ECMWF reanalysis at both polarisations, from 2010 to 2016

SMOS multi-year monitoring

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



Seasonal biases successfully removed

- 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

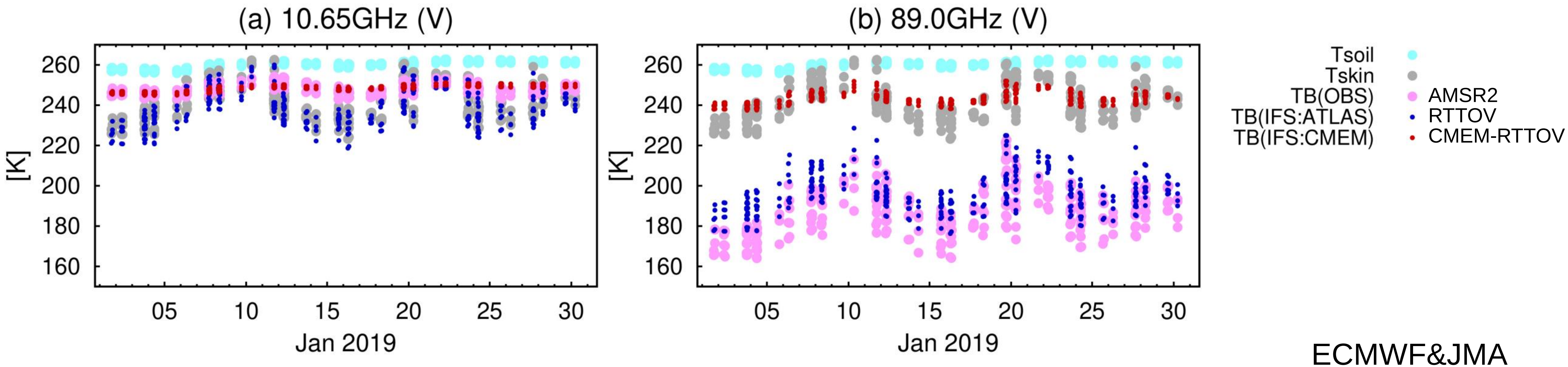
Pete Weston

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

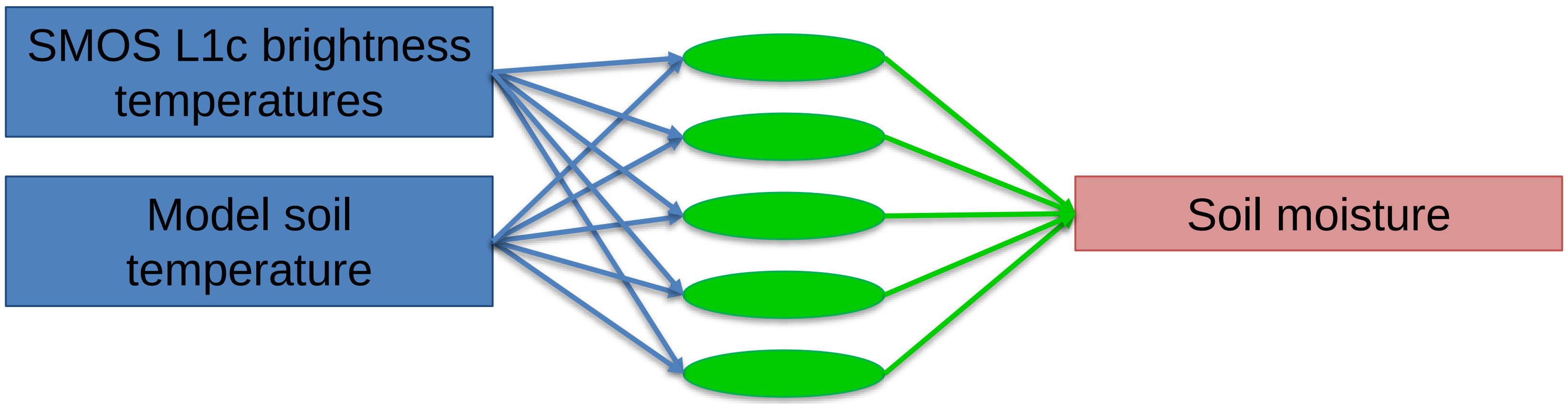
- Implementation of multi-layer snow radiative transfer scheme in CMEM



ECMWF&JMA

Hirahara et al., RS, 2020

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

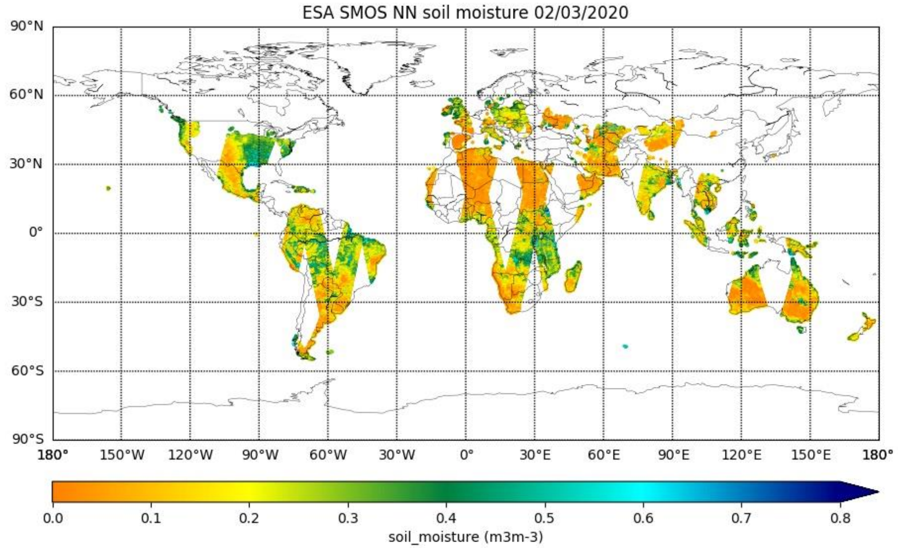


Designed by CESBIO/Estellus, Implemented by ECMWF

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

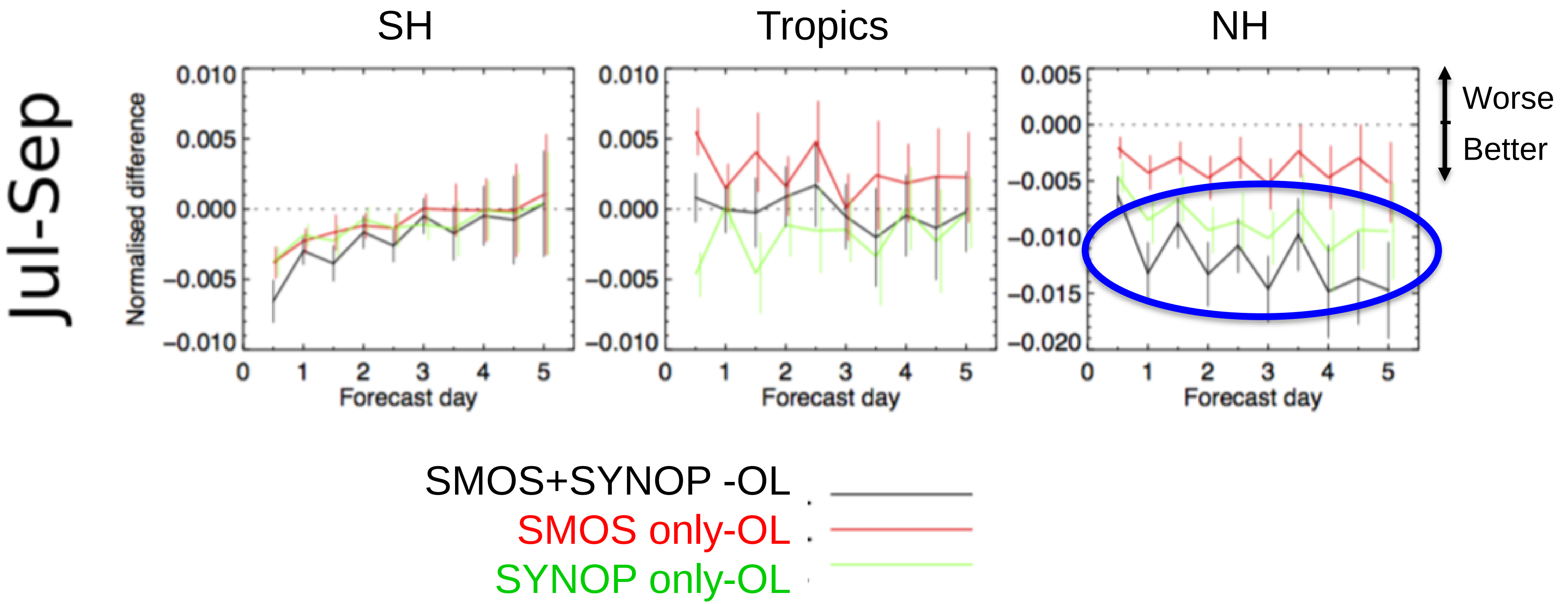
https://smos-ds-02.eo.esa.int/oads/access



ECMWF esa CESBIO

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)

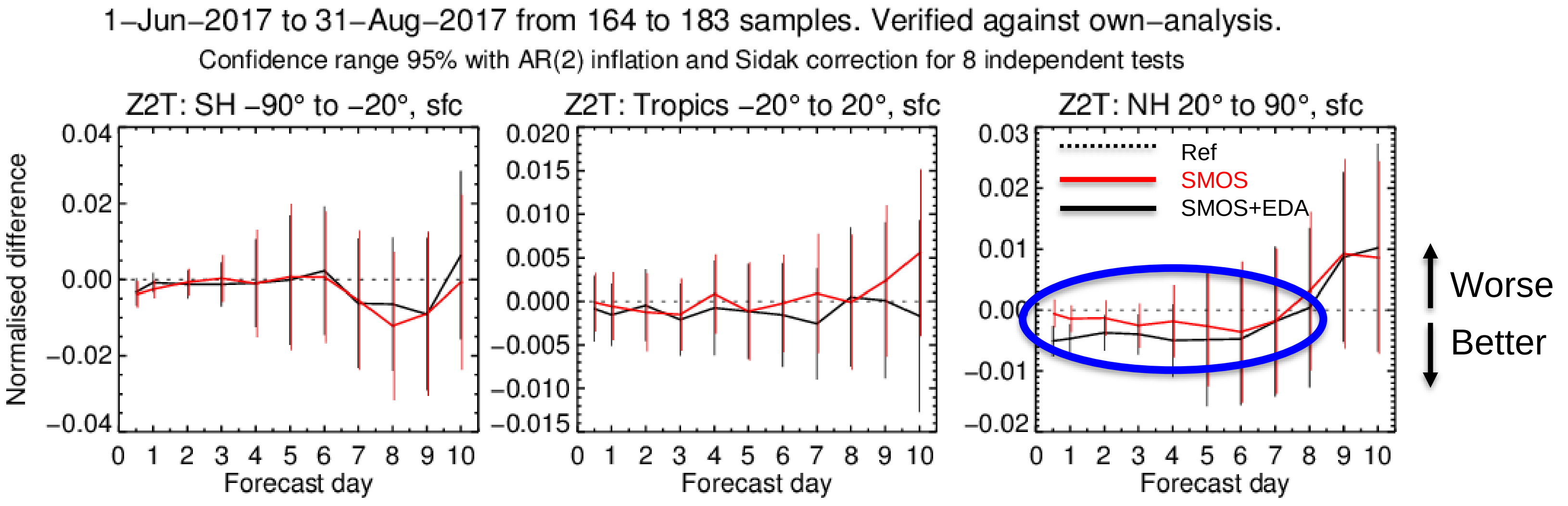


→ Proof of concept of offline SMOS NN assimilation for NWP initialisation

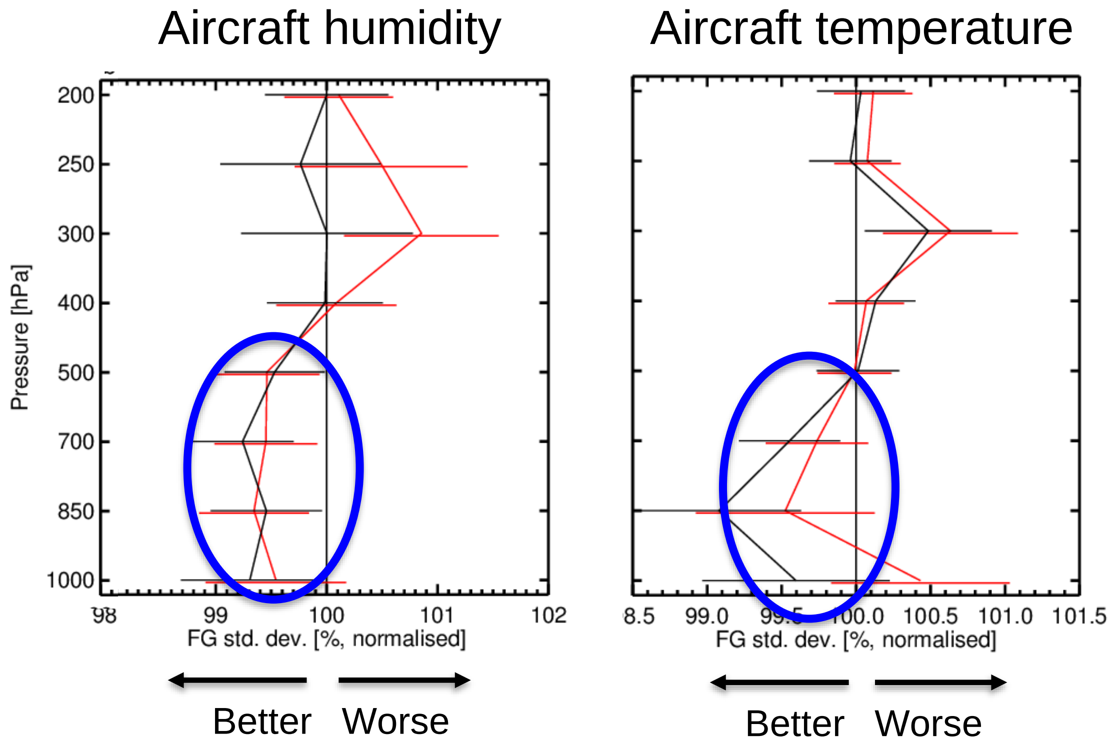
Rodriguez-Fernandez et al, Remote sensing, 2019

ECMWF

SMOS neural network assimilation operational in the IFS



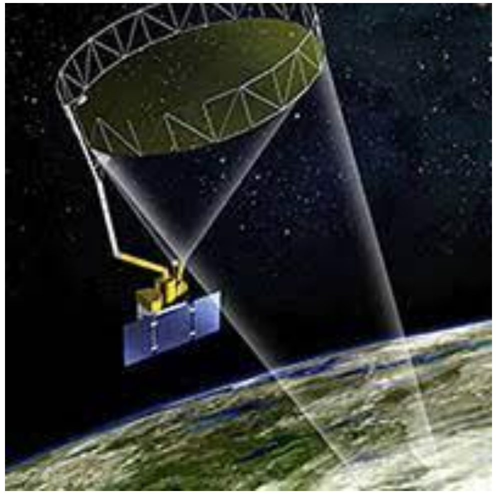
- Results from assimilating soil moisture from SMOS in coupled land-atmosphere forecasting system:
  - Neutral/slightly positive impact on T2m in the Northern hemisphere
  - Improved first-guess fits to aircraft humidity and temperature in lower troposphere

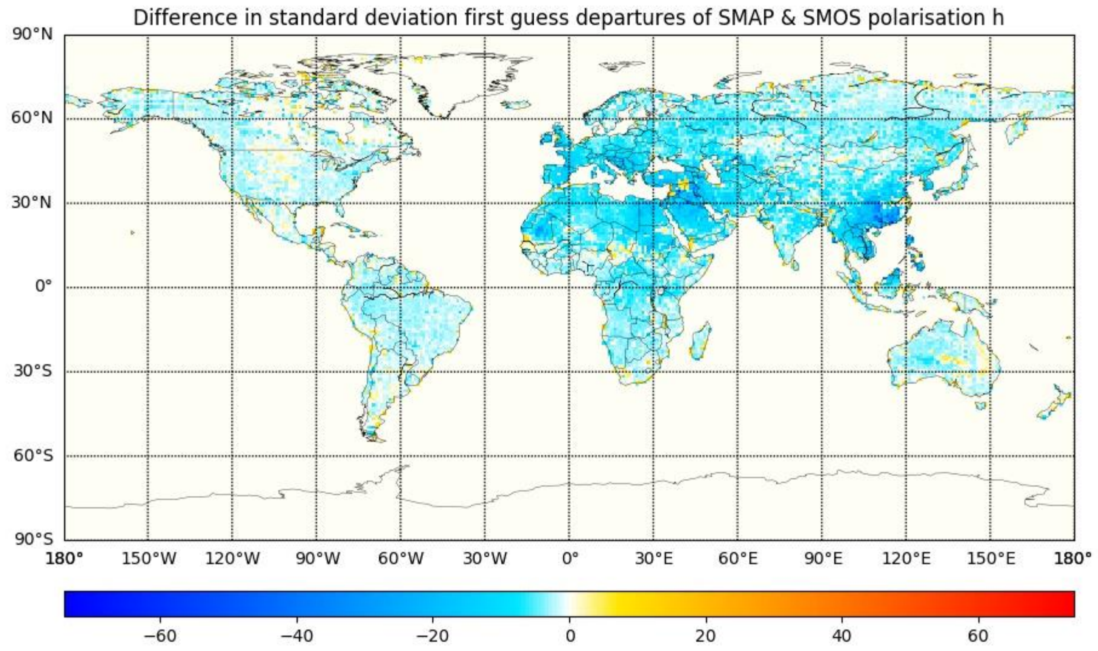


SMAP monitoring

- 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

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 (Hersbach et al 2020)
- 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
- Ongoing developments: multi-layer soil moisture and snow forward modelling and assimilation
- Longer term: Assimilation of integrated hydrological variables such as river discharge
- Also not shown, importance of LAI and albedo conditions on energy partitioning (Calvet et al., 2019, Boussetta et al., 2013)

Bibliography

- Arduini et al. Impact of a Multi-Layer Snow Scheme on Near-Surface Weather Forecasts, JAMSE 2019
- Balsamo et al. A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System. JHM 2009
- Boussetta et al.: Impact of a satellite-derived leaf area index monthly climatology in a global numerical weather prediction model. Int. J. of Rem. Sens., Vol. 34, 2013
- Calvet et al: "Satellite data assimilation: application to the water and carbon cycle",Book Chapter in Baghdadi N. et Zribi M. (eds), Land Surface Remote Sensing in Continental Hydrology, Volume 4, ISTE Press, London and Elsevier, Oxford, ISBN :9781785481048, 2016
- de Rosnay et al.: "SMOS brightness temperature forward modelling and long term monitoring at ECMWF", Remote Sensing of Environment, 237 2020
- de Rosnay et al: Snow data assimilation at ECMWF, ECMWF Newsletter no 143, article pp 26-31, Spring 2015
- de Rosnay et al: Initialisation of land surface variables for Numerical Weather Prediction, Surveys in Geophysics, 35(3), pp 607-621, 2014
- de Rosnay et al: A simplified Extended Kalman Filter for the global operational soil moisture analysis at ECMWF, Q. J. R. Meteorol. Soc., 139:1199-1213, 2013
- Draper et al.: “An EKF assimilation of AMSR-E soil moisture into the ISBA land surface scheme” J.Geophys Res. VOL. 114, D20104, 2009
- Dutra, E., et al:An improved snow scheme for the ECMWF land surface model: description and offline validation, J. Hydrometeorol., 11, 899–916, 2010.
- Entekhabi, D., et al.: The Soil Moisture Active Passive (SMAP) Mission. Proceedings of the IEEE, 98(5):704–716, 2010
- Fairbairn et al "The new stand-alone surface analysis at ECMWF: Implications for land-atmosphere DA coupling", Journal of Hydrometeorology 20, 2023-2042, 2019
- Hersbach et al.: The ERA5 Global Reanalysis, QJRMS, , 146, 1999-2049,2020
- Hirahara, Y. et al "Evaluation of a Microwave Emissivity Module for Snow Covered Area with CMEM in the ECMWF Integrated Forecasting System", Remote Sensing, Special Issue "Remote Sensing of Land Surface and Earth System Modelling", 12(18), 2946, 2020.
- Karlsson, K.-G., and Coauthors, 2017: CLARA-A2: CM SAF cLoud, Albedo and surface RAdia-397tion dataset from AVHRR data - Edition 2, Satellite Application Facility on Climate Monitoring.
- Kerr, Y. et al.: Overview of SMOS performance in terms of global soil moisture monitoring after six years in operation. Remote sens. environ., 180:40–63, 2016
- Mecklenburg, S. et al.: ESA’s Soil Moisture and Ocean Salinity mission: From science to operational applications. Remote sens. environ., 180:3–18, 2016
- Muñoz Sabater et al.: "Assimilation of SMOS Brightness Temperatures in the ECMWF Integrated Forecasting System", 145, issue 723, pp. 2524-2548, QJRMS, 2019
- Muñoz Sabater J. et al: Use of SMOS data at ECMWF; ECMWF Newsletter no 127, spring 2011, pp23-27
- Orsolini et al: "Evaluation of snow depth and snow-cover over the Tibetan Plateau in global reanalyses using in-situ and satellite remote sensing observations", The Cryosphere, 2019
- Rodríguez-Fernández N., J. Muñoz Sabater, P. Richaume, P. de Rosnay, Y. Kerr, C. Albergel, M. Drusch, and S. Mecklenburg: SMOS near real time soil moisture product: processor overview and first validation results. Hydrol and Earth Sci Syst 2017
- Rodriguez-Fernandez et al.: "SMOS Neural Network Soil Moisture Data Assimilation in a Land Surface Model and Atmospheric Impact", Remote Sens., 11(11), 1334, 2019
- Weston, P. and P. de Rosnay: SMOS brightness temperature monitoring quality control review and enhancements, accepted, Remote Sens., 2021