ECMWF Data Assimilation Training course

Land Surface Data Assimilation – Part 2

Patricia de Rosnay

Outline

Part I (Monday 7 March)

- **Introduction**
- Snow analysis
- Screen level parameters analysis

Part II (Tuesday 8 March)

- **Soil moisture analysis**
- Summary and future plans

Soil Moisture – Atmosphere interactions

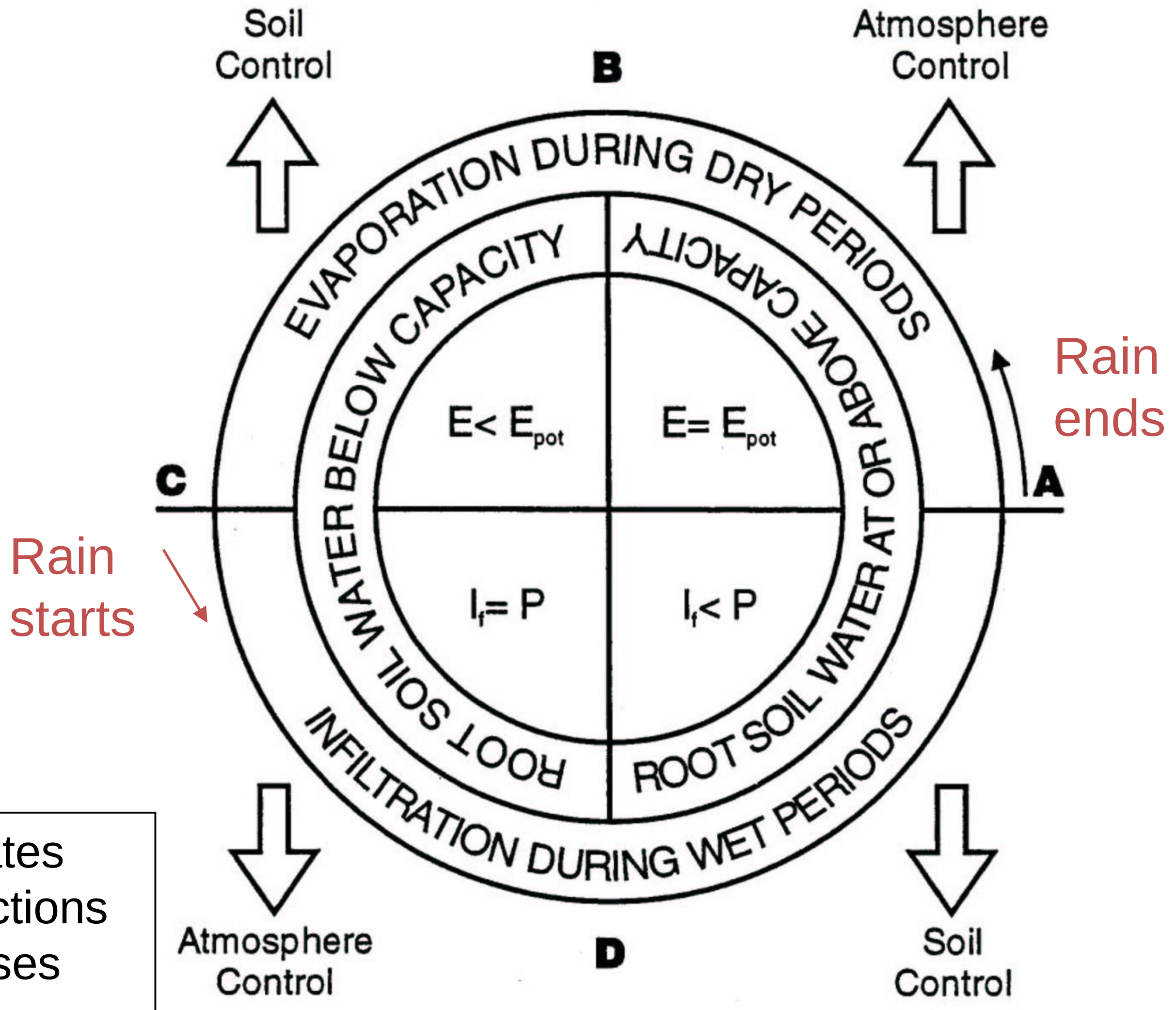
The hydrological 'Rosette' (P. Viterbo, PhD thesis, «The representation of surface processes in General Circulation Models » ECMWF, 1996)

A → B: After rain,
Evaporation at potential rate,
Atmospheric control.

B → C: Below field capacity soil moisture,
Limitation of root extraction,
Soil control.

C → D: Precipitation & relatively dry soils,
High infiltration rate I,
Atmospheric control.

D → A: Precipitation and soil near saturation,
Soil infiltration is reduced.
Excess goes in runoff,
Soil control.

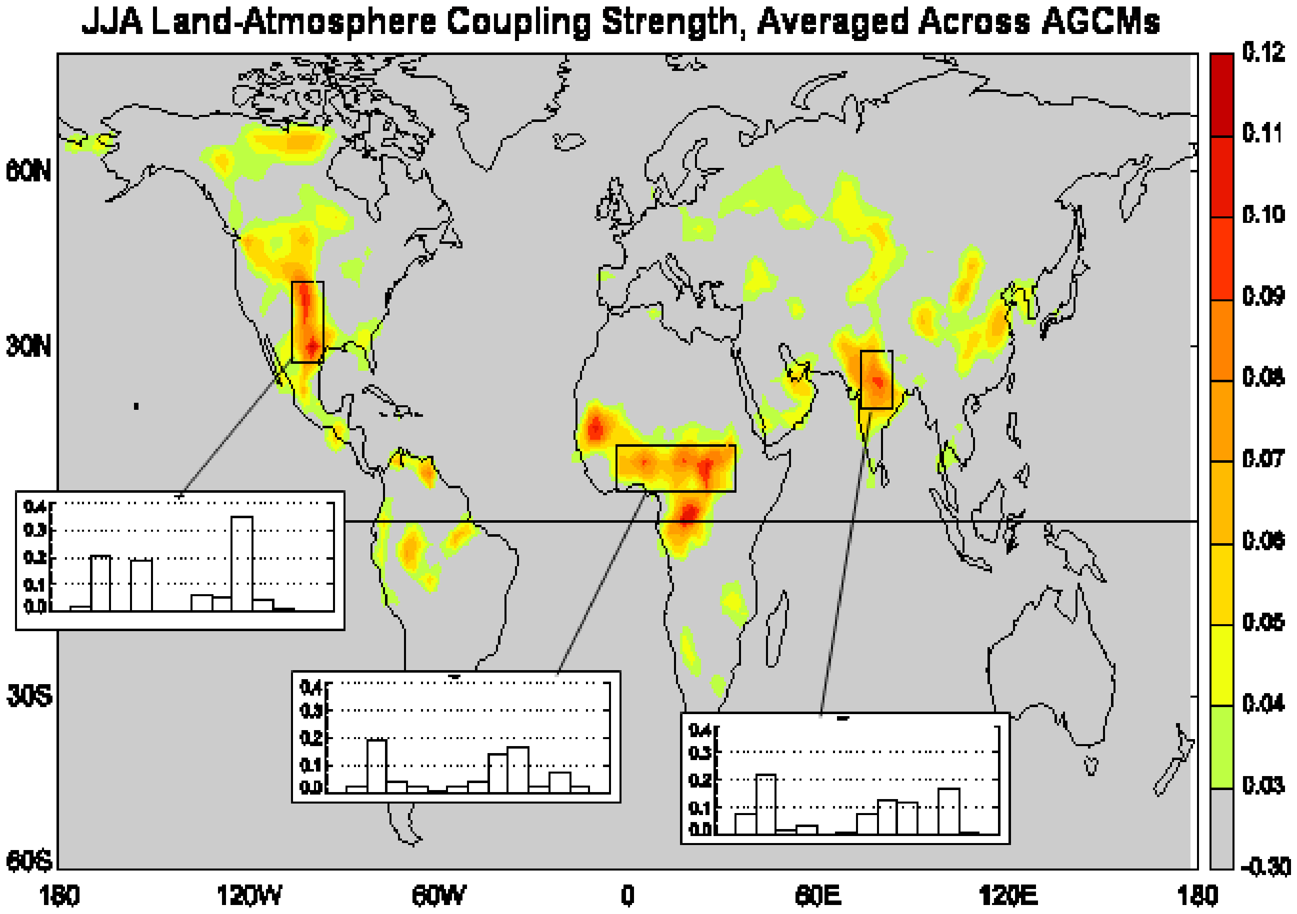


Simple representation, but illustrates how soil-plant-atmosphere interactions are controlled by different processes depending on the conditions.

Soil Moisture – Atmosphere interactions

Based on a multi-model approach: characterization of the strength of the coupling between surface and atmosphere.

(Koster et al, Science 2004).



SM, variable of interface

Partition LE/H

Vegetation phenology,

Soil respiration,

Biogeochemical cycle

Hot spot areas → strong soil moisture-precipitation feedback

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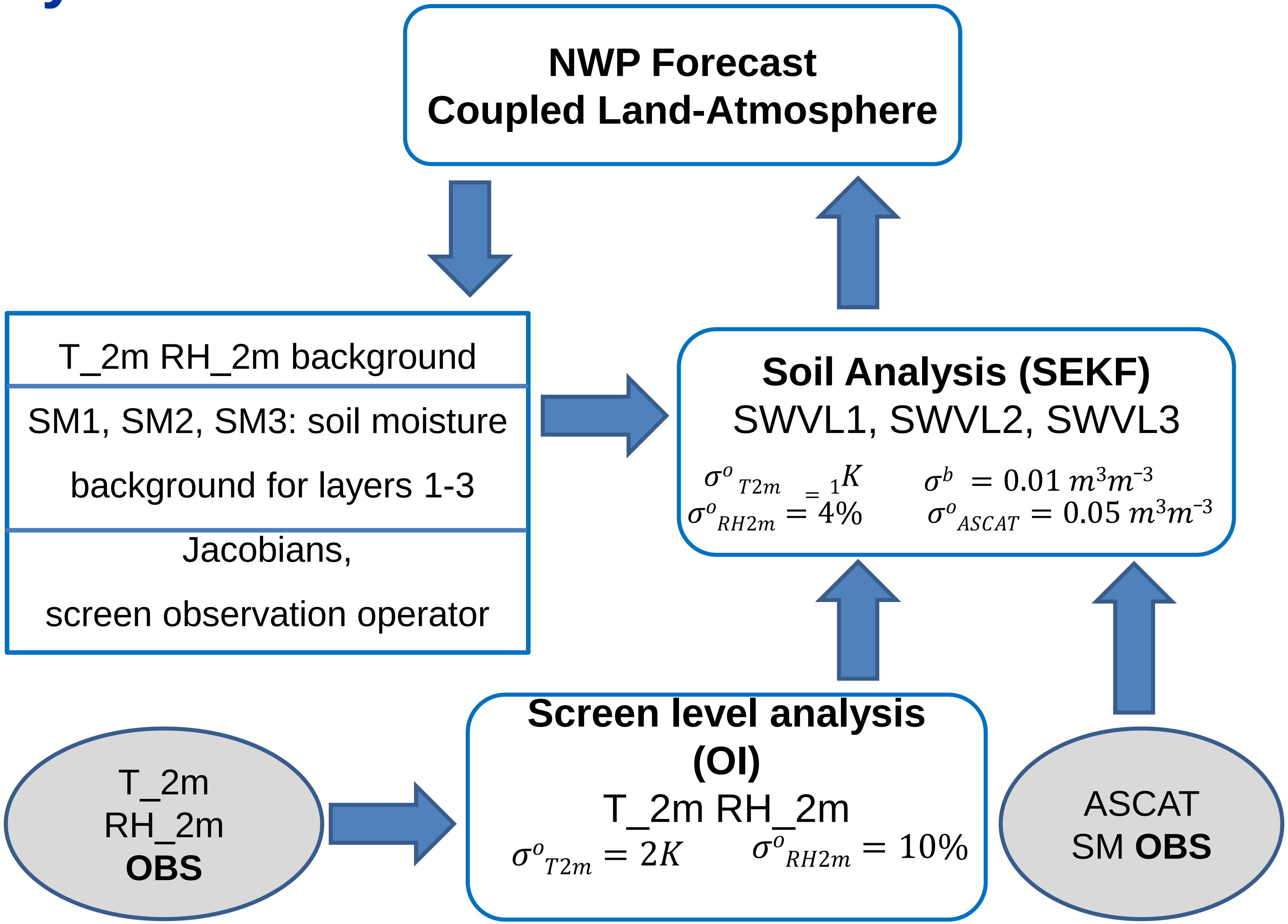
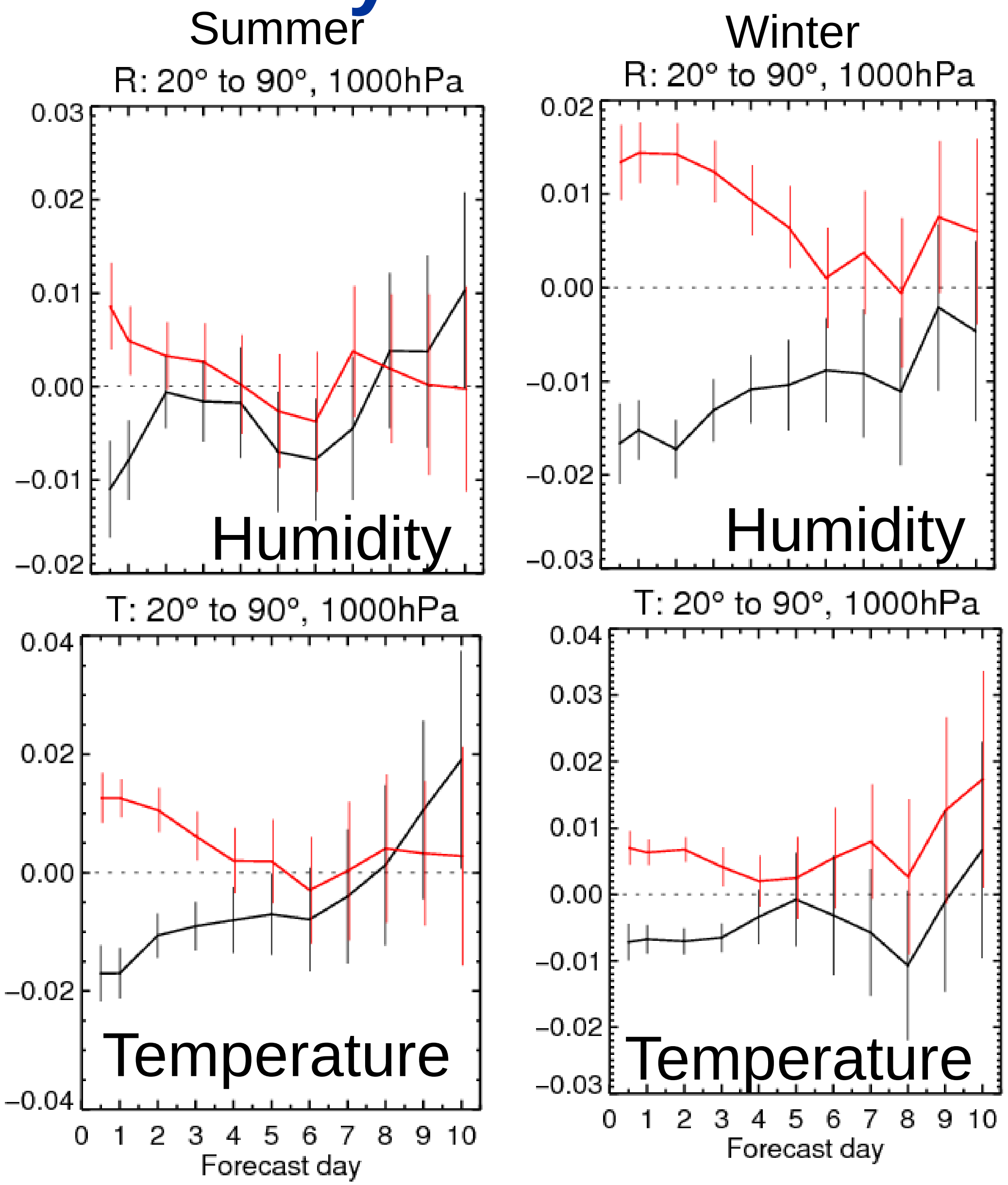
- **Soil moisture analysis**
    - **OI and SEKF soil moisture analyses**
    - Use of satellite data: ASCAT and SMOS
- Summary and future plans

Soil Analysis for NWP



Soil Analysis for NWP: What impact on the forecast ?



No soil Analysis

IFS cycle 40r1 soil analysis

IFS cycle 41r1 soil analysis (revised observation errors)

→ Very large impact of soil moisture initialisation on near-surface weather forecast

A history of soil moisture analysis at ECMWF

- **Nudging scheme (1995-1999): soil moisture increments $\Delta\Theta$ (m^3m^{-3}):**

$$\Delta\Theta = \Delta t \, D \, C_v \left(q^a - q^b\right)$$

D: nudging coefficient (constant=1.5g/Kg), Δt = 6h, q specific humidity
Uses upper air analysis of specific humidity
Prevents soil moisture drift in summer

- **Optimal interpolation 1D OI (1999-2010)**

$$\Delta\Theta = \alpha \left(T^a - T^b\right) + \beta \left(Rh^a - Rh^b\right)$$

Mahfouf, ECMWF News letter 2000,
Douville et al., Mon Wea. Rev. 2000

α and β: optimal coefficients
OI soil moisture analysis based on a dedicated screen level parameters (T2m Rh2m) analysis

- **Simplified Extended Kalman Filter (EKF), Nov 2010**

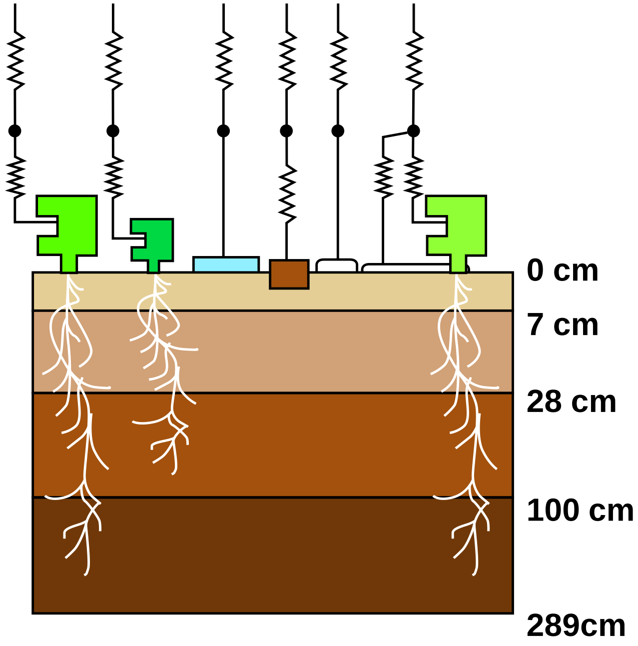
Drusch et al., GRL, 2009
de Rosnay et al., QJRMS 2013

- Motivated by better using T2m, RH2m
- Opening the possibility to assimilate satellite data related to surface soil moisture.

1D Optimal Interpolation (OI) analysis

- 1D-OI Soil Moisture analysis : used at ECMWF in operations form 1999 to 2010, and currently in ERA-Interim, Météo-France, ALADIN, HIRLAM
- Relies on the link between soil variables and the lowest atmospheric level:
  - Too dry soil soil → 2m air too dry & too warm
  - Too wet soil soil → 2m air too moist & too cold

H-TESSEL Land Surface Model



References HTESSEL:
Balsamo et al., JHM 2009

→ Soil Moisture increments based on the T2m and RH2m analysis increments:

$$\Delta\Theta_i = \alpha_i \left(T^a - T^b\right) + \beta_i \left(rH^a - rH^b\right)$$

For snow temperature and soil temperature (ERA-Interim and operations):

$$\Delta T = c\,(T^a - T^b)$$

a and b: analysis and background ; i: soil layer.
Optimal Coefficients α **,** β **and c**

Quality Control: no OI when Rain, snow, freezing, wind

References OI: Mahfouf, JAM, 1991,
Mahfouf et al, ECMWF NL 88, 2000

Simplifed EKF soil moisture analysis

For each grid point, analysed soil moisture state vector $\boldsymbol{\theta}_a$:

$$\boldsymbol{\theta}_a = \boldsymbol{\theta}_b + \boldsymbol{K}\,(\boldsymbol{y} - \mathcal{H}[\boldsymbol{\theta}_b])$$

$\boldsymbol{\theta}$ background soil moisture state vector,
$\mathcal{H}$ non linear observation operator
$\boldsymbol{y}$ observation vector
$\boldsymbol{K}$ Kalman gain matrix, fn of
H (linearsation of $\mathcal{H}$), **B** and **R** (covariance matrices of background and observation errors).

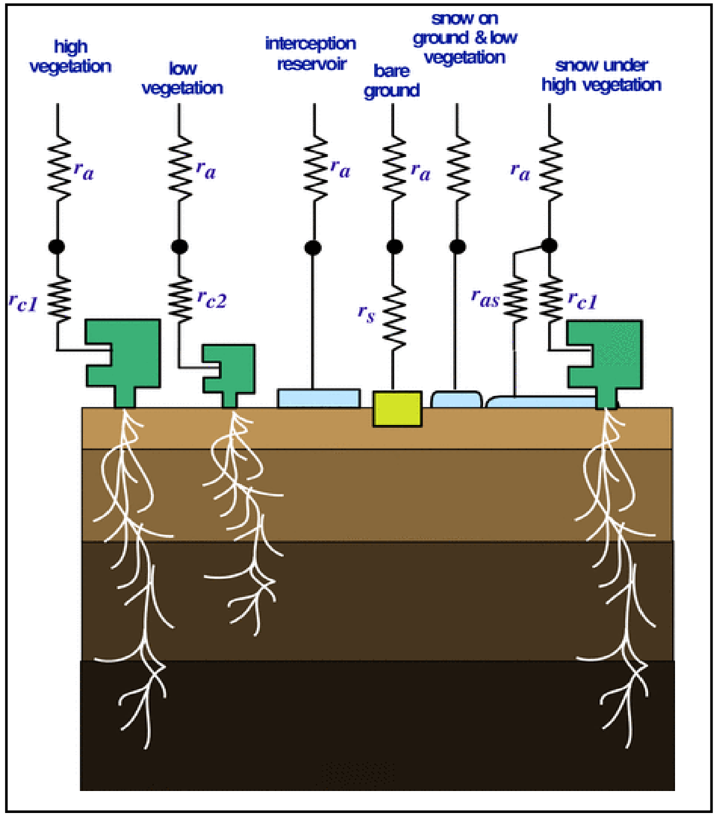
Used at ECMWF (operations and ERA5), DWD, UKMO

Observations used at ECMWF:
For operational NWP:

- Conventional SYNOP pseudo observations (analysed T2m, RH2m)
- Satellite MetOp-A/B ASCAT soil moisture

Research: SMOS Data Assimilation

The simplified EKF is used to corrects the soil moisture trajectory of the Land Surface Model



Drusch et al., GRL, 2009
de Rosnay et al., ECMWF News Letter 127, 2011
de Rosnay et al., QJRMS, 2013

Simplifed EKF soil moisture analysis

The analysis is obtained by an optimal combination of the observations and the background (short-range forecast):

$$\theta_{\mathbf{a}}(t) = \theta_{\mathbf{b}}(t) + \mathbf{K}\left(\mathbf{y}(t) - \mathcal{H}[\theta_{\mathbf{b}}(t)]\right)$$

where $\mathbf{K}$ is the gain matrix:

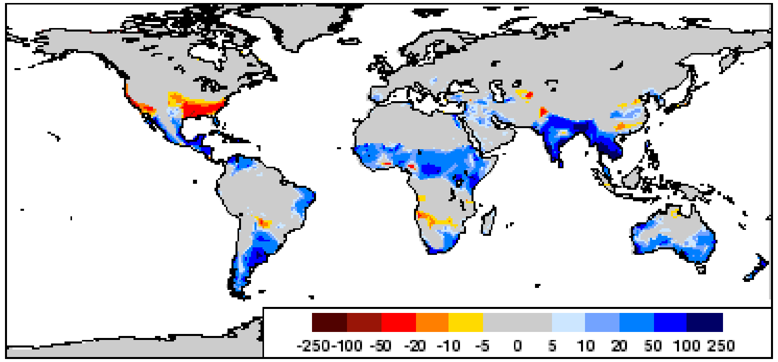
$$\mathbf{K} = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

The observation operator $\mathbf{H}$ is the Jacobian matrix of:

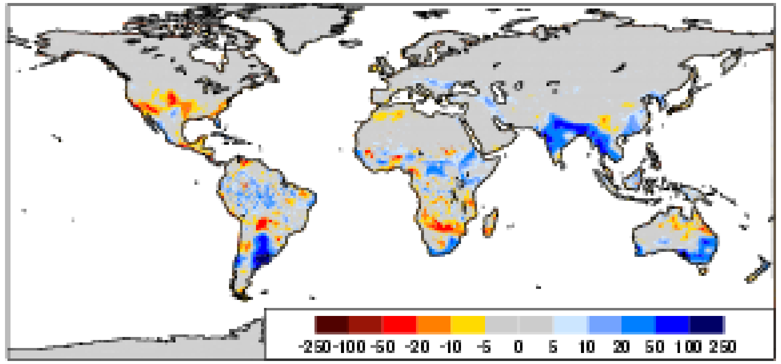
$$H_{ij} = \frac{\delta y_i}{\delta \theta_j} \simeq \frac{y_i\left(x + \delta\theta_j\right) - y_i\left(x\right)}{\delta\theta_j}$$

In finite differences, the elements of the Jacobian matrix are estimated by perturbing individually each component θ_j of the control vector $\mathbf{x}$ by a small amount $\delta\theta_j$. A sensitivity as been conducted to find the optimum perturbation $\delta\theta_j$. With j obs and I model layer

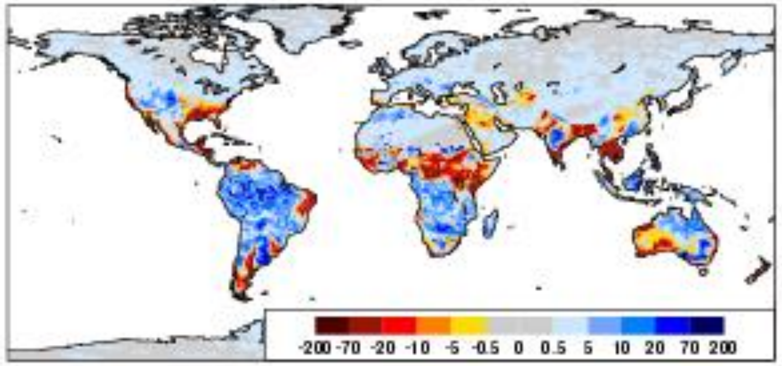
Simplified EKF and OI Comparison



OI



EKF



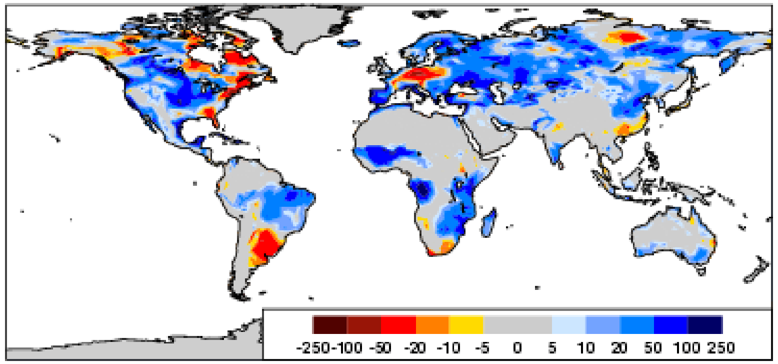
|EKF|-|OI|

0-1m Soil Moisture increments (mm)
January 2009

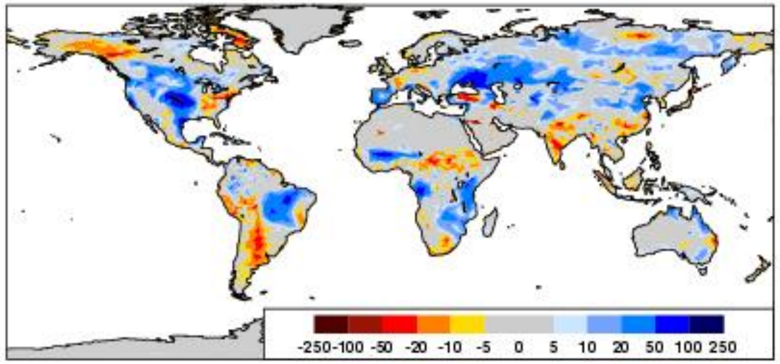
Soil moisture analysis more active in the summer hemisphere than in the winter hemisphere

Simplified EKF and OI comparison

0-1m Soil Moisture increments (mm)
July 2009

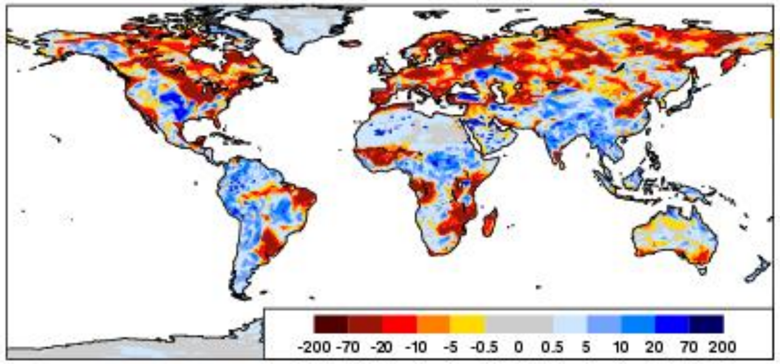


OI



EKF

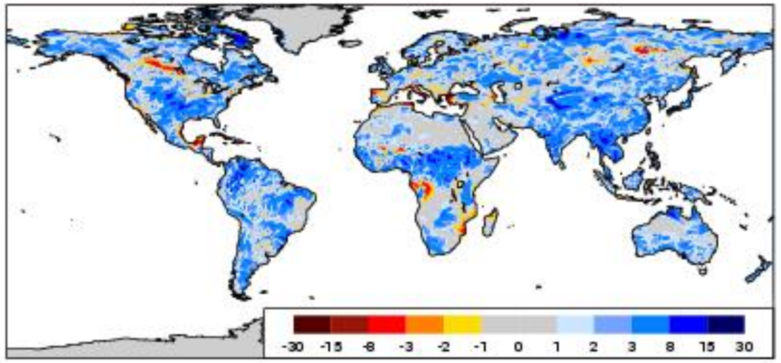
Much reduced root zone increments with the EKF compared to the OI



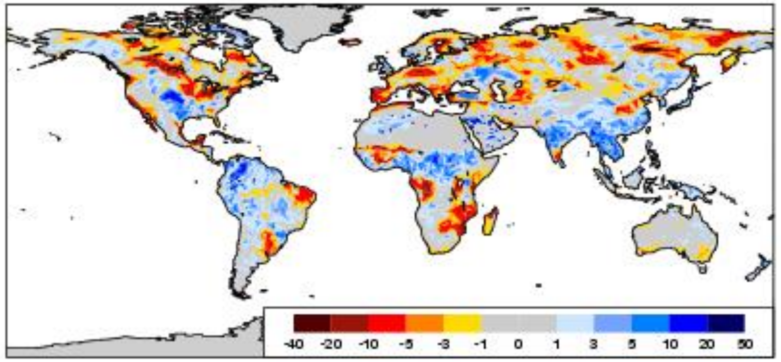
|EKF|-|OI|

Simplified EKF and OI comparison

Vertical Profile
of Soil Moisture increments
difference |EKF|-|OI| July 2009

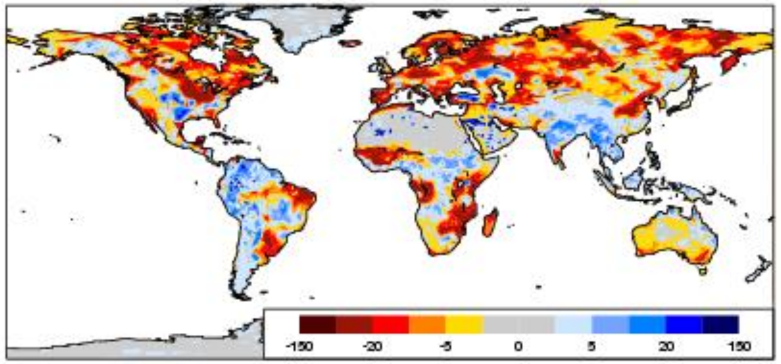


Layer 1 (0-7cm)



Layer 2 (7-28cm)

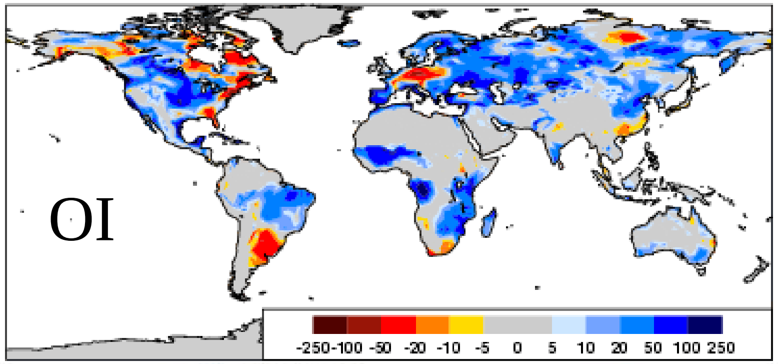
EKF compared to OI:
. Reduce increments at depth
. Increase increments for top soil layer
. Overall reduced increment

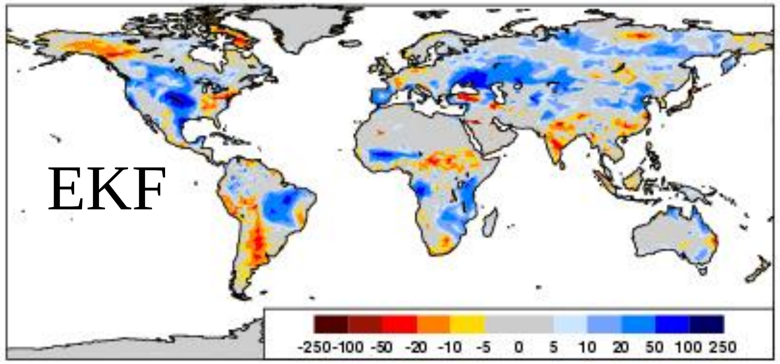


Layer 3 (100-289 cm)

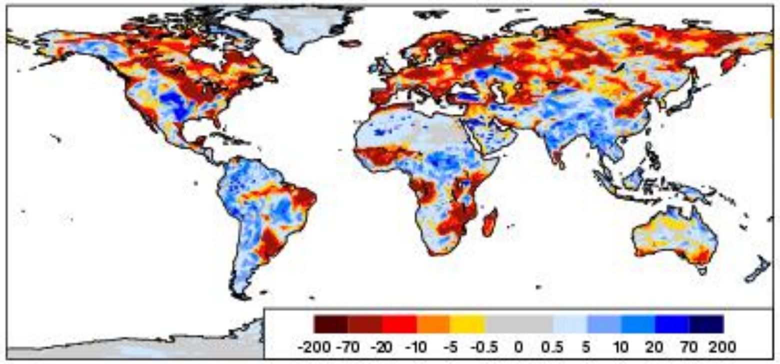
Simplified EKF and OI comparison

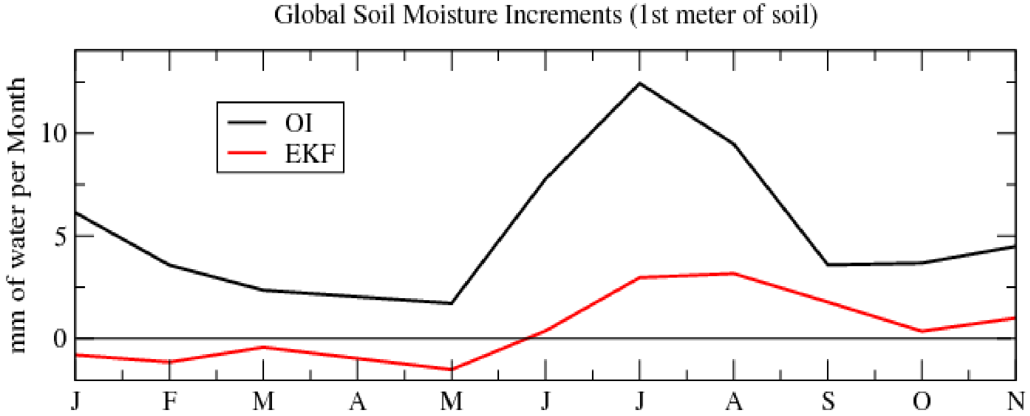
0-1m Soil Moisture increments for July 2009 (mm)





|EKF|-|OI|





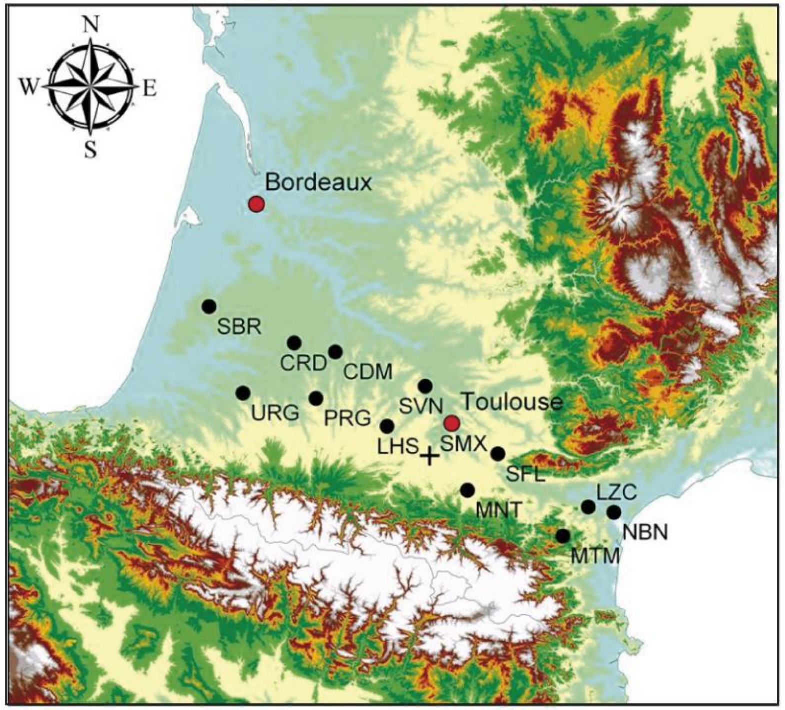
-Two 1-year analysis experiments using the OI and the EKF

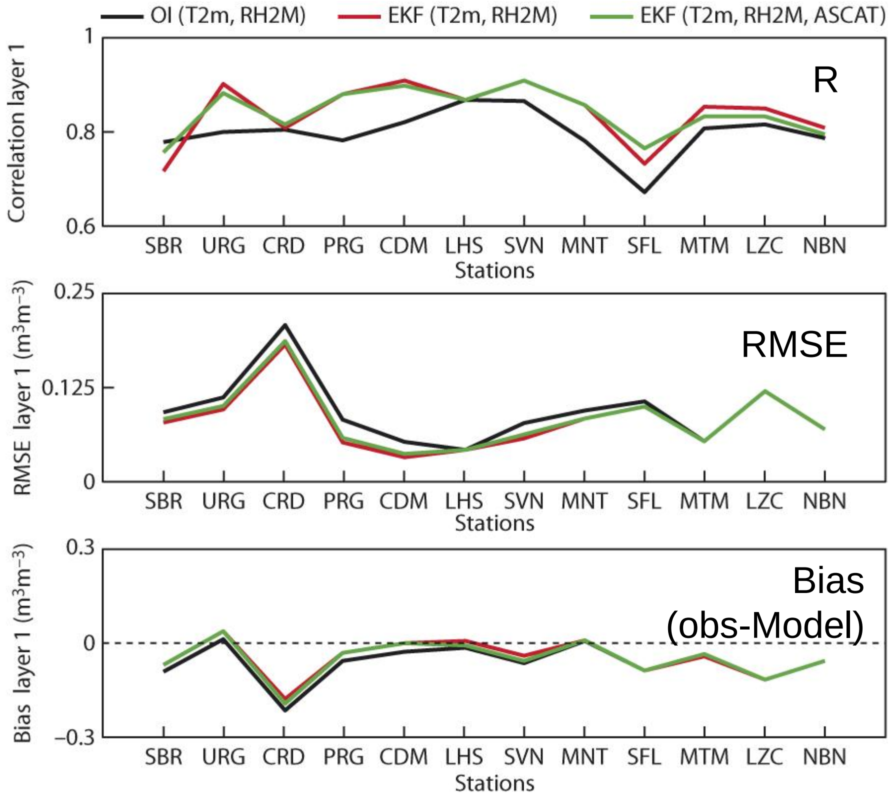
- Reduced increment with the EKF compared to the OI
- EKF accounts for non-linear control on the soil moisture increments: meteorological and soil moisture conditions
- **EKF prevents undesirable and excessive soil moisture corrections**

Soil Moisture Analysis verification

Validated for several sites across Europe (Italy, France, Spain, Belgium)

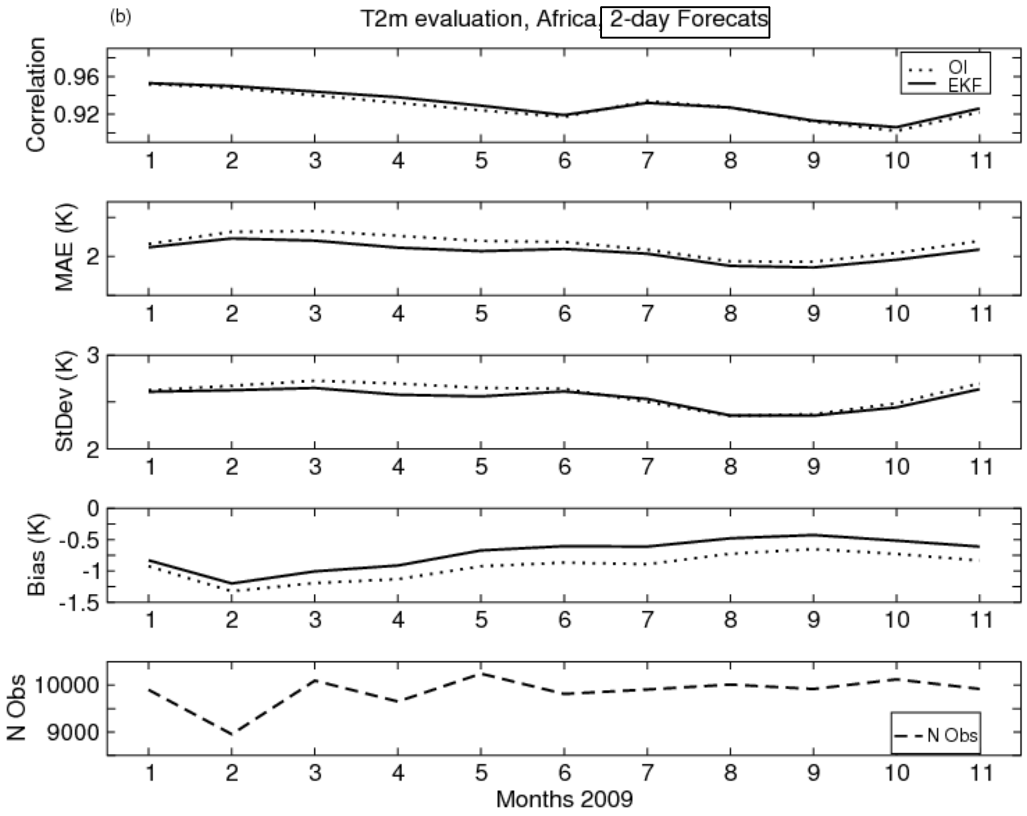
Verification of ECMWF SM over the SMOSMANIA Network

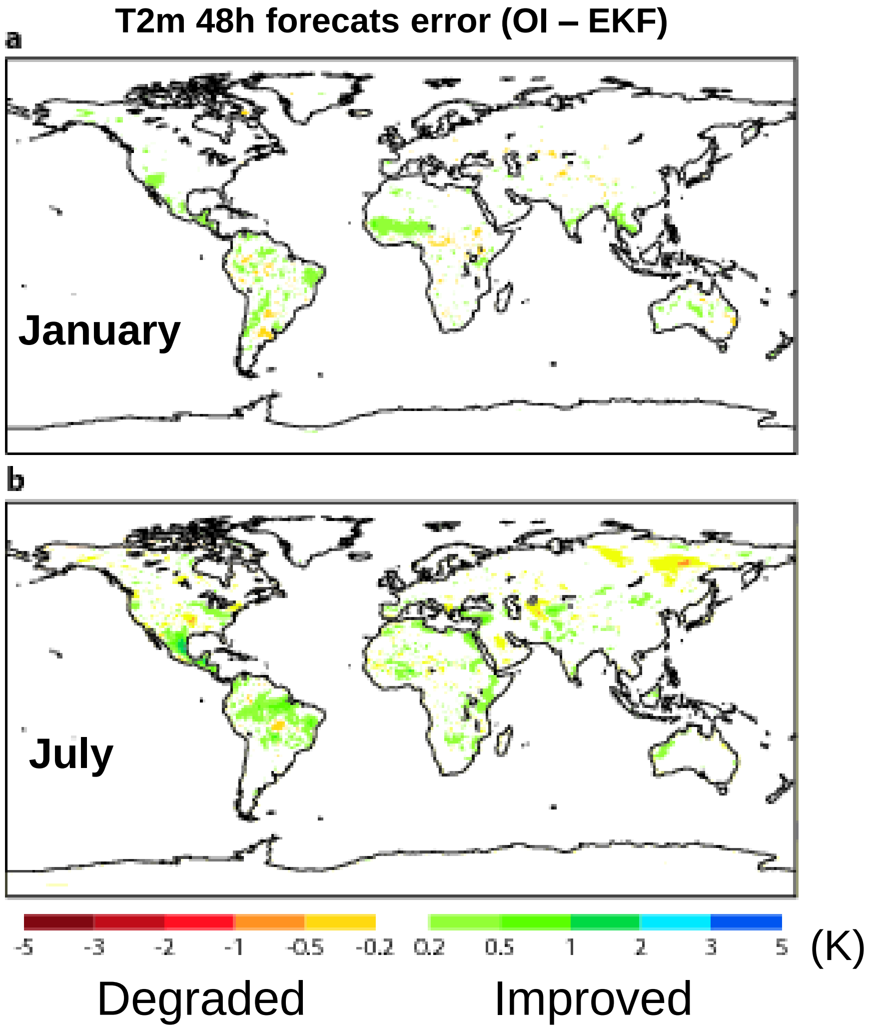




Compared to the OI, the EKF improves soil moisture

T2m 48-h Forecast Evaluation





Compared to the 1D-OI, the SEKF improves analysis and forecasts of soil moisture and two-meter temperature. It also enables satellite data assimilation in the land data assimilation system.

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Satellite data for NWP soil moisture analysis

Active microwave data:
ASCAT: Advanced Scatterometer
On MetOP-A (2006-), MetOP-B (2012-)
C-band (5.6GHz)
NRT Surface soil moisture

Operational product
→ ensured operational continuity

Passive microwave data:
SMOS: Soil Moisture & Ocean Salinity
2009-
L-band (1.4 GHz)
NRT Brightness Temperature

Dedicated soil moisture mission
→ Strongest sensitivity to soil moisture

Active and Passive:
SMAP
L-band TB 2015-
Dedicated
soil moisture mission

STATISTICS FOR SOIL MOISTURE FROM METOP-B/ASCAT

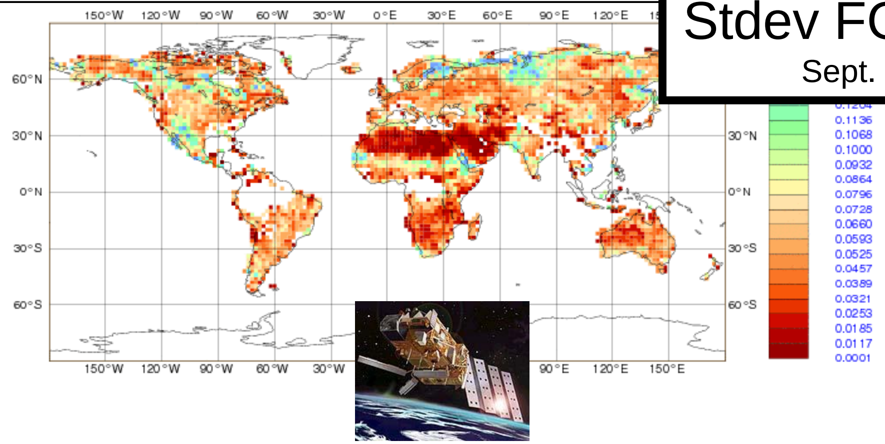
STATISTICS FOR RADIANCES FROM FROM SMOS

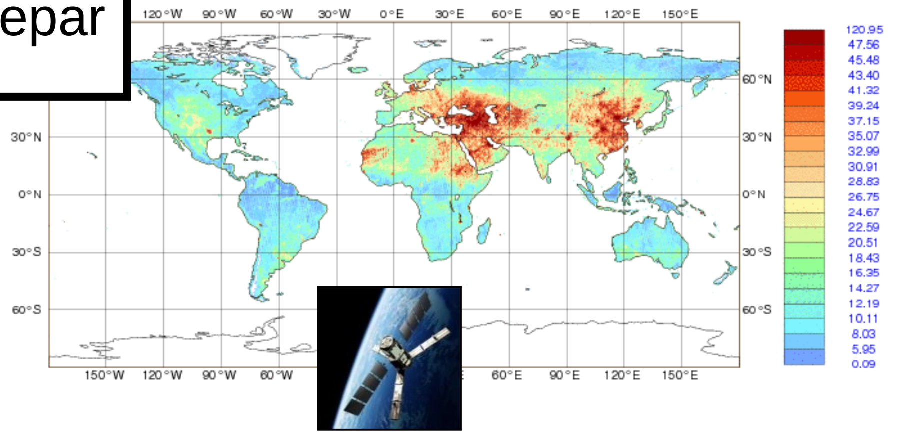
Operational Monitoring of surface soil moisture related satellite data:

ASCAT soil moisture (m^3m^{-3})

SMOS Brightness temperature (K)

Stdev FG_depar
Sept. 2013





ASCAT soil moisture

- ASCAT is a soil moisture index (0-1) ; models soil moisture variable is a volumetric quantity (m^3m^{-3})
- Systematic differences between model and observations
- Data assimilation aims at correcting for the model random errors, so a bias correction method is necessary to match the observations 'climatology' to that of the model

(→ See D. Dee's Lecture on Bias Correction)

→ **For soil moisture data assimilation systems simplified Bias correction method often used**

Cumulative Distribution Function Matching: CDF-Matching (e.g. Scipal et al. WRR 2008, Draper et al, JGR 2009)

Revised in 2011 to account for seasonal cycle (de Rosnay et al., ECMWF Res. Memo. 2011)

ASCAT Bias Correction (CDF matching)

- ASCAT soil moisture index ms_{ASCAT}
- Model soil moisture θ (m^3/m^{-3})

→ Simple Cumulative Distribution Function (CDF) matching (Scipal et al., 2008)

$$\theta_{ascat} = a + b\, ms_{ascat}$$

with $a = \overline{\theta}_{model} - \overline{ms}_{ascat}\,(\sigma_{model}/\sigma_{ms\_ascat})$

$b = \sigma_{model} / \sigma_{ms\_ascat}$

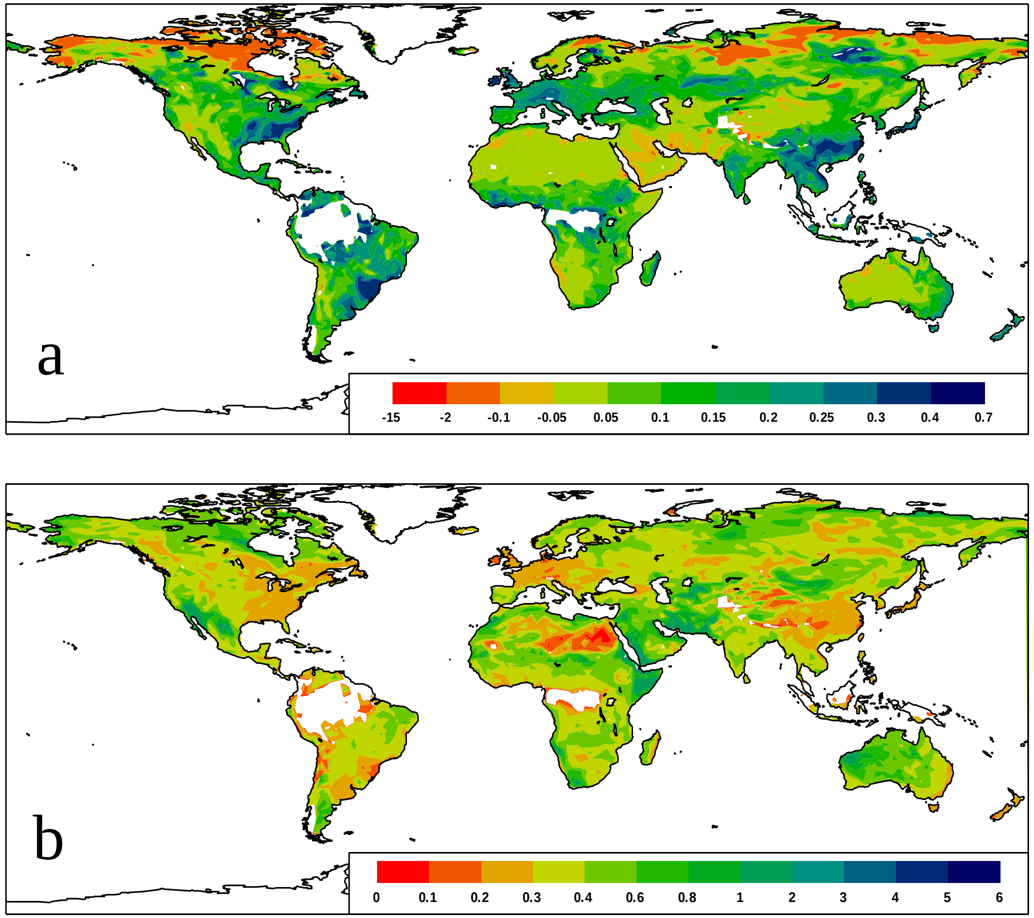
→ Matches mean and variance

a and b are CDF matching parameters computed **on each model grid point**

ASCAT CDF-matching has two objectives:

→ **ASCAT index converted to model equivalent volumetric soil moisture**

→ **Bias correction**



ASCAT matching parameters
(de Rosnay et al., ECMWF Res memo R43.8/PdR/11100, 2011)

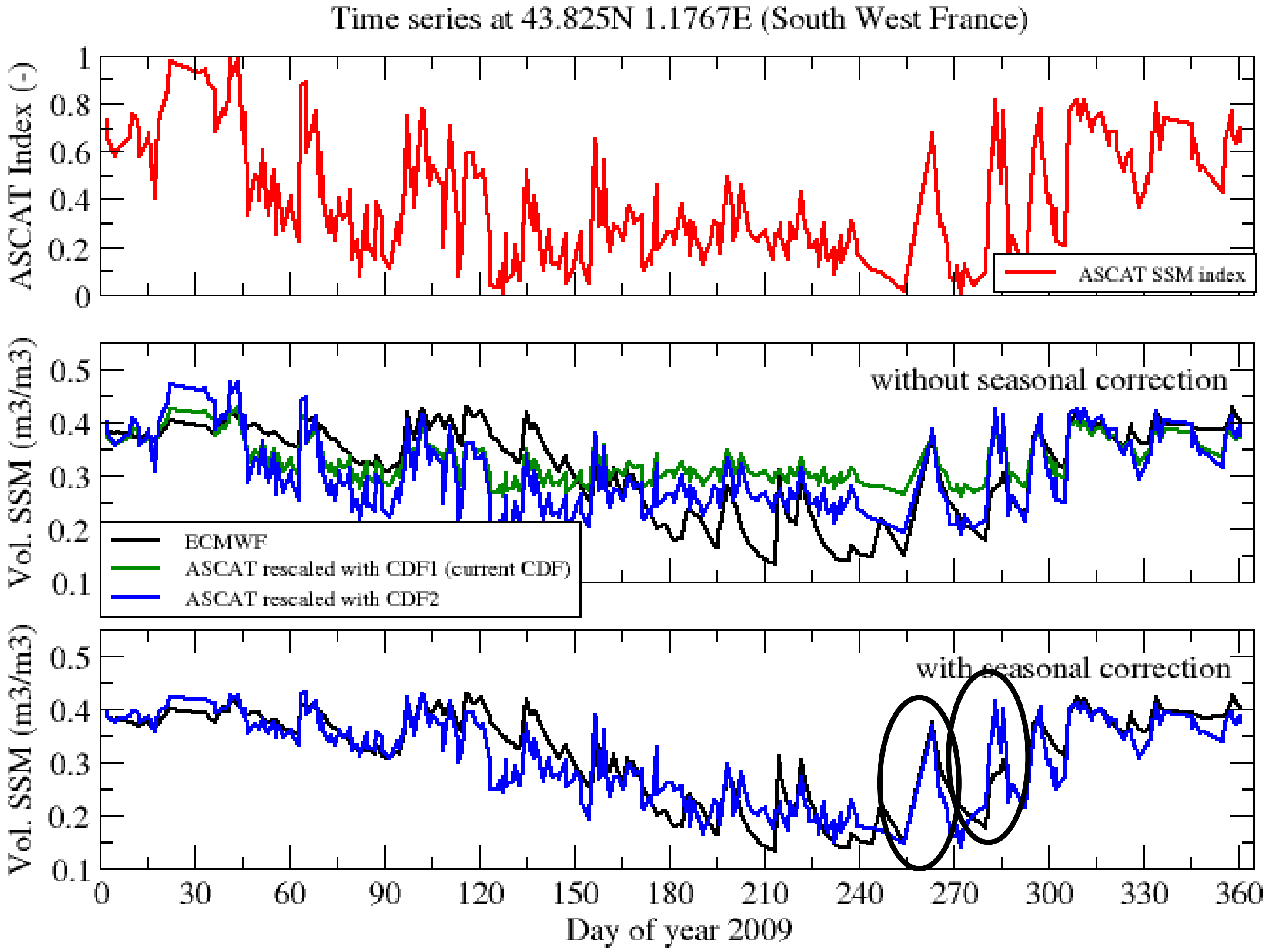
ASCAT Bias Correction (CDF matching)

Efficient data assimilation relies on accurate bias correction

ASCAT index

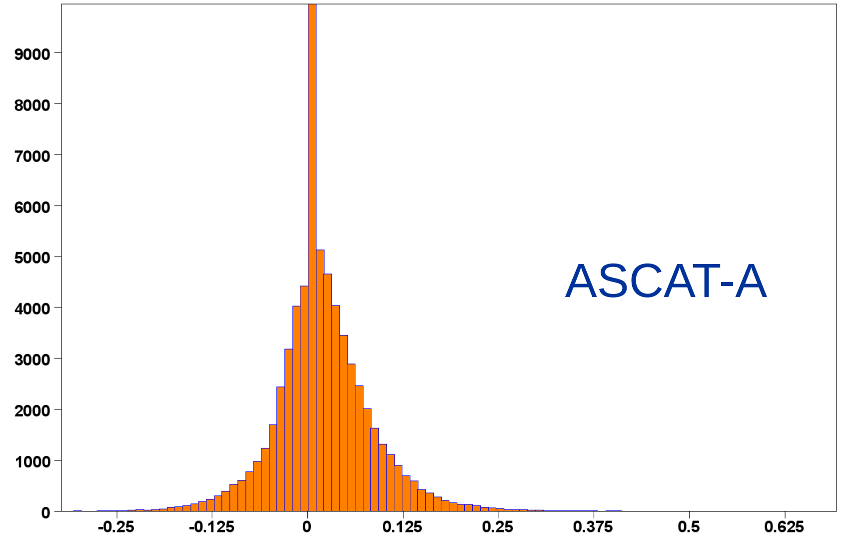
ECMWF model soil moisture
(ASCAT old BC)
ASCAT with static BC

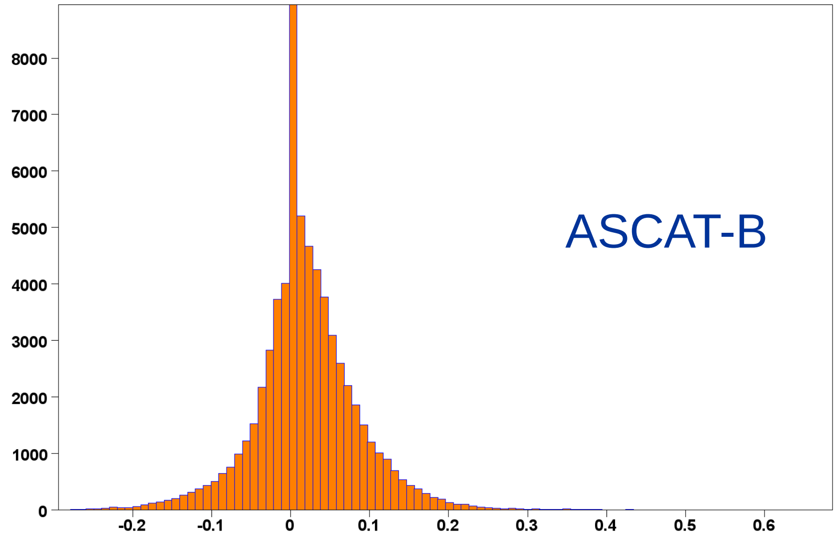
ASCAT with dynamic (seasonal) BC



ASCAT-A and ASCAT-B

ASCAT SM – Model
(First guess departure, $m^3.m^{-3}$)
23-24 Nov 2012





Metop-A launched in 2006 Metop-B launched in 2012

Consistent ASCAT-A and ASCAT-B soil moisture

Departure statistics:

	Nb	Mean $m^3.m^{-3}$	Std $m^3.m^{-3}$
ASCAT-A	64893	0.0152	0.0645
ASCAT-B	65527	0.0149	0.0663

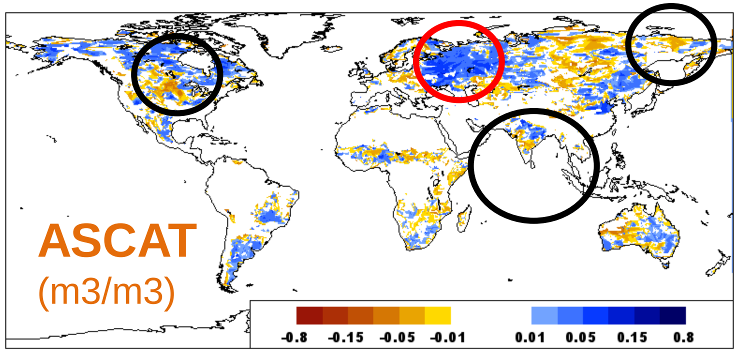
Operational monitoring:

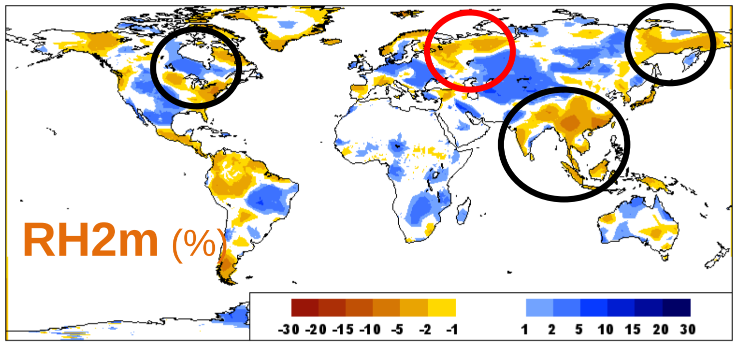
http://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring/soil-moisture-monitoring

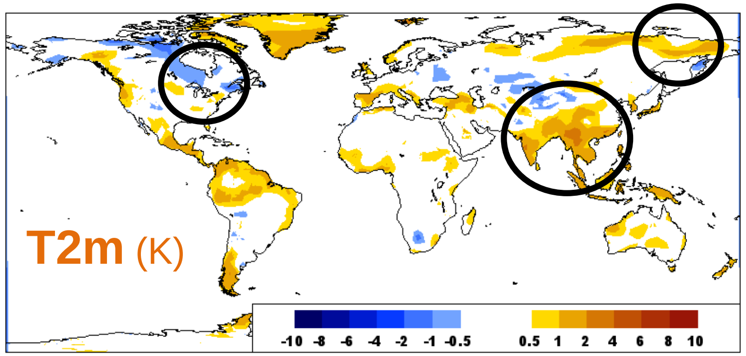
ASCAT Soil Moisture data assimilation for NWP

Innovation (Obs- model)

25-30 June 2013

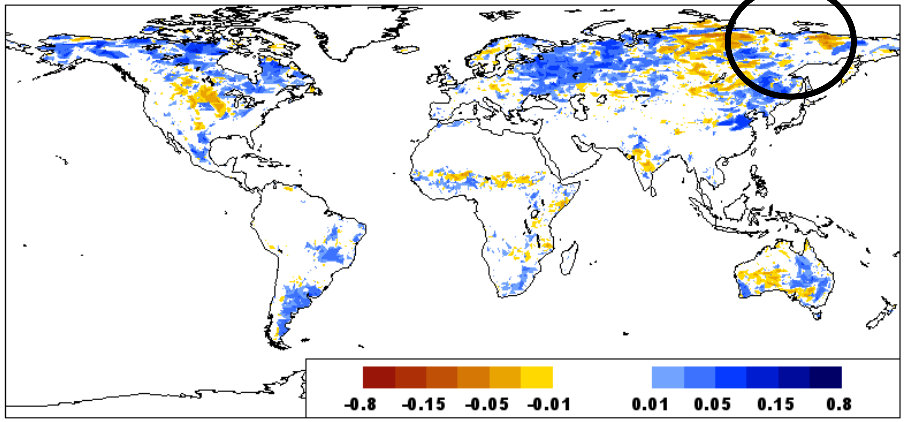




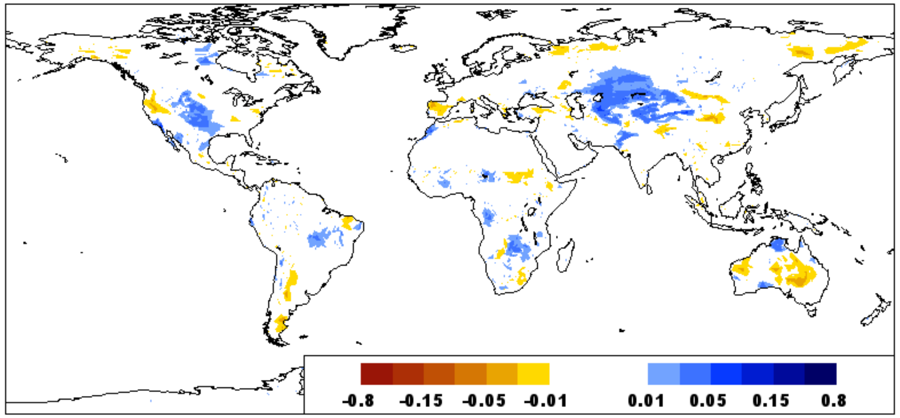


Accumulated Increments (m³/m³)

in top soil layer (0-7cm)



Due to ASCAT

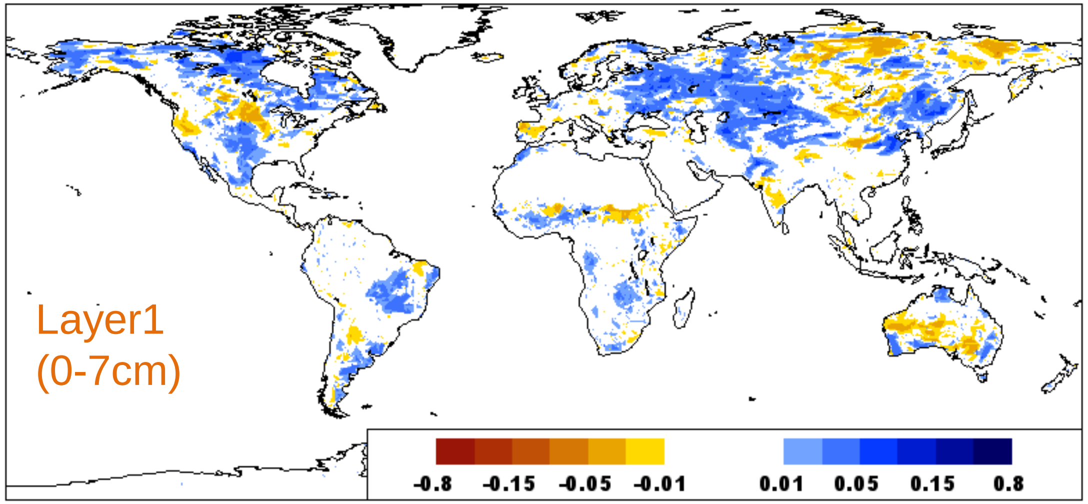


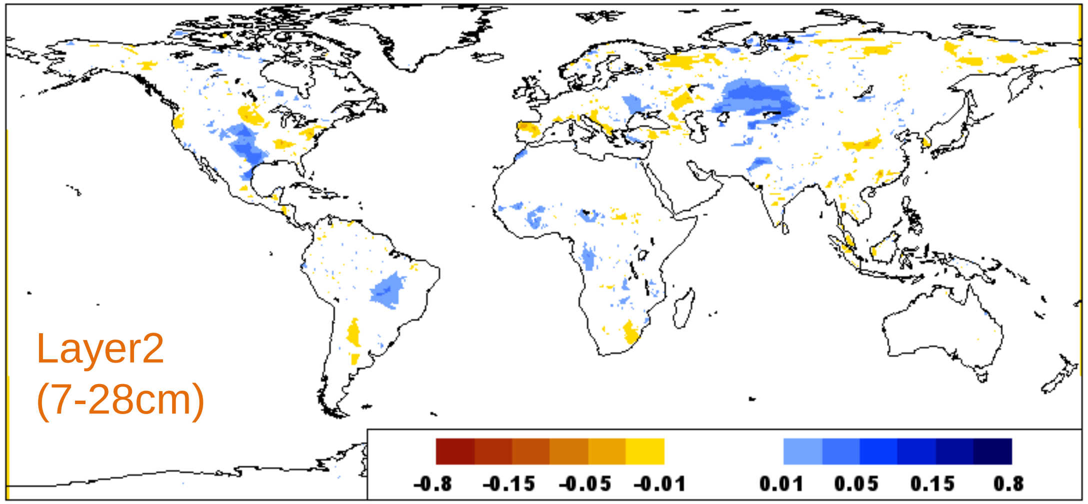
Due to SYNOP T2m and RH2m

ASCAT Soil Moisture data assimilation for NWP

Volumetric Soil Moisture increments (m^3/m^3) (accumulated)

25-30 June 2013





Vertically integrated Soil Moisture increments (stDev in mm)

	SYNOP	ASCAT
Layer 1	0.68	**1.43**
Layer 2	**1.48**	0.68
Layer 3	**4.28**	0.46

ASCAT more increments than SYNOP at surface
SYNOP give more increments at depth
→ For 12h DA window, link obs to root zone stronger for T2m,RH2m than for surface soil moisture observations

Root Zone Soil Moisture Retrieval

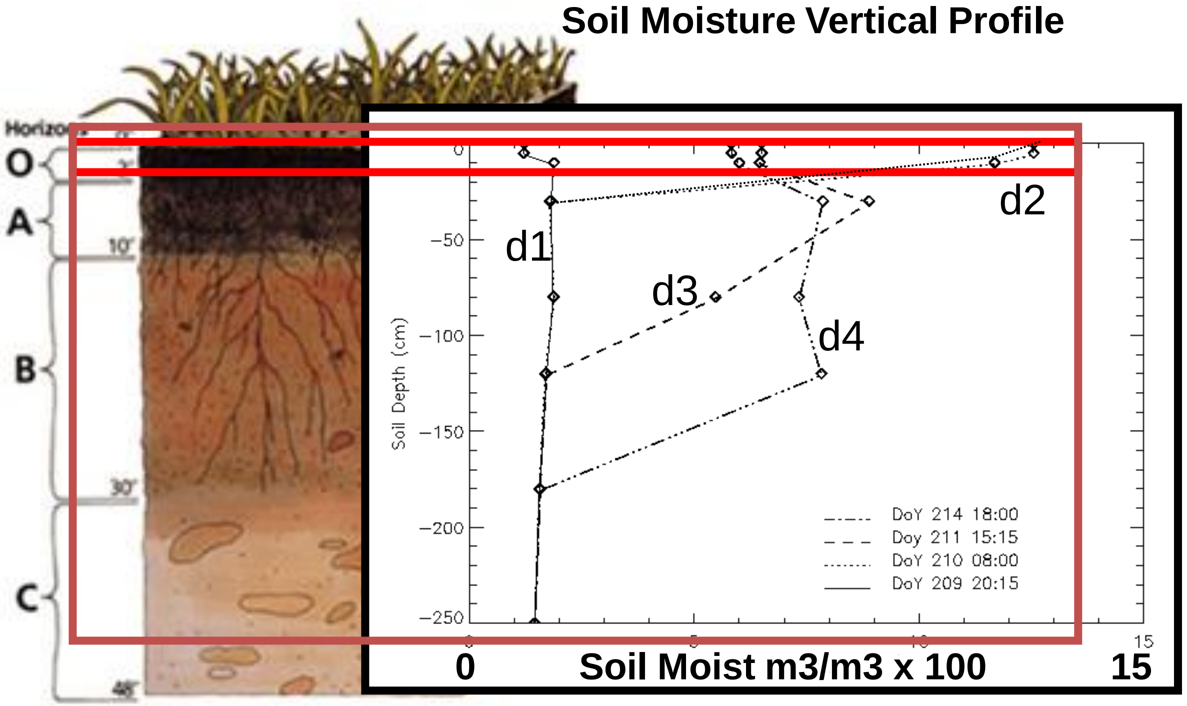
Satellite data → Surface information

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

Root Zone SM Profile

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

Accurate retrieval requires to account for physical processes



→ Retrieval of root zone soil moisture using satellite data requires data assimilation approaches

ASCAT soil moisture data assimilation

The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

EUMETSAT Hydrology SAF

ECMWF Atmospheric conditions

SYNOP
T2m RH2m
analysis

ASCAT
Surface SM
Bias corrected

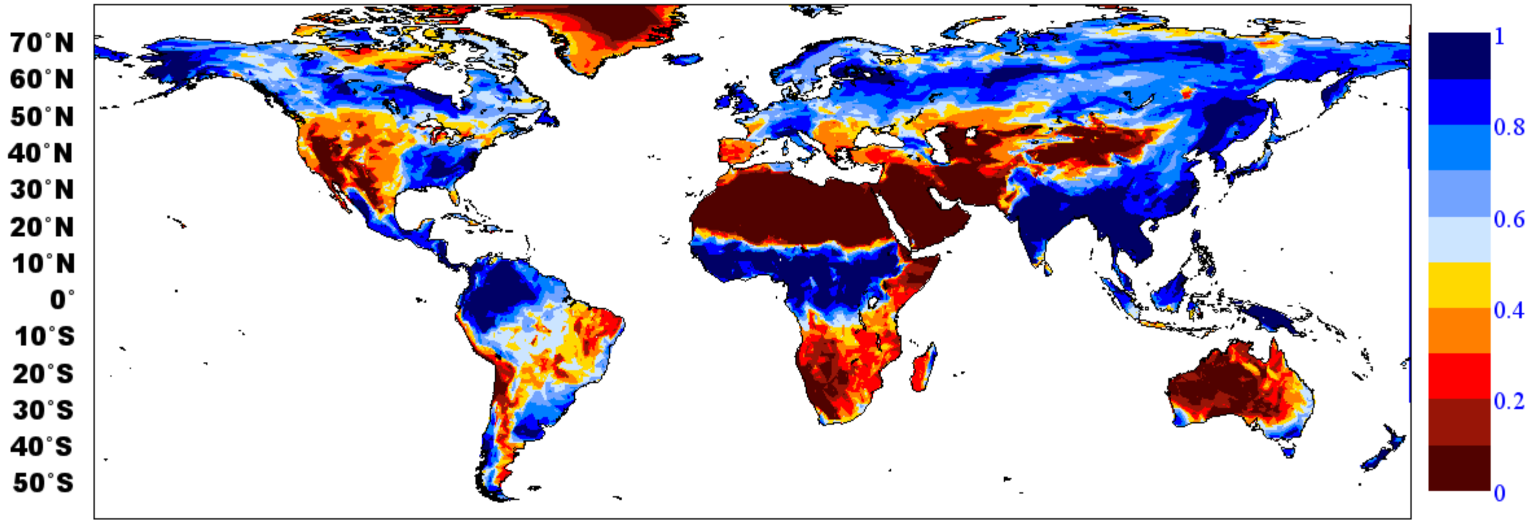
SEKF
Soil Moisture
Analysis

ASCAT Root Zone product (SM-DAS-2)

Quality Control → use data when:
- Topographic complexity ≤ 20
- Wetland Fraction ≤ 15
- Noise level ≤ 8
- processing flag=0

Analysed root zone
soil moisture on model levels
4 layers:
0-7cm
7-28 cm
28-100 cm
100-289cm

ASCAT soil moisture data assimilation



Assimilated ASCAT Surface (0-7cm) soil moisture index (0-1)

04 Sept 2012 00UTC

ASCAT Root Zone Soil Moisture Product (H-SAF SM-DAS-2): Data assimilation used to propagate in space and time the ASCAT surface swath soil moisture information
- Daily Soil Moisture product valid at 00:00 UTC
- Daily Global coverage

SM-DAS-2: Operational H-SAF since July 2012;

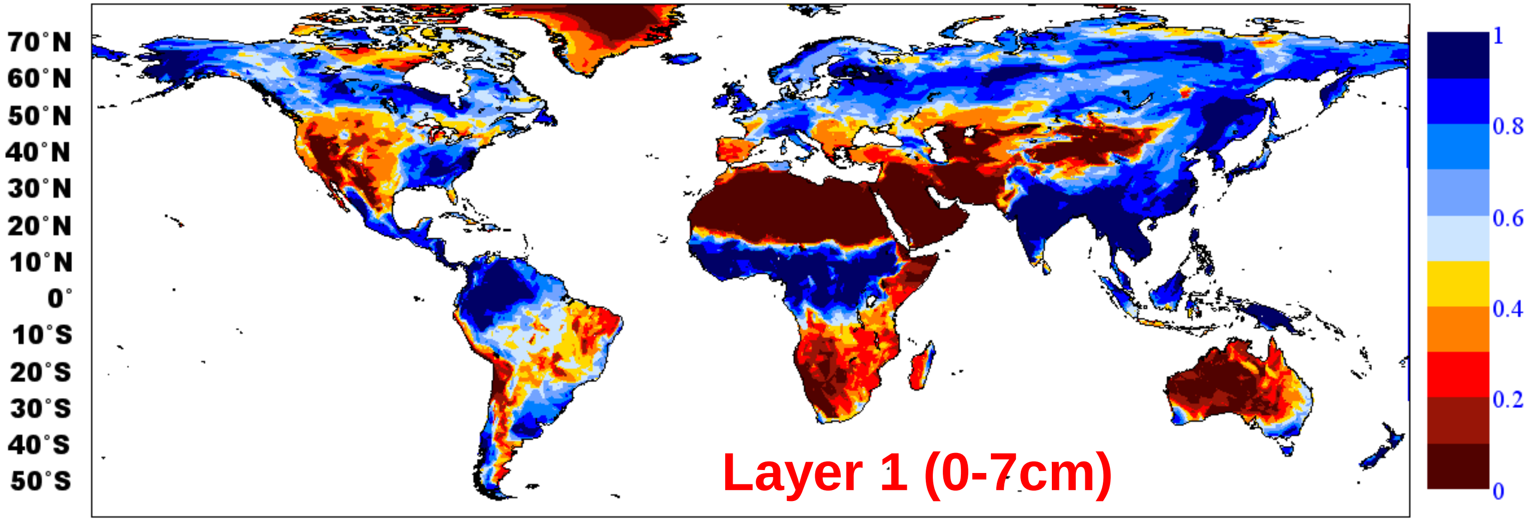
hsafcdop@meteoam.it

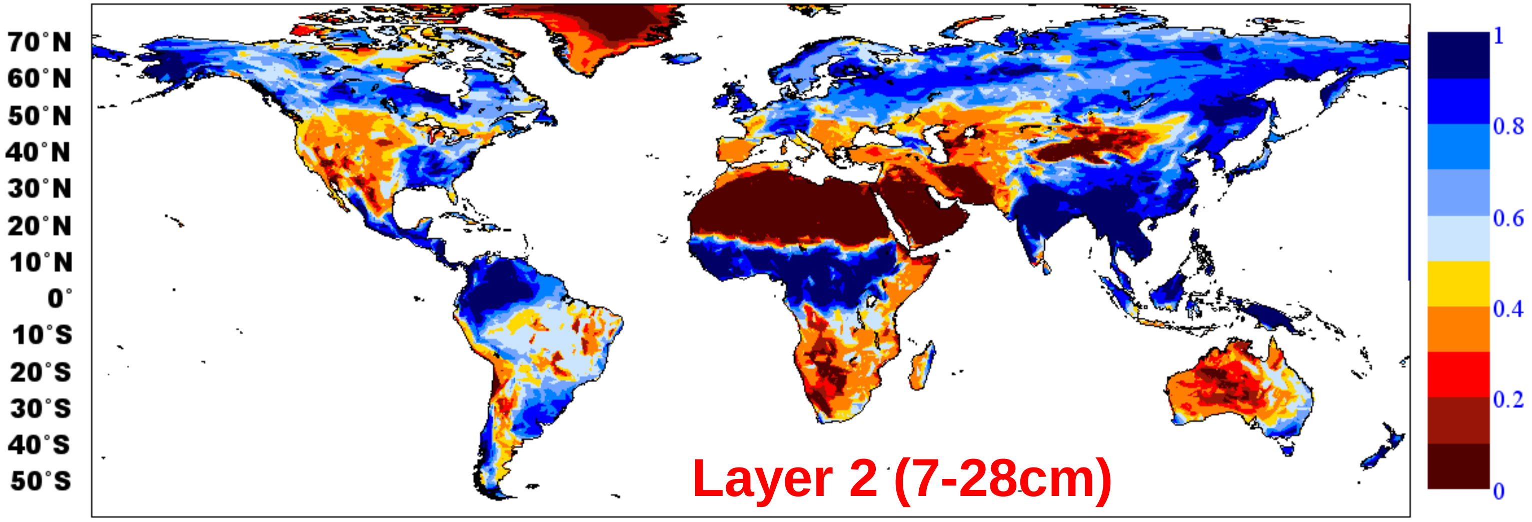
The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

ASCAT soil moisture data assimilation

SM-DAS-2 available on 4 soil layers





Assimilated ASCAT
soil moisture index (0-1)

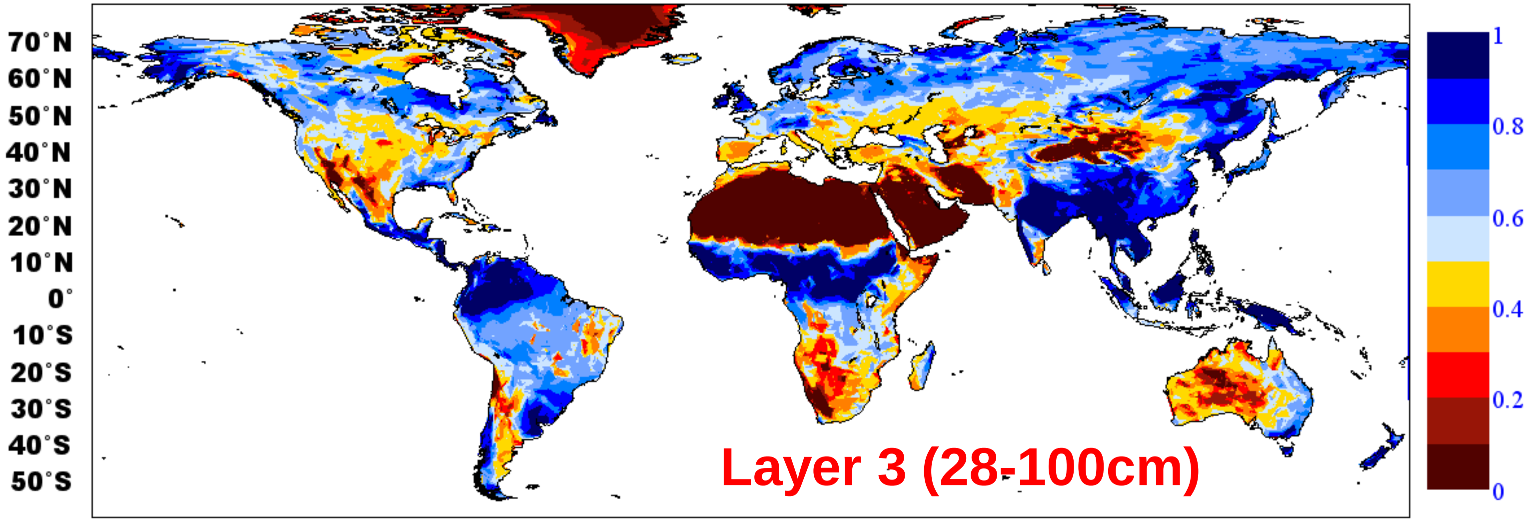
04 Sept 2012 00UTC

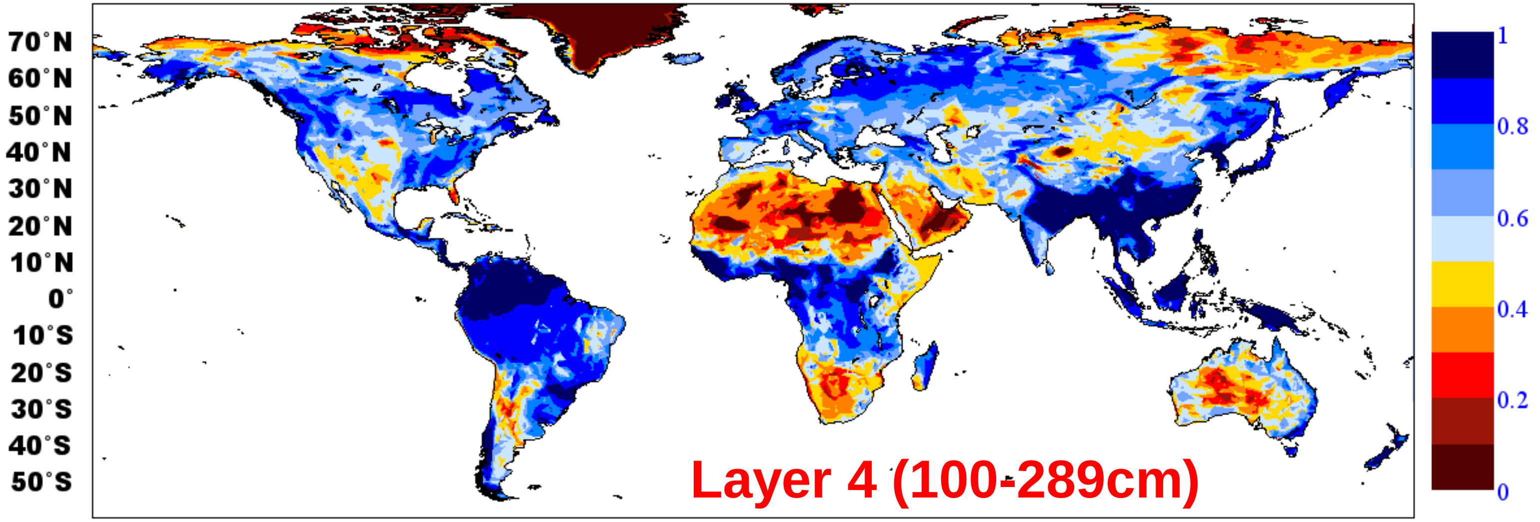
The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

ASCAT soil moisture data assimilation

SM-DAS-2 available on 4 soil layers





Assimilated ASCAT
soil moisture index (0-1)

04 Sept 2012 00UTC

The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

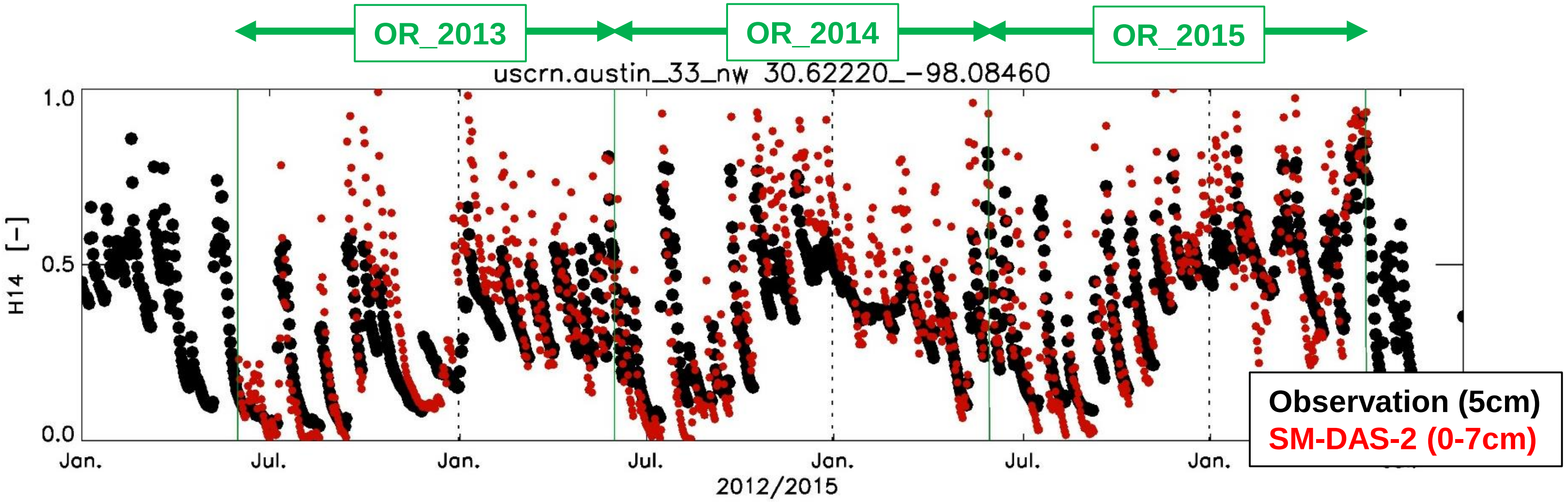
Soil moisture Validation

Scatterometer root zone soil moisture based on data assimilation

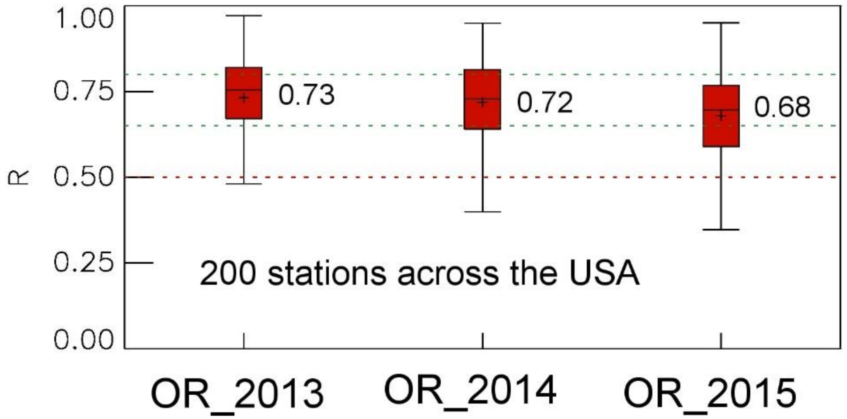
Albergel et al.

Evaluation of SM-DAS-2/H14

Surface and root zone liquid soil moisture content



Accuracy requirements for product SM-DAS-2 [R]			
Unit	**Threshold**	**Target**	**Optimal**
Dimensionless	0.50	0.65	0.80



Satellite data for NWP soil moisture analysis

Active microwave data:
ASCAT: Advanced Scatterometer
On MetOP-A (2006-), MetOP-B (2012-)
C-band (5.6GHz)
NRT Surface soil moisture

Operational product
→ ensured operational continuity

Passive microwave data:
SMOS: Soil Moisture & Ocean Salinity

L-band (1.4 GHz)
NRT Brightness Temperature

Dedicated soil moisture mission
→ Strongest sensitivity to soil moisture

Active and Passive:
SMAP
L-band TB 2015
Dedicated
soil moisture mission

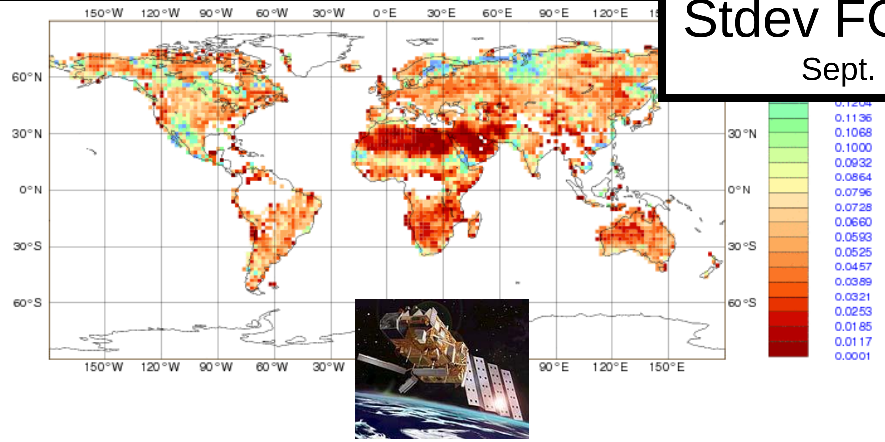
STATISTICS FOR SOIL MOISTURE FROM METOP-B/ASCAT

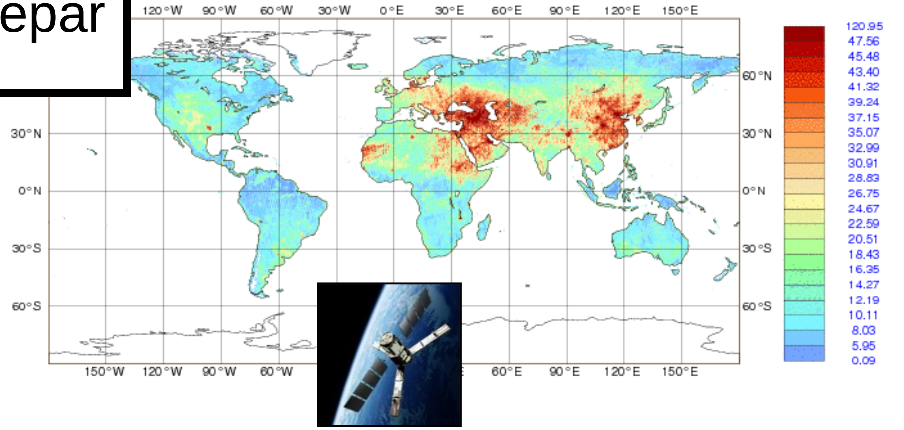
STATISTICS FOR RADIANCES FROM FROM SMOS

Operational Monitoring of surface soil moisture related satellite data:

ASCAT soil moisture (m^3m^{-3}) SMOS Brightness temperature (K)

Stdev FG_depar
Sept. 2013





Passive microwave remote sensing
Soil Moisture and Ocean Salinity mission

SMOS ESA Earth Explorer mission (2009-present)

L-band (1.4 GHz) instrument. Optimal frequency for soil moisture remote sensing

Sun-synchronous, quasi-circular orbit at altitude 758 km. 06.00 hrs local solar time at ascending node. Three days revisit at Equator

Dual polarisation: H and V in the Earth reference, xx and yy in the antenna frame reference

Multi-angular measurements 0 to 60°

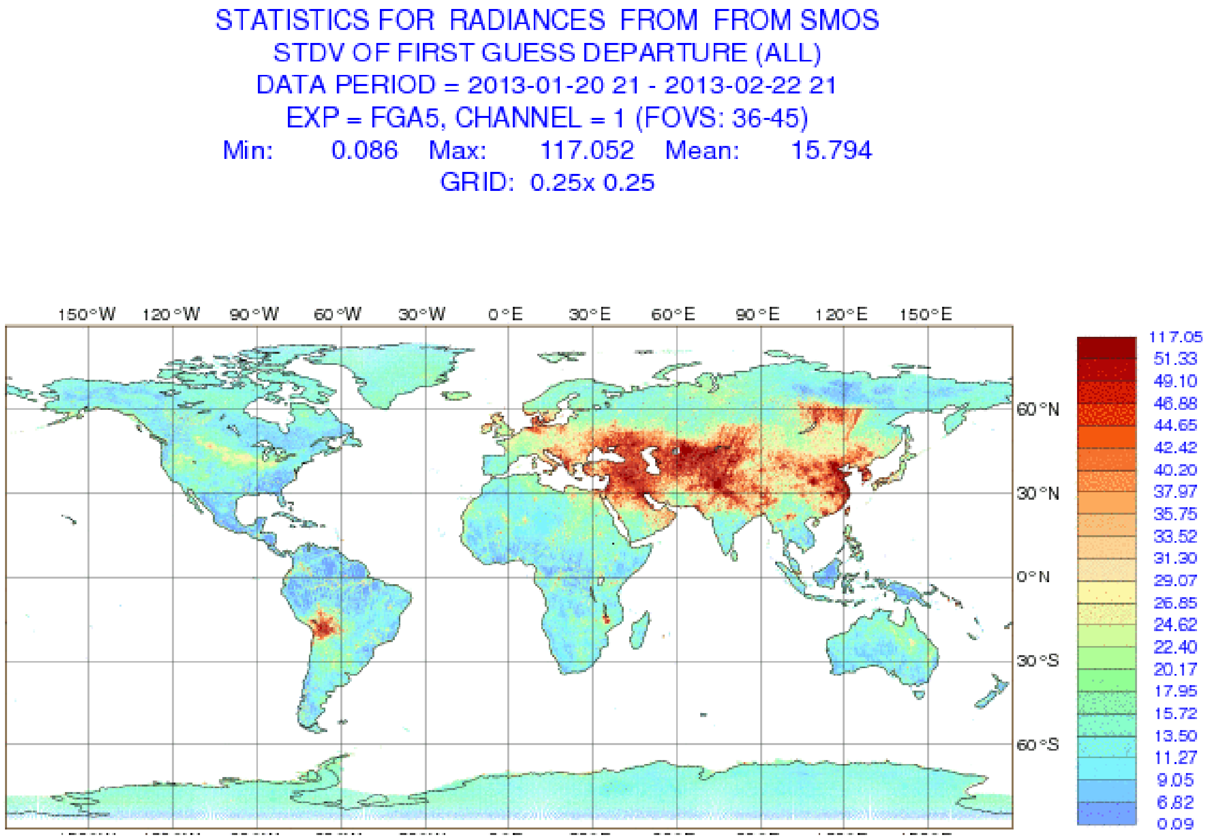
ECMWF and CMC: use NRT SMOS Brightness Temperature (TB) data

→ Use observation operator to simulate L-band TB: Community Microwave Emission Modelling Platform (CMEM)

SMOS Monitoring

Near real time (NRT) monitoring of SMOS TB at ECMWF
(Muñoz Sabater et al. ECMWF Newsletter & IEEE TGRS 2011)

RFI (Radio Frequency Interference) sources impact on FG departures (Obs-model) : large standard deviation (StDev); Lots of RFI sources switched off in Europe, new sources identified in 2012,major issue in Asia.

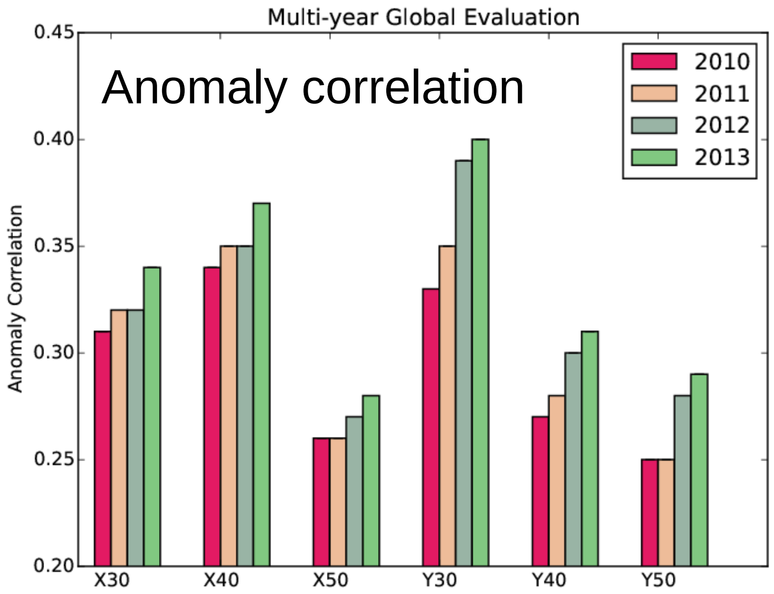


StDev first guess departure (Obs-Model)
In Kelvin for Jan-Feb 2013

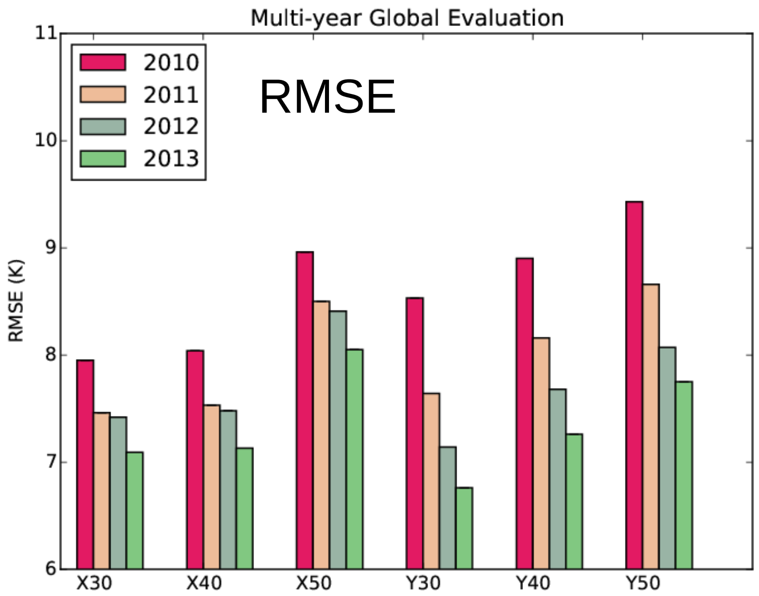
SMOS Forward modelling and Bias correction

- CMEM: ECMWF Community Microwave Emission Modelling Platform
  → produce reprocessed ECMWF SMOS TB for 2010-2013
- Comparison between ECMWF TB and SMOS NRT TB (both reprocessed)
- **Consistent improvement of SMOS data at Pol xx and yy, for incidence angles 30, 40, 50 degrees**

de Rosnay et al, in prep



Polarisation (xx or yy) and incidence angle (30, 40, 50)



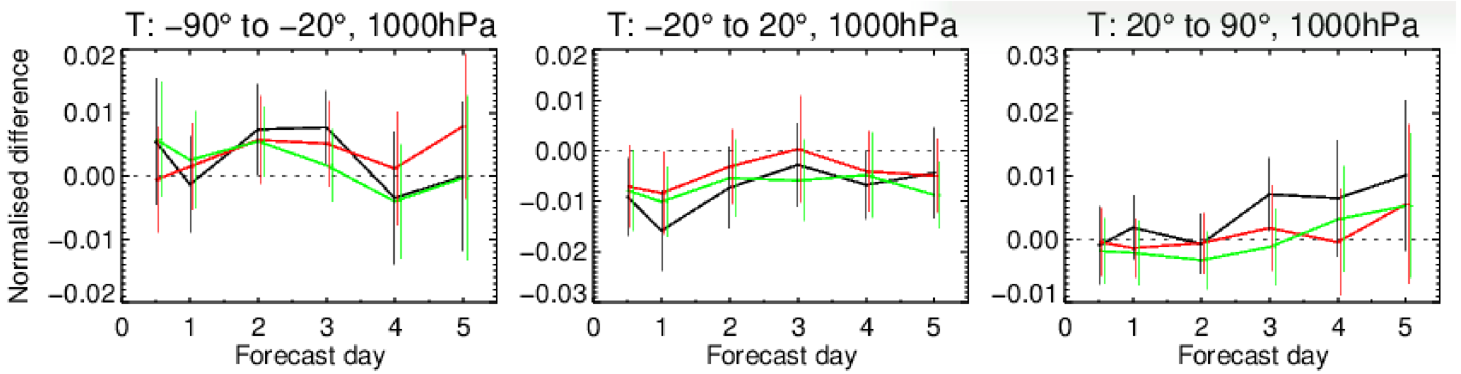
Polarisation (xx or yy) and incidence angle (30, 40, 50)

SMOS data assimilation impact on atmospheric scores

Muñoz-Sabater et al. in prep

Normalized change in rms of fc error:

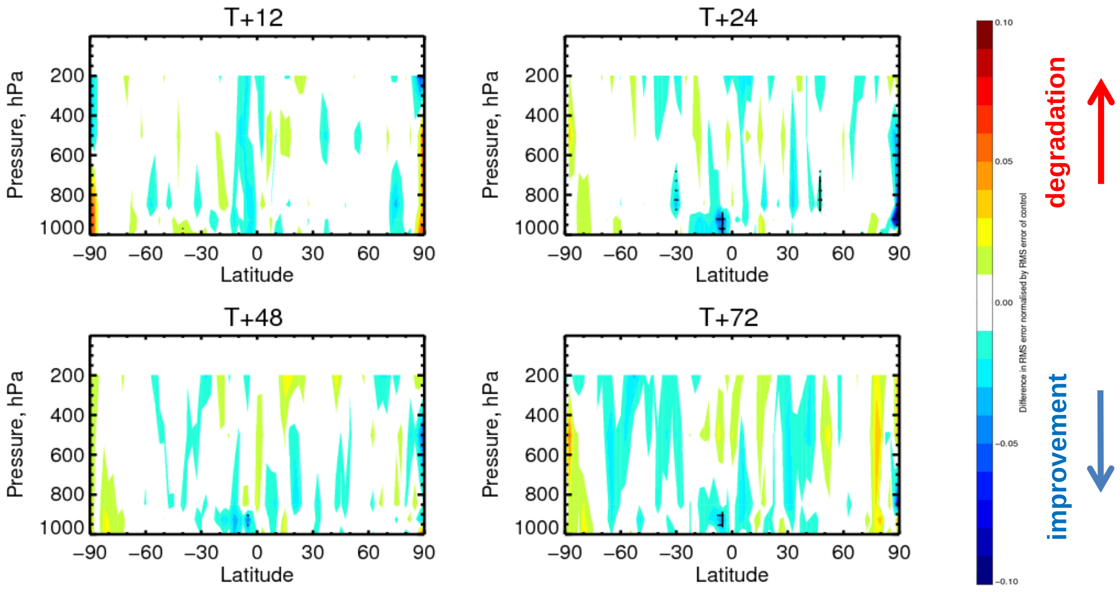
Config.1
Config.2
Config.3



SH- extratropics ***Tropics*** ***NH- extratropics***

Several configurations tested with different background and observation errors

Based on short experiments
Longer experiment under evaluation



Outline

Part I

- Introduction
- Snow analysis
- Screen level parameters analysis

Part II

- Soil moisture analysis
    - OI and EKF analyses
    - Use of Satellite data ASCAT and SMOS
- **Summary and future plans**

Summary and future plans

- Most NWP centres analyse soil moisture and/or snow depth
- Land Data Assimilation Systems: run separately from the atmospheric data assimilation
- Variety of approaches for snow and soil moisture

- **Operational snow analysis systems:**
  - Rely on simple analysis methods (Cressman, 2D-OI, or climatology)
  - Uses in situ snow depth data (SYNOP and national networks) and NOAA/NESDIS snow cover data
  - No Snow Water Equivalent products used for NWP (yet)

Summary and future plans

Operational Soil Moisture analysis systems for NWP:

- **Approaches**: **1D-OI** (Météo-France, CMC, ALADIN, HIRLAM, ECMWF ERA-I); **EKF** (DWD, ECMWF, UKMO); **Offline Land Surface Model (LSM)** using analysed atmospheric forcing (NCEP: GLDAS / NLDAS)

- **Data**: Most Centres rely on screen level data (**T2M and RH2m**) through a dedicated OI analysis, **ASCAT** (UKMO, ECMWF NWP & EUMETSAT H-SAF)

- Compared to the OI, the EKF analysis improves both Soil Moisture and T2m:

→ Relevance of screen level parameters to analyse soil moisture (ECMWF,CMC)

→ Consistency in the Land surface models between soil moisture and screen level parameters

Summary and future plans

- Developments of multi-variate and ensemble approaches (ECMWF, CMC, Météo-France)
- Continuous developments to assimilate ASCAT soil moisture and SMOS brightness temperature in NWP systems
- Use of new satellites, e.g. NASA SMAP (launched January 2015)
- Assimilation of vegetation parameters (Leaf Area Index)
- Increase coupling between land and atmospheric assimilation

- Long term perspectives:
  - Importance of horizontal processes (river routing)
  - Assimilation of integrated hydrological variables such as river discharges: e.g. Surface Water Ocean Topography (SWOT 2019)

Thank you for your Attention!

Useful links:

ECMWF LDAS: https://software.ecmwf.int/wiki/display/LDAS/LDAS+Home

Snow Watch: http://globalcryospherewatch.org/reference/documents/

HarmoSnow COST Action: http://www.cost.eu/COST_Actions/essem/Actions/ES1404
http://costsnow.fmi.fi/

ECMWF Land Surface Observation monitoring:
https://software.ecmwf.int/wiki/display/LDAS/Land+Surface+Observations+monitoring