Outline

Part I (Monday)

- Introduction
- Snow analysis
- Screen level parameters analysis

Part II (Tuesday)

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

Soil moisture : Essential Climate Variable (GCOS)

- Crucial variable for numerical weather and climate predictions

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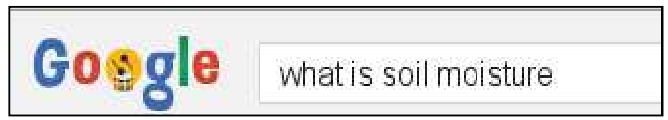


Soil moisture : Essential Climate Variable (GCOS)

- Crucial variable for numerical weather and climate predictions


About 6,140,000 results (0.34 seconds)

Google what is soil moisture

Soil moisture

Soil moisture is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration. As a result, **soil moisture** plays an important role in the development of weather patterns and the production of precipitation.

Soil Moisture Study - Global Hydrology and Climate Center
wwwghcc.msfc.nasa.gov/landprocess/lp_home.html

Feedback

Soil moisture : Essential Climate Variable (GCOS)

- **Crucial variable for numerical weather and climate predictions**

→ Influence weather through its impact on evaporation and other surface energy fluxes

  - Controls the partitioning of Energy (latent / sensible heat fluxes) at the soil-atmosphere interface

Soil moisture : Essential Climate Variable (GCOS)

- **Crucial variable for numerical weather and climate predictions**

→ Influence weather through its impact on evaporation and other surface energy fluxes

  - Controls the partitioning of Energy (latent / sensible heat fluxes) at the soil-atmosphere interface

- **Key variable in hydrological processes**
  - Controls the partitioning of Precipitation into infiltration/runoff
  - Evaporation from bare soil, transpiration from vegetation

- **Impact on plant growth and carbon fluxes**

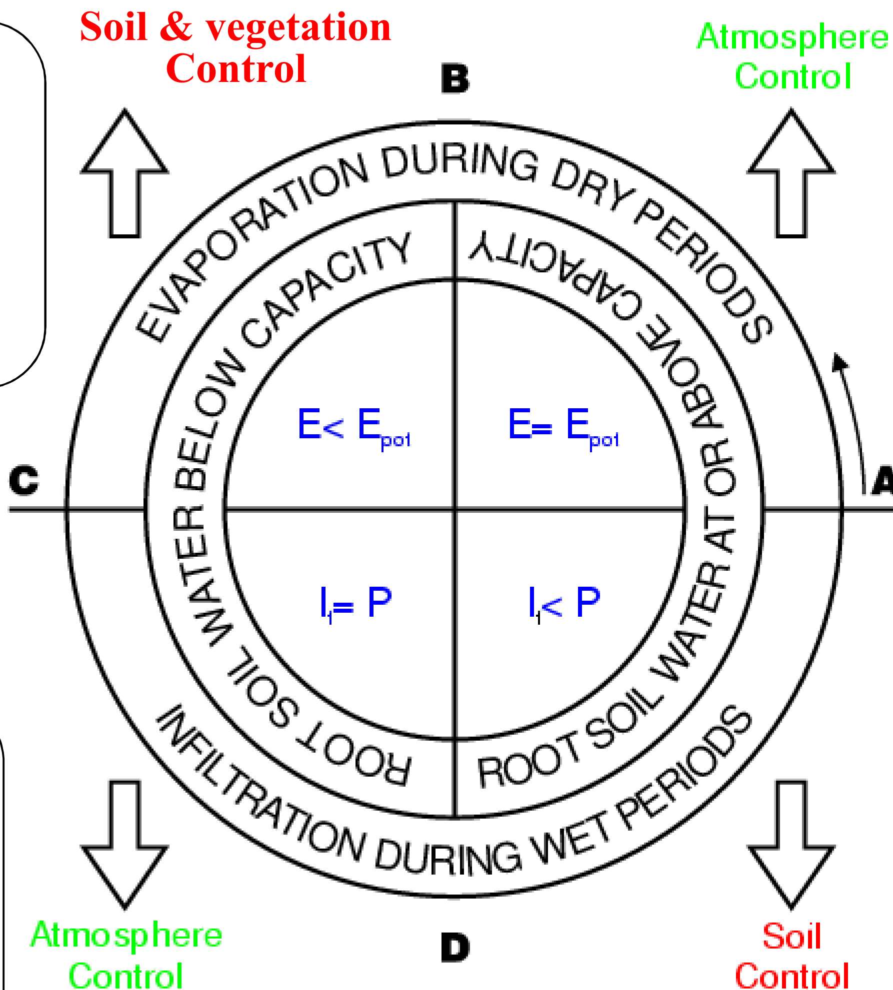
Schematic depiction of the interaction between the soil hydrology and the atmosphere: illustrates the behaviour of the soil and the atmosphere within a complete cycle (wet period followed by a dry period) [Dooge 1992]

B-C : SM has decreased below a certain level

- E limited by plant-physiological mechanism
- E drops below its maximal value ($E<E_{po}$)

A-B : after a long episode of rainfall

- Soil saturated with water
- SM is determined by E
- Atmosphere controls E rate (at $E=E_{pot}$)



C-D : Precipitation starts again

- Dry soil is taking up water
- Infiltration equals precipitation ($I_f=P$)

D-A : Maximum soil water level is reached

- Soil's ability to take up precipitation ↓
- Part of the precipitation goes into runoff ($I_f<P$)

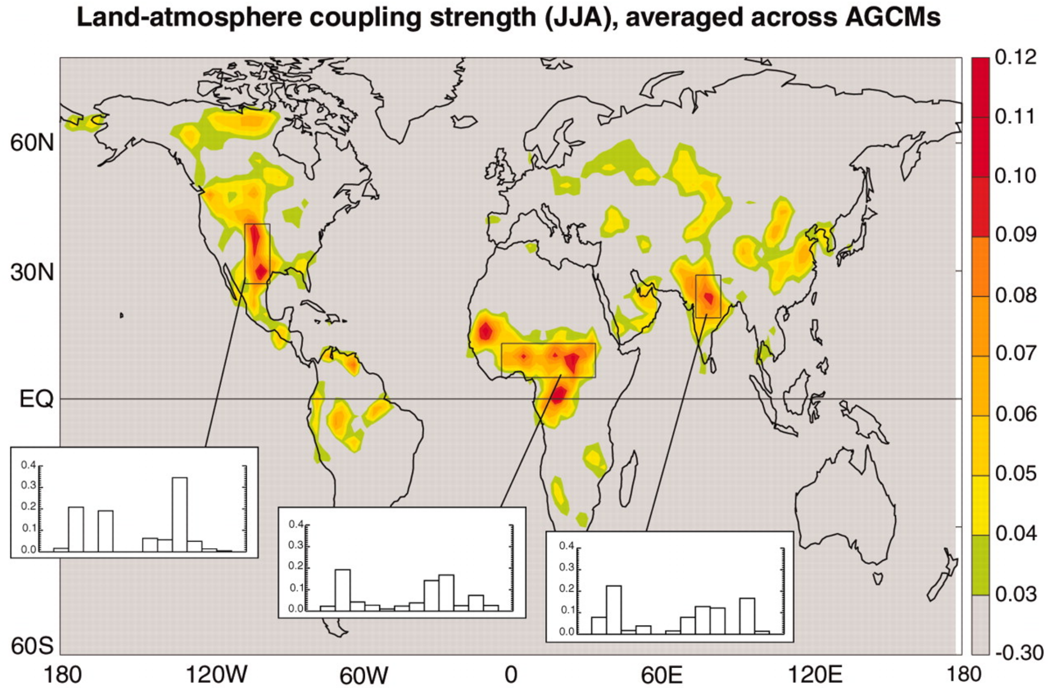
ECMWF

Impact of soil moisture on precipitation : Koster et al., Science, 2004

The GLACE Team: *Regions of Strong Coupling Between Soil Moisture and Precipitation*. **Science** 20 August 2004: Vol. 305 no. 5687 pp. 1138-1140 DOI: 10.1126/science.1100217

Multimodel estimation of land atmosphere coupling strength :

A global initialization of soil moisture may enhance precipitation prediction skill during Northern Hemisphere summer (*in the transition zones between wet and dry climates*)

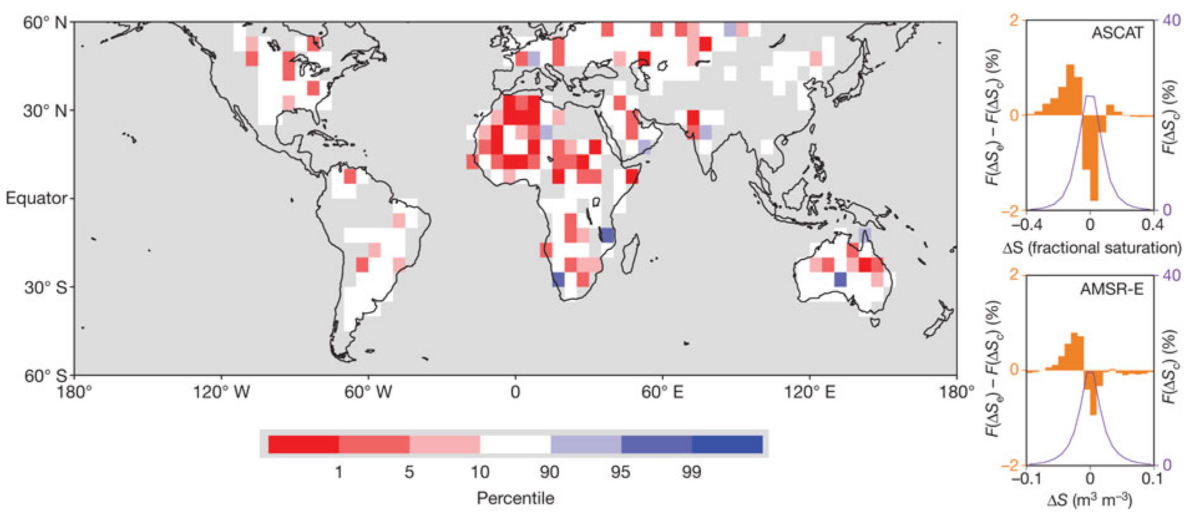


Multimodel estimation of the regions on Earth where precipitation is affected by soil moisture anomalies during Northern Hemisphere summer [*Koster et al., Science, 2004*]

Impact of soil moisture on precipitation : Taylor et al., Nature, 2012

Taylor et al.: *Afternoon rain more likely over drier soils*. **Nature**, 489, 423–426 (20 September 2012) . doi:10.1038/nature11377

“[…] During dry periods, soil-water deficit can limit evapotranspiration, leading to warmer and drier conditions in the lower atmosphere. Soil moisture can influence the development of convective storms through such modifications of low-level atmospheric temperature and humidity, which in turn feeds back on soil moisture […]”



Regions of the world where afternoon precipitation is observed more frequently than expected over wet (blue) or dry (red) soils,

Impact of soil moisture on hot extremes: Mueller & Seneviratne, PNAS, 2012

Mueller & Seneviratne : *Hot days induced by precipitation deficits at the global scale*. **Proceedings of the National Academy of Sciences of the United States of America** PNAS. doi: 10.1073/pnas.1204330109

"[…] Soil moisture deficits were mostly found to affect hot extremes through the energy balance: Low soil moisture availability reduces evaporative cooling and increases atmospheric heating from sensible heat flux. Nonetheless, indirect feedbacks with cloud cover and dry air advection may also play a role […]"

"[…] surface moisture deficits are a relevant factor for the occurrence of hot extremes in many areas of the world. This suggests that hot day predictions could be substantially improved in operational forecasts in these regions with the aid of soil moisture initialization […]"

Land surface modelling & Land data assimilation system

- In atmospheric models land surface processes are simulated by the involved Land Surface Model (LSM)

- LSM represents the lowest boundary conditions and the surface part of the continental hydrological cycle, prognostic variables include :
  - Soil Moisture, Soil temperature
  - Snow mass, temperature, density, albedo

- LSM provides the initial conditions for the Land Data Assimilation System

Soil moisture analysis evolution at ECMWF

1994 / 99

- **Nudging scheme**

Viterbo et al. (1996),

- Prevents soil moisture drifts in summer of dry periods
- Soil moisture increments are linearly related to errors of the lowest model level specific humidity
- But diurnal and annual cycle are systematically damping, because nudging scheme compensates to model biases but it does it too rapidly.
- The resulting SM is not always realistic.

$$\theta_i^a = \theta_i^f + C_v D \Delta t \times (q^a - q^f) \,,$$

D: nudging coefficient (constant=1.5g/Kg),

Cv: fraction of vegetation

Δt = 6h, q specific humidity

1999 / 2010

- **Optimal Interpolation**

Mahfouf (1991),

Mahfouf (2001)

- Takes into account forecast and observations errors statistics
- Uses also observations of 2m temperature,
- However forecast errors on screen level variables are often not linked to errors in SM → OI contains many switches
- The OI using screen level variables improves fluxes but degrades soil moisture → requirement to use future satellite soil moisture data (more direct SM information)

$$\Delta\theta_i = \theta_i^a - \theta_i^f = \alpha_i (T^a - T^f) + \beta_i (RH^a - RH^f) \,.$$

α, β: OI optimal coefficients

However they are not optimal as in the OI a linear assumption is assumed, whereas the lowest atmosphere has a non-linear response to SM variations.

2010 - today

- **SEKF**

Drusch et al. (2009)

de Rosnay et al. (2013)

- Need for an advance data assimilation system, which also is able to integrate non regular spatial-temporal observations
- The physical relationship between observations and soil moisture is computed in a dynamical way through the jacobians.
- It is flexible to account for land surface model evolution and new analysed variables


$$\theta^a_i = \theta^f_i + K\,(y - \mathcal{H}[\theta^f_i])$$

K= Kalman gain, depends on the background and observation errors

y: vector of observations

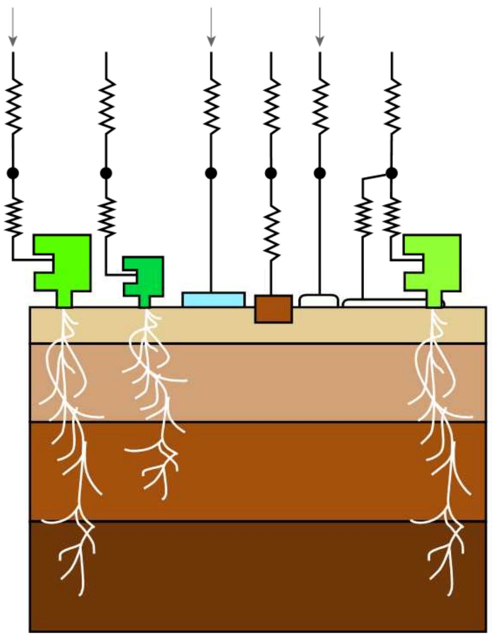
H: non-linear observation operator

1D Optimal Interpolation (OI) analysis

1D-OI for SM : used in operations from 1999 to 2010, and currently in ERA-Interim, Météo-France, CMC, ALADIN, HIRLAM

Relies on the link between soil variables and the lowest atmospheric level:

- **Too dry soil → 2m air too dry & too warm**
- **Too wet soil → 2m air too moist & too cold**



References HTESSEL:
Balsamo et al., JHM 2009

H-TESSEL Land Surface Model

→ 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):

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

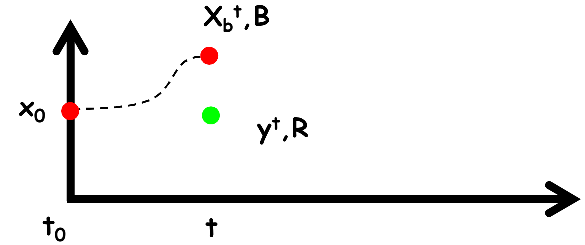
a and b: analysis and background ; i: soil layer.
Optimal Coefficients α , β and c

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

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

ECMWF

EKF Equations (1/3)



$$\boxed{\mathbf{x_a}^t = \mathbf{x_b}^t + \mathbf{K}(\mathbf{y_0}^t - \mathcal{H}[x_b^t])}$$

We consider a control vector x (dimension N_x) that represents the prognostic equations of the land surface model M that evolves with time as:

$$x^t = M(x^0)$$

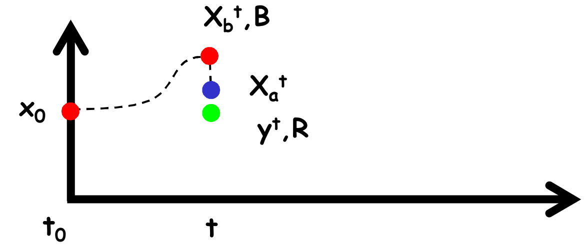
At a given time t a vector of observations is available y (dimension N_y) characterized by an error covariance matrix R

An observation operator $\mathcal{H}$ allows to get the model counterpart of the observations:

$$y^t = \mathcal{H}(x^t)$$

The background vector (short range forecast) at time t (x_b^t) is characterised by an error covariance matrix B.

EKF Equations (2/3)



A new value of x written x_a^t (the analysis), obtained by an optimal combination between the observations and the background is :

$$\mathbf{x_a^t = x_b^t + K(y_0^t} - \mathcal{H}[x_b^t])$$

Where K is the gain matrix defined by :

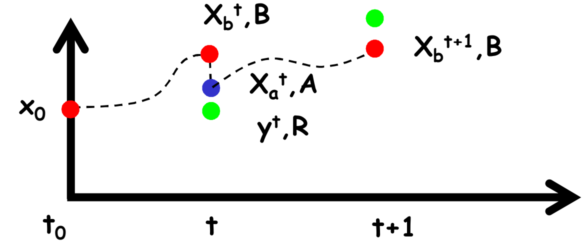
$$\mathbf{K = BH^T(HBH^T+R)^{-1}}$$

The operator H (together with its transpose H^T) is the jacobian matrix of $\mathcal{H}$ defined as (N_y raws and N_x columns) :

$$H_{ij} = \frac{\partial y_i}{\partial x_j} \approx \frac{y_i(x + \delta x_j) - y_i(x)}{\delta x_j}$$

The elements of H are estimated by finite differences by individually perturbing each component x_j of the control vector x by a small amount δx_j

EKF Equations (3/3)



The analysis state is characterized by an analysis error covariance matrix :

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

The analysis is cycled by propagating in time the two quantities x_a and A up to the next time where observations are available :

$$\mathbf{X}_b^{t+1}= \mathcal{M}(\mathbf{x}_a^t)$$

$$\mathbf{B}^{t+1} = \mathbf{M}\mathbf{A}^t\mathbf{M}^T+\mathbf{Q}$$

This equations requires the Jacobian matrix M of the model M that is defined as (between time t and time t_0) :

$$M_{ij} = \frac{\partial y_{i\,t}}{\partial x_{j\,0}}$$

A new matrix Q (model error covariance matrix) needs to be defined

→ In our case the error covariance matrix B is not cycled (assumed to be constant); **Simplified Extended Kalman Filman**

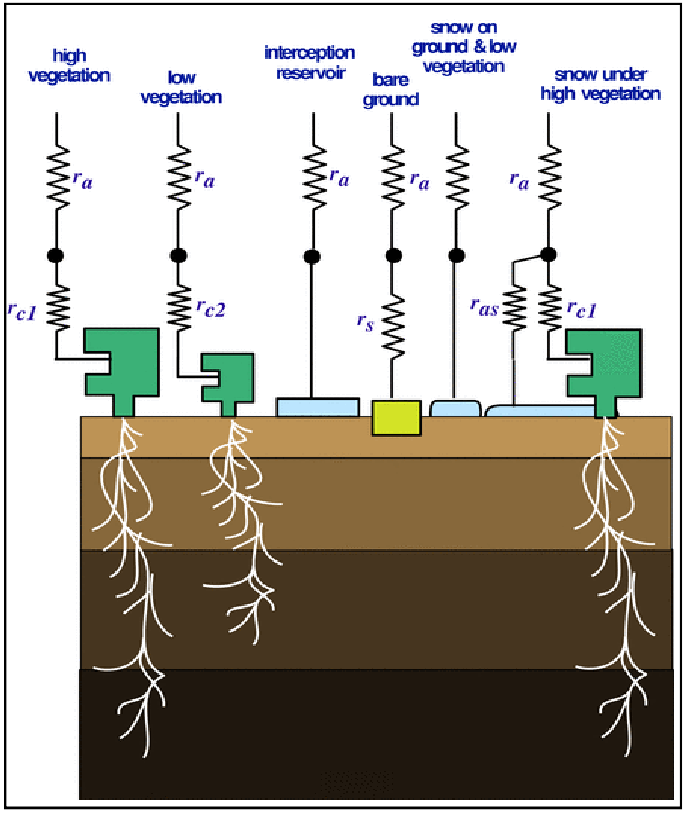
Simplifed EKF soil moisture analysis

Simplified EKF corrects the trajectory of the Land Surface Model

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

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

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



Observations used:

- **Operational NWP**: Conventional SYNOP observations **(T2m, RH2m)**
- **Operational ASCAT DA for EUMETSAT: SM-DAS-2**
- **Research**: **SMOS Data Assimilation**

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

Simplified EKF computing cost

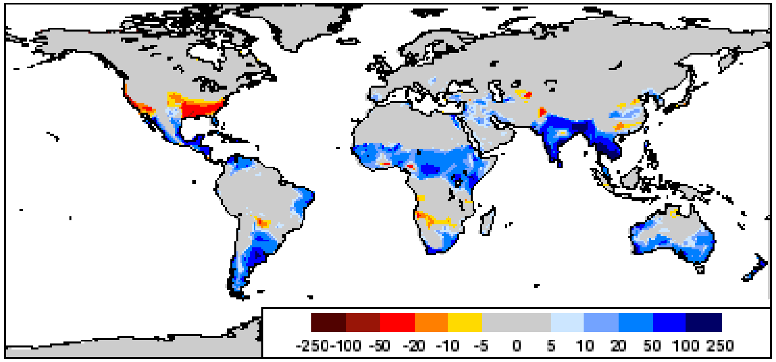
Computing Time (CPU in s) per 12h cycle:

	T159 (125km)	T255 (80km)	T799 (25km)	T1279 (16km)
1D OI	3	10	20	30
EKF	3.10^3	10^4	2.10^5	5.10^5
4D-Var		$4.\ 10^5$	10^6	$2.5\ .10^6$

EKF running on several processors → Elapsed time ~ 500s at the operational high resolution (T1279)

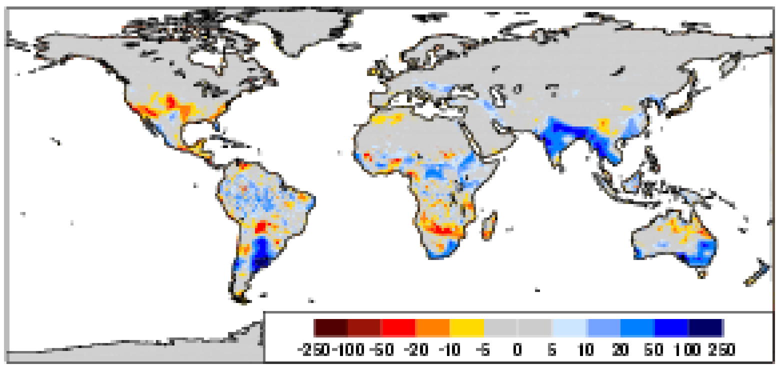
Simplified EKF and OI Comparison

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

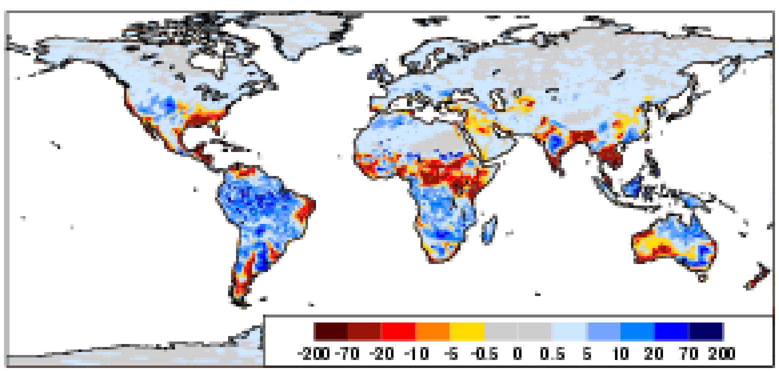


OI

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



EKF

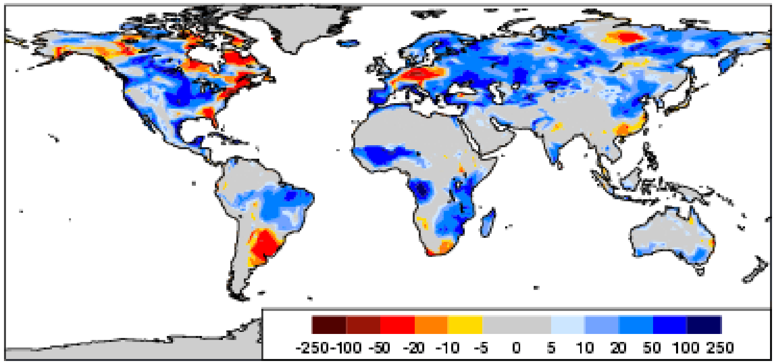


|EKF|-|OI|

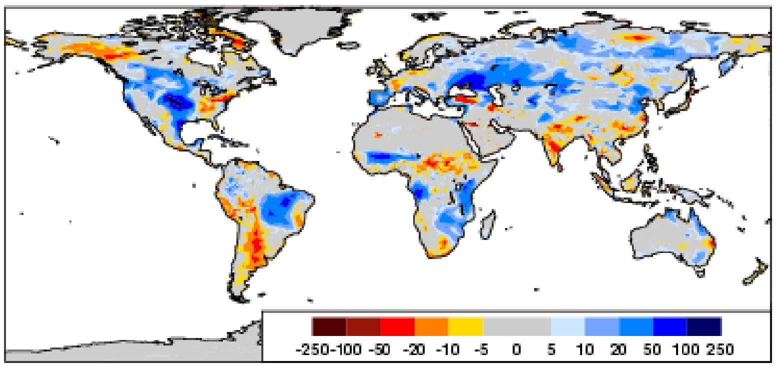
ECMWF

Simplified EKF and OI comparison

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

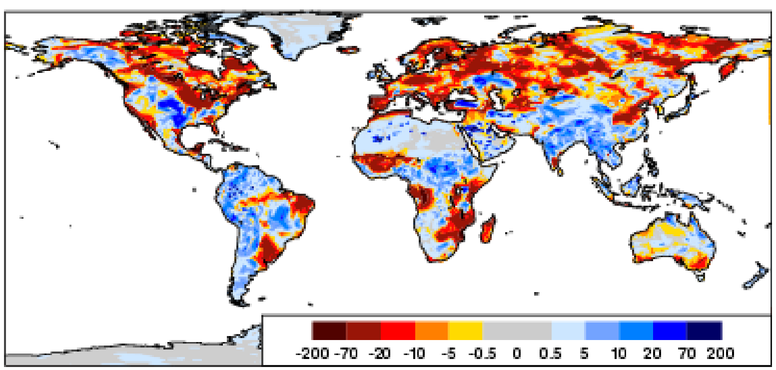


OI



EKF

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

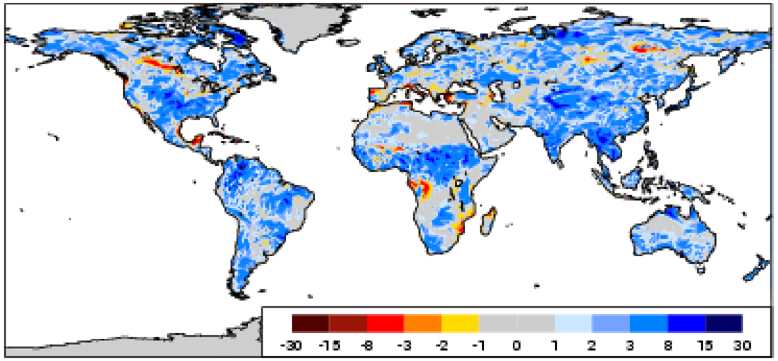


|EKF|-|OI|

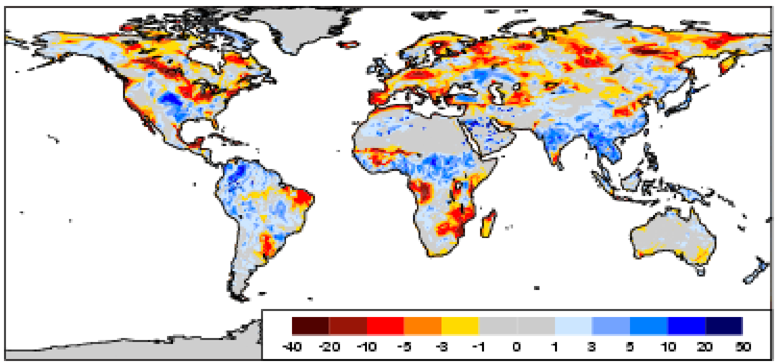
ECMWF

Simplified EKF and OI comparison

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

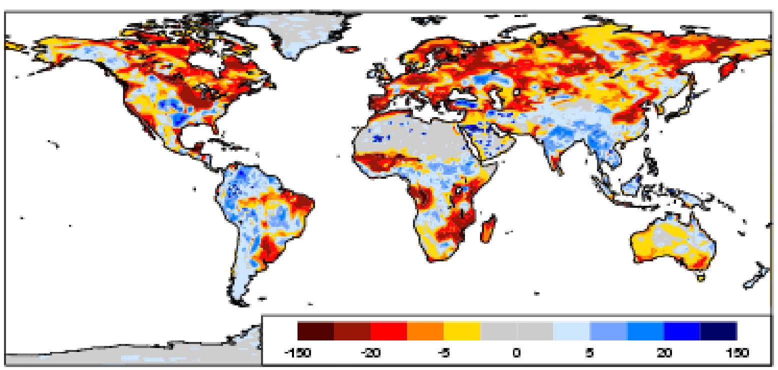


Layer 1 (0-7cm)



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)

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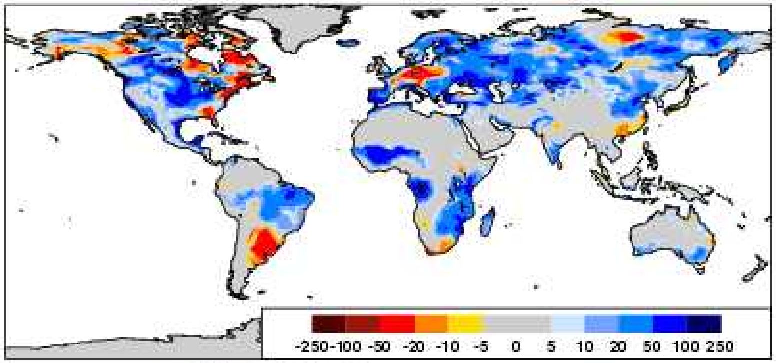
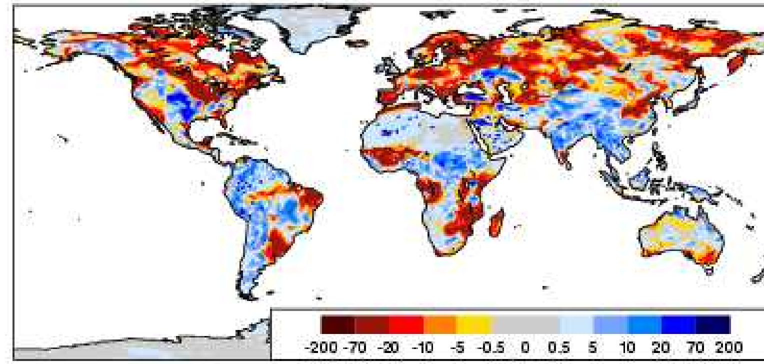
Simplified EKF and OI comparison

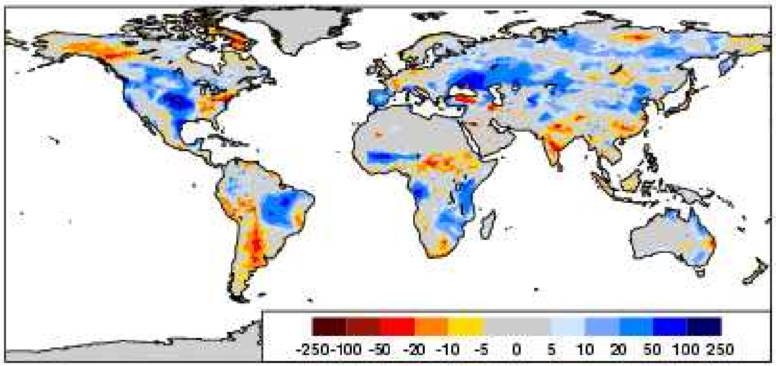
0-1m Soil Moisture increments for July 2009 (mm)

|EKF|-|OI|



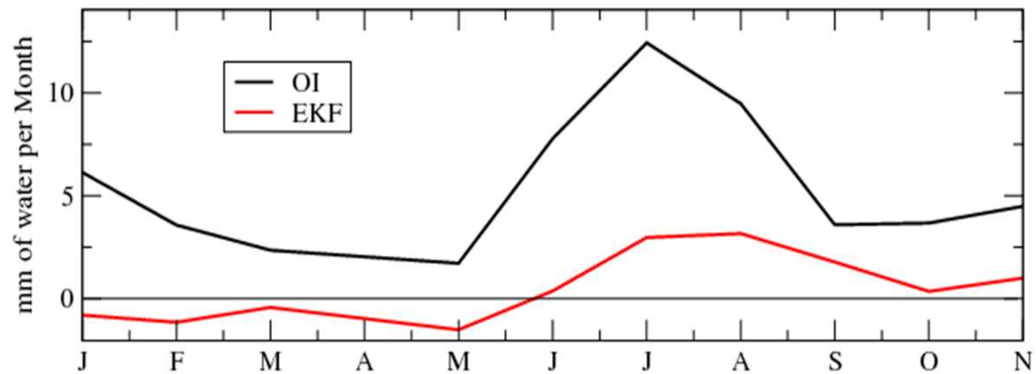
OI





EKF

Global Soil Moisture Increments (1st meter of soil)



-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

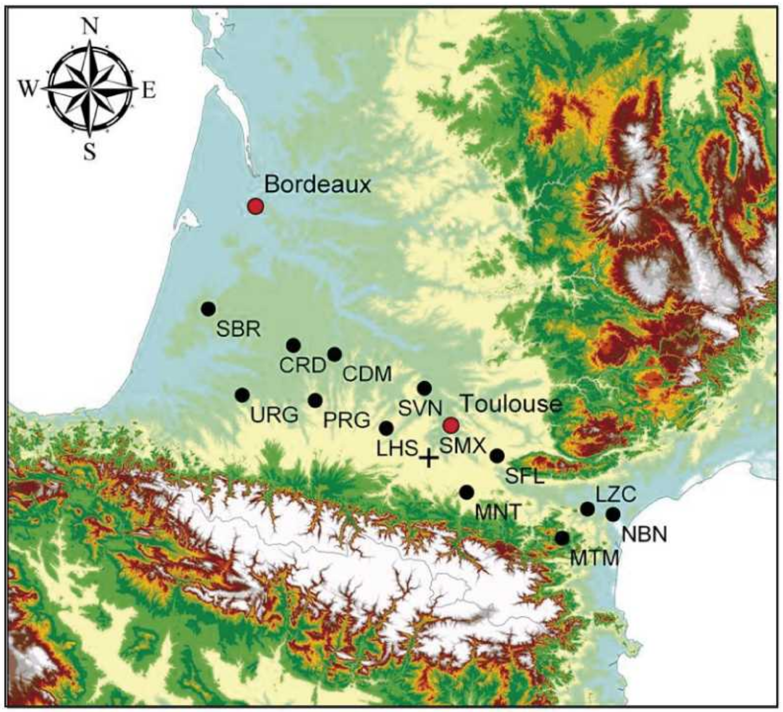
- **EKF prevents undesirable and excessive soil moisture corrections**

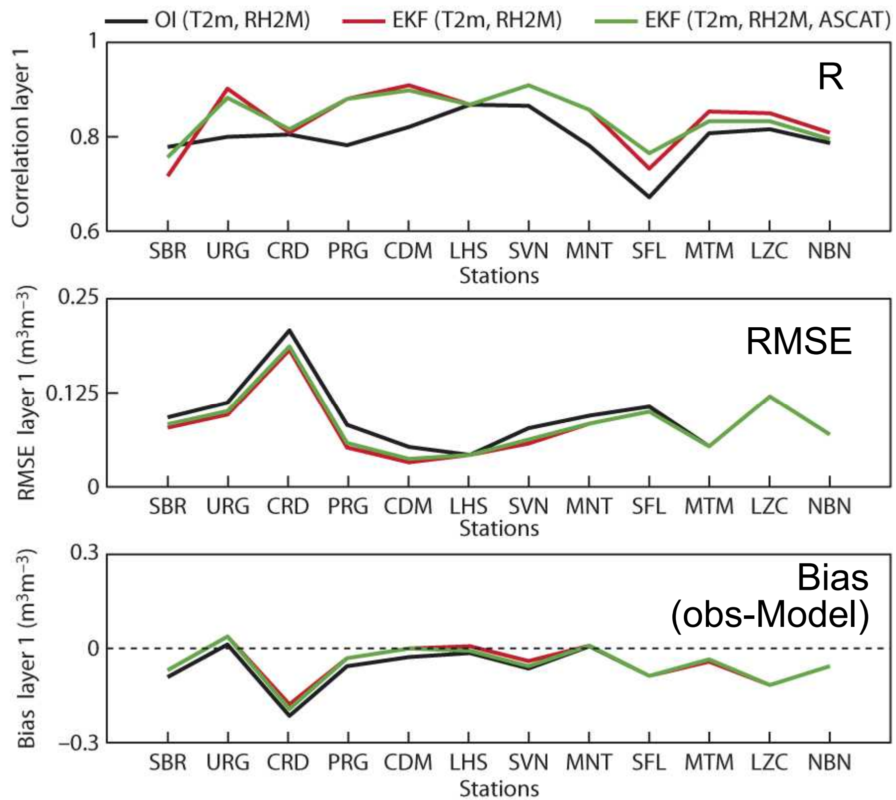
ECMWF

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

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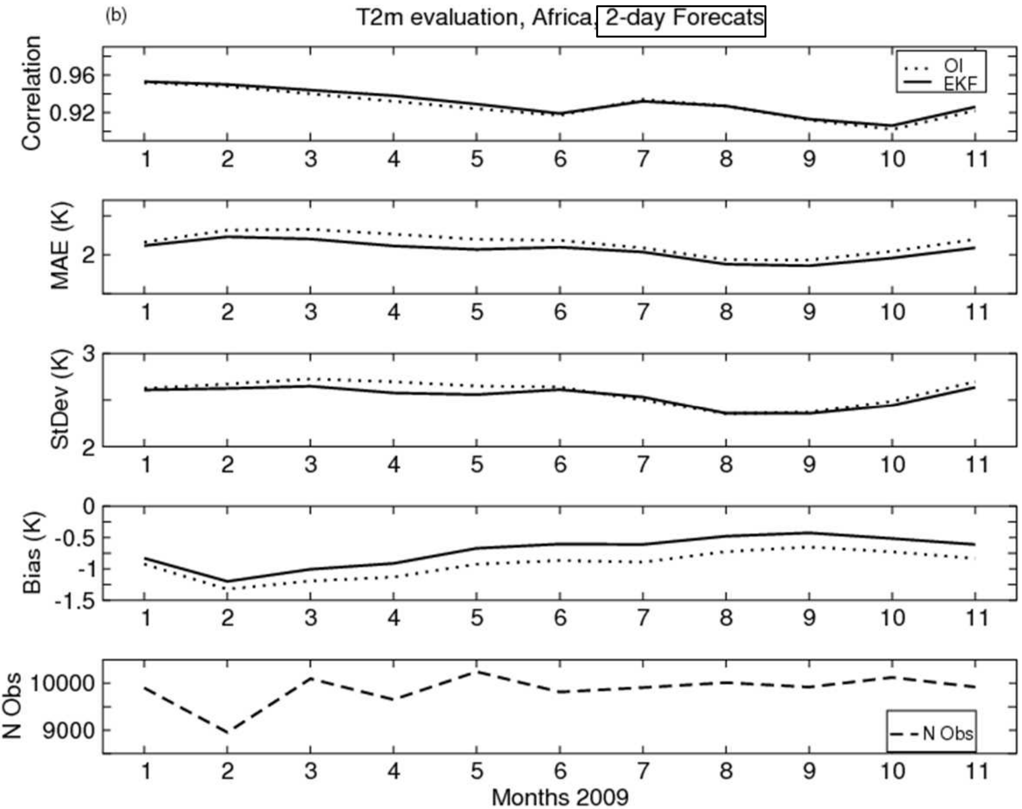
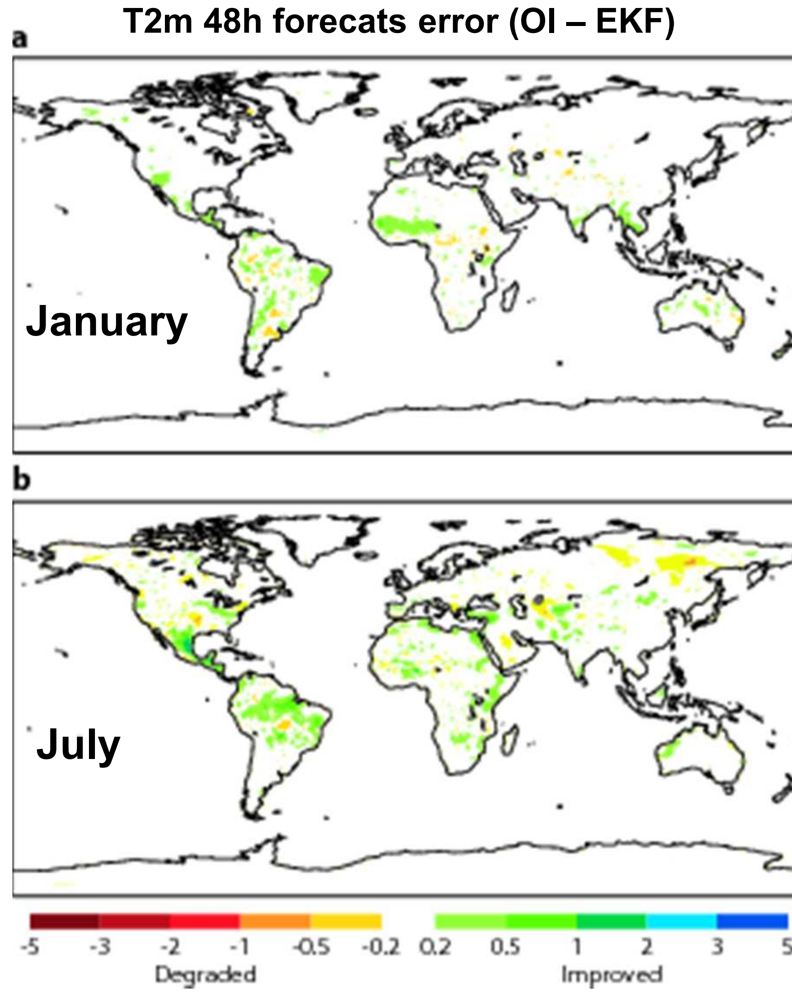
T2m 48-h Forecast Evaluation





- EKF improves (compared to the 1D OI) analysis and FC of Soil Moisture and Screen level parameters
- EKF enables the use of satellite data for the surface

EKF surface analysis

- Dynamical estimates of the Jacobian Matrix that quantify accurately the physical relationship between observations and soil moisture

  → Improves (compared to 1D OI) both soil moisture and screen level parameters (T2m, RH2m)

- Flexible to account for the land surface model evolution

- Possible to use of new generation of satellite data:

  - SM active microwave (MetOp/ASCAT, L-band SMAP)

  - SM passive microwave (L-band SMOS, SMAP)

- Makes it possible to combine different sources of information

SYNOP

ASCAT

SMOS

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

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

STATISTICS FOR SOIL MOISTURE FROM METOP-B/ASCAT

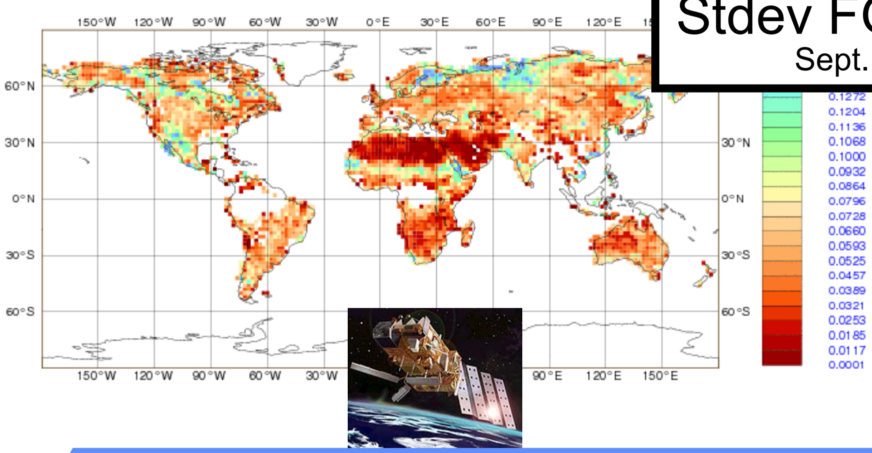
STATISTICS FOR RADIANCES FROM FROM SMOS

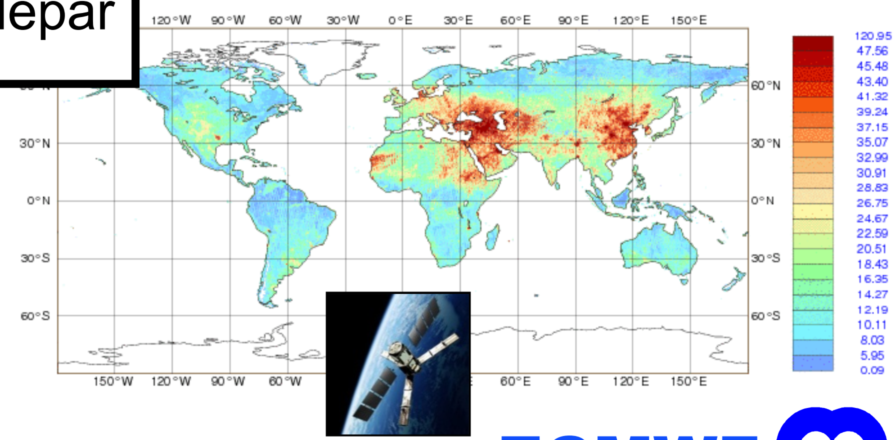
Operational Monitoring of surface soil moisture related satellite data:

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

Stdev FG_depar

Sept. 2013





ECMWF

ASCAT Bias Correction

- ASCAT is a soil moisture index (0-1) ; ECMWF uses volumetric SM

- 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 course of Hans Hersbach on Bias Correction)

→ **For soil moisture, we follow the simplified Bias correction** proposed by Scipal et al., WRR 2008, based on Cumulative Distribution Function Matching: **CDF-Matching**

Revised in 2011 to account for seasonal cycle (de Rosnay et al., 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 $a = \overline{\theta}_{model} - \overline{ms}_{ascat}\,(\sigma_{model} / \sigma_{ms\_ascat})$

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

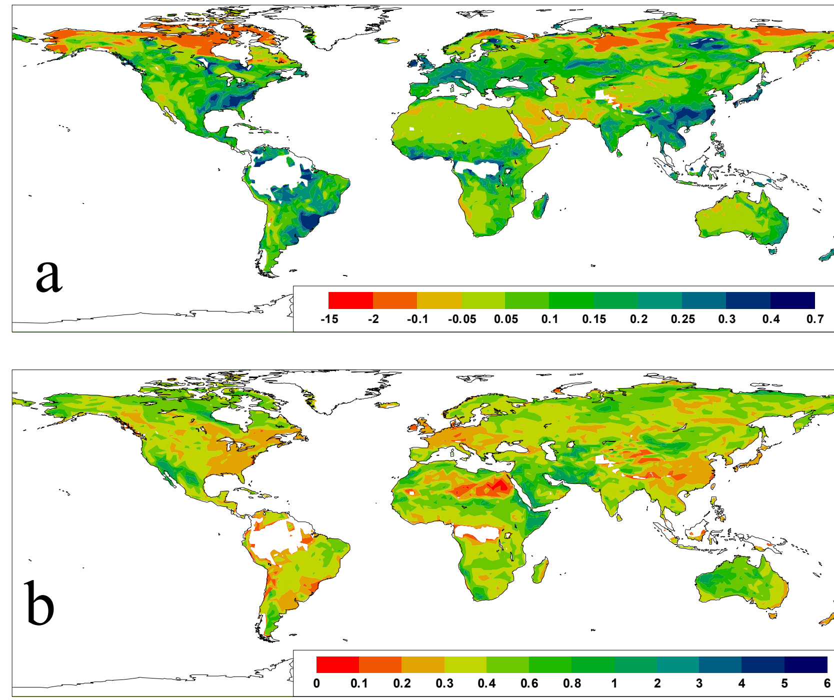
→ Matches mean and variance

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

Efficient data assimilation relies on accurate bias correction

ASCAT revised bias correction

de Rosnay et al., RD memo 2011

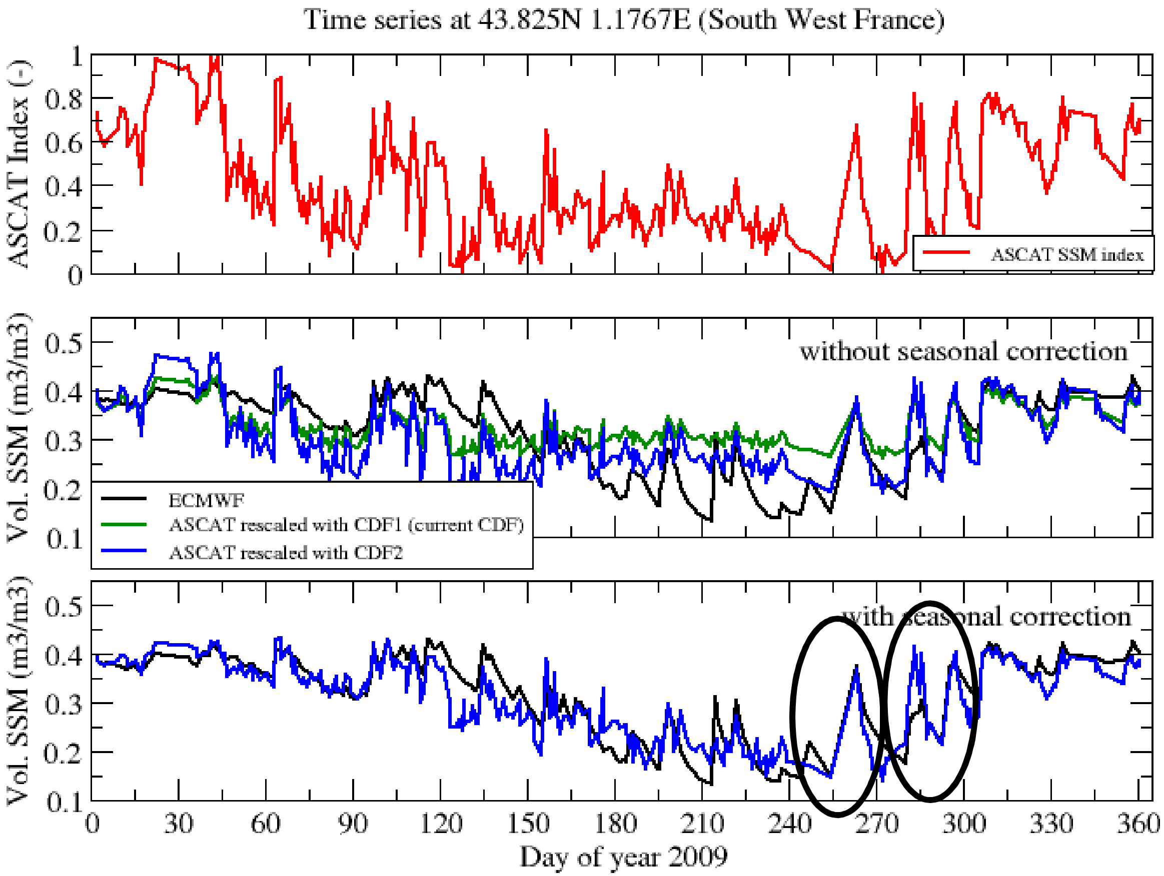
ASCAT index

ECMWF soil moisture

(ASCAT old BC)

ASCAT new BC static

ASCAT new BC dynamic

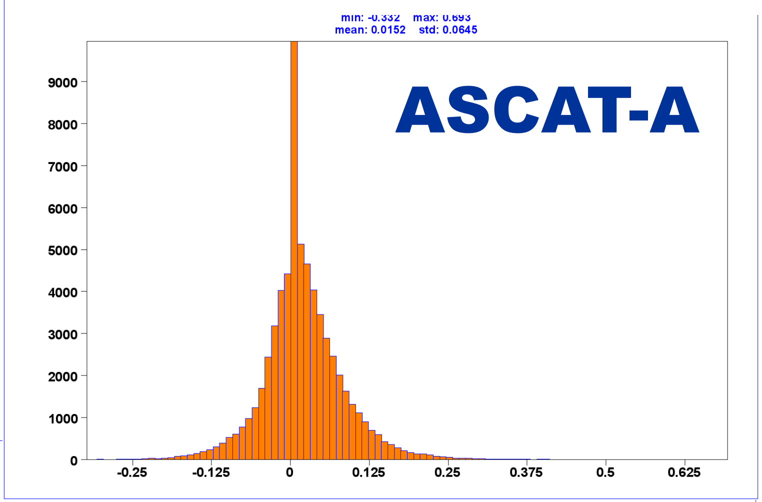


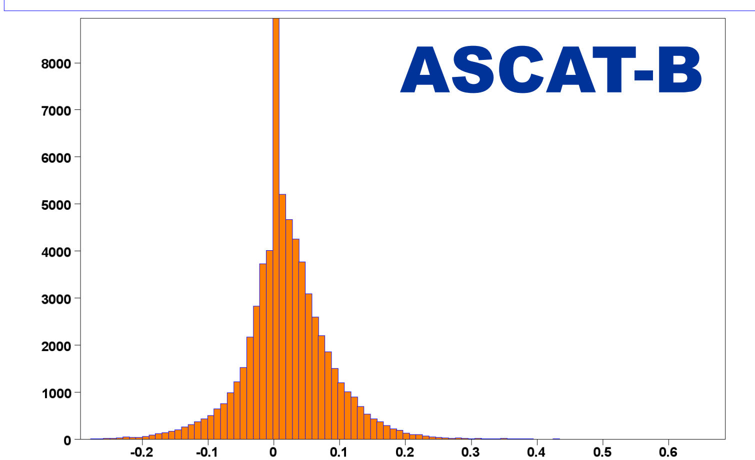
ECMWF

ASCAT-A and ASCAT-B

- Metop-B launched in September 2012
- ASCAT-B soil moisture acquisition since 23 November 2012, soil moisture operational monitoring since 06 December 2012
- Consistent ASCAT-A and ASCAT-B soil moisture

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



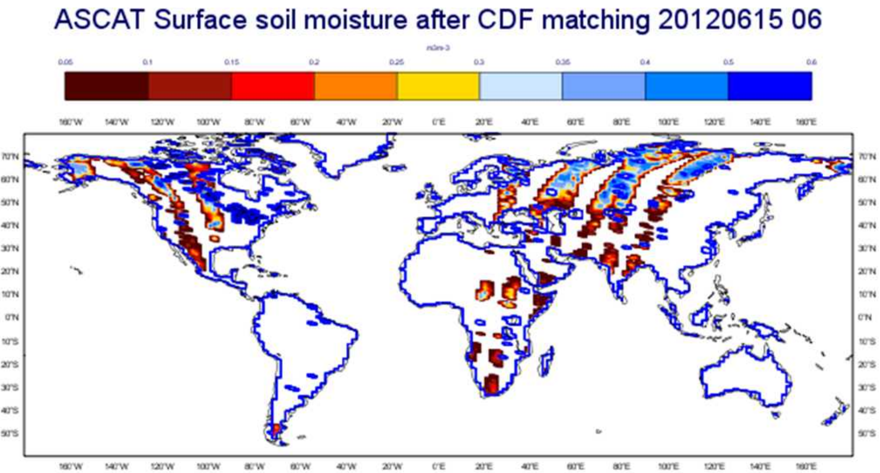


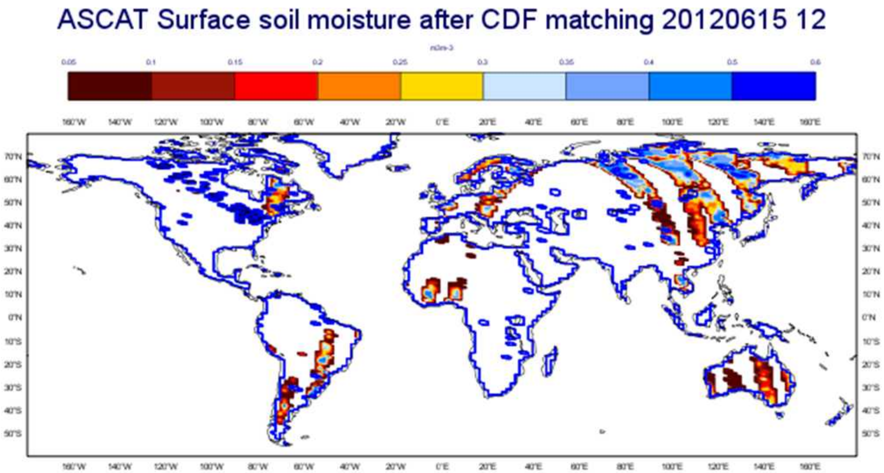
	Nb	Mean $m^3.m^{-3}$	Std $m^3.m^{-3}$
ASCAT-A	64893	0.0152	0.0645
ASCAT-B	65527	0.0149	0.0663

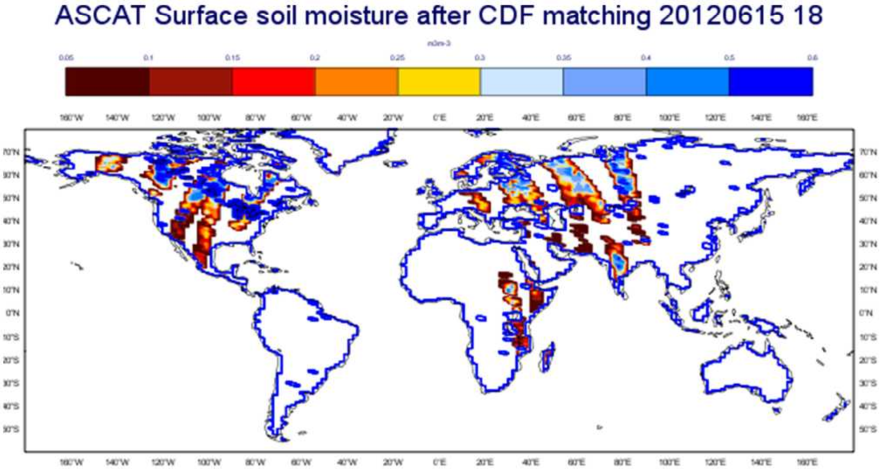
Operational monitoring:

http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/slmoist/

ASCAT data [0-1] / Bias correction [m^3m^{-3}]







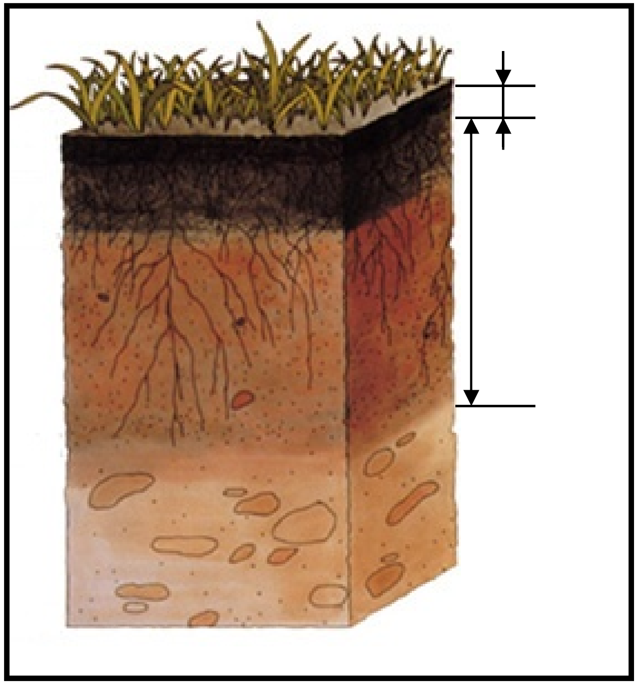
Quality Control on ASCAT data :

- Topographic complexity ≤20
- Wetland Fraction ≤ 15
- Noise level ≤8
- Processing flag = 0

Soil moisture from remote sensing

- Remote Sensing : Provides quantitative information about the water content of a **shallow near surface layer**

- Main variable of interest for applications such as meteorological modelling and hydrological studies : **root-zone soil moisture**



→ Accurate retrieval requires to account for physical processes: Complementarities between satellite data and models

Space agencies retrieval of level 3 / level 4 products rely on data assimilation approaches

ASCAT Soil Moisture data assimilation

The EUMETSAT Network of Satellite Application Facilities

H SAF
Support to Operational Hydrology and Water Management

operational from Jul. 2012

ECMWF Atmospheric conditions

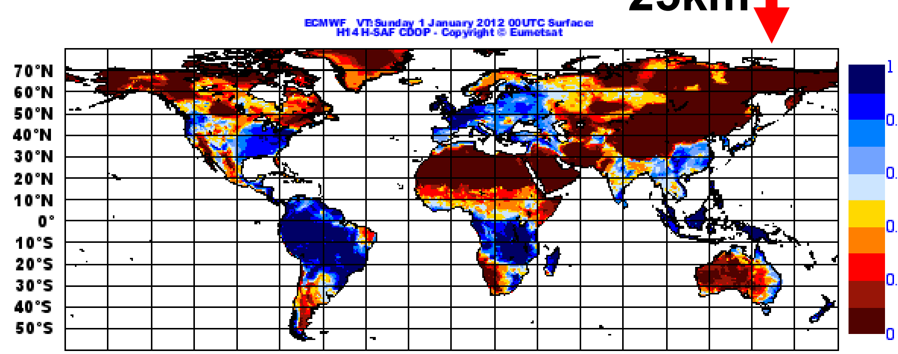
SYNOP
T2m RH2m

ASCAT
Surface SM

EKF
Soil Moisture Analysis

SM-DAS-2:
Soil Moisture Profile

~25km



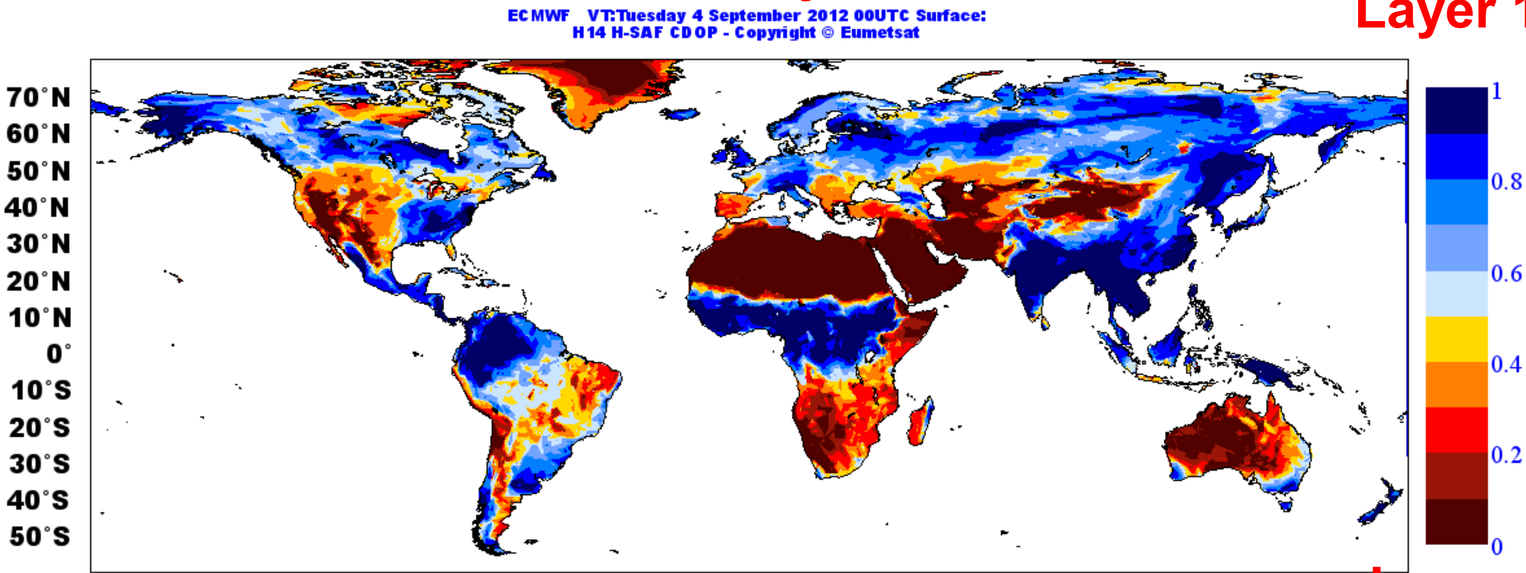
EKF corrects the trajectory of the Land Surface Model

http://hsaf.meteoam.it/soil-moisture.php

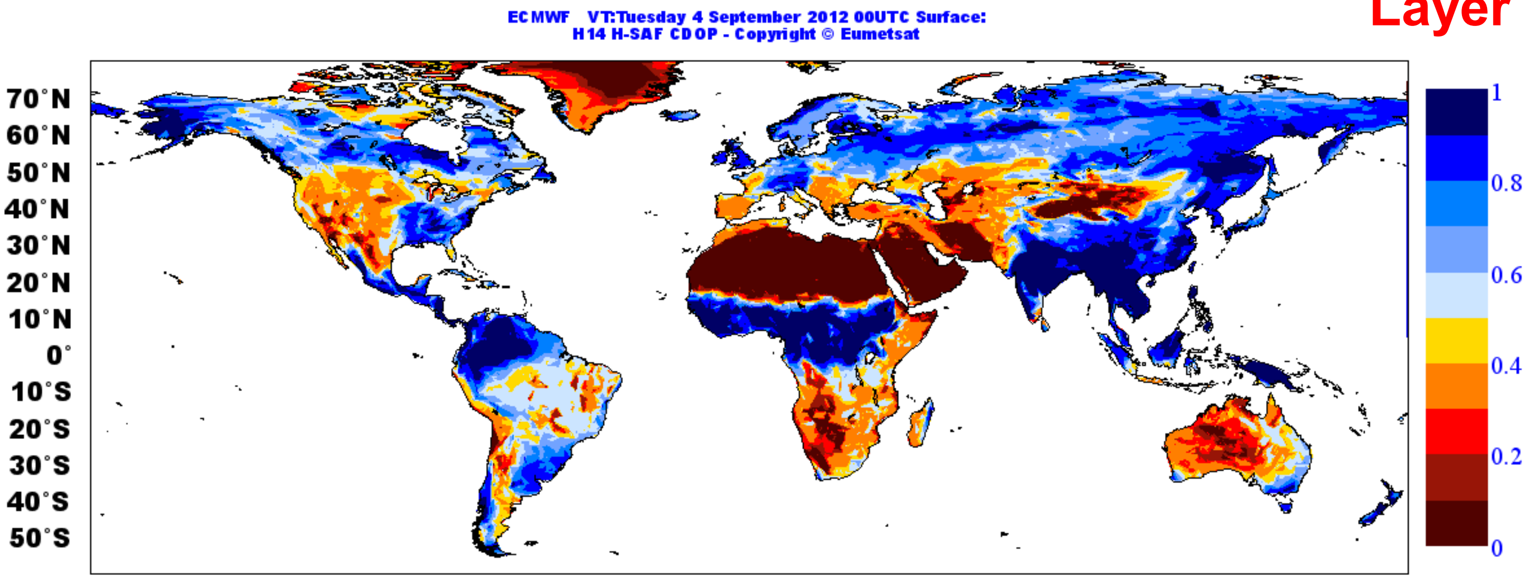
ASCAT soil moisture data assimilation

SM-DAS-2 available on 4 soil layers

Layer 1 (0-7cm)



Layer 2 (7-28cm)



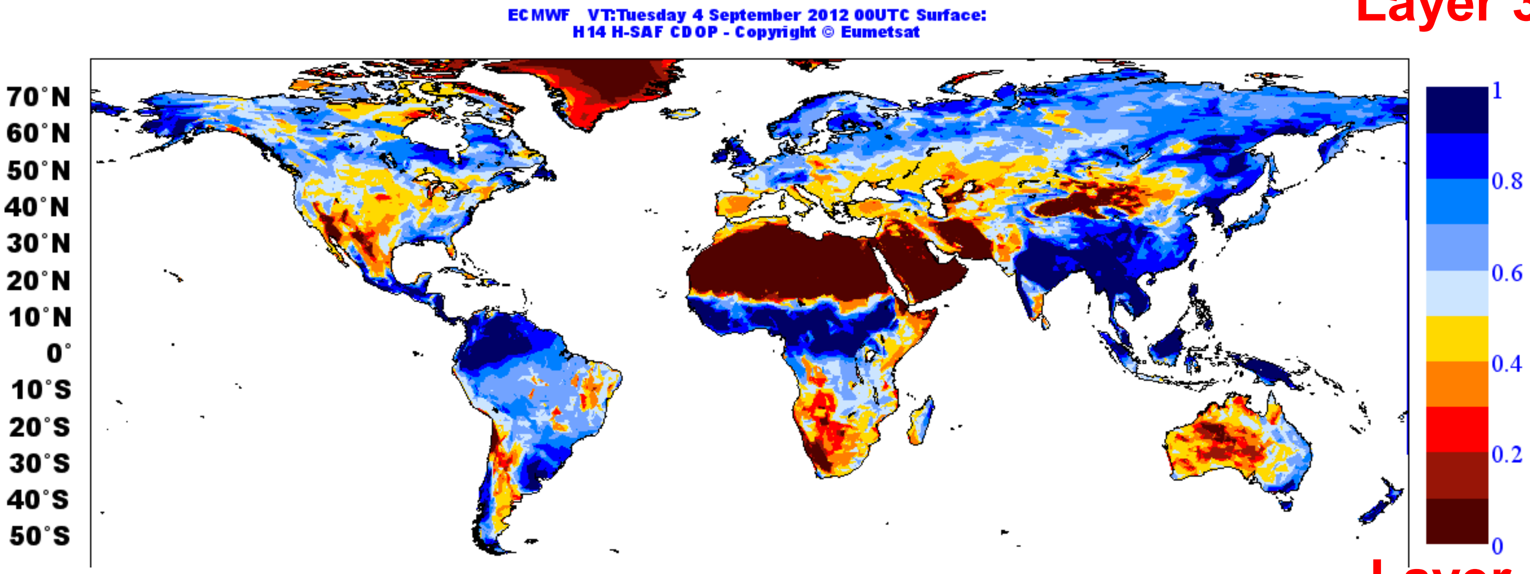
H SAF
Support to Operational Hydrology and Water Management

ECMWF

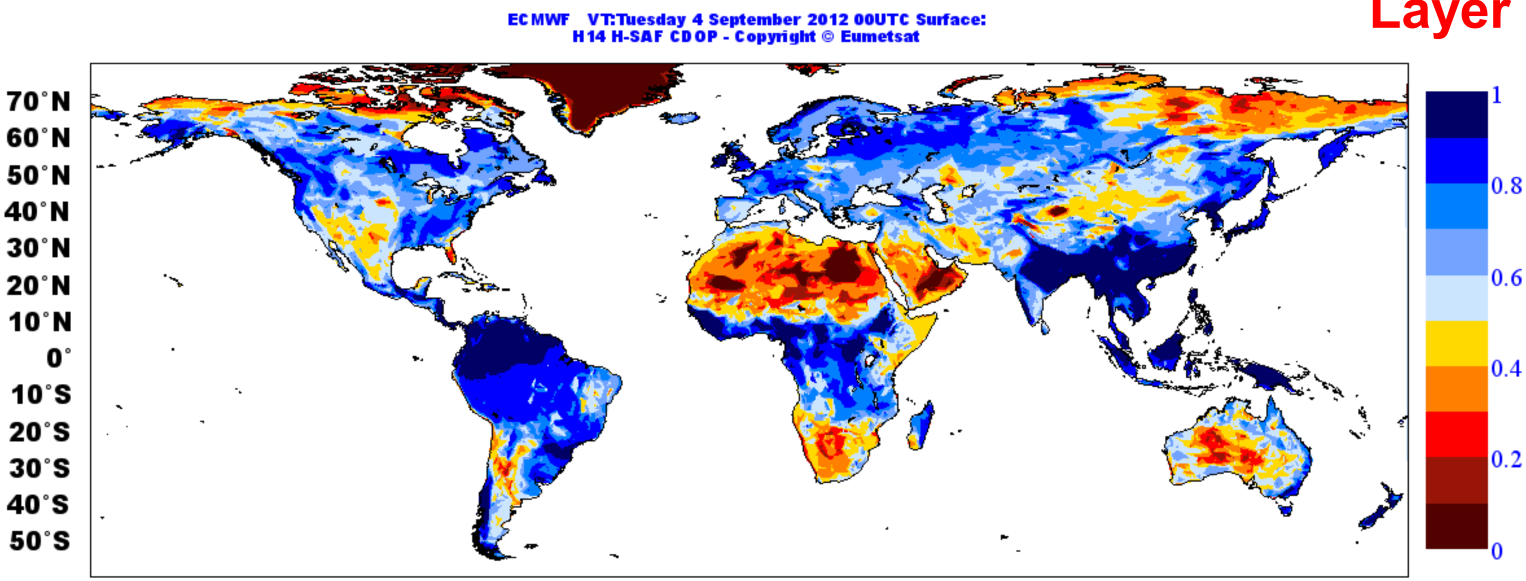
ASCAT soil moisture data assimilation

Available on 4 soil layers

Layer 3 (28-100 cm)



Layer 4 (1-3 m)



H SAF
Support to Operational Hydrology and Water Management

ECMWF

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), multi-angular

NRT Brightness Temperature

Dedicated soil moisture mission

→ Strongest sensitivity to soil moisture

STATISTICS FOR SOIL MOISTURE FROM METOP-B/ASCAT

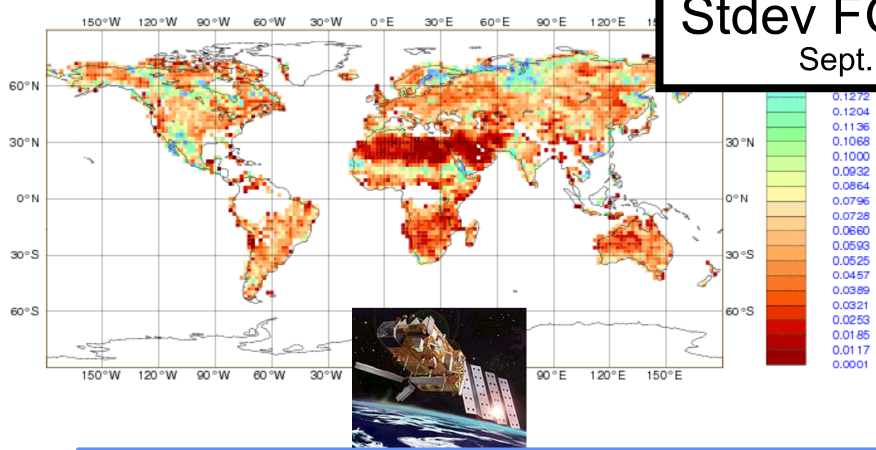
STATISTICS FOR RADIANCES FROM FROM SMOS

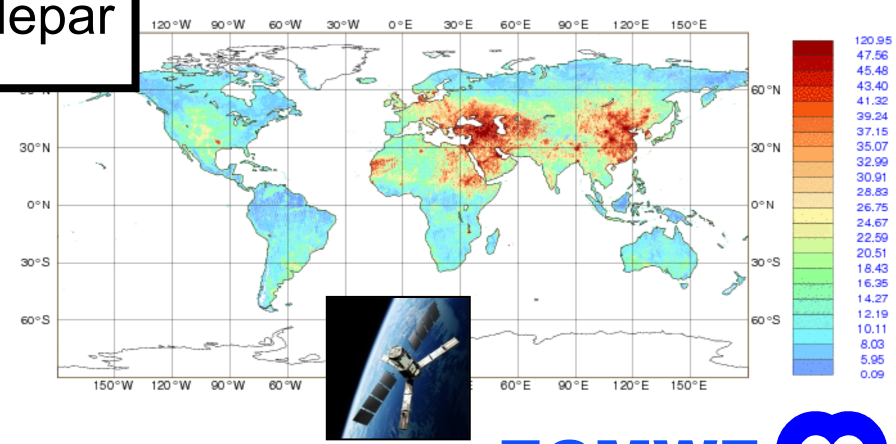
Operational Monitoring of surface soil moisture related satellite data:

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

Stdev FG_depar

Sept. 2013





ECMWF

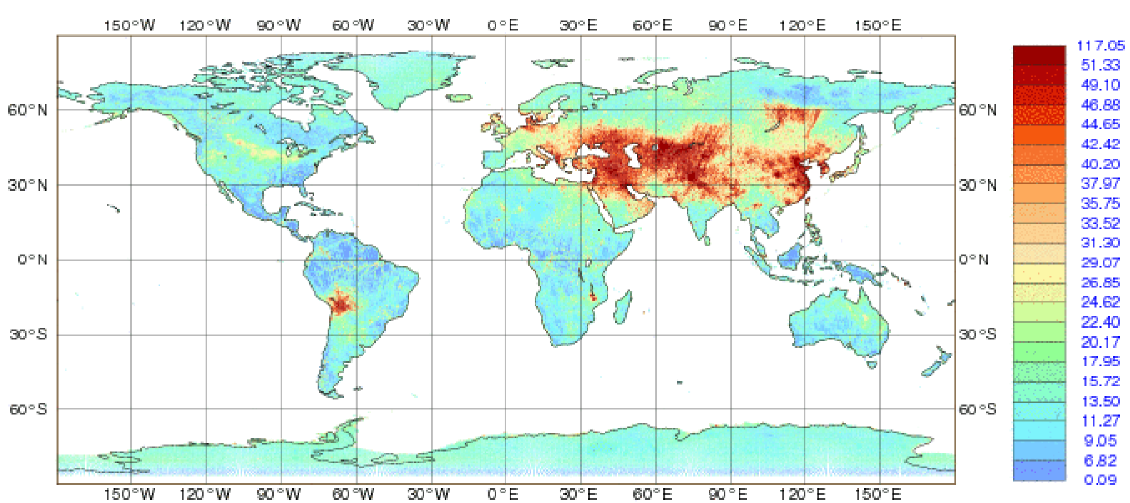
SMOS Monitoring

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.

STATISTICS FOR RADIANCES FROM FROM SMOS
STDV OF FIRST GUESS DEPARTURE (ALL)
DATA PERIOD = 2013-01-20 21 - 2013-02-22 21
EXP = FGA5, CHANNEL = 1 (FOVS: 36-45)
Min: 0.086 Max: 117.052 Mean: 15.794
GRID: 0.25x 0.25

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

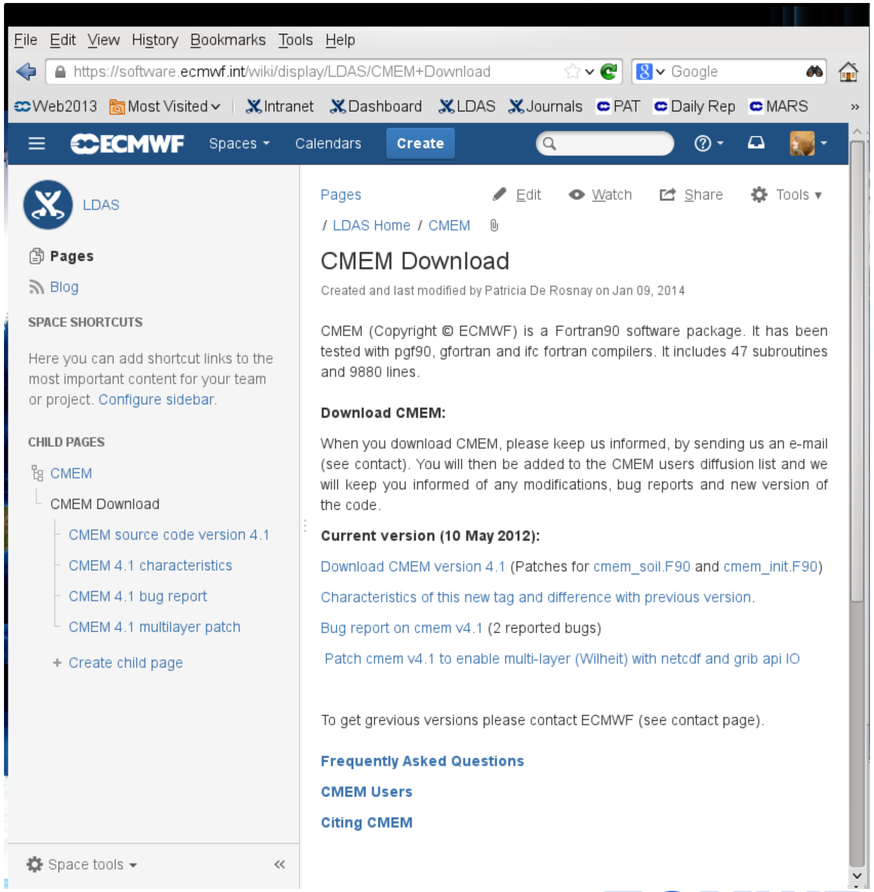


ECMWF

Microwave emission modelling

- → **Forward operator: microwave emission model**
- **ECMWF Community Microwave Emission Modelling Platform (CMEM)**
- I/O interfaces for the Numerical Weather Prediction Community.

https://software.ecmwf.int/wiki/display/LDAS/CMEM



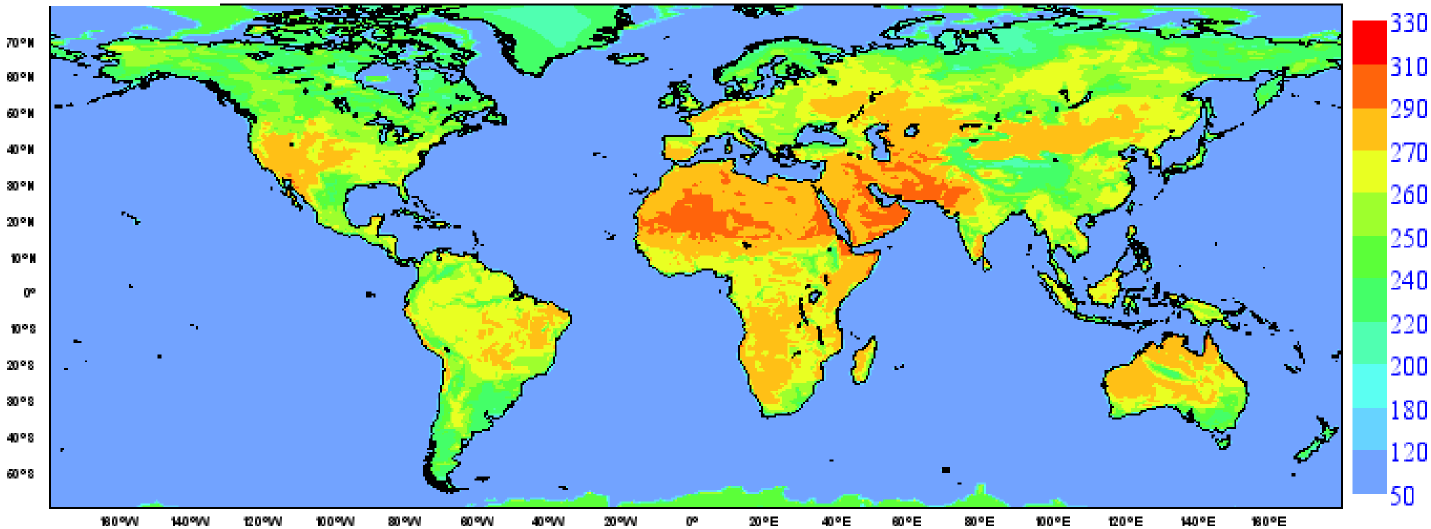
Also used at CMC, CSIRO, GSFC, and others centres

Current version 4.1 (May 2012)

References:
Drusch et al. JHM, 2009
de Rosnay et al. JGR, 2009
de Rosnay, ESA Report, 2009

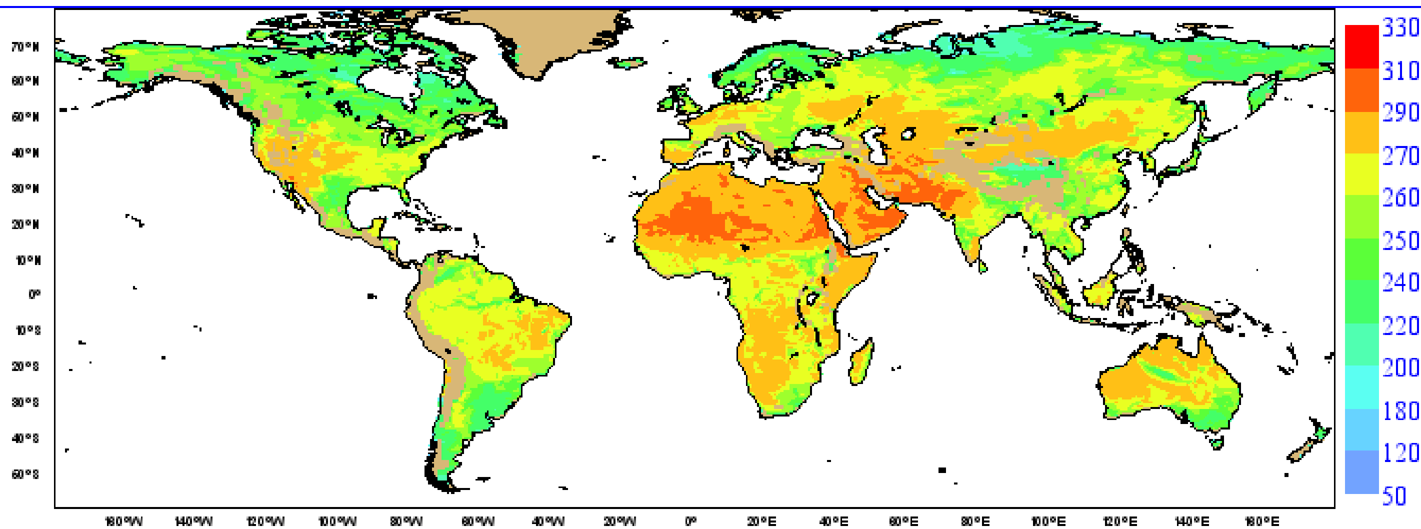
CMEM Simulations

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



July
2010
TOA TBH

Before QC



After QC
(snow,
Freeze,
Orography)

ECMWF SMOS forward operator and Bias correction

SMOS forward operator: Community Microwave Emission Modelling Platform (CMEM)

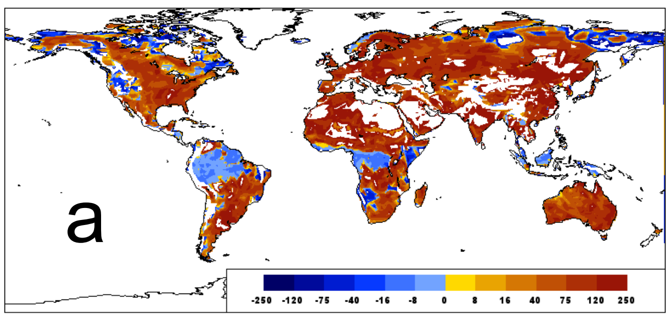
CDF-matching matches mean and variance of two distributions

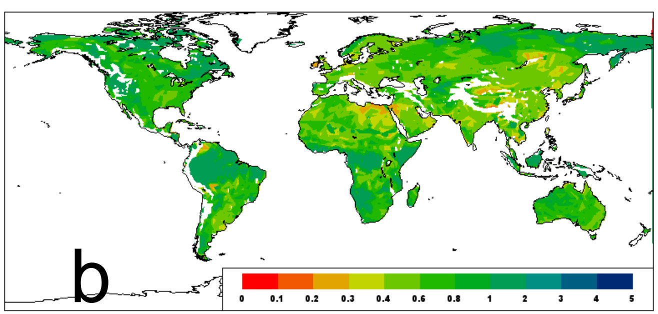
$$TB^*_{SMOS} = a + b\, TB_{SMOS}$$

with $a = \overline{TB}_{CMEM} - \overline{TB}_{SMOS}\,(\sigma_{CMEM} / \sigma_{SMOS})$

$b = \sigma_{CMEM} / \sigma_{SMOS}$

→ Matches mean and variance





ECMWF

ECMWF SMOS forward operator and Bias correction

SMOS forward operator: Community Microwave Emission Modelling Platform (CMEM)

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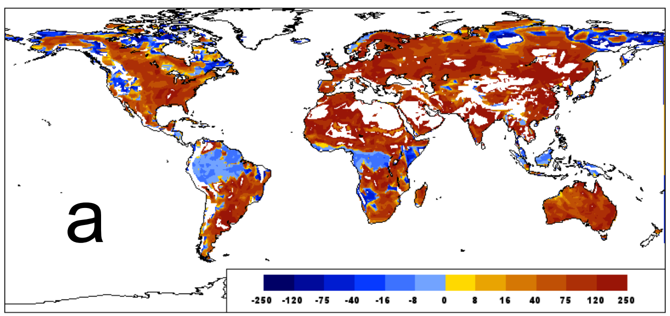
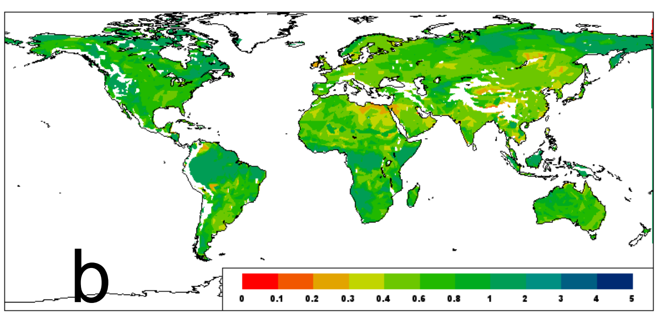
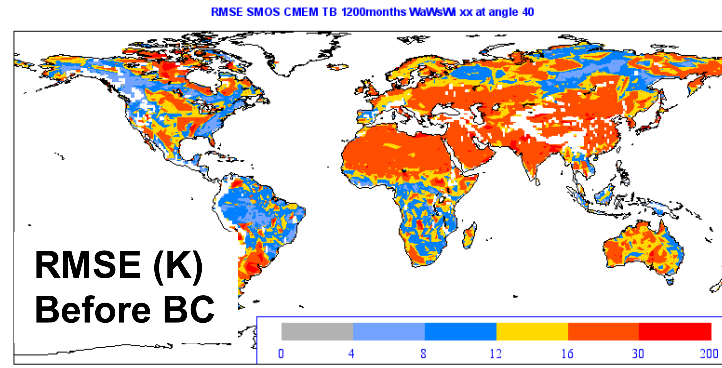
$b = \sigma_{CMEM} / \sigma_{SMOS}$

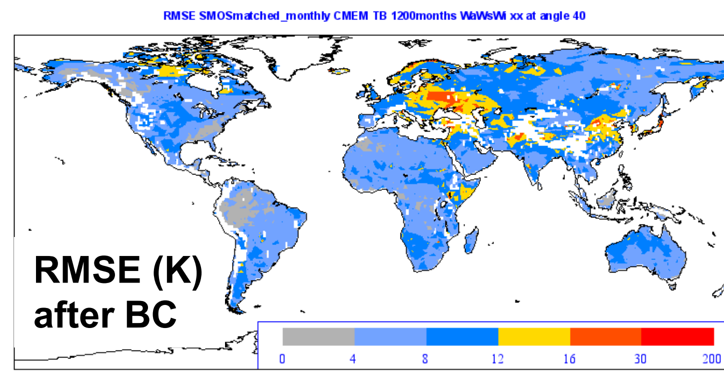
→ Matches mean and variance

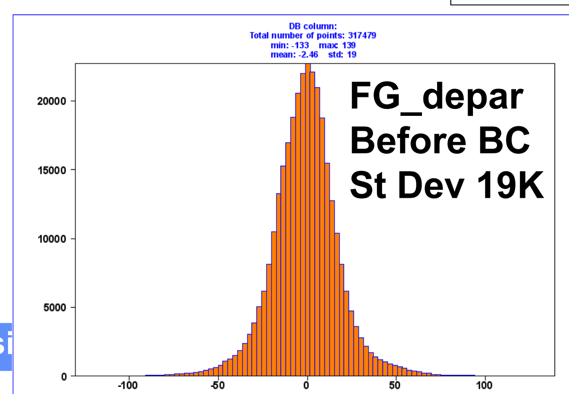


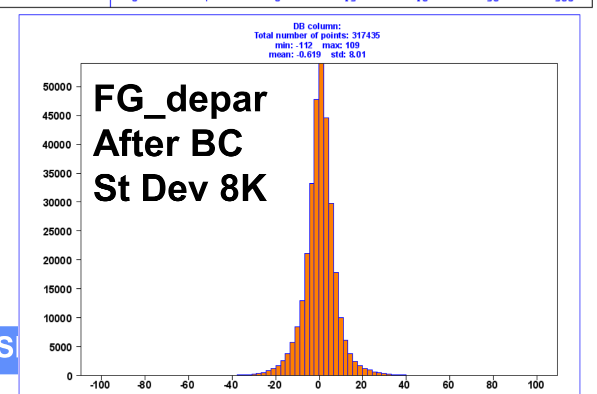


Evaluation for July 2012 →









Passive microwave remote sensing

Past current and future missions:

Skylab, NASA, L-band, 1973-1974 (but only 9 overpasses available)

AMSR-E 2002-2011 (Advanced Scanning Radiometer on Earth Observing System), NASA, C-band (6.9GHz)

SMOS (Soil Moisture and Ocean Salinity Mission): ESA Earth Explorer, L-band (1.4 GHz), launched November 2009
First satellite specifically devoted to soil moisture remote sensing

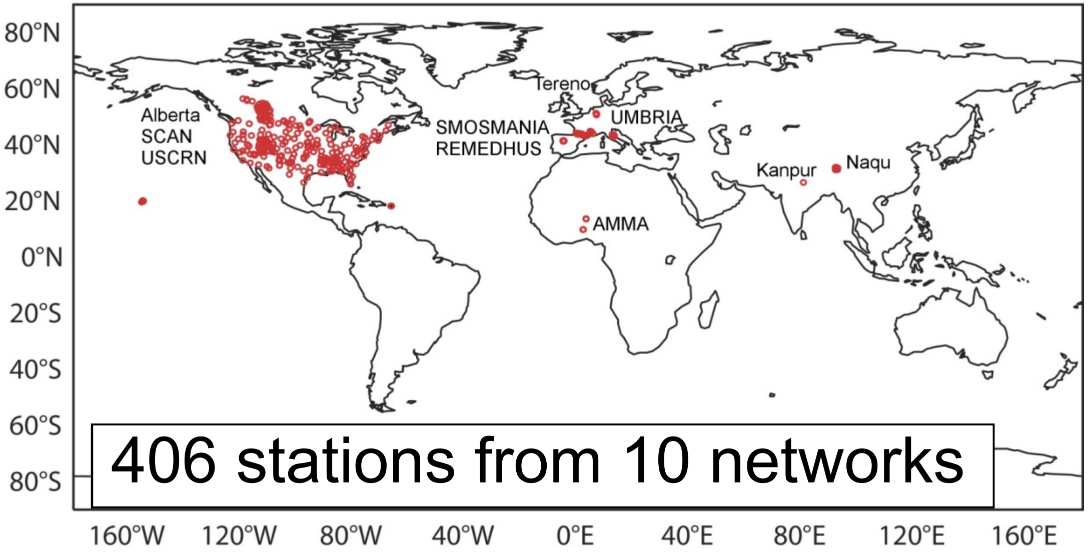
AMSR-2 on GCOM-W1 (Global Change Observation Mission) launched in 2012

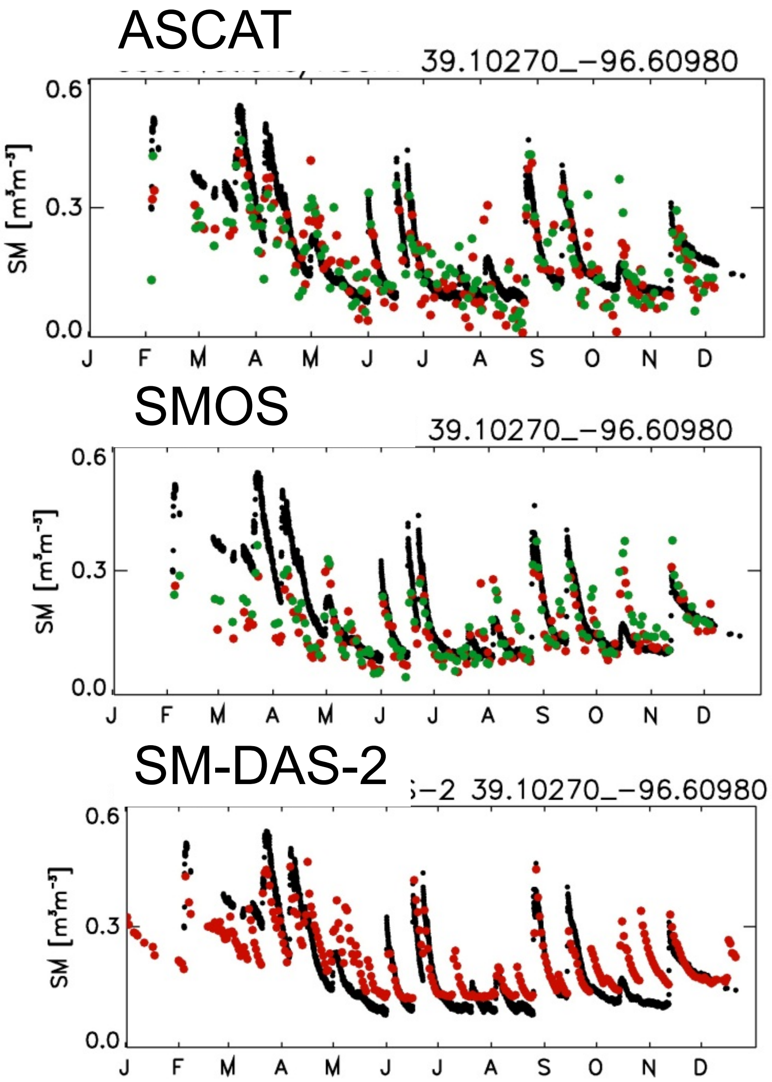
SMAP (Soil Moisture Active and Passive), NASA, L-band, recently launched !
Also specifically designed for soil moisture → continuity of SMOS

ECMWF

Validation with in situ soil moisture data

Albergel et al.





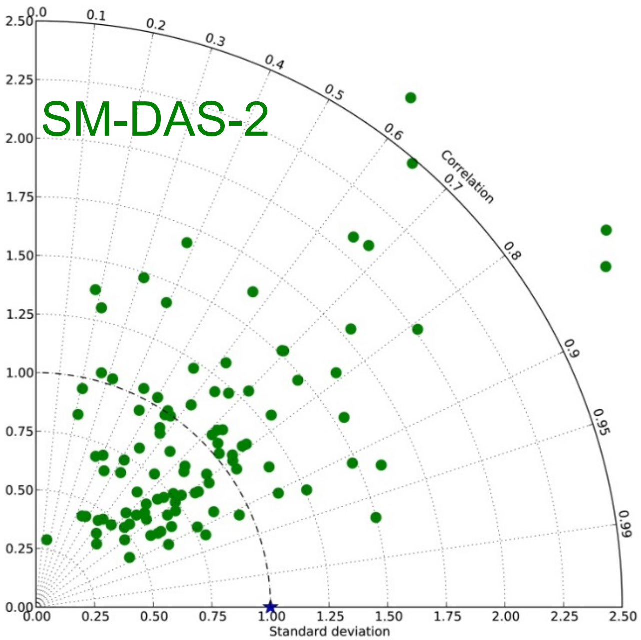
International Soil Moisture Network

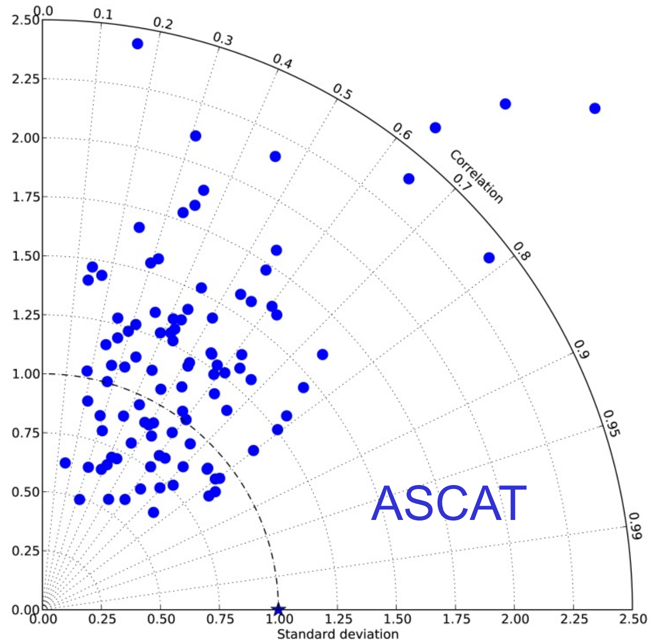
Validation for 2012 of ASCAT, SMOS and SM-DAS-2

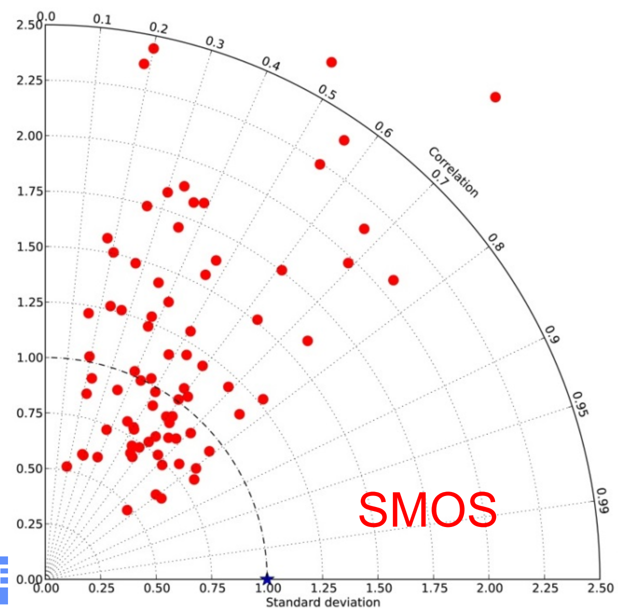
For each station, time series are compared

Validation with in situ soil moisture data

(USCRN)







Correlation [-] (for stations with significant values)		
SM-DAS-2	***ASCAT***	***SMOS***
0.67 (104 stations)	**0.50** (104 stations)	**0.50** (84 stations)

ECMWF

Validation with in situ soil moisture data

Albergel et al. RSE, 2012

Normalized Product (nb stations with significant R)	SM-DAS-2 (333)	ASCAT (322)	SMOS (258)
Correlation	0.68	0.54	0.54
Bias (In Situ - Product)	-0.084	-0.005	0.027
RMSD	0.120	0.110	0.105

Normalized Product (nb stations with significant R)	SM-DAS-2 (310)	ASCAT (291)	SMOS (234)
Correlation on Anomaly	0.56	0.41	0.42

All products expressed as soil moisture index (no unit)

- SMOS and ASCAT surface soil moisture have similar quality
- Assimilated product (SM-DAS-2) has a larger bias, but in terms of dynamics it shows the best agreement with in situ soil moisture data

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 4D-Var
- Variety of approaches for snow and soil moisture

- **Operational snow analysis:**
  - 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); **Nudging** (BoM); **Offline 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 monitored & assimilated for 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

→ Consistency in the LSM between soil moisture and screen level parameters

Developments of multi-variate approaches (ECMWF, CMC, Météo-France)

Summary and Future plans

- Continuous developments to assimilate ASCAT soil moisture and SMOS brightness temperature in NWP systems
- Use of recent satellites: NASA SMAP
- Assimilation of vegetation parameters (Leaf Area Index)
- Increase coupling between LDAS and 4D-Var

- 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)

Summary of ECMWF Land Surface Data Assimilation System

- Snow depth analysis
- 2D Optimal Interpolation (OI) (operational)
- Ground data (SYNOP and national networks data)
- High resolution NESDIS/IMS snow cover data

-Screen level analysis
- 2D OI using SYNOP data

-Snow and Soil Temperature
- 1D OI using T2m analysis increments as input

- Soil Moisture analysis
- Simplified Extended Kalman Filter (EKF) (Operational)
- Uses screen level parameters analysis as input

- Satellite data for Soil Moisture

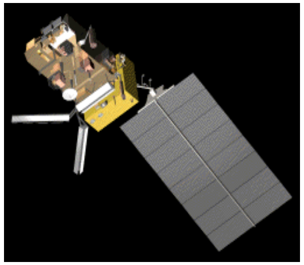
METOP-ASCAT (H-SAF) and SMOS Monitoring

Data assimilation
- for NWP
- for Root zone retrieval SM-DAS-2 (operational for EUMETSAT H-SAF)

- Validation activities

Rely on International Soil Moisture Network in situ soil moisture data base

ASCAT



SMOS

Land surface data assimilation

1999	2004	2010/2011	2013/2014

OI screen level analysis

Douville et al. (2000)

Mahfouf et al. (2000)

Soil moisture 1D OI

based on Temperature and relative humidity analysis

Revised snow analysis

Drusch et al. (2004)

Cressman + NESDIS IMS Snow cover extend data (24km)

(OI) snow

de Rosnay et al. (2014)

NESDIS IMS 4km

Additional in situ

SEKF SM (36r4)

de Rosnay et al. (2013)

Conv Obs monitoring

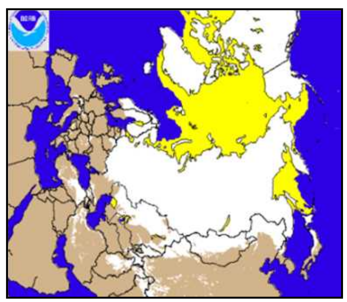
OI code cleaning

EDA OBS perturbations

Snow DA (40r1)

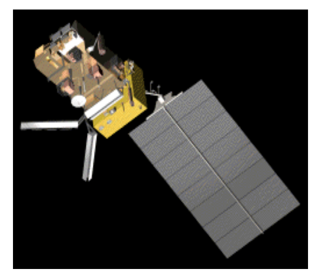
EKF ASCAT DA (40r3)

SYNOP Data



NOAA/NESDIS IMS

Use of satellite data



METOP-ASCAT

SMOS

Sabater et al.,2011

SM validation: Albergel et al. 2011,2012,2013

Further Reading:

Integrated Forecasting System documentation (IFS cycle 40r1):

http://www.ecmwf.int/research/ifsdocs/CY40r1/

Land surface model, analysis and SMOS: ECMWF Newsletter 127, Spring 2011:
http://www.ecmwf.int/publications/newsletters/

ECMWF Surface analysis web pages:
https://software.ecmwf.int/wiki/display/LDAS/LDAS+Home

Interaction between Soil Moisture (SM) and Atmosphere

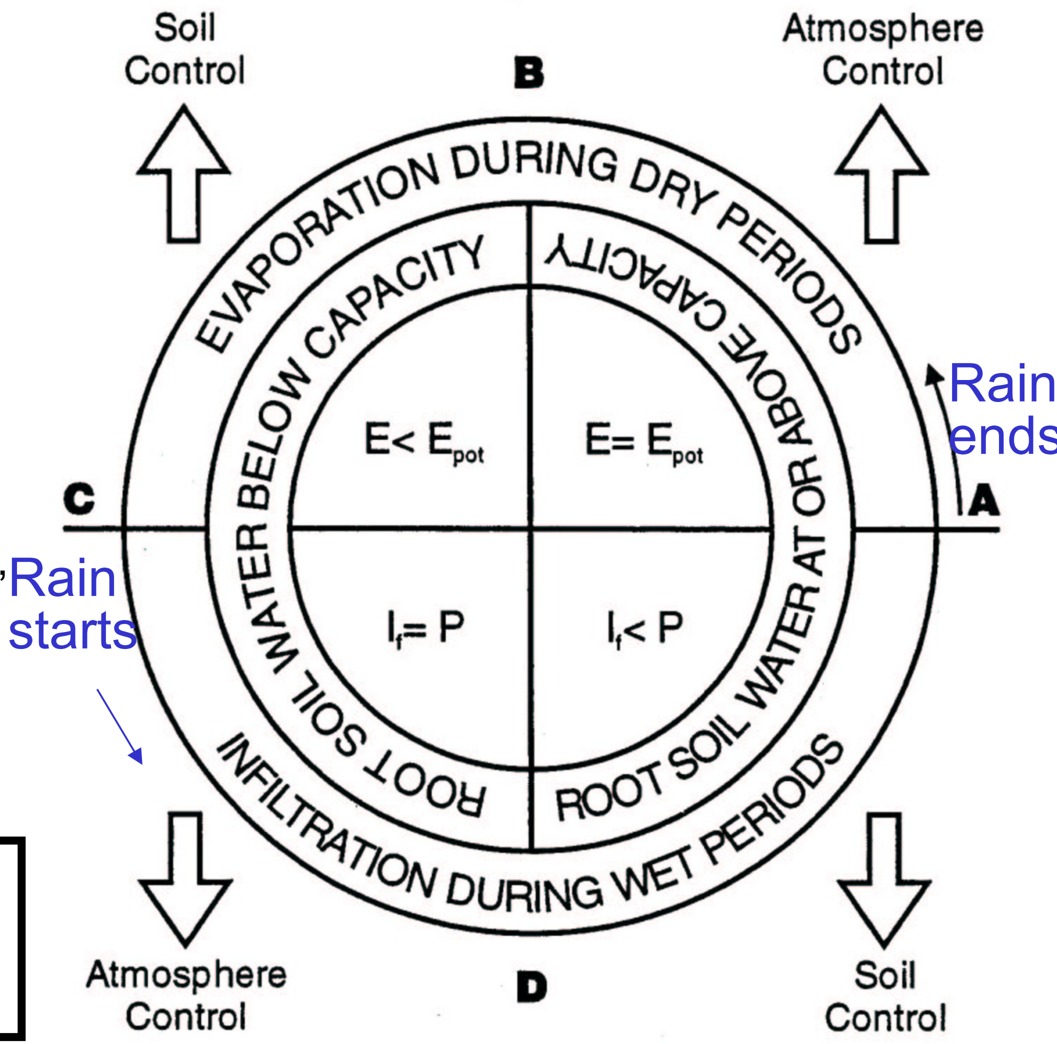
The hydrological 'Rosette' (P. Viterbo, PhD thesis, «The representation of surface processes in General Circulation Models » ECMWF, 1996)

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.

Interaction between Soil Moisture (SM) and Atmosphere

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

(Koster et al, Science 2004).

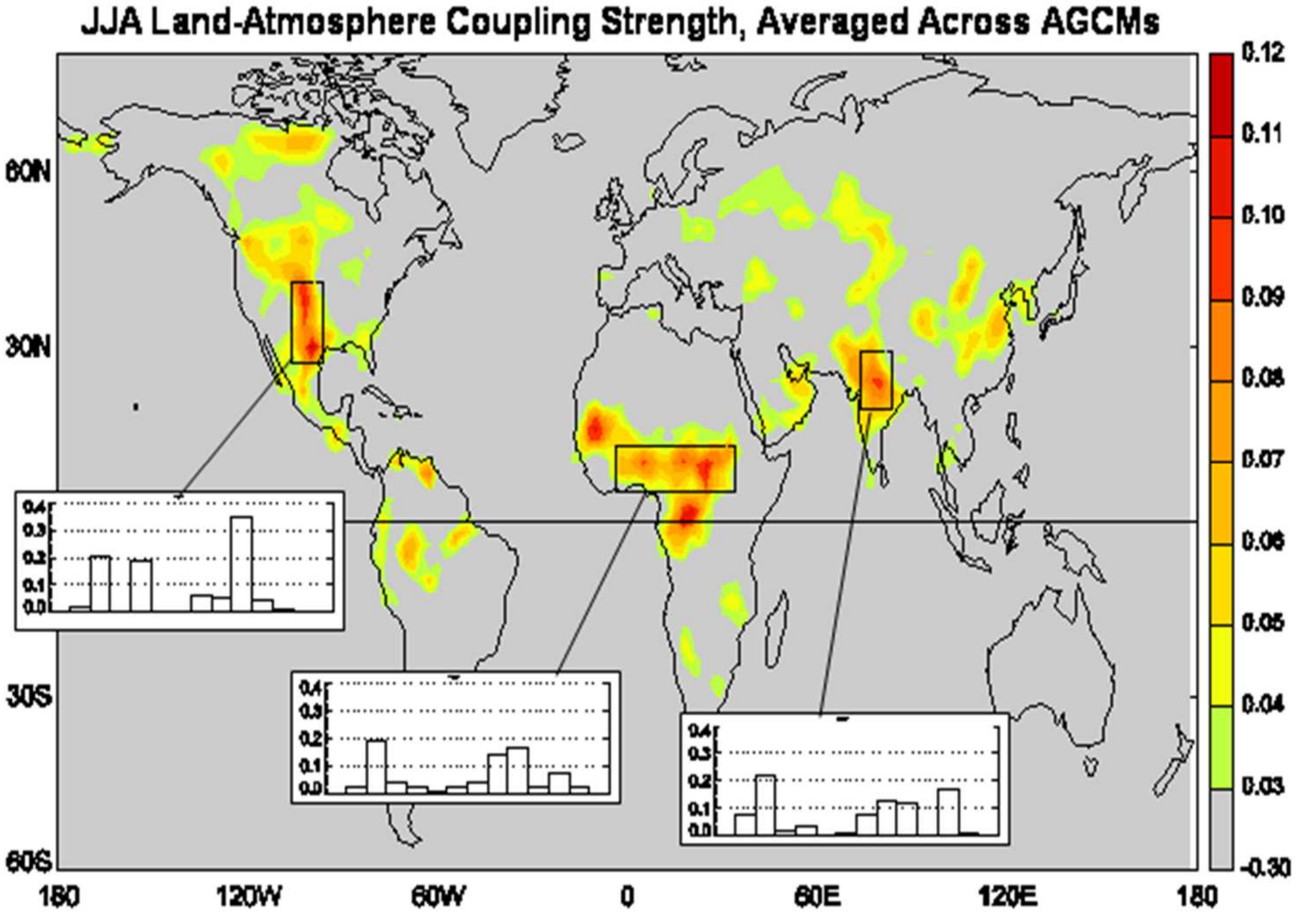
SM, variable of interface

Partition LE/H

Vegetation phenology,

Soil respiration,

Biogeochemical cycle



Hot spot areas → strong feedback of soil moisture on precipitation

ECMWF

A short 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)**

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

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

A and B: optimal coefficien

OI soil moisture analysis ba **rameters (T2m Rh2m) analysis**

➢ **Simplified Extended I** **10-**

- Motivated by bett
- Opening the poss ita related to surface soil moisture.

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

Simplified EKF surface analysis

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

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

where K is the gain matrix:

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

The observation operator H is the Jacobian matrix of:

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

In finite differences, the elements of the Jacobian matrix are estimated by perturbing individually each component θ_j of the control vector : by a small amount $\delta\theta_j$. A sensitivity as been conducted to find the optimum perturbation $\delta\theta_j$.

Root Zone Soil Moisture Retrieval

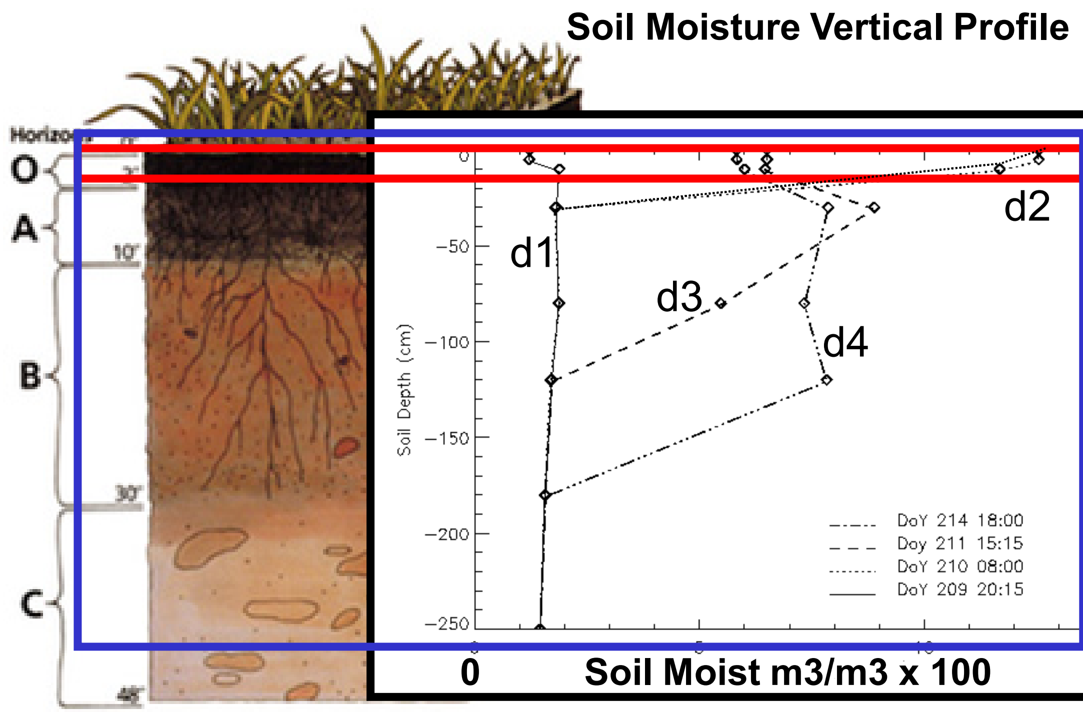
Satellite data → Surface information

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



→ Space agencies retrieval of level 3 / level 4 products rely on data assimilation approaches.

ECMWF

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

ASCAT
Surface SM
Bias corrected

(de Rosnay et al., ECMWF Res. Memo, 2011)

EKF
Soil Moisture
Analysis

SM-DAS-2:
ASCAT Root Zone

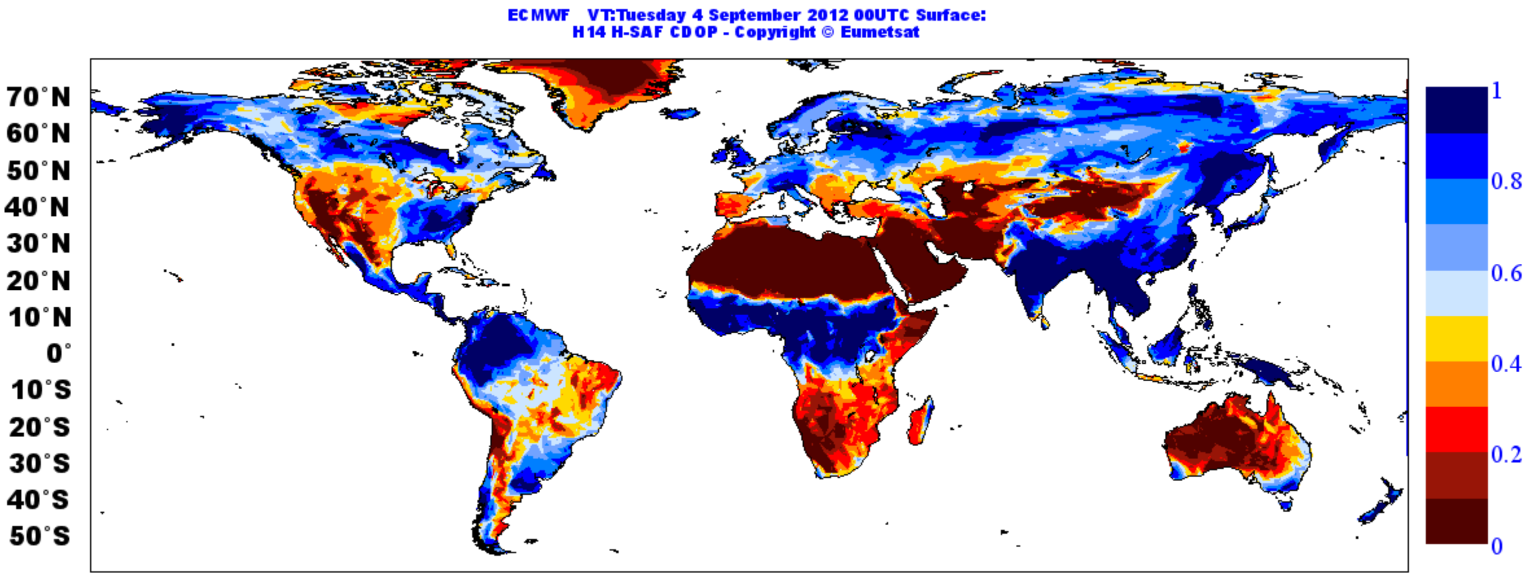
H-SAF CDOP: SM-DAS-2 Production chain

4 layers:
0-7cm
7-28 cm
28-100 cm
100-289cm

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

ECMWF

ASCAT soil moisture data assimilation



SM-DAS-2: ASCAT Root Zone Soil Moisture Product
- **Daily Soil Moisture product valid at 00:00 UTC**
- **Daily Global coverage**

The EUMETSAT Network of Satellite Application Facilities

H SAF Support to Operational Hydrology and Water Management

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

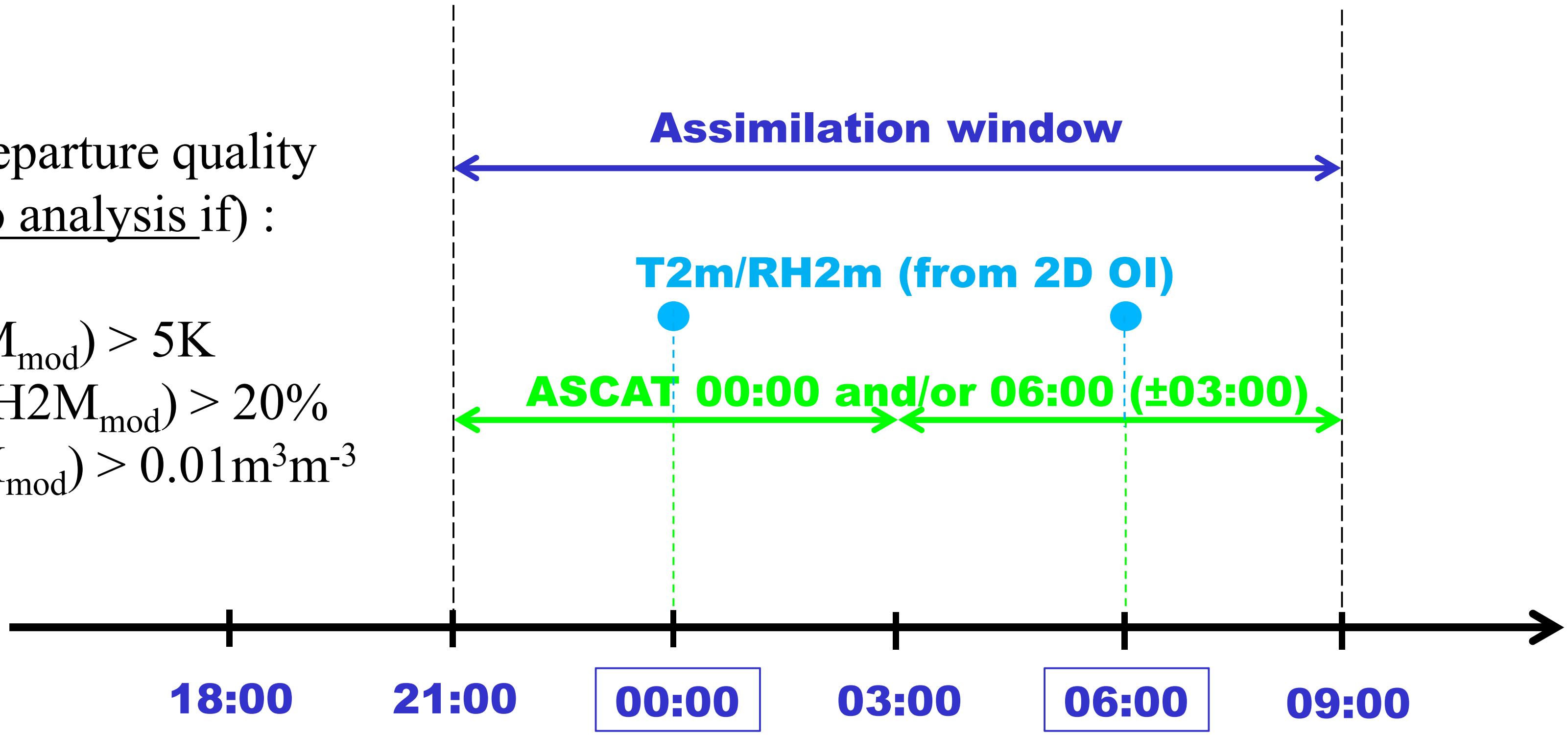
hsafcdop@meteoam.it

ECMWF

Soil Moisture analysis at 00:00, 06:00, 12:00, 18:00

First guess departure quality check (i.e. no analysis if) :

(T2M$_{obs}$-T2M$_{mod}$) > 5K
(RH2M$_{obs}$-RH2M$_{mod}$) > 20%
(SM$_{obs}$-SMM$_{mod}$) > 0.01m^{3}m^{-3}



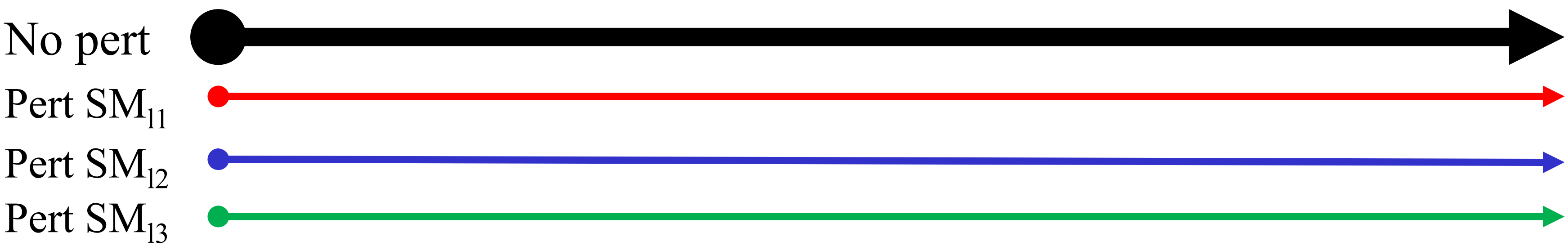
Model first guess for analysis at 00:00 (d) ➔ Fc 18:00 (d-1) step 6
Model first guess for analysis at 06:00 (d) ➔ Fc 18:00 (d-1) step 12
[…]

H27 liquid root zone soil moisture

- **Jacobians computation**

Estimated by finite differences by individually perturbing each component x_j of the control vector x by a small amount δx_j

➔ Perturbation size is $0.01 m^3 m^{-3}$



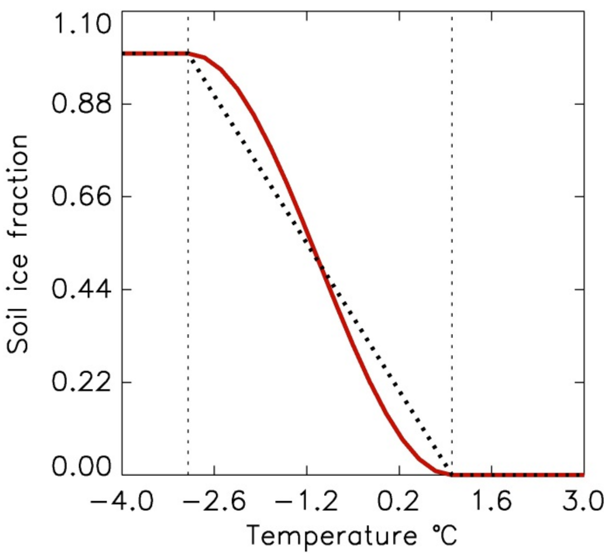
$$H = \begin{pmatrix} \frac{T_{2m}pert. - T_{2m}}{\delta SM_{l1}} & \frac{T_{2m}pert. - T_{2m}}{\delta SM_{l2}} & \frac{T_{2m}pert. - T_{2m}}{\delta SM_{l3}} \\ \frac{RH_{2m}pert. - RH_{2m}}{\delta SM_{l1}} & \frac{RH_{2m}pert. - RH_{2m}}{\delta SM_{l2}} & \frac{RH_{2m}pert. - RH_{2m}}{\delta SM_{l3}} \\ \frac{SM_{l1}pert. - SM_{l1}}{\delta SM_{l1}} & \frac{SM_{l1}pert. - SM_{l1}}{\delta SM_{l2}} & \frac{SM_{l1}pert. - SM_{l1}}{\delta SM_{l3}} \end{pmatrix}$$

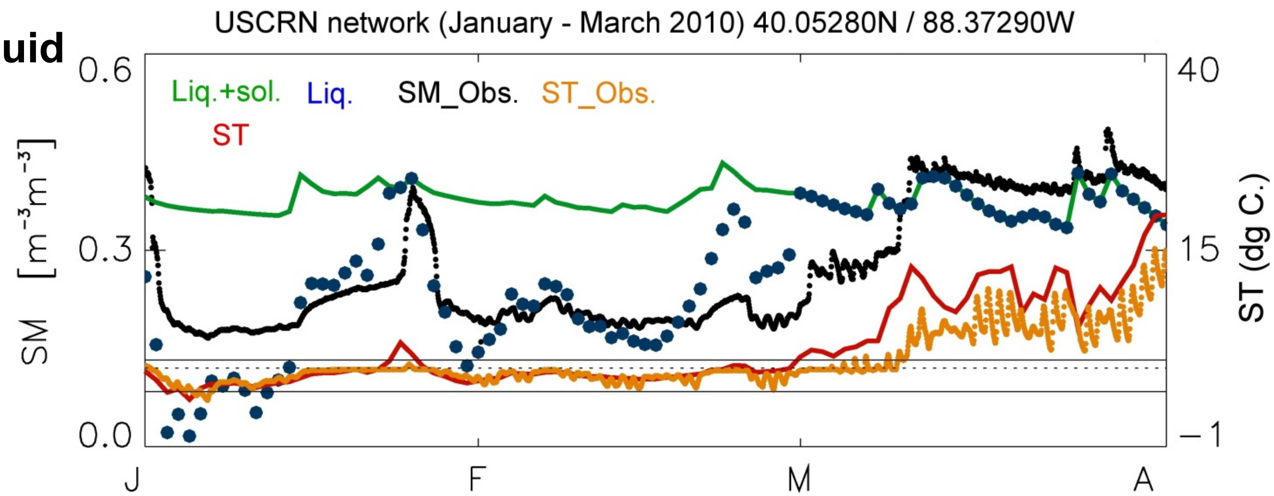
⟶ At observation time

⟶ At initial time

Liquid root zone soil moisture Index

- **Rational for having a liquid Product :**





2010-2013	Scores	Liq.+sol.	Liq.
USCRN (US) 1 station	R	0.72	0.74
	Ano_R	0.56	0.57
	RMSD	0.074	0.069
	Bias	-0.024	-0.005

- **Rational for having an index [0-1] :** Spatial variability of SM is very high, differences in soil properties ➔ difference in the mean & variance

➔ True information of modelled/analysed soil moisture does not necessarily relies on their absolute magnitudes but instead on their time variations

ECMWF