ECMWF Land Surface Analysis: Current status and developments

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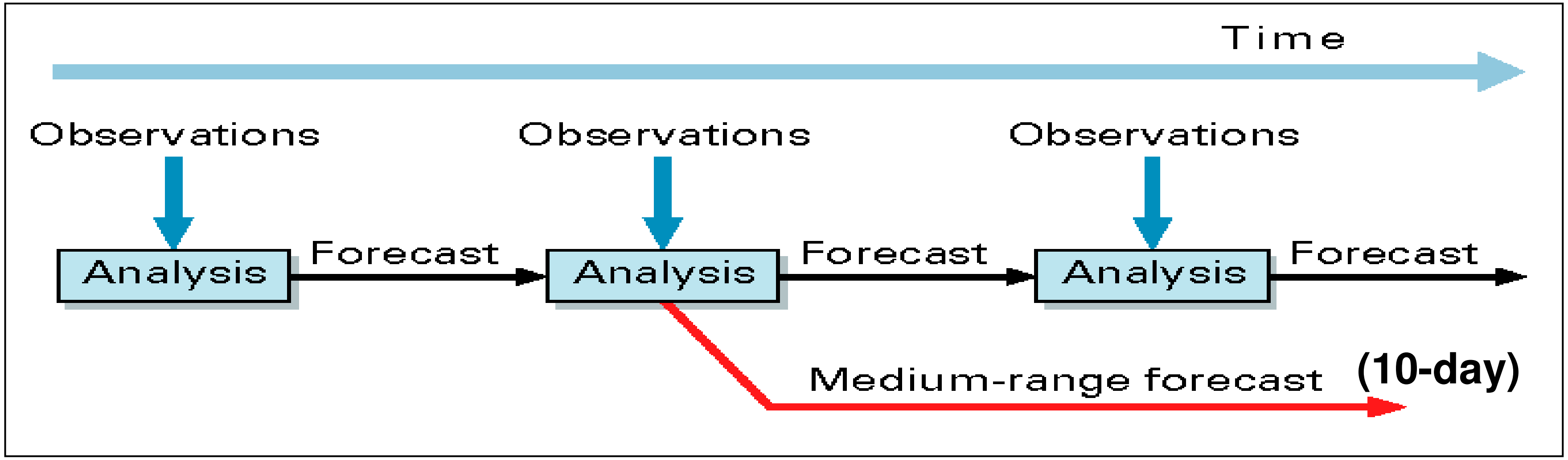
ECMWF

- **Introduction on surface analysis**
- Current status
  - Surface analysis structure in IFS cycle 35R2
  - Operational Soil moisture analysis (OI)
- Current developments
  - EKF surface analysis
  - Use of active and passive microwave data for soil moisture analysis
  - Surface analysis structure from IFS cycle 35R3

The ECMWF Integrated Forecasting System (IFS)

data assimilation system



Data Assimilation System objective:
Provide best possible accuracy of initial conditions to the forecast model

Analysis:
- 4D-VAR for atmosphere
- Surface analysis

- **The observations are used to correct errors in the short forecast from the previous analysis time.**
- **Every 12 hours we assimilate 7 – 9,000,000 observations to correct the 80,000,000 variables that define the model's virtual atmosphere.**
- **This is done by a careful 4-dimensional interpolation in space and time of the available observations; this operation takes as much computer power as the 10-day forecast.**

Surface analysis ?

Ocean surface analysis:

- Sea Surface Temperature: SST (2D interpolation, based on OSTIA)
- Sea Ice concentration: CI (2D interpolation, based on OSTIA)
- Sea surface salinity (global constant) ;
  for seasonal forecast, analysed from Argofloat (Optimum Interpolation)

Land surface analysis:

- Snow Water Equivalent (Cressman analysis, SYNOP Snow depth corrected according to NOAA/NESDIS snow extend information)
- 2m air Relative humidity and air Temperature (SYNOP, Optimum Interpolation)
- Soil moisture and soil temperature (SYNOP Optimum Interpolation ; Extended Kalman Filter under implementation)

Current developments at ECMWF focus on soil moisture analysis improvements

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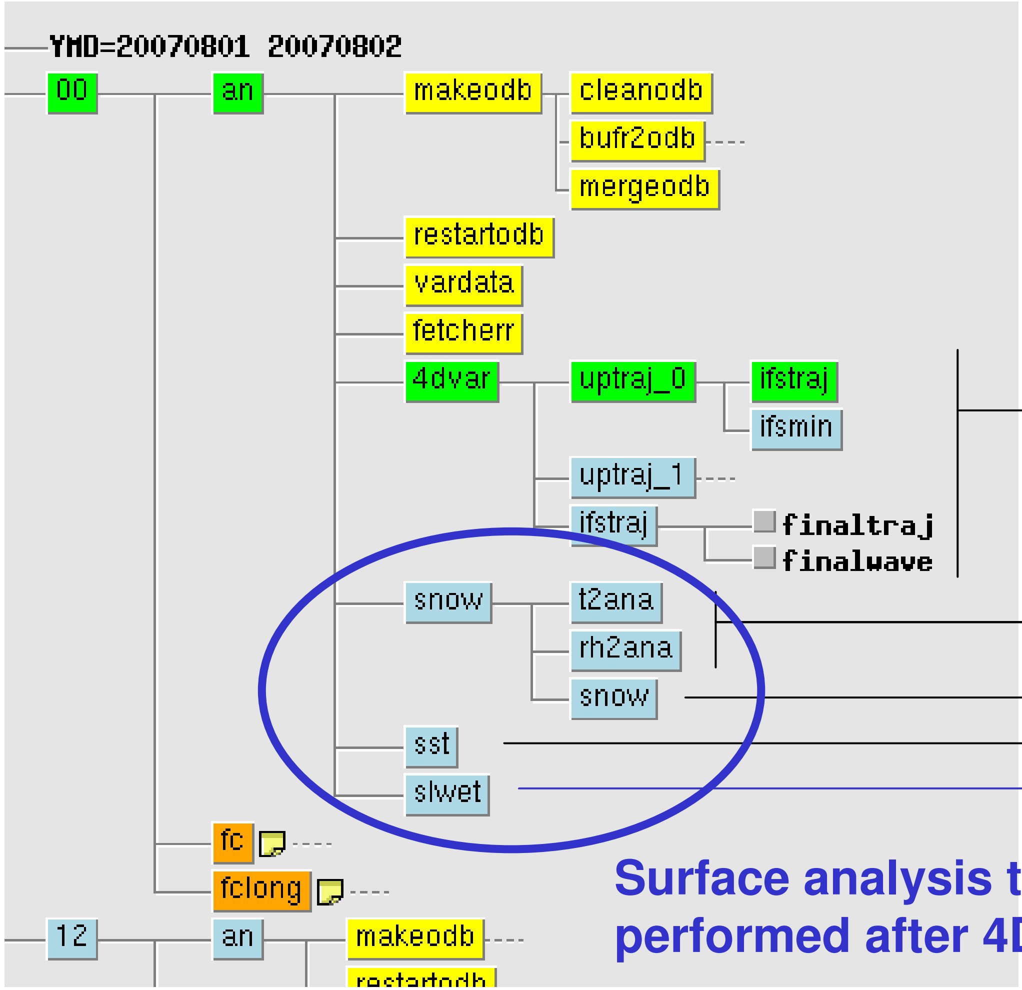
Surface analysis structure in Integrated Forecasting System IFS cycle 35R2

IFS cycle 35R2 is the current operational cycle
SMS: Supervisor Monitor Scheduler

Different tasks performed for the analysis.

Colour code:
-Yellow: task completed
- Green: running
- Blue: in queue
- Orange: suspended
- Red: failed



4D-VAR

Screen level parameters

Snow

SST and CI

Soil Moisture and Temperature

Surface analysis tasks: performed after 4D-VAR.

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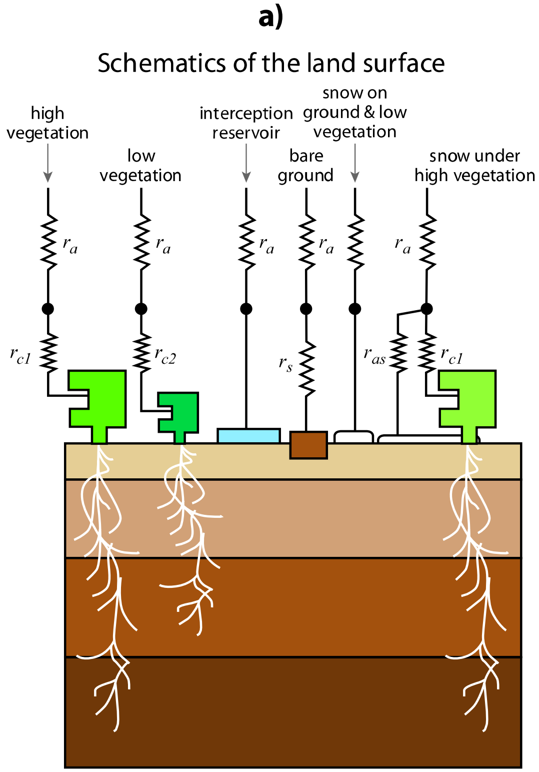
Operational soil moisture analysis

HTESSEL Land Surface Model



Soil moisture analysis: Optimum interpolation (OI)

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**

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

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

And for the first soil temperature layer:

$$\Delta T = c \times \left(T^a - T^b\right)$$

Superscripts a and b denote analysis and background respectively, i denotes the soil layer.
Coefficients ai and bi are defined as the product of optimum coefficients αi and βi minimizing the variance of analysis error and of empirical functions F1, F2, F3.

References HTESSEL:
Viterbo et al., 1995
Van den Hurk et al., 2000
Balsamo et al., 2009

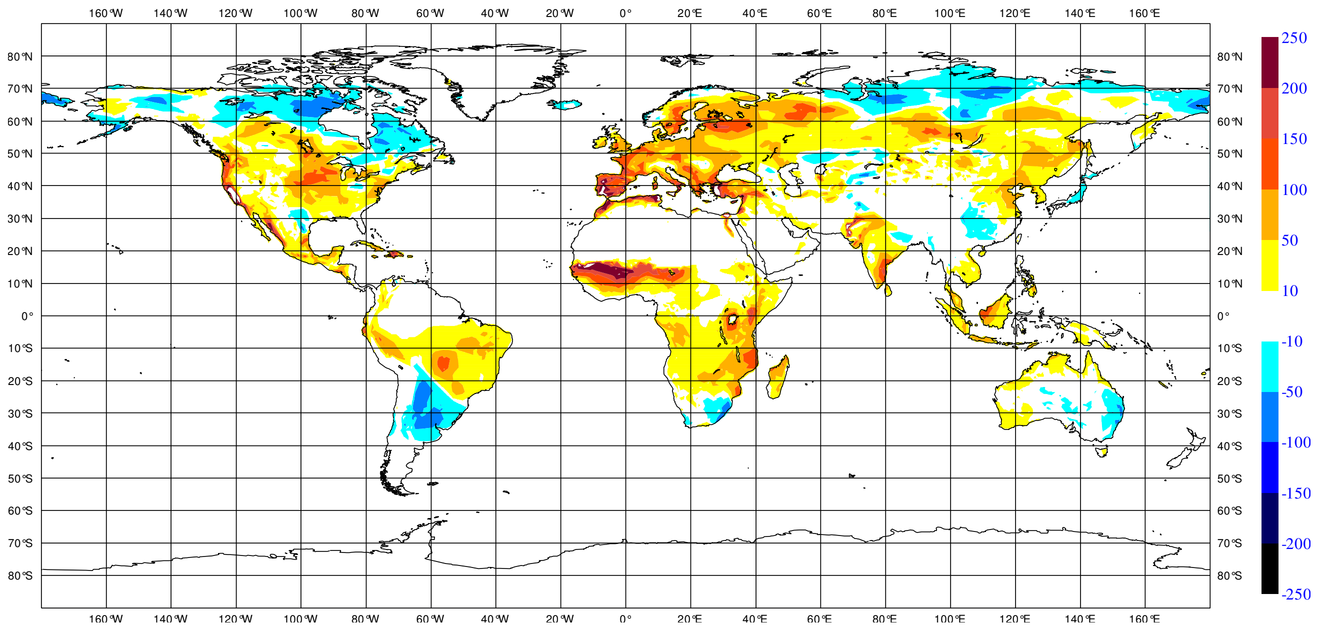
References OI:
Douville et al., 2000
Mahfouf, 1991

OI is used operationally at ECMWF for the soil moisture analysis

Illustration of the OI results

Numerical experiment for June-July 2002

Soil Moisture
Increments [mm]
(analysis – background)



Optimum interpolation for soil moisture analysis:

→ Efficiently improves the turbulent surface fluxes and the weather forecast on large domains.

→ But root zone soil moisture is the variable in which errors accumulate.

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Optimum Interpolation limitations

• Link between screen parameters (T2m rH2m) and soil parameters relying on very complex and non-linear land-surface-atmosphere processes

• Ad hoc thresholds to switch off the OI in particular conditions: wind, freezing, snow, precipitation,

• Difficult to interface with new features of the Land Surface Model (HTESSEL)

• Difficult to include new types of observations directly linked to soil moisture or vegetation:

  • SM form active microwave (C-band ERS, ASCAT on MetOp, SMAP)
  • SM from passive microwave (L-band SMOS, SMAP, C-band AMSR-E)
  • Leaf Area Index (MODIS, SPOT-VEGETATION)
  • Snow Water Equivalent products (H-SAF)

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Extended Kalman Filter surface analysis

Current operational surface analysis system (Optimum Interpolation) relies on screen level parameters data assimilation. It is not suitable to use satellite data.

→ An EKF soil moisture analysis has been developed.

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

$$\mathbf{x_a}(t) = \mathbf{x_b}(t) + \mathbf{K}\left(\mathbf{y}(t) - \mathbf{H}\mathbf{x_b}(t)\right)$$

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

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

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

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

In finite differences, the elements of the Jacobian matrix are estimated by perturbing individually each component x_j of the control vector $\mathbf{x}$ by a small amount δx_j. sensitivity as been conducted to find the optimum perturbation δx_j.

Sensitivity of the Jacobian matrix elements to soil moisture perturbation has been conducted to determine the soil moisture perturbation **(Drusch et al., GRL 2009)**

Comparison between the OI and the EKF soil moisture analysis

- OI soil moisture analysis based on screen level parameters.
- EKF opens the possibility to use and to combine a large range of data types, including SYNOP data (as in the OI) and satellite measurements.

- Validation of the EKF approach before it is used to assimilate satellite data.

Experimental setup

- Experiments using the Integrated Forecasting System (IFS)
- IFS cycle 33R1, T159 (~125km) for May 2007, 6h assimilation window
- Observations T2m and Rh2m
- Observation errors: σ_{T2m} =2K; σ_{RH2m}=10% ; σ_B=0.01m^3m^{-3}
- Matrix B not cycled
- Two experiments:
    - OI experiment (SM and ST)
    - EKF experiment (SM)

Comparison between OI and EKF

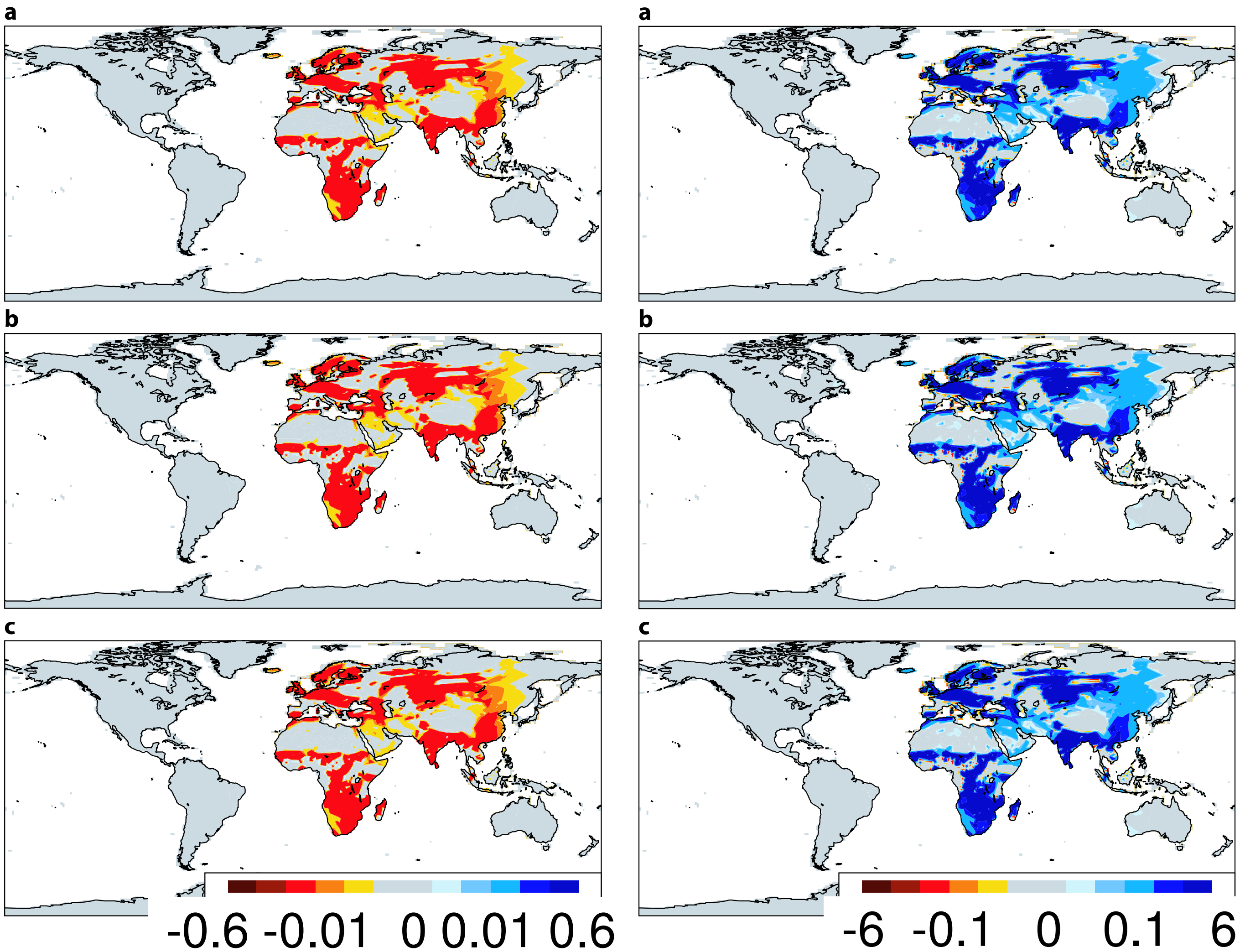
1- OI Gain matrix coefficients 01 May 2007 12UTC

T2m component ($\%m^3m^{-3}/K$) | RH2m Component ($\%m^3m^{-3}$)

Top 0-7cm

Layer2 7-28cm

Layer3 0.28-1m



- Opposite sign
- 1 order of magnitude larger for RH than T2m
- Limited to 20W-130E
- Low values over mountains, snow, deserts

Comparison between OI and EKF

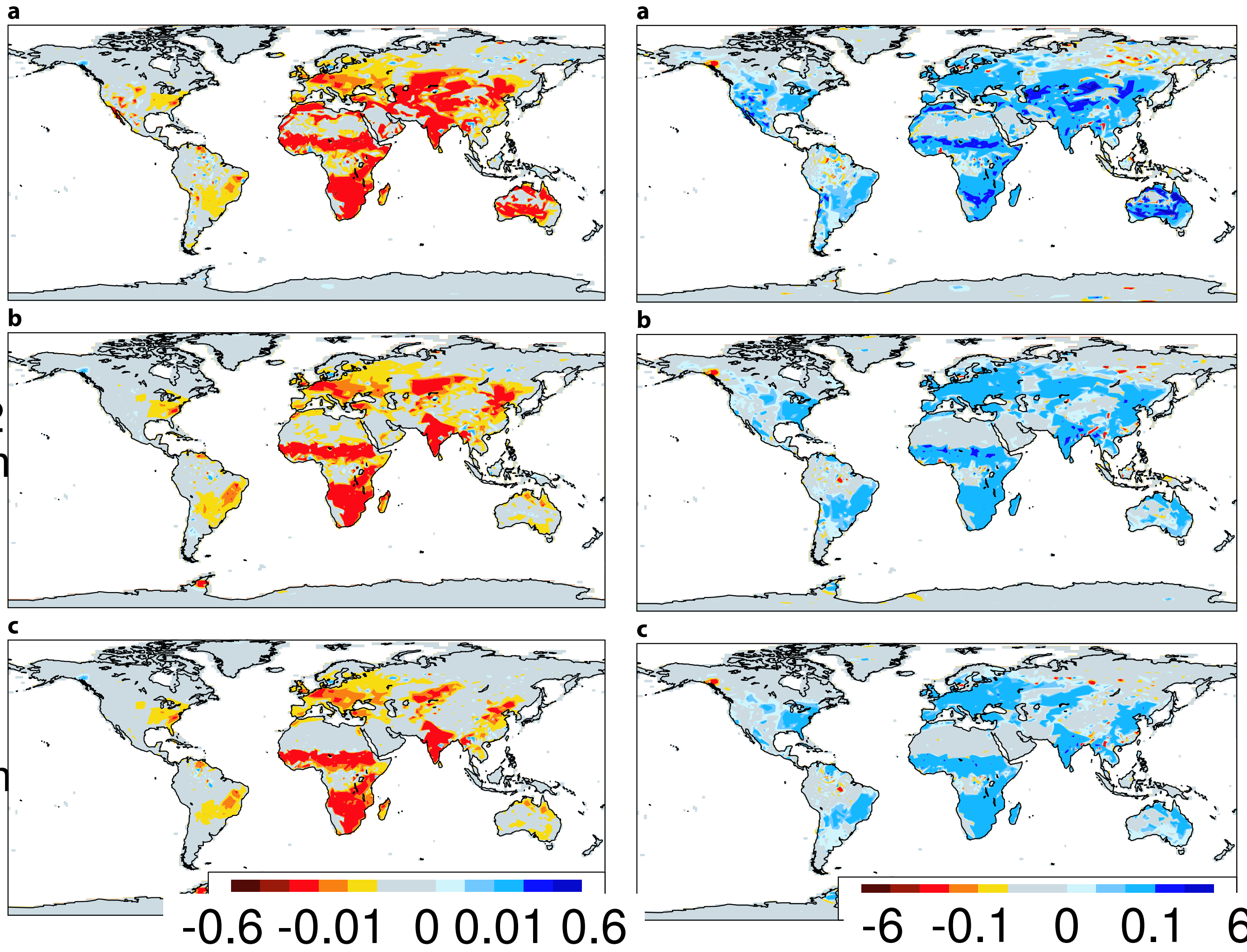
2- EKF Gain matrix coefficients 01 May 2007 12UTC

T2m component (%m^3m^{-3}/K) | RH2m Component (%m^3m^{-3})

Top 0-7cm

Layer2 7-28cm

Layer3 0.28-1m



- Similar pattern
- Same order of magnitude than OI gain
- Extended to the global scale
- Reduced gain at depth -> hydrological consistency

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EKF surface analysis system

• Accounts for the complex and non-linear link between screen parameters (T2m RH2m).

• Provide similar results than the OI when screen level parameters are used.

• Tested and validated in research mode.

• Flexible to include new type of observations that are more directly linked to soil moisture:

  - SM form active microwave (C-band ERS and ASCAT on MetOp)
  - SM from passive microwave (L-band SMOS, C-band AMSR-E)

• Long term perspective: possibilities to extend the EKF for snow mass and vegetation characteristics analysis.

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Soil Moisture from Active microwave remote sensing

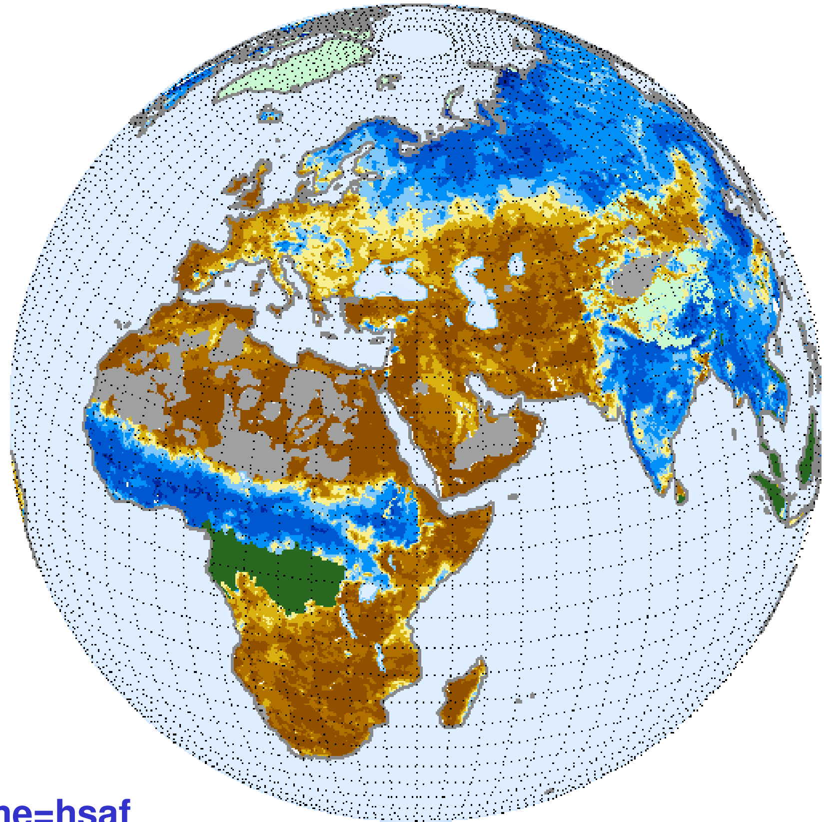
ERS-1/2 scatterometer data and MetOp ASCAT

- Active microwave instruments operating at C-band (5.6GHz)
- ERS-1: August 1991 – May 1996
- ERS-2: March 1996 – January 2001 and May 2004 – now
- **MetOp ASCAT** (EUMETSAT): Since Nov 2006

TUWien retrieval scheme Wagner et al., 1999)
→ Ws: surface soil moisture index
between 0 and 100

H-SAF project → ASCAT Ws
received NRT at ECMWF via EUMETCAST

ECMWF observation operator:
Cumulative Distribution Function (CDF)
of ws (ASCAT or ERS SM index)
and ECMWF soil moisture



Global Soil Moisture Map (August 1995)

H-SAF Project: http://www.meteoam.it/modules.php?name=hsaf

ERS &MetOp SM: http://www.ipf.tuwien.ac.at/radar/index.php?go=ascat

Use of ASCAT soil moisture data in the IFS

Use of ASCAT soil moisture data in the IFS:

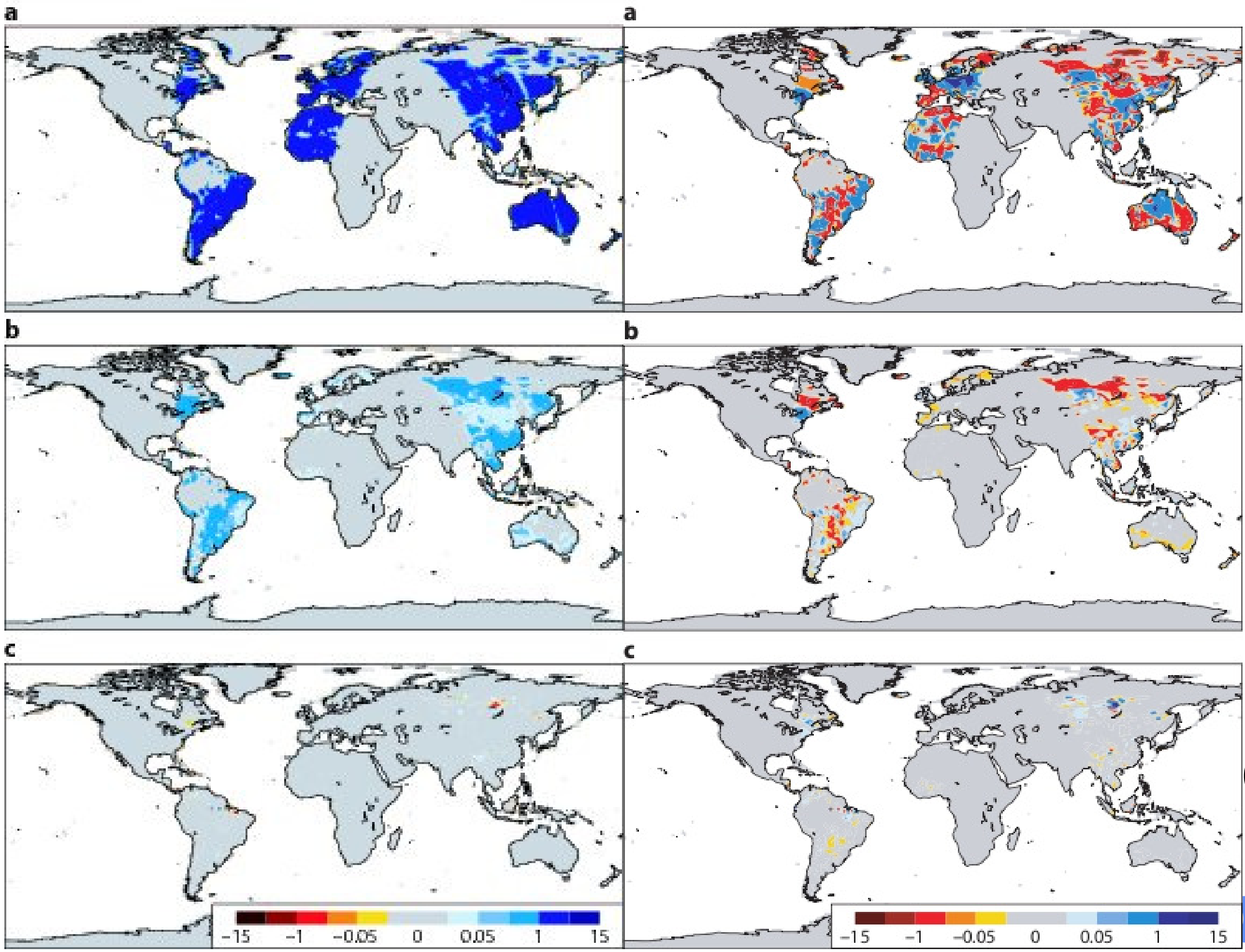
- Currently used in research mode for soil moisture analysis developments

- CDF match of the ASCAT SM observation to the ECMWF soil moisture (Scipal et al., 2008)
- Quality control and screening, data are reject if:
  - OBS errors > 6% (excludes area of dense vegetation)
  - or Wetland coverage > 15%
  - or Topography complexity index > 20%
  - or Snow covered or frozen soil (in the model)

Use of ASCAT soil moisture in the IFS

ASCAT assimilation in the EKF:
1-3 May 2007, T159

Gain 10 x (m3/m3)/(m3/m3)   Increment (mm)



Top layer
0-7cm

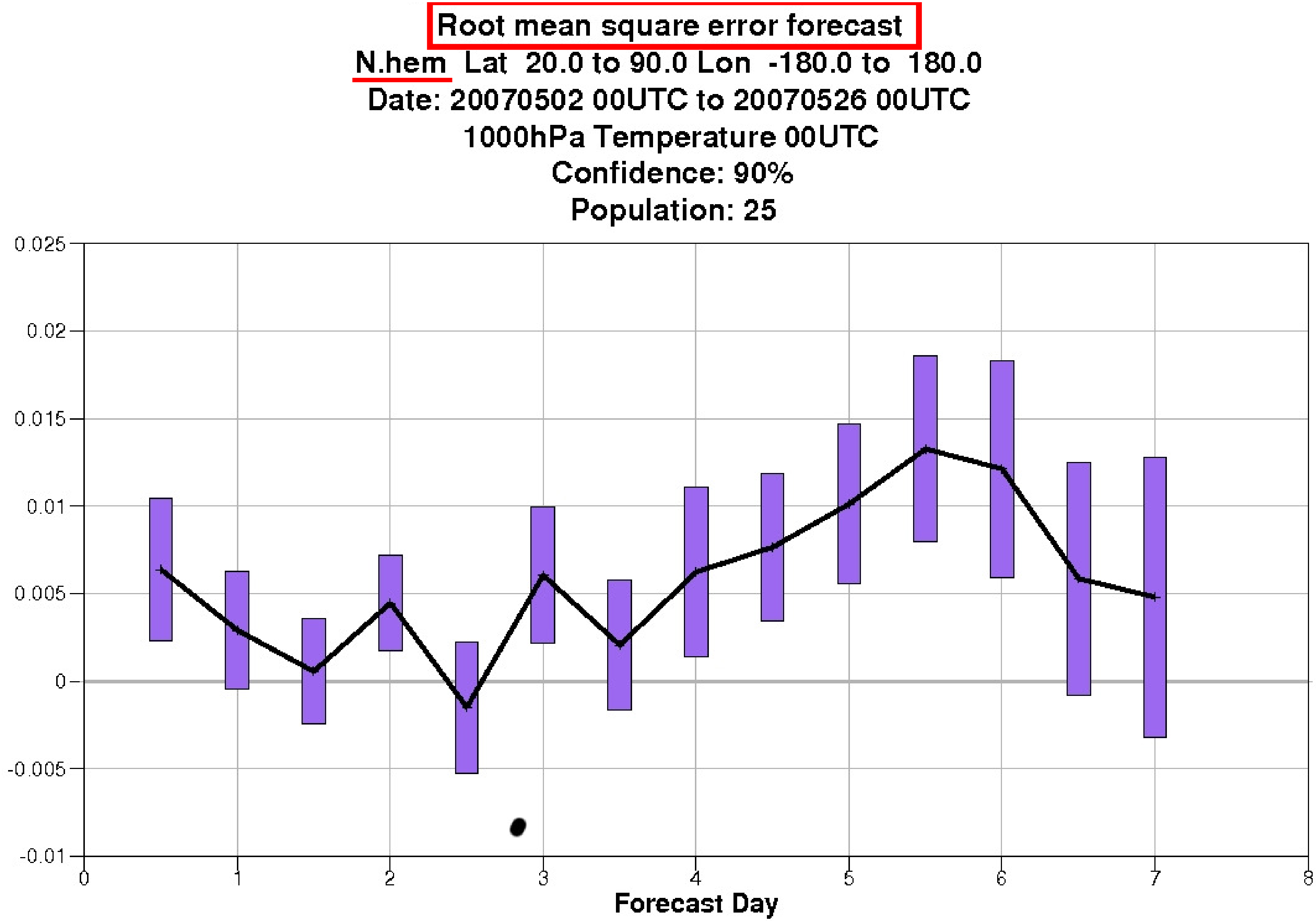
- No gain over tropical Forest.
- Similar amplitude at night (US) and day (Europe).
- Strong decrease at depth.

Layer 2
7-28 cm

Layer 3
0.28-1m

Forecast Error

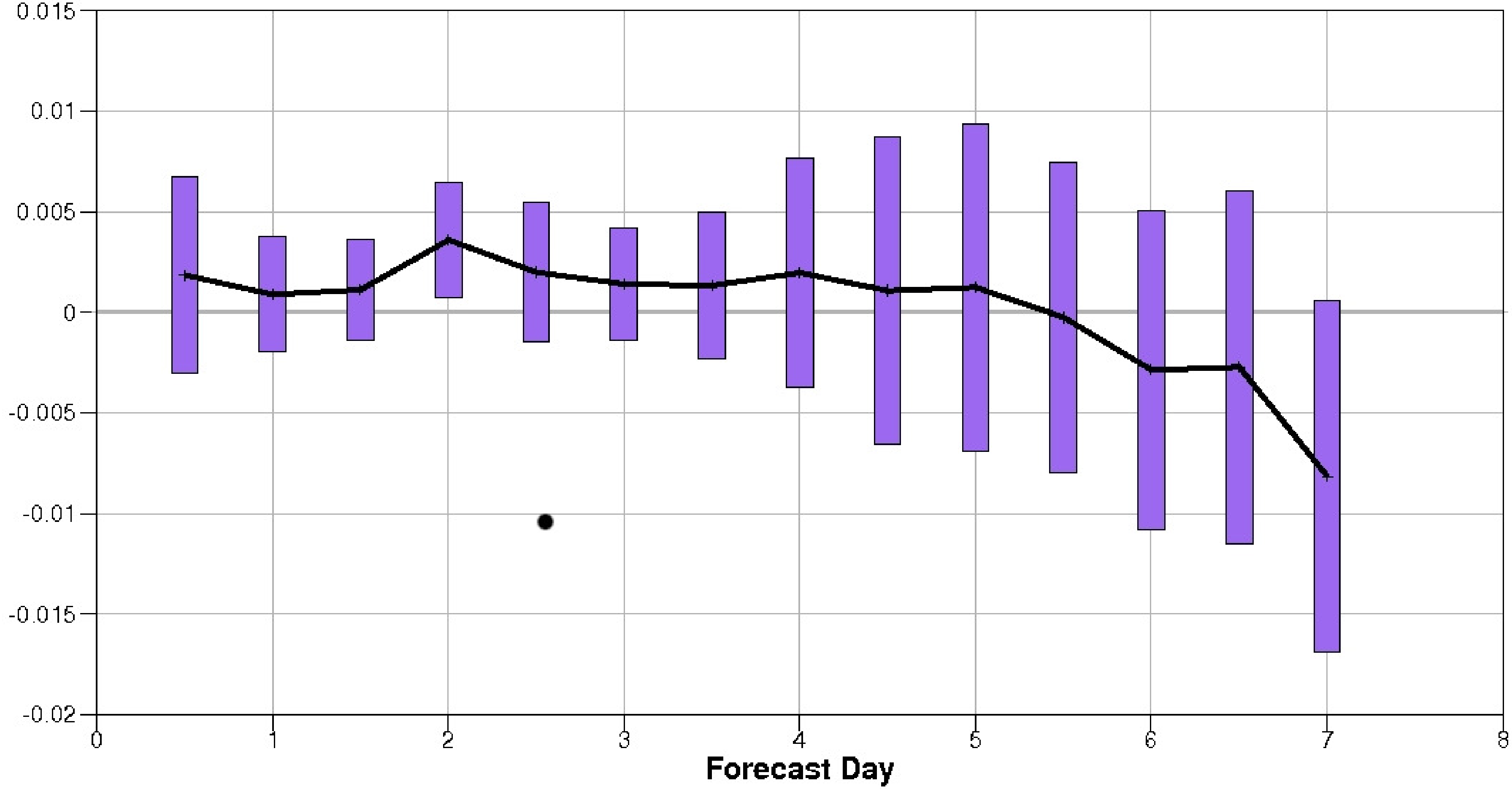
Difference between Control experiment and ASCAT Assimilation experiment



Forecast Error

Difference between Control experiment and ASCAT Assimilation experiment

Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20070502 00UTC to 20070526 00UTC
1000hPa Temperature 00UTC
Confidence: 90%
Population: 25



Passive microwave remote sensing

Past current and future missions for passive MW remote sensing of soil moisture:

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

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

SMOS (Soil Moisture and Ocean Salinity Mission): ESA Earth Explorer,
L-band (1.4 GHz), launch September 2009

SMAP (Soil Moisture Active and Passive), NASA, L-band, launch 2013

SMOS will be the first satellite missions specifically devoted to soil moisture remote sensing.

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In NWP, Near Real Time constraint imposes to use the brightness temperatures (TB)
→ Importance of the forward operator to transform model variable (soil moisture temperature…) to observable variable (TB)

Community Microwave Emission Model (CMEM)

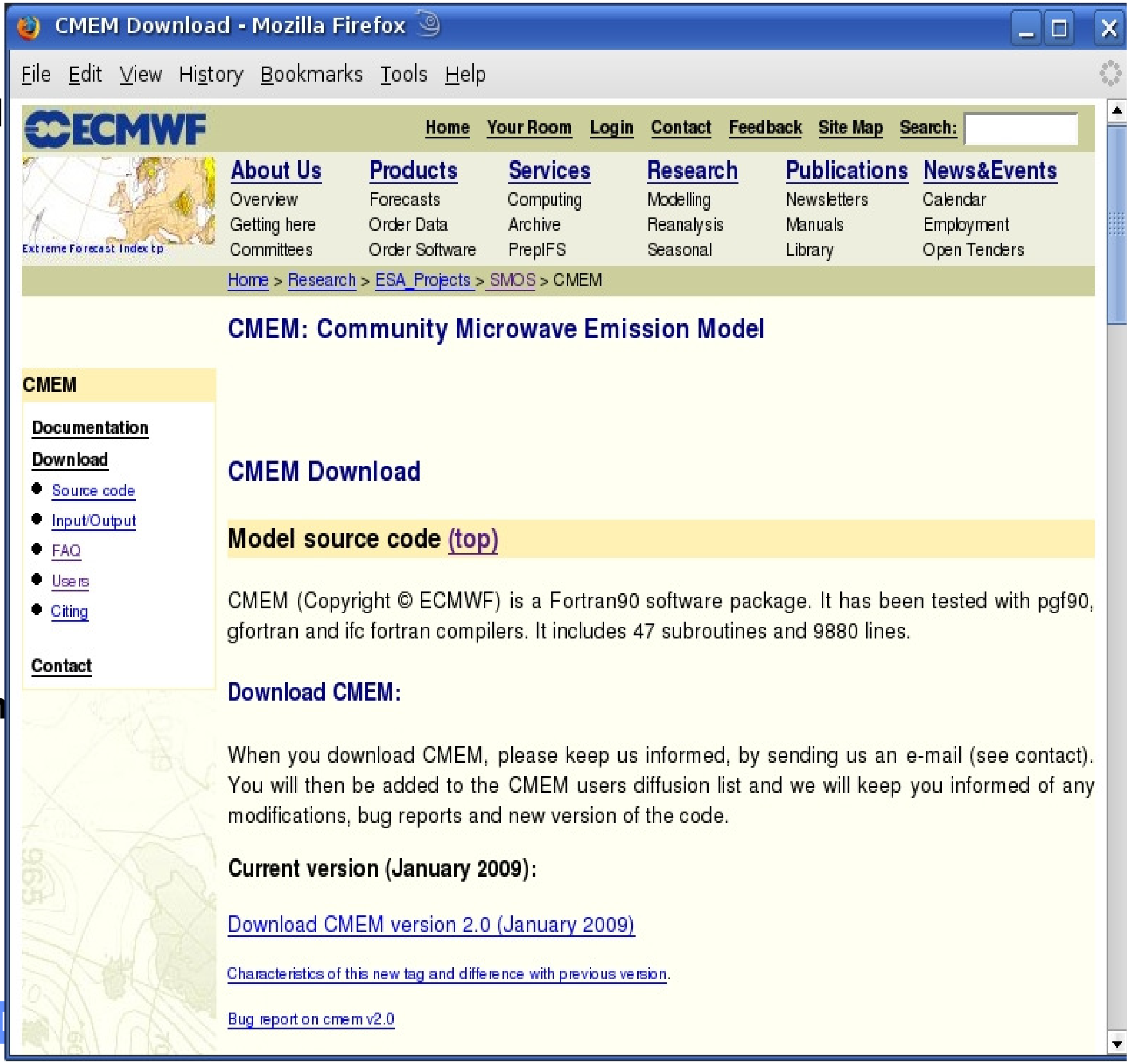
http://www.ecmwf.int/research/ESA_projects/SMOS/cmem/cmem_index.html

Land surface MW emission model developed at ECMWF for NWP.

Specifically developed as forward Operator for SMOS, but also Suitable at higher frequencies (C-Band and X-Band).

Currently being implemented in IFS CY35R3 (following the all-sky Radiances processing).

Use of SMOS data at ECMWF: see the presentation by J. Muñoz Sabater this afternoon



References:

Holmes et al. IEEE TGRS, 2008
Drusch et al. JHM, 2009
de Rosnay et al. JGR, 2009
Muñoz Sabater et al., sub 2009

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EKF surface analysis system

Operational implementation:

- The EKF surface analysis is far more expansive than the OI (x 1000 in CPU).
- When using satellite data it is even more consuming.
- In addition High resolution needed because of surface heterogeneities over land.
- Current OI operational surface analysis is performed after the 4D-VAR in very short time slot (a few minutes).

→ In order to make the EKF surface analysis affordable in operation we needed to:

1. Allow more time for the surface analysis: new structure of the analysis developed and implemented in the Integrated Forecast System (CY35R3).
2. Reduce the cost of the EKF surface analysis to be able to use satellite data.

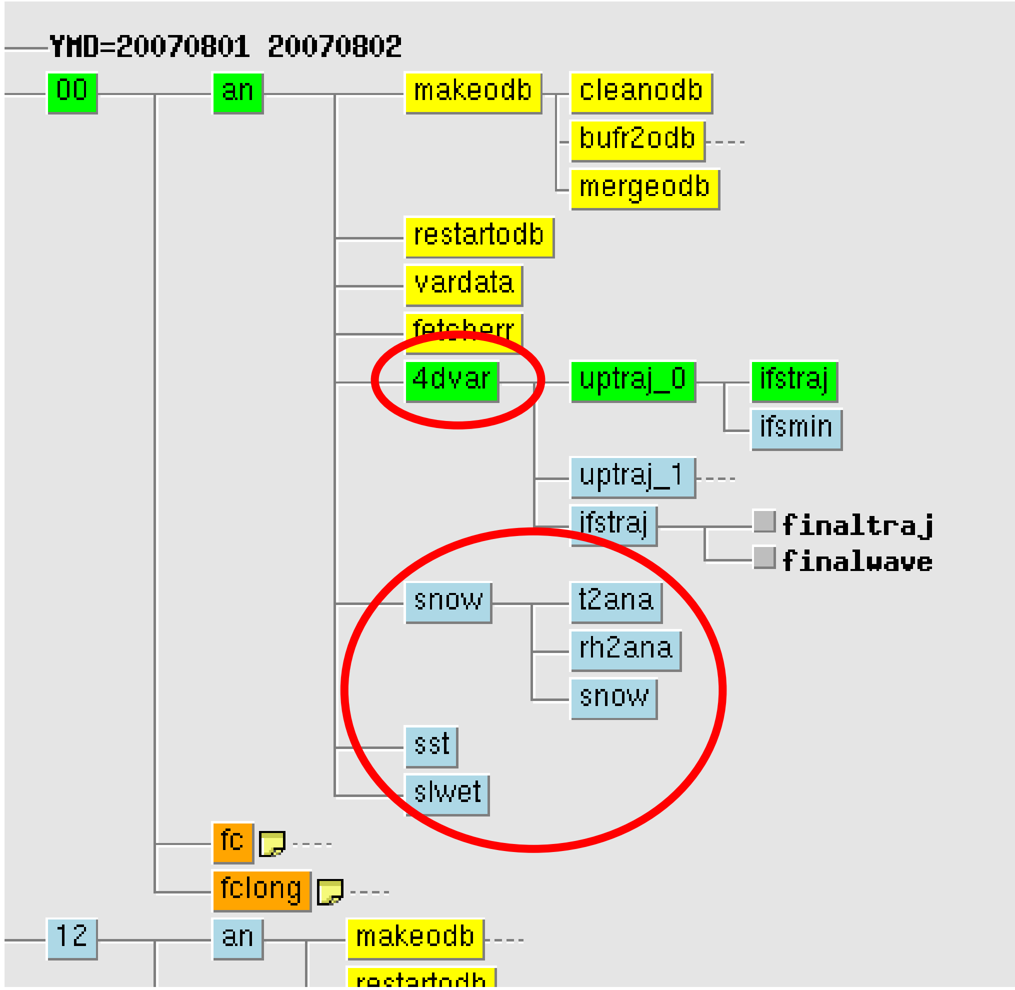
The main costs is due to the perturbed coupled simulations required to estimate the Jacobian matrix (1 simulation per analysed layer).
→ cost reduction relies on decoupling the Jacobian computation from the atmosphere.

The operational EKF surface analysis at ECMWF will open the possibility for operational data assimilation of ASCAT surface soil moisture index and SMOS brightness temperatures.

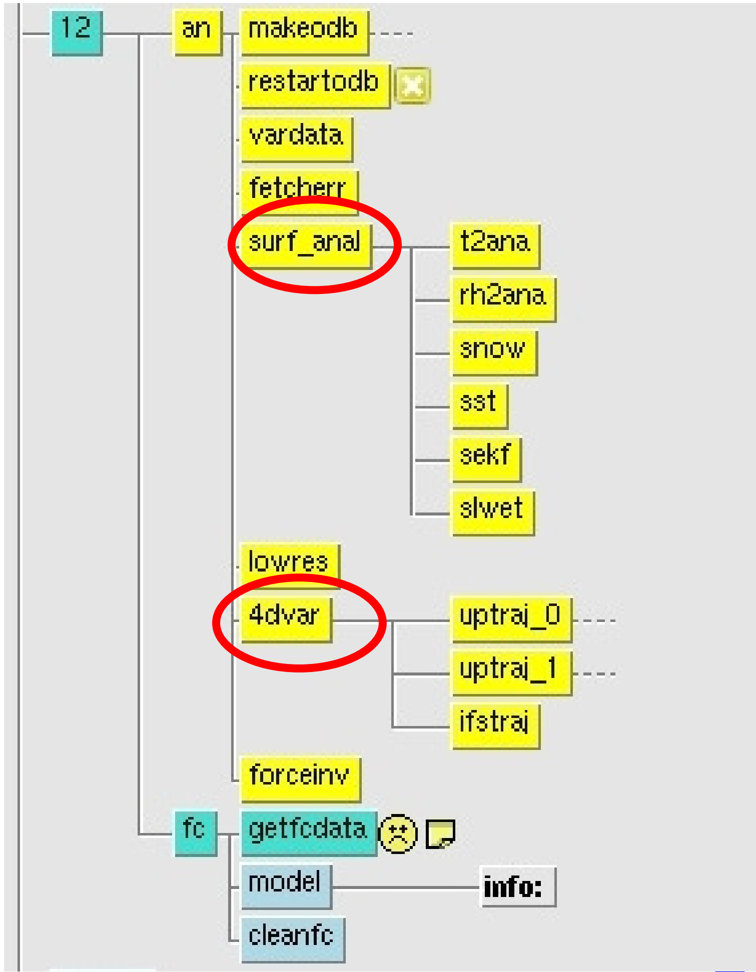
Surface Analysis

organisation within the ECMWF Integrated Forecasting System (IFS)

Up to CY35R2
Current operational system:
- Surface analysis after 4D-VAR
- no EKF



From CY35R3:
-Surface analysis before 4D-VAR
From 36R2
- EKF soil moisture analysis
- Offline Jacobians



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Summary

• ECMWF has been developing and testing an EKF land surface analysis.

• CPU time is a crucial issue for NWP. It required a complete re-organisation of the surface analysis in the ECMWF assimilation system and a decoupling of the Jacobian computation.

• The EKF surface analysis will be implemented in operation in winter 2009/2010. It will open the possibility to assimilate satellite data, such as SMOS and ASCAT.

• Within H-SAF ECMWF produce root zone soil moisture products
→ First step toward consistent NWP and operational hydrology

Thank you for your attention

More information on the ECMWF Land surface analysis:

IFS documentation:

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

Data Assimilation training courses:

http://www.ecmwf.int/newsevents/training/meteorological_presentations/MET_DA.html

ECMWF SMOS page:

http://www.ecmwf.int/research/ESA_projects/SMOS/index.html

ECMWF H-SAF page:

http://www.ecmwf.int/research/EUMETSAT_projects/SAF/HSAF/