EKF development and results
Use of satellite data for soil moisture analysis

M. Drusch, K. Scipal, P. de Rosnay, G. Balsamo

EKF results presented to the Scientific Advisory Committee (SAC) in October 2008

SAC topical paper -> Tech Memo:
http://www.ecmwf.int/publications/library/ecpublications/_pdf/tm/501-600/tm576.pdf

GRL paper in prep (to be submitted today)

Thanks to: J.-F. Mahfouf (Météo-France), E. Andersson (ex DA), P. Bougeault (HR), A. Boone (Météo-France), T. Holmes (Univ. Amsterdam), H. Hersbach (OW) , N. Bormann (SD), M. Dragosavac (MA), D. Vasiljevic (DA), I. Mallas (MA), A. Hofstadler (MA), J. Urban (NA), A. Brady (SD), the calldesk team and others

Introduction

What variable ? Current work ?

Ocean surface:

- **Sea Surface Temperature (2D interpolation, based on NCEP → OSTIA)**
- Sea Ice (Cressman analysis, from NCEP, based on SSM/I)
- Sea surface salinity (global constant) ;
  for seasonal forecast, analysed from Argofloat (OI)

Land surface:

- Snow Water Equivalent (Cressman analysis, SYNOP and NOAA/NESDIS)
- 2m Relative humidity and Temperature (Optimum Interpolation)
- **Soil moisture and soil temperature (Optimum Interpolation ⇢ sEKF)**

2007-2008-2009: focus on the EKF surface analysis development and implementation

Surface analysis system developments

- **Questions**
- 1- Current operational Optimum Interpolation (OI) scheme ; weaknesses
- 2- The EKF surface analysis
- 3- Active microwave remote sensing
- 4- Passive microwave remote sensing
- 5- Evolving structure of the surface analysis

Questions

- Why do we need a new surface analysis system ?
- What are the weaknesses of the current soil (M & T) analysis (OI) ?
- How structured must be the surface analysis ?

Surface analysis system developments

- Questions
- **1- Current operational OI scheme ; weaknesses**
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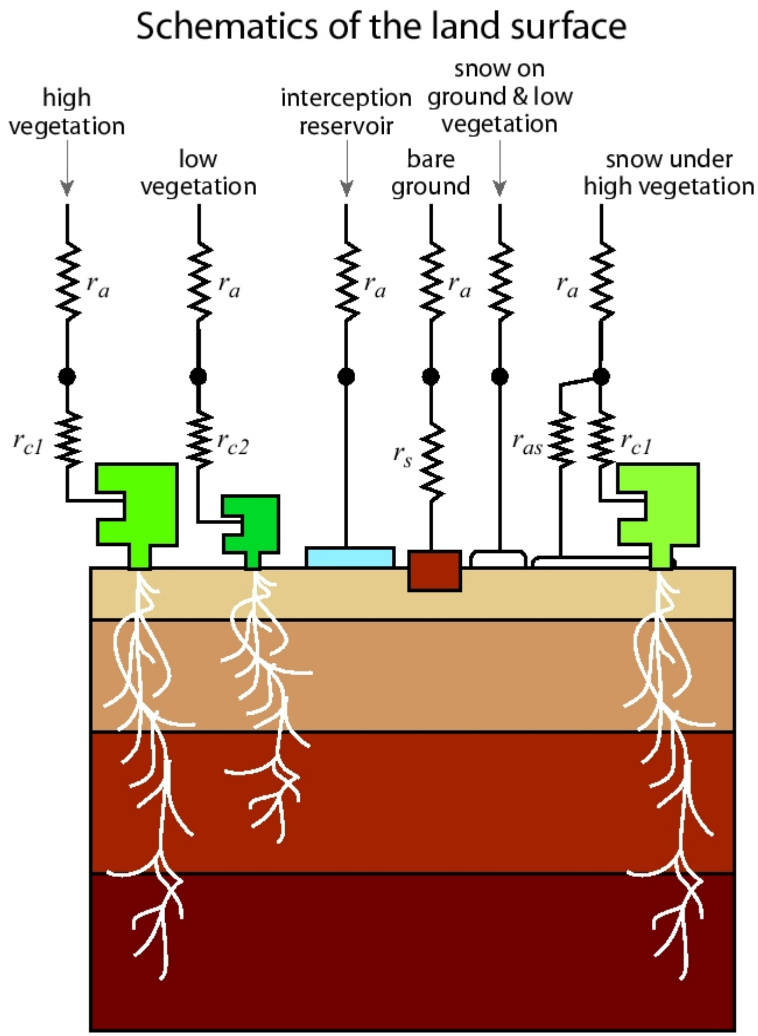
2- Current Optimum Interpolation (OI)

HTESSEL Land Surface Model



Link between soil variables and surface boundary layer (SBL):

- **Soil Moisture and Surface EvapoTR:**
  - **SM above field Capacity -> Hi LE**
  - **SM below wilting point -> Low LE**

- **Soil Moisture and Screen level Parameters:**
  - **Too low SM -> SBL too dry & too warm**
  - **Too high SM -> SBL too moist & too cold**

→ The analysis increments for the T2m and RH2m analysis are used to compute the soil moisture increments

$$DQ_i = A_i \left(T^a - T^b\right) + B_i \left(\mathrm{rH}^a - \mathrm{rH}^b\right)$$

ECMWF

Current OI weaknesses

- Link between screen parameters (T2m RH2m) and soil parameters relies on very complex and non-linear land-surface-atmosphere processes

- OI includes many thresholds to switch off the OI in conditions of wind, soil freezing, snow, precipitation

- Complexity of the Land surface model HTESSEL increases for future NWP applications (now HTESSEL, current work on CTESSEL)

- OI Not flexible to include new type of observations that are more directly linked to soil moisture or vegetation:
    - SM form active microwave (C-band ERS and ASCAT on MetOp)
    - SM from passive microwave (L-band SMOS, SMAP, C-band AMSR-E)
    - Leaf Area Index (MODIS, SPOT-VEGETATION)

Advances in soil moisture analysis since 1991

Dimension	Method	Jacobian	Variable used	Institute & authors
3D	simplified EKF	coupled	T2m, RH2m	DWD, Hess 2001
1D	simplified EKF	coupled	T2m,RH2m, TB	ECMWF, Seuffert et al. 2004
3D	simplified 2D-VAR	coupled	T2m,RH2m	Météo-France, Balsamo et al. 2004
	EnKF	stand-alone	Tb	USDA, Crow et al. 2001 NASA GSFC, Reichle et al. 2002
	simplified 2D-VAR	stand-alone	Tb	CMC, Balsamo et al. 2006
	simplified 2D-VAR	stand-alone	R2m, Tb, Ts	CMC, Balsamo et al. 2007
	simplified 2D-VAR	stand-alone	SM, LAI	Muñoz Sabater et al. 2007

	simplified EKF	stand-alone	T2m, RH2m	Météo-France, Mahfouf et al., 2008
3D	Simplified EKF	coupled	T2m, RH2m, ASCAT SM	ECMWF, Drusch et al., 2008 (SAC paper + TM soon)

Surface analysis system developments

- Questions
- 1- Current operational OI scheme ; weakness
- **2- The EKF surface analysis (MD, KS, PDR, GB)**
- 3- Active microwave remote sensing
- 4- Passive microwave remote sensing
- 5- Evolving structure of the surface analysis

3- The simplified Extended Kalman Filter surface analysis

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:

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

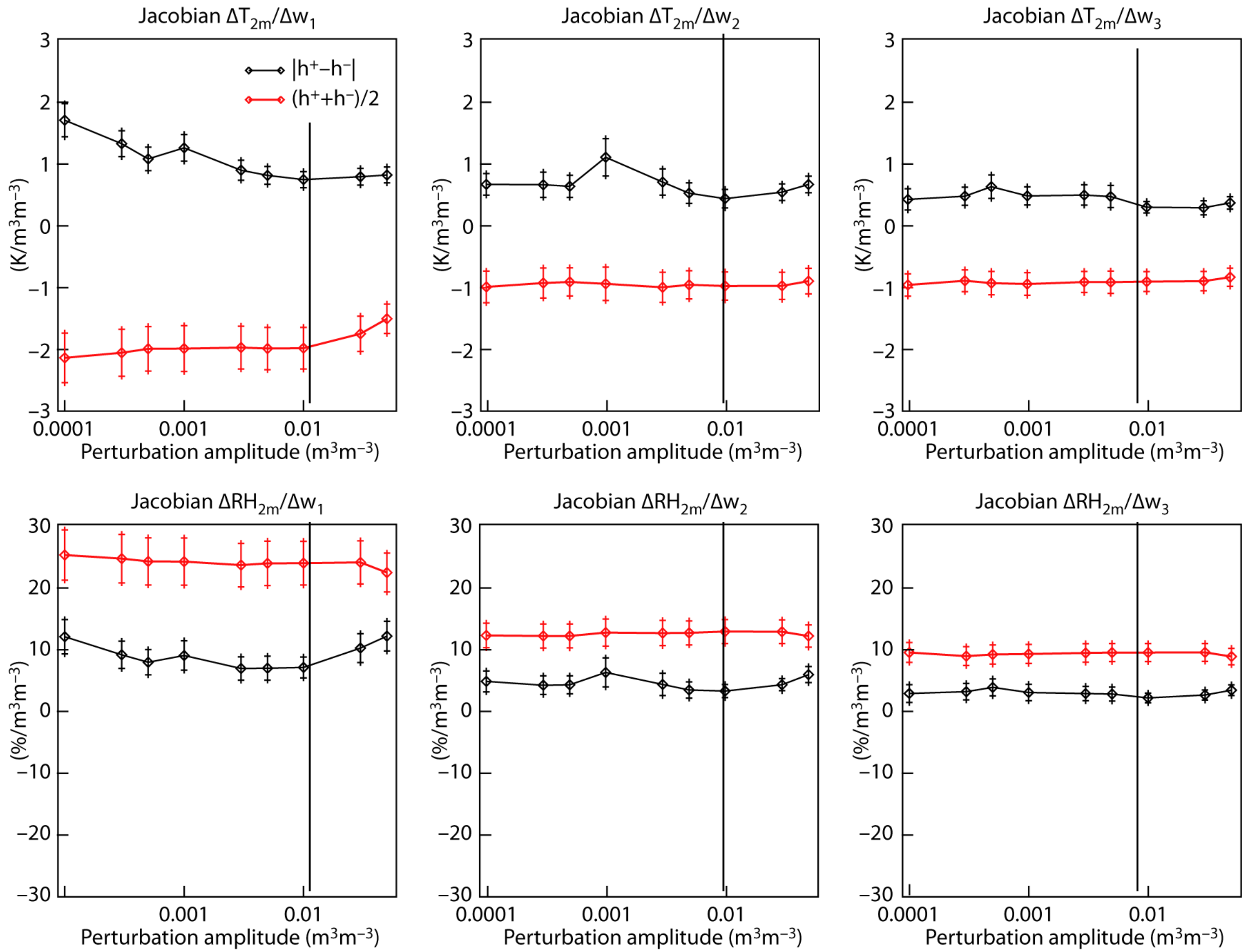
In finite differences, the elements of the Jacobian matrix are estimated by perturbing individually each component x_j of the control vector $\mathbf{x}$ by a small amount δx_j. sensitivity as been conducted to find the optimum perturbation δx_j.

Sensitivity of the Jacobian Matrix to the perturbation amplitude

Top Layer | Layer2 | Layer3

T2m component

RH2m component



Positive & negative perturbations -> [(h^+ + h^-) / 2] constant

-> [[(h^+ - h^-) / 2] tend to zero

→ Perturbation of 0.01 m^3/m^3 suitable to estimate the Jacobian matrix

Comparison between the OI and the EKF soil moisture analysis
Experimental setup

- IFS CY33R1, T159 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 SEKF

1- OI Gain matrix coefficients 01 May 2007 12UTC

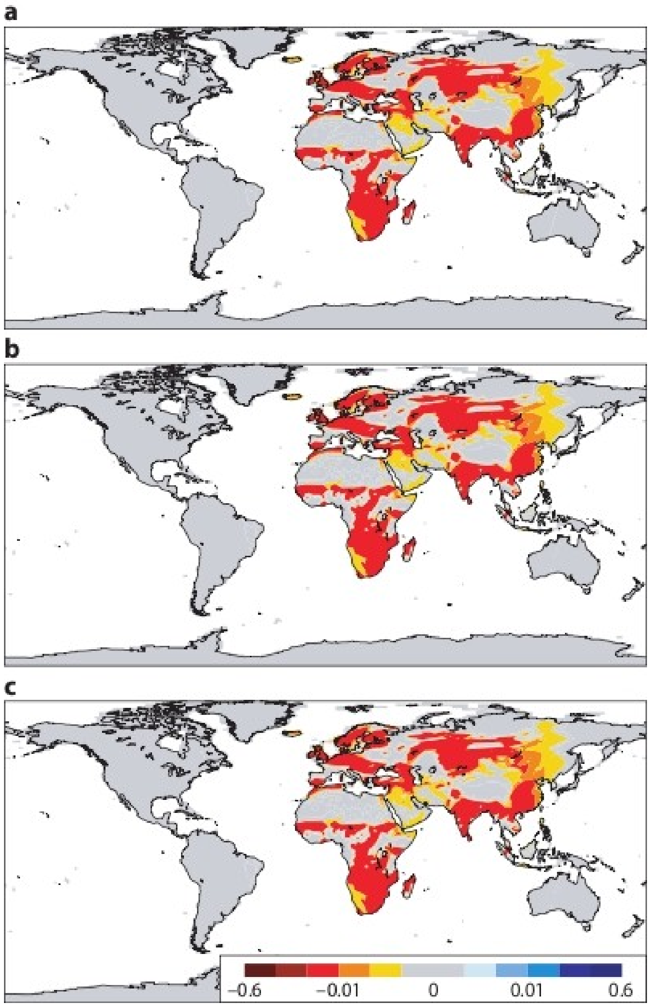
T2m component (%m^3m^{-3}/K)

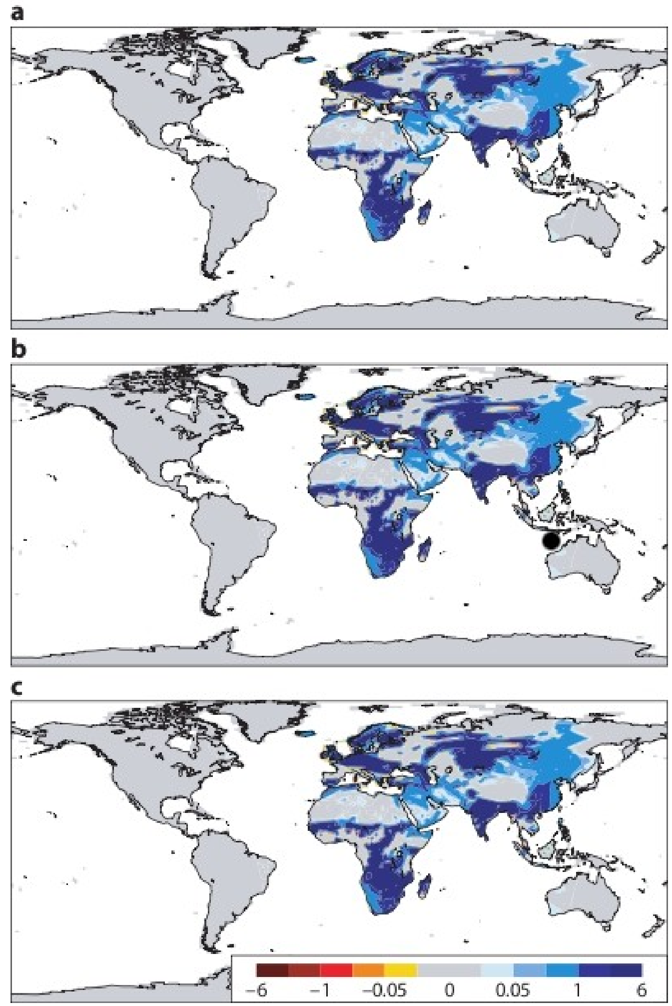
RH2m Component (%m^3m^{-3})

Top
0-7cm

Layer2
7-28cm

Layer3
0.28-1m





-0.6 -0.01 0 0.01 0.6

-6 -0.1 0 0.1 6

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

ECMWF

Comparison between OI and SEKF

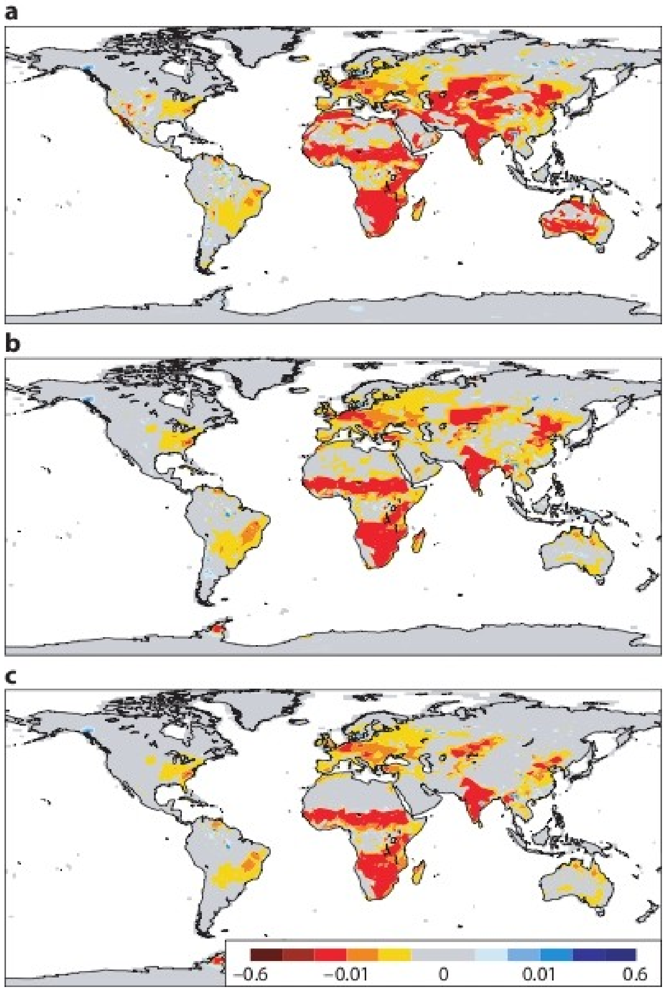
2- SEKF Gain matrix coefficients 01 May 2007 12UTC

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

Top 0-7cm

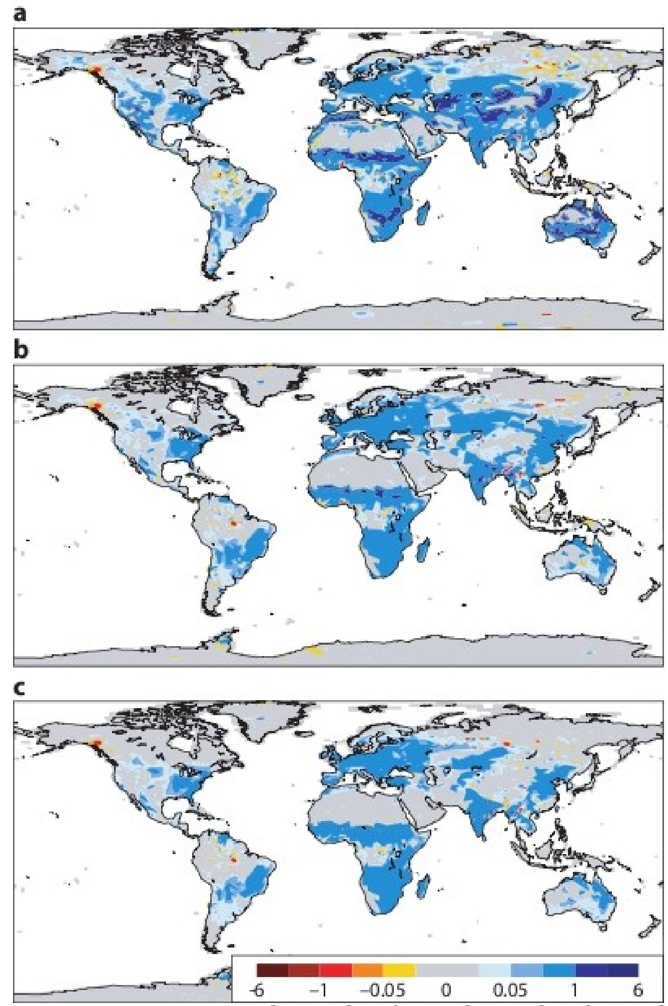
Layer2 7-28cm

Layer3 0.28-1m



-0.6 -0.01 0 0.01 0.6

RH2m Component (%m^3m^{-3})



-6 -0.1 0 0.1 6

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

ECMWF

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

- Flexible to include new type of observations that are more directly linked to soil moisture or vegetation:
  - SM form active microwave (C-band ERS and ASCAT on MetOp)
  - SM from passive microwave (L-band SMOS, C-band AMSR-E)
  - Leaf Area Index (MODIS, SPOT-VEGETATION)

Surface analysis system developments

- Questions
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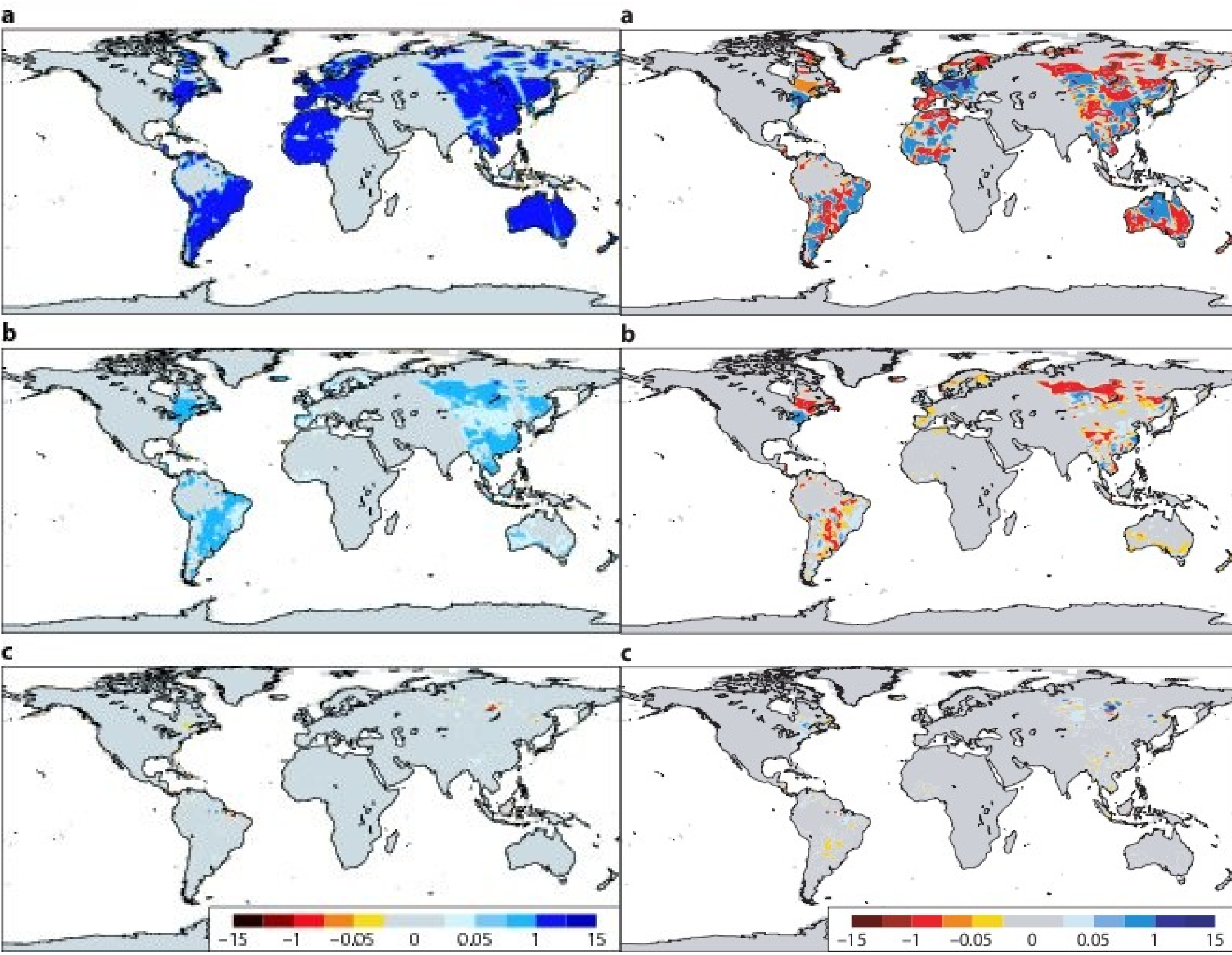
ASACT assimilation in the EKF:

Scipal et al., in prep

1-3 May 2007, T159

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



Top layer
0-7cm

- Values at high latitudes
- No gain over trop Forest

Layer 2
7-28 cm

-Simular amplitude at night (US) and at day (Europe)

Layer 3
0.28-1m

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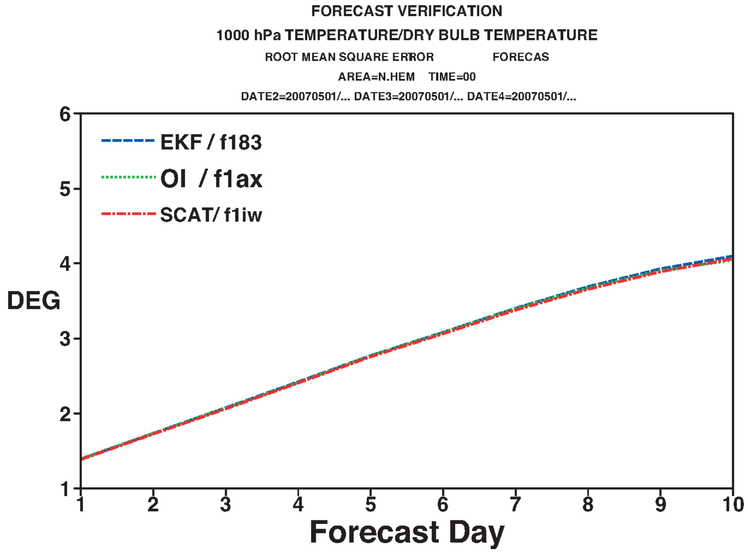
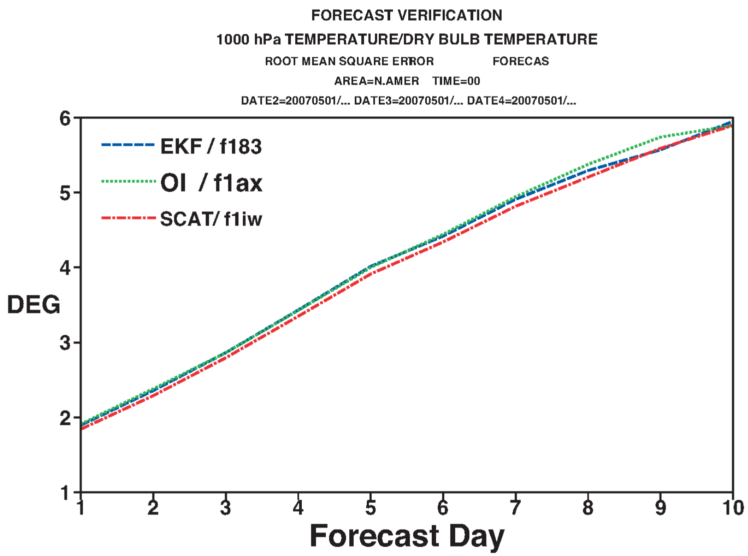
Forecast Verification





- Score plots
  - Based on a 1 month run (May 2007).
  - RMSE of 1000 hPa Temp.
- Global
  - Impact is neutral for the ASCAT ass. using the EKF compared to the operational OI and the EKF
- Local
  - significant differences
  - ASCAT ass. for example outperforms OI and EKF over North America
  - Negative impact for example over Europe

Surface analysis system developments

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- **4- Passive microwave remote sensing (PDR,MD,GB)**
- 5- Evolving structure of the surface analysis

ALMIP-MEM

de Rosnay et al., TM 565,
and in revison to JGR

AMMA Land Surface Model Intercomparison Project – Microwave Emission Model

Context: SMOS / AMMA (African Monsoon Multidisciplinary Analysis)

ALMIP (**AMMA Land Surface Model Intercomparison Project**, **Boone et al.,, 2008**)

Concept:

- Combined **8 LSMs and 12 microwave models** inter-comparison
- Simulation of C-Band Brightness Temperature (TB) for 2006 over West Africa
- Evaluation against AMSR-E (C-band)

Aim:

- Sensitivity of simulated TB to the LSM and microwave parameterisations
- Evaluation of surface soil moisture simulated by LSMs
- Identify key parameterisations for the CMEM forward operator

Time-latitude TB

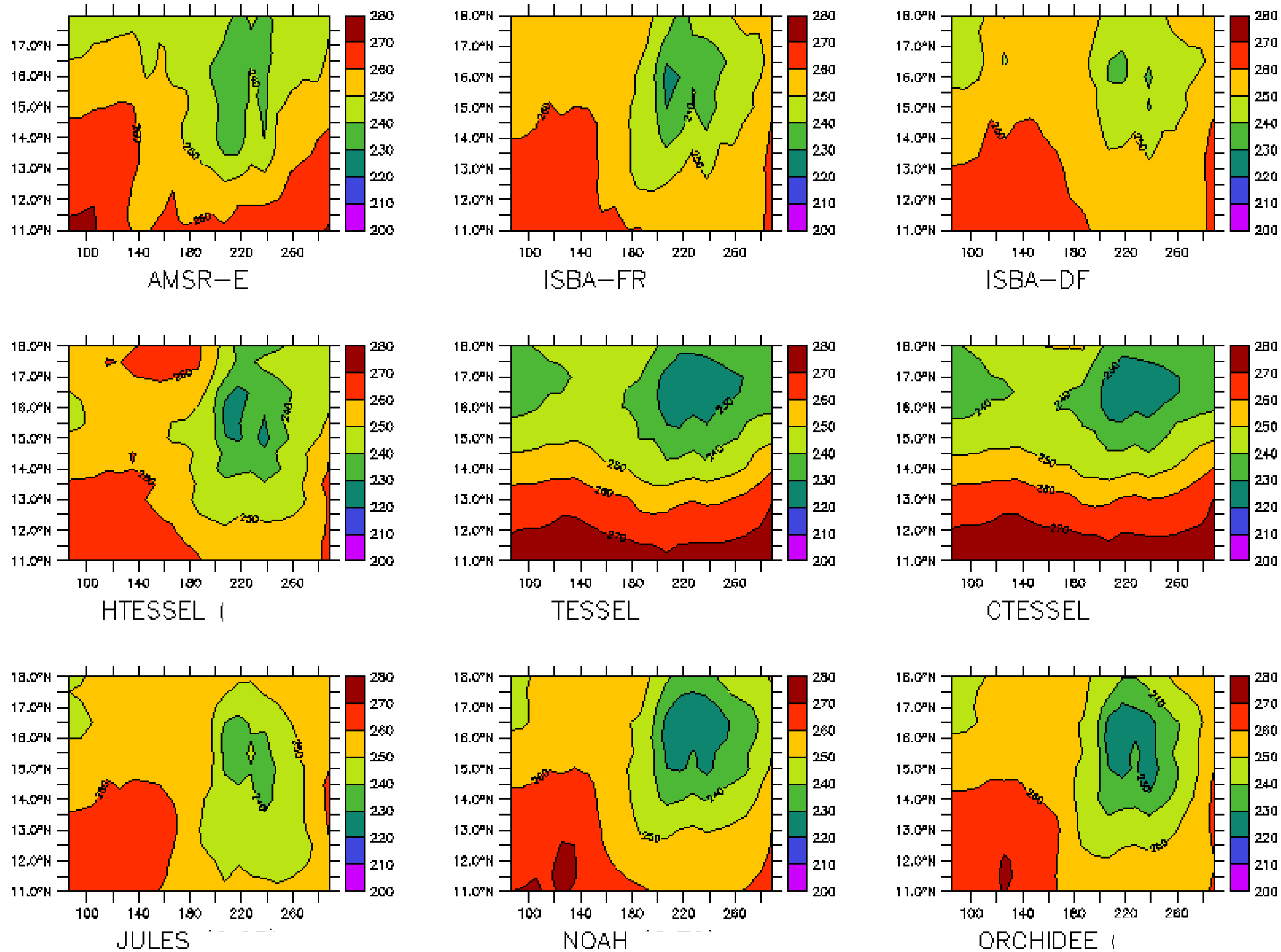
(at horizontal Pol)
Average 10W-10E

AMSR-E
8 ALMIP-MEM LSM

CMEM configuration 10
(Wang&Schmugge
+ Kirdyashev)

Bias correction
Applied for each LSM

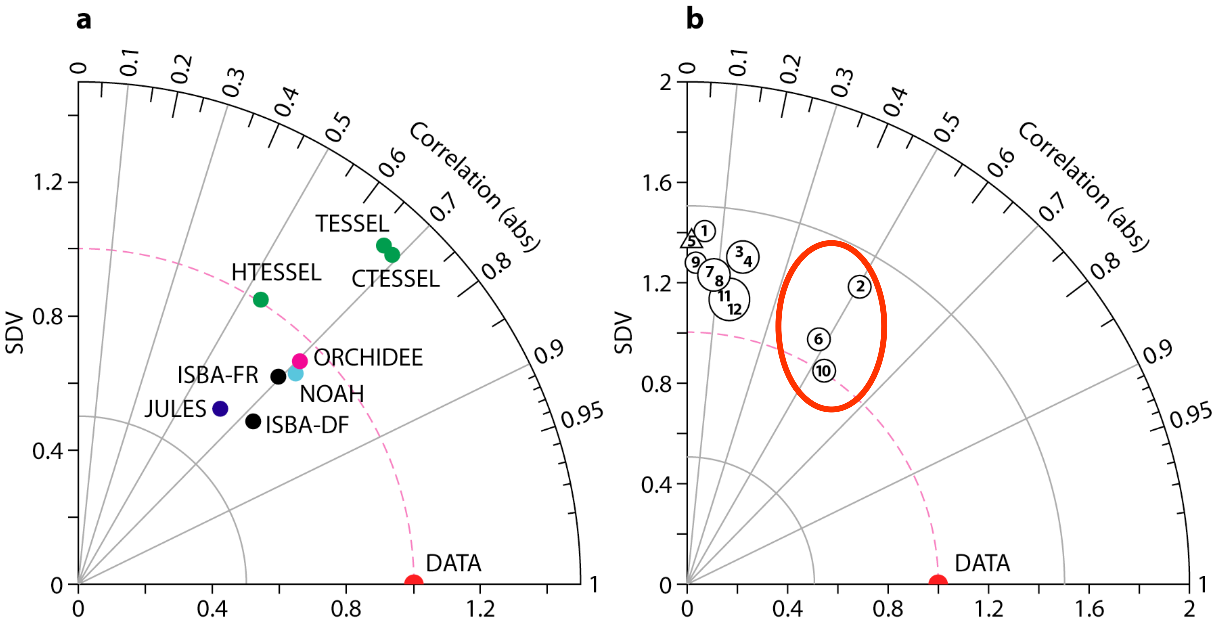
- Time-latitude wet Patch Well captured by most of the LSMS



ECMWF

Comparison between simulated and observed TBH over West Africa

Taylor Diagram for the year 2006



Large scatter for LSM and MW models

Best MW modelling configuration: Kirdyashev and Wang & Schmugge models

Consistent with Skylab study
-> Key parameterisation identified.

ECMWF

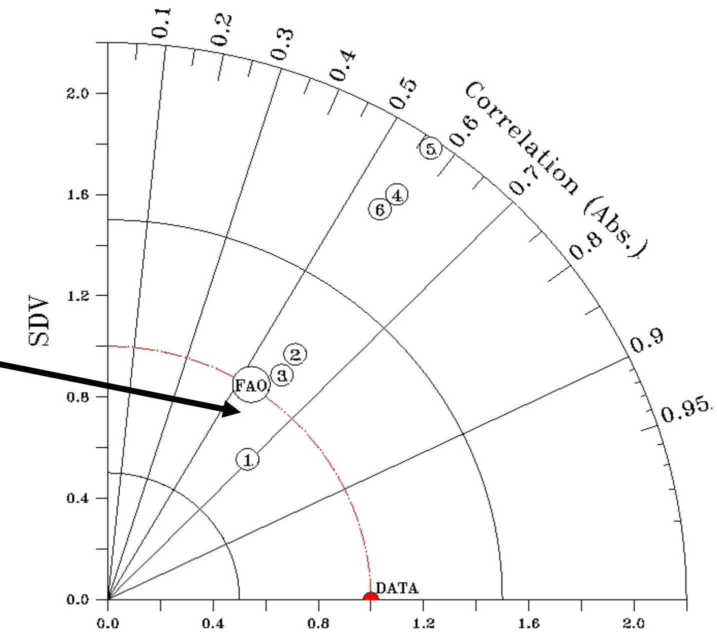
Impact of soil texture on TB errors with HTESSEL
(additional/complementary study)

Taylor Diagram for the year 2006
HTESSEL with different soil texture maps

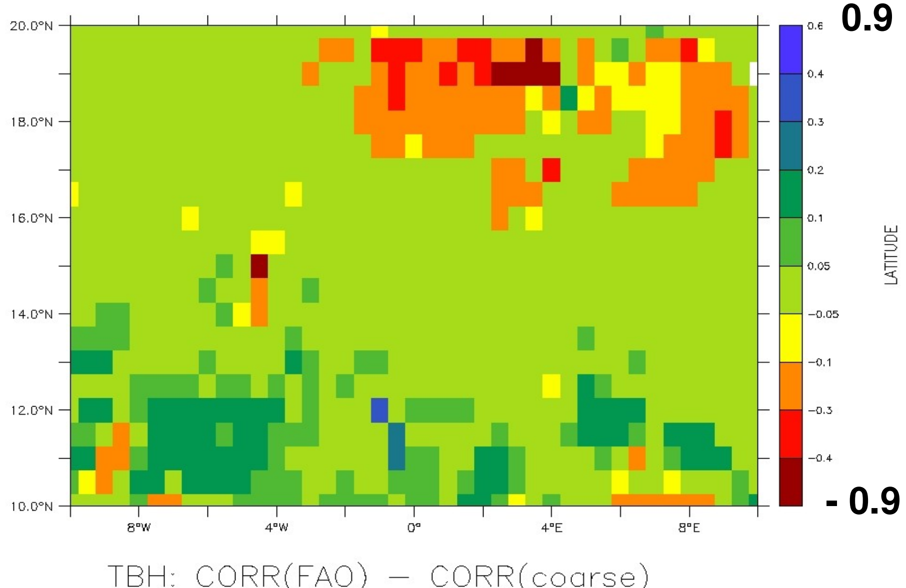
Coarse textured soil lead to better agreement between simulated and observed TB

Impact of texture on soil moisture dynamics -> affects the simulated TB

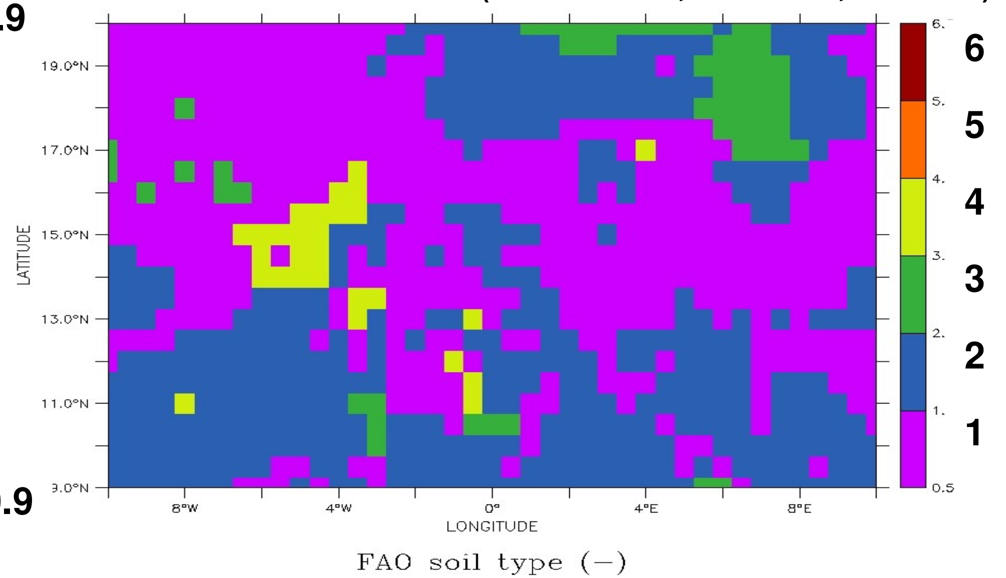
AMSR-E C-band data show texture maps pbs



Diff of TBH Corr (FAO – Coarse)



Soil texture FAO (1 coarse, 2 med, 3 fine)



Passive microwave

ALMIP-MEM:

- Based on LSM community experience in inter-comparison (PILPS, GSWP2), but focus on West Africa and extended to compare different combinations of LSMs and radiative transfer models
- **1st inter-comparison exercise of land surface MW emission models**
- Coupled LSM-CMEM models capture convective system occurrence in Sahel, as well as latitude-time feature of TB
- **Stronger sensitivity of simulated TB to microwave model than to LSM**
- Robustness of the Kirdyashev opacity model to simulate TB in best agreement with AMSR-E measurements, for any LSM.

Consistence between Skylab and ALMIP-MEM (different angle, freq, LSM, scale): best modeling configuration Kirdyashev + Wang&Schmugge

High importance of suitable MW modeling approach for SM retrieval and SM assimilation

AMMA SMOS Cal-Val

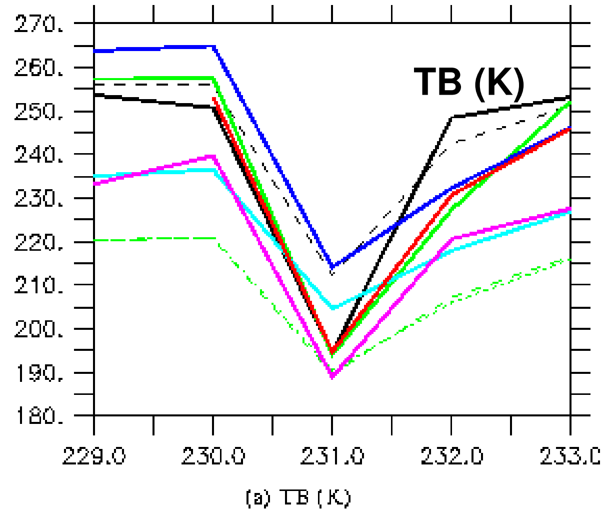
Temporal dynamics

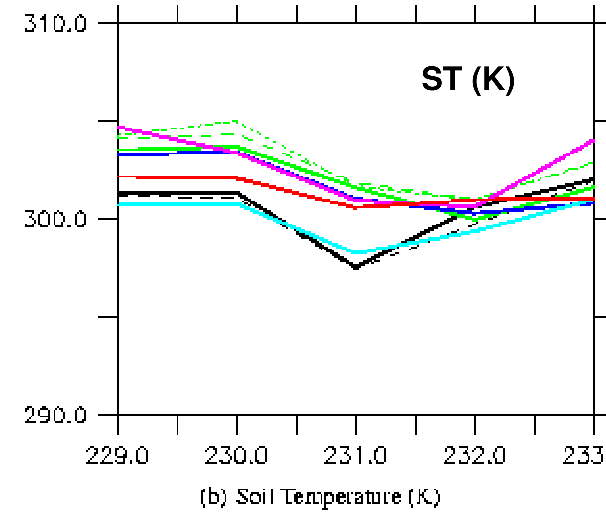
Agoufou site (15.3N,1.5W)
(SMOS vaidation site)

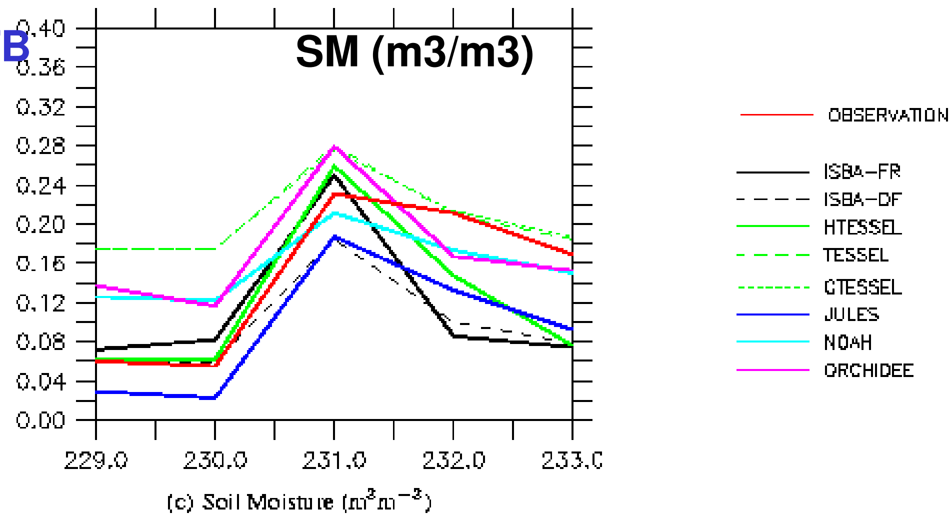
Independent Observations:

- AMSR-E TB
-Ground Soil Moisture & Temperature

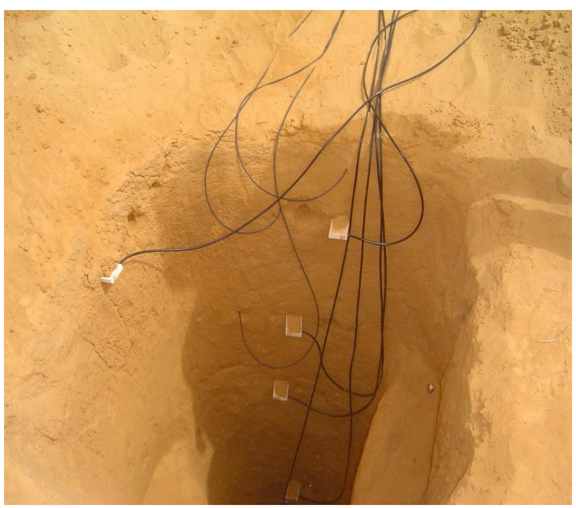
Validation of simulated SM and TB







DoY 229 (17 August) to DoY 233 (21 August)



AMMA – Gourma soil moisture network AMMA-EOP
(de Rosnay et al., submitted JH 2008)

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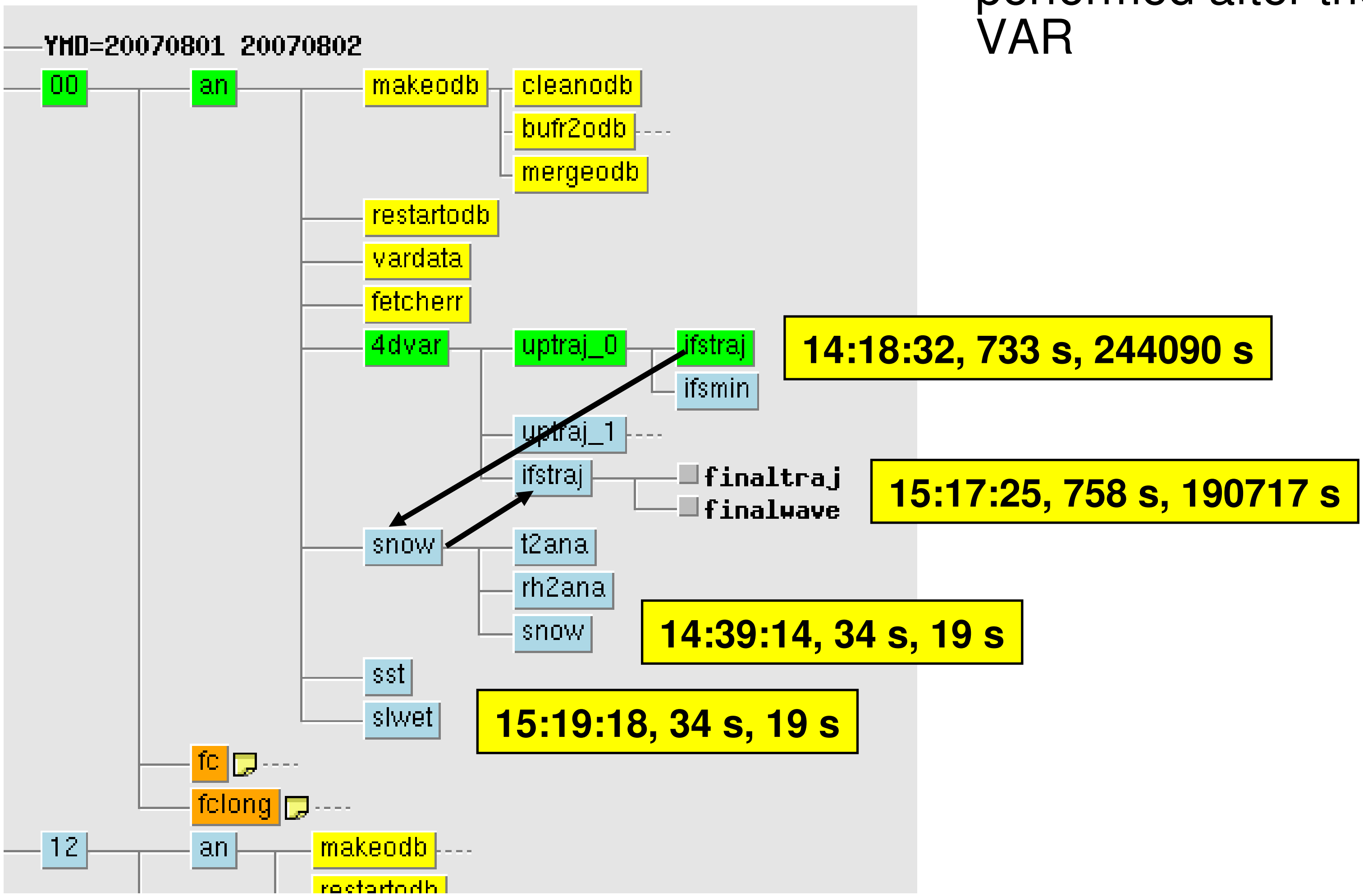
Surface Analysis

current operational SMS structure

The surface analysis is performed after the 4D-VAR



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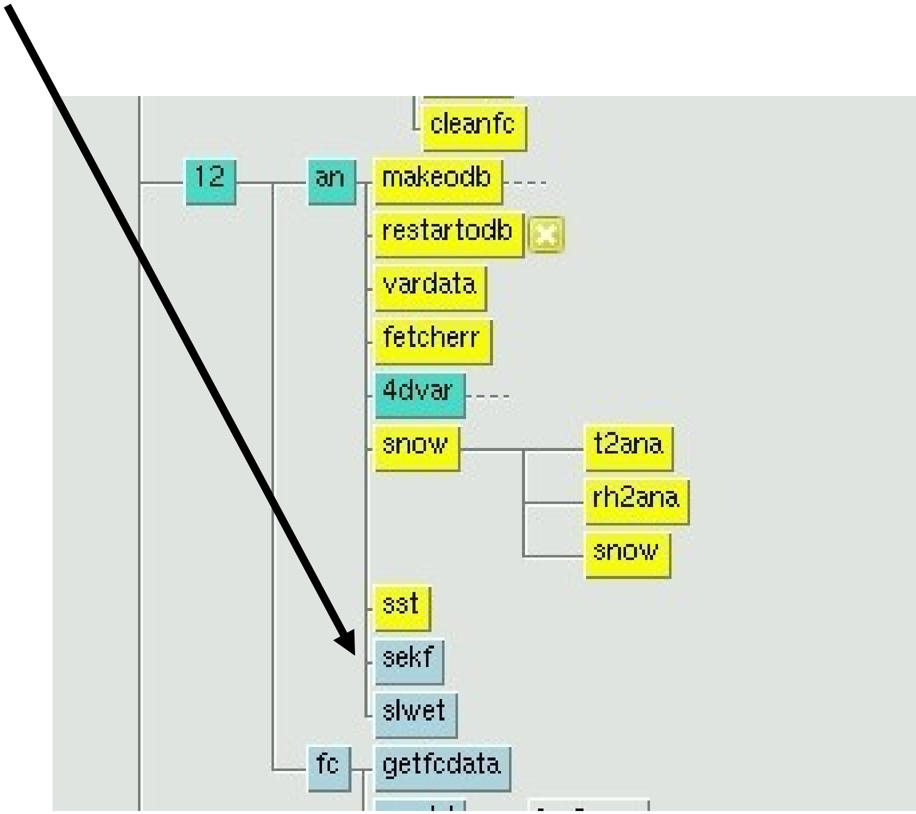
Surface Analysis

The EKF surface analysis
Is included in this structure



The EKF surface analysis is far more expansive than the OI: ~10s with the OI -> ~6min with the EKF surface analysis of soil moisture …

The main costs is due to the perturbed coupled simulations required to estimate the Jacobian matrix (1 simulation per analysed layer)

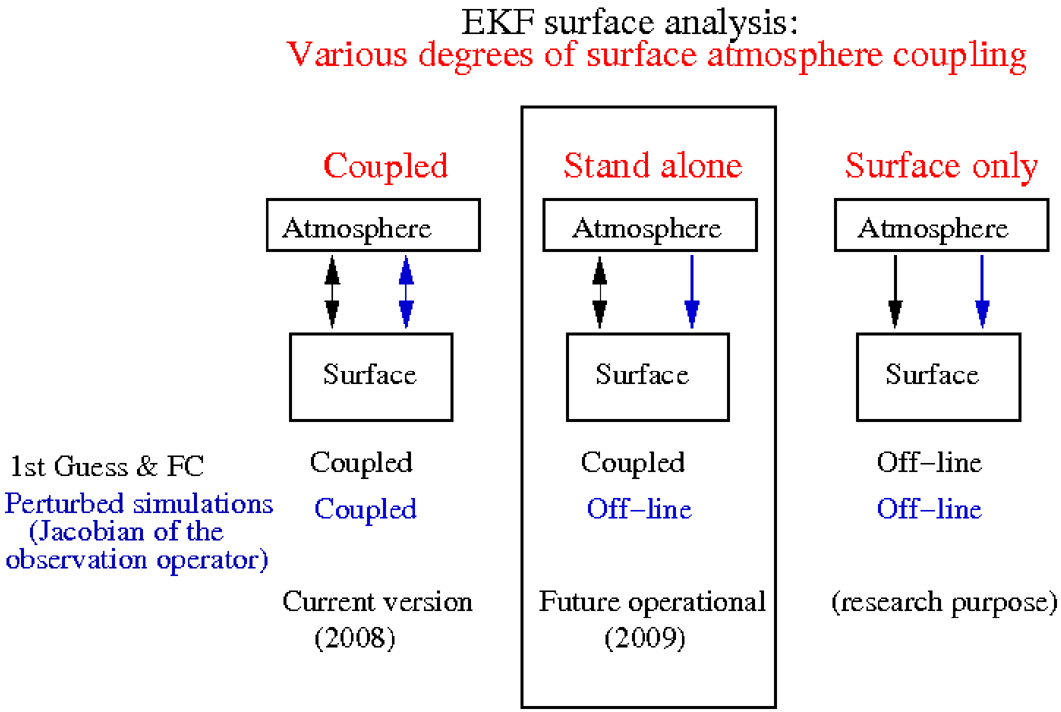
High resolution needed because of surface heterogeneities

-> need to reduce the cost of the EKF surface analysis

EKF development and updates

- The EKF surface analysis is implemented in the research branch
- It is expensive in term of computing time
- Its operational implementation requires a cheaper stand-alone version, (Jacobians are computed with off-line Land surface model perturbations)
- In addition, major on going changes in the surface analysis structure are on-going. SA is moving to be before the 4D-VAR.

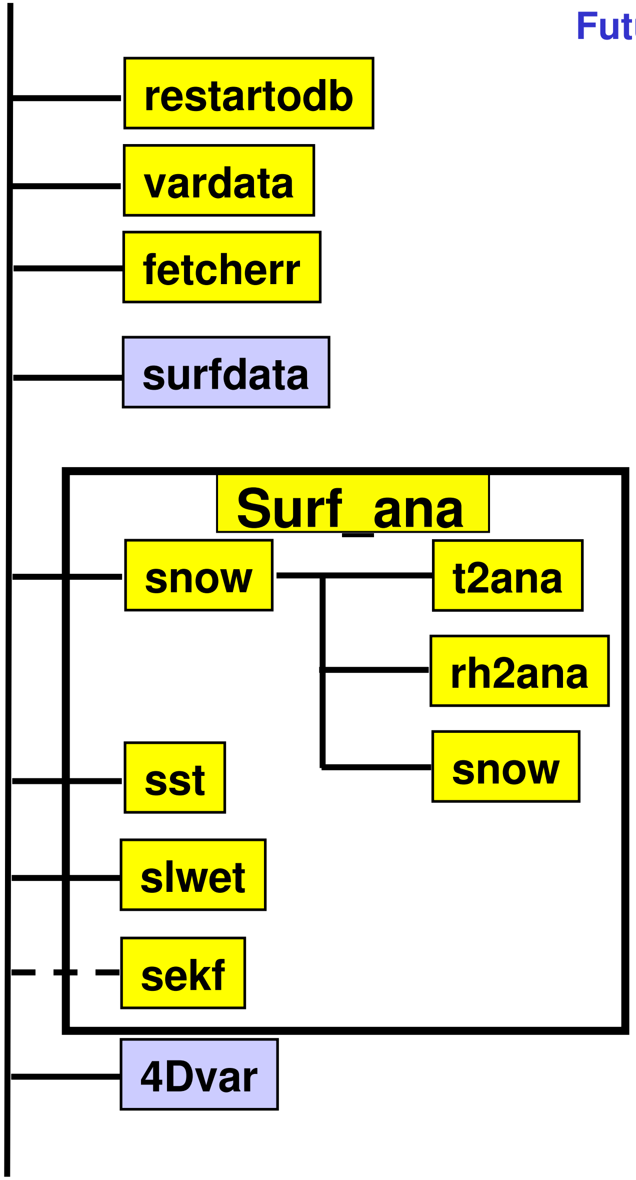
Surface data assimilation updating (on going):



Will be used for the future SMOS data assimilation

Surface Analysis

Future operational structure



Surface analysis **before** the 4D var

New task ‘surfdata’ & modifications
to 4Dvar (observation handling)
(~ 6 weeks).

New operational data extraction
for delayed surface cut-off with 2-3 hours

Implemented in CY33R1 D. Vasiljevic
Update CY35R1 in Oct 2008

Development of:

- **a version without 4DVAR (but with fc)**
- **surface only version**

(Drasko, Patricia, Gianpaolo)

Modification of the EKF surface analysis

We can not compromise on resolution: Soil texture, vegetation data sets, topography, snow properties and soil moisture can not be scaled correctly.

Running the EKF in a stand-alone mode before the 4DVar
- necessary step to make the EKF surface analysis affordable for the operational NWP
- takes the task out of the critical path
- allows fast 're-analysis' experiments (make possible to have consistent surface model between initial state and monthly forecast)
- provides a flexible system for future observations
- save 1 perturbed coupled forecast
- costs n perturbed HTESSEL forecast (negligible time cost)

Major development to be done in 2008-2009 in strong interaction with the physical aspect section (G. Balsamo), Numerical aspect section (J. Urban)

Current OSSE (PDR and GB) test of the EKF, to be repeated with the new structure.