Land surface: constraining model errors via data assimilation

Land surface lecture 2

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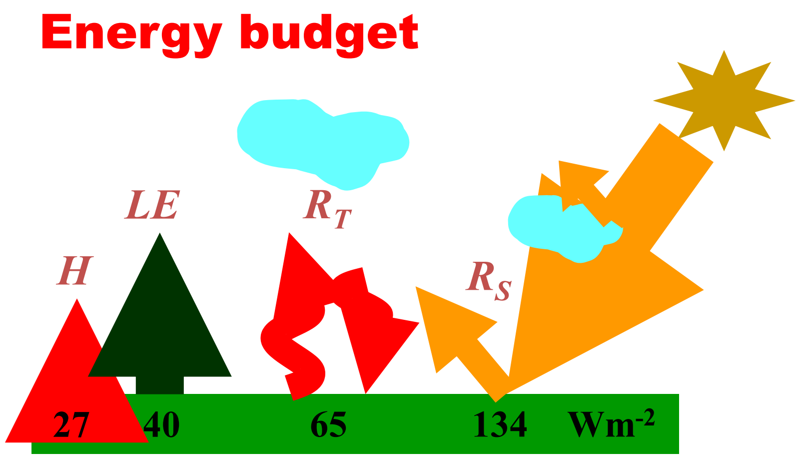
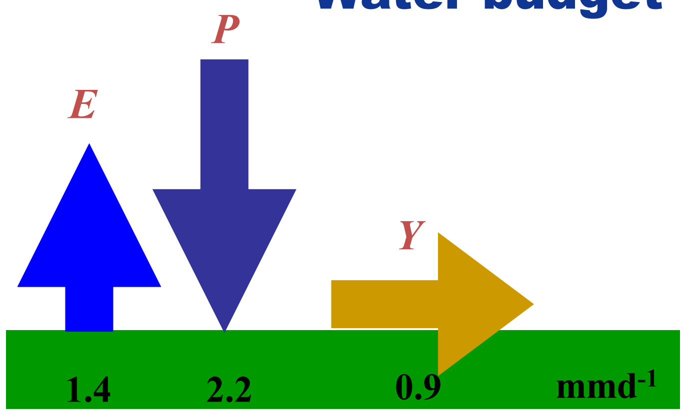
Outline

- Introduction: the role of land surface assimilation
- Evolution of land surface assimilation from minimizing error to consistency
- Frontiers of land surface assimilation towards parameter adjustment

Energy and Water budgets: the model perspective





$$(\rho C)D\frac{\partial T_s}{\partial t} = R_n + LE + H + G$$

$$\frac{\partial S}{\partial t} = P + E + R$$

Energy and Water budgets: the data assimilation perspective

$$T_s^A = T_s^F + \Delta T_s$$

$$S^A = S^F + \Delta S$$

Data Assimilation Techniques applied for Land Surface

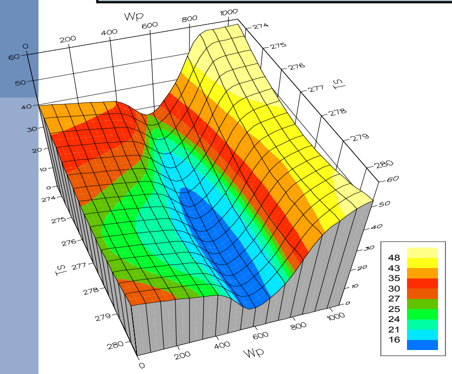
Variational

$$\square\, J(\mathbf{x}) \rightarrow 0$$

Optimum Interpolation

$$\mathbf{K} = \alpha$$

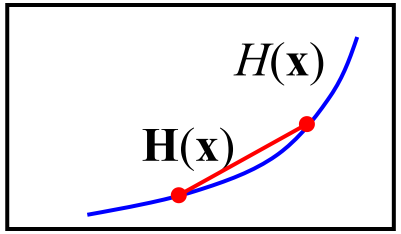
$$\alpha = f(\ldots)$$



Optimal Estimation Theory

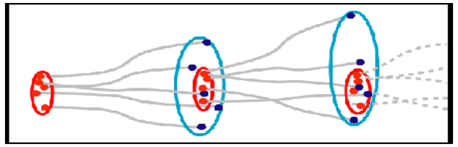
$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{K}\left(\mathbf{y} - H(\mathbf{x}^b)\right)$$

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



Extended / Ensemble Kalman Filter

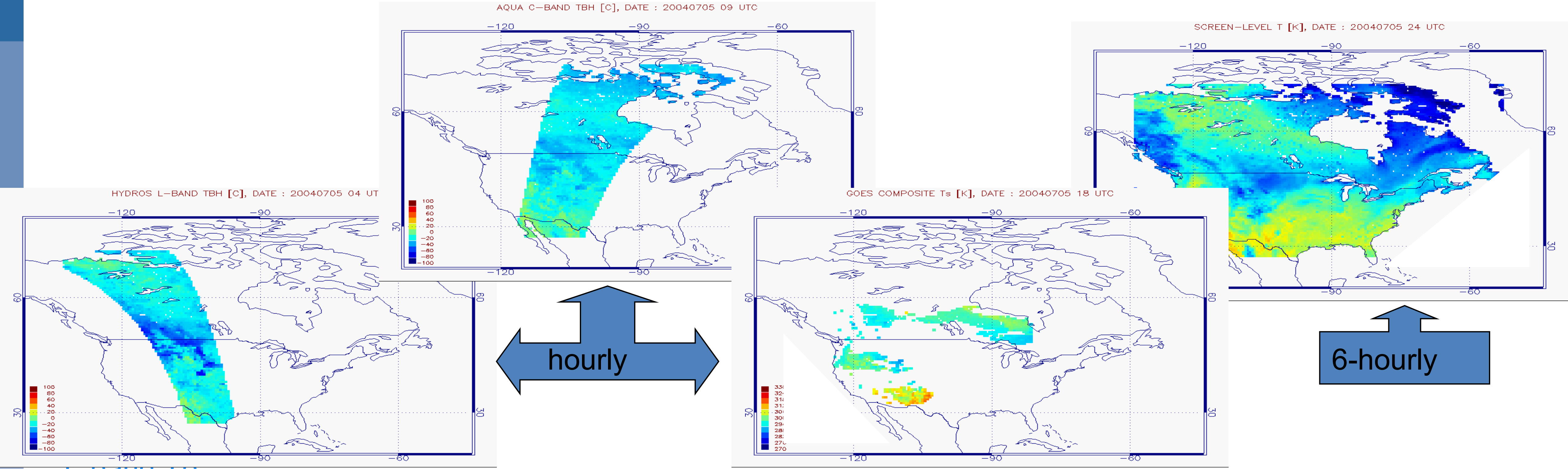
$$\mathbf{B}^{t+1} = \mathbf{M}\mathbf{A}^t\mathbf{M}^{\mathrm{T}} + \mathbf{Q}$$



Simplified VAR/EKF Methods

$$H(\mathbf{x} + \delta\mathbf{x}) = H(\mathbf{x}) + \mathbf{H}\,\delta\mathbf{x}$$

EVOLUTION OF LAND SURFACE DATA ASSIMILATION SYSTEMS

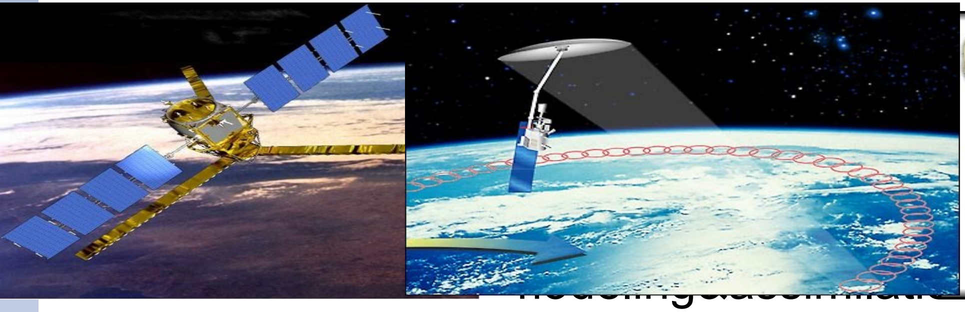


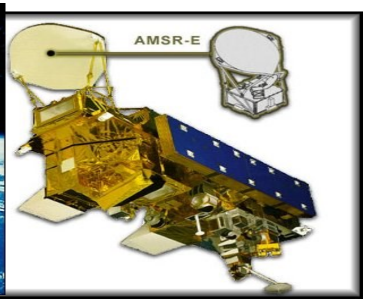
L-band Tb

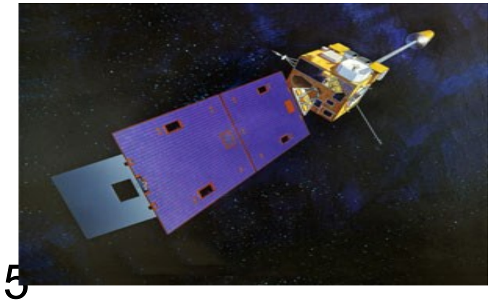
C-band Tb

C-band scat. IR Ts

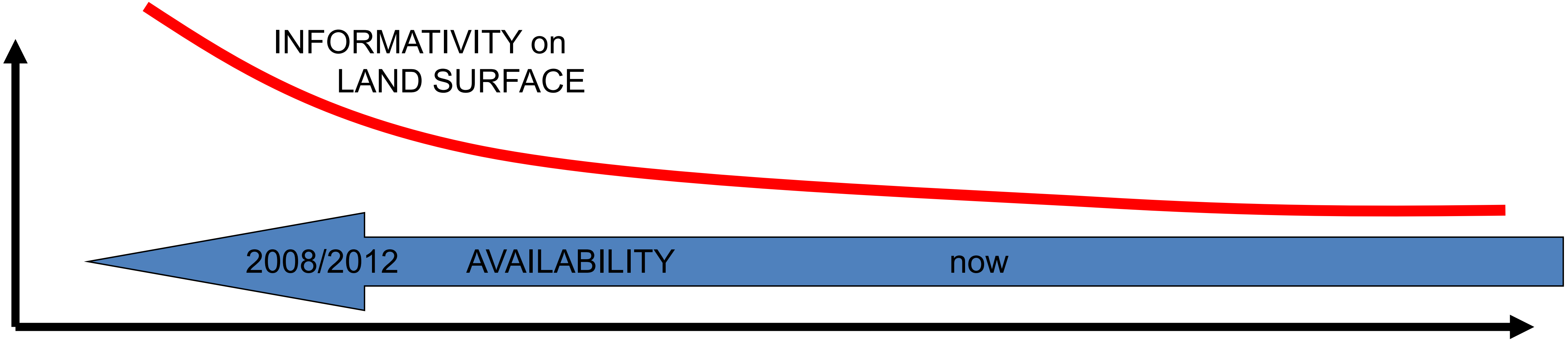
T/H 2m







OBSERVATIONS FOR SOIL MOISTURE ANALYSIS



L-band Tb

C-band Tb

C-band scat.

IR Ts

T/H 2m

L-band Tb

+ Large Information content

+ Global Coverage

+ Reduced Atmospheric Contrib.

-Not Available 'till 2009

C-band Tb

+ Global coverage

+ Relatively reduced Atmospheric contrib.

- RFI

- Vegetation masking VCW>1kg/m^2

IR Ts

+ Large coverage

- Cloud Masking

- Model Bias

T/H 2m

+ Wide validation

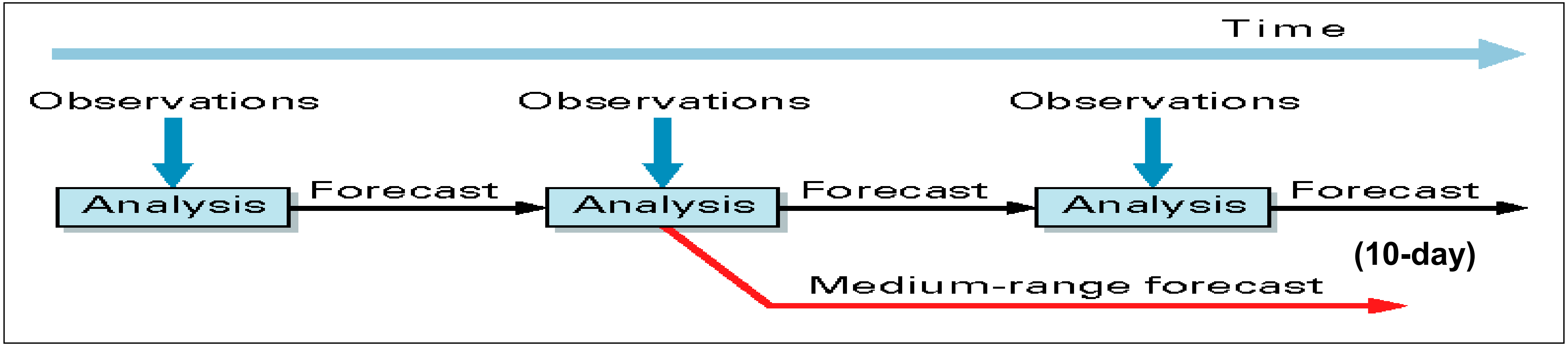
-Coverage

-Variable Information Content

The ECMWF Integrated Forecasting System (IFS) data assimilation system

From L. Isaksen's training courses

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



Data Assimilation System:
Provides 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 at ECMWF

Ocean surfaces:

- Sea Surface Temperature (SST) and sea ice (2D interpolation, based on OSTIA)
- Sea surface salinity (global constant for medium-range forecast)

Land surfaces:

- **Snow**
  - Uses SYNOP Snow depth corrected according to NOAA/NESDIS snow cover
  - Cressman (until 2010), Optimum Interpolation (OI) since 2010
- **Screen level parameters**: OI 2m air Relative humidity and air Temperature SYNOP
- **Soil moisture and soil/snow temperature**:

  -OI using 2m air Relative humidity and air Temperature (1999-2010)

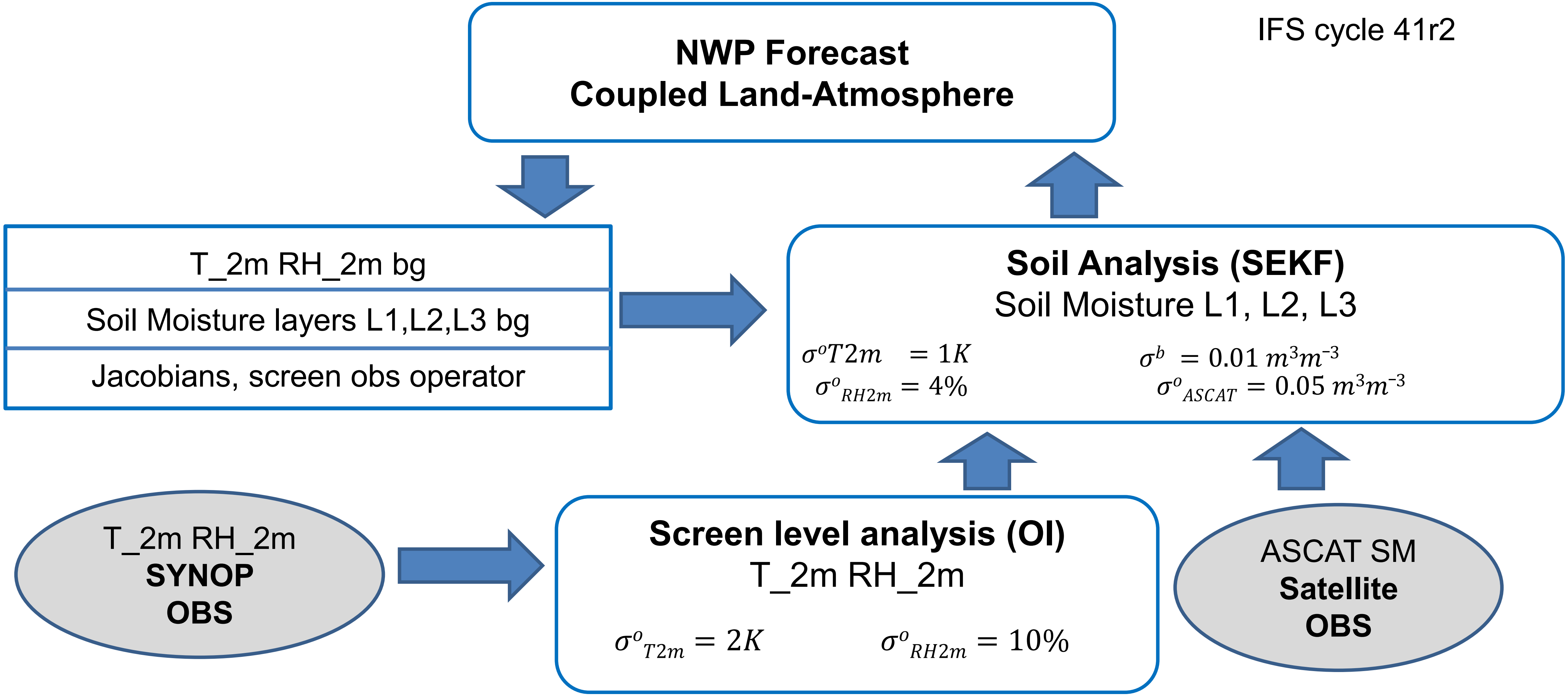
  - OI (1999-2010), Extended Kalman Filter (EKF) since 2010

Recent advances at ECMWF focus on:

- Soil moisture analysis improvements (EKF) and use of satellite data (ASCAT and SMOS)
- Snow analysis new OI scheme

Soil Analysis in the IFS

IFS cycle 41r2



→ Operational soil moisture data assimilation: combines SYNOP and satellite data

Snow Analysis

Snow Quantities:

- Snow depth SD (m)
  - Snow water equivalent SWE (m)
  - Snow Density ρ_s, between 100 and 400 kg/m3

$$SWE = \frac{SD \times \rho_S}{1000} \quad [\mathrm{m}]$$

Observation types:

- SYNOP: snow depth (S^O)
- Satellite: Snow extent (NOAA/NESDIS)

Background variable used in the snow analysis:

- Snow depth S^b

  (computed from forecast SWE and SD)

NOAA/NESDIS Snow extent data

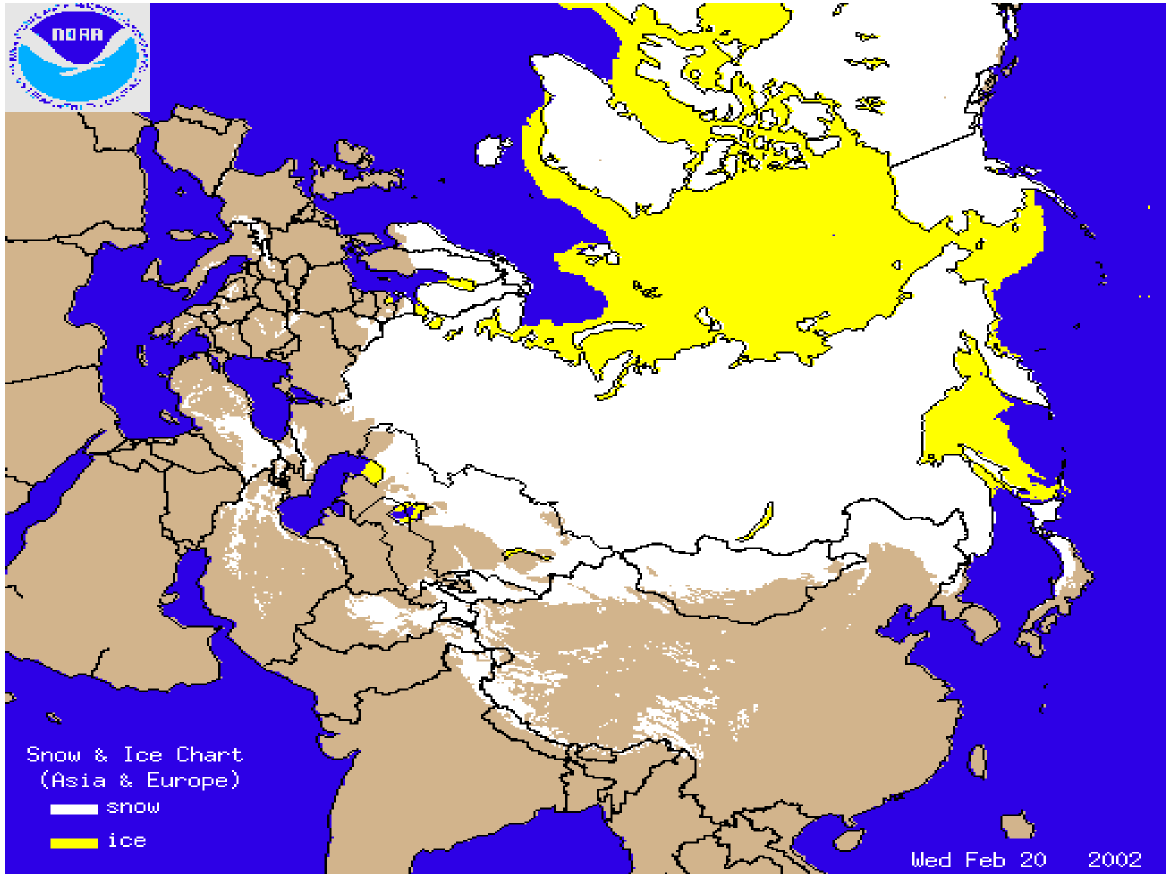
Interactive Multisensor Snow and Ice Mapping System:
- Time sequenced imagery from geostationary satellites,
- AVHRR,
- SSM/I,
- Station data,
- Previous day's analysis

Northern Hemisphere product
- Daily
- Polar stereographic projection

Resolution:
- 24 km product (1024 × 1024)
- 4 km product (6044 x 6044)

Information:
Snow or Snow free

Format: Since Nov. 2010, use ASCII product at 4km



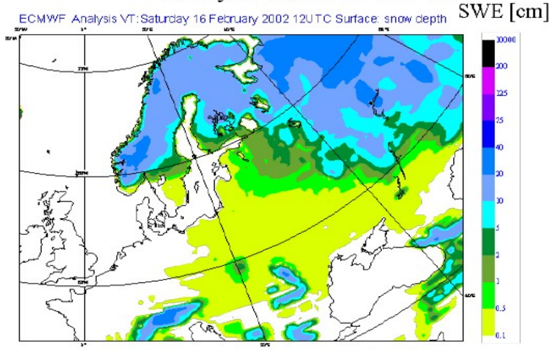
More information at: http://nsidc.org/data/g02156.html

The snow analysis at ECMWF

Analyses vs Satellite Data

MODIS 16/02/2002

Analysis based on SYNOP



Snow extent is overestimated in the analysis
when it is ba

2004: use of the IMS 24km product (Drusch et al.)

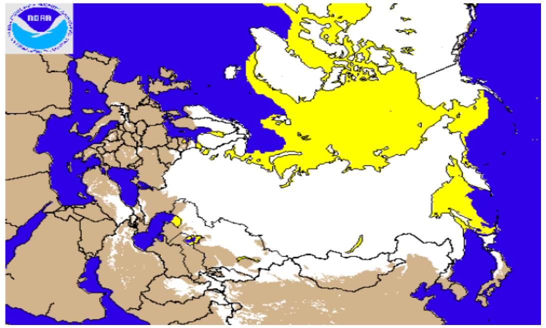
NOAA/NESDIS Snow extent

Interactive Multisensor Snow and Ice Mapping System:

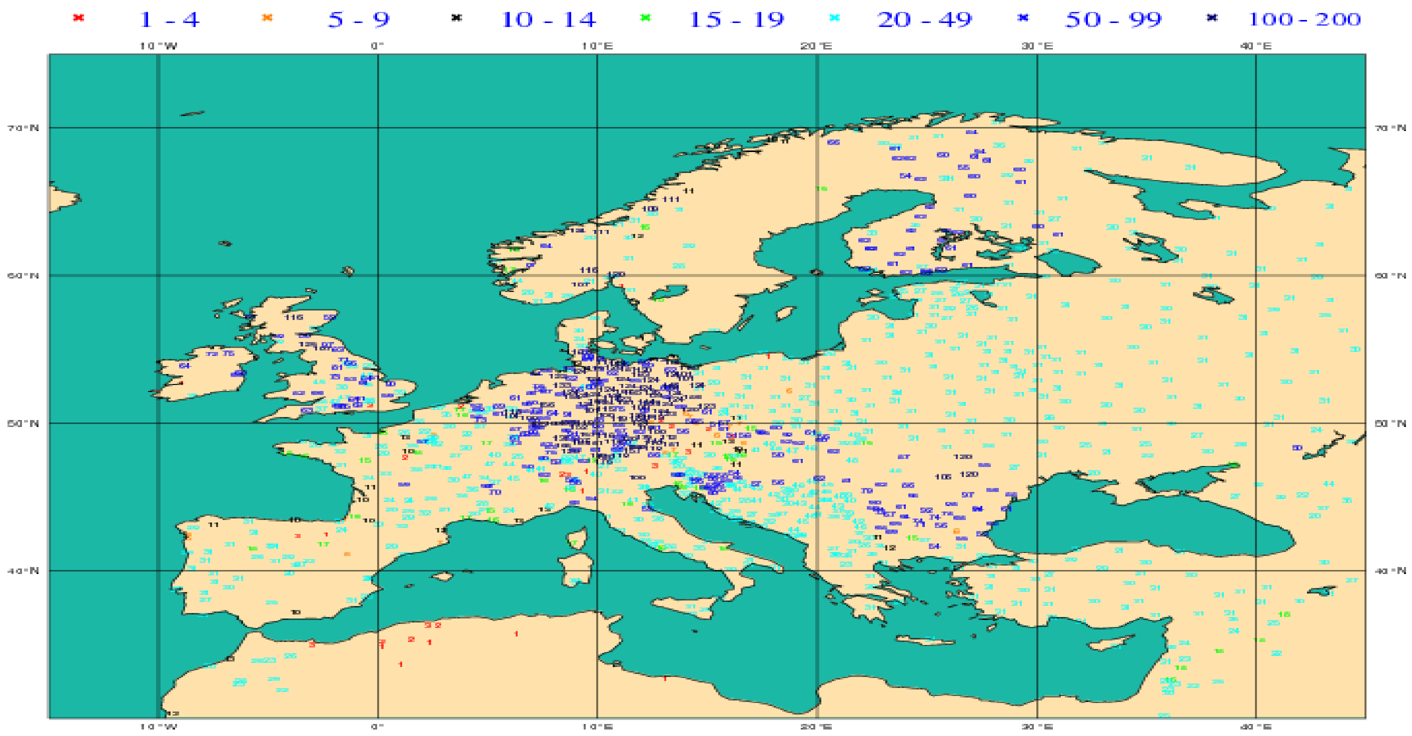
- time sequenced imagery from geostationary satellites,
- AVHRR,
- SSM/I,
- station data,
- previous day's analysis

Northern Hemisphere product

- real time
- polar stereographic projection
- 1024 x 1024 elements



Number of SYNOP data used in the Analysis in January 2010



Snow analysis uses SYNOP snow depth data and NOAA/NESDIS IMS snow cover

2010 implementation:

- New Snow analysis based on the Optimum Interpolation with Brasnett 1999 structure functions

-A new IMS 4km snow cover product to replace the 24km product

-Improved QC (monitoring, Blacklisting)

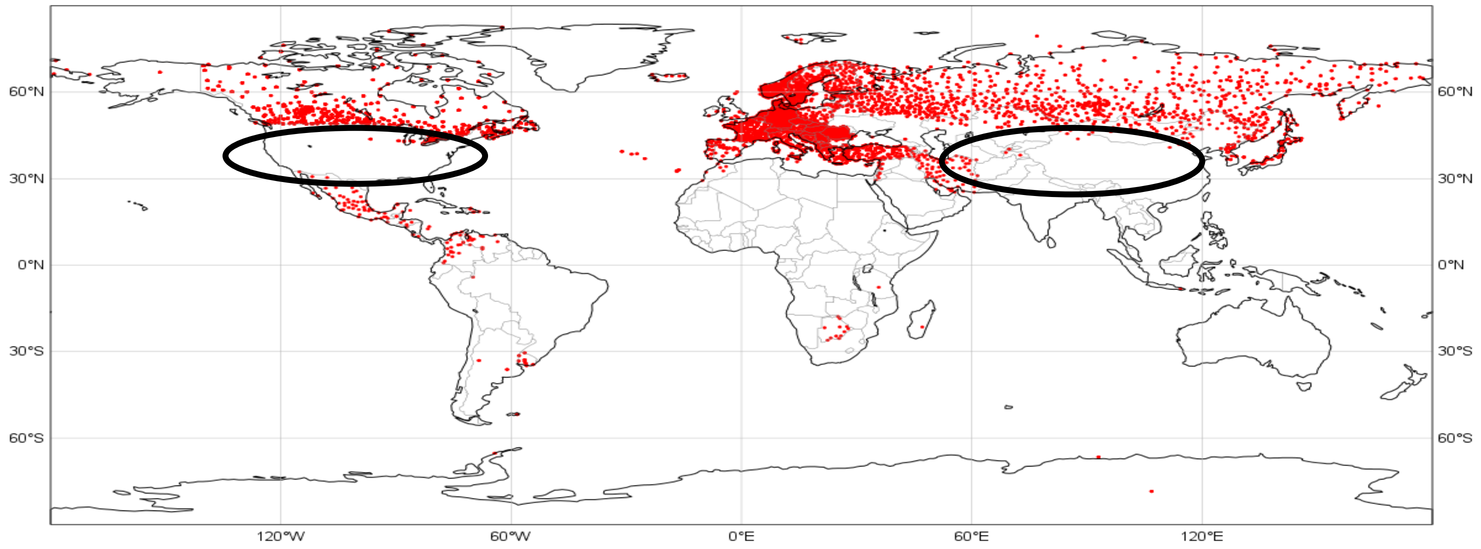
(de Rosnay et al., 2011)

Snow Observations

GTS SYNOP Snow depth availability

Status on 1 March 2016

Operational snow observations monitoring
(SYNOP TAC + SYNOP BUFR + national BUFR data):
http://old.ecmwf.int/products/forecasts/d/charts/monitoring/conventional/snow/



For regional renalyses:
Some regions don’t have observations!
→ Importance of regional data rescue

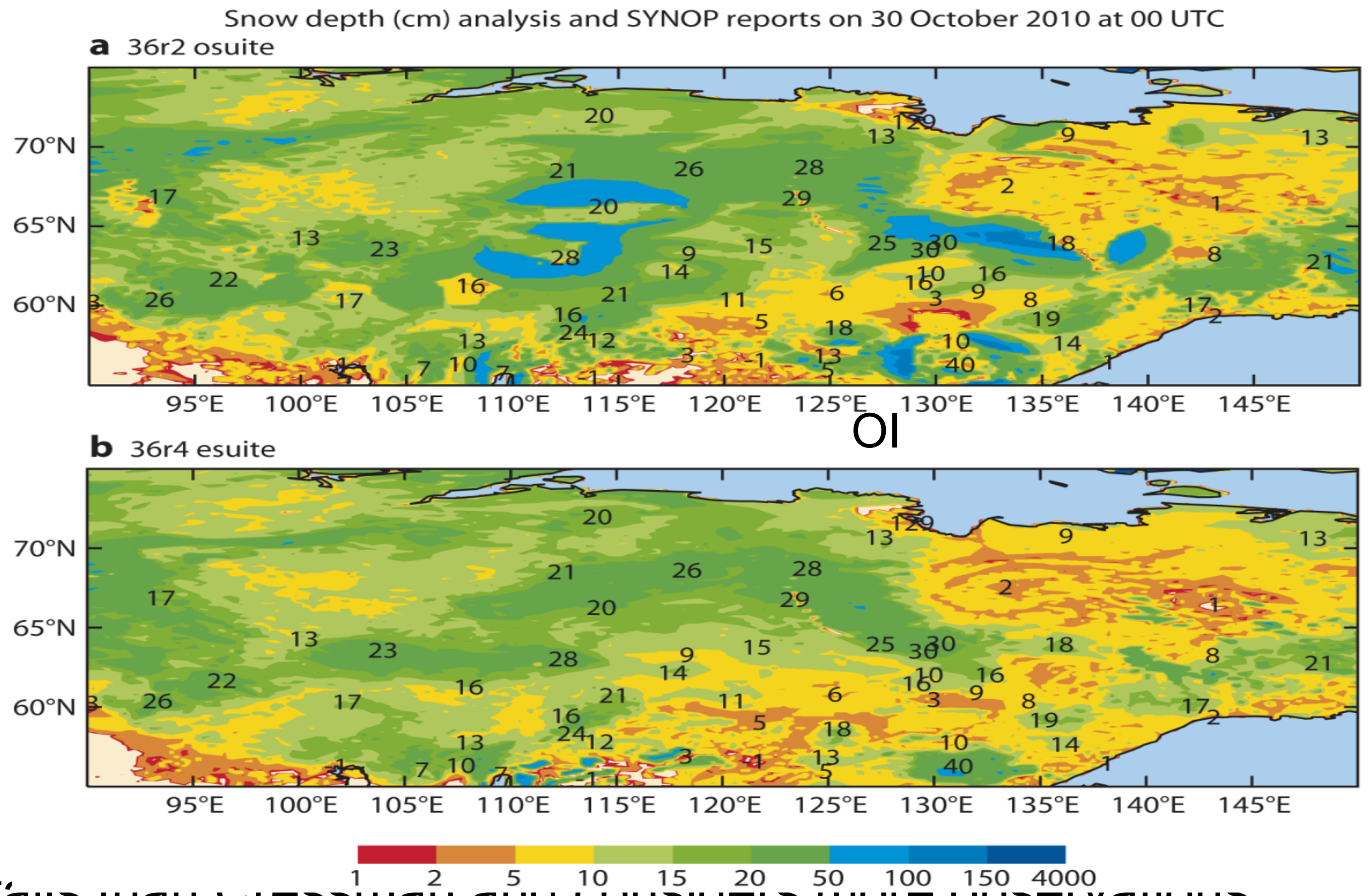
WMO Members States encouraged to put their snow depth data on the GTS

- BUFR template for national data approved by WMO in April 2014
- WMO GCW **Snow Watch** initiative on snow reporting, (Brun et al 2013)

Impact of the snow analysis method

Cressman

Cressman +24km NESDIS



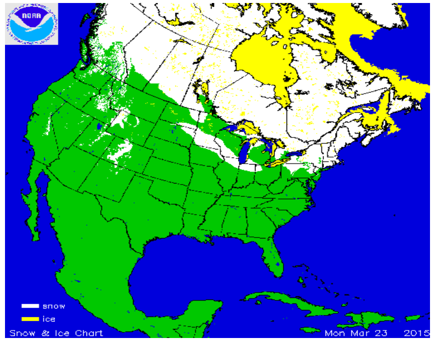
OI

- OI has longer tails than Cressman and considers more observations.

- Model/observation information optimally weighted by an error statistics.

Snow analysis impact

Revised IMS snow cover data assimilation



Impact on snow October 2012 to April 2013 (using 251 independent observations)

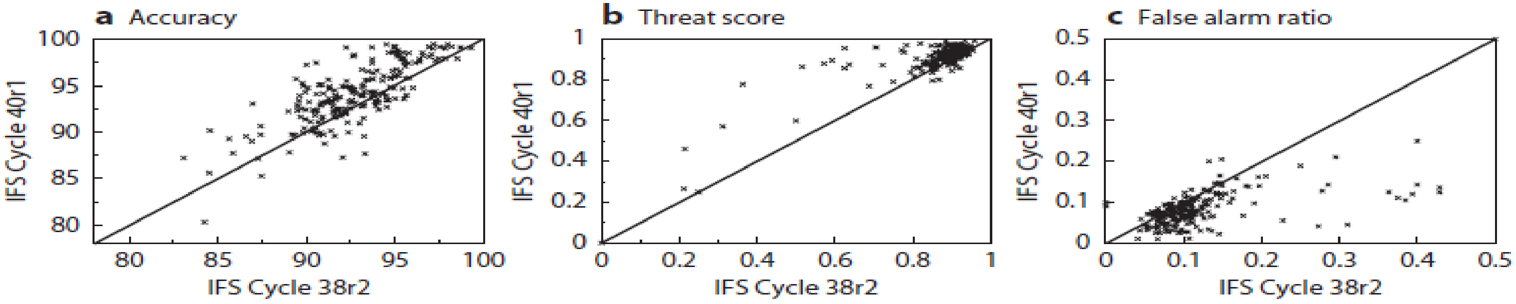


Figure 2 Snow analysis scores for the revised IFS 40r1 snow analysis versus the IFS 38r2 analysis for (a) accuracy, (b) threat score, and (c) false alarm ratio in the period October 2012 to April 2013. Each cross represents the scores computed against 251 independent in situ snow depth observations for a given date. The scatter plots show the results for each of the 212 days from 1 October 2012 to 30 April 2013. The black line represents the one-to-one line.

Impact on atmospheric forecasts

October 2012 to April 2013 (RMSE new-old)

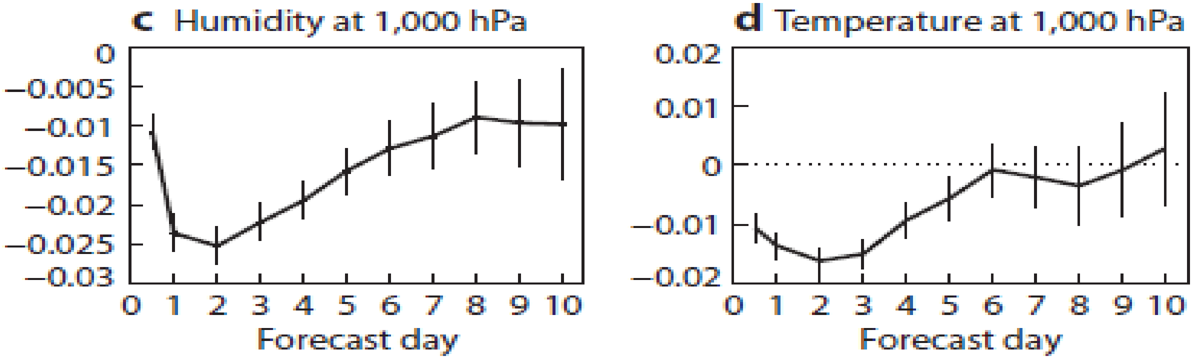


Figure 4 Impact of the revised snow analysis on the normalised root mean square error difference between IFS Cycles 40r1 and 38r2 (40r1 minus 38r2) for (a) humidity forecasts at 850 hPa;

→ Consistent improvement of snow and atmospheric forecasts

Screen Level parameters analysis

2m Air Temperature (T) and 2m Relative humidity (RH) Analyses based on an Optimum Interpolation using SYNOP observations, every six hours: 0, 6, 12, 18UTC.

1. Increments ΔX_i are estimated at each observation location i from the observation and the interpolated background field (6 h or 12 h forecast).

2. Analysis increments ΔX_j^a at each model grid point j are calculated from:

$$\Delta X_j^a = \sum_{i=1}^{N} w_i \times \Delta X_i$$

3. The optimum weights w_i are given by: (**B** + **O**) **w** = **b**

b : error covariance between observation i and model grid point j (dimension of N observations)

B : error covariance matrix of the background field (N × N observations)
$B(i_1,i_2) = \sigma^2_b \times \mu(i_1,i_2)$ with the horizontal correlation coefficients $\mu(i_1,i_2)$ and σ_b = 1.5 K / 5 % rH the standard deviation of background errors.

$$\mu(i_1, i_2) = \exp\left(-\frac{1}{2}\left[\frac{r_{i_1 i_2}}{d}\right]^2\right)$$

O : covariance matrix of the observation error (N × N observations):
O = σ^2_o × **I** with σ_o = 2.0 K / 10 % rH the standard deviation of obs. errors

Screen Level parameters analysis (2)

- Number of observations N = 50, d = 300 km, scanned radius 1000km.
- Gross quality checks as rH $\in$ [2,100] and T > $T_{dewpoint}$

- Observation points that differ more than 300 m from model orographie are rejected.

1. Observation is rejected if it satisfies: $|\Delta X_i| > \gamma\sqrt{\sigma_o^2 + \sigma_b^2}$ with γ = 3 (tolerance)

1. Number of used observations ~ 6000 (40% of the available observations) every 6 hours.

6. Increments are computed

Optimum Interpolation land surface analysis
(oper. surface analysis at Météo-France/MSC/ECMWF…)

Mahfouf 1991, Bouttier 1993, Giard and Bazile 2000, Mahfouf et al. 2003, Belair et al 2003

Optimum Interpolation of T_{2m} and RH_{2m} using SYNOP observations interpolated at the model grid-point (by a 2m analysis)

$$\Delta T_{2m} = T_{2m}^{a} - T_{2m}^{f} \qquad \Delta RH_{2m} = RH_{2m}^{a} - RH_{2m}^{f}$$

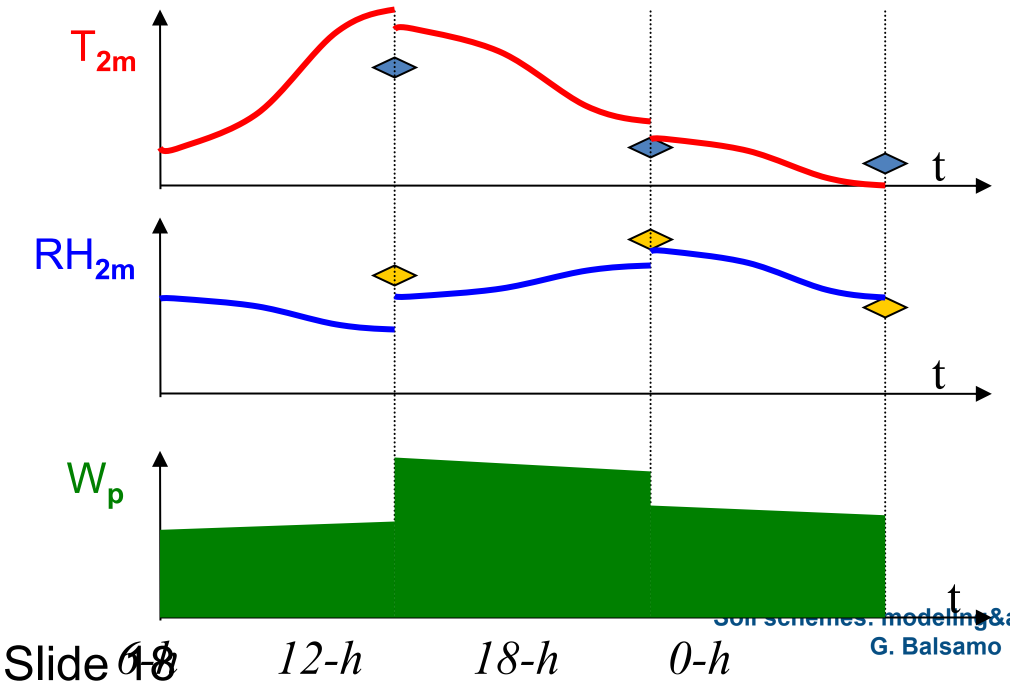
Correction of surface parameters (T_s, T_p, W_s, W_p) using 2m increments between analysed and forecasted values

$$T_s^{a} - T_s^{f} = \Delta T_{2m}$$
$$T_p^{a} - T_p^{f} = \Delta T_{2m} / 2\pi$$
$$W_s^{a} - W_s^{f} = \alpha_{WsT} \Delta T_{2m} + \alpha_{WsRH} \Delta RH_{2m}$$
$$\boxed{W_p^{a} - W_p^{f} = \alpha_{WpT} \Delta T_{2m} + \alpha_{WpRH} \Delta RH_{2m}}$$

$$\alpha_{Wp/sT/RH} = f\,(t,\ veg,\ LAI/Rs_{min},\ texture,\ atm.cds.)$$

Tuning of the OI statistics and regressions and accuracy of 2m analyses are key components

Sequential analysis (every 6h)



Variational surface analysis

Mahfouf (1991), Callies et al. (1998), Rhodin et al. (1999), Bouyssel et al. (2000), Hess (2001), Seuffert et al. (2004), Balsamo et al. (2004)

Formalism:

$$J(\mathbf{x}) = J^{\,b}(\mathbf{x}) + J^{\,o}(\mathbf{x})$$

$$= \tfrac{1}{2}\,(\mathbf{x} - \mathbf{x}^b)^T\,\mathbf{B}^{-1}\,(\mathbf{x} - \mathbf{x}^b) + \tfrac{1}{2}(\mathbf{y} - H(\mathbf{x}))^T\,\mathbf{R}^{-1}\,(\mathbf{y} - H(\mathbf{x}))$$

x is the control variables vector
y is the observation vector
H is the observation operator

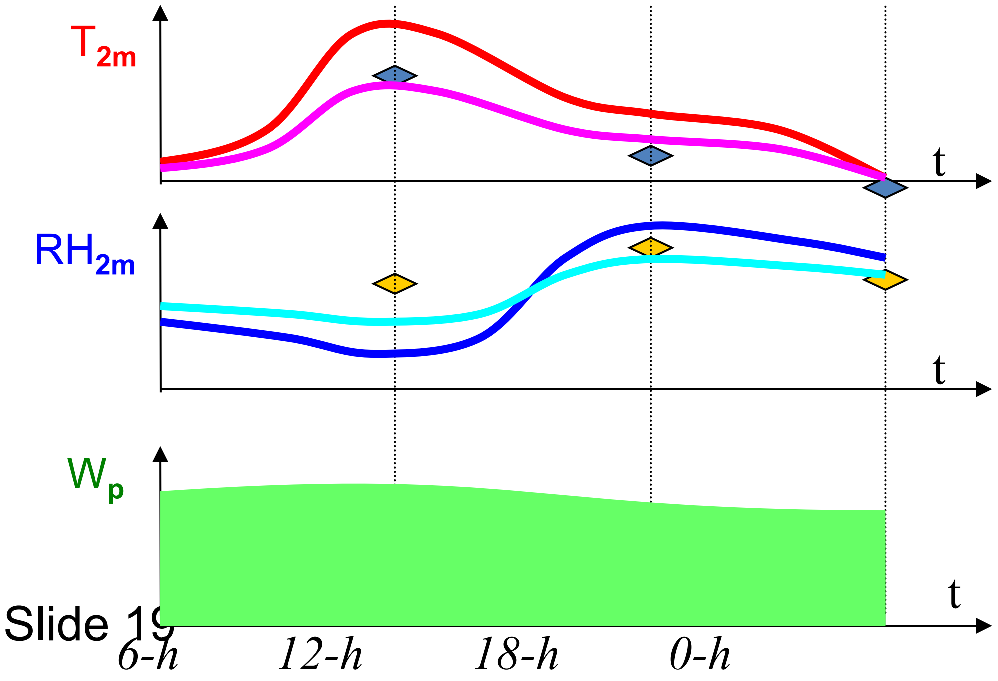
The analysis is obtained by the minimization of the cost function $J(\mathbf{x})$

B is the background error covariance matrix

R is the observation error covariance matrix

- Advantages: Easier assim. asynop. obs. Extension on longer assim. Window (24-h)

Continuous analysis



Why an EKF soil moisture analysis ?

- Dynamical estimates of the Jacobian Matrix that quantify accurately the physical relationship between observations and soil moisture
- Flexible to account for the land surface model H-TESSEL evolution
- Makes it possible to combine different sources of information
- Possible to investigate the use of new generation of satellite data:
    - SM active microwave (C-band ERS, MetOp/ASCAT, L-band SMAP)
    - SM passive microwave (L-band SMOS, SMAP)

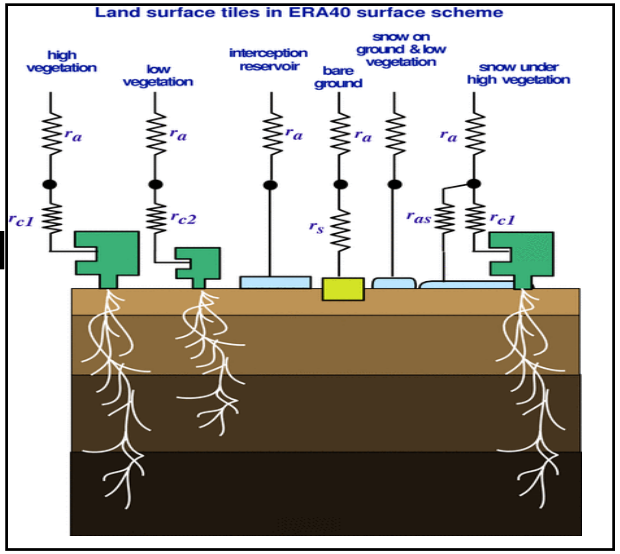
EKF soil moisture analysis

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

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

$\boldsymbol{\theta}_b$ background soil moisture state vector,
H Jacobian matrix of the observation operator
Estimated in finite differences (perturbed simulations)
y observation vector
K the Kalman gain matrix, fn of H and covariance matrix of background **Bg** and observation errors **R**.

EKF corrects the trajectory of the Land Surface Model



H-TESSEL
(Balsamo et al., 2009)

Observation can be:

- Conventional observations (T2m, RH2m)
- Satellite data related to soil moisture (e.g. ASCAT product, SMOS).

SYNOP

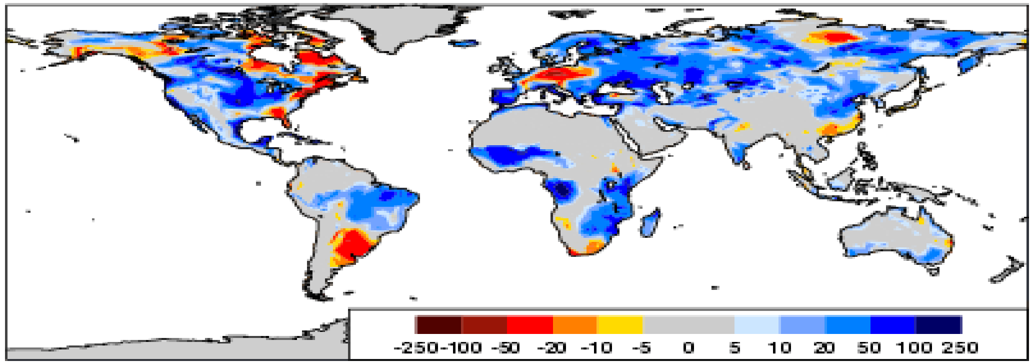
ASCAT

SMOS

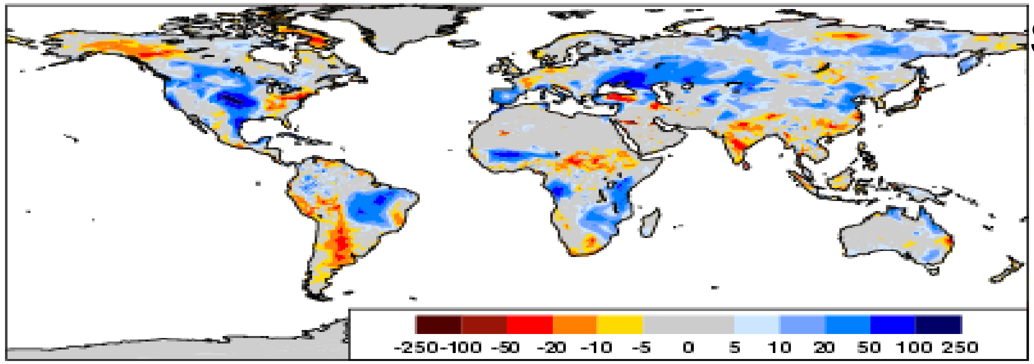
EKF evaluation

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

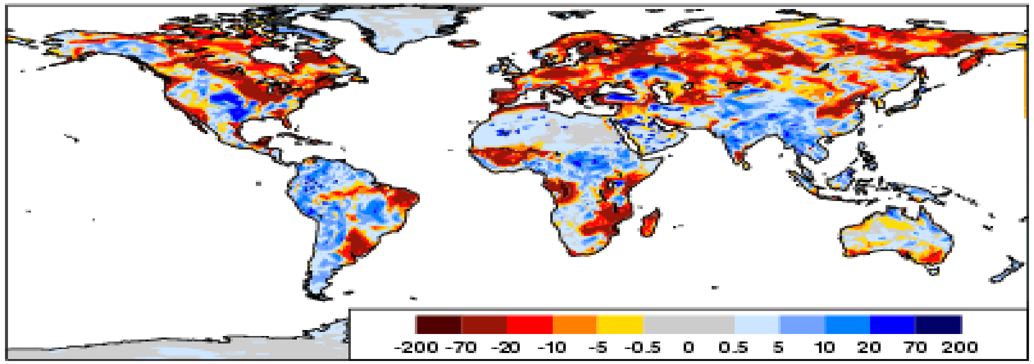
|SEKF|-|OI|



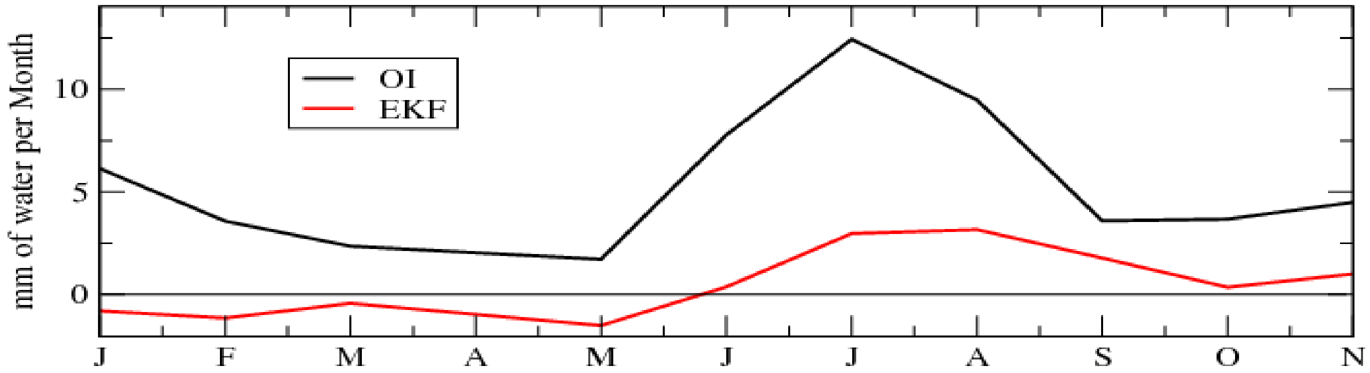
OI



SEKF



Global Soil Moisture Increments (1st meter of soil)

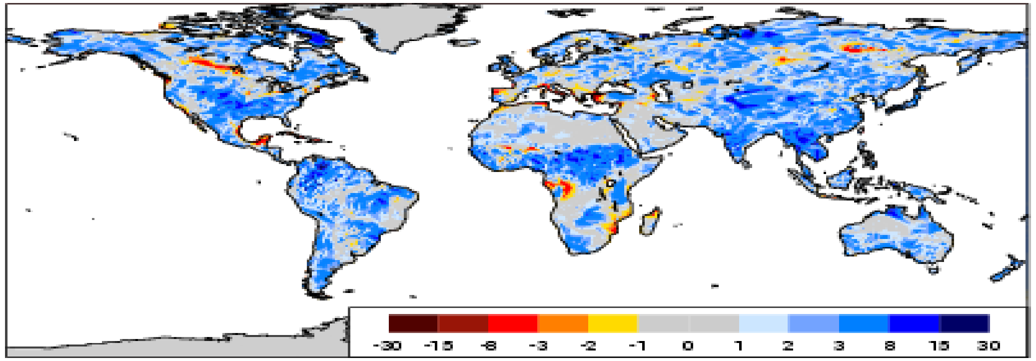


- EKF accounts for (non-linear) control on the soil moisture increments (meteorological forcing and soil moisture conditions)
- **Prevents undesirable and excessive soil moisture corrections**, and reduces the soil moisture analysis increments.
- **Improves soil moisture** (Albergel et al., Brocca et al., Roulin et al., Su et al.)

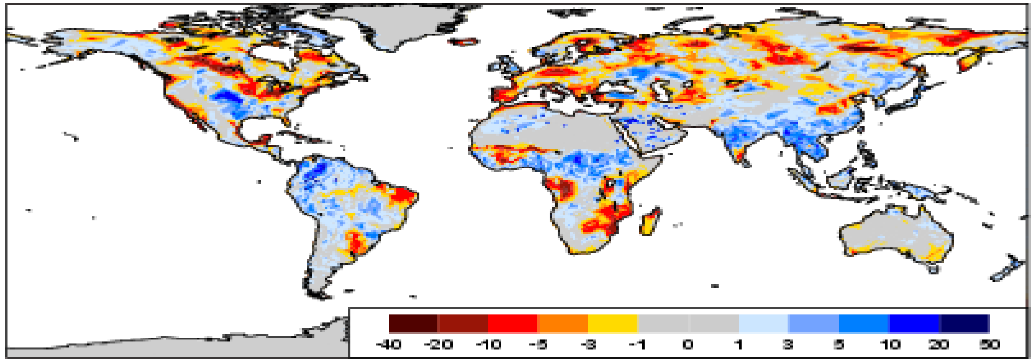
EKF Comparison/validation

Profile of Soil Moisture increments

difference |SEKF|-|OI| July 2009

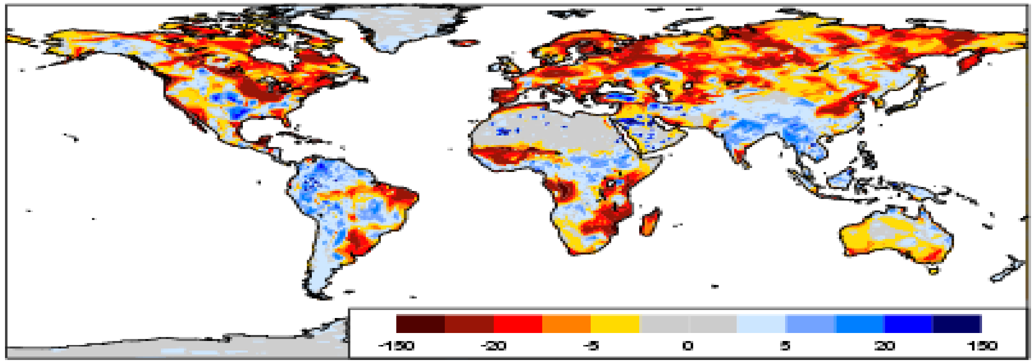


Layer 1 (0-7cm)



Layer 2 (7-28cm)

Increments reduction: mainly at depth

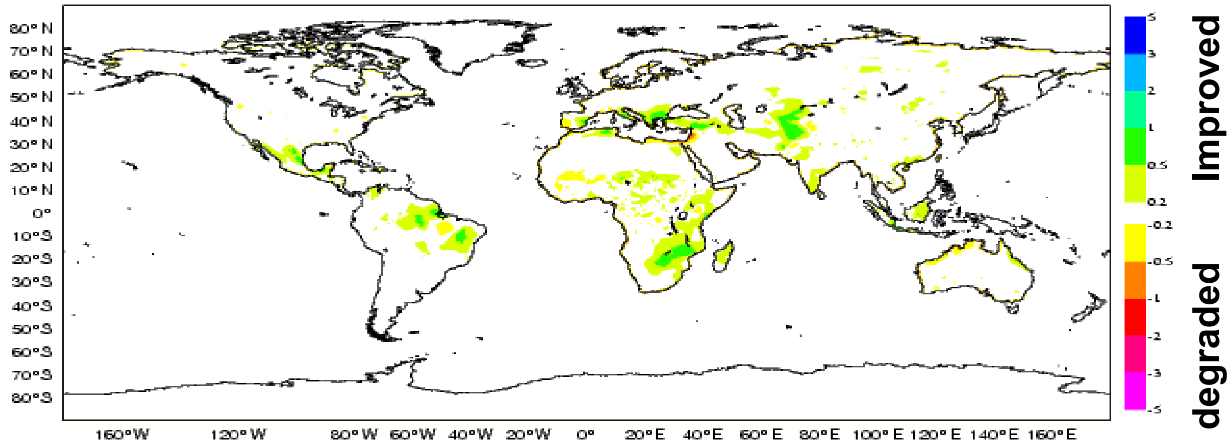


Layer 3 (100-289 cm)

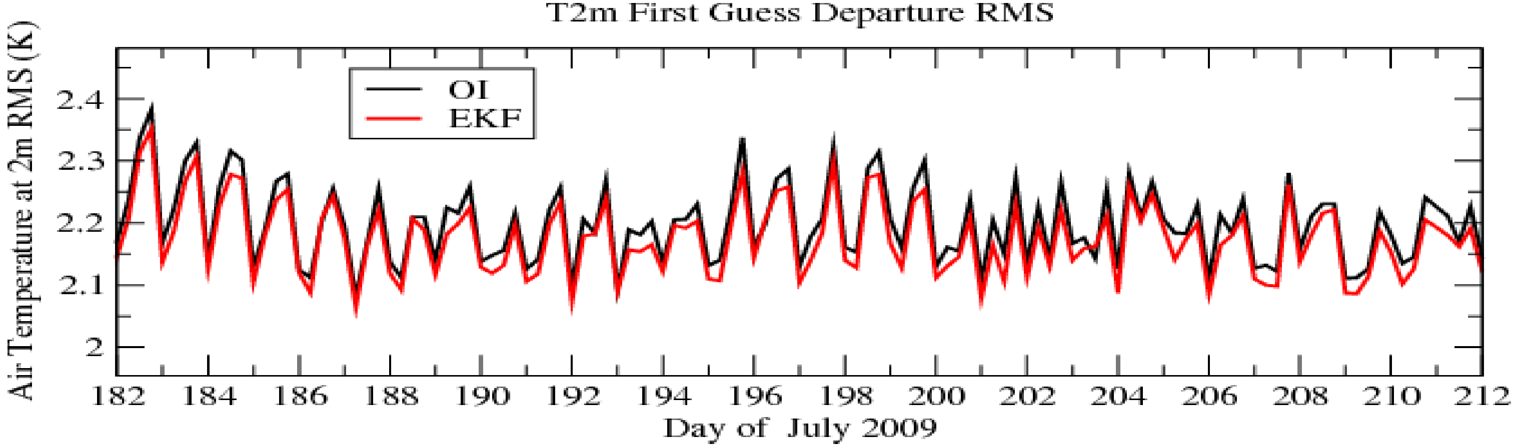
Impact on 2-meter Temperature

- EKF consistently improves SM & T2m
- EKF implemented in 2010 in operations
- Makes it possible to assimilate satellite data to analyse soil moisture

T2m error (OI-SEKF)
→ EKF improves T2m



Global mean RMS (against SYNOP)

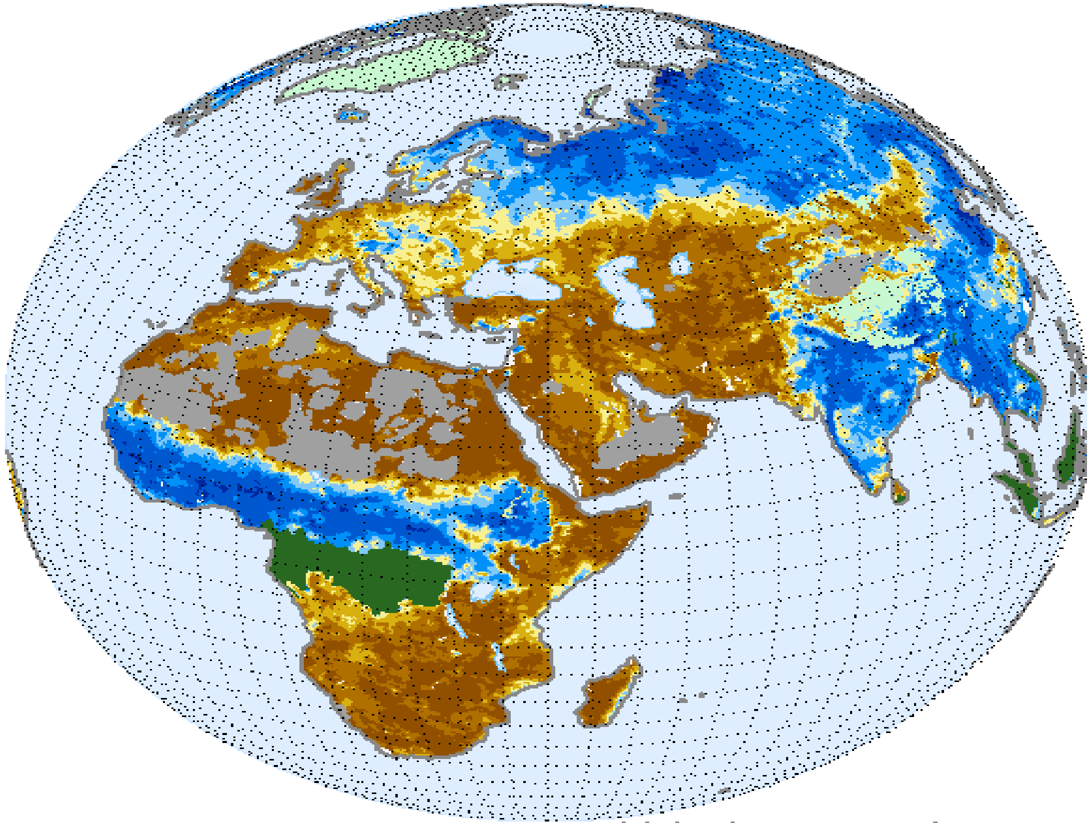


Active microwave remote sensing

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):
  November 2006 – now. Near Real Time (NRT)
  surface soil moisture index (ws) based on the
TUWien retrieval scheme (Wagner et al. 1999)

ASCAT: First operational SM product



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

Active microwave remote sensing

Correlation of ERS and ERA-40 SM abs. values and anomalies

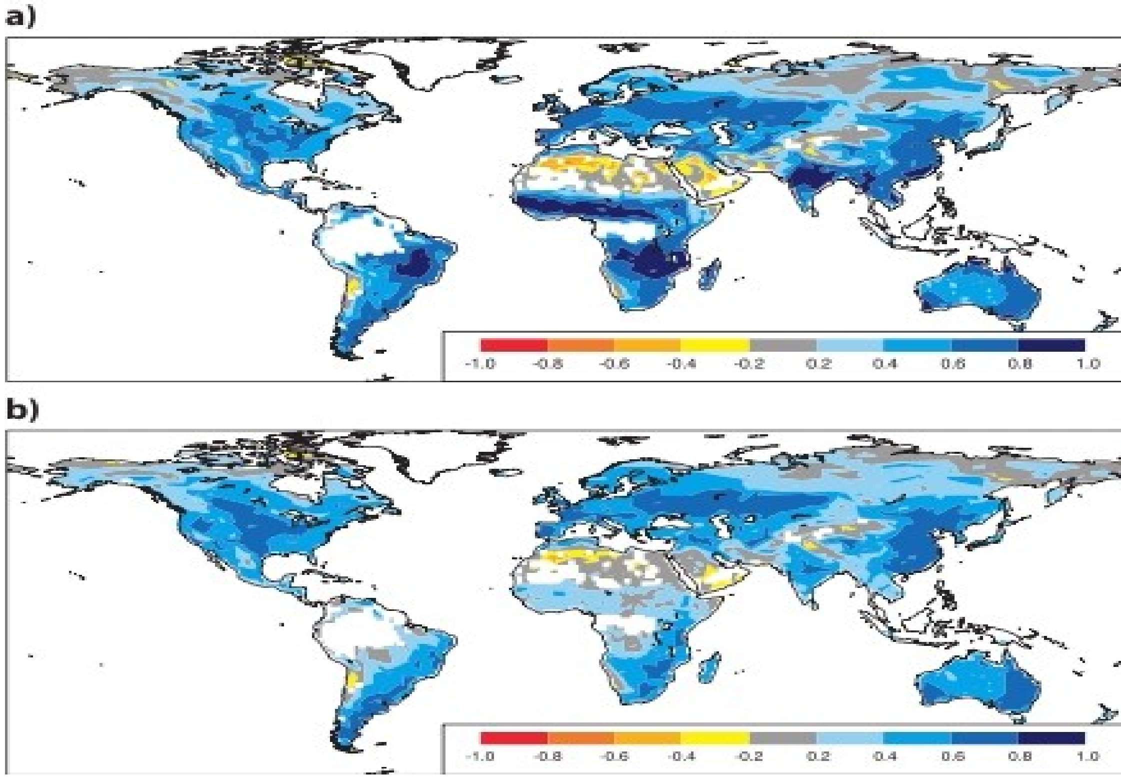
General good agreement between ERS and ERA-40 soil moisture products.

For 85% of the land points, correlation is significant at the 0.05 level.

High correlation where strong SM seasonal cycle (e.g. monsoon regions).

Relatively low correlation in the eastern part of the North America (high amount of biomass).

ASCAT provides good SM information in semi-arid and moderately vegetated area.



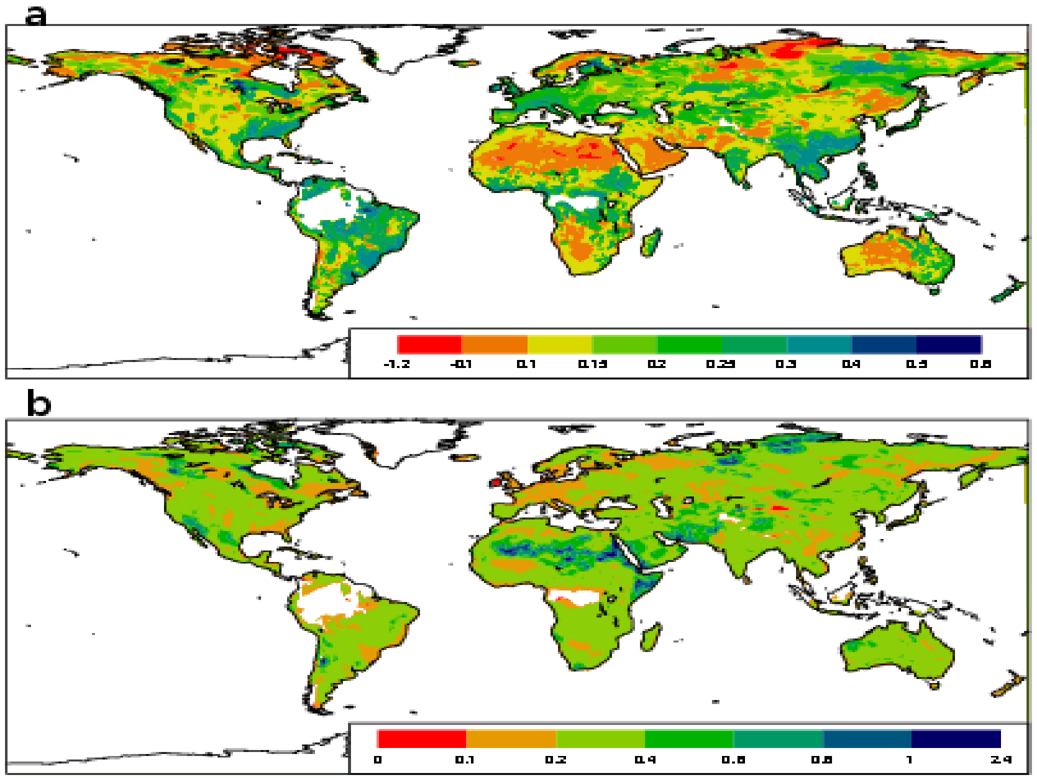
Scipal et al., ADWR 2008

Use of ASCAT SM data at ECMWF

Bias correction

- Simplified CDF matching (Mean and Range)
- Matching uses 9 years of data (1992-2000)
- Biases are estimated for each point separately

CDF-matching coefficients ASCAT_rescaled = a+ b*ASCAT/100



T1279 (16km) resolution

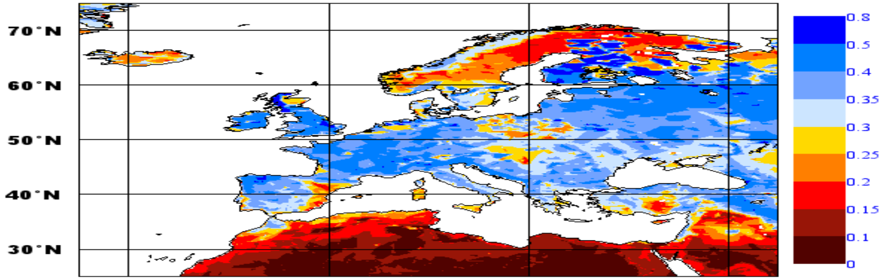
de Rosnay, ECMWF Res. Mem, 2009

ASCAT data assimilation

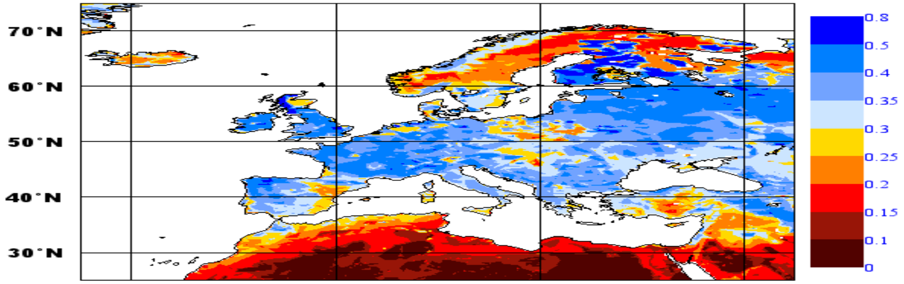
H-SAF (Hydrology Satellite Application Facility)

- Assimilation of ASCAT SSM in the IFS using the SEKF
- → Root zone Soil Moisture profile
- July 2008 - August 2010 daily data

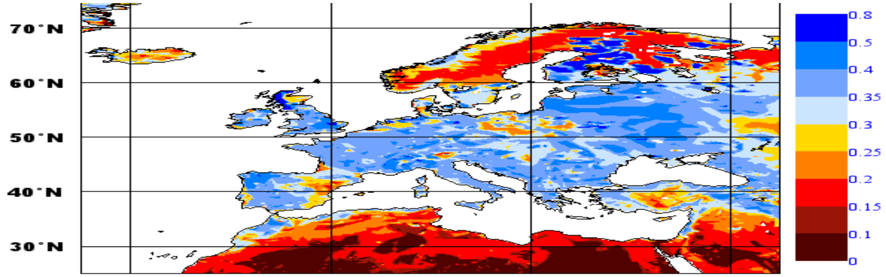
Layer 1: 0-7 cm



Layer 2: 7-28 cm



Layer 3: 28-100 cm



Passive microwave remote sensing

Soil Moisture and Ocean Salinity mission

ESA SMOS launched on 2nd of November 2009

ECMWF contribution:

- **Global monitoring**
- **Data assimilation**
  (Brightness Temperatures, TB).

A Key component of TB monitoring and assimilation is the **forward operator** that transforms model variables (eg soil moisture and temperature) into observed variable (SMOS TB)

Passive microwave remote sensing

Past current and future missions:

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

SMAP (Soil Moisture Active and Passive), NASA, L-band, launch 2015

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

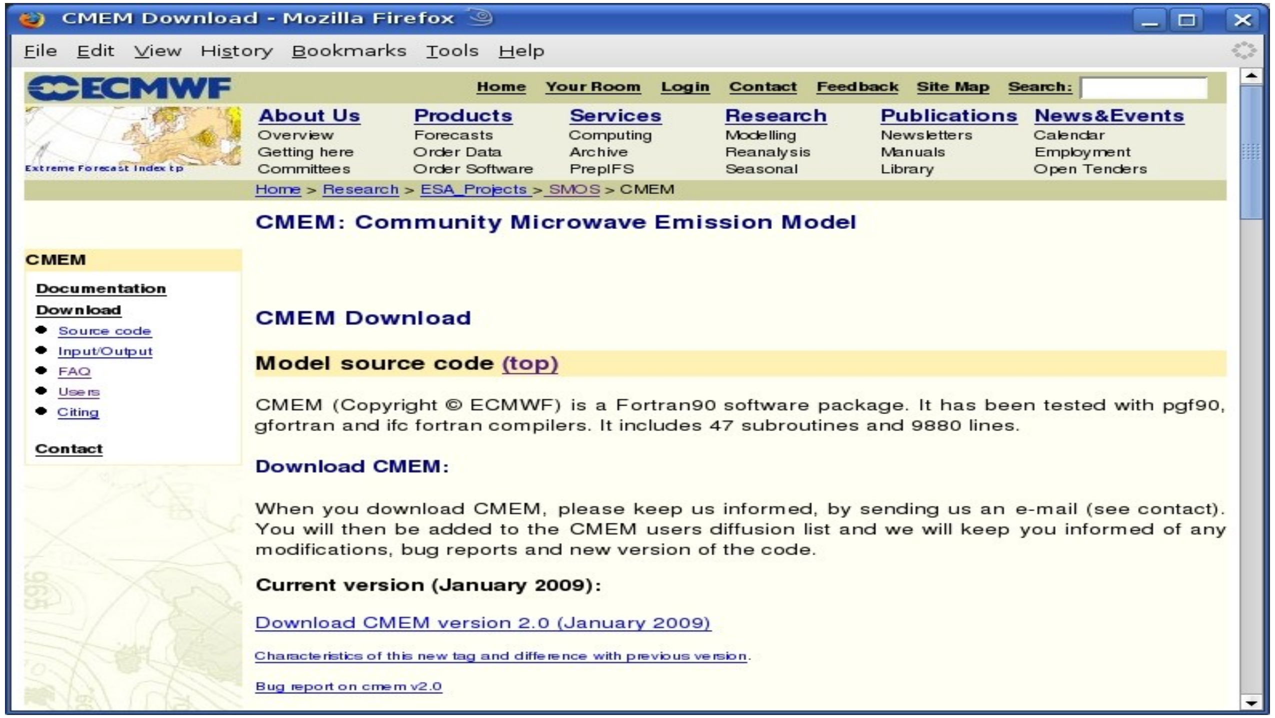
Skylab, NASA, L-band, 1973-1974 (but only 9 overpasses available)

SMOS: first satellite missions specifically devoted to soil moisture remote sensing.

The Community Microwave Emission Model

- SMOS forward operator at ECMWF.
- I/O interfaces for the Numerical Weather Prediction Community.
- CMEM Input/Output interface is flexible: grib (gribex, gribAPI), netcdf, ascii.
- CMEM is a Fortran 90 software, portable for unix/linux systems
- Web interface available

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



Tool for the ESA SVRT (SMOS Validation and Retrieval Team)

References:
Drusch et al. JHM, 2009
de Rosnay et al. JGR, 2009
Muñoz Sabater et al., IJRS 2010

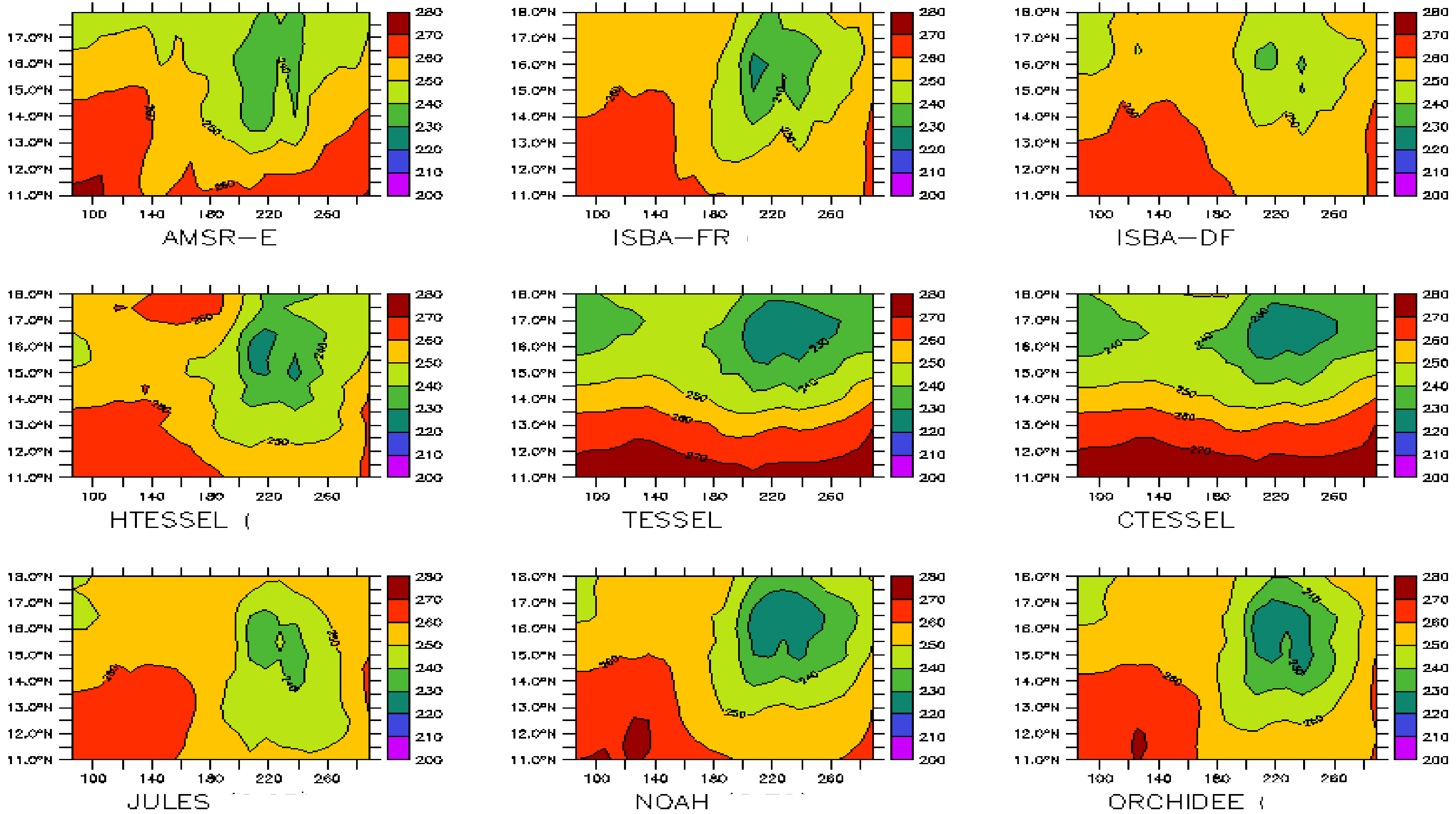
Time-Latitude diagram of TBH

AMSR-E and 8 LSMs

CMEM configuration with Wang&Schmugge + Kirdyashev

Bias correction Applied for each LSM

- Time-latitude wet Patch well captured by most LSMS

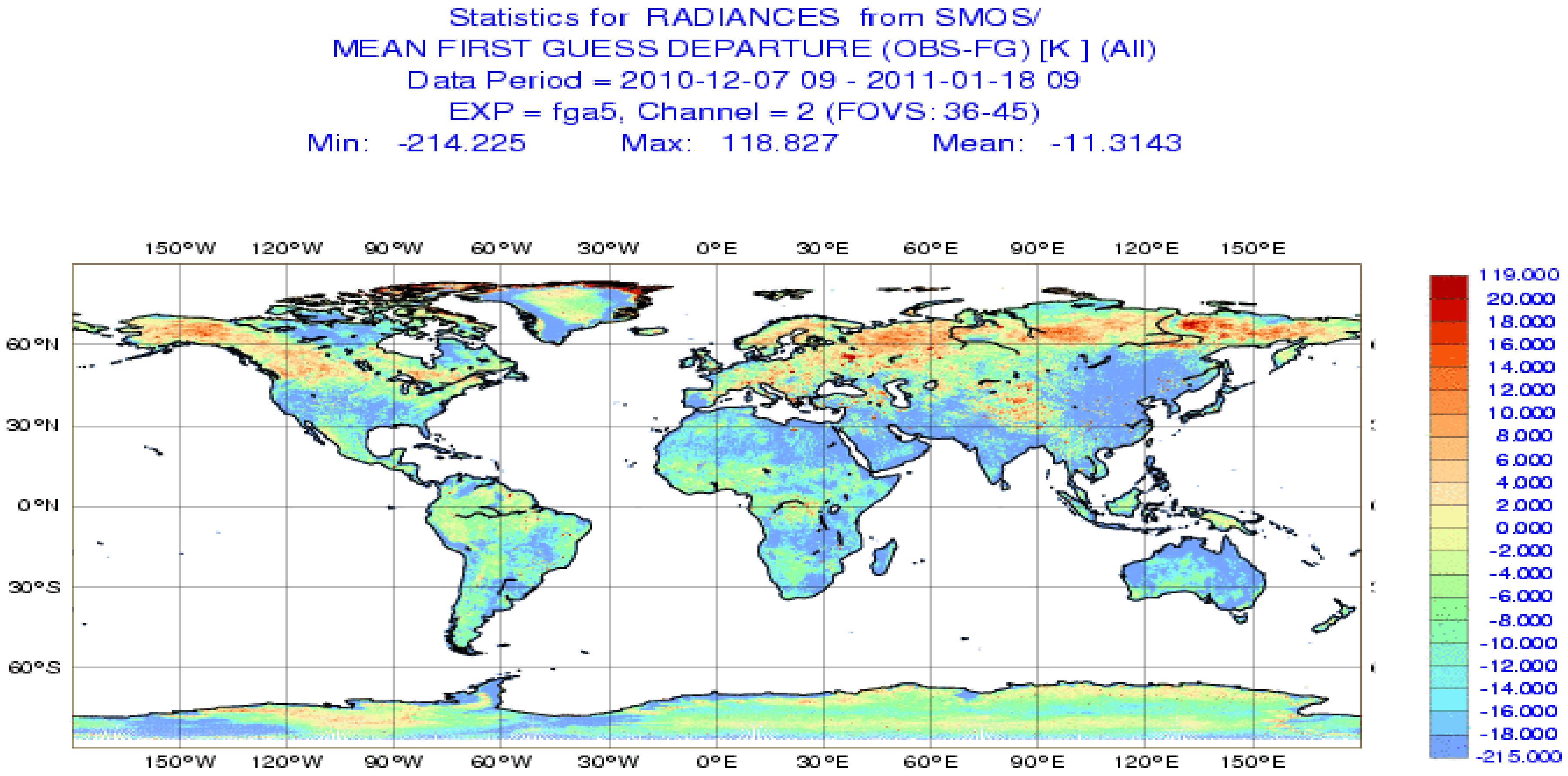


de Rosnay et al., JGR 2009

SMOS monitoring

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

First Guess Departure (Obs-Model) Incidence 40°, TBYY



ECMWF reanalyses based on Integrated Forecasting System (IFS)

- **Model:** GCM including the H-TESSEL land surface model
    - Fully coupled land-atmosphere (for NWP, ERA-Interim, ERA5)
    - HTESSEL offline (ERA-Interim Land, ERA5L), forced by the atmospheric conditions

- **Data Assimilation:** for NWP, ERA-Interim, ERA5; weakly coupled DA
    - **4D-Var for atmosphere**
    - **Land Data Assimilation System**

Systems	Model	Coupling	Land Data Assimilation	Resolution/ Domain
NWP	IFS	yes	Yes cycle 41r2	9km/Glob
ERA-Interim	IFS	yes	Yes cycle 31r1	79km/Glob
ERA-Interim Land	H-TESSEL	no	No	79km/Glob
ERA5	IFS	yes	Yes cycle 41r2	32km/Glob
ERA5 Land	H-TESSEL	no	No	9km?/Glob

Summary and Outlook

- **Data assimilation systems** are designed to constrain model errors and improve the forecasts
- Data assimilation systems are also **ideal tools to validate** parameterizations because of their constant confrontation with observations
- Forecast systems are sensitive to mis-representation of longer time scales in the land-surface/atmosphere interaction, therefore DA is also interesting for **tuning parameters**.
- Efforts up to present towards **reduce atmospheric errors**
- Moving towards Earth System for **Environment prediction & Extended-range** requires:
  - An increased attention to the **consistency** of water and energy cycle applying DA increments
  - A **better use of EO data** in data assimilation methods that can tune parameters
  - A **large collaborative efforts** (@ECMWF and within the NWP & Climate community)