Land Data Assimilation Systems for Numerical Weather Prediction

Patricia de Rosnay

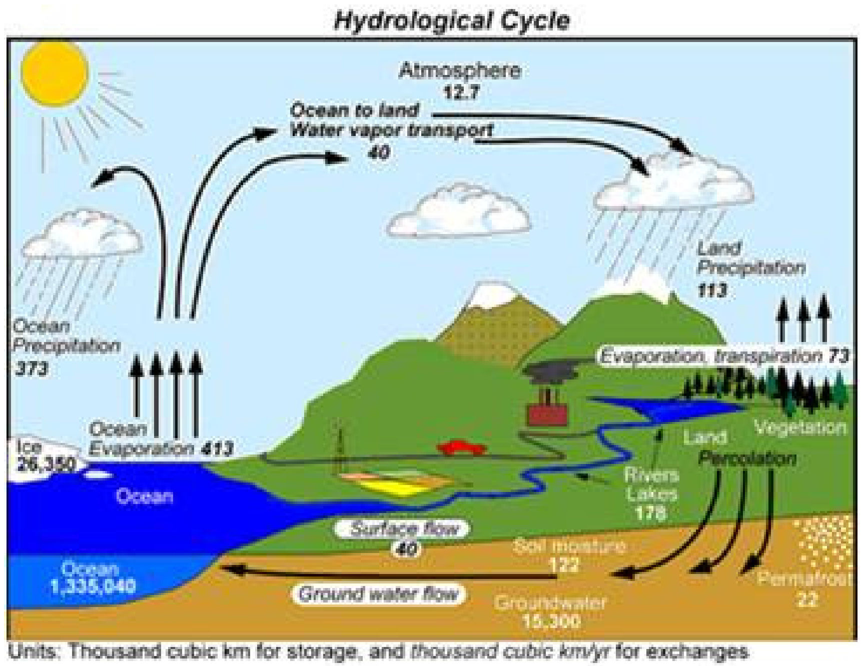
Thanks to: Clément Albergel, Gianpaolo Balsamo, Joaquin Muñoz Sabater and many colleagues at ECMWF

Introduction: Land Surface Modelling

• **In Numerical Weather Prediction (NWP) systems, Land Surface Models (LSMs) represent the lowest boundary conditions and the surface branch of the continental hydrological cycle**

• **Land Surface Models much improved in the past decade:**

- Multi-layer vertical soil hydrology, texture, drainage, runoff,
- Snow parameterization (depth, density, albedo),
- Vegetation parameters (e.g. LAI),
- Heterogeneities, sub-grid scale parameterizations,
- Lake temperature,
- Carbon cycle, link with surface fluxes,
- Urban areas, …



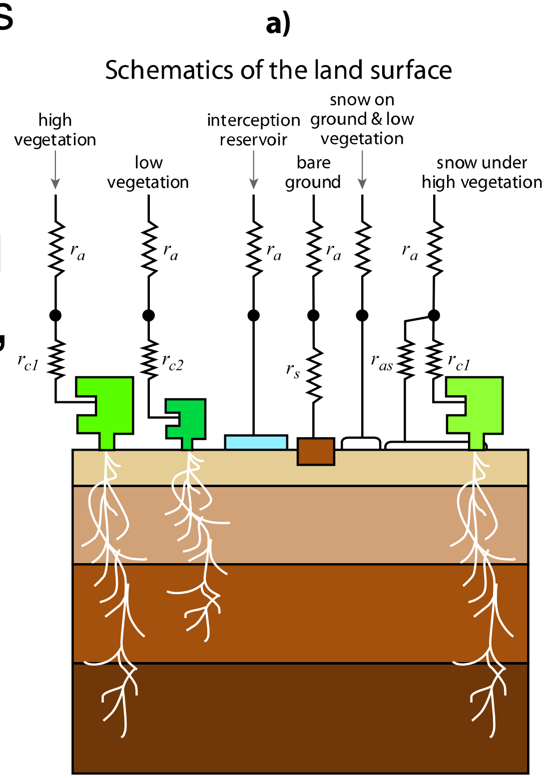
Trenberth et al. (2007)

Introduction: Land Surface Modelling

- **Land Surface Models prognostic variables include :**
  - Soil Moisture
  - Soil Temperature

  } Multi-layer in most LSMs
  - Snow mass, temperature, density, albedo

- **Land surface initialization: Important for NWP and Seasonal Prediction (Beljaars et al., Mon. Wea. Rev, 1996, Koster et al., 2004 & 2011)**

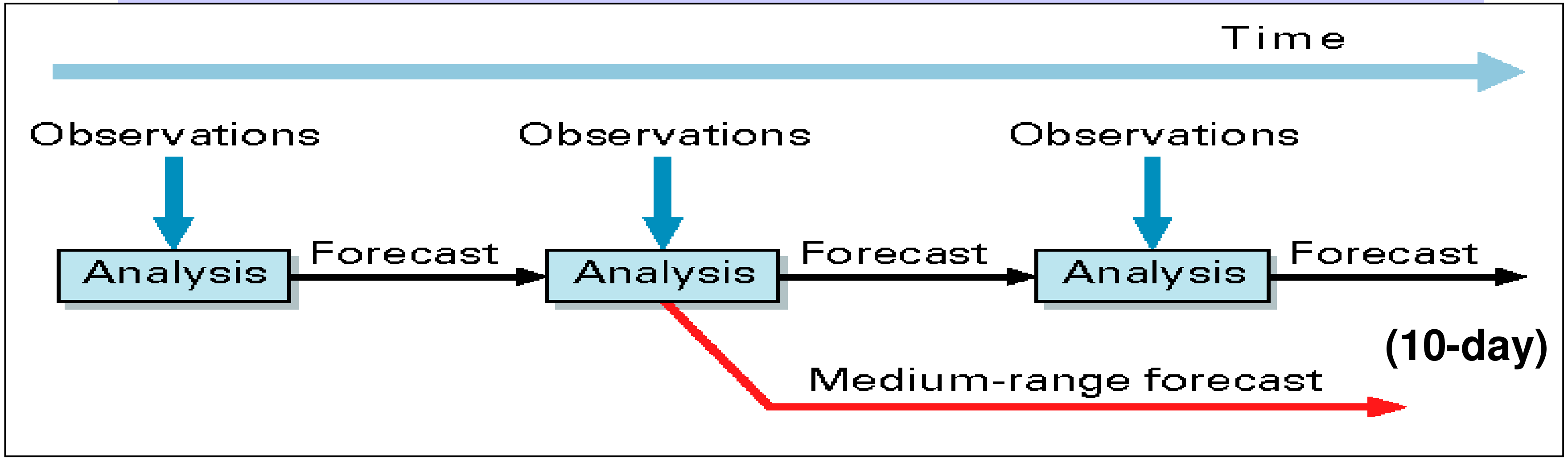


ECMWF LSM: H-TESSEL
4 soil layers / 12 prognostic variables
Balsamo et al., JHM 2009

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 11 to 13,000,000 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.

ECMWF

Introduction: Land Surface analysis

Land surface initialization: snow depth, soil moisture, snow and soil temperature

- **Snow depth analysis**
  - Approaches: Cressman (DWD, ECMWF ERA-I), 2D Optimal Interpolation (ECMWF, CMC, JMA)
  - Observations: SYNOP snow depth and NOAA/NESDIS Snow Cover (ECMWF)
- **Soil Moisture analysis**
  - Approaches:
    - 1D Optimal Interpolation (Météo-France, CMC, ALADIN and HIRLAM)
    - Analytical nudging approach (BoM)
    - Simplified Extended Kalman Filter (DWD, ECMWF, UKMO)
    - Offline LSM using analysed atmospheric forcing (NCEP: GLDAS / NLDAS)
  - Conventional observations: SYNOP data of 2m air relative humidity and air temperature ; **Dedicated 2D OI screen level parameters analysis**
  - Satellite data : ASCAT soil moisture (UKMO)

Soil Temperature and Snow temperature also analysed

- 1D OI for the first layer of soil and snow temperature (ECMWF, Météo-France)

Outline

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

Snow Analysis

Snow Model:

- Snow depth S (m) (diagnostic)
- Snow water equivalent SWE (m), ie snow mass
- Snow Density ρ_s, between 100 and 400 kg/m^3

} **Prognostic variables**

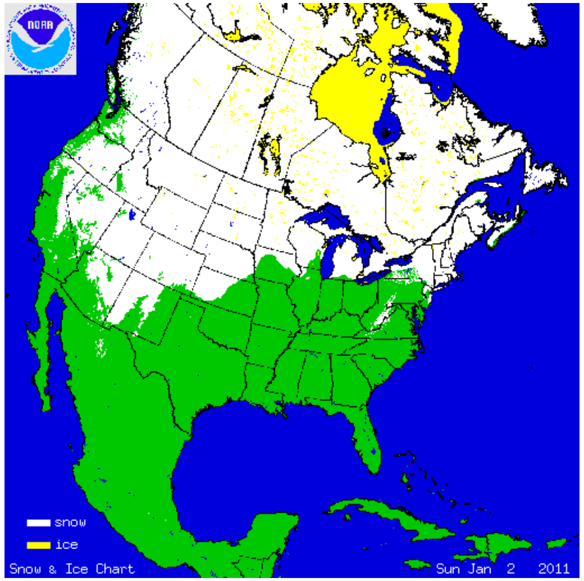
(Dutra et al., JHM, 2010)

$$SWE = \frac{S \cdot \rho_S}{1000} \quad [\mathrm{m}]$$

Observations types used:

- Conventional snow depth data: SYNOP and National networks
- Snow cover extent: NOAA NESDIS/IMS daily product (4km)

(Drusch et al. JAM, 2004)
(de Rosnay et al. Res. Mem. 2010, 2011)



Data Assimilation Approaches:

- Cressman Interpolation in ERA-I
- Optimal Interpolation in Oper (from IFS cycle 36r4)

(de Rosnay et al, SG 2013)

NOAA/NESDIS IMS Snow extent data

Interactive Multisensor Snow and Ice Mapping System

- Time sequenced imagery from geostationary satellites
- AVHRR,
- SSM/I
- Station data

Northern Hemisphere product

- Daily
- Polar stereographic projection

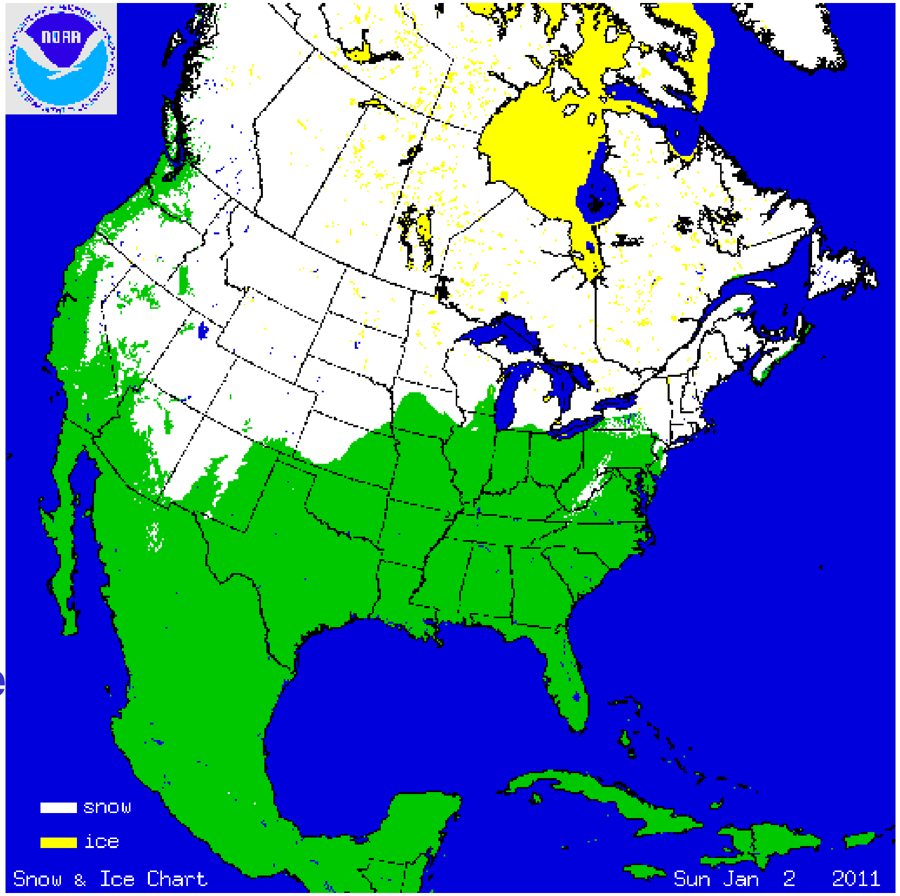
Resolution

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

Information content: Snow/Snow free

Format:

- 24km product in Grib
- 4 km product in Ascii

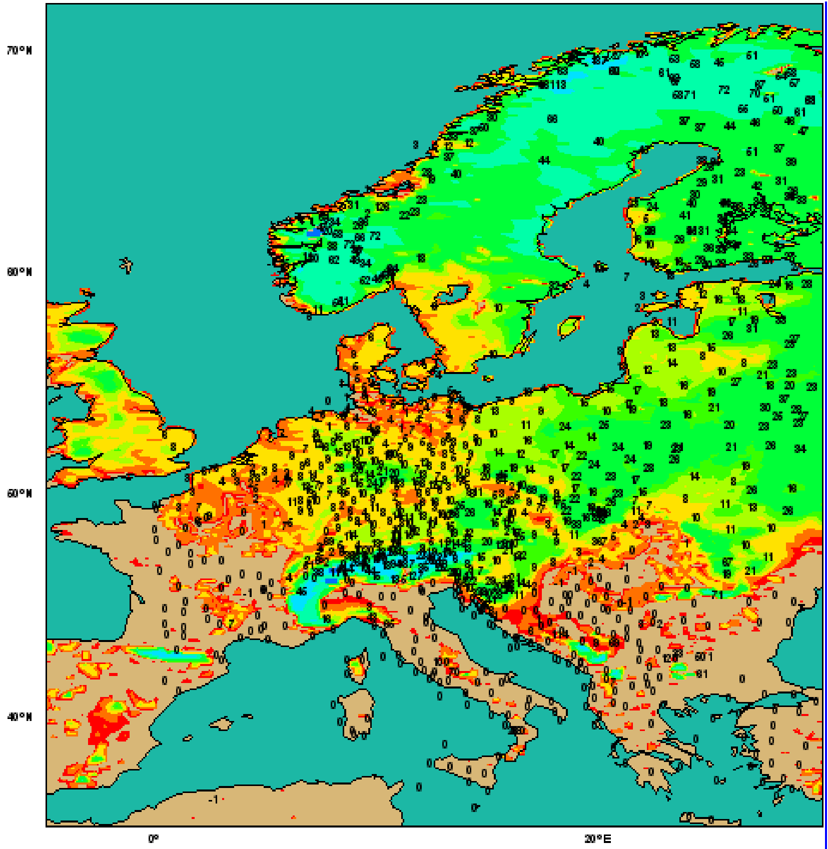


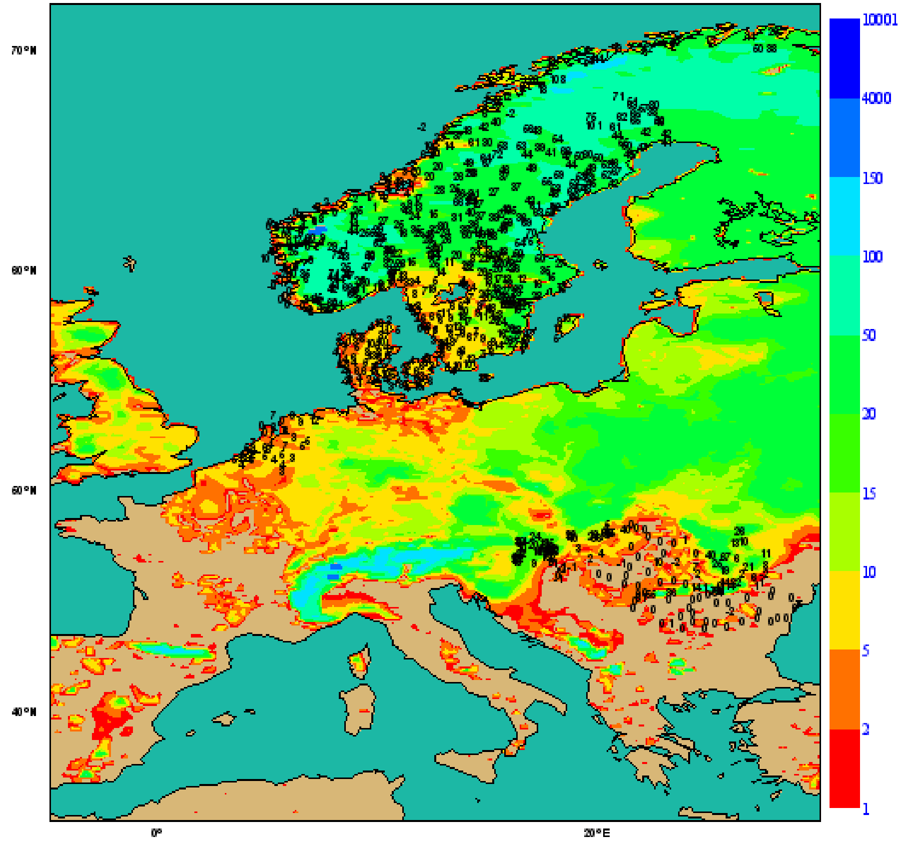
More information at: http://nsidc.org/data/g02156.html

ECMWF

Use of SYNOP and National Network data

SYNOP **2013 01 23 at 06 UTC** **National snow data**

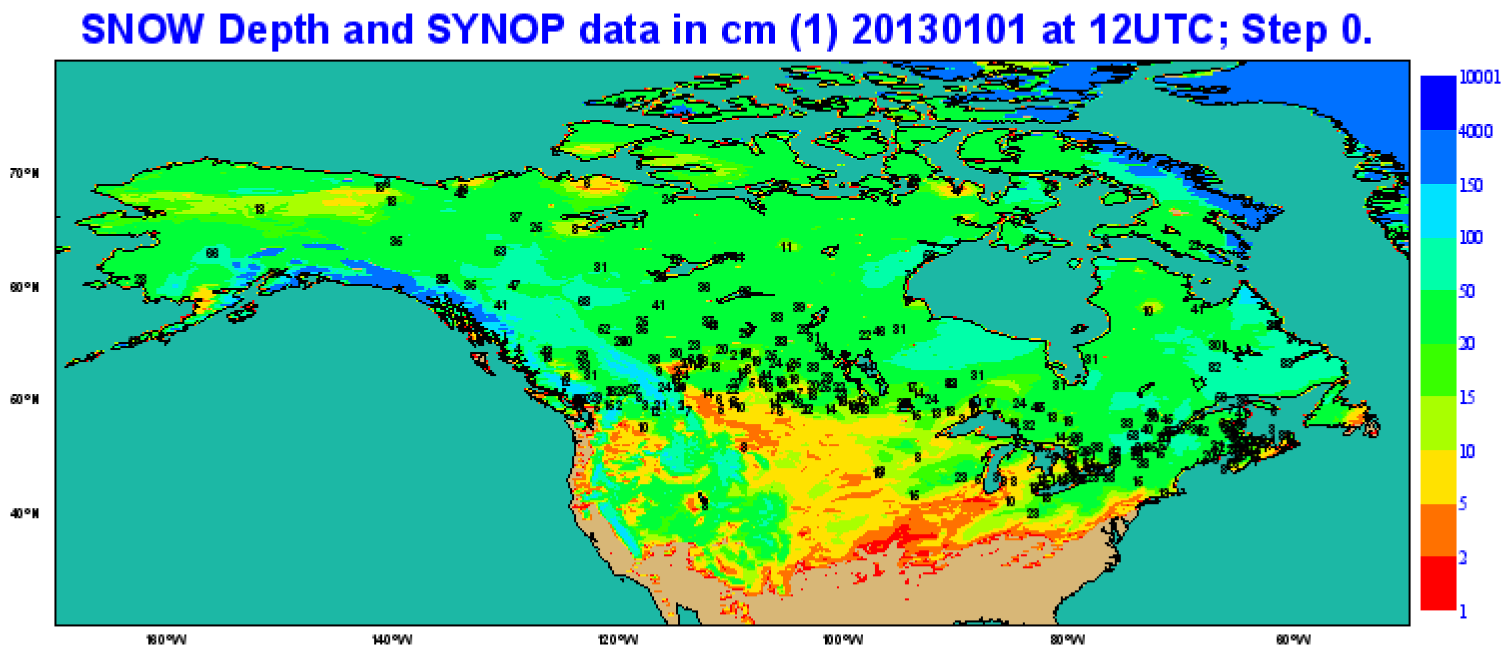




National networks data:
- GTS: Sweden (>300), Romania(78), The Netherlands (33), Denmark (43), Norway (183)
- FTP: Hungary (61)

Use of SYNOP data

-Not much SYNOP reports in North America, particularly in the US
- Would be valuable to have more snow depth data on the GTS (Global Telecommunication System)



Snow Analysis at ECMWF

Pre-Processing:

- SYNOP reports converted into BUFR files.
- IMS converted to BUFR (and orography added)
- SYNOP BUFR data is put into the ODB (Observation Data Base)

Snow depth analysis in two steps: (Drusch et al., J. Appl. Meteo. 2004)

1- NESDIS IMS data (once per day):

NESDIS \ FG	Snow	No Snow
Snow	x	BG: 10cm
No Snow	DA	DA

errors:

BG	$\sigma_b = 3cm$
OBS	$\sigma_o = 4cm$

2- Snow depth analysis at 00, 06, 12, 18 UTC :

- Cressman interpolation: Operations: 1987-2010
  Still used in ERA-Interim
- Optimal Interpolation (OI): Operational since November 2010

(de Rosnay et al; SG 2013)

Validation data: NWS/COOP

- NWS Cooperative Observer Program
- Independent data relevant for validation

- Used to validate a set of numerical experiments considering different assimilation approaches and IMS snow cover

Numerical Experiments	Bias (cm)	R	RMSE (cm)
Cressman, IMS 24 km	1.1	0.66	18.0
OI, IMS 4km <1500m	- 1.5	0.74	10.1

- Oper until Nov 2010
- ERA-Interim

- Oper since Nov 2010

Validation against ground data
→ Main improvement due to the OI compared to Cressman

Validation data: NWS/COOP

- NWS Cooperative Observer Program
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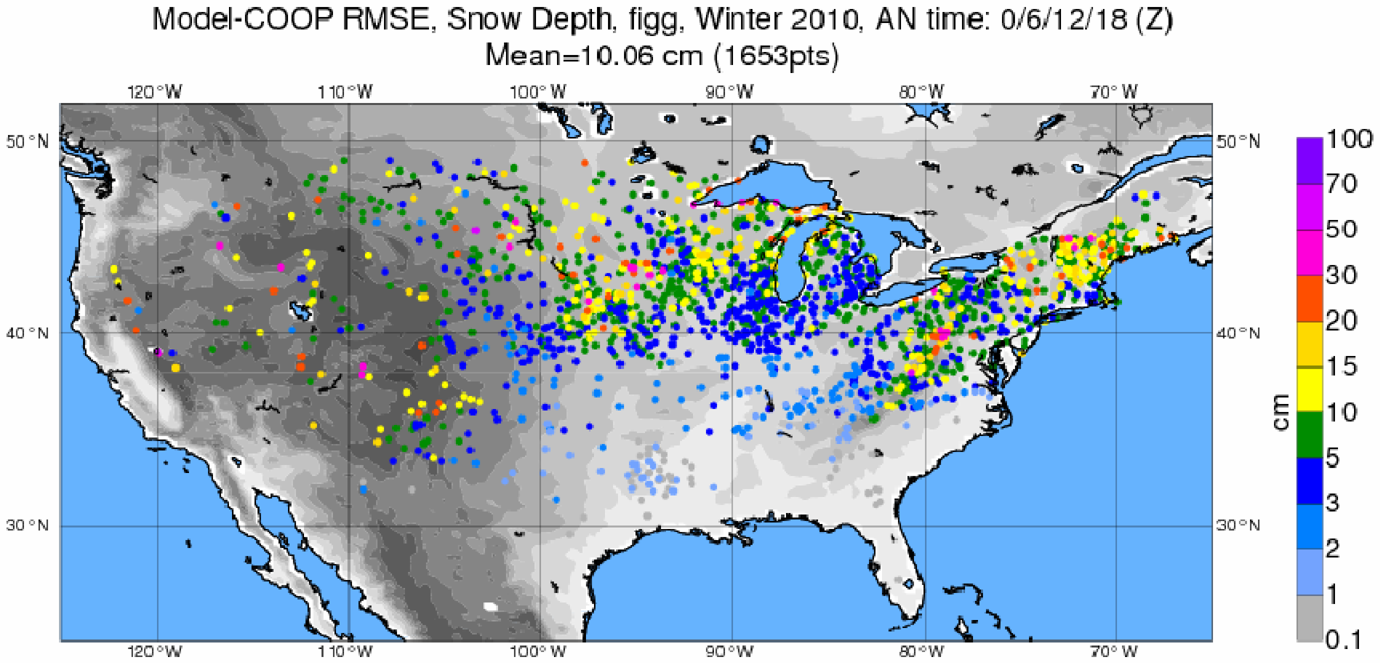
RMSE (cm) for the new snow analysis
(OI, IMS 4km except in mountainous areas)

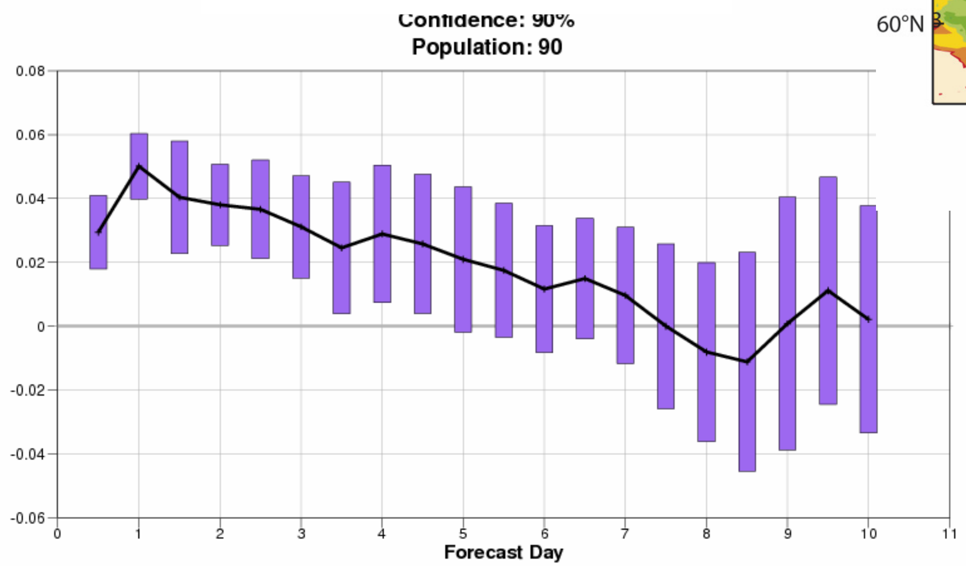


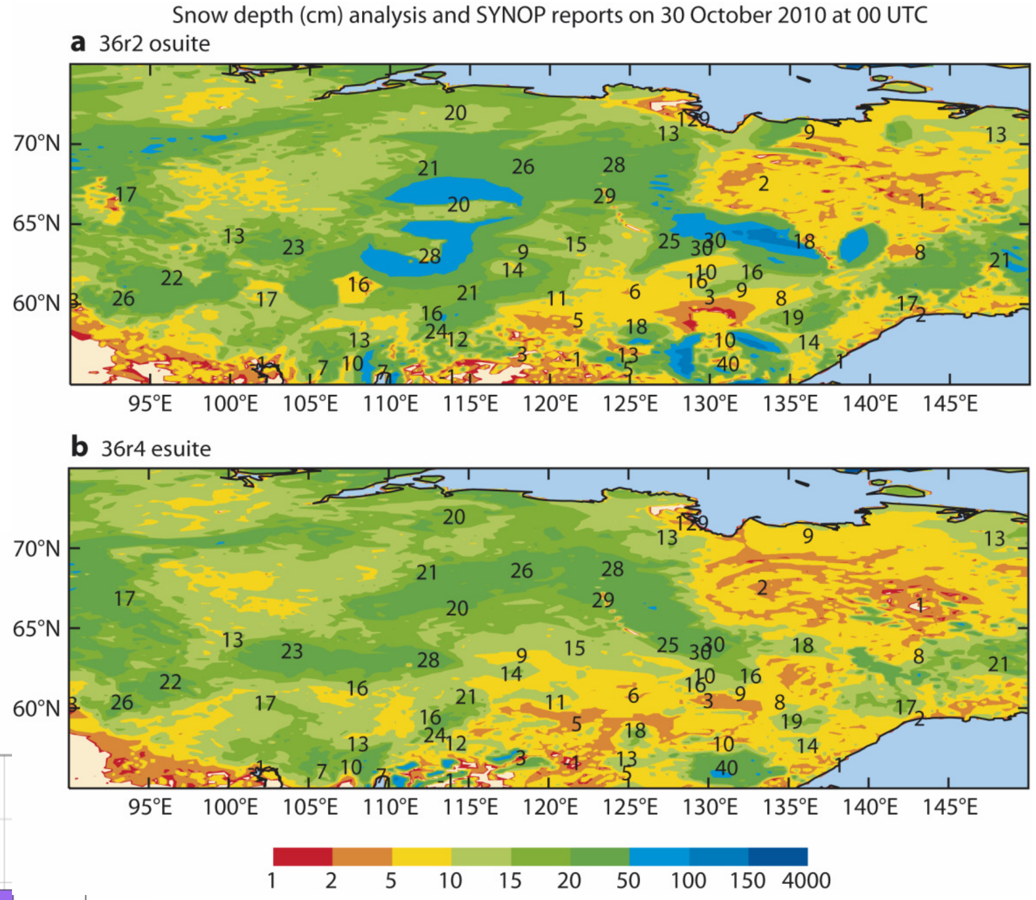
New snow Analysis in Operations

Old: Cressman
NESDIS 24km

New: OI
NESDIS 4km

FC impact (East Asia):



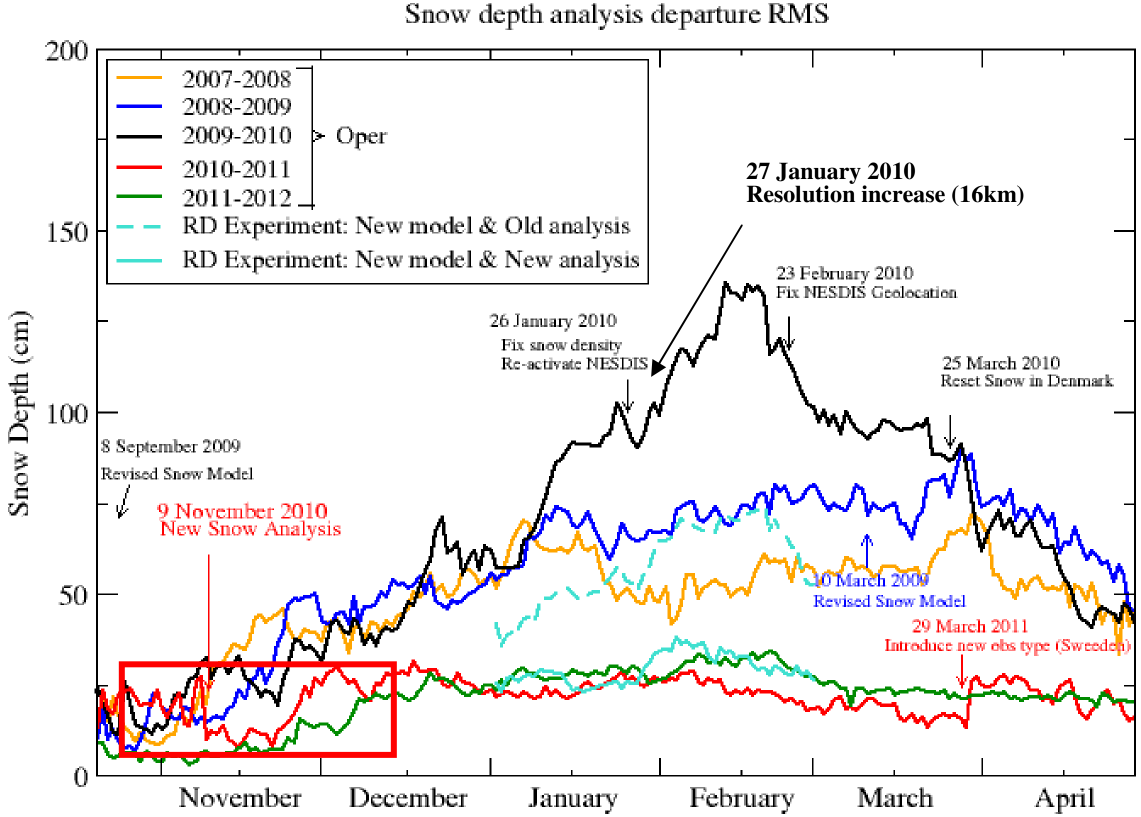


RMSE forecast (Old-New)
500 hPa geopotential height
in East Asia

(de Rosnay et al; SG 2013)

Snow depth analysis

Operational Snow Depth
Analysis departure (Observations minus Analysis) RMS
from 2008 to 2012



Major improvement in the Operational Snow Depth analysis From November 2010

Consistent Improvement for the entire winters 2010-2011 and 2011-2012

Outline

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

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), Dt = 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 coefficients

OI soil moisture analysis based on a dedicated screen level parameters (T2m Rh2m) analysis

Drusch and Viterbo, Mon. Weath. Rev., 2007 showed that the OI using screen level variables improves fluxes but degrades soil moisture → requirement to use future satellite soil moisture data (more direct SM information)

Drusch et al., GRL, 2009
De Rosnay et al. ECMWF NL 2011
de Rosnay et al., QJRMS 2013

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

Simplifed EKF soil moisture analysis

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

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

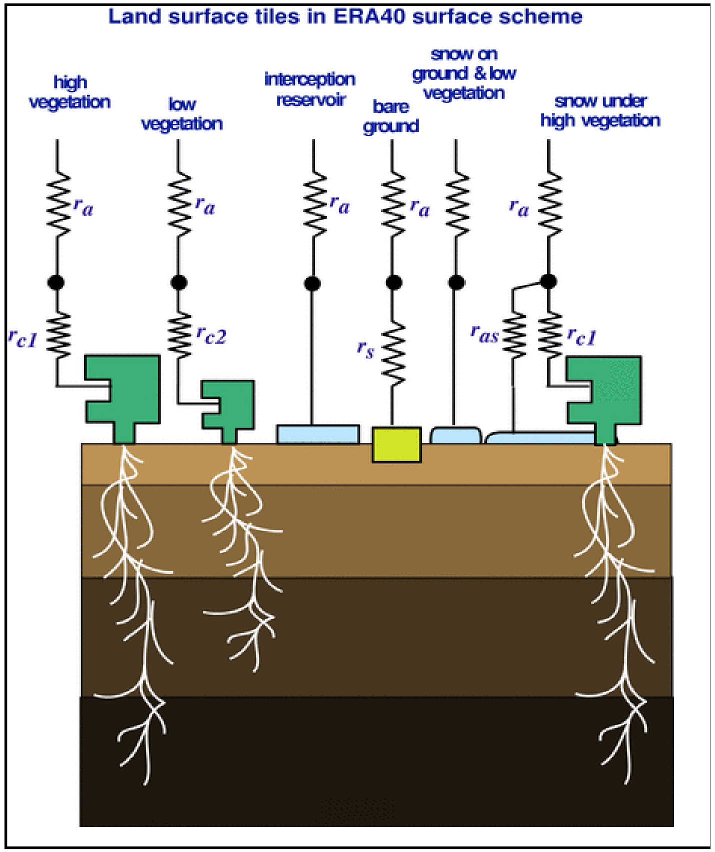
$\boldsymbol{x}$ background soil moisture state vector,
$\mathcal{H}$ non linear observation operator
$\boldsymbol{y}$ observation vector
$\boldsymbol{K}$ Kalman gain matrix, fn of
H (linearsation of $\mathcal{H}$), **B** and **R** (covariance matrices of background and observation errors).

Observations used:

- **Operational**: Conventional SYNOP observations **(T2m, RH2m)**

- **Research**: Satellite data **ASCAT, SMOS**

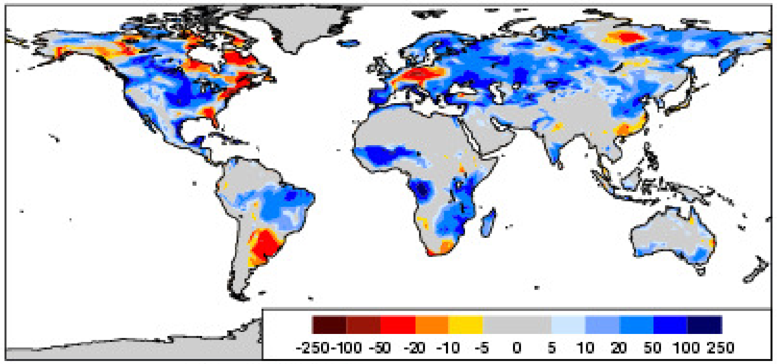
Simplified EKF corrects the trajectory of the Land Surface Model



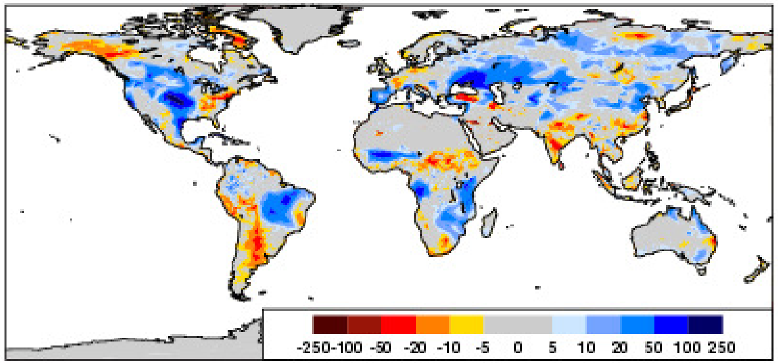
Drusch et al., GRL, 2009
de Rosnay et al., ECMWF News Letter 127, 2011
de Rosnay et al., QJRMS in press, 2013

Simplified EKF and OI comparison

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

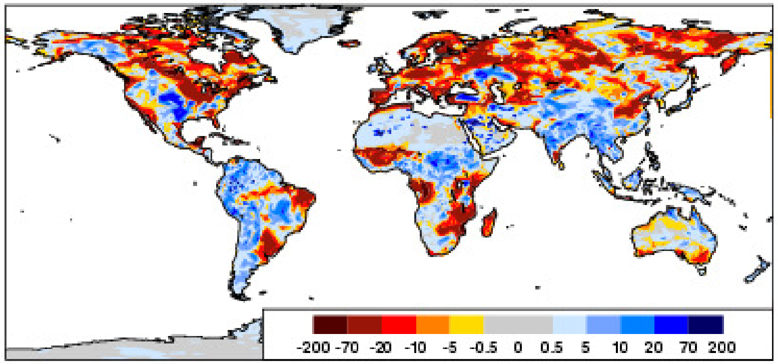


OI

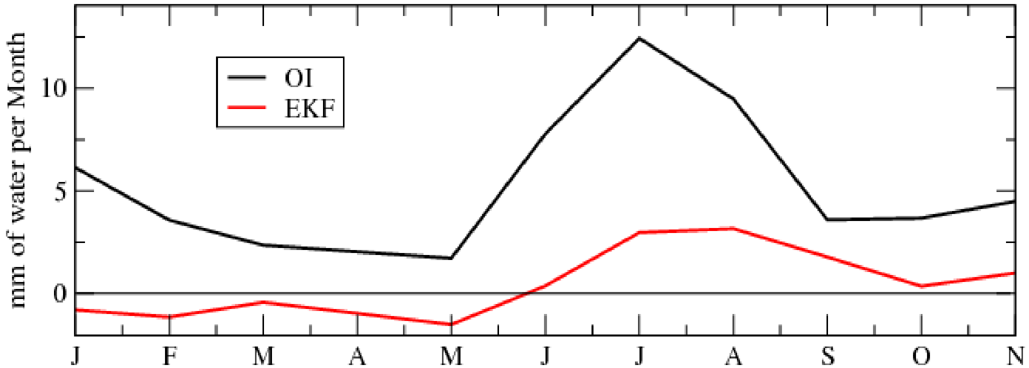


EKF

|EKF|-|OI|



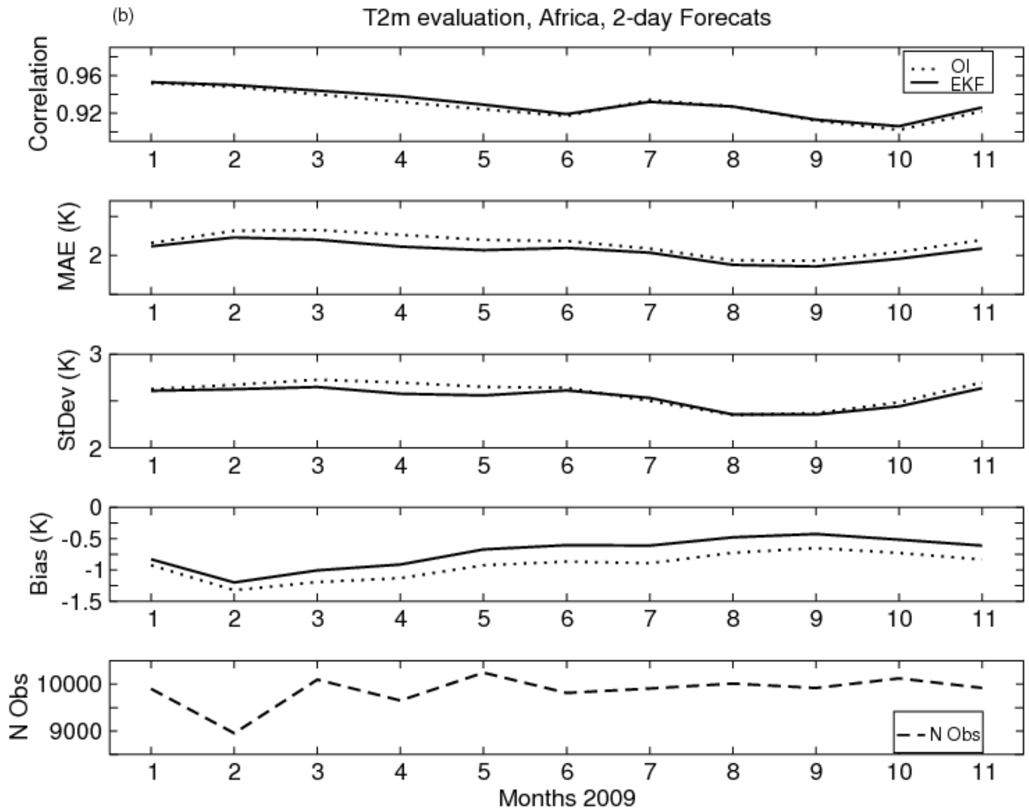
Global Soil Moisture Increments (1st meter of soil)

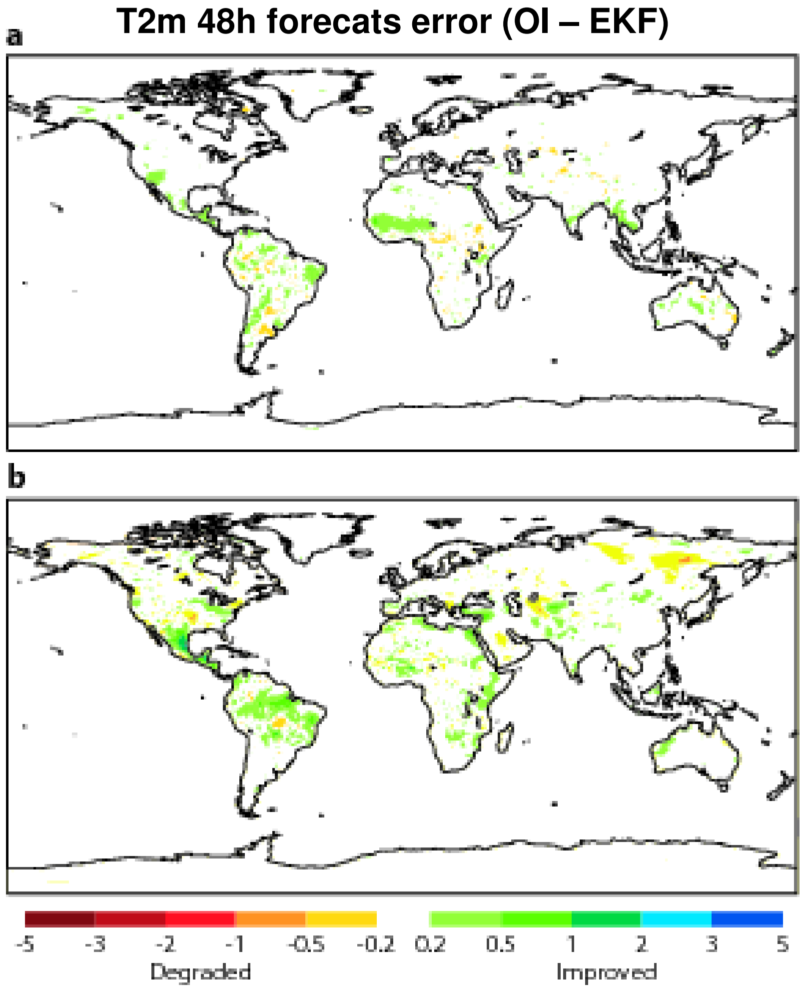


-Two 1-year analysis experiments using the OI and the EKF

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

T2m 48-h Forecast Evaluation





(de Rosnay et al, QJRMS, in press, 2013)

- EKF improves analysis and FC of Soil Moisture and Screen level parameters
- EKF enables the use of satellite data for the surface

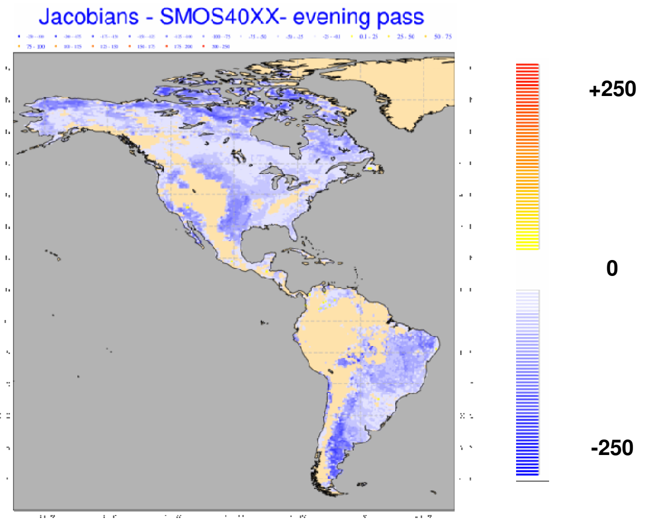
ECMWF

SMOS: Soil Moisture and Ocean Salinity

- ESA Earth Explorer mission ; RD developments:

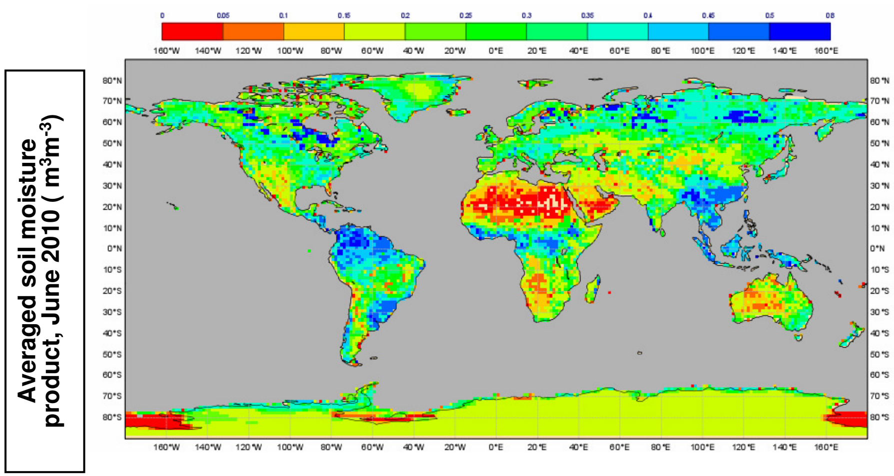
Global assimilation of SMOS brightness temperatures in the ECMWF Simplified Extended Kalman Filter

Sensitivity of TB to soil moisture (K/ m^3m^{-3})



(J. Muñoz Sabater et al)

- Soil moisture from SMOS
- Expect operational in 2014/2015
- Future SMAP (NASA) in 2015



ECMWF

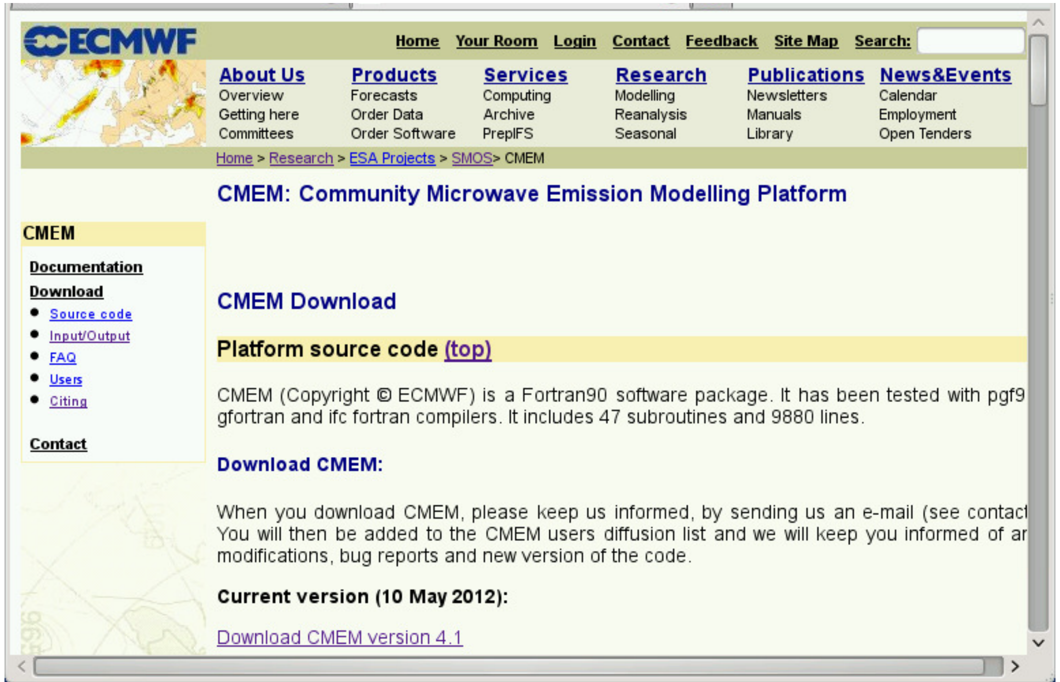
Microwave emission modelling

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

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

Also used at CMC, IPSL, CSIRO, GSFC, CNRM, and others centres…

Current version 4.1 (May 2012)



References:
Holmes et al., TGRS, 2008
Drusch et al. JHM, 2009
de Rosnay et al. JGR, 2009
Sabater et al., IJRS, 2011

SMOS Monitoring

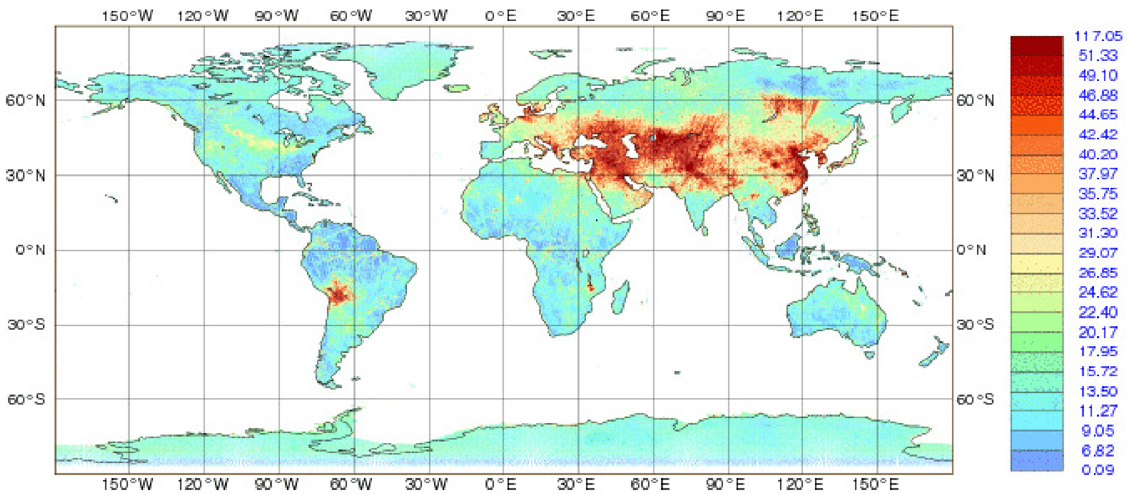
Near real time (NRT) monitoring of SMOS TB at ECMWF

(Muñoz Sabater et al. ECMWF Newsletter & IEEE TGRS 2011)

RFI (Radio Frequency Interference) issue in Asia and Eastern Europe

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

Active microwave data: ASCAT

Advanced Scatterometer on MetOP (launched in 2006)
Continuity of ERS/SCAT (1-1992; 2-1996)

Active microwave instruments operating at C-band (5.2GHz)

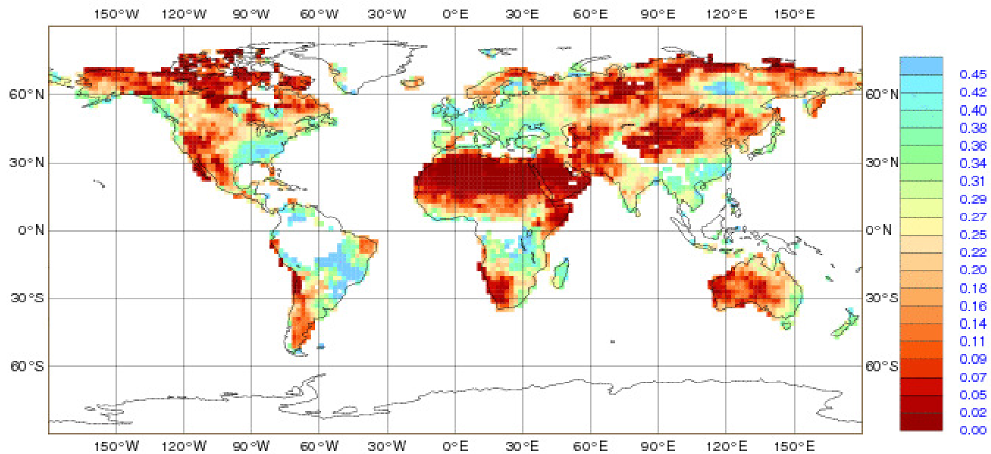
Surface soil moisture index (ms) based on the
TUWien retrieval scheme (Wagner et al. 1999)

ASCAT operational EUMETSAT
SM product

ASCAT Monitoring

Soil Moisture Monitoring
Dec2011-Jan2012

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



ASCAT Root Zone soil moisture

Production chain based on an Extended Kalman Filter (EKF) approach

ECMWF Atmospheric conditions

SYNOP
T2m RH2m

ASCAT CAF
Surface SM

EKF
Soil Moisture
Analysis

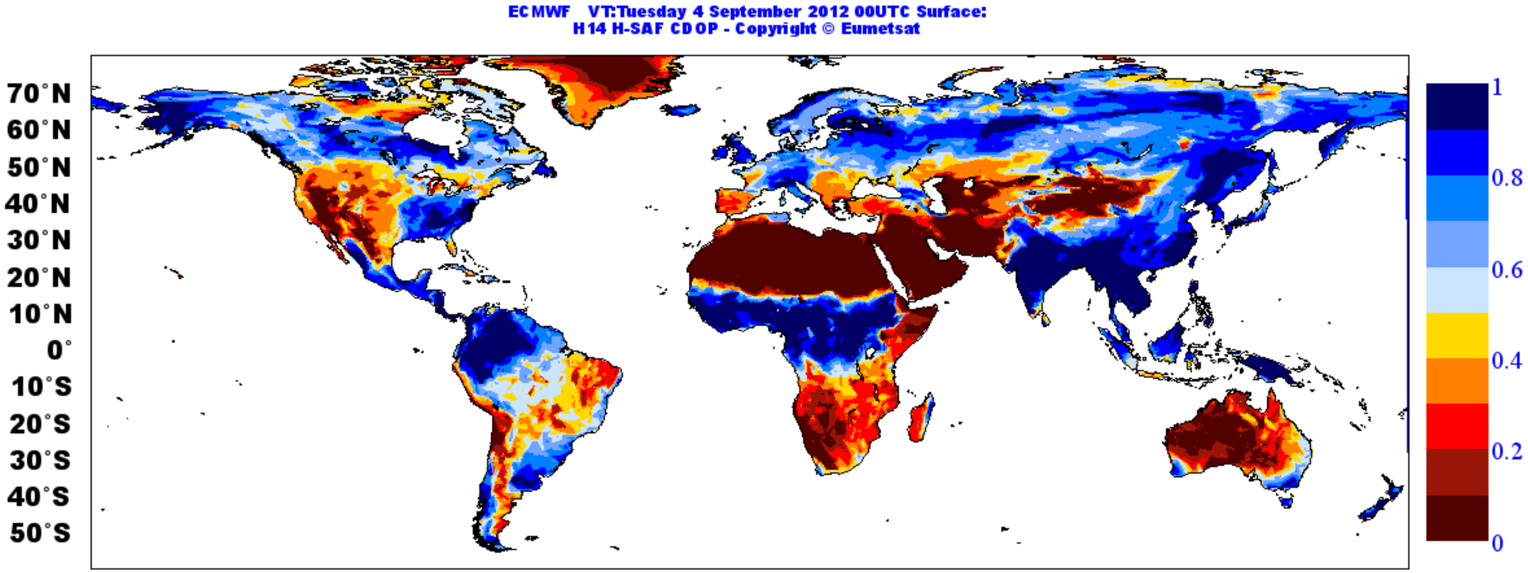
SM-DAS-2:
Soil Moisture
Profile

The EUMETSAT Network of Satellite Application Facilities

H SAF
Support to Operational Hydrology and Water Management

EUMETSAT H-SAF product SM-DAS-2 (H14)

ASCAT Root Zone soil moisture SM-DAS-2



SM-DAS-2:
- **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

H-14: Operational H-SAF since July 2012;

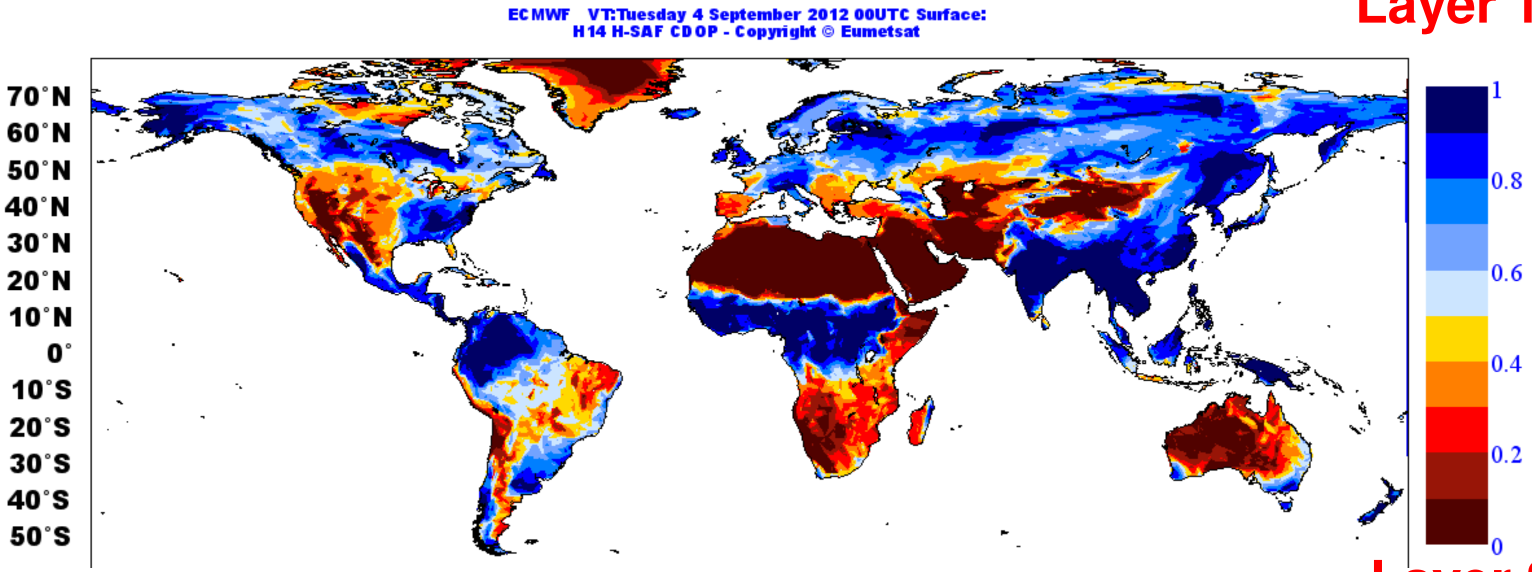
hsafcdop@meteoam.it

ECMWF

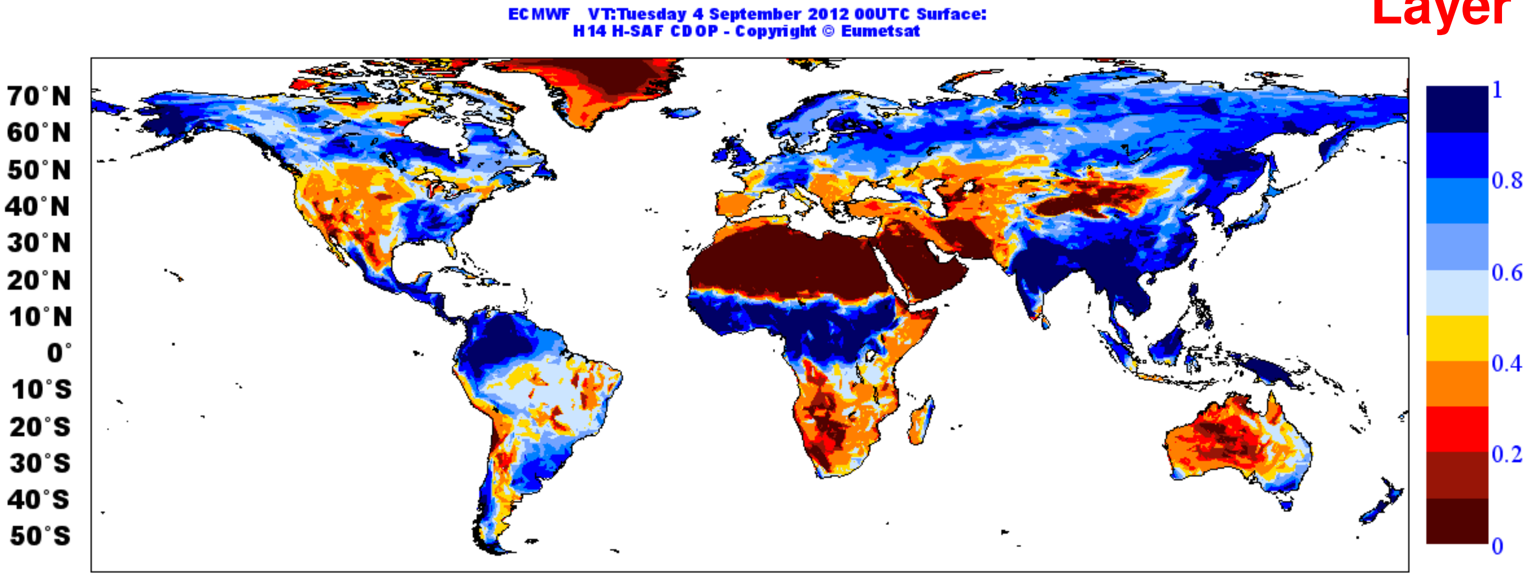
ASCAT Root Zone soil moisture SM-DAS-2

Available on 4 soil layers

Layer 1 (0-7cm)



Layer 2 (7-28cm)

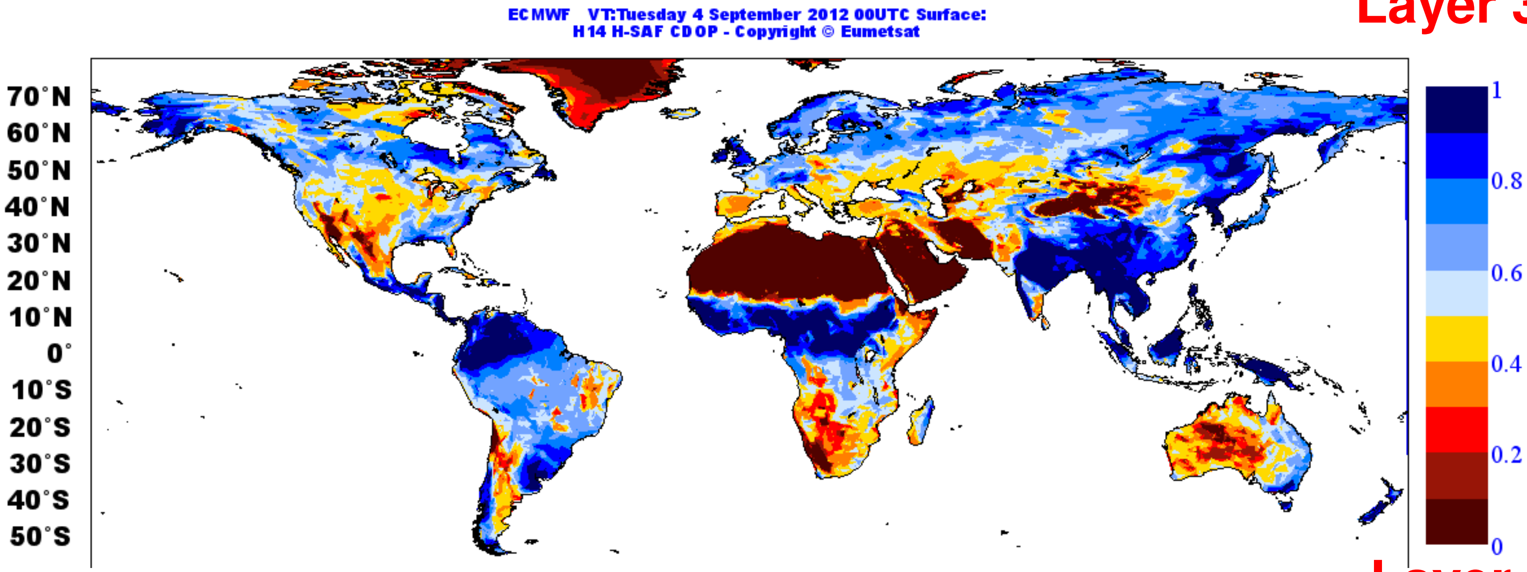


H SAF
Support to Operational Hydrology and Water Management

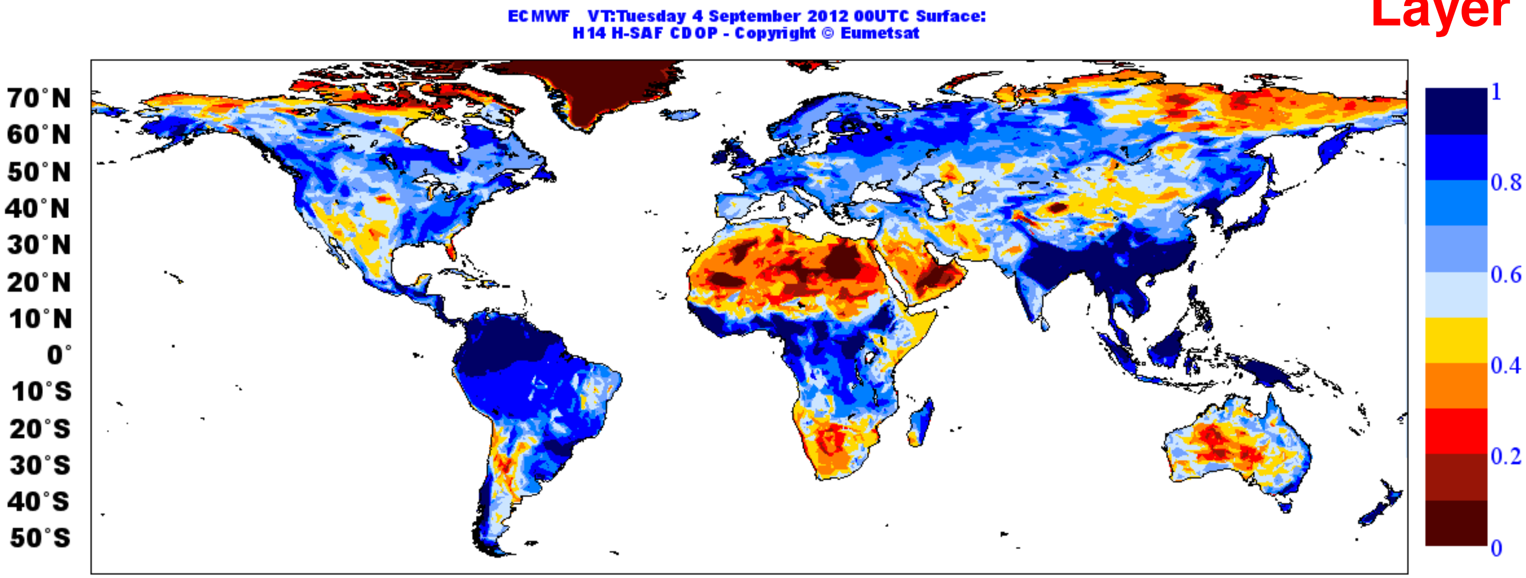
ASCAT Root Zone soil moisture SM-DAS-2

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

Soil Moisture products: Evaluation

Surface soil moisture

- Within H-SAF evaluation and comparison of H14, ASCAT and SMOS Validation against more than 200 stations across 4 continents

	SM-DAS-2	ASCAT L2	SMOS L2
Correlation	**0.70**	**0.53**	**0.54**
Bias (index)	**-0.05**	**-0.07**	**0.12**
RMSD (index)	**0.23**	**0.25**	**0.24**

- Global evaluation SM-DAS-2 / ASCAT / SMOS:
  SM-DAS-2 best capture soil moisture dynamics,
  lowest bias and lowest RMSD

(Albergel et al., RSE 2012)

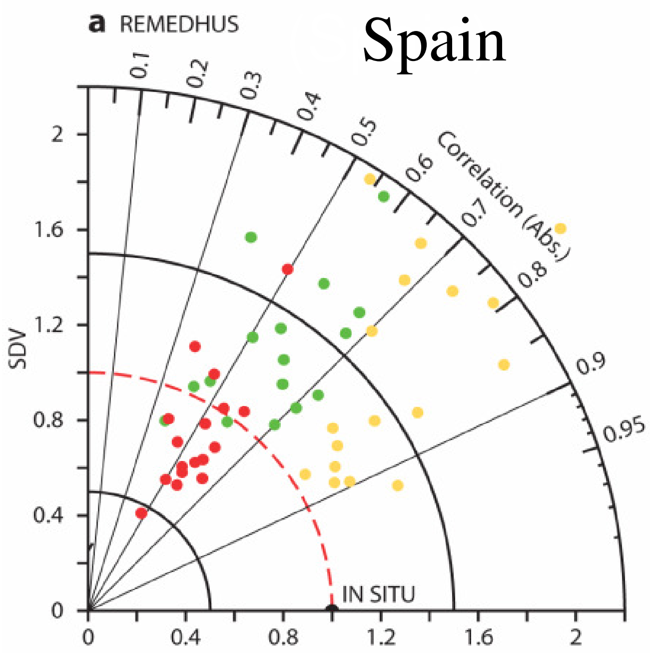
The EUMETSAT Network of Satellite Application Facilities

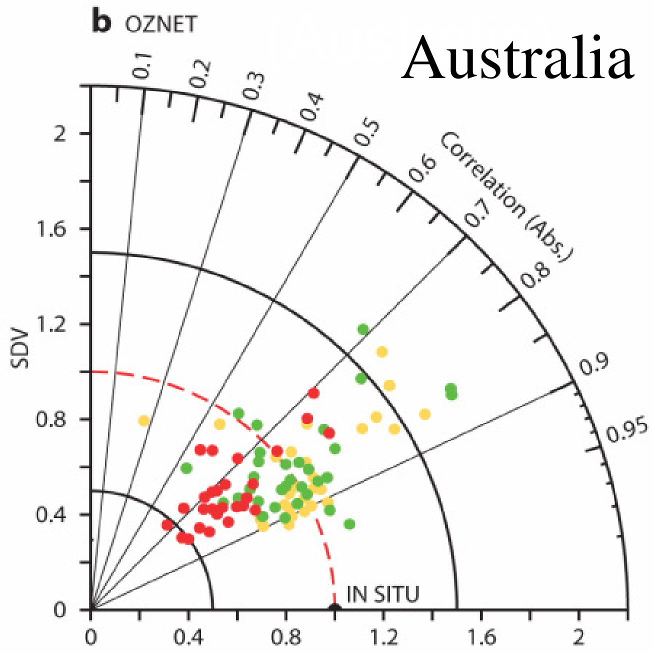
H SAF Support to Operational Hydrology and Water Management

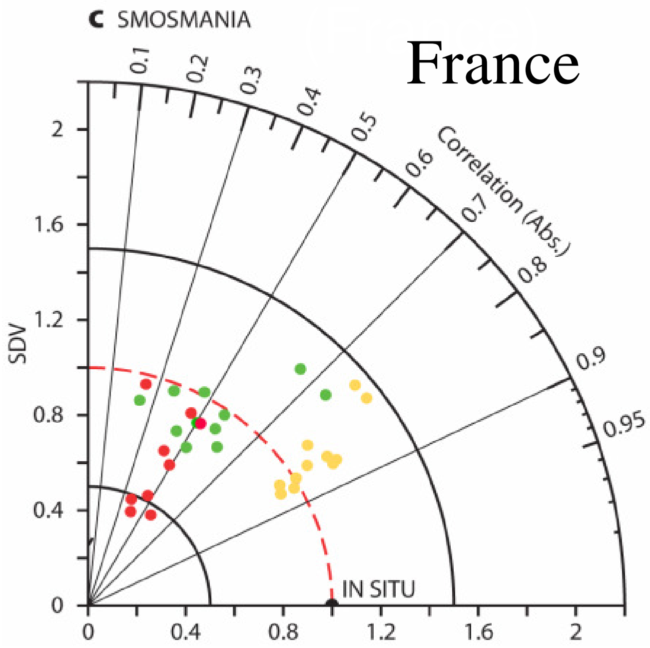
-Global comparison: **Gruhier et al, H-SAF VS11_02:**

http://www.ecmwf.int/research/EUMETSAT_projects/SAF/HSAF/ecmwf-hsaf/index.html

Soil Moisture Evaluation







Evaluation against
situ surface soil moisture

SM-DAS-2
ASCAT
SMOS

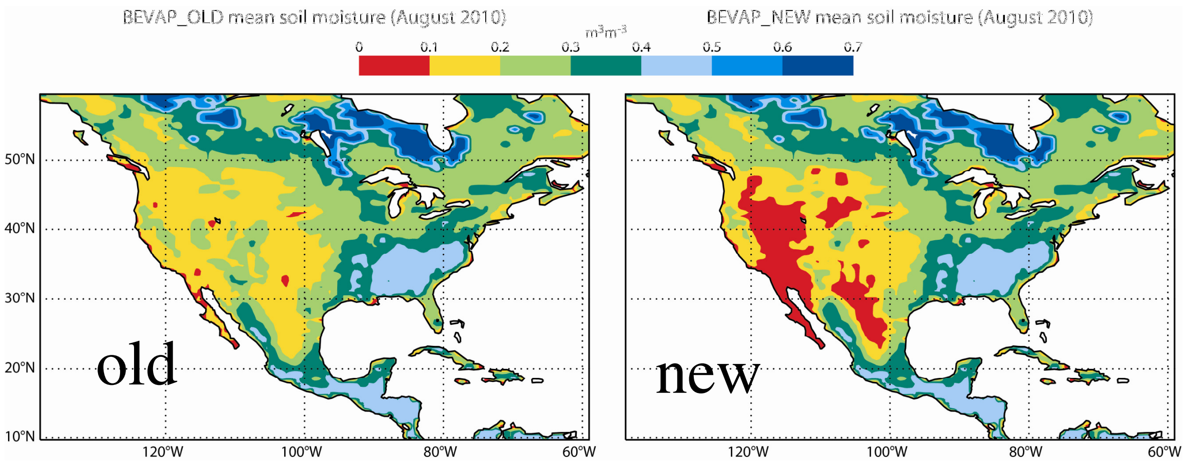
Albergel et al, RSE 2012

The EUMETSAT Network of Satellite Application Facilities

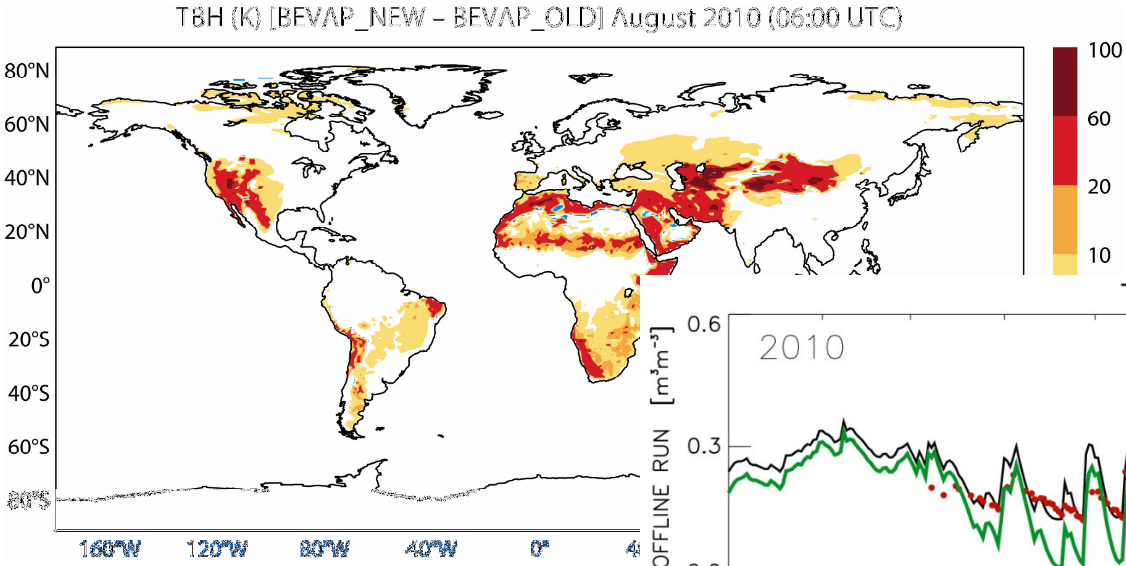
H SAF Support to Operational Hydrology and Water Management

ECMWF

Soil moisture in H-TESSEL

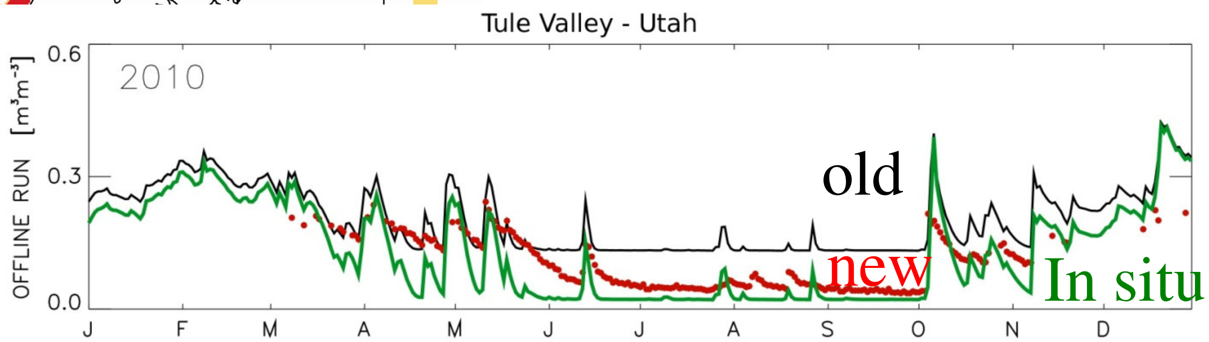


←Soil Moisture (m^3m^{-3})



←Simulated SMOS TB (K)

SM Time series



Albergel et al. HESS, 2012

Summary LDAS

- **Operational Land Data Assimilation at ECMWF → NWP model initialization**
- **New snow analysis from November 2010**
  - OI, uses ground data and 4km NESDIS/IMS

  → strong positive impact on snow depth and on atmospheric forecasts
- **New EKF Soil Moisture analysis :** improves SM and screen level analysis and forecasts; flexible for future developments (soil and snow temperature, + satellite data)

- **ASCAT SM monitoring and data assimilation**
  - New ASCAT soil moisture bias correction
  - Importance of pre-processing and noise filtering on DA results
  - ASCAT DA experiments using new BC: slight positive impact on FC and SM
- **SMOS monitoring, and DA developments (EKF and Bias correction)**
- **Validation**: similar quality of SMOS L2 and ASCAT L2 SSM products;
- **SMAP** (Soil Moisture Active and Passive) NASA mission to be launched in 2014

Land Surface Analysis

- Operational NWP
- Objective of high quality surface and near surface weather products
- Land Surface Model: H-TESSEL **(Balsamo et al., ECMWF NewsLetter 2011)**
- Land Data Assimilation (**de Rosnay et al., ECMWF NewsLetter 2011**)

- Snow depth analysis

- **New 2D Optimum Interpolation (OI) (operational)**
- **Ground data (SYNOP and other NRT data)**
- **High resolution NESDIS/IMS snow cover data**

(de Rosnay et al., Surv. Geophys., 2013)

- Soil Moisture analysis

- **Simplified Extended Kalman Filter (EKF) (Operational)**
- **Uses screen level parameters analysis**

Drusch et al. GRL (2009)
de Rosnay et al. QJRMS (2013)

- Satellite data related to Soil Moisture

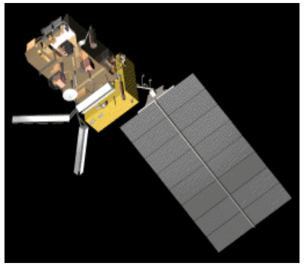
METOP-ASCAT (Operational)
de Rosnay et al., QJRMS 2013

SMOS Monitoring
Sabater et al., TGRSL 2011

ASCAT data assimilation

- Validation activities (EUMETSAT H-SAF)

Albergel et al. RSE 2012, HESS 2012, JHM 2012



NESDIS/IMS snow cover
(16 Jan. 2012)