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

**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.

[Google search results for soil moisture](https://www.google.com/search?q=what%20is%20soil%20moisture)
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
Rain starts 

A-B: After a long episode of rainfall
- Soil saturated with water
- SM is determined by E
- Atmosphere controls E rate (at E=E\(_{\text{pot}}\))

B-C: SM has decreased below a certain level
- E limited by plant-physiological mechanism
- E drops below its maximal value (E<E\(_{\text{po}}\))

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)

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


Multimodel estimation of land atmosphere coupling strength:

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


“[…] 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.

  \[
  \theta^a_i = \theta^f_i + C_v D \Delta t \times (q^a - q^f),
  \]

  - D: nudging coefficient (constant=1.5g/Kg),
  - Cv: fraction of vegetation
  - \(\Delta t = 6h\), 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)

  \[
  \Delta \theta_i = \theta^a_i - \theta^f_i = \alpha_i(T^a - T^f) + \beta_i(RH^a - RH^f).
  \]

  - \(\alpha, \beta\): 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

  \[
  \theta^a_i = \theta^f_i + K (y - H[\theta^f_i]).
  \]

  - 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 $\rightarrow$ 2m air too dry & too warm
- Too wet soil $\rightarrow$ 2m air too moist & too cold

$\rightarrow$ Soil Moisture increments based on the T2m and RH2m analysis increments:

$$\Delta \Theta_i = \alpha_i (T^a - T^b) + \beta_i (rH^a - rH^b)$$

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 $\alpha$, $\beta$, and c

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


References HITESSEL: Balsamo et al., JHM 2009

**H-TESSEL Land Surface Model**
EKF Equations (1/3)

\[ x_a^t = x_b^t + K(y_0^- H[ x_b^t]) \]

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 \( H \) allows to get the model counterpart of the observations:

\[ y^t = H(x^t) \]

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:

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

Where \( K \) is the gain matrix defined by:

\[
K = BH^T(HBH^T + R)^{-1}
\]

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 \( \delta x_j \).
EKF Equations (3/3)

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

\[ A = (I-KH)B = (B^{-1} + H^TR^{-1}H)^{-1} \]

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

\[ X_{b,t+1} = M(x_a^t) \]
\[ B^{t+1} = MA^TM^T + Q \]

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
Simplified EKF soil moisture analysis

For each grid point, analysed soil moisture state vector $\theta_a$:

$$\theta_a = \theta_b + K (y - H[\theta_b])$$

$\theta$  background soil moisture state vector,
$H$  non linear observation operator
$y$  observation vector
$K$  Kalman gain matrix, fn of
  $H$ (linearsation of $H$), $B$ 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
Computing Time (CPU in s) per 12h cycle:

<table>
<thead>
<tr>
<th></th>
<th>T159 (125km)</th>
<th>T255 (80km)</th>
<th>T799 (25km)</th>
<th>T1279 (16km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D OI</td>
<td>3</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>EKF</td>
<td>$3 \times 10^3$</td>
<td>$10^4$</td>
<td>$2 \times 10^5$</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>4D-Var</td>
<td>$4 \times 10^5$</td>
<td>$10^6$</td>
<td>$2.5 \times 10^6$</td>
<td></td>
</tr>
</tbody>
</table>

EKF running on several processors $\rightarrow$ Elapsed time $\sim$ 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|
Simplified EKF and OI comparison

0-1m Soil Moisture increments (mm)

July 2009

|EKF|-|OI|

Much reduced root zone increments with the EKF compared to the OI
Simplified EKF and OI comparison

Vertical Profile of Soil Moisture increments difference $|\text{EKF}| - |\text{OI}|$ 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)
Simplified EKF and OI comparison

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

- 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**
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
- 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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  - **Use of Satellite data ASCAT and SMOS**
- Summary and future plans
Satellite data for NWP soil moisture analysis

Active microwave data:
ASCAT: Advanced Scatterometer
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

Operational Monitoring of surface soil moisture related satellite data:
ASCAT soil moisture (m$^3$m$^{-3}$)
SMOS Brightness temperature (K)

Stdev FG depar
Sept. 2013
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 $m_{\text{ASCAT}}$
- Model soil moisture $\theta$ (m$^3$/m$^{-3}$)

$\rightarrow$ Simple Cumulative Distribution Function (CDF) matching (Scipal et al., 2008)

$$\theta_{\text{ASCAT}} = a + b \, m_{\text{ASCAT}}$$

with

$$a = \overline{\theta_{\text{model}}} - \overline{m_{\text{ASCAT}}} \left( \frac{\sigma_{\text{model}}}{\sigma_{m_{\text{ASCAT}}}} \right)$$

$$b = \frac{\sigma_{\text{model}}}{\sigma_{m_{\text{ASCAT}}}}$$

$\rightarrow$ Matches mean and variance

a and b are CDF matching parameters computed on each model grid point

ASCAT CDF-matching has two objectives:

$\rightarrow$ ASCAT index converted to model equivalent volumetric soil moisture

$\rightarrow$ 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

Time series at 43.825N 1.1767E (South West France)
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, m³.m⁻³)
23-24 Nov 2012

<table>
<thead>
<tr>
<th></th>
<th>Nb</th>
<th>Mean m³.m⁻³</th>
<th>Std m³.m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCAT-A</td>
<td>64893</td>
<td>0.0152</td>
<td>0.0645</td>
</tr>
<tr>
<td>ASCAT-B</td>
<td>65527</td>
<td>0.0149</td>
<td>0.0663</td>
</tr>
</tbody>
</table>

Operational monitoring:
http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/slmoist/
ASCAT data [0-1] / Bias correction [m$^3$m$^{-3}$]

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

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

operational from Jul. 2012
ASCAT soil moisture data assimilation

SM-DAS-2 available on 4 soil layers

Layer 1 (0-7cm)

Layer 2 (7-28cm)
Available on 4 soil layers

ASCAT soil moisture data assimilation

Layer 3 (28-100 cm)

Layer 4 (1-3 m)
Satellite data for NWP soil moisture analysis

**Active microwave data:**

**ASCAT:** Advanced Scatterometer  
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

Operational Monitoring of surface soil moisture related satellite data:  
ASCAT soil moisture \((m^3/m^3)\)  
SMOS Brightness temperature (K)

**Stdev FG depar**  
Sept. 2013
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.

```
STADISTICS FOR RADIANCES FROM SMOS
STDEV OF FIRST GUESS DEPARTURE (ALL)
DATA PERIOD = 2013-01-20 21 - 2013-02-22 21
EXP = FGA5, CHANNEL = 1 (FOV: 35-45)
Min: 0.086 Max: 117.052 Mean: 15.794
GRID: 0.25x0.25
```

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

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

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

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

Current version 4.1 (May 2012)

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

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

Before QC

July 2010
TOA TBH

After QC
(snow, Freeze, Orography)
SMOS forward operator: Community Microwave Emission Modelling Platform (CMEM)

CDF-matching matches mean and variance of two distributions

\[ \text{TB}^*_{\text{SMOS}} = a + b \text{TB}_{\text{SMOS}} \]

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

\( b = \sigma_{\text{CMEM}} / \sigma_{\text{SMOS}} \)

\( \rightarrow \) Matches mean and variance
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

\[ TB_{SMOS}^* = a + b \cdot TB_{SMOS} \]

with \[ a = \overline{TB}_{CMEM} - \overline{TB}_{SMOS} \left( \frac{\sigma_{CMEM}}{\sigma_{SMOS}} \right) \]

\[ b = \frac{\sigma_{CMEM}}{\sigma_{SMOS}} \]

→ 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
Validation with in situ soil moisture data

406 stations from 10 networks

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)

<table>
<thead>
<tr>
<th></th>
<th>Correlation [-] (for stations with significant values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM-DAS-2</td>
<td>0.67 (104 stations)</td>
</tr>
<tr>
<td>ASCAT</td>
<td>0.50 (104 stations)</td>
</tr>
<tr>
<td>SMOS</td>
<td>0.50 (84 stations)</td>
</tr>
</tbody>
</table>
### Validation with in situ soil moisture data

<table>
<thead>
<tr>
<th>Normalized Product (nb stations with significant R)</th>
<th>SM-DAS-2 (333)</th>
<th>ASCAT (322)</th>
<th>SMOS (258)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td>0.68</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>Bias (In Situ - Product)</td>
<td>-0.084</td>
<td>-0.005</td>
<td>0.027</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.120</td>
<td>0.110</td>
<td>0.105</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalized Product (nb stations with significant R)</th>
<th>SM-DAS-2 (310)</th>
<th>ASCAT (291)</th>
<th>SMOS (234)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation on Anomaly</td>
<td>0.56</td>
<td>0.41</td>
<td>0.42</td>
</tr>
</tbody>
</table>

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
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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)
- 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
# Land surface data assimilation

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>OI screen level analysis</td>
</tr>
<tr>
<td></td>
<td>- Douville et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>- Mahfouf et al. (2000)</td>
</tr>
<tr>
<td>2004</td>
<td>Revised snow analysis</td>
</tr>
<tr>
<td></td>
<td>- Drusch et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>- Cressman + NESDIS</td>
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<td>- IMS Snow coverextend data (24km)</td>
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<tr>
<td>2010/2011</td>
<td>(OI) snow</td>
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<td></td>
<td>- de Rosnay et al. (2014)</td>
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<td>- NESDIS IMS 4km</td>
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<td>- Additional in situ</td>
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<td>- SEKF SM (36r4)</td>
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<td>- de Rosnay et al. (2013)</td>
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<td>2013/2014</td>
<td>Conv Obs monitoring</td>
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<td>- OI code cleaning</td>
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<td>- EDA OBS perturbations</td>
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<td>- NESDIS IMS 4km</td>
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<td>- de Rosnay et al. (2013)</td>
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## Use of satellite data

- **SYNOP Data**
- **NOAA/NESDIS IMS**
- **METOP-ASCAT**
- **SMOS**
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


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
A short history of soil moisture analysis at ECMWF

- **Nudging scheme (1995-1999)**
  - Soil moisture increments $\Delta \Theta$ ($m^3m^{-3}$):
    $$\Delta \Theta \,=\,\Delta t \,D \,C_v \,(q^a - q^b)$$
    - $D$: nudging coefficient (constant=1.5g/Kg), $\Delta t = 6h$, $q$ specific humidity
    - Uses upper air analysis of specific humidity
    - Prevents soil moisture drift in summer

- **Optimal interpolation 1D OI (1999-2010)**
  $$\Delta \Theta \,=\,A \,(T^a - T^b) + B \,(Rh^a - Rh^b)$$
  - $A$ and $B$: optimal coefficients
  - OI soil moisture analysis based on dedicated screen level parameters (T2m Rh2m) analysis

- **Simplified Extended Kalman Filter (EKF), Nov 2010**
  - Motivated by better using T2m, RH2m
  - Opening the possibility to assimilate satellite data 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):

\[ \theta_a(t) = \theta_b(t) + K(y(t) - H[\theta_b(t)]) \]

where \( K \) is the gain matrix:

\[ K = (B^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1} \]

The observation operator \( H \) is the Jacobian matrix of:

\[ H_{ij} \approx \frac{\delta y_i}{\delta \theta_j} = \frac{y_i(x + \delta \theta_j) - y_i(x)}{\delta \theta_j} \]

In finite differences, the elements of the Jacobian matrix are estimated by perturbing individually each component \( \theta_j \) of the control vector \( \theta \) 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.
ASCAT soil moisture data assimilation

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

Quality Control → use data when:
- Topographic complexity ≤ 20
- Wetland Fraction ≤ 15
- Noise level ≤ 8
- processing flag=0
SM-DAS-2: ASCAT Root Zone Soil Moisture Product
- Daily Soil Moisture product valid at 00:00 UTC
- Daily Global coverage

SM-DAS-2: Operational H-SAF since July 2012;
hsafcdop@meteoam.it
Soil Moisture analysis at 00:00, 06:00, 12:00, 18:00

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

\[
\begin{align*}
(T2M_{\text{obs}} - T2M_{\text{mod}}) &> 5K \\
(RH2M_{\text{obs}} - RH2M_{\text{mod}}) &> 20\% \\
(SM_{\text{obs}} - SMM_{\text{mod}}) &> 0.01m^3m^{-3}
\end{align*}
\]

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

\[\ldots\]
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 $\delta x_j$

- Perturbation size is $0.01 \text{m}^3\text{m}^{-3}$

No pert

Pert $\text{SM}_{l_1}$

Pert $\text{SM}_{l_2}$

Pert $\text{SM}_{l_3}$

\[
H = \frac{T_{2m}^{\text{pert.}} - T_{2m}}{\delta \text{SM}_{l_1}} \quad \frac{\text{RH}_{2m}^{\text{pert.}} - \text{RH}_{2m}}{\delta \text{SM}_{l_1}} \quad \frac{\text{SM}_{l_1}^{\text{pert.}} - \text{SM}_{l_1}}{\delta \text{SM}_{l_1}}
\]

$\rightarrow$ At observation time

$\rightarrow$ At initial time
**Liquid root zone soil moisture Index**

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

- **Rational for having an index [0-1]:** Spatial variability of SM is very high, differences in soil properties $\Rightarrow$ 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