ECMWF Data Assimilation Training course
24-28 February 2020

Coupled land-atmosphere data assimilation

Patricia de Rosnay
Outline

• Introduction
  • Snow analysis
  • Soil moisture analysis
  • Summary
Earth system approach

- Consistency of the infrastructure and coupling approaches across the different components
- Modularity to account for the different components in coupled assimilation
Coupled assimilation terminology


Coupled assimilation: observations increments in one component impact the other components

- **Now**, i.e. during the data assimilation window → strongly coupled data assimilation
  - Multiple systems approach (e.g. outer loop coupling): QuasiSCDA
  - Single Integrated system: SCDA
- **Later**, e.g. next assimilation window, -> weakly coupled data assimilation (WCDA)
  - For example: independent DA for all components and interaction through model coupling

Coupled assimilation continuum

- No coupling
- Weakly Coupled Data Assimilation
- Full coupling

See lecture on Coupled DA from P. Browne
Current operational NWP system at ECMWF

Weakly coupled land-atmosphere-wave and sea ice assimilation

Relevant lectures:
- Ocean and sea ice DA → H Zuo
- Coupled DA -> P. Browne
- Reanalysis -> D. Schepers
Coupled land-atmosphere data assimilation

Vertical correlations dominate land surface processes. Each grid point is analysed independently. Land data assimilation is a 2D problem, whereas atmospheric DA is a 4D problem → Separate Land & atmospheric DA systems.

- Flexibility to run offline land analysis without the expensive 4D-Var component

Weakly coupling

Used for the ERA5 reanalysis & NWP
Introduction: Land Surface Data Assimilation (LDAS) for NWP

Snow depth
- **Methods:** Cressman Interpolation (DWD, ECMWF ERA-I), 2D Optimal Interpolation (OI) (ECMWF operational and ERA5, Env. Canada Clim. Ch.)
- **Conventional Observations:** in situ snow depth
- **Satellite data:** NOAA/NESDIS IMS Snow Cover Extent (ECMWF), H-SAF snow cover (UKMO in dvpt)

Soil Moisture
- **Methods:**
  - 1D Optimal Interpolation (Météo-France, Env. Canada CC, ALADIN and HIRLAM)
  - 1D-EnKF (Env. Canada CC)
  - Simplified Extended Kalman Filter (EKF) (DWD, ECMWF, UKMO)
- **Conventional observations:** Analysed SYNOP 2m air relative humidity and temperature, from 2D OI screen level parameters analysis
- **Satellite data:** ASCAT soil moisture (UKMO, ECMWF), SMOS (ECMWF, 2019)

Soil Temperature and Snow temperature
- 1D OI for the first layer of soil and snow temperature (ECMWF, Météo-France)
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  • Soil moisture analysis
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Snow in the ECMWF IFS for NWP

**Snow Model:** Component of H-TESSEL (Dutra et al., JHM 2010, Balsamo et al JHM 2009)

- Single layer snowpack
  - Snow water equivalent SWE (m)
  - Snow Density $\rho_s$

**Observations:** de Rosnay et al ECMWF Newsletter 2015
- Conventional snow depth data: SYNOP and National networks
- Snow cover extent: NOAA NESDIS/IMS daily product (4km)

**Data Assimilation:** de Rosnay et al SG 2014
- Optimal Interpolation (OI) is used to optimally combine the model first guess, in situ snow depth and IMS snow cover
- The result of the data assimilation is the analysis of SWE and snow density → used to initialize NWP.
Interactive Multisensor Snow and Ice Mapping System (IMS)
- Time sequenced imagery from geostationary satellites
- AVHRR,
- VIIRS,
- SSM/I, etc….
- Station data

Northern Hemisphere product
- Daily
- Polar stereographic projection

Information content: Snow/Snow free
Data used at ECMWF:
- 4 km product (NWP, ERA5)

Latency:
Available daily at 23 UTC. Assimilated in the subsequent analysis at 00UTC

http://nsidc.org/data/g02156.html
Snow Observations
Snow SYNOP and National Network data in Europe

In general, good coverage in Europe, but …
- Zero snow depth reporting is an issue with some countries providing observations only when snow depth > zero (e.g. Ukraine)
- Still areas with relatively few snow depth reports

Dedicated network to exchange meteorological data: Global Telecommunication System (GTS)
In situ snow depth observations
Snow depth reports on the GTS

SYNOP TAC + SYNOP BUFR + national BUFR data

Status on 10-15 December 2013
In situ snow depth observations
Snow depth reports on the GTS

SYNOP TAC + SYNOP BUFR + national BUFR data

Status on 10-15 December 2017

See more on snow DA and observations in de Rosnay et al, ECMWF Newsletter article, issue 143, 2015
1. Observed first guess departure $\Delta f_i$ are computed from the interpolated background at each observation location $i$.

2. Analysis increments $\Delta S_k^a$ at each model grid point $k$ are calculated from:

$$\Delta S_k^a = \sum_{i=1}^{N} w_i \times \Delta f_i$$

3. The optimum weights $w_i$ are given for each grid point $k$ by: $(P + R) w = p$

$p$ : **background error vector** between model grid point $k$ and observation $n$ (dimension of $N$ observations) $p(i) = \sigma^2_b \mu(i,k)$

$P$ : **correlation coefficient matrix of background field error** between all pairs of observations ($N \times N$ observations); $P(i_1,i_2) = \sigma^2_b \times \mu(i_1,i_2)$ with the correlation coefficients $\mu(i_1,i_2)$.

$R$ : **covariance matrix of the observation error** ($N \times N$ observations): $R = \sigma^2_o \times I$

with and $\sigma_b = 3$cm the standard deviation of background errors, $\sigma_o$ the standard deviation of observation errors (4cm in situ, 8cm IMS)
Snow depth Optimal Interpolation

Correlation coefficients $\mu(i_1,i_2)$ (structure function):

$$\mu(i_1,i_2) = (1 + \frac{r_{i_1i_2}}{L_x})\exp\left(-\frac{r_{i_1i_2}}{L_x}\right)\cdot\exp\left(-\frac{Z_{i_1i_2}}{L_z}\right)$$

$L_z$: vertical length scale: 800m, $L_x$: horizontal length scale: 55km

$r_{i_1i_2}$ and $Z_{i_1i_2}$ the horizontal and vertical distances between points $i_1$ and $i_2$

Quality Control: reject observation if first guess departure $> \text{Tol} \left(\sigma_b^2 + \sigma_o^2\right)^{1/2}$ with $\text{Tol} = 5$

→ Observation rejected if first guess departure larger than 25 cm for insitu (and 43cm for IMS)

Redundancy rejection: use observation reports closest to analysis time
And use a maximum of 50 observations per grid point
**OI vs Cressman**

Cressman still used in ERA-Interim and at DWD

In both OI and Cressman, snow depth increments computed as:

\[ \Delta S_k^a = \sum_{i=1}^{N} w_i \times \Delta f_i \]

**Cressman**: weights are function of horizontal and vertical distances. Do not account for observations and background errors. (Cressman, MWR 1959)

**OI**: The correlation coefficients of P and p follow a second-order autoregressive horizontal structure and a Gaussian for the vertical elevation differences.

OI has longer tails than Cressman and considers more observations. Model/observation information optimally weighted using error statistics.
Snow data assimilation OI vs Cressman

IFS oper before 2010 and ERA-Interim
Cressman Interpolation

IFS oper from 2010 and ERA5
Optimal Interpolation
Assimilation of IMS snow cover

- IMS snow cover (SC) means SC>50%
- But no quantitative information on snow depth
- Relation snow cover (SC)/Snow Depth (SD): SC=50% corresponds to SD=5cm
- Previously: direct insertion of 10cm when IMS has snow & model has no snow
- Issues with overestimated snow
- IFS revision for current cycle: assimilate IMS and account for IMS observation error

Current system:

<table>
<thead>
<tr>
<th>NESDIS</th>
<th>Fst Guess</th>
<th>Snow</th>
<th>No Snow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>x</td>
<td>DA 5cm</td>
<td></td>
</tr>
<tr>
<td>No Snow</td>
<td>DA</td>
<td>DA</td>
<td></td>
</tr>
</tbody>
</table>

Error specifications:

BG: $\sigma_b = 3$ cm
SYNOP: $\sigma_{SYNOP} = 4$ cm
IMS: $\sigma_{IMS} = 8$ cm
Snow assimilation: Forecast impact

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

Revised IMS snow cover data assimilation (2013)

<table>
<thead>
<tr>
<th>Snow observed</th>
<th>No snow observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow in analysis</td>
<td>a Hits</td>
</tr>
<tr>
<td>No snow in analysis</td>
<td>c Misses</td>
</tr>
</tbody>
</table>

The following scores are used for the evaluation:

- Accuracy = \( \frac{a+d}{a+b+c+d} \)
- False alarm ratio = \( \frac{b}{a+b} \)
- Threat score = \( \frac{a}{a+b+c} \)
Snow assimilation: Forecast impact

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

Impact on atmospheric forecasts October 2012 to April 2013 (RMSE new-old)

→ Consistent improvement of snow and atmospheric forecasts

de Rosnay et al., ECMWF Newsletter 143, Spring 2015
Summary on snow analysis

1. Snow initialisation has a large impact on Numerical Weather Forecast

2. Not all NWP systems have a snow analysis
   Snow data assimilation in NWP systems relies on relatively simple approaches

3. DA of *in situ* snow depth and snow cover (IMS used at ECMWF)
   - In situ snow depth reporting: issues on availability and reporting practices
   - National Met services encouraged to improve snow depth reports availability on the Global Telecommunication System (GTS)

4. Current and future developments: aim at using level 1 satellite data to analyse snow water equivalent (mass) → Require appropriate satellite mission and adequate observation operator
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• Soil moisture analysis
• Summary
A history of soil moisture analysis at ECMWF

➢ Nudging scheme (1995-1999): soil moisture increments $\Delta x \ (\text{m}^3\text{m}^{-3})$:

$$\Delta x = \Delta t \ D \ C_v(q^a - q^b)$$

- $D$: 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)

$$\Delta x = \alpha (T^a - T^b) + \beta (R^a - R^b)$$

- $\alpha$ and $\beta$: optimal coefficients
- OI soil moisture analysis based on a dedicated screen level parameters (T2m Rh2m) analysis

➢ Simplified Extended Kalman Filter (SEKF), Nov 2010-2019

- Motivated by better using T2m, RH2m
- Opening the possibility to assimilate satellite data related to surface soil moisture

➢ EDA-SEKF (since 2019)

- Use the Ensemble Data Assimilation to compute the SEKF Jacobians
ECMWF Soil Analysis in the current operational IFS (cycle 46r1)

Ensemble Data Assimilation (EDA)

EDA Jacobians
T2m, RH2m
& soil moisture
Background

NWP Forecast
Coupled Land-Atmosphere

Soil Analysis (SEKF)
SM1, SM2, SM3

Screen level analysis
(2D-OI)

T_2m RH_2m

\[ \sigma_{T2m} = 2K \quad \sigma_{RH2m} = 10\% \]

In situ Observations
T_2m RH_2m

Land initial conditions

Soil Analysis (SEKF)
SM1, SM2, SM3

\[ \sigma_{O-T2M} = 1K \quad \sigma_b = 0.01 m^3/m^3 \quad \sigma_{SMOS_NN} = 0.02 + 3*smos\epsilon \]
\[ \sigma_{O-RH2M} = 4\% \quad \sigma_{ASCAT} = 0.05 m^3/m^3 \]

Satellite
ASCAT SM
SMOS SM

SMOS Neural network
SMOS TB
SYNOP T2m, RH2m in situ data assimilated in a 2D-OI

Screen level observations are:
- T2m, two meter temperature
- RH2m, relative humidity (RH2m)

Diversity of Report types:
- Drifting buoys, automatic and manual stations on ships, etc..
- Automatic and manual SYNOP stations, METAR (METeorological Airport Reports), etc...

The output of the 2D-OI, the analysed T2m, TH2m, is used as input of the soil analysis
Soil moisture satellite observations

Active microwave data:
**ASCAT**: Advanced Scatterometer
C-band (5.6GHz) backscattering coefficient
EUMETSAT Operational mission

Passive microwave data:
**SMOS**: Soil Moisture & Ocean Salinity (2009-)
L-band (1.4 GHz) Brightness Temperature
ESA Earth Explorer, edicated soil moisture mission

Data from **SMAP** (Soil Moisture Active Passive),
NASA soil moisture mission, also available

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ASCAT soil moisture (m$^3$m$^{-3}$)

SMOS Brightness temperature (K)

Stdev(O-B) Sept. 2013
Simplified EKF soil moisture analysis

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

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

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

Used at ECMWF (operations and ERA5), DWD, UKMO

Observations used at ECMWF:
For operational NWP:
- Conventional SYNOP pseudo observations (analysed T2m, RH2m)
- Satellite: MetOp-A/B/C ASCAT and SMOS soil moisture

The simplified EKF is used to corrects the soil moisture trajectory of the Land Surface Model

→ See KF lecture from M Bonavita on Tuesday

Drusch et al., GRL, 2009
de Rosnay et al., ECMWF News Letter 127, 2011
de Rosnay et al., QJRMS, 2013
Simplified EKF soil moisture analysis

\[ \mathbf{x}_a = \mathbf{x}_b + K (\mathbf{y} - \mathbf{H}[\mathbf{x}_b]) \]

Elements of the SEKF for each individual grid point in the case of:
- Assimilation of 4 observations: T2m, RH2m, ASCAT_{sm}, SMOS_{sm}
- State vector \( \mathbf{x} \): volumetric soil moisture (SM) of the model layers, l1, l2, l3 (in m^3/m^3)

Control vector

\[
\mathbf{x}_{b(t)} = \begin{bmatrix}
SM_{l1(t)} \\
SM_{l2(t)} \\
SM_{l3(t)}
\end{bmatrix}
\]

Observations vector

\[
y(tobs) = \begin{bmatrix}
T_{2m} \\
RH_{2m} \\
ASCAT_{sm} \\
SMOS_{sm}
\end{bmatrix}
\]

Observations operator

\[
\mathbf{H}[x_{b(t)}] = \begin{bmatrix}
T_{2m} \\
RH_{2m} \\
ASCAT_{sm} \\
SMOS_{sm}
\end{bmatrix}
\]

Observation error

\[
\begin{pmatrix}
1^2 & 0 & 0 & 0 \\
0 & 4^2 & 0 & 0 \\
0 & 0 & 0.05^2 & 0 \\
0 & 0 & 0 & (0.02 + 3 smos\varepsilon)^2
\end{pmatrix}
\]

Background error

\[
\begin{pmatrix}
0.01^2 & 0 & 0 \\
0 & 0.01^2 & 0 \\
0 & 0 & 0.01^2
\end{pmatrix}
\]
Simplified EKF soil moisture analysis (2010-2019)

Jacobians computation in Finite differences (until June 2019)

Estimated by finite differences by perturbing individually each component $x_j$ of the control vector $\mathbf{x}$ by a small amount $\delta x_j$. One perturbed model trajectory is computed for each control variable.

In the ECMWF soil analysis the perturbation size is set to $0.01\text{m}^3\text{m}^{-3}$.

$$H = \begin{bmatrix}
\frac{T_{2m\text{pert}1} - T_{2m}}{\delta SM_{l1}} & \frac{T_{2m\text{pert}2} - T_{2m}}{\delta SM_{l2}} & \frac{T_{2m\text{pert}3} - T_{2m}}{\delta SM_{l3}} \\
\frac{RH_{2m\text{pert}1} - RH_{2m}}{\delta SM_{l1}} & \frac{RH_{2m\text{pert}2} - RH_{2m}}{\delta SM_{l2}} & \frac{RH_{2m\text{pert}3} - RH_{2m}}{\delta SM_{l3}} \\
\frac{SM_{l1\text{pert}1} - SM_{l1}}{\delta SM_{l1}} & \frac{SM_{l1\text{pert}2} - SM_{l1}}{\delta SM_{l2}} & \frac{SM_{l1\text{pert}3} - SM_{l1}}{\delta SM_{l3}} \\
\frac{SM_{l2\text{pert}1} - SM_{l1}}{\delta SM_{l1}} & \frac{SM_{l2\text{pert}2} - SM_{l1}}{\delta SM_{l2}} & \frac{SM_{l2\text{pert}3} - SM_{l1}}{\delta SM_{l3}} \\
\frac{SM_{l3\text{pert}1} - SM_{l1}}{\delta SM_{l1}} & \frac{SM_{l3\text{pert}2} - SM_{l1}}{\delta SM_{l2}} & \frac{SM_{l3\text{pert}3} - SM_{l1}}{\delta SM_{l3}} 
\end{bmatrix}$$
Simplified EKF soil moisture analysis (since June 2019)

**Jacobians computation based on the Ensemble Data Assimilation (EDA)**
Use the EDA spread to compute covariances and the SEKF Jacobians

In the case of assimilation of four observations T2m, RH2m, ASCAT, SMOS:

\[
H = \begin{bmatrix}
\text{Covar}(T_{2m}, \text{SM}_1) / \text{Var}(\text{SM}_1) & \text{Covar}(T_{2m}, \text{SM}_2) / \text{Var}(\text{SM}_2) & \text{Covar}(T_{2m}, \text{SM}_3) / \text{Var}(\text{SM}_3) \\
\text{Covar}(RH_{2m}, \text{SM}_1) / \text{Var}(\text{SM}_1) & \text{Covar}(RH_{2m}, \text{SM}_2) / \text{Var}(\text{SM}_2) & \text{Covar}(RH_{2m}, \text{SM}_3) / \text{Var}(\text{SM}_3) \\
\text{Covar}(\text{SM}_1, \text{SM}_1) / \text{Var}(\text{SM}_1) & \text{Covar}(\text{SM}_1, \text{SM}_2) / \text{Var}(\text{SM}_2) & \text{Covar}(\text{SM}_1, \text{SM}_3) / \text{Var}(\text{SM}_3) \\
\text{Covar}(\text{SM}_2, \text{SM}_1) / \text{Var}(\text{SM}_1) & \text{Covar}(\text{SM}_2, \text{SM}_2) / \text{Var}(\text{SM}_2) & \text{Covar}(\text{SM}_2, \text{SM}_3) / \text{Var}(\text{SM}_3) \\
\text{Covar}(\text{SM}_3, \text{SM}_1) / \text{Var}(\text{SM}_1) & \text{Covar}(\text{SM}_3, \text{SM}_2) / \text{Var}(\text{SM}_2) & \text{Covar}(\text{SM}_3, \text{SM}_3) / \text{Var}(\text{SM}_3)
\end{bmatrix}
\]

\[
\rho = \begin{bmatrix}
\rho_1 & \rho_2 & \rho_3 \\
\rho_1 & \rho_2 & \rho_3 \\
\rho_1 & \rho_2 & \rho_3 \\
\rho_1 & \rho_2 & \rho_3
\end{bmatrix}
\]

with \( i \) soil layer index, \( \rho_i = 1/[1+ (i-1) \alpha_{\text{sekf}}] \) and \( \alpha_{\text{sekf}} = 0.6 \) tapering coefficient
Soil moisture increments: Case study with ASCAT, T2m, RH2m

Volumetric Soil Moisture increments (m³/m³) (accumulated) 25-30 June 2013

Vertically integrated Soil Moisture increments (stDev in mm)

<table>
<thead>
<tr>
<th></th>
<th>SYNOP</th>
<th>ASCAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>0.68</td>
<td>1.43</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1.48</td>
<td>0.68</td>
</tr>
<tr>
<td>Layer 3</td>
<td>4.28</td>
<td>0.46</td>
</tr>
</tbody>
</table>

ASCAT more increments than SYNOP at surface
SYNOP give more increments at depth
⇒ For 12h DA window, link obs to root zone stronger for T2m,RH2m than for surface soil moisture observations
Soil analysis for NWP: impact on the atmospheric forecast

- Test with no soil Analysis (Open Loop land)
- Reference with 2013 version of soil analysis
- NWP with current surface analysis (reduced obs error compared to 2013)

→ Very large impact of soil moisture initialisation on near-surface weather forecast
Summary on soil moisture analysis

- Significant **impact** of soil moisture analysis on low level atmospheric forecasts

- **Approaches**: 1D-OI (Météo-France, ECMWF ERA-I); SEKF (DWD, ECMWF, UKMO); SEKF-EDA (ECMWF), **Offline Land Surface Model (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 NWP & EUMETSAT H-SAF), **SMOS** soil moisture (ECMWF)
Summary

➢ Most NWP centres analyse soil moisture and/or snow depth
➢ Variety of DA methods for snow and soil moisture at ECMWF and other NWP centres
➢ Land Data Assimilation Systems: run separately from the atmospheric data assimilation, but first guess forecast is coupled → weakly coupled assimilation, coupling enhanced with SEKF-EDA
➢ Longer term: coupling with river routing
Bibliography

- de Rosnay P., Isaksen L., Dahoui M.: Snow data assimilation at ECMWF, ECMWF Newsletter no 143, article pp 26-31, Spring 2015
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