ECMWF Data Assimilation Training course
11-15 March 2019

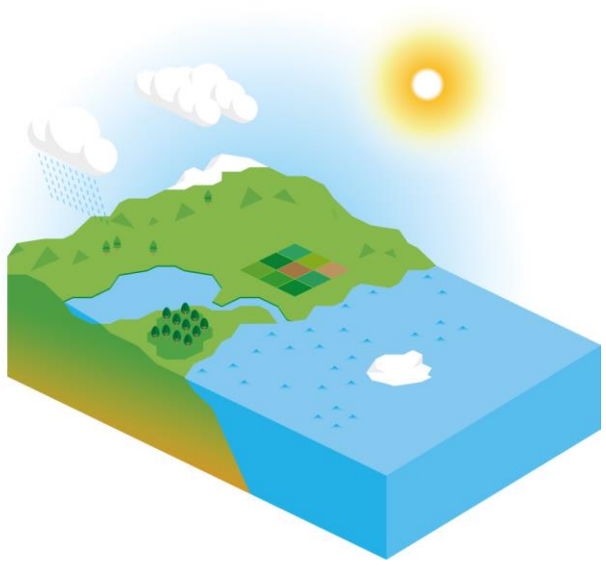
Coupled land-atmosphere data assimilation

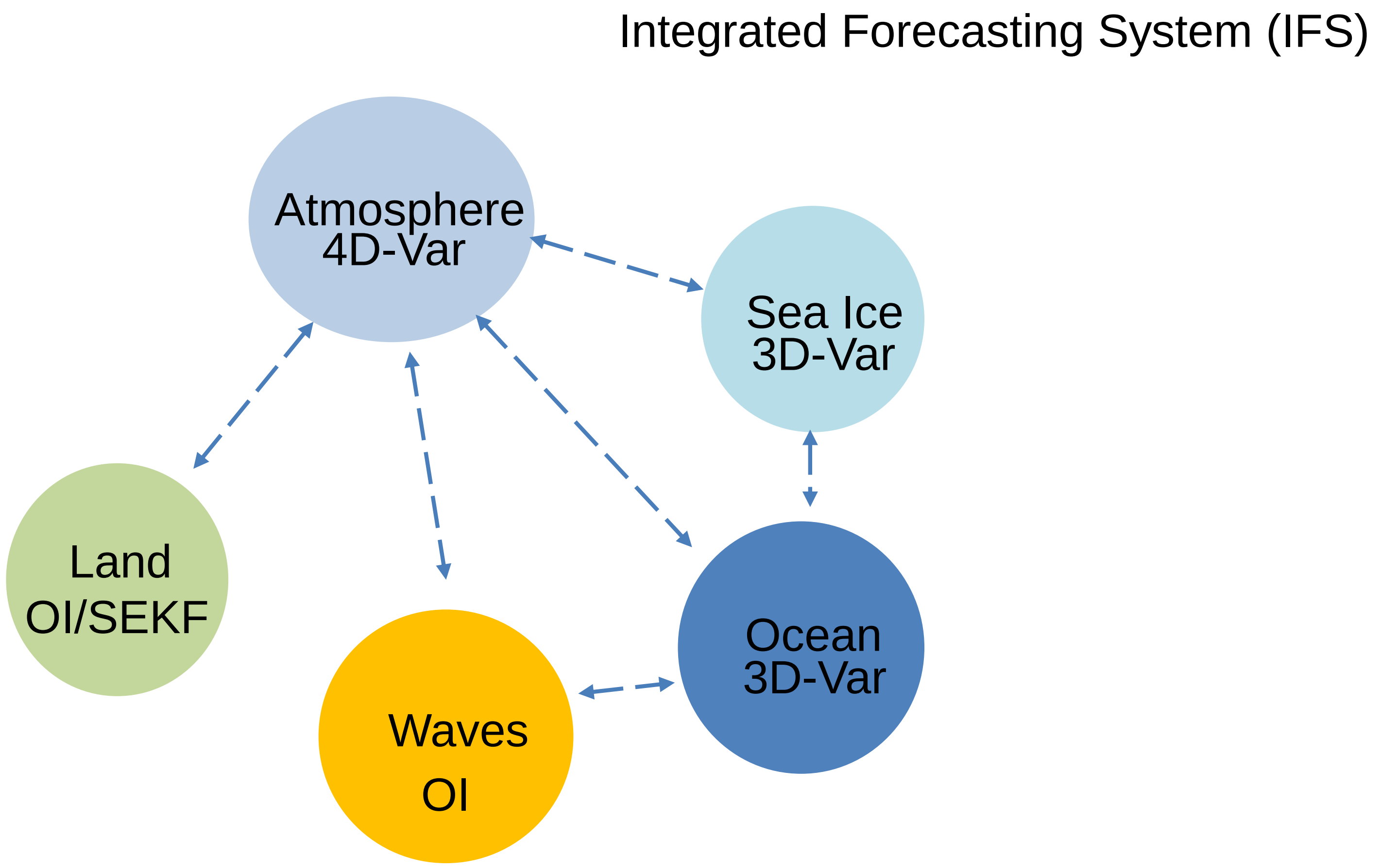
Patricia de Rosnay

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

Penny et al., 2017 Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations. World Meteorol. Org. (WMO), WWRP 2017-3

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

- In the next assimilation windows -> weakly coupled data assimilation (WCDA)
  - i.e.: independent DA for all components and interaction through model coupling

- During the data assimilation window → strongly coupled data assimilation
  - Multiple systems approach (e.g. outer loop coupling): QuasiSCDA
  - Single Integrated system: SCDA

Coupled assimilation continuum

- No coupling

WCDA

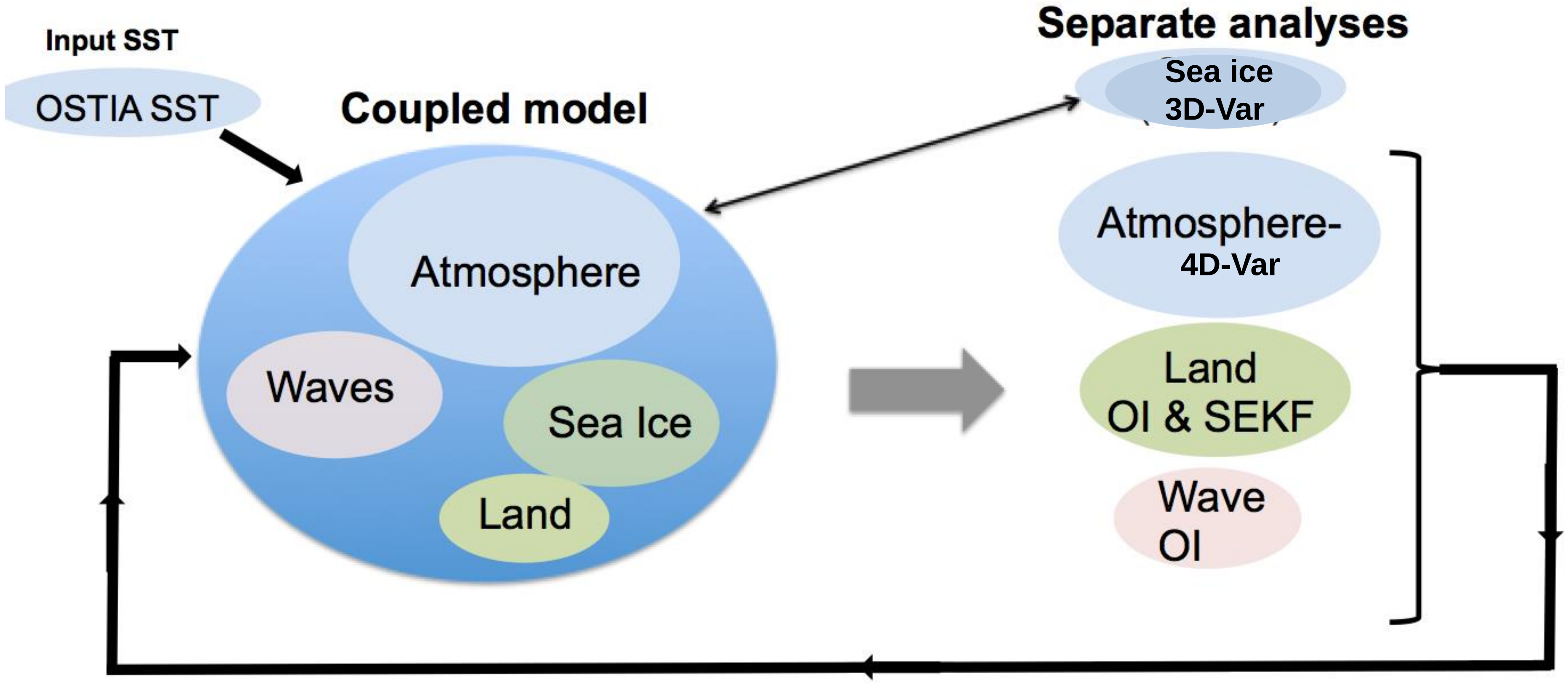
QuasiSCDA

\+ Full coupling

Weakly Coupled Data Assimilation | **Strongly coupled Data Assimilation**

Current operational NWP system at ECMWF

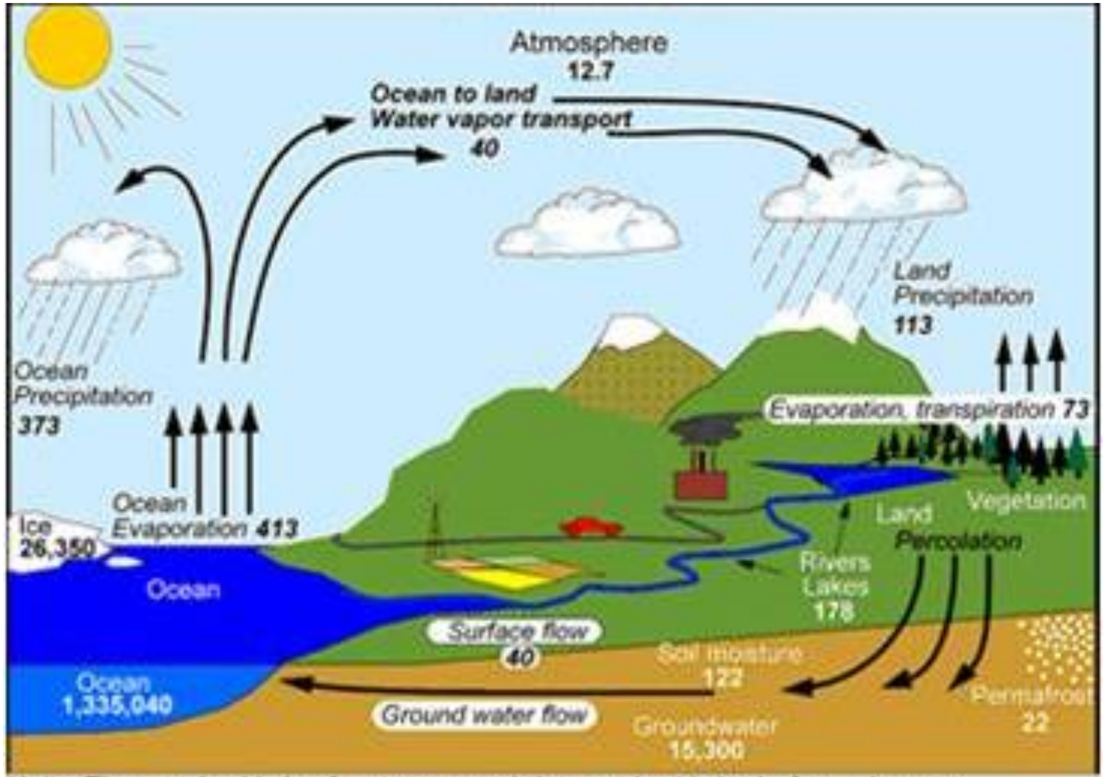
Weakly coupled land-atmosphere-wave and sea ice assimilation



Ocean and sea ice DA → H Zuo
Coupled DA -> P. Browne
Reanalysis -> D. Schepers

Coupled land-atmosphere data assimilation

Image: Trenberth et al J. Hydrometeorol. 2007



Units: Thousand cubic km for storage, and thousand cubic km/yr for exchanges

Weakly land-atmosphere CDA

Used for reanalysis (ERA5) & NWP

- 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 land analysis without the expensive 4D-Var component

Introduction: Land Surface Data Assimilation (LDAS)

Snow depth

- Methods: Cressman (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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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 ρ_s

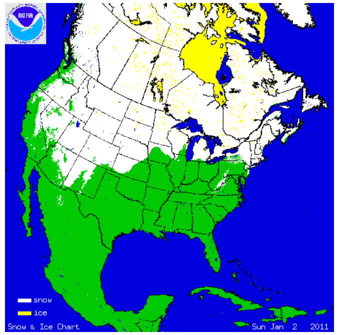
} **Prognostic variables**

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.



Snow cover observations

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

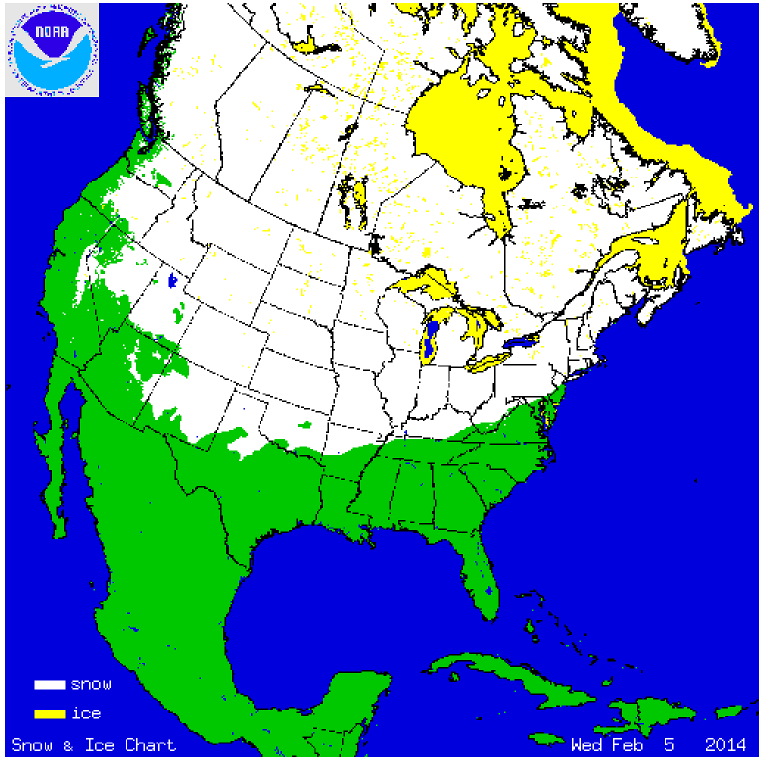
Data used at ECMWF:

- **4 km product** (NWP, ERA5)

Latency:

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

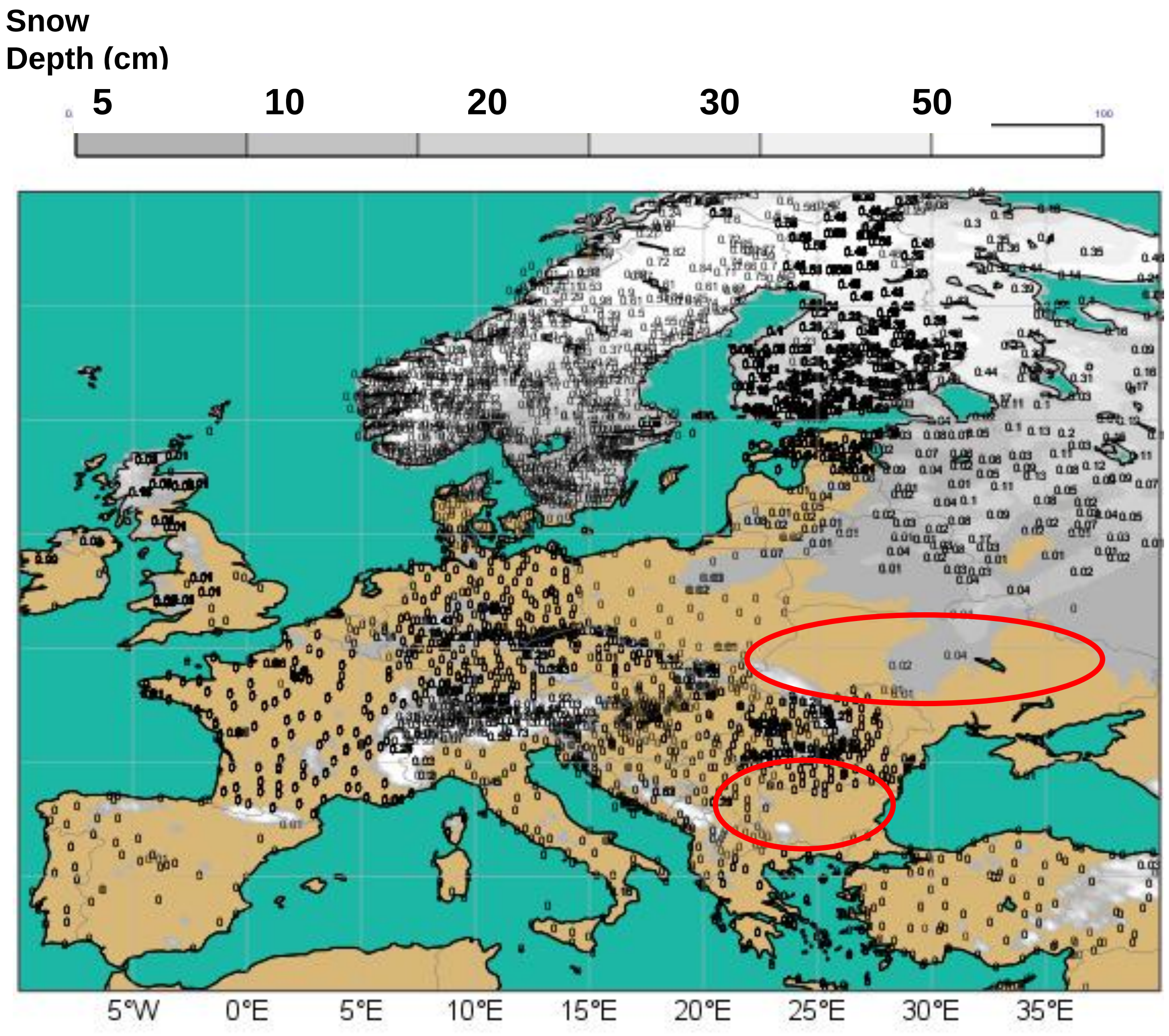
NOAA/NESDIS
IMS Snow extent data



http://nsidc.org/data/g02156.html

Snow Observations

Snow SYNOP and National Network data in Europe



15 Dec 2017

In general, good coverage in Europe, but …

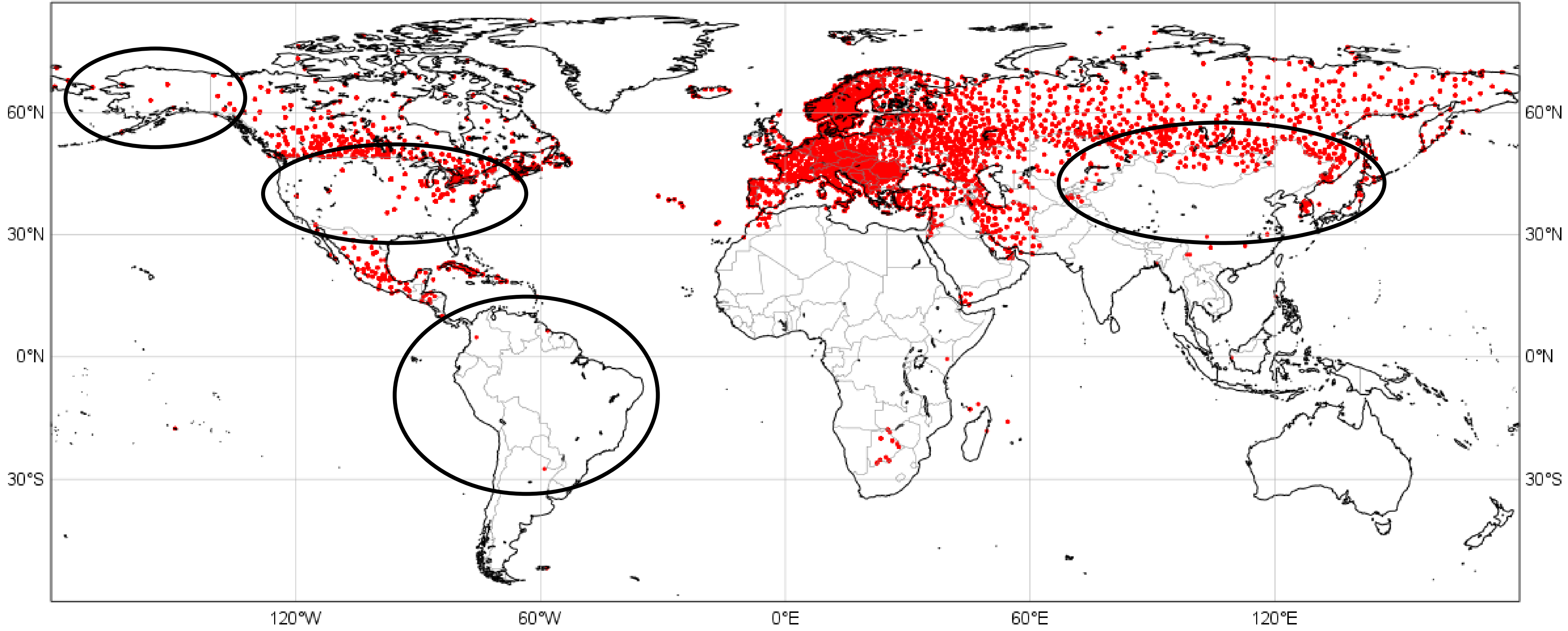
- Zero snow depth reporting is an issue with some countries providing observations only when snow depth > zero (e.g. Ukraine)
- Still area with relatively few snow depth reports

In situ snow depth observations

GTS Snow depth availability

SYNOP TAC + SYNOP BUFR + national BUFR data

Status on 10-15 December **2013**



In situ snow depth observations

GTS Snow depth availability

SYNOP TAC + SYNOP BUFR + national BUFR data

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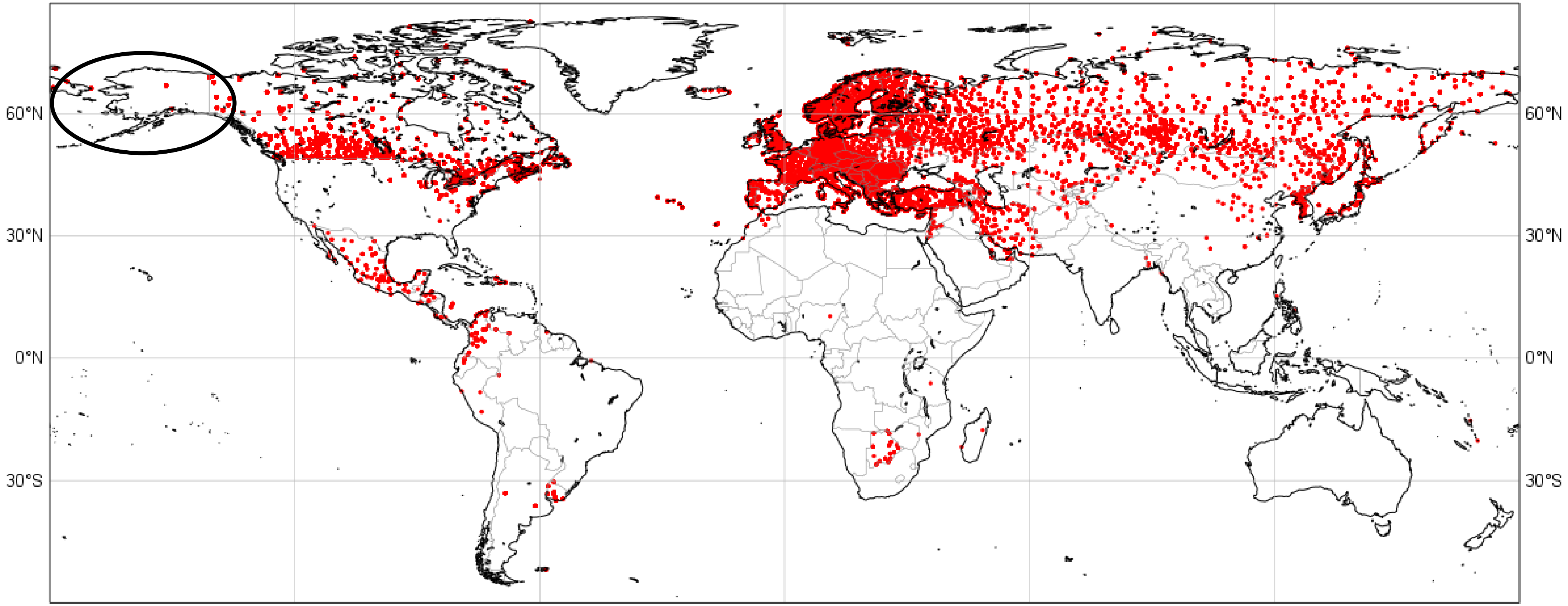


See more on snow DA and observations in de Rosnay et al, ECMWF Newsletter article, issue 143, 2015

Snow depth Optimal Interpolation

Based on Brasnett, j appl. Meteo. 1999

1. Observed first guess departure Δf_i are computed from the interpolated background at each observation location i.

2. Analysis increments ΔS_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) $p(i) = \sigma^2_b \cdot \mu(i,k)$

P : correlation coefficient matrix of background field error between all pairs of observations (N × 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 × N observations):

$\mathbf{R} = \sigma^2_o \times \mathbf{I}$

with and σ_b = 3cm the standard deviation of background errors, σ_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):

$$\mu(i_1,i_2) = \left(1 + \frac{r_{i_1 i_2}}{Lx}\right)\exp\left(-\left[\frac{r_{i_1 i_2}}{Lx}\right]\right).\exp\left(-\left[\frac{z_{i_1 i_2}}{Lz}\right]^2\right)$$

Lz; vertical length scale: 800m, **Lx:** horizontal length scale: 55km
$r_{i1,i2}$ and $Z_{i1,i2}$ the horizontal and vertical distances between points i_1 and i_2

Quality Control: reject observation if $\Delta S_n > Tol\ (\sigma_b^2 + \sigma_o^2)^{1/2}$ with Tol = 5
→Observation rejected if first guess departure larger than 25 cm for insitu (and 42cm 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 :

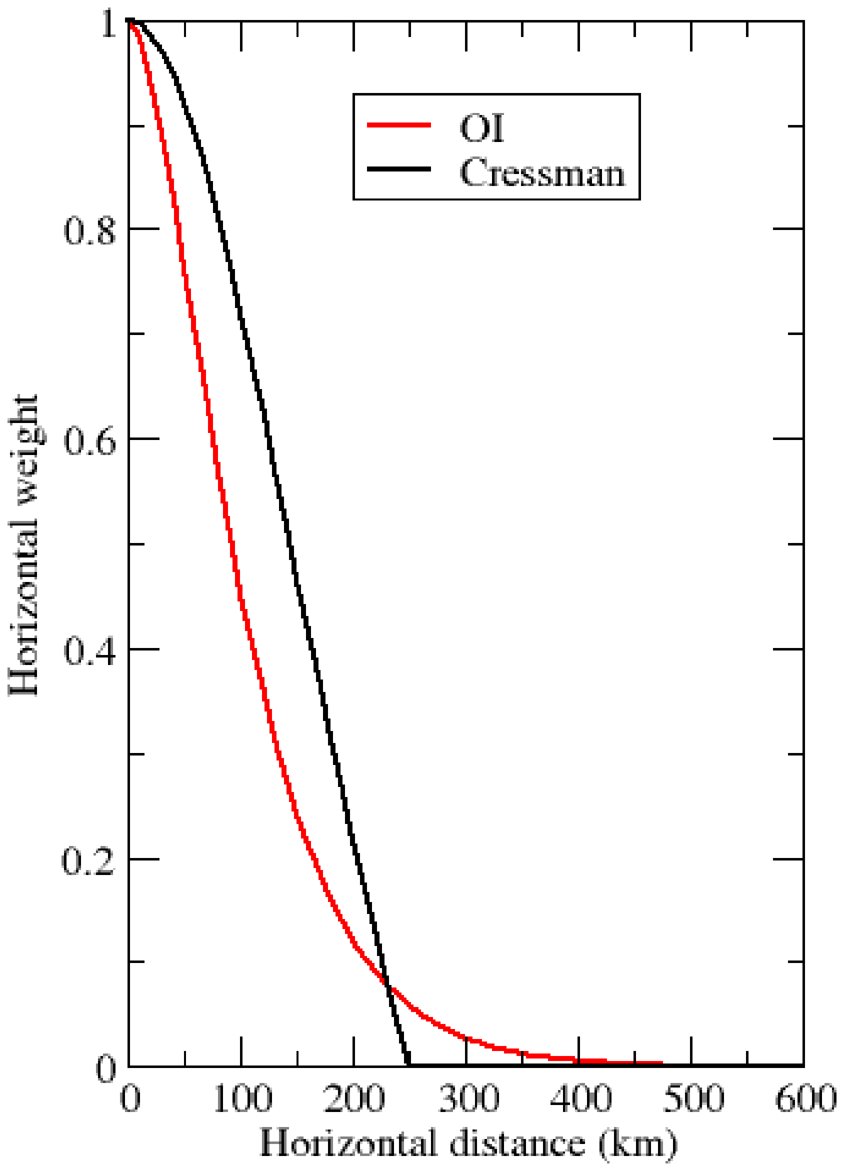
$$\Delta S_k^a = \sum_{i=1}^{N} w_i \times \Delta f_i$$

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.

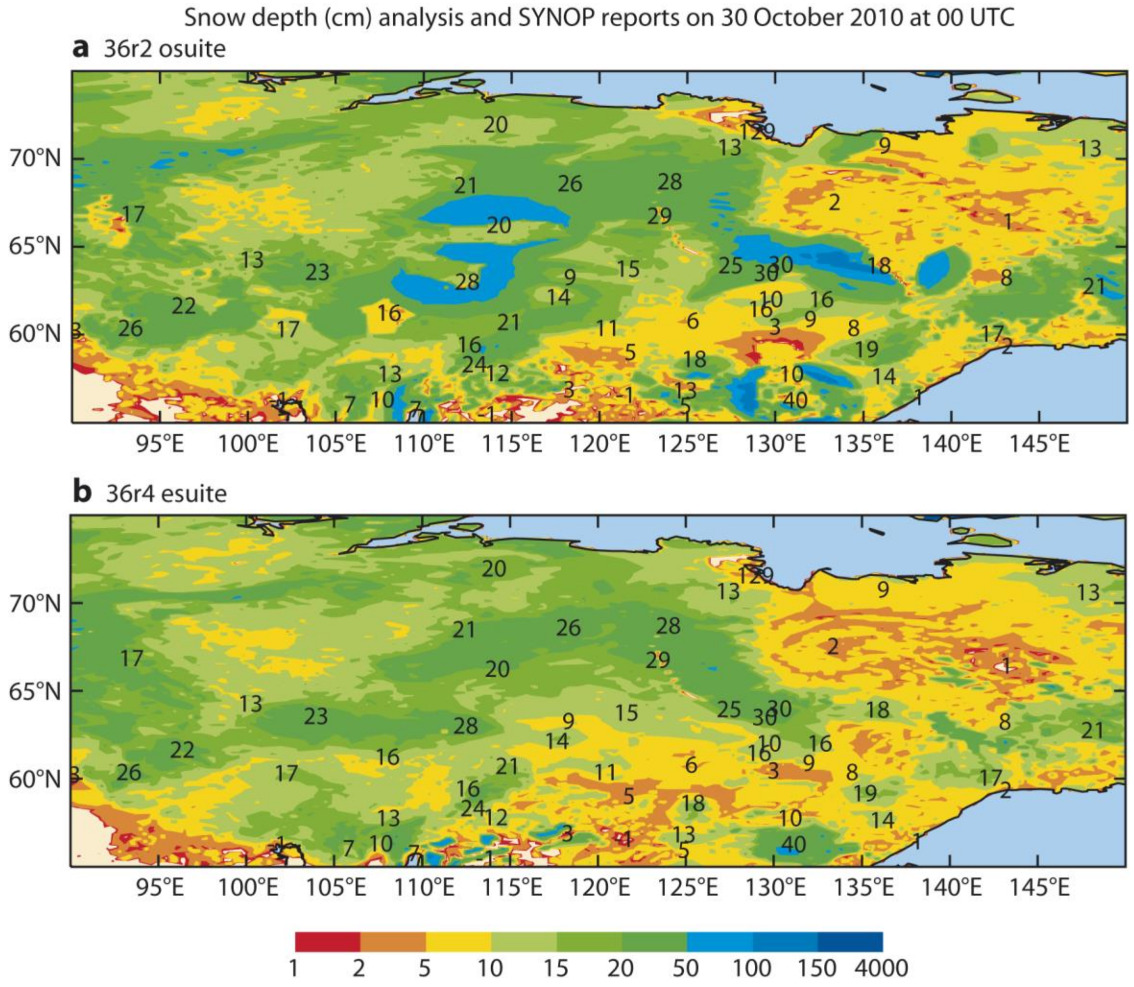
Structure function



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

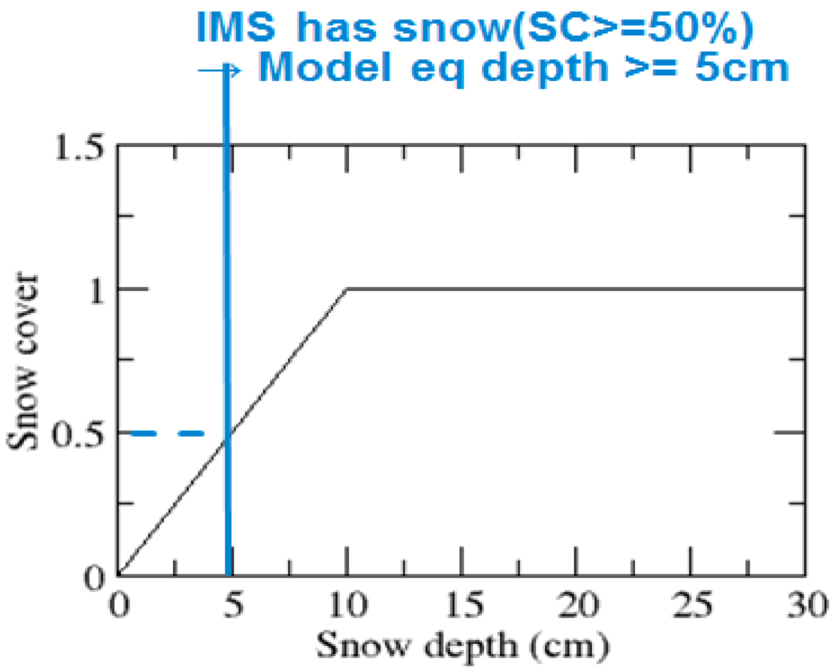
- IMS snow cover (SC) means SC>50%
- But no quantitative information on snow depth
- Relation snow cover (SC)/Snow Depth (SD): SC=50% corresponds to SD=5cm
- Previously: direct insertion of 10cm when IMS has snow & model has no snow
- Issues with overestmated snow
- IFS revision for current cycle: assimilate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

Revised Nov 2013 (IFS 40 r1 and 41r1)

Fst Guess / NESDIS	Snow	No Snow
Snow	x	**DA** 5cm
No Snow	DA	DA

Error specifications:

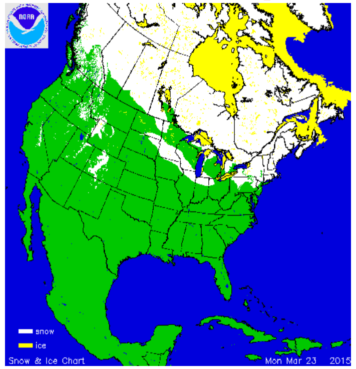
BG:	σ_b	= 3cm
SYNOP	σ_{SYNOP}	= 4cm
IMS	σ_{ims}	= 8cm



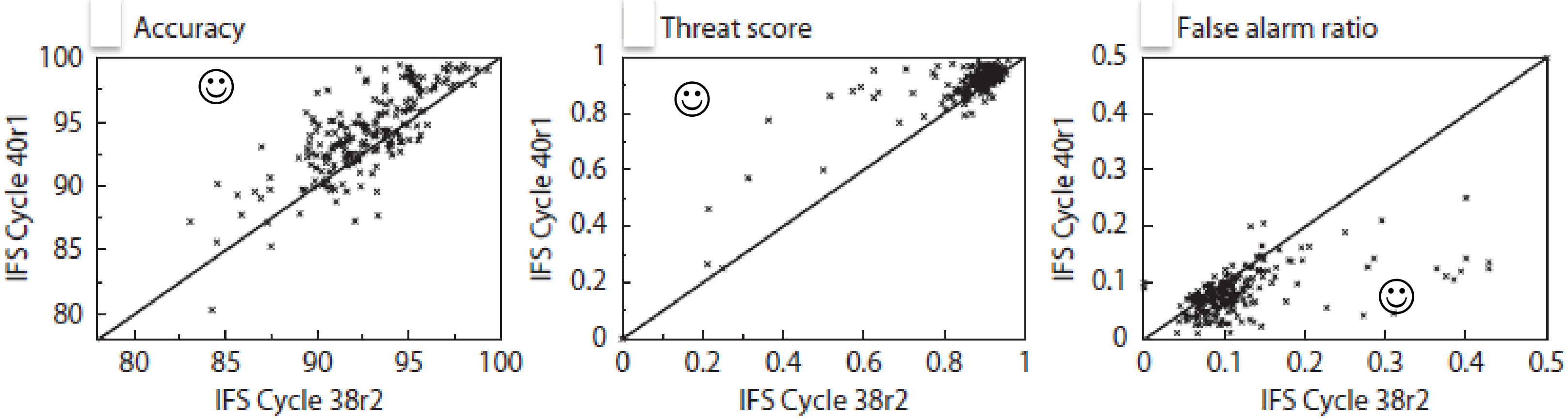
Model relation between SC and SD

Snow analysis: Forecast impact

Revised IMS snow cover data assimilation (2013)



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



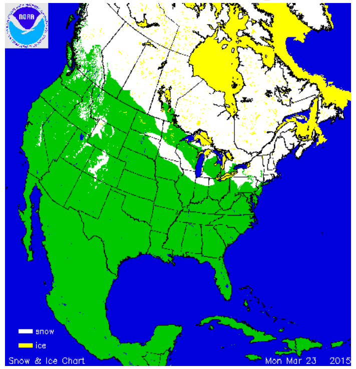
	Snow observed	No snow observed
Snow in analysis	a Hits	b False alarm
No snow in analysis	c Misses	d Correct no snow

The following scores are used for the evaluation:

- Accuracy = a+d / (a+b+c+d)
- False alarm ratio = b / (a+b)
- Threat score = a / (a+b+c)

Snow analysis: Forecast impact

Revised IMS snow cover data assimilation (2013)



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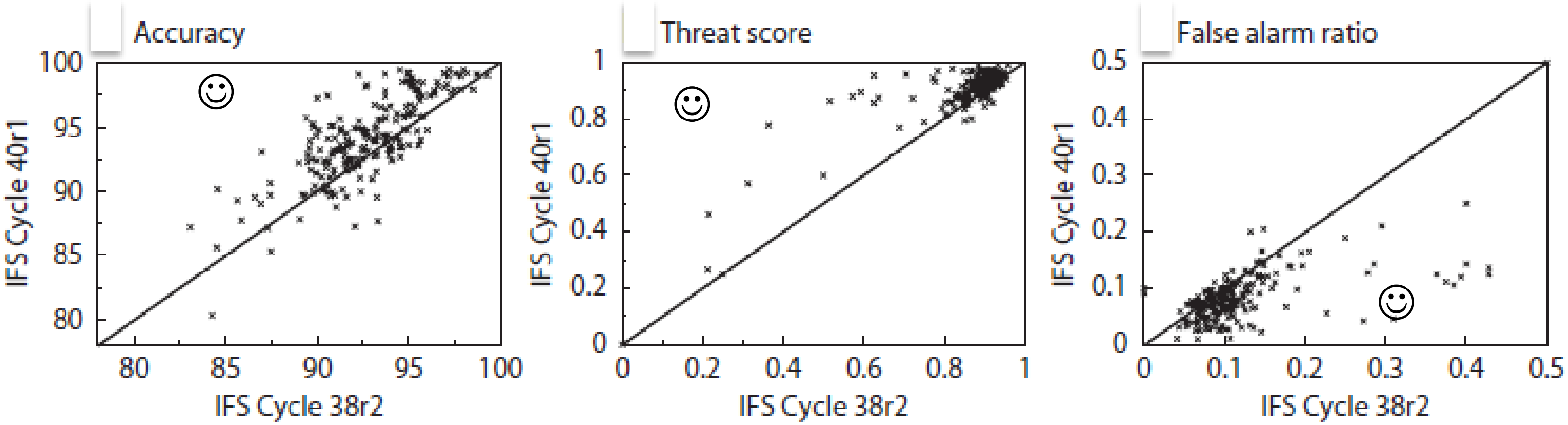
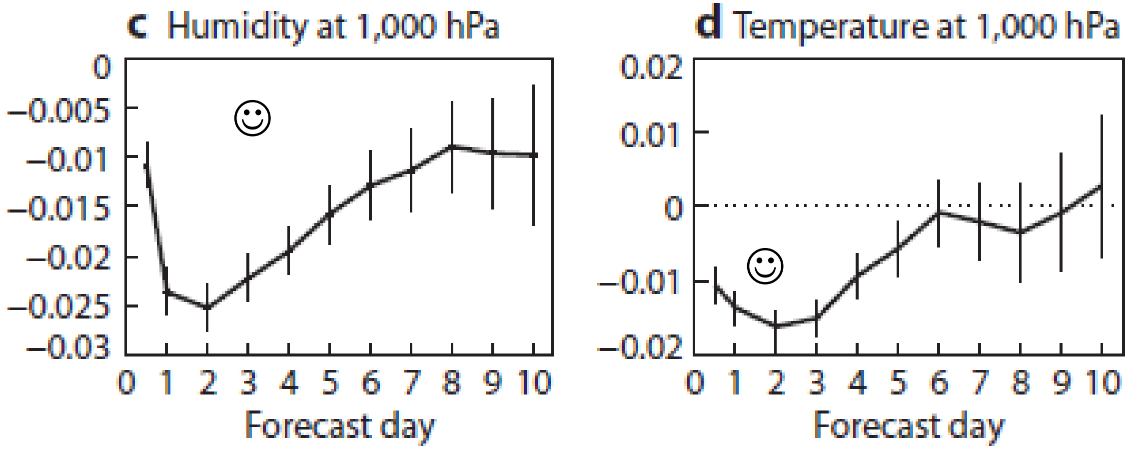


Impact on atmospheric forecasts
October 2012 to April 2013 (RMSE new-old)



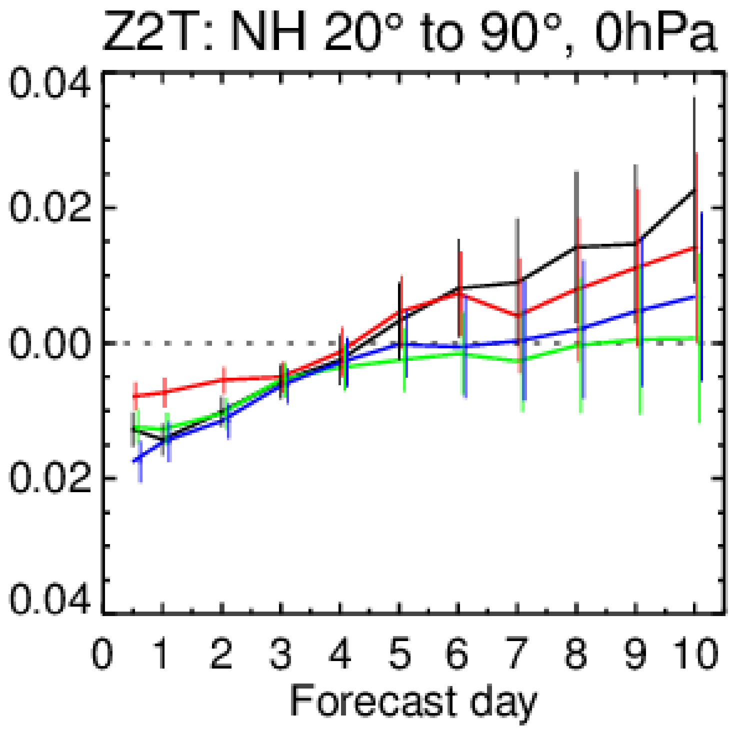
→ Consistent improvement of snow and atmospheric forecasts

de Rosnay et al., ECMWF Newsletter 143, Spring 2015

Observing System Experiments

Winter 2014-2015 (December to April) - Assess the impact of the snow observing system

Expts	SYNOP	National Data	IMS snow cover
0- OL (no snow data assimilation)			
1- Snow DA: SYNOP+IMS	✓		✓
2- Snow DA: SYNOP+Nat (all in situ)	✓	✓	
3- Snow DA SYNOP+Nat+IMS (all)	✓	✓	✓

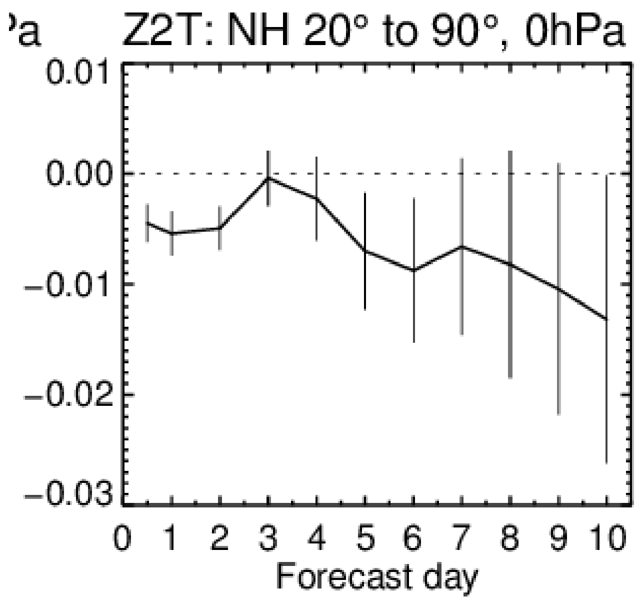


Impact on T2m Forecasts:
Normalized RMSE for T2m FC difference compared to the reference (OL)

SYNOP+IMS (1-0)
SYNOP+Nat (2-0)
SYNOP+Nat+IMS (3-0) -> oper

Best T2m Forecast when all observations, combining in situ and IMS, are assimilated.

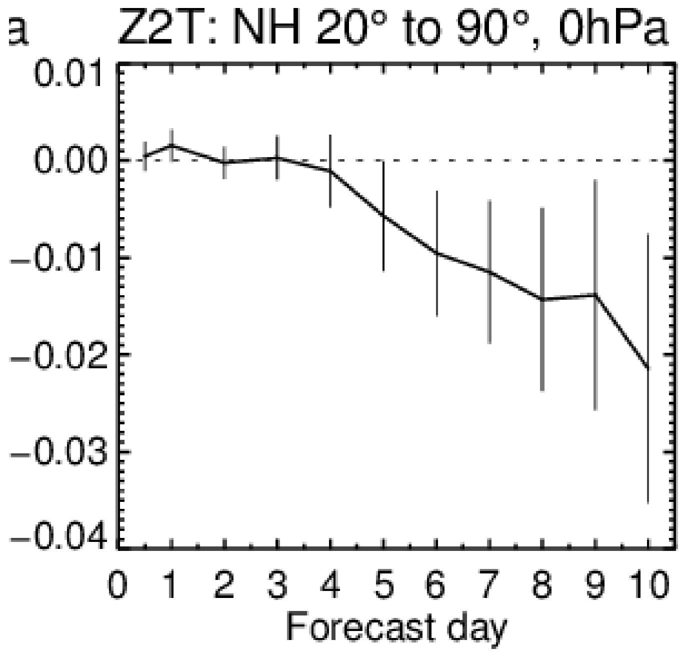
Impact of IMS snow cover assimilation (case 3-2)



All data assimilated (Synop+Nat+IMS)
compared to all in situ data assimilated (SYNOP+Nat)
-> Further T2m forecasts error reduction,
significant at short range

Impact of National data (case 3-1)

All data assimilated (SYNOP+Nat+IMS)
compared to SYNOP+IMS assimilation
-> Further T2m forecasts error reduction at medium range



Contribution & complementarities of each observation types to improve T2m forecasts at short and medium ranges

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 systems relies on relatively simple approaches (Cressman,OI)

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)
   - Future: 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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A history of soil moisture analysis at ECMWF

- **Nudging scheme (1995-1999): soil moisture increments Δx (m^3m^{-3}):**

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

D: nudging coefficient (constant=1.5g/Kg), Δt = 6h, q specific humidity
Uses upper air analysis of specific humidity
Prevents soil moisture drift in summer

- **Optimal interpolation 1D OI (1999-2010)**

$$\Delta x = \alpha \left(T^a - T^b\right) + \beta \left(Rh^a - Rh^b\right)$$

α and β : optimal coefficients
OI soil moisture analysis based on a dedicated screen level parameters (T2m Rh2m) analysis

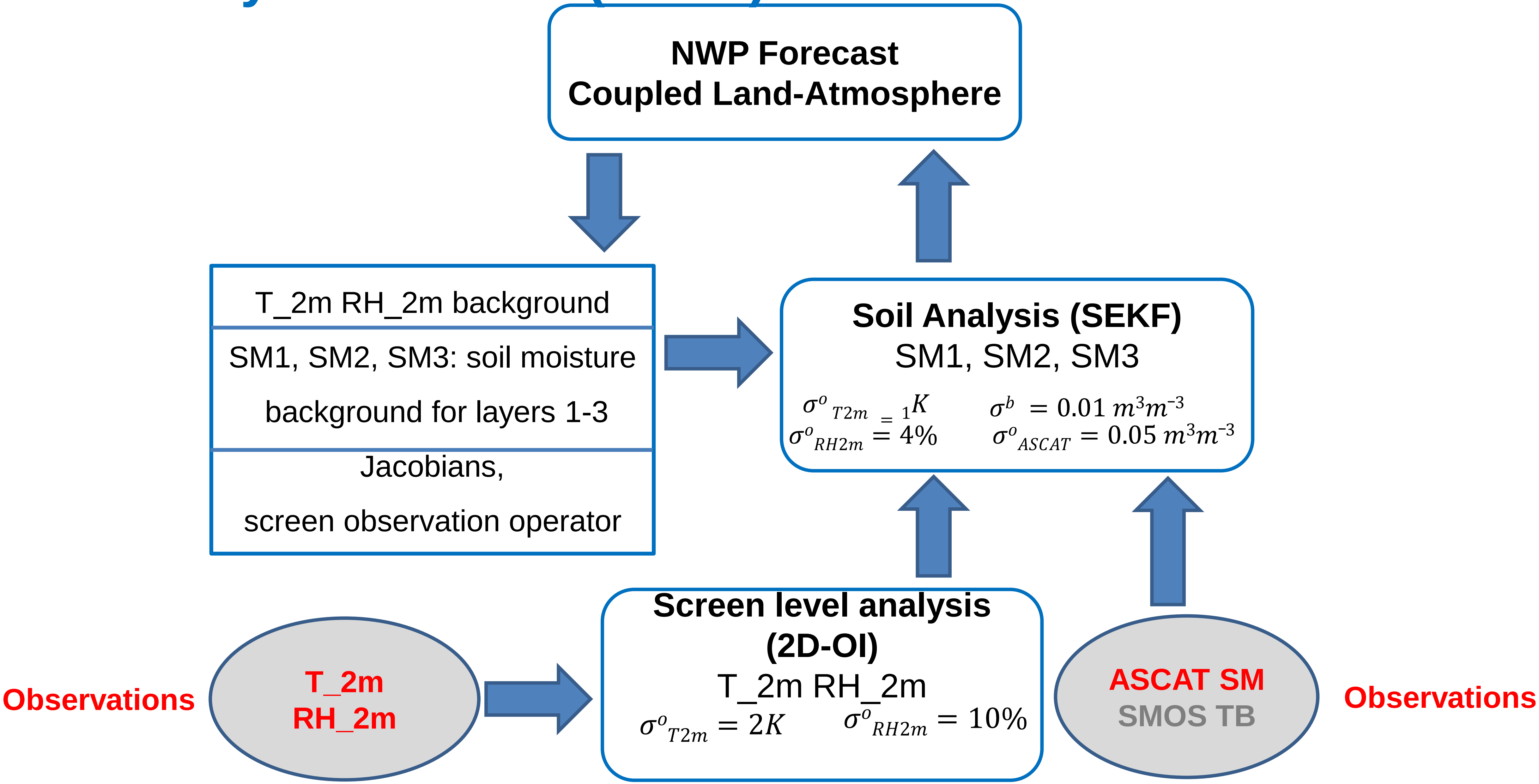
Mahfouf, ECMWF News letter 2000,
Douville et al., Mon Wea. Rev. 2000

- **Simplified Extended Kalman Filter (EKF), Nov 2010-2019**
  - 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

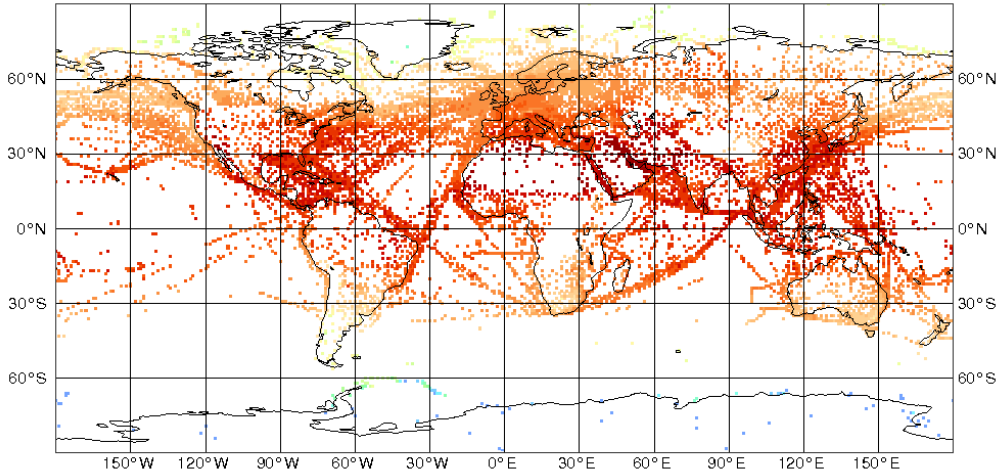
- **EDA-SEKF (June 2019)**
  - Use the Ensemble Data Assimilation to compute the SEKF Jacobians

Soil Analysis for NWP (SEKF)

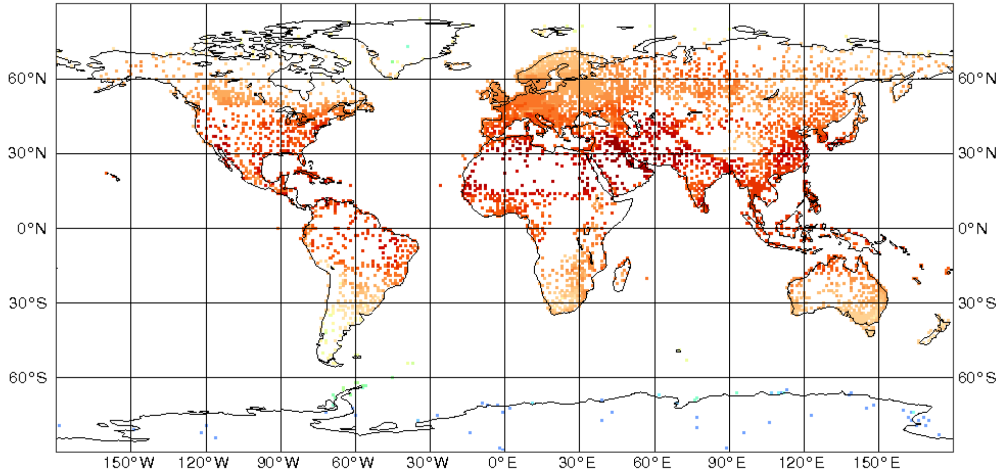


SYNOP T2m, RH2m in situ data assimilated in a 2D-OI

Ocean and Land observations



Used for Land Data Assimilation



Screen level observations are: two meter temperature and relative humidity. Observations are available on the GTS:

Diversity of Report types:

- Drifting buoys, automatic and manual stations on ships, etc..
- Automatic and manual SYNOP stations, METAR (METeorological Airport Reports), etc…

Analysed T2m, RH2m (output of the 2D-OI) is used as input of the soil analysis

Soil moisture satellite observations

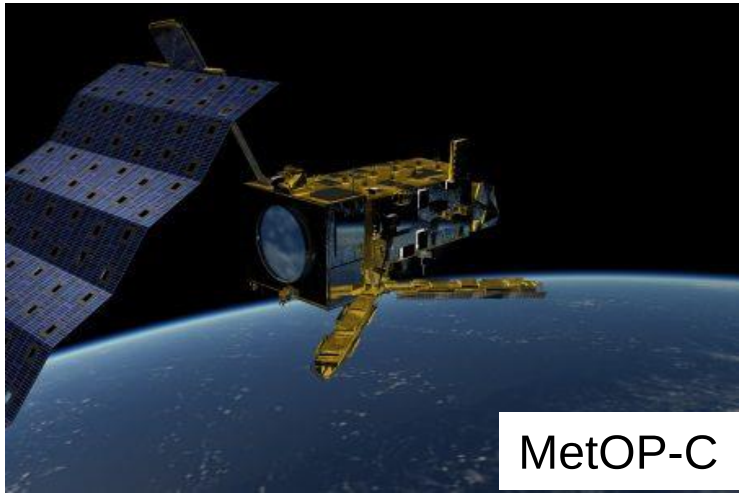
Active microwave data:

ASCAT: Advanced Scatterometer

On MetOP-A (2006-), MetOP-B (2012-), MetOP-C (2018-)

C-band (5.6GHz) backscattering coefficient

EUMETSAT Operational misison



MetOP-C

Passive microwave data:

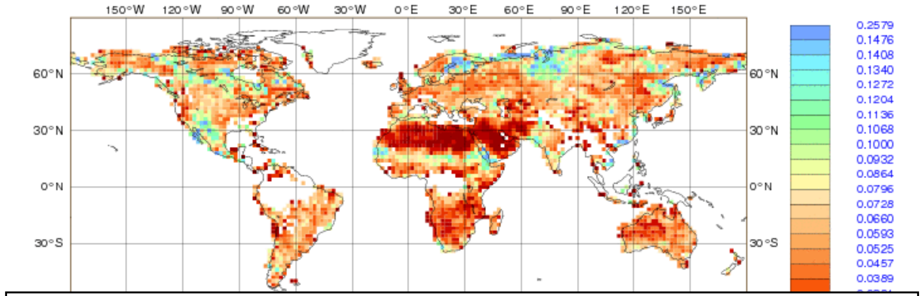
SMOS: Soil Moisture & Ocean Salinity (2009-)

L-band (1.4 GHz) Brightness Temperature

ESA Earth Explorer, edicated soil moisture mission

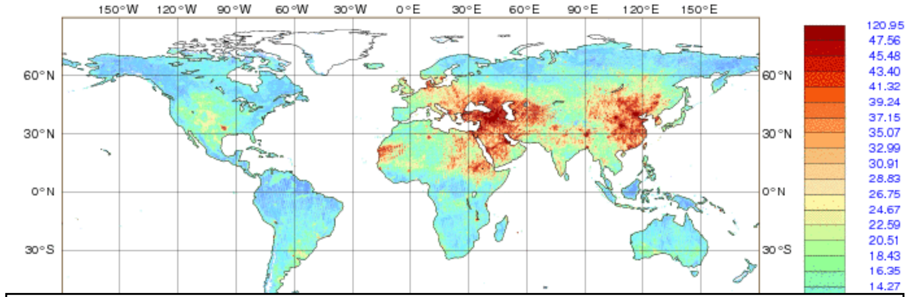
SMOS

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



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

Stdev(O-B)
Sept. 2013



SMOS Brightness temperature (K)

Simplifed EKF soil moisture analysis

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

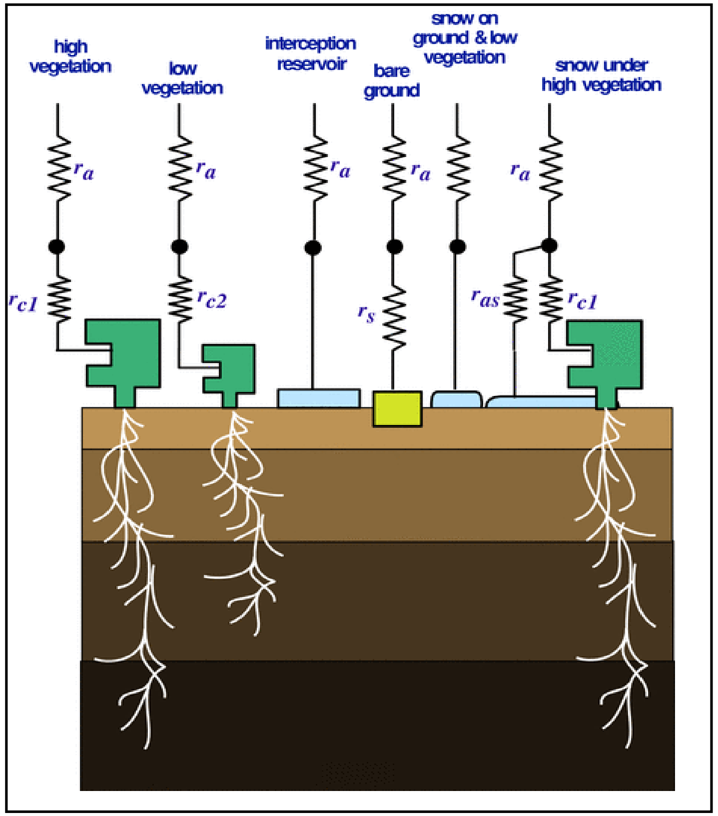
$$\boldsymbol{x}_a = \boldsymbol{x}_b + \boldsymbol{K}(\boldsymbol{y} - \mathcal{H}[\boldsymbol{x}_b])$$

$\boldsymbol{x}$ 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 $\mathcal{H}$), **P** and **R** (covariance matrices of background and observation errors).

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

→ See KF lecture from M Bonavita on Tuesday

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



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

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

Simplifed EKF soil moisture analysis

$$\mathbf{x_t^a = x_t^b + K\,(y_t - \mathcal{H}[x_t^b])}$$

Elements of the SEKF for each individual grid point in the case of assimilation of three observations T2m, RH2m, ASCAT:

Control vector

$$\mathbf{x}b_{(t)} = \begin{bmatrix} SM_{l1(t)} \\ SM_{l2(t)} \\ SM_{l3(t)} \end{bmatrix}$$

Observations vector

$$y_{(tobs)} = \begin{bmatrix} T_{2m} \\ RH_{2m} \\ ASCAT_{sm} \end{bmatrix} \begin{matrix} [K] \\ [\%] \\ [m^3/m^3] \end{matrix}$$

Observations operator

$$\mathcal{H}[x_b^t]) = \begin{bmatrix} T_{2m} \\ RH_{2m} \\ SM_{top} \end{bmatrix}$$

Background error

$$\mathbf{P} = \begin{bmatrix} 0.01^2 & 0 & 0 \\ 0 & 0.01^2 & 0 \\ 0 & 0 & 0.01^2 \end{bmatrix}$$

Observation error

$$\mathbf{R} = \begin{bmatrix} 1^2 & 0 & 0 \\ 0 & 4^2 & 0 \\ 0 & 0 & 0.05^2 \end{bmatrix}$$

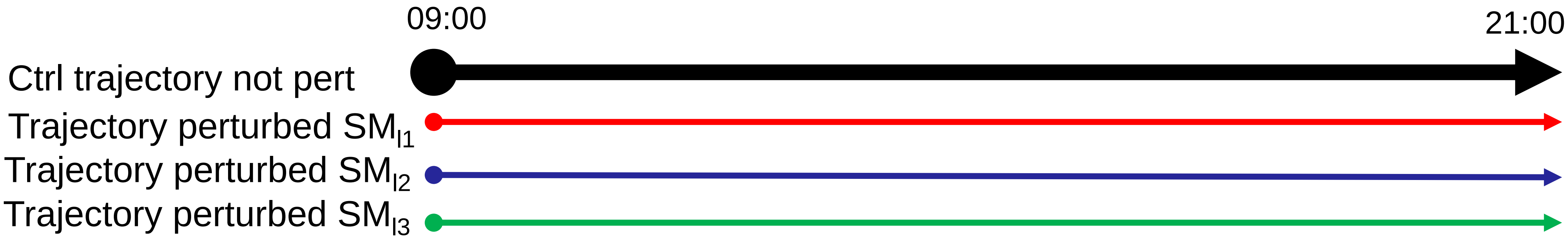
SM: volumetric soil moisture of the model layers in m3/m3

Simplifed EKF soil moisture analysis (2010-2019)

Jacobians computation in Finite differences (until June 2019)

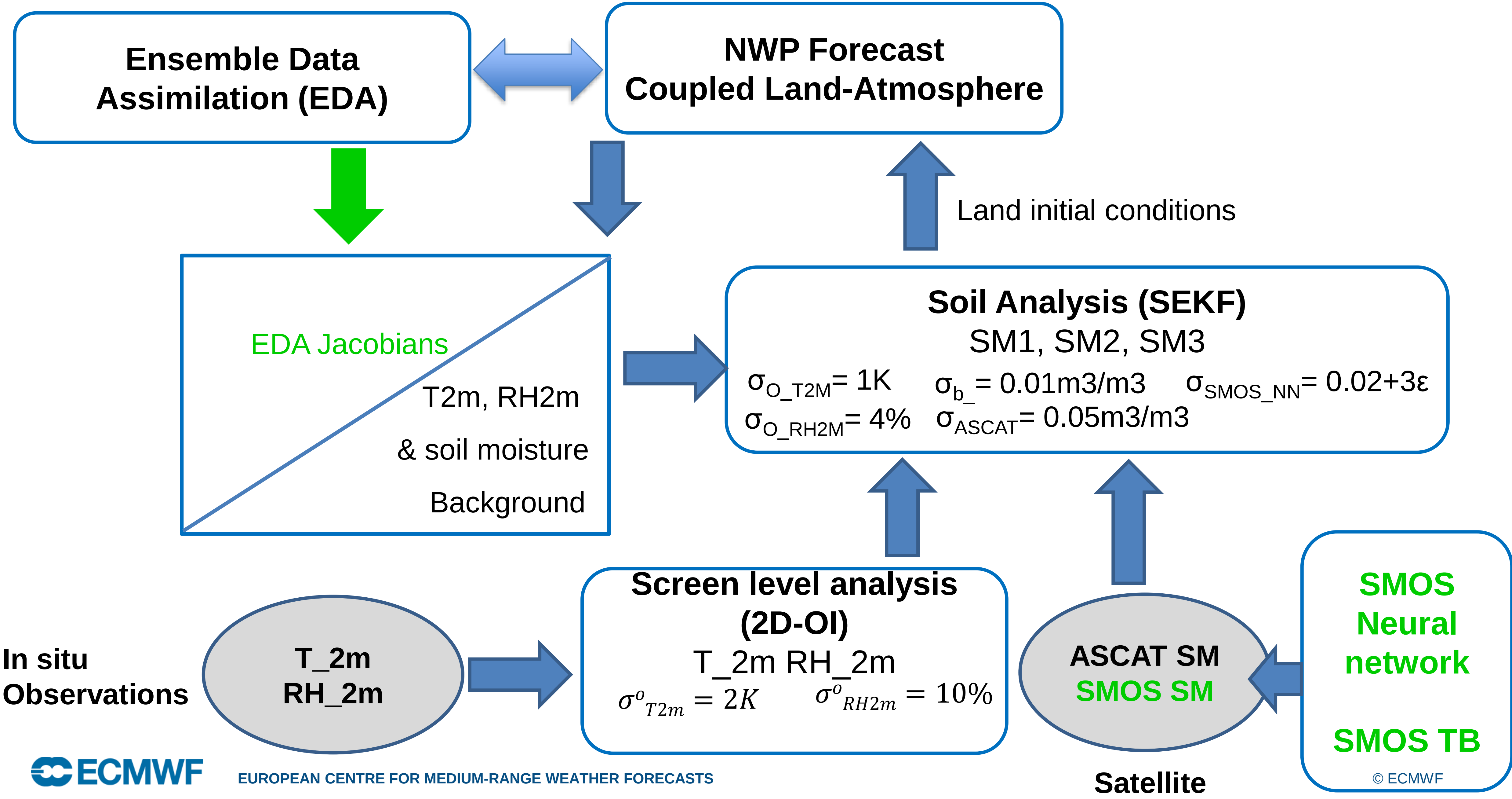
Estimated by finite differences by perturbing individually each component x_j of the control vector **x** by a small amount δx_j . One perturbed model trajectory is computed for each control valriable

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



$$H=\begin{bmatrix} \frac{T_{2m}pert1-T_{2m}}{\delta SM_{l1}} & \frac{T_{2m}pert2-T_{2m}}{\delta SM_{l2}} & \frac{T_{2m}pert3-T_{2m}}{\delta SM_{l3}} \\ \frac{RH_{2m}pert1-RH_{2m}}{\delta SM_{l1}} & \frac{RH_{2m}pert2-RH_{2m}}{\delta SM_{l2}} & \frac{RH_{2m}pert3-RH_{2m}}{\delta SM_{l3}} \\ \frac{SM_{l1}pert1-SM_{l1}}{\delta SM_{l1}} & \frac{SM_{l1}pert2-SM_{l1}}{\delta SM_{l2}} & \frac{SM_{l1}pert3-SM_{l1}}{\delta SM_{l3}} \end{bmatrix}$$

ECMWF Soil Analysis in IFS 46r1 (from June 2019)



Simplifed EKF soil moisture analysis (from June 2019)

Jacobians computation based on the EDA (from June 2019)

Use the Ensemble Data Assimilation (EDA) spread to compute the SEKF Jacobians

(in the case of assimilation of four observations T2m, RH2m, ASCAT, SMOS)

Single trajectory 09:00 → 21:00

$$H = \begin{bmatrix} \frac{Covar(T_{2m},SM_1)}{Var(SM_1)} & \frac{Covar(T_{2m},SM_2)}{Var(SM_2)} & \frac{Covar(T_{2m},SM_3)}{Var(SM_3)} \\ \frac{Covar(RH_{2m},SM_1)}{var(SM_1)} & \frac{Covar(RH_{2m},SM_2)}{Var(SM_2)} & \frac{Covar(RH_{2m},SM_3)}{Var(SM_3)} \\ \frac{Covar(SM_1,SM_1)}{var(SM_1)} & \frac{Covar(SM_1,SM_2)}{Var(SM_2)} & \frac{Covar(SM_1,SM_3)}{Var(SM_3)} \\ \frac{Covar(SM_1,SM_1)}{var(SM_1)} & \frac{Covar(SM_1,SM_2)}{Var(SM_2)} & \frac{Covar(SM_1,SM_3)}{Var(SM_3)} \end{bmatrix} \circ \begin{bmatrix} \rho_1 & \rho_2 & \rho_3 \\ \rho_1 & \rho_2 & \rho_3 \\ \rho_1 & \rho_2 & \rho_3 \\ \rho_1 & \rho_2 & \rho_3 \end{bmatrix}$$

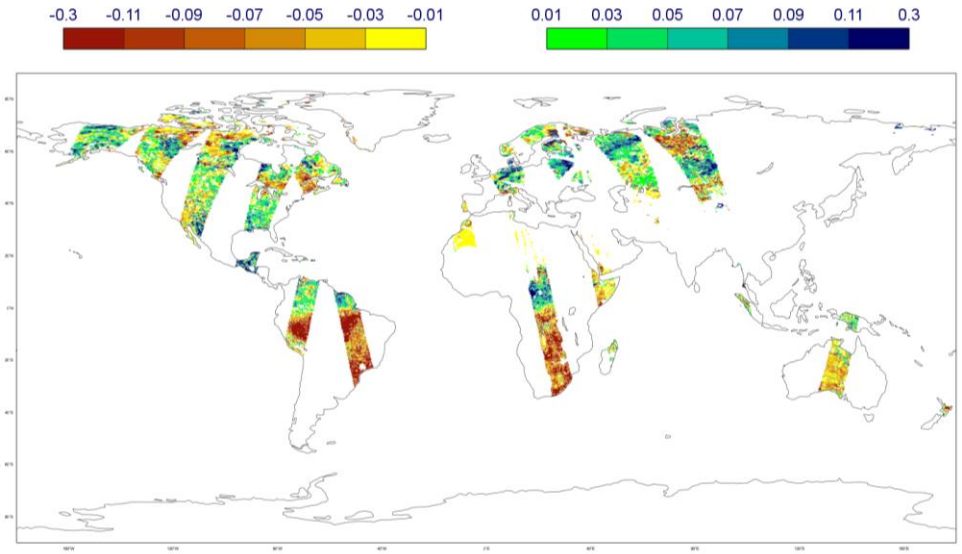
with i soil layer index, $\rho_i = 1 + (i-1)\,\alpha_{sekf}$ and $\alpha_{sekf} = 0.6$ tapering coefficient

EDA SEKF and SMOS NN DA impact

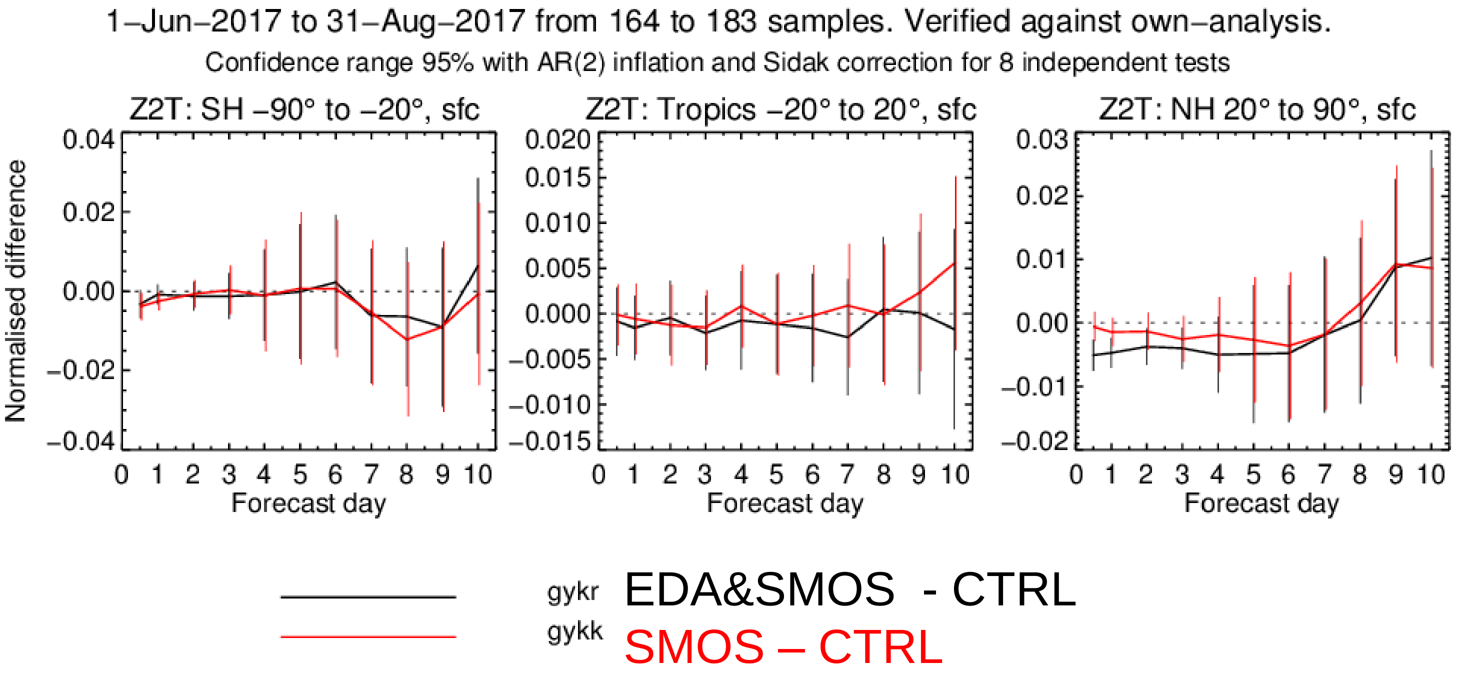
- **Enhanced coupling:**
  - Use the EDA to compute the SEKF Jacobian
- **Improved efficiency:**
  - CPU reduction from EDA SEKF, cost neutral for SMOS

Reduction of the SEKF CPU cost by a factor ~3.6

	NPES*THREADS	45r1	46r1
Tco1279	300*9	1580s	435s
Tco399	54*6	815s	235s



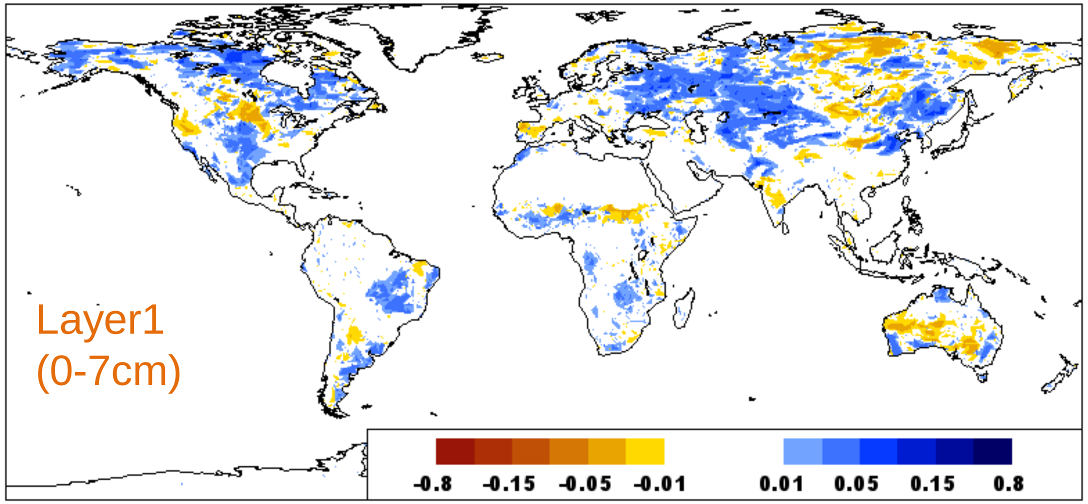
SMOS innovation (obs-model)
01 August 2017 (m3/m3)

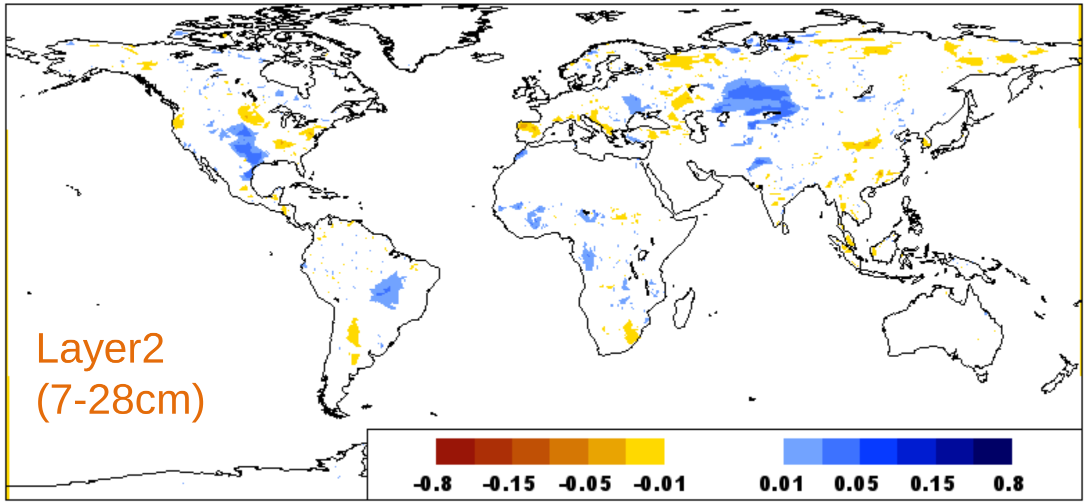


Atmospheric impact (T2m)
compared to 45r1 CTRL

ASCAT Soil Moisture data assimilation for NWP

Volumetric Soil Moisture increments (m^3/m^3) (accumulated) 25-30 June 2013



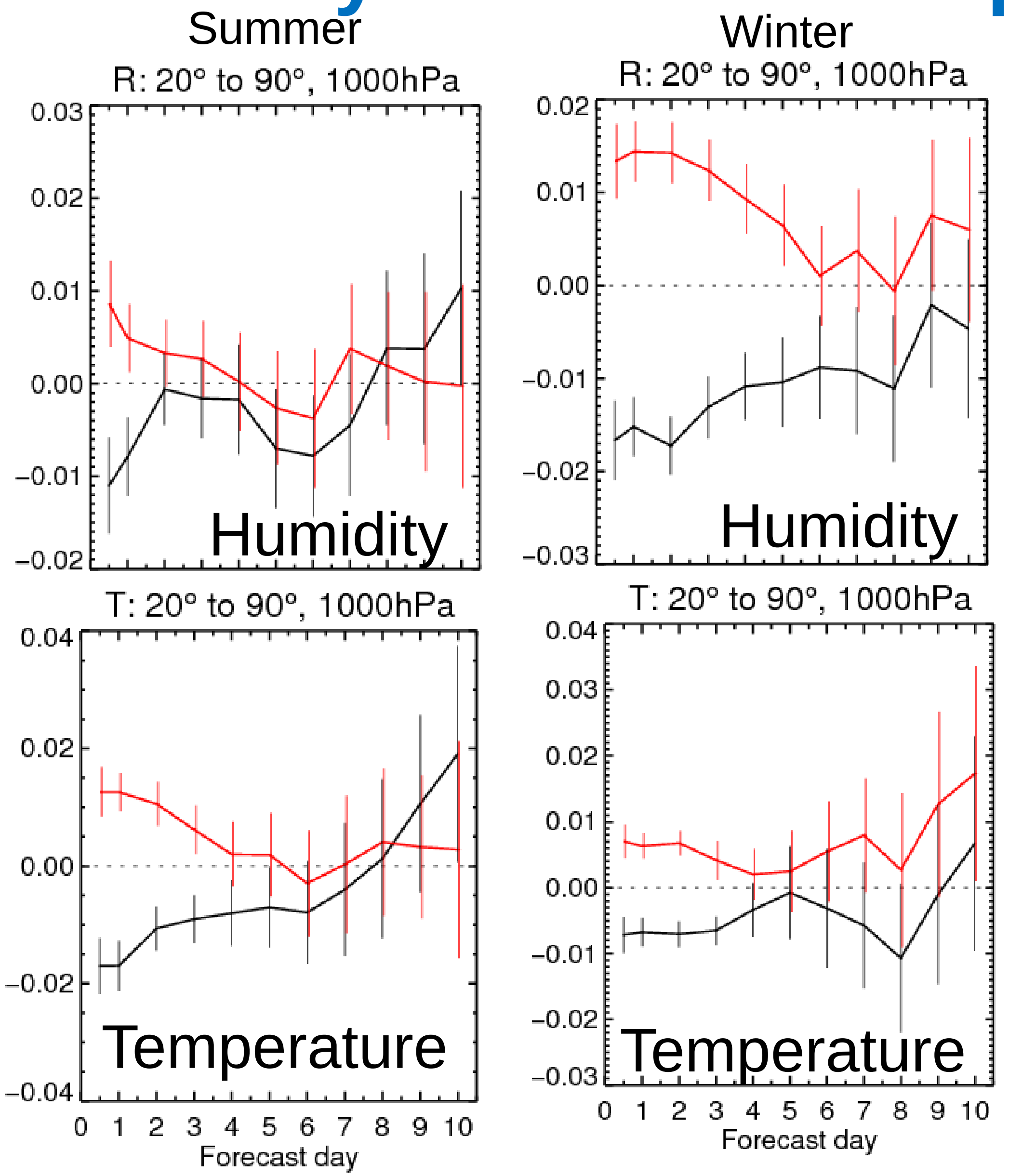


Vertically integrated Soil Moisture increments (stDev in mm)

	SYNOP	ASCAT
Layer 1	0.68	**1.43**
Layer 2	**1.48**	0.68
Layer 3	**4.28**	0.46

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



NWP with no soil Analysis

NWP with 2013 version of soil analysis

NWP with current surface analysis

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

Summary on soil moisture analysis

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

2. 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)

3. 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

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

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