ECMWF Data Assimilation Training course

Land Surface Data Assimilation

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ECMWF

Outline

Part I (Monday 10 March)

- **Introduction**
- Snow analysis
- Screen level parameters analysis

Part II (Tuesday 11 March)

- Soil moisture analysis
- Summary and future plans

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Introduction: Land Surface in NWP

• Land surfaces: Boundary conditions at the lowest level of the atmosphere

• Land surface processes → Continental hydrological cycle, interaction with the atmosphere on various time and spatial scales, strong heterogeneities

• Crucial for near surface weather conditions, whose high quality forecast is a key objective in NWP

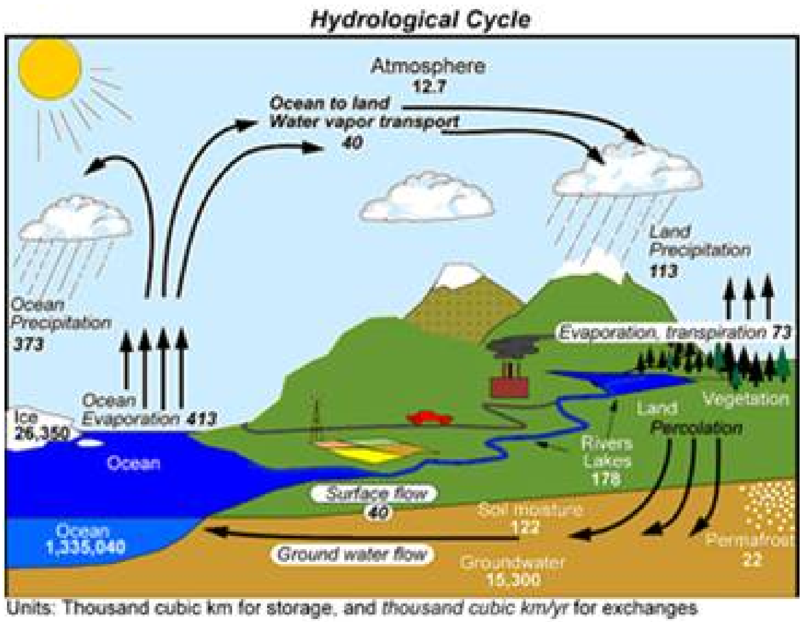
• Land Surface Models (LSMs) prognostic variables include:

- Soil moisture
- Soil temperature
- Snow water equivalent, snow temperature, snow density

• Land surface initialization:

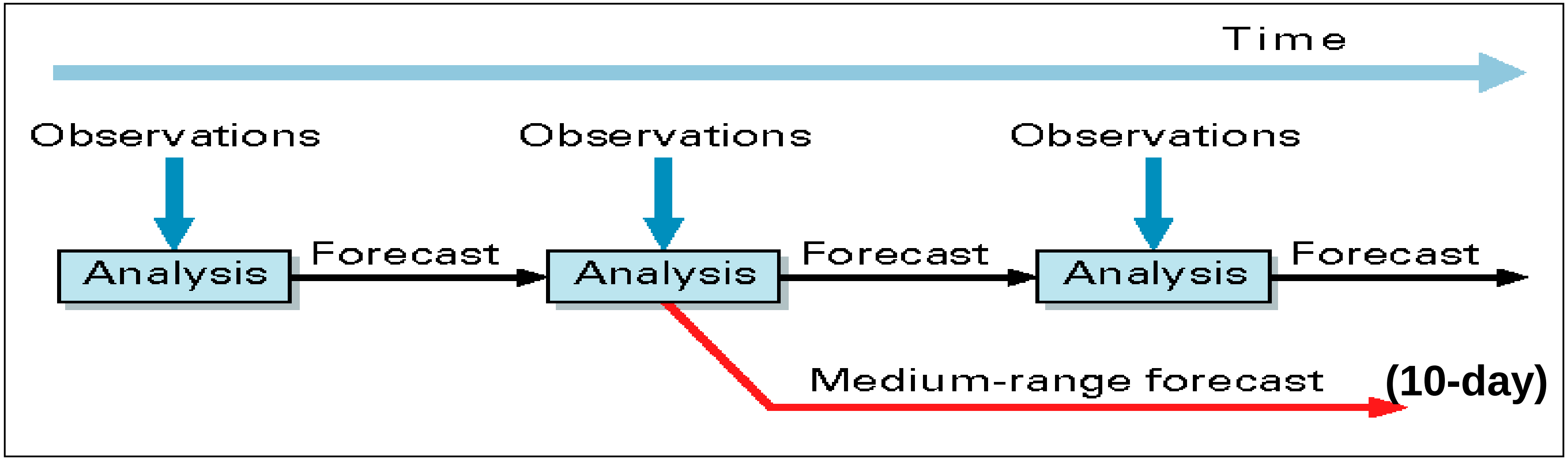
Important for NWP & Seasonal Prediction

(Beljaars et al., Mon. Wea. Rev, 1996, Koster et al., 2004 & 2011)



Trenberth et al. (2007)

Introduction: ECMWF Integrated Forecasting System (IFS) data assimilation system



Data Assimilation System:
Provides best possible accuracy of initial conditions to the forecast model

- **4D-Var for atmosphere**
- **Land surface data assimilation**
- **SST and Sea Ice analysis**

→

- **Surface and upper air analyses are running separately in parallel**
- **Feedbacks provided through the first guess forecast initialised with the analysed fields**

→ **Surface and Atmospheric DA are weakly coupled**

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Introduction: Land Surface Data Assimilation (LDAS)

Snow depth analysis

- Approaches: Cressman (DWD, ECMWF ERA-I), 2D Optimal Interpolation (OI) (ECMWF, CMC, JMA)
- Observations: *in situ* snow depth and NOAA/NESDIS IMS Snow Cover

Soil Moisture analysis

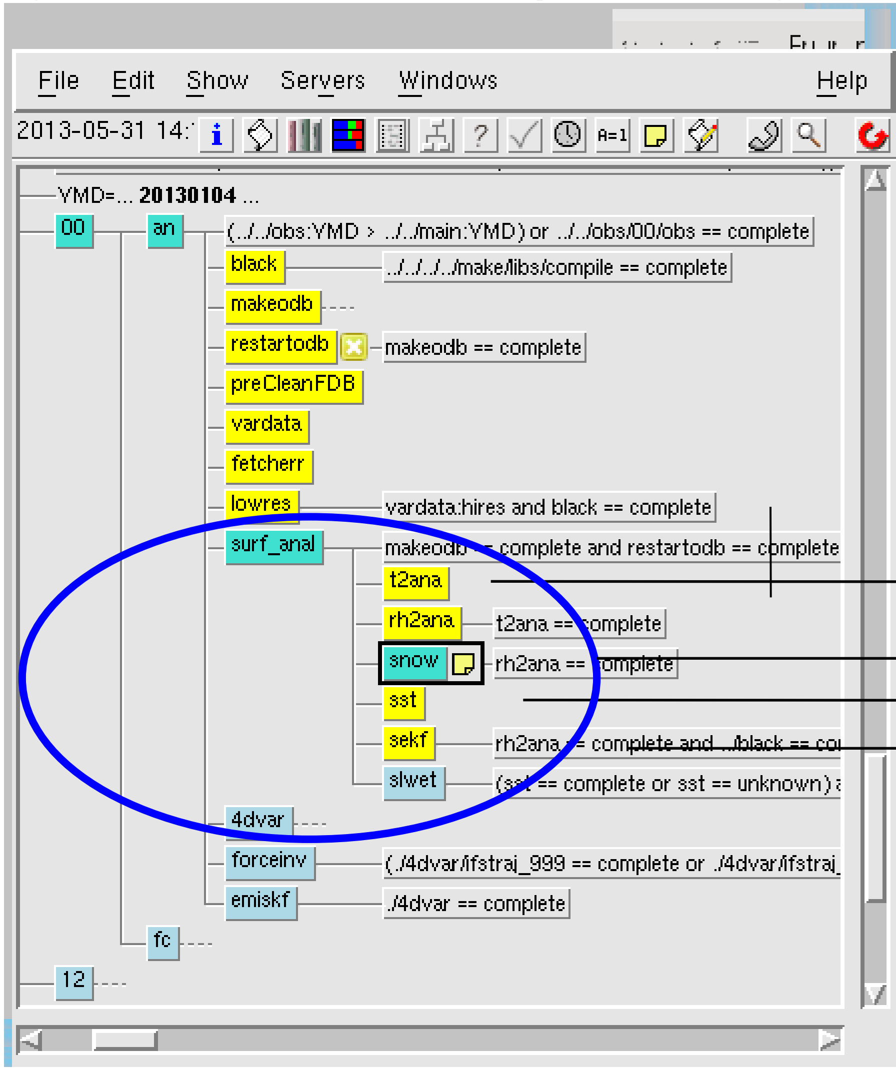
- Approaches:
  - 1D Optimal Interpolation (Météo-France, CMC, ALADIN and HIRLAM)
  - Analytical nudging approach (BoM)
  - Simplified Extended Kalman Filter (EKF) (DWD, ECMWF, UKMO)
- Conventional observations: SYNOP data of 2m air relative humidity and air temperature ; **Dedicated 2D OI screen level parameters analysis**
- Satellite data : ASCAT soil moisture (UKMO), SMOS (dvpt ECMWF, UKMO, Env.Canada)

Soil Temperature and Snow temperature also analysed

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

Introduction:
LDAS tasks organisation

IFS cycle 40r1 is the current operational cycle



SMS: Supervisor Monitor Scheduler

Different tasks performed

Colour code:
- Yellow: task completed
- Green: running
- Blue: in queue
- Red: failed

Screen level parameters

Snow

SST and Sea Ice

Soil Moisture and Temperature

Surface and and 4D-Var are running separately and in parallel.

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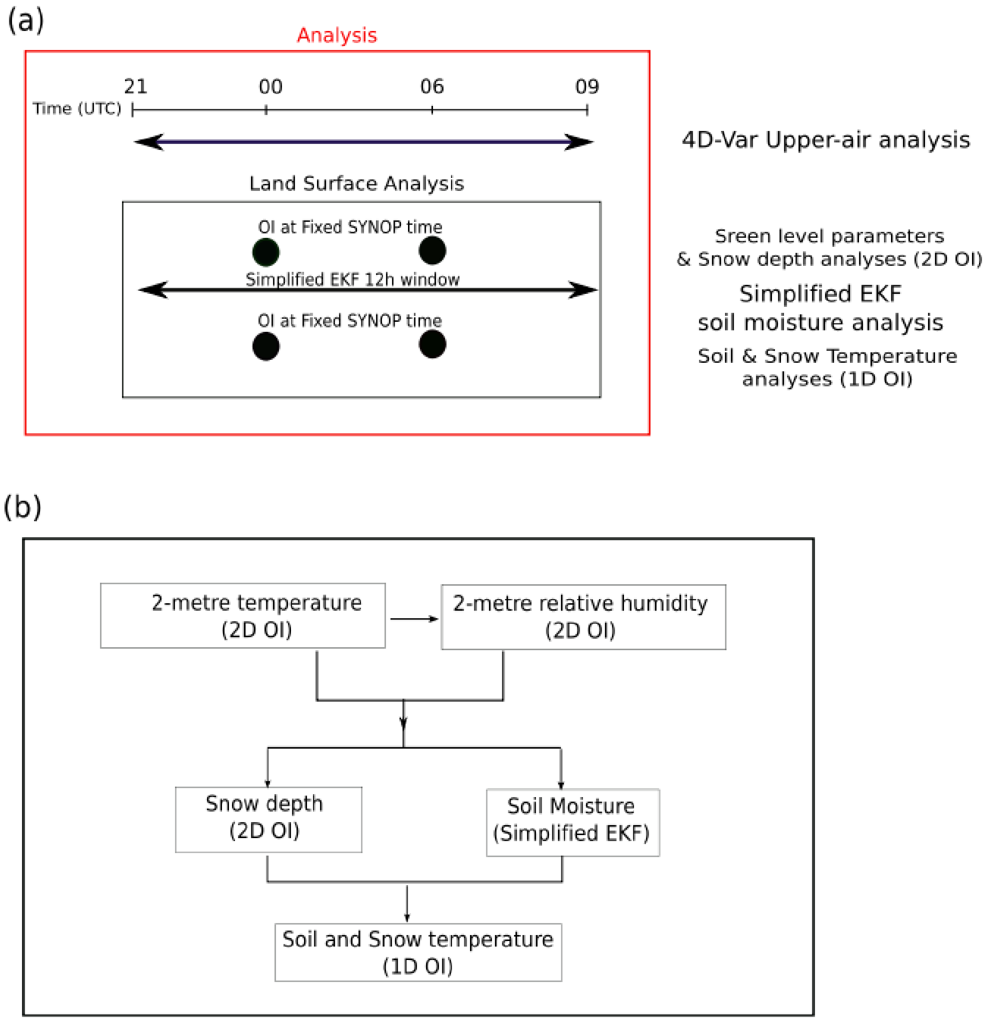
Introduction:
LDAS tasks organisation



LDAS:
- 2D OI:
  - Screen-level for T and humidity
  - Snow depth
- EKF
  - Soil moisture
- 1D OI:
  - Snow & soil temperature

Analysed surface fields: used as initial conditions for the next forecast.

→ Influence the forecast which will be used as first guess for the next data assimilation window, for both 4D-Var and LDAS

→ Feedback surface-atmosphere.

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Snow data assimilation

Snow Model: Component of H-TESSEL

(Balsamo et al., JHM 2009, Dutra et al., 2010)

- 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**

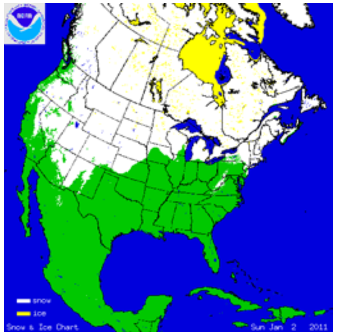
$$SWE = \frac{S \times \rho_S}{1000} \quad [\mathrm{m}]$$

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, SG 2013

de Rosnay et al. Res. Mem. R48.3/PdR/1028 2010, and Res. Mem. R48.3/PdR/1139 2011



Data Assimilation Approaches:

- Cressman Interpolation in ERA-Interim
- Optimal Interpolation in operations

de Rosnay et al, Survey of Geophysics 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

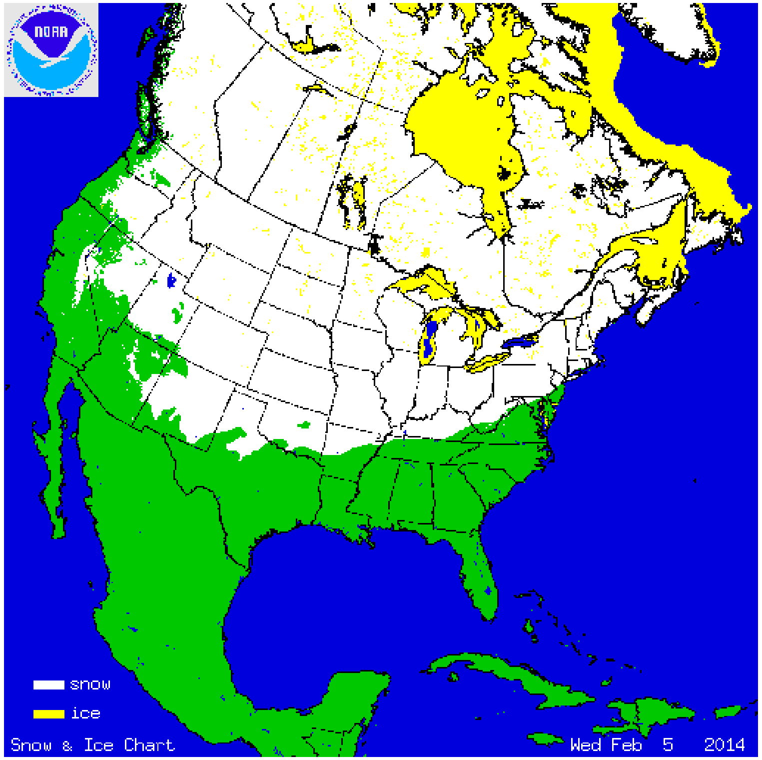
Northern Hemisphere product

- **Daily, no time stamp**
- Polar stereographic projection

Information content: Snow/Snow free

Data used at ECMWF:

- **24km product in Grib**
  Used in ERA-Interim (2004-present)
  and in operations (2004-2010)
- **4 km product in Ascii**
  Revised pre processing
  Used in operations (Nov 2010-present)



IMS Snow Cover 5 Feb. 2014

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

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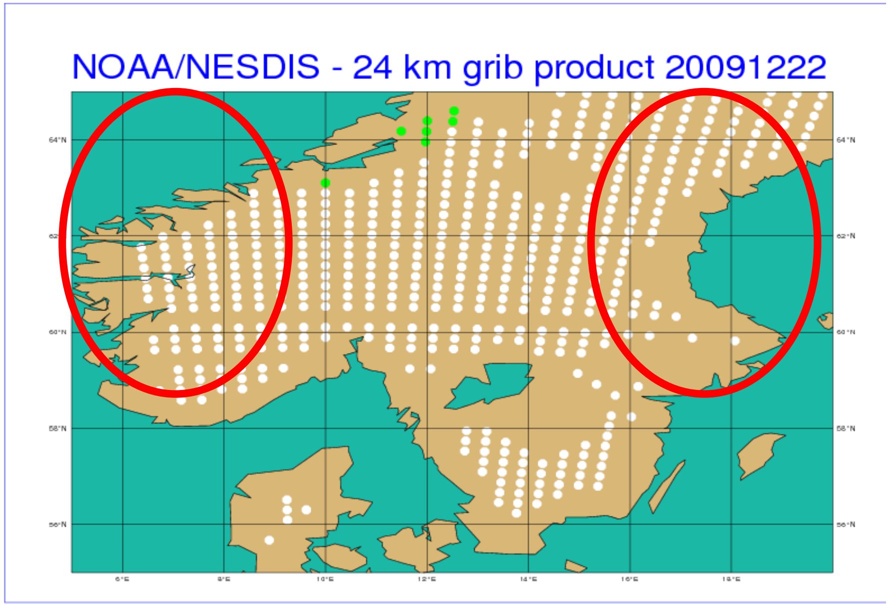
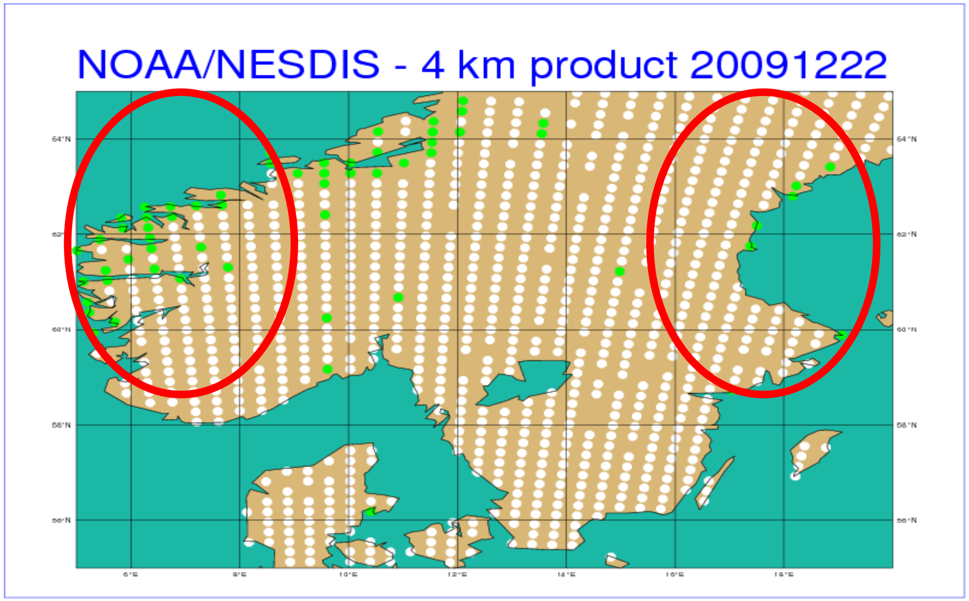
Snow Cover 24km vs 4km product





IMS Products after pre-processing at ECMWF

- Coast mask applied in the 24km product (lack of geolocation information in the grib product)
- Data thinning (1/36) of the 4km product -> same data quantity, improved quality

4km product provides more local information than 24km product

→ consistent with the way IMS is used in the data assimilation system

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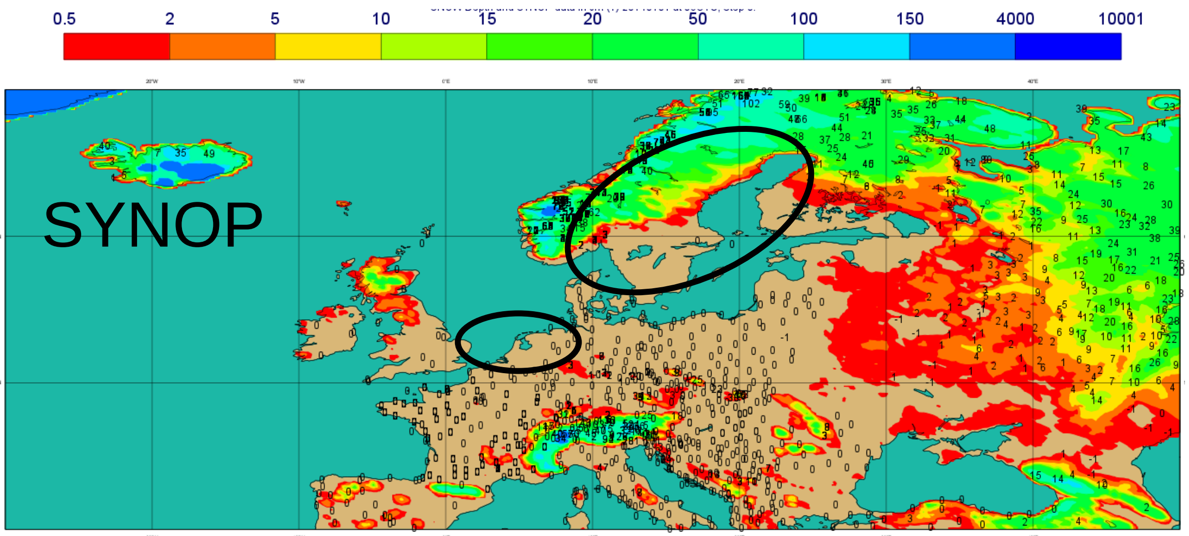
Snow SYNOP

2014 01 01 at 06UTC



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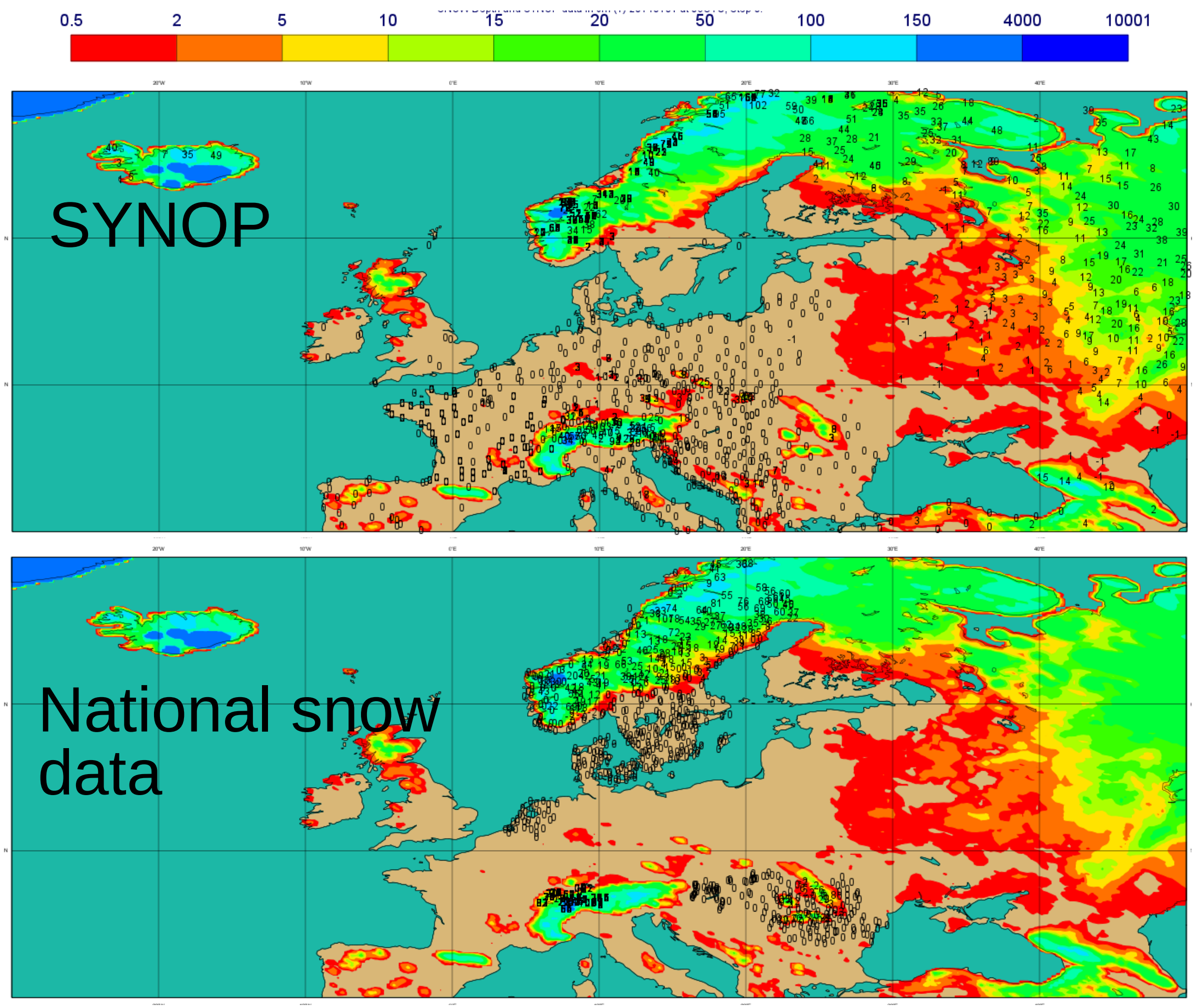
Snow SYNOP and National Network data

2014 01 01 at 06UTC



Additional data from national networks from 7 countries:

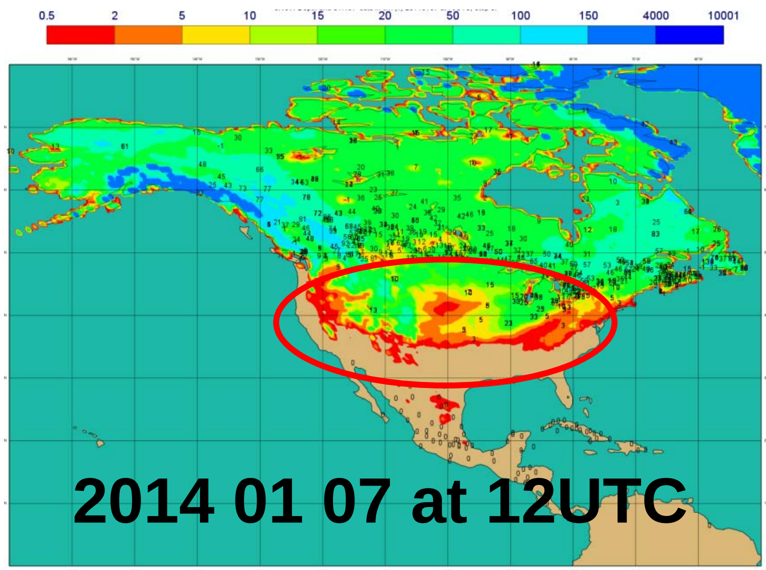
Sweden (>300), Romania(78), The Netherlands (33), Denmark (43), Hungary (61), Norway (183), Switzerland (332).

→ Dedicated BUFR

(de Rosnay et al. ECMWF Res. Memo, R48.3/PdR/1139, 2011)

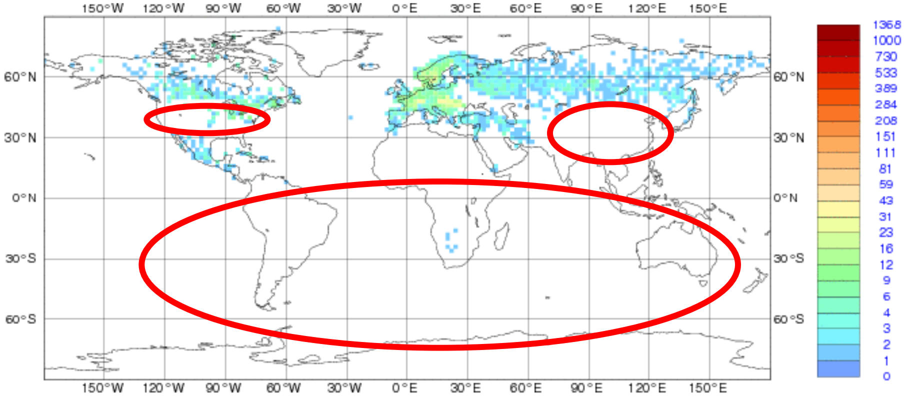
SYNOP Snow depth availability

ECMWF Operational monitoring of SYNOP snow depth: number of observations on 2014 01 04 at 00UTC (21-09 UTC):
observations gap in USA, China and southern hemisphere



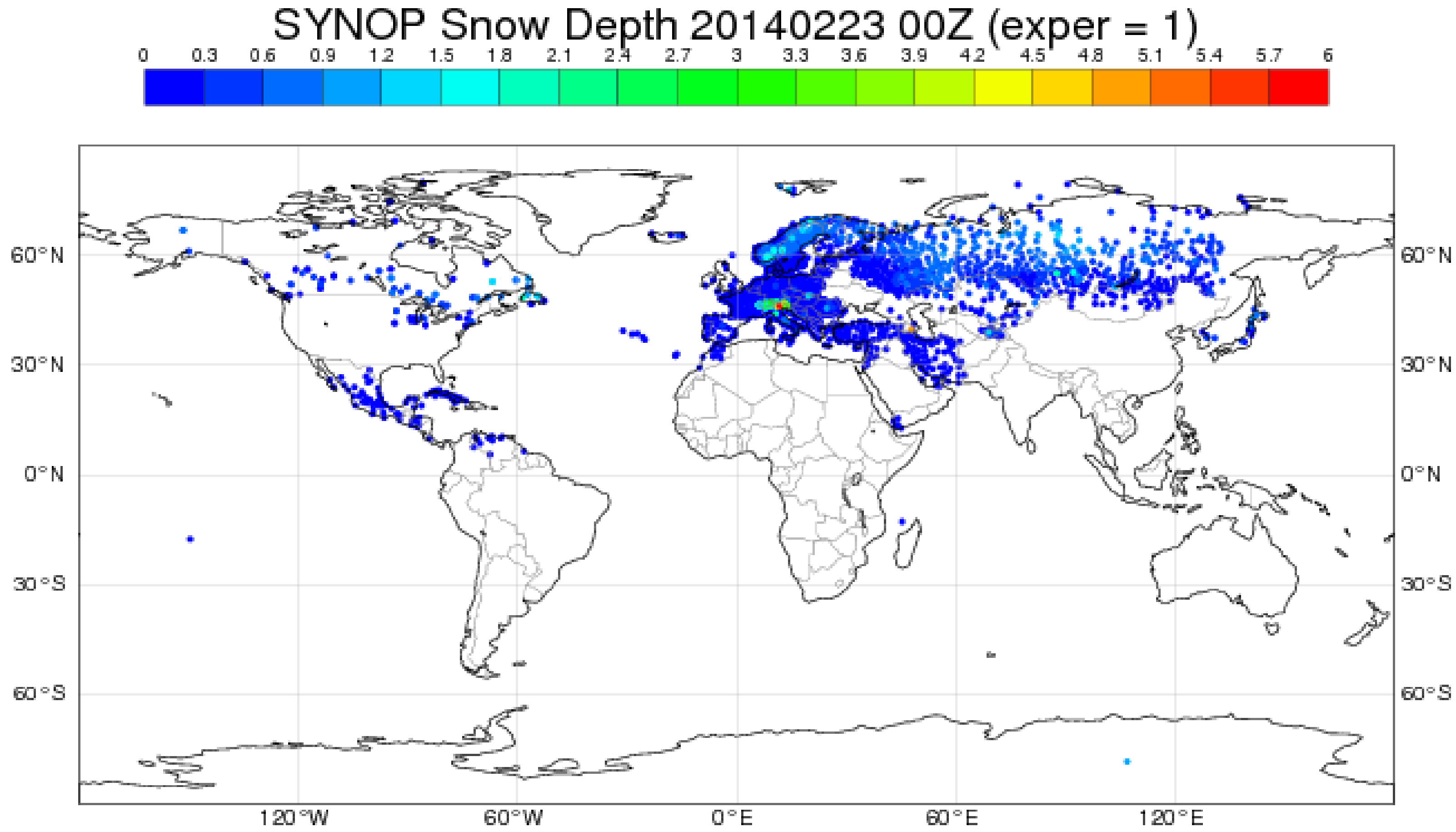
GCW Snow Watch initiative to improve in situ snow depth data access (NRT and rescue), Brun et al 2013

http://www.ecmwf.int/products/forecasts/d/charts/monitoring/conventional/snow/



Snow depth observations

Snow depth observations available (>4500 per day in winter time)



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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 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)

Observation errors:

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

Use NESDIS IMS data in the OI (00 UTC):

NESDIS: \ 1st Guess:	**Snow**	**No Snow**
Snow	x	**DA** 5cm
No Snow	DA	DA

Snow depth Optimal Interpolation

Used at CMC, JMA, ECMWF

Based on Brasnett, j appl. Meteo. 1999

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

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

$$\Delta S_j^a = \sum_{i=1}^{N} w_i \times \Delta S_i$$

3. The optimum weights w_i are given for each grid point j by: (**B** + **O**) **w** = **b**

   b : **background error vector** between model grid point j and observation i (dimension of N observations) $b(i) = \sigma_b^2 \cdot \mu(i,j)$

   B : correlation coefficient matrix of background field errors between all pairs of observations (N × N observations)
   $B(i_1,i_2) = \sigma_b^2 \times \mu(i_1,i_2)$ with the horizontal correlation coefficients $\mu(i_1,i_2)$ and σ_b = 3cm the standard deviation of background errors.

   O : **covariance matrix of the observation error** (N × N observations):
   $\mathbf{O} = \sigma_o^2 \times \mathbf{I}$
   with σ_o the standard deviation of observation errors (4cm in situ, 8cm IMS)

Snow depth Optimal Interpolation

Used at CMC, JMA, ECMWF

Based on Brasnett, j appl. Meteo. 1999

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 i1 and i2

Quality Control: reject observation if $\Delta S_i > Tol\ (\sigma_b^2 + \sigma_o^2)^{1/2}$ with Tol = 5

→Observation rejected if first guess departure larger than 25 cm

Redundancy rejection: use observation reports closest to analysis time

And use a maximum of 50 observations per grid point)

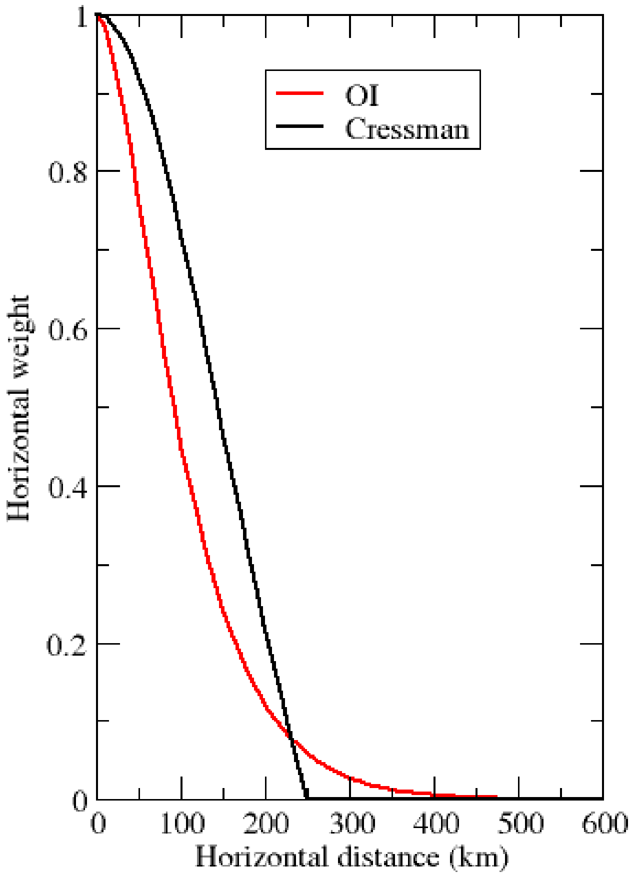
OI vs Cressman

In both cases: $$\Delta S_j^a = \sum_{i=1}^{N} w_i \times \Delta S_i$$

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

OI: The correlation coefficients of B and b 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.



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 24 km	- 2.0	0.74	10.1
OI, IMS 4km	- 2.1	0.73	10.3
OI, IMS 4km <1500m	- 1.5	0.74	10.1

- Oper until Nov 2010
- ERA-Interim

- Oper since Nov 2010

Validation against ground data

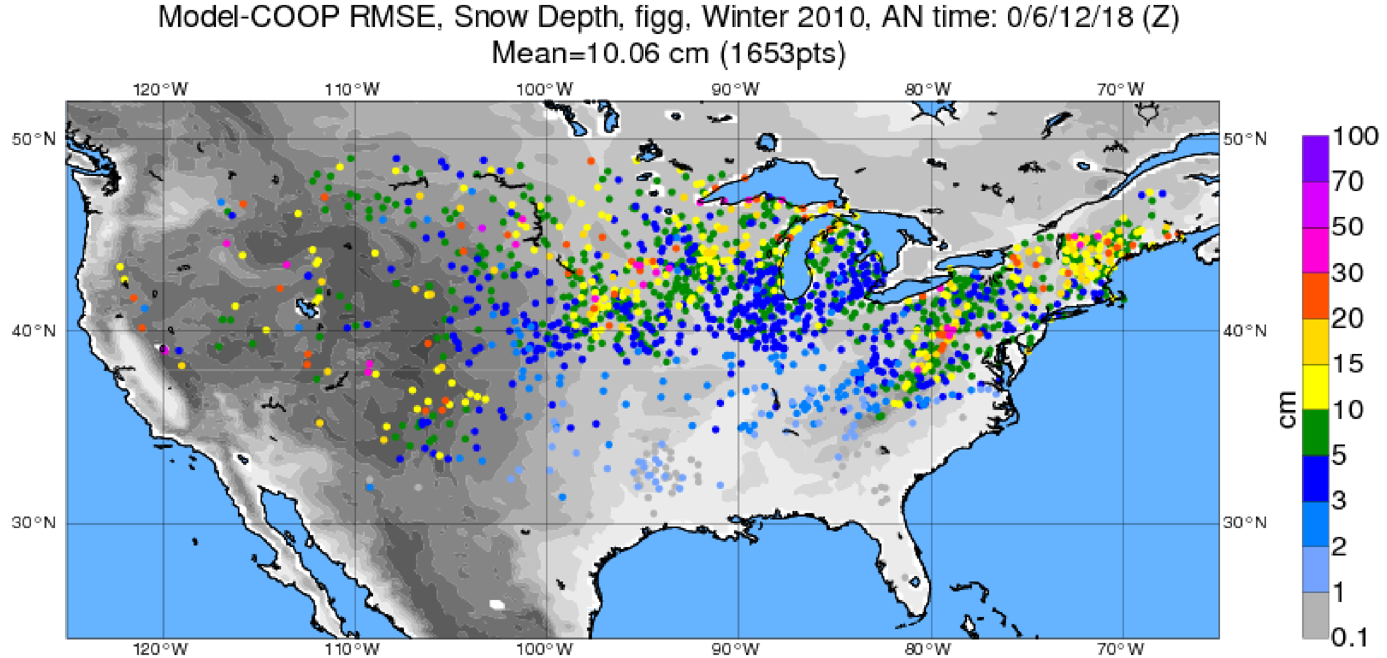
→ Main improvement due to the OI compared to Cressman

Validation data: NWS/COOP

- NWS Cooperative Observer Program
- Independent data relevant for validation

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

RMSE (cm) for the new snow analysis
(OI, IMS 4km except in mountainous areas)



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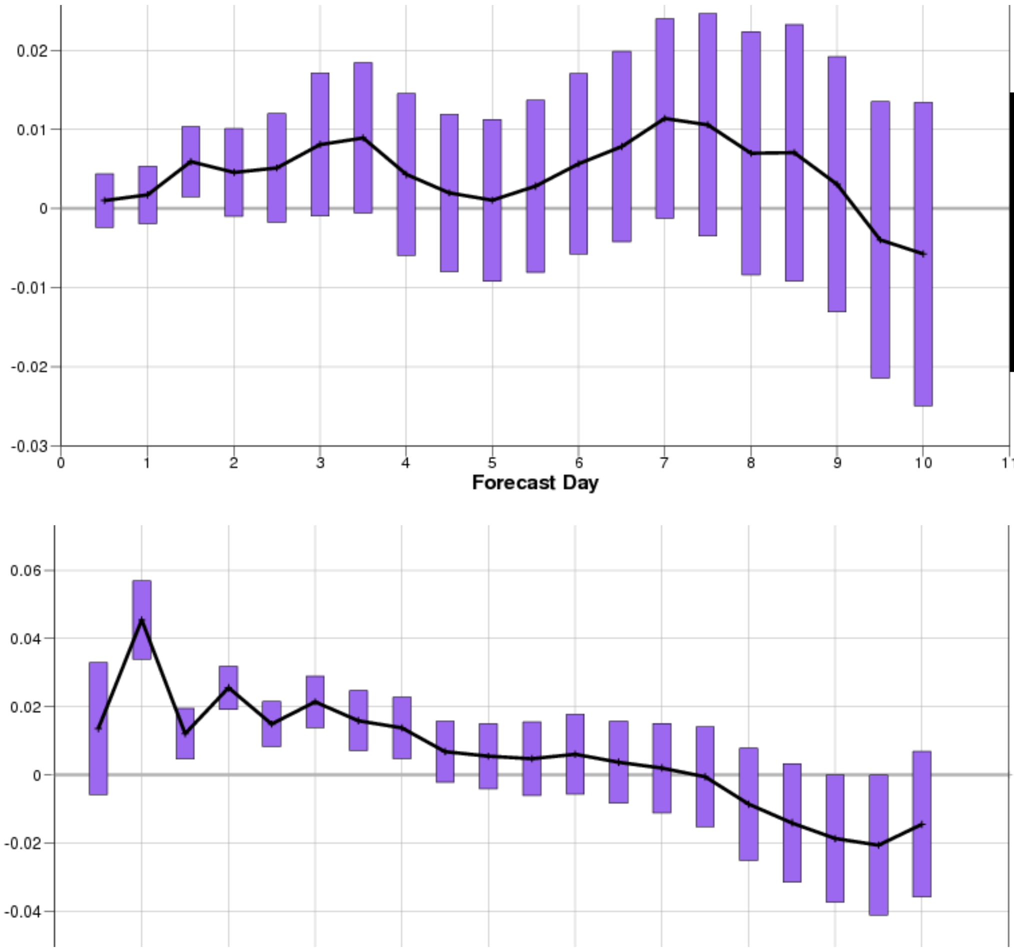
Impact on the Atmospheric Forecasts

RMS 1000hPa Geopotential height
Northern Hemisphere
DJF 2009-2010



Top: OI vs Cressman impact
(both use IMS 24km)

Positive means OI improves

Bottom: Overall impact

New OI,IMS 4km
vs Cressman, IMS 24km

Positive means new analysis improves

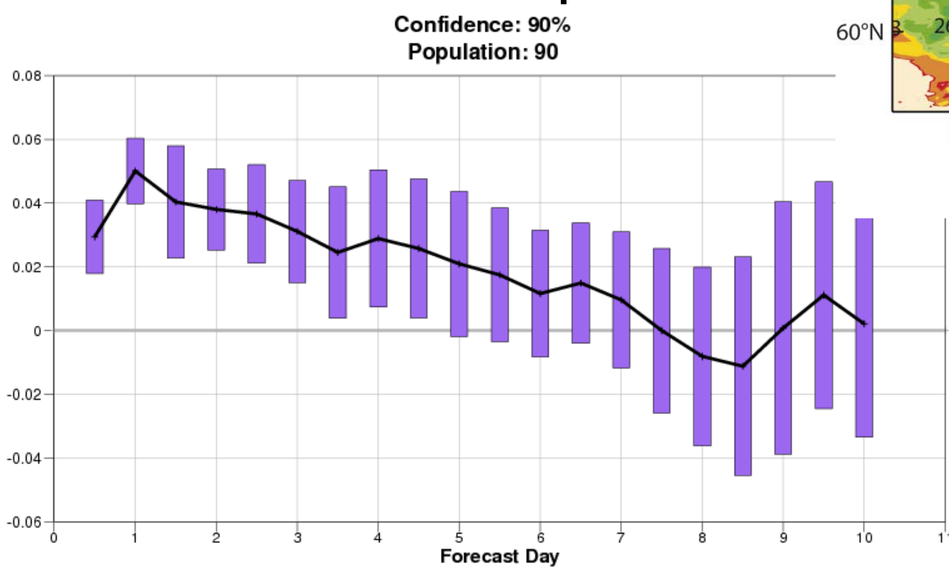
Validation with atmospheric forecasts
→ Main improvement due to the IMS 4km and pre-processing

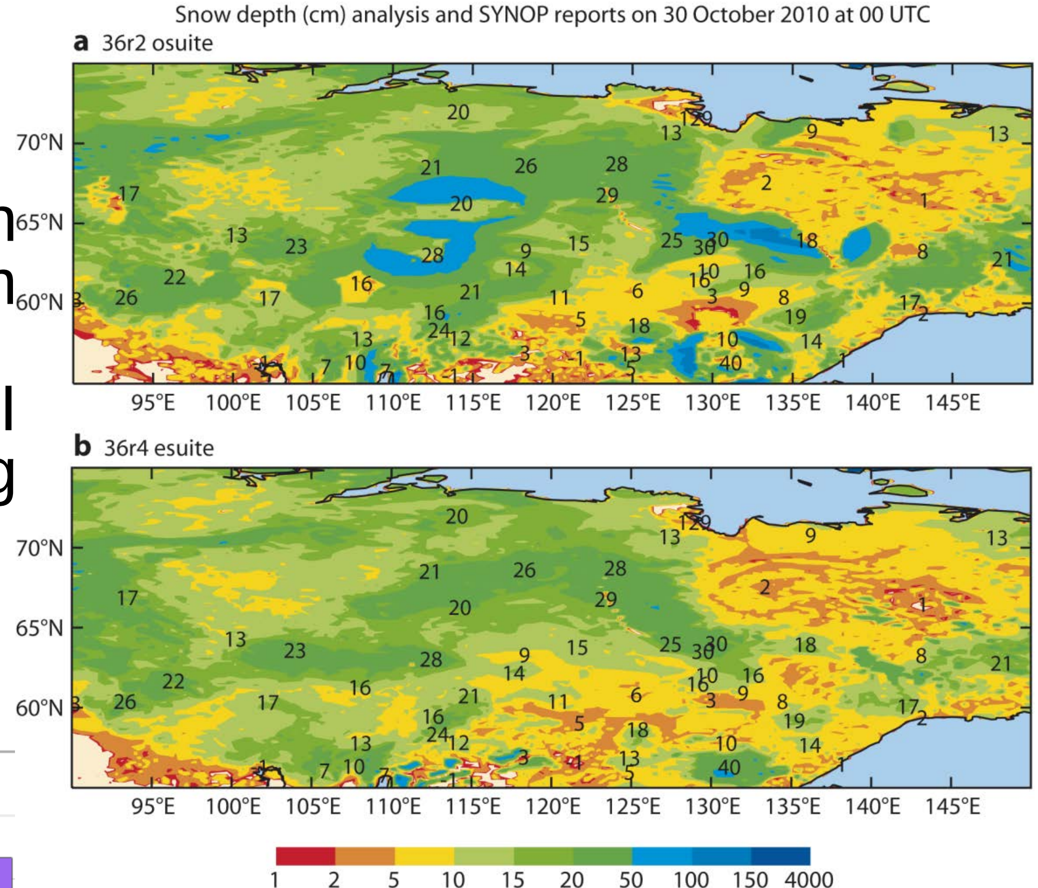
OI snow Analysis in Operations From Nov 2010

Old: Cressman
IMS 24km

New: OI
IMS 4km & new preprocessing

FC impact (East Asia)
RMSE 500 hPa Geopot H





New snow analysis improves both the snow depth patterns and the atmospheric forecasts

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Snow Analysis latest improvements

- 2010: replace Cressman by OI and improved IMS use (4km data and revised preprocessing)

- 2013: further improvement in the ECMWF snow analysis in IFS 40r1:

  -Revised observations error specification for IMS snow cover and assimilation of 5cm of snow instead of direct insertion,
  -Generic snow blacklist,
  -Revised surface analysis code and Observation data base (ODB) feedback
  - New Land surface observations monitoring for conventional and IMS data

https://software.ecmwf.int/wiki/display/LDAS/Land+Surface+Observations+monitoring

Snow Analysis latest improvements

Improved use of NESDIS/IMS snow cover data

Current version:

Cycle 40r1:

NESDIS \ FG	Snow	No Snow
Snow	x	**DA** 5cm
No Snow	DA	DA

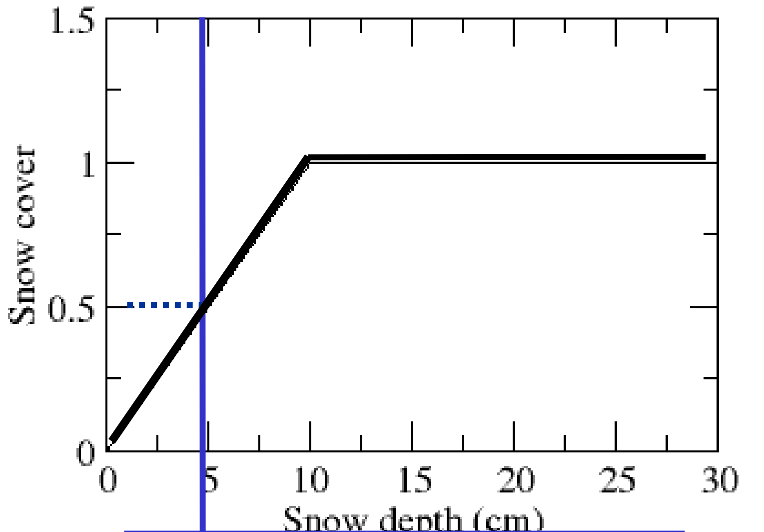
OI

40r1 errors:

BG: σ_b = 3cm

SYNOP σ_{SYNOP} = 4cm

IMS σ_{ims} = 8cm



40r1:

- Obs assimilated

- SC=1 → SD=5cm

Snow Analysis latest improvements

Improved use of NESDIS/IMS snow cover data

Previous version: IFS Cycle 38r2

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

38r2:
- **BG overwritten**
- **SC=1 → SD=10cm**

OI

Previous cycles errors:
BG: σ_b= 3cm
OBS: σ_{SYNOP}=4cm

Current version: Cycle 40r1:

NESDIS \ FG	Snow	No Snow
Snow	x	**DA** 5cm
No Snow	DA	DA

OI

40r1 errors:
BG: σ_b = 3cm
SYNOP σ_{SYNOP}= 4cm
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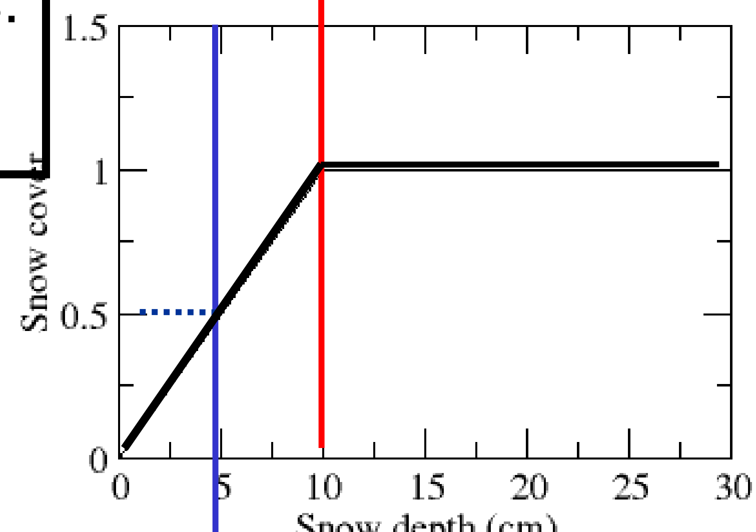
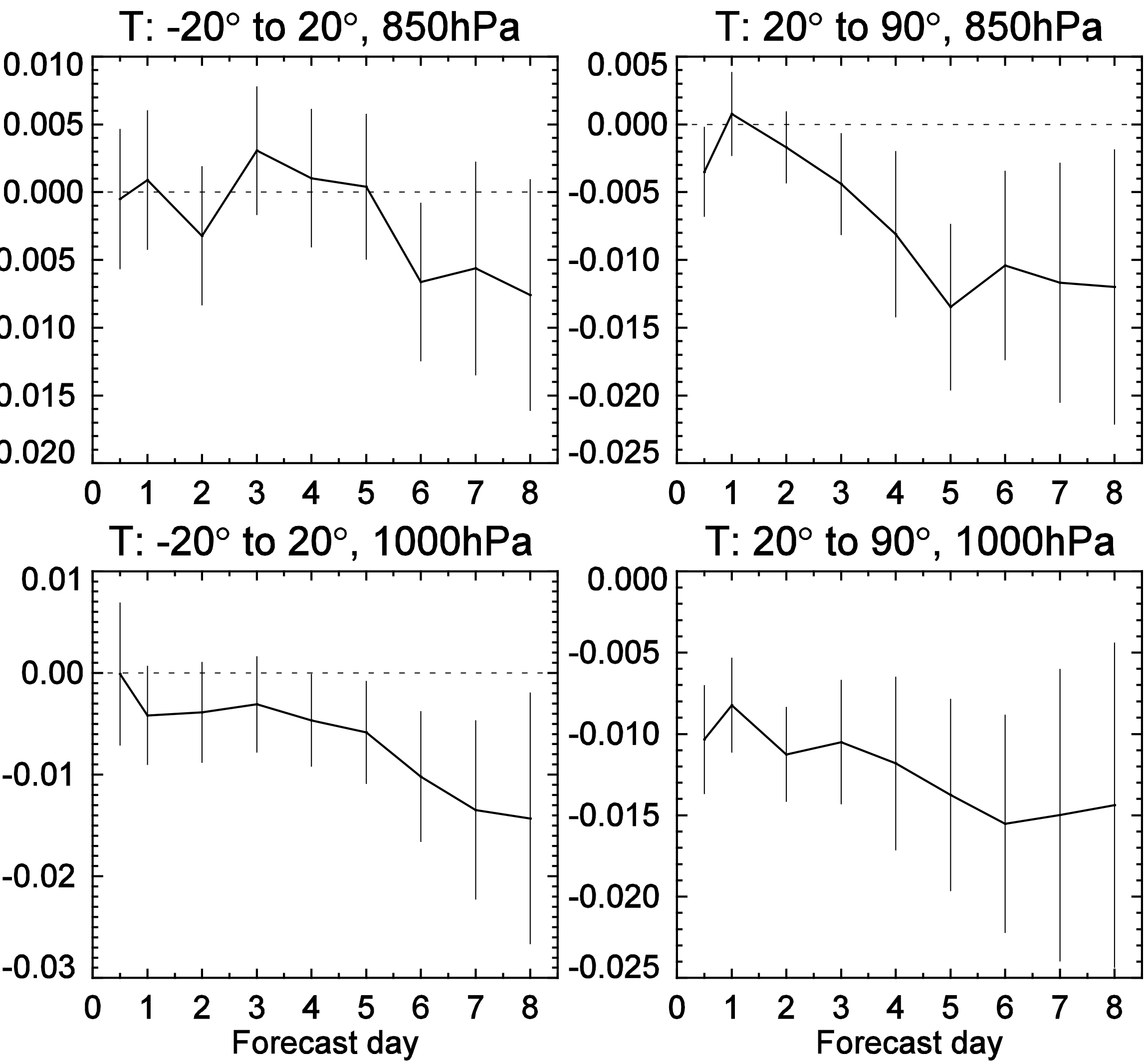


40r1:
- **Obs assimilated**
- **SC=1 → SD=5cm**

Snow analysis latest improvements: Temperature FC verification

Tropics **NH extra-tropics**



Temp FC RMSE
Verified against own analysis
(20 Dec 12 – 08 Mar 13)

40r1-38r2 (current-previous cycle)

Improved use of IMS snow cover → Significant impact on the atmosphere and error reduction in forecasts

de Rosnay et al. in prep 2014

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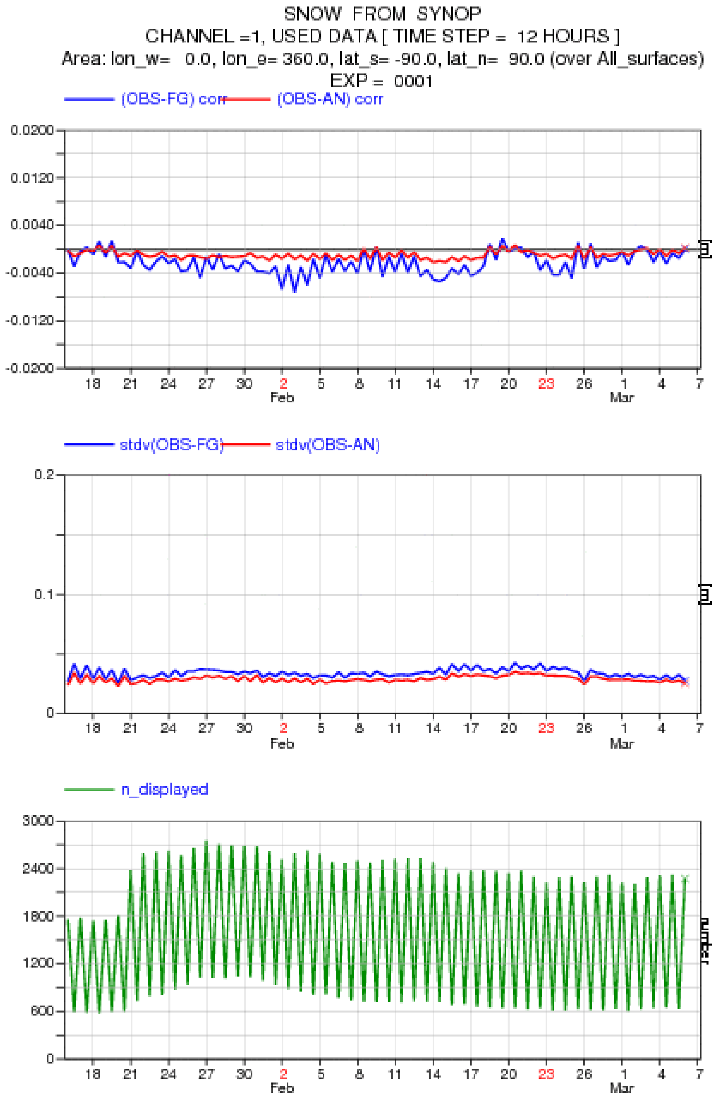
Snow observations monitoring



2014

Global first guess departure

Global analysis departure

Standard deviation of departure statistics

Number of in situ observations used:
~600 to 2500 per 12 hours

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Summary on Snow Analysis

- Large sensitivity of atmospheric forecasts to snow data assimilation (DA method, observations pre-processing, error specification)
- Current snow analysis based on 2D-OI (CMC, JMC, ECMWF), old approach was based on Cressman (still used in ERA-Interim)

- Importance of in situ snow depth data availability
- Scarce snow depth observations in some areas → European initiative (new BUFR for additional snow data) – action to extend it to WMO Member States
- Snow cover data used (NOAA/NESDIS IMS product)
- **No** use of Snow Water Equivalent product in NWP
- Future investigations on using satellite radiances

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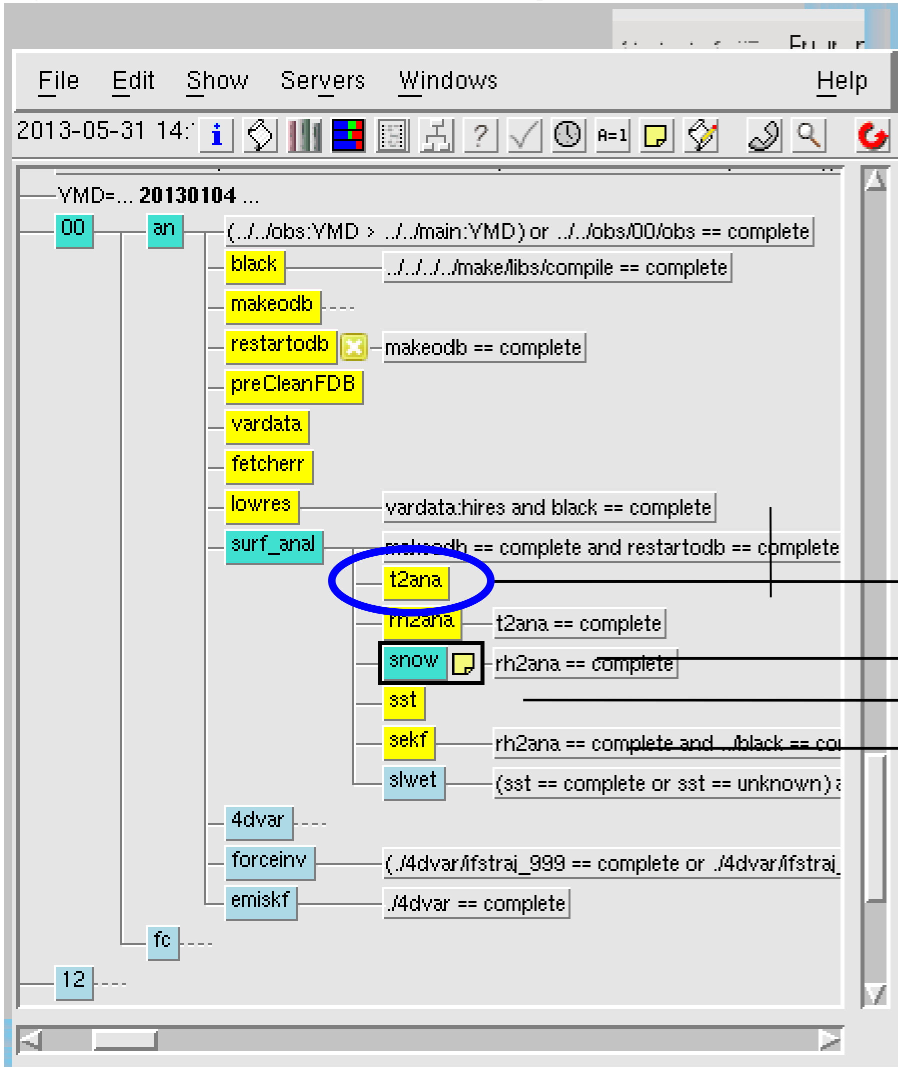
IFS cycle 38r1 is the current operational



Screen level parameters

Snow

SST and Sea Ice

Soil Moisture and Temperature

SMS: Supervisor Monitor Scheduler

Different tasks performed

Colour code:
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Screen Level parameters analysis

- Screen level variables: 2m Air Temperature (T2m) and air Relative humidity (RH2m), both diagnostic variables.
- Analysis based on an Optimal Interpolation using SYNOP observations, every six hours: 00UTC, 06UTC, 12UTC, 18UTC.

- Screen level analysis increments are used for the soil moisture analysis (OI system, e.g. at Météo-France and ECMWF ERA-Interim),
- Screen level analysis fields are used as input of the SEKF soil moisture analysis (ECMWF)

- T2m and RH2m are diagnostic variables of the model, so their analysis only has an indirect effect on atmosphere through the soil and snow variables.
- Relevance of screen level analysis for evaluation purposes

OI Screen Level parameters analysis

Mahfouf, J. Appl. Meteo. 1991, & ECMWF News Lett. 2000

Same approach as snow analysis:

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

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

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

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

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

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

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

O : covariance matrix of the observation error (N × N observations):
$\mathbf{O} = \sigma^2_o \times \mathbf{I}$ with σ_o = 2.0 K / 10 % rH the standard deviation of obs. errors

Screen Level parameters analysis

Quality control:

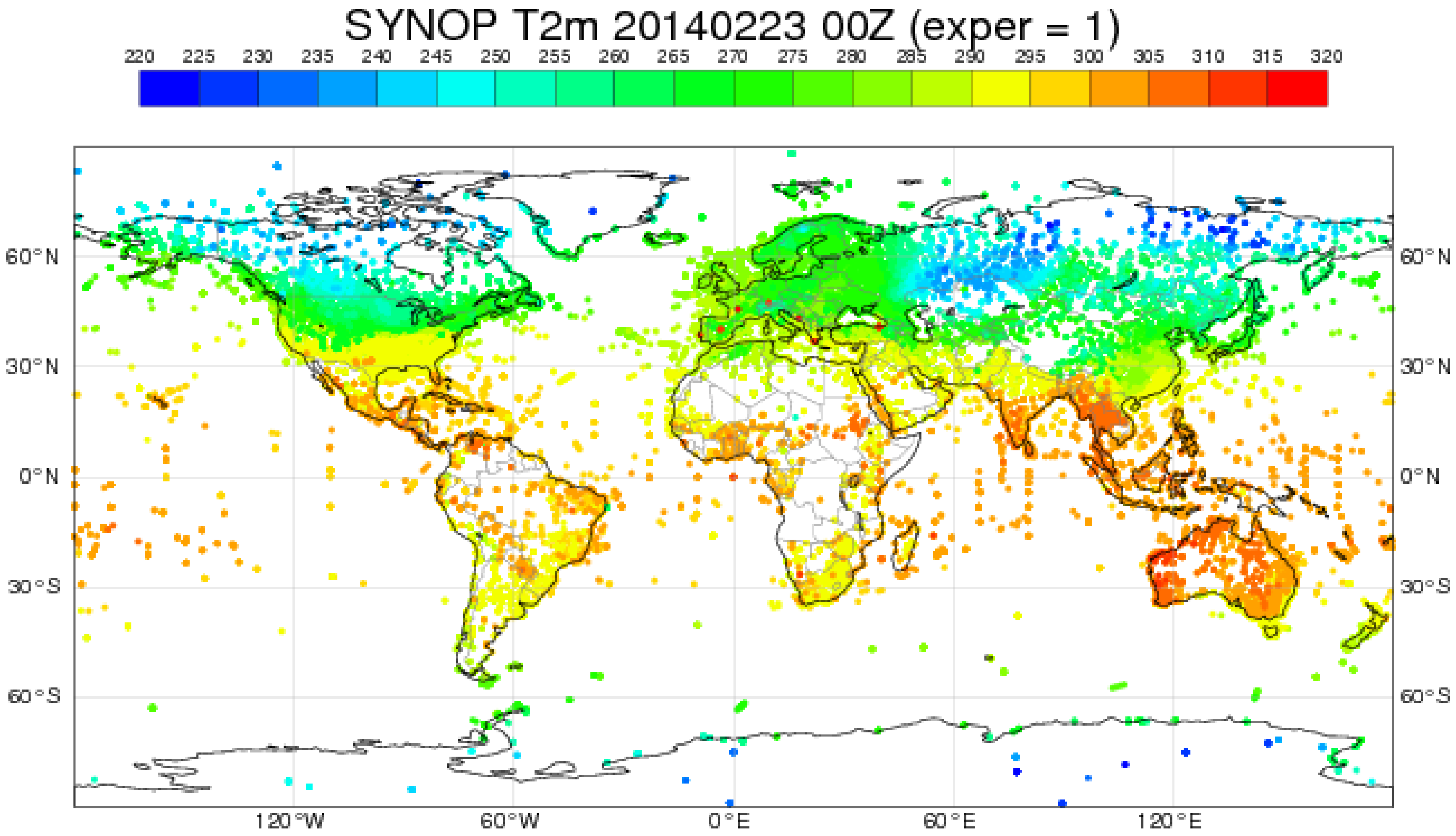
- Number of observations N = 50, d = 300 km, scanned radius 1000km.
- Gross quality checks as rH $\in$ [0,100] and T > $T_{dewpoint}$
- Observation points that differ more than 300 m from model orography are rejected.
- First-guess check:

  Observation is rejected if : $|\Delta X_i| = \gamma\sqrt{\sigma_o^2 + \sigma_b^2}$ with γ = 3 (tolerance)
- Redundancy rejection

- Number of active observations > 16000 per 12 hour (less than 20% of the available observations).

Screen level observations

All T2m observations available (>180000 per day)



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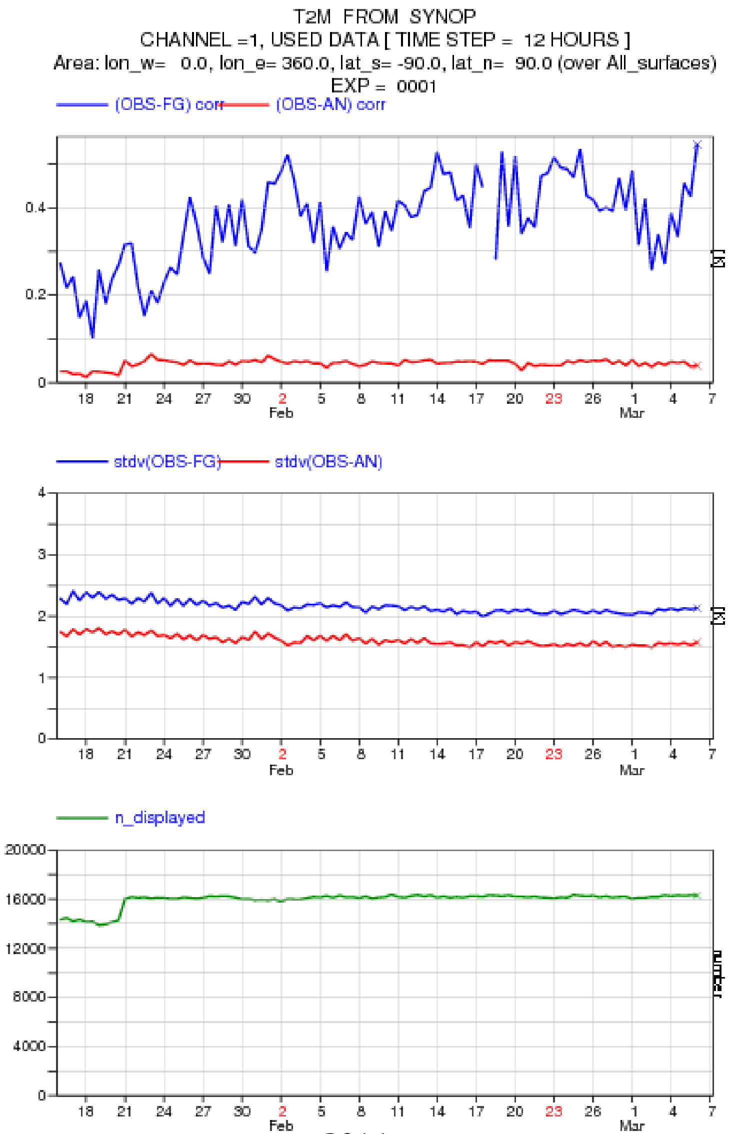
Screen level observations monitoring



2014

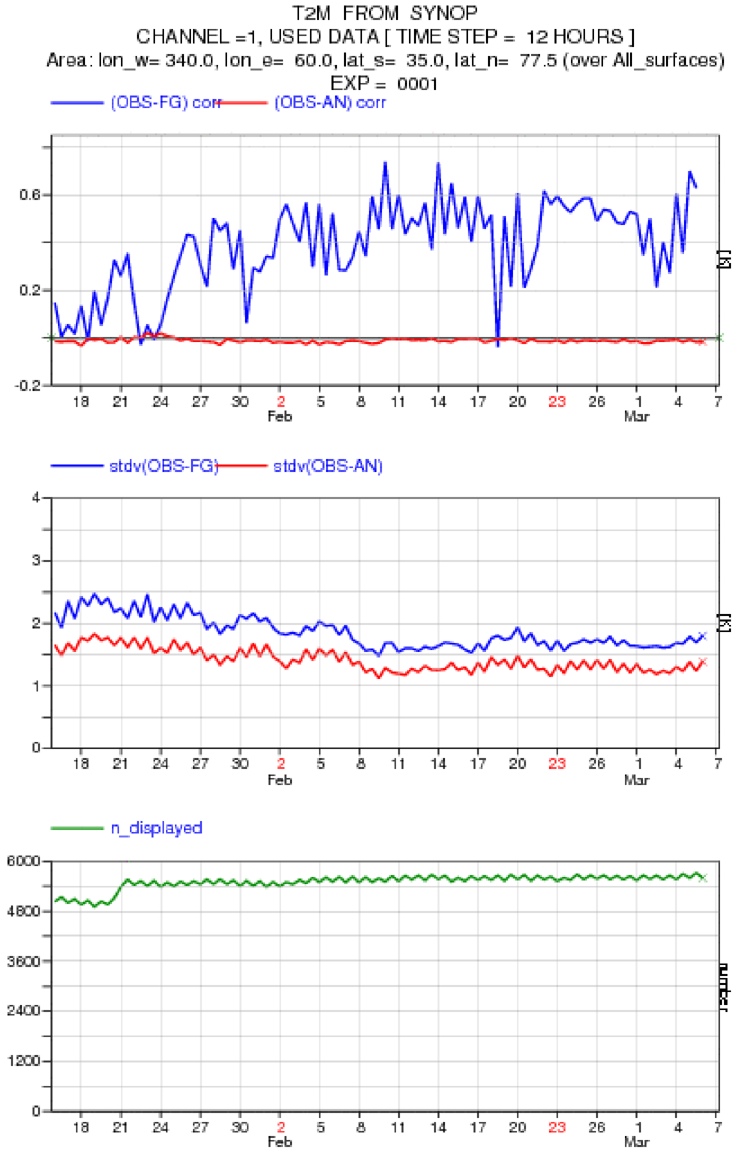
Global first guess departure

Global analysis departure

Standard deviation of departure statistics

Number of observations used:
>16000 per 12 hours

Screen level observations monitoring



Europe first guess departure

Europe analysis departure

Standard deviation of departure statistics

Number of observations used over Europe:
~5000 per 12 hours

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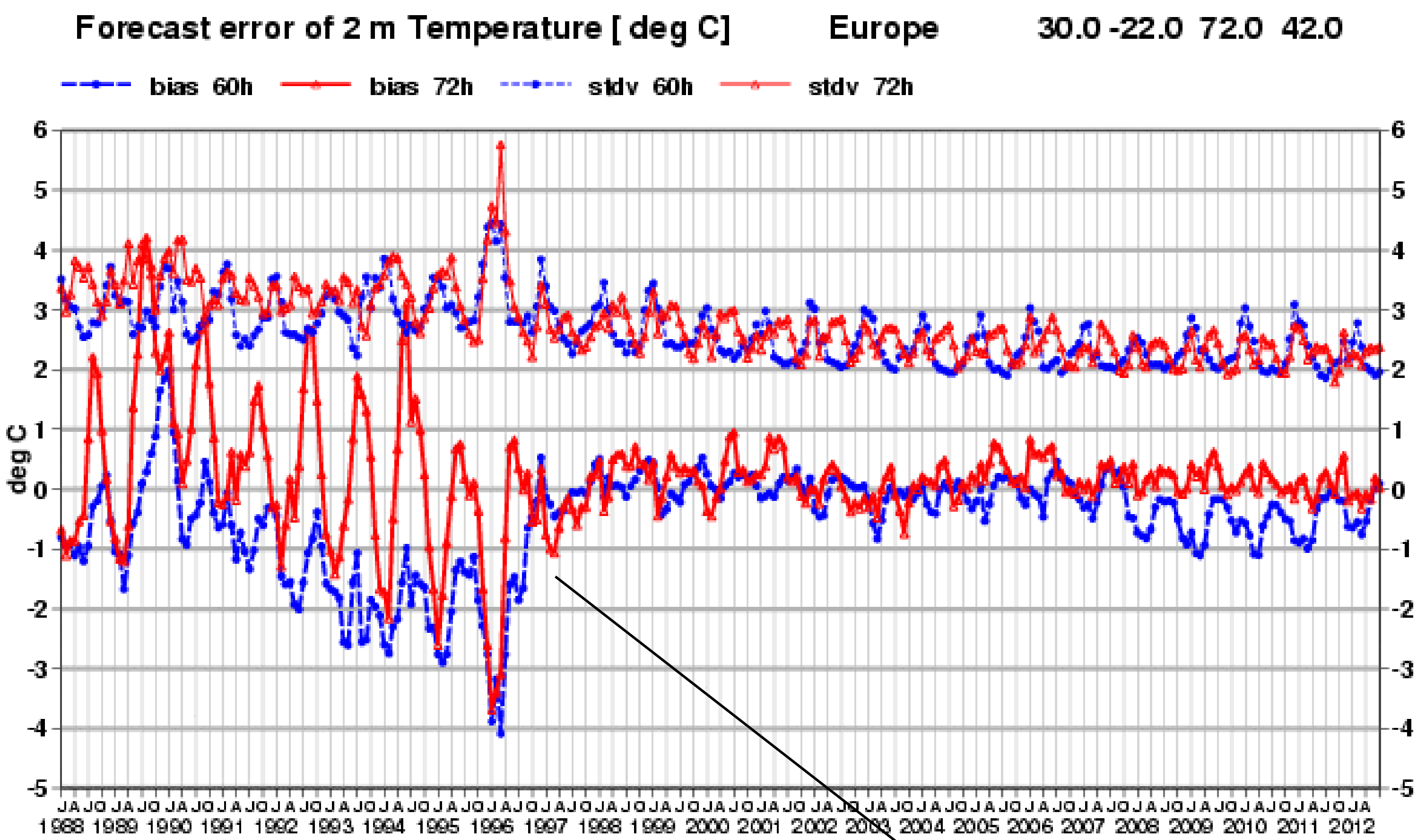
Screen level analysis: 2m temperature forecast verification



Verification for 60h (night time) and 72h (day time)

Soil freezing parameterisation
Snow albedo parameterisation

From Richardson et al., 2012, ECMWF Tech. Memo 688

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