Preliminary study for the use of soil moisture information for Nowcasting-Short Range NWP Forecast

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final report

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in collaboration with German Weather Service (DWD)

TASK OF THE FELLOWSHIP

H-SAF ASCAT product

COMET NWP system

Use of **satellite soil moisture data** into an **high-resolution short range forecasting model** with an **ensemble based data assimilation system**

KENDA-LETKF algorithm

Outline

- Ensemble-Based Data Assimilation: LETKF (Local Ensemble Transform Kalman Filter)
- COSMO Priority Project KENDA (Km-scale Ensemble-Based Data Assimilation)
- COMET NWP system
- H-Saf ASCAT Soil Moisture products
- Assimilation of ASCAT Soil Moisture data in the KENDA-LETKF system
- Future developments

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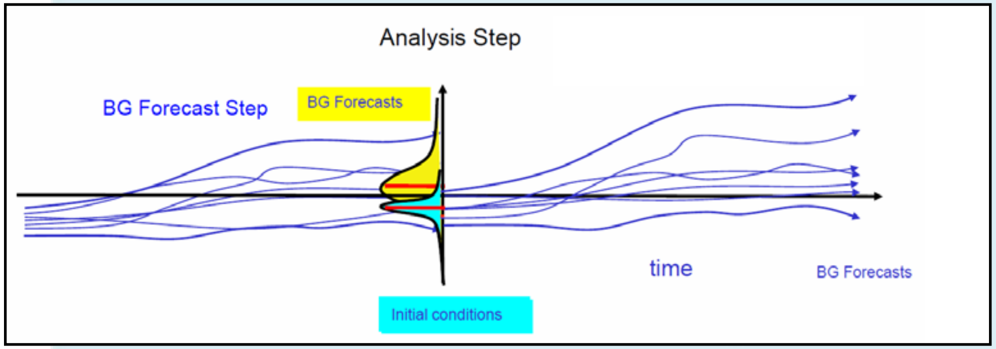
Ensemble-Based
Data Assimilation (1)

NWP is an initial/boundary value problem: given an estimate of the present state of the atmosphere (initial conditions), and appropriate surface and boundary conditions, the model simulates (forecasts) the atmospheric evolution.

Currently, operational NWP centers produce initial conditions (**analysis**) through a statistical combination of observations and short-range forecast, approach known as **DATA ASSIMILATION**

ensemble data assimilation



Ensemble-based data assimilation delivers the best estimate and a representation of the probability density function for the atmospheric state

Main characteristics

- Monte Carlo techniques
- starting point: ensemble of forecasts
- forecast ensemble perturbations used to represent the forecast error

$$\mathbf{P}^b = \frac{1}{m-1}\mathbf{X}^b\left(\mathbf{X}^b\right)^T \qquad X_b = x_b - \bar{x}_b$$

- analysis ensemble produced

Ensemble-Based Data Assimilation (2)

ADVANTAGES

- flow-dependent error structures
- No Adjoint operator needed
- intrinsically parallel

LIMITATIONS

- sample size (sampling errors)
- model error representation (filter divergence)

$$P^b_{i+1} = MP^a_i M^T + Q$$

How to count this behavior in practice

- Covariance localization techniques
- Inflation techniques

LETKF theory
(Local Ensemble Transform Kalman Filter)

- **Hunt et al. (2007)**

Operational at COMET (Italian Air Force Operational Met. Center) since 2011
First Met. Center which uses operationally a pure EnKF DA to initialize a deterministic NWP model

Main characteristics

- analysis done in the space of ensemble perturbations
- analysis computed separately for each grid point selecting only the observations in the vicinity. The observation error covariance R elements are modified by distance-dependent localization factors so that far-away observations have large errors.

  (**explicit localization**)
- Analysis ensemble members are locally linear combinations of background ensemble members

- do analysis in the k-dimensional ensemble space

$$\bar{\mathbf{w}}^a = \tilde{\mathbf{P}}^a (\mathbf{Y}^b)^T \mathbf{R}^{-1} (\mathbf{y} - \bar{\mathbf{y}}^b)$$
$$\tilde{\mathbf{P}}^a = [(k-1)\mathbf{I} + (\mathbf{Y}^b)^T \mathbf{R}^{-1} \mathbf{Y}^b]^{-1}$$

- in model space we have

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{X}^b \bar{\mathbf{w}}^a$$
$$\mathbf{P}^a = \mathbf{X}^b \tilde{\mathbf{P}}^a (\mathbf{X}^b)^T$$

- Now the analysis ensemble perturbations - with $\mathbf{P}^a$ given above - are obtained via

$$\mathbf{X}^a = \mathbf{X}^b \mathbf{W}^a,$$

where $\mathbf{W}^a = [(k-1)\tilde{\mathbf{P}}^a]^{1/2}$

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COSMO Priority Project KENDA

COSMO: **Co**nsortium for **S**mall-scale **Mo**deling (Germany, Switzerland, Italy, Greece, Poland, Romania and Russia)

KENDA
(Km-Scale Ensemble-Based Data Assimilation)

TASK: To develop a separate DA scheme for the convective scale (in which conditions such as non gaussianity, strong non linearity, flow dependent and poorly know balance are much more dominant), and to use a similar approach for a generalized system for global and regional modelling.

The main FOCUS of the KENDA project has been on the algorithmic development of the LETKF

↓

Assimilation of conventional observations and (work in progress) high resolution remote sensing data (radiances, RADAR data, screen level observations, ground based GNSS slant path delay, **ASCAT soil moisture**)

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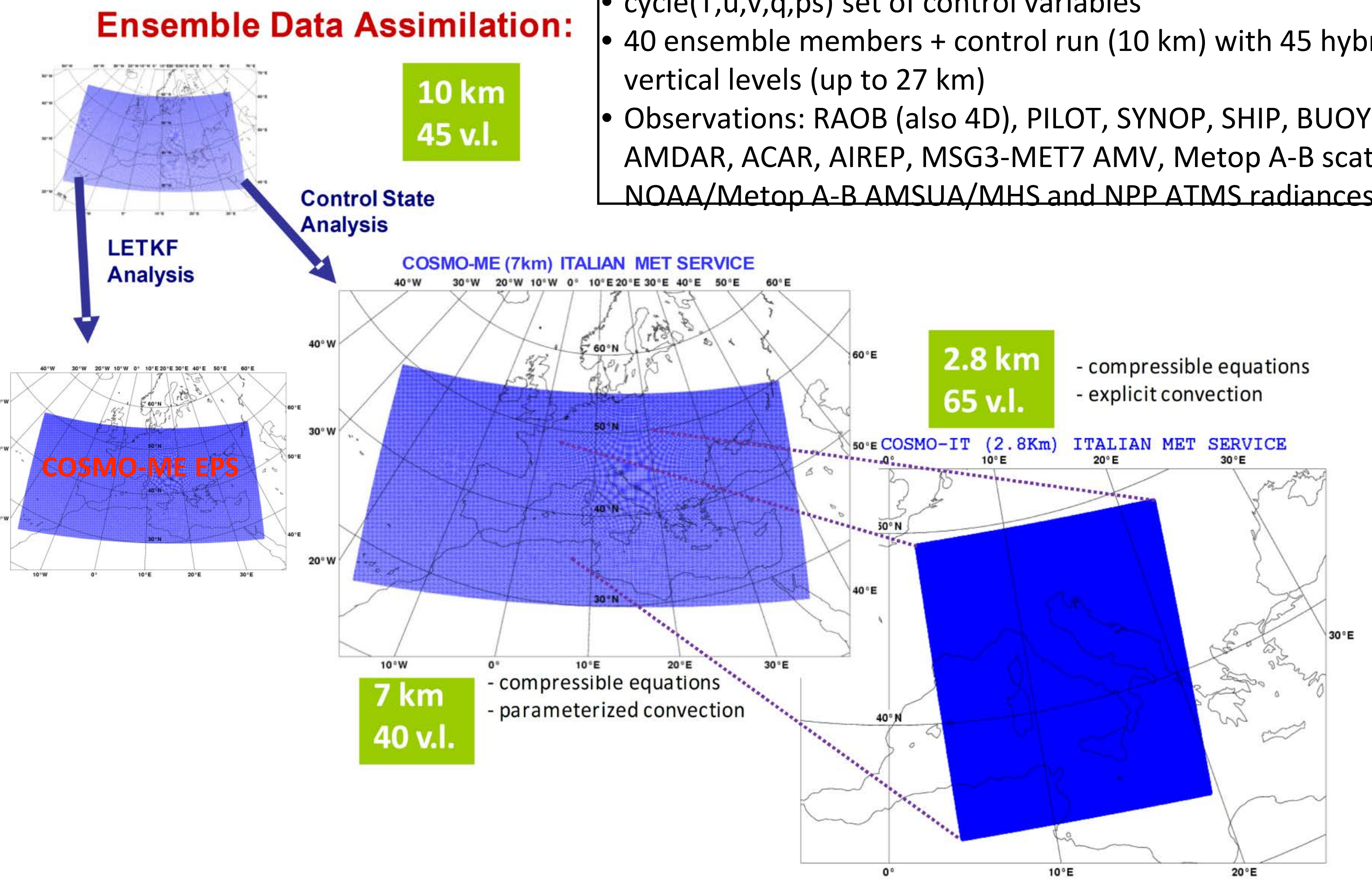
COMET NWP system

- 6 hourly intermittent data assimilation
- cycle(T,u,v,q,ps) set of control variables
- 40 ensemble members + control run (10 km) with 45 hybrid z-sigma vertical levels (up to 27 km)
- Observations: RAOB (also 4D), PILOT, SYNOP, SHIP, BUOY, Wind Profiler, AMDAR, ACAR, AIREP, MSG3-MET7 AMV, Metop A-B scatt winds, NOAA/Metop A-B AMSUA/MHS and NPP ATMS radiances



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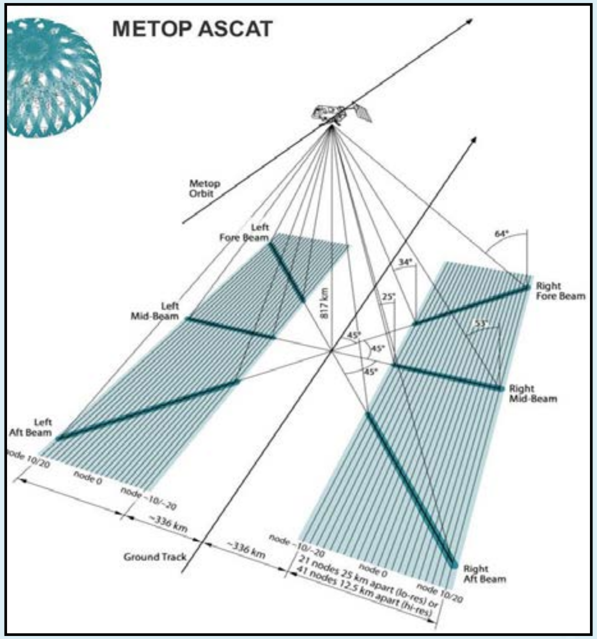
H-SAF ASCAT Soil moisture products (1)

ASCAT soil moisture Data provided by EUMETSAT within the H-SAF project, one of the 8 EUMETSAT SAFs, lead by the Italian Air Force Met Service



- frequency: 5.3 GHz (microwave C-band)
- VV polarization
- Able to provide a triplet of backscattering coefficients σ_0 for each swath
- 25 km resolution

From backscattering coefficient measurements it is possible to retrieve the **soil moisture content** in **the first 2 cm below the soil** by mean of **microwave technique** thanks to the high sensitivity of microwaves to the water content in the soil surface layer (for microwave frequencies in the C-band (< 10 GHz) the addition of liquid water to the soil strongly increases the soil dielectric constant, and so the backscattering coefficients).

H-SAF ASCAT Soil moisture products (2)

σ_0 affected by:

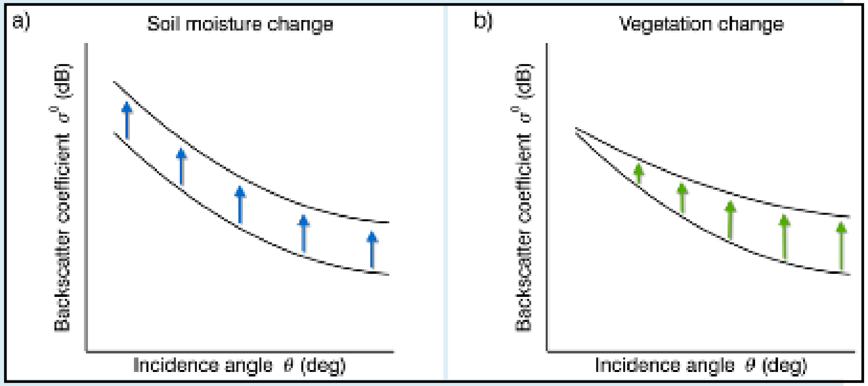
- soil moisture content
- incidence angle
- land cover (vegetation)
- surface roughness

CHANGE DETECTION ALGORITHM (TU Wien):

Backscatter measurements are extrapolated to a reference incidence angle (40°) and corrected for the influence of vegetation; then they are compared to equivalent existing wet and dry backscatter reference, also defined at 40°. As a result, time series of the topsoil (2 cm) moisture content are obtained in relative units <u>(degree of saturation)</u>

Basic assumptions:

1. The relationship between the backscattering coefficients and the surface soil moisture content is linear.
2. The backscattering coefficient depends strongly on the incidence angle.



3. An increase in soil moisture simply shift the backscattering-angle of incidence curve upwards, while a change in vegetation affects its shape. For sparse vegetation, the curve tends to drop off rapidly, while for fully grown vegetation it becomes less steep.

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Adaptation of COMET NWP system to KENDA

September 2015:

Start of the migration from COMET-LETKF code to the KENDA-LETKF code

PRE-OPERATIONAL

WHAT HAS BEEN DONE ?

- Creation of feedback files (containing observations and observation increments) as KENDA-LETKF input. Both for conventional and satellite observations
- Introduction of a different reference atmosphere
- Introduction of a variable horizontal localization with different length scales for different vertical levels
- Some modifications to run the KENDA-LETKF code in full resolution
- Bug errors fixed

NEXT STEP →

Implementation of soil moisture observations assimilation within the KENDA-LETKF code

- Adaptation of COMET NWP system to KENDA (implementation of KENDA-LETKF code in the COMET NWP system)
- Processing of available satellite soil moisture products: computation and monitoring of ASCAT soil moisture observation increments
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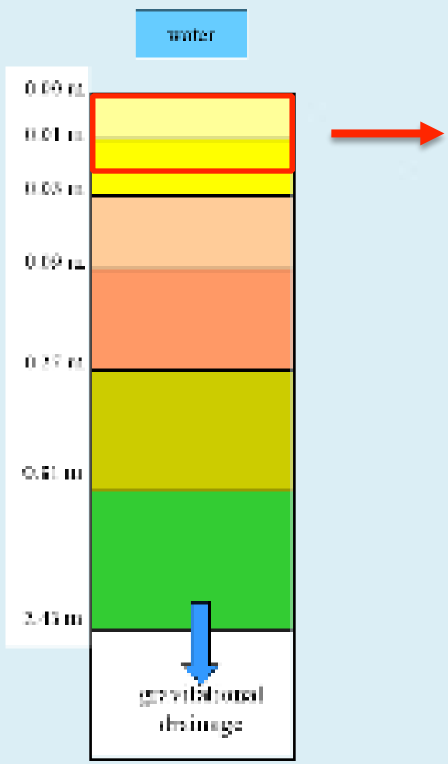
Transformed SOIL MOISTURE

- ASCAT derived Soil Moisture: **<u>degree of saturation</u>** (%) in the first 2 cm
- COSMO TERRA_ML model soil moisture: **<u>liquid water content</u>** (m H_2O) in the various model layers



layer structure of the hydrological part of the COSMO TERRA_ML soil model

To compare observed and model values the model values are transformed (to have quantities independent from the thickness of the layers) in **<u>volumetric water content</u>** (m^3/m^3) and then interpolated in the first 2 cm

+

NEED TO RESCALE THE SATELLITE OBS TO THE MODEL VALUES

- CDF matching method
- Normalization methods

CDF matching

To scale the ASCAT derived soil moisture to the model climatology so that the cumulative distribution functions (CDF) of satellite and model soil moisture match.

SAMPLE CDF definition

Let $X_1,\ldots,X_n$ be independent and identically distributed aleatory variables with distribution function (cdf) F(x).

The sample cumulative distribution function is defined as

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} 1(x_i \le x)$$

The concept of CDF was used in similar studies (Drusch et al 2005, Drusch 2007) to effectively remove biases of soil moisture observations.

This method doesn't allow deriving "correct" soil moisture. Rather it removes differences between satellite observations and model data by ensuring statistical consistency.

CDF matching: our implementation

<u>OUR STUDY:</u>

preliminary test on operational COMET NWP configuration (10 km)

- **16 months time series of ASCAT and model SM data (january 2015 - April 2016)**
- **model data from COMET-LETKF system (10 km grid spacing)**
- **2 options investigated for the choice of the soil type to assign to an ASCAT observation**

  - the soil type of the grid point closest to the observation
  - the most probable soil type among these of the 9 grid points closest to the observation

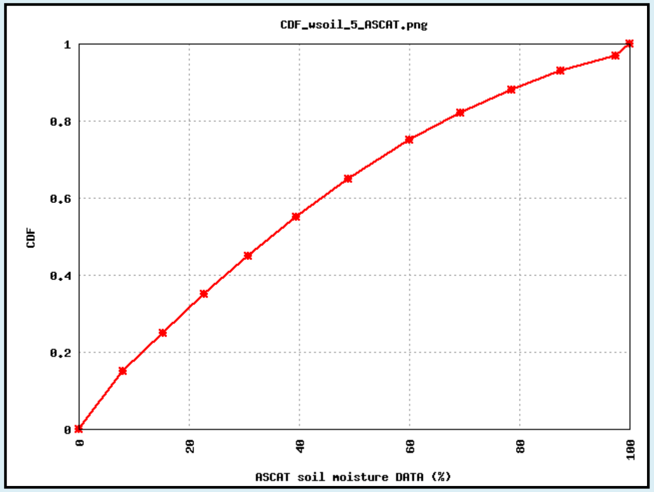
  (ASCAT resolution: 25 km, 10 km grid spacing)
- **CDF matching performed for each soil type separately**

  - COSMO TERRA_ML soil types: sand, sandy loam, loam, loamy clay, clay, peat
- **Piece wise sample CDF for ASCAT and model sm data, using 13 percentiles**

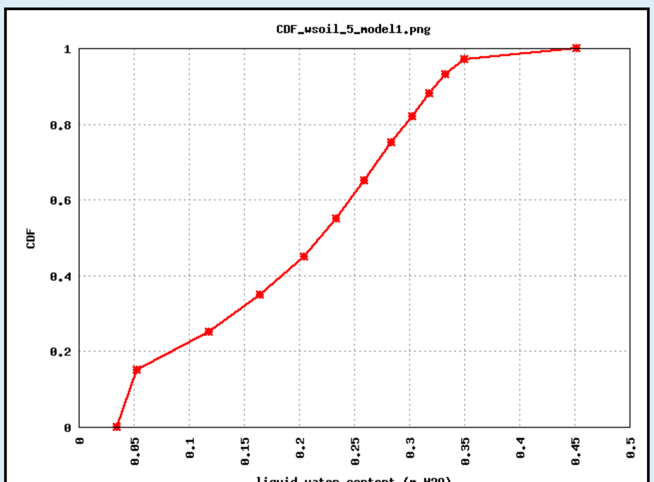
  0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95, 1
- **Linear regression analysis of ASCAT data plotted against model data**

  2 options investigated:
  - total regression analysis
  - local regression analysis

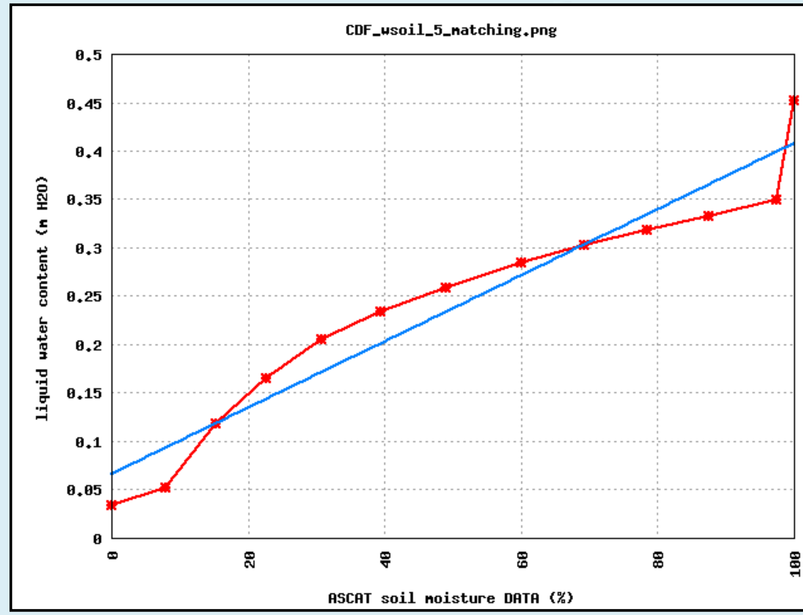
CDF matching: example



ASCAT sample CDF, loam, closest grid point



model sample CDF, loam, closest grid point



CDF matching:

local regression analysis

global regression analysis

$$\omega_{obs} = max\left(0, a + b\,\frac{\theta_{obs}}{100}\right)$$

b slope, a intercept

Normalization methods

$$\omega_{obs} = \omega_{ADP} + \frac{\theta_{obs}}{100}(\omega_{PV} - \omega_{ADP})$$

$$\omega_{obs} = \omega_{ADP} + \frac{\theta_{obs}}{100}\left(\frac{\omega_{PV} + \omega_{FC}}{2} - \omega_{ADP}\right)$$

soil type	1 ice	2 rock	3 sand	4 sandy loam	5 loam	6 loamy clay	7 clay	8 peat
volume of voids w_{PV} [1]	-	-	0.364	0.445	0.455	0.475	0.507	0.863
field capacity w_{FC} [1]	-	-	0.196	0.260	0.340	0.370	0.463	0.763
permanent wilting point w_{PWP} [1]	-	-	0.042	0.100	0.110	0.185	0.257	0.265
air dryness point w_{ADP} [1]	-	-	0.012	0.030	0.035	0.060	0.065	0.098

soil parameters values in the COSMO TERRA_ML soil model
8 different soil types: ice, rock, sand, sandy loam, loam ,loamy clay, clay, peat

Volume of voids: maximum possible volume of water that the soil can hold
Field capacity: amount of soil moisture held in the soil after excess water has drained away and the rate of downward movement has decreased.
Wilting point: the minimal amount of water the plant requires not to wilt
Air Dryness point: minimum possible amount of water that can remain in the soil

Observation increments statistics

The transformed ASCAT soil moisture data has to be compared to the equivalent model values

- **difference between the observed value and its model equivalent value (ensemble mean)**
- first guess values linearly interpolated in time
- 2 methods for space interpolation:
  - nearest grid point
  - average on the 9 nearest grid points
- model values calculated using the COMET-LETKF system
- 10 km resolution

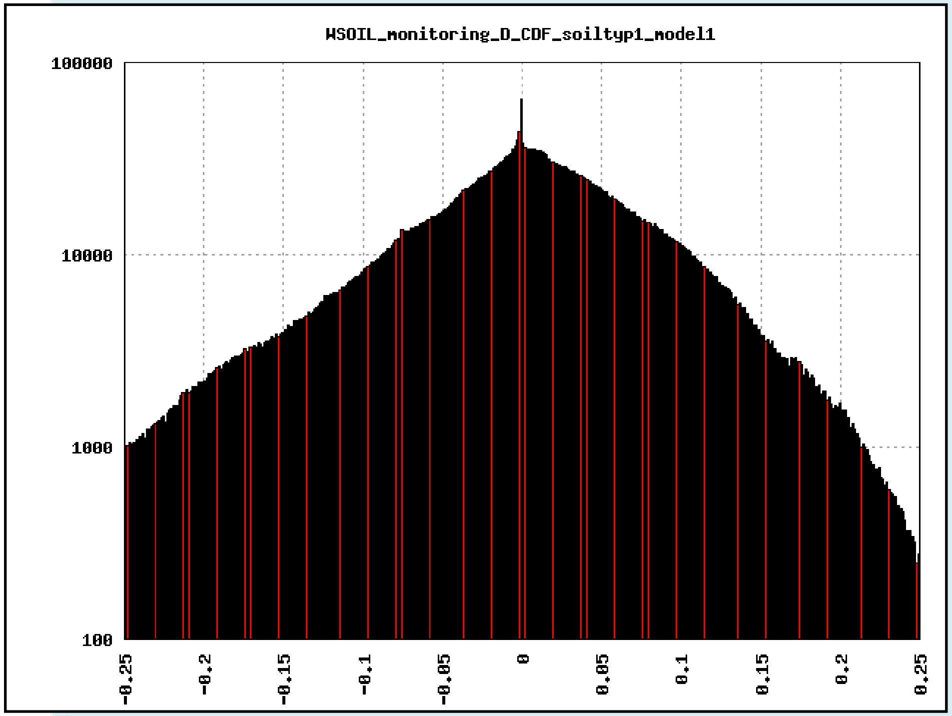
OBSERVATION INCREMENTS

quantity directly used in the LETKF algorithm

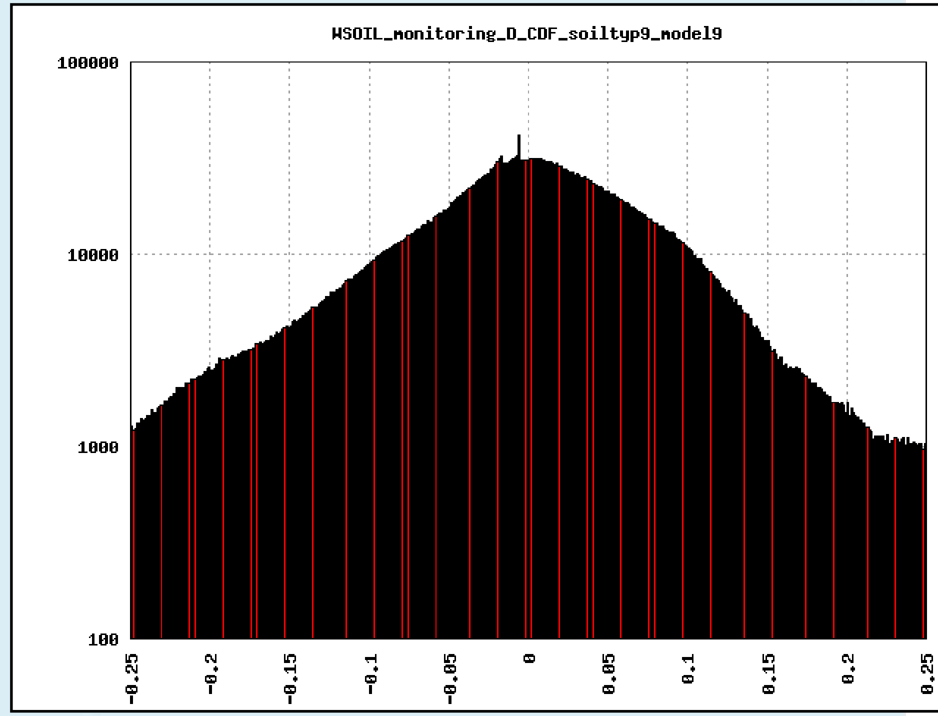
Because of the assumption of no bias and gaussianity for the ensemble-based DA, their distribution in terms of bias and symmetry will be analyzed

Evaluation of results (CDF) (1)

observation increments (january 2015 - April 2016)



soil type of the closest grid point



soil type most probable among the closest 9 grid points

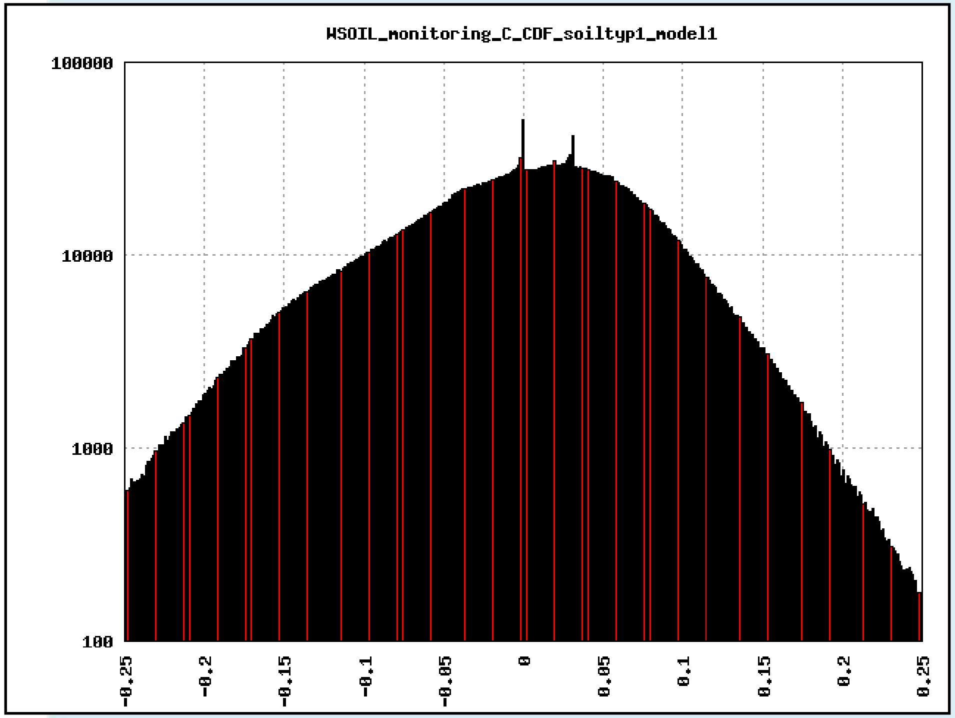
bias: 0.0008242
stdv: 0.0840188
symm: -0.3009857

local *regression analysis*

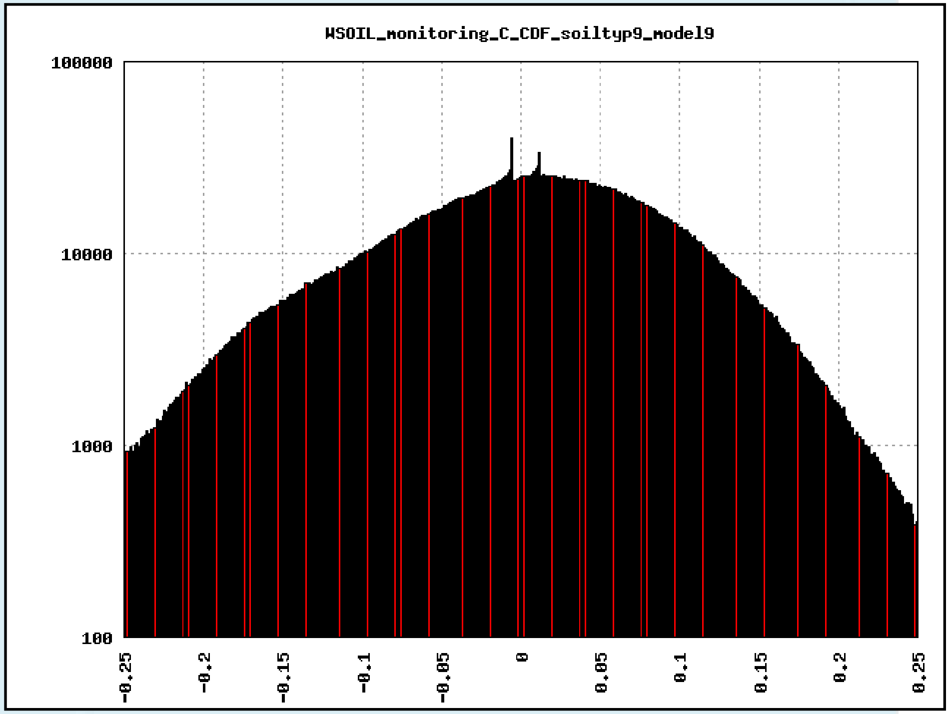
bias: 0.0030642
stdv: 0.0964125
symm: 0.2132559

Evaluation of results (CDF) (2)

observation increments (january 2015 - April 2016)



soil type of the closest grid point



soil type most probable among the closest 9 grid points

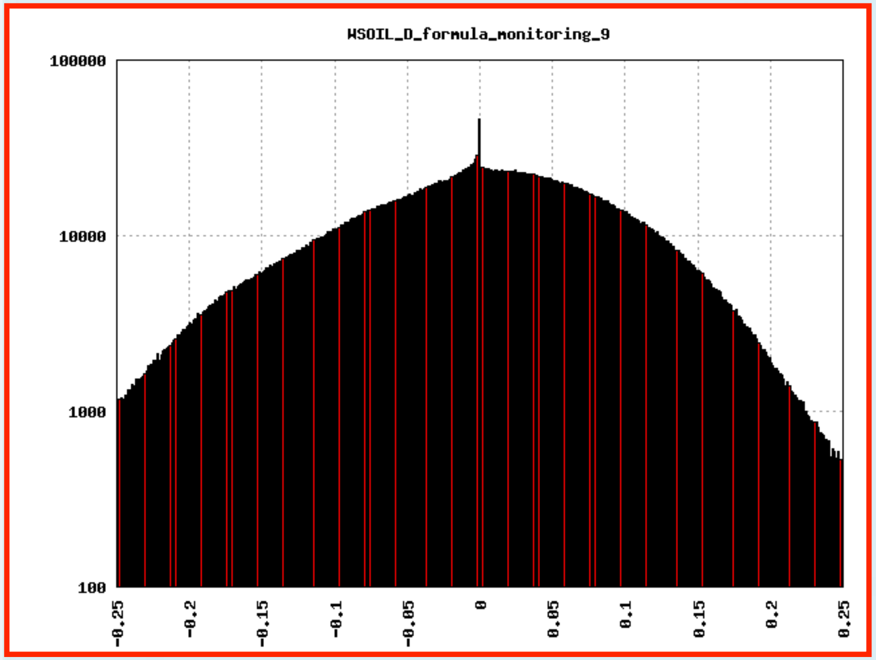
bias: -0.0012186
stdv: 0.0800698
symm: -0.3240673

***total** regression analysis*

bias: 0.0029384
stdv: 0.0905940
symm: -0.2627874

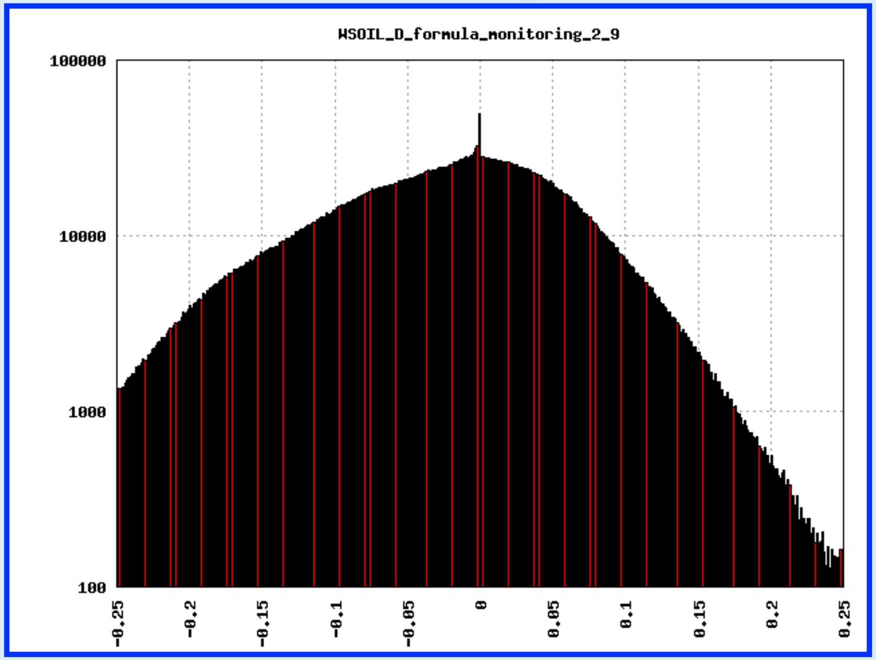
Evaluation of the results: normalization methods comparison

observation increments (january 2015 - April 2016)



***first formulation**, soil type most probable among the 9 closest grid points*

BIAS: 0.0004021
SYMM: -0.2597088



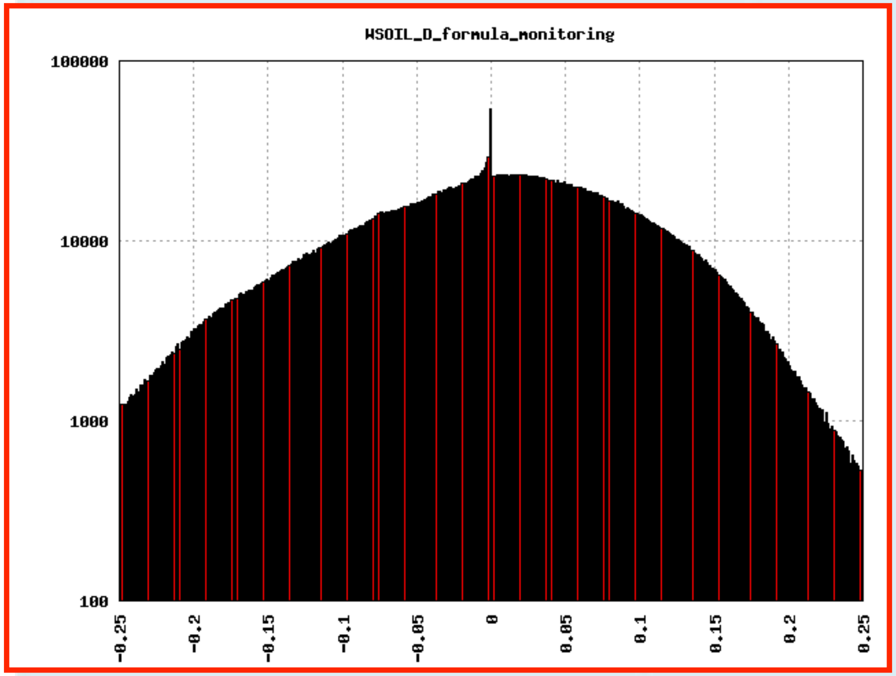
***second formulation**, soil type most probable among the 9 closest grid points*

BIAS: -0.0251703
SYMM: -0.3667752

The first formulation is better in terms of bias and symmetry

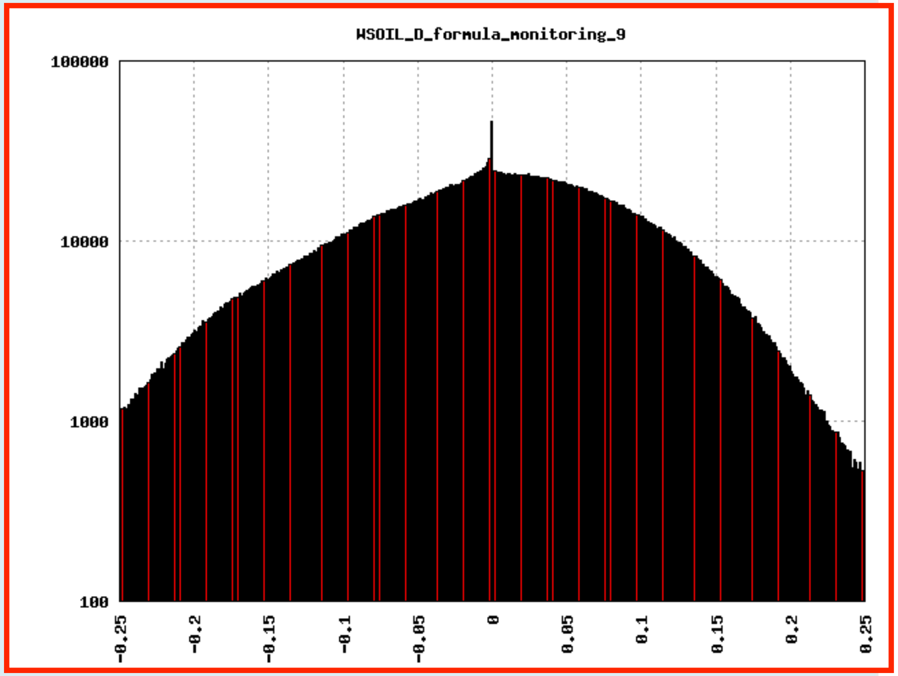
Evaluation of the results (first normalization method)

observation increments (january 2015 - April 2016)



soil type of the grid point closest to the obs

BIAS: 0.0012154
SYMM: -0.3793990



soil type most probable among the 9 grid points closest to the obs

BIAS: 0.0004021
SYMM: -0.2597088

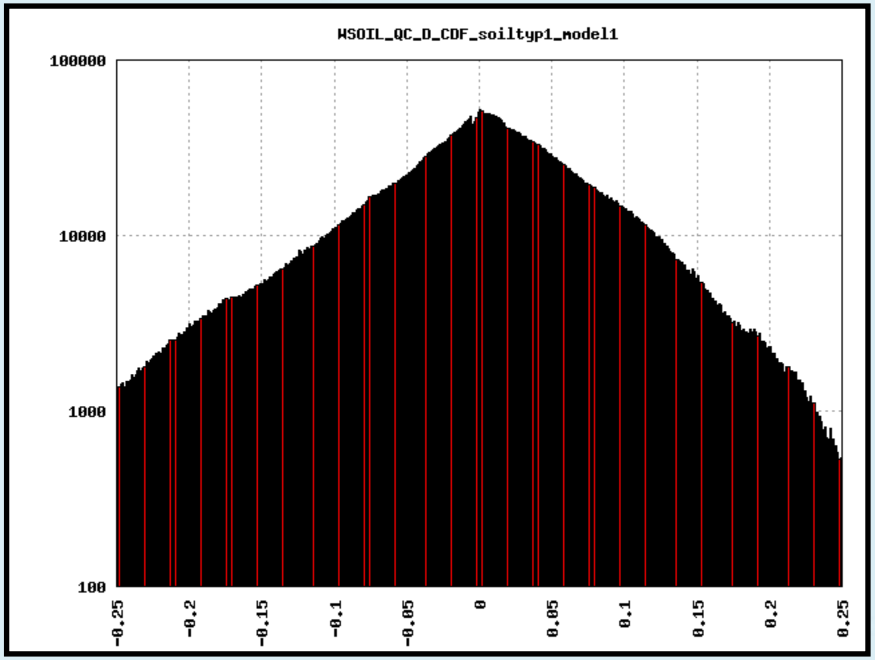
Conversely with respect to the CDF matching method, with this normalization the choice of soil type most probable among the 9 closest grid point is better in terms ob bias and symmetry

Evaluation of the results

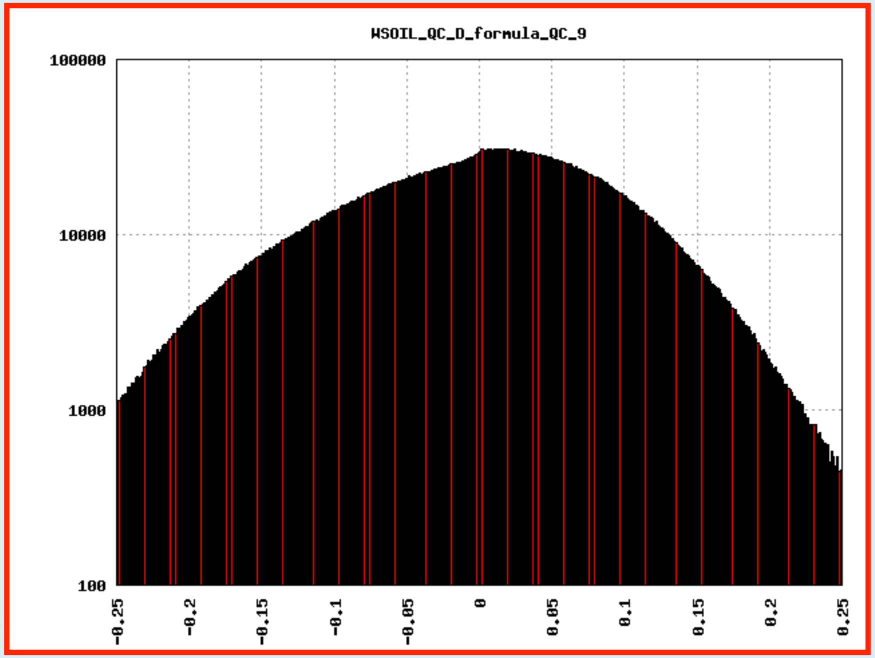
observation increments (january 2015 - April 2016)

The soil moisture's observation increments are **highly non gaussian**, too concentrated around the value 0, due to a **large percentage of dry conditions**

OBSERVATION INCREMENTS STATISTICS WITHOUT 0 VALUE OBSERVATIONS



CDF method, soil type of the closest grid point



first formulation, soil type most probable among the 9 grid points closest to the obs

Evaluation of the results (CONCLUSIONS)

In terms of the observation increments, the best results have been obtained with:

- **CDF matching method**

  soil type of the nearest grid point

  local regression analysis

- **Normalization method**

  First formulation

  soil type = most probable among the soil types of the 9 closest grid points

BOTH THE METHODS WILL BE TESTED IN THE ASSIMILATION USING THE KENDA-LETKF CODE

- Adaptation of COMET NWP system to KENDA (implementation of KENDA-LETKF code in the COMET NWP system)
- Processing of available satellite soil moisture products: computation and monitoring of ASCAT soil moisture observation increments
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Quality Control before assimilation of ASCAT soil moisture DATA (1)

Soil moisture cannot be estimated if the fraction of dense vegetation, open water, snow/frozen soils, mountains, sand dunes and/or wetlands dominates the scatterometer footprint

PRELIMINARY CHECKS

ASCAT data is rejected where:

- *snow:* the analysed snow amount is greater than 0.05 kg/m^2
- *frost:* the 2m Temperature analysis is below 275.15 K
- *wetlands:* the inundation and wetland amount has a value greater than 15%
- *mountains:* the topographic complexity has a value greater than 20%
- *ASCAT estimated error:* the error in the ASCAT surface soil wetness is estimated to be greater than 7% (Met Office) or 8% (ECMWF). This check rejects ASCAT data from regions with dense vegetation and sand dunes.

Quality Control before assimilation of ASCAT soil moisture DATA (2)

BACKGROUND QUALITY CONTROL → an observation is discarded if its observation increment is larger (in absolute value) than a value which is typically in a range between 2 and 3 times a typical climatological standard deviation

The standard deviation is calculated considering a long period of data (observation increments) and pulling out the **gaussian distribution** that best fits them

BUT:

The soil moisture's observation increments are **highly non gaussian**, too concentrated around the value 0 (due to the fact that the obs incr are very close to the 0 value in dry and saturated condition) → **To avoid discarding good quality observations, a control variable for the soil moisture whose increments have a gaussian behavior could be obtained, so to apply the quality control to this control variable**

Construction of a gaussian control variable for the ASCAT soil moisture DATA (1)

method proposed by Holm (2001) to find a variable for humidity with gaussian forecast differences

- Find a variable φ whose forecast difference $\delta\varphi$ follows a gaussian conditional error distribution $P(\delta\varphi|\Phi)$ as a function of some variable Φ;
- Determine the bias ($b(\Phi)$) and standard deviation ($\sigma(\Phi)$) of the forecast differences as a function of Φ, with the bias preferably negligible;
- Normalize forecast differences by the bias and standard deviation,

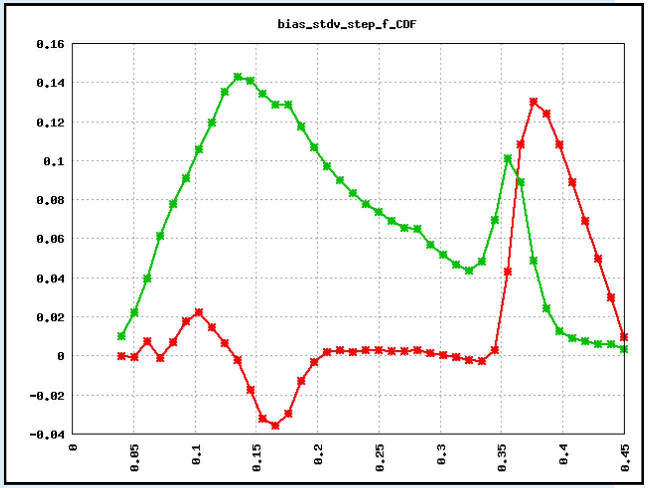
$$\bar{\delta\varphi} = \frac{\delta\varphi - b(\Phi)}{\sigma(\Phi)}; \qquad (1)$$

- Change the control variable according to equation 1.

IDEA: to apply the Holm method to the obs increments instead of to the forecast differences

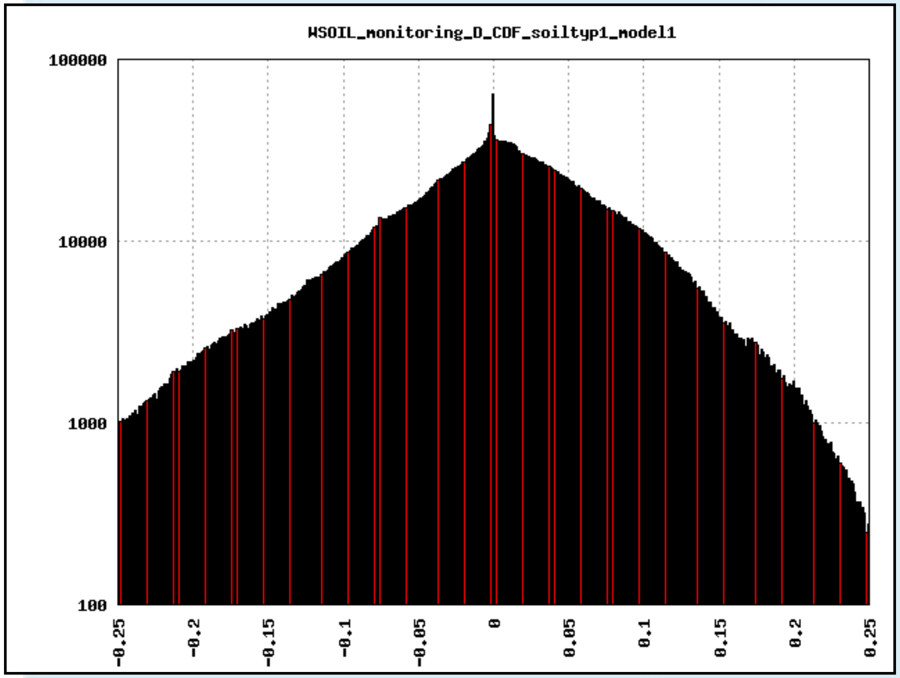
- φ = soil moisture observation
- Φ = average between soil moisture obs and its model equivalent
- Step functions for bias and stdv **for each soil type**, partitioning the interval between the max and min value of Φ 40 bins

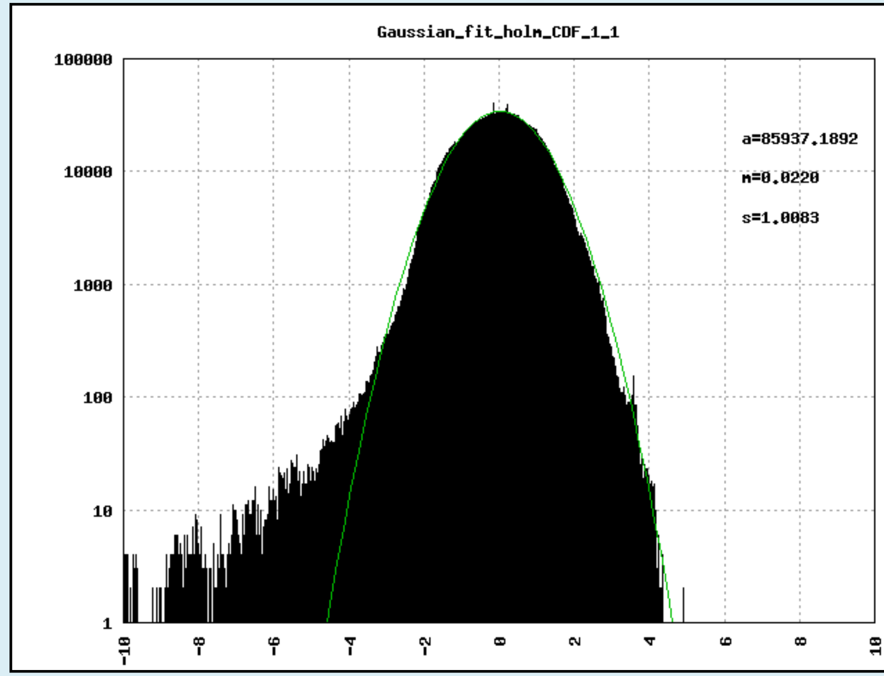
soil type: loam



Construction of a gaussian control variable for the ASCAT soil moisture DATA (2)

obs increments (CDF method) (january 2015 - April 2016)





not normalized obs incr

bias: -0.0012186
stdv: 0.0800698
symm: -0.3240673

normalized obs incr

bias ~ 0
stdv ~ 1
symm = -0.18

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Soil moisture assimilation in KENDA-LETKF code

Assimilation of ASCAT soil moisture observations to influence low levels atmospheric variables

Implementation of a suitable soil moisture analysis

Soil moisture assimilation in KENDA-LETKF code

FIRST STEP → Definition of soil moisture feedback files (containing the observation increments - only related to the good quality obs):
INPUT for KENDA-LETKF code

Properties:

Values introduced in the KENDA-LETKF code (mo_dfbk_tabkes.f90) to indentify an ASCAT soil moisture observation in the fdbk file:

obstype = 15 (observation type)

codetype = 305 (code type)

varno = 10 (liquid water content, quantity observed)

Soil moisture assimilation in KENDA-LETKF code

Values stored in fdbk files, to describe the characteristics of the ASCAT soil moisture observations:

surftype = definition of soil type of the closest grid point or the most probable among the 9 grid points closest to the obs (from 1 to 8)

obs = value of soil moisture obs in form of volumetric water content - m^3/m^3

veri_data = first guess value (2cm = level1+ ½ level2)

e_o = variable that contains the error associated to the soil moisture obs: 2 x BUFR estimated error (suggested by P. De Rosnay ECMWF 1 │3 → to be estimated by Desroziers statistics after data assimilation cycle)

level = 0 (hight of station)

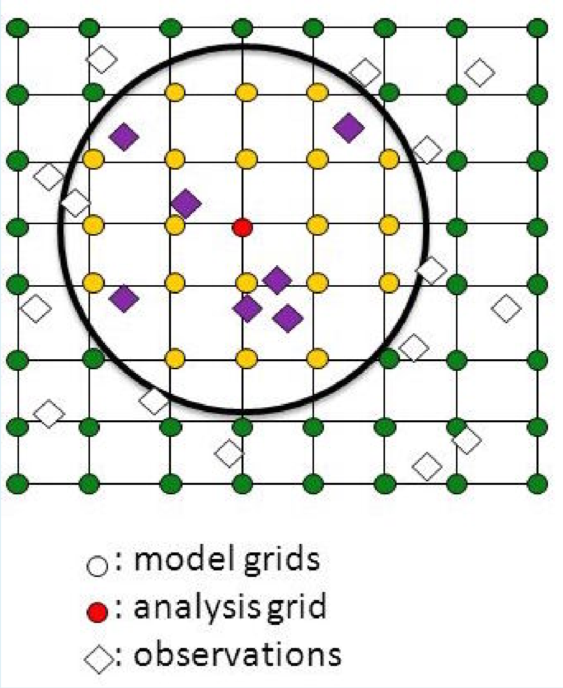
level_type =0 (number of channel … spurious!!)

plevel = first guess sfc pressure (at the nearest grid point)

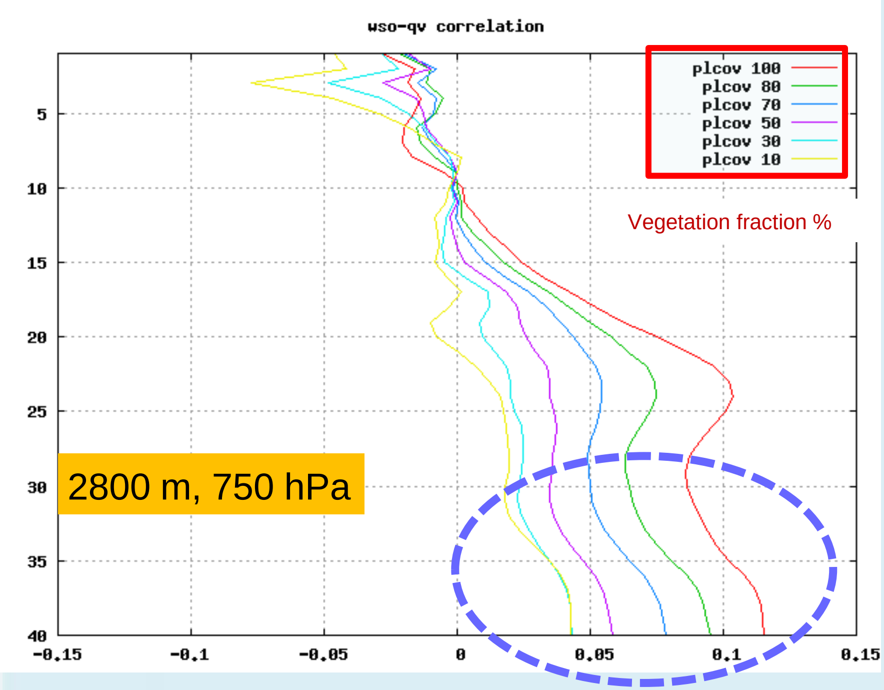
Soil moisture assimilation in KENDA-LETKF code

SECOND STEP → Reading of the ASCAT soil moisture feedback files in the KENDA-LETKF code, in order to use them to influence the atmospheric variables at low levels, in particular temperature and humidity.

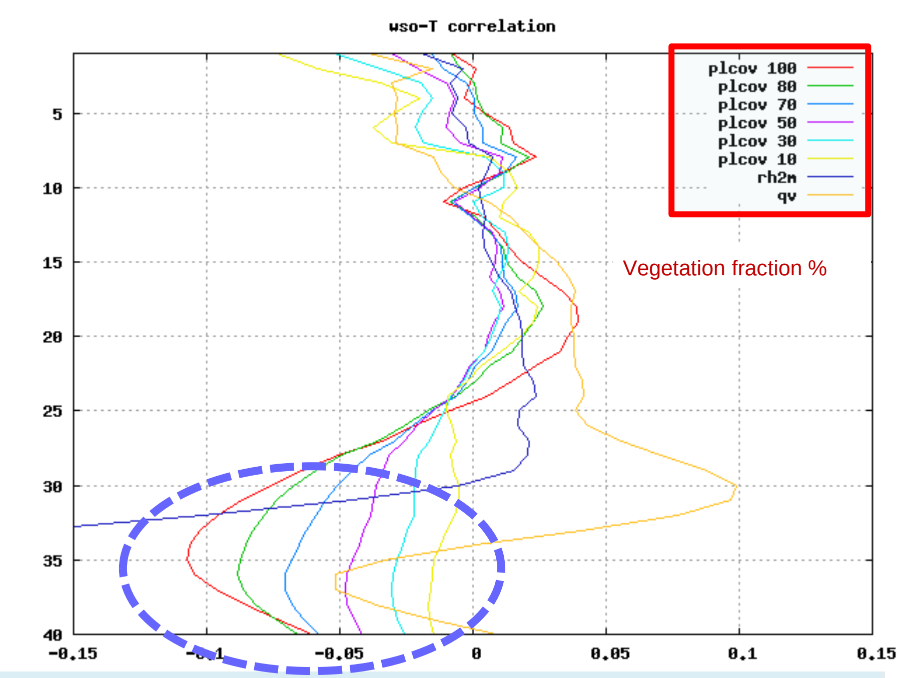
WHICH CHOICE FOR THE HORIZONTAL AND VERTICAL LOCALIZATION LENGHTSCALE?



Soil moisture assimilation in KENDA-LETKF code



soil moisture - humidity vertical correlation



soil moisture - temperature vertical correlation

lv_wso (vertical lenghscale) set in order to influence the atmospheric variables until level 30 approximately

lh_wso (horizontal lenghscale) set actually to have an influence radius of 100 kms approximately

Soil moisture assimilation in KENDA-LETKF code

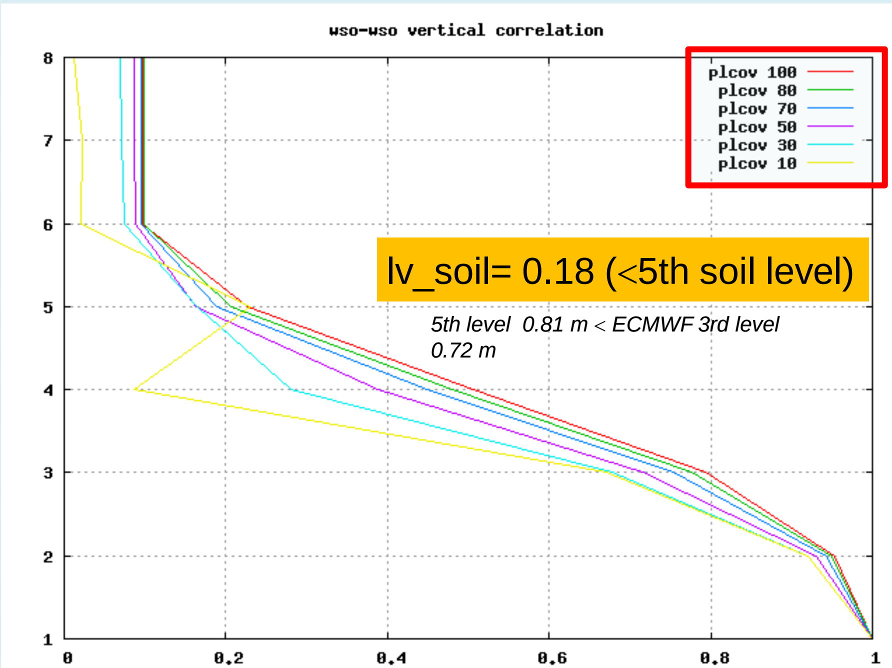
THIRD STEP → ***Definition of a suitable soil moisture analysis***

Main characteristics:

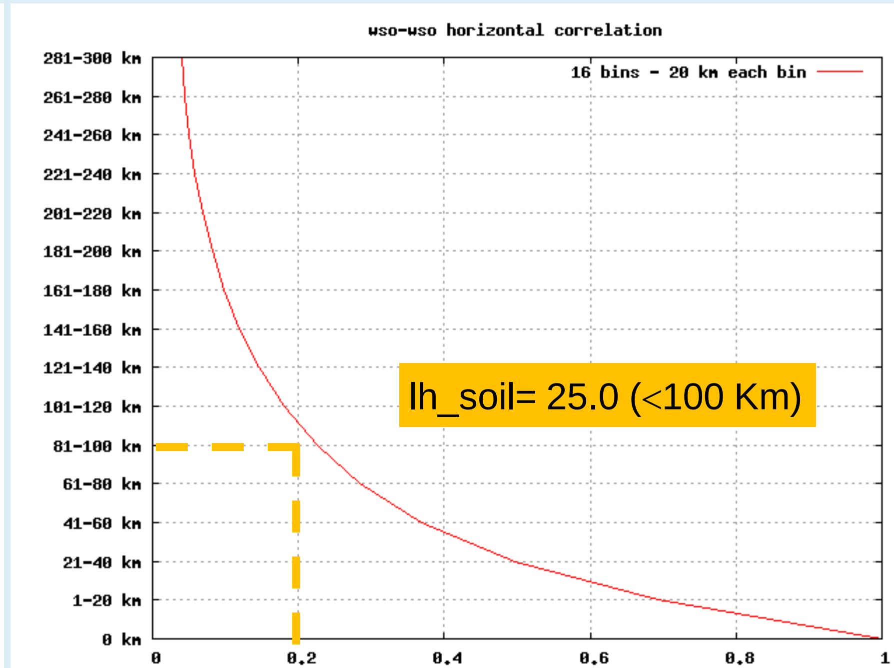
- soil moisture analysis based on the same LETKF algorithm used for the atmospheric analysis, but with a different suitable weight matrix
- same horizontal resolution of the atmospheric analysis
- eight different vertical soil levels (possibility to decide by namelist which levels to consider for the analysis - default value: the first 5 levels)
- use of ASCAT soil moisture observations to assimilate in the soil moisture analysis, and optionally (by namelist) possibility to assimilate the T2m and RH2m synop observations

WHICH CHOICE FOR THE HORIZONTAL AND VERTICAL LOCALIZATION LENGHTSCALE?

Soil moisture assimilation in KENDA-LETKF code



soil moisture - soil moisture vertical correlation



soil moisture - soil moisture horizontal correlation

lv_soil choosen to influence the first five soil levels, according to the soil moisture vertical correlation and the ECMWF choice
lh_soil choosen to influence the first 100 km, according to the soil moisture horizontal correlation

Comparison between old and new version of soil moisture analysis in the KENDA-LETKF code

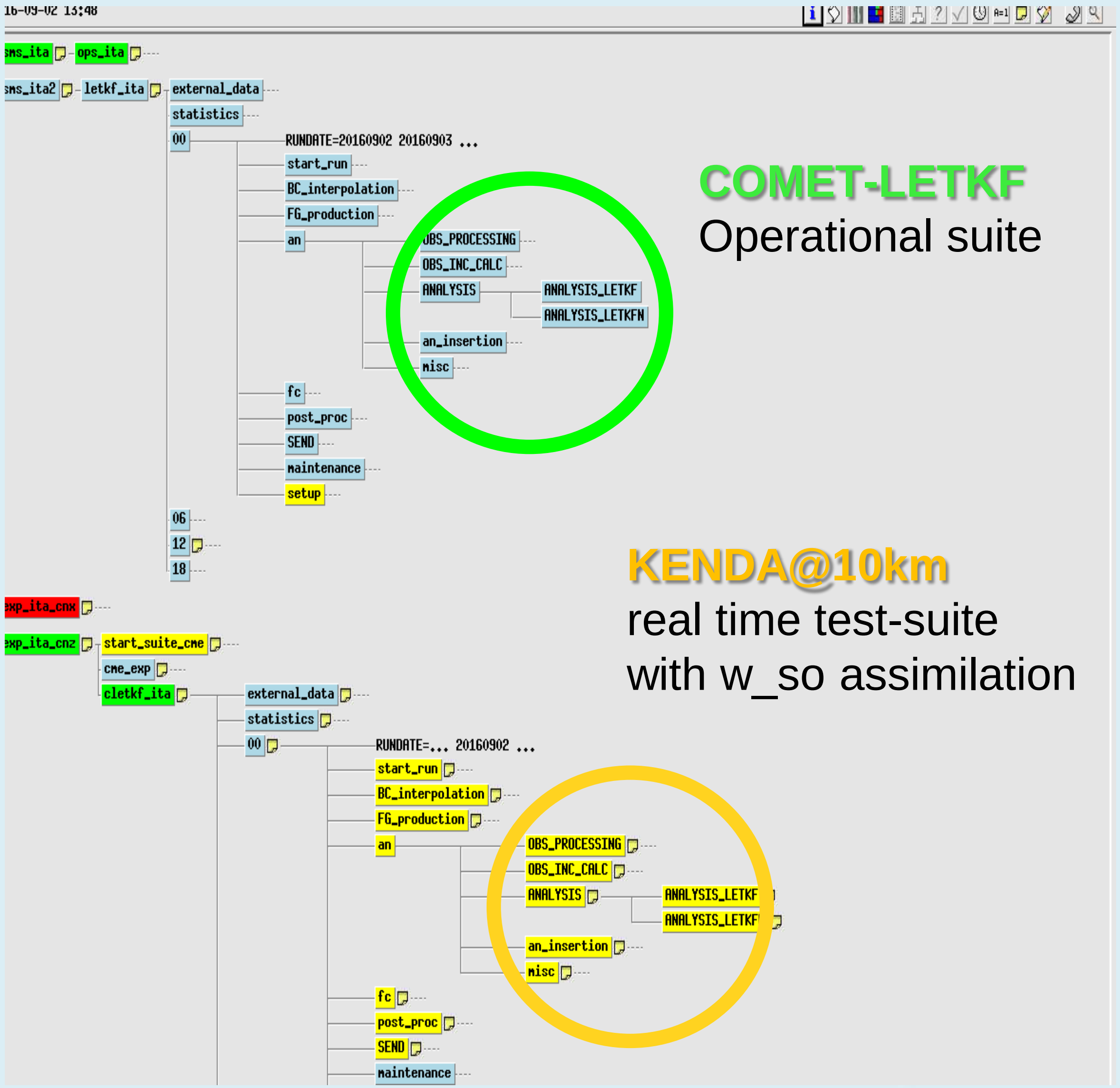
OLD VERSION

- ***Soil moisture and soil temperature analyzed together***
- ***Weight matrix (lower level) computed using all observations (except soil moisture obs)***
- ***It is possible to run the old version of KENDA-LETKF setting the namelist variable l_soil_ana to false.***

NEW VERSION

- ***Soil moisture and soil temperature analyzed separately***
- ***New version can be run setting the namelist variable l_soil_ana to true***
- ***SOIL MOISTURE ANALYSIS: Ad hoc weight matrix computed considering the soil level and only the soil moisture observations (eventually it is possible to assimilate also the 2m temperature and the 2m humidity synop observations)***
- ***ATMOSPHERIC ANALYSIS: soil moisture observations also influence the low level atmospheric variables***
- ***Different localization scales for soil moisture observations***

Soil moisture assimilation in KENDA: implementation of a parallel suite…waiting for results



COMET-LETKF
Operational suite

KENDA@10km
real time test-suite
with w_so assimilation

Soil moisture assimilation: future developments

1. Evaluation of results, and comparison considering different lenghtscales

2. tuning at higher resolution (2.8 km), in the framework of using LETKF algorithm to initialize COSMO-IT model

Thanks for your attention!

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