# Validation of EKF surface assimilation scheme

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# Motivation I

- Surface affect screen level variables directly through heat and vapor fluxes
- Indirectly it affects also cloudiness and precipitation

- Most important soil state variables over NATURE covers are:
    - Soil water content (this should include also ice)
    - Soil temperature
    - Snow cover: alters soil-air heat exchange and water transport

# Soil water content

Soil water content plays crucial role

- It alter heat conduction in the soil: thermal conductivity $\lambda$ varies over several order with soil water content

Main soil-atmosphere water exchange processes

- Soil water is transported into atmosphere by *evapotranspiration*
- Transpiration from vegetation $\approx 80\%$
- Direct evaporation from bare soil surface $\approx 20\%$
- Water is transported to soil from atmosphere by precipitation

# Soil analysis at OMSZ for AROME 2.5 km

## Operational surface analysis

- Downscaled ALARO 8km surface analysis

Two alternative methods are currently tested at OMSZ:

1. OI_MAIN (Optimal interpolation) – in parallel suit since 09/2016
2. EKF (Extended Kalman filter) – implementation phase, requires validation

# OI_MAIN vs. EKF comparison

- It is believed that properly implemented EKF could bring a superior result over the OI_MAIN
- Main difference between OI_MAIN and EKF surface analysis is that OI_MAIN uses fixed weights in calculation analysis increments from background departures while EKF uses Kalman gain recalculated at each assimilation cycle to minimize analysis error, instead of fixed weights.
- Helga Tóth on 2016 DAWD presented comparison of OI_MAIN and EKF for AROME-HU domain. Results were rather contradicting: Spatial distribution and magnitude of analysis increments differ substantially for all control variables (TG1, TG2, WG1, WG2)

# Goals

- Implement EKF for assimilation conventional and satellite observations in AROME-HU parallel suite.
- Compare scores with OI_MAIN par-suite and operational ALARO downscaled analysis.
- If EKF proves its superiority use it as primary option in operational suite.

## Intermediate steps

1. Validation of SURFEX-EKF method with 1-column setup using only conventional observations first [ongoing]
2. Validation of EKF implementation for AROME-HU
3. Parallel execution of reference an perturbed offline SURFEX
4. Consider using the SODA framework with NETCDF forcing files (currently ASCII forcing)
5. Assimilate satellite SWI observations

# Validation of SURFEX-EKF method I

## Atmospheric situation

1. Begin with most simple situations:
   no precipitation, no snow cover
2. Should some situations be rather discarded from analysis as they can mess EKF?

## SURFEX related options

# Validation of SURFEX-EKF method II

1. Compare 3 ISBA soil schemes: 2-L, 3-L, DIF and consider proper initialization of each
2. Compare Geleyn's diagnostic scheme and Masson prognostic CANOPY scheme as observation operator
3. Compare 1-patch vs multiple-patches
4. Sensitivity to PGD, i.e. changing cover type

## EKF related options

1. Combination of LBEV and LBFIXED option
2. Validity of calculated analysis increment (beginning or end of assimilation window)
3. Possibility to specify size of perturbations in relative and absolute units

# Method

**Main ideas**

- Only conventional screen level observations were assimilated
- 1-column SURFEX configuration
- Observation and model location is same
- Observation vector $\mathbf{y}_o = (T2M, RH2M)$: CANARI gridded observations replaced with in-situ observations
- Offline SURFEX forcing: AROME short range forecast replaced with in-situ 10m tower observations

# Full-grid VS. validation setup

Main differences:

1. Horizontal domain
    - FG: Full AROME-HU grid (490x310 boxes)
    - 1C: Only 1 grid box
2. Observation vector (T2M, HU2M)
    - FG: CANARI (OI analysis) gridded observations
    - 1C: 2m measurements from same location as model location
3. Offline SURFEX forcing series
    - FG: Short-range (1-6 h) AROME forecasts (analysis) for lowest model level $\approx 10m$ + surface radiative and precip.
    - 1C: 10m tower observations from same location as model one

# Why 1-column SURFEX setup

- Principle is same as for full-grid
- Run-time reduced by several orders ⇒ increases efficiency of validation proportionally
  e.g., we can test more options for less time

# Why to replace CANARI gridded obs. with real observations

- More controlled conditions
- Runs with exact observation have minimal error and can be used as reference
- Errors can be put-in separately in controlled manner and examine its effect on analysis result

# Initialization of ISBA soil schemes I

- Mostly force-restore scheme were tested
- Using the observations of soil temperature and water content at 10, 20, 30, 40, 50, 60, 80, 100, 200 cm.

# Soil heat transport scheme initialization

- Heat transfer: 2L force-restore scheme
- TG1: superficial temperature (average temperature of thin $\approx 1cm$ soil layer including vegetation)
- TG2: average of TG1 for last 24 hours
- SURFEX automatically adds height correction $k * \mathsf{ZS}$ for manually prescribed temperatures using vertical gradient $k = -0.0065\,\mathrm{K/m}$
- This was eliminated by subtracting correction prior to be written to `&NAM_PREP_ISBA`:

$$\mathrm{TG}_{\mathrm{nml}} = \mathrm{TG}_{\mathrm{prep}} - k * \mathrm{ZS} \tag{1}$$

where $\mathrm{TG}_{\mathrm{prep}}$ is intended initial soil temperature written to output PREP.txt.

# Water transport scheme initialization I

- Water transport: 2L or 3L force-restore scheme
- WG1: superficial soil volumetric water content (VWC) – average VWC of thin $\approx 1cm$ soil layer
- WG2: Average VWC in bulk soil layer (2L scheme) or average VWC in root zone layer (3L scheme)
- WG3: Average VWC in deep soil layer (3L)
- Prescribed values in `&NAM_PREP_ISBA` are assumed to be soil wetness index (SWI) but observations represent VWC. Conversion:

$$\mathrm{SWI} = \frac{W_g - W_{\mathrm{wilt}}}{W_{\mathrm{fc}} - W_{\mathrm{wilt}}} \tag{2}$$

- Ensured that same pedo-transfer function is used in EKF source code as in SURFEX for hydrolimits calculation

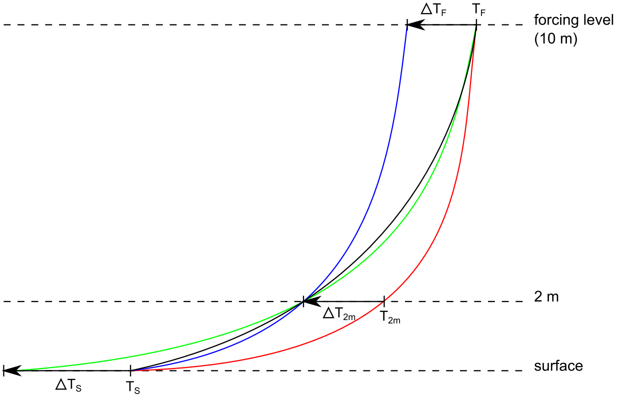
# Soil diffusion scheme

- Water and heat transport
- Arbitrary number of layers, default 14
- If used in EKF analysis, control vector should contain same variables as with force-restore scheme
- Integration is in full state space, $\approx 3 \times 14$ variables for default configuration
- Reduction operator from state space to control space expresses averaging over all layers which are in depths of bulk or root layer of 2L/3L scheme
- TG1, WG1 correspond to upper-most layer of DIF scheme

# Observation model $\mathcal{H}$ (SURFEX vertical scheme)

- Observation model maps soil variables (TG1, TG2, WG1, WG2) to screen-level variables (T2M, RH2M)
- In offline SURFEX there are 2 different options:
  1. Prognostic CANOPY (Masson)
  2. Diagnostic (Geleyn)
- Prognostic variant: Calculating T2M, RH2M involves integrating coupled ISBA + CANOPY from some previous time step
- Diagnostic variant: Does not involve ISBA integration in time, it requires just soil state and forcing at current time step

# Diagnostic vertical scheme



# Mapping the covariance matrix of estimation error in EKF theory I

- Matrices **M**, **H** are used to map covariance matrix of estimation error **B** (background) or **A** (analysis)
- They are linearized representations of models $\mathcal{M}$, $\mathcal{H}$
- **M** maps **B** or **A** from start to end of the assimilation window

$$\mathbf{M} = \left.\frac{\partial \mathcal{M}}{\partial \mathbf{x}}\right|_{\mathbf{x}_{k-1}} \approx \frac{\delta \mathbf{x}_k}{\delta \mathbf{x}_{k-1}}$$

- **H** maps **B** from control space to observation space in Kalman gain calculation. It represents local behavior of obs. model $\mathcal{H}$ in the vicinity of the guess $\mathbf{x}_b$ at the end of the assimilation window

$$\mathbf{H} = \left.\frac{\partial \mathcal{H}}{\partial \mathbf{x}}\right|_{\mathbf{x}_{k}} \approx \frac{\delta \mathbf{y}_k}{\delta \mathbf{x}_k}$$

# Mapping the covariance matrix of estimation error in EKF theory II

- Conventional Kalman gain matrix calculation

$$\mathbf{K} = \mathbf{B}^k \mathbf{H}^T (\mathbf{H}\mathbf{B}^k \mathbf{H}^T + \mathbf{R}^k)^{-1}$$

where

$$\mathbf{B}^k = \mathbf{M}\mathbf{A}^{k-1}\mathbf{M}^T + \mathbf{Q}$$

# Mapping the covariance matrix of estimation error in EKF source code I

- In Mahfouf et al., 2009 paper and in source code observation matrix is:

$$\tilde{\mathbf{H}} = \left.\frac{\partial \tilde{\mathcal{H}}}{\partial \mathbf{x}}\right|_{\mathbf{x}_{k-1}} \approx \frac{\delta \mathbf{y}_k}{\delta \mathbf{x}_{k-1}} \approx \mathbf{HM}$$

- Kalman gain calculation in source code:

$$\mathbf{K} = \mathbf{B}^k \tilde{\mathbf{H}}^T (\tilde{\mathbf{H}} \mathbf{B}^k \tilde{\mathbf{H}}^T + \mathbf{R}^k)^{-1}$$

## LBFIXED=TRUE, LBEV arbitrary

- Background error covariance matrix at time $k$ (end of assim win) is set from namelist (even if LBEV=TRUE):

$$\mathbf{B} = \mathbf{B}_{nam}$$

- For each assimilation window different $\mathbf{B}_{nam}$ can be set through namelist
- This effectively disables recursivity (cycling) of EKF as $\mathbf{B}$ is always reset to $\mathbf{B}_{nam}$
- Map $\mathbf{M}$ is not applied explicitly but implicitly by $\tilde{\mathbf{H}}$ in gain formula
- Model error covariance matrix $\mathbf{Q}$ is not added
- From that it seems that $\mathbf{B}_{nam}$ should correspond to beginning of assimilation window, i.e. it acts like $\mathbf{A}^{k-1}$ in recursive EKF

## LBFIXED=FALSE, LBEV=FALSE, cycling=NO

- $\mathbf{B}$ is initialized with $\mathbf{B}_{nam}$, then $\mathbf{Q}$ is added
- Matrix $\mathbf{M}$ is not applied (since LBEV=FALSE) but implicitly it is applied by $\tilde{\mathbf{H}}$ in $\mathbf{K}$ calculation
- New analysis is calculated but it is not used in next assimilation cycle because cycling is off.
- This is same as in previous mode only difference is that $\mathbf{Q}$ is now added

$$\mathbf{B}^k = \mathbf{B}_{nam} + \mathbf{Q}$$

## LBFIXED=FALSE, LBEV=TRUE

- $$\mathbf{B}^k = \mathbf{M}\mathbf{A}^{k-1}\mathbf{M}^T + \mathbf{Q}$$
- e.g. formula for $\mathbf{B}$ is conventional but in gain calculation $\tilde{\mathbf{H}} = \mathbf{H}\mathbf{M}$ is used instead of $\mathbf{H}$
- Is this combination allowed? Isn't $\mathbf{M}$ applied effectively *twice* in $\mathbf{K}$? Isn't it confusing?

# Validity time of analysis increment

- In EKF analysis equation analysis increment is valid at at time of observation
- In SURFEX-EKF some people indicated that $\Delta \mathbf{x}_a$ is valid for beginning of assimilation window and addition SURFEX integration is required to get to the end of assimilation window

Thank You