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Assimilation of Surface Soil Moisture using the Ensemble Kalman Filter

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Introduction: Why is Land Surface Modelling Important?

- Strong influence on atmospheric boundary layer forecast, through incoming energy (latent and sensible heat) and precipitation runoff [1].
- Improving short term weather forecast [2].
- Soil moisture is classified as an essential climate variable by ESA, through ESA's Climate Change Initiative (CCI) Program.
- Important for drought and flood monitoring/forecasting, and water management in general [3].
- Important constituent in the hydrological cycle [4].

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Theory: Surfex Land Surface Model

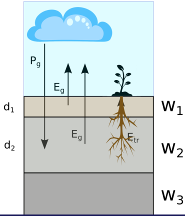
- Surfex (Surface externalisée), developed by Météo-France.
- Physical models for natural land surface, urbanized areas, lakes and oceans.
- Chemistry and aerosol surface processes.
- Stand alone (offline) or coupled to an atmospheric model.
- For validation and testing we used the 3-Layer Force restore scheme from Deardorff [5].
- ISBA - DIF is more physical correct and will be used for later analyses.
- Horizontal subsurface flow is neglected.

Theory: Force-Restore Scheme

- Increase our knowledge on the root zone soil moisture w_2 from assimilation of surface soil moisture w_1.
- Why? As we see from the equation this is important for plant transpiration/evotranspiration.
- $d_1 = 0.01\,\mathrm{m}$ and $d_2 = 0.24 \sim 3.8\,\mathrm{m}$.

$$\partial w_1/\partial t = \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau}(w_1 - w_{eq})$$

$$\partial w_2/\partial t = \frac{1}{\rho_w d_2}(P_g - E_g - E_{tr}) - \frac{C_3}{\tau}\max[0, (w_2 - w_{fc})]$$



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Theory: Why use the Ensemble Kalman Filter? [6]

- Flow dependent error estimate rather than a climatological (used in the SEKF at ECMWF).
- Diffusion scheme (Decharme et al 2011) would increase the number of layers and substantially increase the cost of the SEKF Jacobian calculations.
- EnKF can stocastically represent random forcing and model errors, not feasible with an SEKF.
- The EnKF may take into account background-error covariances between gridpoints, neglected here.
- Finally: These test are done to validate our implementation of the Data Assimilation system in a large land surface model.

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Theory: Ensemble Kalman Filter (EnKF)

- We use the Ensemble Kalman Filter (EnKF) formulations from Sakov & Oke [8, 9].
- The Ensemble square root Kalman Filter (EnsrKF) and the Deterministic Ensemble Kalman Filter (DEnKF) are implemented in Surfex v8 using SODA (Surface Offline Data Assimilation).
- Hope that Météo France, the Norwegian and Swedish Met Offices will use the setup we created.
- Easy to implement other schemes in this setup, e.g. Particle Filters.

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Theory: EnKF

The Kalman filter equations [8]:

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{K}(\mathbf{d} - \mathbf{H}\mathbf{x}^f)$$
$$\mathbf{P}^a = (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{P}^f$$
$$\mathbf{K} = \mathbf{P}^f\mathbf{H}^\mathsf{T}(\mathbf{H}\mathbf{P}^f\mathbf{H}^\mathsf{T} + \mathbf{R})^{-1}$$

Here $\mathbf{x}^a$ is the analysis; $\mathbf{x}^f$ is the forecast; $\mathbf{d}$ is the vector of observations; $\mathbf{H}(=1)$ maps state vector to observation space; $\mathbf{R}$ is the observation error covariance matrix; $\mathbf{P}^f$ is the forecast error covariance matrix and $\mathbf{P}^a$ is the analysis error covariance matrix.

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Theory: EnsrKF Sakov&Oke [8]

Analysis scheme for the EnsrKF:

i. Given the forecast ensemble $\mathbf{X}^f$, calculate the ensemble mean $\mathbf{x}^f$ and anomalies $\mathbf{A}^f$.
ii. Calculate the analysis using the Kalman analysis equation.
iii. Calculate the analyzed anomalies by $\mathbf{A}^a = (\mathbf{I} - \mathbf{KH})^{1/2}\mathbf{A}^f$.
iv. Calculate the analyzed ensemble by offsetting the analyzed anomalies by the analysis, $\mathbf{X}^a = \mathbf{A}^a + [\mathbf{x}^a, ..., \mathbf{x}^a]$.

Theory: DEnKF Sakov&Oke [9]

Analysis scheme for the DEnKF:

i. Given the forecast ensemble $\mathbf{X}^f$, calculate the ensemble mean $\mathbf{x}^f$ and anomalies $\mathbf{A}^f$.

ii. Calculate the analysis using the Kalman analysis equation.

iii. Calculate the analyzed anomalies by $\mathbf{A}^a = \mathbf{A}^f - \frac{1}{2}\mathbf{KHA}^f$.

iv. Calculate the analyzed ensemble by offsetting the analyzed anomalies by the analysis, $\mathbf{X}^a = \mathbf{A}^a + [\mathbf{x}^a, ..., \mathbf{x}^a]$.

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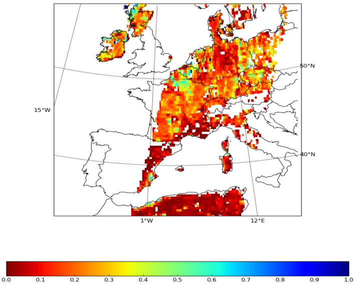
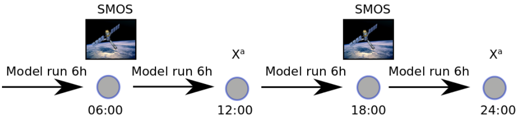
Method: Satellite Observations

- Assimilation of surface soil moisture from the Soil Moisture and Ocean Salinity (SMOS) satellite.
- Level 3 product of surface soil moisture, acquired through a forward model, $2 \sim 5$ cm depth.
- Spatial resolution: 25 km.
- Temporal resolution: Overpass at 06.00 and 18.00.



Method: Model Setup

- Forcing files from the Weather Research Forecast Model (WRF).
- Provides, precipitation, surface temperature, wind etc..
- 9.5 km $\times$ 9.5 km model grid over central Europe, 289 $\times$ 289 points.
- Time-step 15 min, output every 3'rd hour.
- SMOS observations are assimilated at 06.00 and 18.00.
- Perturbation: $WG1 \sim 12\%$ and $WG2 \sim 2\%$.



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Method: Numerical Experiments

- Part of the validation of the ESA CCI soil moisture product.
- Seven assimilation experiments have been conducted over a European domain.
- Three runs with the EnsrKF and different observation error, 0.15, 0.3 and 0.6.
- Two runs using normalized satellite data and observation error of 0.6 and 0.8; 5 ensemble members.
- Two runs with 20 ensembles for the DEnKF and the EnsrKF using observational error of 0.6.
- One open-loop run, no assimilation, only model run.

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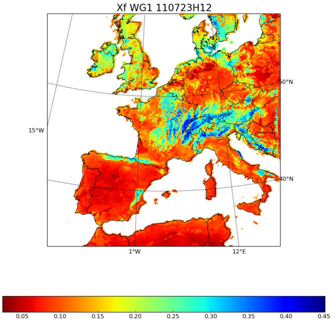
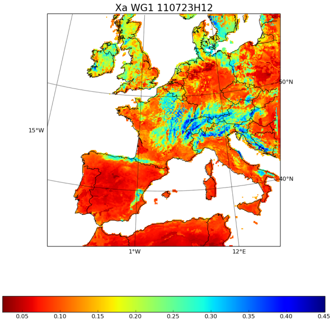
Results: Forecast and Analysis WG1 (m^3/m^3)

Example output forecast and analysed state, using 5 ensemble members:





Note:

Surfex time 12.00 is start of window, so 12.00 is system state at 18.00.

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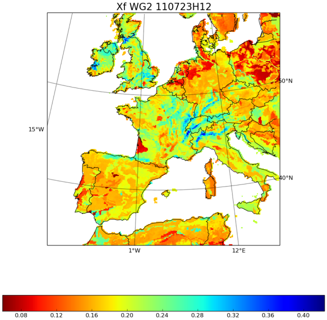
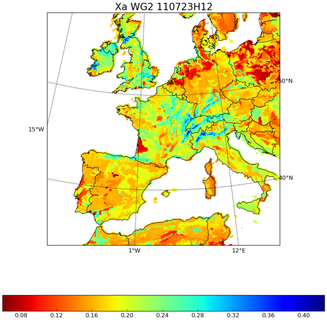
Results: Forecast and Analysis WG2 (m^3/m^3)

Example output forecast and analysed state, using 5 ensemble members:





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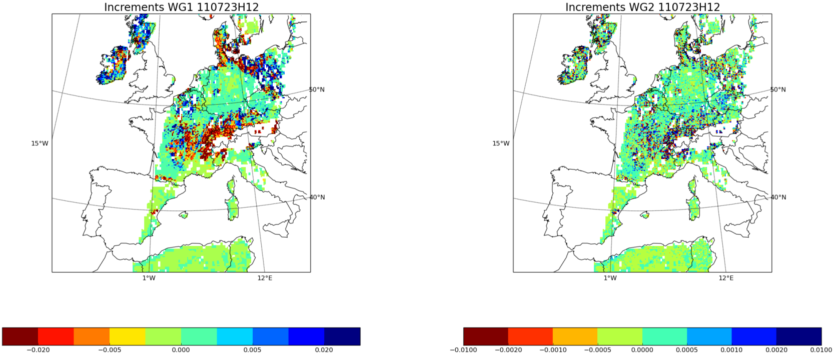
Results: Increments WG1 and WG2 (m^3/m^3)



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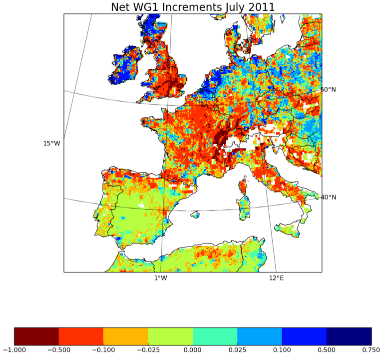
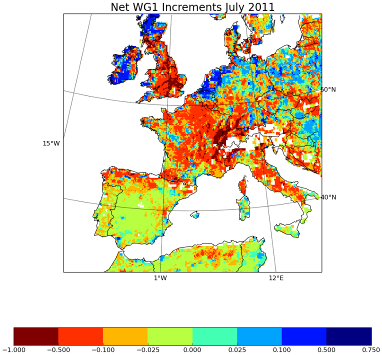
Results: Net Increments WG1 5 and 20 ensembles (m^3/m^3)





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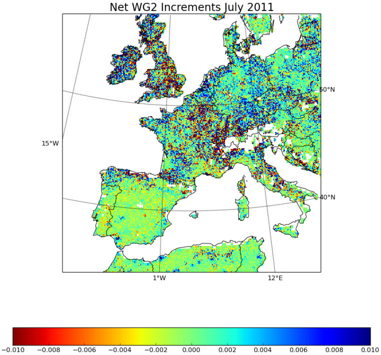
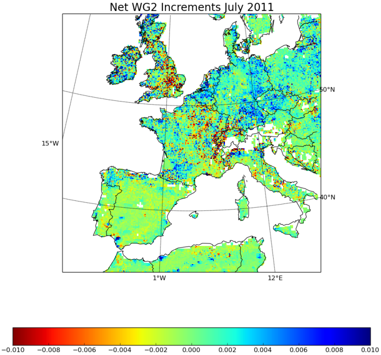
Results: Net Increments WG2 5 and 20 ensembles (m^3/m^3)





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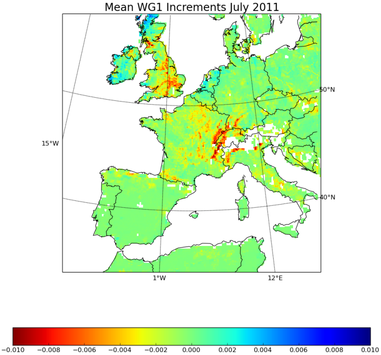
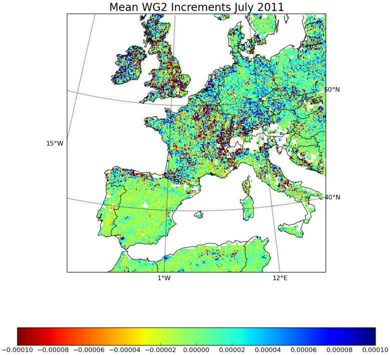
Results: Mean Increments WG1 and WG2 (m^3/m^3)





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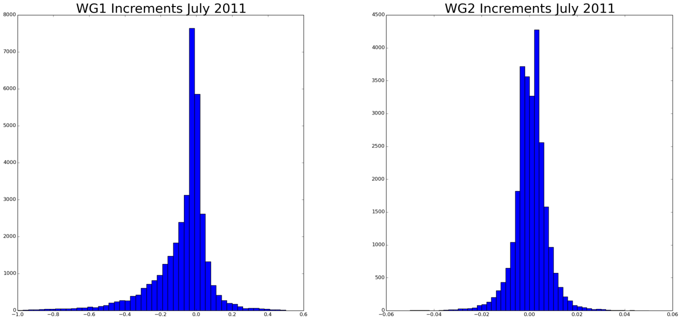
Results: Net distribution of increments WG1 and WG2, 5 Ensembles

Note the dry bias from the Satellite.



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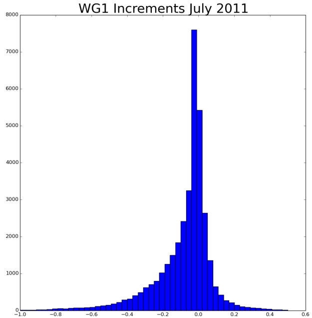
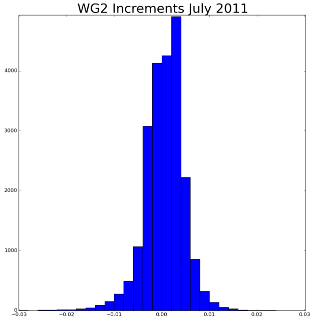
Results: Net distribution of increments WG1 and WG2, 20 Ensembles

Note the dry bias from the Satellite and smaller spread in WG2.





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Results: Normalizing Satellite Data

- We normalize the satellite data by using an open-loop model run.
- Use the model mean and standard deviation for July to normalize the satellite data [10].

$$w_i^{\text{new}} = (w_i^{\text{old}} - \bar{w}_{\text{satellite}})\left(\frac{\sigma_{\text{model}}}{\sigma_{\text{satellite}}}\right) + \bar{w}_{\text{model}} \,.$$

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Results: χ^2 – tests

- The χ^2 – test provides a measure on the quality of the assimilation.
- Quantify model and observation error.
- Use the standard results from G. Desroziers et al [11]:

$$E[\mathbf{d}_a^o(\mathbf{d}_b^o)^{\mathsf{T}}] = \mathbf{R}\,,$$

where $\mathbf{d}_b^o = \mathbf{y}^o - \mathbf{H}(\mathbf{x}^b)$ and $\mathbf{d}_a^o = \mathbf{y}^o - \mathbf{H}(\mathbf{x}^b + \delta\mathbf{x}^a)$.

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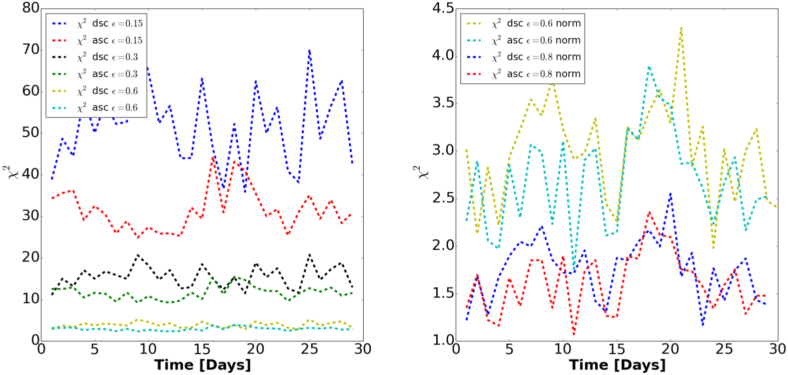
Results for **R** using unormalized and normalized satellite data:



Still underestimating the error of representativeness.

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Results: Error Budget

- From the χ^2-tests we can perform a simple error budget to decide the approximate size of the error of representativeness.
- We know that the SMOS error is in the range $\sim 0.04\,\mathrm{m}^3/\mathrm{m}^3 (\mu_{\mathrm{measure}})$.
- From the mean clay fraction over all points we can calculate the observational error in the correct units:
- $\mu_{\mathrm{total}} = 0.8 \times \mu_{\mathrm{clay}} \approx 0.069\,\mathrm{m}^3/\mathrm{m}^3$.
- Using: $\mu_{\mathrm{total}} = \mu_{\mathrm{repres}} + \mu_{\mathrm{measure}}$, we get $\mu_{\mathrm{repres}} \approx 0.03\,\mathrm{m}^3/\mathrm{m}^3$.
- A bit low?

Conclusion and Future Work

- We have tested our implementation of the EnsrKF and the DEnKF in the Surfex Land Surface Model.
- From χ^2-tests we got a better knowledge about our parameter setting of the observational (and model error).
- Plan to use this new knowledge on a larger European domain and include other satellites.
- SMAP, ASCAT and AMSR-E.
- Want to see if assimilation of soil moisture could improve the short term numerical weather prediction over Northern Latitudes, collaboration with Met Norway.

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