Towards operational earth system assimilation: challenges and priorities

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Main purpose of this presentation

- Provide a summary of key challenges and future directions on earth system assimilation (discussed during this seminar)

- Illustrate some of them with examples from ongoing developments at Météo-France in the framework of short-range weather forecasting and limited-area modelling

Outline of the presentation

- Introduction
- Challenges and priorities seen from the coupling with :
    - Continental and oceanic surfaces
    - Ocean and sea-ice
    - Atmospheric composition
- Final conclusions

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The different components

Stratosphere/mesosphere/ionosphere

Atmospheric composition: gases and aerosols

Troposphere: N_2, O_2, H_2O, CO_2, O_3

Atmospheric composition: hydrometeors

Ocean waves

Sea-ice

Continents

Ocean

Hydrology

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Continental surfaces

- Prognostic variables for the « soil/vegetation/snow » have been included for a long time in NWP models (atmospheric/surface coupling)
- The need for having dedicated analyses has been recognized since the 90's (issues with either climatology or free-runs)
- Current land surface assimilation schemes use a weak coupling DA approach
- <u>Current challenges</u>: simpler assimilation schemes than in the atmosphere, analyses performed at full model resolution, non-linearity issues, new surface types (urban areas, lakes) requiring dedicated observations
- <u>Ongoing evolutions</u>: use ensemble DA for the surface, use information from « atmospheric » observations in surface analyses

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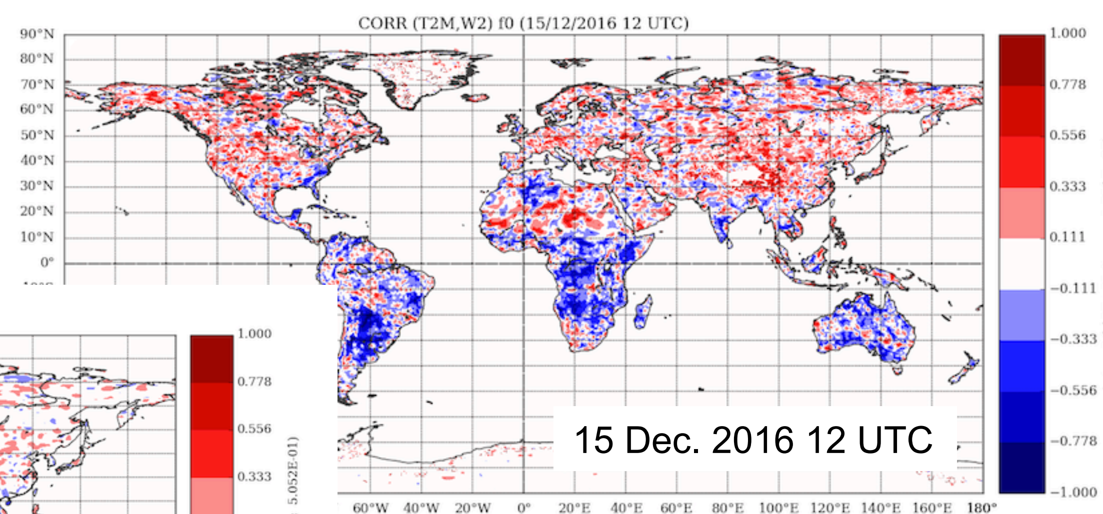
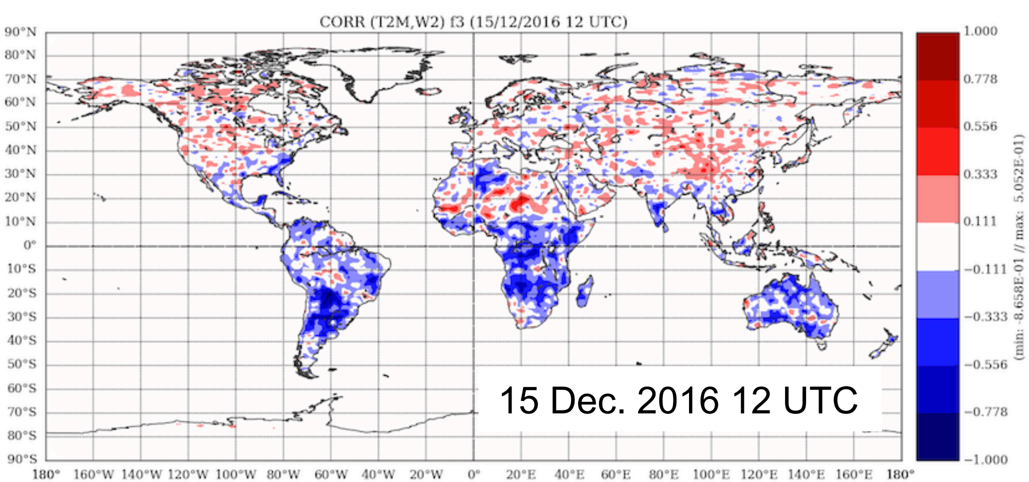
Use of atmospheric EDA

- $\Delta x = cov(x^b,y^b)(cov(y^b,y^b) + cov(y^o,y^o))^{-1}\Delta y$
- Compute the gain of a Kalman filter from an EDA system (where the atmosphere and continental surfaces are coupled)
- Replace simple analytical OI coefficients or Jacobians in finite differences

Raw (AEARP 25)
cor (T_{2m},w_2)





Filtered
cor (T_{2m},w_2)

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Coupling of atmospheric and surface analyses

ATMOSPHERE

- Assimilation of IR and MW channels sensitive to the surface over continents and sea-ice
- Skin temperature (T_s) from the model is not accurate enough
- Need to:
  - Retrieve T_s from emissivity atlases (IR)
  - Retrieve ε using T_s from model (MW)
  - Use T_s as a sink variable in the assimilation process
- None of this information is used for surface analyses

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CONTINENTAL SURFACES

- Surface and soil temperatures are corrected over continents using spatialized T_{2m} observations
- Use information provided from the adjustment of T_s for atmospheric assimilation in the soil (and sea-ice) analyses
- Need to separate systematic (model) and random errors -> identification of bias origin
- Need to define a methodology in order to keep the signal in the soil (T_s has small memory)
- Use of ε retrievals to get additional information on surface properties

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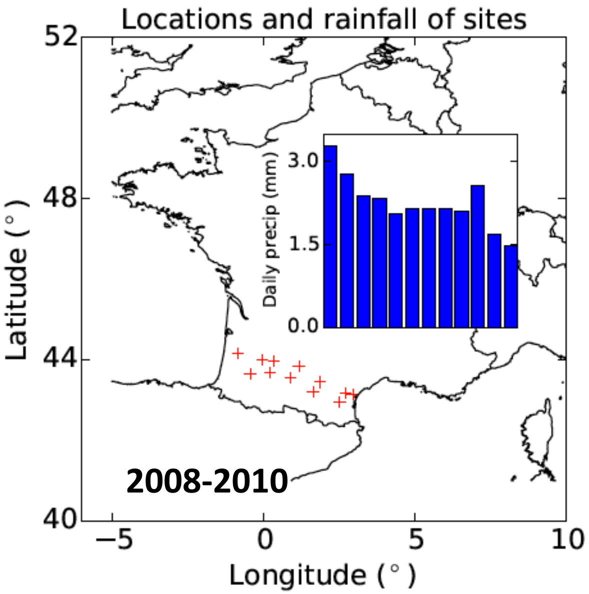
Importance of synergy between spectral domains

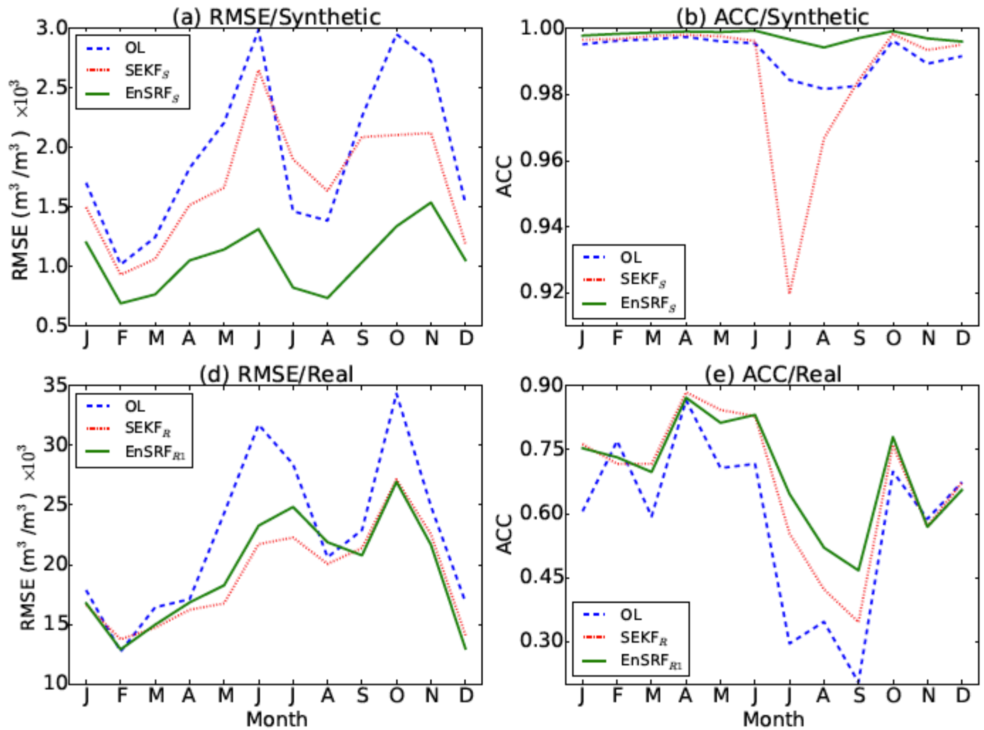
Non-linearity issues (soil/vegetation)

ISBA-3L
- Assimilation of WG1
- Evaluation of WG2

Fairbairn et al. (2015) HESS



OL - SEKF - EnSRF



Synth. obs

Real obs

- SEKF and EnSKF are both affected by the non-linear behaviour of the land surface scheme.
- Ensemble approach => improved consistency with atmospheric DA

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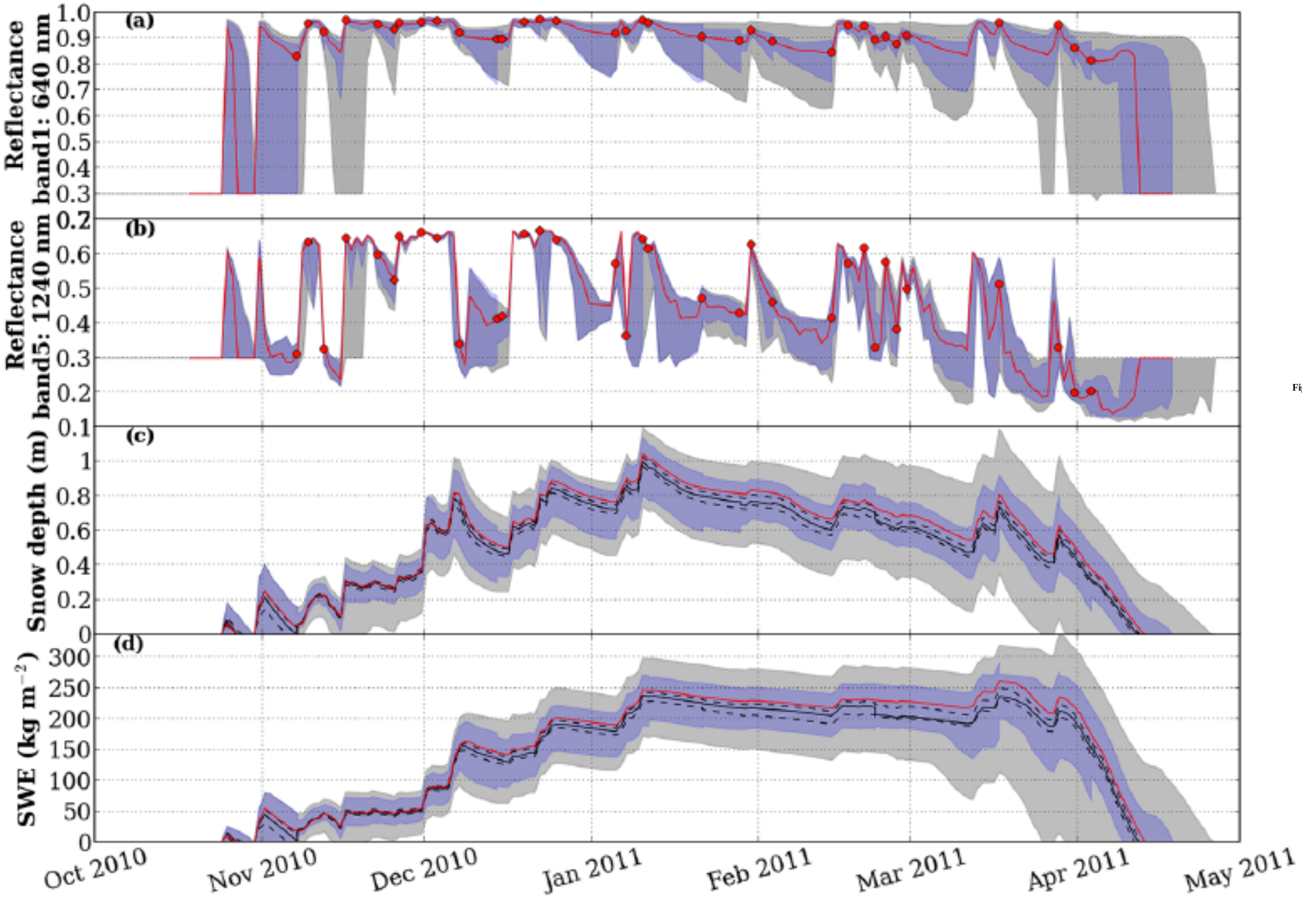
Non-linearity issues (snow)



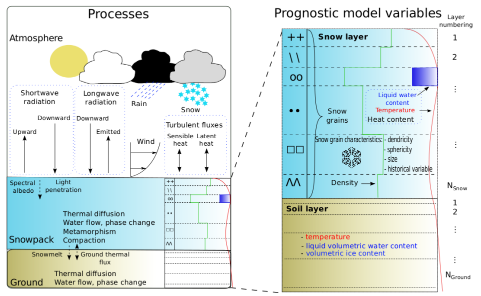


Fig. 1. Main physical processes and model variables.

CROCUS

- **NO ASSIMILATION**
- **ASSIMILATION**

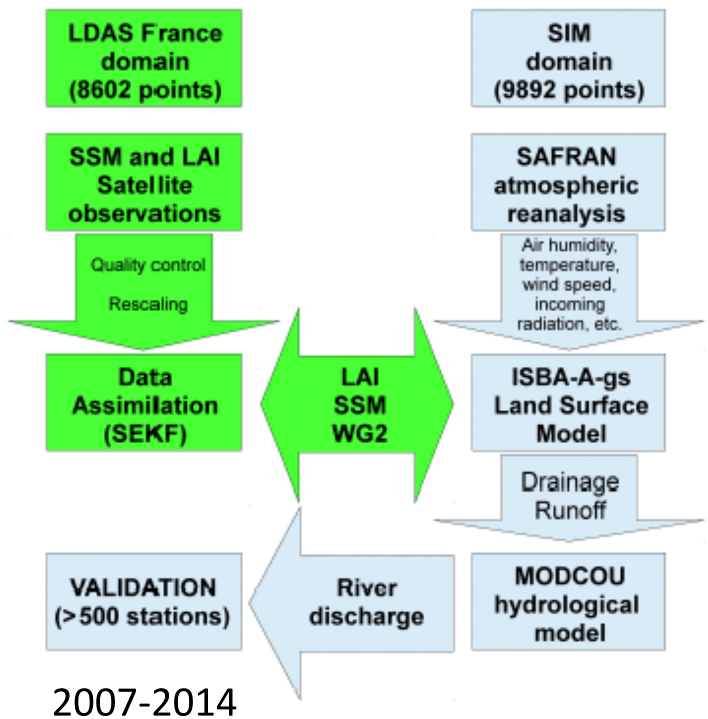
Charrois et al. (2016)

Use of a **SIR particule filter** to assimilate « simulated » MODIS reflectances in a multi-layer (variable) snow model (+RT model)

Model biases in the hydrological context

Can assimilation of soil moisture and LAI improve river discharges ?

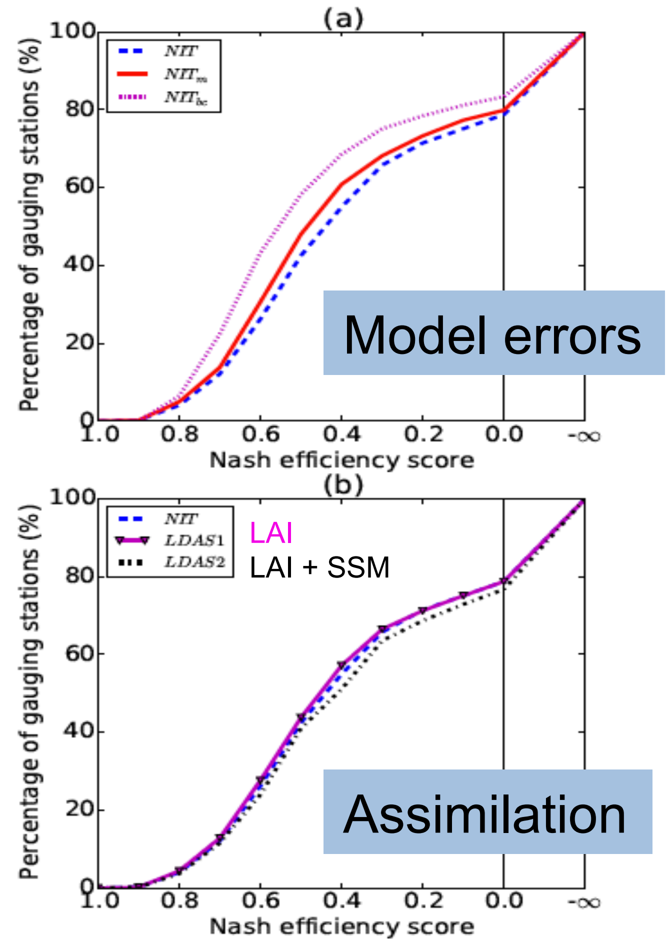
Fairbairn et al. (2017) HESS



2007-2014

Figure 1. Flowchart of the SIM hydrological model and how LDAS France is connected with SIM.

--- NIT (ref)



Hydrological constraints (additional observations) can highlight land data assimilation issues -> model errors, forcing errors, non-linearities

Oceanic surfaces

- Ocean wave models are run operationally in NWP centres with some level of coupling with atmospheric models (e.g. ECMWF: turbulent fluxes depend upon sea state)

- Current challenges: simpler assimilation schemes than in the atmosphere

- Ongoing evolutions: use information from wave models (sea state), ocean models (surface currents) and from satellite instruments (SAR, altimeters) in atmospheric observation operators (microwave emissivities, backscatter coefficients, surface wind speed) ; need for improved observation operators

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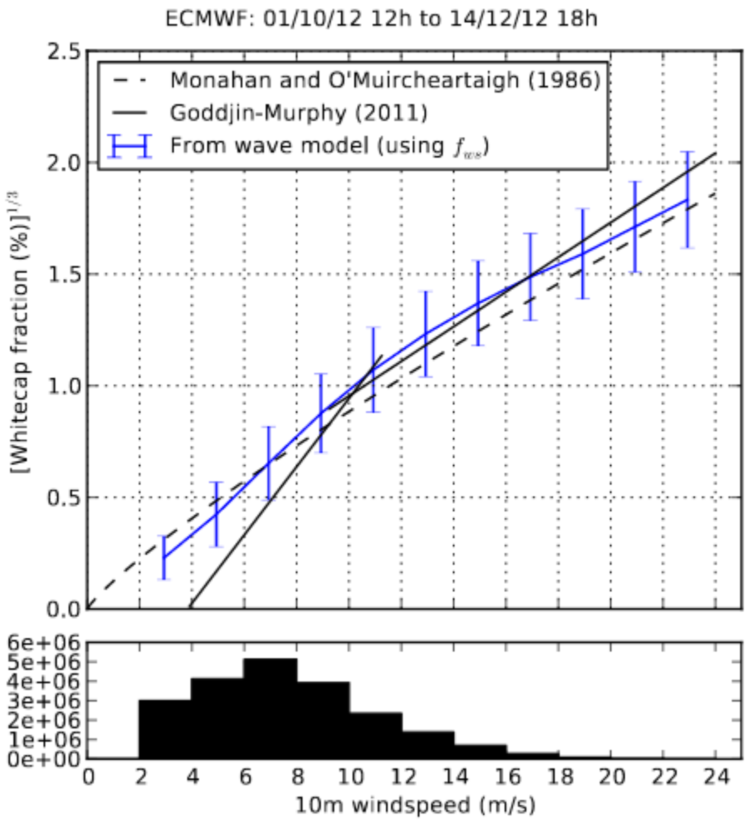
Surface emissivity over oceans

Surface emissivity

$\varepsilon=(1-W)\varepsilon_{water} + W\,\varepsilon_{foam}$ with $\varepsilon_{water} \sim 0.5$ and $\varepsilon_{foam} \sim 1$



Meunier et al. (2014)

<u>White cap fraction W</u> :

(1) $W = W(U_{10m})$ FASTEM

(2) $W = -\rho_a m X/\gamma\rho_w E_*$

m = normalised flux from waves to ocean
X = wave age
E_*= dimensionless wave variance

Use information provided by a wave model (ECWAM) in order to better simulate microwave T_bs over oceans

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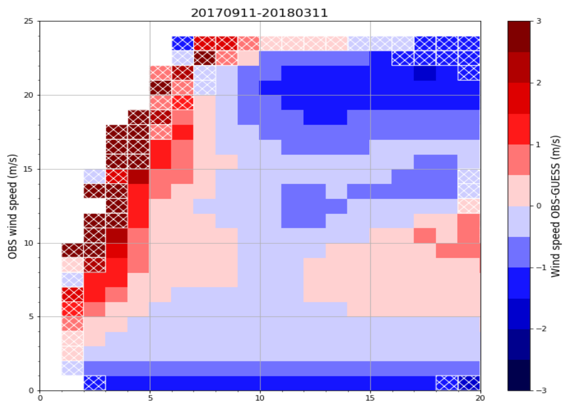
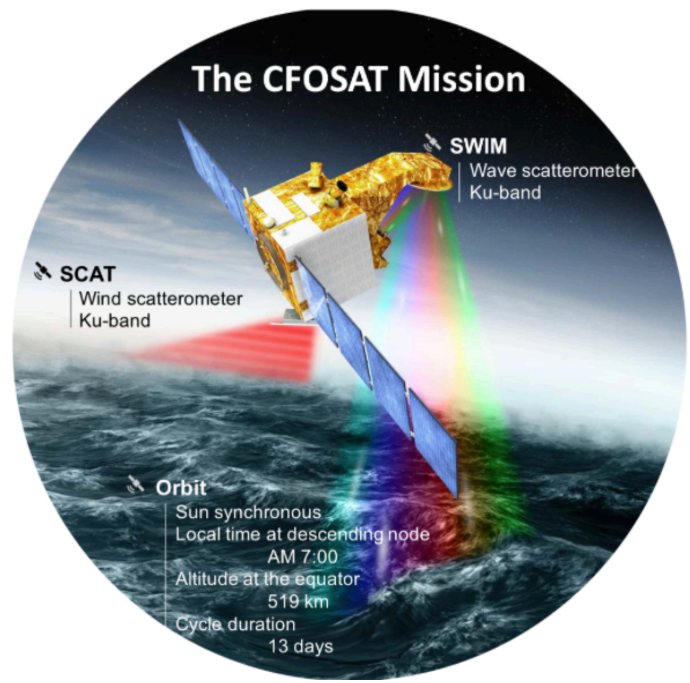
Scatterometer winds and sea state

- On the use of wave model information for improving the assimilation of scatterometer wind
- Synergy between instruments -> CFOSAT mission (SCAT + SWIM)
- Towards improved GMF for surface wind retrievals – assimilation of σ^0



10-m wind bias (ScatSat-1 minus ARPEGE) dependency with the mean period of primary swell waves from MFWAM (09/2017 –> 02/2018)

A.-L. Dhomps (personal communication)



Ocean and sea-ice

- Coupled models (atmosphere/ocean/sea-ice) developed for climate applications are now used in NWP for medium to seasonal forecast ranges (including reanalyses)
- DA systems are rather similar between the atmosphere and the oceans (same equations, developments made in parallel)
- Most efforts on coupled DA are undertaken in this area
- Evolution from weak to strong coupling DA (outer loop coupling)
- Level of complexity required for short-range weather forecasting ?
    - ➢ 1D mixed layer ocean: simple in terms of modelling and data assimilation (use of similar methods as for continental surfaces with SST observations)
    - ➢ Full 3D ocean: more realistic but requires more complex DA methods (-> analyses produced by an external centre ?)
- Similar questions for sea-ice modelling (1D thermodynamics vs 3D dynamics)

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Atmospheric composition: hydrometeors

- Nowadays NWP models include hydrometeors as prognostic variables (various levels of complexity : global -> mesoscale)
- Currently no dedicated analyses in operational context despite the assimilation of observations sensitive to clouds (« all-sky » radiances, radar reflectivities)
- Present solutions: diagnostic cloud and precipitation schemes in observation operator, 2-step approach with 1D inversion first
- Extension of the control vector: need for a dedicated background error covariance matrix, gaussianity issues (thresholds, non-linearities)
- Need to evaluate which variables require a dedicated analysis (equilibrium time scales, evolution of cloud microphysics in NWP models)
- Interest in addressing these issues using ensemble assimilation systems

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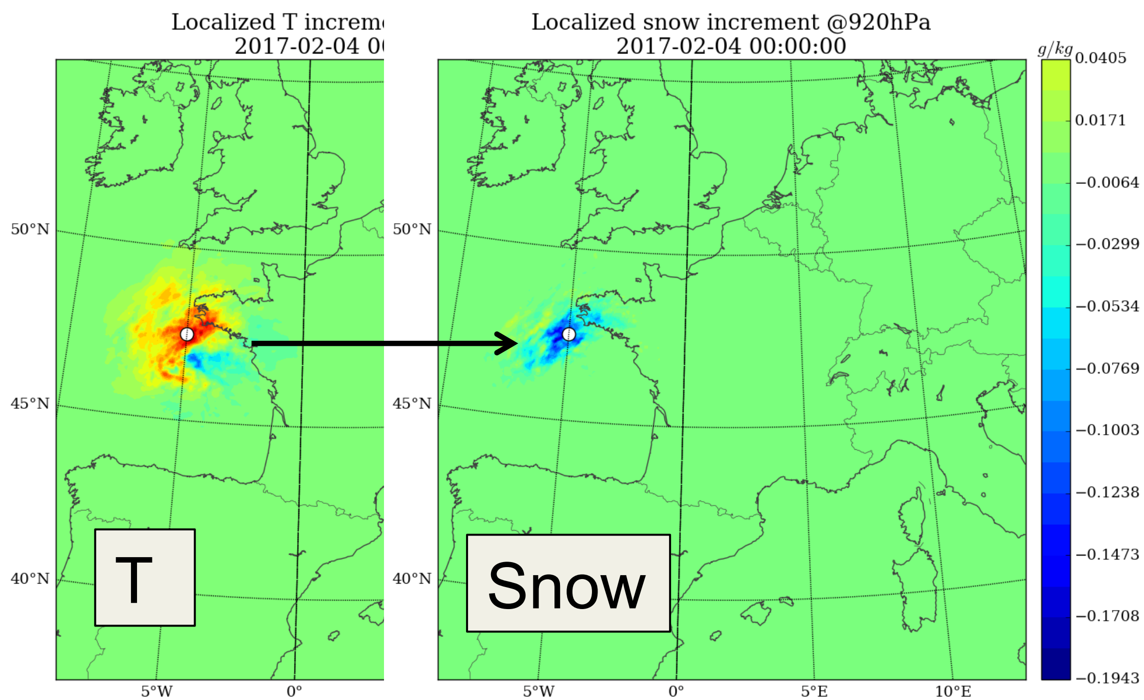
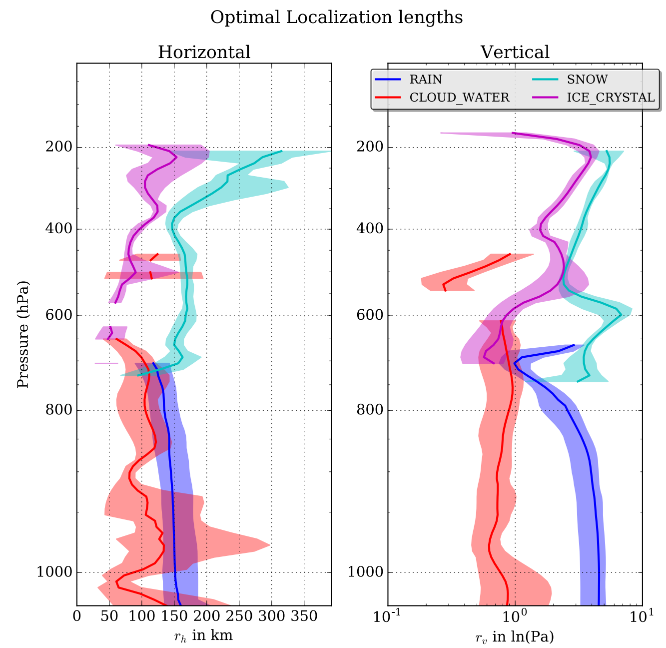
Extension of the control vector in EnVar

- Hydrometeors in the control vector of a 3D-EnVar AROME system (with OOPS)
- Cross-correlations from the ensemble between (T,u,v,q_v,P_s) and (q_l,q_i,q_r,q_s,q_g)
- Need of a scale dependent localisation for each variable

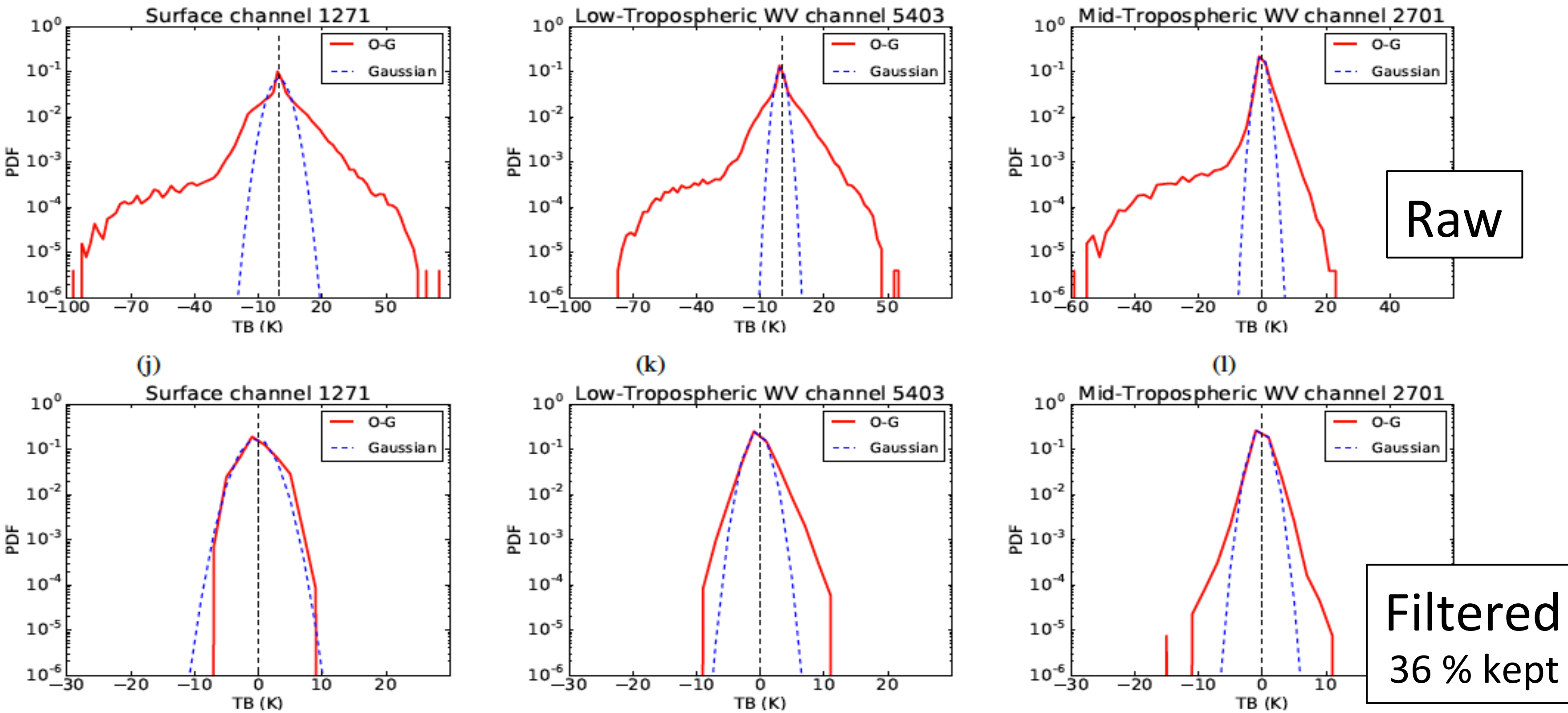




Single observation experiment T@925 hPa

M. Destouches (personal communication)

Non-gaussian errors for cloudy Tbs



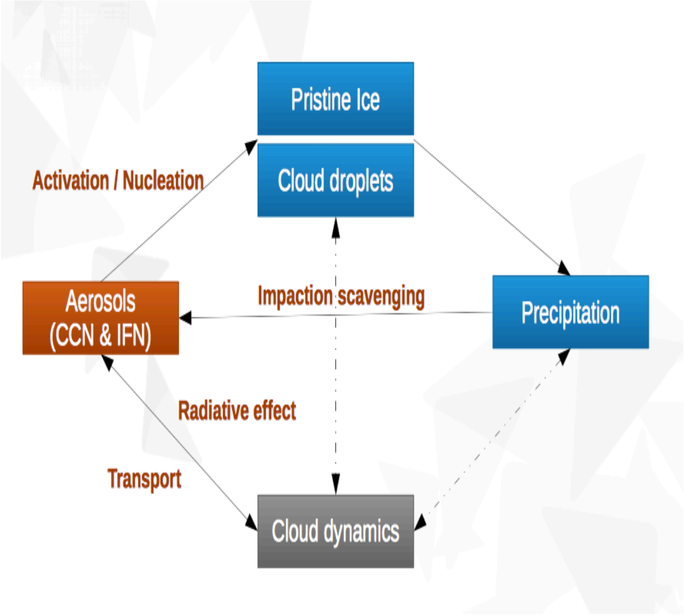
Simulation of IASI Tbs in cloudy sky with RTTOV-CLD and ARPEGE
Farouk et al. (2018)

Gaussianity increased through:

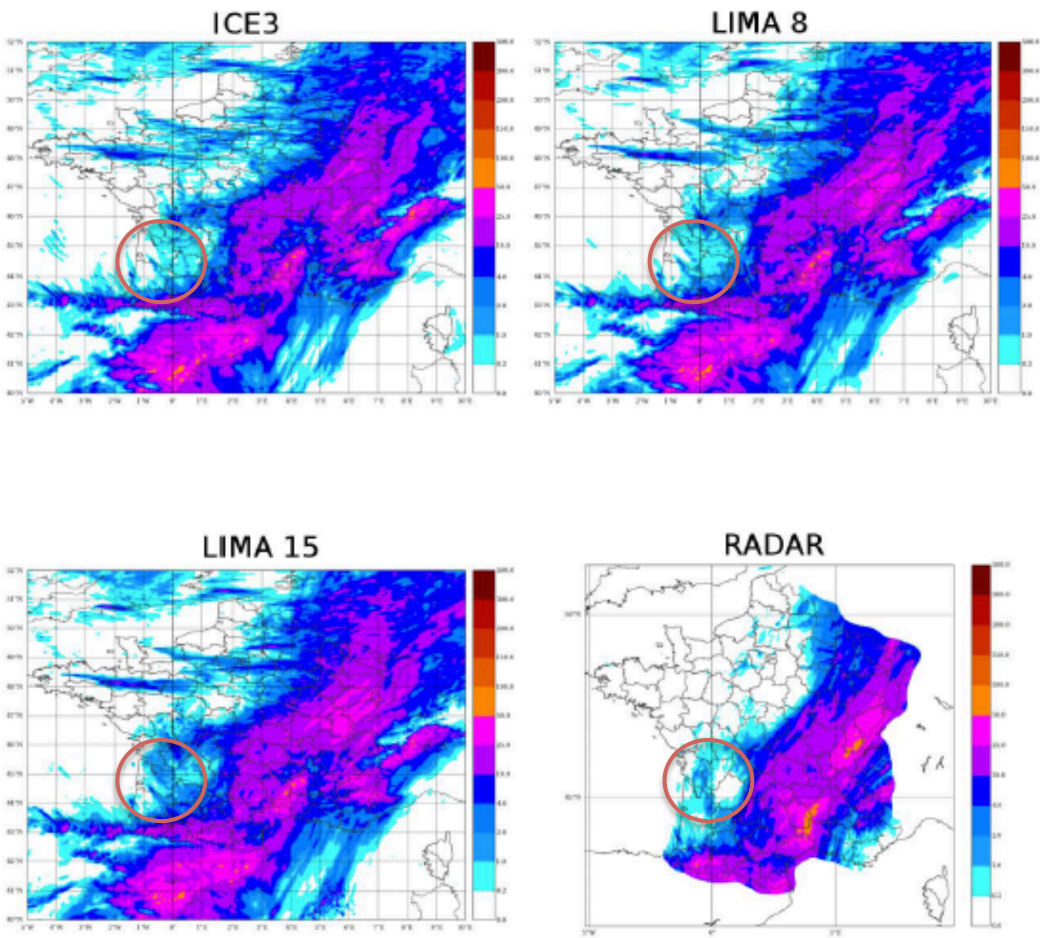
- quality controls -> selection of homogeneous scenes
- revised observation error model

Atmospheric composition: aerosols

- Importance of aerosols on cloud formation and radiative budget
- Increased complexity in the description of cloud microphysics: hydrometeor number concentration as prognostic variables
- Need to include several aerosol types (natural and anthropogenic) and to prescribe/describe associated sources and sinks
- What is the optimal level of complexity to handle the processes without an excessive number of variables to initialize ?
- Need to explore the visible spectrum in terms of observation operator (AEOLUS, EarthCare, FCI/ MTG, 3MI/METOP-SG, METimage/METOP-SG, …)



A two-moment microphysical scheme



ICE-3: one-moment scheme

- 5 prognostic variables for hydrometeor mixing ratio (q_r,q_s,q_g,q_l,q_i)

LIMA : two-moment scheme (Vié et al., 2016):

- 3 additional prognostic variables for N_c,N_i,N_r
- 5 ->12 additional variables for CCN and IFN number concentration

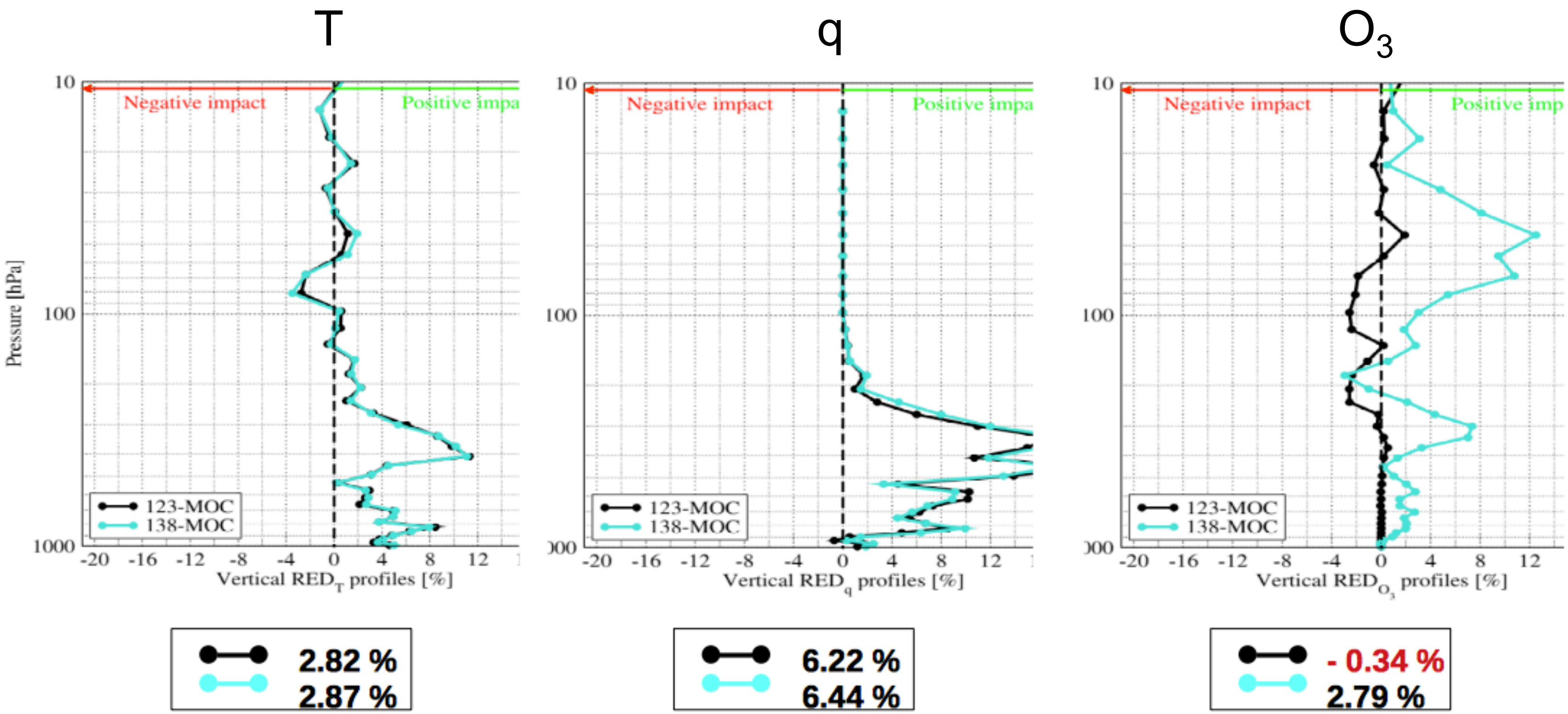
Homonnai and Seity (2016)

24-h accumulated precipitation with AROME and three microphysical schemes (LIMA initialized from CTM MOCAGE)

Atmospheric composition: gases

- The large number of prognostic variables and chemical reactions (reactive gases) to include makes the explicit coupling with atmospheric NWP models challenging (but possible C-IFS for CAMS)
- 3D atmospheric chemistry-transport models (CTMs) use wind fields from NWP models and consider similar transport processes (turbulence, convection)
- For atmospheric DA, gas concentration of relevant species for satellite radiances could be taken from CTMs (CO_2, O_3)
- Inclusion of O_3 mixing ratio in the control vector of NWP DA systems : stratospheric O_3 photo-chemistry parametrization; model radiative forcing ; forecast error correlations with other variables ; observations sensitive to various atmospheric quantities

Ozone retrieval from IASI channels



123 IASI channels (CO_2, H_2O, surface)

138 IASI channels (CO_2, H_2O, surface + O_3)

Coopmann et al. (2018) JGR

Slight improvement of temperature and humidity profile retrievals when IASI O_3 channels are assimilated in a 1D-Var

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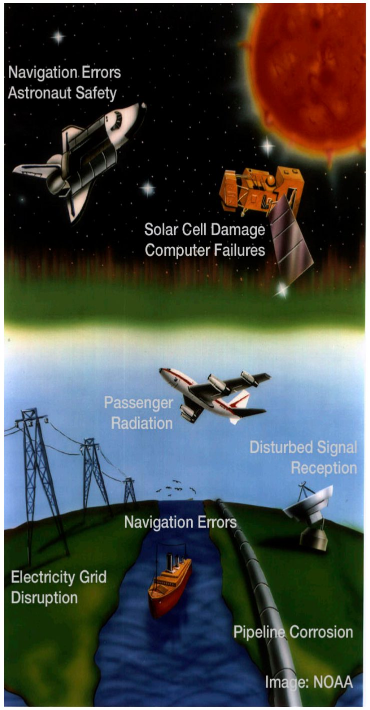
The upper atmosphere

- Importance of stratosphere and mesosphere for the predictability of the troposphere and climate monitoring
- Coupling with stratosphere/mesosphere is rather straightforward -> defined by model top geometry (vertical discretization)
- Need to describe relevant processes (O_3 photochemistry, GW breaking)
- Importance of ionosphere for space weather predictions (protection and mitigation of solar threats on human activities)
- MHD models for the prediction of electron contents outside meteorological expertise
- Interest in GNSS-RO data that are sensitive to both the ionosphere and the neutral atmosphere
- Lack of dynamical information above 30 km => use of infra-sound propagation in the stratosphere/mesosphere from surface sources (volcanic eruptions, tsunamis, ocean swell, ….)



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Final conclusions (1)

- Earth system modelling has been defined with a goal towards « seamless predictions » covering a wide range of spatial and temporal scales
- The focus has been on global and (sub-)seasonal scales (coupling with ocean and sea-ice, that are sources of predicability) but smaller spatial and temporal scales can also benefit from this framework (coupling between surface-clouds-aerosols)
- Earth system assimilation shall provide the initial conditions of its various components in a consistent manner
- This can be achieved by extracting more efficiently information from observations sensitive to several components of the Earth system
- There is need for improved observation operators and improved physics (towards L1 satellite data)

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Final conclusions (2)

- Incremental DA approaches allow to account for non-linearities and outer loop coupling
- Ensemble DA approaches allow a rather easy extension of the control vector by providing cross-covariance background errors
- Earth system assimilation should allow a better identification of model errors (biases that could otherwise project on components not observed nor analyzed)
- The assimilation system will increase in complexity with additional modules => issues with code maintenance, evolutions (e.g. validation of individual modules) and expertise (external collaborations)
- Earth system assimilation needs to evolve towards a highly flexible and modular common software environment for its various components

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Thank you for your attention !