Discussion on short and long term plans for coupled DA in Accord

1st Accord ASW, surface side meeting
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Roel Stappers

Background

New project (H20) at MET Norway

Project leader: Jostein Blyverket

WP5 Coupled DA

- Postdoc 36 PM (Stephanie Guedj, start June 2021)
- Roger 6 PM
- Roel 8 PM (lead)

Main objective of WP5 is to implement and examine the benefits of coupled DA in Harmonie-Arome e.g. to improve the balances in the analysis.

DA in Harmonie-Arome

- In Harmonie UA DA we have 3DVAR (operational) and 4DVAR (operational soon). Research code available for LETKF (based on Mats Hamrud's code for IFS), Hybrid EnVar.
- MF has Hybrid Envar in OOPS (Will be ported to CY46h)

- Canari/gridpp (optimal interpolation)
- Wide range of approaches for soil ((S)EKF). Will move towards EnKF

What is the most promising approach for CDA in Accord?

Option 1. Implement (weakly) coupled DA in existing 3DVAR/4DVAR framework.

Coupling in variational DA

From Sergey Frolov, Comparison of data assimilation coupling strategies for Earth system models presented at the ECMWF annual seminar on coupled DA 2018.

For didactic purposes, lets start with something simple:

- Observational space estimator with one outerloop

$$x_k^a = \mathcal{M}(x_{k-1}^a) + \underbrace{\mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{H}\mathbf{M}\mathbf{P}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}}\left[y - \mathcal{H}(\mathcal{M}(x_{k-1}^a))\right]$$

Kalman gain: maps observation misfits to model space s/ocean/surface/g

Strongly coupled data assimilation

$$x_k^a = \mathcal{M}(x_{k-1}^a) + \mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{HMP}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}\left[y - \mathcal{H}(\mathcal{M}(x_{k-1}^a))\right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathcal{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix}\right)$$

Coupled TLM/ADJ of the forecast model:

$$\mathbf{M}^{coupled} = \begin{bmatrix} \mathbf{M}^{AA} & \mathbf{M}^{AO} \\ \mathbf{M}^{OA} & \mathbf{M}^{OO} \end{bmatrix}$$

Coupled TLM/ADJ of the observation operator:

$$y^{radiance} = \mathbf{H}^{rtm-coupled}x^{coupled} = \begin{bmatrix} \mathbf{J}^{atm} \\ \mathbf{J}^{ocean} \end{bmatrix}\begin{bmatrix} x^{atm} \\ x^{ocean} \end{bmatrix}$$

Coupled initial-time covariance:

$$\mathbf{P}_0^{coupled} = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{P}^{AO} \\ \mathbf{P}^{OA} & \mathbf{P}^{OO} \end{bmatrix}$$

Weakly coupled data assimilation

$$x_k^a = \mathcal{M}(x_{k-1}^a) + \mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{HMP}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}\left[y - \mathcal{H}(\mathcal{M}(x_{k-1}^a))\right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathcal{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix}\right)$$

TLM/ADJ of the forecast model:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

TLM/ADJ of the observation operator:

$$y^{radiance} = \mathbf{H}^{rtm}x^{atm} = \begin{bmatrix} \mathbf{J}^{atm} \\ 0 \end{bmatrix}\begin{bmatrix} x^{atm} \\ 0 \end{bmatrix}$$

Initial-time covariance:

$$\mathbf{P}_0 = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}^{OO} \end{bmatrix}$$

Data assimilation coupled through 4DVAR outerloop

$$x_k^{a[i]} = \mathcal{M}(x_{k-1}^a + \sum_i \delta x_{k-1}^{[i]}) + \mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{HMP}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}\left[y - \mathcal{H}\left(\mathcal{M}(x_{k-1}^a + \sum_i \delta x_{k-1}^{[i]})\right) - \mathbf{H}\sum_i \delta x_{k-1}^{[i]}\right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathcal{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix}\right)$$

TLM/ADJ of the forecast model:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

TLM/ADJ of the observation operator:

$$y^{radiance} = \mathbf{H}^{rtm} x^{atm} = \begin{bmatrix} \mathbf{J}^{atm} \\ 0 \end{bmatrix}\begin{bmatrix} x^{atm} \\ 0 \end{bmatrix}$$

Initial-time covariance:

$$\mathbf{P}_0 = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}^{OO} \end{bmatrix}$$

Data assimilation coupled through observation operator

$$x_k^a = \mathcal{M}(x_{k-1}^a) + \mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{H}\mathbf{M}\mathbf{P}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}\left[y - \mathcal{H}(\mathcal{M}(x_{k-1}^a))\right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathcal{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix}\right)$$

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Initial-time covariance:

$$\mathbf{P}_0 = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}^{OO} \end{bmatrix}$$

Data assimilation coupled through initial time covariance

$$x_k^a = \mathscr{M}(x_{k-1}^a) + \mathbf{P}_0\mathbf{M}^T\mathbf{H}^T\left(\mathbf{H}\mathbf{M}\mathbf{P}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R}\right)^{-1}\left[y - \mathscr{H}(\mathscr{M}(x_{k-1}^a))\right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathscr{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix}\right)$$

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$$\mathbf{P}_0^{coupled} = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{P}^{AO} \\ \mathbf{P}^{OA} & \mathbf{P}^{OO} \end{bmatrix}$$

Data assimilation coupled through Tangent Linear and Adjoint

$$x_k^a = \mathscr{M}(x_{k-1}^a) + \mathbf{P}_0 \mathbf{M}^T \mathbf{H}^T \left(\mathbf{H}\mathbf{M}\mathbf{P}_0\mathbf{M}^T\mathbf{H}^T + \mathbf{R} \right)^{-1} \left[y - \mathscr{H}(\mathscr{M}(x_{k-1}^a)) \right]$$

Coupled forecast model:

$$x_{k+1}^{coupled} = \begin{bmatrix} x_{k+1}^{atm} \\ x_{k+1}^{oce} \end{bmatrix} = \mathscr{M}^{coupled}\left(\begin{bmatrix} x_k^{atm} \\ x_k^{oce} \end{bmatrix} \right)$$

TLM/ADJ of the forecast model:

$$\mathbf{M}^{coupled} = \begin{bmatrix} \mathbf{M}^{AA} & \mathbf{M}^{AO} \\ \mathbf{M}^{OA} & \mathbf{M}^{OO} \end{bmatrix}$$

TLM/ADJ of the observation operator:

$$y^{radiance} = \mathbf{H}^{rtm} x^{atm} = \begin{bmatrix} \mathbf{J}^{atm} \\ 0 \end{bmatrix} \begin{bmatrix} x^{atm} \\ 0 \end{bmatrix}$$

Initial-time covariance:

$$\mathbf{P}_0 = \begin{bmatrix} \mathbf{P}^{AA} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}^{OO} \end{bmatrix}$$

Extend existing 3DVAR/4DVAR/Envar

- Extend B Matrix with T2m RH2m U10m and use existing UA DA code to unify the 2D spatialization with the UA DA (replace CANARI, gridPP)
- Use Hybrid 4DVAR/4DEnVar to allow for flow dependency in the 2D spatialization.
- Also see Patrick Laloyaux, et al. (2018). *Implicit and explicit cross-correlations in coupled data assimilation*, Explicit coupling (i.e. cross covariances in B-matrix) is preferable for data assimilation systems with short assimilation windows (e.g. 6 hr or less). For ocean atmosphere coupling.
- Use OOPS to stay close to developments at ECMWF and MF to benefit from future ML applications? Accept possible limitations to move to “fully” coupled DA?

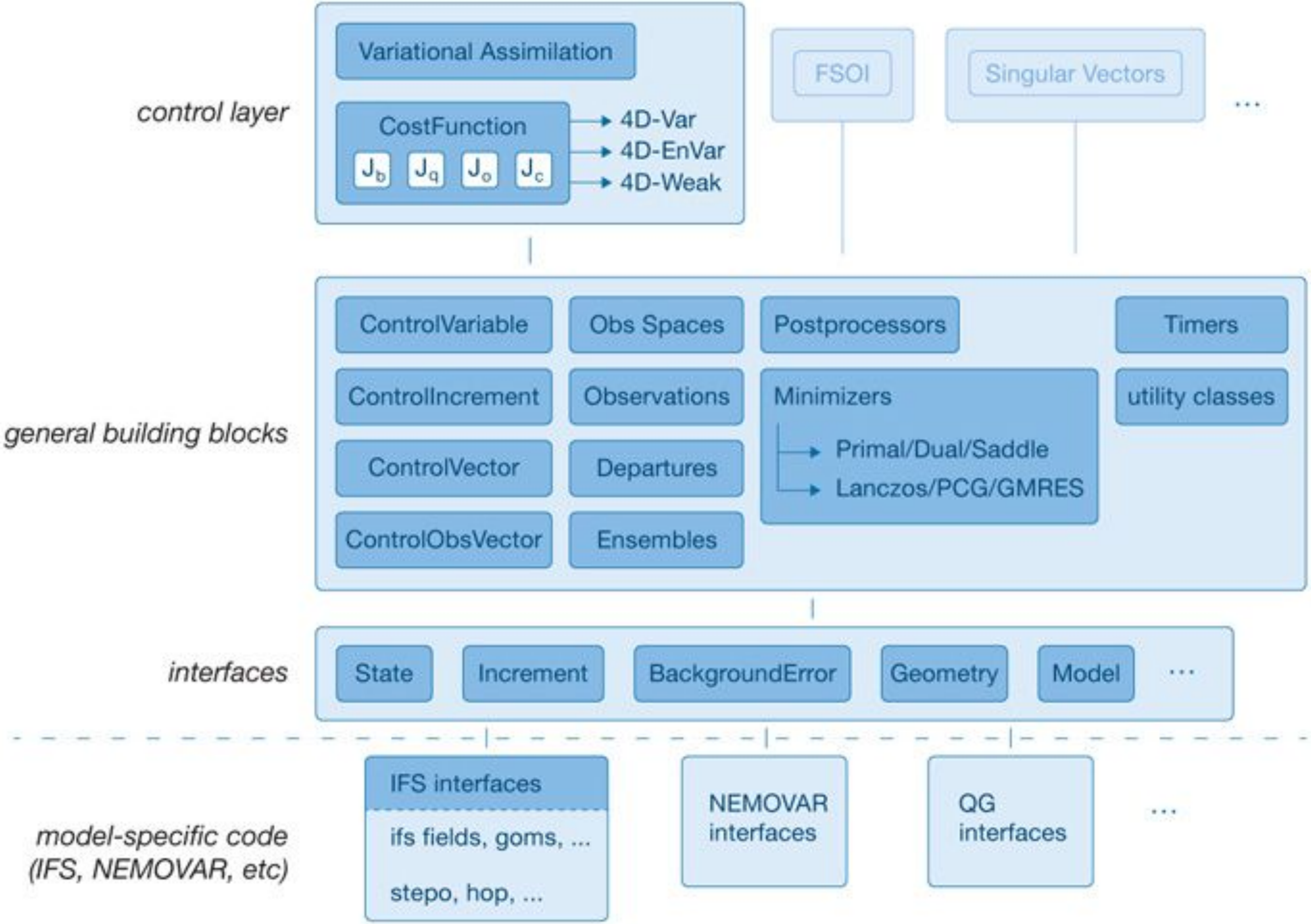
Option 2 EnKF

- After discussion with Patrick, Jelena and Roger
- Implement generic “model independent” EnKF (LETKF), that can be used by both the surface and UA groups and flexible enough to support CDA.
- Also see Yurii’s presentation for more generic DA code
- Fortran does not support generic programming, i.e. algorithms that work with arbitrary types (UA/SU states), which probably excludes the current LETKF use in UA DA as an option.
- C++ would be an option using template programming (like done in OOPS) but cumbersome and verbose.

Most promising (coupled) DA method?

- Both technical and scientific considerations.
- At ECMWF OOPS has been developed as future DA framework but unclear if it can be used for CDA in Accord. What refactoring are need in surfex to make it OOPS compatible?

OOPS



https://www.ecmwf.int/en/about/media-centre/news/2020/flexible-data-assimilation-framework-offers-opportunities-innovation

Meeting with ECMWF/MF/Hirlam 06/04/2020

1. 2D-OI in OOPS: Adding the ability of OOPS to do 2D-OI in support of land DA applications including in coupled systems form part of multiple centre's thinking. It would be good to work together on development and testing of this capability in the OOPS framework. Such capability could evolve towards 2D-Var or 2D-EnVar algorithms.
2. It was noted that a lot of problems in running IFS code in different configurations come at interfaces, therefore with land DA developments it is critical that care is taken over developing and testing interfaces work for a range of configurations (IFS, Arpege, HIRLAM).
3. It was noted that ECMWF have developed a very useful standalone tool for testing the land DA cheaply. It is standalone in the sense it take the atmosphere from an existing analysis rather than running 4D-Var. Whilst the ECMWF scripts for this do not lend themselves to sharing, the concept is one that could be taken up more widely to facilitate testing.
4. EnKF features strongly in plans, with the intention to use OOPS to test algorithmic developments. At present OOPS does not support EnKF but the JEDI-OOPS developments will, and it is likely the EnKF developments in JEDI-OOPS can be ported back to OOPS. This will be investigated by ECMWF and information shared.
5. It was agreed that tests for land DA configurations could be shared to be included in ECMWF overnight testing and Meteo-France's davai system.
6. It was noted that screen level T, q assimilation in the atmospheric 4D-Var is relevant, and information on progress with this will be shared.

https://confluence.ecmwf.int/display/OOPS/6+April+2020+HIRLAM-MeteoFrance-ECMWF+meeting+on+Land+DA