Coupling requirements for various flavours of coupled variational data assimilation at ECMWF

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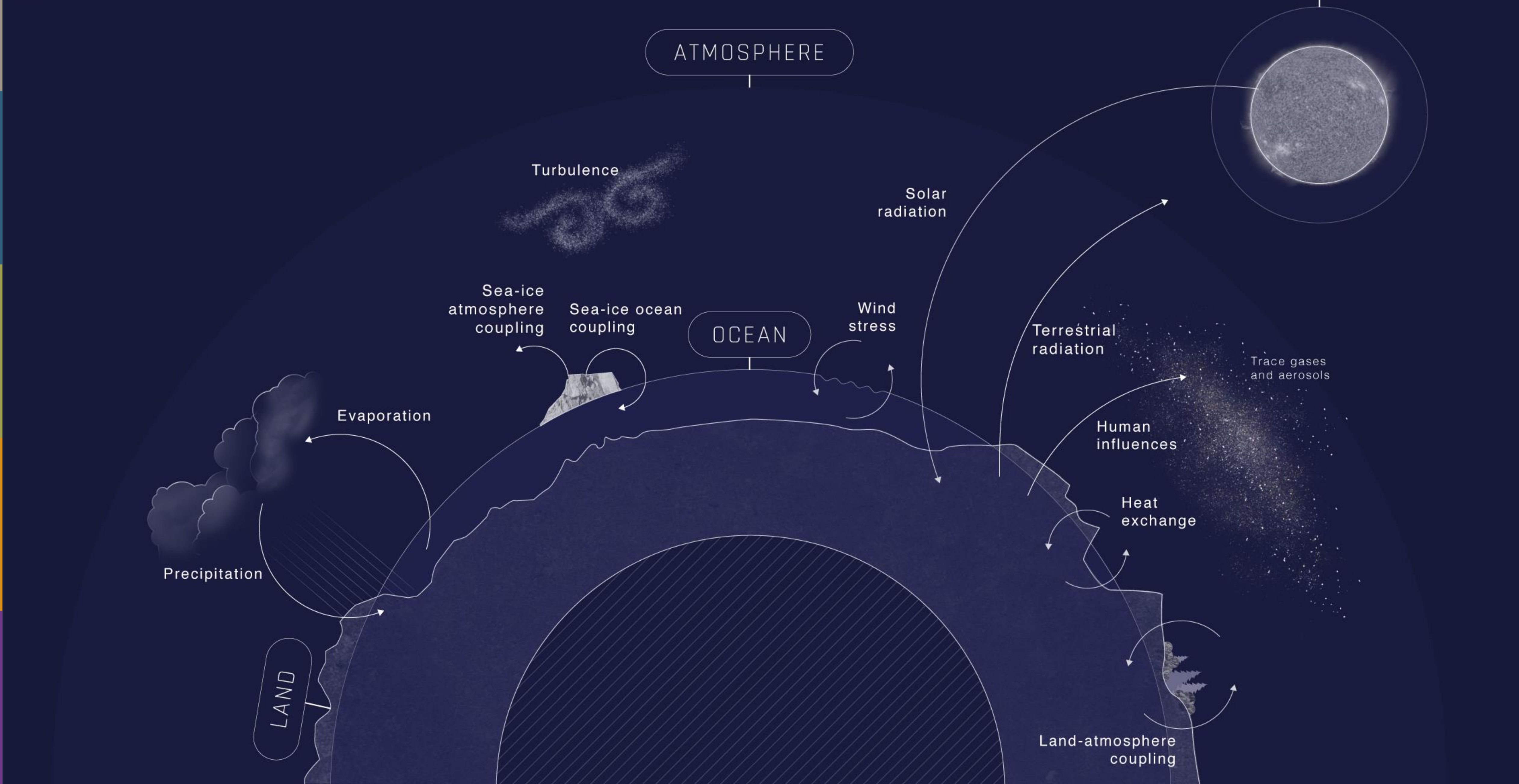
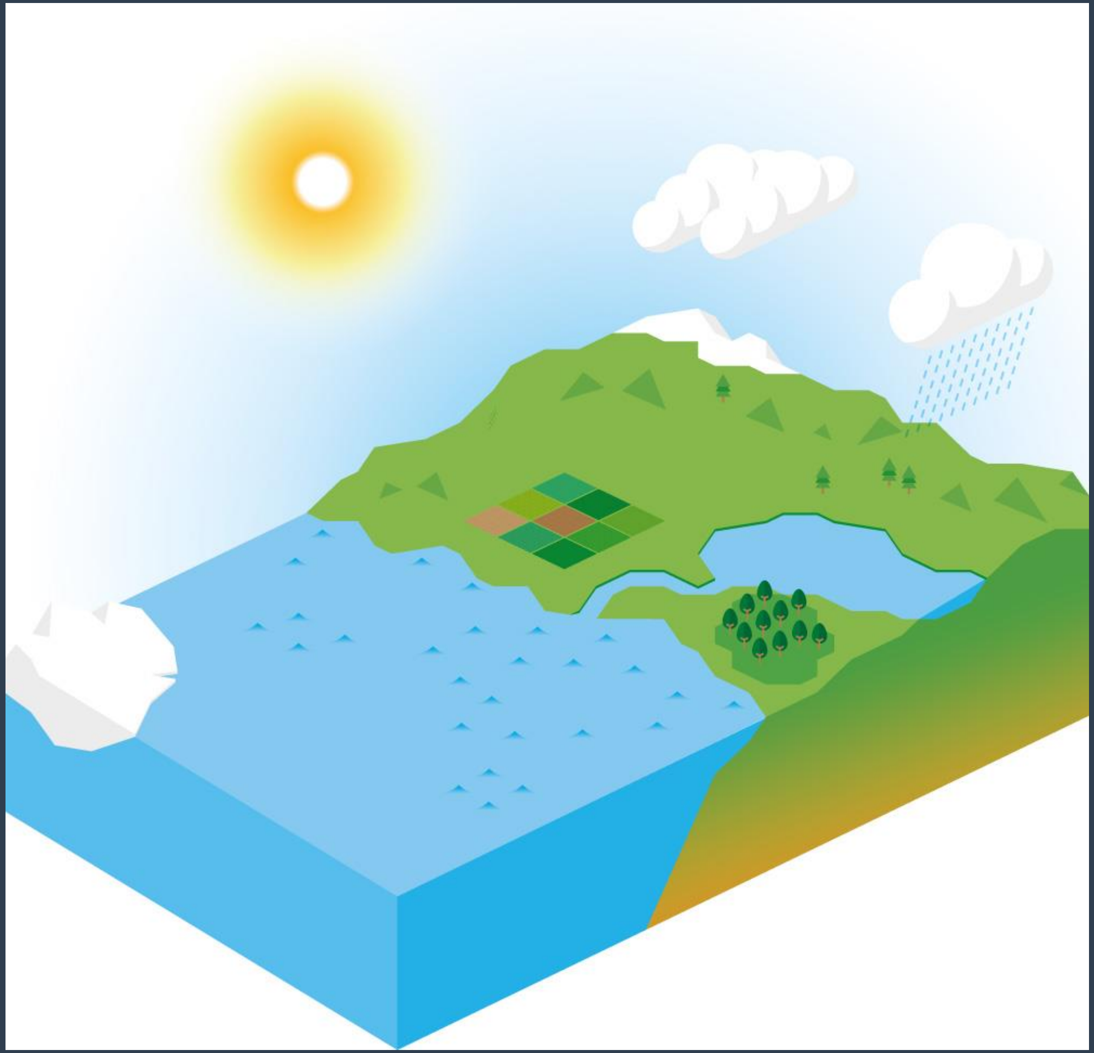
ECMWF EARTH SYSTEM



ECMWF coupled forecasts

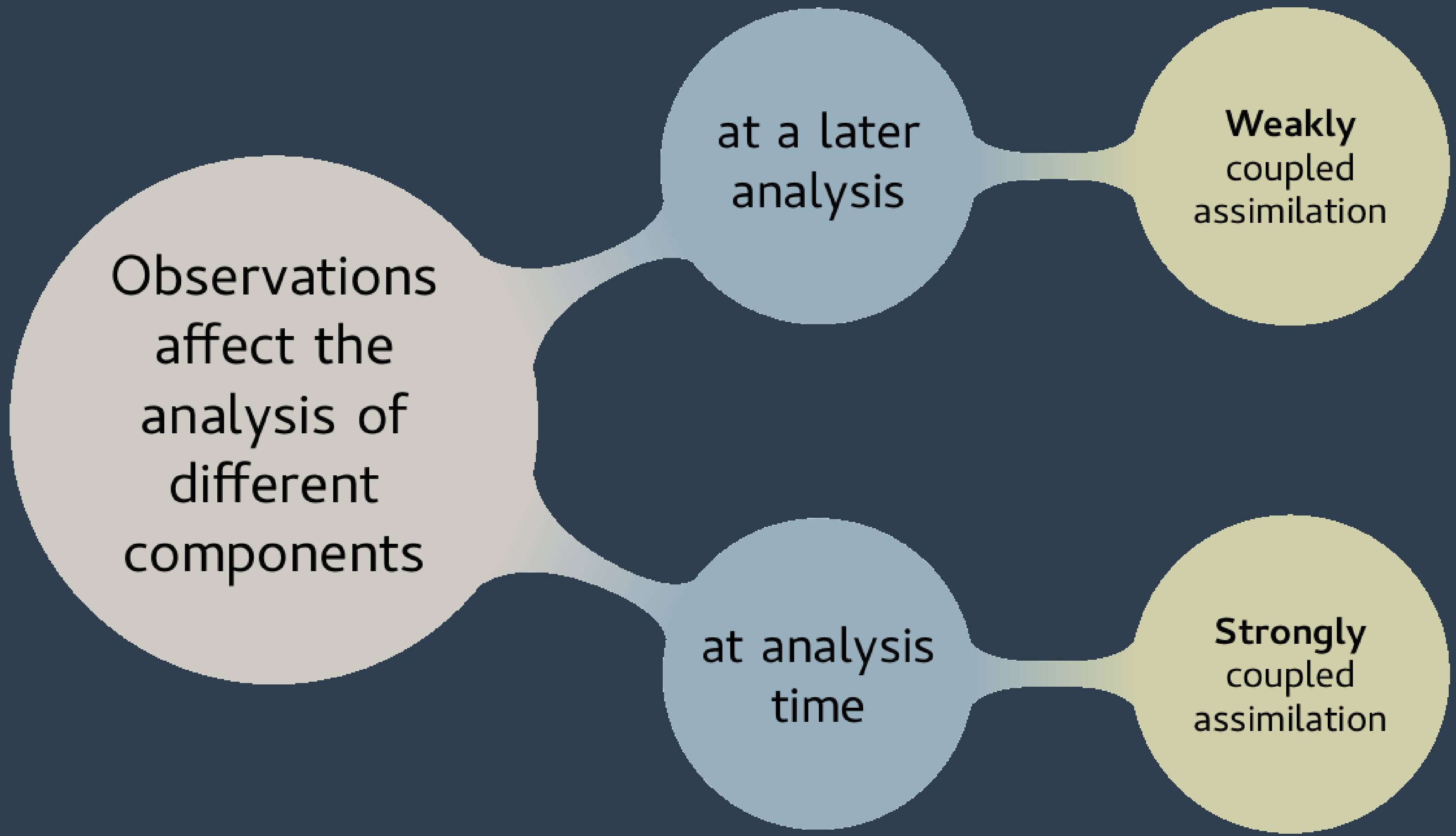


Components of ECMWF’s IFS Earth System.

Along with the atmosphere, there are models of the

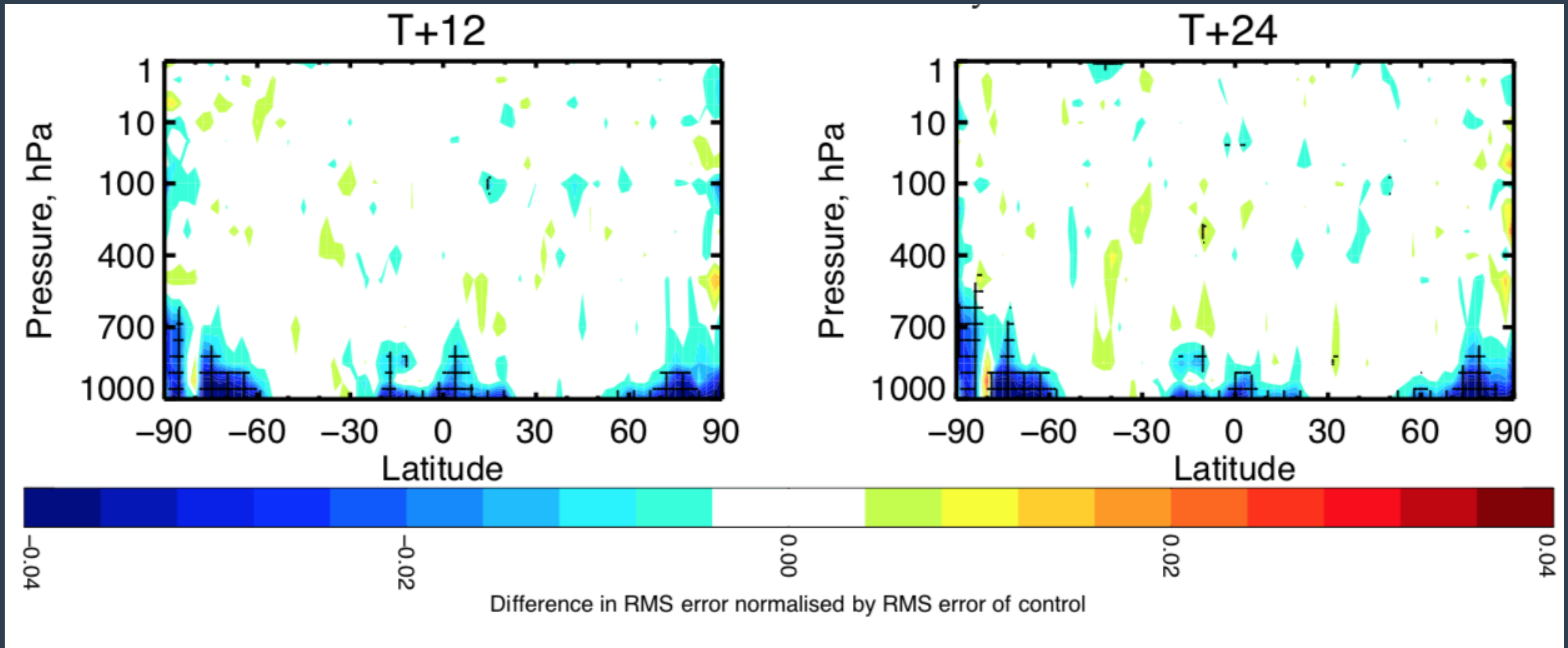
- ocean,
- waves,
- sea ice,
- land surface,
- snow,
- lakes

Categories of coupled assimilation



We have weakly coupled data assimilation for waves, land, ocean and sea ice

Ocean-atmosphere weakly coupled assimilation through sea ice and SST



(b) dRMSE of temperature

June 2017-May 2018

Impact on Temperature FC

Normalized RMSE difference (coupled DA – uncoupled DA)

Browne et al.,

Remote Sensing, 2019

- Our weakly coupled configuration works by exchanging boundary conditions between the marine system and the atmospheric system.
- It is very flexible and allows to have different assimilation window lengths in different components

- As we want to move to more strongly coupled analyses, what might we want to have available?

Coupling within 4DVar

$$x = \begin{bmatrix} x_{atmos} \\ x_{ocean} \end{bmatrix}$$

$$J(x) = \frac{1}{2}(x_b - x)^T \boldsymbol{P}_b^{-1}(x_b - x) + \frac{1}{2}\sum_k \left(y_k - \mathcal{H}_k\mathcal{M}_k(x)\right)^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$-\nabla J(x) = \boldsymbol{P}_b^{-1}(x_b - x) + \sum_k M_k^T H_k^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$x_b = \mathcal{M}(x_a)$$

- $\mathcal{M}$ is the coupled model – see all other talks!
  - If we have the coupled model we can implement a system like the CERA system
- This is due to restrictions on the other operators – we want to relax these restrictions
  - What does this mean for design of coupled systems?

Coupled observation operators

$$J(x) = \frac{1}{2}(x_b - x)^T \boldsymbol{P}_b^{-1}(x_b - x) + \frac{1}{2}\sum_k \left(y_k - \mathcal{H}_k \mathcal{M}_k(x)\right)^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k \mathcal{M}_k(x))$$

$$-\nabla J(x) = \boldsymbol{P}_b^{-1}(x_b - x) + \sum_k M_k^T H_k^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k \mathcal{M}_k(x))$$

- Consider a microwave observation in the polar regions – it might be sensitive to:
  - The atmospheric column
  - Sea ice concentration
  - Melt pond concentration
- Should we correct the atmosphere, or the ice, or the ponds?
- The observation departure should be available to the top level assimilation control structure, not just limited to the model component

Coupled TL/AD

$$J(x) = \frac{1}{2}(x_b - x)^T \boldsymbol{P}_b^{-1}(x_b - x) + \frac{1}{2}\sum_k \left(y_k - \mathcal{H}_k\mathcal{M}_k(x)\right)^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$-\nabla J(x) = \boldsymbol{P}_b^{-1}(x_b - x) + \sum_k \boxed{M_k^T} H_k^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$M^T = \begin{bmatrix} M_{atmos}^T & M_{atmos2ocean}^T \\ M_{ocean2atmos}^T & M_{ocean}^T \end{bmatrix}$$

- How can a coupled adjoint be computed?
  - Could be only a subset of processes
  - How can it be maintained?
- This is key for variational data assimilation methods and very powerful if it can be achieved

Coupled background error covariances

$$J(x) = \frac{1}{2}(x_b - x)^T \boxed{\boldsymbol{P}_b^{-1}}(x_b - x) + \frac{1}{2}\sum_k \left(y_k - \mathcal{H}_k\mathcal{M}_k(x)\right)^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$-\nabla J(x) = \boxed{\boldsymbol{P}_b^{-1}}(x_b - x) + \sum_k M_k^T H_k^T \boldsymbol{R}_k^{-1}(y_k - \mathcal{H}_k\mathcal{M}_k(x))$$

$$P_b = \begin{bmatrix} P_b^{atmos} & P_b^{coupled} \\ P_b^{coupled} & P_b^{ocean} \end{bmatrix}$$

- The background error covariance matrix spreads information
- It is a non local operator which needs to be tuneable to spread different information on different scales
- Can any coupling methodology allow for the construction of such an operator?

Summary

- Our operational weakly coupled data assimilation system works at the scripts level and so requires no coupled model developments
- Having the coupled model alone can allow a further degree of coupling within 4DVar (i.e. similar to the CERA system)
- Having a unified observation operator code across model components can introduce more coupling
- Coupled tangent linear/adjoint codes are needed for coupled 4DVar ‘proper’
- Are there coupling approaches that can facilitate applications of operators across components rather than fields, for building coupled background error covariances operators?

References

Laloyaux, P., et al. (2018). CERA-20C: A coupled reanalysis of the twentieth century. *Journal of Advances in Modeling Earth Systems*, 10, 1172– 1195. https://doi.org/10.1029/2018MS001273

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