Exploring strategies for coupled 4D-Var data assimilation using an idealised atmosphere-ocean model

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Introduction

- Typically, initial conditions for coupled atmosphere-ocean model forecasts are provided by combining analyses from independent (uncoupled) data assimilation systems.
- Operational centres want to move to coupled data assimilation systems
  - strongly coupled assimilation is technically and scientifically challenging
  - weakly coupled assimilation systems being developed as a first step
- We have been using an idealised 1D coupled atmosphere-ocean model framework to assess the expected benefits of moving towards coupled data assimilation in the context of incremental 4D-Var.
- Focus on
  - imbalance at initial time
  - transfer of information across the air-sea interface

Incremental 4D-Var

Solve iteratively

set $\mathbf{x}_0^{(0)} = \mathbf{x}_b$

outer loop: for $k = 0, \ldots, N_{outer}$

compute $\mathbf{d}_i^{(k)} = \mathbf{y}_i - h(\mathbf{x}_i^{(k)})$, where $\mathbf{x}_i^{(k)} = m(t_i, t_0, \mathbf{x}_0^{(k)})$

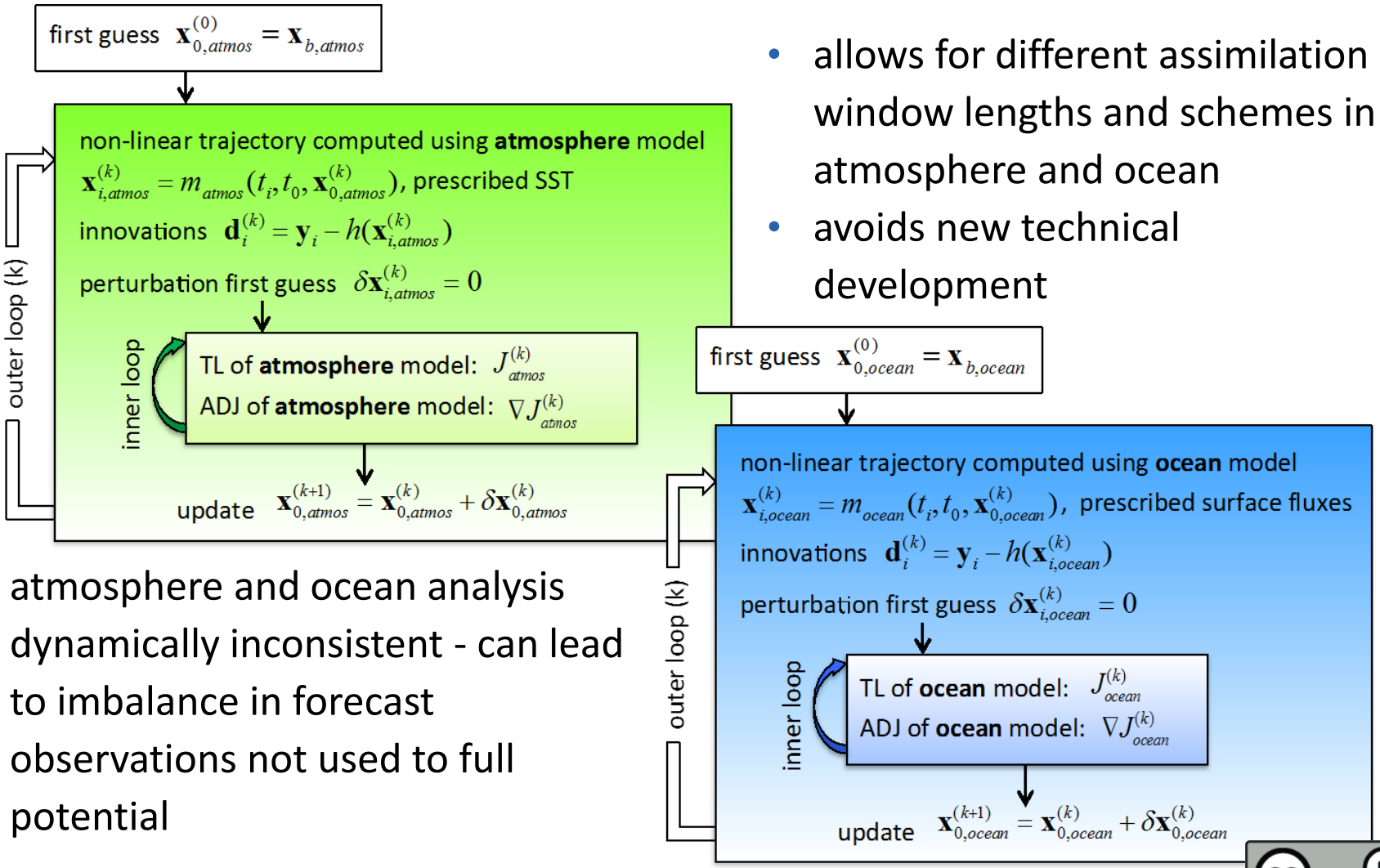
inner loop: minimise

$$\mathrm{J}^{(k)}\left(\delta\mathbf{x}_0^{(k)}\right) = \frac{1}{2}\left(\delta\mathbf{x}_0^{(k)} - \left(\mathbf{x}_b - \mathbf{x}_0^{(k)}\right)\right)^T \mathbf{B}^{-1}\left(\delta\mathbf{x}_0^{(k)} - \left(\mathbf{x}_b - \mathbf{x}_0^{(k)}\right)\right) + \frac{1}{2}\sum_{i=0}^{n}\left(\mathbf{H}_i\delta\mathbf{x}_i^{(k)} - \mathbf{d}_i^{(k)}\right)^T \mathbf{R}_i^{-1}\left(\mathbf{H}_i\delta\mathbf{x}_i^{(k)} - \mathbf{d}_i^{(k)}\right)$$

subject to $\delta\mathbf{x}_i^{(k)} = \mathbf{M}(t_i, t_0, \mathbf{x}^{(k)})\delta\mathbf{x}_0^{(k)}$

update $\mathbf{x}_0^{(k+1)} = \mathbf{x}_0^{(k)} + \delta\mathbf{x}_0^{(k)}$

Uncoupled incremental 4D-Var



- allows for different assimilation window lengths and schemes in atmosphere and ocean
- avoids new technical development

- atmosphere and ocean analysis dynamically inconsistent - can lead to imbalance in forecast
- observations not used to full potential

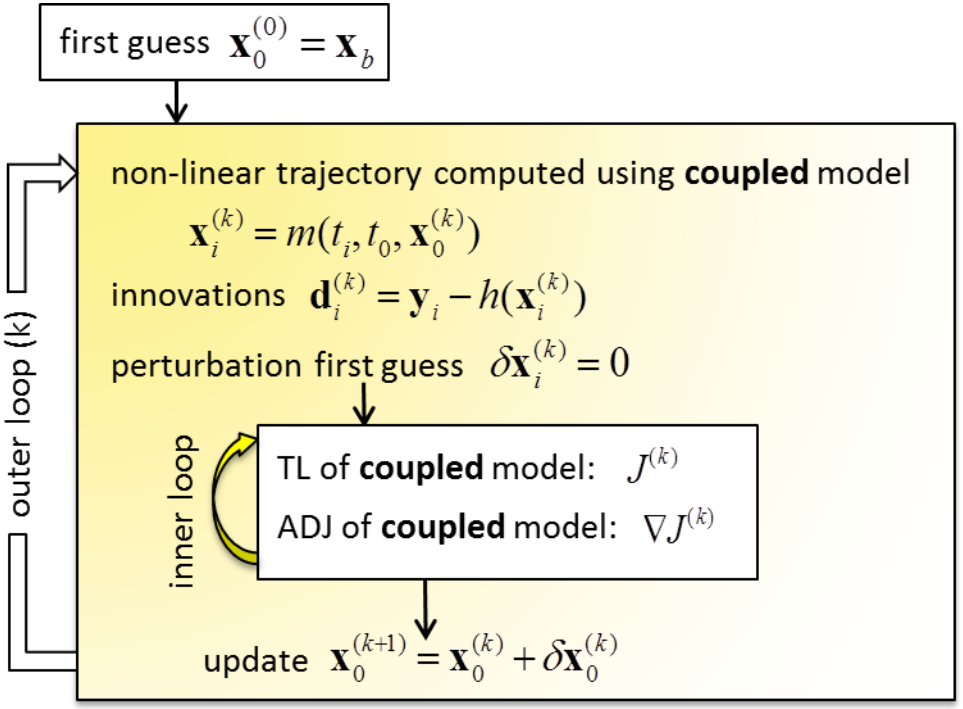
Strongly coupled incremental 4D-Var

Single minimisation process

- allows for cross-covariances between atmosphere and ocean

$$\mathbf{B} = \begin{pmatrix} \mathbf{B}_A & \mathbf{B}_{AO} \\ \mathbf{B}_{OA} & \mathbf{B}_O \end{pmatrix}$$

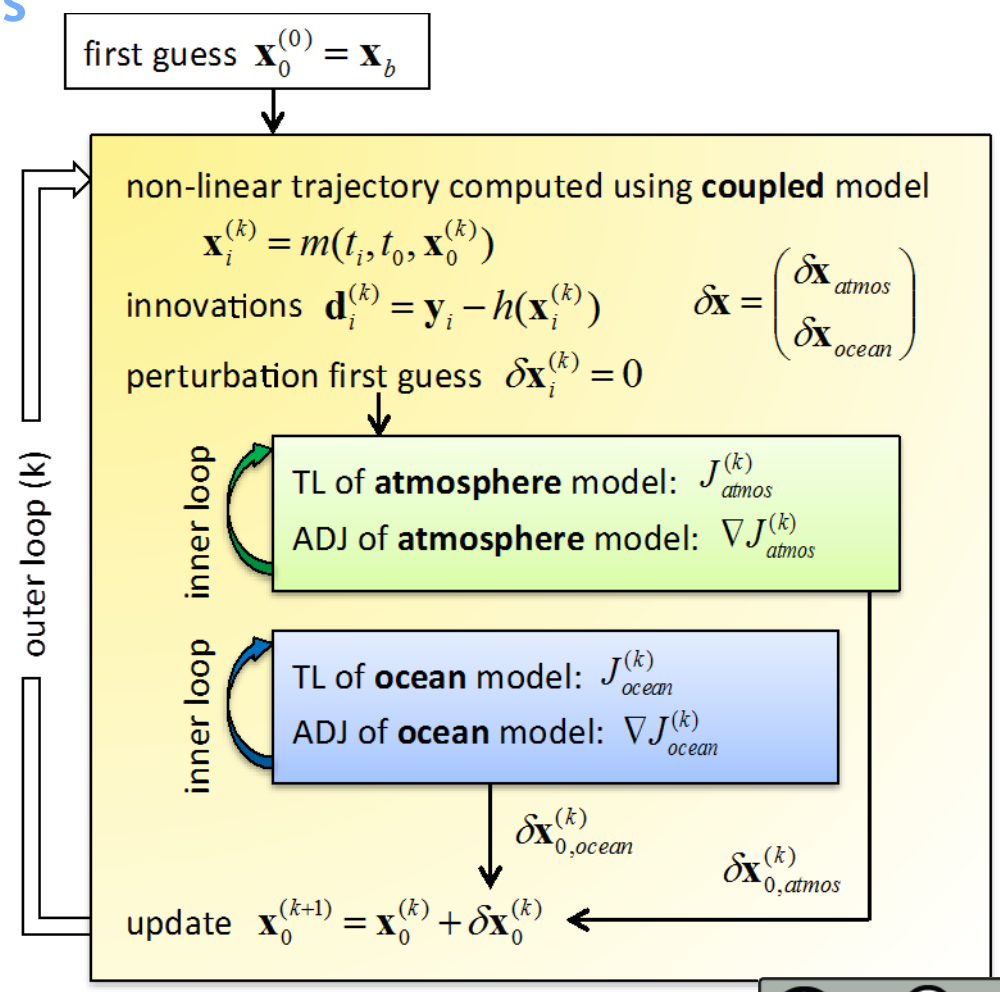
- better use of near surface observations - atmosphere observations can influence ocean analysis and vice versa
- requires same window length in atmosphere and ocean



Weakly coupled incremental 4D-Var

Separate minimisation process for atmosphere and ocean

- limits amount of new technical development
- no explicit cross-covariances between atmosphere and ocean
- atmosphere (ocean) observations can only influence ocean (atmosphere) analysis if multiple outer-loops used
- allows for different assimilation window lengths and schemes in ocean and atmosphere



Idealised system

Atmosphere

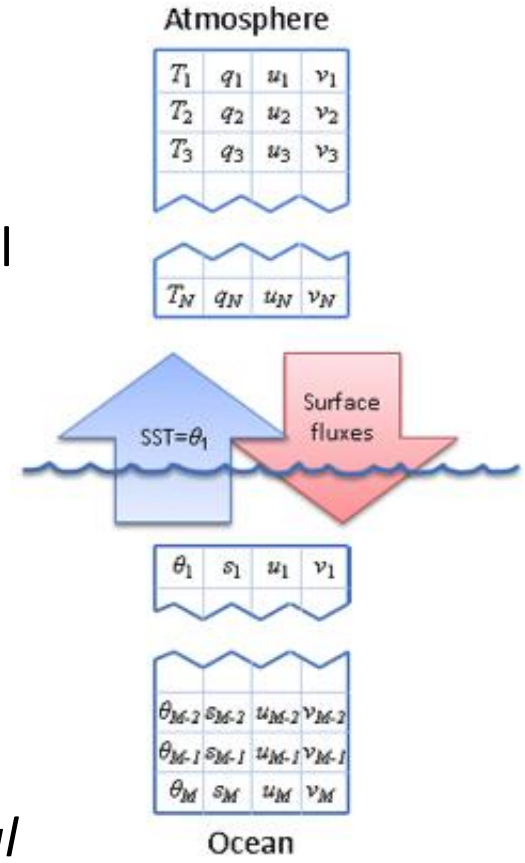
Simplified version of the ECMWF single column model

- based on early version of the IFS code
- adiabatic component + vertical diffusion
- 4 state variables on 60 model levels
- forced by large scale horizontal advection

Ocean

Single column K-Profile Parameterisation (KPP) mixed-layer model based on the scheme of *Large et al*

- developed by the NCAS climate group at UoR
- 4 state variables on 35 model levels
- forced by short and long wave radiation at surface



coupled via SST and surface fluxes of heat, moisture & momentum

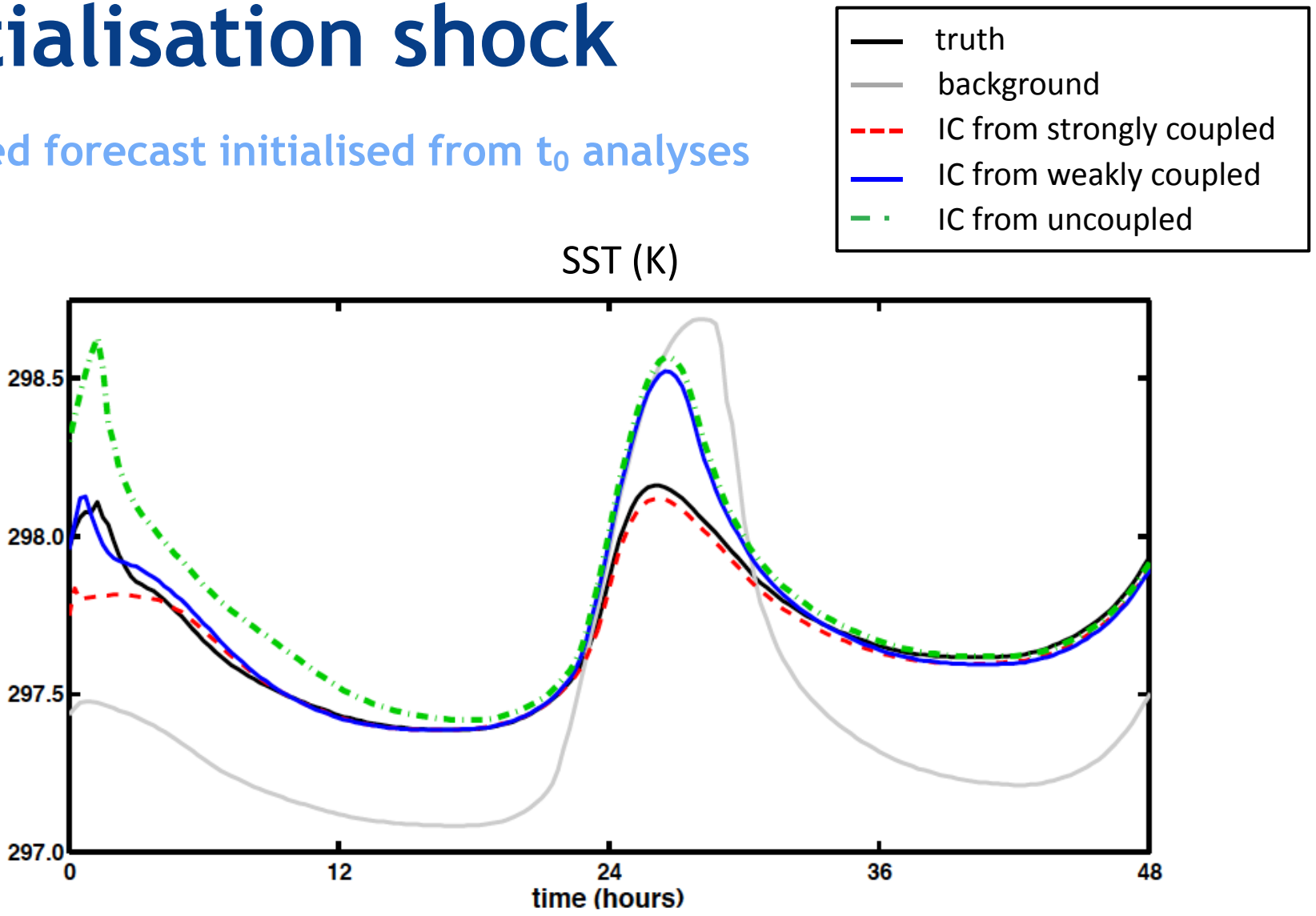
Identical twin experiments

comparison of uncoupled, weakly coupled and fully coupled systems

- 12 hour assimilation window, 3 outer loops
- data from June 2013, for the point 188.75°E, 25°N (Pacific Ocean)
- 'true' initial state is coupled model forecast initialised using ERA Interim and Mercator Ocean data
- initial background state is a perturbed coupled model forecast
- observations are generated by adding random noise to *'truth'*
- uncoupled assimilations - SST & surface fluxes from ERA interim
- error covariance matrices $\mathbf{B}$ and $\mathbf{R}$ are diagonal
- simple preconditioning of cost function using $\mathbf{B}^{1/2}$

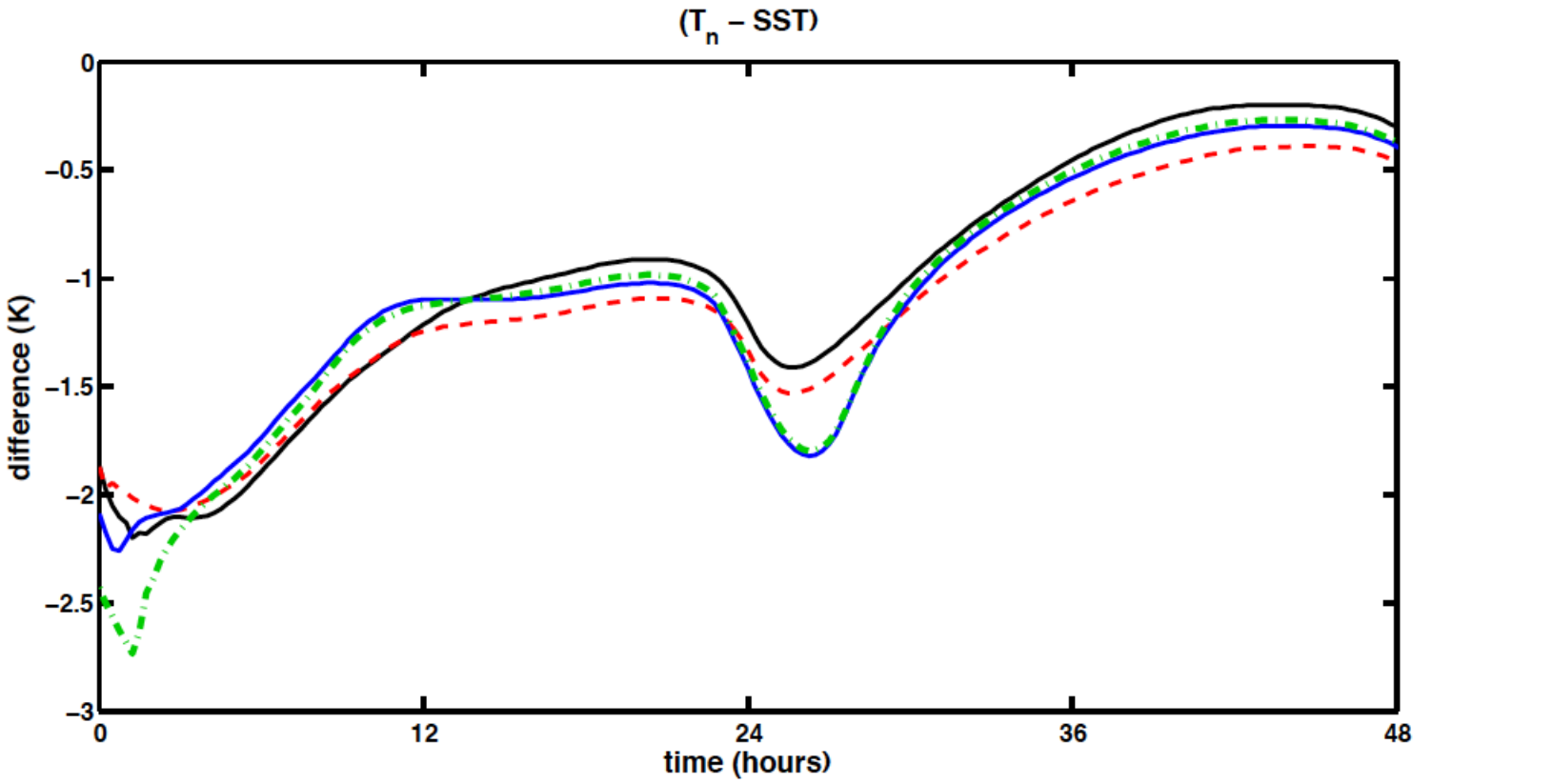
Initialisation shock

coupled forecast initialised from t_0 analyses



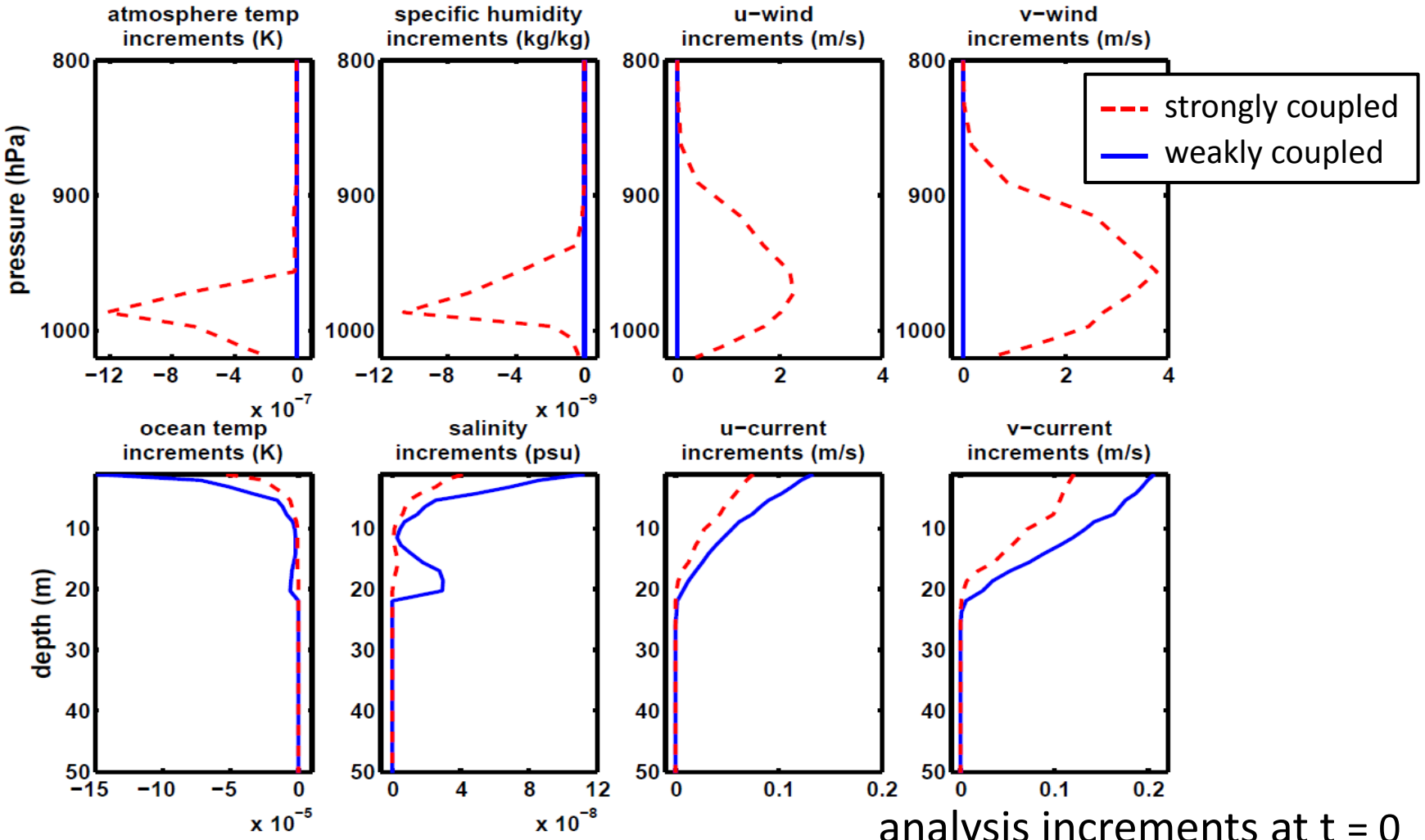
Initialisation shock

atmosphere-ocean temperature difference



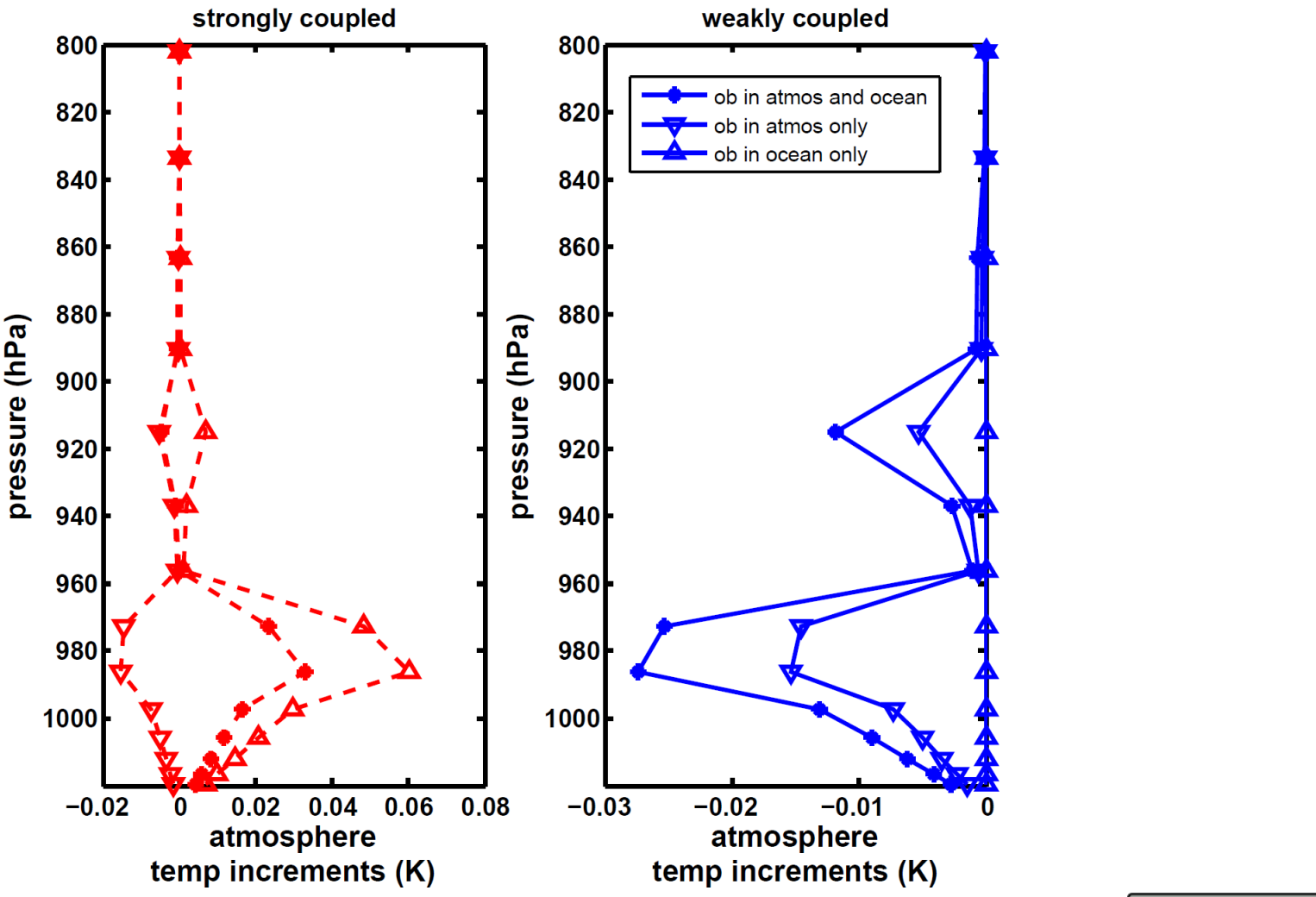
Single observation experiments

Observing ocean surface current at end of assimilation window



analysis increments at t = 0

Double observation experiment



Summary

- demonstrated some of the potential benefits expected from coupled data assimilation systems.
- when compared to uncoupled initialisation, coupled assimilation is able to reduce initialisation shock and its impact on the subsequent forecast - although it may not eliminate it completely.
- weakly coupled system is sensitive to input parameters of the assimilation but still offers benefits over uncoupled system.
- single observation experiments demonstrate how coupled assimilation systems enable improved use of near-surface data by transferring information across the air-sea interface.
- greater transfer of information in weakly-coupled assimilation if both systems are observed.

Additional info

Research to better understand the nature and structure of the atmosphere-ocean cross-covariances and how they should be represented in both strongly and weakly coupled systems is currently underway ...

Paper in revision for *Tellus* A, pre-print available at
www.reading.ac.uk/maths-and-stats/research/maths-preprints.aspx
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