Exploring coupled data assimilation using an idealised atmosphere-ocean model

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Problem

- Seasonal-decadal forecasting requires initialisation of coupled atmosphere-ocean models
- Current approach uses analyses generated from independent atmosphere and ocean data assimilation systems
  - ignores interactions between systems
  - analysis states likely to be unbalanced
  - inconsistency at interface can lead to imbalance when states are combined for coupled model forecast (initialisation shock)
  - near surface data not properly utilised, e.g. SST, scatterometer winds
- Operational centres moving towards coupled assimilation systems

Objective

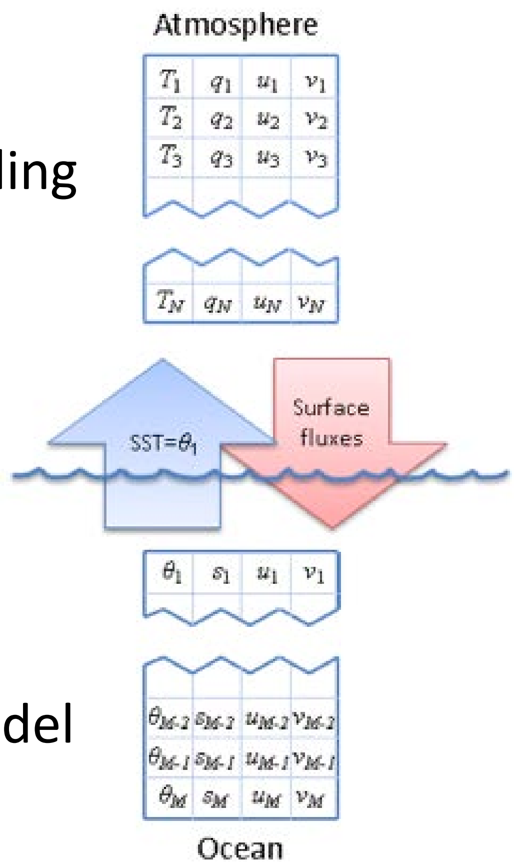
To investigate some of the fundamental questions in the design of coupled atmosphere-ocean data assimilation systems within the context of an idealised strong constraint incremental 4D-Var system:

- avoids issues associated with more complex models
- allows for more sophisticated experiments than in an operational setting
- easier interpretation of results
- guide the design and implementation of coupled methods within full 3D operational scale systems

Idealised system

The system needs to be

- simple and quick to run
- able to represent realistic atmosphere-ocean coupling



Ocean

- single column KPP (K-Profile Parameterisation) mixed-layer model

Atmosphere

- simplified version of the ECMWF single column model

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

Incremental 4D-Var

Solve iteratively

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

outer loop: for k = 0, … , Nouter

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

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

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

first guess $\mathbf{x}_{0,atmos}^{(0)} = \mathbf{x}_{b,atmos}$

outer loop (k)

non-linear trajectory computed using **atmosphere** model

$\mathbf{x}_{i,atmos}^{(k)} = m_{atmos}(t_i, t_0, \mathbf{x}_{0,atmos}^{(k)})$, prescribed SST

innovations $\mathbf{d}_i^{(k)} = \mathbf{y}_i - h(\mathbf{x}_{i,atmos}^{(k)})$

perturbation first guess $\delta\mathbf{x}_{i,atmos}^{(k)} = 0$

inner loop

TL of **atmosphere** model: $J_{atmos}^{(k)}$

ADJ of **atmosphere** model: $\nabla J_{atmos}^{(k)}$

update $\mathbf{x}_{0,atmos}^{(k+1)} = \mathbf{x}_{0,atmos}^{(k)} + \delta\mathbf{x}_{0,atmos}^{(k)}$

first guess $\mathbf{x}_{0,ocean}^{(0)} = \mathbf{x}_{b,ocean}$

outer loop (k)

non-linear trajectory computed using **ocean** model

$\mathbf{x}_{i,ocean}^{(k)} = m_{ocean}(t_i, t_0, \mathbf{x}_{0,ocean}^{(k)})$, prescribed surface fluxes

innovations $\mathbf{d}_i^{(k)} = \mathbf{y}_i - h(\mathbf{x}_{i,ocean}^{(k)})$

perturbation first guess $\delta\mathbf{x}_{i,ocean}^{(k)} = 0$

inner loop

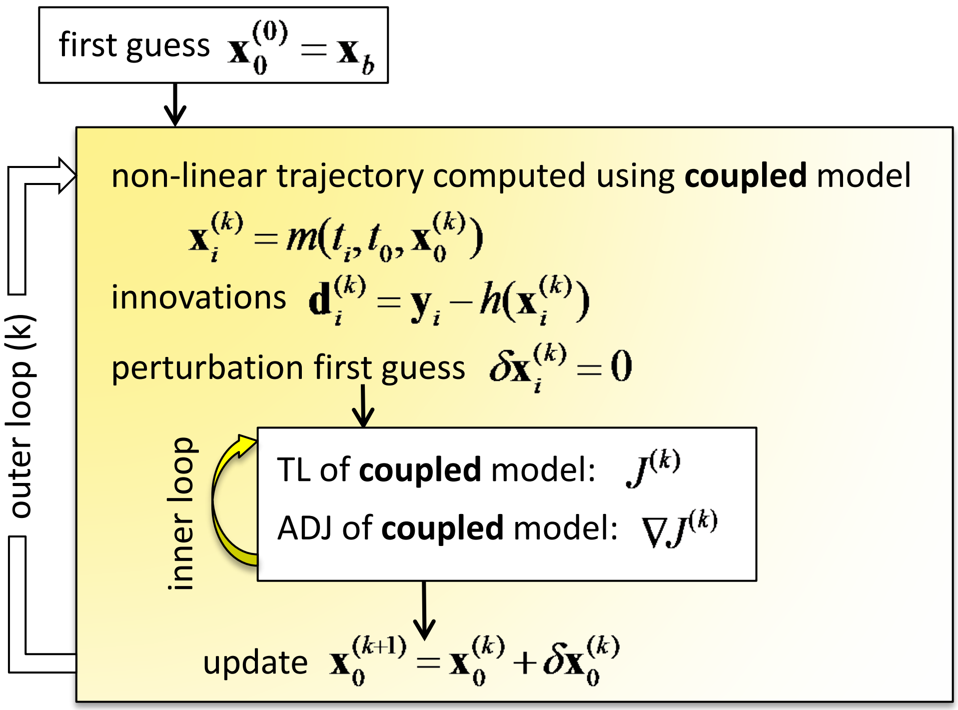
TL of **ocean** model: $J_{ocean}^{(k)}$

ADJ of **ocean** model: $\nabla J_{ocean}^{(k)}$

update $\mathbf{x}_{0,ocean}^{(k+1)} = \mathbf{x}_{0,ocean}^{(k)} + \delta\mathbf{x}_{0,ocean}^{(k)}$

- allows for different assimilation window lengths and schemes
- avoids large technical development

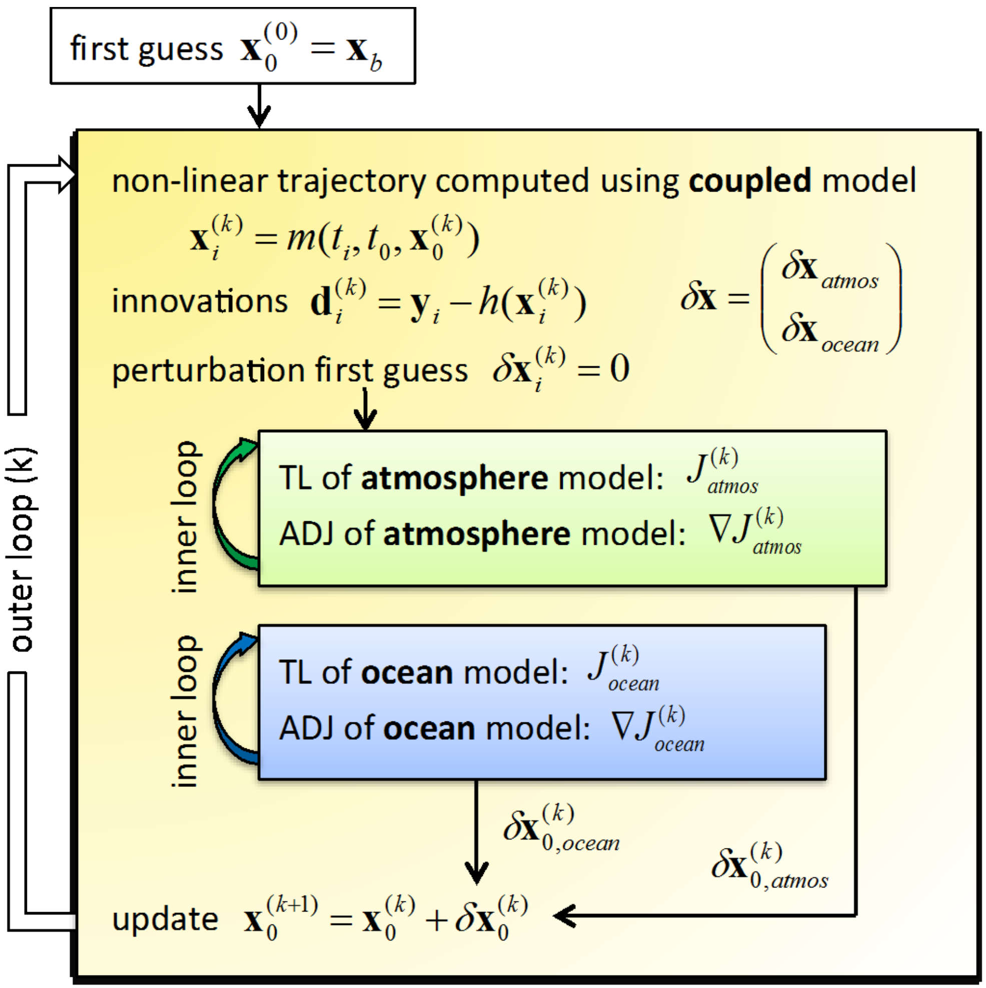
Fully coupled incremental 4D-Var



single minimisation process:

- allows for cross-covariances between atmosphere and ocean
- requires same window length in atmosphere and ocean
- technically challenging

Weakly coupled incremental 4D-Var



separate minimisation for atmosphere and ocean:

- new technical development limited
- allows for different assimilation windows (and schemes) in ocean and atmosphere
- no explicit cross-covariances between atmosphere and ocean
- balance?

Identical twin experiments

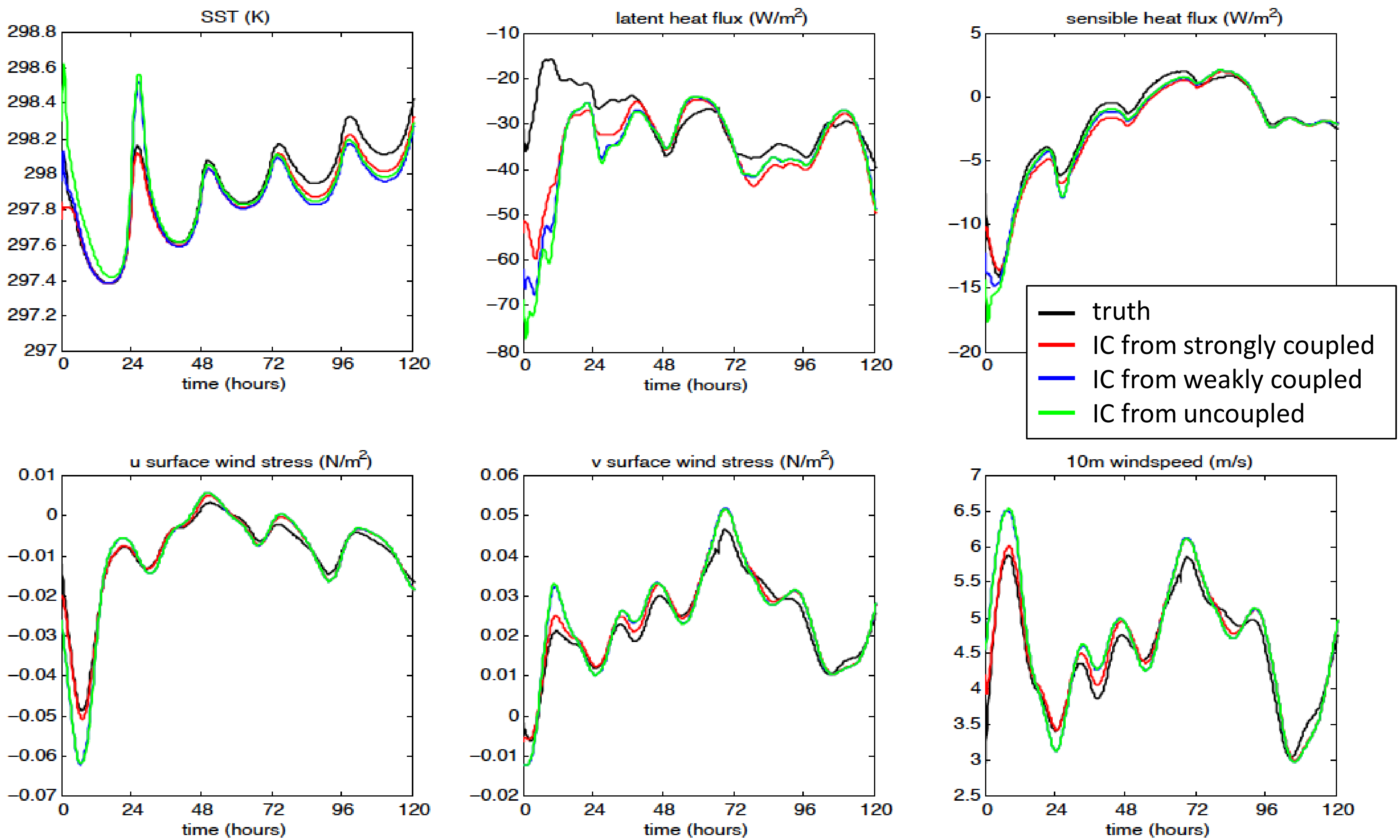
comparison of uncoupled, weakly coupled and fully coupled systems

- 12 hour assimilation window, 3 outer loops
- data for June 2013, 188.75ºE, 25ºN (North West Pacific Ocean)
- *'true'* initial state is coupled non-linear forecast valid at 00:00 UTC on 3rd June, with initial atmosphere state from ERA Interim and initial ocean state from Mercator Ocean
- initial background state is a perturbed non-linear model forecast valid at same time
- observations are generated by adding random Gaussian noise to true solution => operator h is linear

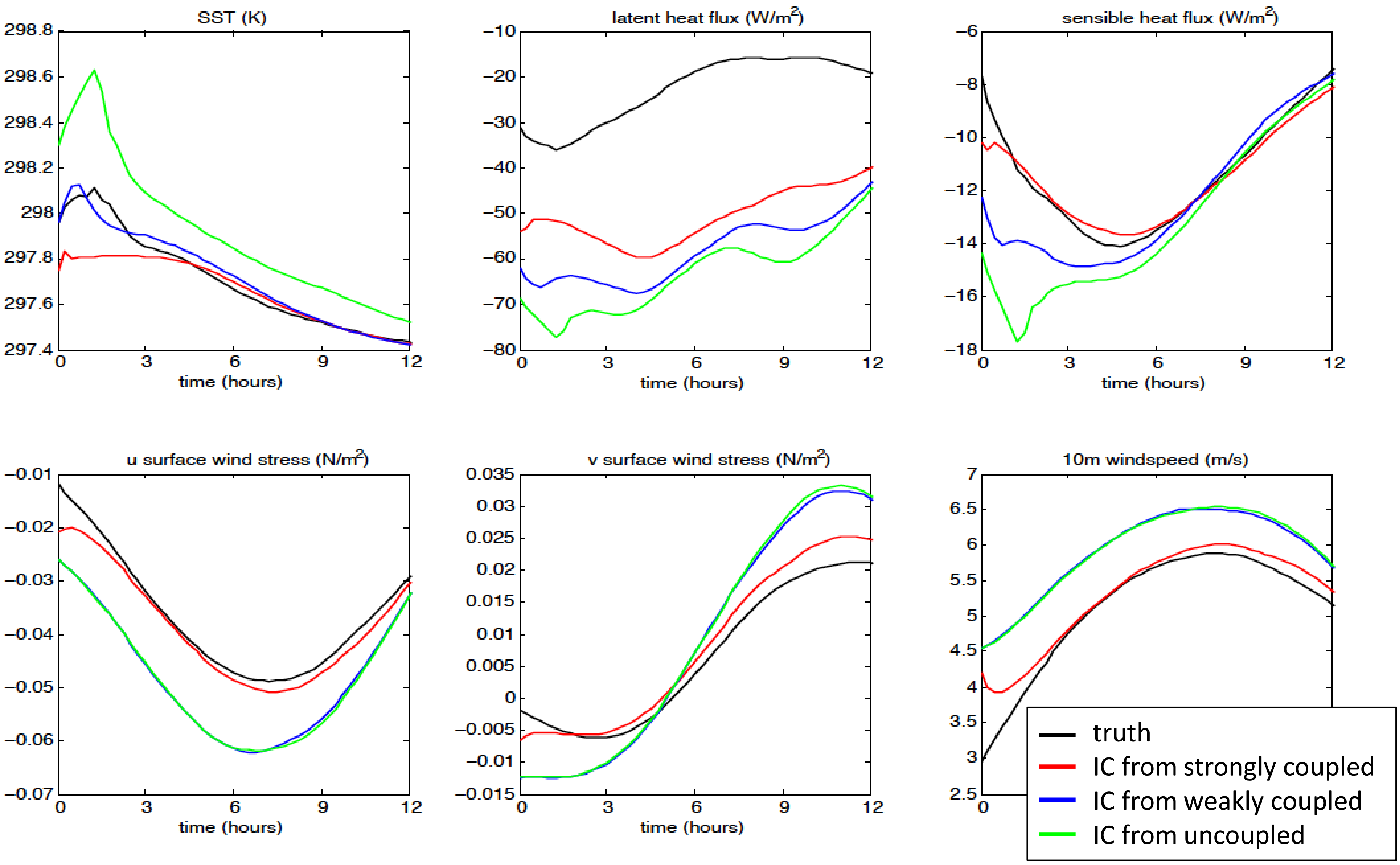
Identical twin experiments

- atmosphere: 3 hourly observations of temperature, u and v wind components taken at 17 of 60 levels
- ocean: 6 hourly observations of temperature, salinity, u and v currents taken at 23 of 35 levels
- no observations at initial time
- error covariance matrices $\mathbf{B}$ and $\mathbf{R}$ are diagonal
- uncoupled assimilations: 6 hourly SST/ surface fluxes from ERA interim

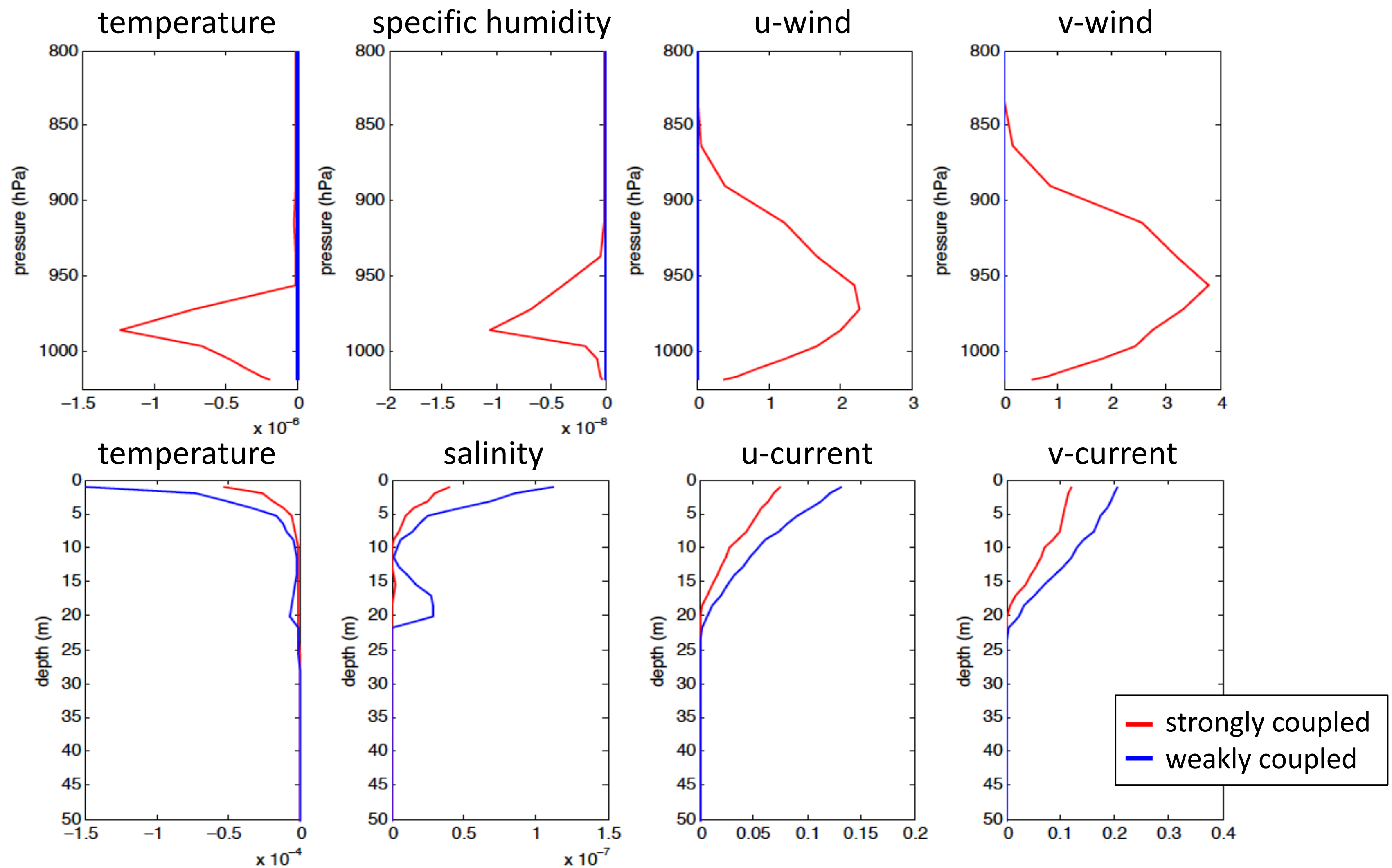
SST & surface fluxes



Initialisation shock



Near-surface observations



observing ocean velocity at top level of ocean model, at end of 12hr window

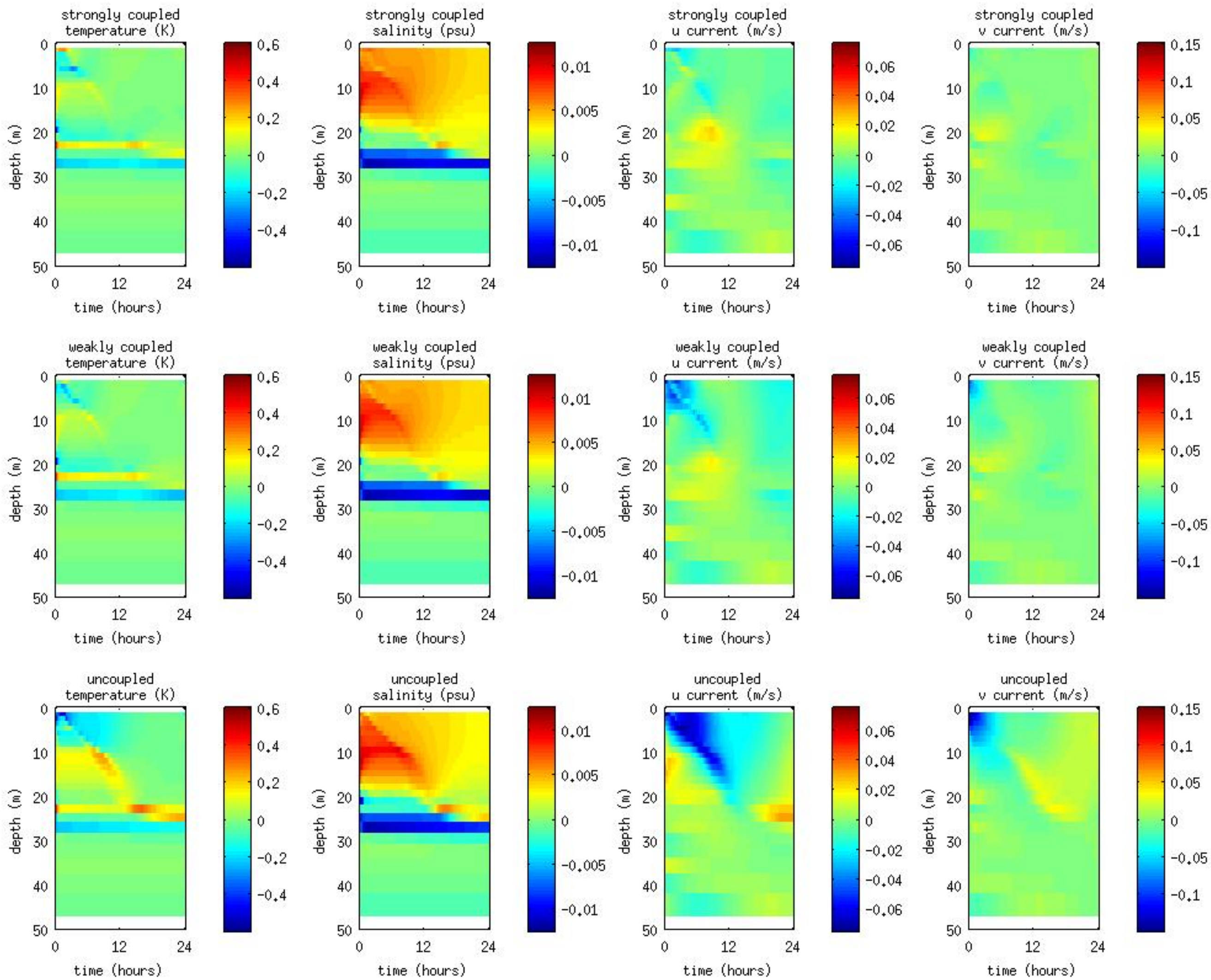
Coupled model forecast errors

temperature | salinity | u-velocity | v-velocity

strongly coupled

weakly coupled

uncoupled



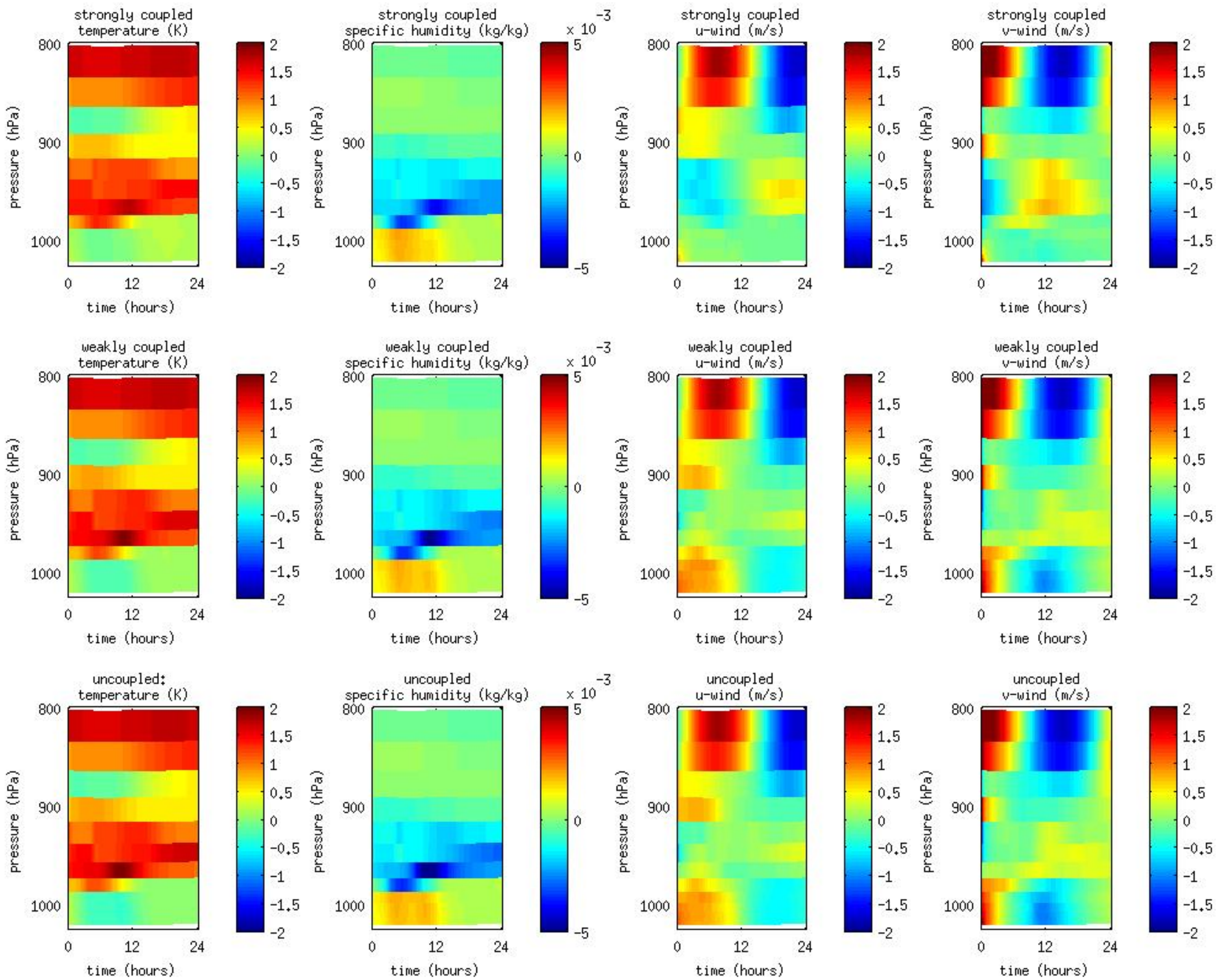
Coupled model forecast errors

temperature | specific humidity | u-wind | v-wind

strongly coupled

weakly coupled

uncoupled



Summary

Demonstrated potential benefits of moving towards coupled data assimilation systems:

- coupled assimilation has overall positive impact on analysis and coupled model forecast errors.
- strongly coupled system generally outperforms the weakly and uncoupled systems.
- weakly coupled system is sensitive to the input parameters of the assimilation.
- coupled data assimilation is able to reduce initialisation shock.
- coupled assimilation systems enable greater use of near-surface data through generation of cross covariance information.