Coupled atmosphere-ocean variational data assimilation in the presence of model error

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(work with Alison M. Fowler)

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Aim

Compare how different strategies for coupled 4D-Var behave in the presence of model error.

- Using idealised experiments in simplified model.
- Especially interested in longer windows.

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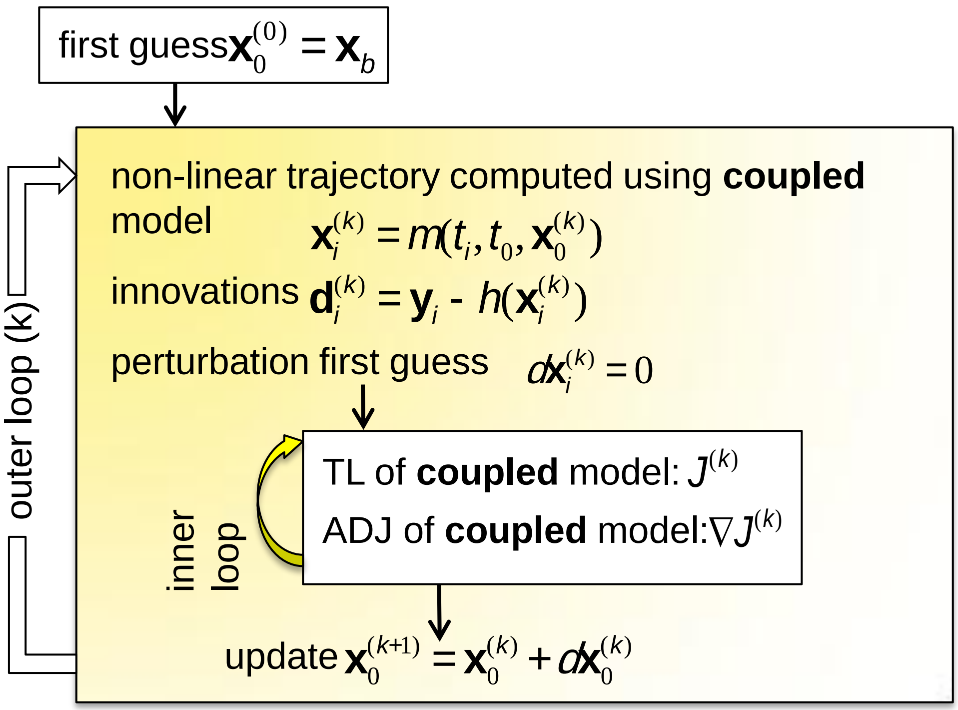
Strongly coupled incremental 4D-Var



- Allows for consistent estimate between atmosphere and ocean
- Offers possibility of better use of near-interface observations
- Requires same window length in atmosphere and ocean

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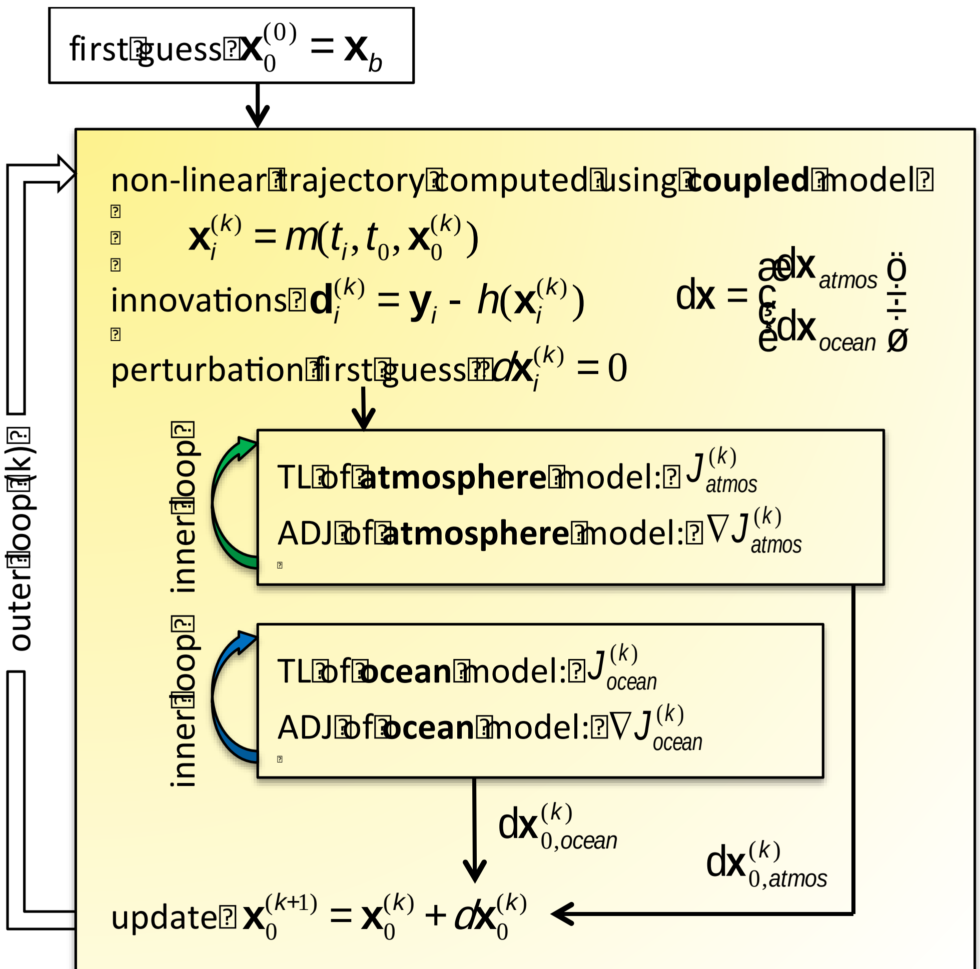
Weakly coupled incremental 4D-Var



- New technical development limited
- Can have different windows (and schemes) in ocean and atmosphere

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Uncoupled incremental 4D-Var

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

outer loop (k)

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

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

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

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

inner loop

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

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

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

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

outer loop (k)

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

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

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

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

inner loop

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

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

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

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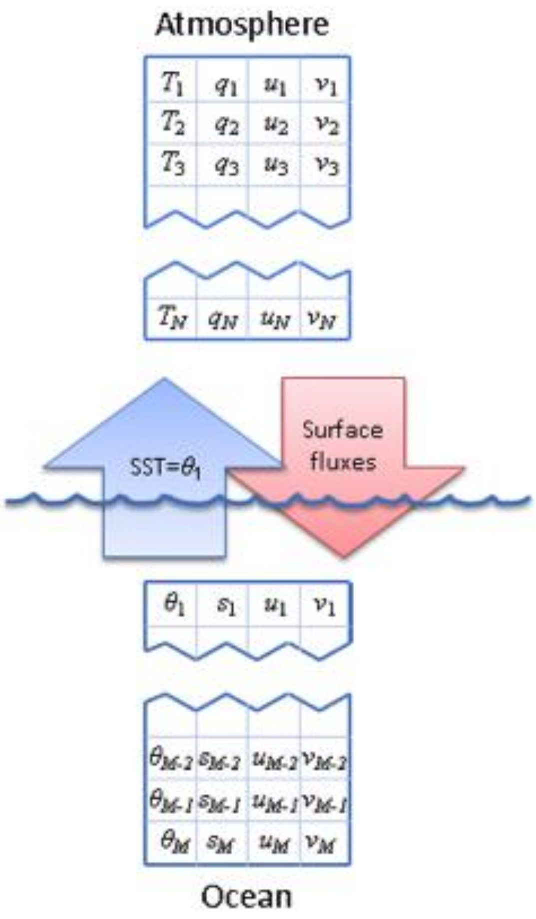
Idealised system

Atmosphere

Simplified version of the ECMWF single column model (SCM)

- based on early version of the IFS code
- 4 state variables on 60 model levels
- forced by large scale horizontal advection
- vertical advection with 2-time-level Eulerian (upwind) scheme



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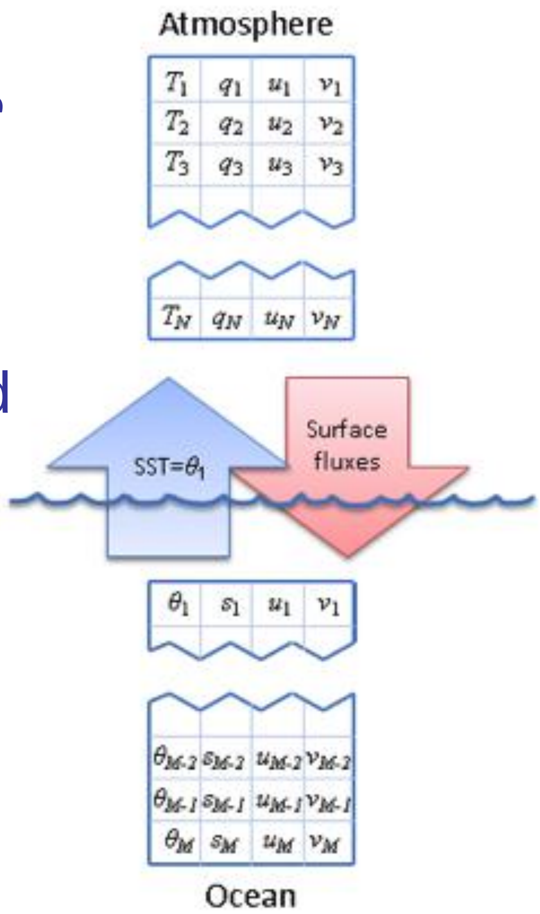
Idealised system

Ocean

Single column K-Profile Parameterisation (KPP) mixed-layer model based on the scheme of *Large et al*[1]

- developed by the NCAS climate group at UoR
- 4 state variables on 35 model levels (increased resolution near to the surface)
- forced by short and long wave radiation at surface

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



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Previous results – no model error

- Initialisation from coupled assimilation has positive impact on initial balance.
- Coupling allows transfer of information across interface.
- Weakly coupled systems are more sensitive to the frequency and number of observations.

Smith, P.J., Fowler, A.M. and Lawless, A.S. (2015), Exploring strategies for coupled 4D-Var data assimilation using an idealised atmosphere-ocean model. *Tellus A*, 67, 27025

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Experimental design

- Fraternal twin experiments
  - Truth model includes more physics and different ocean parameters
- Full observations every 3h in atmosphere and 6h in ocean.
- Test of 4D-Var with long assimilation windows
- Uncoupled with poor boundary conditions (ERA-Interim) and good boundary conditions (truth).

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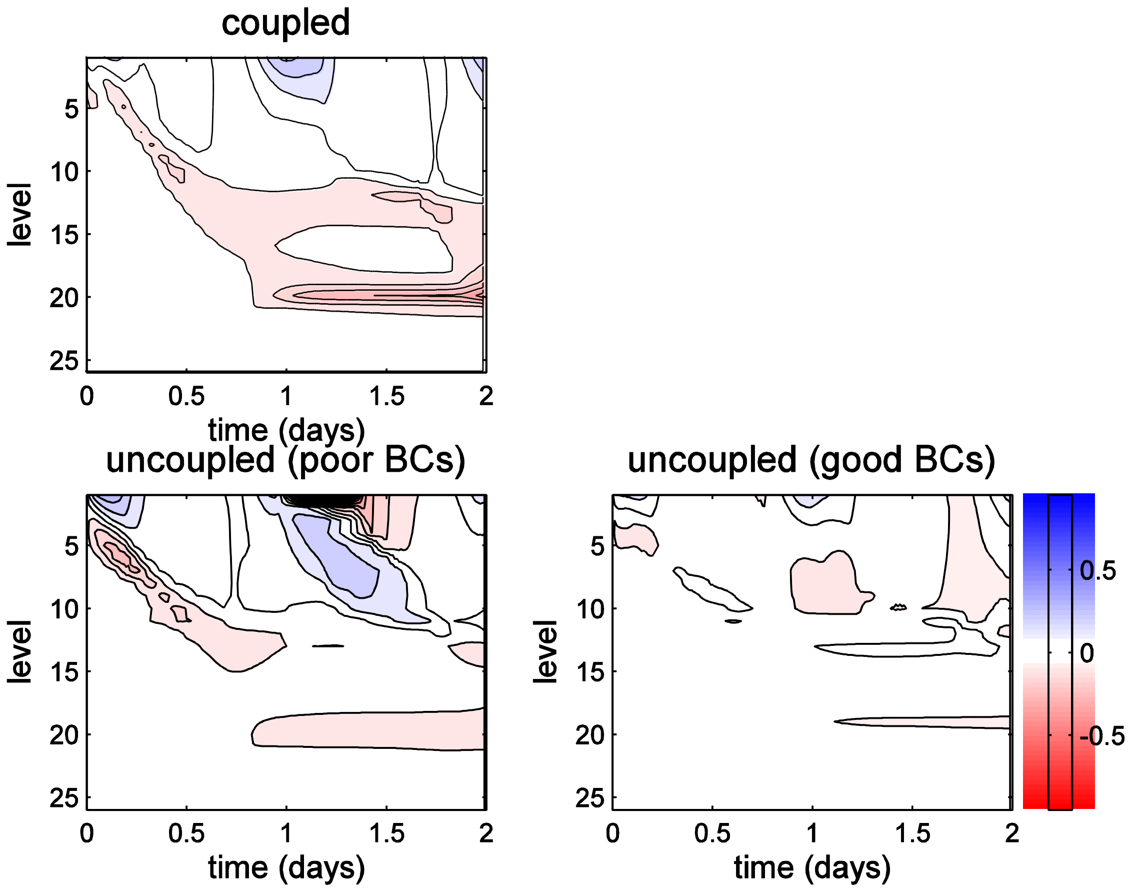
Effect of model error on forecast



Ocean temperature forecast errors in first 2 days (no assimilation)

- Coupled ocean forecasts very sensitive to upper boundary

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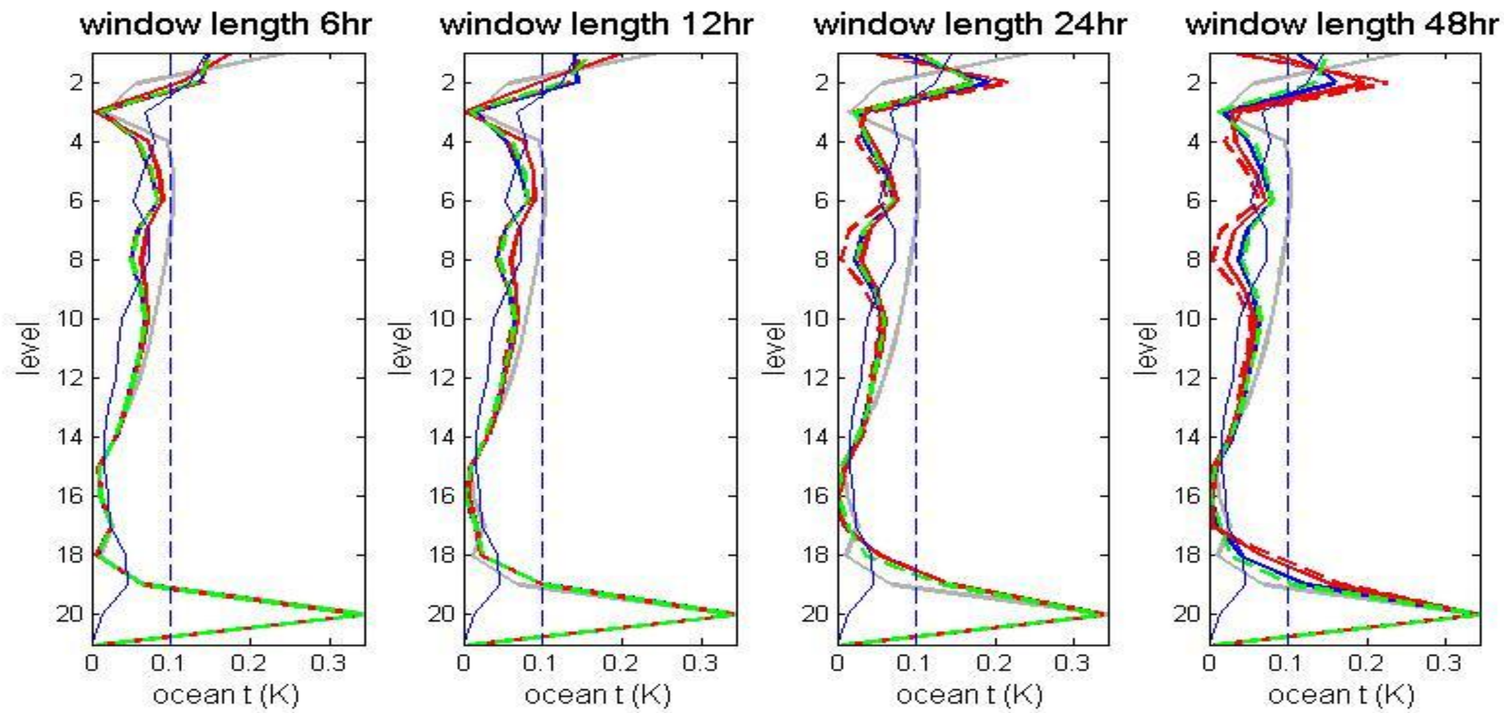
Assimilation – Absolute initial error in ocean temperature



- - - Strongly coupled

- - - Weakly coupled

- - - Uncoupled

As window length increases, uncoupled analysis is better at initial time.

But …

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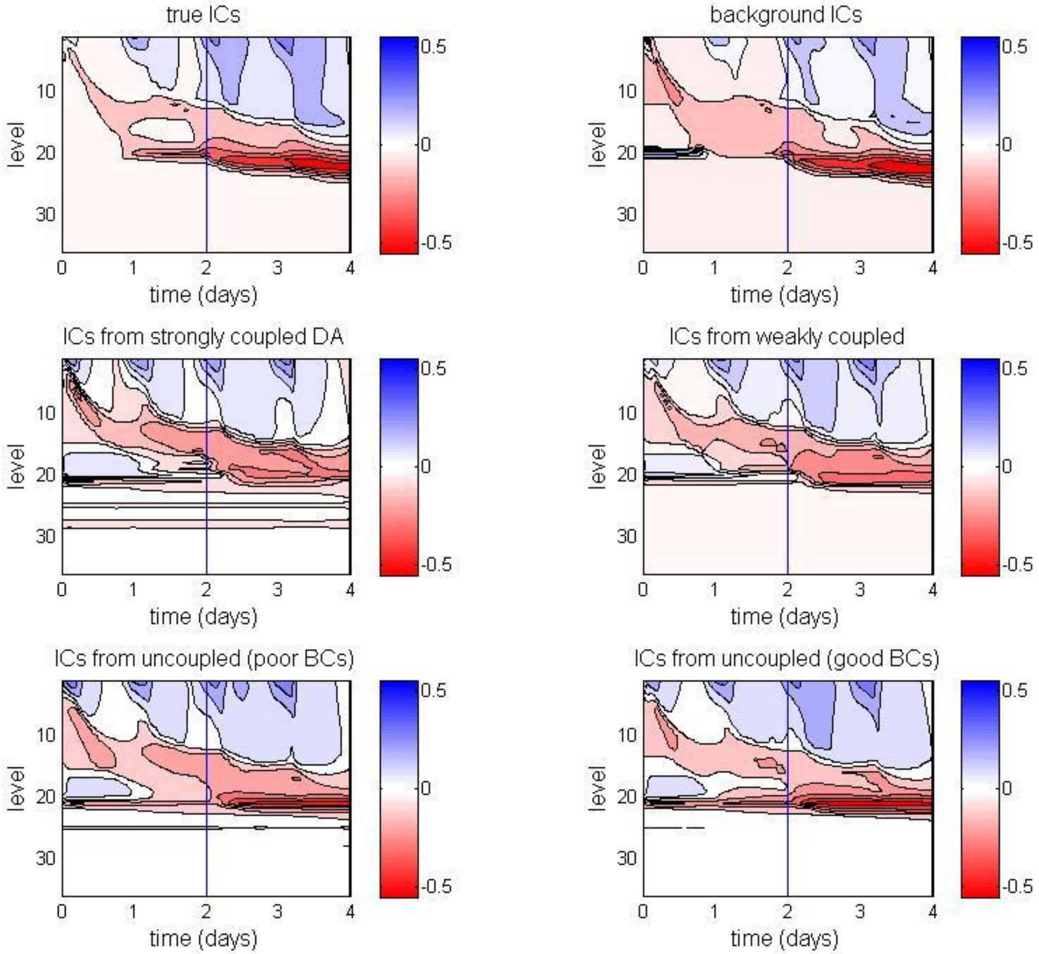
Assimilation – Forecast error in ocean temperature (48h assimilation window)



Coupled DA produces better forecasts, even if initial error worse.

Coupling of model allows coupled DA to compensate for model error.

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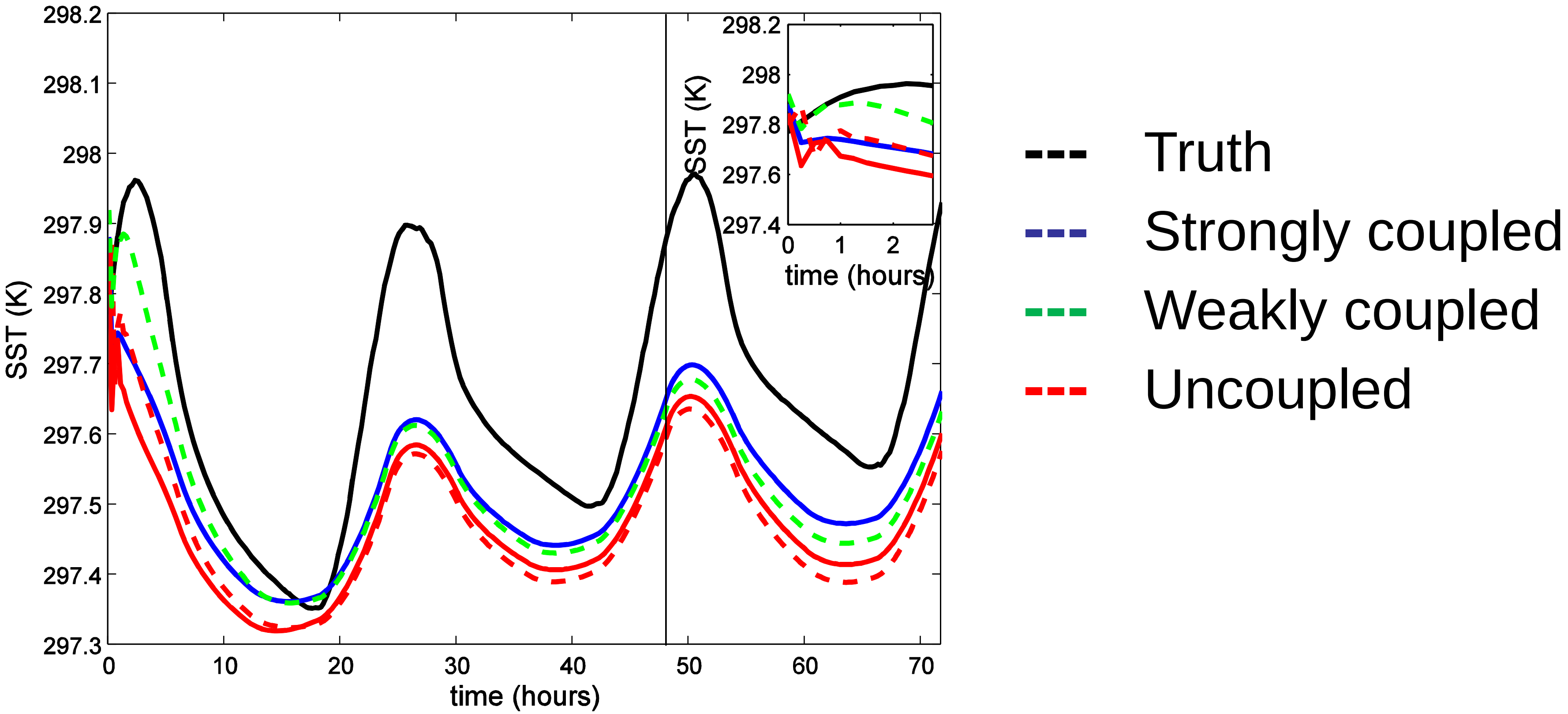
Initialisation shock



Coupled DA still able to reduce initialisation shock

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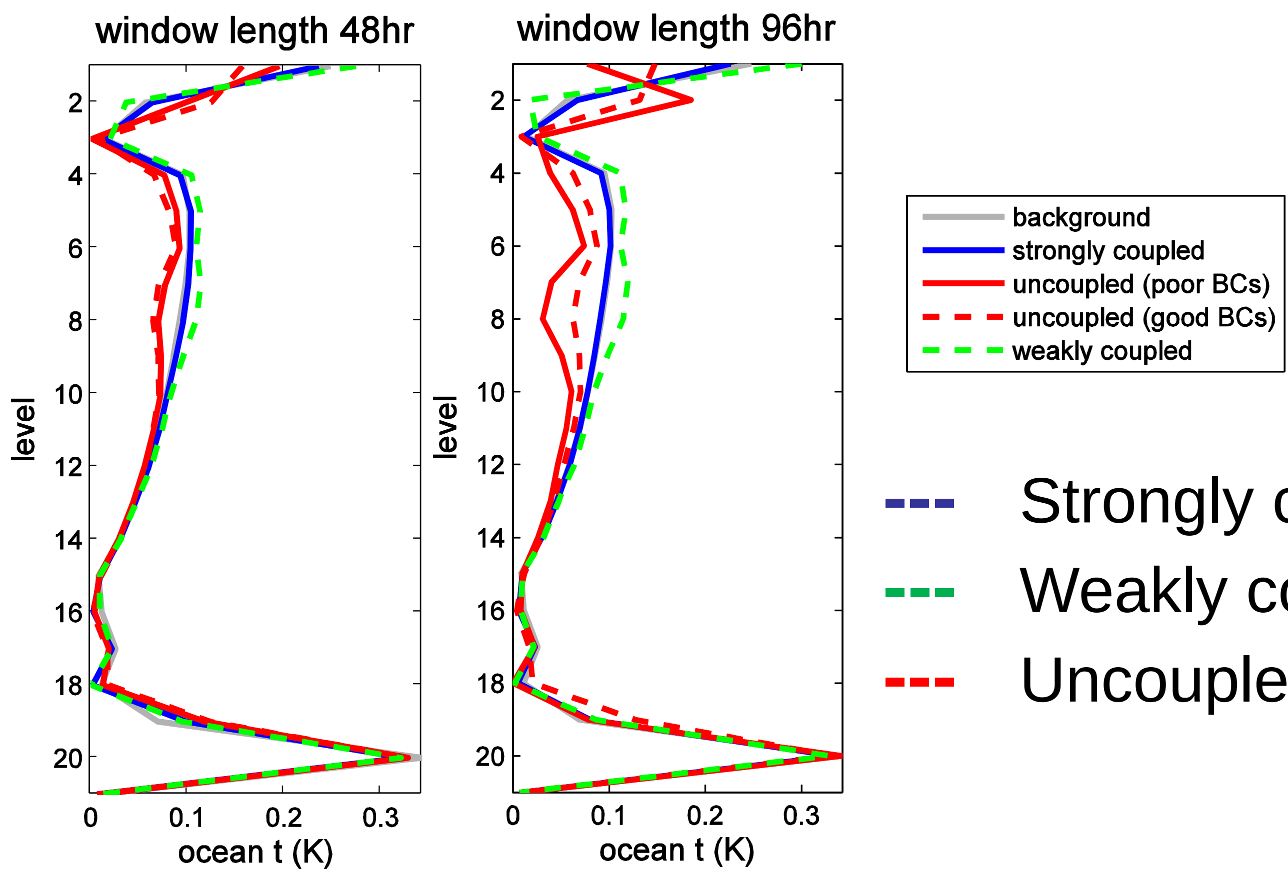
Reduced observations



Strongly coupled

Weakly coupled

Uncoupled

With reduced observations 96h window comparable to previous 48h window

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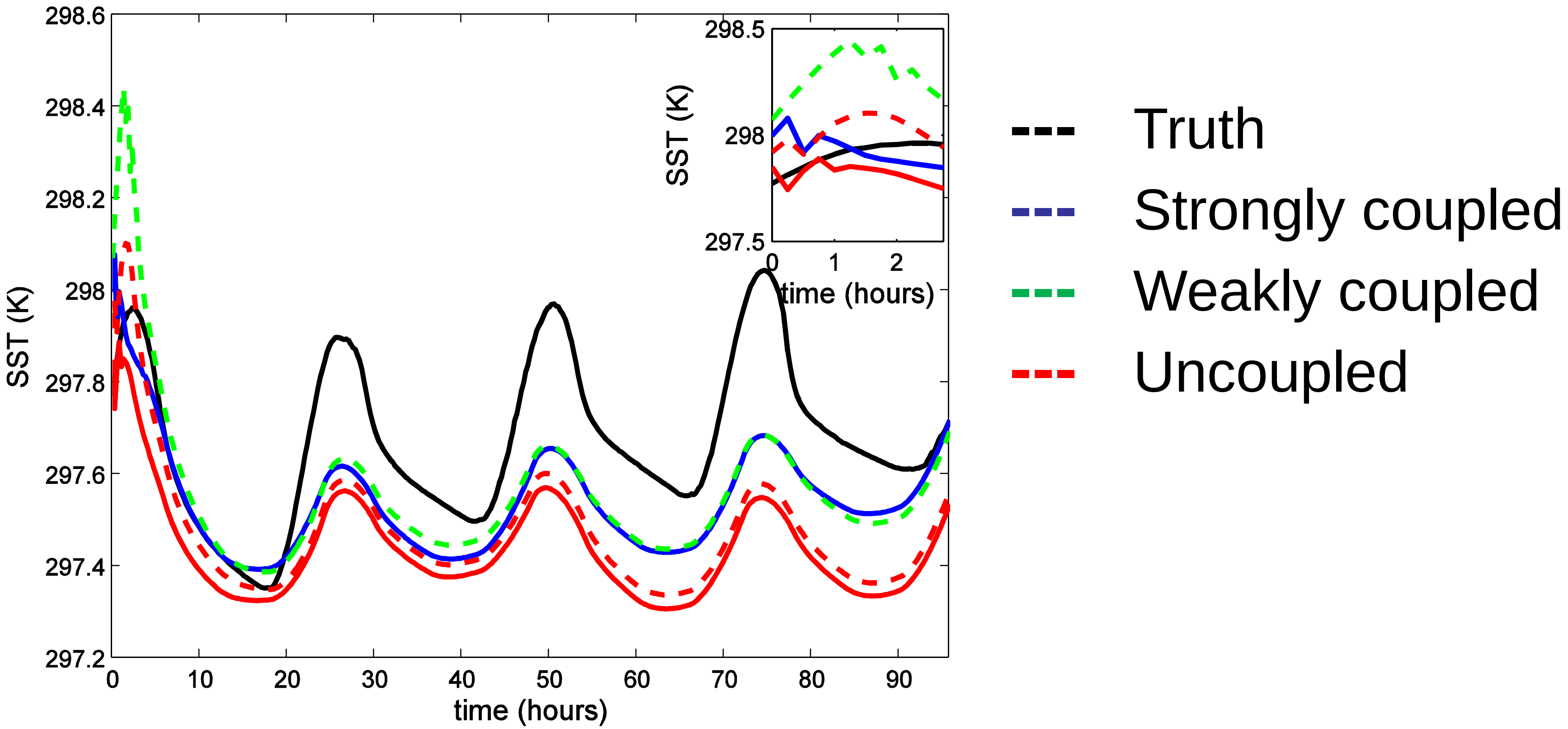
Reduced observations - Initialisation



Initialisation shock increased in weakly coupled DA

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Conclusions

- In the presence of model error uncoupled DA can produce a better initial state estimate than coupled DA for long windows.
- Coupled DA is better able to alter initial conditions to allow for later errors and produce a better forecast.

  → Optimal window length depends on application.
- Weakly coupled DA can be as good as strongly coupled with dense observations, but with sparse observations can have worse balance than uncoupled DA.

Fowler, A.M. and Lawless, A.S. (2016), An idealized study of coupled atmosphere-ocean 4D-Var in the presence of model error. *MWR,* 144, 4007-4030.

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