Department of Mathematics and Statistics

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

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## Aim

**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.**

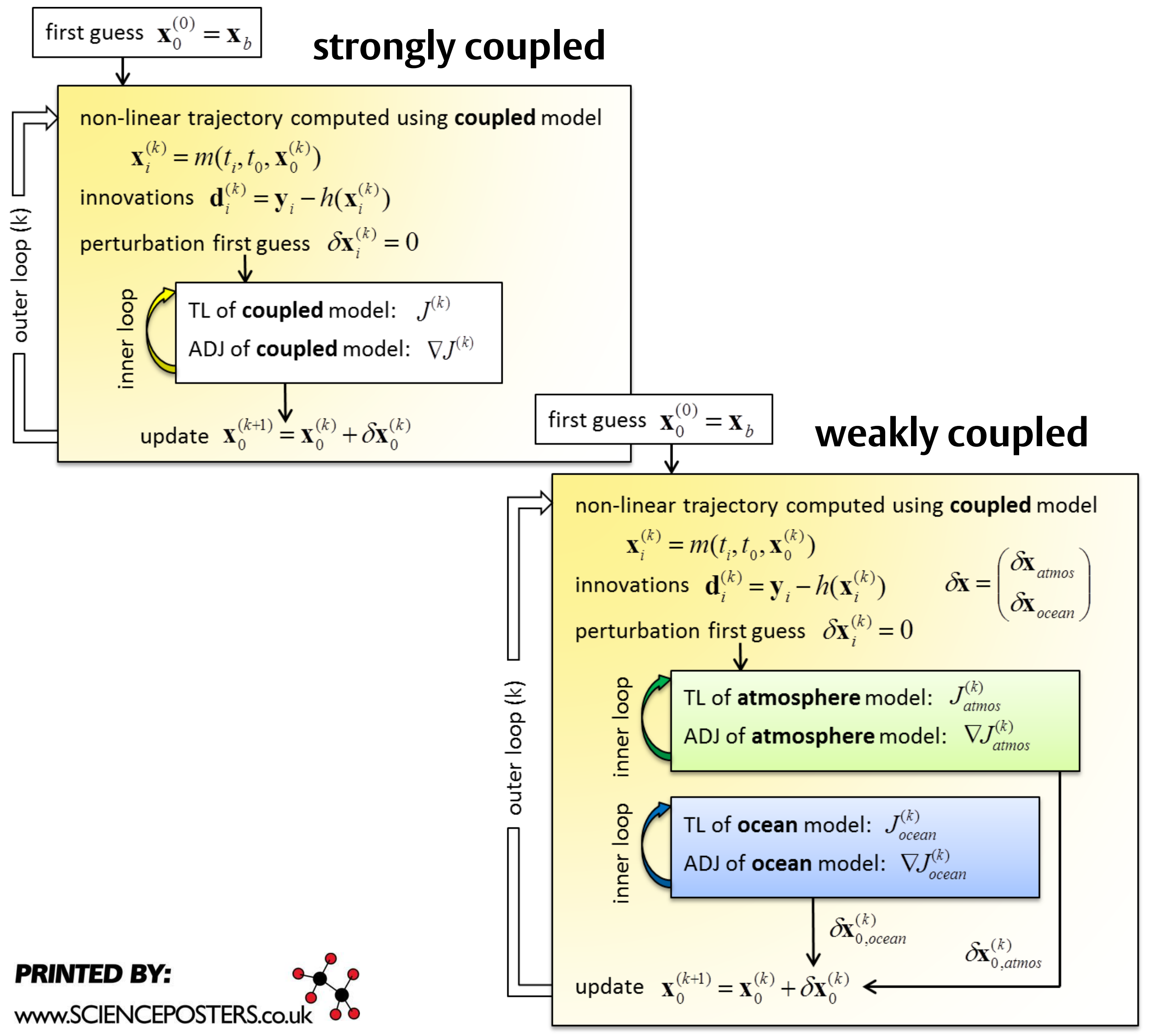
## Coupled data assimilation

### Strongly coupled incremental 4D-Var

- initial background guess from coupled model forecast and coupled model used for non-linear background trajectory,
  - ✓ balanced fields
- single minimisation process,
  - ✓ single balanced analysis
- coupled tangent linear (TL) and adjoint (ADJ) models
- requires covariances between atmosphere and ocean
- offers possibility of estimating coupling parameters

### Weakly coupled incremental 4D-Var

- initial background guess from coupled model forecast and coupled model used for non-linear background trajectory,
  - ✓ balanced fields
- separate minimisation for atmosphere and ocean,
  - × two analyses that may not be balanced
- avoids development of new TL and adjoint code



**strongly coupled**

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

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

$\mathbf{x}_i^{(k)} = m(t_i, t_0, \mathbf{x}_0^{(k)})$

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

perturbation first guess $\delta\mathbf{x}_i^{(k)} = 0$

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

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

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

**weakly coupled**

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

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

$\mathbf{x}_i^{(k)} = m(t_i, t_0, \mathbf{x}_0^{(k)})$

innovations $\mathbf{d}_i^{(k)} = \mathbf{y}_i - h(\mathbf{x}_i^{(k)})$ $\quad \delta\mathbf{x} = \begin{pmatrix} \delta\mathbf{x}_{atmos} \\ \delta\mathbf{x}_{ocean} \end{pmatrix}$

perturbation first guess $\delta\mathbf{x}_i^{(k)} = 0$

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

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

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

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

$\delta\mathbf{x}_{0,ocean}^{(k)}$ $\quad \delta\mathbf{x}_{0,atmos}^{(k)}$

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

## Idealised system

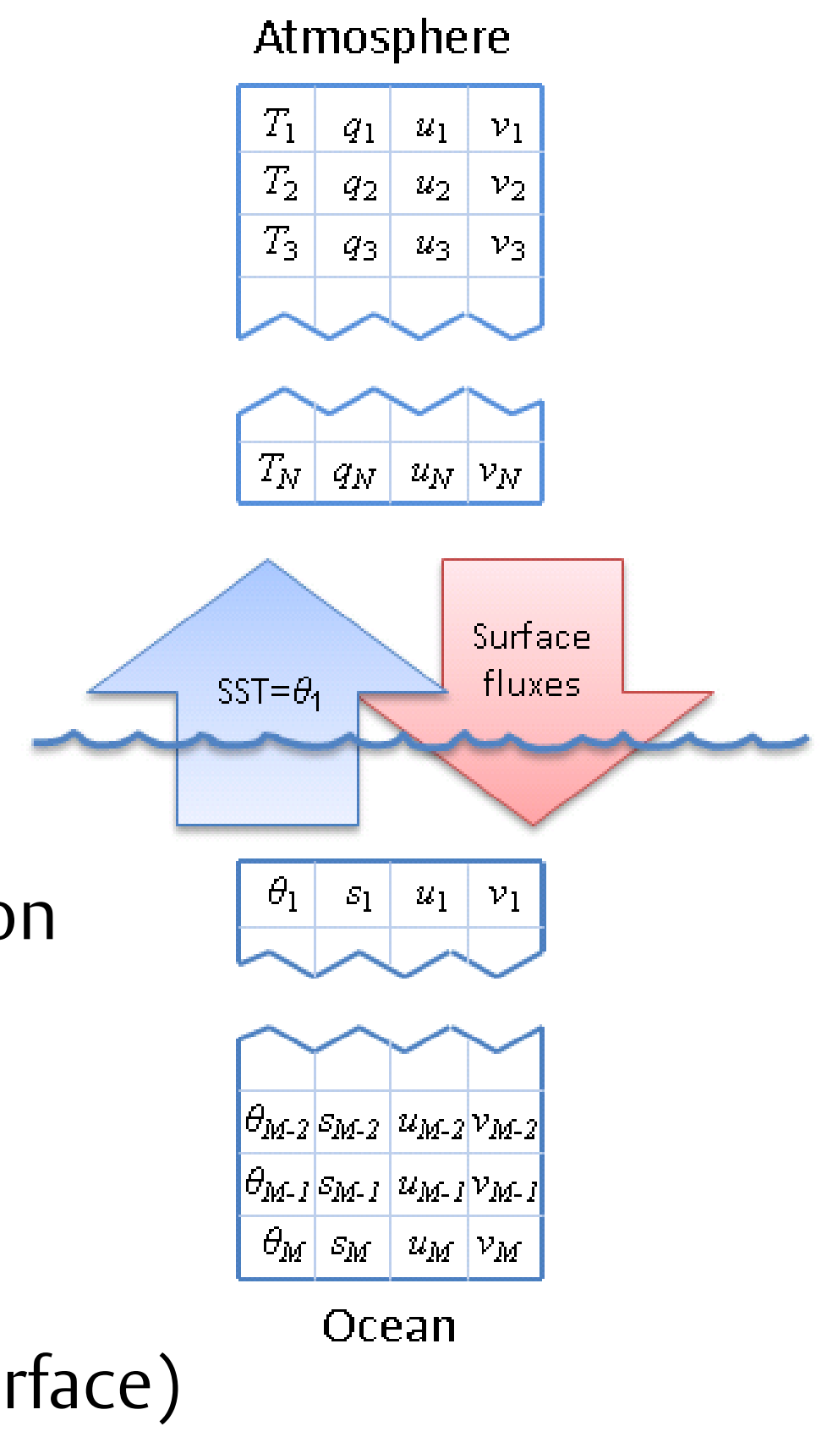
- avoids issues associated with more complex models
- allows for more sophisticated experiments than in an operational setting,
- easier interpretation of results
- help guide the design and implementation of coupled methods within full scale systems

The system needs to be simple and quick to run but also able to represent realistic atmosphere-ocean coupling.

### Atmosphere

Simplified version of the ECMWF single column model

- based on the IFS code[1]
- 4 state variables on 60 model levels
- hybrid (eta) coordinate system
- forced by large scale horizontal advection



### Ocean

Single column K-Profile Parameterisation (KPP) mixed-layer model based on the scheme of *Large et al*[2]

- 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***

### Simplifications made for 4D-Var development

- atmospheric model reduced to the adiabatic component plus parameterisation schemes for vertical diffusion and surface fluxes.
- perturbations to the diffusion coefficients ignored in tangent linear model.
- non-local turbulent mixing term in the KPP-model switched off.

### References

1. IFS documentation is available from **www.ecmwf.int/research/ifsdocs/**
2. Large, W.G., McWilliams, J. C. and Doney, S.C. (1994). Oceanic vertical mixing: a review and a model with non-local boundary layer parameterization. *Rev. Geophys.*, **32**, 363-403.

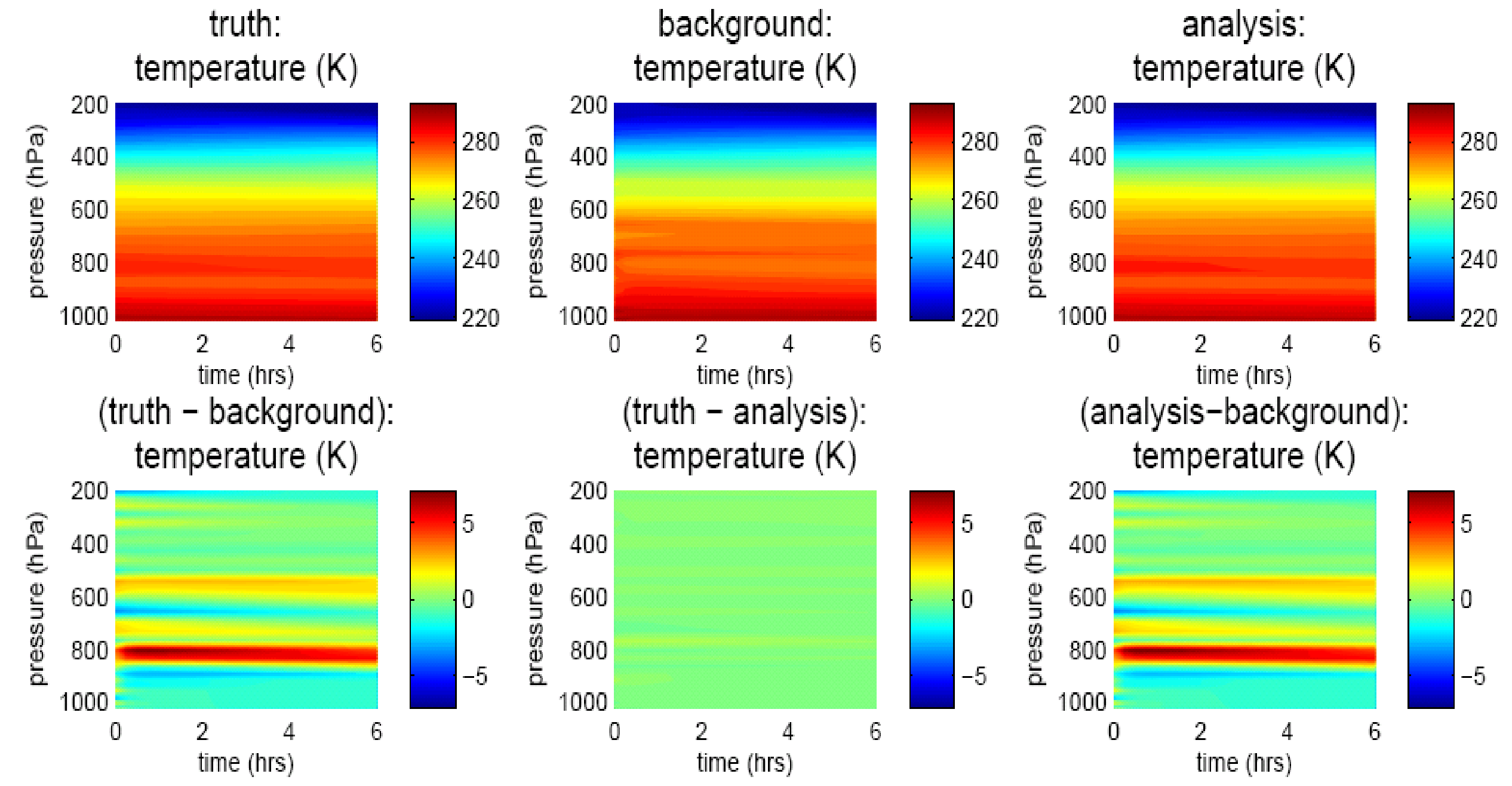
## Identical twin experiments

### set up

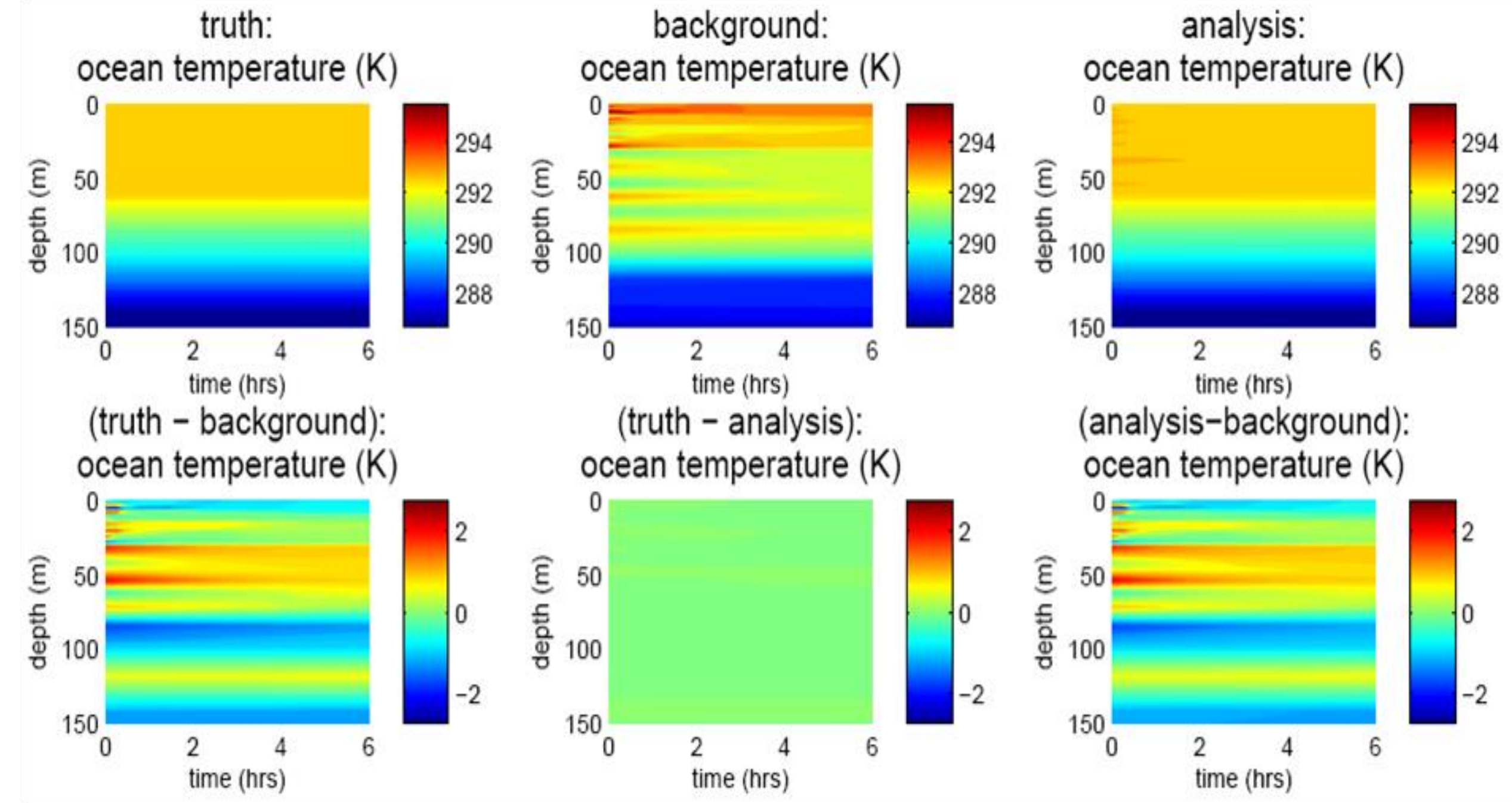
- strongly coupled, incremental 4D-Var with10 outer loops
- 6 hour assimilation window
- '*true*' solution is non-linear model run with initial atmosphere state from ERA Interim and initial ocean state from Mercator Ocean
- data are for January 2013, 235.5ºE, 24.5ºN
- initial background state generated by adding random Gaussian noise to true initial state
- observations are generated by adding random Gaussian noise to true solution
- observations taken at every model level and every time step
- error covariance matrices $\mathbf{B} = \sigma_b\mathbf{I}$ , $\mathbf{R} = \sigma_o\mathbf{I}$ , with $\sigma_o / \sigma_b = 0.1$

## Results

### Atmosphere



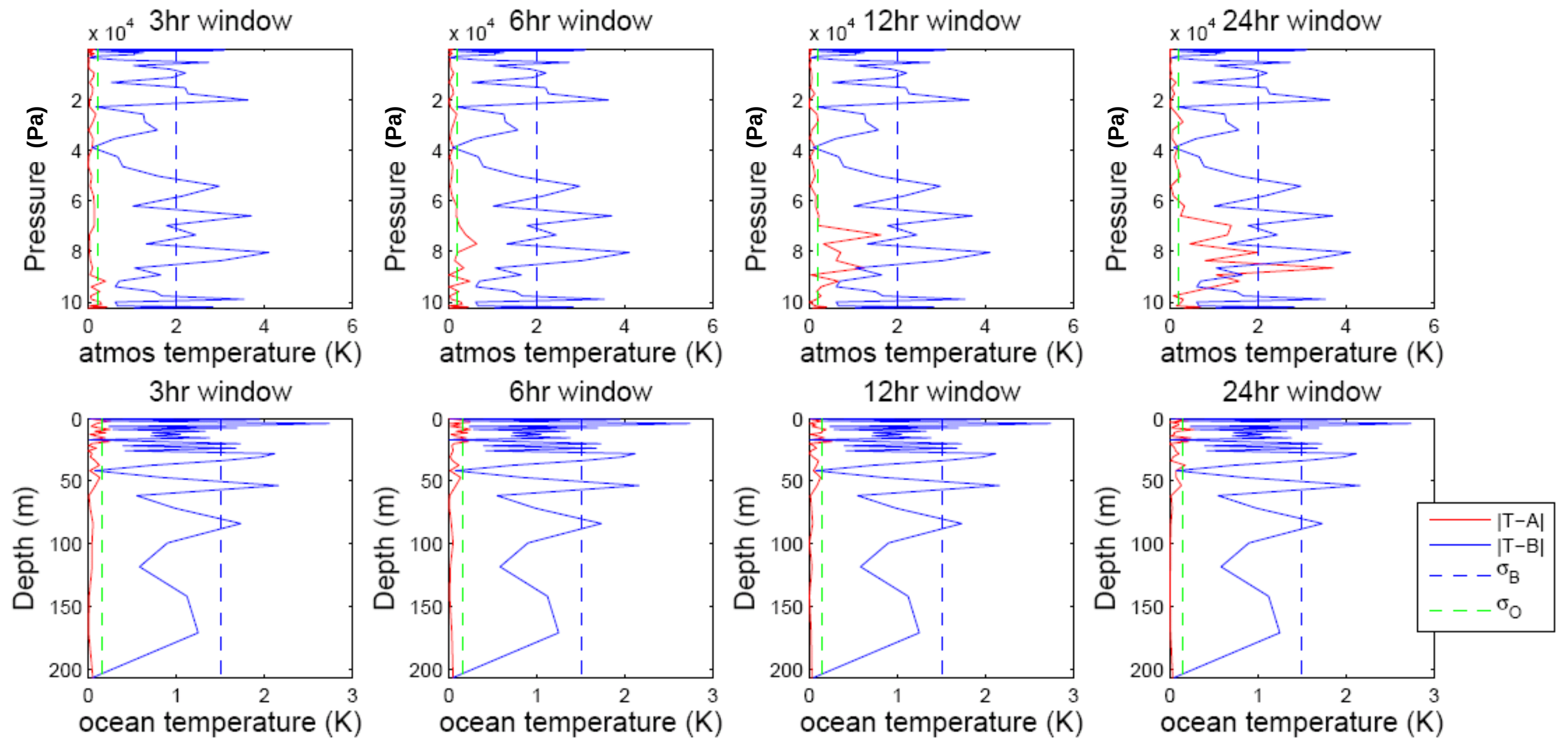
### Ocean



The above figures show the atmosphere and ocean temperature fields (top rows) and their errors (bottom rows) from a preliminary assimilation run using the set-up described above. We are able to successfully recover the true state and are satisfied that our assimilation system is working correctly. Similar results were seen in the other model fields.

## Assimilation window length

We need to consider the different timescales of the atmosphere and ocean when choosing the length of our assimilation window. Typically, a much longer assimilation window is used for (uncoupled) ocean data assimilation.



The above figures show the absolute background (T-B) and analysis (T-A) errors at $t_0$ for the atmosphere and ocean temperature fields as the assimilation window is increased from 3 to 24 hours. The errors grow rapidly in the lower part of the atmosphere but the ocean error profiles show little change.

We can use the TL validity test to determine the linear regime of the atmosphere model for given initial perturbations; this will help guide our choice of assimilation window length.

## Questions we will address

- how do different coupling strategies compare?
  - coupled vs. uncoupled
  - strong vs. weakly coupled
- does fully coupled DA reduce/ eliminate initialisation shocks?
- how do the different strategies handle information from near surface observations?
- what constraints do different coupling strategies impose on the assimilation window length?
- how does model bias affect the coupled assimilation?

### Contact information

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- See also: **www.esa-da.org/content/coupled-model-data-assimilation**

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