The role of cross-domain error correlations in strongly coupled 4D-Var atmosphere-ocean data assimilation

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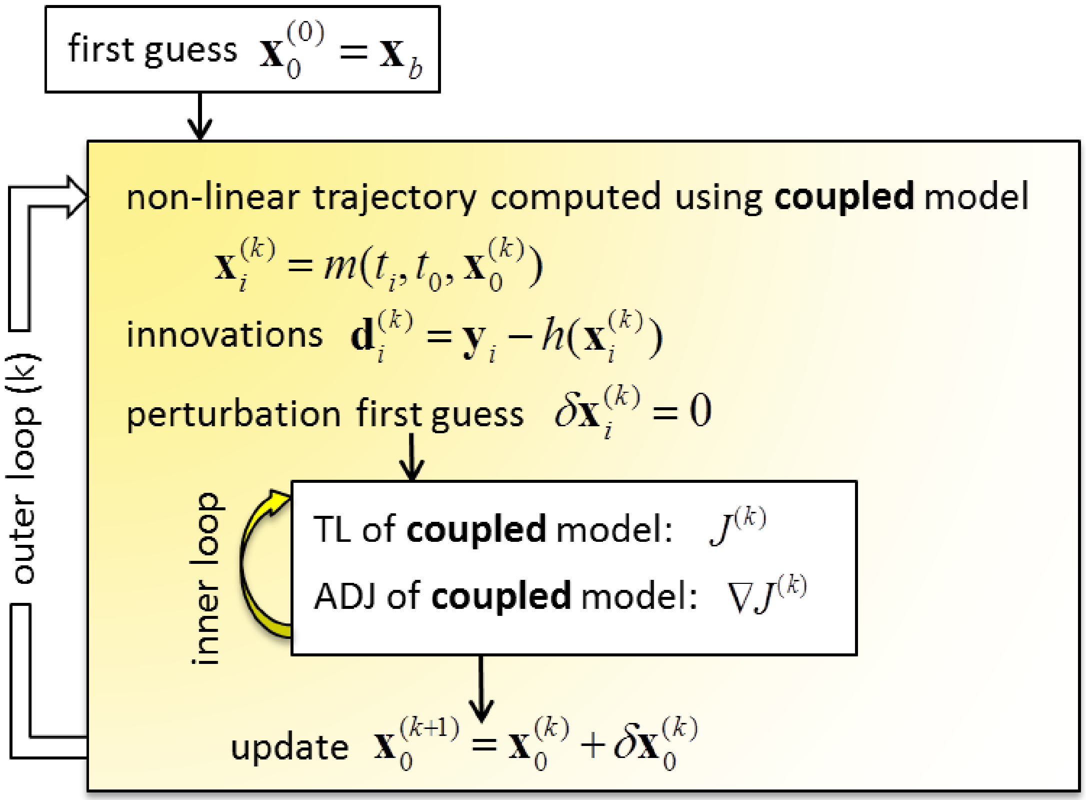
Supported by NCEO and NERC grant NE/M001482/1

Strongly coupled incremental 4D-Var

- Control vector contains both atmosphere & ocean model variables
- Fully coupled tangent linear & adjoint models
- Allows for cross-domain covariances between atmosphere & ocean forecast errors

$$\mathbf{B}_0 = \begin{pmatrix} \mathbf{B}_{\mathrm{AA}} & \mathbf{B}_{\mathrm{AO}} \\ \mathbf{B}_{\mathrm{AO}}^{\mathrm{T}} & \mathbf{B}_{\mathrm{OO}} \end{pmatrix}$$

- Atmosphere observations can influence ocean analysis and vice versa
- Leads to greater balance



Idealised system

single-column, coupled atmosphere-ocean model

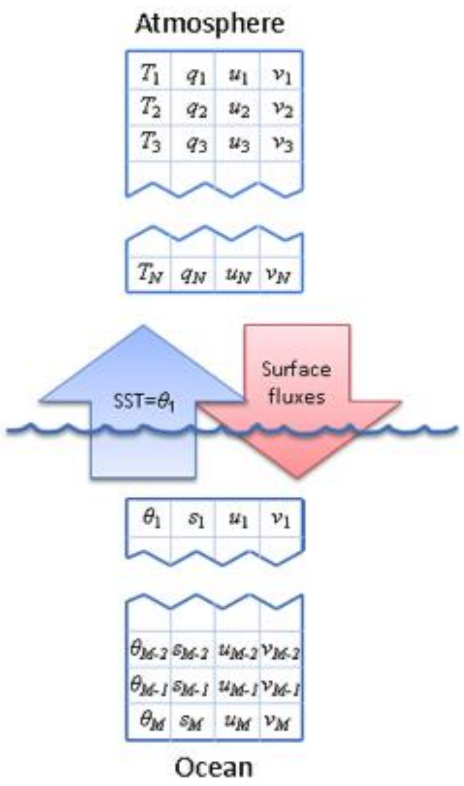
Atmosphere

- simplified version of the ECMWF single column model adiabatic component + vertical diffusion (no convection)
- 4 state variables on 60 model levels (surface to ~0.1hPa)
- forced by large scale horizontal advection

Ocean

- K-Profile Parameterisation (KPP) mixed-layer model
- 4 state variables on 35 model levels (1-250m)
- forced by short and long wave radiation at surface

Smith et al 2015, *Tellus,* doi:10.3402/tellusa.v67.27025



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

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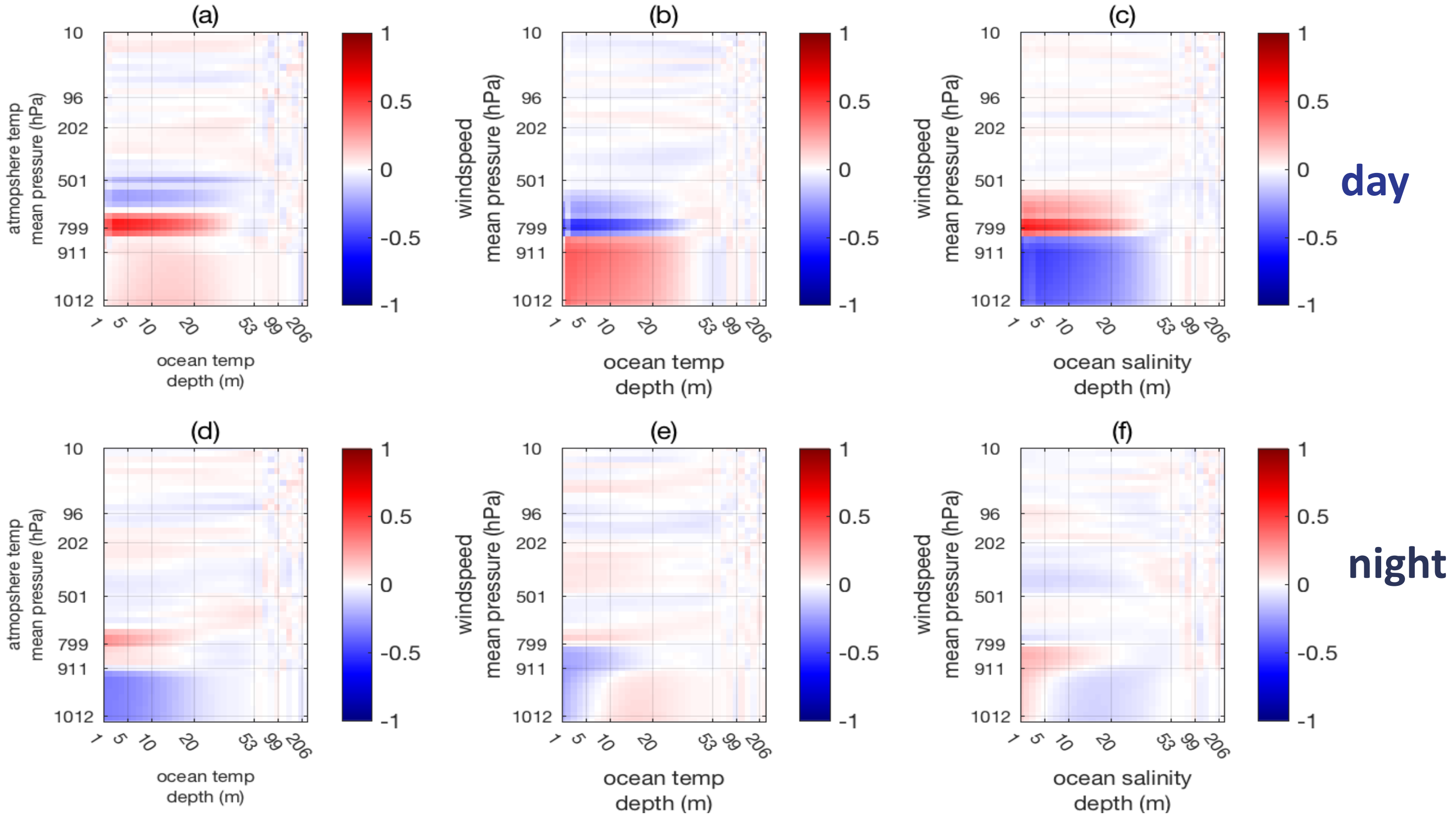
December case



Smith et al 2017, *MWR*, doi:10.1175/MWR-D-16-0284.1

Atmosphere-ocean cross-correlation. Left to right: atmosphere-ocean temp, wind speed-ocean temp, wind speed-ocean salinity

Method

- Idealised twin experiments, 12 hr window.
- Define

$$\mathbf{B}^{full} = \begin{pmatrix} \mathbf{B}_{AA} & \mathbf{B}_{AO} \\ \mathbf{B}_{AO}^T & \mathbf{B}_{OO} \end{pmatrix} \qquad \mathbf{B}^{diag} = \begin{pmatrix} \mathbf{B}_{AA} & 0 \\ 0 & \mathbf{B}_{OO} \end{pmatrix}$$

- Use eigenvectors of correlation matrix for control variable transform.
- Compare assimilation observing only meridional wind *v*, only SST and both, at end of time window.
- Investigate effect of explicit and implicit covariances.

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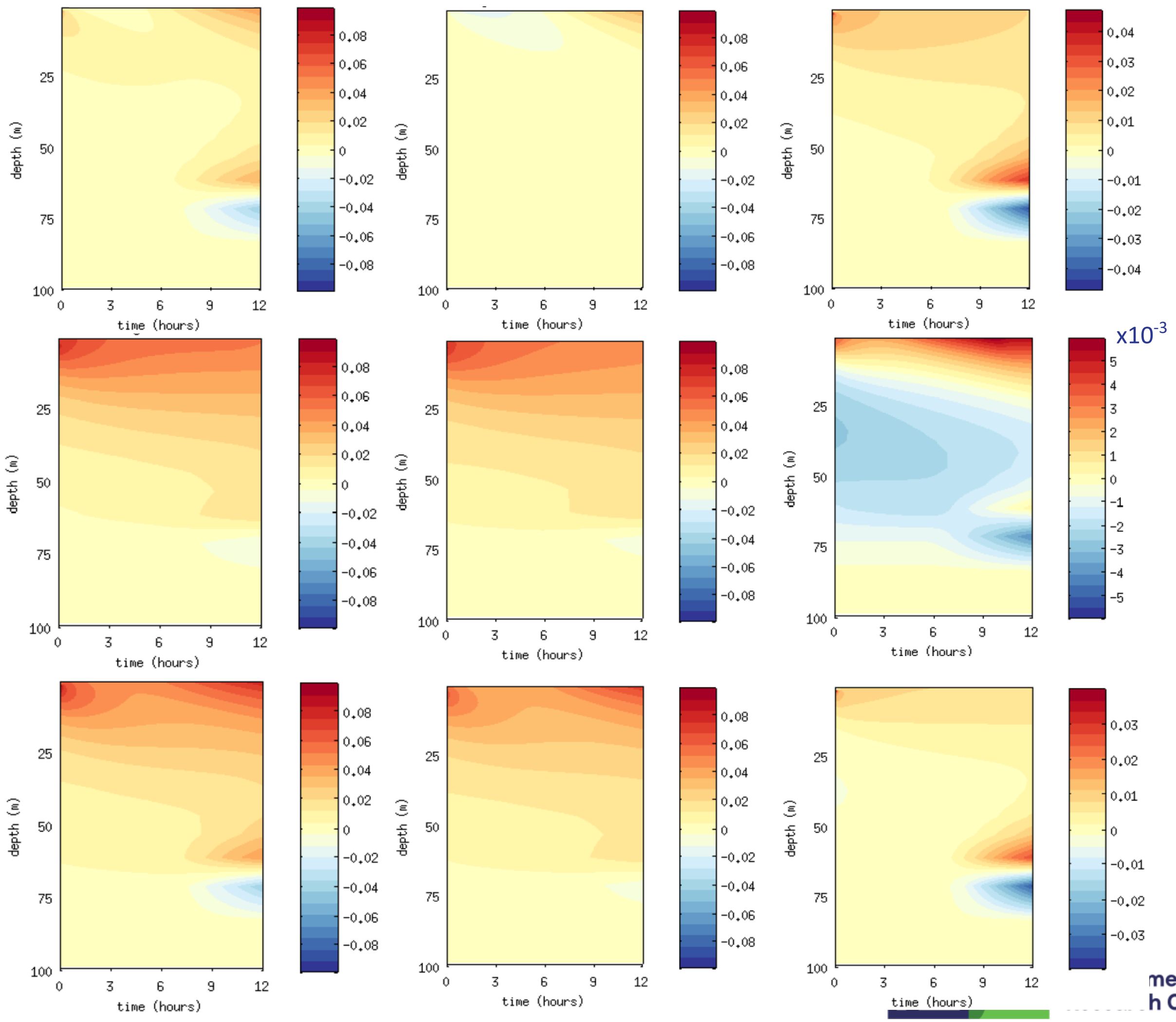
Analysis increments: Ocean temperature

(a) full **B** | (b) Block diag **B** | difference (a)-(b)

Single surface v-wind observation

Single SST observation

Both single surface v-wind observation and single SST observation



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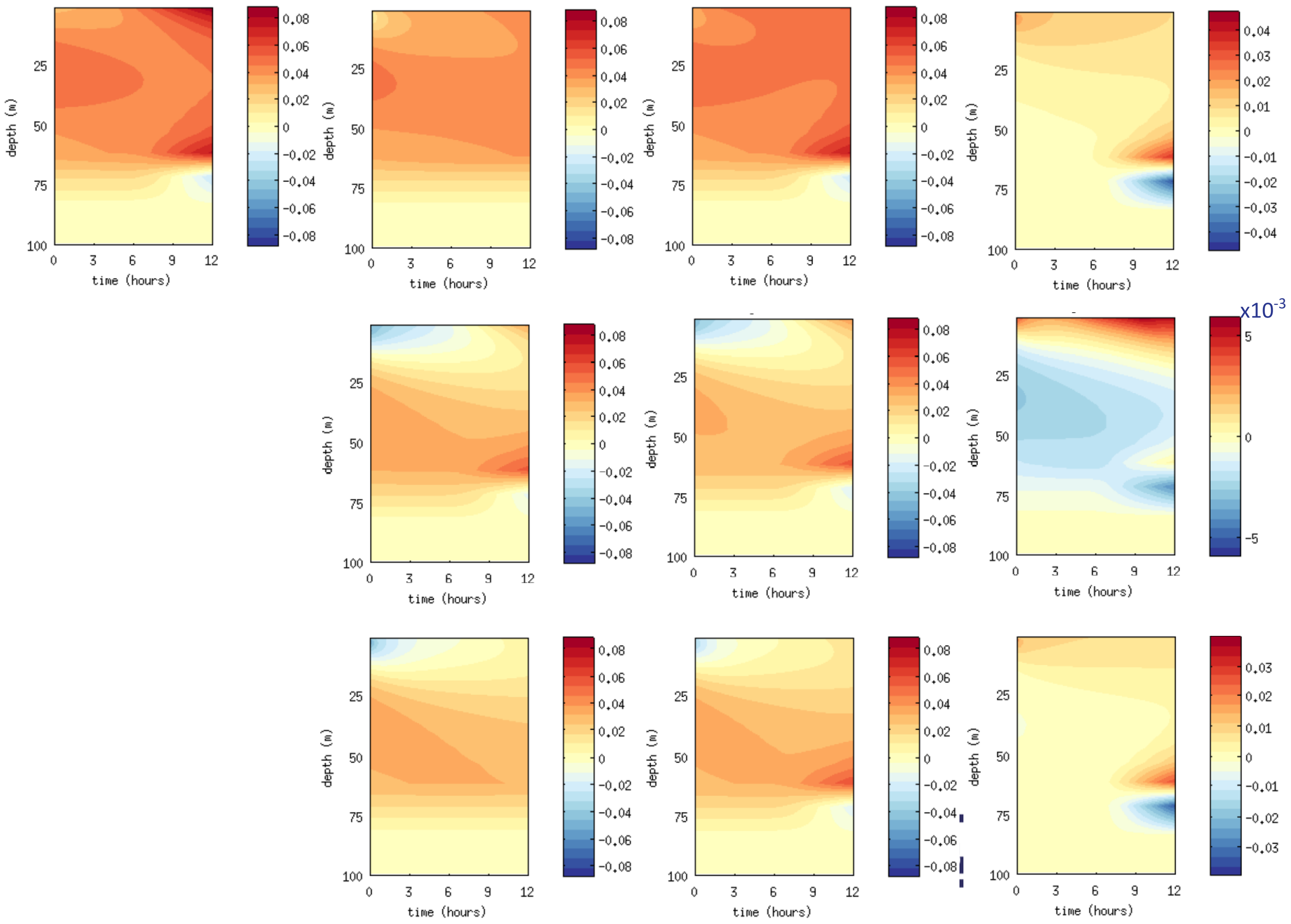
Analysis errors: Ocean temperature

(a) Background | (b)full **B** | (c) Block diag **B** | difference (b)-(c)

Single surface v-wind observation

Single SST observation

Both single surface v-wind observation and single SST observation



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Conclusions

If only a single domain is observed:

- including explicit cross-domain forecast error covariances (**$\mathbf{B}_{AO} \neq \mathbf{0}$**) mostly impacts the unobserved domain.
- if **$\mathbf{B}_{AO}$** = **$\mathbf{0}$** the initial increments in the unobserved domain rely on the implicitly generated cross-domain error covariances, which in turn depend on the strength of coupling in the TL model.
- setting **$\mathbf{B}_{AO}$** = **$\mathbf{0}$** will always lead to a loss of information; the unobserved domain is unable to influence the structure of the increments in the observed domain and so is unlikely to produce a balanced initial state.

If both domains observed:

- Explicitly specified covariances may still allow a better-balanced analysis state.

Smith, P.J., Lawless, A.S. and Nichols, N.K. (2020), *Q.J.R.M.S.* doi.org/10.1002/qj.3802.