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Estimating atmosphere-ocean forecast error cross-covariances for strongly coupled 4D-Var data assimilation

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Introduction

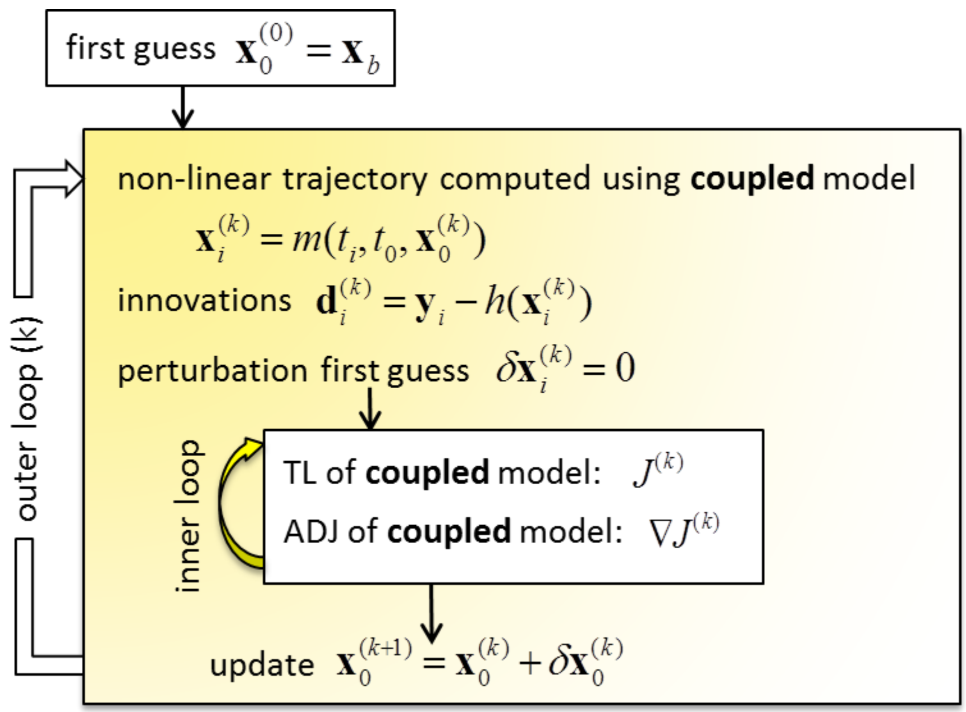
- strongly coupled atmosphere-ocean data assimilation solves the assimilation problem for a single coherent atmosphere-ocean state
- requires specification of the relationship between the errors in the atmosphere and ocean model forecasts
  - non-trivial ...
- we've been using an idealised strongly coupled 4D-Var system to investigate the nature and structure of coupled atmosphere-ocean forecast error cross-correlations

Strongly coupled incremental 4D-Var

- control vector contains both atmosphere and ocean model variables
- allows for cross-covariances between atmosphere and ocean background errors

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

- atmosphere obs can influence ocean analysis & vice versa
- more balanced analysis state



single minimisation process

Ensemble of 4D-Vars

Estimate background error covariance from a ensemble of perturbed strongly coupled 4D-Var analyses

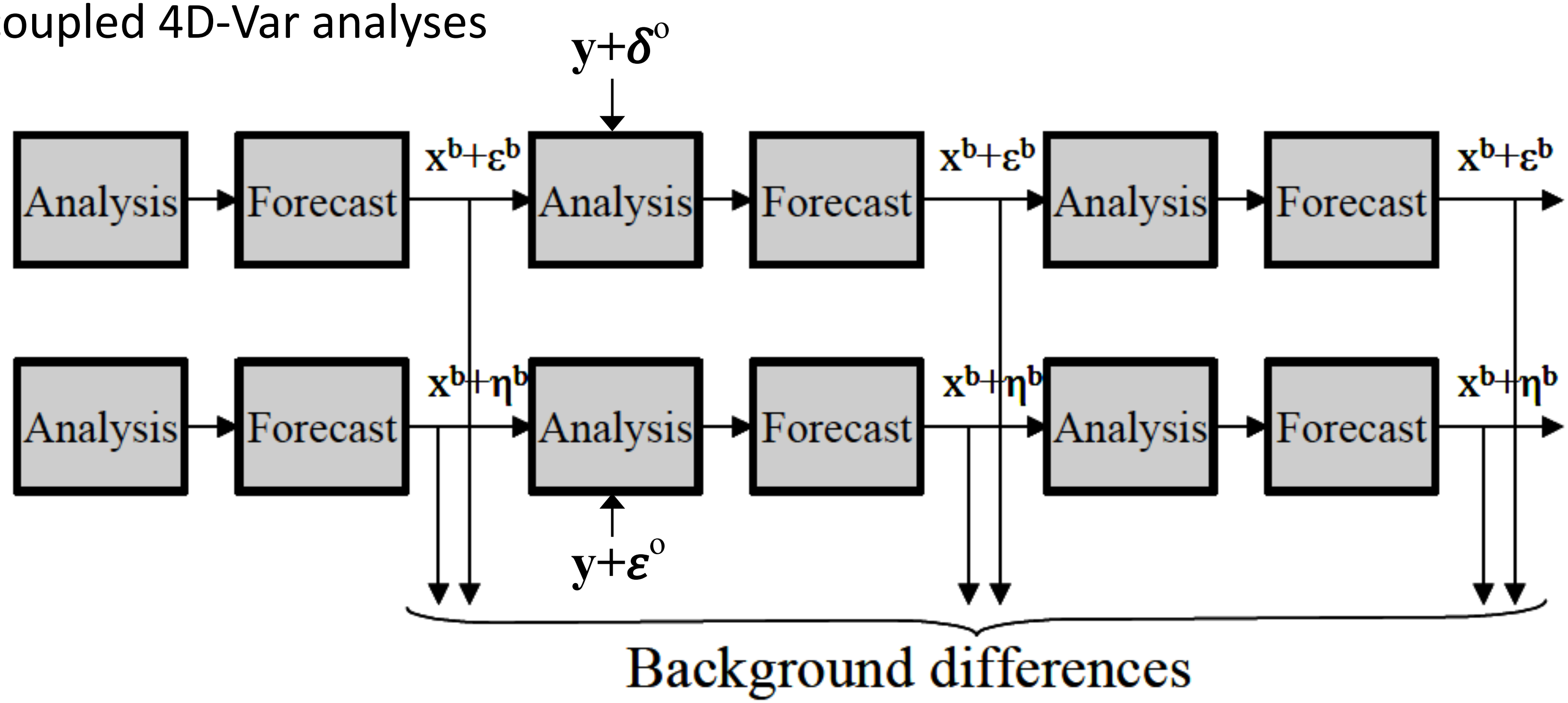


Figure 3: Schematic illustration of the analysis-ensemble method of generating fields of background difference.

adapted from Fisher 2003

Differences between pairs of background fields have same **correlation** structure as background error (but twice the variance)

Idealised system

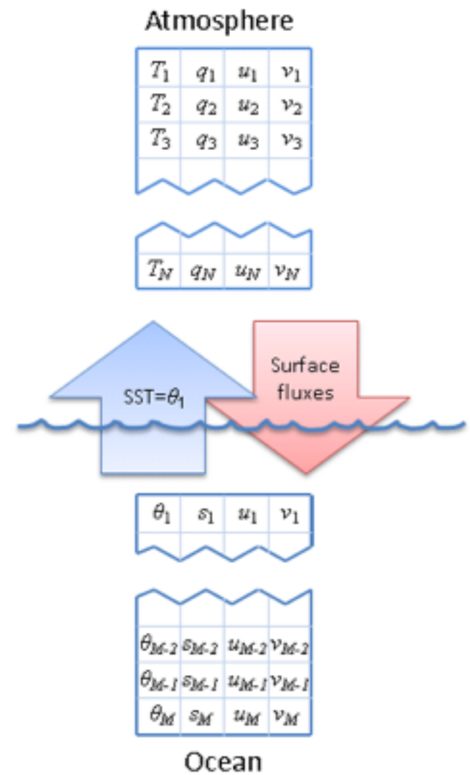
single-column, coupled atmosphere-ocean model

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 based on the scheme of *Large et al*[1]
4 state variables on 35 model levels (1-250m)
forced by short and long wave radiation at surface



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

1. *DOI: 10.1029/94RG01872*

Identical twin experiments

- 12 hour assimilation window, 3 outer-loops, 8 cycles
- experiments repeated using data for June 2013 & Dec 2013 (point is 188.75^{o}E, 25^{o}N, 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
- 3 hourly observations are generated by adding random noise to 'truth'
- error covariance matrices $\mathbf{B}$ and $\mathbf{R}$ are diagonal (same for all cycles)
- ensemble of 500 members - generated by perturbing initial background state and observations
- average pairs over a several assimilation cycles to increase effective ensemble size

Comments

- each cycle starts at either 12 UTC or 00 UTC which corresponds to the early hours of the morning and early afternoon local time.
- one set of error correlations from 12 hour forecast ensembles from day to-night and one set of error correlations from 12 hour forecast ensembles from night-to-day.
- allows comparison of day-night plus summer-winter error correlations.

Questions

- how do the atmosphere-ocean error cross correlation structures vary between summer and winter, and between day and night?
- where are the atmosphere-ocean error cross-correlations strongest?
- can we explain our results by considering the underlying model physics, forcing and known atmosphere-ocean feedback mechanisms?
- what happens if we use a smaller ensemble?

December case:

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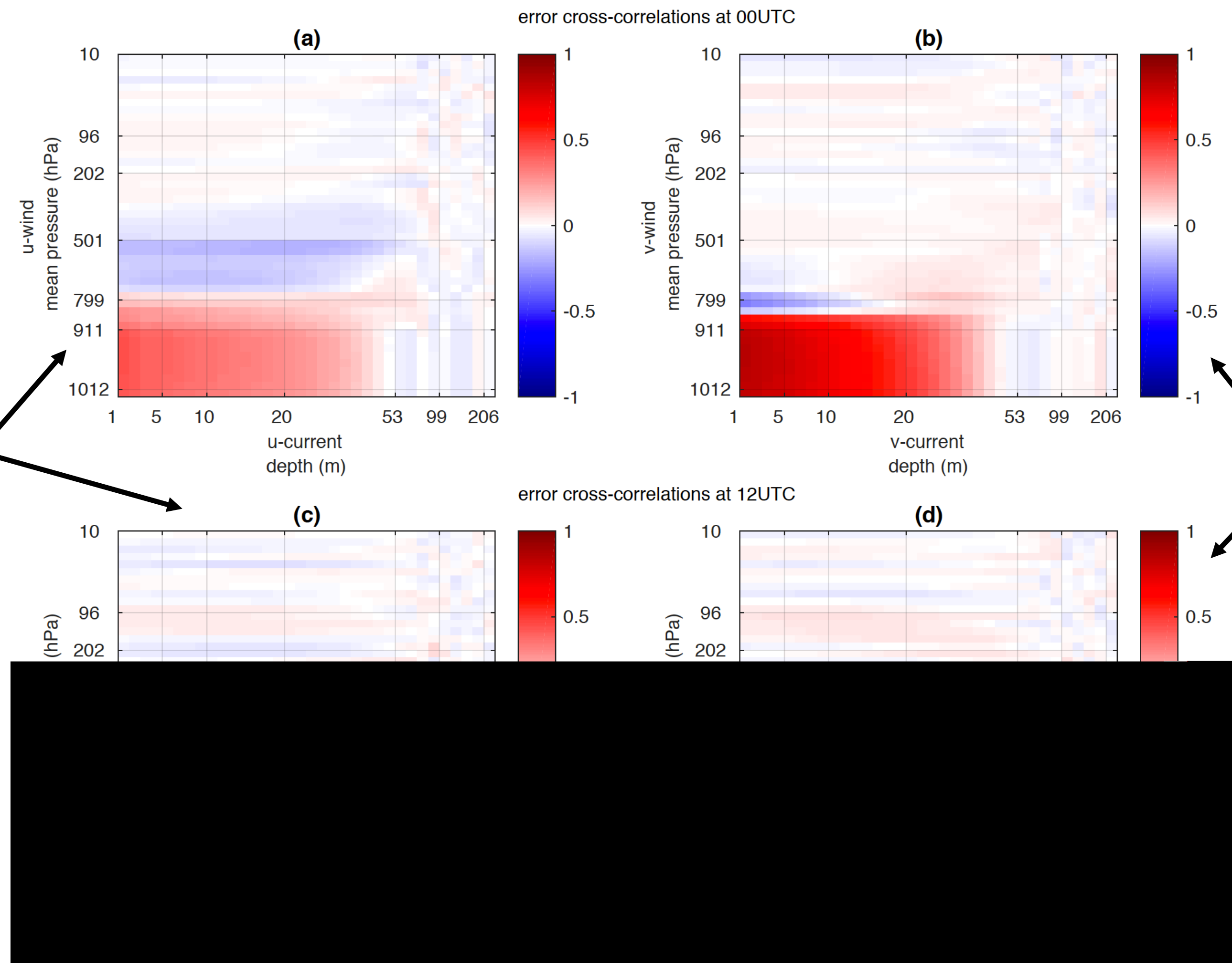
u-wind & u-current



day

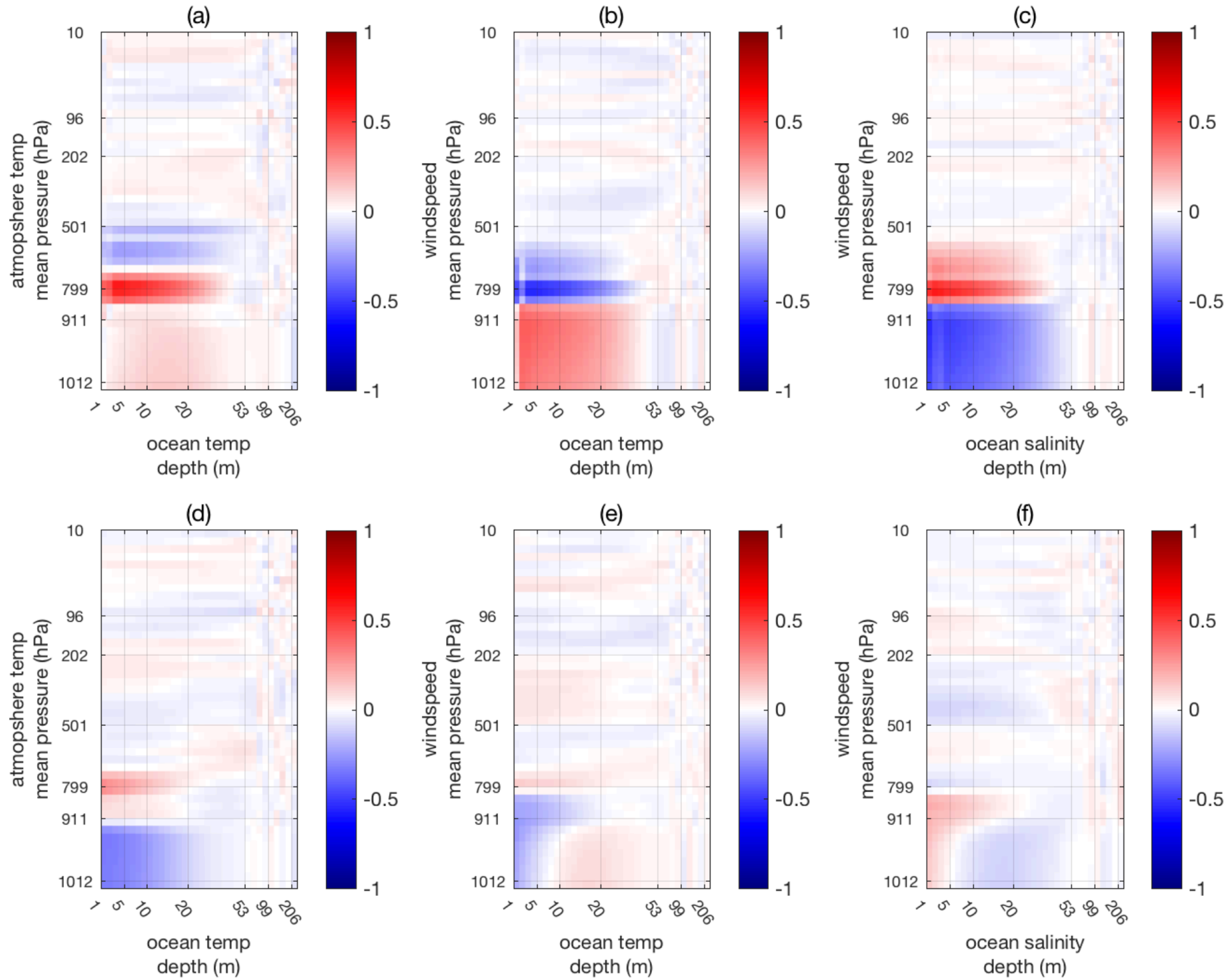
v-wind & v-current

night

atmosphere wind-ocean current error cross-correlations

December case:

atmosphere-ocean error cross-correlations



day

night

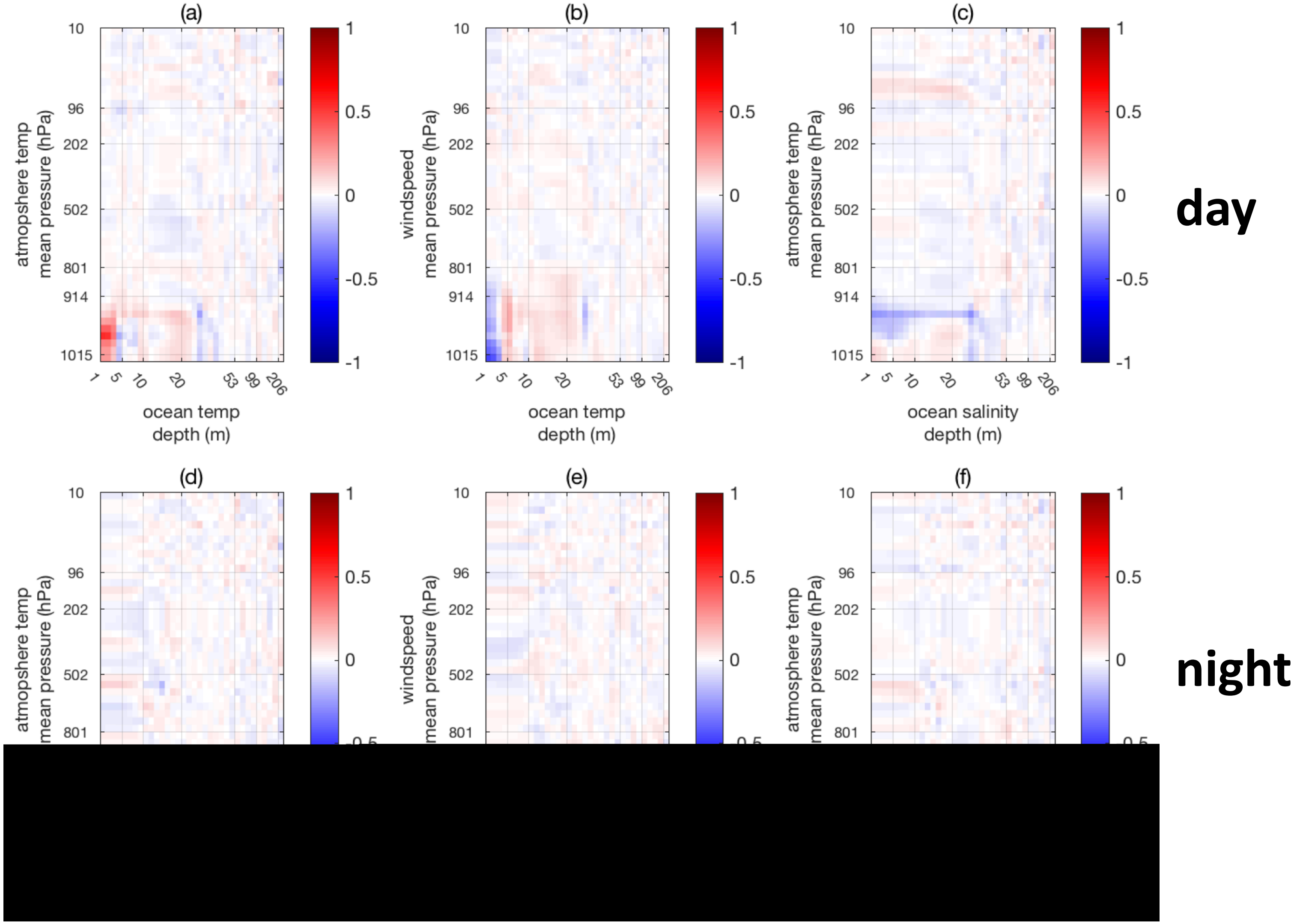
atmosphere temp & ocean temp

windspeed & ocean temp

windspeed & salinity

June case:

atmosphere-ocean error cross-correlations



[redacted]

atmosphere temp & ocean temp

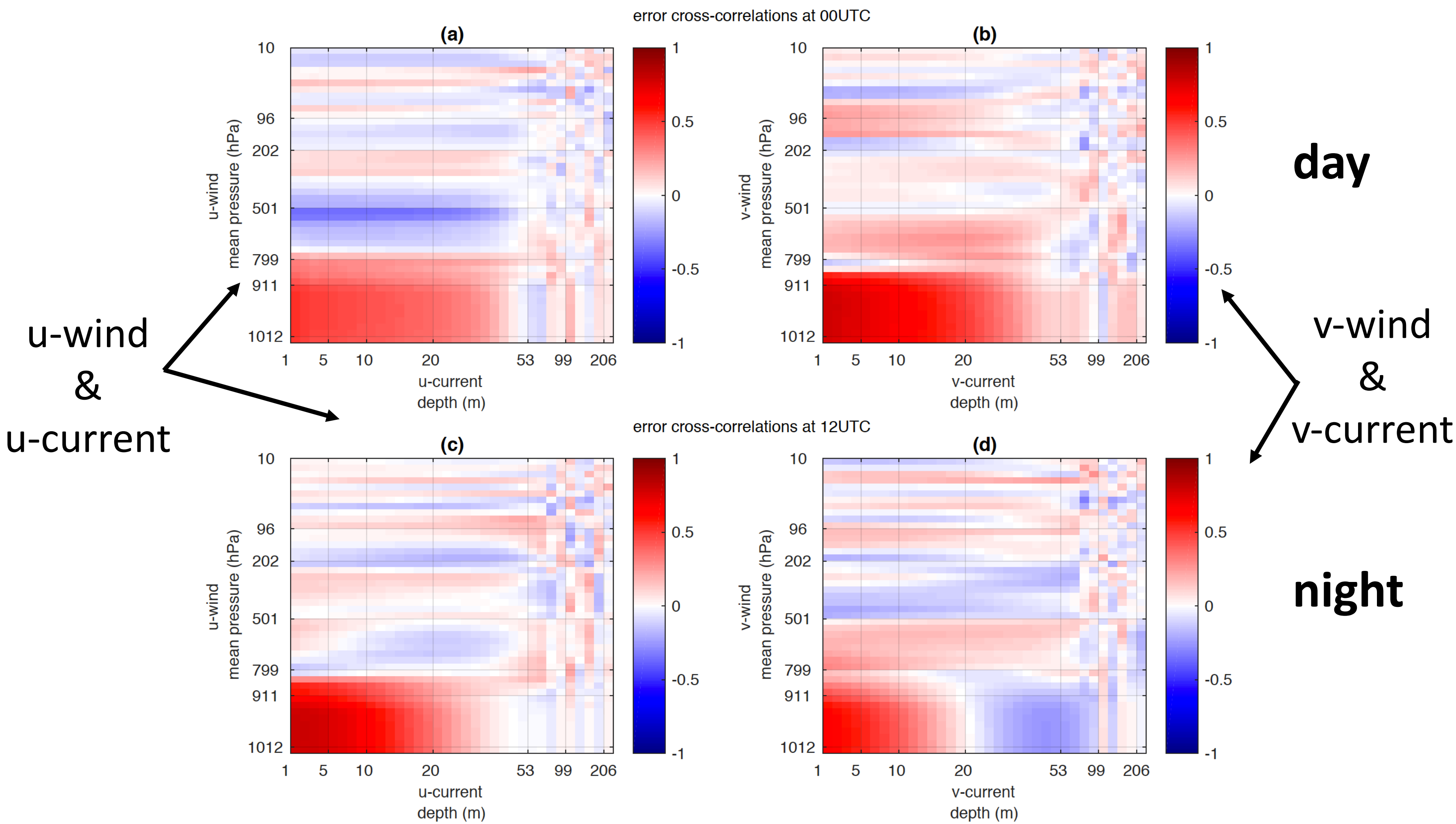
windspeed & ocean temp

windspeed & salinity

Questions

- how do the atmosphere-ocean error cross correlation structures vary between summer and winter, and between day and night?
- where are the atmosphere-ocean error cross-correlations strongest?
- can we explain our results by considering the underlying model physics, forcing and known atmosphere-ocean feedback mechanisms?
- **what happens if we use a smaller ensemble?**

December case: 50 members



atmosphere wind-ocean current error cross-correlations

December case: 500 members

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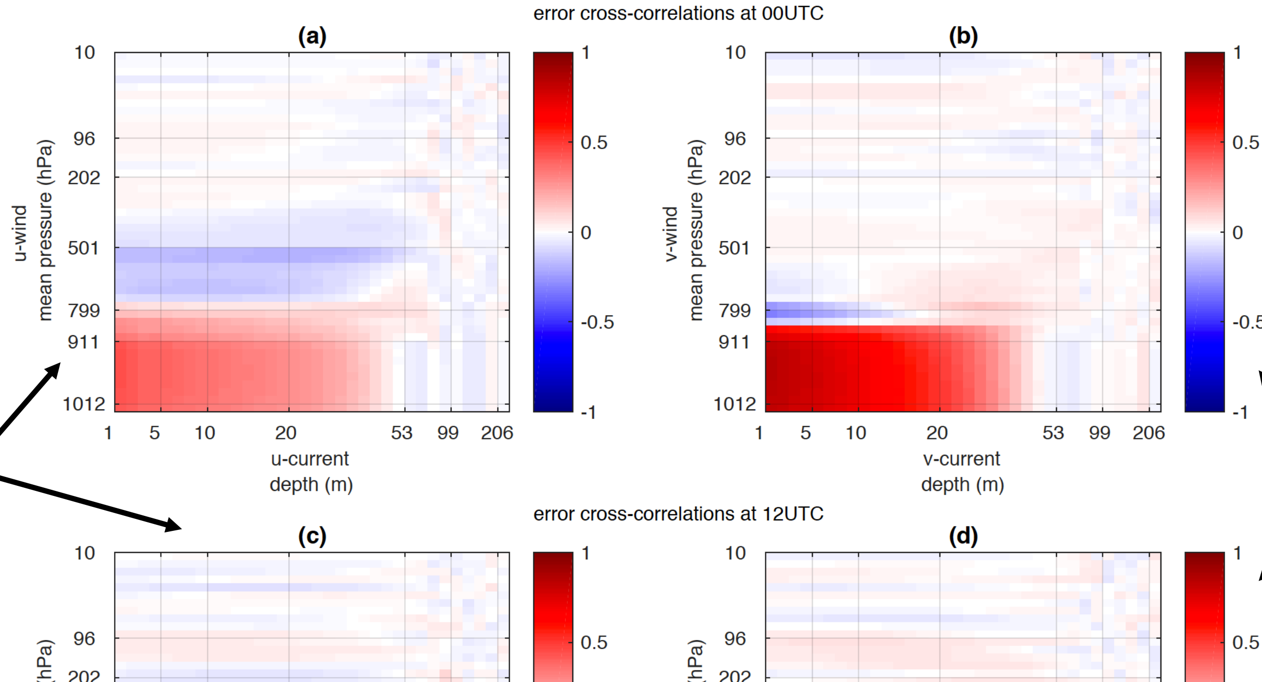


[redacted]

day

night

u-wind
&
u-current

v-wind
&
v-current

atmosphere wind-ocean current error cross-correlations

Localisation

- statistics of smaller ensemble may be sufficient if combined with an appropriate vertical localisation method (Schur product)
- construct multivariate localisation function using a univariate function (Gaspari & Cohn) - apply block by block
- need to define co-ordinate for distance, correlation length-scale:
  - atmosphere and ocean model components use different vertical co-ordinate systems
  - very different length-scales in atmosphere and ocean

Localisation

Distance between a given pair of atmosphere and ocean model levels (in metres)

$$d(z_a(i), z_o(j)) = z_a(i) + z_o(j)$$

where $z_a(i)$ is the height at atmosphere model level i and $z_o(j)$ is depth at ocean model level j.

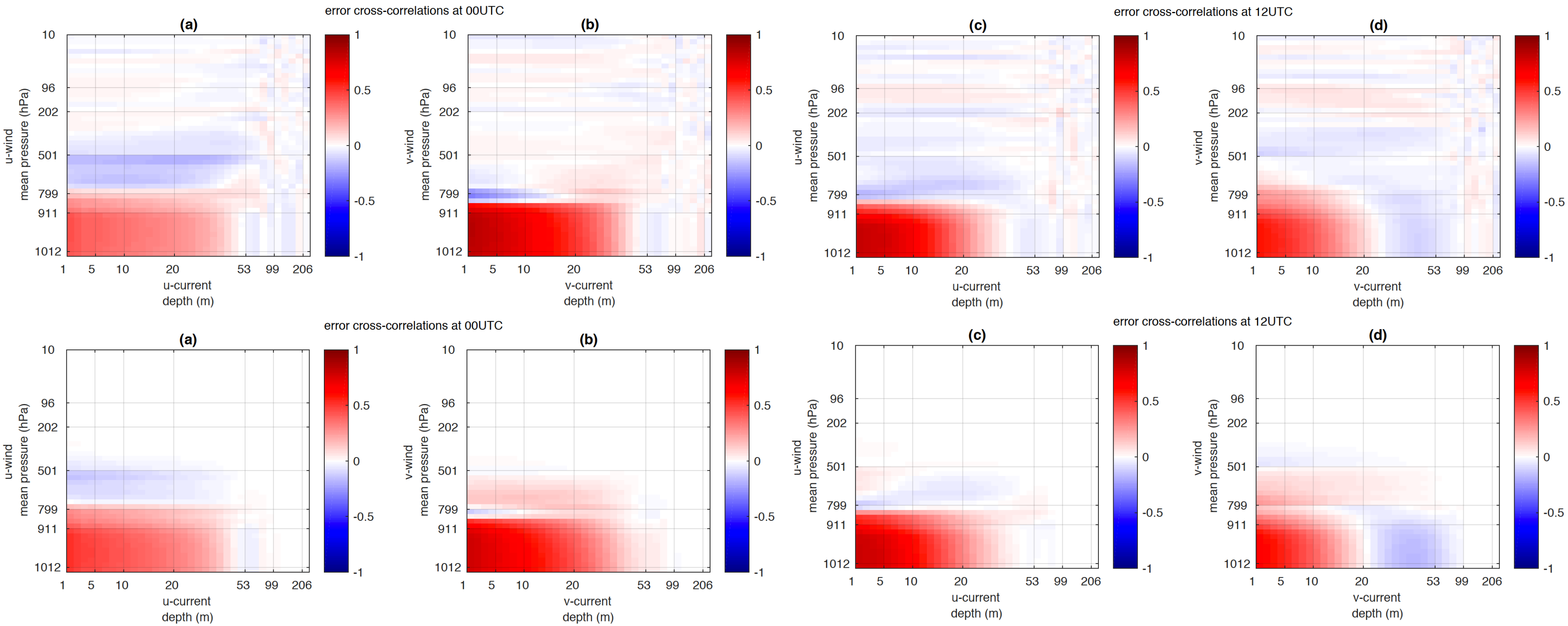
Rescale

$$\widehat{d}(z_a(i), z_o(j)) = \left(\frac{z_a(i)}{L_a} + \frac{z_o(j)}{L_o} \right)$$

where L_a and L_o define the height of the atmosphere boundary layer and depth of the ocean boundary layer.

Localisation results

atmosphere wind-ocean current error cross-correlations



day **night**

top: 500 member ensemble

bottom: 50 member ensemble + localisation with L_a = 7000m, L_o = 75m;

Summary

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- significant variation in atmosphere-ocean error cross correlation structures between summer and winter, and between day and night.
- strongest cross-correlations are in near surface atmosphere-ocean boundary, beyond this atmosphere-ocean errors appear to be mostly uncorrelated.
- results can be explained using knowledge of underlying model physics, forcing and known atmosphere-ocean feedback mechanisms.
- with a limited ensemble size ensemble error correlations are noisy.
- vertical localisation with a scaled distance dependent localisation function offers a potential solution.

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Questions?