The role of flow-dependent oceanic background-error covariance information in air-sea coupled data assimilation during tropical cyclones: a case study

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Overview

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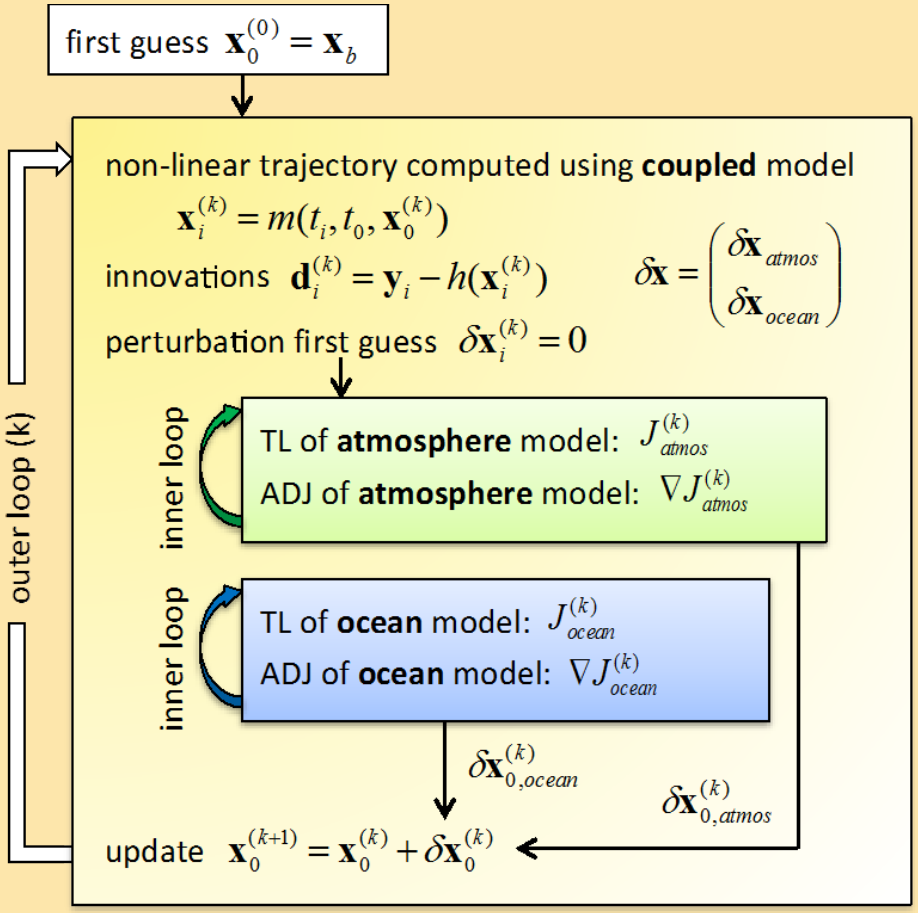
- Successful forecasting of tropical cyclones relies on a good initialisation of the coupled atmosphere-ocean model state using data assimilation (DA)
- Successful DA relies on a good approximation of the statistics of the model forecast errors (background-error covariances)
- We are exploring new methods for incorporating flow dependent information into variational weakly coupled assimilation systems via the inclusion of information from ocean ensembles
- Methods are being developed and tested using an idealised single-column atmosphere-ocean incremental 4D-Var assimilation system

Weakly coupled DA

- Analysis computed independently for each model component
- Model-observation misfits (the ‘innovations’) measured against the coupled model forecast state
- Immediate impact of observations limited to domain in which they reside
- Atmosphere (ocean) observations can influence ocean (atmosphere) analysis if multiple outer loops used



Background-error covariances

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- Background (or forecast) error covariance $\mathbf{B}$ determines how information from observations is spread to unobserved variables
  - Should contain information on the statistics of the errors in the background state
- In variational DA, $\mathbf{B}$ is traditionally modelled based on climatology and has limited flow-dependence
- In hybrid ensemble-variational DA we replace standard modelled $\mathbf{B}$ with $\mathbf{B} = (1-\alpha)\mathbf{B}_{\mathbf{mod}} + \alpha\mathbf{B}_{\mathbf{ens}}$, where is $\mathbf{B}_{\mathbf{ens}}$ is estimated from an ensemble, $0 \leq \alpha \leq 1$
- What is the best method for producing the ocean ensemble? → Part 1
- How does the hybrid DA perform in a state-of-the-art NWP model? → Part 2

Part 1:

Ensemble-generation methods

Ensemble-generation methods

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- We explore 4 methods, both individually and in combination:
  - Perturbed initial atmosphere and/or ocean background state
  - Perturbed atmosphere and/or ocean observations
  - Perturbed radiation forcing
  - Stochastically perturbed parameterisation tendencies (SPPT)

How do the ocean ensemble error correlation matrices change when different ensemble generation methods are used?

Idealised system

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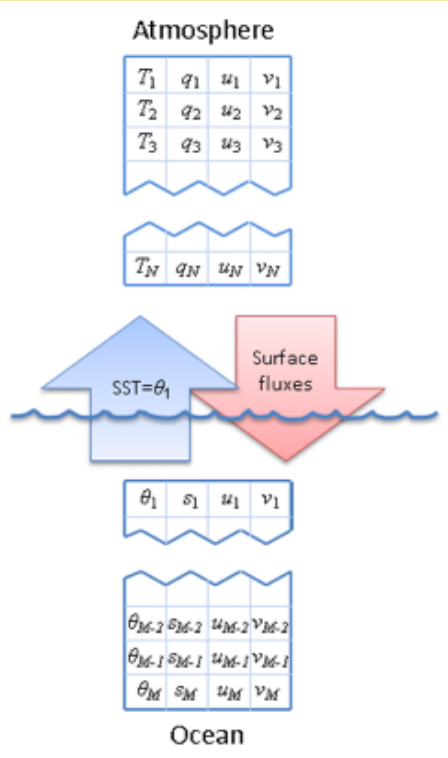
Single-column, coupled atmosphere-ocean model

Atmosphere

- simplified version of the ECMWF single column model
- forced by large scale horizontal advection

Ocean

- K-Profile Parameterisation (KPP) mixed-layer model
- forced by short and long wave radiation at surface



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

Full model details in Smith *et al.* (2015), DOI:10.3402/tellusa.v67.27025

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Experiments

- Data are for December 2013 at the point 25°N, 188.75°E (NW Pacific Ocean)
- Initial atmosphere and ocean states and forcing data derived from the ERA-Interim and Mercator Ocean reanalyses
- Fixed atmosphere and ocean $\mathbf{B}$ matrices taken from Smith *et al.* (2017)
- 20-member ensemble of weakly coupled incremental 4D-Var
- 12-hour assimilation window
- Identical twin: 3-hourly observations are generated by adding random Gaussian noise to 'true' solution
- Diagonal observation-error covariance matrix $\mathbf{R}$

More details in Smith *et al.* (2017), DOI: 10.1175/MWR-D-16-0284.1

Results

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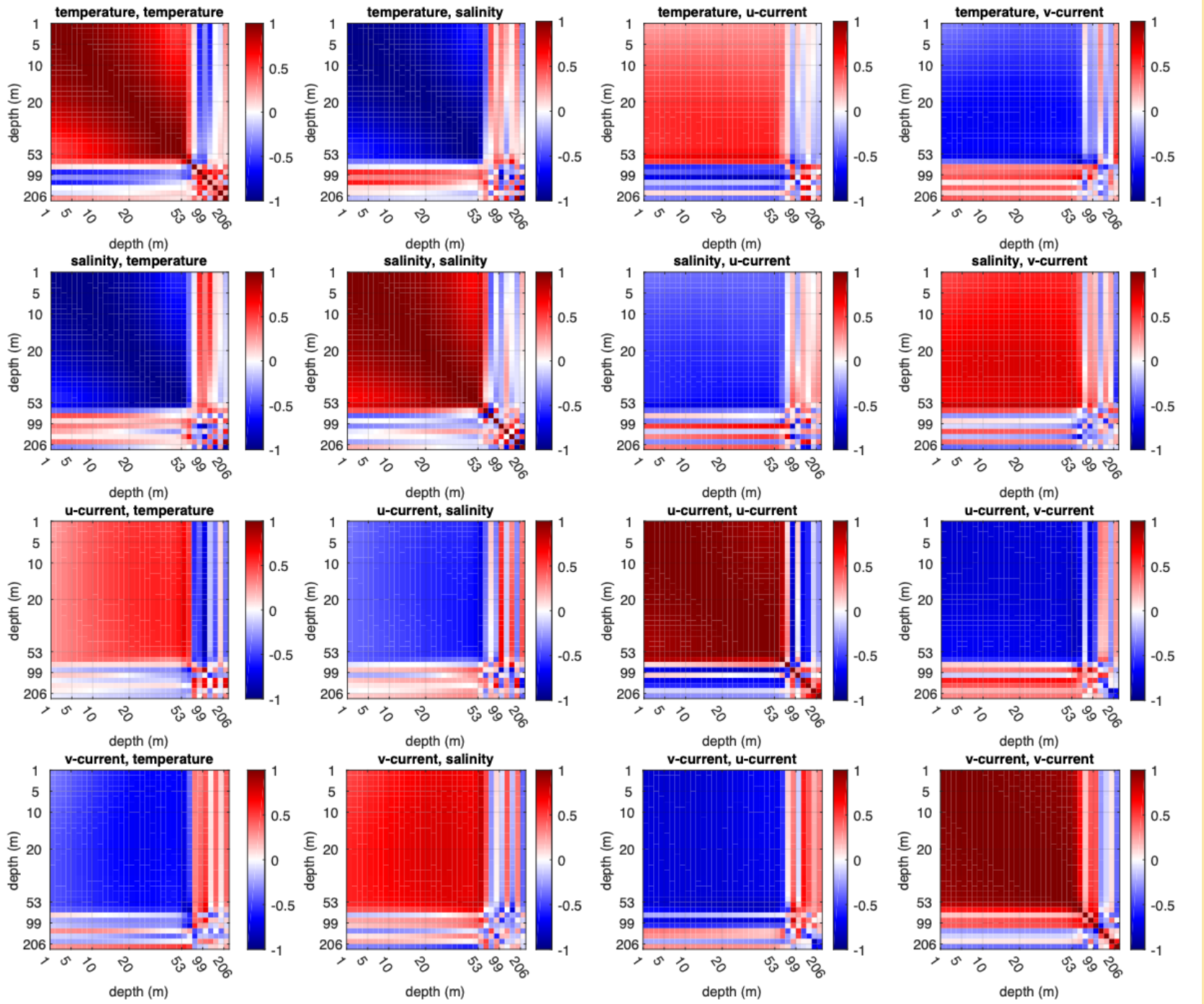
Note:

- Raw ocean ensemble error correlation matrices are derived from the coupled analysis ensemble at the end of the assimilation window
- Figures show error correlations rather than error covariances because different components of the ocean state vector have different levels of variability; standardising prevents large error variances from dominating the matrix structure



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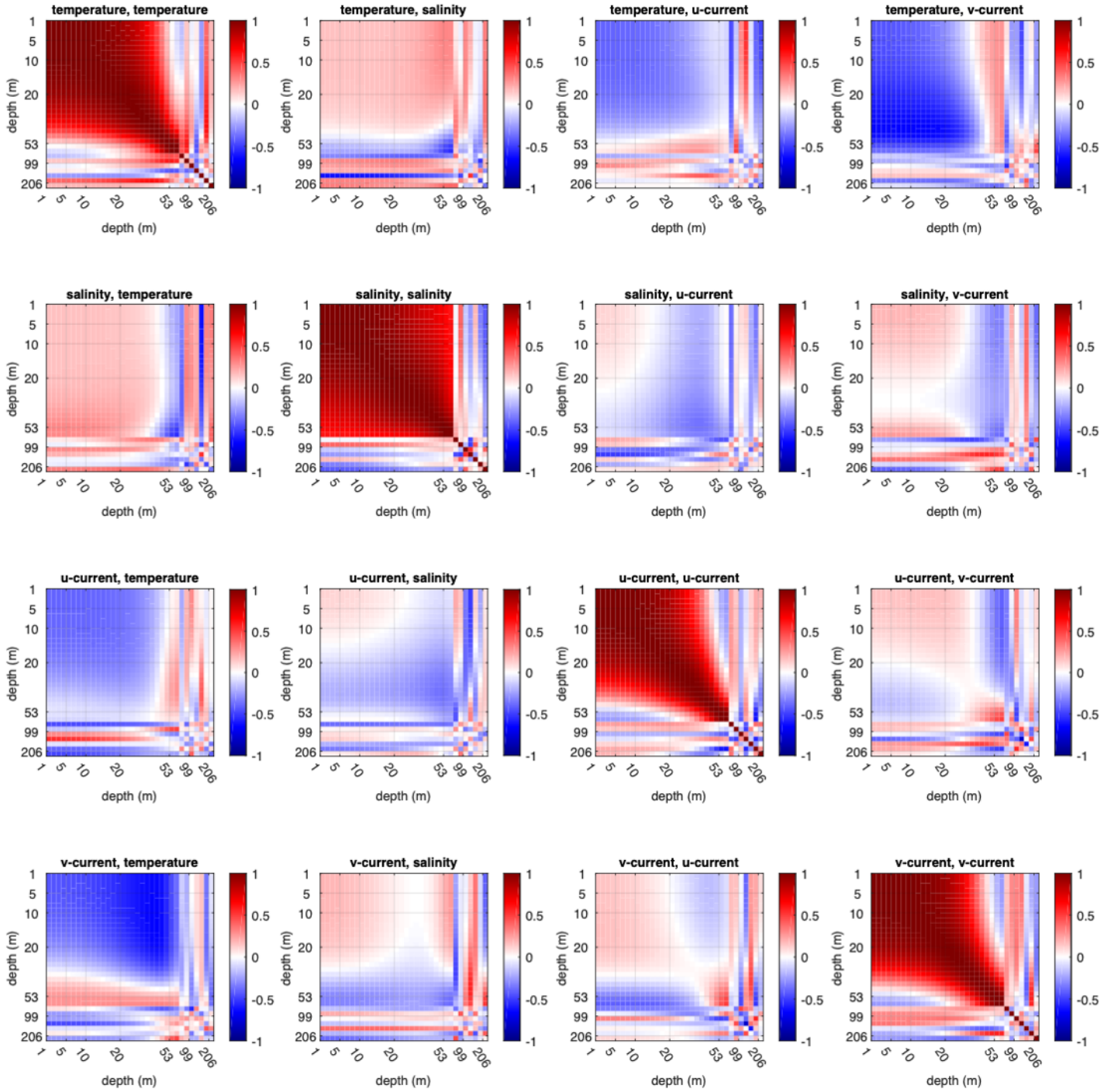
Ocean ensemble error correlations

- 20-member 4D-Var ensemble generated by perturbing initial atmosphere background state, atmosphere observations and radiation forcing



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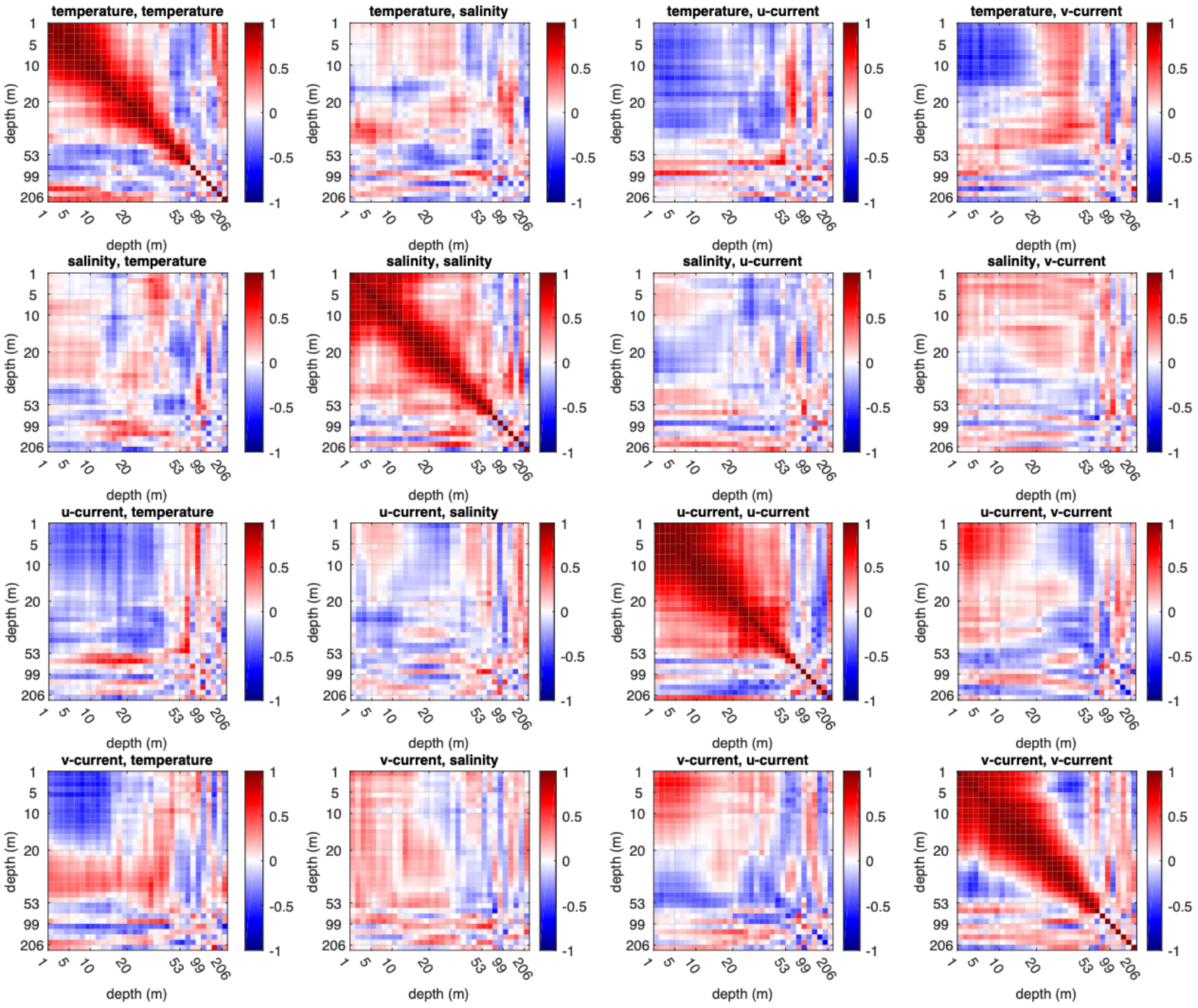
Ocean ensemble error correlations

- 20-member 4D-Var ensemble generated by perturbing initial ocean background state and observations



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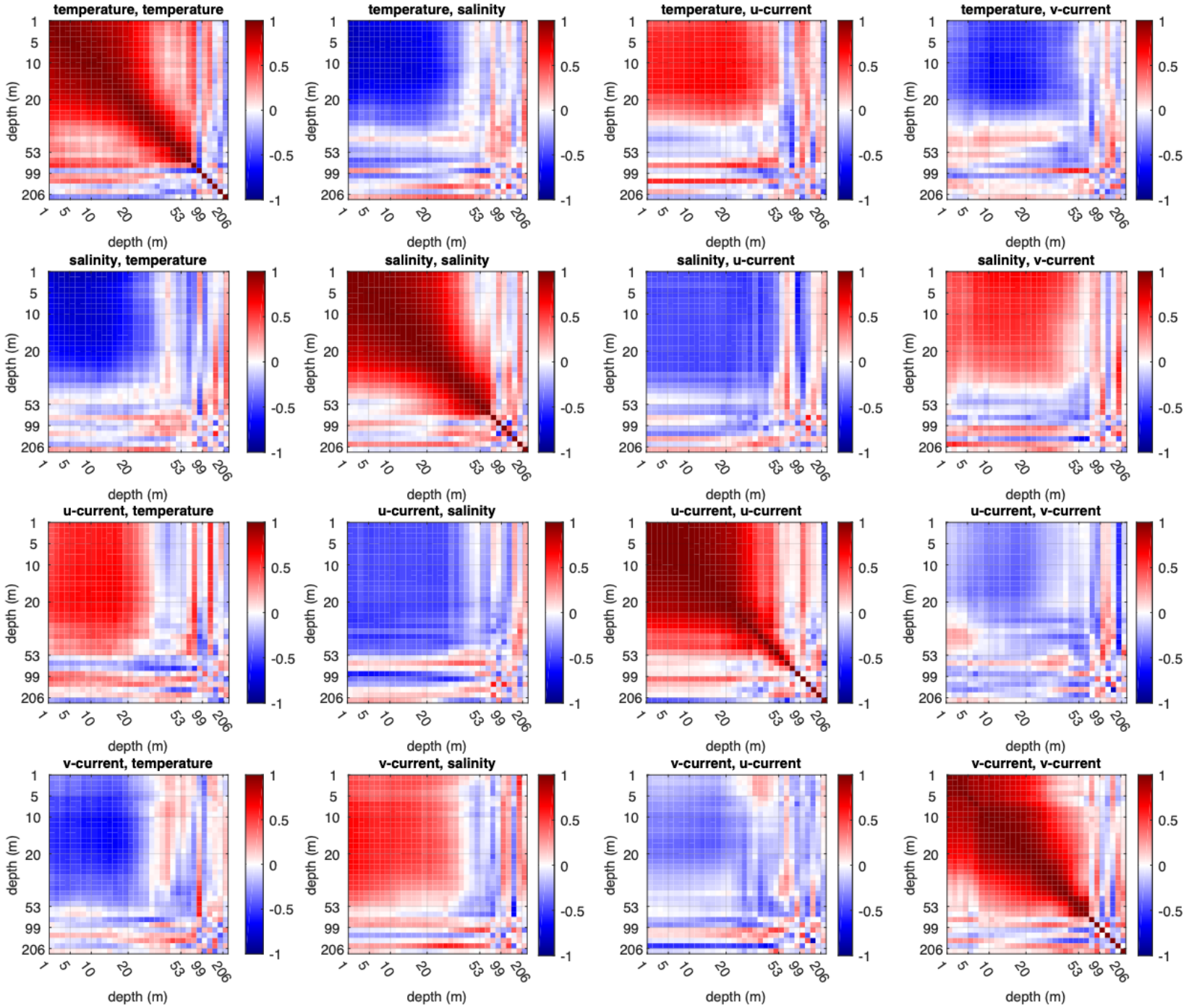
Ocean ensemble error correlations

- 20-member 4D-Var ensemble generated by applying the SPPT scheme with white noise drawn from $\mathcal{N}(0, 0.5)$



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Ocean ensemble error correlations

- 20-member 4D-Var ensemble generated by combining all methods

Summary

1. Perturbing the atmosphere initial state, atmosphere observations and surface radiation forcing produces very strong error correlations both within and across ocean fields throughout the entire mixed layer (~75m)
   - Acts to generate an ensemble of surface boundary conditions for the ocean
   - The effect (in our model) is to introduce an almost constant bias in the ocean profiles within the mixed layer that gradually tapers off; below the mixed layer the effect of perturbations applied at the surface becomes negligible
2. Perturbing the ocean background and ocean observations produced weaker cross-variable ensemble error correlations
   - Clearest correlation structures are again seen within the mixed layer; there is some variation in sign
   - Direct ocean perturbations act to introduce white noise into the ocean fields, which will create imbalance; it is likely that here the ensemble error correlations are capturing the nature of the errors in the unbalanced fields

Summary (continued)

3. SPPT scheme introduces variability throughout the ocean column
   - Leads to relatively unstructured ensemble error cross correlations when applied alone
   - Error auto correlations are strong within the mixed layer but correlation length-scales are generally shorter than other methods

4. Differences between 1, 2 & 3 show how different perturbation methods allow different sources of ocean uncertainty to be captured by the ensemble

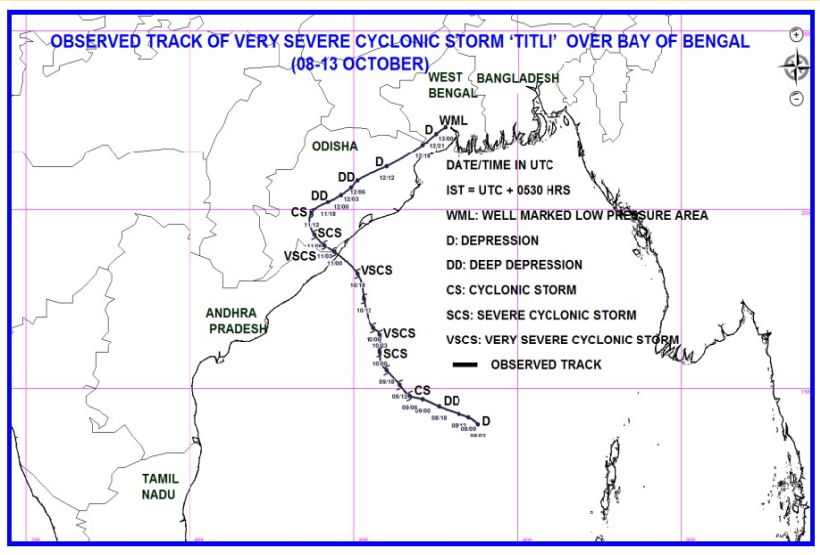
5. Structure of error correlations when all methods are combined suggests that the perturbed surface boundary conditions are key in driving the behaviour of the ensemble within the ocean mixed layer (in our model)

Part 2:

Tests in the Met Office ocean and coupled DA systems

Modelling of $\mathbf{B}$ for the ocean

- Traditionally, this is done through parametrisations ($\mathbf{B} = \mathbf{B_{mod}}$) that have limited dependence on local conditions
- **Problematic for tropical cyclones** which have different variability patterns
- New hybrid method in development: $\mathbf{B} = (1-\alpha)\mathbf{B_{mod}} + \alpha\mathbf{B_{ens}}$ where $\mathbf{B_{ens}}$ is estimated from an **ensemble of the day**
- Case study: Tropical Cyclone Titli
  - 8 – 13 Oct 2018, Bay of Bengal
  - To investigate the impact of hybridising oceanic covariances in an air-sea coupled NWP model



Courtesy of the India Meteorological Department

Single-observation experiments: theory

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$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x_b})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x_b}) + \frac{1}{2}(\mathbf{y} - H(\mathbf{x}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x}))$$

- Variational DA problem: minimise cost function $J(\mathbf{x})$, given background field $\mathbf{x_b}$ and observations $\mathbf{y}$
- The background-error covariance matrix $\mathbf{B}$ contains **important information about how information from observations propagate to unobserved parts**
- If only a single direct observation y is available, then

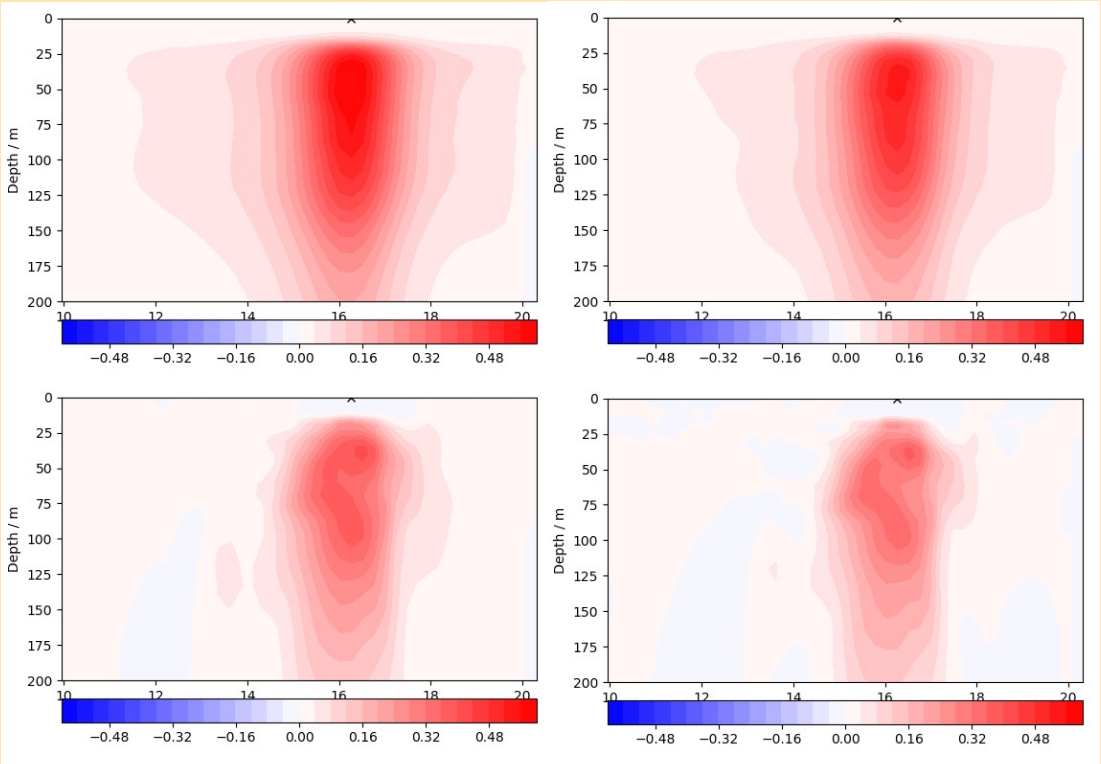
$$\mathbf{\Delta x} = \mathbf{x} - \mathbf{x_b} = \frac{y - x_{\mathrm{b}k}}{b_{kk} + \sigma_{\mathrm{o}}^2}\mathbf{b_k}$$

- Hence analysis increment $\mathbf{\Delta x}$ is proportional to a column $\mathbf{b_k}$ of $\mathbf{B}$, thereby revealing the background-error covariance structure

Single-observation experiments

- We first examine the structure of hybrid covariances through single-observation experiments within the uncoupled ocean model, with $\alpha = 0.0, 0.2, 0.8$ and 1.0
- Analysis increments are generally more anisotropic and vertically less uniform as more weight is given to $\mathbf{B}_{\mathbf{ens}}$
- Magnitudes are also smaller, though this is probably because the ensemble generating $\mathbf{B}_{\mathbf{ens}}$ is not inflated in this particular experiment

$\alpha = 0.0$ $\alpha = 0.2$



$\alpha = 0.8$ $\alpha = 1.0$

Temperature response (°C), along 87°E, to a sea-level anomaly observation (innovation 0.08 m) at 16.25°N, 87°E

Coupled experiments

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- 6-hourly cycled assimilation experiments with the Met Office's NWP model
- Weak coupling, i.e. separate assimilations for atmosphere and ocean, but coupled model integration to generate the background field
- This is the **first time the Met Office's <u>coupled</u> model is run with <u>hybrid</u> ocean covariances**
- 2 experiments: Control ($\alpha = 0.0$) & Hybrid ($\alpha = 0.8$) – identical except the ocean $\mathbf{B}$ matrix
  - Deterministic run with a daily offline ensemble (inflated) providing $\mathbf{B}_{\mathbf{ens}}$
  - Approx. 2-week spin-up before Titli's active period

Hybrid B: impact on the ocean

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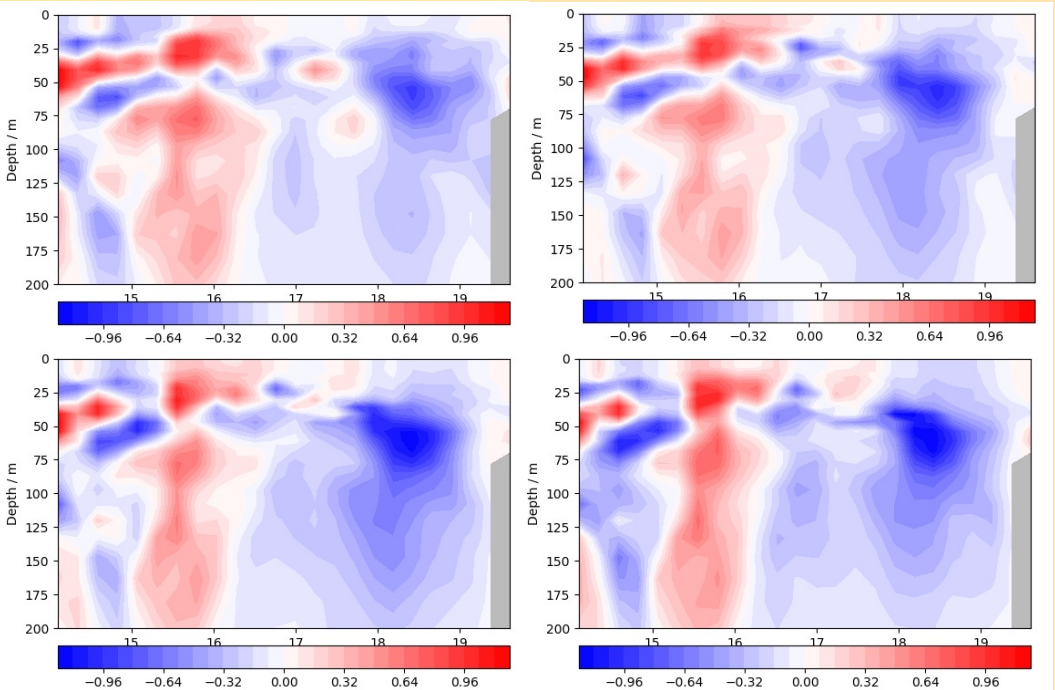
- About a week before the cyclone, the different treatments of a particular track of sea-level anomaly observations led to the development of a sub-surface dipole in the Hybrid-Control temperature difference

- As the cyclone passed, vertical mixing induced by the strong surface winds brought this temperature difference to the surface

04:30Z 10:30Z



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Sub-surface temperature differences along 86°E (Hybrid – Control; °C) throughout 10 Oct 2018

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Hybrid B: impact on air-sea interaction

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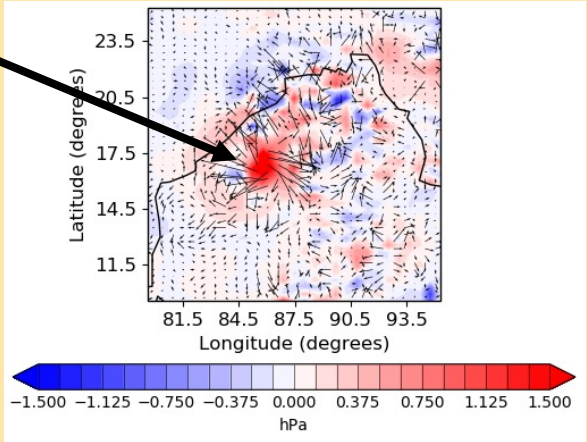
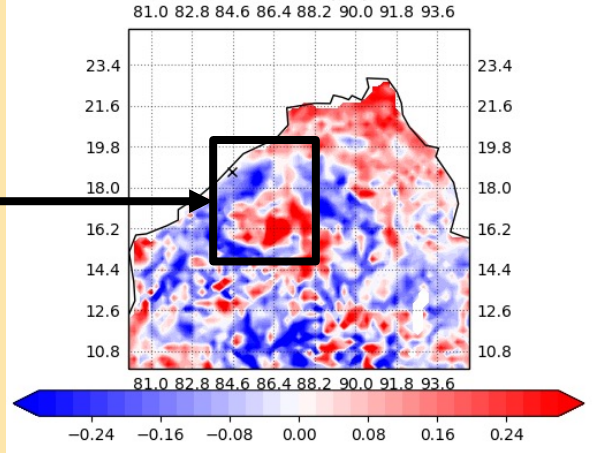
- The cyclone in the Control run intensifies earlier
- As the intensification in the Control run takes place, more heat is transferred from the ocean to the atmosphere, leaving the ocean with cooler surface waters than the Hybrid run
- Later, as the cyclone in the Hybrid run catches up with the intensification, the SST is cooler than the Control run for the same reason; but the cyclone has moved closer to land by that time!
- This results in the formation of an SST dipole along the cyclone's track



10 Oct 2018 06Z MSLP and surface wind differences (Hybrid – Control)



10 Oct 2018 22:30Z SST differences (Hybrid – Control;°C)

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Take-home messages

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- In an ocean-only DA model, introducing flow-dependence to background-error covariances leads to more irregular spatial structures

- Our case study demonstrates that, when coupled to an atmospheric model, these sub-surface differences can extend to the surface and hence induce differences in the atmosphere during the passage of a tropical cyclone

- In other words, coupled modelling with hybrid oceanic covariances could impact the atmosphere not only through a more realistic description of SST, but also through the extra information on sub-surface oceanic mesoscale eddy structures