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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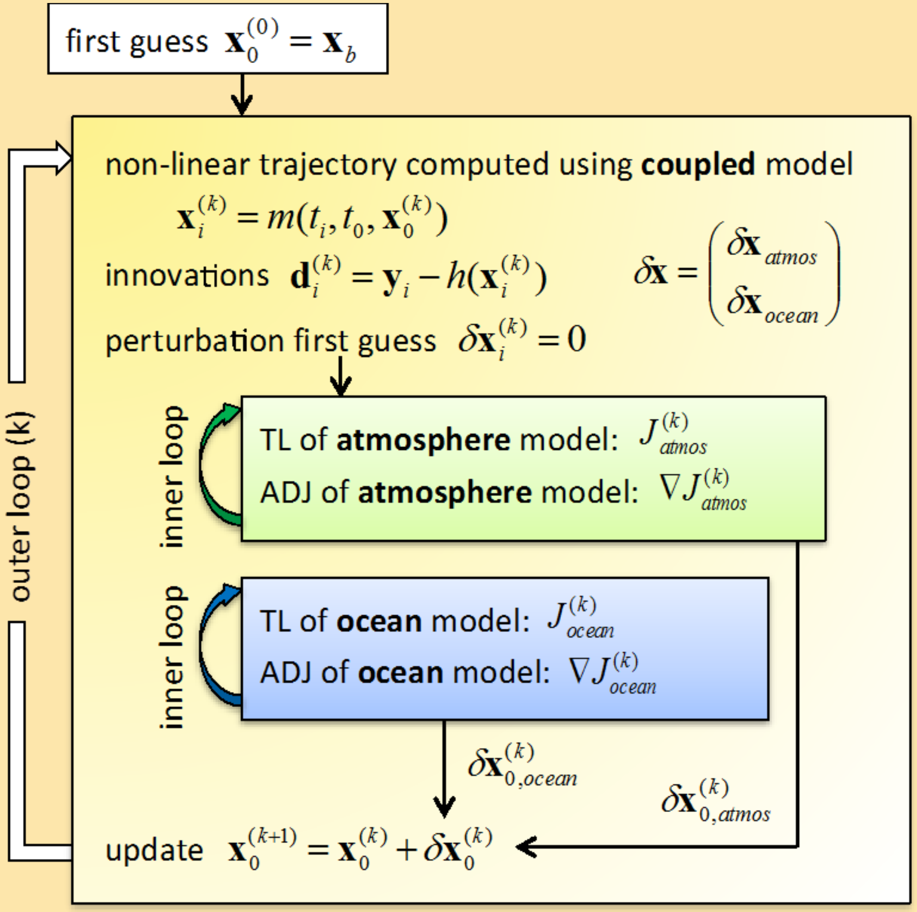
Overview

- 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, $\mathbf{B}$)
- We are exploring new methods for incorporating flow-dependent information into variational **weakly coupled** assimilation systems via the **inclusion of information from ocean ensembles**

Weakly coupled DA

- Model-observation misfits (innovations) measured against the coupled forecast state
- Analysis computed independently for each model component
- Immediate impact of observations limited to domain in which they reside
- Atmosphere observations can influence ocean analysis, and vice versa, if multiple outer loops are used or the assimilation model is cycled



Background-error covariances

- 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

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Part 1:

Ensemble-generation methods

Ensemble-generation methods

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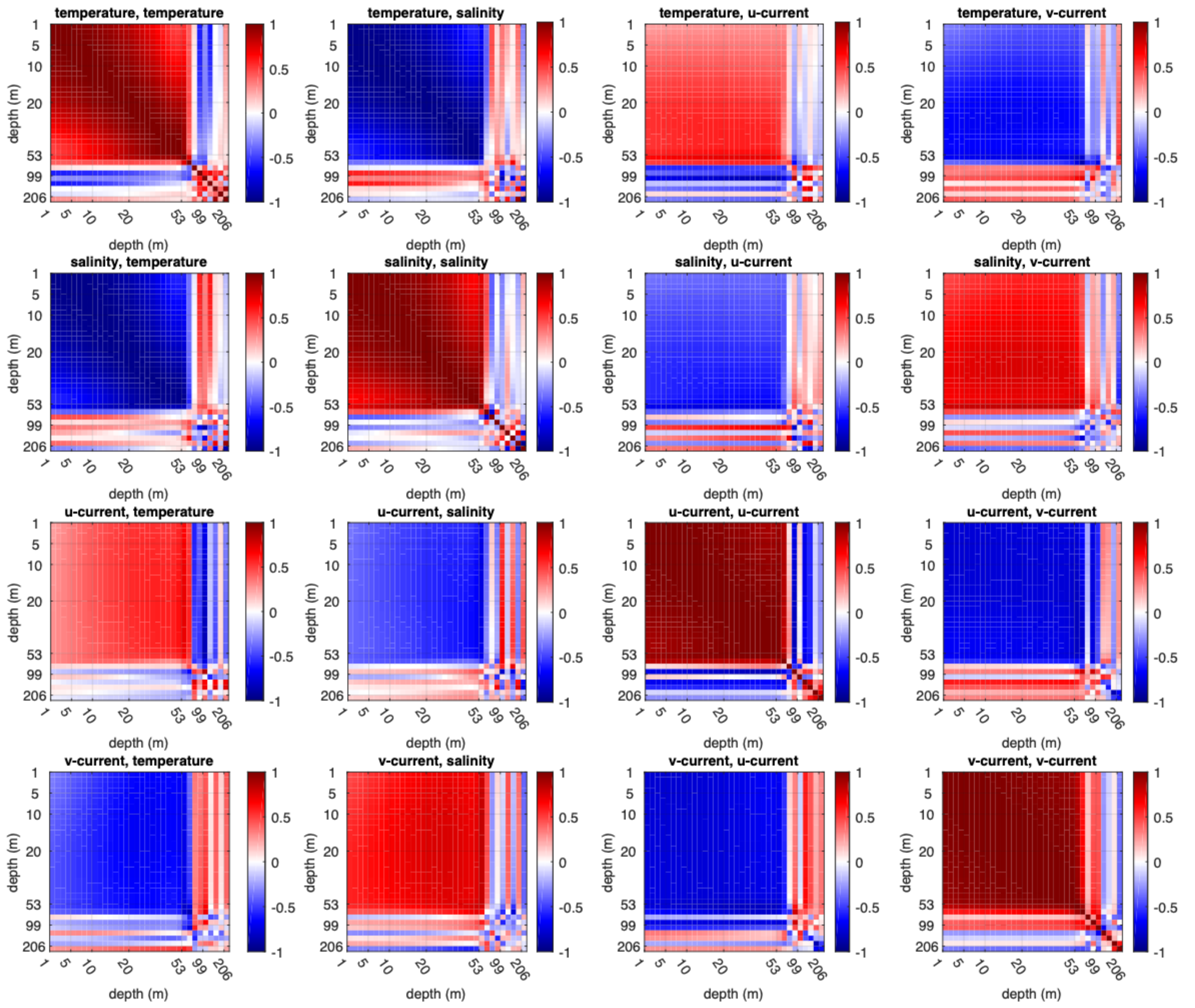
- We explore 4 methods, both individually and in combination:
  - Perturbed initial atmosphere and/or ocean background state
  - Perturbed atmosphere and/or ocean observations
  - Perturbed radiation forcing
  - Stochastically perturbed parameterisation tendencies (SPPT)
- **How do the ocean ensemble error correlation matrices change when different ensemble generation methods are used?**
  - This is explored in a weakly coupled incremental 4D-Var single-column atmosphere-ocean system (20 ensemble members), in a separate case study

Smith, Fowler & Lawless (2015), *Tellus A* **67**, 27025
Smith, Lawless & Nichols (2017), *MWR* **145**, 4011 – 4035



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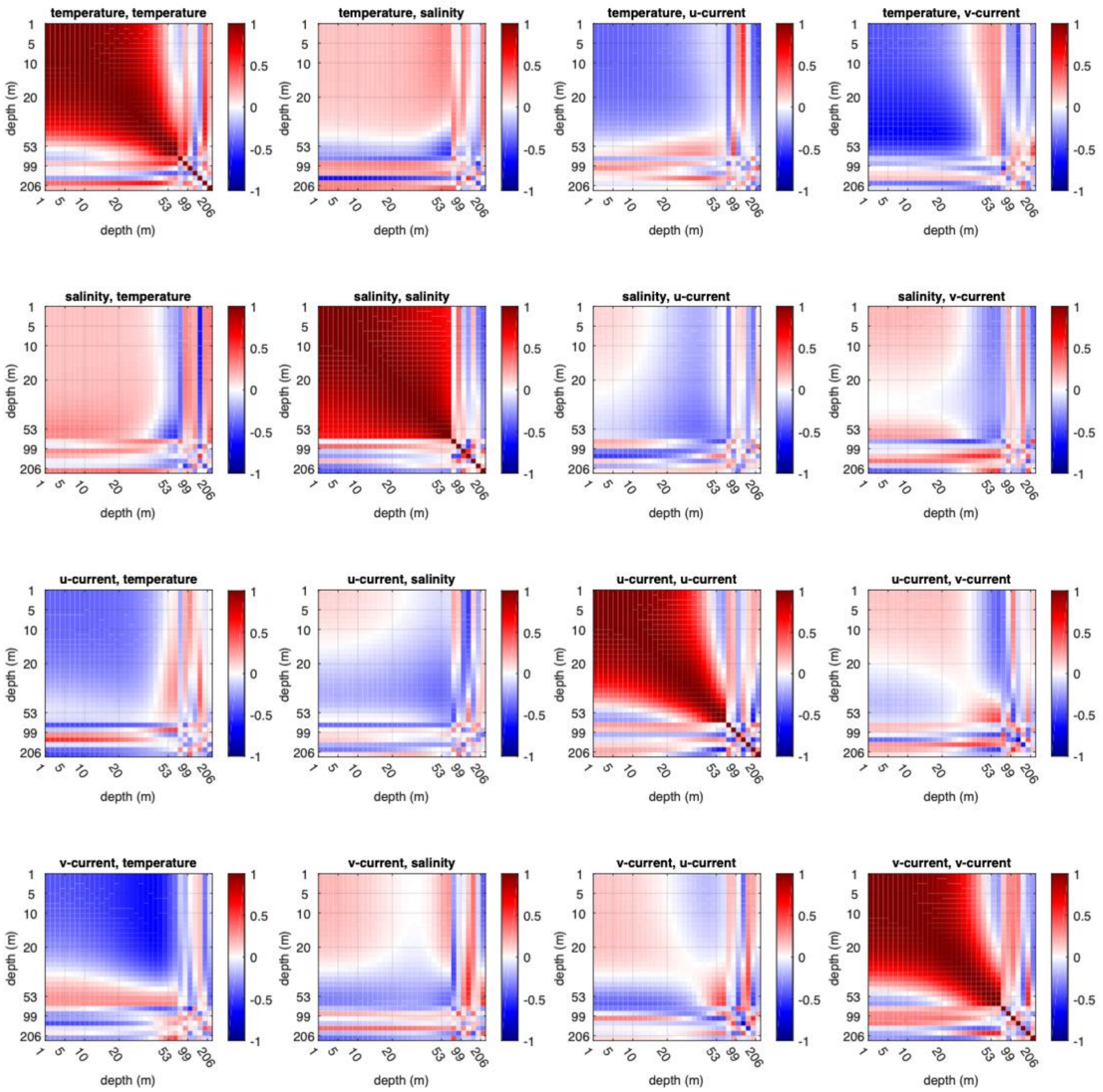
Ocean ensemble error correlations

- **Perturbed atmosphere initial state & observations, perturbed radiation forcing**
- Creates ensemble of surface boundary conditions for the ocean
- Introduces near-constant bias in the ocean profiles within mixed layer (~75m) that gradually tapers off
- Below mixed layer effect of surface perturbations becomes negligible



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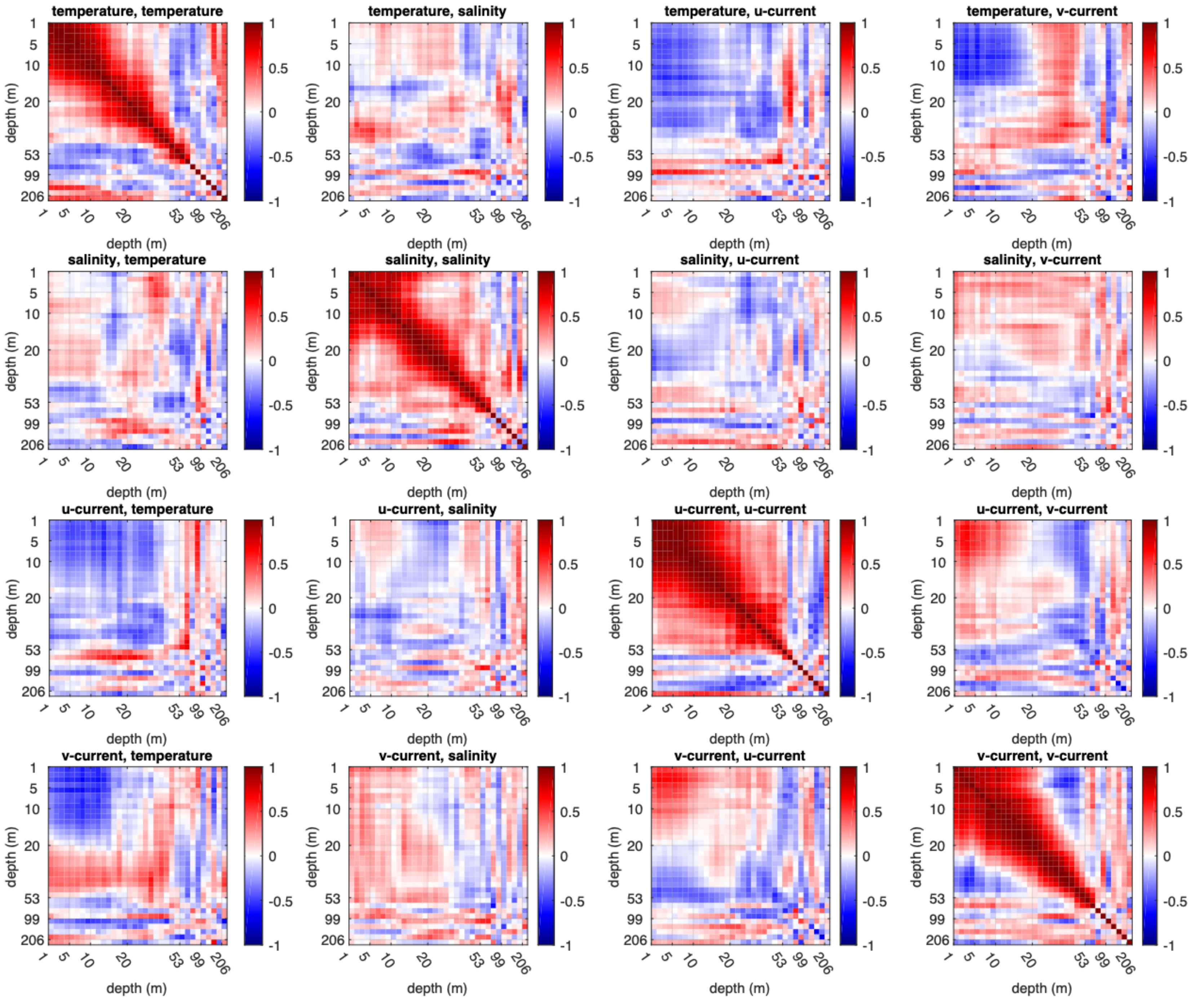
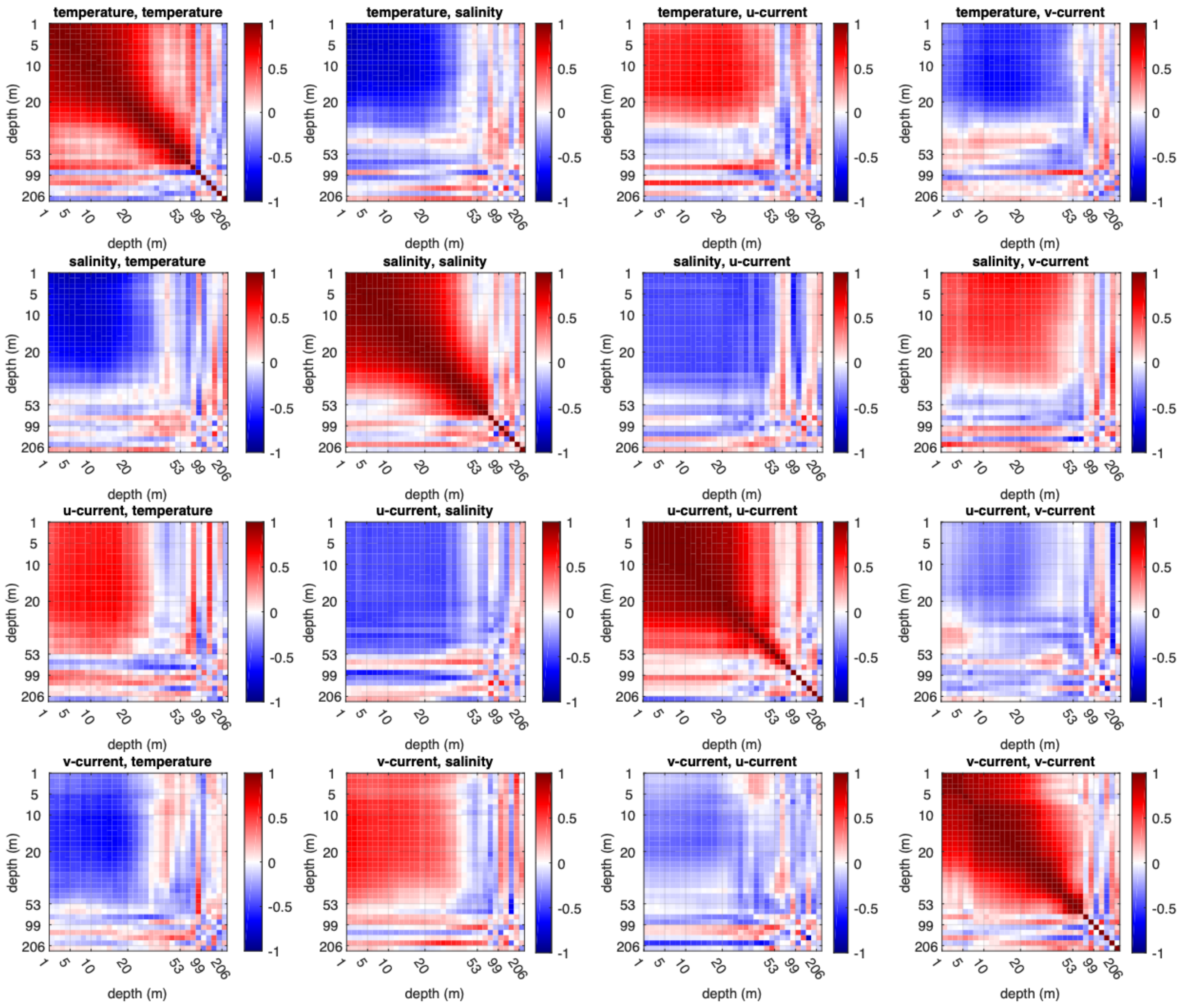
Ocean ensemble error correlations

- **Perturbed initial ocean state and ocean observations**
- Cross-variable ensemble error correlations weaker
- Clearest structures in mixed layer; some variations in sign
- Direct ocean perturbations introduce white noise, which creates imbalance
- Likely that these correlations are capturing nature of errors in unbalanced fields



Ocean ensemble error correlations

- **SPPT scheme with white noise** $\sim N(0, 0.5)$
- Introduces variability throughout the ocean column
- Gives relatively unstructured ensemble error cross-correlations
- Error auto-correlations strong within mixed layer, correlation length-scales generally shorter than other methods



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Ocean ensemble error correlations

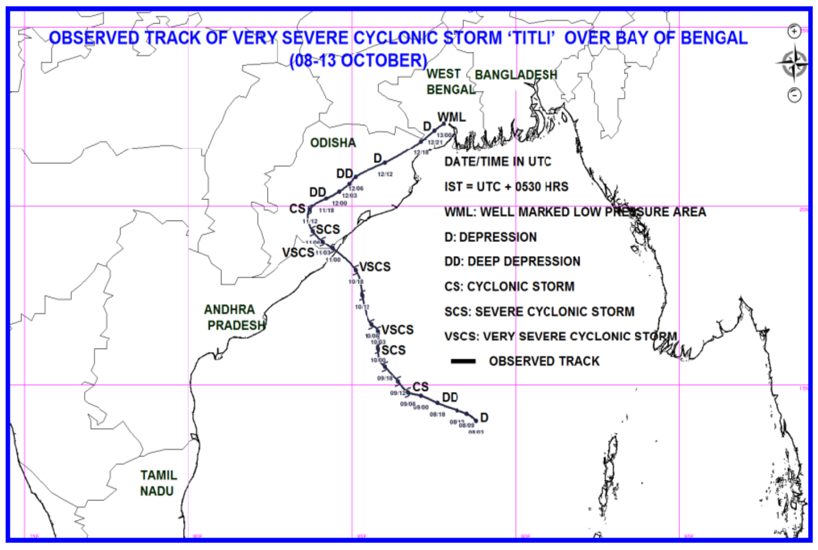
- **All methods combined**
- Different perturbation methods allow different sources of ocean uncertainty to be captured
- Structure of these error correlations suggests that perturbed surface boundary conditions are key in driving the behaviour of the ensemble within the ocean mixed layer (in our model)

Part 2:

Tests in the Met Office ocean and coupled DA systems

Case study: Tropical Cyclone Titli

- 8th – 13th October 2018, Bay of Bengal
- Rapid intensification on 10th October
- 150 km/h sustained winds shortly before landfall at ~00Z of 11th October
- Claimed tens of lives and brought significant damage to eastern India
- Research question: How does hybridising the oceanic $\mathbf{B}$ matrix change the evolution of the cyclone in a coupled model?



Courtesy of the India Meteorological Department

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Single-observation tests in the ocean

- If only a single direct observation y is available, then the analysis increment is

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

- Hence single-observation assimilation experiments reveal the underlying background-error covariance structure
- 4 values of α: 0.0, 0.2, 0.8 and 1.0
- 2 types of observation: SLA and a single T observation at 100 m depth
- Innovations ($y - x_{\mathrm{b}k}$): 0.08 m and 1.0°C respectively
- Observation at 12Z on 9th October 2018 at 87.0°E, 16.25°N
- Background from a cycled 3DVar ensemble; no inflation

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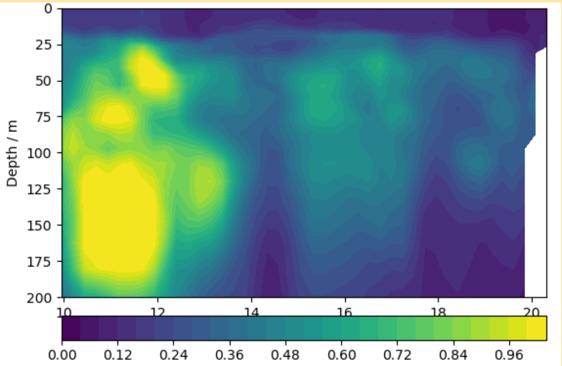
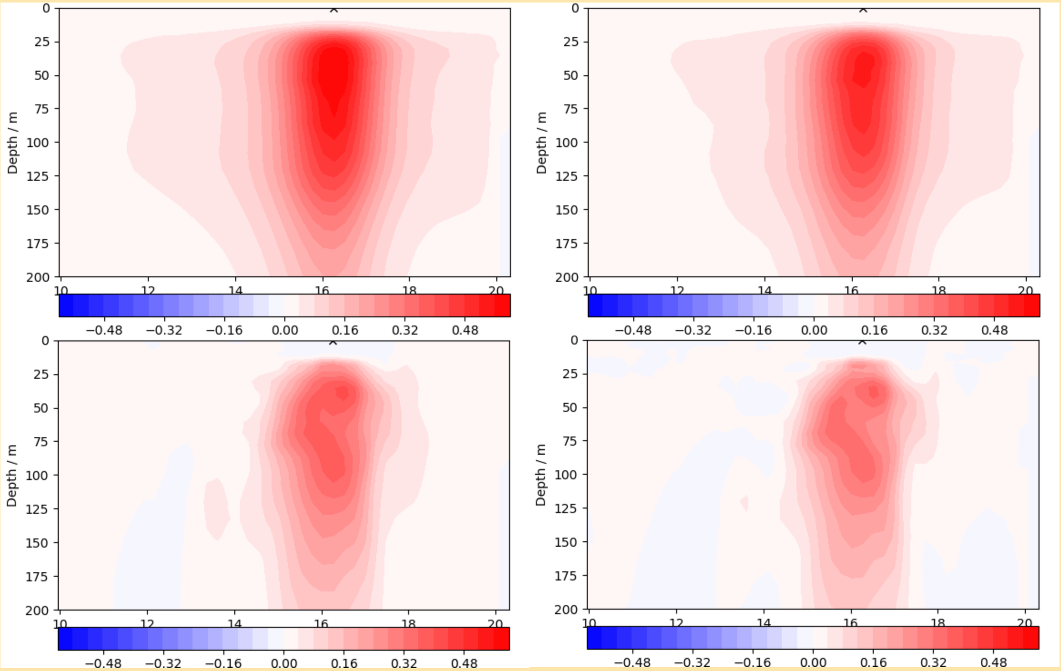
An SLA observation

- An SLA observation doesn't change ocean fields in the mixed layer but yields increments beneath it
- The analysis increment is more anisotropic and vertically less uniform as more weight is given to $\mathbf{B}_{\mathbf{ens}}$
- There is some resemblance between the tilting of the increment and tilting seen in the ensemble mean and spread of the day



Ensemble spread of T along 87°E

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



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

T increment along 87°E

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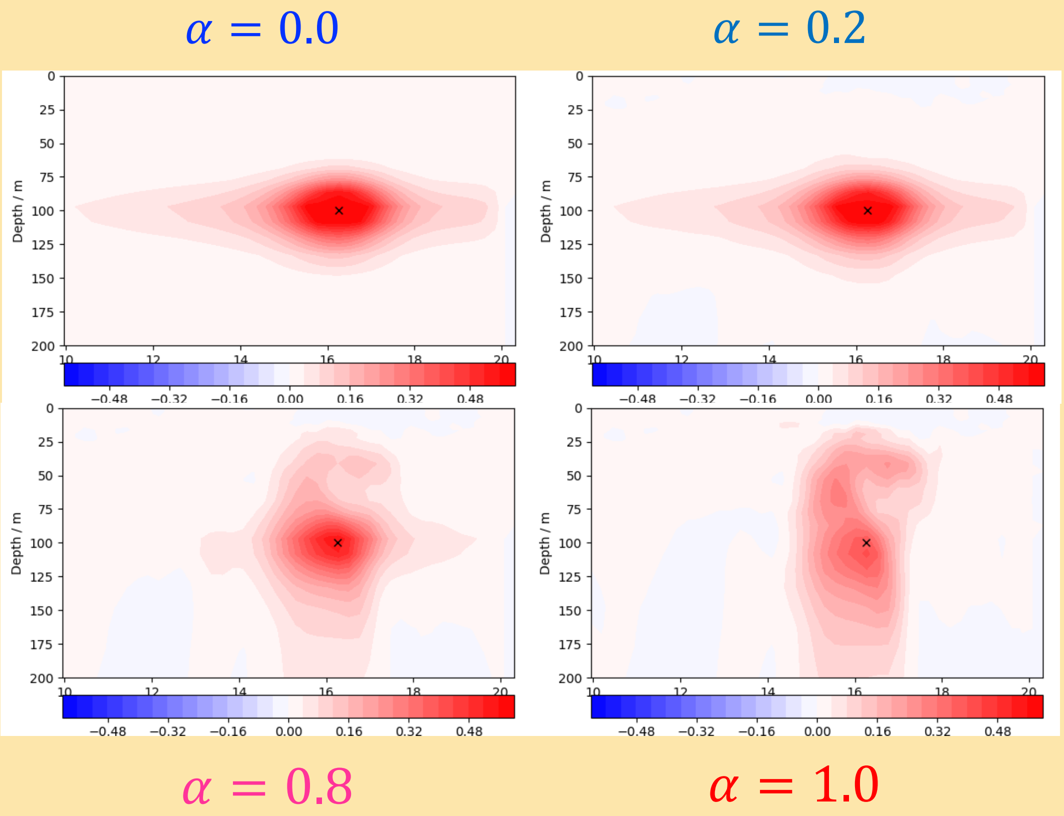
A sub-surface (100 m) T observation

- A significant change in the horizontal and vertical extents as α increases
- The effect of the absence of vertical localisation in $\mathbf{B}_{\mathbf{ens}}$ is clear, and the imperfect specification of vertical correlations in $\mathbf{B}_{\mathbf{mod}}$ is highlighted by using only one observation (rather than a profile)
- Horizontally, the correlation length scale of $\mathbf{B}_{\mathbf{mod}}$ for T is less than the localisation length scale of $\mathbf{B}_{\mathbf{ens}}$, but small-$\alpha$ experiments have larger increments overall



T increment along 87°E

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Coupled experiments

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- This is the **first time the Met Office's weakly <u>coupled</u> model is run with <u>hybrid</u> ocean covariances**
- Atmosphere: N320, En4DVar, coupled to ocean using GC3
- Deterministic run (ensembles used to compute $\mathbf{B}_{\mathbf{ens}}$ drawn offline for both fluids)
- The ocean assimilation cycle is reduced from 24 hours to 6 hours, yet the $\mathbf{B}$ matrix hasn't been re-modelled based on 6-hourly covariances
- 2 cycled experiments: Control ($\alpha = 0.0$) & Hybrid ($\alpha = 0.8$) – identical except the ocean $\mathbf{B}$ matrix
  - Ensemble inflation for oceanic $\mathbf{B}_{\mathbf{ens}}$
  - Approx. 2-week spin-up before Titli's active period

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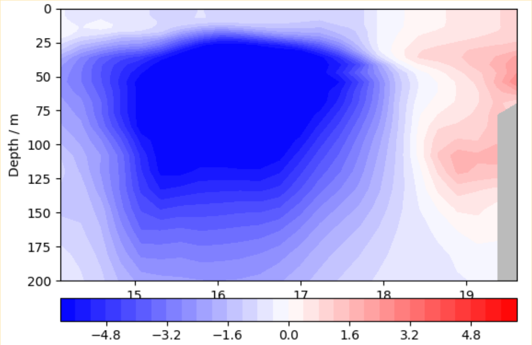
Hybrid B: impact on ocean

- About a week before the cyclone, the different treatments of two particular tracks 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



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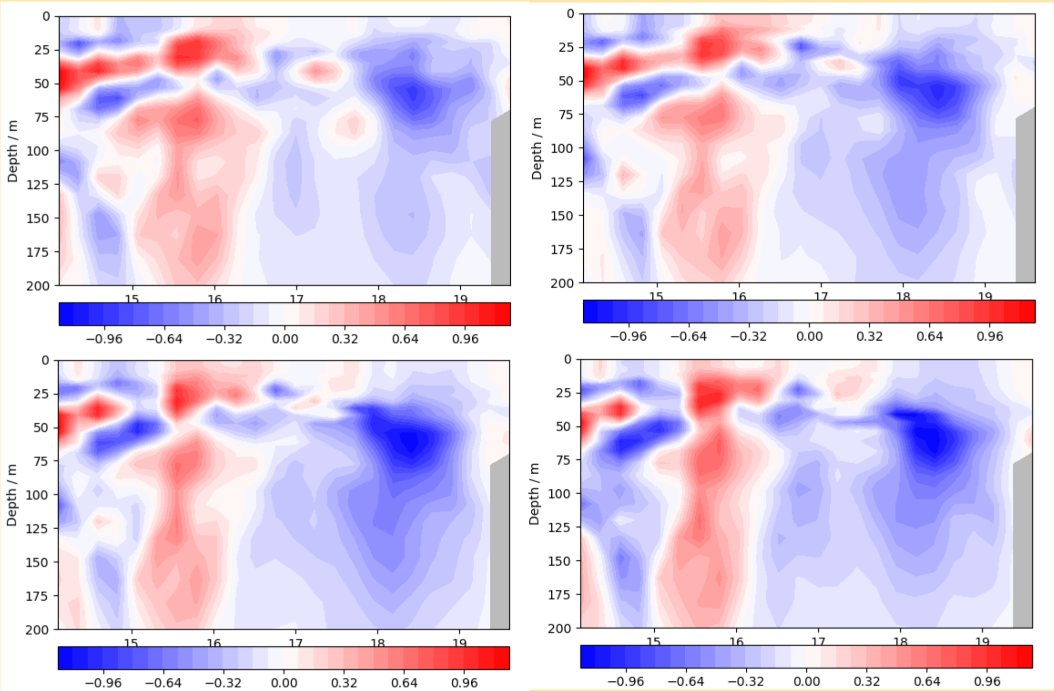
10 Oct 2018 22:30Z
Control-run T anomaly along 86°E

04:30Z

10:30Z



16:30Z

22:30Z

T differences along 86°E (Hybrid − Control; °C) throughout 10 Oct 2018

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Hybrid B: impact on sea surface

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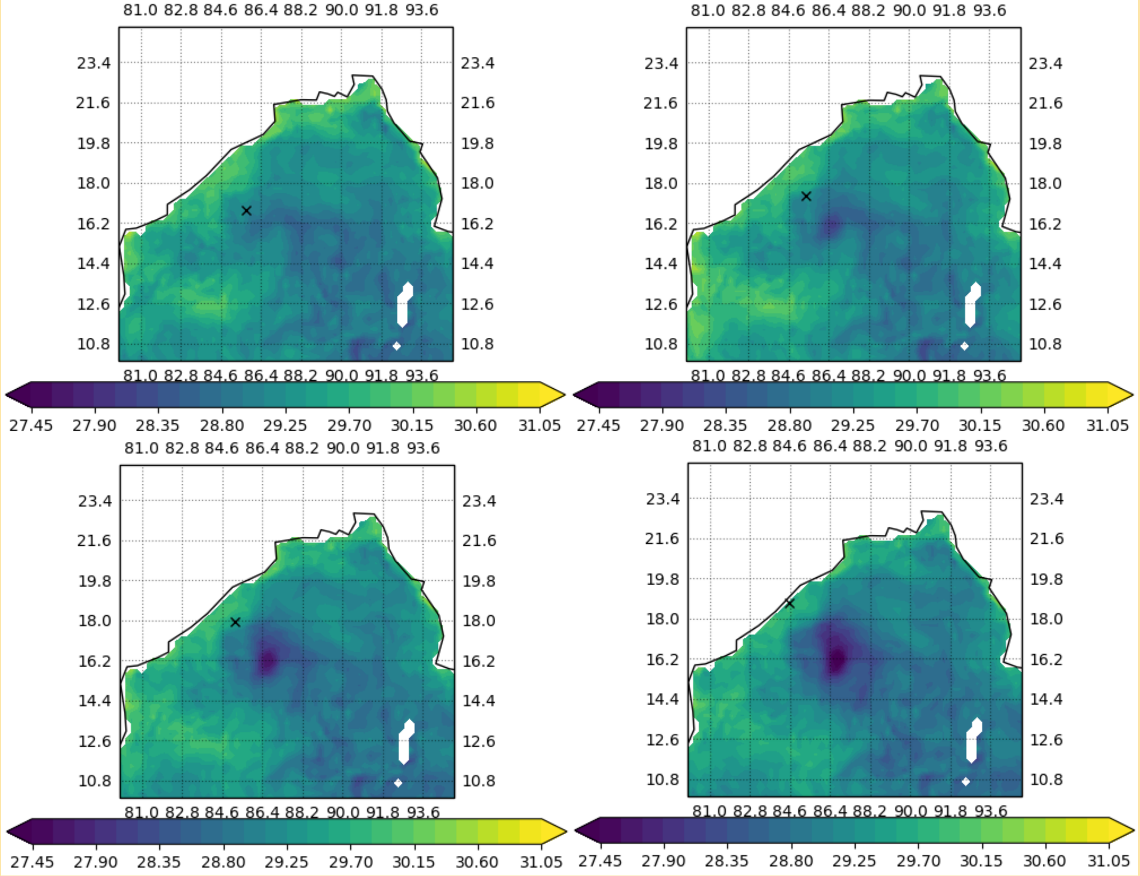
04:30Z 10:30Z



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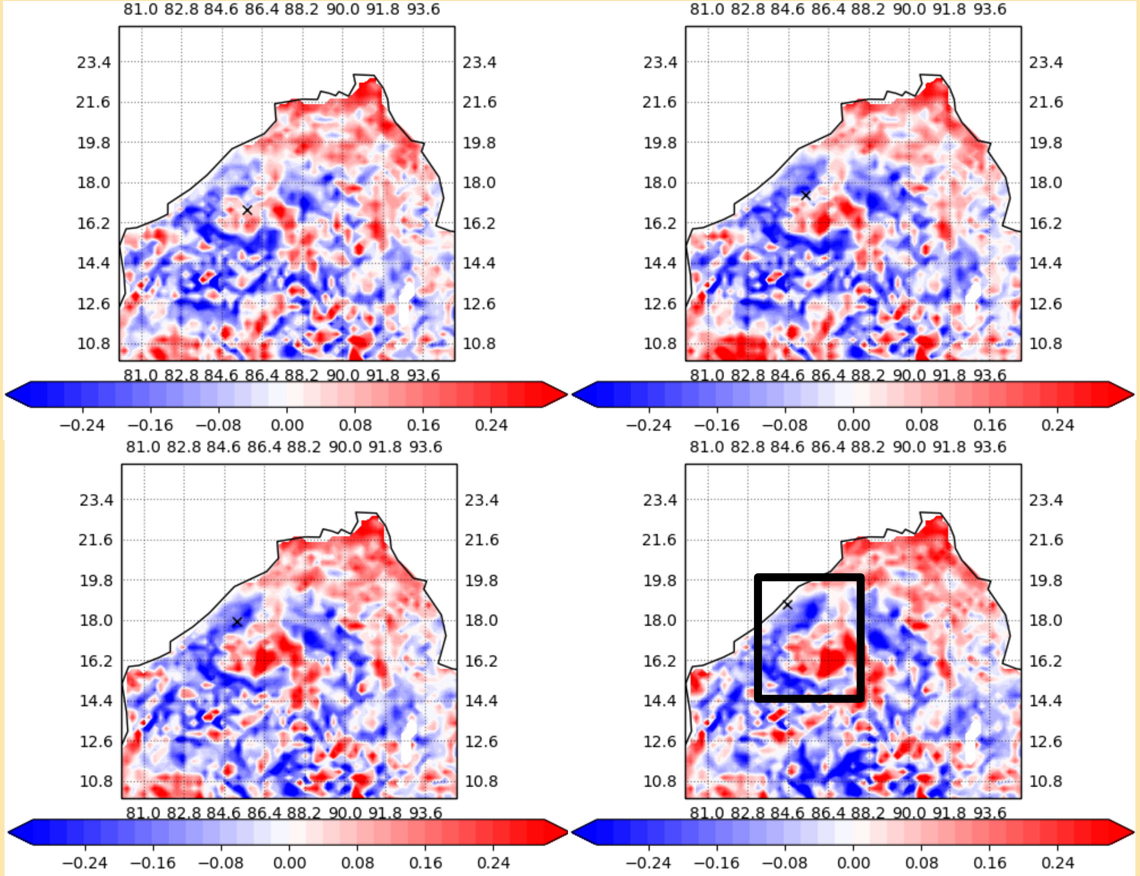
04:30Z 10:30Z



16:30Z 22:30Z

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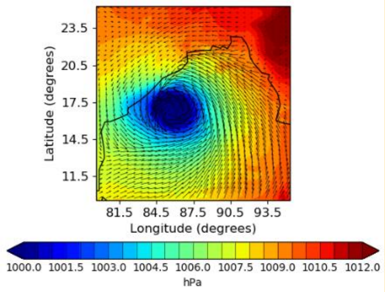
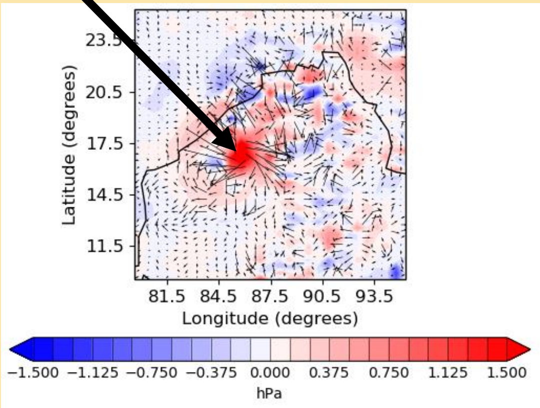
(Left panel) Control-run SST and (right panel) Hybrid – Control SST differences (°C) throughout 10 Oct 2018

Hybrid B: impact on air-sea interaction

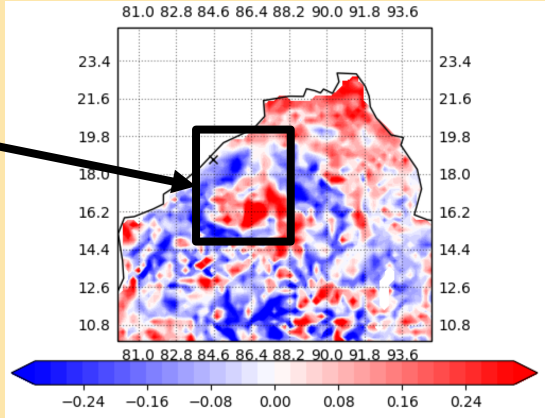
- The cyclone in the Control run intensifies earlier
- As the intensification in the Control run takes place, more heat is transferred from the ocean to the atmosphere, leaving the ocean with cooler surface waters than the Hybrid run
- Later, as the cyclone in the Hybrid run catches up with the intensification, 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 Control-run MSLP and surface wind





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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Summary

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

- 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

Future work

- Verification on analyses and forecasts to show whether hybrid oceanic covariances indeed bring **benefits**
- Run with a higher-resolution atmospheric component of the coupled model to better resolve the tropical cyclone
- A more comprehensive assessment, with more case studies & using ensembles
- Ongoing developments of weakly coupled DA with hybrid oceanic covariances:
  - Online estimation of $\mathbf{B}_{\mathbf{ens}}$
  - Modelling of the $\mathbf{B}$ matrix based on 6-hourly error statistics
    - How to treat the different timescales between the atmosphere and ocean?

Supplementary slides for Part 1

Idealised system

Single-column, coupled atmosphere-ocean model

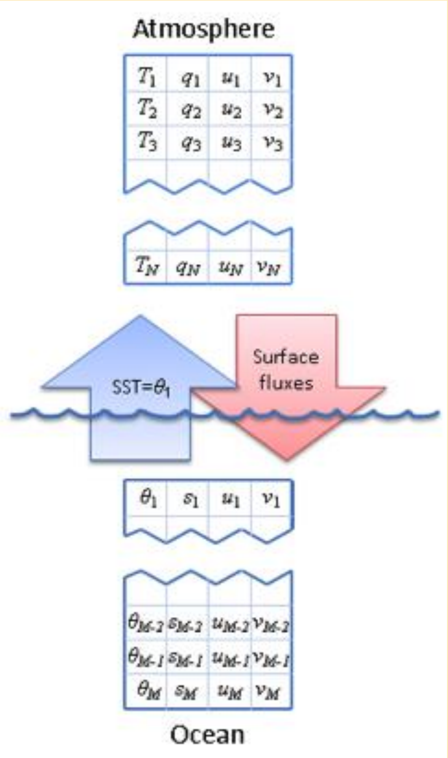
Atmosphere

- 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

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



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

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

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Results

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

Summary of results

1. Perturbing the atmosphere initial state, atmosphere observations and surface radiation forcing (i.e. generating an ensemble of surface boundary conditions for the ocean) produces very strong error correlations both within and across ocean fields throughout the entire mixed layer (~75m)
   - 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 in this case the ensemble error correlations are capturing the nature of the errors in the unbalanced fields

Summary of results (continued)

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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)