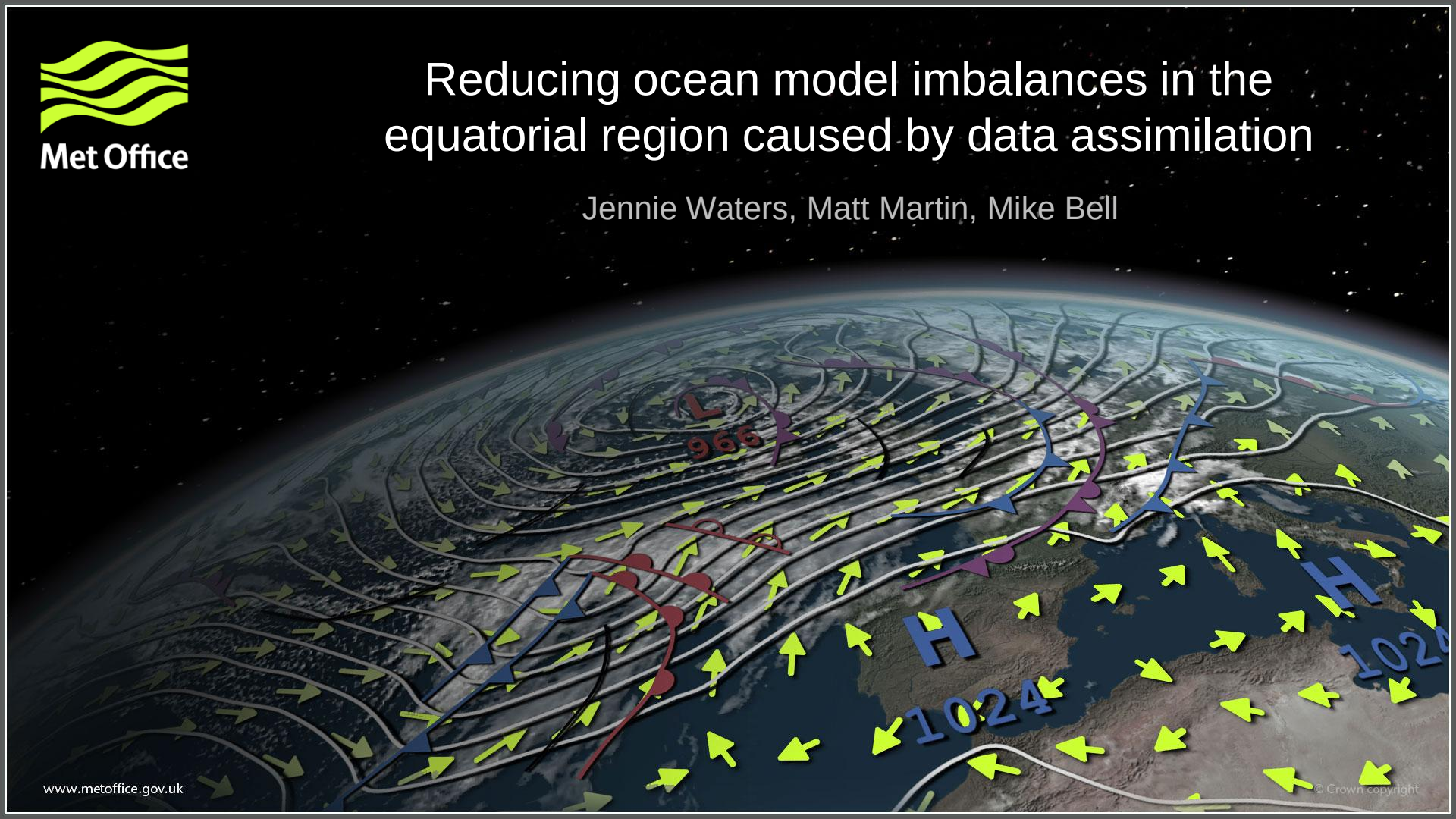
Reducing ocean model imbalances in the equatorial region caused by data assimilation

Jennie Waters, Matt Martin, Mike Bell



Contents

- The problem with DA at the equator.
- A method for improving DA at the equator.
- Some results applying this new method
- Summary

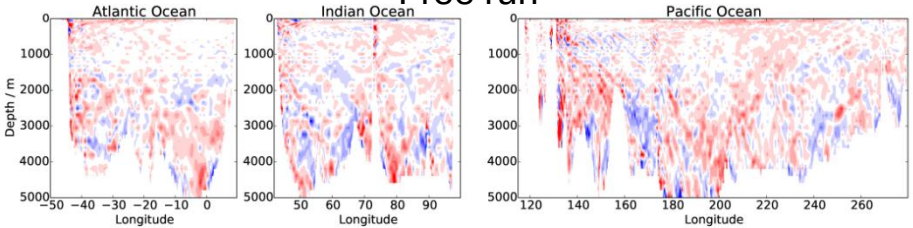
The problem with DA at the equator.
What and why.

Spurious Vertical velocities

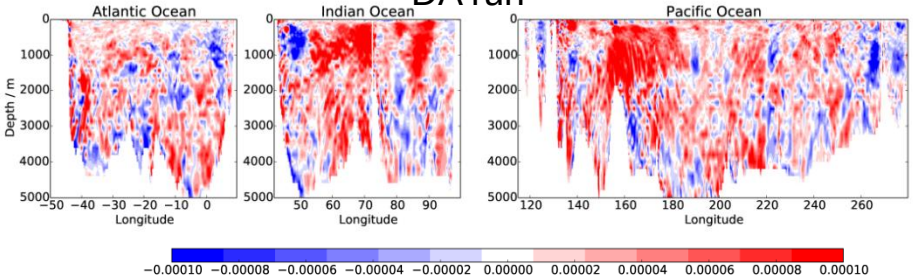
Data assimilation produces increased vertical velocities in the tropics. This has been linked to an over-estimation of nutrients in these regions

Monthly mean W – Dec 2011

Free run

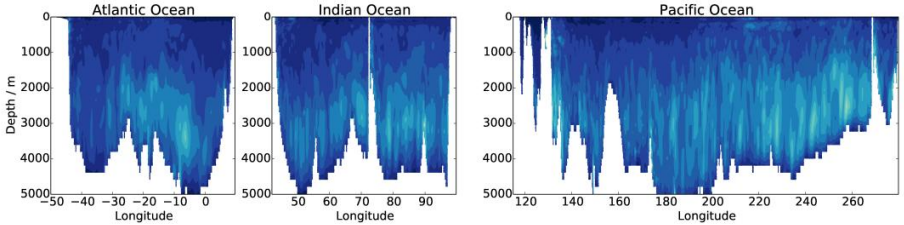


DA run

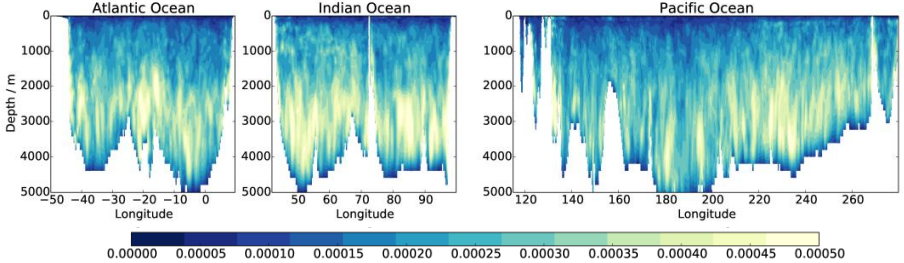


Monthly sdev W – Dec 2011

Free run



DA run

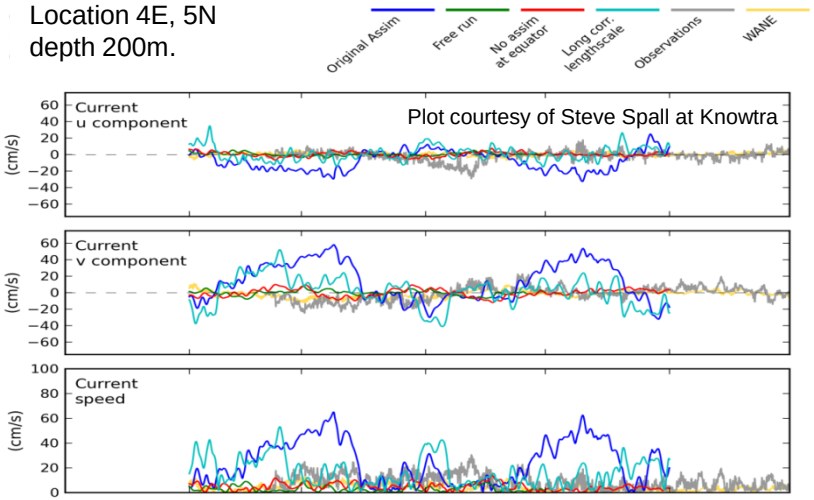


Spurious horizontal currents

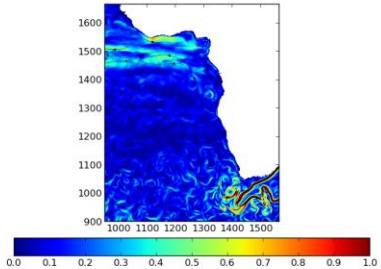
Data assimilation can also cause spurious currents in the Tropics. This was seen in a 12th of a degree Southern Atlantic model

Comparisons to ADCP observations showed the data assimilation near the equator causes current speeds which are significantly larger and more variable than those observed.

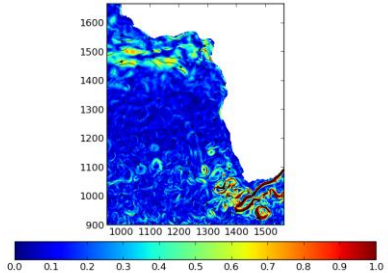
Location 4E, 5N
depth 200m.



Free run



DA run



This response in the currents may be specific to the eastern Tropical Atlantic. We have had similar issues in this region in an ORCA025 run. The problem appears to arise when there is a period of relatively dense observation sampling (e.g glider missions).

Dominant balance at the equator

• In normal conditions, strong easterly winds blow along the equator. As the Coriolis term tends to zero at the equator it is unable to balance the force associated with these trade winds.

• The winds drive westward ocean flow which causes water to pile up on the western edge of the basin and this increases the east-west near surface pressure gradients.

• The horizontal pressure gradients balance the applied wind stress at the equator and the momentum equation reduces to:

$$\boxed{\frac{\partial p}{\partial x} = \frac{\partial X}{\partial z}}$$

•This relationship can be used to understand why equatorial data assimilation is so problematic.

Impact of ocean DA on balance at the equator

• When a density increment is applied to an ocean model, it changes the ocean's horizontal pressure gradients which disrupts the balance with the wind stress.

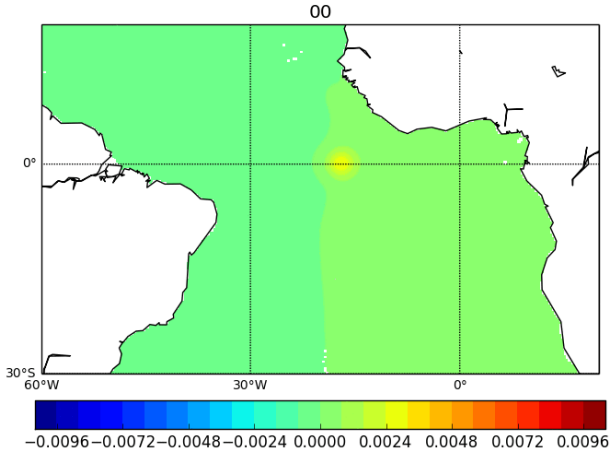
• The response of the ocean is analogous with its response to a westerly wind burst.

• A westerly wind burst generates a westerly propagating Kelvin wave and easterly propagating Rossby wave.

• DA generates spurious equatorial waves. (see plot)

• Kelvin waves play an important role in the dynamics of ENSO.
- impact of problems with data assimilation could persist over long timescales.
E.g Liu et al (2016).

• We have tried to develop a scheme which reduces initialisation shock by retaining model balance.



SSH anomaly field generated when an SSH innovation of 10cm is assimilated at the equator.

A method for reducing the initialisation shock from the DA.

The bias pressure correction method

- Bell et al (2004) proposed a method for reducing the systematic biases associated with the wind stress.

- A slowly evolving pressure bias field is estimated through the data assimilation increments and is applied as a correction to the pressure fields in the models horizontal momentum equations.

- The biases are estimated by the data assimilation system by augmenting the state vector with the bias vector. For an optimal interpolation scheme, the equation for calculating the state and bias increments are:

Kalman gain

state increment

bias increment

$$\begin{aligned} \delta \mathbf{x}_k^a &= \mathbf{K}[\mathbf{y}_k - H(\mathbf{x}_k^f)] \\ \delta \beta_k^a &= -\mathbf{K}_\beta[\mathbf{y}_k - H(\mathbf{x}_k^f)], \end{aligned}$$

bias Kalman gain

- In Bell et al (2004) a simple form of the bias Kalman gain is chosen, the bias Kalman gain is proportional to the state Kalman gain.
Where γ_1 << 1 is a positive constant.

$$\mathbf{K}_\beta = \gamma_1 \mathbf{K},$$

The bias pressure correction method cont....

•Therefore, the bias analysis equation can be rewritten as:

$$\delta\beta_k^a = -\gamma_1 \delta \mathbf{x}_k^a$$

• In the pressure correction method we use the analysis to estimate bias fields for temperature and salinity:

$$\delta\theta_k^{a\beta} = -\gamma_1 \delta\theta_k^a$$
$$\delta\mathbf{s}_k^{a\beta} = -\gamma_1 \delta\mathbf{s}_k^a.$$

In FOAM we set γ_1=0.1.

• The bias analysis fields are then given by:

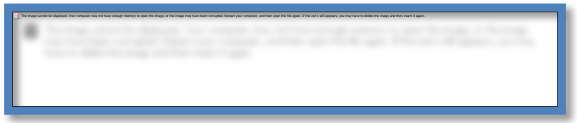
$$\theta_k^{a\beta} = \theta_k^{f\beta} + \delta\theta_k^{a\beta}$$
$$\mathbf{s}_k^{a\beta} = \mathbf{s}_k^{f\beta} + \delta\mathbf{s}_k^{a\beta}$$

• And the forecast model for the bias is a simple decay model:
and α_1= 0.008 which is equivalent to an e-folding scale of 125 days.

$$\theta_{k+1}^{f\beta} = (1-\alpha_1)\theta_k^{a\beta}$$
$$\mathbf{s}_{k+1}^{f\beta} = (1-\alpha_1)\mathbf{s}_k^{a\beta}.$$

The bias pressure correction method cont....

• The temperature and salinity bias fields are then used to calculate a bias corrected density field, using the equation of state:



• And this is used in the hydrostatic equation to calculate a bias corrected pressure field

• This corrected pressure field is then used in the model equations.

• Given the balance between the pressure gradients and the wind stress, making a change to the pressure fields in the equations of motion is analogous to making a direct adjustment to the wind forcing.

The Incremental pressure correction method

• The bias pressure correction aims to reduce the impact of slowly varying biases, we want to provide a scheme which can balance the ocean increments and reduce initialisation shock.

• The Incremental pressure correction (IPC) scheme is based on the bias pressure correction, but aims to reduce imbalances over shorter time scales. It can be thought of as an extension of the BPC to a second time scale.

• For the IPC, temperature and salinity balance increments are defined as: where γ_2 is close to 1 (so the balance increments are of a similar magnitude to the state increments)

$$\delta\theta_k^I = -\gamma_2 \delta\theta_k^a$$
$$\delta\mathbf{s}_k^I = -\gamma_2 \delta\mathbf{s}_k^a$$

• The forecast IPC fields are given by:

$$\theta_k^{fI} = (1-\alpha_2)\theta_{k-1}^I$$
$$\mathbf{s}_k^{fI} = (1-\alpha_2)\mathbf{s}_{k-1}^I$$

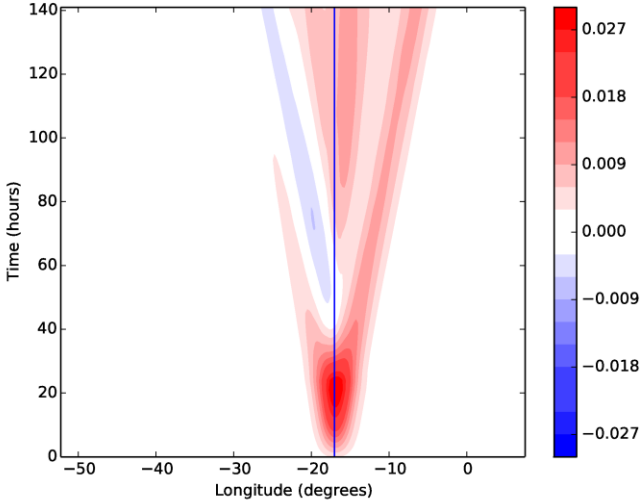
We want the time scales in the forecast model to be consistent with the persistence of the increments in the forecast, so that balance is retained throughout the forecast. In these first experiments we use α_2=0.1 which is an e-folding scale of 10 days.

Results with the IPC

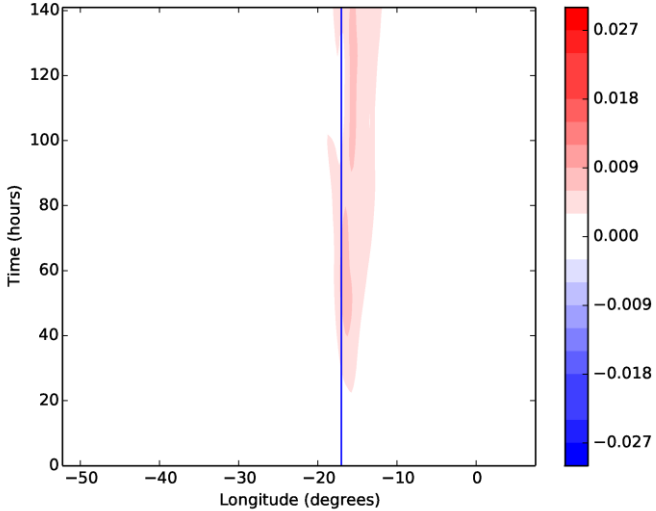
The impact of the IPC for simple forecast experiments

Hovmoller plots of the anomaly fields generated when an SSH innovation of 10cm is assimilated at the equator at 17W.
In these experiments $\gamma 2$ =1.0 which means that the IPC has the same magnitude as the increments in the IAU.

SSH anomaly: No IPC



SSH anomaly: With IPC

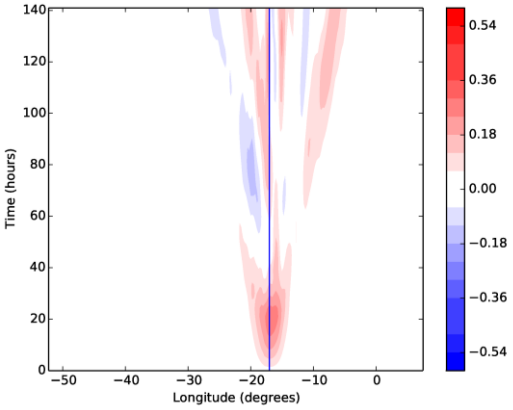


The first 24 hours is the IAU, the remaining 120 hours are a forecast

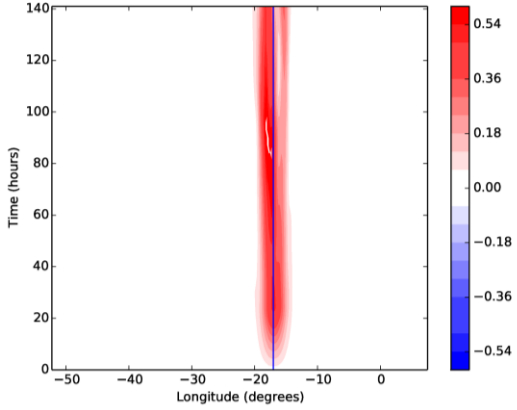
The impact of the IPC for simple forecast experiments cont...

- Anomalies at approx 85m depth.
- Persistence of T improved.
- Initialisation shock reduced.

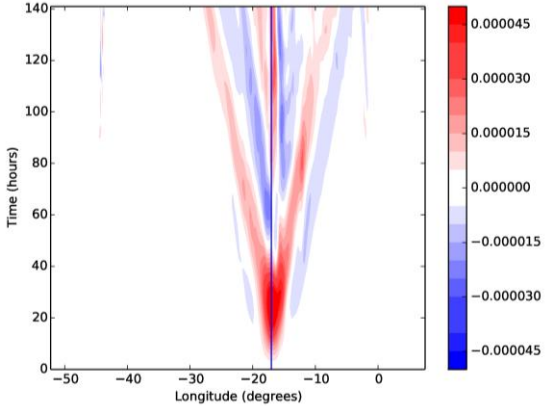
Temperature anomaly: No IPC



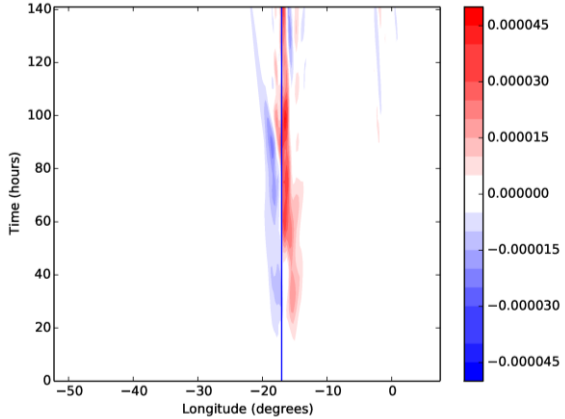
Temperature anomaly: With IPC



W anomaly: No IPC



W anomaly: With IPC



Re-analysis experiments

We have run various re-analysis experiments to test the impact of the IPC. All the experiments are based on the V12 FOAM system and all assimilative experiments are spun up from 04/08/2010 until 31/12/2010.
Our assessment period is 2011.

Exp name	Exp description	Pressure correction parameters
Exp-BPC	The FOAM v12 re-analysis. Bias pressure correction only	gamma1=0.1 alpha1=0.008 gamma2=0.0 alpha2=0.0
Exp-freerun	The FOAM v12 free run.	NA
Exp-noPC	Based on FOAM v12 but with no pressure correction	gamma1=0.0 alpha1=0.0 gamma2=0.0 alpha2=0.0
Exp-IPC	Based on FOAM v12 but with the IPC only	gamma1=0.0 alpha1=0.0 gamma2=1.0 alpha2=0.1
Exp-IPC-BPC	Based on FOAM v12 but with the IPC and BPC	gamma1=0.1 alpha1=0.008 gamma2=0.8 alpha2=0.1

Equatorial Sections: sdev W

Equatorial sections of monthly standard deviation of W for December 2011.
Last month of analysis period.

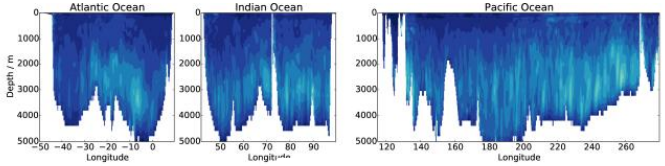
- There are small reductions in EXP-BPC compared to EXP-noPC

- In Exp-IPC the values are substantially reduced in the Atlantic and Indian Ocean, but are slightly larger in the Pacific

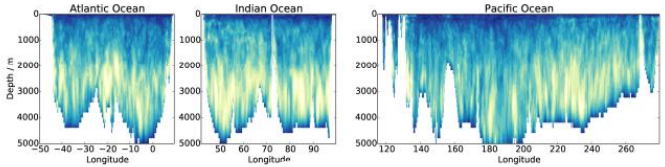
- In Exp-IPC-BPC values are generally reduced in all basins, although some larger values are seen in the western Atlantic.

- The reduction in monthly standard deviation of W is thought to indicate a reduction in shock to the system

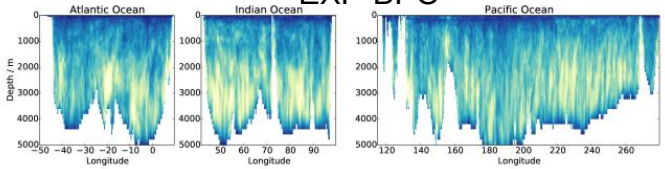
EXP-freerun



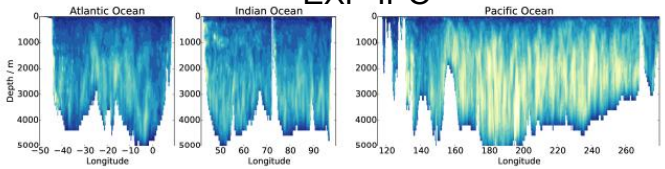
EXP-noPC



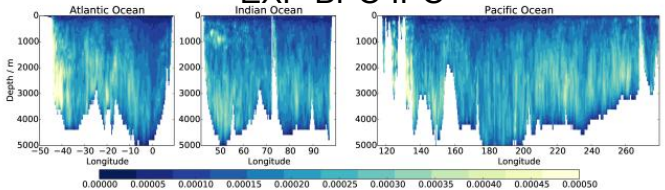
EXP-BPC



EXP-IPC



EXP-BPC-IPC



Equatorial Sections: mean T incs

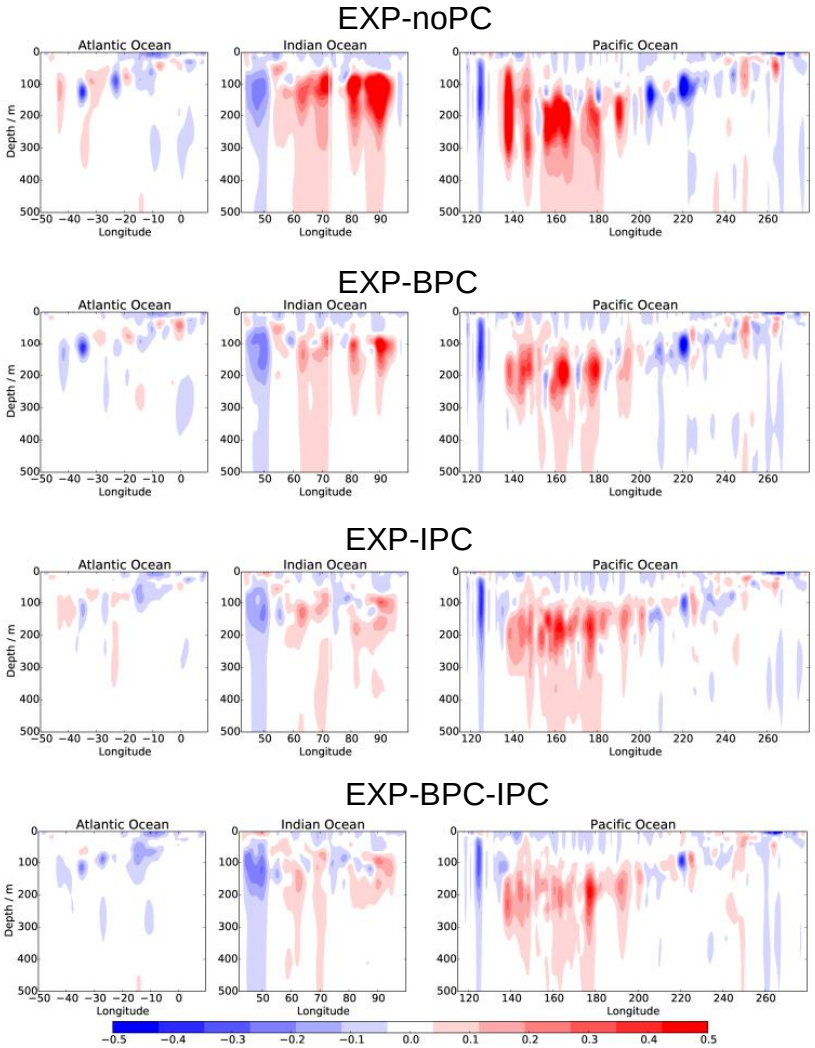
Equatorial sections of monthly mean temperature increments for December 2011.

• In Exp-BPC the magnitude and range of the mean increments are reduced in all basins

• In Exp-IPC the mean increments are further reduced in the Atlantic and Indian Ocean.

• In Exp-IPC-BPC the mean increments are also reduced in the Pacific.

• The reduction in mean temperature increments suggests that increments are being better persisted in the model and that the DA doesn't need to work so hard.



Innovation stats for 2011 period

We have compared the innovation stats from exp-IPC-BPC with the exp-BPC (v12) . The headline results are:

• SSH: RMSE and mean error are the same in both experiments in the tropics.

• Salinity profiles: RMSE degradation of 4% in Tropical pacific, RMSE improvement of 6% in the Tropical Atlantic

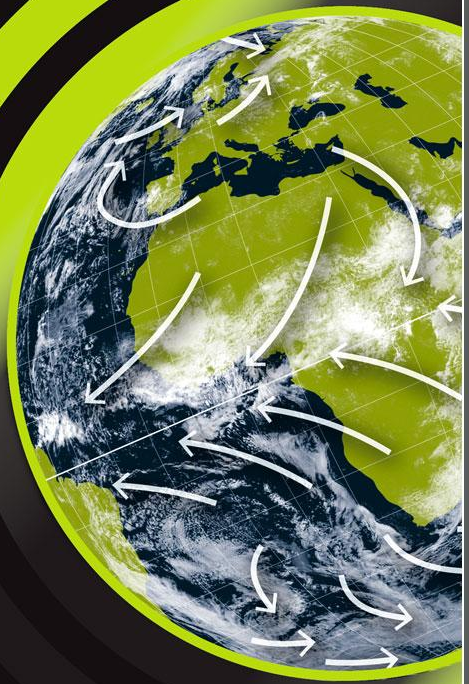
• Temperature profiles: RMSE degradation of 5% in the Tropical Pacific and 2% in the Indian Ocean, RMSE improvement of 17% in the Tropical Atlantic.

Summary

Summary

- We have proposed a new scheme which aims to reduce the shock cause by imbalances between the ocean pressure gradient and the wind stress when data are assimilated.
- The scheme is based on the bias pressure correction of Bell et al. (2004) but it designed to operate on shorter time-scales.
- The scheme has been shown to reduce the initialisation shock in single observation experiments.
- The single observation experiments also suggest that the new scheme improves the persistence of T increments.
- The scheme has been applied along side the bias pressure correction in an 17 month re-analysis experiment.
- The re-analysis results show a dramatic reduction in the monthly standard deviation of W.
- We also see a reduction in mean Temperature increments which supports the idea that the IPC is improving the persistence of the increments.
- The impact on the stats is a bit mixed.

Met Office

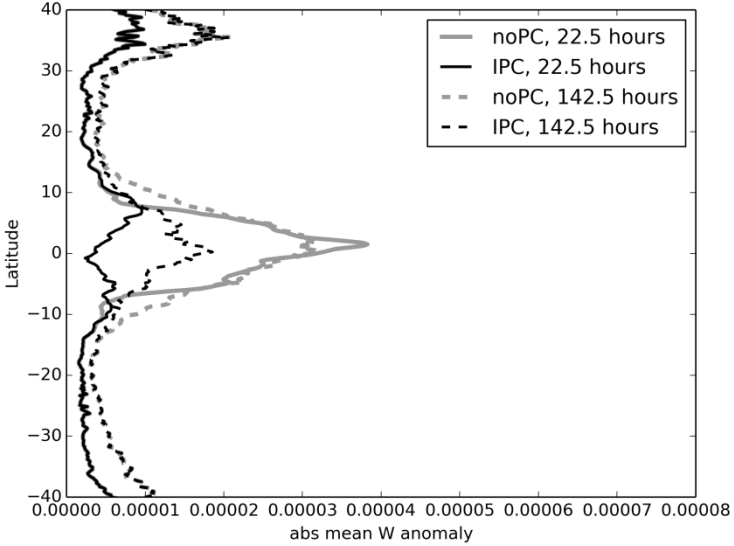


www.metoffice.gov.uk

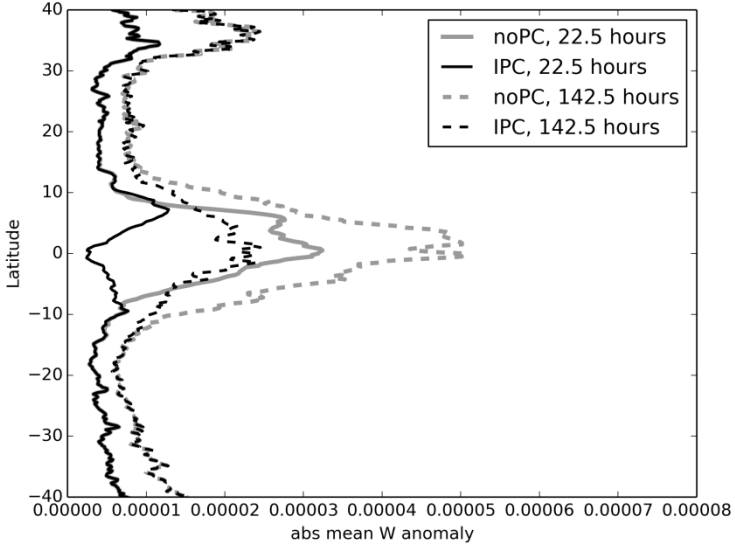
The impact of the IPC for simple forecast experiments cont...

W anomaly field generated when all ocean observations are assimilated. The plots show that zonally averaged absolute W fields as a function of latitude.

Depth 317m



Depth 2345m



Caveat: a different latitudinal ramp has been used in this experiment

Equatorial Sections: mean W

Equatorial sections of monthly mean W for December 2011.

•Some of the large scale biases are removed when the bias pressure correction is applied

• Smaller impact than that documented in Bell et al (2004). Due to general improvements in model bias? They focused more on the near surface.

•The other DA exps look quite similar.

• The Exp-IPC produces the smallest values in the Atlantic, while the Exp-IPC-BPC produces the smallest values in the Indian Ocean.