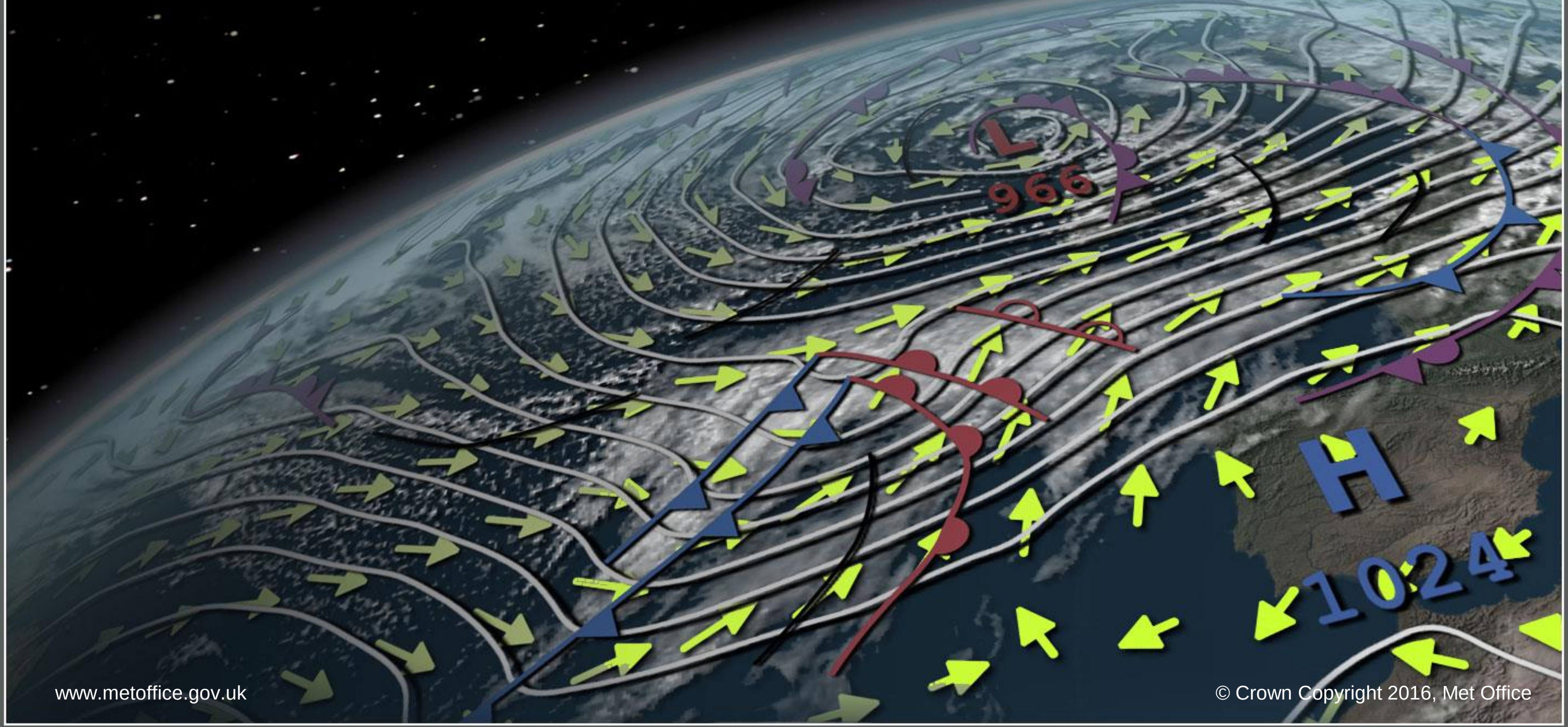
Ocean data assimilation in the tropics

Jennie Waters, Mike Bell and Matt Martin.
Met Office.

ECMWF/ESA Workshop: Tropical modelling, observations and assimilation. 09/11/16



Met Office

Contents

1. Introduction

Introduction

Ocean Forecasting systems

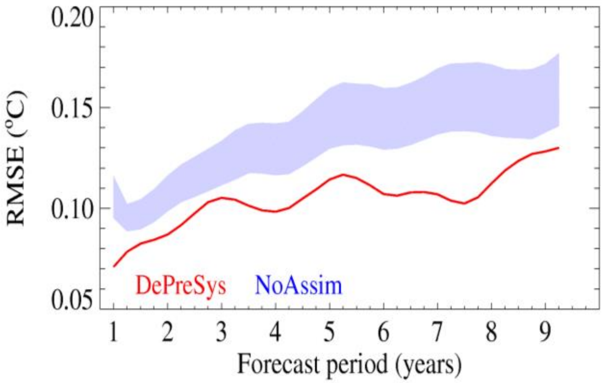
Met Office systems which produce ocean forecasts for different time ranges:

- Forecasting Ocean Assimilation Model (FOAM):
  - Data assimilation and short-range forecasts out to 7-days.
  - coupled ocean-ice model.
  - Global configuration at ¼ degree horizontal resolution, 75 vertical levels.

- Global seasonal coupled forecasting system (GloSea):
  - Uses ocean initial conditions from FOAM.
  - Atmosphere initial conditions from Met Office NWP system.
  - coupled ocean-ice-atmosphere model
  - GloSea is also used to produce a reanalysis which covers the past few decades - coupled ocean-ice only model

- Decadal Prediction System (DePreSys):
  - Currently uses a different method for initialisation.

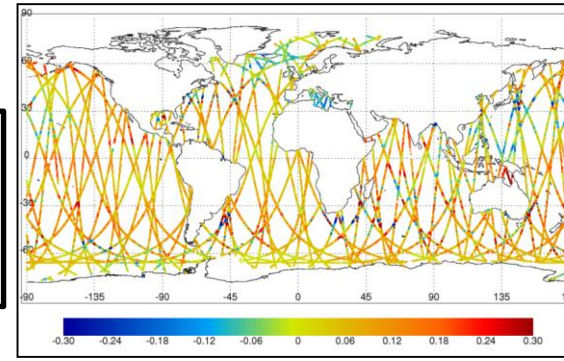
DePreSys initial conditions were shown to affect the prediction throughout 10-year forecasts.
=> Good Initialisation is important for ocean forecasting



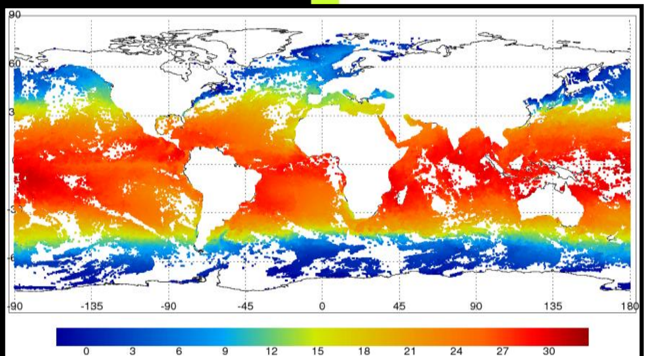
Global annual mean surface temperature (T_S)

Introduction
Assimilated observations

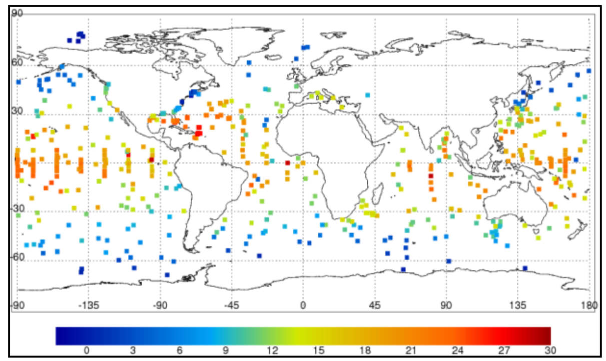
Observations available on one day.



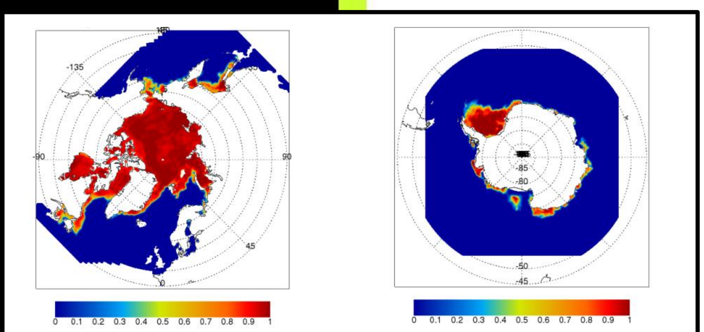
Satellite altimeter SSH data (Jason-2, Jason-3, Cryosat, Altika)



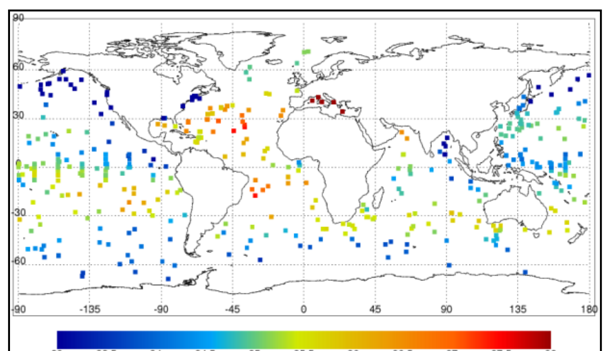
SST data (NOAA/AVHRR, AMSR2/MetOp/insitu)



Temperature profiles (Argo, moored buoys, XBTs, CTDs, marine mammals, gliders)



Satellite sea-ice concentration data (SSMI/S)



Salinity profiles (Argo, moored buoys, CTDs, gliders)

www.metoffice.gov.uk

Met Office

Introduction
Ocean Data Assimilation

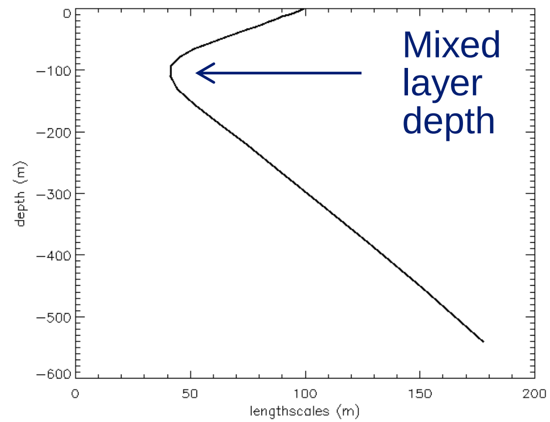
- Uses a multivariate, incremental 3D-VAR, FGAT data assimilation scheme called NEMOVAR
- NEMOVAR is a collaboration between the Met Office, Cerfacs, ECMWF and INRIA
- Features of NEMOVAR:
  - Assimilates Temperature, Salinity, SSH and sea ice concentration
  - Has observation bias correction for SST and altimeter
  - Uses the diffusion operator to model the background error correlations
  - Includes multivariate balance relationships
- At the Met Office we use a 24 hour data assimilation time window. ECMWF use 10 days and Mercator use 7 days.
- Increments are applied using the IAU method over a 1 day model cycle.

Ocean Data assimilation

Background error covariances in NEMOVAR

- We specify the univariate parts of **B** as:
  - a set of error variances (the diagonal elements of **B**).
  - a set of horizontal correlation scales to spread information horizontally.
  - a set of vertical correlation scales to spread information vertically.

Vertical correlation length scales

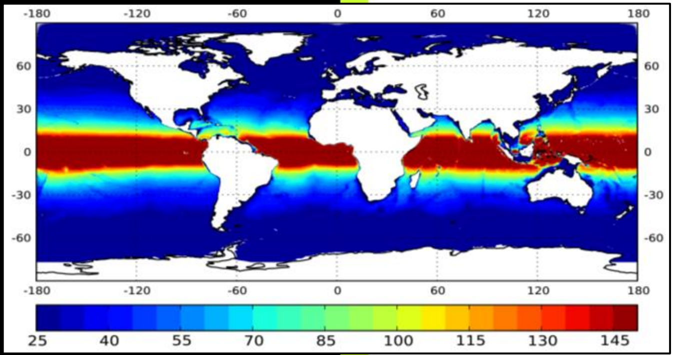


- The multivariate parts of **B** are specified using linearised physical balance relationships:
  - T-S water mass properties from the background model state are used to spread information from T to S.
  - The equation of state is used to estimate density changes from T & S.
  - Hydrostatic balance is used to spread information from density to SSH.
  - Geostrophic balance is used to spread information to velocity.
  - The adjoints of all these relationships are also used so that information is spread the other way.
- Sea ice is currently treated as a totally unbalanced variable (as univariate)
- Velocity observations are not assimilated in NEMOVAR

Met Office

Ocean Data assimilation

Design of the background error covariances



- In FOAM-NEMOVAR the temperature and salinity background error covariances have 2 scales:
  - A mesoscale component with Rossby radius dependent horizontal length-scales.
  - A large-scale component with constant 4 degrees horizontal length-scales.
  - Both horizontal scales uses the same mixed-layer dependent vertical correlation length-scales.
- Unbalanced SSH has a single 4 degree horizontal length-scale

- The dependence of the Rossby radius on 1/f becomes a problem near the equator as f tends to zero. We therefore set a maximum cap for the Rossby radius.
- This maximum cap was chosen from analysis of correlations computed using the NMC method. The results suggested a scale of 150km in both the x and y direction is most appropriate at the equator.
- In ocean data assimilation it's fairly common for the background error covariances at the equator to be specified as anisotropic with longer scales in the x-direction to represent the dominant zonal flow. Our error covariances are isotropic at the equator but we think this relates to our relatively short data assimilation window (24 hours) compared with other centres (e.g 10 days at ECMWF).

Met Office

2. Status of data assimilation in the Tropics.

Data Assimilation in the tropics

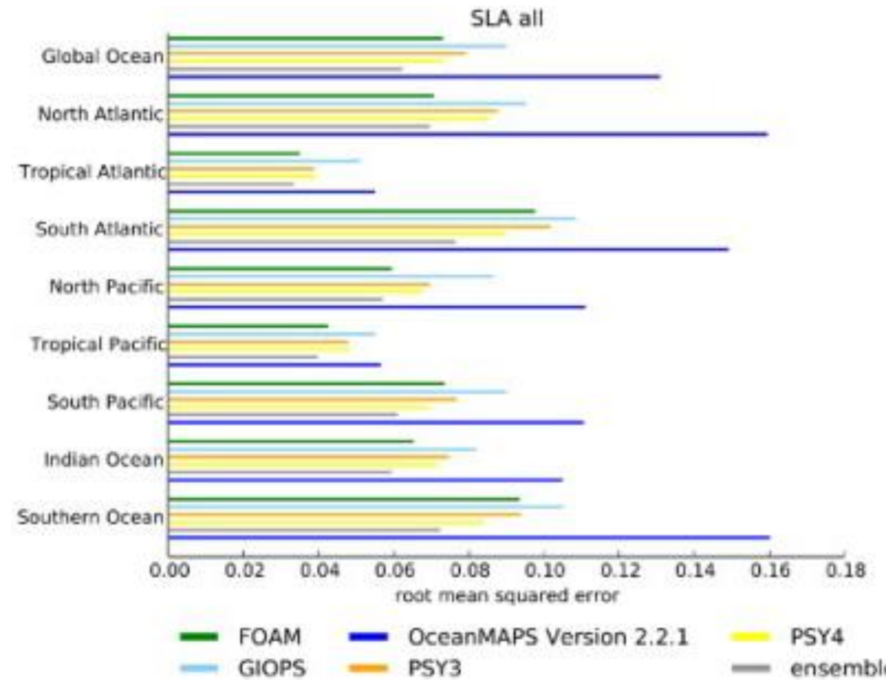
Ocean data assimilation has been demonstrated to give substantial benefits in the tropics, for example:

- More realistic thermocline structure – data assimilation acts to tighten the thermocline (Bell et al; 2004)

- Good simulation of the tropical mixed layer depth in reanalysis systems – important for climate variability studies (Balmaseda et al; 2014).

- Improvements to ENSO predictability (Zheng and Zhu; 2015, Smith et al; 2013, MacLachlan et al; 2014, Schneider et al; 1999)

- Good quality short range forecasts of SST, SLA and subsurface temperature in operational ocean forecasting systems (Ryan et al; 2015)



From Figure 7 from Ryan et al (2015). Bar charts indicating the 12 hour forecast RMSE from different centres, grouped by geographical region.

Data Assimilation in the tropics

While the benefits of data assimilation in the Tropics are demonstrable, there remain some challenges.

•Several studies have found that the vertical structure of the equatorial currents are degraded by data assimilation (Balmaseda et al; 2007, Burgers et al; 2002, Xie and Zhu; 2007)

• Huddelstone et al (2004) found an under-estimation of the surface currents and over-estimation of the equatorial under-current with data assimilation using different wind-stress products.

• Vidard et al (2007) reported some spurious signals in model sea level in the Tropical Atlantic when moored buoys are assimilated

• Bell et al (2004) found unrealistically large monthly mean vertical velocities near 250m depth with data assimilation.

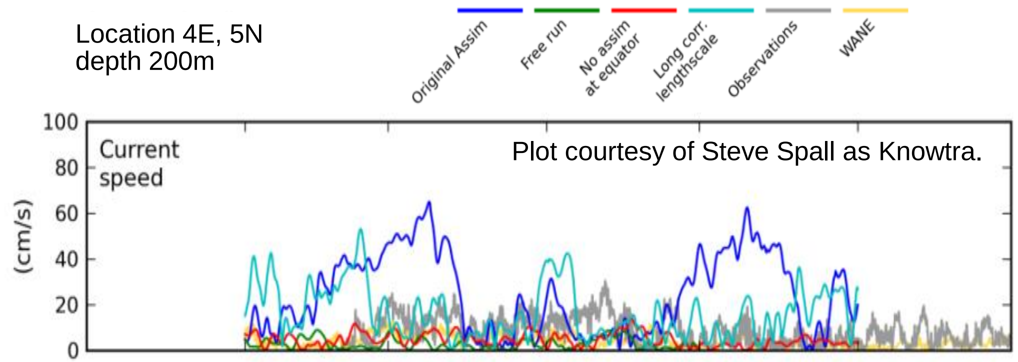
Ocean Data assimilation in the tropics

equatorial currents

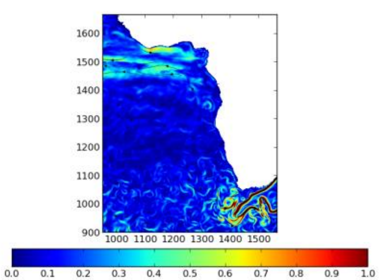
Data assimilation was found to cause spurious currents in a recent 12th of a degree Southern and Equatorial Atlantic model run at the Met Office.

Location 4E, 5N
depth 200m

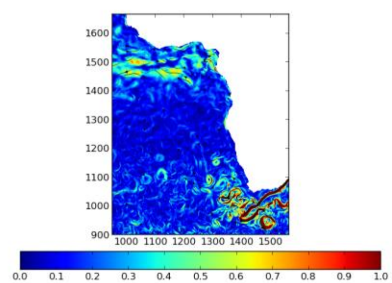
Comparisons of current speeds from a mooring off the coast of Nigeria and 12th of a degree ocean model runs.



Free run



DA run

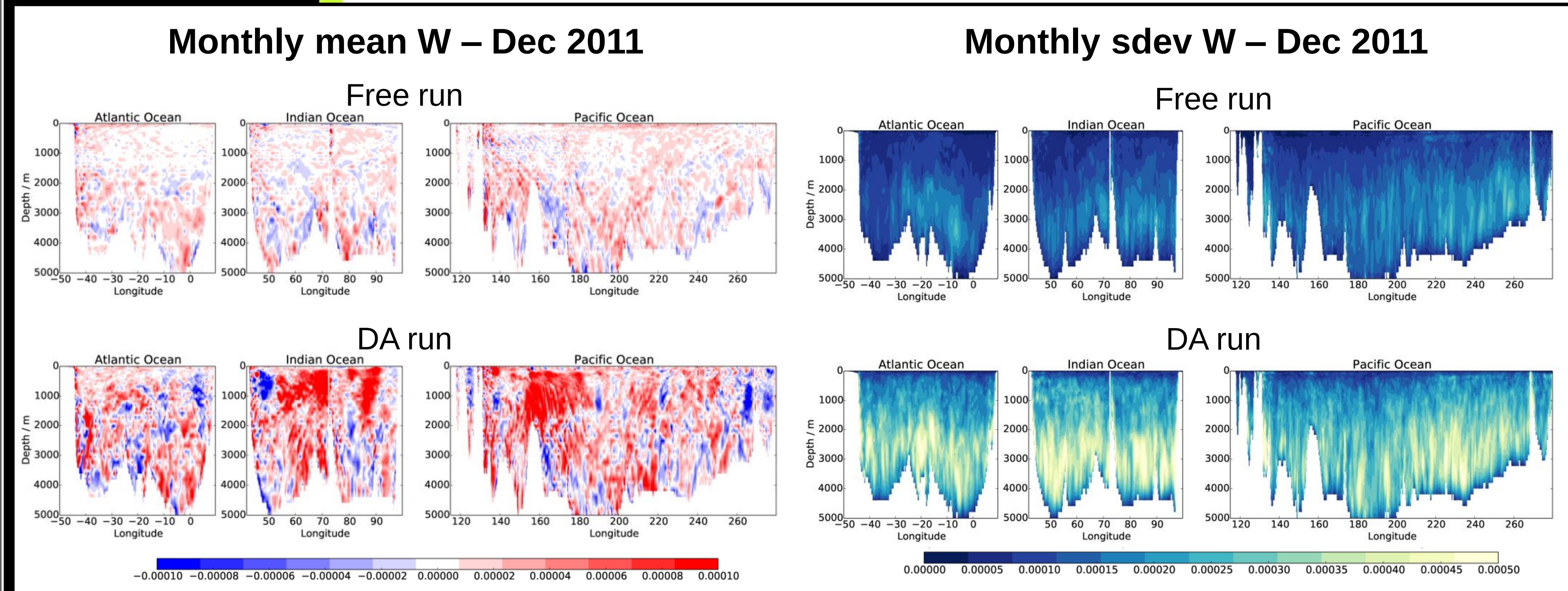


This response seems to be triggered by fairly large (but correct) increments in this region. A similar response was also seen in the FOAM ORCA025 system.

Ocean Data assimilation in the tropics

Vertical velocities

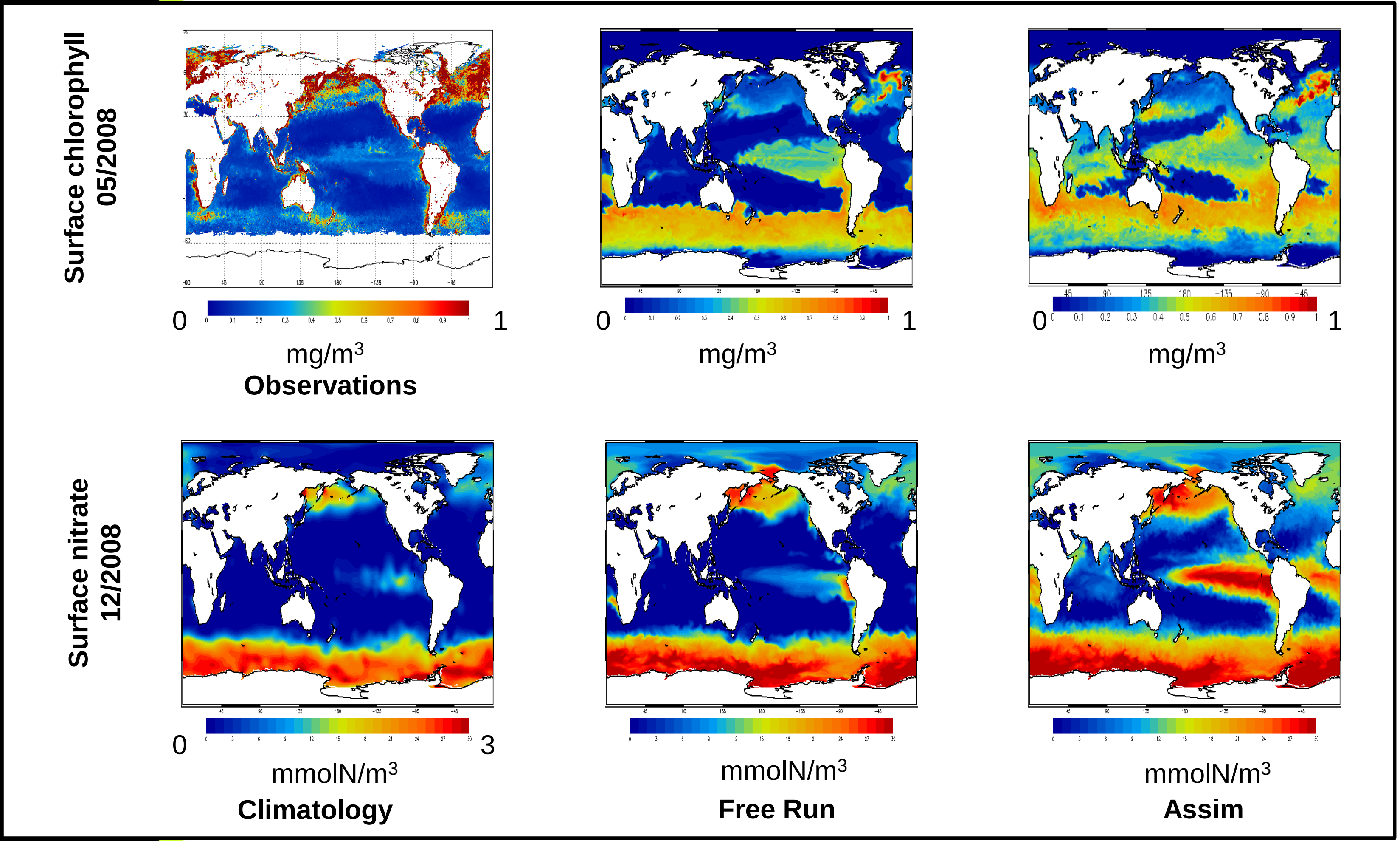
Sections along the equator of the monthly mean/standard deviation of vertical velocities from a free run and a run with data assimilation from a recent version of FOAM.



- Similar results are produced with different DA systems, e.g 4DVAR. Arthur Vidard has looked at applying a digital filter in the 4DVAR cost function with limited success.

Ocean Data assimilation in the tropics

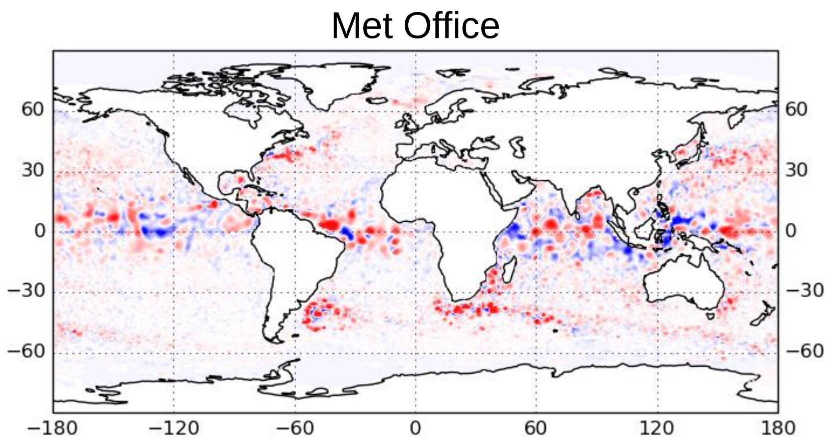
Impact on coupled biogeochemistry models



• David Ford (Met Office) has investigated applying divergence damping to try and reduce this impact. This hasn't resolved the problem.

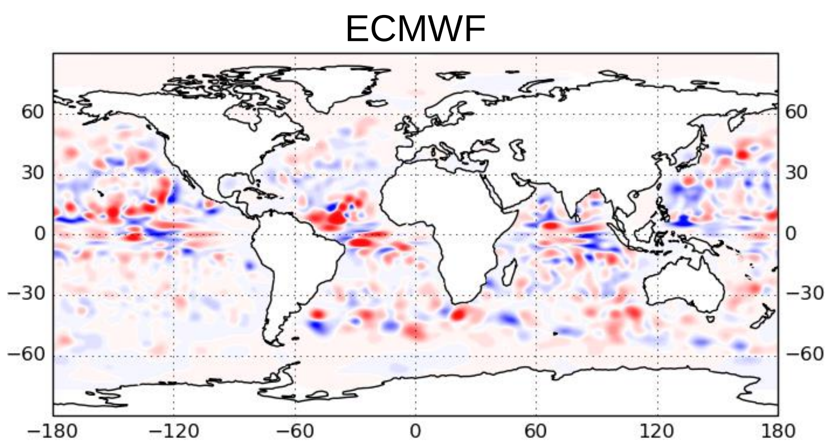
Ocean Data assimilation in the tropics

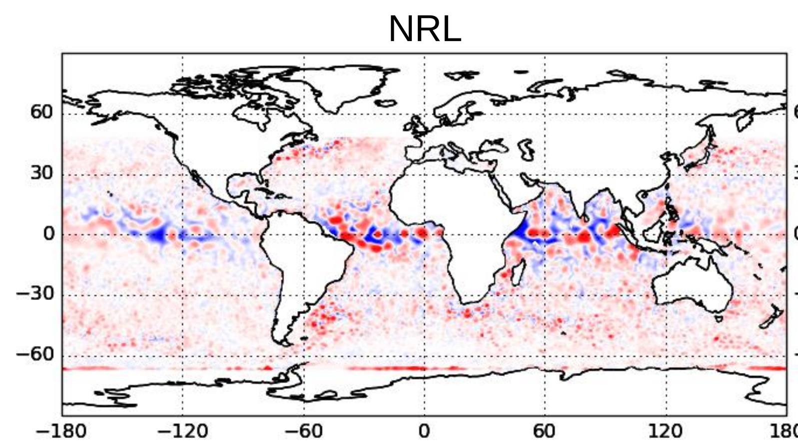
Mean increments



Normalised monthly mean Temperature increments at approx 100m from the Met Office, ECMWF and NRL.

Figures from Figure 6 in Martin et al 2015.





Met Office

3. Balance at the equator.

Ocean Data assimilation in the tropics

Introduction

- The degradation of model circulation in the tropics with data assimilation has generally been attributed to a lack of balance in the data assimilation increments at the equator.

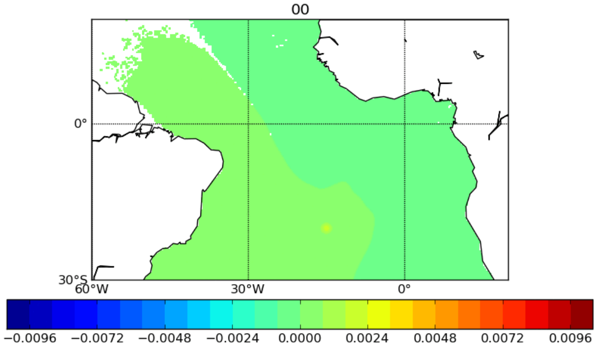
- Bell et al (2004) found that data assimilation was warming/cooling the ocean model by up to 3 degrees a month in the tropics. They argued that this implies poor dynamical balance at the equator when increments are applied.

- Away from the equator geostrophic balance is used to produce dynamically balanced velocity increments.

- Close to the equator this relationship is no longer appropriate (again due to the dependency on 1/f).

- What schemes are available to improve data assimilation at the equator?

Response of the model to an increment



SSH anomaly fields generated when an SSH innovation of 10cm is assimilated.

Ocean Data assimilation in the tropics

Geostrophic balance at the equator

- A specific equatorial velocity balancing scheme is available in NEMOVAR.

- Following Burgers et al (2002) a beta-plane (f=beta y) approximation is used to generate geostrophically balanced zonal velocities at the equator, while the balanced meridional velocities are reduce to zero.

- In the beta-plane approximation, the zonal velocities are proportional to the second order horizontal derivatives of the pressure, divided by beta.

- Either a Gaussian weighting function (Lagerloef et al.(1999).) or a linear weighting function is used to transition between the f-plane and beta-plane balance.

- This equatorial balance has been successfully applied in lower resolution simulations, however, we have found that the dependency on the second order pressure gradients makes this scheme very sensitive in eddy resolving models. The resulting balanced increments at the equator tend to be very large.

- We apply normal geostrophic balance outside of the equator, this is ramped down between 5 and 1 degrees from the equator. No geostrophic balance is applied in FOAM within 1 degree of the equator.

Ocean Data assimilation in the tropics

Balance with the wind stress at the equator

• Additionally we can consider the dominant balance between the ocean pressure gradient and the applied wind stress at the equator.

• Assimilating observations at the equator changes the ocean pressure gradients.

• The wind and ocean are no longer in balance.

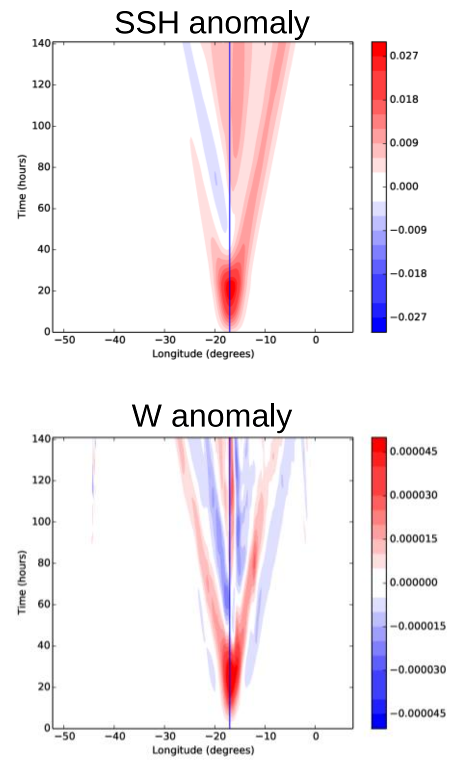
• This imbalance is broadly analogous with the ocean's response to a Westerly Wind Burst event, i.e a sudden change in the equatorial winds causes dynamical imbalance with the ocean pressure gradients.

• The ocean responds by triggering equatorial waves.

• The impact of spurious equatorial waves could persist over long timescales.

E.g Liu et al (2016) demonstrated that initialisation shocks at the equator can generate pseudo ENSO events.

Response of the model to an increment



Anomaly fields generated when an SSH innovation of 10cm is assimilated at the equator.

www.metoffice.gov.uk

Ocean Data assimilation in the tropics

A bias pressure correction scheme

• The bias pressure correction scheme (Bell et al, 2004; Balmaseda et al 2007) attempts to correct for long term biases in the wind stress and the way the wind stress is applied in the model.

• The scheme aims to improve the performance of assimilative models at the equator by reducing the impact of systematic model biases and therefore reducing the work done by the data assimilation

• A bias pressure correction term is calculated by gradually accumulating temperature and salinity increments over many months and converting these to a pressure correction using the equation of state and hydrostatic equation. This bias pressure correction is then applied in the model's equations of motion. This correction removes the imbalance associated with the bias.

• The scheme is designed to be equivalent to removing a bias in the applied wind stress in the model's equations. We don't want to directly correct the forcing winds as they are unlikely to be the main source of the bias. The bias is more likely associated with the way the winds are applied in the ocean model.

• The bias pressure correction scheme is applied operationally at both the Met Office and ECMWF and has previously been demonstrated to reduce mean vertical velocities.

Ocean Data assimilation in the tropics

The incremental pressure correction (IPC) scheme

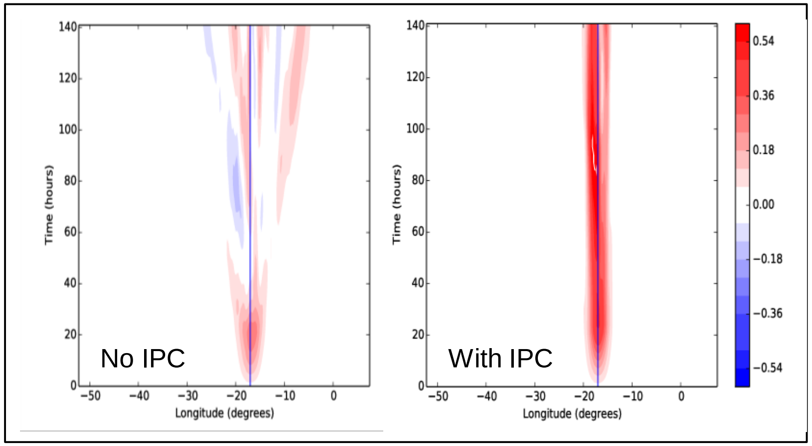
Met Office

- The bias pressure correction aims to reduce the impact of slowly varying biases, Can we also balance the ocean increments in the IAU and reduce initialisation shock?

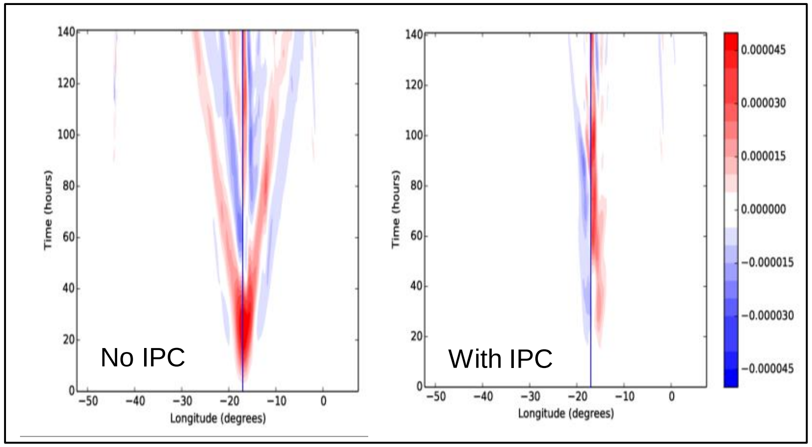
- The Incremental pressure correction scheme (Waters et al; 2016) is based on the bias pressure correction, but aims to reduce imbalances over shorter time scales. It can be thought of as an extension of the bias scheme to a second time scale.

- The pressure correction field in the IPC scheme is calculated from the temperature and salinity increments from the current assimilation step, plus a historical component which is decayed with a 10 day time-scale.

Temperature anomaly



W anomaly



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

Met Office

Ocean Data assimilation in the tropics

Parameter tuning for the pressure correction schemes

- Both in bias and incremental pressure correction schemes have 2 key tuneable parameters: γ which determines what proportion of the increments are used to update the pressure correction on each cycle and α which determines the decay rate of the pressure correction.

- Bias pressure correction: γ_β=0.1, α_β=0.008 which is equivalent to an decay timescale of 125 days.

- Incremental pressure correction: γ_I=0.8, α_I=0.1 which is equivalent to an decay timescale of 10 days.

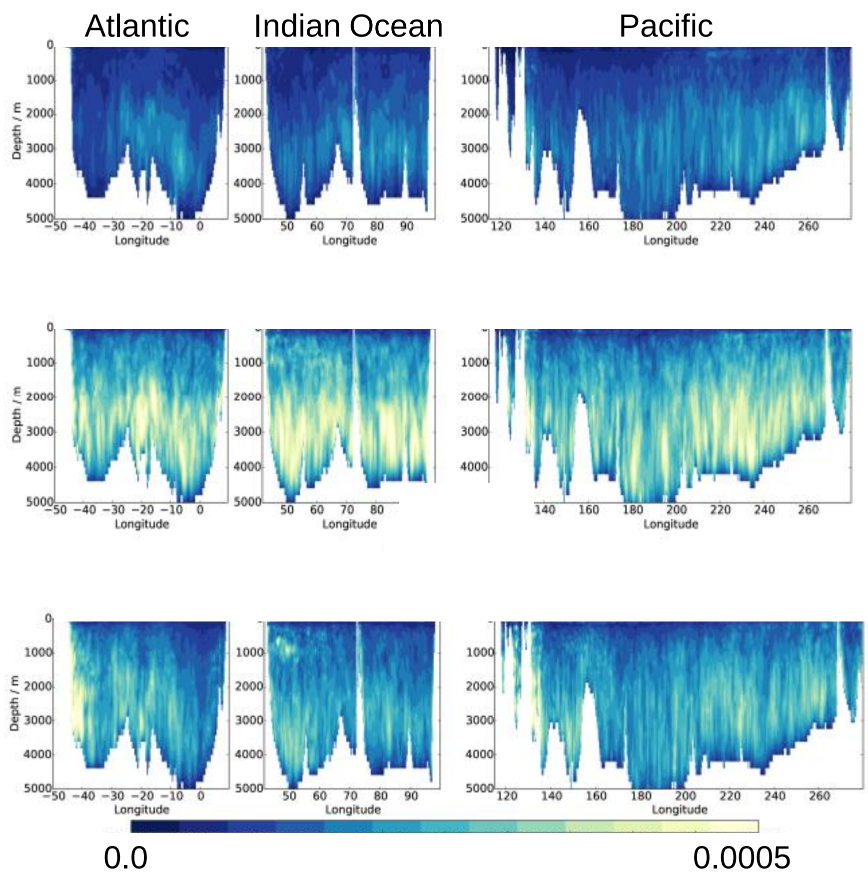
- An investigation of the energetics of the errors for the bias and incremental pressure correction scheme found that the condition $\gamma_\beta+\gamma_I<1$ should be satisfied to ensure that the error is reduced by data assimilation.

- We may need to tune the respective weights of the bias and incremental pressure correction schemes. These parameters might be different for difference basins.

Ocean Data assimilation in the tropics

Impact of pressure correction on vertical velocities

Sections along the equator of the monthly standard deviation of vertical velocities.



Free run

No pressure correction

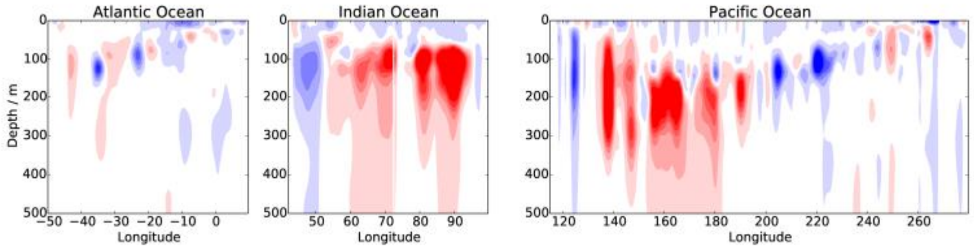
Both the bias pressure correction and Incremental pressure correction applied.

www.metoffice.gov.uk

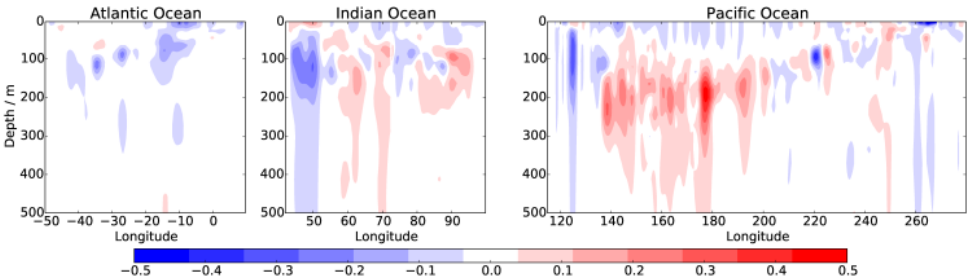
Ocean Data assimilation in the tropics

Impact of pressure correction on mean increments

Sections along the equator of the monthly mean temperature increments.



No pressure correction



Both the bias pressure correction and Incremental pressure correction applied.

4. Conclusion and Future work.

Met Office

Conclusions

- For standard ocean metrics (e.g Temperature, SSH and SST) ocean data assimilation performs well in the tropics.

- However, data assimilation can lead to the degradation of circulation in the tropics.

- High quality forecasts and hindcasts of ocean current are in high demand for commercial applications e.g oil and gas industry.

- The impact of ocean data assimilation on coupled biogeochemistry models is also very important.

- The new incremental pressure correction is being tested for operational implementation at the Met Office.

- The scheme reduces initialisation shock and improves retention of increments at the equator

- Early results suggest that it slows down the development of unrealistic chlorophyll in coupled biogeochemistry models, but doesn’t completely solve the issue.

Met Office

Other options for improving equatorial DA

• Reducing the observation weight (e.g increase observation errors). There is some indication that we may be over fitting observations in the tropics.

• The new version of NEMOVAR produces smoother increments near coasts and island. The beta plane geostrophic balance may perform better for this version of NEMOVAR.

• Coupled data assimilation? We have a weakly coupled data assimilation system at the Met Office. We haven't yet performed a detailed assessment of equatorial circulation. The equatorial imbalance could be an additional problem for strongly coupled DA. We wouldn't want to make corrections to the atmosphere winds to compensate for an error in the way the winds are applied in the ocean model!

• Developing a hybrid 3D-VAR-ensemble data assimilation system at Met Office. Ensemble could be useful for assessing multivariate relationships in the tropics.

References

Balmaseda et al; 2007, A multivariate treatment of bias for sequential data assimiltion: Application to the tropical oceans. QJRMS

Balmaseda et al; 2014,The Ocean Reanalyses Intercomparison Project (ORA-IP) . Journal of operational oceanography

Bell et al; 2004, Assimilation of data into an ocean model with systematic errors near the equator. QJRMS

Burgers et al; 2002, Balanced ocean data assimilation near the equator. American Meteorological Society.

Huddelston et al; 2004, Assessment of wind-stress errors using bias corrected ocean data assimilation. QJRMS

Lagerloef et al; 1999,Tropical Pacific near-surface currents estimated from altimeter, wind and drifter data .Journal of Geophysical Research.

Liu et al; 2016, Impact of in-consistency between the climate model and its initial conditions on climate prediction. Climate Dynamics.

MacLachlan et al; 2014, Global Seasonal forecast system version 5 (GloSea5): a high-resolution seasonal forecast system. QJRMS.

Ryan et al; 2015, GODAE OceanView Class 4 forecast verification framework: global ocean inter-comparison. Journal of Operational Oceanography.

Schneider et al; 1999, Ocean Data Assimilation, Initialization, and Predictions of ENSO with a Coupled GCM. Monthly weather review.

Smith et al; 2013, A comparison of full-field and anomaly initialization for seasonal to decadal climate prediction. Climate Dynamics.

Vidard et al; 2007, Impact of ocean observing systems on ocean analysis and seasonal forecasts. American Meteorological Society.

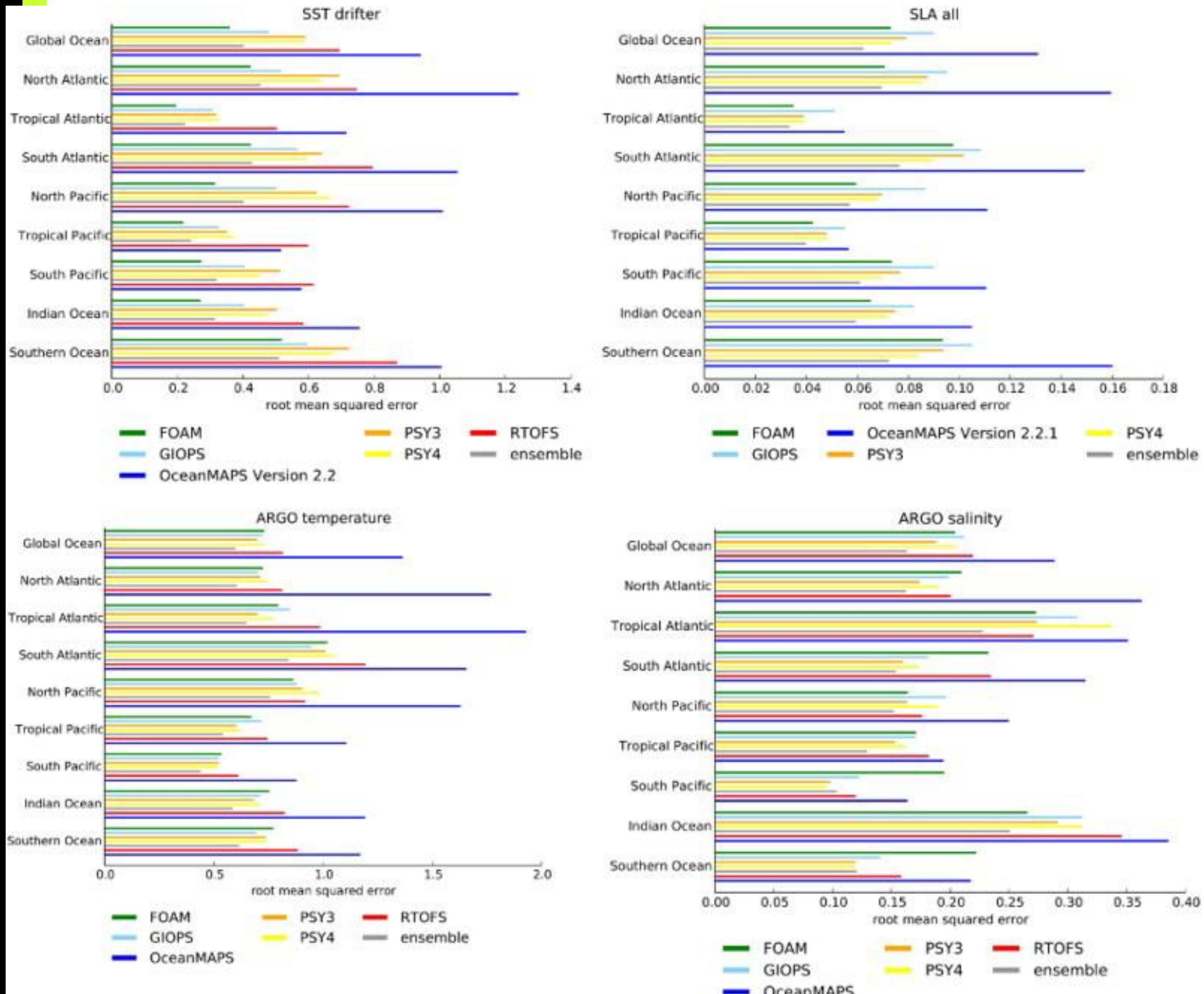
Waters et al; 2016, Reducing ocean model imbalances in the equatorial region caused by data assimilation. Accepted by QJRMS.

Xie and Zhu; 2007, Ensemble optimal interpolation schemes for assimilating argo profiles into a hybrid coordinate ocean model. Journal of Geophysical Research, Oceans.

Zheng and Zhu; 2015, Roles of initial ocean surface and subsurface states on successfullypredicting 2006–2007 El Niño with an intermediate coupled model. Ocean Science.

Met Office

Met Office



SST drifter
Global Ocean
North Atlantic
Tropical Atlantic
South Atlantic
North Pacific
Tropical Pacific
South Pacific
Indian Ocean
Southern Ocean
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
root mean squared error
FOAM
GIOPS
OceanMAPS Version 2.2
PSY3
PSY4
RTOFS
ensemble
SLA all
Global Ocean
North Atlantic
Tropical Atlantic
South Atlantic
North Pacific
Tropical Pacific
South Pacific
Indian Ocean
Southern Ocean
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18
root mean squared error
FOAM
GIOPS
OceanMAPS Version 2.2.1
PSY3
PSY4
ensemble
ARGO temperature
Global Ocean
North Atlantic
Tropical Atlantic
South Atlantic
North Pacific
Tropical Pacific
South Pacific
Indian Ocean
Southern Ocean
0.0 0.5 1.0 1.5 2.0
root mean squared error
FOAM
GIOPS
OceanMAPS
PSY3
PSY4
RTOFS
ensemble
ARGO salinity
Global Ocean
North Atlantic
Tropical Atlantic
South Atlantic
North Pacific
Tropical Pacific
South Pacific
Indian Ocean
Southern Ocean
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
root mean squared error
FOAM
GIOPS
OceanMAPS
PSY3
PSY4
RTOFS
ensemble