Met Office

Assimilation of SST data in the FOAM ocean forecasting system

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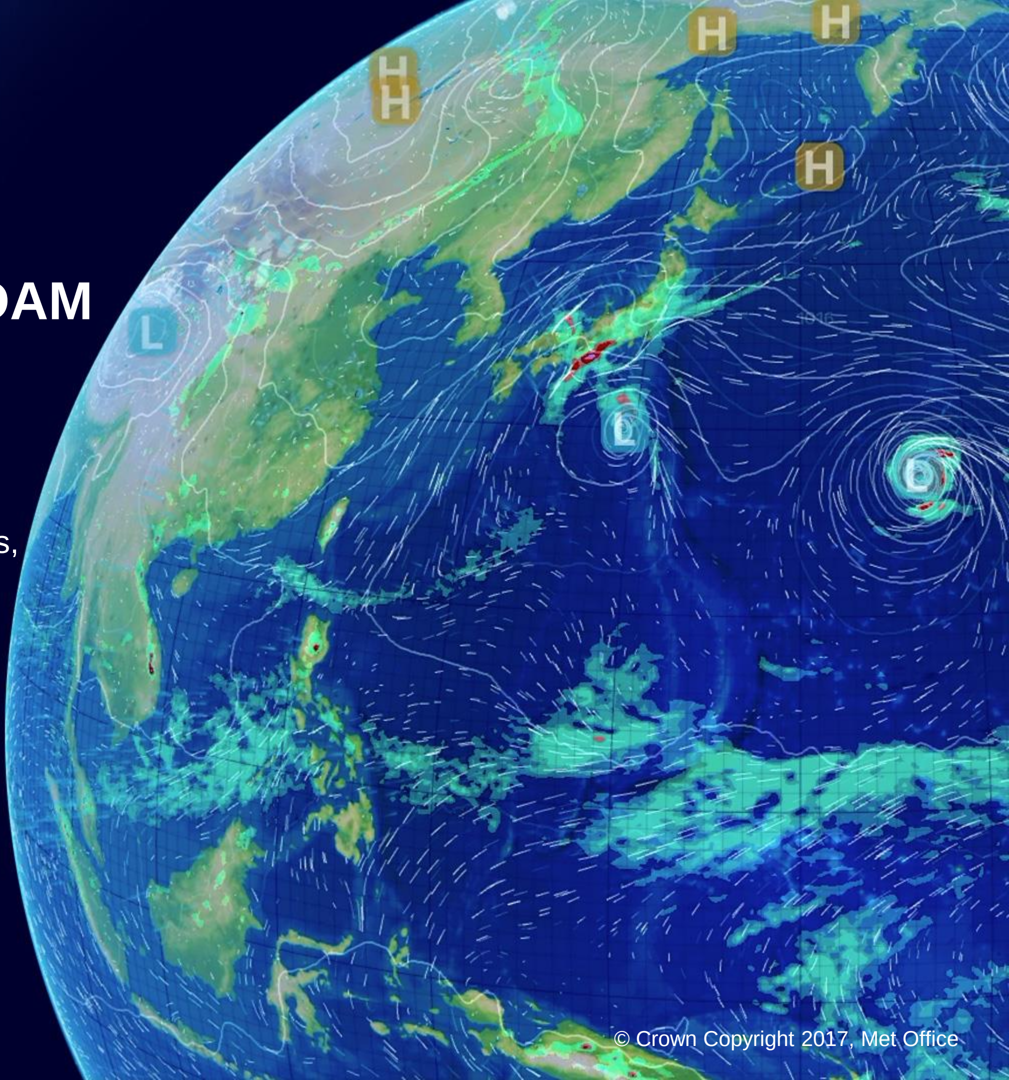
Workshop on SST and Sea Ice analysis and forecast

ECMWF, 22-25th January 2018.



Contents

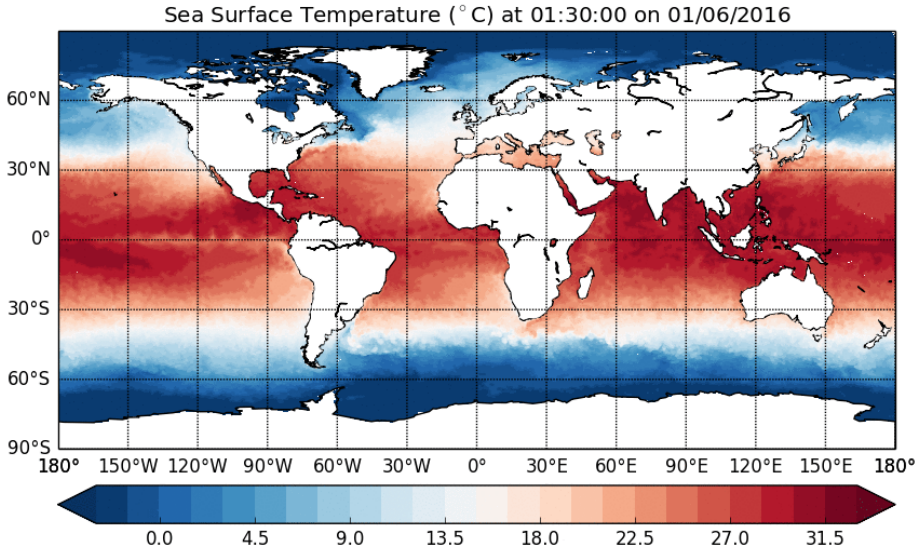
- Introduction and description of data assimilation in FOAM using NEMOVAR
- Improving the bias correction of L2 satellite SST data
- Vertical propagation of SST information
- Conclusions and future work

Introduction

Introduction

- Met Office's operational **ocean forecasting** system: Forecasting Ocean Assimilation Model (FOAM). (Focus here on FOAM v14 which is planned to be operational later this year)
- FOAM also provides the initial ocean conditions for coupled **seasonal forecasts** using GloSea.

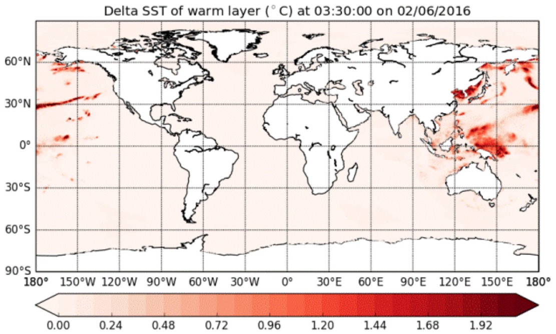
- The FOAM system is used to produce **global reanalysis** of the altimeter period (1993 – present) for GloSea re-forecast initialisation.
- The same set-up as FOAM is used as the ocean component of the Met Office operational **weakly coupled data assimilation** system (WCDA).
- The only difference in the ocean DA is the time-window in WCDA is **6 hours** whereas FOAM is **24 hours**. The WCDA system provides ocean forecasts to CMEMS.

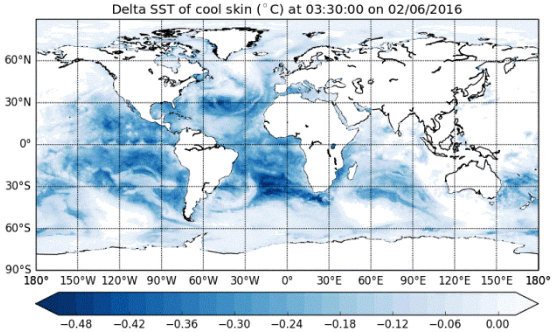


Introduction
Ocean and sea-ice model

- Global (1/4°), basin-scale (1/12°) and shelf-seas (~7km) configurations.
- Global configuration with 75 vertical levels with ~1m resolution in the top 10m.
- Ocean and sea-ice model:
    - NEMO vn3.6: TKE vertical mixing scheme. Non-linear free surface.
    - CICE vn5: 5 thickness categories, multi-layer thermodynamics.

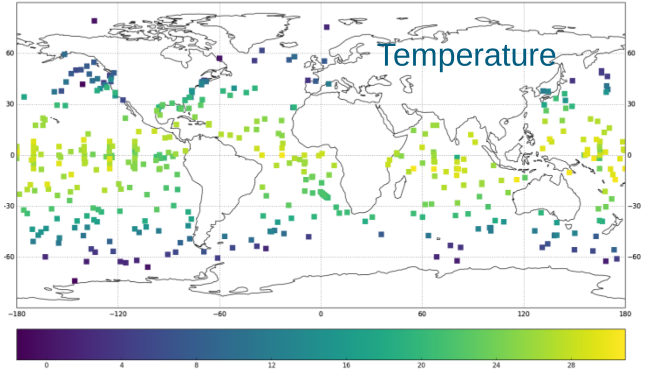
- Surface atmospheric forcing:
    - In near-real time: forced by Met Office NWP surface atmospheric fields with 3-hour frequency (and 1-hour frequency for the winds).
    - For reanalysis, forced by ERA-Interim surface forcing.
- Additional skin model (described in While et al.) to provide skin SST estimates to the Royal Navy.

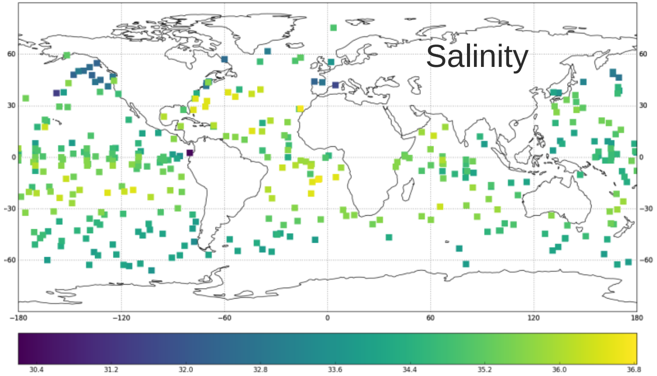


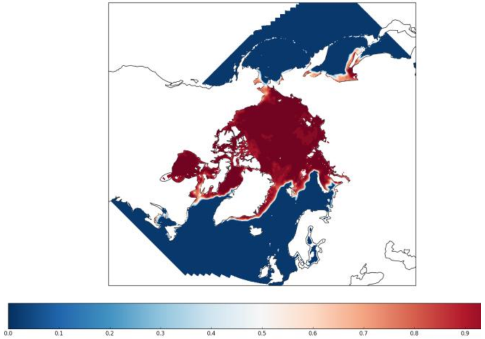


1 day of observations assimilated on 6th Jan 2018

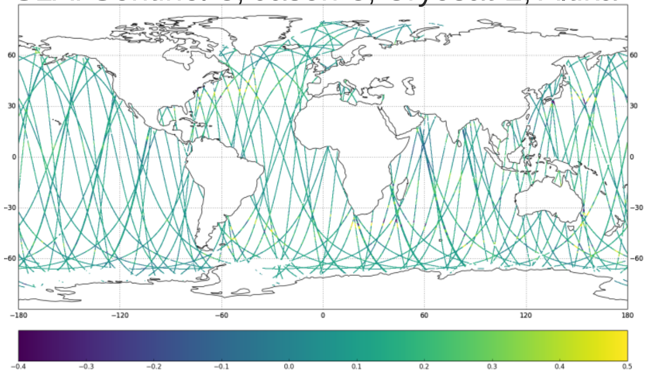
Profiles: Argo, moored buoys, gliders, marine mammals, XBTs

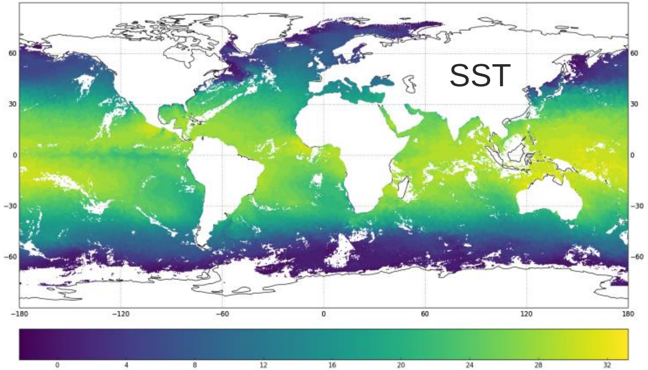




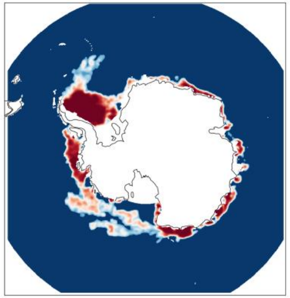


SLA: Sentinel-3, Jason-3, Cryosat-2, Altika





Sea-ice concentration: SSMIS (OSI-SAF)



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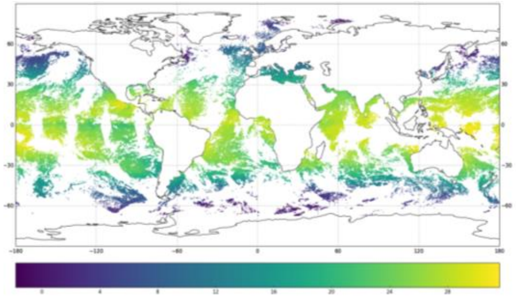
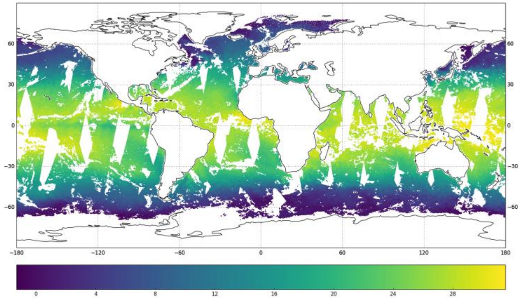
1 day of SST L2p observations assimilated on 6th Jan 2018

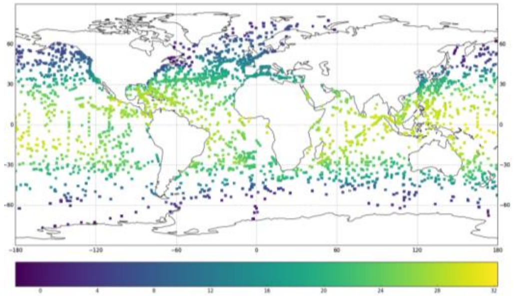
NOAA AVHRR

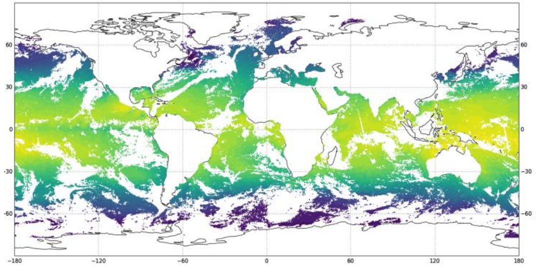


AMSR2

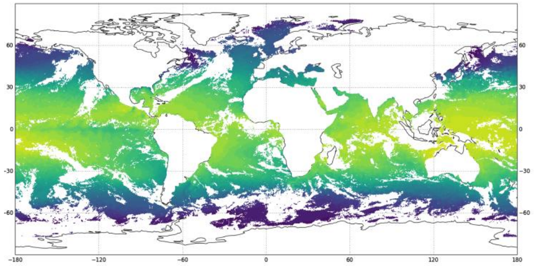


In situ SST: ships, drifters, moored buoys





MetOp AVHRR

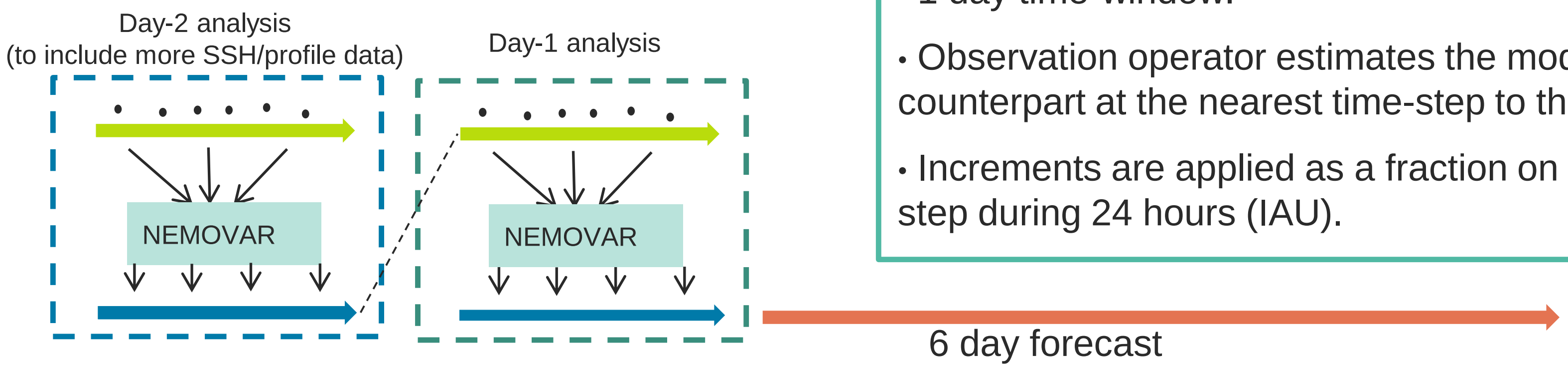


VIIRS

- Satellite data are super-obbed (averaged) with 13km radius.
- QC includes background check using 1-day f/c, and diurnal check (obs valid during the day-time with wind speed < 6m/s are rejected).
- Aim to use these data to adjust the foundation SST and leave the model’s diurnal cycle to evolve.

Assimilation scheme: overview

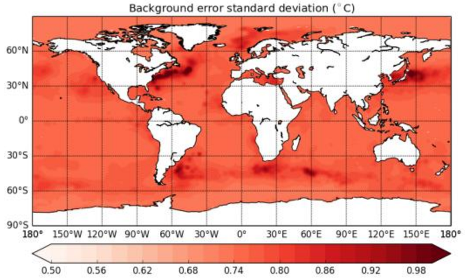
- Data assimilation using the NEMOVAR scheme, developed jointly by CERFACS, ECMWF, INRIA and the Met Office. 3DVar-FGAT scheme.
- Multi-variate relationships specified using linearised physically-based balance below the mixed layer. No multi-variate balance specified in the mixed layer.
- Observation bias correction: SST bias correction to calibrate the L2p SST data from each satellite. SSH bias correction to account for errors in the mean dynamic topography.
- Model bias correction: In the tropics, a pressure correction is applied to reduce the impact of model bias on vertical motions.



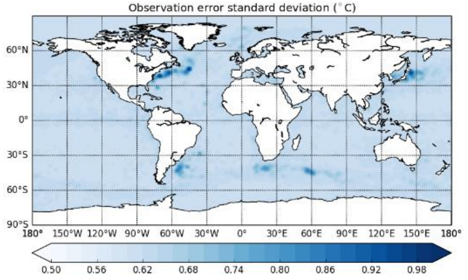
- 1 day time-window.
- Observation operator estimates the model counterpart at the nearest time-step to the obs.
- Increments are applied as a fraction on each time-step during 24 hours (IAU).

Assimilation scheme: temperature error variances

- Total background error variances specified as:
  - Spatially and seasonally varying values at the surface,
  - A minimum value is defined as a function of depth starting at the surface value, and decaying with depth.
  - The actual value is then specified proportional to the local background dT/dz at each level, where that is bigger than the minimum value.
  - Values at the surface estimated from outputs of a previous reanalysis (based on combination of innovations and differences between f/cs of different lengths).



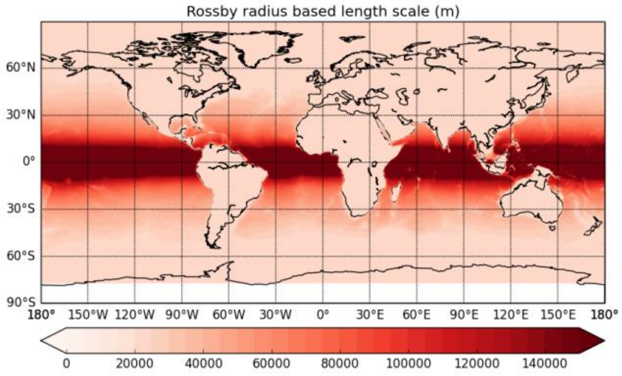
- Observation error variances specified also based on outputs of previous renalaysis. Combination of measurement and representativity errors.
- Spatially and seasonally varying estimates.
- Capability to use the measurement errors from GHRSST, but currently not used in global FOAM.



Assimilation scheme: horizontal covariances

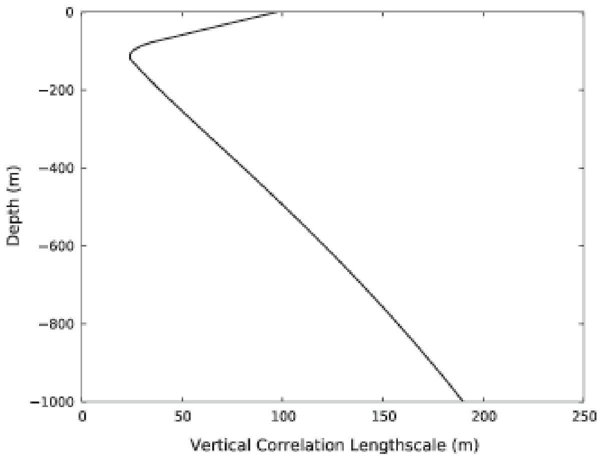
- Horizontal covariances represented as combination of two Gaussian functions, each with their own variance and length-scale.
  - Modelled using 2D implicit diffusion equation which is efficient to run, but need to estimate the re-normalisation factors which is expensive – they depend on the length-scales.
  - If length-scales vary in time then normalisation factors need to be recalculated every cycle which is very expensive.

- Horizontal length-scales specified as: (i) Rossby radius (with min/max as 25km/150km) and (ii) 400km.
- Variances associated with each length-scale are spatially varying, so the effective length-scale of the combined function also varies due to the ratio of the two variances, without the need to recalculate the normalisation factors.



Assimilation scheme: vertical aspects

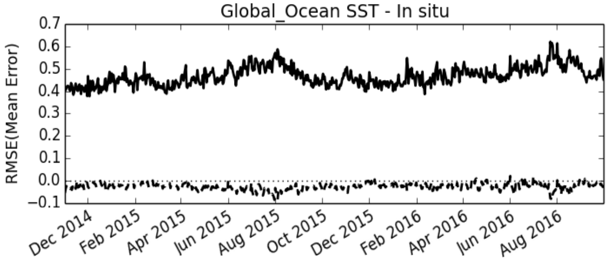
- Vertical correlations represented as a Gaussian function with specified length-scales, and modelled using the diffusion equation.
- Flow-dependent vertical length-scales (L) specified based on the background MLD for the current assimilation cycle.
    - At the surface, L=MLD
    - At the base of the mixed-layer and below, L=2 x dz
    - L varies smoothly between the surface and base of the mixed-layer.

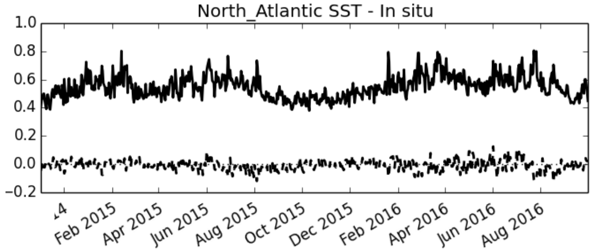


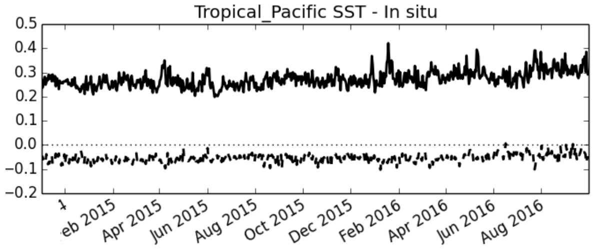
- To avoid recalculating the (3D) normalisation factors every cycle, we generate a look-up table (LUT) of normalisation factors:
    - one 3D field of normalisation factors for a set of discrete MLDs based on the top 42 model levels (<600m depth) in orca025.
    - when running, the current background MLD at a particular location is calculated and a vertical profile of the normalisation factors associated with that value are read from the LUT for that horizontal location.

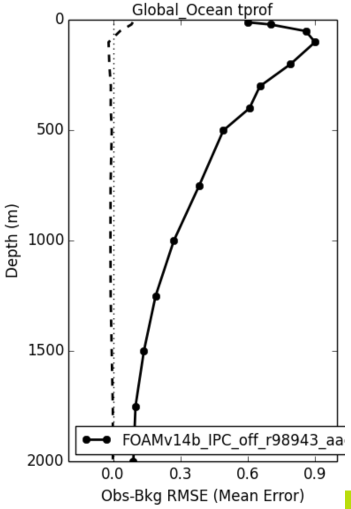
Assessment of SST accuracy

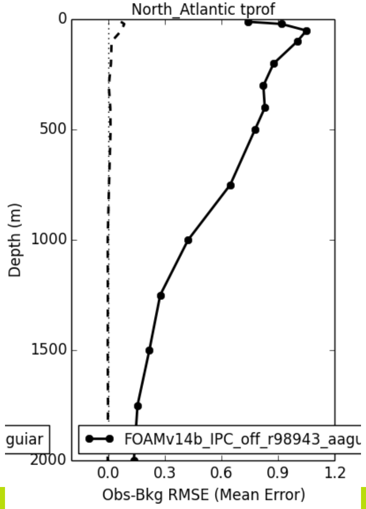
FOAM v14 innovation (observation-minus-background) statistics

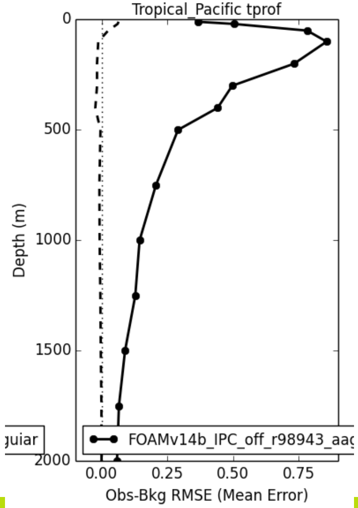












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SST bias correction

SST bias correction

- Satellite SST retrievals contain biases, and so the assimilation of numerous different SST data-sets requires satellite-specific bias correction (inter-calibration).

- Previously the Met Office has corrected for biases 'offline' by trying to minimise differences between co-located biased observations and assumed 'unbiased' reference observations (drifting buoys, some satellite data)
    - This scheme is dependent upon the presence of reference observations, and will be poor in time-periods and regions lacking in these data.

- We have developed a new variational bias correction scheme that is less dependent on reference data, but can make good use of such data when it is available.

- Reference data are used by differencing them with 'biased' data to generate Observations-of-bias. These observations-of-bias are then included as part of the data assimilation.

Met Office

Bias correction System

theory

J:- cost
x:- state vector
y:- observations
b:- observation bias
c:- model bias
k:- matchups
B:- background error covariance
S:- model bias error covariance
O:- observation bias error covariance
L:- matchup error covariance
$\mathbf{H}_y$:- observation operator for observations
$\mathbf{H}_k$:- observation operator for matchups

Our scheme is a variational method where biases are calculated within the assimilation itself.

Specifically we aim to minimise the function:

$$J = (\mathbf{x} - (\mathbf{x}^{\mathrm{f}} - \mathbf{c}))^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - (\mathbf{x}^{\mathrm{f}} - \mathbf{c})) + (\mathbf{c} - \mathbf{c}^{\mathrm{f}})^{\mathrm{T}}\mathbf{S}^{-1}(\mathbf{c} - \mathbf{c}^{\mathrm{f}})$$
$$+ (\mathbf{b} - \mathbf{b}^{\mathrm{f}})^{\mathrm{T}}\mathbf{O}^{-1}(\mathbf{b} - \mathbf{b}^{\mathrm{f}}) + (\mathbf{y} - H_y(\mathbf{x} + \mathbf{b}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y} - H_y(\mathbf{x} + \mathbf{b}))$$
$$+ (\mathbf{k} - H_k(\mathbf{b}))^{\mathrm{T}}\mathbf{L}^{-1}(\mathbf{k} - H_k(\mathbf{b}))$$

Bias correction System

Experimental tests

The bias correction scheme has been tested by running 4 experiments over a 3 year period (2008-2010):

1. No-bias: A run without any bias correction.
2. ObsOnlyBias: A run using an offline bias correction using only observations-of-bias (similar to the old Met Office system)
3. VarOnlyBias: A run using a pure variational bias correction method (i.e. no observations-of-bias)
4. ObsVarBias: A run with the new varational system with observations-of-bias.

All experiments used the same data; however, if an observation was used to calculate an observation-of-bias, it was not assimilated directly.

• SST data assimilated: In situ (HadIOD); ESA CCI data: AATSR, NOAA AVHRR 18 and 19, MetOp-A AVHRR; RSS AMSRE.

• All other standard FOAM data-sets also assimilated.

2008

- All satellite data available.
- 90% drifting buoys available
- 10% drifting buoys withheld for validation

2009

- *AATSR data withheld to simulate effect of lack of reference data.*
- Other satellite data available
- 90% drifting buoys available
- 10% drifting buoys withheld for validation

2010

- All satellite data available.
- 90% drifting buoys available
- 10% drifting buoys withheld for validation

2011 (end)

Met Office

Mean bias fields for AMSRE

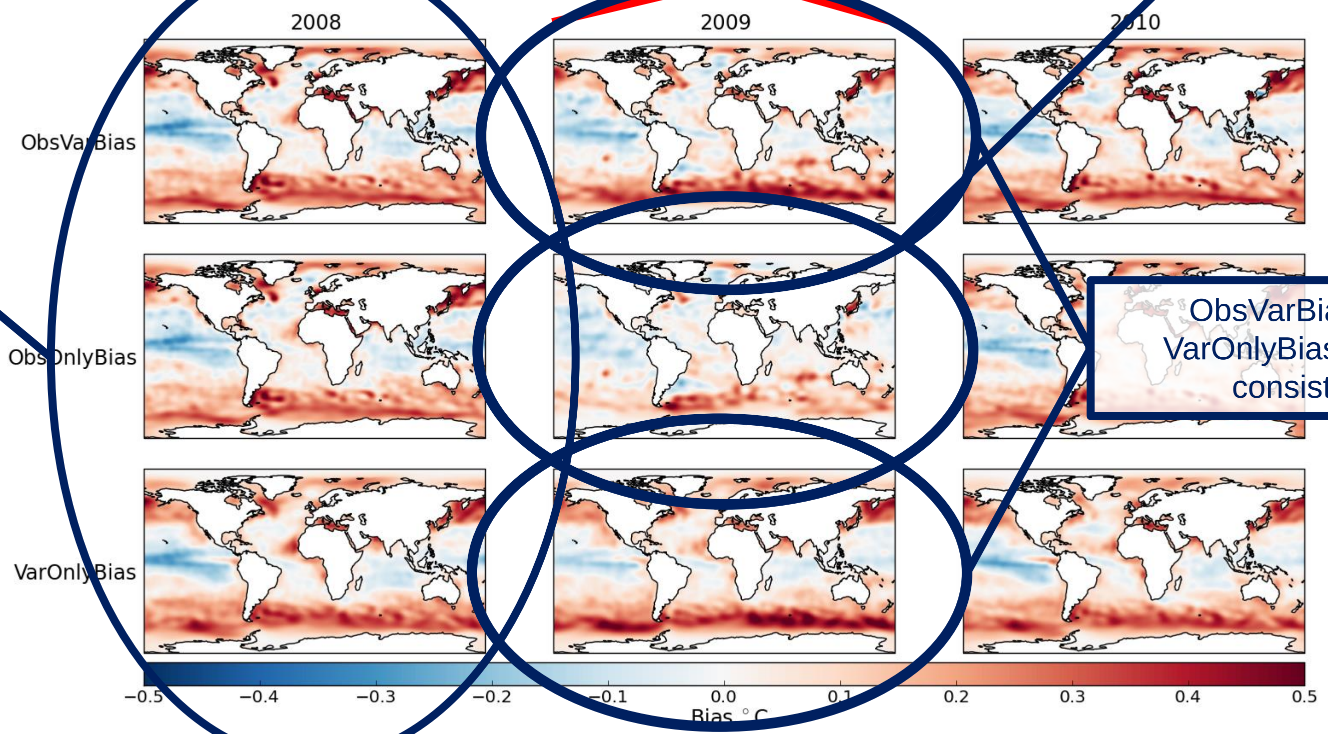
In 2008 (and 2010), bias fields are very similar for all 3 methods.

ObsVarBias and ObsOnlyBias are almost identical.

VarOnlyBias has slightly weaker biases in some areas, and slightly stronger biases in others, but has a similar pattern

In 2009 we used many fewer reference observations

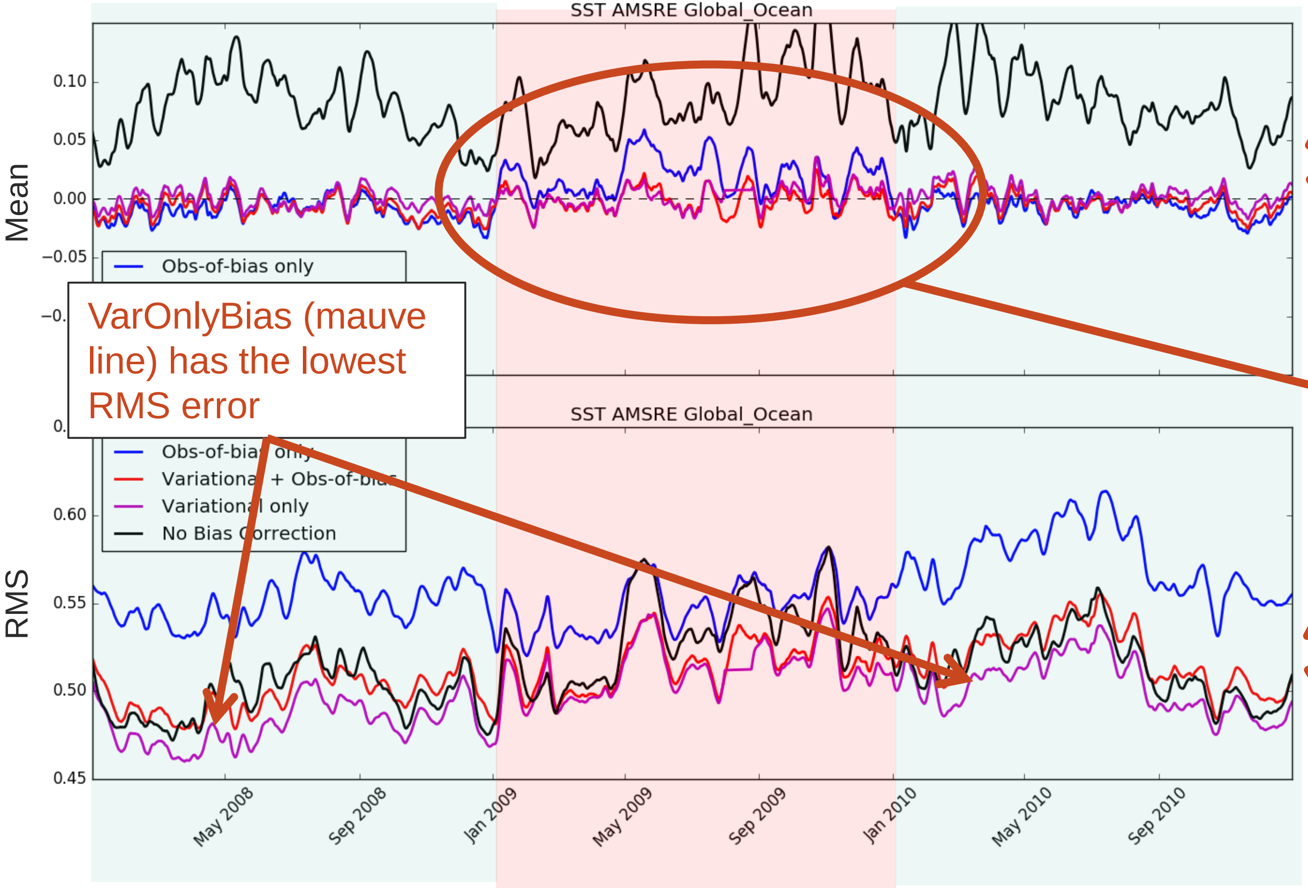
In 2009, ObsOnlyBias is very patchy and inconsistent with the other years



ObsVarBias and VarOnlyBias remain consistent

Global Obs minus Bkg for AMSRE

The plots show the difference between AMSRE data and a 1 day forecast of the model.



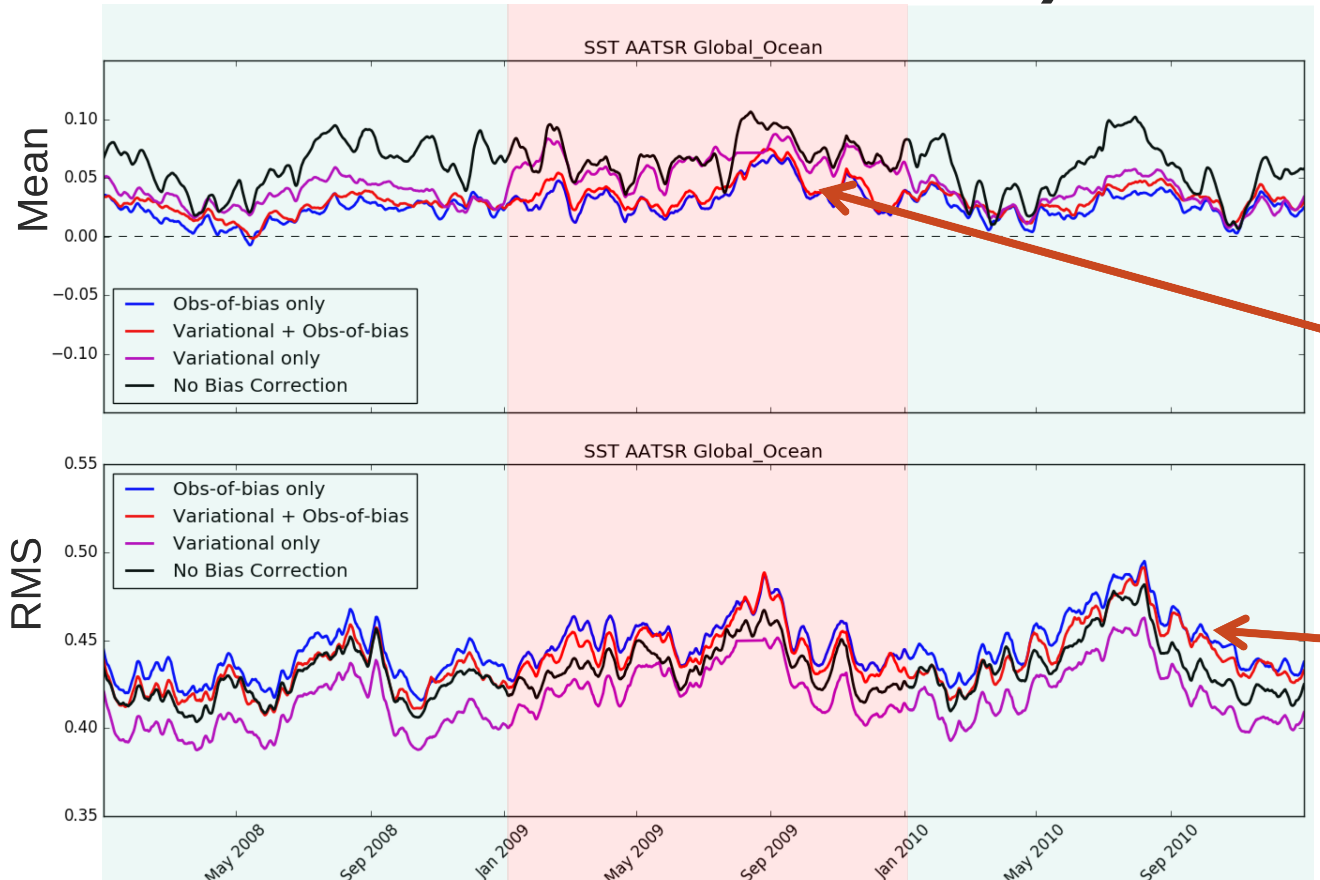
VarOnlyBias (mauve line) has the lowest RMS error

The overall bias is much reduced

In the period with fewer reference observations, ObsOnlyBias (blue line) does not do as well

The RMS error for the ObsOnlyBias system is also worse

Global Obs minus Bkg for AATSR (a reference dataset)



The Obs based bias corrections ObsOnlyBias and ObsVarBias are less biased than VarOnlyBias.

But have increased RMS values, often exceeding NoBias. Too many obs-of-bias rather than direct observations?

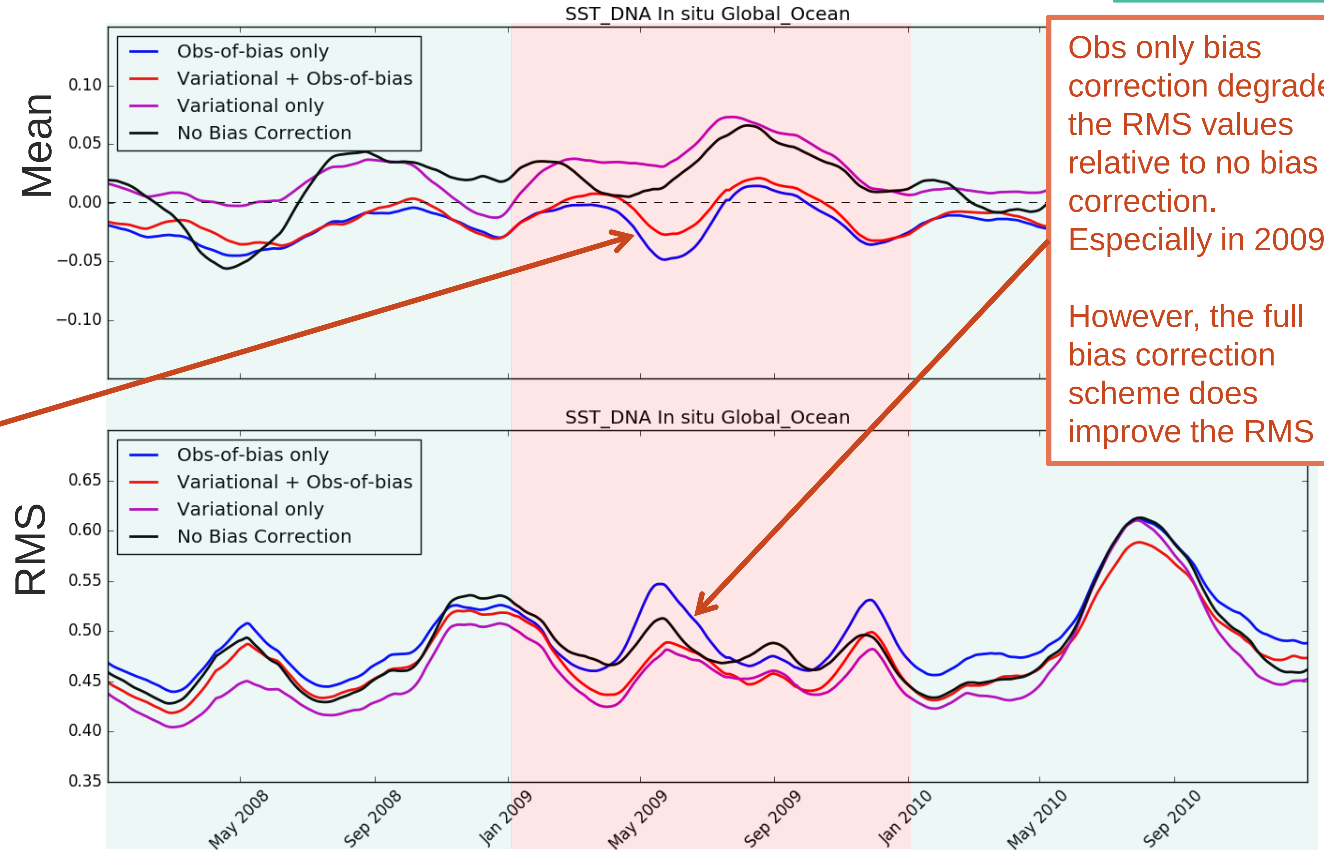
Global Obs minus Bkg for validation In-Situ

As with the AATSR data. The variational only bias correction, is more biased than the other methods.

But has the lowest RMS.

The full bias correction is less biased than the obs-only bias correction. Especially in the period without AATSR.

6 month smoothing used



Obs only bias correction degrades the RMS values relative to no bias correction. Especially in 2009

However, the full bias correction scheme does improve the RMS

SST bias correction summary

- The Met office has implemented a new variational bias correction scheme for SST that uses observations-of-bias.

- The scheme has been tested in 3 year runs and compared against an ‘offline’ scheme, a pure variational scheme and a run without bias correction.

- Results showed that:
  - Biases appeared to be smallest when using observations-of-bias.
  - RMS values were smallest when using a pure variational scheme.
  - Loss of a reference data source has a larger impact on the statistics when using an offline scheme.

- The scheme as it stands needs further tuning. In particular we think the elevated RMS values (relative to the variational scheme) are because we are using too many observations-of-bias rather than direct observations. Tuning experiments are ongoing.

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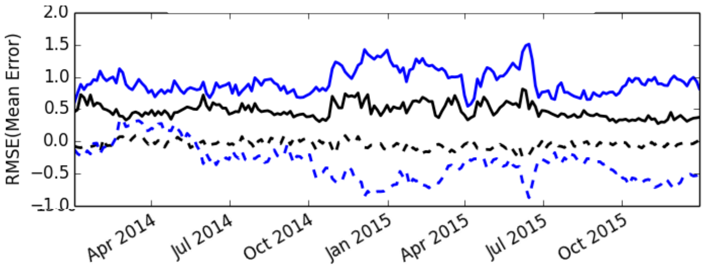
Vertical propagation of SST information

Met Office

Issues with SST assimilation scheme

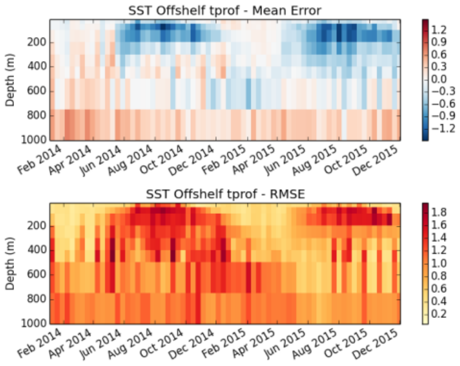
- SST assimilation in FOAM (focus here on regional system in NE Atlantic) produces accurate analyses and forecasts for SST.

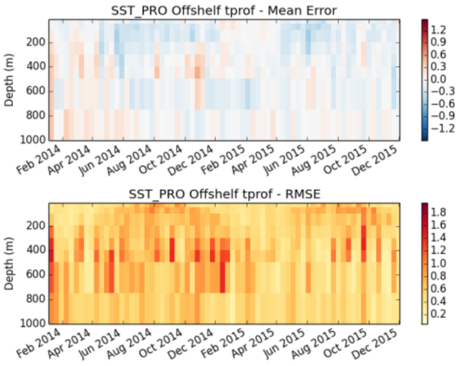


Blue line – free model SST
Black line – with SST assimilation

- However, it can degrade the sub-surface temperature analysis.
- Vertical propagation very important, particularly when there is a lack of in situ profile data.

SST- only assimilation
T profile errors





SST and profile assimilation
T profile errors

Issues with SST assimilation scheme

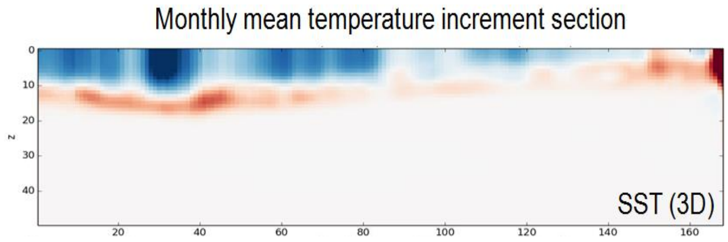
- Cross-section of average temperature increments (July) show dipolar structure in the vertical, when assimilating only SST data.
- One explanation:
    - SST increments affect the MLD due to changing the stratification (Gaussian function causes vertical gradients in the temperature)

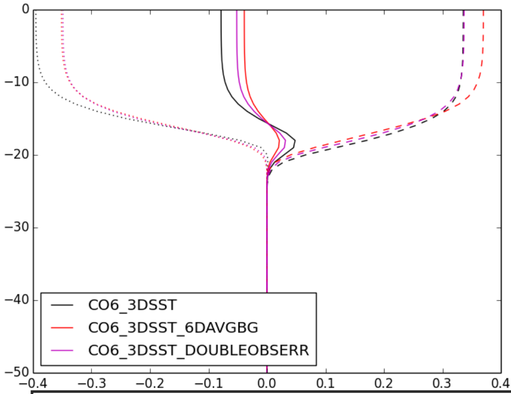
    -ve increments => reduce stratification

    ⇒ deeper MLD

    ⇒ -ve SST error (heat input over larger vertical region, or mixing colder water from below)

    ⇒ +ve incs (when the ML is deep) => increase stratification, etc
- Reducing variability in the increments by increasing the obs errors, or by temporal smoothing of the MLD used in the vertical projection.
- Both these ideas reduce the problem, but do not solve the issue.



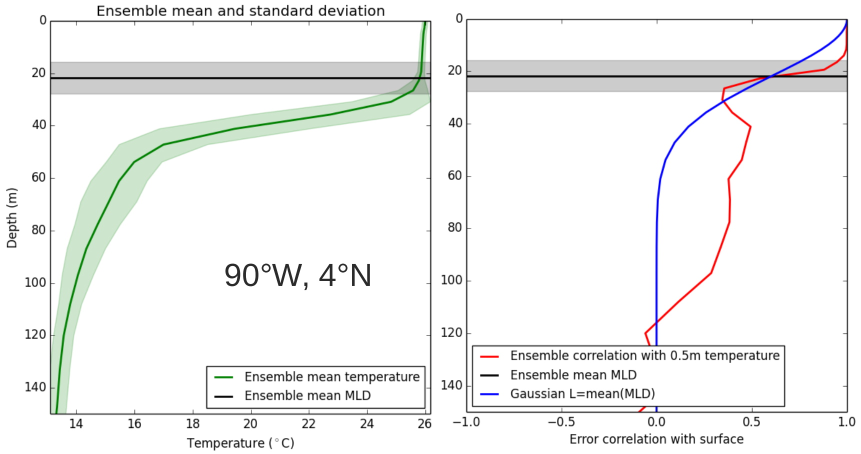


Monthly average T increments at a location in the NE Atlantic
Dotted lines: average of the –ve incs
Dashed lines: average of the +ve incs
Solid lines: average of all the incs

Information about the error structures from ensembles

- One way of getting additional information about the structure of the errors and how they should be propagated vertically is to look at outputs of an ensemble system.
- 10-member ensemble of global FOAM (ensemble of 3DVars) with perturbed wind and heat forcing, and perturbed observations. Started on 1st Jan 2011.
- The ensemble information was not used in the DA in this experiment (but could be in the future).
- An ensemble of errors is available on each DA cycle.

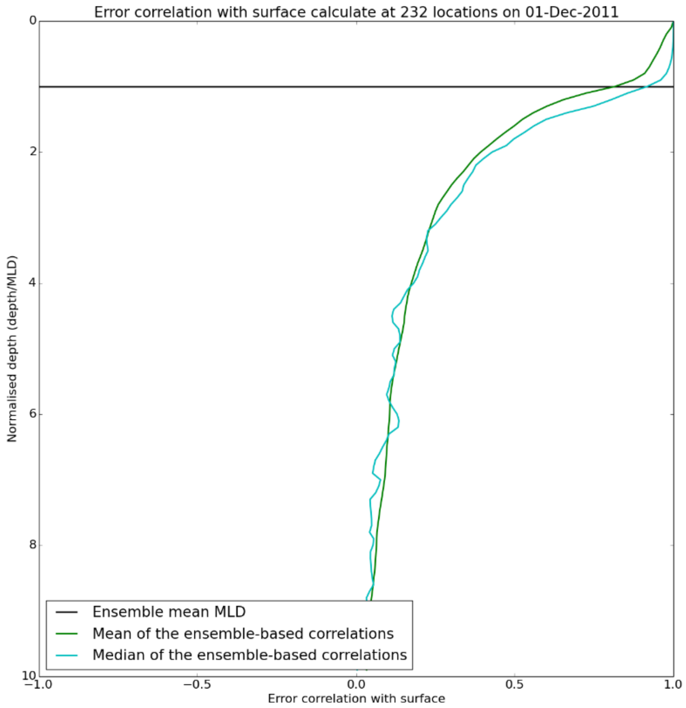
- To have a first look at whether the ensemble outputs agree/disagree with our existing parametrisation, we've looked at the raw ensemble outputs on 1st Dec 2011 at one grid point.
- No vertical localisation here, so sampling issues.
- Red line: raw ensemble correlation with 0.5m T



Information about the error structures from ensembles

- In this example, we've calculated the vertical correlations at many locations, transformed the vertical coordinate to be normalised by the local MLD, then average the resulting correlations (mean and median).
- Vertical propagation in the existing parameterisation is not strong enough, particularly in the mixed layer.
- Ensemble (hybrid) background error covariance could improve the vertical propagation of SST data.

- Green lines: vertical correlations with the surface calculated as a function of normalised depth (depth/MLD), calculated from the ensemble.



Summary

Met Office

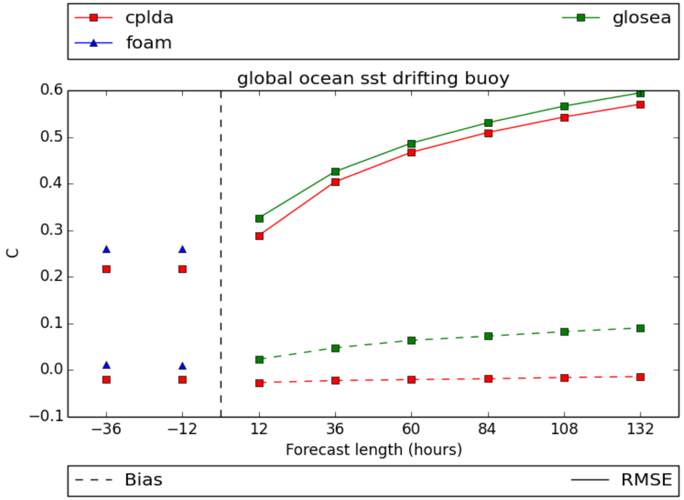
Summary (1)

- Improved bias correction scheme for SST data which is more robust to changes in the reference data-sets.
  - Further improvements and tuning still being worked on, e.g. how many data to use for estimating the bias vs how many to use to estimate the state.

- Vertical propagation of the SST information is an issue, particularly in regions/times when there are few temperature profiles.
  - Using information from an ensemble to improve the vertical propagation of SST data could improve this, but sampling issues/vertical localisation could be a significant issue.

Summary (2)

- SST assimilation in FOAM using NEMOVAR:
  - Latest version of global FOAM (v14) is being implemented operationally later this year.
  - Now developing 1/12 degree resolution version of global FOAM.
- Weakly coupled DA system uses the same set-up as FOAM for the ocean analysis (including SST), except that the time window is 6-hours.



Impact of coupled DA on ocean forecasts

Global obs-minus-forecast statistics against surface drifters over 2015

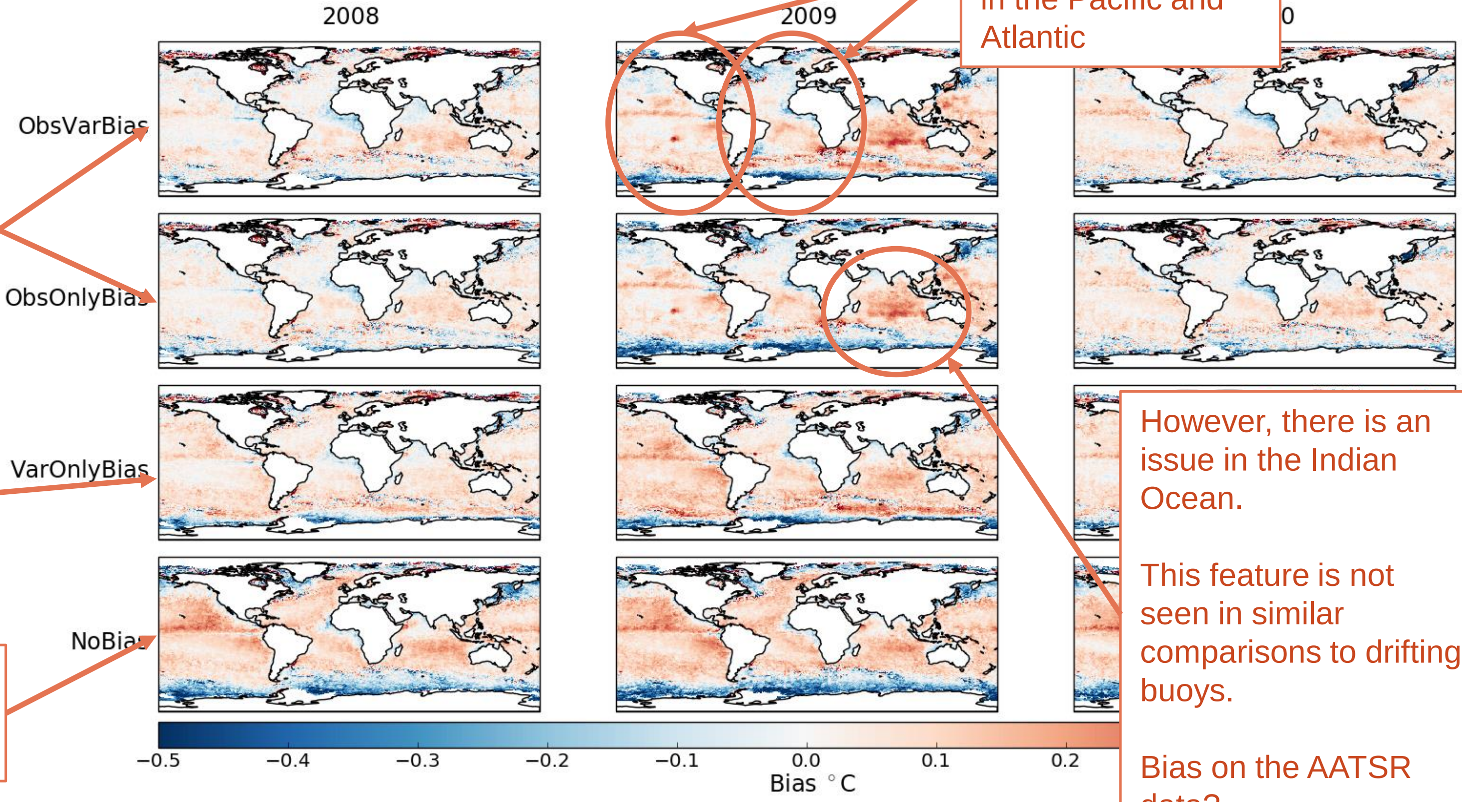
Red – weakly coupled DA and coupled f/cs
Blue – uncoupled ocean DA (FOAM)
Green – coupled f/cs from uncoupled DA.

Thank you for listening

Mean Obs minus Bkg for AAT s)

In 2009, the obs based systems have lower bases in the Pacific and Atlantic

The Obs based bias corrections. Have the smallest biases in 2008 and 2010



Variational only has slightly larger biases

No bias correction has the largest biases

However, there is an issue in the Indian Ocean.

This feature is not seen in similar comparisons to drifting buoys.

Bias on the AATSR data?

Mean Obs minus Bkg for validation obs (5° Bins)