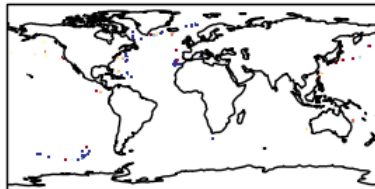
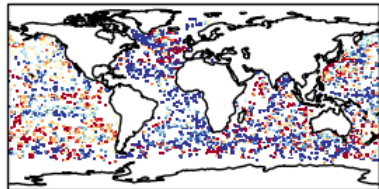


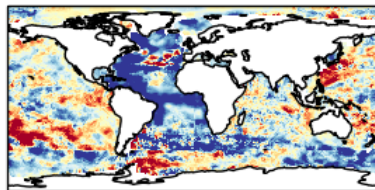
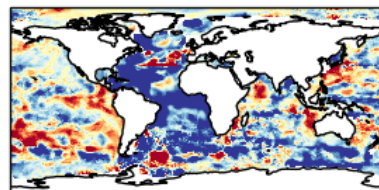
## Ocean temperature at 1500m

Observations Oct 2011

Observations subsampled to 1960



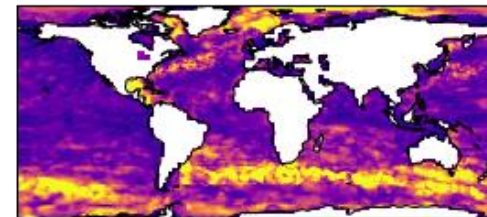
Re-analysis fields created with global covariances



The similarity of the re-analyses above show that this method<sup>1</sup> is able to create realistic gridded fields even with limited observations

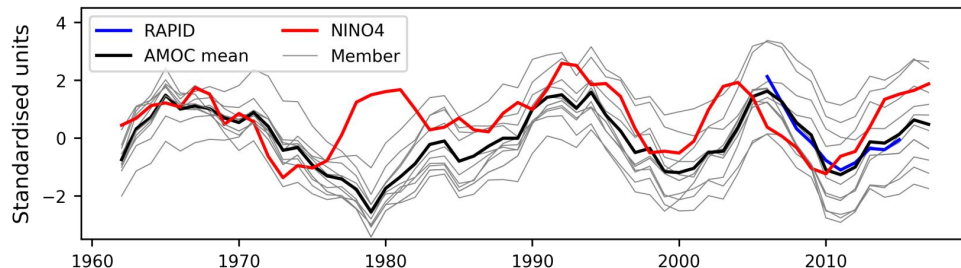
MOSORA now has ten ensemble members sampling the uncertainty in the global covariances used to make a 3-D gridded data set of T & S covering 1950-present

Yellow regions highlight where the MOSORA ensemble members disagree on 700m ocean heat content in the 2000s



MOSORA is nudged into the ocean of the HadGEM3-GC3.1-MM coupled model and the resulting AMOC at 26°N follows RAPID observations.

When time series are detrended and smoothed by a 5-year rolling window the correlation with ENSO is 0.6 (ENSO leads by 2 years).



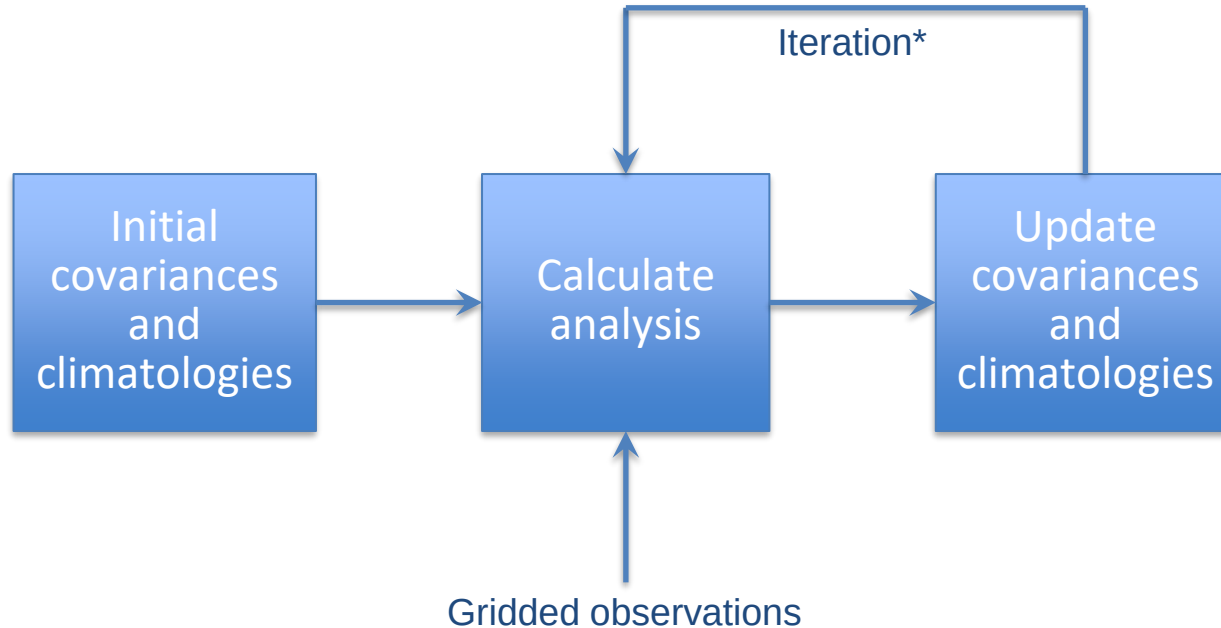
# Outline

- Met Office Statistical Ocean Re-Analysis (MOSORA)
- Testing MOSORA by withholding observations
- Uncertainties in the MOSORA ensemble
- Met Office Decadal Prediction System v4 (DePreSys4)
- The AMOC in DePreSys4 assimilation
- Mechanism of a possible link to Pacific

# Met Office Statistical Ocean Re-Analysis (MOSORA)

- An ensemble of 3-D potential temperature and salinity analyses
- Starting 1950, monthly means up to present
- Uses gridded observations (EN4) and SST (HadISST1.1 from 1982, HadSST2 before)
- Global covariance optimal interpolation with iteration (Smith & Murphy, 2007)
- Based on HadCM3 ocean grid:
  - $1.25^{\circ} \times 1.25^{\circ}$
  - 20 levels
- Nudged into assimilation run (together with ERA in atmosphere) to initialize decadal hindcasts

# Iteration procedure for MOSORA



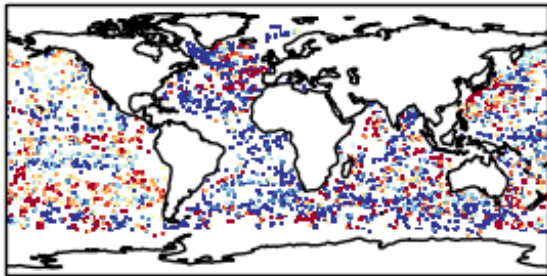
\*Usually two iterations are done

- There is a clear improvement in RMSE between the initial and first iteration
- The second iteration generally has larger anomalies, but no better RMSE

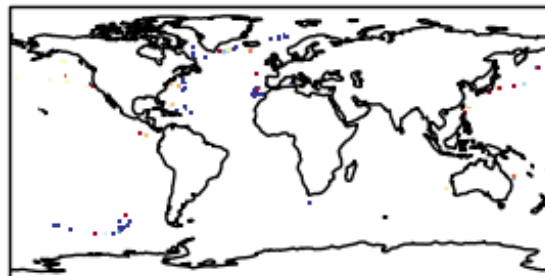
# Iteration tests: temperature at 1500m

All observations

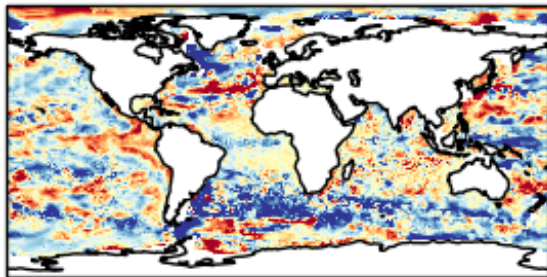
2011-10  
nemocov



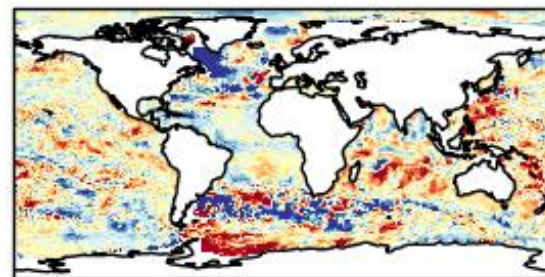
Keeping only  
a subset of  
observations



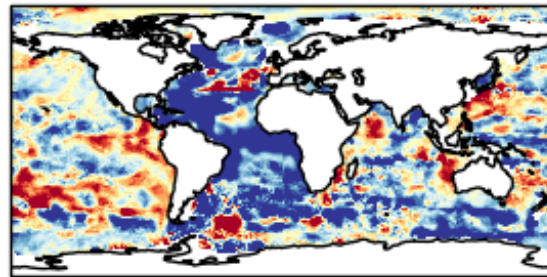
All obs  
First covariances



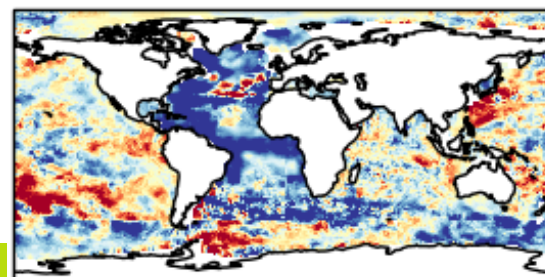
Subset obs  
First covariances



All obs  
2<sup>nd</sup> iteration



Subset obs  
2<sup>nd</sup> iteration



General pattern from all  
observations well  
reproduced with a  
subset

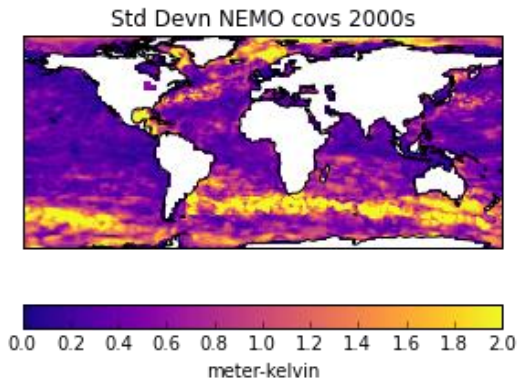
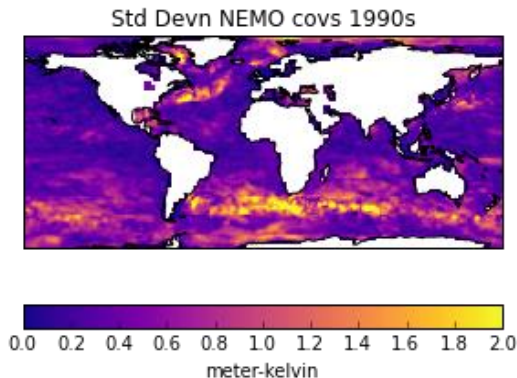
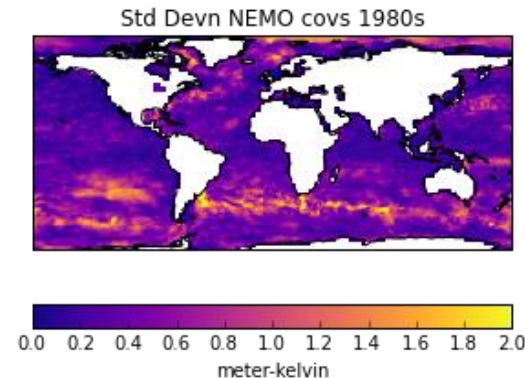
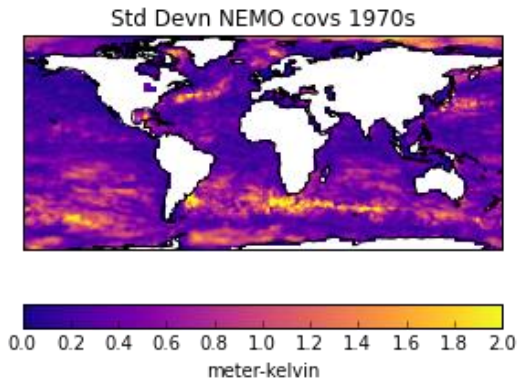
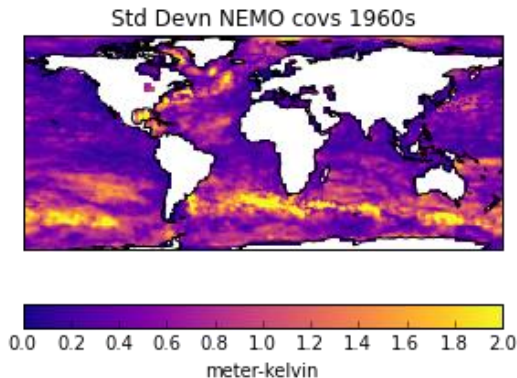
# Observation withholding experiments

| TEMPERATURE<br>Iteration | Difference<br>from full<br>analysis | RMSE of<br>all obs | RMSE of<br>withheld obs |
|--------------------------|-------------------------------------|--------------------|-------------------------|
| 0                        | 0.305                               | 0.970              | 0.956                   |
| 1                        | 0.300                               | 0.945              | 0.932                   |
| 2                        | 0.315                               | 0.939              | 0.929                   |
| 3                        | 0.326                               | 0.938              | 0.930                   |

| SALINITY<br>Iteration | Difference<br>from full<br>analysis | RMSE of<br>all obs | RMSE of<br>withheld obs |
|-----------------------|-------------------------------------|--------------------|-------------------------|
| 0                     | 0.101                               | 0.204              | 0.199                   |
| 1                     | 0.093                               | 0.201              | 0.195                   |
| 2                     | 0.088                               | 0.203              | 0.197                   |
| 3                     | 0.082                               | 0.206              | 0.200                   |

- For 2010-2013 (48 months)
- Subsampled as 1960s
- All depths and locations included
- Last column shows:
  - Covariances can reconstruct withheld temperature observations better with every iteration until iteration 3
  - No improvement in reconstructing salinity observations after iteration 1
- This is also true when comparing to all observations (third column)
- We therefore use iteration 2 as the final analysis

# Spatial distribution of uncertainties in MOSORA



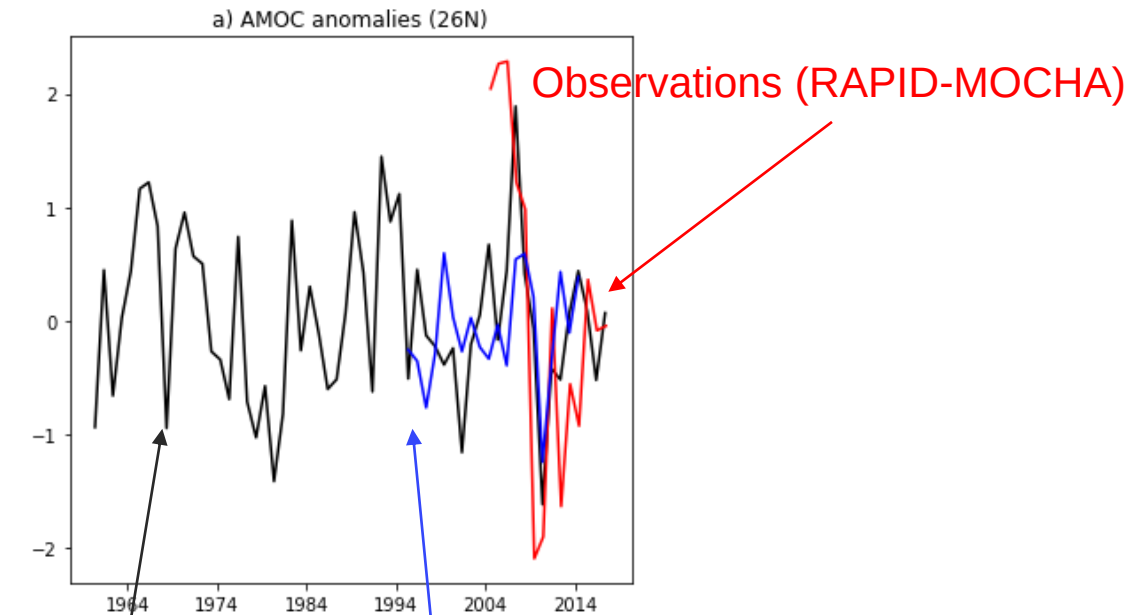
Maps of ensemble standard deviation of 700m ocean heat content.  
Units:  $10^4$  J

**Regionally increased uncertainties in Argo period but errors are smaller overall.**

- DePreSys4 hindcasts are 10 member ensembles
- Each member has initial conditions from the assimilations of different ocean analyses
- Each ocean analysis uses a different model to provide the initial covariances
- The models are all HadGEM3-GC3, but use different atmospheric parameters in the parametrizations (Perturbed Physics Ensemble)
- Two exceptions:
  - one analysis that uses the standard HadGEM3-GC2
  - one analysis that use data from a GO5 forced run

- Submitted to CMIP6 Decadal Climate Prediction Project
- Based on HadGEM3-GC3.1-MM historical simulation suite
  - The iteration of climatology means that each hindcast member is initialized with a different climatology as well as different anomalies
- Ocean initial conditions based on an assimilation of the ensemble of ocean re-analyses (MOSORA)
- Assimilation: Full field potential temperature and salinity are nudged into the ocean at all depths
- Sea-ice and atmospheric winds and temperatures are also nudged
- All nudged variables are close to observations, but ocean velocities and the AMOC are the model's own

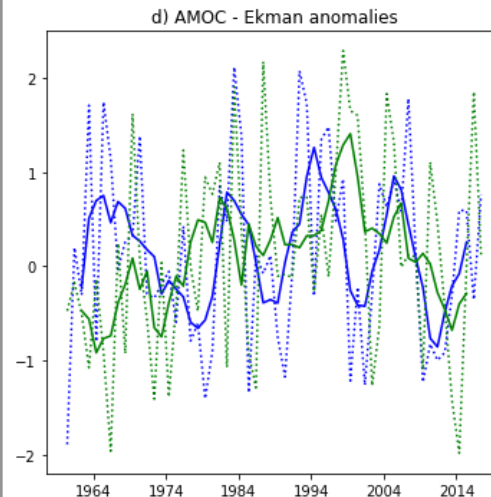
# Annual mean AMOC 26°N



DePreSys4  
assimilation  
ensemble mean

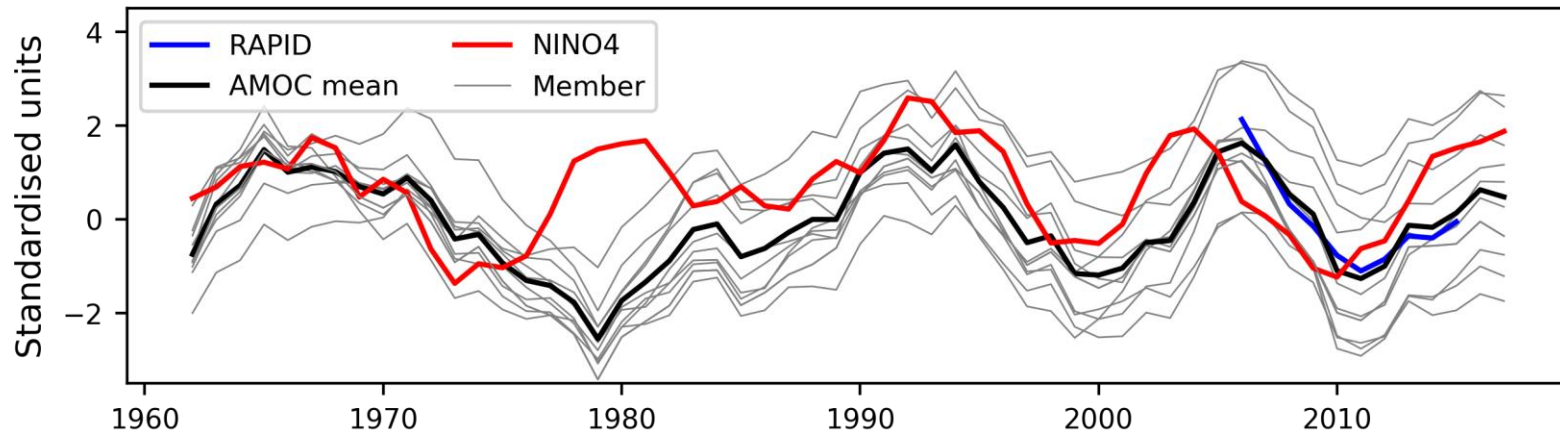
GloSea5  
(Met Office seasonal forecasts:  
Jackson et al, 2016, Nature Geosci 9, 518–522  
<https://doi.org/10.1038/ngeo2715>)

DePreSys4 assimilation  
26N 1 & 5 year smoothed  
45N 1 & 5 year smoothed



# DePreSys4 AMOC 26°N links to ENSO?

All time series detrended and smoothed by 5-year rolling window

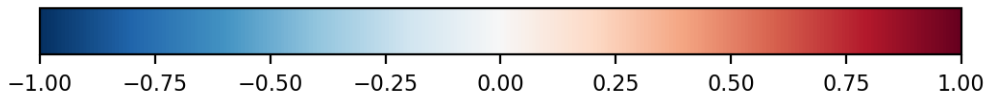
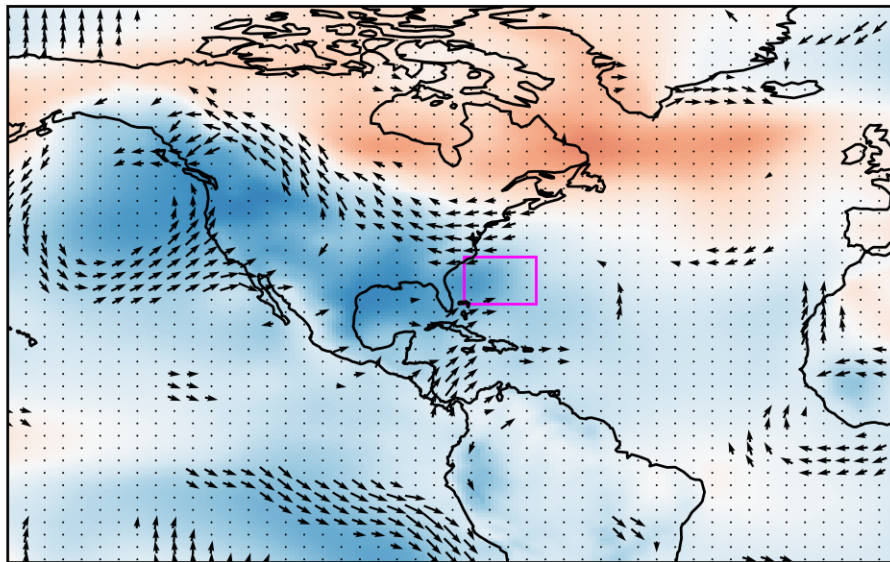


# DePreSys4 NINO4 impacts

The low pressure East of Florida has several origins:

- Locally warm SST gives a thermal low.
- The Walker Circulation over the East Pacific is close during ENSO, creating low pressure over the whole region.
- The Pacific jet stream is shifted South, bringing lows over Florida instead of the Carolinas.
- The PNA will also add to the low.

(a) NINO4 lag 3: mslp & 850hPa winds



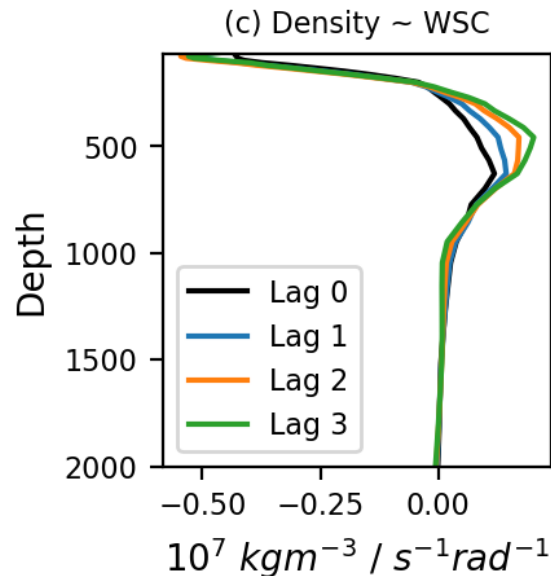
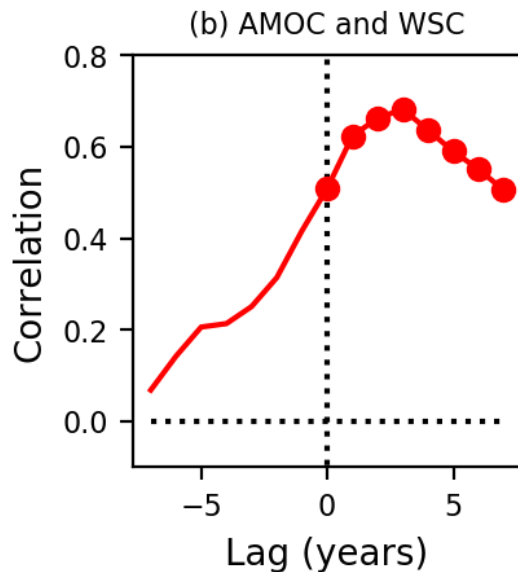
Correlation between NINO4 and mslp/winds obtained with detrended and smoothed time series.

The correlations change when trend is retained, so **more work is needed to understand this link.**

# DePreSys4 NINO4 impacts

Wind stress curl East of Florida:

- Has a strong correlation with AMOC at 26N at many lags (b)
- Would create westward propagating Rossby waves
- Rossby waves become southward propagating Kelvin waves at western boundary
- Western boundary density (c) changes AMOC

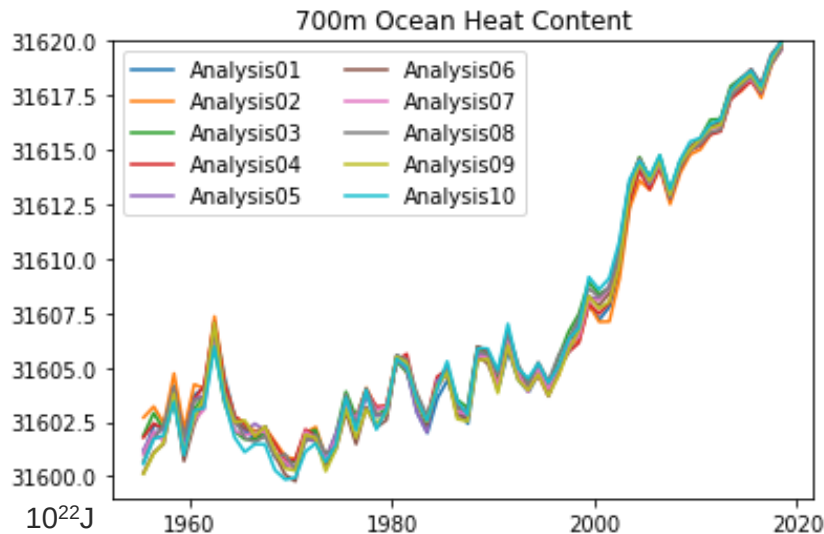


# DePreSys4 forecasts

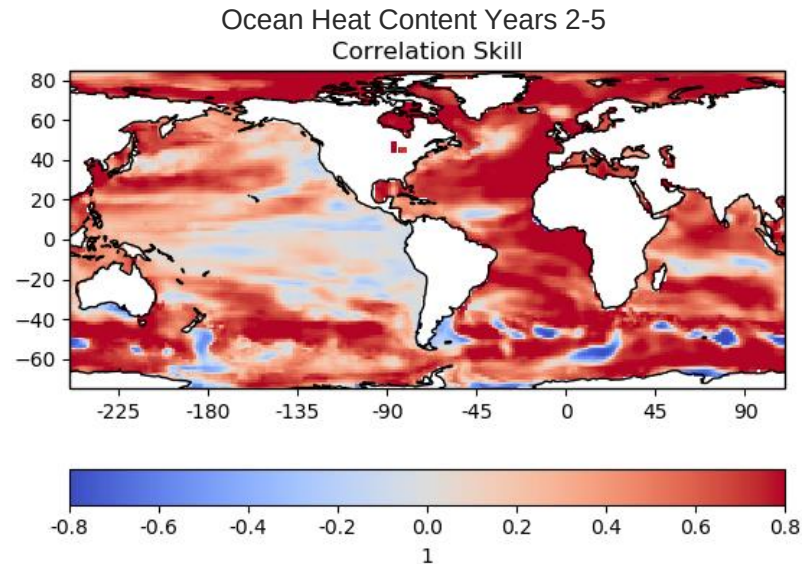
|                        | DePreSys4                                  |
|------------------------|--------------------------------------------|
| Atmos. resolution      | <b>HadGEM3 GC3.1 N216 (60km) 85 levels</b> |
| Atmos. reanalysis data | <b>ERA 40/interim nudged 6 hours</b>       |
| Ocean resolution       | <b>NEMO ¼° 75 levels</b>                   |
| Ocean analysis data    | <b>MOSORA (10 members)</b>                 |
| Ocean relaxation       | <b>10 days</b>                             |
| Sea-ice conc. data     | <b>HadISST ice</b>                         |
| Sea-ice thickness      | <b>No</b>                                  |
| Sea-ice relaxation     | <b>1 day</b>                               |
| Assimilation method    | <b>Full field</b>                          |
| Ensemble creation      | <b>10 assimilation runs</b>                |
| Ensemble size          | <b>10 members</b>                          |

Comparison to DePreSys3:

- New coupled configuration
- New initialization
- Hindcasts every year and run for 10 years



The Met Office Statistical Ocean Re-Analysis (MOSORA) has ten ensemble members sampling the uncertainty in the global covariances used to make the gridded data set covering 1950-present



Hindcasts initialized with this data are particularly skilful at predicting future ocean heat content in the Atlantic, Arctic and parts of the Indian and Southern Oceans. This skill is fundamental for a successful decadal prediction system.

# Conclusions

- MOSORA is an independent ocean re-analysis ensemble
- It uses global covariances that can make complete fields with few observations
- Experiments with withholding observations show method is good even in 1960s
- MOSORA is assimilated (nudged) into a dynamic model to initialise decadal predictions
- There are 14 years of AMOC observations at 26°N, the DePreSys4 assimilation can reproduce the decline from 2004 to 2010 and the subsequent increase
- On decadal time scales, the model AMOC at 26N correlates with ENSO, the mechanism is through induced wind stress curl East of Florida
  - Wind stress curl alters the pycnocline and creates Rossby waves that change the AMOC
  - This mechanism is not robust to detrending, so more research is needed