Using a multi-model ensemble of ocean reanalyses to understand recent changes in the North Atlantic.

L Jackson, C Dubois, D Iovino and many, many others.

We are examining **recent changes in the North Atlantic** (during the satellite period – after 1993) with global ocean reanalyses with the aim of answering the following questions:

- Where is there agreement/disagreement?
- Can we learn what makes a reanalysis good at specific processes?
- Are there processes/time periods where we believe the reanalyses are adding information?

Scientific themes:

- Dynamics
  - AMOC (incl RAPID and OSNAP sections)
  - Gyres
  - Convection regions (mixed layer depth, densities)
- Heat and fresh water
  - OHC and water mass properties
  - Surface fluxes
  - Ocean transports

Analysis is ongoing …

Ocean reanalyses

These are forced ocean models that assimilate various observational data sets

- Advantages of reanalyses over observations alone
  - Infill regions with sparse data
  - Give dynamics (ie transports) that are difficult to measure
  - Provide consistent budgets (ie heat)
- Disadvantages
  - How reliable are the reanalyses? Can we believe them?
  - Assimilation/relaxation of terms can dominate budgets

Note that there are 6 NEMO models (one 1/12 degree and five ¼ degree).

There are two models that use 4DVar (ECCO and GECCO) where surface fluxes are modified instead of increments added to T and S.

There are also two coupled reanalyses (NorCPM)

Reanalysis	Ocean model	Resolution	Vertical coordina	Surface forcing	What is assimilated and how?
C-GLORSv7	NEMO 3.6	0.25	75 depth levels	ERA Interim + CORE bulk	Nudging: SST, SIC, Arctic SIT; 3DVAR: SLA,T,S
ORAS5	NEMO 3.4	0.25	75 depth levels	ERA Interim + NWP + CORE bulk	in-situ T/S, SIC, SLA+MSLA, SST, 3DVAR-FGAT
GloSea5	NEMO 3.4	0.25	75 depth levels	ERA Interim + CORE bulk	SST,SSH,T,S,SIC 3DVAR full field
UR025.4	NEMO 3.2	0.25	75 depth levels	ERAi + CORE Bulk fluxes	SST, SSH, T, S, SIC, Optimal Interpolation
GLORYS2V4	NEMO3.1	0.25	75 depth levels	ERA-Interim + Core bulk fluxes	SST (AVHRR)+Altimetry+InSitu(T/S),MDT
GLORYS12V1	NEMO3.1	1	50 depth levels	ERA-Interim + Core bulk fluxes	SST(AVHRR)+Altimetry+InSitu(T/S),MDT
GECCO2	MITgcm	1/3 to 1		NCEP	SST,SLA, MTD,T,S, 4DVAR
ECCO V4 R3	MITgcm	1	50 depth levels	ERA Interim (initial guess) + CORE bu	SSH/T/S, in situ T/S, SIC, GRACE OBP, MDT; 4DVA
NorCPM-V0	MICOM	1		Fully-coupled	SST; EnKF anomaly
NorCPM-V1	MICOM	1		Fully-coupled	SST, T, S; EnKF anomaly
GONDOLA100A	MRI.COM v4.2	1x0.3-0.5	60 levels + BBL	JRA55-do v1.3, CORE bulk	in-situ T/S, SST, SSH, SIC; IAU, 3DVAR
ECDA	MOM5	1 x 1/3 to 1		NCEP	in-situ T/S, SST,Coupled Ensemble Kalman Filte

AMOC: The AMOC streamfunction in many reanalyses looks similar to that found in free-running models, however there are occasional discontinuities by latitude. Gloseа5 is odd below 20N (due to method of assimilating ssh which is now being corrected). Some models are too strong at 26.5N and some do not capture the deep return flow

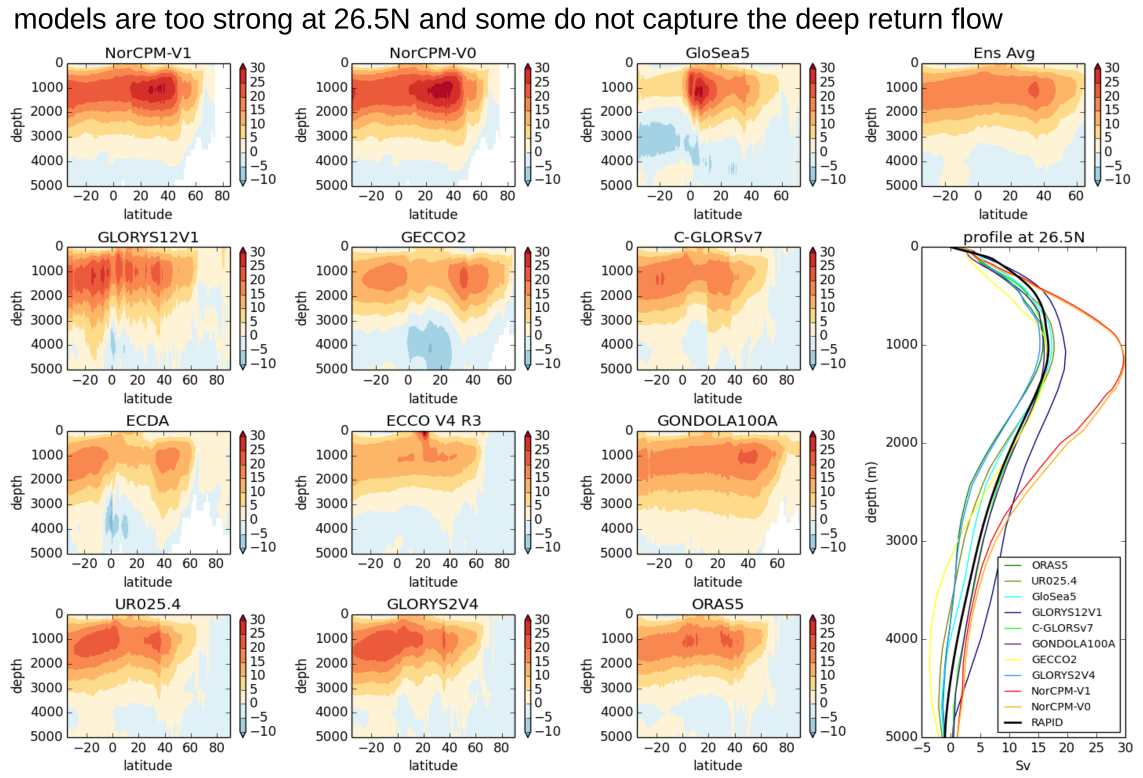


Fig 1. AMOC streamfunctions (from velocities) and profiles at 26.5N (calculated using the RAPID methodology).

At 26.5N about half get the magnitude of AMOC and there are signs of a temporary weakening in winter 2009/10 and also the weakening since 2005. There are suggestions of a strengthening from 2001-2006 (see Fig 4)

At 50N most models show coherent variability although there is a wide range of magnitudes. Much of this interannual/multiannual variability is from the wind-driven Ekman transport. The residual shows a weakening since the mid 90s

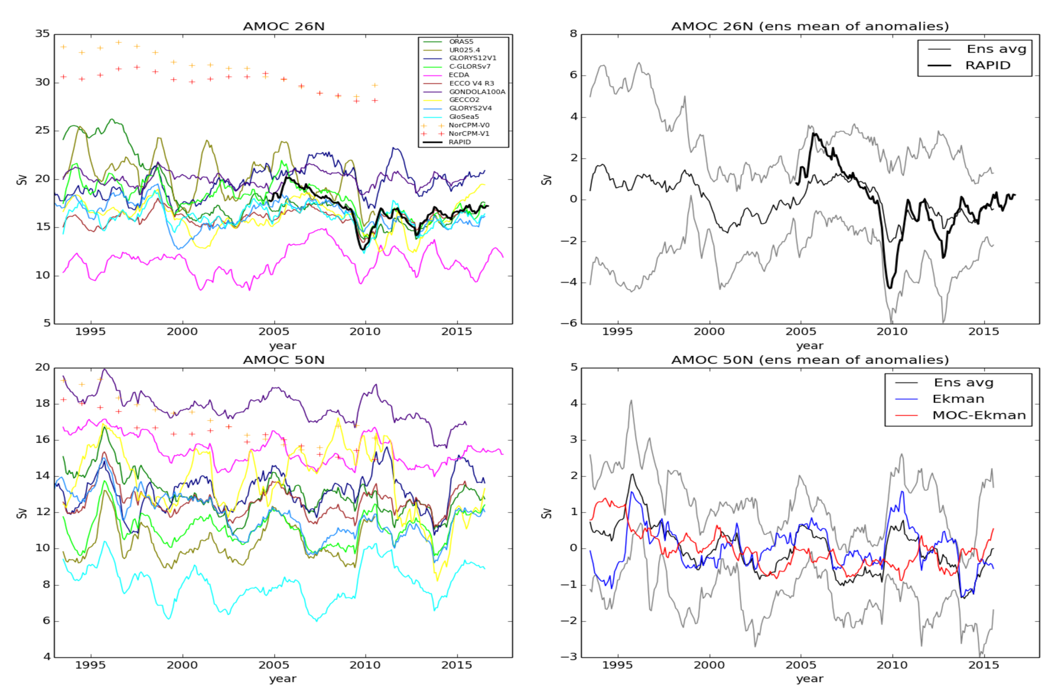


Fig 2. Timeseries of AMOC strength (with 12 month running mean). Top panels: at 26.5N (solid black line is timeseries from RAPID); Bottom panels: at 50N. Left panels: each individual timeseries; Right panels: ensemble mean (black) and 2 x standard deviation (grey) of timeseries minus their own climatological mean. Bottom right also shows the Ekman transport calculated from ERA Interim winds (blue) and the ensemble mean minus Ekman (red)

The reanalyses that compare best to the observations of AMOC variability (calculated by velocity) are: ORAS5, GloSea5, Glorys2v4, C-Glorsv7 and ECCO V4 R3. The first four all use 0.25º NEMO, but ECCO is very different (Fig 3 top)

The AMOC strength is the sum of Ekman, Upper mid ocean and Florida current components. Ekman is reproduced very well (apart from GECCO which adjusts winds).

The variability of the deep return flow is dominated by Lower NADW in the observations. Reanalyses generally have more variability in the Upper NADW that in observations (Fig 3 right)

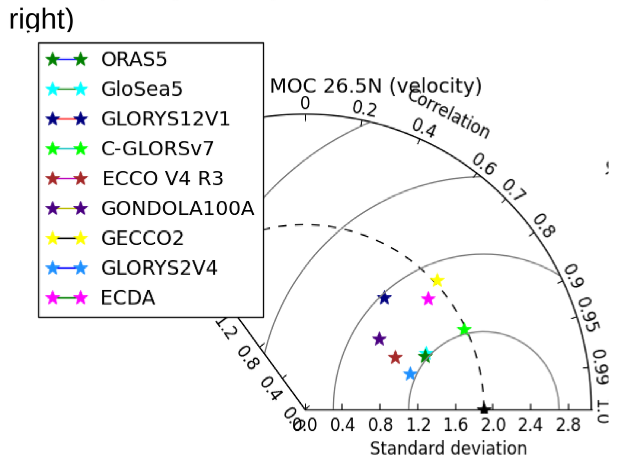
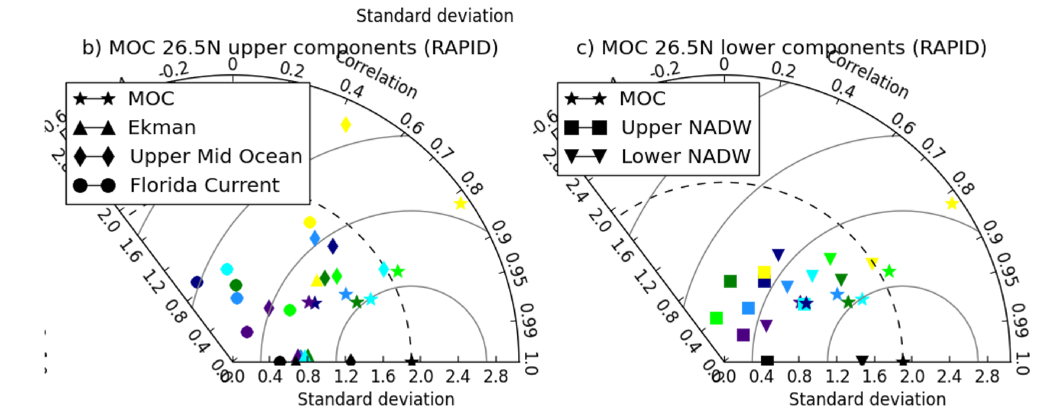


Fig 3. Taylor diagrams comparing reanalysis AMOC components (as calculated using the RAPID methodology, except for top panel which uses velocities) to the RAPID observations. Colours show different reanalyses, symbols show different components. Black symbols on the x axis show the standard deviation of the observational components. Note that not all the models have calculated the RAPID decomposition (bottom panels).



All models show a weak AMOC in 2009/10 although the weakening is not significant in many and is less than observed for all but Gloseа5 (Fig 4 left)

All models show a weakening of the AMOC from 2006-2013 like in the observations, and show a previous strengthening from 2001-2006. In most models these changes are significant.

At 50N most models show a significant weakening since the mid 90s (in agreement with other studies). There is no signal of a consistent trend at 26N over this period.

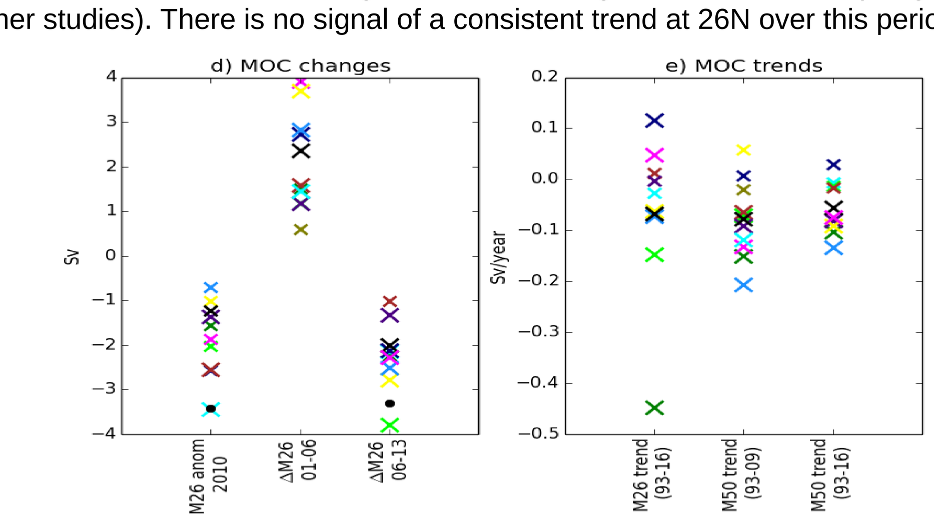
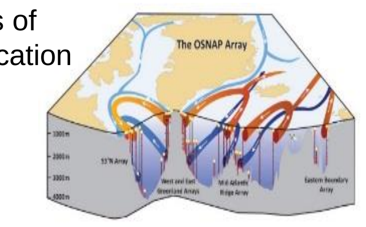


Fig 4. Comparisons of AMOC changes across the ensemble. Each cross is a model, with large crosses assessed as significant changes compared to each model timeseries. Black crosses are the changes for the ensemble mean and black circles are from the observations. Left panel: MOC 26N anomaly in 2009/10 compared to 2011-2015 climatology; MOC 26N in 2005-2007 minus 2000-2002; MOC 26N in 2012-2014 minus 2005-2007. Right panel: trend in MOC at 26N (1993-2016); trend in MOC at 50N (1993-2009); trend in MOC at 50N (1993-2016).

OSNAP: For some models the overturning across the OSNAP section in density space has been calculated



There is some coherence of interannual variability of timeseries of OSNAP overturning in the last decade. There is also some indication of a seasonal cycle (strong in spring and weak in autumn).

Most models show a dip in December 2014 followed by a strengthening mid 2015, then a weakening late 2015. This is in agreement with the observations (personal communication).

Although the timing of variability in 2015 fits the seasonal cycle, the magnitude is too large. A theory is that it is wind driven.

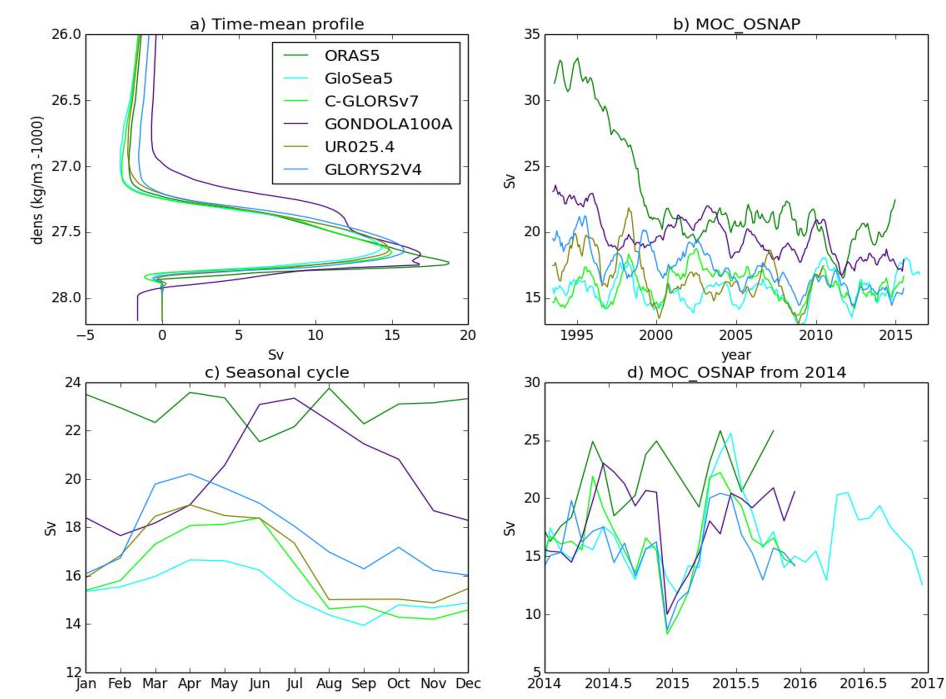


Fig 5. Overturning in density space along the OSNAP line. a) The time mean profile in density space. b) The overturning strength (maximum in density space) with a 12 month running mean. c) Seasonal cycle of the overturning strength. d) Monthly values of last few years of overturning strength.

Gyres: There is some consistency of high frequency variability of the gyre strengths among NEMO models (not GONDOLA) which use the same forcing sets.

There are some indications of coherent low frequency variability

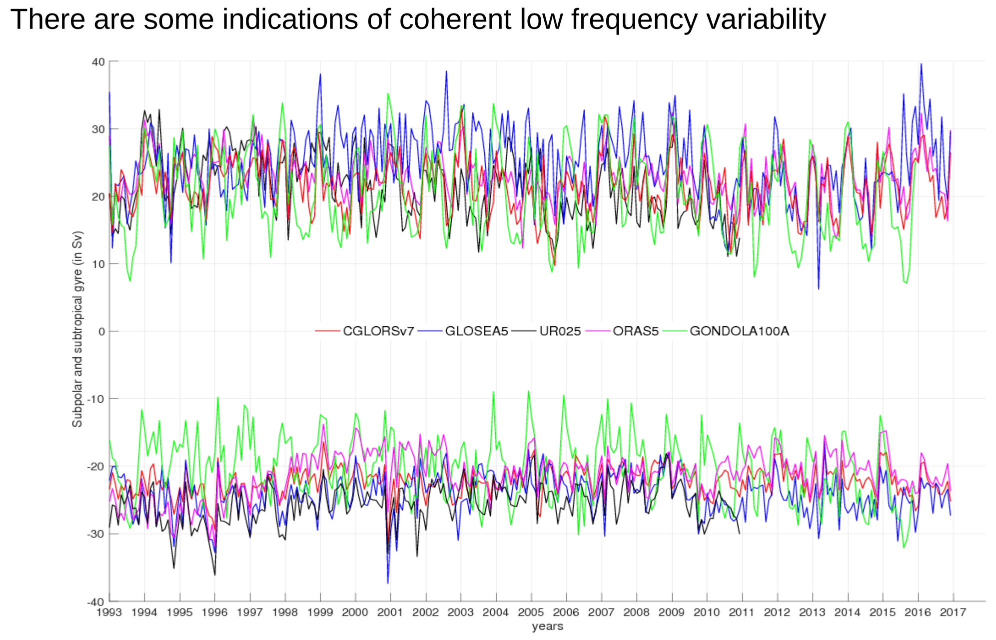


Fig 6. Strengths of the subtropical gyre (positive values) and subpolar gyre (negative values) for some of the reanalyses

Labrador Sea: Density anomalies in the central Labrador sea show (in most reanalyses) a decrease in deep density from the mid 90s (start of the run). The large negative spike in 1999 in some reanalyses is an artefact of the data assimilated (EN4)

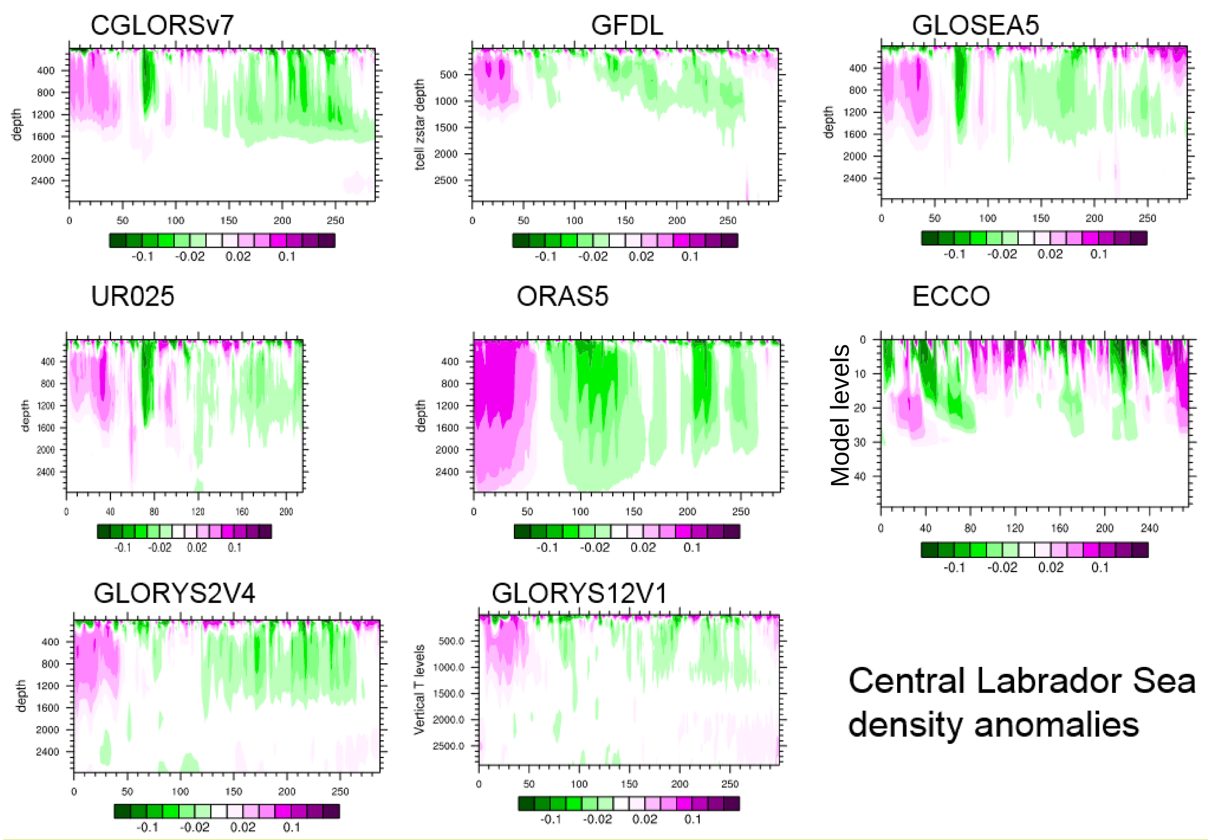


Fig 7: Density anomaly in the central Labrador Sea for each reanalysis by depth and month since 1993.

Mixed layer depths in some reanalyses are very deep (reaching the bottom) with little variability. Some reanalyses, however have more reasonable mixed layer depths.

Amongst the latter there is a convergence between the reanalyses from 2010, showing a gradual deepening (Fig 8 top)

Fig 8: Maximum mixed layer depth (using a criteria of 0.03 kg/m3 with monthly mean T and S) over the Labrador Sea and as a maximum each year. The reanalyses have been split into two groups with the reanalyses chosen for the upper panel being those with more realistic mean and variability.

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