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Magdalena A. Balmaseda[1], Gregory C. Smith[2], Keith Haines[2], David Anderson[1], T.N. Palmer[1] and Arthur Vidard[3]

[1]European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK.

[2] ESSC, Harry Pitt Bld, Earley Gate,Reading University, Reading RG6 6AL, UK.

[3] INRIA, LJK - B.P. 53 - 38041 - Grenoble cedex 9, France.

A reconstruction of the Atlantic Meridional Overturning Circulation (MOC) for the period 1959-2006 has been derived from the ECMWF operational ocean reanalysis. The reconstruction shows a wide range of time-variability, including a downward trend. At 26N, both the MOC intensity and changes in its vertical structure are in good agreement with previous estimates based on trans-Atlantic surveys. At 50N, the MOC and strength of the subpolar gyre are correlated at interannual time scales, but show opposite secular trends. Heat transport variability is highly correlated with the MOC but shows a smaller trend due to the warming of the upper ocean, which partially compensates for the weakening of the circulation. Results from sensitivity experiments show that although the time-varying upper boundary forcing provides useful MOC information, the sequential assimilation of ocean data further improves the MOC estimation by increasing both the mean and the time variability.

1. Introduction

The Atlantic meridional overturning circulation (MOC) is composed of a warm near-surface branch flowing northward as part of the Gulf Stream and a return flow of cold waters at depth. It plays a major role in the heat transport of the ocean, in turn affecting the climate of Europe and North America (e.g. Cubash et al 2001), and its variability plays an important role in future climate change scenarios. However, reliable estimates and understanding of the variability remain elusive. Bryden et. al. (2005), (hereafter BLC05) using density measurements from five transatlantic research cruises at approximately 26°N between 1957-2004, found a 30% decrease in MOC intensity, with a notable reduction in the southward flow of the lower North Atlantic Deep Water (NADW) coming from high latitudes, although these conclusions were based on very limited temporal sampling. In contrast, estimates relying on ocean model simulations have produced an intensification of the MOC (e.g. Böning et. al. 2006), which could be attributed to the prevailing positive phase of the North Atlantic Oscillation (NAO) since 1980's (Eden and Willebrand (2001).

The contradictory results between observational and model estimates illustrate the underlying uncertainties in the different methodologies: the observational BLC05 data clearly have insufficient temporal sampling to estimate trends, and the model results can be affected by errors in the forcing fluxes and model formulation. A hybrid approach is the synthesis of ocean model and observations using data assimilation techniques, to produce an ocean analysis (for a summary of ongoing activities see http://www.clivar.org/organization/gsop/synthesis/synthesis.php). In theory, the error in the MOC from an ocean analysis should be smaller than the errors in ocean model or observational estimates alone. In practice, some new uncertainties may be introduced from different assimilation techniques or observations of varying density/accuracy.

Ocean analyses such as ECCO have previously been used to derive reconstructions of the MOC (Wunsch and Heimbach (2006) and Köhl and Stammer (2007)). These ECCO analyses are based on long-window adjoint methods, and typically rely on the correction of the ocean initial conditions and surface forcing to get close to the observed ocean data. Here we present a 48 year historical reconstruction of the MOC (for the period 1959-2006) from the ECMWF operational ocean reanalysis System 3 (ORAS3 in what follows), which uses a sequential assimilation method to directly correct the density field, which is critical to circulation indices such as the MOC.

The paper is organized as follows: we describe the ocean analysis system, and the sensitivity experiments in secn 2, the reconstruction of the MOC, including the meridional and vertical structure in secn 3 and the implications for the meridional heat transports in secn 4. Results from sensitivity experiments are presented in secn 5 and conclusions in secn 6.

2 The data assimilation system

The analysis of the ocean state is obtained by integrating a global ocean model with atmospheric surface fluxes acting as time-dependent upper boundary conditions. The ocean model is HOPE (Wolff et al. 1997, Balmaseda 2004), 1° x 1° resolution, with a tropical enhancement to 1/3°, and 29 vertical levels, with partial step topography and explicit free surface. From 1959 to August 2002, the forcing fluxes are from the ERA40 atmospheric reanalysis with corrected freshwater fluxes, and from the operational atmospheric analysis thereafter (ERA40/OPS in what follows). The ocean observations are assimilated sequentially via an optimal interpolation (OI) method, which imposes dynamical and physical constraints. The analysis cycle is repeated every 10 days. A detailed description of the system is given in Balmaseda et al 2007a.

The subsurface observations consist of vertical profiles of temperature and salinity from Bathythermographs (MBT, XBT) , Conductivity Temperature Depth (CTD) sensor measurements from scientific cruises, TAO/TRITON and PIRATA moorings, and more recently Argo floats. Historical salinity data are scarce, and it is only with the advent of Argo floats that a near-global coverage of salinity observations is available (from 2000 onwards). For the period 1959-2004 the subsurface data are from the comprehensive quality-controlled data set ENACT-ENSEMBLES (Ingleby and Huddleston, 2006) , which contains 5.1 million temperature and 1.4 million salinity profiles. From 2005 onwards, the subsurface data are from the ECMWF operational archive, and are subject to a different automatic quality control procedure. For the later period, a typical 10-day assimilation window contains 2500 profiles of temperature and 1100 profiles of salinity. Maps of sea surface temperature (Reynolds et al 2002) are also assimilated and, from 1993 onwards, satellite-derived sea level anomaly maps (Le Traon et al 1998) are used. Supplementary figure 1 shows a timeseries of the number of temperature profile observations used in a 10-day assimilation cycle in the North Atlantic (20N-50N) as a function of depth. The observation coverage maps for the individual assimilation cycles can be seen at http://www.ecmwf.int/products/forecasts/d/charts/ocean/reanalysis/obsmap/.

The ORAS3 is part of the operational monthly and seasonal forecasting system, where a reliable reconstruction of the time variability of the ocean is required to improve the skill of the system. Special attention has been paid to the tuning of the error covariances, where the correlation scales and the diagonal elements have been chosen so as to improve both the mean state and the interannual variability. In addition, to reduce spurious time-variability resulting from the changing nature of the observing system, ORAS3 uses low frequency bias-corrections to both the pressure gradient and the temperature and salinity fields (Balmaseda et al 2007b). Only a weak relaxation to the full temperature and salinity climatology is used (10-year time scale), which does not significantly damp the interannual variability.

To assess the impact of assimilating data, a control experiment (ORA-nobs) is conducted by integrating the ocean model with the ERA40/OPS fluxes but without assimilating profiles or altimeter data. Everything else (spin up, relaxation to SST and 3D climatology) is the same as in ORAS3. To assess the impact of the forcing fluxes and spin up an additional experiment is conducted, identical to ORA-nobs but using a climatology of the daily fluxes as forcing. The effect of initial conditions on the MOC in ORAS3 at the beginning of the record is explored by a set of 10-year assimilation experiments starting from perturbed initial conditions in 1956.

3. The historical reconstruction of the MOC

Balmaseda et al 2007a show that the ORAS3 reanalysis is consistent with the observed profile data, and quantitatively reproduces the expected mean circulations and time variations in temperature, salinity and surface currents. The Atlantic meridional heat transports in ORAS3 are in good agreement with WOCE estimates (Ganachaud and Wunsch 2003, supplementary table1). Figure 1 shows the Atlantic MOC at 26°N for ORAS3, calculated by integrating the zonal-mean velocity from the surface to 1200m (chosen as the depth of maximum overturning in the model). The agreement between ORAS3 and the BLC05 values is remarkably good for 1981, 1992 and 1998, but differs in 2004, where the BLC05 value is substantially lower. However, more recent estimates from the RAPID array (Cunningham et al 2007) yield an average MOC value of 18.7Sv for 2004, which is in good agreement with ORAS3. Although the agreement is very encouraging, one should remember that there are only four points and there are likely substantial uncertainties in both the section/array estimates and model values.

Figure 1 also indicates the large seasonal (1.8 Sv) and interannual (1.9Sv) variability of the MOC. The seasonal variability of the MOC at 26°N can be attributed mainly to the seasonality of the Ekman transport, which has a standard deviation of 1.9Sv. Ekman transport makes up about 25% of the time-mean and interannual transports (4.9 Sv and 0.56 Sv respectively). The MOC at 26°N in ORAS3 shows a small decrease over the 48-year period which amounts to –0.07 ± 0.01 Sv/yr, equivalent to a reduction of 4% per decade, although from figure 1 it is clear that this trend is not constant (e.g. the trend after the mid-1970's is only 2% per decade).The weakening MOC is associated with changes in vertical structure of the circulation (figure 2a). Consistent with BLC05, there is a reduction in the southward transport of the lower North Atlantic Deep Water (NADW) in ORAS3, associated with a shallower and weaker recirculation cell. This is an important difference from the 11-year ECCO-GODAE reanalysis (Wunsch and Heimbach, 2006), which also shows a slow-down of the MOC, but with an intensification of the southward NADW flow. (The differences between ORA-S3 and ECCO-GODAE are likely to stem from the different assimilation methods). IThe coherent changes in the vertical structure of the circulation occur at low frequency, and do not seem to be affected by the seasonal variability of the Ekman transport. This implies that vertical structure comparisons with BLC05 are more robust, since they are not contaminated by high frequency variability.

Figure 2a also shows a reduction of the northward transport within the thermocline which, according to Cunningham and Alderson 2007, results from an intensified southward geostrophic transport caused by the increased east-west thermocline slope, and is consistent with the changes in the vertical density structure in ORAS3. There is a general warming and salinification in the upper subtropical ocean, indicative of thermocline deepening, which is more pronounced in the western part of the basin. ORAS3 also reproduces an increase in temperature and salinity (0.42 K and 0.07 psu respectively at 450m) in the Eastern Atlantic between 1992 and 2002, noted by Vargas-Yáñez et al (2004) from a cruise survey at 24°N.

The time variability of the MOC in ORAS3 changes considerably as a function of latitude (figure 2b). Within the subtropical gyre (south of 30N) the interannual variability is dominant, while in subpolar latitudes decadal variability is stronger. A reduction in the MOC (2-4% per decade, supplementary table 2 and supplementary figure 4) is apparent in most of the North Atlantic domain, and is particularly pronounced after 1995, with a visible reduction in the meridional extension of the MOC. Häkkinen and Rhines (2004) attribute this reduction of the MOC after 1995 to the weakening of the subpolar gyre (SPG), characterized by a decrease in sea level gradients from satellite altimetry. The intensity of the SPG in ORAS3 (measured by the sea level differences between 40N and 60N) is correlated with the MOC at 50N at interannual time scales (r=0.8), in agreement with Böning et al (2006), with the MOC in ORAS3 lagging the subpolar gyre by 18 months (figure 3). But contrary to other model studies, the secular trends of the MOC and the SPG found here are of opposite sign. There are several possible reasons for this: i) the atmospheric forcing fluxes (ORAS3 uses ERA40/OPS instead of NCEP) ii) the surface heat flux closure (in ORAS3 there is strong relaxation to time-varying SST, which may compensate for errors in the heat fluxes, thus contributing to a better simulation of the upper ocean warming); and iii) the representation of the overflows. For instance, Böning et al (2006) impose climatological boundary conditions at 70N, while ORAS3 overflow properties may vary in time and be affected by the assimilation of ocean observations.

4 Heat transports

It has been suggested that any slowdown of the MOC could have significant implications for the climate of Europe (Vellinga and Wood 2002) due to a resulting reduction in heat transport in the northward flowing upper limb. In ORAS3, the interannual variability in the heat transport at 26°N follows closely the MOC variability (correlated at $r = 0.9$), and also shows a small downward trend of -0.0029 ± 0.0007 PW/yr, equivalent to a reduction of 2.7% per decade. This fractional trend in heat transport is weaker than for the MOC over the whole North Atlantic domain (supplementary table 2 and supplementary figure 4). This is a consequence of the increased vertical temperature gradient resulting from a general upper ocean warming (Fig. 4). At 26°N there is a modest warming trend in the upper 300 m of 0.05± 0.01 K/decade, while at 40°N this increases to 0.26±0.04 K/decade. The increased upper ocean temperatures in the poleward moving branch of the MOC intensify the poleward heat transport, partially cancelling the effect of the weakening MOC, in agreement with the simulations of Drijfhout and Hazeleger (2006).

5. Sensitivity experiments

The time variability of the MOC reconstruction could be affected by variations in the observing system and spin-up effects. Here we use sensitivity experiments to assess the robustness of the ORAS3 results. The agreement with the observed temperature and salinity profiles is better for ORAS3 than for ORA-nobs (about 30% in the North Atlantic, supplementary figure 2). The improved representation of the density field affects both the mean overturning strength and the amplitude of the variability, improving dramatically the agreement with the BLC05 values relative to the ORA-nobs (fig 1), as well as the heat transports, which are underestimated in ORA-nobs (supplementary table 1). The coherence between ORAS3 and ORA-nobs is also apparent at 50N, where the MOC and the SPG intensity in ORA-nobs show positively correlated interannual variability and opposite secular trends (not shown).

The large degree of coherence between the time evolution of the MOC in ORAS3 and ORA-nobs is indicative of the atmospherically-driven component. ORA-nobs simulates the same large MOC values during the 60's, increased variability during the 80's, and the quasi-biennial signals after 2000. ORA-nobs also shows a decline in MOC intensity, although of a smaller magnitude than ORAS3 (2% per decade), suggesting that some trend is directly linked to changes in the atmospheric forcing. In contrast, the experiment with climatological forcing (supplementary figure 3), shows no significant trend after an initial adjustment, supporting the attribution of part of the MOC decline to the time-varying upper boundary forcing.

Direct comparison with the BLC05 value for 1957, outside the ORAS3 record, is not possible. Additional experiments, similar to ORAS3 but starting from 1956 were conducted. Prior to 1958 there is no ERA40 forcing, and so climatological forcing was used. Different ocean initial conditions were used: a) ORAS3 spin up, b) ORAS3 (1 Jan 1962) and c) ORAS3 (1 Jan 1965). None of these experiments reproduced the BCL05 MOC value for 1957, probably because of the scarcity of information (both observational and forcing). Results also show that the MOC converges to the ORAS3 value by 1962, suggesting that the spin up is not a determining factor in ORAS3 after 1962.

Additional experiments show that the estimated MOC trend and the specific agreement with the BLC05 values remain unchanged even if all the specific section data used by BLC05 are withdrawn from the ORAS3 reanalysis. This illustrates the ability of data assimilation systems to propagate observational information either directly, via the prescribed error correlation functions, or via physical processes represented by the ocean model.

6. Summary

These results show that assimilating data in ORAS3 improves the representation of the Atlantic MOC against section-based estimates, and permits a 48-year reconstruction, for the period 1959-2006, which exhibits a wide range of time variability (seasonal, interannual and secular trends). ORAS3 results suggest a slow-down of the MOC (2-4% per decade) for most of the North Atlantic basin, although the trends are not constant, being much smaller in the second half of the record.

The MOC variability in the subtropical gyre is highly correlated with the heat transport variability, but the trends in heat transport are weaker, due to slow changes in the vertical thermal structure, with the pronounced upper ocean warming partially compensating for the reduction in the MOC.

Sensitivity experiments suggest that either ERA40 atmospheric forcing and/or the strong constraint on the SST can explain some of the reduction of the MOC, but that the trend is enhanced by the assimilation of in situ ocean data. The results presented here support the paradigm of the North Atlantic Oscillation (NAO) as providing the primary forcing for the MOC at 50N on interannual timescales (Eden and Willebrand, 2001), with positive NAO conditions leading to the intensification of the MOC. However, the reduction of the MOC at 50N in ORAS3 under prevailing positive NAO conditions during recent decades, accompanied by the decline in the southward transport of the lower NADW, suggest that other factors are more important for the MOC on longer timescales.

These results illustrate the potential of ocean reanalysis for the study of ocean climate. In the latest IPCC Assessment Report, it was stated that due to the conflict between model and observational studies, “no coherent evidence” of a trend in the MOC over the last 50 years existed, and hence no baseline comparison was possible for climate model simulations. It is shown here that data assimilation can reconcile model and observations, giving a self consistent MOC timeseries which agrees with traditional section-based estimates where available. Sensitivity experiments can test robustness and further reanalyses based on other models and methods are underway (within CLIVAR-GSOP panel) that will further reduce the uncertainty in these estimations of the MOC. Ocean reanalysis should be able to provide a past baseline for MOC estimates, and more generally, a valuable gauge on the quality of climate models used for future climate projections. The uncertainties in the ocean reanalysis will be reduced, as the quality of the assimilation methods, ocean model and atmospheric reanalyses improves.

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Figures

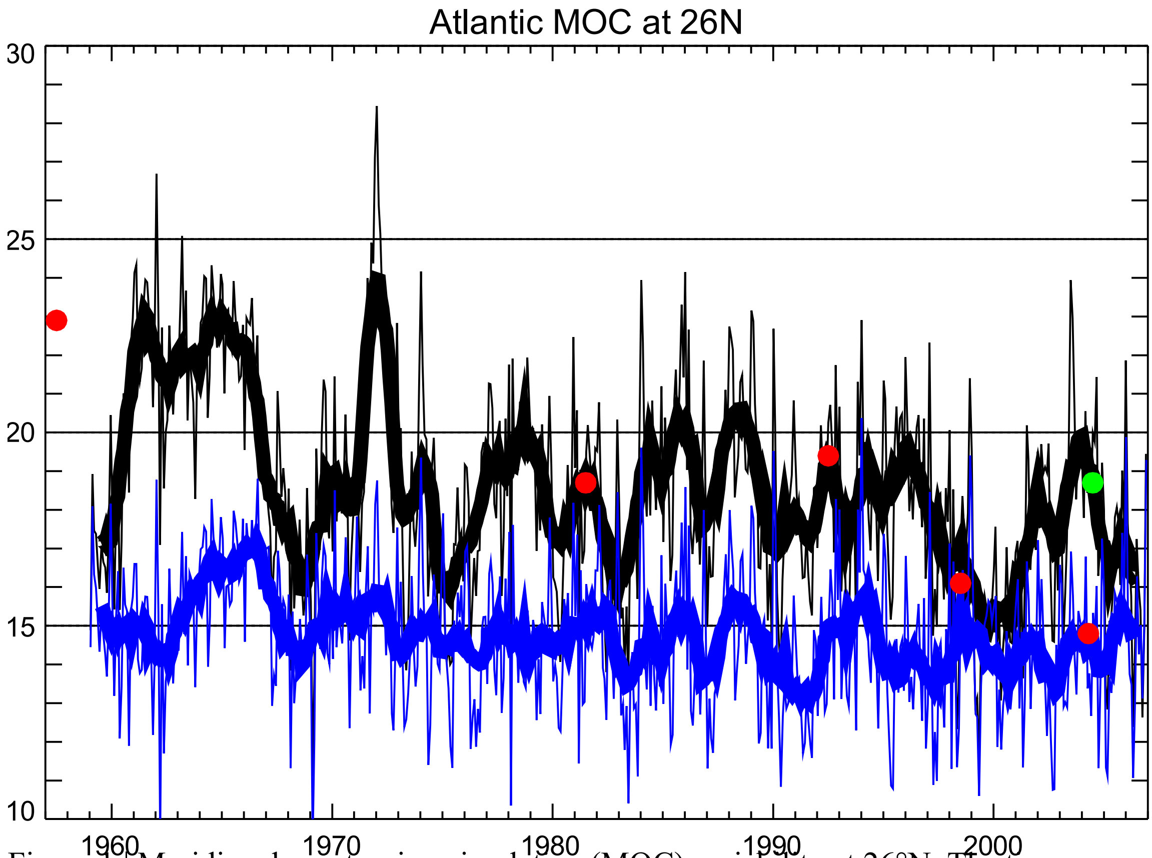

Figure 1 | Meridional overturning circulation (MOC) variability at 26°N. The time evolution of the MOC for both ORAS3 (black) and ORA-nobs (blue) is shown using monthly values (thin lines) and annual means (thick lines). Over-plotted are the annual-mean MOC values from BLC05 (red circles) and Cunningham et al 2007 (green circle).

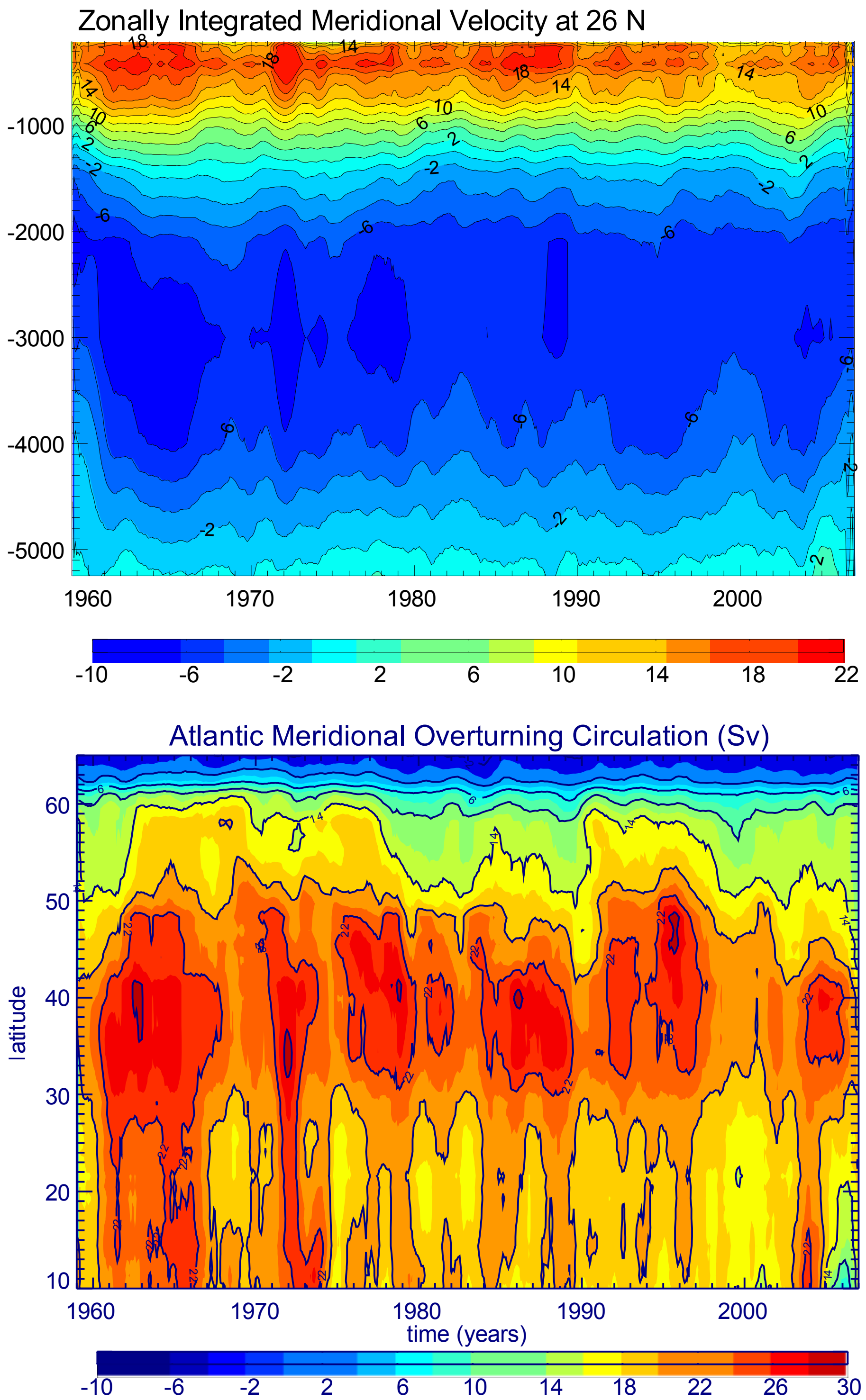

Figure2 | Vertical (a) and meridional (b) structure Atlantic MOC as a function of time. In (a) the vertical structure of the MOC is represented by the zonally integrated meridional velocity at 26°N, and units are $10^3 m^2/s$. Both the poleward transport within the upper 1000 m and the equatorward transports below 2000 m are decreasing with time. In (b), the MOC is calculated as the integrated meridional velocity above a reference depth of 1200m in units of Sv.

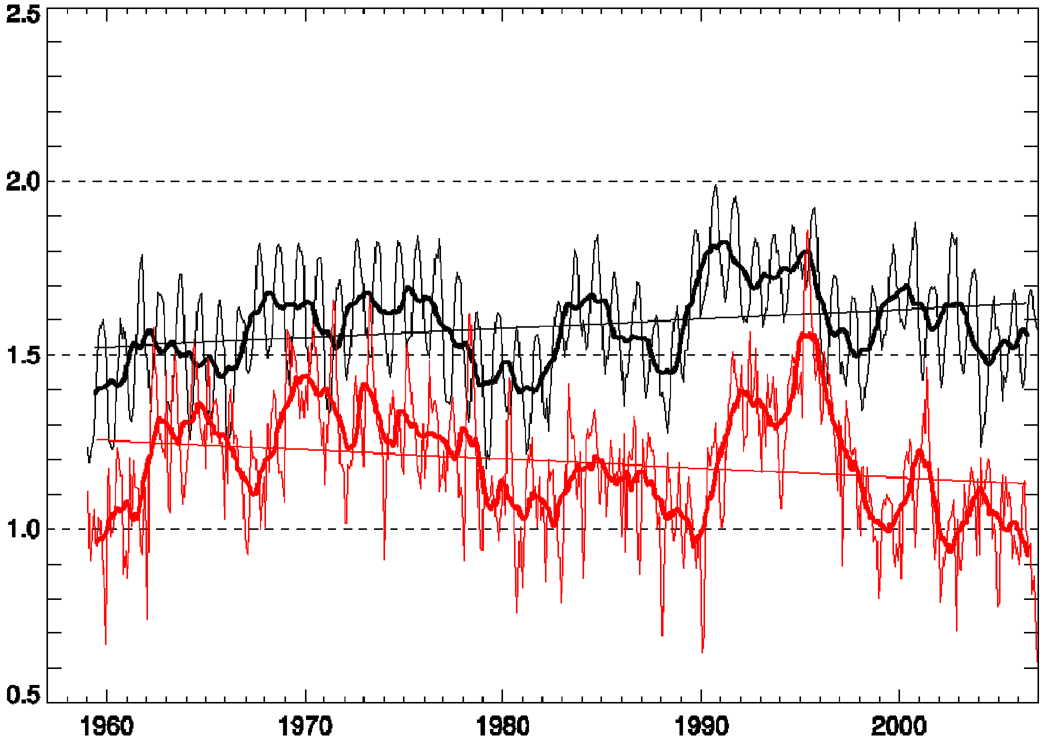

Figure 3 | Normalized timeseries of the subpolar gyre index (black) and MOC at 50N (red) from ORAS3. Overplotted are the linear trend estimates. The subpolar gyre index is computed as the sea level differences at 40N and 60N. The decrease in subpolar gyre intensity during the 90's is consistent with Hakkinen and Rhines 2004. The subpolar gyre variability leads the MOC variability at interannual time scales, but the trends are opposite.

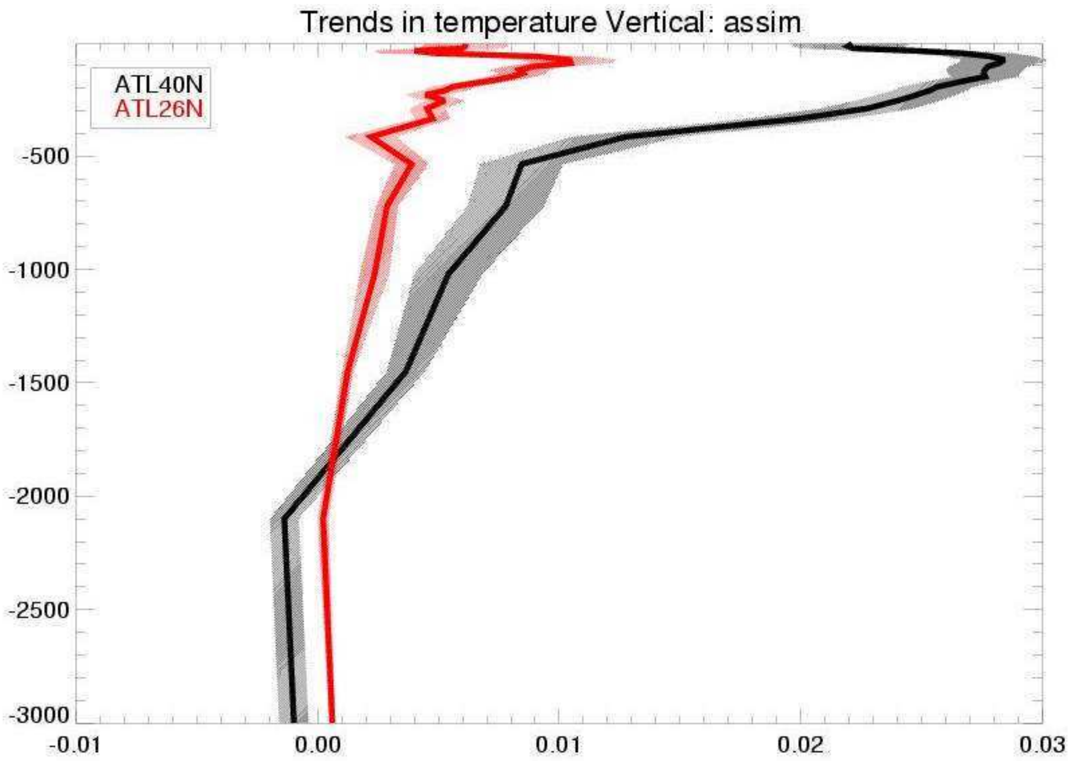

Figure 4 | Trends in the vertical temperature structure from the 48-year ORAS3 analysis, at 26°N (red) and 40°N (black). Units are K/yr. Shaded are the trend values within the 95% C.I.

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