Thermohaline circulation at three key sections in the North Atlantic over 1985–2002

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[1] Efforts are presently underway to monitor the Thermohaline Circulation (THC) in the North Atlantic. A measuring strategy has been designed to monitor both the Meridional Overturning Circulation (MOC) in the subtropics and dense outflows at higher latitudes. To provide a historical context for these new observations, we diagnose an eddy-permitting ocean model simulation of the period 1985–2002. We present time series of the THC, MOC and heat transport, at key hydrographic sections in the subtropics, the northeast Atlantic and the Labrador Sea. The simulated THC compares well with observations. We find considerable variability in the THC on each section, most strikingly in the Labrador Sea during the early 1990’s, consistent with observed changes. Overturning in the northeast Atlantic declines by ~20% over the 1990’s, coincident with an increase in the subtropics. We speculate that MOC weakening may soon be detected in the subtropics, if the decline continues in mid-latitudes.


1. Introduction

[2] The large-scale “Thermohaline Circulation” (THC) of the North Atlantic comprises the northward transport of warm, salty waters and the southward transport of colder, fresher waters. The associated ~1 PW of heat released to the overlying atmosphere in the subtropical and mid-latitude North Atlantic [Bryden and Imawaki, 2001] has a major influence on regional climate. Over much of the Atlantic, the THC can be characterized as a vertical structure of light upper flows and dense deep flows, amounting to a Meridional Overturning Circulation (MOC). Direct estimates of the MOC are based on only a few hydrographic sections in recent years [Lavin et al., 1998; Koltermann et al., 1999; Alvarez et al., 2002; M. O. Baringer and A. M. Macdonald, Subtropical North Atlantic Circulation and heat flux: 24.5N revisited, manuscript in preparation, 2005, hereinafter referred to as Baringer and Macdonald, manuscript in preparation, 2005].

[3] Efforts are presently underway to more routinely monitor the MOC, at selected hydrographic sections occupied during the World Ocean Circulation Experiment (WOCE). Under the auspices of CLIVAR, an Atlantic circulation observing system has been established (see http://www.clivar.org/organization/atlantic/IMPL/index.htm). Particular attention is being paid to WOCE section A5 at 26.5°N (Figure 1), as this latitude is close to the maximum in meridional ocean heat transport and has been occupied by five modern hydrographic sections over 1957–2004. A monitoring array is now in place at A5 (see http://www.soc.soton.ac.uk/rapidmoc/).

[4] The MOC monitoring array is complemented by the Arctic-Subarctic Ocean Fluxes Project (see http://asof.nopolar.no). A consensus view is that the THC is maintained by the formation, at high latitudes, of two dense water masses: Labrador Sea Water (LSW) and North Atlantic Deep Water (NADW). Here we consider that NADW comprises all dense overflows from the Nordic Seas that cross the ridges between Scotland and Greenland. The transport of LSW and NADW can be monitored on WOCE sections AR7W and A25 respectively (Figure 1). Repeat occupations of a further basin-wide section at around 48°N (A2) capture both LSW and NADW outflows, but monitoring near A2 is believed to be problematic [Baehr et al., 2004], and so is not considered here.

[5] Observations from the new MOC monitoring arrays and repeat occupations of the hydrographic sections are most fully interpreted in combination with state-of-the-art ocean model simulations. Such simulations can also establish the extent to which the MOC is a proxy for the THC, and the associated heat transport. Here we analyse an eddy-permitting model simulation of the global ocean circulation over 1985–2002 to hindcast the THC, MOC and heat transport at A5, A25 and AR7W.

2. Model Description and Experiment

[6] We use the Ocean Circulation and Climate Advanced Model (OCCAM), an ocean general circulation model coupled to a state-of-the-art sea ice model with elastic-viscous-plastic dynamics [Hunke and Dukowicz, 1997] and 3-layer thermodynamics. The version of OCCAM used here combines 1/4° × 1/4° horizontal (eddy-permitting) resolution [Saunders et al., 1999] with high vertical resolution - 66 levels with 14 in the top 100 m. The eddy-permitting resolution of OCCAM supports narrow boundary currents such as the Gulf Stream and frontal features, evident in the surface temperature field shown in Figure 1. These boundary currents are key “branches” of the observed THC. In an equivalent OCCAM simulation at 1° resolution, the boundary currents are unrealistically broad and we consider that the simulated THC is consequently compromised.

[7] Several features of the new model allow us to capture the spatial and temporal variability of the upper ocean. Key to this is the use of a comprehensive set of high frequency...
atmospheric fields together with a realistic bulk formulation of atmospheric forcing. Input fields of wind speed, air temperature, specific humidity, sea level pressure, cloudiness, precipitation and short wave radiation are used, together with the model top level temperature, to compute the heat and freshwater fluxes applied at each time step. Surface salinity is relaxed to monthly-mean observations, to account for runoff and inaccuracies in the precipitation observations. The input data were supplied by NCAR [Large et al., 1997; Kalnay et al., 1996]. Improvements in model physics (especially the mixed layer, isopycnal mixing, and sea ice) and the use of realistic, balanced surface forcing lead to improved simulation of the THC, compared to an earlier OCCAM simulation [Hirschi et al., 2003] in which sea surface temperatures and salinities were restored to monthly climatological values. [8] Initial tracer fields (potential temperature and salinity) are interpolated from the WOCE Special Analysis Centre climatology. The 1985–2002 simulation follows a 4-year spin-up during which 1985–88 forcing is applied and tracer fields are relaxed towards the initial values. For convenience, the A5 section follows 26°N, rather than following exactly the actual section, which deviates between 24°N and 26.5°N.

3. Validating the Simulated THC at A5 and A25

[9] The THC can be formally defined as northward flow of light waters and the southward flow of dense waters. Based on this definition, we partition transports across each section according to potential density ($\sigma_0$, units kg m$^{-3}$, henceforth omitted), in bins of uniform width 0.1 kg m$^{-3}$. Summing the partitioned transports over the range $22 < \sigma_0 < 29$, we obtain cumulative northward and southward transports. Figure 2 shows simulated and observed transports per density bin (Figures 2a and 2b) and corresponding cumulative transports (Figures 2c and 2d), for A5 in 1992 and for A25 in 1997.

[10] Some systematic differences arise between modelled and observed transports of southward-flowing dense waters at the two sections. In OCCAM, these transports occur at slightly lower density than is observed. Despite differences in the density of southward flows, total transports are very similar at both sections – see observed and modelled maxima in Figures 2c and 2d. The 1992 observations at A5 yield an estimated THC strength of $19.3 \pm 5.0$ Sv, where the model THC reaches 19.2 Sv. For A25, the 1997 observed estimate of THC strength is $18.7 \pm 3.6$ Sv, compared to 18.6 Sv in the model. Discrepancies between modelled and observed THC structure at intermediate and low densities (on both sections) may be due to differences between the climatological annual-mean winds used to compute Ekman transport (for the observations) and the reanalysed (6-hourly) winds applied in the model. Overall, we obtain good agreement between model and observations, given that the ocean interior is unconstrained. Based on this preliminary validation, we consider that the model can provide useful information about THC variability during the hindcast period.

4. Variability of the THC, MOC and Heat Transport

[11] In Figure 3 we show time series of southward transport in selected density ranges, and THC strength, on

Figure 1. Surface temperature in the extra-tropical North Atlantic of OCCAM, averaged over March 2002 of the simulation. Temperatures range from −2°C (blue shading) to 27°C (yellow shading). A rotated grid is used. For orientation, we show meridians at 30° intervals and lines of latitude at 15° intervals. The A5, A25 and AR7W sections, indicated in bold, follow the sides of gridcells to exactly capture model transports. The A25 and AR7W sections coincide as close as possible with actual occupations. For convenience, the A5 section follows 26°N, rather than following exactly the actual section, which deviates between 24°N and 26.5°N.
each section. THC strength is defined at the peak in cumulative transport (see Figures 2c and 2d) and captures both vertical and horizontal components of the THC: the MOC, dominant at subtropical latitudes; and the gyre transport, substantial at sub-polar latitudes. Similarities between Figures 3a and 3b reflect the dominant role in the THC of southward transport in the specified ranges of density. Most striking in Figure 3 is enhanced southward transport and THC strength at AR7W during 1989–95, associated with an episode of deep convection in the Labrador Sea. These simulated events are consistent with observations of the oceanic response to a positive phase of the North Atlantic Oscillation (NAO) during this period [Dickson et al., 1996]. At A25, gradual strengthening of southward transport over 1990–95 is followed by more rapid weakening over 1995–98. Southward transport and THC strength at A5 is relatively invariant.

[12] In Figure 4 we show time series of MOC strength and heat transport. MOC strength is defined as the southward transport of NADW, following observational practise for A5 [Lavin et al., 1998; Baringer and Macdonald, manuscript in preparation, 2005] and A25 [Alvarez et al., 2002]. MOC strength on AR7W (not shown) is rather weak and invariant, due to a largely horizontal THC structure, on this section, of northward flow off the west coast of Greenland and southward flow (of slightly denser waters) off the Labrador coast [Cuny et al., 2002]. Heat transports across A5 and A25 are in good agreement with recent estimates, capturing the largely seasonal differences between 1992 and 1998 at A5 (Baringer and Macdonald, manuscript in preparation, 2005) and the rather high value estimated for A25 in 1997 [Alvarez et al., 2002].

[13] Variations in THC strength and MOC strength are highly correlated at A5 and A25 (r = 0.71 in both cases), confirming that one is a reasonable measure of the other. In absolute terms, based on period means, MOC strength over-estimates THC strength at A5 by 2.9 Sv, while under-estimating THC strength at A25 by 3.9 Sv. These differences are attributed as follows: at A5, to the influence of an abyssal Antarctic Bottom Water cell; at A25, to a substantial contribution from the horizontal gyre. Monthly heat transport is significantly correlated with monthly MOC strength at both A5 (r = 0.69) and A25 (r = 0.42). Enhanced THC strength and heat transport at A25 during 1995–97 is consistent with a recent finding that periods of strong LSW formation are followed nearly three years later by stronger heat transport in mid-latitudes [Gulev et al., 2003].

[14] Changes on decadal timescales are also evident, most clearly in MOC strength in the subtropics and northeast Atlantic since the early 1990’s: an increase of ~3 Sv at A5 and a decrease of ~3 Sv at A25. Corroboration of such short-term trends is severely restricted by infrequent occupation of the sections and the conservative error bars on observed transports. However, we argue that this secular change is due to trends in the forcing, rather than model drift linked to poor maintenance of NADW: long-term (1985–2002) change in the volume of NADW (27.9 < σ0

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**Figure 3.** Time series of (a) southward transport (Sv) and (b) THC strength (Sv), at the three sections. The thin (thick) curves show monthly-mean (annual-mean) values. Southward transports are in the selected density intervals: 27.8 < σ₀ < 27.9 at A5 and AR7W; 27.7 < σ₀ < 27.8 at A25. For definitions of THC strength, see text. Also shown are the transports observed at A5 in 1992 and at A25 in 1997 (both in the density interval 27.8 < σ₀ < 27.9), and the THC strength at A5 (1992) and A25 (1997), computed from available hydrographic datasets. Corresponding error bars are based on values estimated in the original transport calculations.

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**Figure 4.** Time series of: (a) MOC strength (Sv) at A5 and A25; (b) Heat transport (PW) at A5, A25 and AR7W. The thin (thick) curves indicate monthly-mean (annual-mean) values. For definitions of MOC strength, see text. Also indicated are recent published estimates of the MOC and heat transport at A5 and A25, including the corresponding error bars.
< 28.1) north of A25 equates to a steady decline at the rate of only \~1 Sv, which is considerably smaller than the changes in transport. Monthly MOC strengths at A5 and A25 are significantly anti-correlated (r = \(-0.38\)). This may reflect opposing changes in winds in the subtropics and the mid-latitudes, associated with a large-scale mode of atmospheric variability such as the NAO, i.e., the changes in MOC strength are due to regional atmospheric forcing. Alternatively, MOC changes in the subtropics could originate at higher latitudes and the decline in southward transport of NADW across mid-latitudes may reach the subtropics after a time delay of around a decade. This timescale is suggested by the interval between peaks in MOC strength at A25 (early 1990’s) and at A5 (around 1998–2001), and estimated transit times for advection between mid-latitudes and the subtropics [Molinari et al., 1998].

5. Summary and Conclusions

In summary, we have sampled a realistic simulation of the ocean circulation to obtain continuous time series of monthly THC and MOC strength, and heat transport, in the North Atlantic over 1985–2002, at three sections where hydrographic monitoring efforts are underway and planned. Several observed phenomena are simulated, notably a reduction in LSW formation and Labrador Current transport (equivalent to THC strength at AR7W) since the early 1990’s, as seen in direct current-meter observations and satellite altimetry data [Häkkinen and Rhines, 2004]. However, strong Labrador Sea convection in the early 1990’s has relatively little impact on transports at A5 and A25, consistent with a hypothesis that LSW plays only a minor role in the MOC [Koltermann et al., 1999].

Our hindcast volume and heat transports in the North Atlantic are closer to observations than estimates for 1993–2000 obtained by an ocean model constrained with WOCE data [Stammer et al., 2003], probably due to our use of realistic surface fluxes and higher resolution. Furthermore, the global domain and eddy-permitting resolution of OCCAM ensure more vigorous transports than those obtained in similar hindcast experiments with a lower resolution Atlantic sector model [Gulev et al., 2003]. Our results are of relevance to measurements that will be obtained from the monitoring array now in place at 26.5°N. In particular, a reduction in overturning may be detected in the next decade, if deep outflows continue to decline in mid-latitudes. The simulation presented here should also help to place in context longer-term THC reconstructions and predictions based on simulations with coupled climate models [e.g., Wu et al., 2004]. Work in progress to investigate the causes of simulated THC variability. Considering further repeat sections and mooring sites, we are also using the simulation to help interpret sparsely located time series of the Atlantic MOC.

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References


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