Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993–2004

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(Manuscript received 14 October 2005, in final form 15 February 2006)

ABSTRACT

Results from a global 1° model constrained by least squares to a multiplicity of datasets over the interval 1992–2004 are used to describe apparent changes in the North Atlantic Ocean meridional overturning circulation and associated heat fluxes at 26°N. The least squares fit is both stable and adequately close to the data to make the analysis worthwhile. Changes over the 12 yr are spatially and temporally complex. A weak statistically significant trend is found in net North Atlantic volume flux above about 1200 m, which drops slightly (-0.19 ± 0.05 Sv yr^{-1}; 1 Sv $\equiv 10^6$ m^3 s^{-1}) but with a corresponding strengthening of the outflow of North Atlantic Deep Water and inflow of abyssal waters. The slight associated trend in meridional heat flux is very small and not statistically significant. The month-to-month variability implies that single-section determinations of heat and volume flux are subject to serious aliasing errors.

1. Introduction

The meridional overturning of the North Atlantic Ocean and its associated heat and salt transports have been the focus of much attention in recent years. That attention arises in part because of claims that "shutdown" of the meridional overturning circulation (MOC) caused the so-called Dansgaard–Oeschger (D–O) events—intervals of abrupt climate change in Greenland—and that modern global warming is likely to induce a similar change (see Broecker 2003; Curry et al. 2003). These and other alarming scenarios have led to a major program to determine the intensity and fluctuations in the North Atlantic MOC (see Srokosz 2003 or Schiermeier 2004).

The great interest in the subject of the MOC raises a number of novel oceanographic issues. In a turbulent fluid such as the ocean, no particular element of the flow is likely to remain absolutely steady through time. Indeed, the absence of variability on any time scale for any spatial scale would imply a spectral gap—none of which has ever been observed. (The existence of a true spectral gap would be of major theoretical importance.) Thus when some element of the ocean circulation is observed, and then variations in its location or strength are found, one must determine whether the changes exceed the expected degree of natural variability—before a true trend, much less a catastrophic one, is publicly proclaimed (e.g., Quadfasel 2005).

Is it likely that the meridional overturning circulation of the North Atlantic (however defined) is steady on all time scales? That is, given some arbitrary time interval τ there are three possibilities: 1) no change, 2) increasing, 3) decreasing. In a noisy system, the probability of finding a strictly zero change is vanishingly small, and thus one expects to see either an increase or a decrease. Whether the magnitude is sufficiently large to warrant comment is a matter of judgment. The ability to detect a statistically significant change depends directly upon the sensitivity of the observation system and the nature of low-frequency variability not connected to a secular process. That is, even statistically strictly stationary geophysical systems are expected to undergo low-frequency variations that can appear to be trendlike in nature, but which are not evidence of any secularity (see, e.g., Wunsch 1999). Until recently, relatively little has been reported about large-scale oceanic flow variability, simply because the observing tools were inadequate to define any instantaneous value, much less detect changes (see, e.g., Siedler et al. 2001). (Model results have been published, but they are difficult to

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evaluate without adequate observations for serious quantitative tests.)

Since the beginning of the World Ocean Circulation Experiment (WOCE) circa 1992, it has finally become possible to assemble data defining the oceanic circulation with an accuracy apparently permitting the detection of true change, whether secular or otherwise. When it comes to the North Atlantic MOC, the following two questions must be answered: 1) What is the nature of the change and how large is it? 2) Does the change represent a trend or is it a mere statistical fluctuation of the magnitude one would expect would always be present? An overview of this problem was given by Baehr et al. (2004). Elsewhere, Wunsch (2006) suggested that the D-O events are a consequence of the existence of the large continental ice sheets of the last glacial period, probably involve the ocean circulation as a secondary effect rather than as a trigger, and have no particular relevance for the modern world. The questions of the nature and magnitude of fluctuations of the modern ocean circulation stand, however, as important and interesting scientific problems irrespective of the probability of truly abrupt climate change.

The purpose of this paper is to exploit a global model and its least squares fit to a large volume of data over a decadal interval to begin characterizing the nature of the fluctuations in the North Atlantic MOC in recent years.[1]

2. Basis of the estimate

The Estimating the Circulation and Climate of the Ocean (ECCO) Consortium has demonstrated (Stammer et al. 2002, 2003) the practicality of global fits of a general circulation model to observations of essentially arbitrary type. As in those previous publications, we use the ECCO form of the Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al. 1997) as modified in the intervening years, now at 1° spatial resolution. The datasets used are listed in the appendix to this paper. There are approximately two billion data used as separate constraints, with the count including the meteorological variables. In comparison with the previously published results (Stammer et al. 2002, 2003) using what we refer to as model version 1, the major changes include the extension of the calculation now through 2004 and the increase in resolution to 1° of latitude and longitude from 2°. The newer Consortium is designated the Global Ocean Data Assimilation Experiment (ECCO-GODAE). Köhl et al. (2006) used a 1° solution that differs in a large number of details from that used here, including our substitution of the Gouretski and Koltermann (2004) climatology below 300 m instead of the *World Ocean Atlas*, extension of the estimation interval through 2004, modified estimates of the errors in most of the data and in the model, and many more iterations are used to reduce the misfits. In addition, the data now include a large number of "Argo" float temperature and salinity profiles, and employment of the Gravity Recovery and Climate Experiment (GRACE) geoid. The modified error estimates, which in many cases are dominated by oceanic variability and thus have an important descriptive oceanography role, will be reported elsewhere (Ponte et al. 2006; Forget and Wunsch 2006; Stammer et al. 2005, manuscript submitted to *J. Atmos. Oceanic Technol.*) Wunsch and Heimbach (2006) provide an overview of the models and methods used. Because of the ongoing nature of the calculations, we label the results here as from model version 2 with an iteration number; thus, the results are from ECCO-GODAE solution 2.177, chosen because the misfit reduction had largely ceased.

The solution is a global one except for the Arctic above 80°N, and near to complete consistency with the data. Total consistency will probably never be achieved, if only because the accuracy and precision of the data and of the model are imperfectly known. Nonetheless, the results appear to be largely insensitive to improving estimates of the data error and to the continuing reduction in the objective function. Nonetheless, as in any least squares problem, the nature of the solution can be controlled to a large extent by the prescribed model and data errors. Furthermore, in a nonlinear least squares problem, one is vulnerable to the possibility of the existence of other, different, acceptable solutions. Experiments are underway to explore the possibility of qualitatively different results, still within error bars, but the outcome of those calculations cannot be anticipated at this time. Thus we cannot, and do not, claim that the solution is "correct," merely that it is the current best estimate using all the listed data, the particular general circulation model, and existing understanding of the error budgets.

The bulk of the available data has been obtained above about 2000 m in the ocean, with the only direct observations below that depth coming from the WOCE hydrographic lines. Although more abyssal observations would be welcome, it is misleading to conclude that the deep ocean is largely unconstrained. Some

[1] We avoid the terminology "thermohaline circulation," which has become debased by sloppy usage. One must distinguish the circulations of mass, heat, and freshwater. Here, "MOC" refers to the mass flux; it has an associated meridional heat flux.

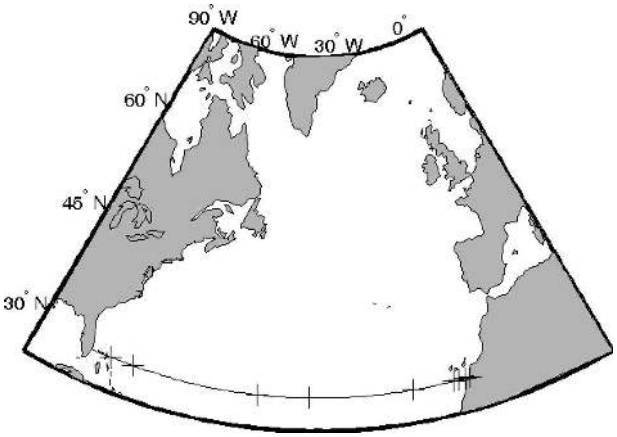

FIG. 1. Line at 26°N across which fluxes are discussed. The plus signs denote positions of U.K. RAPID moorings in the North Atlantic.

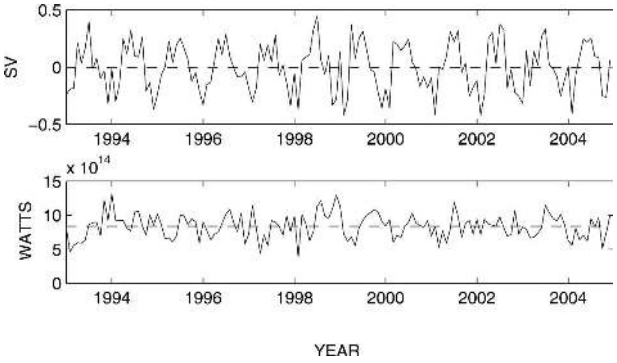

FIG. 2. (top) Net (top to bottom integral) volume transport at monthly intervals across 26°N in the North Atlantic as a function of time from the optimized ECCO-GODAE model (solution V2.177). Values represent primarily fluctuations in seasonal mass storage. (bottom) The monthly mean net heat flux (W). Ticks denote the beginning of the year.

properties, such as volume conservation, involve integrals over the entire system; other constraints, for example, altimetric measurements of sea surface height, reflect vertical integrals over the full water column. Last, and perhaps most important, observed fluctuations in the upper ocean are coupled dynamically to fluctuations in the deeper ocean, and the requirement that the solution must be consistent with the GCM provides powerful constraints on the behavior of the deep sea.

The focus is on latitude 26°N in the Atlantic—a line chosen to be close to the nominal 24°N North Atlantic hydrographic section that has now been repeated five times since 1957 (Baringer and Molinari 1999; Lavin et al. 2003; Bryden et al. 2005), and corresponding to the mooring array deployed at this latitude by the U.K. Rapid Climate Change Programme (RAPID) (see Fig. 1). The major known exceptions to the claim that the model is consistent with the data concern the most recent (years 2003–04) ARGO temperature profiles in the far northeastern North Atlantic, the southeastern South Pacific Ocean, and in the Southern Ocean. These misfits may well disappear as the solution is improved. But, in any case, misfits in these regions so recently are unlikely to have any significant impact on the solutions at 26°N until the corresponding signals can penetrate there. At 24°N, the Gulf Stream is bounded on both sides by land, and the ongoing volume transport estimates there have been widely used in estimating the zonal volume and horizontal heat transports.[2] In the ECCO-GODAE calculations, no volume transport constraints have been used thus far.

An important conceptual point is that although the ECCO-GODAE model is sometimes referred to as "constrained," the solutions displayed are all from a conventional, freely running, forward calculation. The constraints from all observations are used to adjust boundary/initial conditions and model parameters, with the unconstrained GCM then time-stepped with these modified values.

Figure 2 displays the time series of volume transport integrated vertically and zonally across the North Atlantic at the reference latitude. Fluctuations occur, dominantly in the annual cycle, at a magnitude of about ± 0.3 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) and represent temporary water storage effects (the global mean sea level rise of about 3 mm yr^{-1}, if typical of the North Atlantic, requires an undetectable volume transport increase across 26°N). The mean meridional heat transport is $(0.84 \pm 0.18) \times 10^{15}$ W where the error bounds are based purely on the temporal variance—assumed independent month-by-month. Most direct estimates of the heat transport across this line (Lavin et al. 2003; Ganachaud and Wunsch 2003) are higher (e.g., the latter estimate 1.3 ± 0.2 PW, the former 1.4 ± 0.4 PW) and thus the main error (if there is one—note that the estimated two-standard-deviation uncertainty ranges overlap) appears to be a bias of a few tenths of a petawatt. The major generator of this hypothetical bias error is probably the inability of a 1° resolution model to properly reproduce the volume and temperature extremes present in the real ocean. That is, the heat transport involves the integral of the product vT of velocity v and temperature T. Any underestimate of the extreme values of v and T that are collocated (as in the

[2] Because the model employs the Boussinesq approximation, it is more appropriate to refer to the volume flux rather than the mass flux, although for present purposes, there is no difference of interpretation.

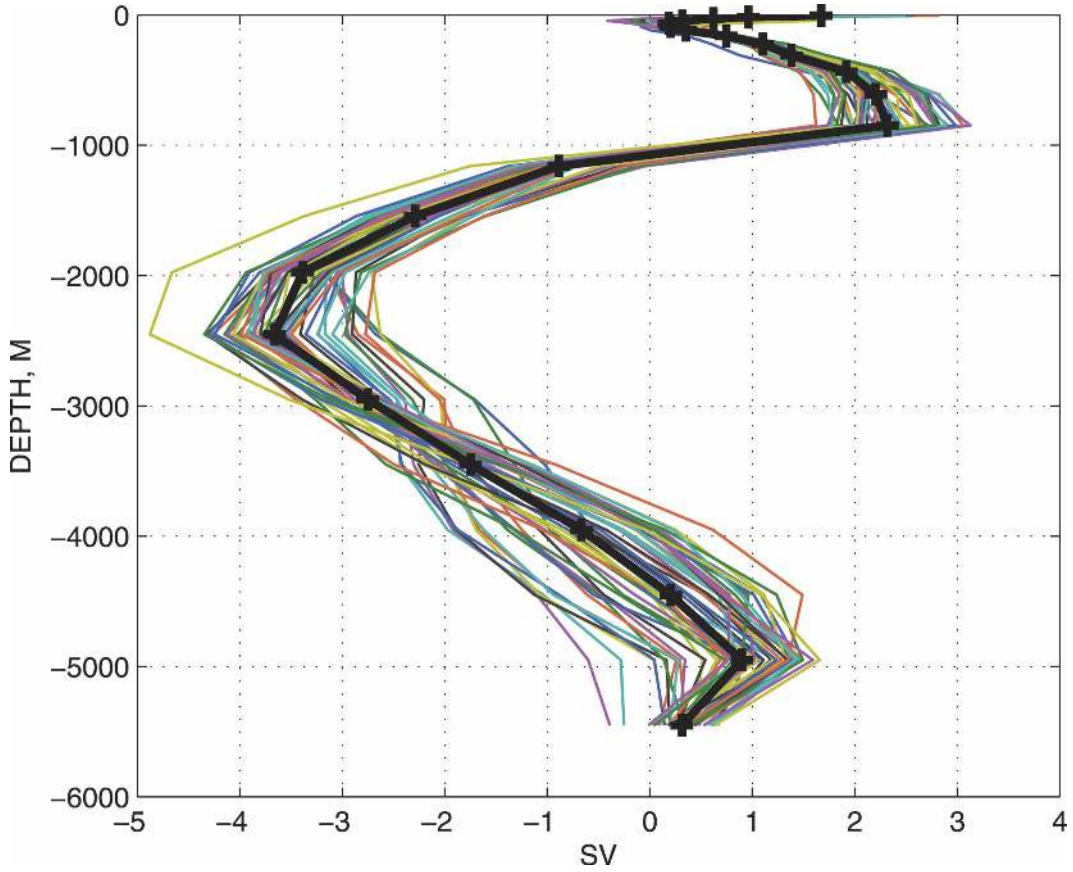

FIG. 3. Zonal integrals (Sv) of the North Atlantic seasonally averaged (3-month mean) velocity fields multiplied by the appropriate layer thickness as a function of depth. There is a near-zero value close to 1165-m depth. Plus signs and heavy line denote the time-mean values.

Gulf Stream warm core and the cold core of the Deep Western Boundary Current) can lead to a bias toward zero of the meridional heat transport. Experiments with coarsening the resolution of hydrographic sections (not shown) confirm a reduction in estimated poleward heat transport. There is a nonadvective heat transport in the model carried by the lateral diffusion and eddy-parameterization terms; at this latitude it is slightly negative on average, but negligible.

3. Diagnosing the variability

Figure 3 shows the 3-month-averaged, zonally integrated velocities as a function of depth. The mean volume transports correspond to an upper ocean moving northward, an intermediate depth flow to the south [roughly identifiable as North Atlantic Deep Water (NADW)], and an abyssal flow of varying sign. Note that both the zonal mean and its variability nearly vanish at about 1165 m, the bottom of model layer 14, and we will use that depth as a convenient division between upper and middepth ocean. The demarcation between the southward-going intermediate waters and the abyssal water is much less clear. Somewhat arbitrarily, we will use depth 4450 m (the bottom of layer 21), where the mean meridional flow crosses zero, as the upper level of the abyssal waters. The season-to-season variability is quite large, and this system noisiness is important for later comparisons with other estimates.

Figure 4 displays monthly values of the zonal integral of the volume transport integrated from the surface to 1165 m, and from 1165 m to the abyssal layer starting at 4450 m. The time-mean volume transport above the upper dividing depth is 13.2 ± 1.8 Sv, and is a measure of the strength of the meridional overturning circulation; the standard error is computed after removal of the trend. (If the mean MOC is measured by determining the depth to which integration produces the maximum northward transport integrated from the surface, it is 14.1 ± 2.3 Sv; both estimates are consistent with independent calculations of the MOC at this latitude, although definitions vary, and the monthly range is

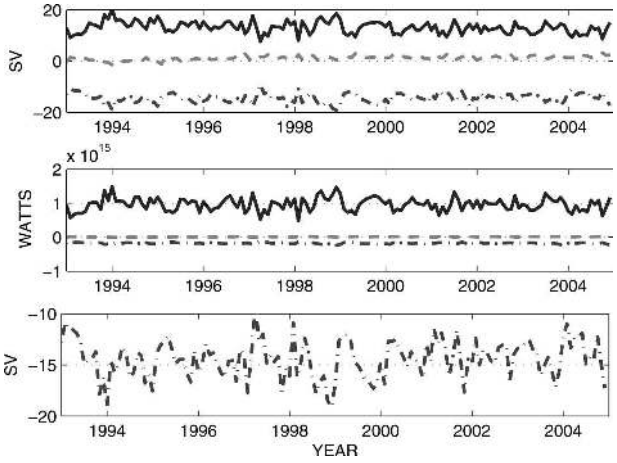

FIG. 4. (top) Monthly mean zonal and vertically integrated volume flux above 1165 m (solid) between 1165 and 4450 m (dash–dot) and 4450 m to the bottom (dashed line). (middle) Vertically integrated temperature flux from the surface to 1165 m and from 4450 m to the bottom. The weak decreasing trend in the volume flux of the upper ocean, and corresponding increases in the flux in the middepth and abyssal waters are visible by eye. The month-to-month variability is large (the 1165–4450-m volume flux varies between −9 and −19 Sv) leading to the high probability of aliasing in subsampled estimates. (bottom) An expanded scale version of the 1165–4450-m curve in the top panel to emphasize the month-to-month variability.

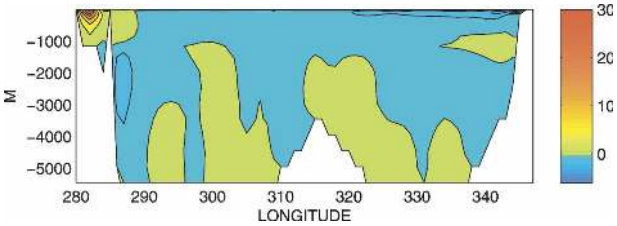

FIG. 5. Twelve-year mean velocity from the constrained model. Blue areas are flowing southward. Note that the flow boundaries do not have a simple connection with the water mass structure, even after 12 yr of averaging. An Antilles Current and a weak Deep Western Boundary Current are visible.

from 8 to 21 Sv.) The main result is that significant volume transport fluctuations occur month to month in which the upper and lower oceans tend to strongly compensate each other. Figure 4 also shows that the temperature-weighted volume transport is dominated by the upper ocean, which has a much larger temperature contrast available than does the lower ocean.

The heat transport variability, from one point of view, is a property almost purely of the upper ocean; on the other hand, the volume transport variability generating the heat transport changes requires mass transport changes in both upper and lower ocean—one cannot really understand the system by ignoring the abyss (cf. Boccaletti et al. 2005; Saenko and Merryfield 2006).

Further description of the variability can be obtained by examining the vertical and zonal structure of the temperature and velocity fields. To that end, Figs. 5 and 6 show the time average of the velocity $\overline{v}(x, z)$ and temperature $\overline{T}(x, z)$ fields. The temperature field is conventional—with the expected thermocline structure and with some structure on the west. The mean velocity field is dominated by the Gulf Stream and an interior southward return flow above about 1165 m, but with a complex structure in the abyss. As one has come to expect, there is no simple layered flow, rather it has, even after 12 yr of averaging, a complex spatial structure. In the flow field, the model Gulf Stream, Antilles Current, and Deep Western Boundary Current are visible on the west. As expected, the model Gulf Stream is somewhat broader than it is in reality.

The mean anomalies of velocity, $v'(x, z, t)$, and temperature, $T'(x, z, t)$, over successive 3-yr intervals are shown in sequence in Figs. 7 and 8. The space–time variability of both temperature and velocity is intricate, and it is difficult to produce a simple verbal description of how the system changes year to year. This structure has consequences, which are taken up at the end, for the in situ detection of change. The general warming trend in the eastern Atlantic near 1000 m and near-surface cooling is not inconsistent with the result of Vargas-Yáñez et al. (2004), but the latter is subject to significant temporal aliasing effects. That the errors in the time means are dominated by temporal variability is consistent with the inferences of Ganachaud (2003).

Three terms $\overline{v}(x, z)T'(x, z, t)$, $\overline{T}(x, z, t)v'(x, z, t)$, and $v'(x, z, t)T'(x, z, t)$ contribute to the temporal variability of the heat transport (not shown) when integrated in z, x. Any of these terms can contribute to a trend, but here $\overline{T}(x, z, t)v'(x, z, t)$ is by far the largest of the four terms; that is, the long-term variability arises primarily from the velocity field, not the temperature changes.

4. Trends

Models drift both because of real physical changes in their forcing and through internal variability. They also drift for numerical reasons, and distinguishing physically meaningful changes from those that arise from numerical issues (inconsistent initial conditions, missing physics, etc.) is necessary. Trends in temperature (not transport) at this latitude can be deduced from the repeated hydrographic lines. Parrilla et al. (1994), using three of the repeats, reported changes between 1957 and 1992 corresponding to a maximum shift of 0.1° (10 yr)$^{-1}$ at 1000 m. Other estimates of trends exist [e.g., Arbic and Owens (2001), who suggest 0.05°C (10 yr)$^{-1}$ in the general area]. These estimated trends include any

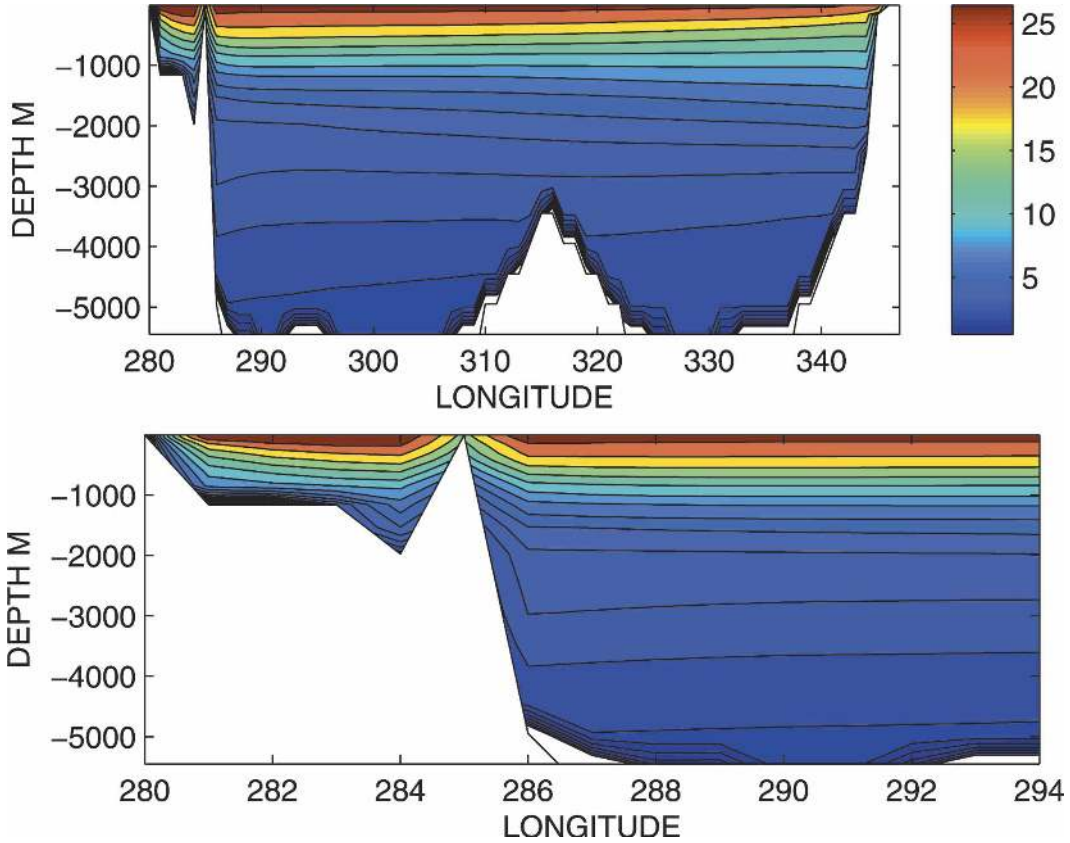

FIG. 6. (top) Twelve-year mean temperature from the constrained model. (bottom) Same as the top, except an expanded version on the west.

high-frequency noise present (eddies, etc.) that, because of the infrequent sampling, can alias into an apparent trend. The observed trends, globally, are poorly determined. The ECCO-GODAE state estimate includes a requirement that the initial and terminal time temperatures in the state should not differ by more than 0.83°C $(10\ \text{yr})^{-1}$ at the surface, with the permitted deviation declining to 0.2°C $(10\ \text{yr})^{-1}$ at 850 m, and finally to 0.1°C $(10\ \text{yr})^{-1}$ at 1975 m, with a bound of 0.08°C $(10\ \text{yr})^{-1}$ below that. For salinity, the corresponding changes are 0.21 (practical salinity scale), 0.03, and 0.016 in the abyss. Constraints are placed on the vertical velocity changes, but not on the horizontal ones. There is no evidence that these constraints are restricting the trends obtained, but the question is one that must be borne in mind. (The total number of data constraints given above includes these trend restrictions.) The ECCO-GODAE state estimates do display significant volume transport trends in the Southern Ocean (to be discussed elsewhere), consistent with the inference that the constraints are not overly restrictive.

One difficulty in assessing changes in optimized models lies with trends in the data distributions. In the present case, some of the datasets being employed (altimetry, CTDs, etc.) are, to a first approximation, homogeneous in time, although data densities and coverage do, however, vary. ARGO data become much more plentiful toward the end of the estimation period, and the consequences of this changing data density are obscure. On the other hand, overall, there is no evidence for a drift in the misfit to the hydrographic data over the period (G. Forget 2005, personal communication).

Figure 9 displays the contours of the zonally summed transport through time and depth $v_i \Delta z_i$. Visually, there appears to be a trend in the transports as a function of depth—with the upper ocean northward flow weakening, and both the middepth return flow and bottom water transport strengthening. As already noted, the absence of changes in a complex fluid flow would be remarkable. In this form of display, the appearance of trends is visually compelling, although the top-to-bottom integrated properties in Fig. 2 do not have so clear a visual structure and one cannot reduce the changes to a single statement about strengthening or weakening of the volume transport. The zonally integrated temperature anomaly through time is shown in Fig. 10. Slight

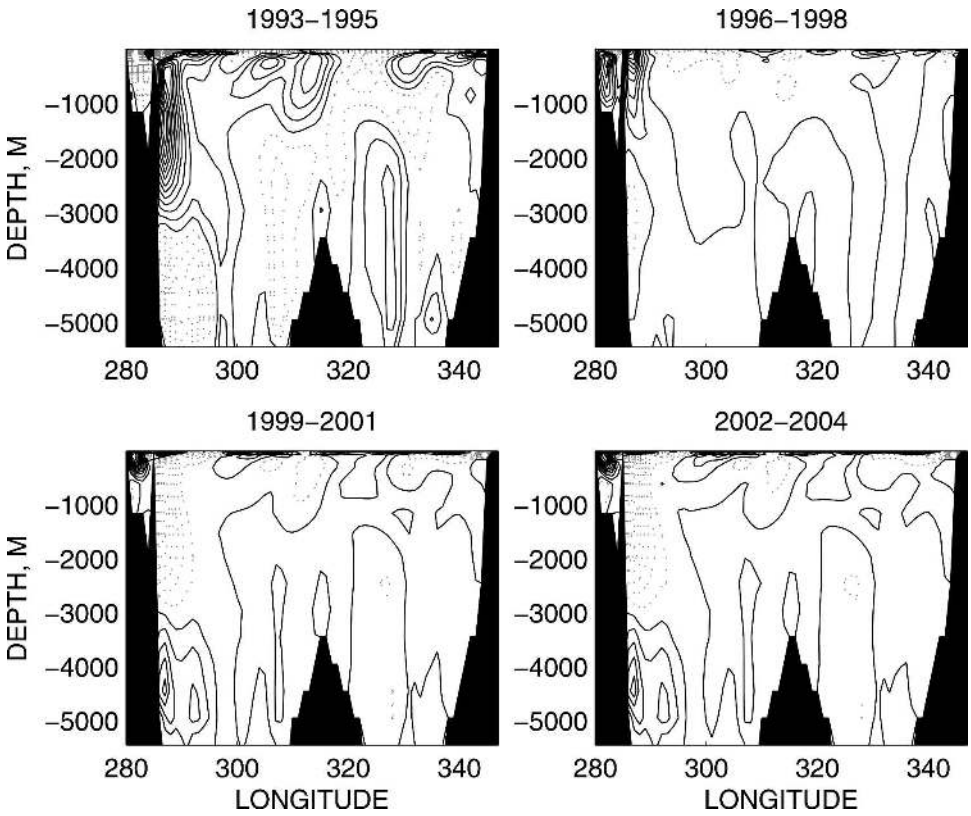

FIG. 7. Velocity anomaly as 3-yr averages from the model, V2.177. Contour interval is 0.05 cm s^{-1}. Dashed contours are negative. Note relative stability of last 6 years.

temperature trends, in the interior of less than 0.1°C net change, are visible. As already noted, the heat transport trend is dominated not by temperature change, but by volume transport change.

The raw trend in the volume transport above 1165 m, is about -0.19 ± 0.05 Sv yr^{-1}, with the uncertainty based upon the assumption that the noise is white in character. A spectral density estimate of the upper ocean volume transport (not shown) displays a slight red-noise character. Trend determination in the upper ocean transport should take this structure into account. [The upper ocean transport is indistinguishable from an AR(1) with coefficient $a_1 = 0.44 \pm 0.07$.] If the uncertainty is inflated by about 1/0.8 to account for the serial correlation, the apparent trend remains statistically significant. Whether the model has systematic errors that would influence the temporal changes is unknown.

The present estimate of an upper ocean volume transport decrease of 0.19 ± 0.05 Sv yr^{-1} is equivalent to a reduction of 2.3 ± 0.6 Sv over 12 yr, which appears roughly consistent with the Bryden et al. (2005, their Table 1) estimate for 1992–2004. We reiterate, however, the reduction is accompanied by a corresponding intensification of the deeper flows, and given the problems of aliasing, raises the question of whether the agreement is fortuitous.

A straight line fit to the net heat transport H_t produces a value $(-1.1 \pm 4.3) \times 10^{12}$ W yr^{-1}, where the uncertainty is calculated under the assumption that fluctuations in the monthly average heat transport are white noise. The spectral density estimate of H_t is indistinguishable from white, and all variables are at least approximately Gaussian. At the nominal value, the implied change is less than 1% yr^{-1} and the inferred trend is indistinguishable from zero.

There is no simple description of how the heat transport is maintained as the upper ocean volume transport decreases—the southward-moving, much colder mid-depth water volume, moves more strongly to the south, and the adjustment of velocity and temperatures in the annual profiles (Figs. 7 and 8) conspires to sustain the temperature/velocity covariances. Distinguishing cause and effect is not simply done.

5. Implications

The estimates made here suggest, on the basis of a combined GCM and a vast dataset, a small, but appar-

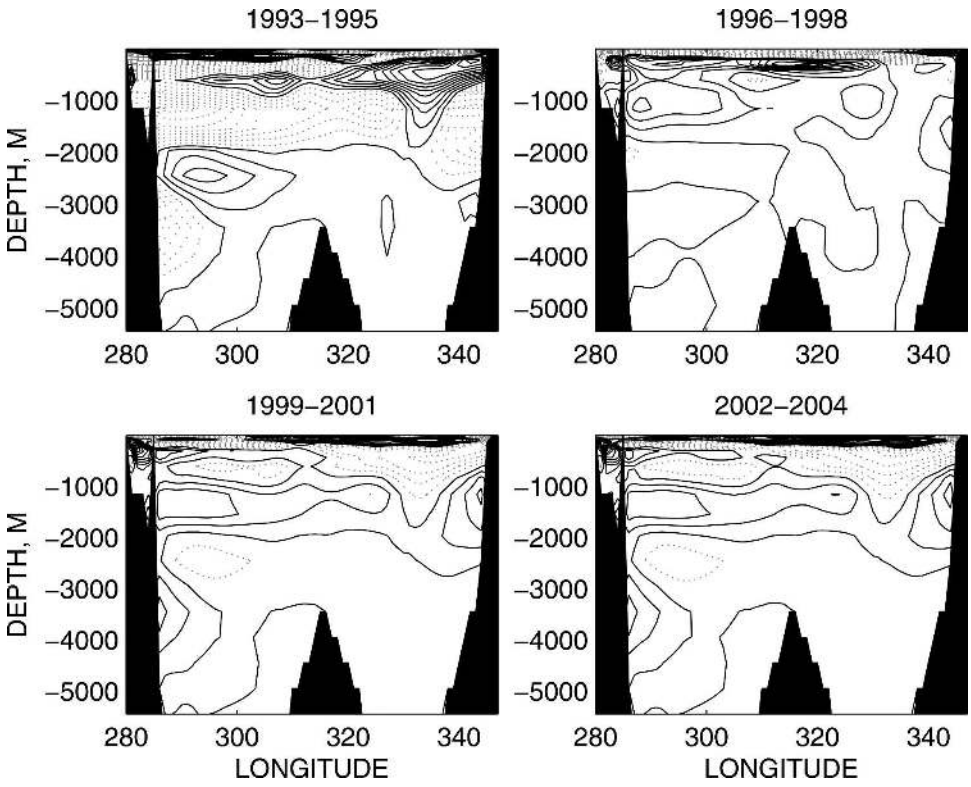

FIG. 8. Temperature anomaly contours averaged over 3 years corresponding to Fig. 7. Here contour interval is 0.025°C. Dashed contours denote negative anomalies. Note relative stability of last 6 years.

ently statistically significant, downward trend in the upper-ocean volume transport of the North Atlantic over the period 1993–2004, but an intensification of the deeper flows. Almost no change is seen in the estimated meridional heat transport. The conclusion raises a number of issues: 1) the physical cause of the volume transport trends; 2) whether the trends represent true secularities of indefinite duration, as opposed to fluctuations of processes varying on time scales much longer than a decade; 3) why the heat transport remains almost unchanged while upper-ocean volume transport decreases; and 4) whether an independent determination, for example, one based upon moorings, would be able to confirm the inferences. Baehr et al. (2004) describe a forward-modeling assessment of the prospects for direct, in situ detection by moored arrays of fixed instruments.

Issues 1 and 2 are closely related. Weak, spatially complex trends (not shown) are found over the estimation period in both the National Centers for Environmental Prediction (NCEP) and the adjusted meteorological fields. For example, over parts of the North Atlantic, there are regions of both increased and decreased zonal wind stress, and wind curl. Regional trends are found everywhere around the world. Attaching a causality relationship between such shifts and what is observed in the state estimates is a very difficult, and perhaps impossible, job—given the shortness of the record and the ability of the ocean to capture and integrate variability over the entire domain over long periods. A serious complication in interpreting these results arises because the ocean has an extended memory of previous forcing. Systems with memory accumulate the past history of time- and space-variable forcing (Hasselmann 1976) and are expected to show a random walk behavior that will manifest itself as an apparent trend over arbitrary periods. It is easy to generate examples of such time series (e.g., Wunsch 1999) where the apparent trend is known to be a transient effect. Changes within the North Atlantic thus can only reasonably be understood in terms of the global variability (to be discussed elsewhere). Here, we note only that at the same latitude in the North Pacific no statistically significant trend is found in either volume or temperature transport (not shown).

In the present case, any North Atlantic decadal trends now present are weak and spatially complex, and as such need to be compared with the recent Bryden

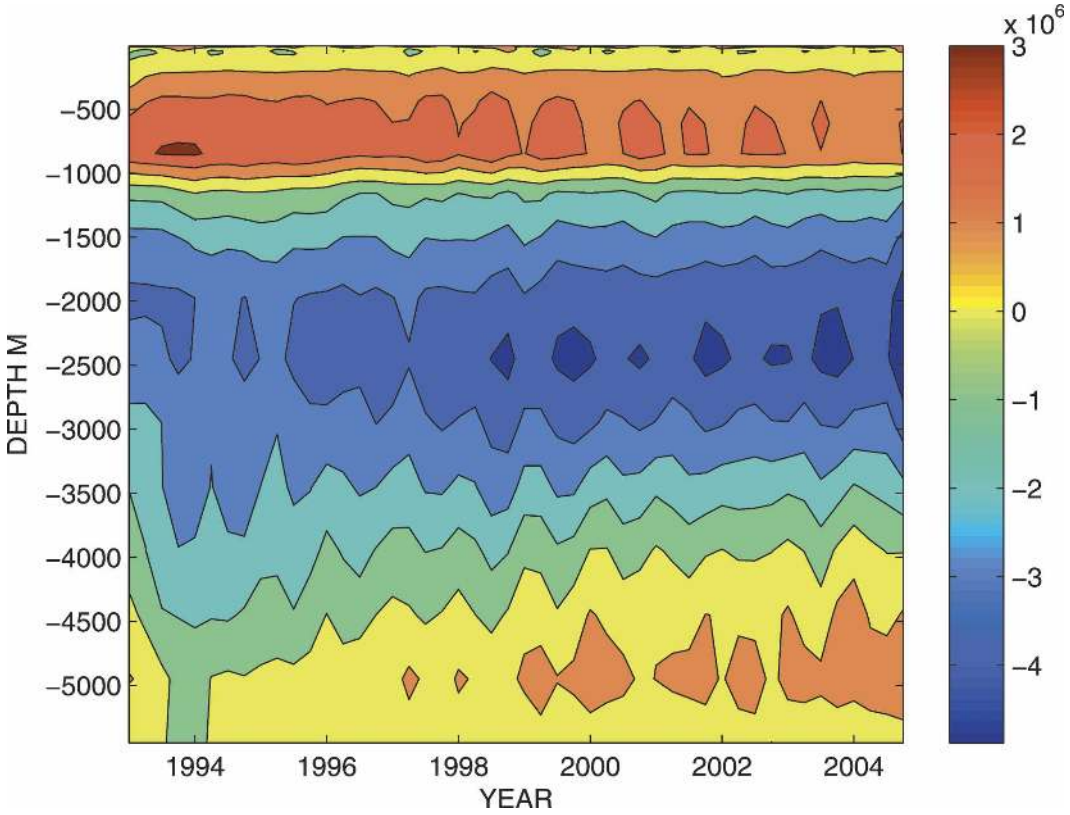

FIG. 9. Seasonal averages (3 months) of volume transport contours ($m^3 s^{-1}$) through time as a function of depth (another rendering of the profiles in Fig. 3).

et al. (2005, hereinafter B2005) conclusions, as well as the dramatic spin put on them (Quadfasel 2005). First note that both the present results and those of B2005 differ from that of Marsh et al. (2005). The latter, in an unconstrained modeling study, concluded that the North Atlantic MOC was *increasing*. (Note that the ECCO-GODAE model, run without any data constraints, also produces an increasing MOC.) In the period of temporal overlap between the present results and those of B2005, there is no conflict within the error bars—whatever changes have been taking place over the past 13 yr are slight and complex. For the period following 1957 to the present, for which B2005 infer a reduction in the gross MOC of 50% (reduction in the mass transport above 1000 m of 8 Sv), one can identify at least two major issues. The degree of variability obvious in the present results (particularly Fig. 4) shows that sampling the system at any five arbitrary times, even if no further assumptions are involved, could lead to the inference of a trend of either sign, depending upon the accidents of timing. Aliasing is a pervasive concern for section-based inferences. [P. Huybers (2006, personal communication) has suggested that undersampling of the known variability of the Florida Current is, all by itself, sufficient to produce the B2005 trend.] B2005 argue that annual means of the Gulf Stream and interior baroclinic structure are quite stable, but any claim that a near-synoptic section and its reference-level velocities produce results representative of an annual, rather than a monthly, sample requires demonstration, not assumption. Furthermore, the datasets used by B2005 are the classical temperatures and salinities historically employed to calculate the circulation. As is well known (e.g., Wunsch 1996), the calculation of mass and other transport from temperature and salinities involves the inference of the absolute flow; unless a systematic inverse or other procedure is used, one necessarily makes assumptions with a large degree of arbitrariness. The accuracy of the assumptions necessarily made by B2005 is not known and net mass transports are sensitive to them, particularly in the shallow water stations at either end of the sections. We make no inferences here about the pre-1992 trends—noting only that the overall database before 1992 is much sparser, and that the 1957 hydrographic section was obtained prior to the recognition of the ubiquity of the oceanic geostrophic eddy field; it is surely *spatially* aliased.

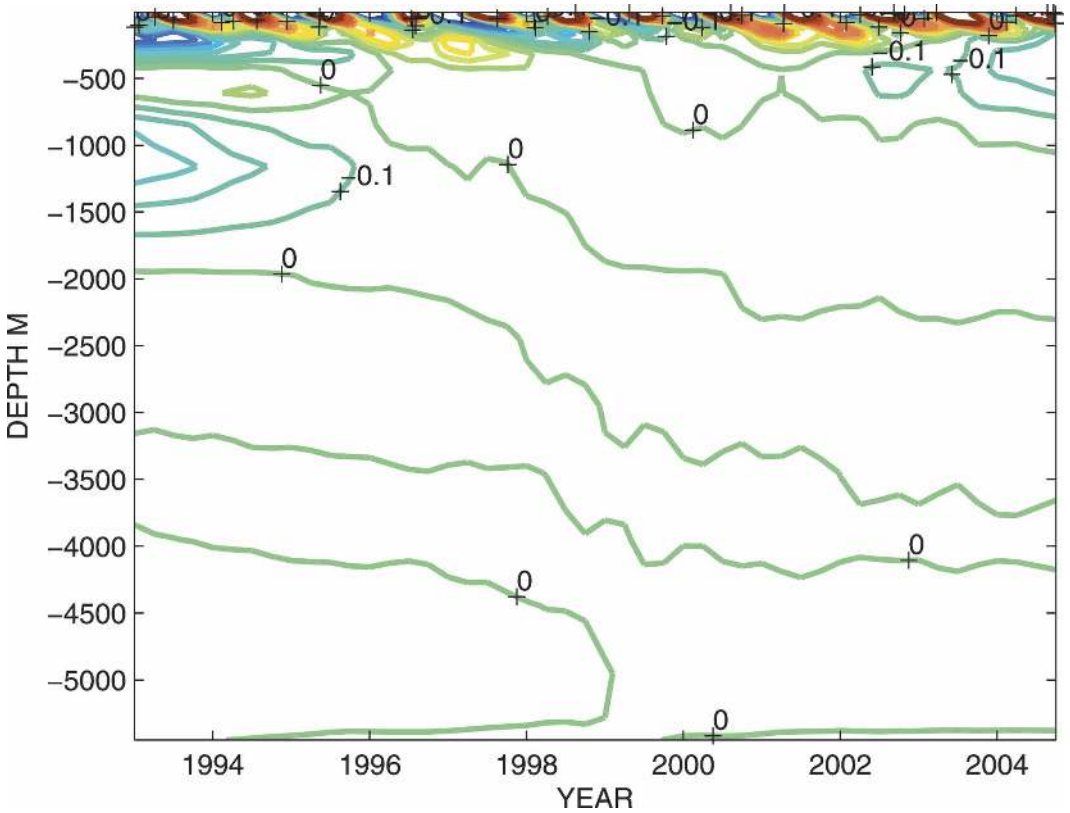

FIG. 10. *Anomaly* of model zonal average temperature through time as a function of depth. Only the zero and ±0.1°C contours are labeled.

Issue 3, the relative stability of the heat transport in the presence of the reduction in the upper-ocean mass transport, is, kinematically, in part a consequence of the increasing mass transport of the southward-bound NADW and northward-bound abyssal waters. Heat transport variability estimation does require knowledge of the full water column behavior.

We will make only a few comments about the observational implications of issue 4, primarily as a supplement to Baehr et al. (2004). In particular, the question of the detectability of the trends appearing here, given the realities of the noise in realistic mooring measurements, is well outside our intended scope, although the problem of detection of a less than 1% yr^{-1} trend in a noisy record is not an inviting prospect in the short term. (The heat transport standard deviation is 0.18 PW, about a mean of 0.84 PW.) To the extent that new data exist at this latitude within our estimation period, we are making a prediction of what might be seen in them. When future data become available (moored velocities, temperatures, and salinities anywhere in the ocean, including 26°N), the optimal approach will be to incorporate those new data into estimates of the type made here, so as to use all data, with their realistic uncertainty estimates.

We can, however, make some gross inferences about the internal structure of the variability leading to fluctuations in heat transport (if that is the field of concern) or of the volume transport of the meridional overturning circulation. Consider the anomaly of meridional velocity $v'(z_i, \phi_j, t_k)$ where the anomaly is relative to the time mean at depth z_j, longitude ϕ_j, at time t_k. Map this into a two-dimensional array, $\mathbf{V}'$, where each row is time, and each column ranges over all depths and longitudes. Then using the singular value decomposition in the form of the Eckart–Young–Mirsky theorem (e.g., Wunsch 1996; or if one prefers, the "empirical orthogonal functions"), it is found that 95% of the variance of v' above 1360 m is described by 21 singular vectors, and 99% by 44 vectors. The corresponding numbers for temperature are 6 and 21, respectively. Thus, to describe 95% of the variance of the temperature field, six independent measurements above 1360 m are required (and which could be designed by using the singular vectors and the resolution matrices, but they are not shown here). Baehr et al. (2004) suggested that the thermal

TABLE A1. The major datasets used to constrain the ECCO-GODAE model leading to solution 2.199.

Data type	Spatial extent	Variable(s)	Duration	No. of values
		Observations		
Altimetry: Ocean Topography Experiment (TOPEX)/ Poseidon	Global, equatorward 1993–2004 of 65°	Height anomaly, temporal average	1993–2004	4500 day^{-1}
Altimetry: Jason	Global equatorward of 65°	Height anomaly, temporal average	2002–04	4500 day^{-1}
Altimetry: *European Remote Sensing Satellite-1/2* (*ERS-1/2*), *European Space Agency Environmental Satellite* (*ENVISAT*)	Global, equatorward of 81.5°	Height anomaly	1995–2004	3800 day^{-1}
Hydrographic climatology	Global, 300 m to seafloor	Temperature, salinity	1900–2000 inhomogeneous average	16×10^6
Hydrographic climatology	Global to 300 m	Temperature, salinity	Multidecadal average seasonal cycle	Included above
CTD synoptic section data	Global, all seasons, to 3000 m	Temperature, salinity	—	17×10^3
XBTs	Global, but little Southern Ocean	Temperature	1992–2004	1.4×10^6
ARGO float profiles	Global, above 2500 m	Temperature, salinity	1997–2004	2.1×10^6
Sea surface temperature	Global	Temperature	1992–2004	5.3×10^6
Sea surface salinity	Tropical Pacific	Salinity	1992–99	24 238
Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI)	Global	Temperature	1998–2003	1.5×10^6
Geoid (GRACE mission)	Global	Mean dynamic topography	—	1° resolution
Bottom topography	Smith/Sandwell to 72.006, ETOP05 to 79.5	Water depth	—	1° resolution
Forcing				
Wind stress-scatterometer	Global	Stress	1992–99, July 1999–2004	9.4×10^6
Wind stress	Global	Stress	1992–2004	192×94 Gaussian grid (~1.875°)
Heat flux	Global	Sensible + latent heat	1992–2004	192×94 Gaussian grid (~1.875°)
Freshwater flux	Global	Evaporation/2.4×10^9 − precipitation	1992–2004	192×94 Gaussian grid (~1.875°)
Short/longwave radiation	Global		1992–2004	192×94 Gaussian grid (~1.875°)
		Withheld		
Tide gauges	Global, sparse	Sea level		
Tropical Ocean and Global Atmosphere–Tropical Atmosphere Ocean (TOGA–TAO) array	Equatorial oceans	Velocity/ temperature		
Tomographic integrals	North Pacific	Heat content		
Florida Current transport	Florida Straits	Mass flux		
Float and drifter velocities	Global	Velocity		

wind as constructed from approximately nine moorings plus an estimate of the Ekman transport would be adequate to determine the meridional overturning circulation at 26°N. At an accuracy of 95% of the variance, such a number is approximately consistent with the number of degrees of freedom suggested here. If the estimated upper ocean volume transport trend of about -0.2 Sv yr^{-1} is correct, and is to be detected by in situ

measurements alone, very close attention will have to be paid to the error structures in the data. As already noted, however, an optimal strategy would combine any new data into a model such as this one along with the existing data.

From the point of view of shipboard sampling, the nearly white noise character of integrated volume and heat transport is not encouraging. White noise processes will inevitably alias the unsampled high frequencies into lower frequencies, and separating trends in temporally sparse observations will be very difficult.

Although we believe the estimate made here of the changes in the North Atlantic MOC is the most complete and robust thus far, the contradictory nature of the various extant calculations suggests that all such conclusions are fragile at the present time. Great caution should be exercised when interpreting any of the results in terms of long-duration climate change. In the ECCO-GODAE results, it remains to examine trends in other regions to obtain a global perspective (preliminary analysis shows significant downward trends only in the Southern Ocean zonal volume transport). The ECCO-GODAE results will continue to change as more data are employed, weights are adjusted as a consequence of better error estimates, the model is improved, and the optimization proceeds.

Acknowledgments. This work was supported in part by the National Ocean Partnership Program (NOPP; NASA, NOAA) through the ECCO and ECCO-GODAE Consortia, the NSF through the ITR program, and NASA through the Jason and GRACE projects. We thank D. Spiegel, C. King, and E. Olson for assistance with the model result analysis, as well as our many ECCO partners for their contributions unsung here. The computations reported here were carried out at the Geophysical Fluid Dynamics Laboratory (NOAA) and at the National Center for Atmospheric Research. The TAF algorithmic differentiation tool from FastOpt was central to the optimizations. Comments by J. Baehr, H. Bryden, P. Huybers, L. Talley, and two anonymous referees were helpful.

APPENDIX

The Datasets

A summary of the data used to constrain the model version 2.177 is displayed in Table A1. "Withheld data" are used for independent tests but are on the priority list for future inclusion.

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