

# Low-frequency variations of the large-scale ocean circulation and heat transport in the North Atlantic from 1955–2008 in situ temperature and salinity data

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## Abstract

On interdecadal timescales, the Atlantic meridional overturning circulation (AMOC) is thought to be in phase with the North Atlantic Sea Surface Temperatures (as measured by the Atlantic Multidecadal Oscillation – AMO – index). However, it appears that we have entered a positive phase of the AMO since 1995–2000 although we fear the Atlantic meridional overturning may be on a declining trend, as suggested by several observational and modelling studies. Here we constrain ocean models with temperature and salinity fields built on observations, and compare the results with various simple methods (namely diagnostic, robust diagnostic and prognostic), models (North Atlantic and global configurations at various resolutions), and forcings. Mean transports of heat and mass are sensitive to the method and model configuration, but their decadal variability is much more coherent and does not depend explicitly on the variations of the surface forcing, its influence being imprinted in the thermohaline structure. Multidecadal variations are of the order of 20% (0.15 PW in heat transport and 4 Sv in overturning), with large transports in the subpolar gyre in the early 1960's and mid 1990's, and low values in the mid 1970's. Declining transports of heat and mass are coherent in several models and methods since 1995, especially in the subpolar gyre, and opposite to the long term tendency from 1958 to 2008.

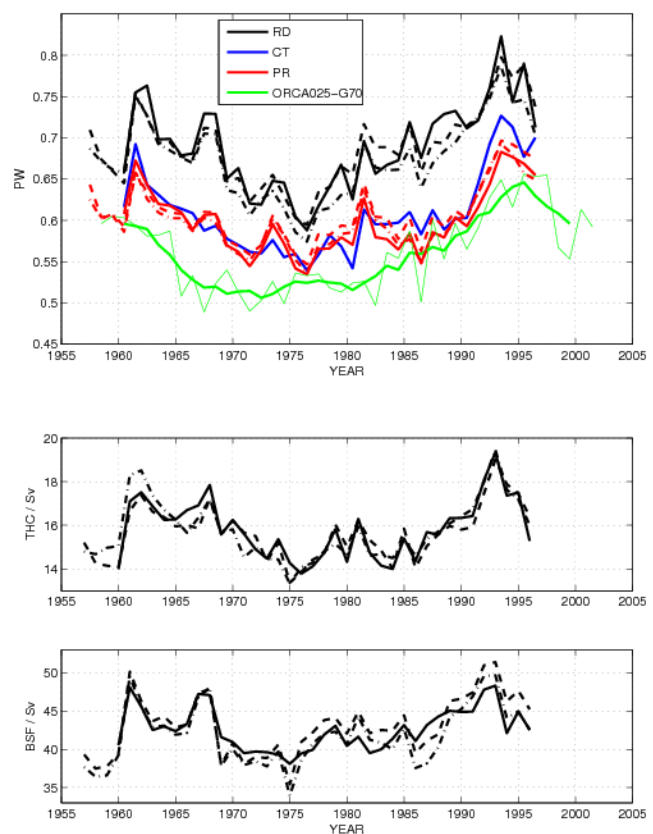
## 1. Introduction

Variations in the oceanic thermohaline structure have been documented over the last decades: surface intensified warming and changes in salinity, as well as deep water properties and formation rates [Dickson et al. 1996, 2002]. However the associated changes in the large-scale ocean circulation are poorly known, and deserve much interest in the context of the ongoing global warming and possible decay of the thermohaline circulation [Bryden et al. 2005; Gregory et al. 2005], or recent decline observed in the North Atlantic subpolar gyre [Häkkinen and Rhines 2004]. Several ocean models have been forced by atmospheric reanalysis forcings, but these forcings have significant uncertainties and well-known heterogeneities over the last 50 years. The main model deficiencies lie in formulation of subgrid-scale mixing with consequences on deep-water formation, usually impacting the overturning circulation on the long term. In situ data assimilation in such models on long time scales requires complex tools and delicate choices on the method, that largely influence the results. On the other hand, to avoid the need for accurate surface fluxes of heat and freshwater, one can use the observed temperature and salinity (TS) fields. Density providing the baroclinic velocities through the thermal wind relation, the barotropic part is obtained from the vorticity equation forced by the wind and a bottom pressure torque [Sarkisyan and Keonjiyan 1975]. Mellor et al. [1982] integrated this equation along  $f/H$  contours, whereas Holland and Hirschman [1972] used the dynamical part of numerical ocean models, although some adjustment of the bottom density field may be necessary [Ezer and Mellor 1994]. These methods have been applied to compare the pentads 1955–59 and 1970–74 [Greatbatch et al. 1991; Ezer et al. 1995], and more recently for 7 pentads from 1950 to 1994 using a finite element formulation [Myers et al. 2005]. NODC has made available global fields of TS pentadal anomalies from 1955–59 to 1994–98 based on hydrographic data. We will diagnose mean ocean currents from these fields to investigate the low-frequency variations of mass and heat transports in the North Atlantic. We first use three simple, well-documented methods: constant tracers, robust diagnostic, and short prognostic. Although the methods provide different results on the mean state, the low-frequency variations are rather coherent. Then, we implement only the robust diagnostic method in a global model continuous simulation with the seasonal cycle and TS anomaly fields updated to 2008.

## 2. First methodological step in a North Atlantic configuration with ROMS

The Regional Ocean Modeling System ROMS [Shchepetkin and McWilliams 2005] is used here, based on topography-following sigma coordinates. A smoothed bottom topography is required for accurate calculations of pressure gradients [Barnier et al. 1998 DSR]. We used a  $1/2^\circ$  resolution and 50 sigma levels to reproduce correctly the ocean bottom topography and capture the signature of the boundary currents in the TS climatologies. The model configuration spans from  $10^\circ\text{N}$  to  $66^\circ\text{N}$  in the Atlantic. The model is used to produce mean fields of T, S and velocities for each 5-yr period from 1955–59 to 1994–98. The initial TS fields were optimally interpolated on the model grid from the pentadal fields available on a  $1^\circ \times 1^\circ$  grid and 33 z-levels. These pentadal fields were constructed from objectively analyzed anomalies of T and S down to 3000 m [Levitus et al. 2005; Boyer et al. 2005] and from the associated mean climatology (down to the bottom). Wind stress and surface fluxes are provided by the atmospheric reanalyses from NCEP [Kalnay et al. 1996 BAMS] and ECMWF ERA-40 [Uppala et al. 2005 QJRMS], averaged over the corresponding 5-yr periods. Three semi-diagnostic methods are implemented. Constant Tracers (hereafter CT): T and S are kept constant during the model integration, only the momentum equations are integrated in time and reach a steady state within months [Holland and Hirschman 1972]; the final velocity fields are averaged over months 6 to 12. Robust Diagnostic (RD): the tracer equations are now integrated in time with an additional relaxation to initial values with a timescale of 30 days [Sarmiento and Bryan 1982]; kinetic and potential energy adjusts within 6 months, and the final fields are averaged over the second year of integration. Short Prognostic (PR): the full dynamics and tracer equations are integrated for 45 days such that the barotropic velocities adjusts but the tracers do not drift away from the initial state [Ezer and Mellor 1994]; the final fields are averaged over the days 31 to 45. Rms differences between the initial and final TS fields are similar for both RD and PR methods (around 0.3 K at 100 m, 0.05 K at 1000 m and less than 0.01 K below 2000 m), although the former is in steady-state while the latter drifts rapidly from the initial state and longer prognostic integration would lead to much larger differences. Because the use of annual mean fields instead of seasonal cycle may be arguable, we have tested that the diagnostic transports of mass and heat on the annual mean climatology very closely resemble the mean of these diagnostics for the seasonal climatologies. Results are shown in Fig.1 for 1957-1996.

*Figure 1: (top) Poleward heat transport maximum in the subpolar gyre ( $45\text{-}60^\circ\text{N}$ ) for the 3 diagnostic methods (RD robust diagnostic, CT constant tracers, SP short prognostic) implemented in a North Atlantic ROMS configuration using NODC pentadal TS anomalies and various forcings: ERA-40 (solid) or NCEP (dashed) 5-yr averaged surface fluxes, ERA-40 40-yr-averaged fields (dash-dotted); global prognostic reference simulation of the Drakkar project, ORCA025-G70, annual and pentadal means (green). (middle) Thermohaline circulation and (bottom) barotropic subpolar gyre intensity at  $48^\circ\text{N}$ , here for the RD method, show coherent variations with the poleward heat transport. Source: Huck et al. (2008).*



### 3. Implementation of the robust diagnostic method in a global model configuration

Several limitations of the previous methods are addressed in this next step. First, to avoid open boundaries, a global model configuration is used with a  $\frac{1}{2}^\circ$  resolution, refined towards the equator: OPA ORCA05 [Molines et al. 2006]. The model integration is now continuous in time from 1958 to 2008. The surface forcing set is DFS4 [Brodeau et al. 2010] based on ERA-40 atmospheric reanalysis. The robust diagnostic method is implemented with relaxation time scale of 50 days in the upper 800m and 1 year in the deep ocean [Madec and Imbard 1996], although comparison with a uniform restoring field of 120 day shows no major change. The restoring TS fields, now varying in time and according to the seasonal cycle, are reconstructed from the annual or pentadal anomaly added to the monthly mean climatology. NODC pentadal fields are used for the period 1958 to 1996 as in the previous section. From 1997 to 2008, annual anomaly fields are used down to 2000m [von Schuckmann et al. 2009, Gaillard et al. 2009]. A twin prognostic experiment (ie. with no restoring in the ocean interior) is run for the same period. The restoring term efficiently removes incorrect trends in heat and salt content (not shown), and the evolutions of MOC and MHT diverge within 15 yr but show similar decadal variability (Fig. 2). Comparison is also performed with the Drakkar project reference experiment at  $\frac{1}{4}^\circ$  resolution, ORCA025-G70 [Barnier et al. 2006]. In general, although the mean values of heat and mass transport significantly vary from one model to the other, especially at  $24^\circ\text{N}$ , the decadal and longer variations show more coherence.

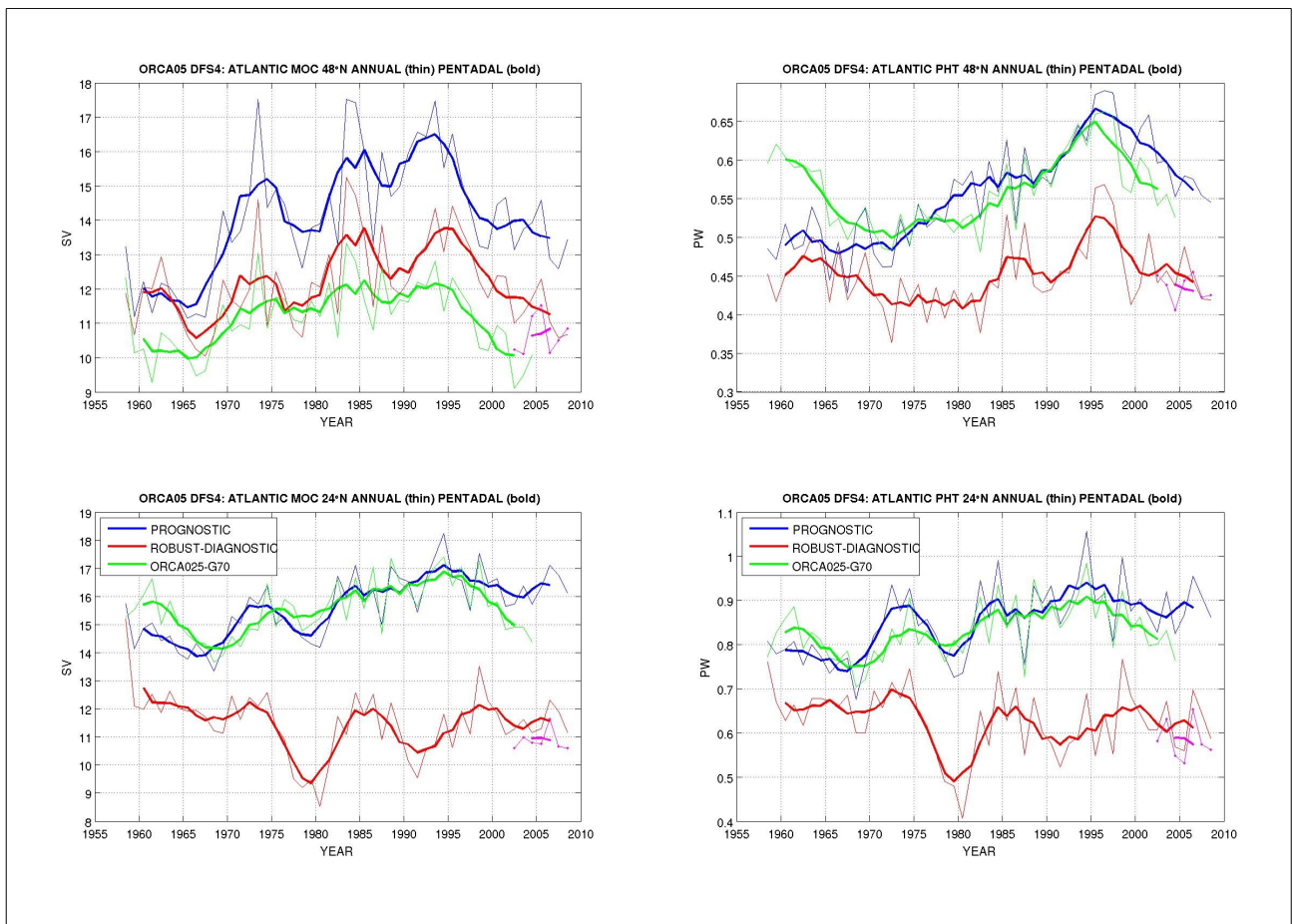


Figure 2: Synthesis of global ORCA05 simulations, prognostic (blue) and robust diagnostic (red), and comparison with Drakkar reference simulation (ORCA025-G70, green) for the evolution of the maximum meridional overturning circulation (MOC) and meridional heat transport (PHT) at  $24^\circ\text{N}$  (bottom) and  $48^\circ\text{N}$  (top) in the Atlantic. Thin (bold) lines are annual (pentadal) means. Dots correspond to average over the last 2 years for "equilibrium" 12-yr long simulations with restoring and DFS4 forcing of the year repeated (magenta). The decline of mass and heat transport at  $48^\circ\text{N}$  since 1995, opposite to the long term 1958-2008 tendency, appears as the most robust signal.

#### 4. Discussion and conclusion

This work provides an estimate of the low-frequency variability in the North Atlantic circulation based on in situ TS data using simple methods: diagnostic, robust-diagnostic and short prognostic. Without finely tuning the model configuration or parameterizations, the variability in mass and heat transports associated with the thermohaline changes has been successfully captured in the subpolar gyre, as compared to state-of-the-art prognostic models: energetic barotropic and overturning circulations drive high heat transport in the early 60's and mid 90's, whereas both circulations and heat transport are at the lowest in the mid 70's, and declining since 1995, in agreement with observational estimates attributed to NAO forcing [Curry and McCartney, 2001]. Our methods also point out an apparent phase opposition in heat transport between the subtropical and subpolar gyres, that could result from the delayed adjustment of the meridional overturning at lower latitude to the low-frequency NAO forcing [Eden and Jung 2001]. The original idea of relying on in situ observations rather than changes in the surface forcing to investigate the variations of the ocean circulation provides an alternative to prognostic hindcast models, with or without assimilation, that avoids potential model drift associated with uncertainties in both subgrid-scale processes parameterizations and surface fluxes. Yet let us recall that these are dynamical and not thermodynamical methods: they allow only limited insight in heat or salt budgets for instance. The pentadal/annual TS fields are certainly not perfectly constrained over the last decades, especially at depth, and due to the scarcity of salinity data: the robustness of our results should be investigated with the use of alternative products, analyzed on isopycnal surfaces for instance. The large smoothing in the NODC data set, as discussed by Myers et al. [2005], may also have some influence on our results, as well as the transition from NODC to LPO fields. A radical change occurred in the observing system since 2003 with Argo, that allows to build reliable annual fields of TS for the upper 2000m, and we have shown this is sufficient to reconstruct most of the large-scale circulation changes. See Huck et al. [2008] for a detailed analysis of the results.

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