Recent changes in the North Atlantic circulation

Thierry Huck

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Thierry Huck <thuck@univ-brest.fr>
Laboratoire de Physique des Océans (UMR6523 CNRS IFREMER IRD UBO)
UBO-UFR Sciences F308, 6 avenue Le Gorgeu, CS 93837, 29238 Brest Cedex 3, FRANCE

Abstract

The three-dimensional ocean circulation is hardly observable but its quantification has greatly improved over the last two decades, due to moored array observations, deep float trajectories and satellite altimetry. Historical temperature and salinity data reveal changes on various periods in the North Atlantic: a global warming trend of the upper layers, quasi-decadal and multidecadal oscillations. The associated changes in the circulation are not yet clearly determined, but some hints from observations and models are presented.

Introduction

The large-scale ocean circulation is driven by the winds and exchanges of heat and freshwater with the atmosphere at the surface. It plays a role equivalent to the atmosphere in the Earth climate system and contributes to 1/3 of the poleward heat transport, reducing the temperature gradient at the Earth surface. The North Atlantic and Arctic Oceans are the very unique places where most of the transformation of warm surface waters into cold deep waters occurs and feed the global conveyor belt or thermohaline circulation, although this may not have always been the case in the past. In fact the intensity of this transformation through convection has varied over the last decades, in response to changes in the atmospheric conditions. Reciprocally, deep water formation releases a large amount of heat to the atmosphere that is brought to Europe by the predominant westerlies in the midlatitudes, modulating temperature and precipitations. The observed freshening of the North Atlantic, reducing the seawater density hence its ability to convect, analyses of repeated hydrographic sections, and coupled climate models results, have raised uncertainty in the maintenance of the thermohaline circulation within the ongoing global warming.

Unfortunately, the large-scale ocean circulation is difficult to measure directly: historical currentmeter data are often short, very localized and polluted by very energetic high-frequency signals due to tides and mesoscale eddies; recent Acoustic Doppler Current Profiler data allow continuous monitoring on moored arrays or along ship tracks, but suffer otherwise the same limitations. Hence currents are often deduced from hydrology, namely temperature and salinity, that have been measured accurately since the 1950's, continuously on the vertical through CTD (conductivity-temperature-depth) deployments from ships since the 1970's, and now on autonomous profilers as in the Argo program. The combination of the equations of movements (the geostrophic equilibrium between pressure gradient and Coriolis force, and the hydrostatic balance) leads to the thermal wind balance, that provides the vertical derivative of the horizontal velocity given the density field (computed from temperature and salinity). One finally needs some additional information or hypothesis for the absolute velocity at a given depth (the famous level of no motion) to compute the absolute velocity field.

Fortunately, the development of satellite altimetry has provided continuous almost-global observations of sealevel since late 1992 that proves the most complete oceanographic dataset nowadays. Surface geostrophic currents can be computed at 1/2° resolution from 70°S to 70°N on a weekly basis in near real time. Associated with the deployment of the Argo array of profiling floats since 2003 (the target 3000 floats spread worldwide was reached in 2009), providing vertical profiles of temperature and salinity down to 2000m every 10 days as well as trajectories at their usual parking depth of 1000m, the global observing system of the ocean has never been so dense, maybe at the expense of reduced funding for measurements below 2000m...

Given these landmarks in the evolution of the observing system of the ocean and the associated uncertainties to estimate the ocean currents, we will successively describe the North Atlantic general circulation and its reported variations during the last decades.

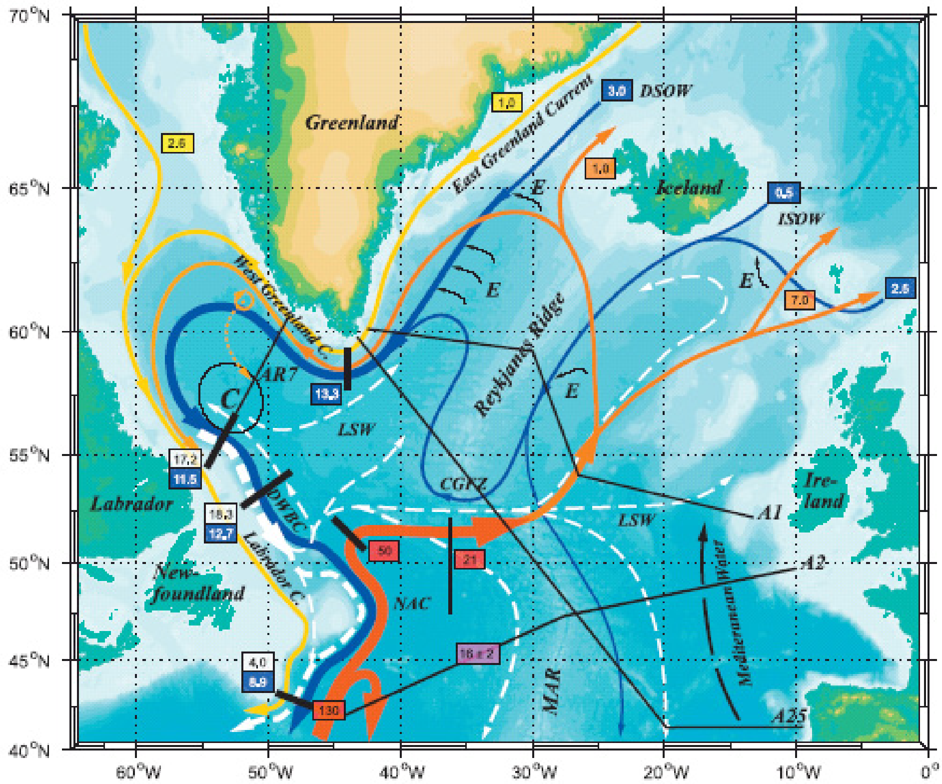

Figure 1: Schematic circulation of the subpolar North Atlantic with topographic features and different current branches identified (CGFZ Charlie Gibbs Fracture Zone, MAR Mid-Atlantic Ridge; DWBC Deep Western Boundary Current, NAC North Atlantic Current, DSOW and ISOW Denmark-Strait and Iceland-Scotland Overflow Water, LSW Labrador Sea Water; C Convection, E Entrainment). Locations of moored current-meter arrays of quoted transports (Sv = 10^6 m^3/s) are marked by heavy black bars. Also shown are the WOCE Hydrographic Program lines A1, A2 and A25 (Ovide) across the Atlantic and AR7 across the Labrador Sea (thin black). Transports are marked for the mean DWBC (LSW layer in white box, deeper layers in blue box), for the NAC (red box) and extensions (orange box) as well as for the shallow Arctic inflow (yellow box); MOC Meridional Overturning Circulation across A2 (magenta box) as obtained from inverse models (after Schott and Brandt 2007).

The ocean general circulation in the North Atlantic

The surface circulation of the North Atlantic Ocean is composed of the anticyclonic subtropical gyre, between 5°N and 45°N, and the cyclonic subpolar gyre, between 45°N and the sills around 65°N between Greenland, Iceland, Faroe and Scotland. The intense western boundary current of the subtropical gyre, the famous Gulf Stream, follows the eastern coast of the USA from Florida to Cape Hatteras, where it detaches from the coast and heads eastward as the North Atlantic Current. Part of it recirculates southward in the subtropical gyre, the other part heading northward in the subpolar gyre and ultimately crossing the sills into the nordic seas. This upper circulation is estimated through surface drifters data for instance, and its variations can be monitored through satellite altimetry. The deep circulation is far more difficult to monitor: from the north, it is composed of the overflows from the sills, that find their way along the complex bathymetry as Western Boundary Currents. The Iceland-Scotland Overflow Water follows first the eastern slope of Reykjanes Ridge, than the western slope into the Irminger Sea, where it joins the Denmark Strait Overflow Water along the east coast of Greenland, around Cape Farewell, than flows cyclonically in the Labrador Sea, and exits as the Deep Western Boundary Current along the Grand Banks of Newfoundland. More details for the subpolar gyre surface and deep currents and transports are shown in Figure 1.

The transformation of warm surface waters into cold deep waters occurs through convection in regions of intense surface cooling, in the Nordic, Irminger and Labrador Seas. The associated large-scale circulation, named the thermohaline circulation or also conveyor belt, originates from temperature and salinity - hence density - contrasts that drives gravity currents. Its complexity results from multiscale interaction of dynamical and thermodynamical processes: the global balance of deep water formation and consumption remains relatively unclear since the processes controlling diapycnal (vertical on first order) mixing are not yet known, the overflows interaction with bottom topography induces entrainment and mixing difficult to quantify, convective chimneys are intermittent and their size is of order of kilometers, surface water densification is intensified by brine rejection through sea ice formation...

The Meridional Overturning Circulation, the two-dimensional latitude-depth view of these currents, results from the northward flow in the upper layers (NAC) and the southward flow at depth (DWBC). Estimates for the intensity of the Atlantic MOC are obtained from inverse model calculations, along hydrographic sections or for regional configurations, and yields values from 13 to 18 Sv at 48°N (1 Sverdrup is about the cumulated flow of all the world rivers). The associated poleward heat transport, resulting from the northward transport of *warm* upper waters in the North Atlantic Current and the southward return flow of *cold* waters within the Deep Western Boundary Current, is estimated at 0.61±0.07 PW (1 PW = 10^{15} W is 100 times the global energy production of electricity and heat).

Decadal and interdecadal changes in North Atlantic circulation

While hydrographic data have been collected for more than 60 years in the North Atlantic, such a historical dataset is not available for direct measurements of currents. In order to determine the evolution of ocean currents over the last decades, one needs to rely on theoretical links between hydrography and currents. The overflows from the nordic seas and the deep convection in the Labrador (and probably Irminger) Sea lie at the source of the Atlantic overturning. The recent monitoring of the overflows does not show significant variability but may be too short to address decadal and longer periods. The availability of hydrographic data collected in the Labrador Sea since 1948 reveals long term changes of temperature and salinity: cooling and freshening from 1966 to 1992 (Dickson et al. 2002), associated with atmospheric circulation shift from strongly negative to strongly positive values of the North Atlantic Oscillation index.

Analyses of surface data (for which we have the longest historical record) through various statistical techniques (EOF Empiral Orthogonal Fonctions, MSSA Multichannel Singular Spectrum Analysis) usually identify different signals in the North Atlantic: a quasi decadal signal which characteristic SST pattern is tripolar (Alvarez-Garcia et al. 2008); a multidecadal signal named Atlantic Multidecadal Oscillation (AMO, Kerr 2000), which index is defined as the averaged North Atlantic Sea Surface Temperature (SST) from 0 to 70°N (detrended); and a global warming signal, often nonlinear. Distinguishing the two latter may be challenging and an original method based on coupled model ensemble simulations has been proposed (Knight 2009). Although the cold (1905-1925, 1970-2000) and warm (1925-1970, 2000 onward) phases of the AMO appear respectively associated with reduced and strengthened thermohaline circulation and North Atlantic Current (Knight et al. 2005, Álvarez-García et al. 2008), the mechanism sustaining this oscillation is still unclear. A coupled model simulation reproducing AMO-like centennial variability suggest a coupled mechanism involving northward shift of the ITCZ position with strong MOC, increased freshwater input into the tropical North Atlantic Ocean hence generation of negative salinity anomaly that propagates slowly northward and modify after several decades the overturning (Vellinga and Wu 2004).

The analysis of the now 17 year long record of sea surface height (SSH) from satellite altimetry show a remarkable signal in the North Atlantic (Figure 2). The mean surface geostrophic currents flow cyclonically (anticyclonically) around the low (high) values of SSH in the subpolar (subtropical) gyre, in analogy with the surface winds around the icelandic low (Azores high) pressure in the atmosphere. Almost continuously from 1994 to 2004, the lowest SSH in the center of the subpolar gyre have been rising, reducing the intensity of the subpolar gyre surface currents by almost 20% (Häkkinen and Rhines 2004). As the the subpolar gyre shrinks, warmer and saltier waters from the North Atlantic Drift make their way to the Nordic Seas (Häkkinen and Rhines 2009). However the relationship between this upper ocean horizontal subpolar circulation and the vertical Atlantic meridional overturning circulation is still unclear, although some numerical models suggest strong linkages between subpolar gyre circulation, Labrador Sea Water production and the Atlantic MOC. (now associated with ADCP current measurements). A few of these sections have been repeated in the North Atlantic around 24°N, 48°N, and between Greenland and Portugal (Fourex, Ovide). They provide a very instantaneous view of the circulation and contain very energetic mesoscale signals that may be difficult to separate from the lower frequency signal one is looking for. The early results from the repeated hydrographic section along 24°N (Bryden et al. 2005) may be in doubt given the large high-frequency variability observed in the transport (Cunningham et al. 2007). Inversions across 48°N for 5 sections from 1993 to 2000 show no decadal trend (Lumpkin et al. 2008). On the other hand, the ongoing Ovide program of repeated hydraphic sections between Greenland and Portugal, close to the A25 line sampled in 1997 (Fourex), suggest a possible decline of the overturning from 18.5 Sv in 1997, 16.4 Sv in 2002 and 2004, to 11.4 sv in 2006 (in density coordinates, Gourcuff 2008), although the latter value may be unusually low due to high frequency variability.

Results from numerical models, with or without data assimilation, do not help much in sorting out these results: we observe a large dispersion for the mean values of the MOC as well as its variability, although many suggest a declining trend since 1995. Sustained monitoring is required in order to better understand what is going on. Direct measurements of the overturning requires coast to coast hydrographic sections

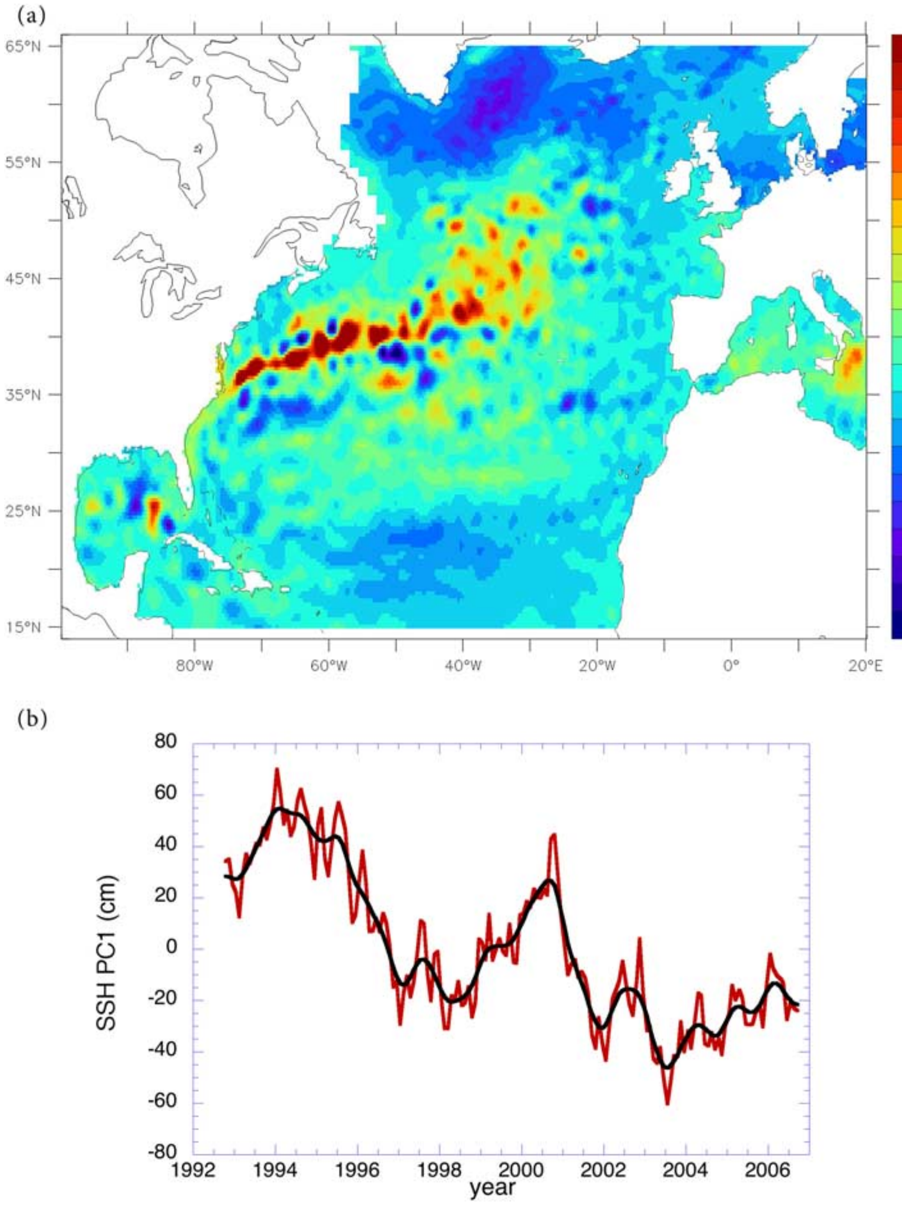

Figure 2: (top) The spatial pattern of the first empirical orthogonal function and (bottom) associated time series for the sea surface height from AVISO altimeter data. The spatial pattern is dimensionless, the time series have units of centimeters (after Häkkinen and Rhines 2009).

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