Shifting pathways of meridional circulation: drifters, altimetry, models

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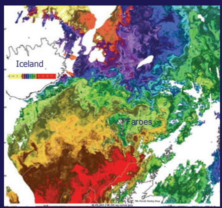
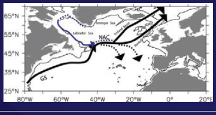




Warm, saline subtropical Atlantic waters have recently increased their penetration northward through the subpolar latitudes.

Prior to 2000, the warm water branches of the North Atlantic Current fed by the Gulf Stream turned southeastward in the eastern Atlantic. **Since 2001**, these paths have shifted toward the north and east, reaching Rockall Trough, through which the most saline North Atlantic waters pass to the Nordic seas. The changes have had far-reaching impacts on climate and ecosystems (Hatun *et al.* Prog. In Oceanog 2009). Decadal variability of this kind is evident in past hydrography, though this is the first time the actual circulation changes have been observed.

Our object here is to show explicitly the Lagrangian (particle-following) and Eulerian (pressure-related) currents that correspond to these thermohaline shifts, to show the image of this transition in the AMOC overturning cells and potential vorticity fields. The wind field responsible appears not to be the 'simple' NAO, but rather a combination of an NAO- and 'intergyre' EOF of the windstress curl.

1.

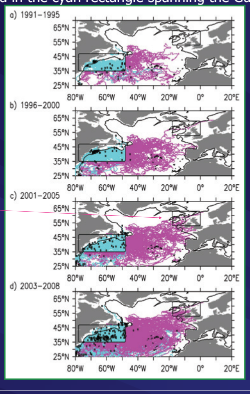
The years 1990-2008 saw remarkable variability in the temperatures and salinities of the high latitude oceans. Here we show explict changes in the Lagrangian (particle-following) currents. Sea surface drifting buoys, all launched in the cyan rectangle spanning the Gulf Stream at (48N-78W, 35W-47N)

1991:1995: during a century-high NAO phase drifters were nearly all retained in the subtropical gyre

1996:2000 sudden reversal of the NAO to a record minimum expands the drifter tracks eastward

2001:2005 drifters penetrate far into the subpolar gyre, entering Rockall Trough and beginning to enter the Norwegian Sea

2003:2008 Continuing to show this cross-gyre exchange.



drifting buoy lifetimes averaged 271 days, and was similar in each time interval. Roughly 450 drifters are present in each of the first three intervals, and 691 in the final period.

data stratified to reflect different NAO phases :

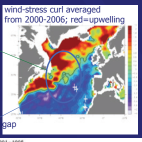
-1991-1995 positive NAO
-1996-2000 reversal of positive NAO trend
-2001-2005 a weak fluctuating NAO

Data source: NOAA/AOML Lagrangian Drifting Buoy database

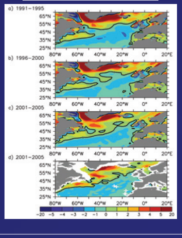
2.

The orientation of the westerly winds, with their mean storm track running SW-NW up the Atlantic, presents ocean forcing that favors penetration of the subtropical gyre far northward, as idealized simulations on the right panels show. Rotating the line of zero windstress curl causes the subtropical gyre to expand, the subpolar gyre to shrink, and warm waters to reach far northward. This orientation of the winds also creates a potential vorticty 'guideway' favoring exchange between north and south: these are observed in the Atlantic (McDowell, Rhines & Keffer 1982, Lozier, 1997)

When the gap in postive curl opens up near Newfoundland it inhibits ocean circulation between the gyres



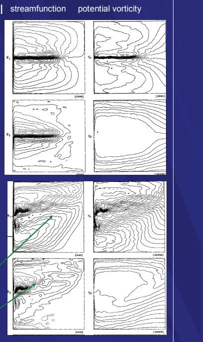
Wind stress curl as January-March average for each 5-year period (figures a-c) from NCEP/NCAR Reanalysis (2.5 x 2.5 degree data).
(d) Wind stress curl from January-March from 2001-2005 computed from QuikSCAT 0.5x0.5 degree data (missing values as marked by white crosses).
Units are 1.E-7 Nm-3.
The black line denotes zero curl isoline.



(right) Circulation and potential vortiicty for idealized 3-layer ocean (QG; *Rhines & Schopp JPO 1991*)

forced by symmetric westerly winds

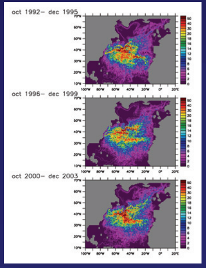
forced by winds with inclined (SW-NE) orientation

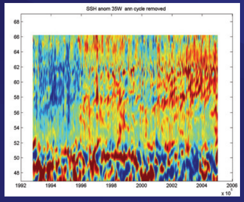


expanded subtropical gyre reaches poleward, subpolar gyre shrinks to northwest. Subthermocline level 'PV guideway'

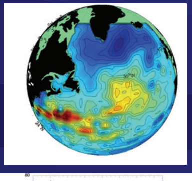
3.

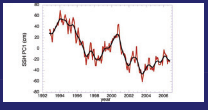
A similar progression of drifter tracks can be inferred using geostrophic currents observed with satellite altimetry (incorporating the Maximenko-Niiler mean dynamic topography) Using the same Gulf Stream box as launch point, a similar picture emerges, of enhanced penetration toward the Nordic Seas following 2000.



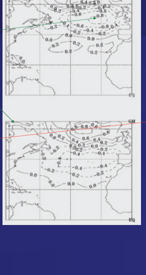


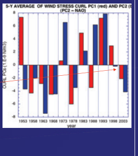
Hovmoeller plot of SSH anomaly along 35W The North Atlantic Current (NAC) passes through Charlie-Gibbs Fracture Zone at 52N. The years 1996 and 2000 mark abrupt changes in SSH of the gyre north of the NAC, with apparent change in Atlantic Water inflow to the Nordic Seas





(right) EOFs of N.Atlantic windstress curl show PC1 'intergyre mode' (upper, 25% of variance) and PC2 'NAO mode' (lower, 16% variance) *The pathway from subtropics to subpolar zone opens when both PCs are negative*

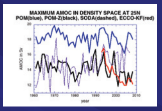


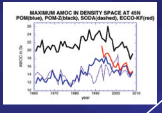


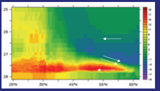
(above) Leading EOF of SSH explains about 70% of the subpolar variance. Note structure in eastern end of gyre where northward flow of warm Atlantic water approaches the Nordic Seas entrance. The time series accompanying this EOF is dominated by a long-term deceleration of the subpolar gyre, particularly the region southeast of Greenland. Additional decadal variability may be involved in the 'opening window'

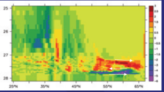
4.

The maximum of the overturning streamfunction in latitude-potential density space shows declining AMOC intensity since the mid-1990s in POM, POM-Z (Häkkinen) and ECCO-K models, with less definite trend in SODA assimilation model.

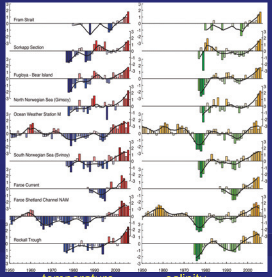




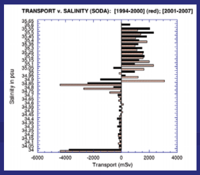


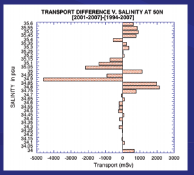


The AMOC overturning streamfunction for the SODA assimilation model shows a change from 1994/2000 to 2001/2006 which contains a small 'intergyre' at 27.0-27.5 potential density, expressing the northward penetration and identifying its density structure. These figures of the AMOC show the ocean above 1650m depth.



The overturning changes correspond to the increasing temperature and salinity along the whole latitude range from Fram Strait (78N) to Rockall Trough in the Atlantic near the entrance to the Norwegian Sea (*Holliday et al., 2008 GRL).* Earlier episodes of warming are evident in the few long records from the Nordic/Barents Seas





Meridional mean transport versus salinity in SODA model, and change 2000/2007 minus 1994/2000 This is the AMOC 'image' of the increasing poleward transport of subtropical water

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