Northern North Atlantic sea surface height and ocean heat content variability

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Warm water \( (\theta > 7^\circ C) \)
cold water \( (\theta < 7^\circ C) \)

*Schmitz & McCartney 1993*

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Atlantic multidecadal variability (or ‘oscillation’)
AMV/AMO northern Atlantic SST index and Atlantic Blocking

Hakkinen et al. Science 2011
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(mauve) mean N Atlantic SST index: AMO (AMV)
(orange) index detrended

Atlantic blocking index (black)

Hakkinen et al. Science 2011
Goal: deconstruct the relatively high-resolution 3D structure of the past 20 years of warming of the upper subpolar Atlantic

(to give the full water column circulation, SST, heat transport, water-mass transformation);
also in prior cycles of the AMO/AMV, like the early 20th Century warming):
using the wealth of subsurface hydrographic, tracer and current observations and high-resolution ocean models: in our case HYCOM

The subpolar Atlantic and Nordic Seas connect the atmosphere to the deep ocean, with some of the highest surface densities in the world…and this connects altimetry to AMOC$_z$, AMOC$_\sigma$ and AMOC$_\theta_S$, the meridional overturning circulations in $z$, $\sigma$ and $\theta / S$ spaces.
cold bias error in SST in coupled climate models:
¼ degree res minus 1 degree res

*Scaife et al GRL 2011*

atmospheric blocking frequency
observed  low res ocean  high res ocean
cold bias error in SST in coupled climate models:
$\frac{1}{4}$ degree res minus 1 degree res

*Scaife et al GRL 2011*

atmospheric blocking frequency
observed  low res ocean high res ocean
Correlation between 0-700m heat content and altimetric SSH is high, but not in Gulf Stream and its subpolar extension

Hakkinen, Rhines & Worthen JGR 2013
pathways toward the Arctic
Brambilla & Talley 2008

these meridional flow branches are difficult to separate from mesoscale eddy noise, yet EKE trends help to locate them
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4-year mean northward transport (accumulated integral in black, velocity in brown) 1999-2002 0-400m, 8 Sverdrups east of the Reykjaness Ridge.
Chafik et al. OceanScope  
Nuka Arctica adcp/geostrophic height using upper 20m v-velocity and upper 55m v-velocity: compared with AVISO mean SSH is remarkably stable, comparing averages from 1992-2012 and 1999-2002 (the latter is the Nuka Arctica observation period)
59.5°N repeat hydrographic section: meridional velocity mean over 2002-2008: deep-reaching structure connects with surface velocity based on AVISO mean with altimetry correction

Sarafanov et al. JGR 2012
59.5°N repeat hydrographic section: dissolved oxygen concentration, with a minimum marking clearly the origins from the tropical Atlantic (2002-2008 mean)

*Sarafanov et al. JGR 2012*

\[ \text{O}_2 \text{ on } \gamma = 27.22 \]
Stentardo & Gruber JGR 2012
dissolved oxygen decline in
northeast Atlantic SPMW
and intermediate water

![Graph showing dissolved oxygen anomaly over time and space.](image)
ocean heat content EOF1-PC1 (red) and wind-stress curl EOF2-PC2: the ‘gyre mode’ of wind-stress curl ≠ NAO: weakening both gyres in 1994-2010

subpolar heat content (red, inverted scale) and SSH PC1
PC2 and EOF2 of whole Atlantic heat content 0-700m; this pattern of warming of the northern seas has recurred in 1930s-50s-2000s (EOF1 is mostly the AMO warming trend)
48N potential temperature averaged over 2007:2011


25W
0-700m heat content change, 2007-2011 minus 1993-1997 with mean surface circulation shows heat added in boundary currents of subpolar gyre

Hakkinen, Rhines & Worthen JGR 2013
pathways toward the Arctic

Brambilla & Talley 2008

these meridional flow branches are difficult to separate from mesoscale eddy noise, yet EKE trends help to locate them
1991-2010
AVISO mean
surface velocity
RAFOS float based circulation in NAC Newfoundland Basin
Bower, Rossby
Along these paths the mixture of cold and warm waters decides the climate of the biologically active zones of the northern seas.

Hakkinen & Rhines JGR 2009, 2013; Desbruyeres et al. JGR 2013; Brambilla & Talley JGR 2008
North Atlantic circulation model ORCA025 forced by observed reanalysis winds: gyre index matches altimetric observations
Desbruyeres, Thierry & Mercier JGR 2013
North Atlantic circulation model ORCA025 forced by observed reanalysis winds: gyre index matches altimetric observations
streamlines from the two sources of northward flow in NE subpolar Atlantic: 12 Sv of subtropical gyre (warm, salty) and 4 Sv of entrained Labrador Current (cold, fresh) (total in the upper branch of AMOC_{\sigma} above \sigma_1=32.0)

As the subpolar gyre weakens, the flow south of 50N decreases less than the flow north of 50N decreases… there is less competition for the warmer southern branch of NAC less dilution of the warm, saline waters (in this model, the northward AMOC transport has not increased but its heat and salt transport have)
change in circulation branches between strong and weak MOC$_{\sigma}$ periods

Subtropical source stronger in 2000s south of 50N and weaker north of 50N

transport (Sv) anomaly accumulated from north vs. latitude
HYCOM model (0.08 degree, 32 layers) EOF-1 of SSH
0-700m heat content
SSH INCREASE OF ~ 13cm IN THE IRMINGER SEA

altimetry measures both surface circulation and ocean water column heat content, ice draft and terrestrial water

The subpolar cyclonic gyre weakened and warmed steadily from 1994-now, and this provided less competition for the North Atlantic Current flowing northward.
EOF1 of altimetric surface velocity field: boundary current deceleration over much of 1994-2010
HYCOM model (0.08 degree, 32 layers) EOF-1 of SSH
0-700m heat content
42.38N SSH altimetry shows clear westward propagation at relatively high frequency and interannual dipolar oscillations

6 cm/sec
tracer released in Florida Straits ($\sigma_\theta < 27.8$) after 5 years and 10 years (release continues steadily); plot vertical integral => need to map diapycnal mixing that obviously (in obs) mixes water masses in N Atlantic Current transition zone

0.08 degree x 32 layer HYCOM simulation, with: X.Xu, E.Chassignet, W.Schmitz
pathways toward the Arctic
Brambilla & Talley 2008

Along these paths the mixture of cold and warm waters decides the climate of the biologically active zones of the northern seas

Hakkinen & Rhines JGR 2009, 2013; Desbruyeres et al. JGR 2013; Brambilla & Talley JGR 2008
Westward shift of subpolar front (in gray, at 55W FLAME model, Burkholder & Lozier 2012 DSR) and SP gyre index (in black, Hakkinen & Rhines 2004, 2013)
origins of FLAME 1/8 deg model floats from western (via NAC) and eastern (deep) subtropics that reach subpolar Rockall Trough

*Burkholder & Lozier*
origins of FLAME $1/8$ deg model floats from western (via NAC) and eastern (deep) subtropics that reach subpolar Rockall Trough

likely source of part of the deep low oxygen water that increasingly reaches the far northern Atlantic

Burkholder & Lozier
PC1 of Gulf Stream position *Pena-Molino & Joyce* GRL 2008

Cooling and increasing transport of Slope Water transport lead to southward shifts of the Gulf Stream
Gulf Stream latitude variability in OFES model
SSH anomalies develop ~ 2 years before reaching Gulf Stream and changing its latitude, propagating as a Rossby wave guided by the boundary current extension. OFES model  

Sasaki & Schneider OM 2010
Climatic episodes of deep-reaching warm, saline invasion of northern Atlantic Ocean occur at decadal to century timescales. They co-vary with

- weakened subpolar ocean gyre and complex weakening of subtropical recirculation gyre
- warmed subpolar heat content
- increased, deep reaching advection of warm subtropical waters to northern subpolar gyre (regardless of weaker AMOC merid. mass transport)
- weak windstress-curl over the SP gyre: the ‘gyre mode’ ≠ NAO
- extreme, breaking jet-stream meanders overhead => Atlantic blocking anticyclones (Hakkinen & Rhines, Science 2011, JGR 2013)
- positive feedback of warm oceanic SST on the atmospheric circulation (e.g. Croci-Maspoli & Davies MWR 2009)
The End

2005/6 winter

Z250 dyn height (contours);
Z850 temperature (colors)
te850-3x.mov
Atlantic SST (sea-surface temperature) and salinity: extreme warming in late 1990s – 2000s

Holliday et al
GRL 2008
SEA SURFACE HEIGHT FROM ALTIMETRY

SSH INCREASE OF ~ 13cm IN THE IRMINGER SEA

SSH EOF1 17.5%

Altimetry measures both surface circulation and ocean water column heat content, ice draft, and terrestrial water.

The subpolar cyclonic gyre weakened and warmed steadily from 1994-now.