Seaglider encounters with key AMOC processes in the northern Atlantic/Nordic/Labrador Seas

P.B. Rhines, C.G. Eriksen, N.L. Beaird, E. Frajka-Williams+
School of Oceanography, University of Washington

*now at National Oceanographic Centre, Southampton U.K.

AMOC June 7, 2010
• Northern Atlantic/Labrador/Nordic Seas Seaglider programs
  • Norwegian Current
  • Davis Strait
  • Labrador Sea
  • Iceland-Faroe Ridge / Faroe Bank Channel
Background AMOC decadal variability

UPPER OCEAN BRANCH:

*Subtropical => subpolar warm invasion: bridging the gyre boundary: Gulf Stream/NAC sensitivity
Background AMOC decadal variability

UPPER OCEAN BRANCH:

*Subtropical => subpolar warm
  invasion: bridging the gyre boundary: Gulf Stream/NAC sensitivity

*Deceleration of subpolar gyre from satellite altimetry (1992-2000’s)
  (unknown trend of deep AMOC branch): NAO-like yet max for principal EOF is in
  Irminger Sea near Greenland: atmospheric wake/tip jet
Background AMOC decadal variability

UPPER OCEAN BRANCH:

*Subtropical => subpolar warm invasion: bridging the gyre boundary: Gulf Stream/NAC sensitivity

*Deceleration of subpolar gyre from satellite altimetry (1992-2000’s)
(unknown trend of deep AMOC branch): NAO-like yet max for principal EOF is in Irminger Sea near Greenland: atmospheric wake/tip jet

* Fresh Water invasions control deep convection and spring plankton bloom in Labrador Sea: sensitive to E and W Greenland coastal currents and NAC’s ‘NW Corner’: retention in subpolar gyre

figure: Brambilla & Talley, JGR 2008
Iceland Faroe Ridge / Faroe Bank Channel
Dense overflow pathways (*Hansen & Osterhus*, PIO 2000)
Overflow ’73 (Koltermann, Meincke & Muller 1976 IFM rep.)
NSF-OCE sponsored Seaglider deployments

From Nov 2006 to Nov 2009, Seaglider launches from the Faroe Islands returned 23 successful ‘cruises’ yielding more than 17,000 profiles, mostly full depth: $\theta$, S, p, $O_2$, fluorescence, red and blue particle backscatter; depth-averaged horizontal velocity, small-scale vertical velocity.

Concentrated on south flank of Ridge and Faroe Bank Channel exit, where the $\sim 3$ Sv of dense water enters Iceland Basin, eventually producing NorthEast Atlantic Deep Water, a constituent of lower North Atlantic Deep Water with potential density $\sim 27.8$. 
Cross-ridge glider temperature section
Bottom potential temperature...all
Bottom potential temperature...all
Bottom potential temperature...all
Bottom dense layer thickness
Average bottom pot. temperature

average bottom temp (°C)

-1 0 1 2 3 4 5 6 7 8

64° N 62° N 14° W 12° W 10° W 8° W 6° W
Extreme observed bottom pot. temperature
Moored observations show dense plume variability at 2-5 days near the FBC exit; here we see such variability along the entire 400 km Ridge pathway.

Prater & Rossby JGR 2005

Geyer et al. JGR 2006.
standard dev. of bottom pot temperature
3-year mean current and potential density 50m above bottom (500-1000m) from thermal wind plus glider depth-averaged horizontal velocity
Rossby-Prater bottom RAFOS drifter tracks (JGR 2005)
thickness ~ 50 – 350m
Downstream evolution with transport projected on $\Theta/S$

Transport weighted circles

Beaird, Eriksen & Rhines, AGU 2010
Rapid mixing events in Mauritzen et al. (DSR 2004) FBC cruise occurred here.
Note reappearance of dense water near Iceland, overflowing through valley at Iceland slope…but with very small transport.
downstream evolution of dense water mean transport ($\sigma > 27.8$)
Entrainment appears to have taken the warmer, more saline upper ocean trend into the deepest densest overflows of the northeast Atlantic. . . the NEADW / ISOW- Yashayaev et al GRL2007: the AMOC really is a triad of fluxes: mass, heat, salt
Entrainment appears to have taken the warmer, more saline upper ocean trend into the deepest densest overflows of the northeast Atlantic....the NEADW / ISOW- Yashayaev et al GRL2007: the AMOC really is a triad of fluxes: mass, heat, salt

1981 – 1999 => fresher, colder
1999-2005 => saltier, warmer
Faroe-Bank Channel outflow and mixing
comparing bottom moored adcp velocities (Fer et al. 2010) and 3-year mean Seaglider velocity 50m above bottom; max speed ~ 1.35 m sec$^{-1}$
synthetic mean Seaglider section 10 km downstream of final sill ($N^2$ and potential density)
Seaglider vertical velocity variance and turbulence probe KE dissipation (Fer et al., GRL 2009)
Fer et al. JGR 2010
Seaglider vertical velocity and mixing
Vertical velocity profiles at Faroe Bank Channel exit
A remarkable image of turbulence and mixing appears in measurements of vertical velocity, in conjunction with hydrography and particle scattering. This is done by comparing the pressure depth with the depth anticipated from glider flight performance (with known pitch angle and buoyancy). Dive 122 of SG104 in August 2007 at the mouth of the Faroe Bank Channel shows extreme vertical velocity in and above the dense plume (here cold, fresh with high oxygen content). The red and hot-pink profiles show the resolved vertical fluid velocity on up- and down dives with amplitude 5 to 10 cm sec⁻¹, from differencing observed fall rate and fall-rate relative to the water (blue curves). Note the up/down trace differences and the long duration (~30min) of some vertical velocity features. The glider depth history (black) further illustrates the up/down drafts. The smallest observable vertical velocity features are a few m in horizontal scale.
Downstream evolution of dense overflows in Iceland Basin
Subpolar salinity: 1966, 1994, 2001 (Yashayaev)

ISOW …NEADW settles at about 2500m, joining the cyclonic subpolar gyre, as a ‘basement’ to Labrador Sea Water in the parfait of North Atlantic Deep Water
CFC-12
AR7/W
Labrador Sea

Azetsu-Scott et al. JGR 2003

Figure 3. CFC-12 distribution along the WOCE AR7W line from 1991 to 2000. In 1992, measurements were limited to the western half of the AR7W line. Access to the shelf stations depended on the ice conditions and was limited in some years.
Riemenschneider & Legg OM 2007 MIT GCM @ 2.5 km x 25m res
Dense plume entering a bowl-shaped basin: surface circulation is excited by vortex stretching

(Univ. of Washington GFD Lab)
Barotropization is powerful! Even with a thin overflow plume
Altimetric sea-surface height and EKE peak above exiting deep overflow plumes Høyer & Quadfasel GRL 2001

- Topex/Poseidon
- ERS-1
- Faroe Bank Channel
- Denmark Strait
Conclusions

• A statistical approach to dense overflows is needed
  • when they have exited narrow channels: while this is formally ‘eddy flux’ its evaluation suggests repeated Iceland Basin surveys extending to ~2500m depth.

• The 3-year Seaglider program did not determine quantitatively the passage of dense overflows at the Iceland Faroe Ridge yet it produced
  – The transport (on the $\theta$/S plane) of the dense water layer on the IF Ridge, showing admixing of the IFR overflow and FBC outflow and its severe dilution with distance.
    • near-bottom, & vertical structure of the circulation near the 1000m isobath was estimated over 3 years, showing the dilution of the transport-weighted density, $\theta$,S and decay of transport from ~ 1.5 Sv to less than 0.5 Sv.
  – The bifurcation of the Faroe Bank Channel outflow was observed, although it will take Deepgliders to follow that (small?) sinking branch to 2500m depth
  – The western IFR overflow pathway near Iceland was found to be very intermittent, unlike the conclusions reached from the 1970s (Saunders, JPO 1996).
• Seaglider observations of vertical velocity show a rich geography of mixing and internal waves relevant to the dilution of the dense overflows, as well as in deep convection in Labrador Sea
  • in conjunction with geostrophic velocity, $\theta$, S, turbidity (light scattering) and other tracers. Gliders are being equipped with turbulence probes.

• The depth-averaged Seaglider velocity field including tides is well resolved to roughly 1 cm sec$^{-1}$, yielding absolute velocity profiles and evidence of strong quasi-barotropic eddies and jets.
  vortex stretching activates the upper ocean above dense overflow jets.
S on the 3.0C $\Theta$ surface (Worthington & Wright atlas)
Seagliders in the Labrador Sea (2003-2005)
Hatun et al. (JPO 2007), Frajka-Williams et al. (DSR 2009)
Figure 1: (a) Map of the Labrador Sea with Seaglider tracks, sg014 (thin) and sg015 (thick). Regions with mixed layer depths greater than 1000 m are in red, while the restratified region post-deep convection is in green. (b) Average winter heat fluxes (latent and sensible heat fluxes, net long wave and net short wave radiation) are in blue shading. Greater heat loss to the atmosphere (oceanic cooling) is in more saturated blue. Salinity convection resistance, the surface to 500 m buoyancy anomaly due to salinity variations in March, is contoured in dashed lines. Negative convection resistance indicates haline stratified (relatively fresh water above 500 m as compared to at 500 m). The blue star in (a) indicates the position of the K1 mooring.
Seaglider $S, \theta$, vertical velocity over about 1500km in Labrador Sea
Figure 21: Scatterplots of sg015 $w_{rms}$ on heat flux (a) and wind speed (b) for lagged daily averages.
Conclusions

• A statistical approach to dense overflows is needed
  • when they have exited narrow channels: while this is formally ‘eddy flux’ its evaluation suggests repeated Iceland Basin surveys extending to ~2500m depth.

• The 3-year Seaglider program did not determine quantitatively the passage of dense overflows at the Iceland Faroe Ridge yet it produced
  – The transport (on the $\theta$/S plane) of the dense water layer on the IF Ridge, showing admixing of the IFR overflow and FBC outflow and its severe dilution with distance.
    • near-bottom, & vertical structure of the circulation near the 1000m isobath was estimated over 3 years, showing the dilution of the transport-weighted density, $\theta$,$S$ and decay of transport from ~ 1.5 Sv to less than 0.5 Sv.
  – The bifurcation of the Faroe Bank Channel outflow was observed, although it will take Deepgliders to follow that (small?) sinking branch to 2500m depth
  – The western IFR overflow pathway near Iceland was found to be very intermittent, unlike the conclusions reached from the 1970s (Saunders, JPO 1996).
• Seaglider observations of vertical velocity show a rich geography of mixing and internal waves relevant to the dilution of the dense overflows, as well as in deep convection in Labrador Sea
  • in conjunction with geostrophic velocity, $\theta$, S, turbidity (light scattering) and other tracers. Gliders are being equipped with turbulence probes.

• The depth-averaged Seaglider velocity field including tides is well resolved to roughly 1 cm sec$^{-1}$, yielding absolute velocity profiles and evidence of strong quasi-barotropic eddies and jets.
  
  vortex stretching activates the upper ocean above dense overflow jets.
In addition to global scope, there is locally intensive sustained observation, for example as virtual weatherships:

ARGO temperature vs. depth in central Labrador Sea, 2002-2009 (Yashayaev, 2009): (though no meteorology or biology or geochemistry)
Linear trend in EKE 1992-2006 (high confidence in blue areas)
Svinøy section: 647 dives Jan-August 2009 (Seaglider ER... extended range... had plenty of battery energy left at end)
Reconstructed SAT relating to AMV
Wood, Overland, Jonsson & Smoliak, JGR subm.
Reconstructed subpolar SAT relating to AMV
Wood, Overland, Jonsson & Smoliak, JGR subm.

with decadal record of flux of warm water from subtropics (Hakkinen & Rhines JGR 2009)
Reconstructed subpolar SAT relating to AMV

Wood, Overland, Jonsson & Smoliak, JGR subm.

with decadal record of flux of warm water from subtropics (Hakkinen & Rhines JGR 2009)
Dense source entering a bowl-shaped basin (Ole Anders Nøst & GFD lab, Univ of Washington): surface signature viewed with optical altimetry. The plume separates into two components, a thin downslope flow and a train of cyclonic eddies.
Transformation of the Norwegian Atlantic Current- Glider Surveys at OWS Mike & Svinoy

Cecilie Mauritzen & Frode Hoydalsvik (Norwegian Meteorological Institute), Edmond Hansen (Norse Polar Institute), Craig Lee (APL-UW), Kjell Orvik (U Bergen)


Fig. 1. Schematic of surface currents showing the Atlantic inflow to the Norwegian Sea and the sea surface temperature from an AVHRR image in March. The Svinoy section with mooring sites is indicated as a full line.
ASOF: Arctic Gateways: Davis Strait Transports and Fluxes

Craig Lee, Jason Gobat, Beth Curry, Richard Moritz, Kate Stafford
*Applied Physics Laboratory, University of Washington*
Brian Petrie, Kumiko Azetsu-Scott, Victor Soukhovtsev
*Bedford Institute of Oceanography*
Malene Simon *Greenland Naturinstitut*

Lee, Petrie, Gobat, Moritz and Azetsu-Scott
Background AMOC decadal variability

UPPER OCEAN BRANCH:

* Subtropical => subpolar warm invasion: bridging the gyre boundary: Gulf Stream/
  NAC sensitivity

* Deceleration of sfc gyre from altimetry
  (unknown trend of deep AMOC branch): NAO-
  like yet max for principal EOF is in
  Irminger Sea near Greenland: atmospheric
  wake/tip jet

* Fresh Water invasions control deep convection
  in Labrador Sea: sensitive to E and W
  Greenland coastal currents and NAC’s ‘NW
  Corner’: retention in subpolar gyre

DEEP OCEAN BRANCH:

• More variability in $\Theta$/$S$ than in volume transport

• Substantial overflow at Iceland-Faroe
  Ridge largely unassessed

• Downslope evolution of Faroe-Bank
  Channel outflow involves bifurcation
  and fragmentation of dense plume
• I. Dense overflow water on the south flank of the Iceland Faroe Ridge: two sources
200m mean currents and density