Why are the densest waters in the North Atlantic formed in the Nordic Seas?

Fiamma Straneo

Acknowledgements/Collaborators

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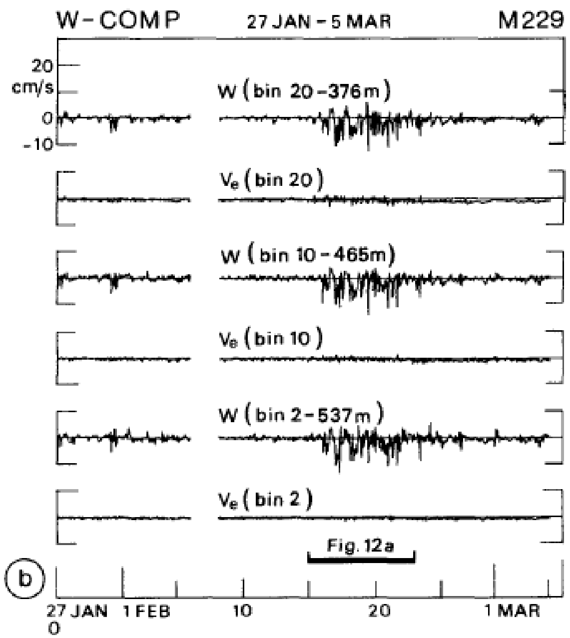
Convective plumes, eddies, the DWBC and the MOC

First observation of convective plumes

Gulf of Lions 1987

Schott and Leaman 91



If we believe the horizontal scale as derived based on the frozen assumption, it implies that there are three different scales present in a convection regime:

1) the scale of the homogeneous patch itself, the chimney scale of some tens of kilometers (MEDOC group 1970; Killworth 1976), and probably up to O (100 km) if several chimneys merge or extended Mistral cooling expands an existing chimney;
2) the scale of the eddies detached from the front around the homogeneous patch of the scale of the Rossby radius of the stratified regime, about 5 km (Gascard 1978);
3) the convection cells of O (1 km) found here.

Plumes as mixing agents:

Greenland Sea, 1988-1989

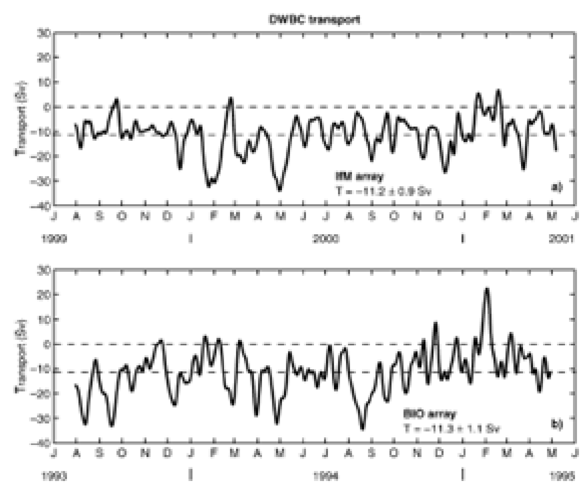
Schott, Visbeck and Fischer 1993

entrainment of surrounding warmer waters on the way down. Mean vertical velocity over a period of convection events was indistinguishable from zero, suggesting that plumes served as a mixing agent rather than causing mean downward transport of water masses. However, different from the surface pool that was governed by mixed-layer physics, the water between 400 and 1400 m was not

Dense water formation and the DWBC

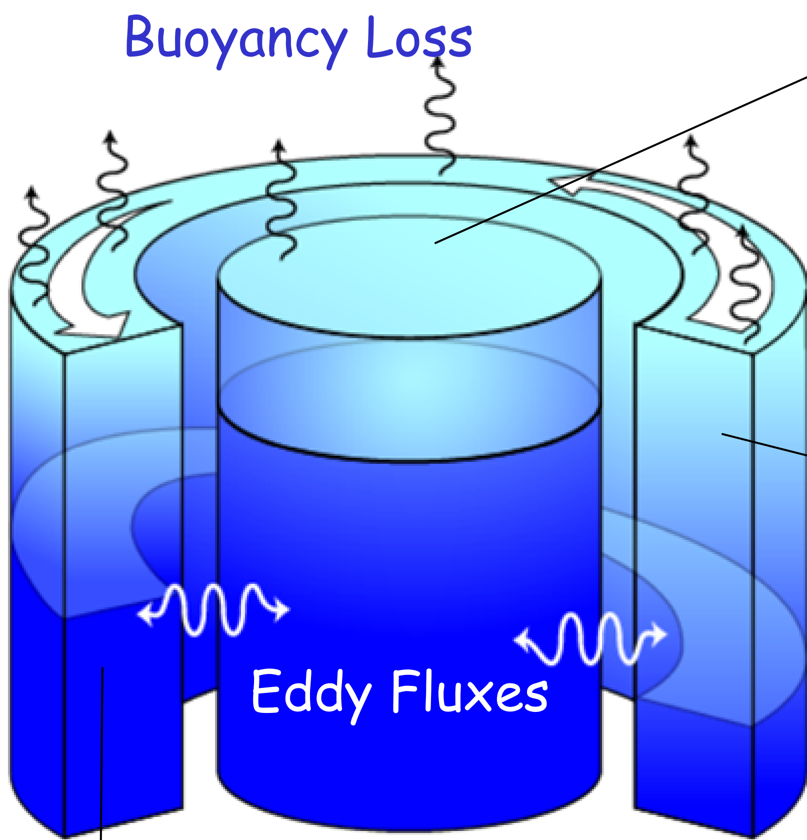
Exit of the Labrador Sea, 1999-2001

Schott at al. 2004



4) While the variance was concentrated in the weeks-to-months time frame, there were also indications of interannual and longer-period changes in currents and transports (Fig. 13); however, it was concluded that the observed trends in the 1993–95 currents and deep-water transports were associated with NAC variability, not with NADW source variability.

Key Elements of a Dense Water Formation Region



Interior Convective Region

- where the densest waters are formed
- weak/no mean flow

Boundary Current Inflow

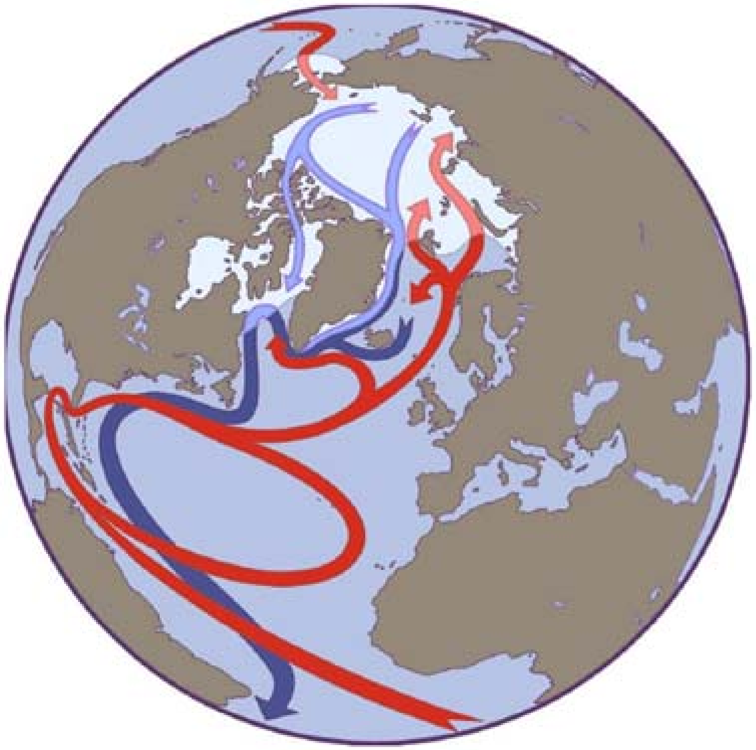
- Warm (light) waters flow around the basin and are made dense by
i) surface buoyancy loss
ii) exchange with the interior (eddy fluxes)

Boundary Current Outflow

- Dense(r) outflow
- Mixture of dense interior water and transformed boundary current waters

Spall 2004, Straneo 2006a and b, Iovino et al. 2008

Warm to cold Conversion in the North Atlantic



Rahmstorf (2006)

Deep/intermediate Branch:

Subpolar Gyre/Nordic Seas

Formation of LSW, ISOW, DSOW (NADW)

Poleward Heat Transport 0.88 PW

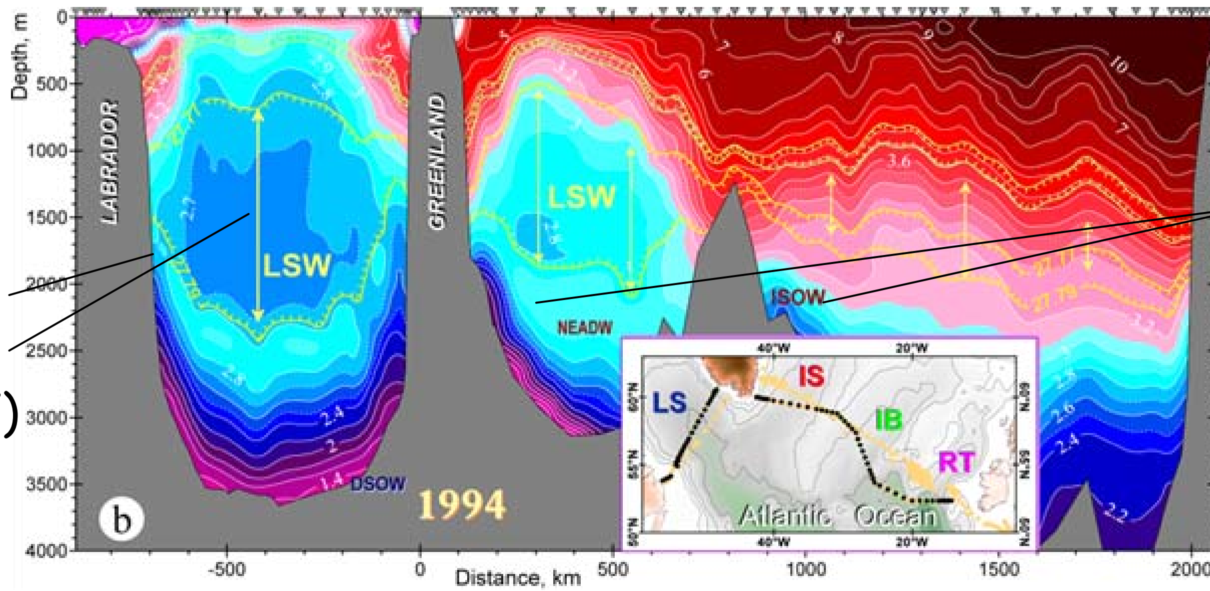
Volume Transport 19 Sv

(24° N Talley 2003)

Subpolar Gyre LSW	Nordic Seas ISOW/DSOW
30 % VT	70 % VT
40% PHT	60% PHT

Nordic Seas Dominate the Intermediate/Deep Branch: Why?

SUBPOLAR GYRE (SP mode waters, LSW)



NORDIC SEAS (ISOW, DSOW)

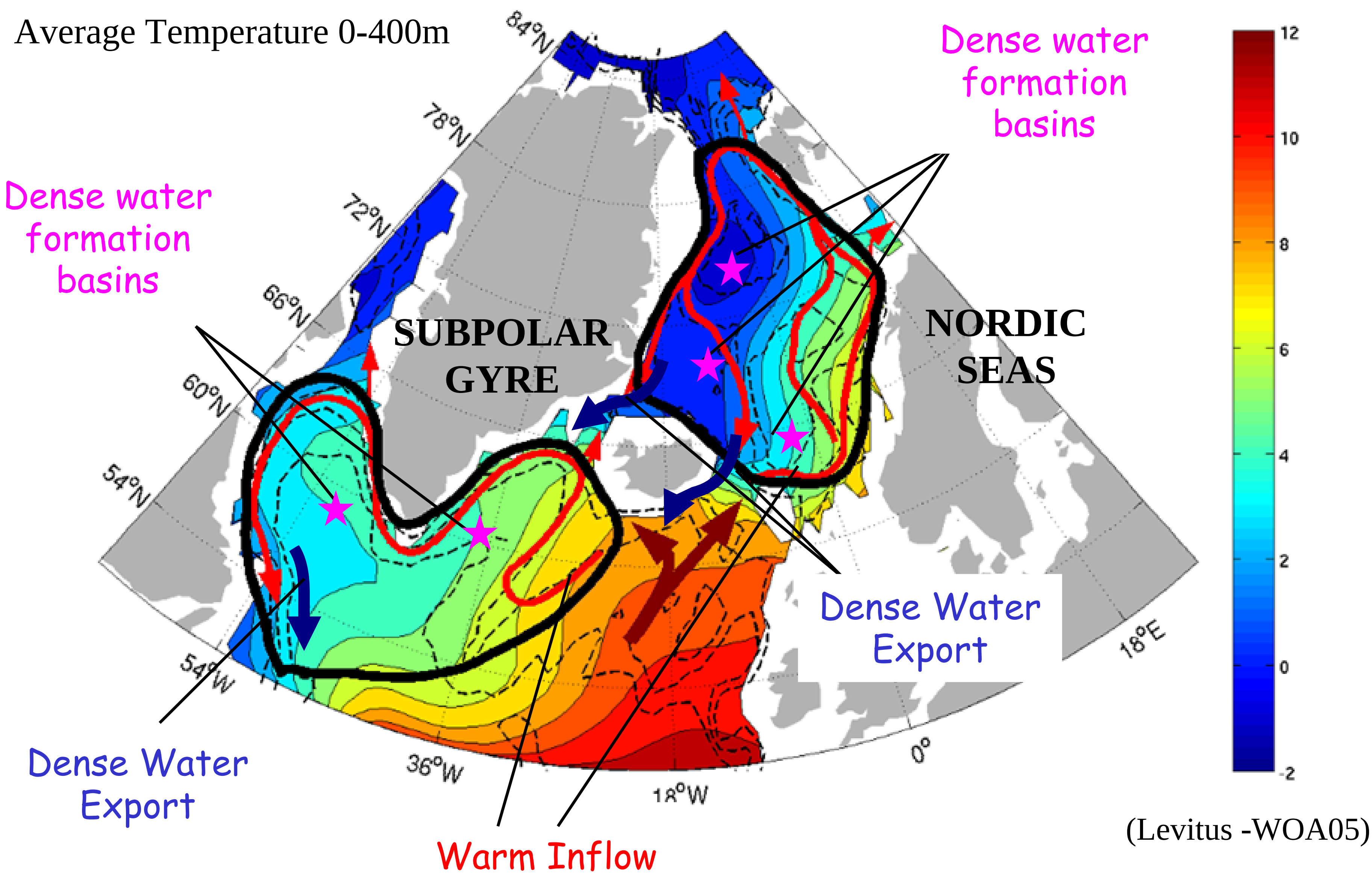
(Yashayaev et al. 2008)

The dense waters exported from the NS are denser than anything formed in the SG and, as such, are the larger contributor to the MOC and PHT

WHY?

Larger buoyancy loss, more/less saline, the Arctic Ocean, the Barents Sea, the topogrpahy?

Warm to Cold Conversion in the North Atlantic



Bower et al. 2002; Jakobsen et al. 2003; Schott and Brandt 2007; Hansen and Østerhus 2000; Nost and Isachsen 2003; Lavender et al. 2004

Steady State Balance Equations for the Model

1. Volume Conservation

$$T_{out} = L\, H_{out} V_{out} = L\, H_{in} V_{in} = T_{in}$$

2. Buoyancy Conservation

$$T_{in}\,(\rho_{out} - \rho_{in}) = F_{tot} A_{tot}$$

3. Geostrophy

$$Vin = g\, \Delta\rho\, Hin/(\rho_0\, f\, L) \qquad \Delta\rho = \rho_D - \rho_{in}$$

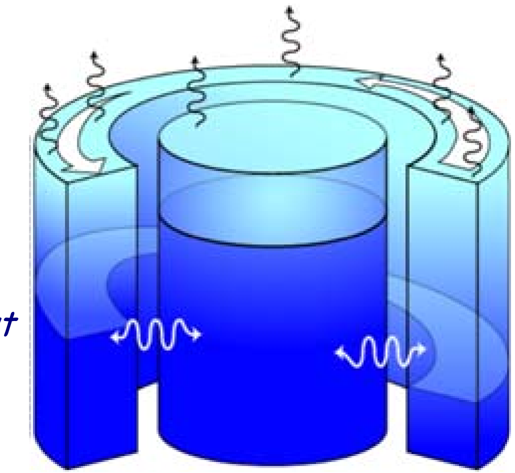
4. Eddy Fluxes

$$u'\rho' = c\, \Delta\rho V_{bcl}$$

$$F_{tot} A_{tot} = F_D A_D + F_{bc} A_{bc}$$

Outflow

V_{out} H_{out} ρ_{out}



Inflow

V_{in} H_{in} ρ_{in}

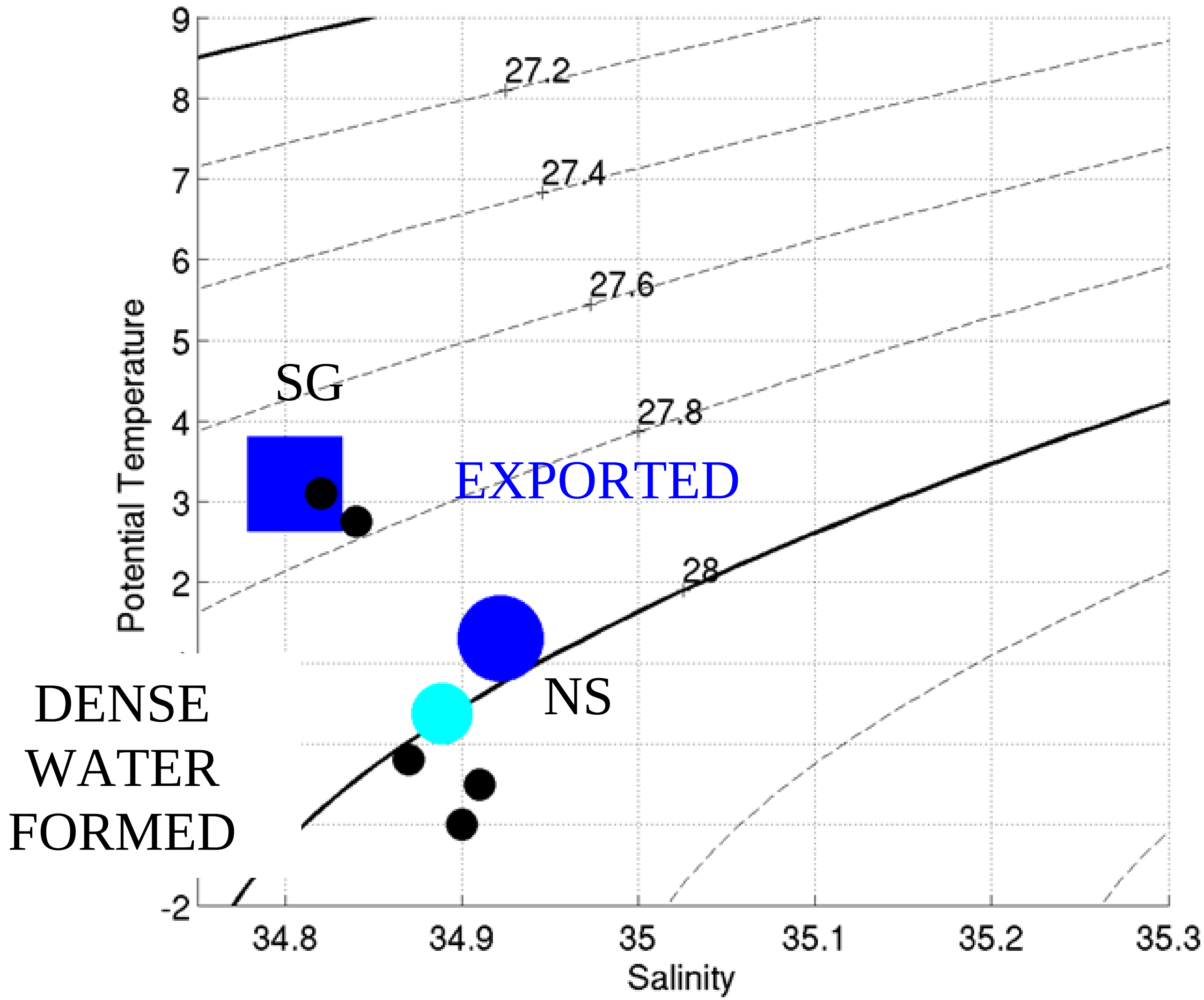
Interior

ρ_D

L – Boundary current width
A_{tot} – Area
F_{tot} – Density Flux ($kg/(m^2\, s)$)

Spall 2004, Straneo 2006a and b, Iovino et al. 2008

Dense Waters Formed and Exported



- ● uLSW, dLSW
- ● GSW, NSDW, NSAIW

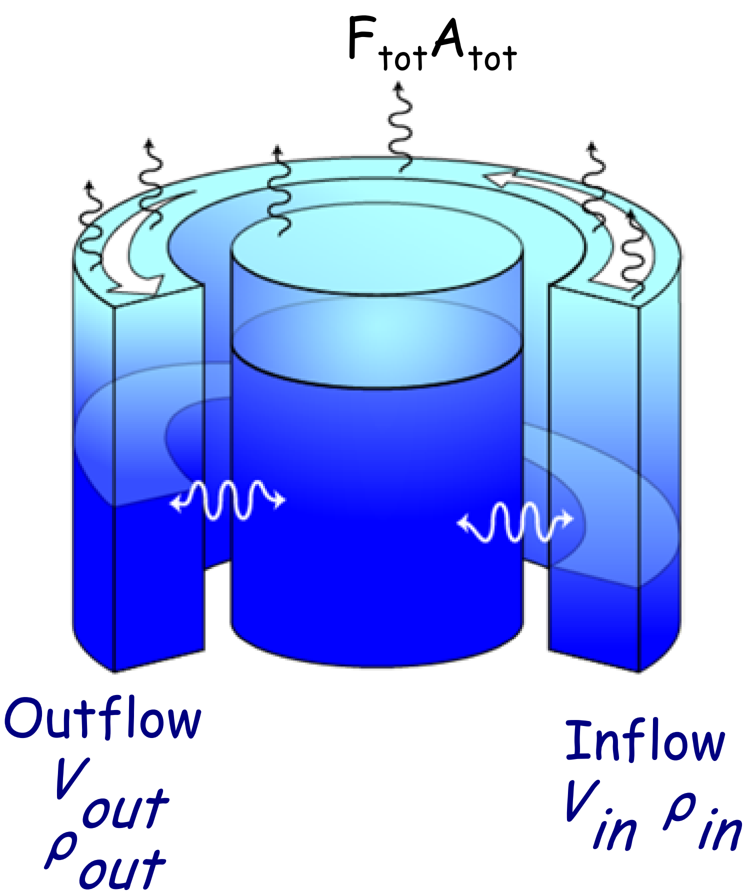
Hansen and Østerhus 2000, Pickart and Spall 2007
Kieke et al. 2007, Lazier 1980, Eldevik et al. 2008
Schott and Brandt 2008

What controls the density of the formed and exported waters?

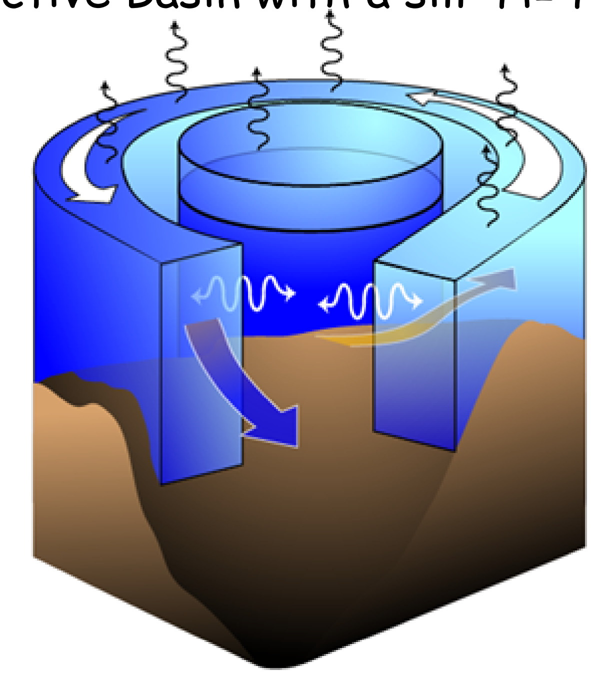
Model links the transformation in the interior and boundary current to
1) the geographical parameters (A_{tot}, A_D, P, L)
2) the inflow conditions (T, ρ_{in}, H_{in})
3) the forcing (F_{tot}, F_D)

$$\rho_{out}-\rho_{in}=\frac{F_{tot}\,A_{tot}}{T}$$

$$\rho_D-\rho_{in}=\frac{1}{H}\sqrt{\frac{F_D A_D f L \rho_0}{P c g}}$$



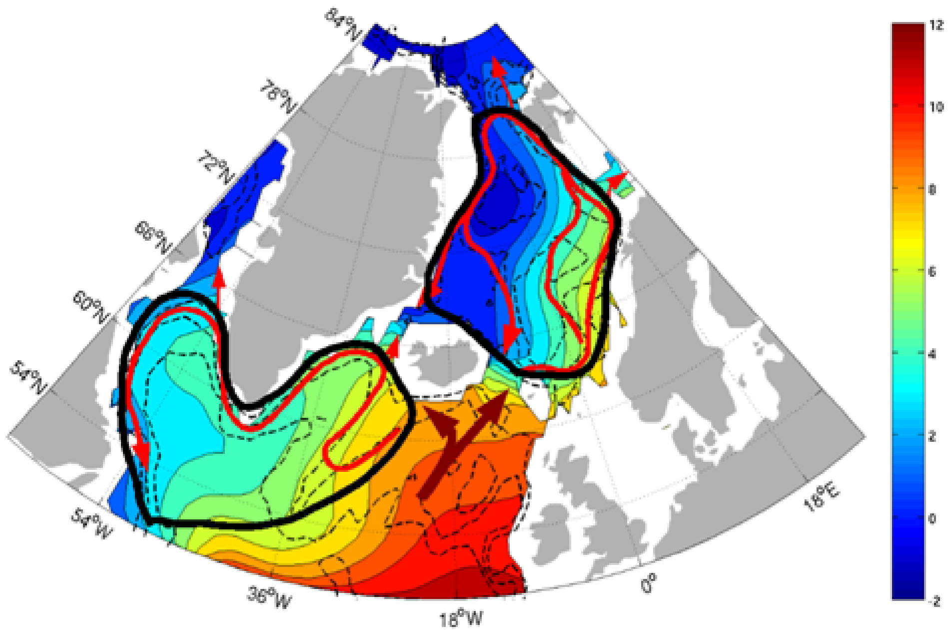
Convective Basin with a sill H= Hsill



1. Geographic Parameters

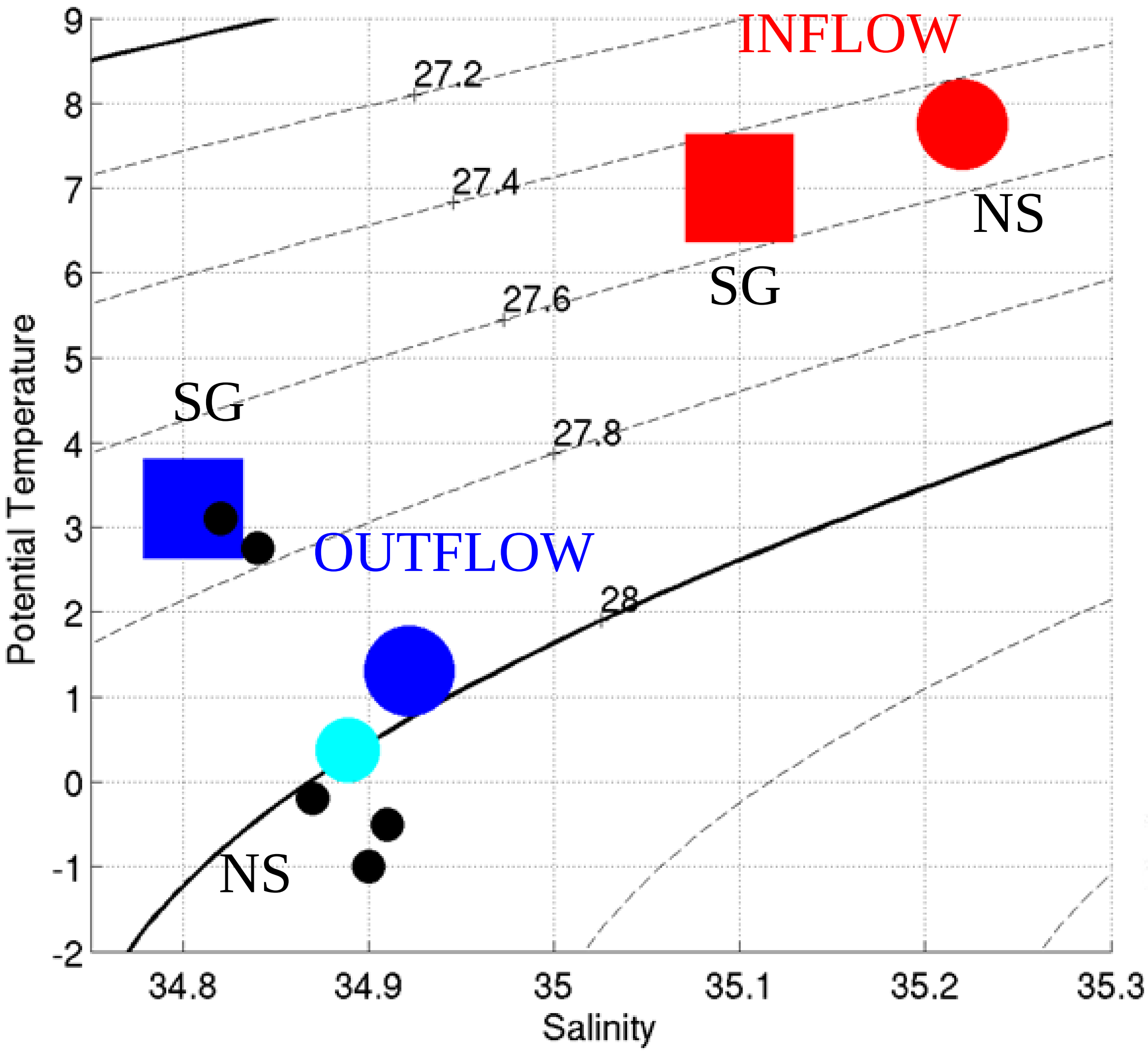
Subpolar Gyre
Area = 1.82×10^6 km^2
L ~ 150 km

Nordic Seas
Area = 1.85×10^6 km^2
L ~ 150 km



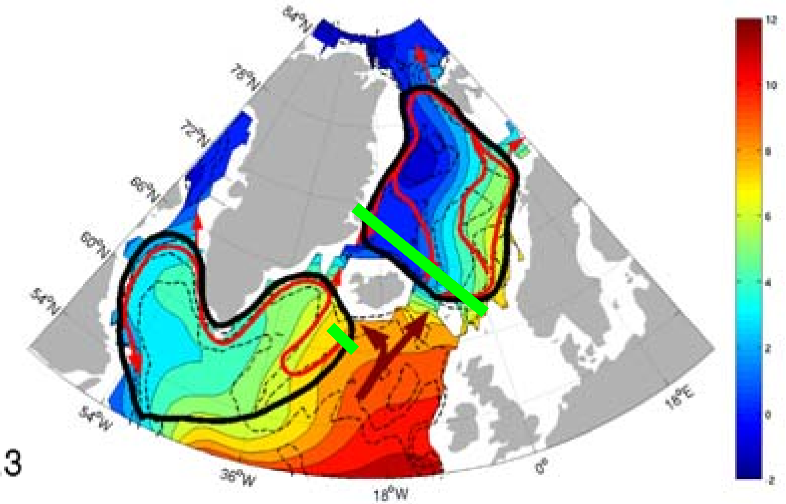
The Nordic Seas and Subpolar Gyre have roughly equal areas and boundary current widths.

Inflow Properties and Transports



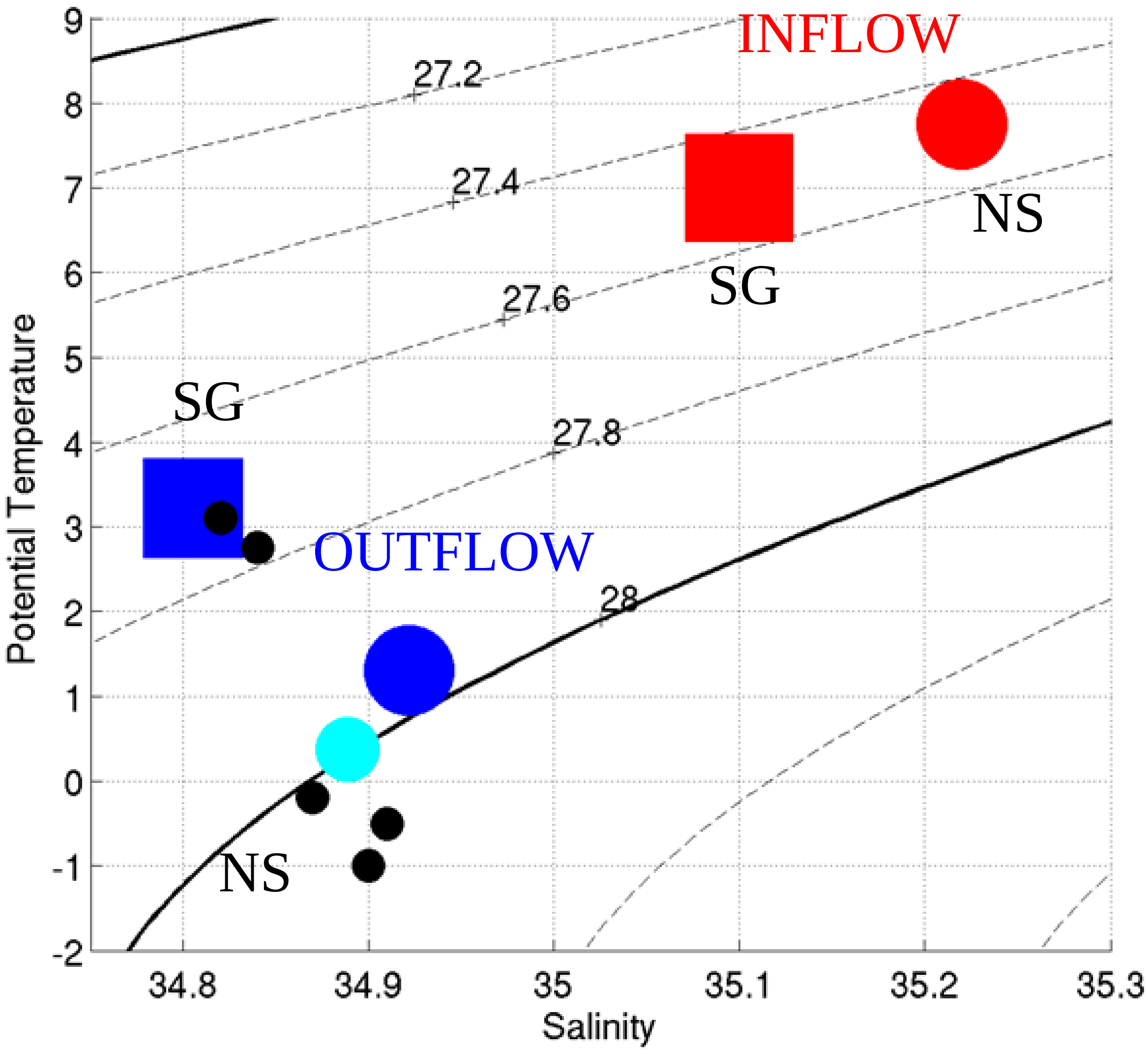
Subpolar Gyre
T = 12 Sv
ρin = 27.5

Nordic Seas
T = 8 Sv
ρin = 27.5



van Aken and Becker 1996; Pickart et al. 2005; Hansen and Østerhus 2000, Pickart and Spall 2007; Kieke et al. 2007, Lazier 1980, Eldevik et al. 2008; Schott and Brandt 2008

Inflow Properties and Transports



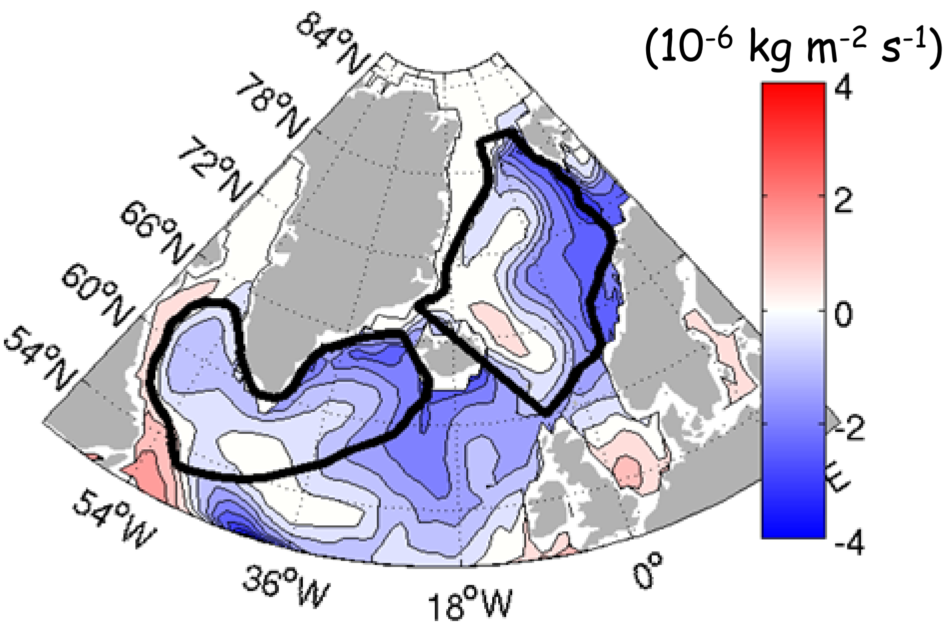
Subpolar Gyre
T = 12 Sv
ρin = 27.5

Nordic Seas
T = 8 Sv
ρin = 27.5

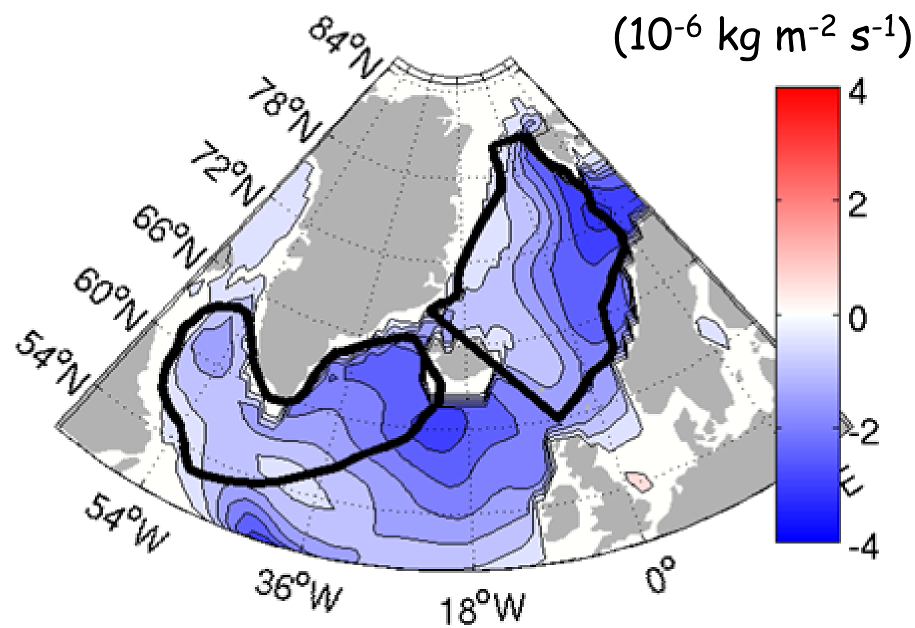
The inflow density is the same but the transport of light water into the Nordic Seas is only 2/3 of that into the Subpolar Gyre.

Comparison of the Mean Density Flux

OAFLUX CLIMATOLOGY
(Yu and Weller 2007)



SOC CLIMATOLOGY
(Josey et al. 1999)



SG **1.1** x 10^6 (kg/s)

NS **1.4** x 10^6 (kg/s)

Ratio NS/SG = 1.3

SG **2.0** x 10^6 (kg/s))

NS **2.5** x 10^6 (kg/s)

Ratio NS/SG = 1.25

Comparison of the Mean Density Flux

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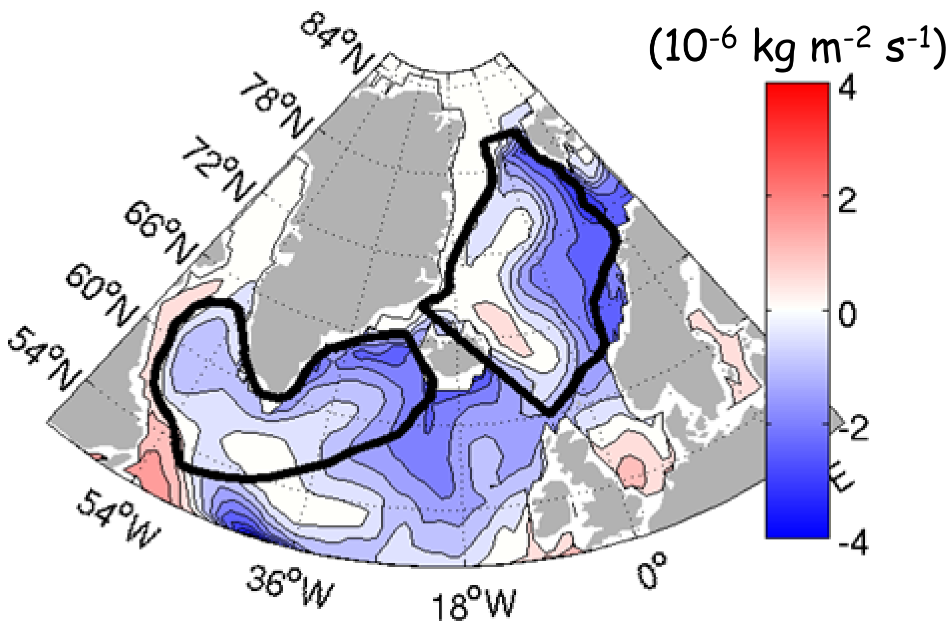

Ratio NS/SG = 1.3

SOC CLIMATOLOGY
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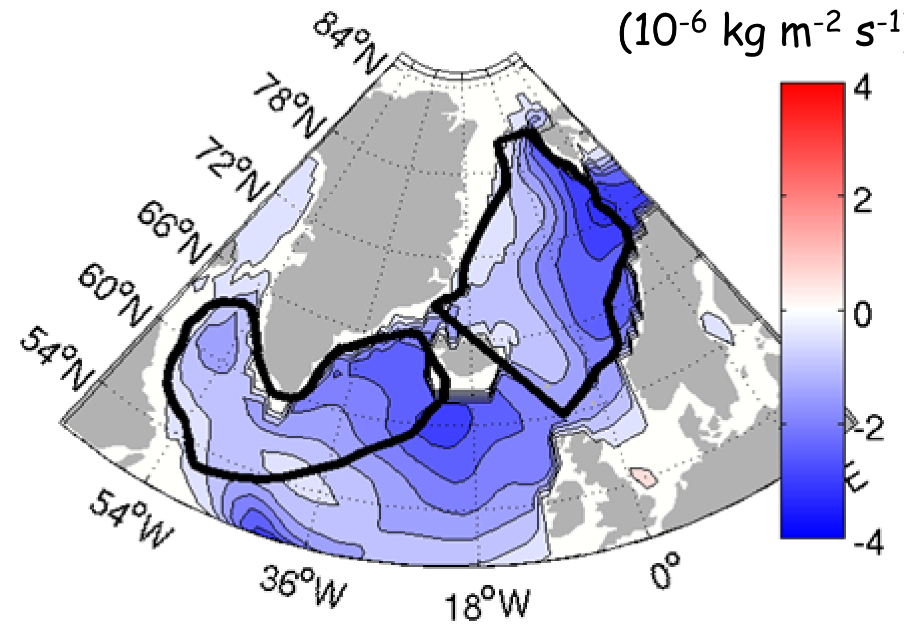


Ratio NS/SG = 1.25

The Nordic Seas experience a somewhat larger buoyancy loss than the Subpolar Gyre.

Why are the exported waters denser?

$$\rho out - \rho in = \frac{Ftot\ Atot}{T}$$

	Subpolar Gyre	*Nordic Seas*
Area (x10^6 km^2)	1.82	1.85
A_{int}/A_{tot}	0.60	0.64
L (km)	150	150
T (Sv)	12	8
H_{in} (m)	1200	500

$$\frac{(\rho out - \rho in)^{NS}}{(\rho out - \rho in)^{SG}} = \frac{(Ftot\ Atot)^{NS}}{(Ftot\ Atot)^{SG}} \frac{T^{SG}}{T^{NS}} = 1.3 x 1.5 = 2$$

Answer: The densification inside the NS is twice that of the SG

i) To a large extent because less light water enters the Nordic Seas (i.e. less water to transform).

ii) In part also because the forcing is larger

Why are the interior waters denser?

$$\rho_D - \rho_{in} = \frac{1}{H}\sqrt{\frac{F_D A_D f L \rho_0}{P c g}}$$

	Subpolar Gyre	*Nordic Seas*
$F_{tot}A_{tot}$ (10^6 kg/s)		
OA	1.1	1.4
SOC	2.0	2.5
$F_D A_D$ (10^6 kg/s)		
OA	0.5 (45%)	0.23 (20%)
SOC	1.2 (60%)	1.0 (40%)

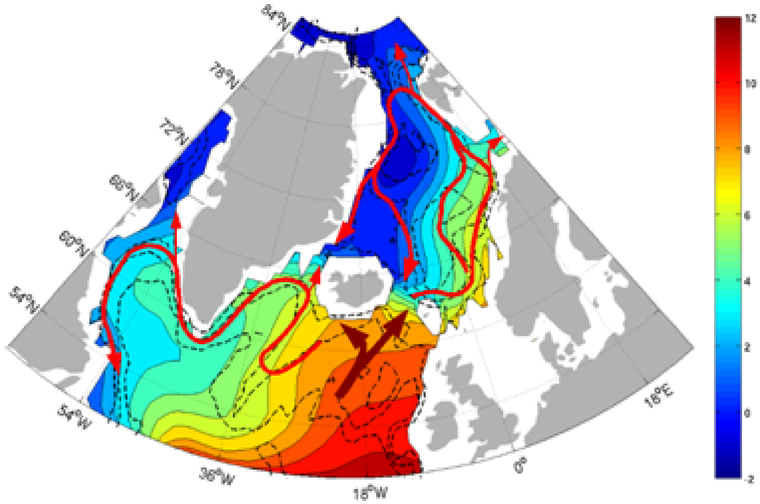
$$\frac{(\rho_{out} - \rho_{in})^{NS}}{(\rho_{out} - \rho_{in})^{SG}} = \frac{H^{SG}}{H^{NS}}\sqrt{\frac{(F_D\, A_D)^{NS}}{(F_D\, A_D)^{SG}}} = 2.4 \times 0.8 \approx 2$$

Answer: The densification in the interior in the NS is twice that of the SG

i) The eddy transport that brings light waters into the interior is much less than in the NS than the SG

ii) This is even if the buoyancy loss over the interior of the NS is less.

Why are the dense waters formed in and exported from the Nordic Seas denser than those of the Subpolar Gyre?



1. SG and NS are quite similar geographic parameters and air-sea forcing

2. Big difference is the Greenland-Scotland Ridge which limits the warm inflow

3. Given the limited warm inflow (and the complex topography) it is easy for the atmosphere to extract the bulk of this warm anomaly

4. Bulk of the transformation is in the advective pathway and the interior of the NS is very cold.