Addressing the Gulf Stream Problem in the 1° POP model

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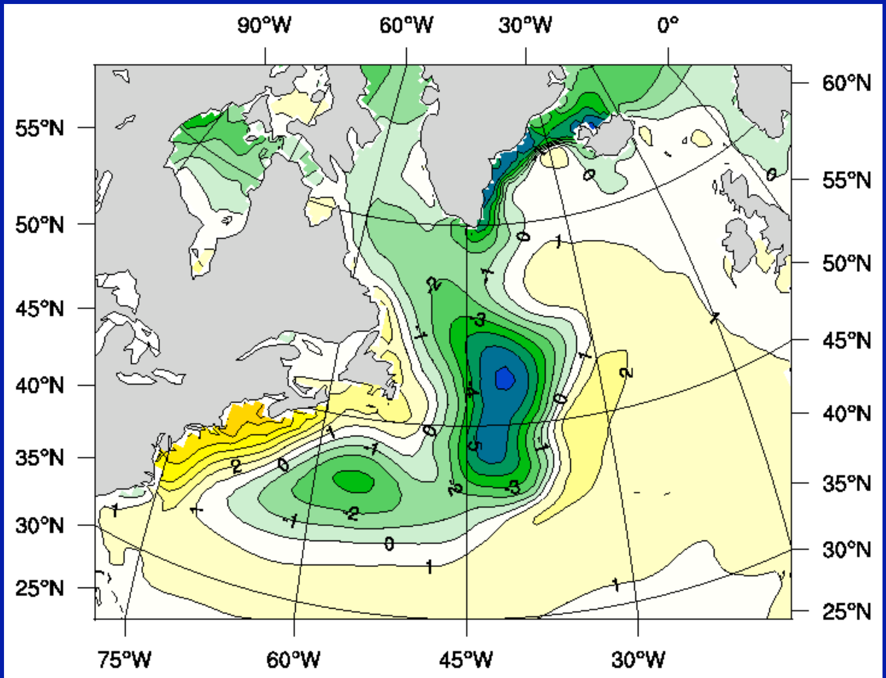
NCAR

SSTA (°C) from a fully
-coupled CCSM3.5 20th
century simulation

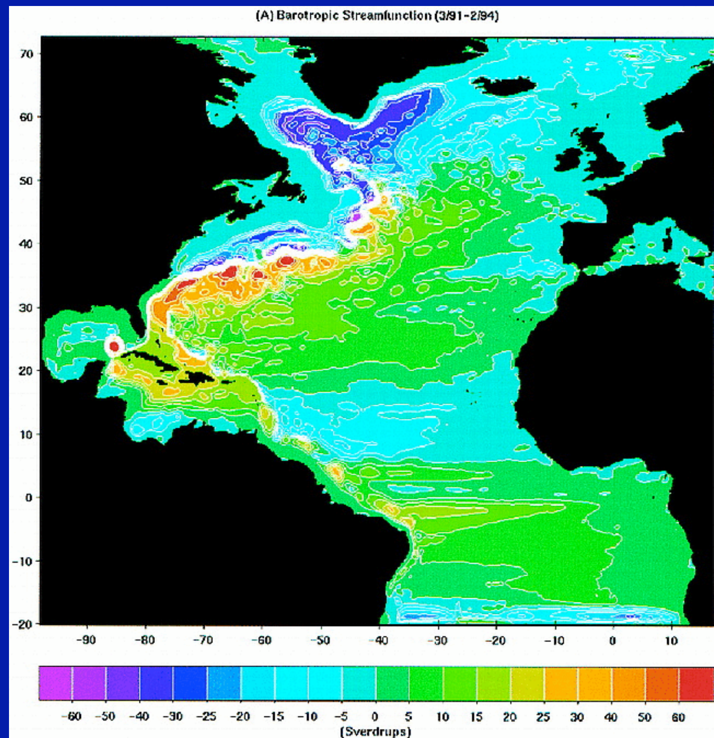


OUTLINE

1. Expected features of the North Atlantic circulation
2. The Gulf Stream in the 1° POP model :
   A. Ocean only hindcast
   B. Ocean-ice hindcast
   C. Fully coupled
3. The connection between the thermohaline circulation and the gyre circulation -- the influence of the deep western boundary current (DWBC)
4. What sets the strength of the DWBC? Gyre spinup and the role of mixed boundary condition feedbacks
5. Water mass transformation in the subpolar seas
6. Conclusion

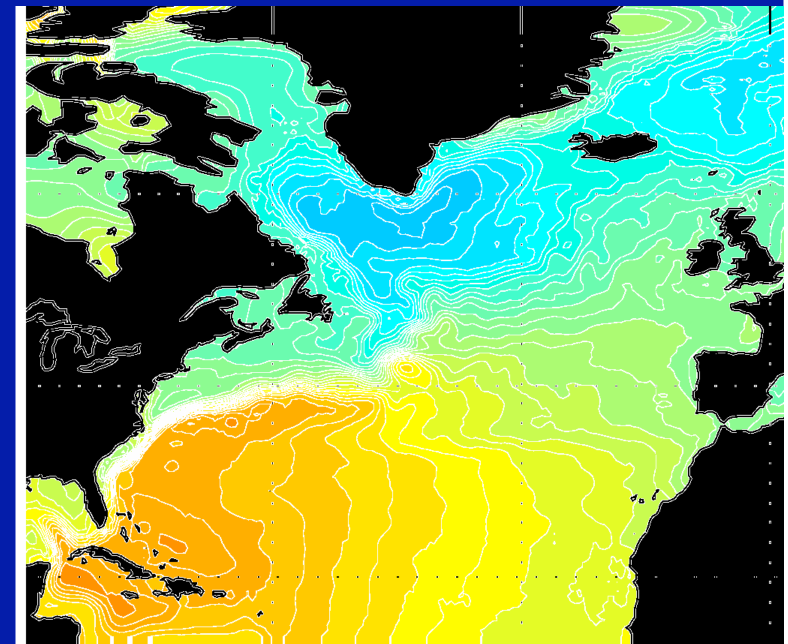
Gyre Circulation

0.1° BSF



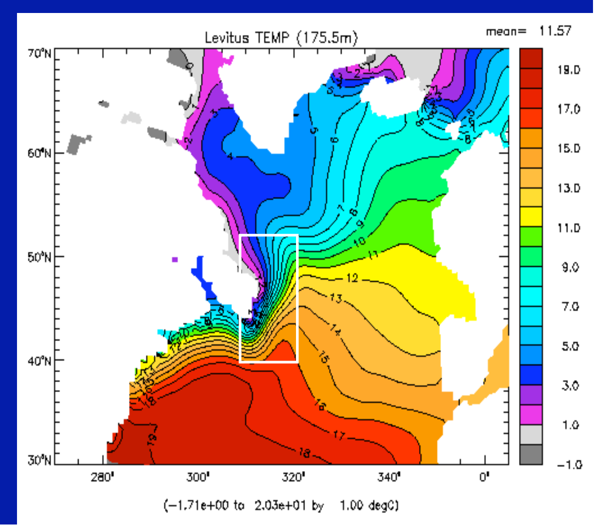
(Smith et al 2000)

1992-2002 Mean SSH



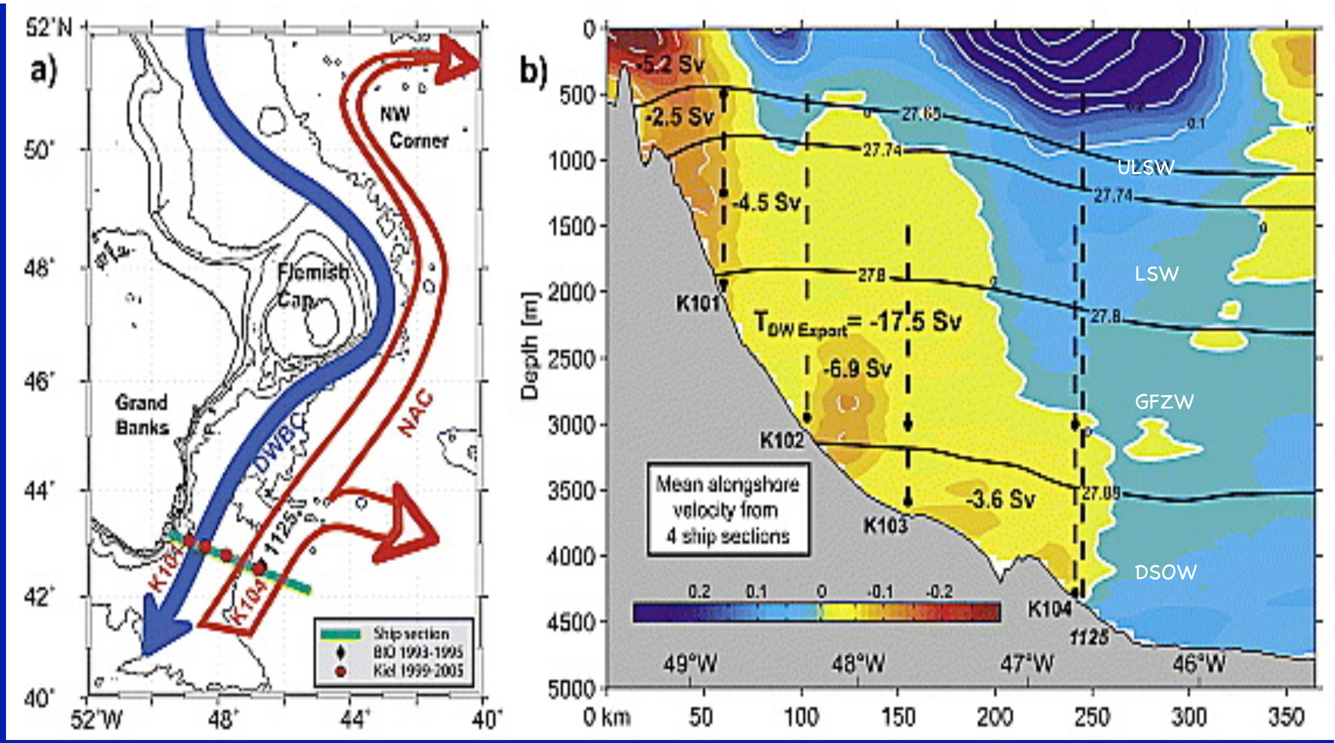
(Maximenko and Niiler 2005)

WOA98 175m TEMP



- Near surface Gulf Stream (GS) jet seperates at Cape Hatteras
- northward North Atlantic Current (NAC) at 45°W
- eastward retroflection of NAC at Northwest Corner
- cyclonic Northern Recirculation Gyre (NRG)

Western Boundary Transports



(Schott et al 2004, 2006)

- Deep Western Boundary Current (DWBC) and North Atlantic Current (NAC)
- 43° N: DWBC flow > 10 Sv ($\sigma_\theta > 27.68$ kg/m^3)

  NAC flow > 100 Sv
- Significant southward transport below 1000m
- current speed ≈10 cm/s (DWBC), ≈60 cm/s (NAC)

POP 1º Experiments

A: ocean-only hindcast
bulk flux forcing with prescribed 1949-2006 atmosphere*
diagnostic sea ice model → prescribes daily observed SSM/I ice extent & ice-ocean thermohaline fluxes based on ocean melt potential

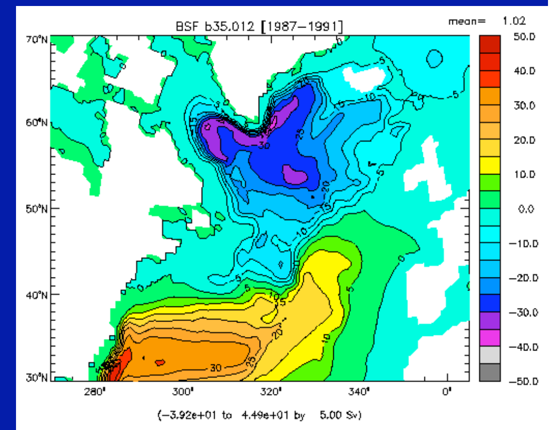
B: coupled ocean-ice hindcast
bulk flux forcing with prescribed 1949-2006 atmosphere*
CICE model → freely evolving sea ice dynamics, thermodynamics

C: fully coupled CCSM3.5 20th century simulation

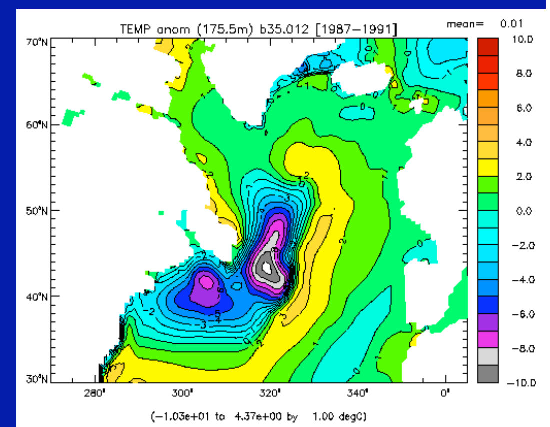
*COREv2 (Large and Yeager 2008)

C: Fully coupled

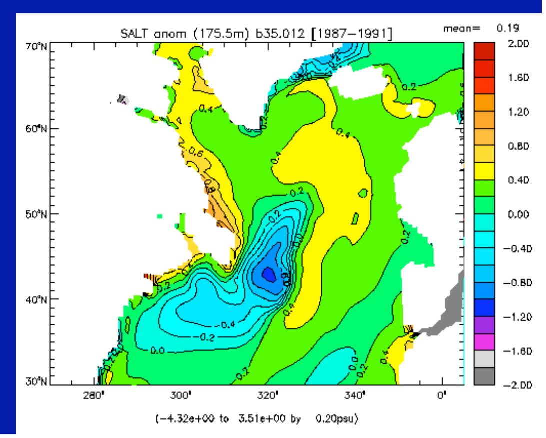
BSF



T′(175m)



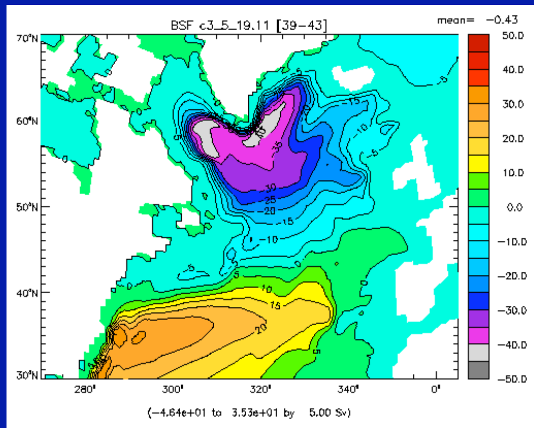
S′(175m)

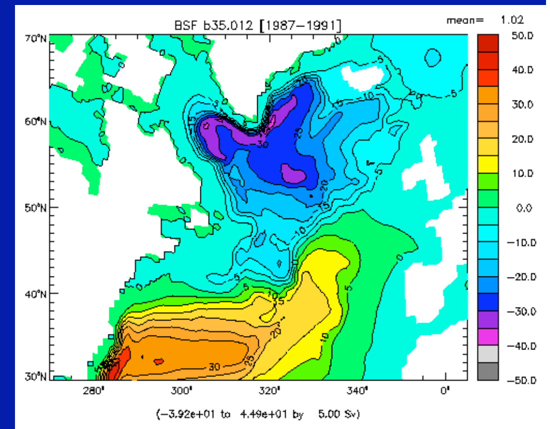


A: Ocean-only

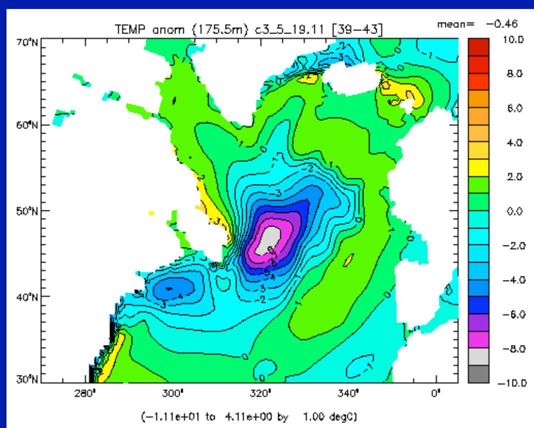
C: Fully coupled

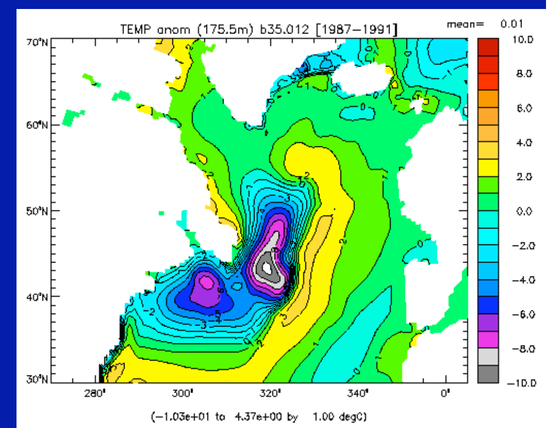
BSF



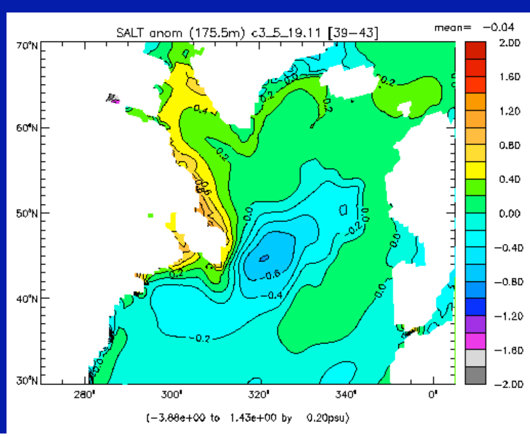


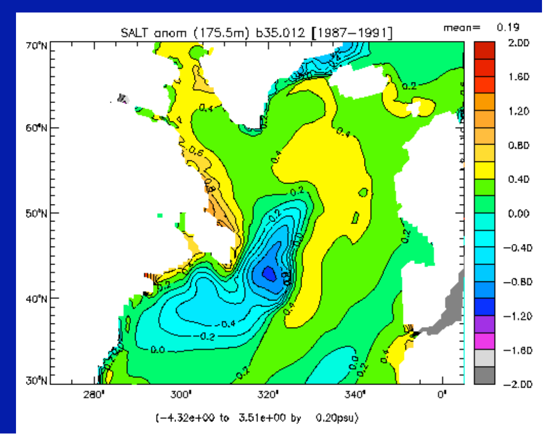
T'(175m)

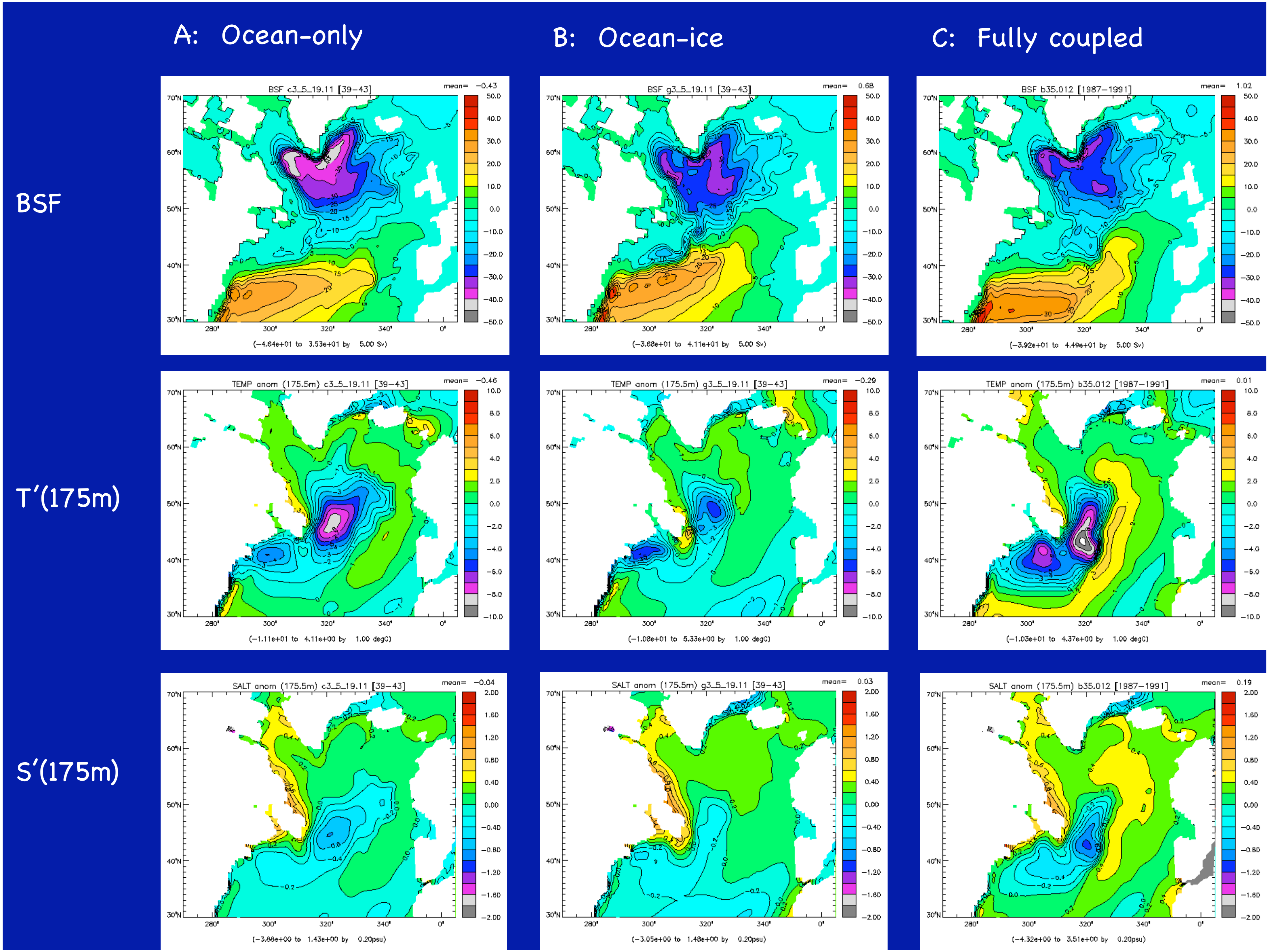




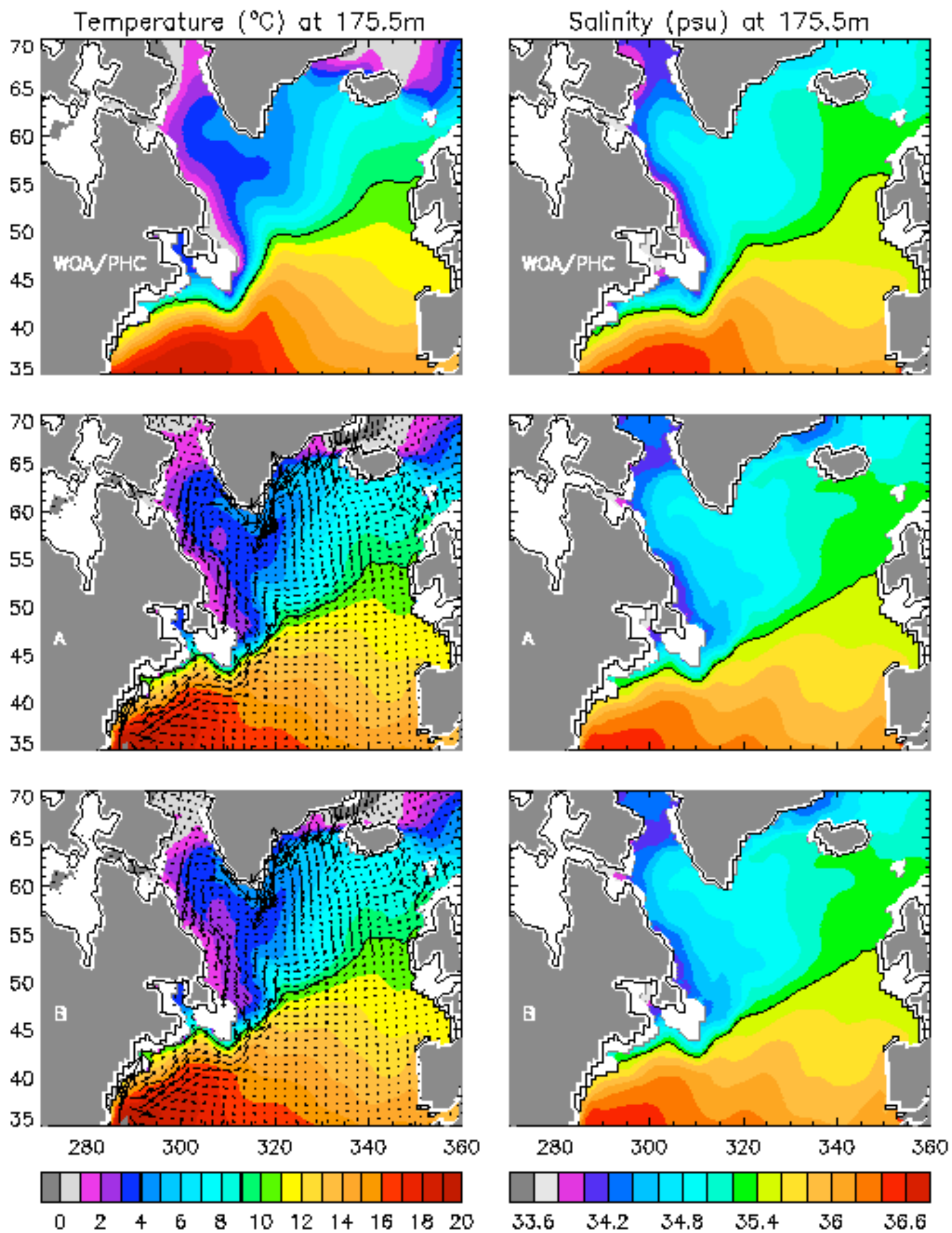
S'(175m)







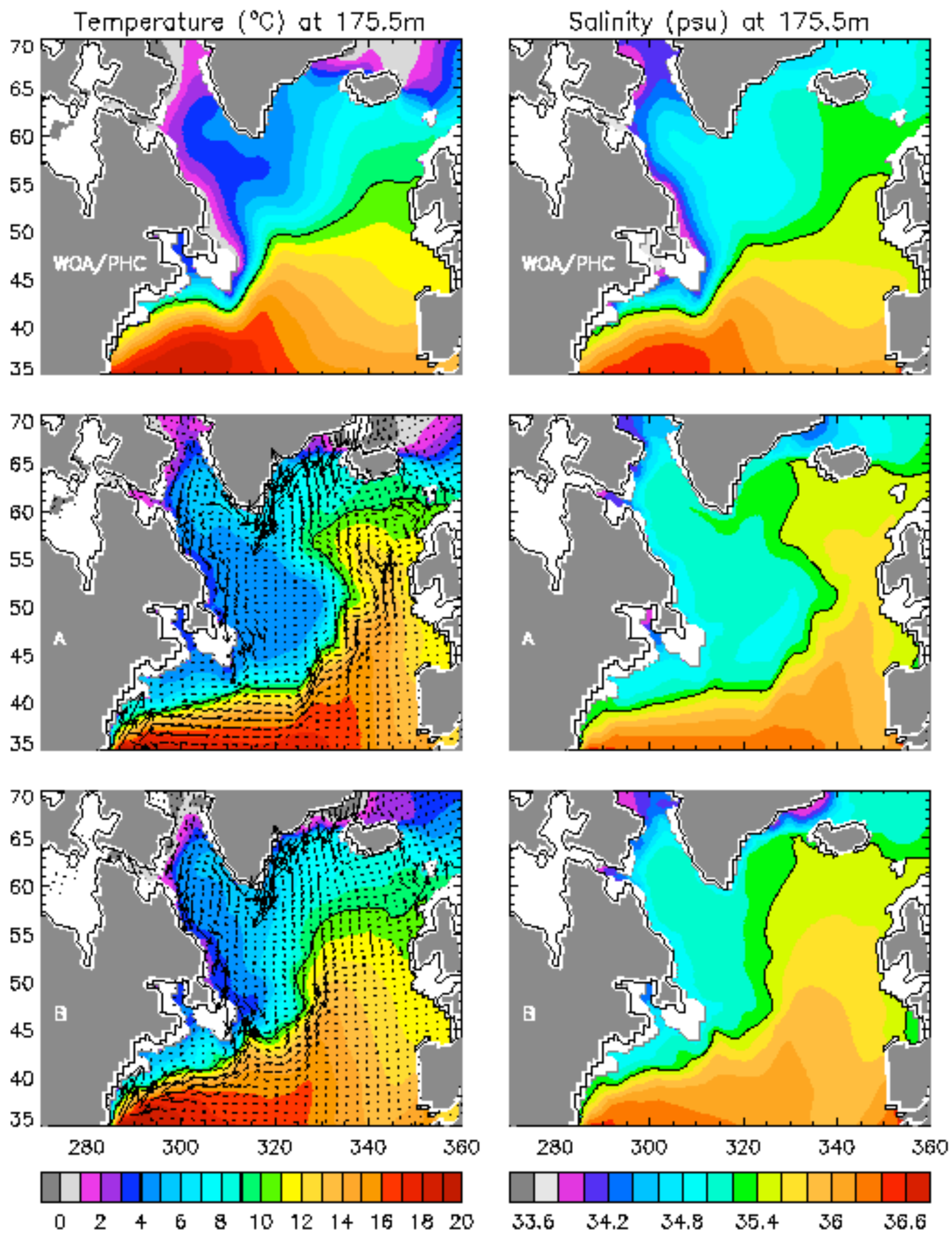
A: Ocean-only
B: Ocean-ice
C: Fully coupled
BSF
T′(175m)
S′(175m)
BSF c3_5_19.11 [39–43]
BSF g3_5_19.11 [39–43]
BSF b35.012 [1987–1991]
TEMP anom (175.5m) c3_5_19.11 [39–43]
TEMP anom (175.5m) g3_5_19.11 [39–43]
TEMP anom (175.5m) b35.012 [1987–1991]
SALT anom (175.5m) c3_5_19.11 [39–43]
SALT anom (175.5m) g3_5_19.11 [39–43]
SALT anom (175.5m) b35.012 [1987–1991]



GS Path

T & S , simulation year 1

- Initial NAC induced by WOA pressure gradients



GS Path

T & S , simulation year 54

→ Complete NAC detachment; core northward transport east of Mid -Atlantic ridge

→ Large negative T′, S′ off Grand Banks

→ Positive T′, S′ in subpolar seas

→ Partial NAC detachment; core northward transport west of Mid -Atlantic ridge

→ Positive T′, S′ in subpolar seas

- Zhang & Vallis (2007) show that a strong downslope DWBC east of the Grand Banks induces bottom vortex stretching which enhances the strengths of the NRG and NAC:

1. $w_B \approx -u_B \cdot \nabla H$ is very large and negative where u_B and ∇H are both large and aligned (Grand Banks shelf)
2. Vertically-integrated vorticity equation:

   $\beta(\partial\psi/\partial x) \quad = \ldots -f_o w_B$

   $w_B < 0 \Rightarrow$ increase in local northward barotropic flow (NAC)

3. $\psi = \ldots + \psi_W = \ldots + (1/\beta)\int_x f_o w_B \, dx'$

   $w_B < 0 \Rightarrow$ basin integral contributes to $\psi < 0$ (NRG)

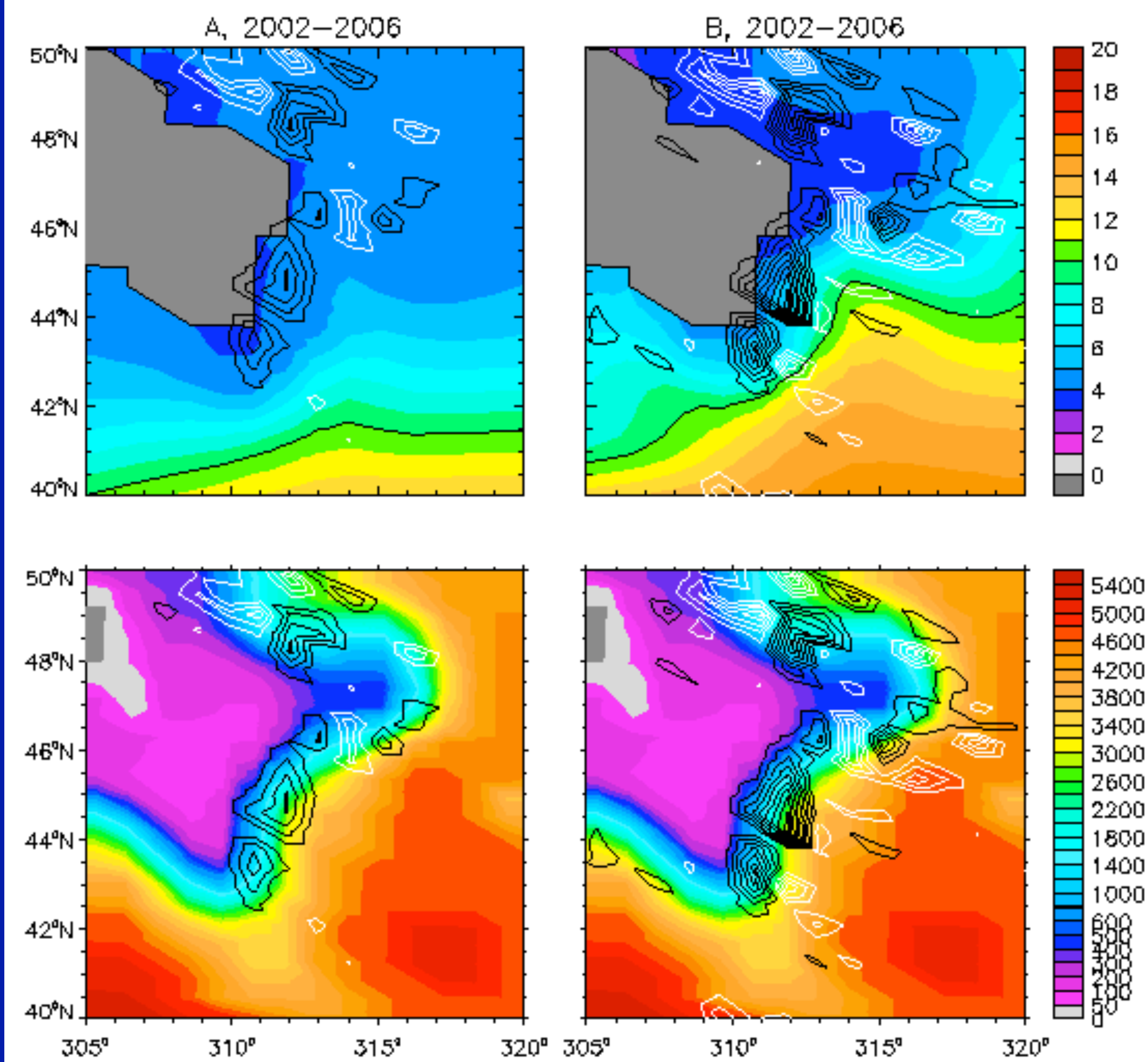
W_B

(contoured at $2x10^{-5}$ m/s)

A B

T(175m)

H



W_B

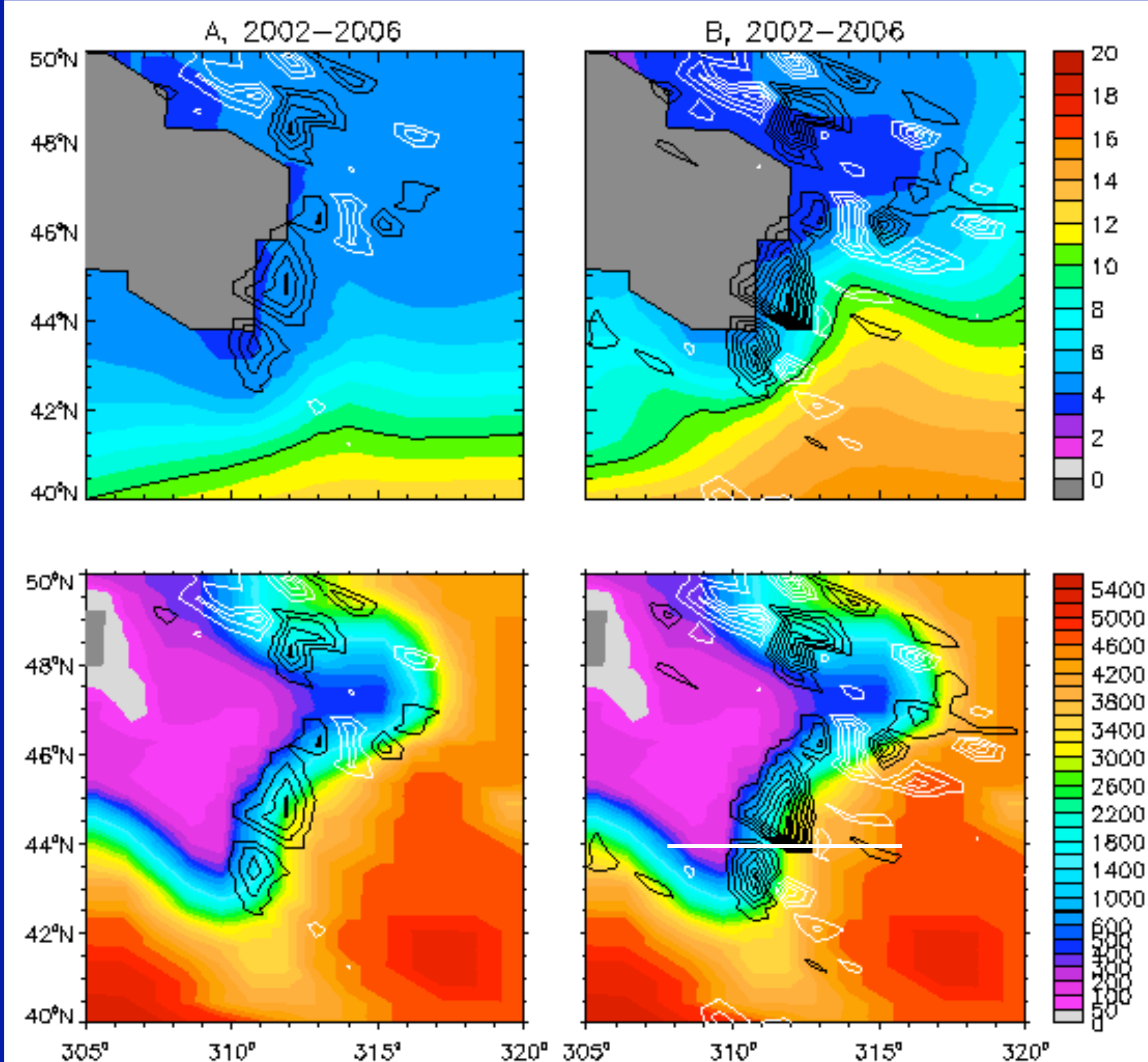
(contoured at 2×10^{-5} m/s)

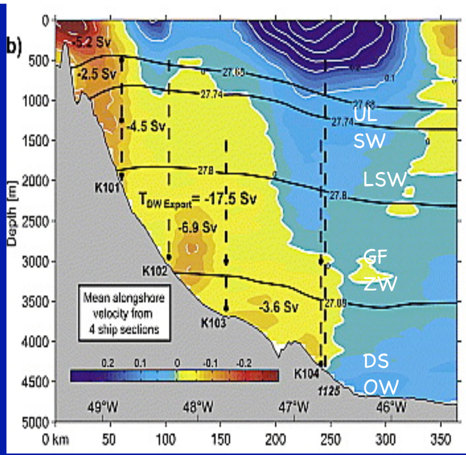
A

B

T(175m)

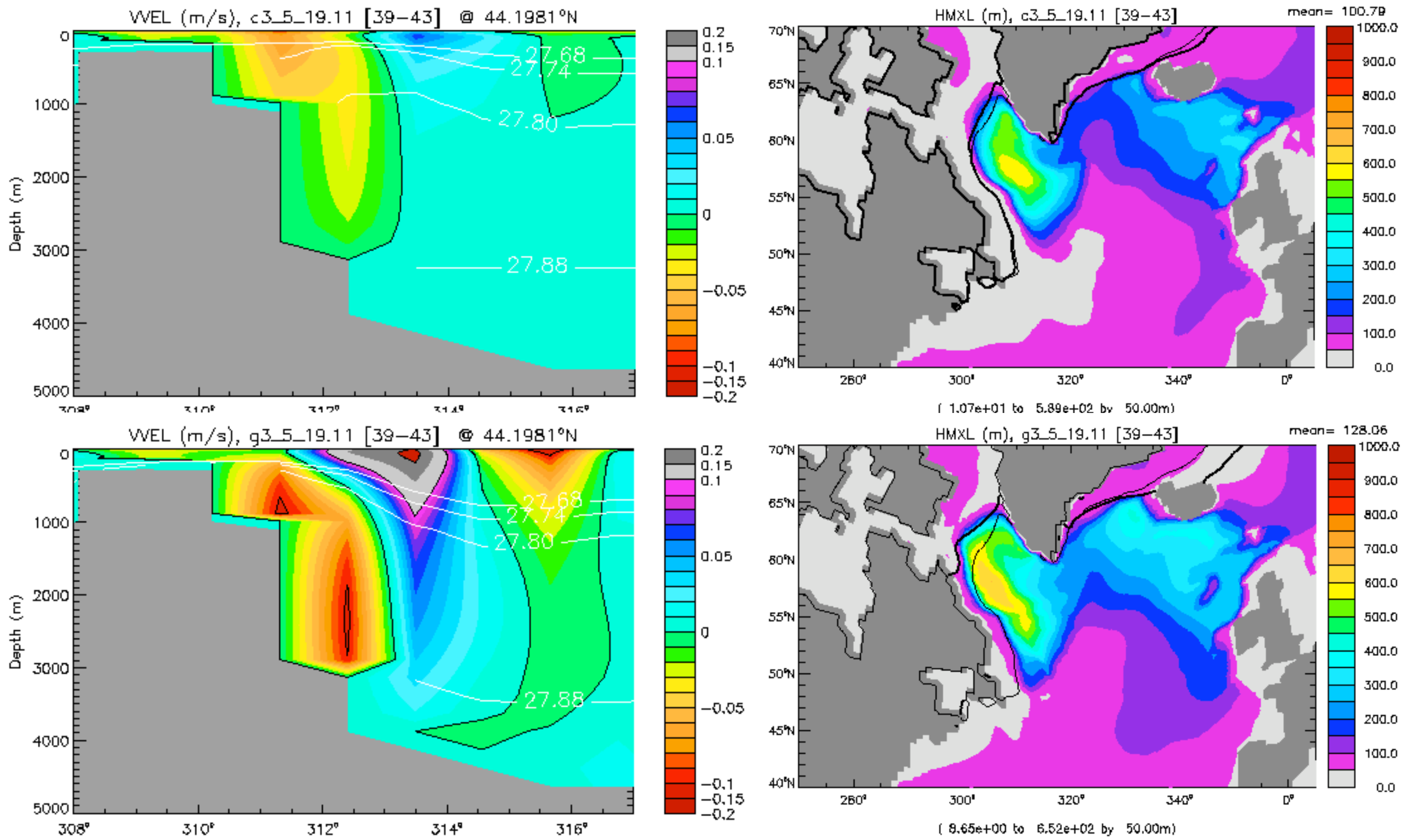
H




b)
Depth [m]
5.2 Sv
-2.5 Sv
-4.5 Sv
K101
T DW Export = -17.5 Sv
-6.9 Sv
K102
-3.6 Sv
K103
K104
Mean alongshore velocity from 4 ship sections
UL
SW
LSW
GF
ZW
DS
OW
49°W
48°W
47°W
46°W
0 km
50
100
150
200
250
300
350

V

MLD


WEL (m/s), c3_5_19.11 [39–43] @ 44.1981°N
Depth (m)
27.68
27.74
27.80
27.88
HMXL (m), c3_5_19.11 [39–43]
mean= 100.79
(1.07e+01 to 5.89e+02 by 50.00m)
WEL (m/s), g3_5_19.11 [39–43] @ 44.1981°N
HMXL (m), g3_5_19.11 [39–43]
mean= 128.06
(8.65e+00 to 6.52e+02 by 50.00m)

A

B

- Improved simulation of the North Atlantic in a low viscosity non-eddy resolving ocean model (BSF, stronger and partially-attached NAC, stronger NRG, reduced upper ocean temperature and salinity bias) is closely tied to increased DWBC strength and density.
- The connections between the DWBC and the North Atlantic gyre circulation appear to be explained by bottom vortex stretching associated with a strong downslope DWBC (Zhang and Vallis 2007).

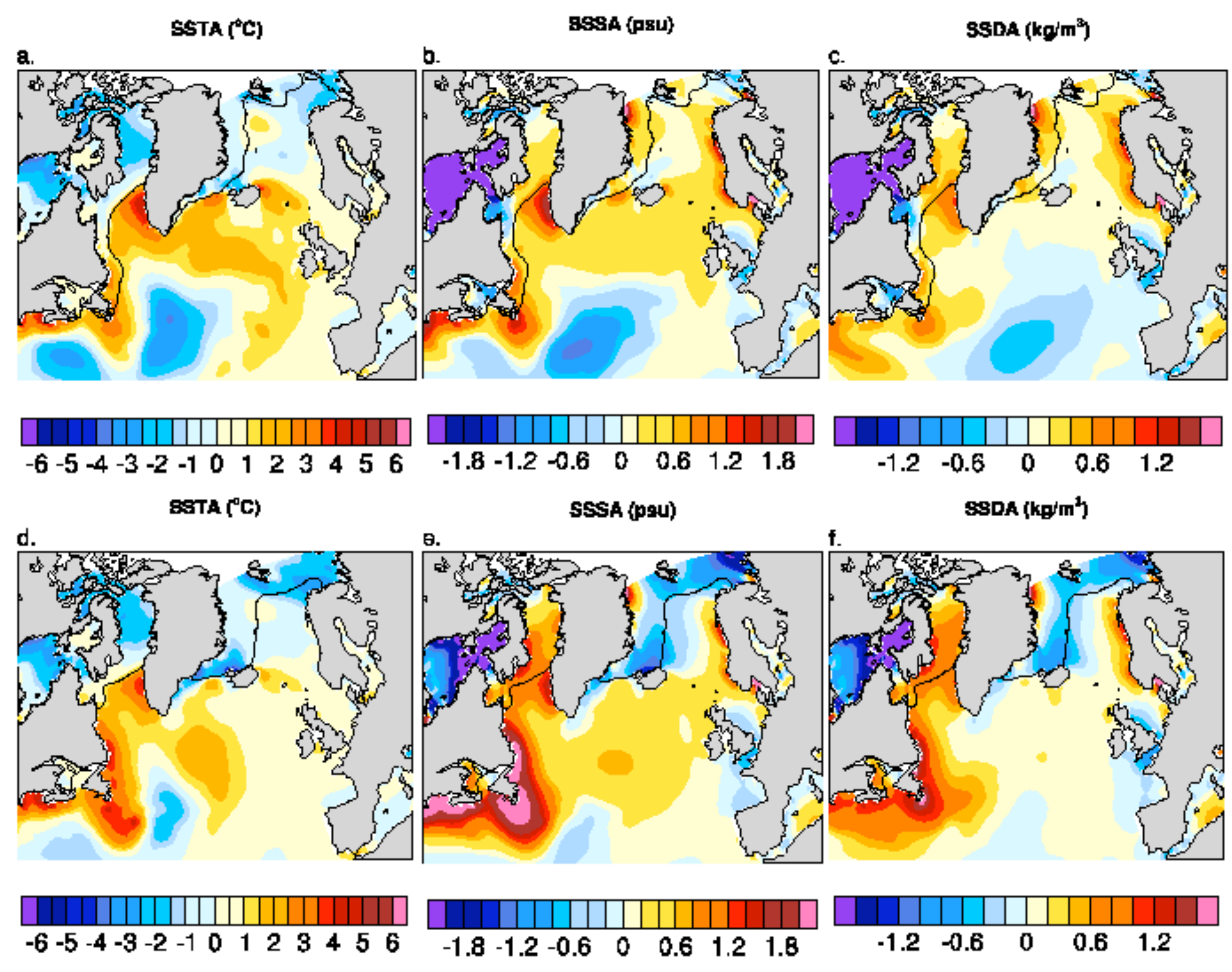
What determines DWBC strength in the model?

Surface bias, years 54-58

- erroneous northward transports generate positive surface bias in the subpolar seas
- advection errors generate positive SSD bias (reflecting SSSA)
- and retreat of winter ice edge in B in the Labrador Sea

A

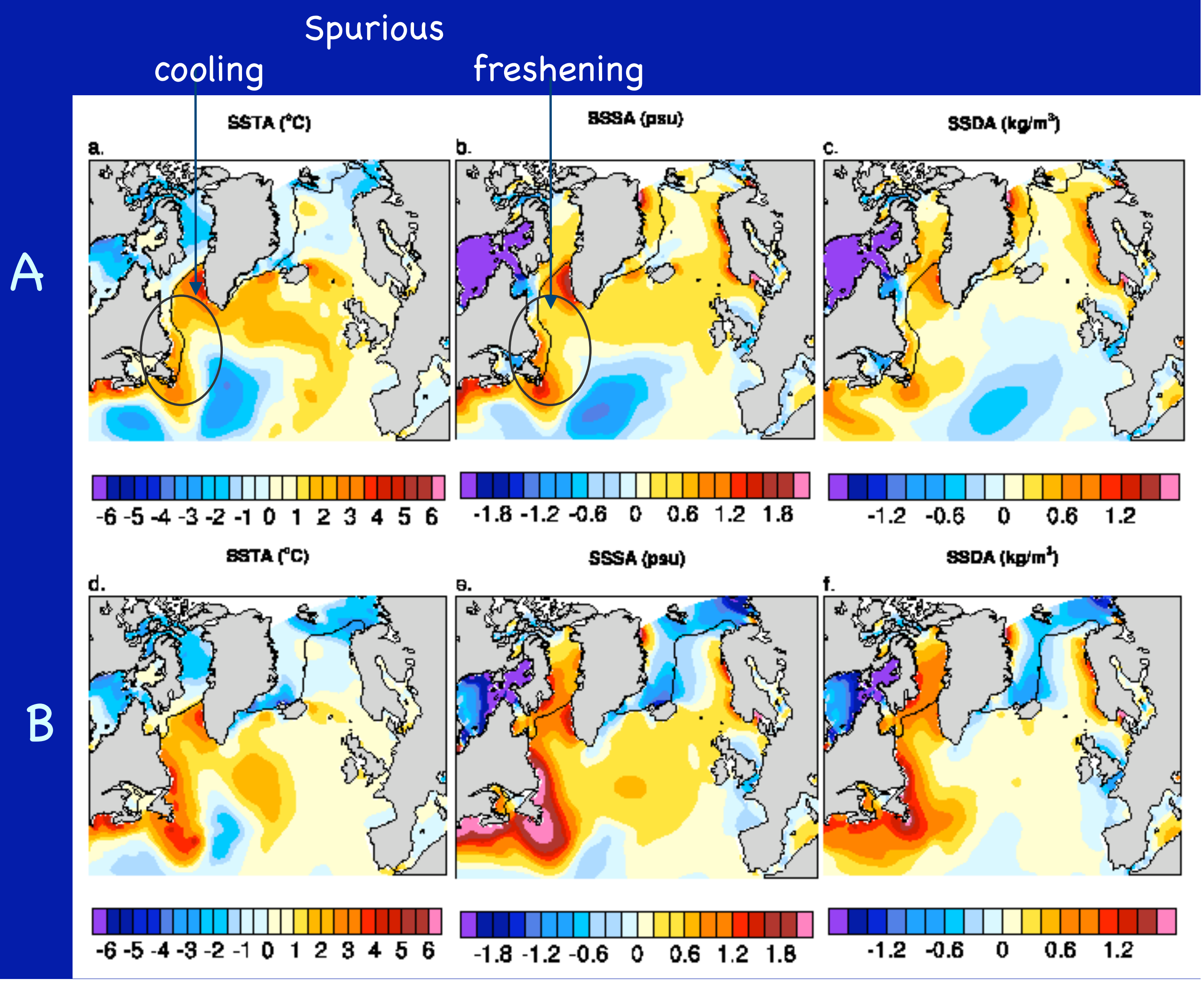
B



Surface bias, years 54-58

- positive surface bias in the subpolar seas associated with erroneous northward transports
- advection errors generate positive SSD bias (reflecting SSA)
- and retreat of winter ice edge in B in the Labrador Sea

- Larger bias in B is an artifact of spurious melt fluxes in A along Labrador Coast ice shelf

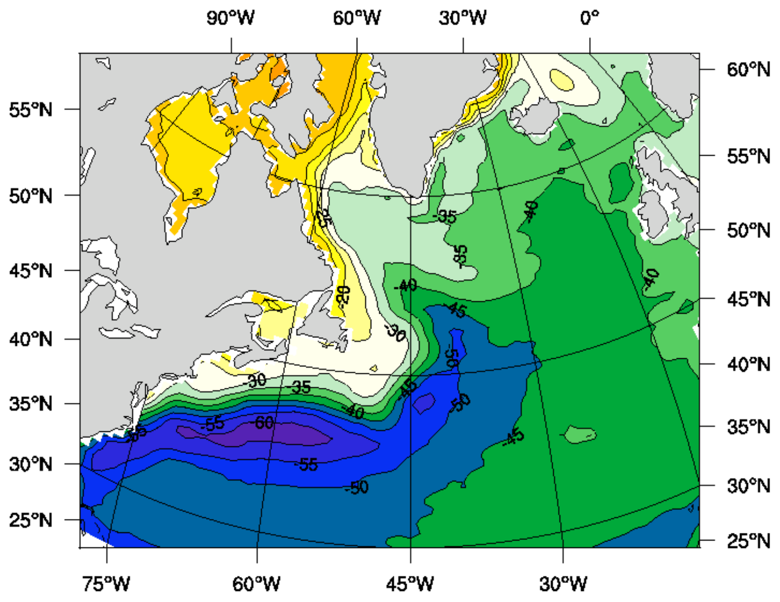


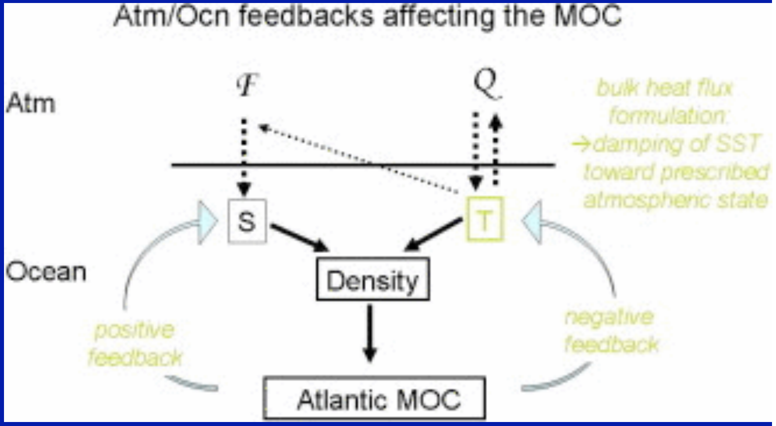
Mixed Thermohaline Boundary Conditions

- Strong restoring of SST with weak restoring of SSS = Mixed boundary conditions
- Forcing with bulk flux formulae which use model SST results in strong effective damping of model SST error: $-30\ W/m^2/^oC$ throughout North Atlantic
- There is no flux feedback on SSS. The only damping of SSS error comes from an artificial weak restoring term: V_p = 50m/(4 years)

⇒ Excess northward heat/salt transport gives rise to a positive MOC feedback

dQ/dSST $(W/m^2/^oC)$



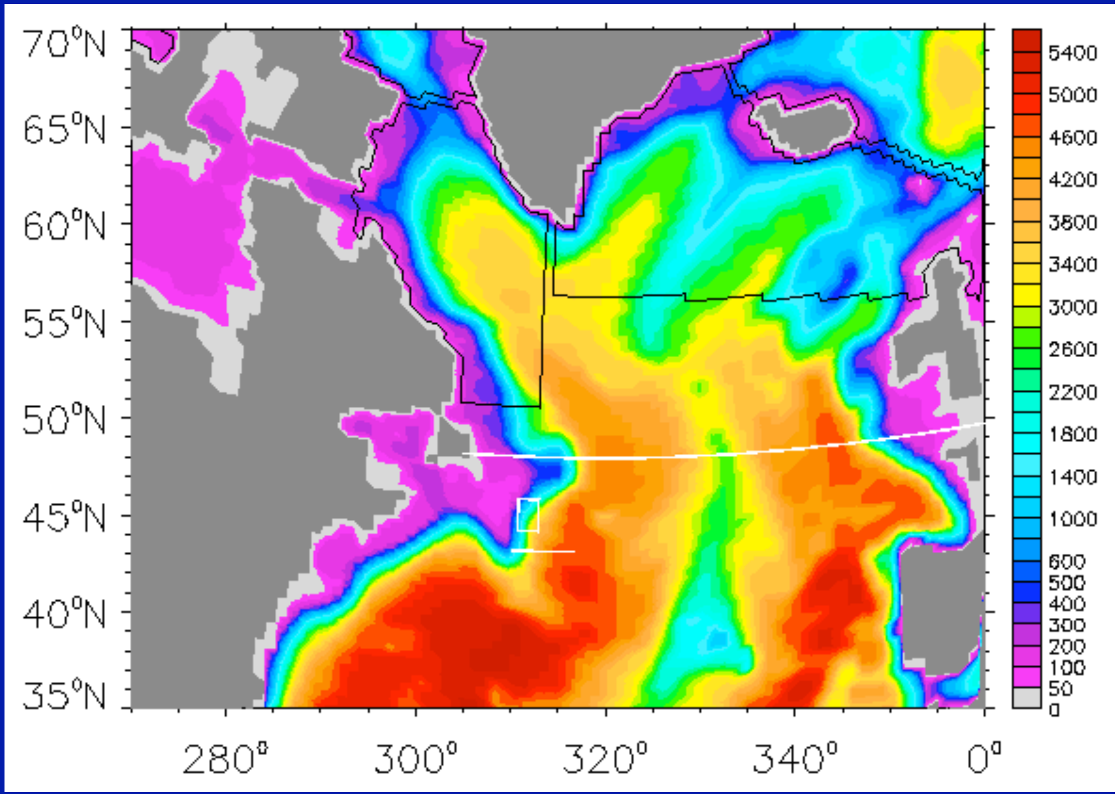


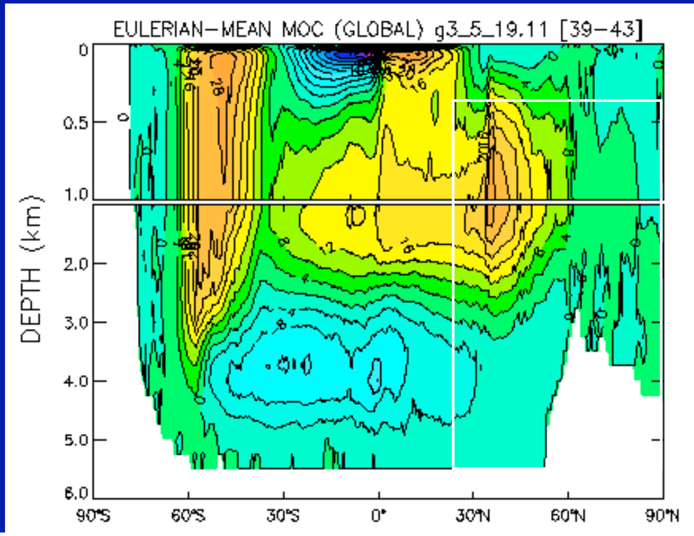
(Griffies et al 2008)

Some Metrics

- Regional averages: Labrador Sea, "North Atlantic", Norwegian Sea
- barotropic heat, salt, and mass transports across 48°N
- mass transports across 43°N (50°W - 44°W); DWBC & NAC
- bottom velocity (W_B) southeast of the Grand Banks
- NRG strength
- MOC strength (maximum north of 28°N, below 460m)

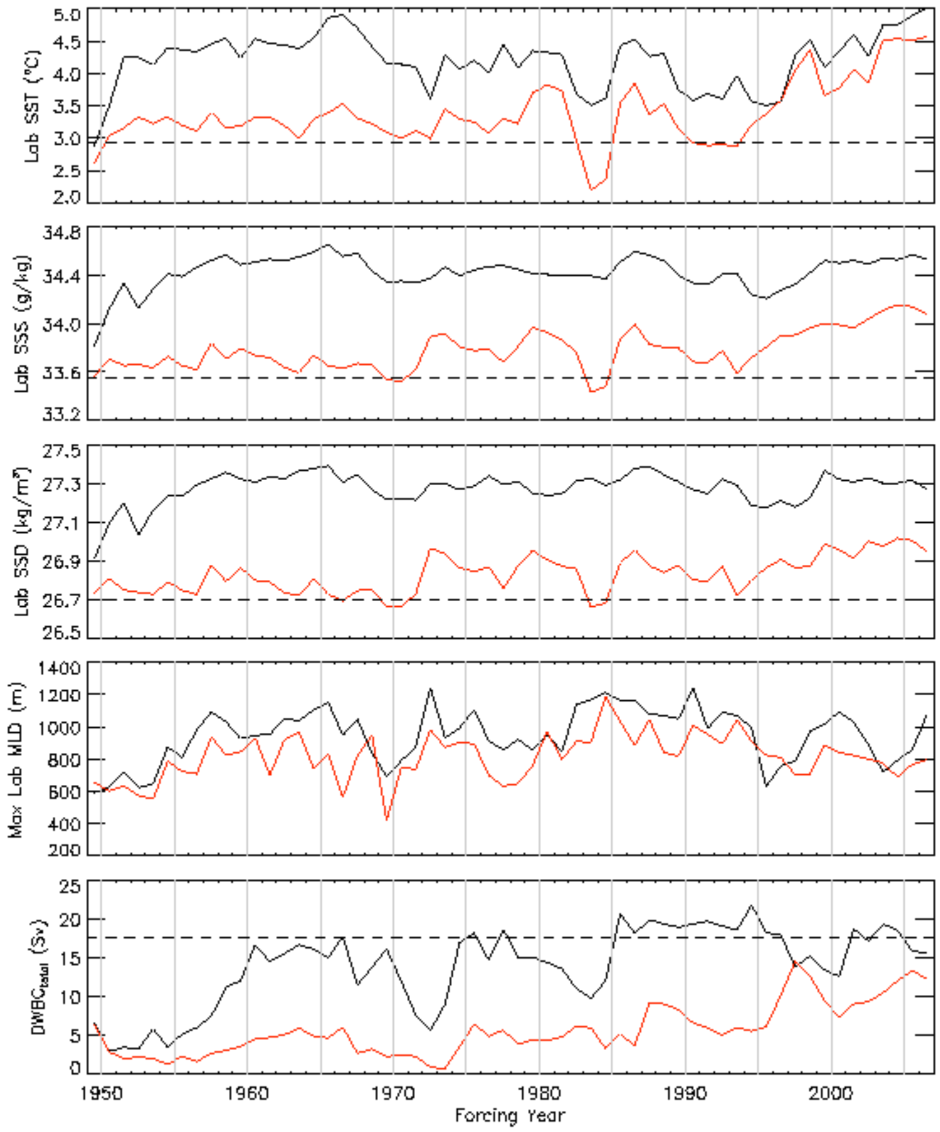
1° bathymetry





Time evolution

A: ocean only
B: ocean-ice

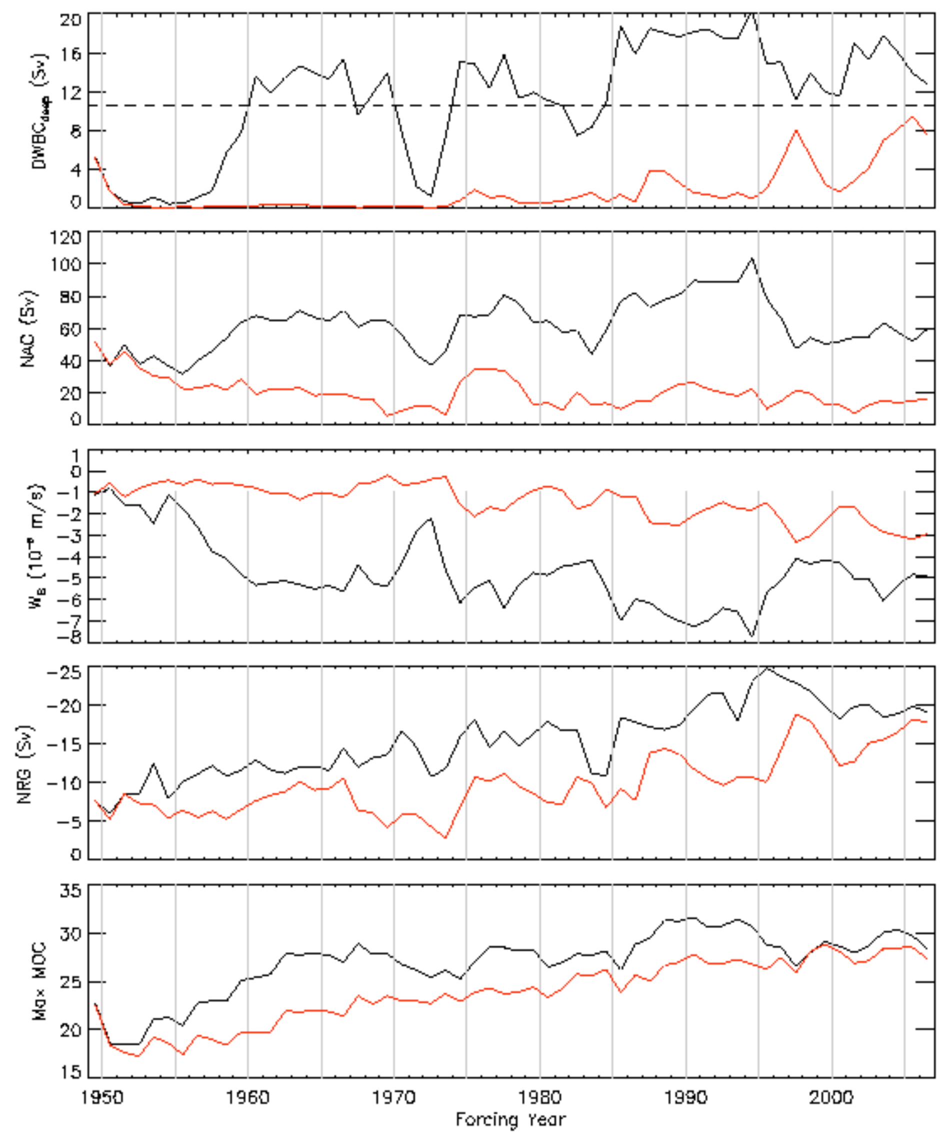


- Rise in Lab Sea surface bias in B due to advection error; regional-average bias in A stays low initially due to spurious melt fluxes
- Warm, salty West Greenland current water enhances convective activity within first decade in both simulations
- Intially small, DWBC transport near observed levels achieved in B after 10 years; Labrador coast ice edge prevents DWBC increase in A

Time evolution

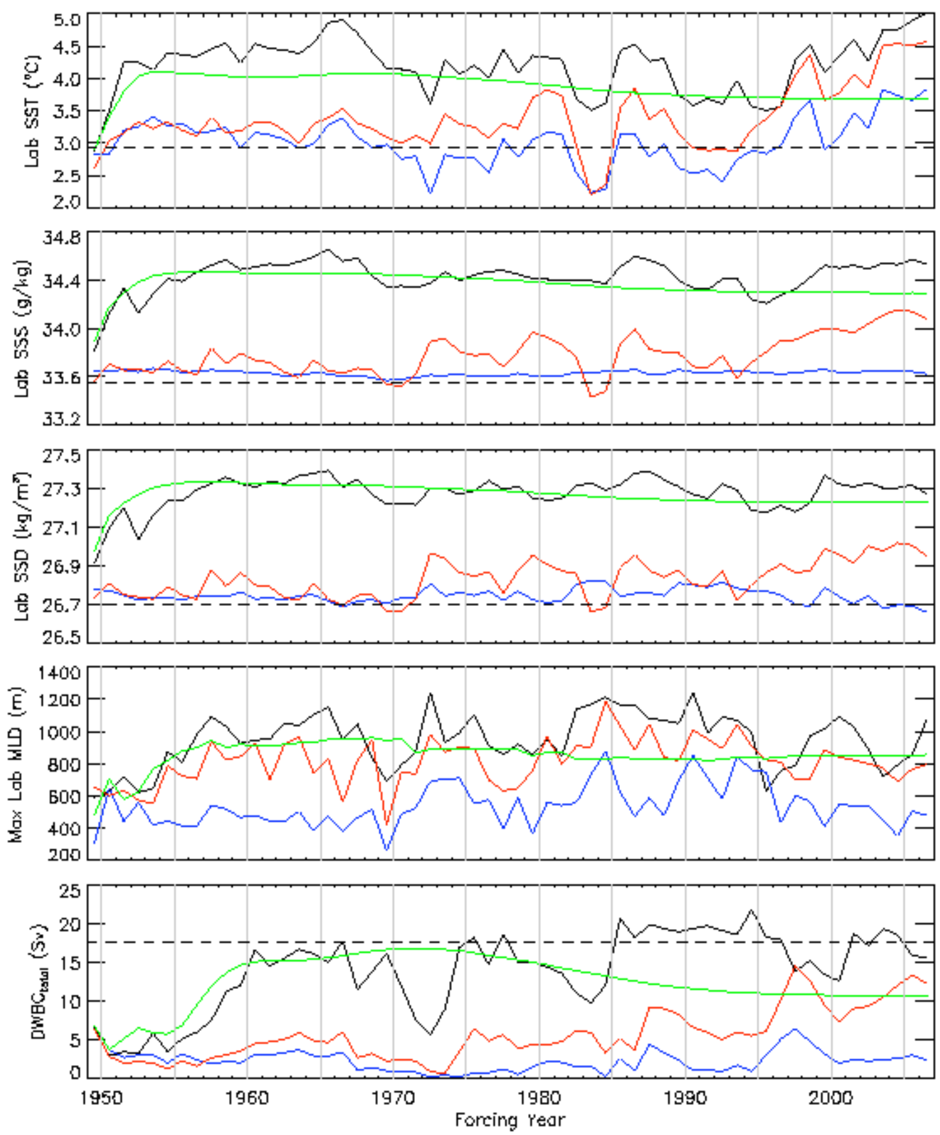
A: ocean only
B: ocean-ice

- Bulk of DWBC transport in B denser than σ_0=27.8 kg/m^3; dense DWBC is minimal in A
- Spinup of the dense DWBC in B reverses the weakening trend in offshore NAC transport
- High correlation between DWBC, NAC, and $-W_B$
- magnitude of hindcast interannual and interdecadal MOC variations is strongly dependent on boundary condition choices



Time evolution

A: ocean only
B: ocean-ice
B1: ocean-ice, strong salinity restoring
B2: ocean-ice, repeat annual forcing



- Adding strong salinity restoring to B removes the mixed boundary condition feedback: SSTA is minimized as well as SSSA, the Labrador coast ice edge is retained, deep mixing is damped, and the DWBC is lost
- Desirable variability is also lost: eg, the "Great Salinity Anomaly" in the late 1960's, Dickson et al (1988)
- Spurious ice melt in A has the effect of a temperature/salinity restoring flux -- it explains much of the difference between A and B spinup

- Gyre spinup highlights the role of the mixed boundary condition feedback in the THC spinup in B, with correlated GS path variations.
- How and where is DWBC water generated?

February Surface Density Flu
(kg/m²/s), years 16-20

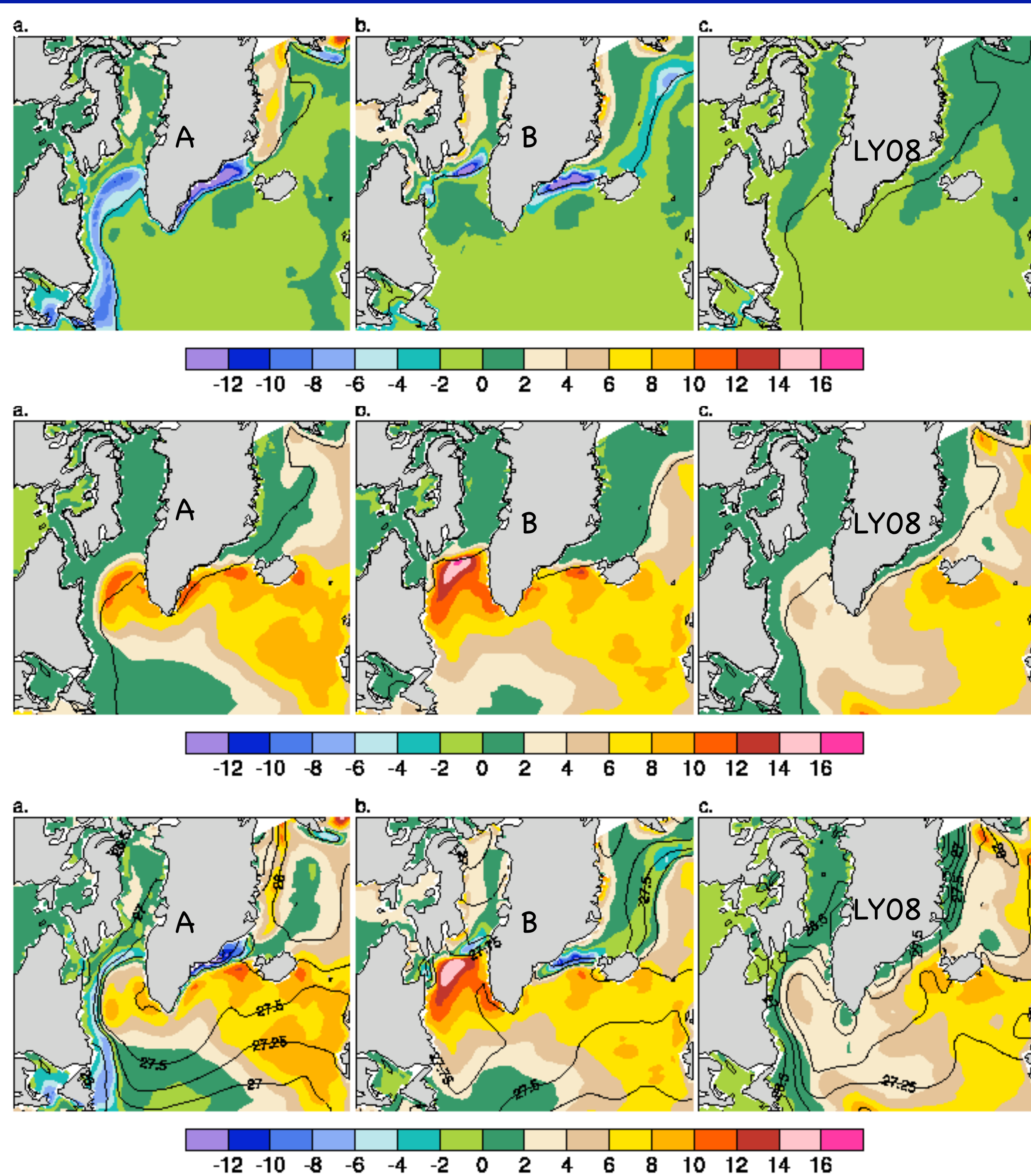
Haline: $-SSS(\rho\beta/\rho_o)W_0$

+

Thermal: $-(\alpha/C_p)H_0$

=

Total: D_0



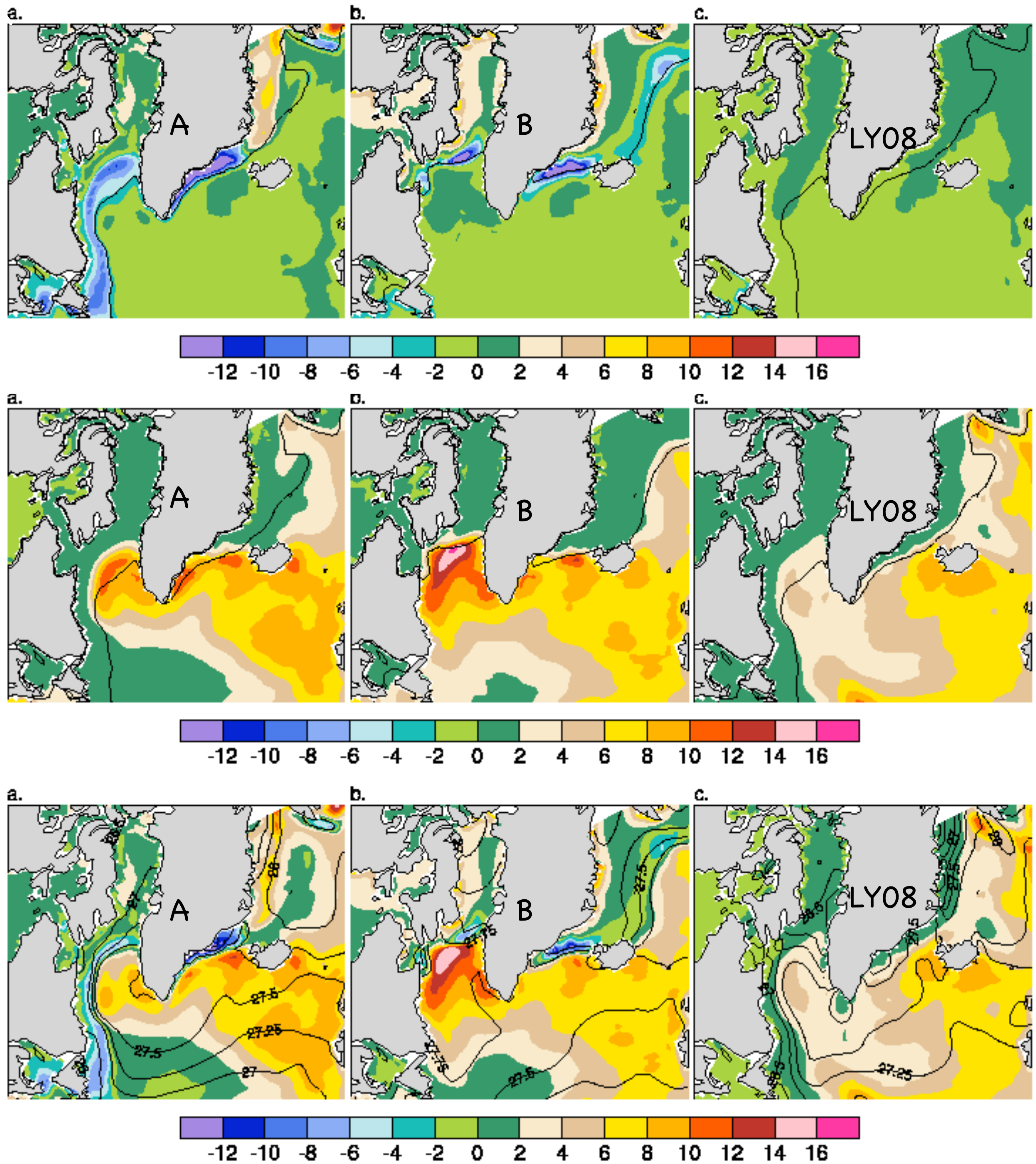
February Surface Density Flu
(kg/m²/s), years 16-20

- Ice melt dominates winter haline density flux and is much more extensive in A. Realistic magnitude is unclear.

- Excessive thermal density flux in both A and B associated with +SSTA dominates total. Less realistic in B due to ice edge retreat.

- Ice melt mitigates excess thermal flux in A and also keeps SSD close to observed.

- More physical ocean-ice interaction in B results in excessive surface transformation at excessively high densities (associated with +SSSA)



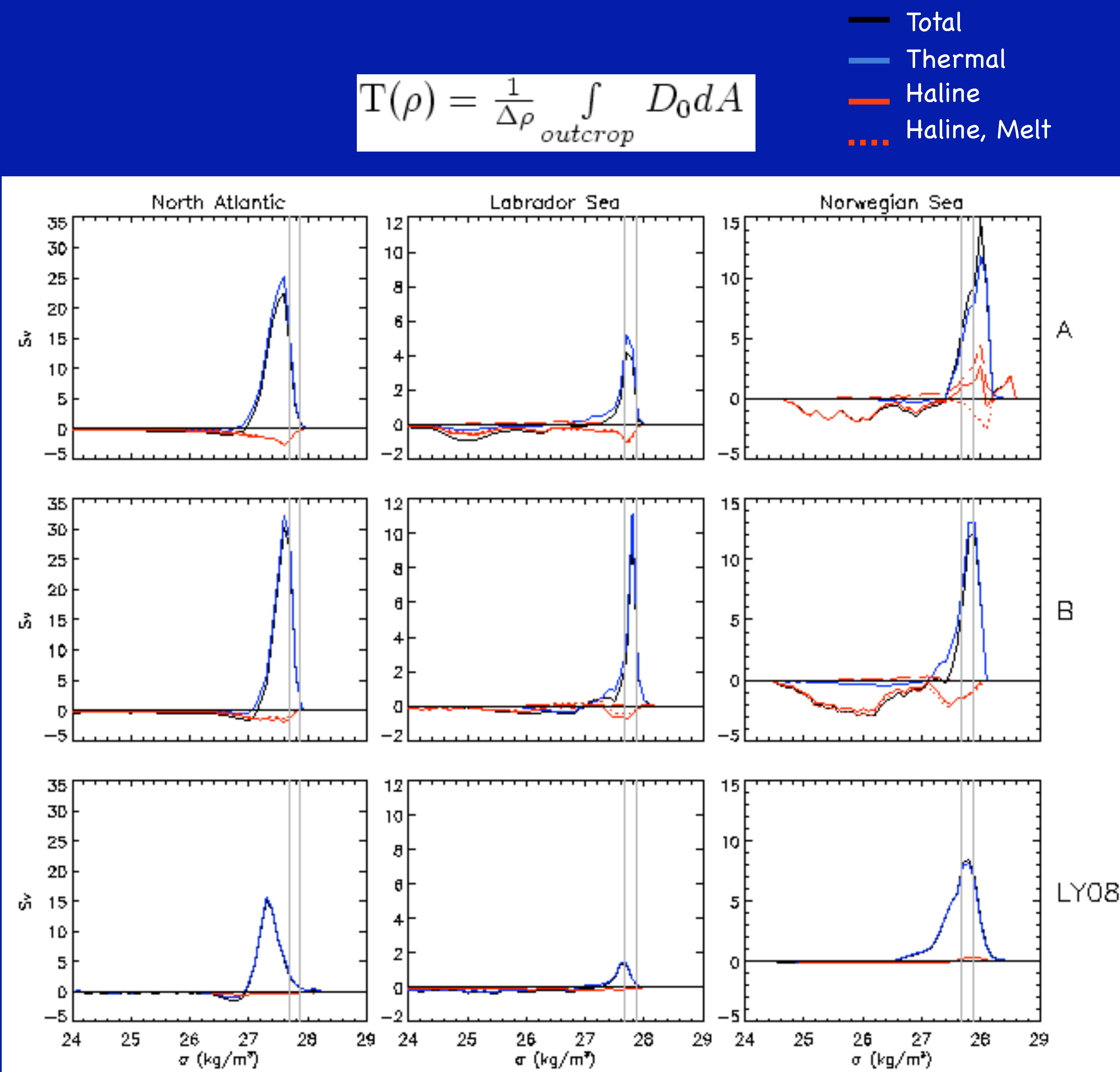
Surface Diapycnal transformation rate (Sv)

- Speer and Tziperman (1992); Large and Nurser (2001)

$$T(\rho) = \frac{1}{\Delta\rho} \int_{outcrop} D_0 \, dA$$

- all subpolar regions show excess positive thermal transformation at too high density in both A and B
- thermal flux dominates dense water formation; haline fluxes (melt) dominate light water formation
- Essential difference between A and B is in the Labrador Sea: T(ρ) 7 times too large in B, 3 times too large in A

⇒ hence the strong, dense DWBC in B



Conclusions

- Improved simulation of the North Atlantic in a low viscosity non-eddy resolving ocean model (BSF, stronger and partially-attached NAC, stronger NRG, reduced upper ocean temperature and salinity bias) is closely tied to increased DWBC strength and density.

- The connections between the DWBC and the North Atlantic gyre circulation appear to be explained by bottom vortex stretching associated with a strong downslope DWBC along the Grand Banks shelf (Zhang and Vallis 2007).

- The strength of the DWBC is related to winter buoyancy loss in the Labrador Sea. In prescribed-atmosphere configurations with bulk flux forcing and weak salinity restoring, mixed thermohaline boundary condition feedbacks exacerbate the model tendency to transport too much warm, salty subtropical water into the subpolar seas. The result is excessive thermal transformation of overly dense surface water, particularly in the Labrador Sea, and THC spinup.

- The feedback is strengthened in ocean-ice configurations, due to ice edge retreat (spurious air-sea density flux); it is weakened in ocean-only configurations, due to spurious melt flux. Strong salinity restoring damps unphysical boundary condition feedbacks, but this does not improve the fidelity of hindcast North Atlantic variability.

Unanswered questions…

- Why is unrealistic surface water mass transformation required to generate realistic DWBC transport?
- What causes the initial NAC detachment from the Grand Banks shelf? Would improved initial conditions (strong DWBC flow) prevent NAC detachment?
- What mechanism maintains the pressure gradients in the NW Corner region?

Water mass formation

Surface Density flux, D_0 (kg/m^2/s):

$$D_0 = -\frac{\alpha}{C_p} H_0 - SSS \frac{\rho}{\rho_o} \beta W_0$$

where H_0 = surface heat flux, W_0 = surface freshwater flux, SSS = surface salinity
ρ_o = 1000 kg/m^3, C_p = 3996 J/kg/K, $\alpha = -\rho^{-1}(\partial\rho/\partial T)$, $\beta = \rho^{-1}(\partial\rho/\partial S)$

Surface Diapycnal transformation rate, T (Sv):

$$T(\rho) = \frac{1}{\Delta\rho} \int_{outcrop} D_0 \, dA$$

Water mass accumulation rate (Sv):

$$-\frac{\partial T}{\partial \rho} d\rho$$

(Speer and Tziperman 1992; Large and Nurser 2001)

Meridional transport across 48° N

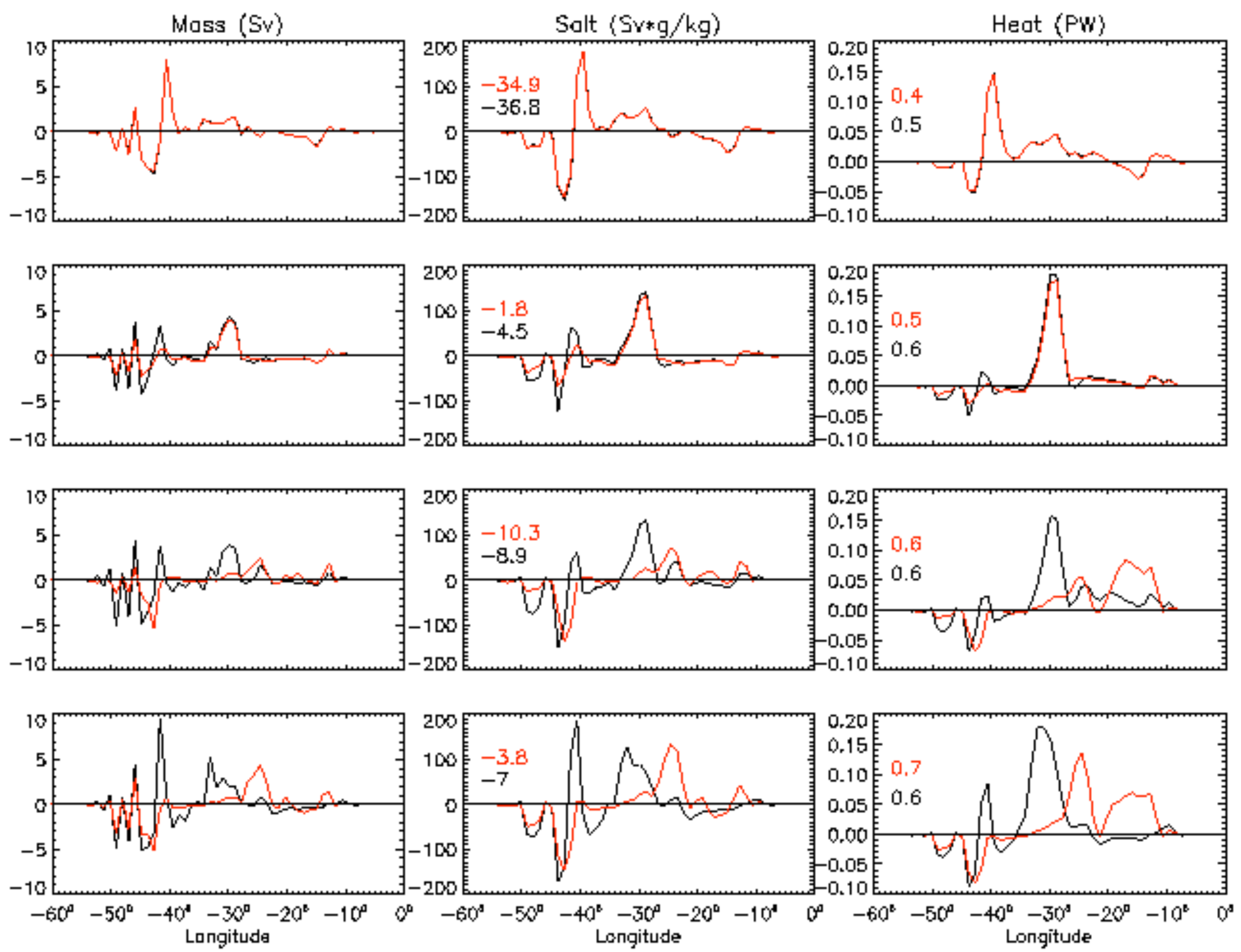
Simulation year

1

5

20

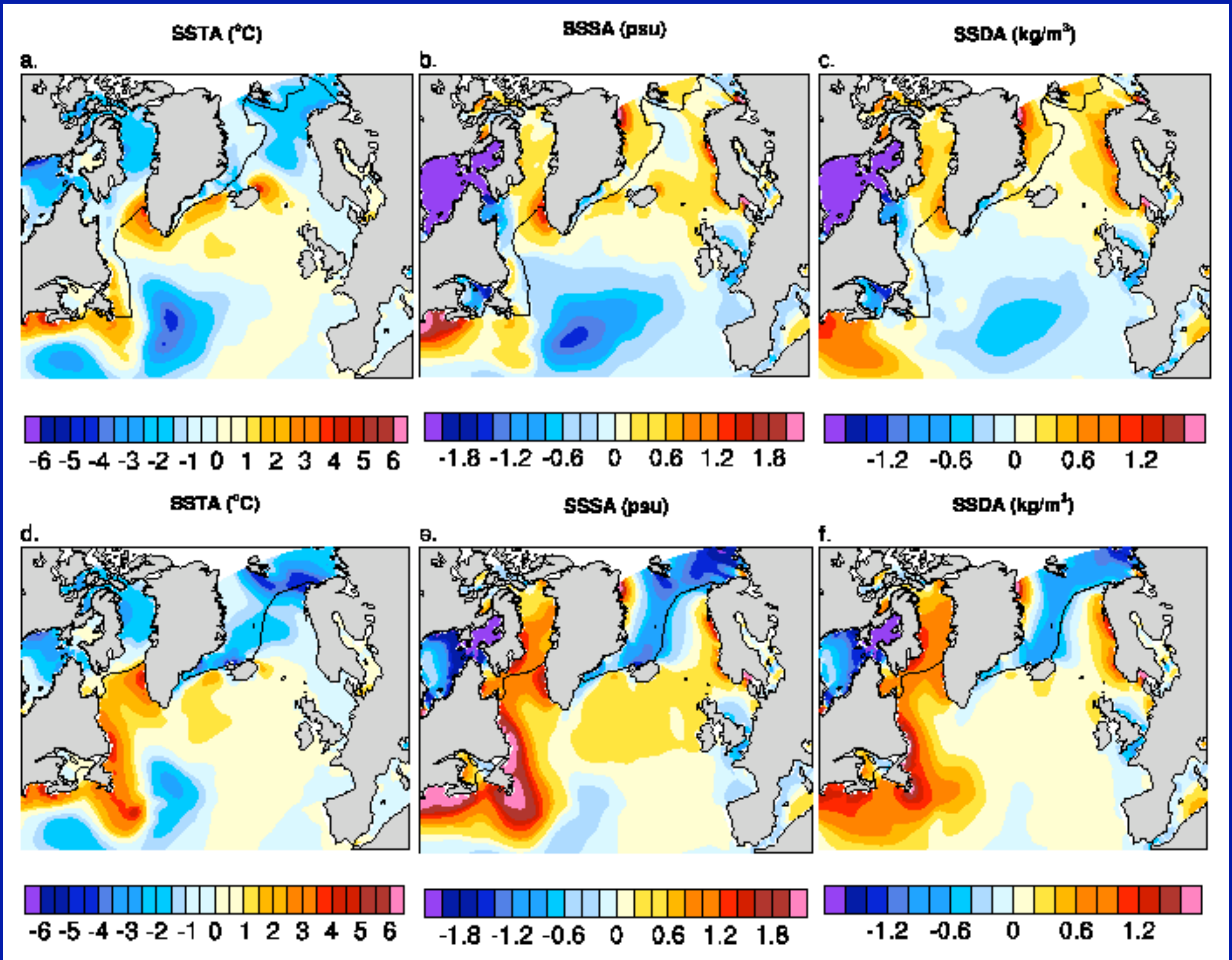
58

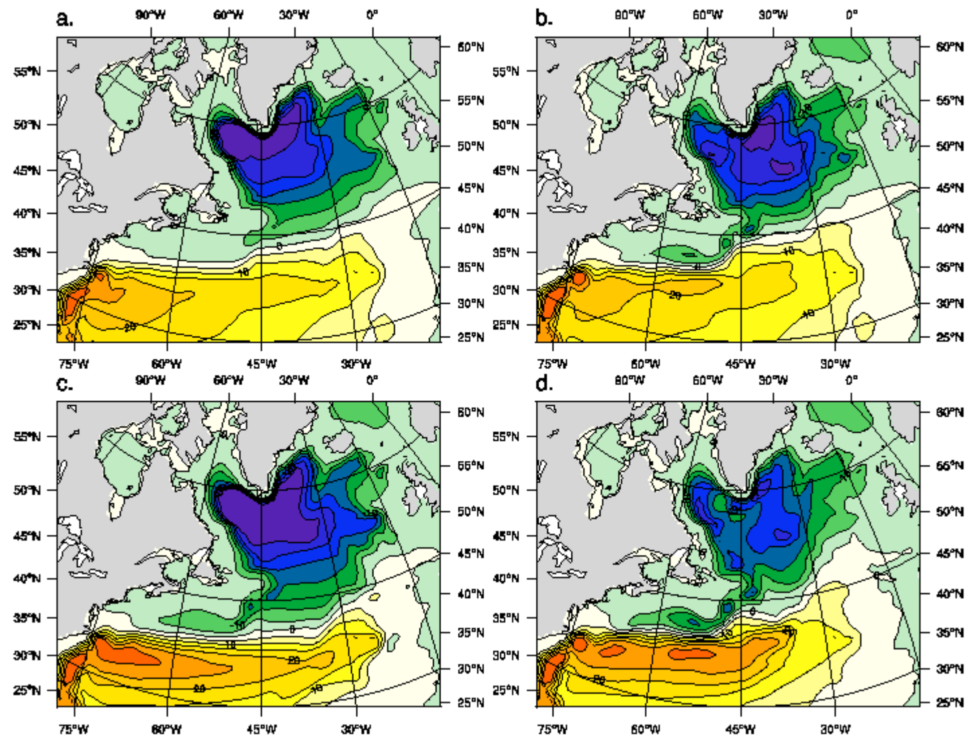


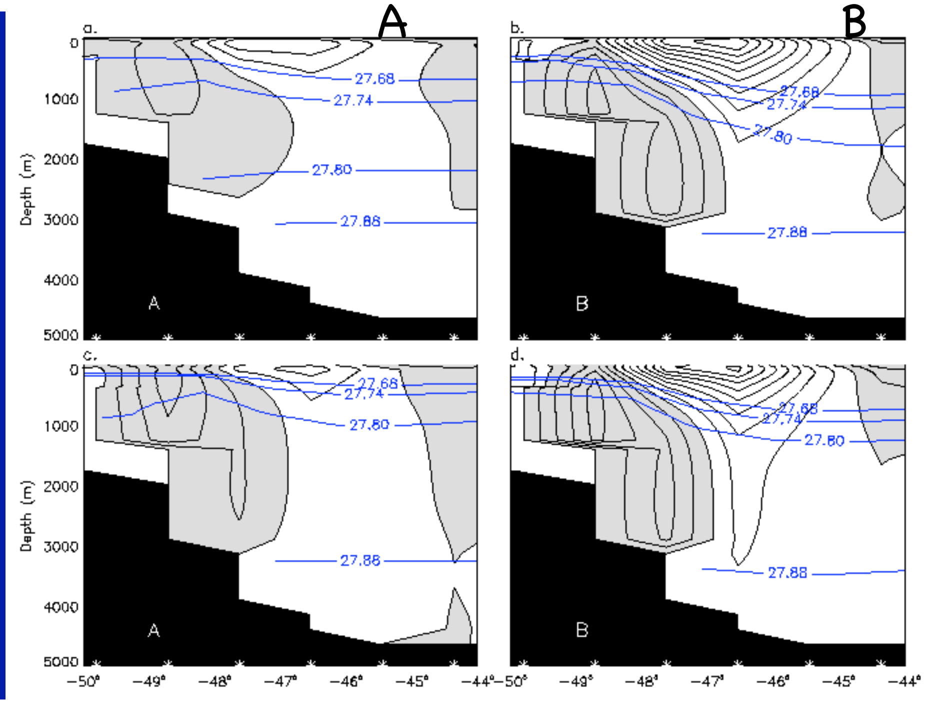
Surface bias, years 16-20

A

B

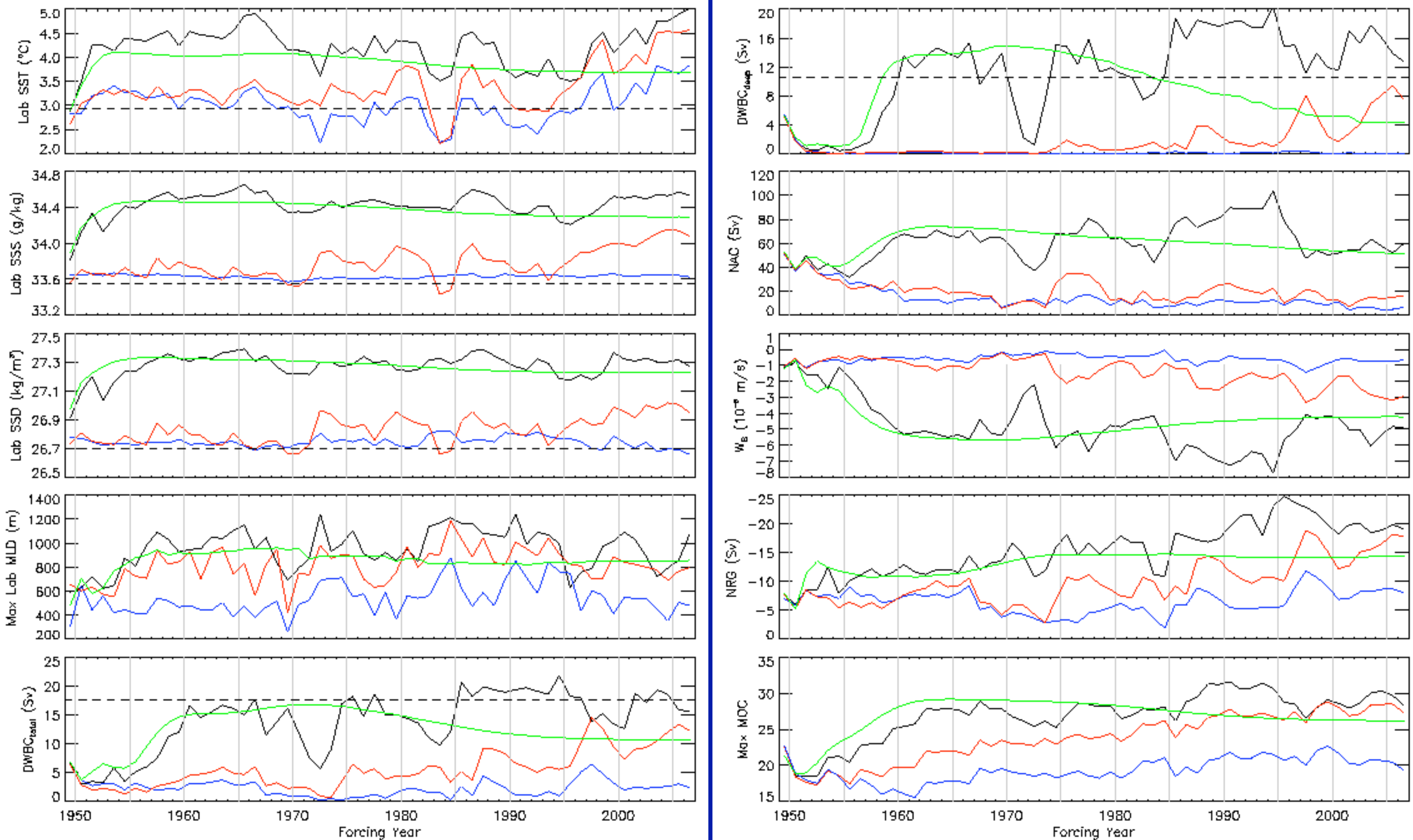



a.
b.
c.
d.
90°W
60°W
30°W
0°
75°W
60°W
45°W
30°W
25°N
30°N
35°N
40°N
45°N
50°N
55°N
60°N


A
B
a.
b.
c.
d.
Depth (m)
0
1000
2000
3000
4000
5000
27.68
27.74
27.80
27.88
A
B
−50°
−49°
−48°
−47°
−46°
−45°
−44°

Time evolution

- A: ocean only
- B: ocean-ice
- B1: ocean-ice, strong salinity restoring
- B2: ocean-ice, repeat annual forcing



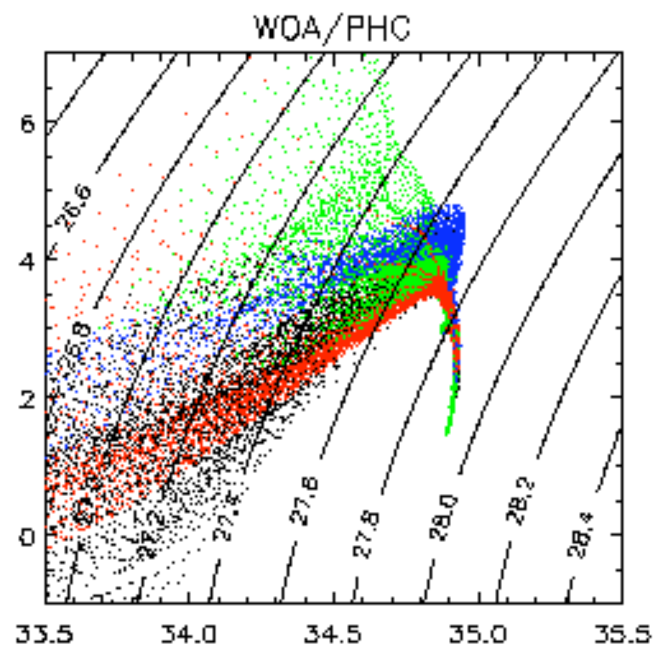
1 → entering Lab Sea → Blue

2 → central Lab Sea → Green

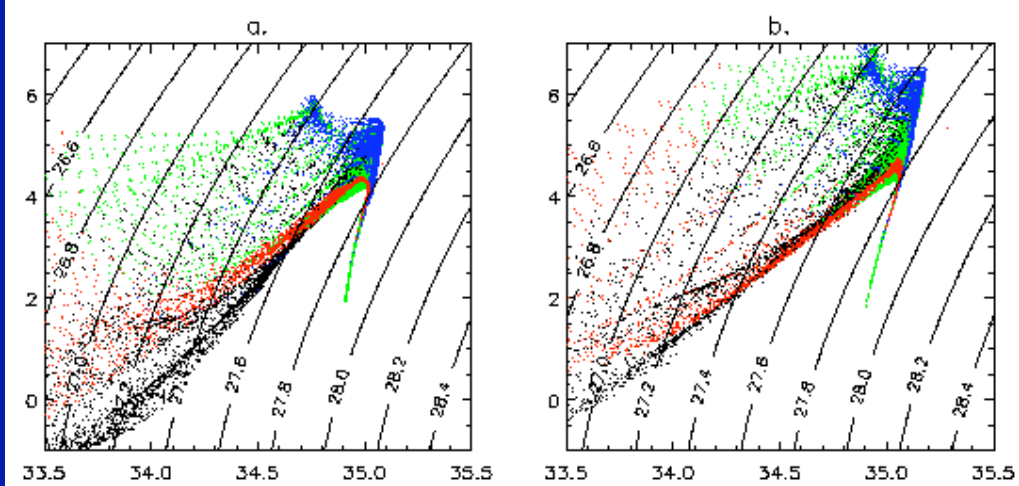
3 → exiting Lab Sea → Red

4 → northern Lab Sea → Black

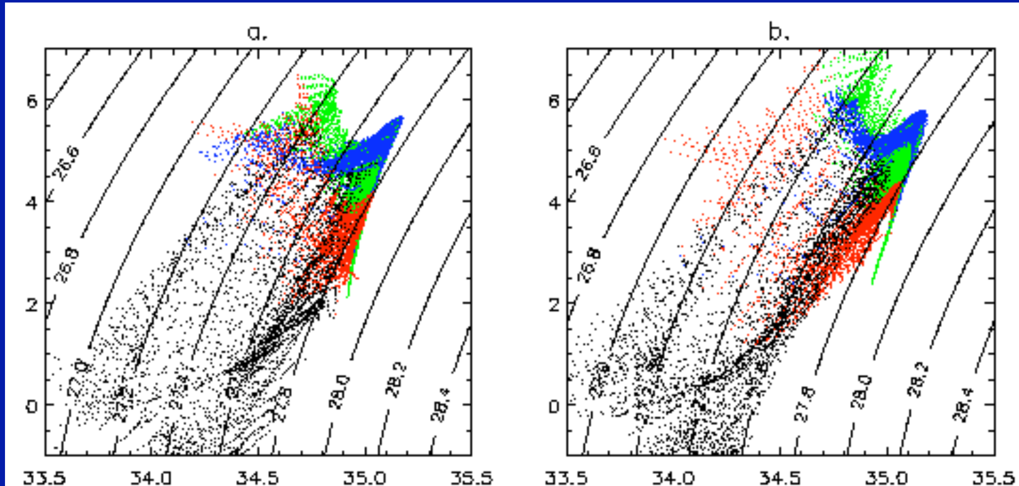
WOA Climatology

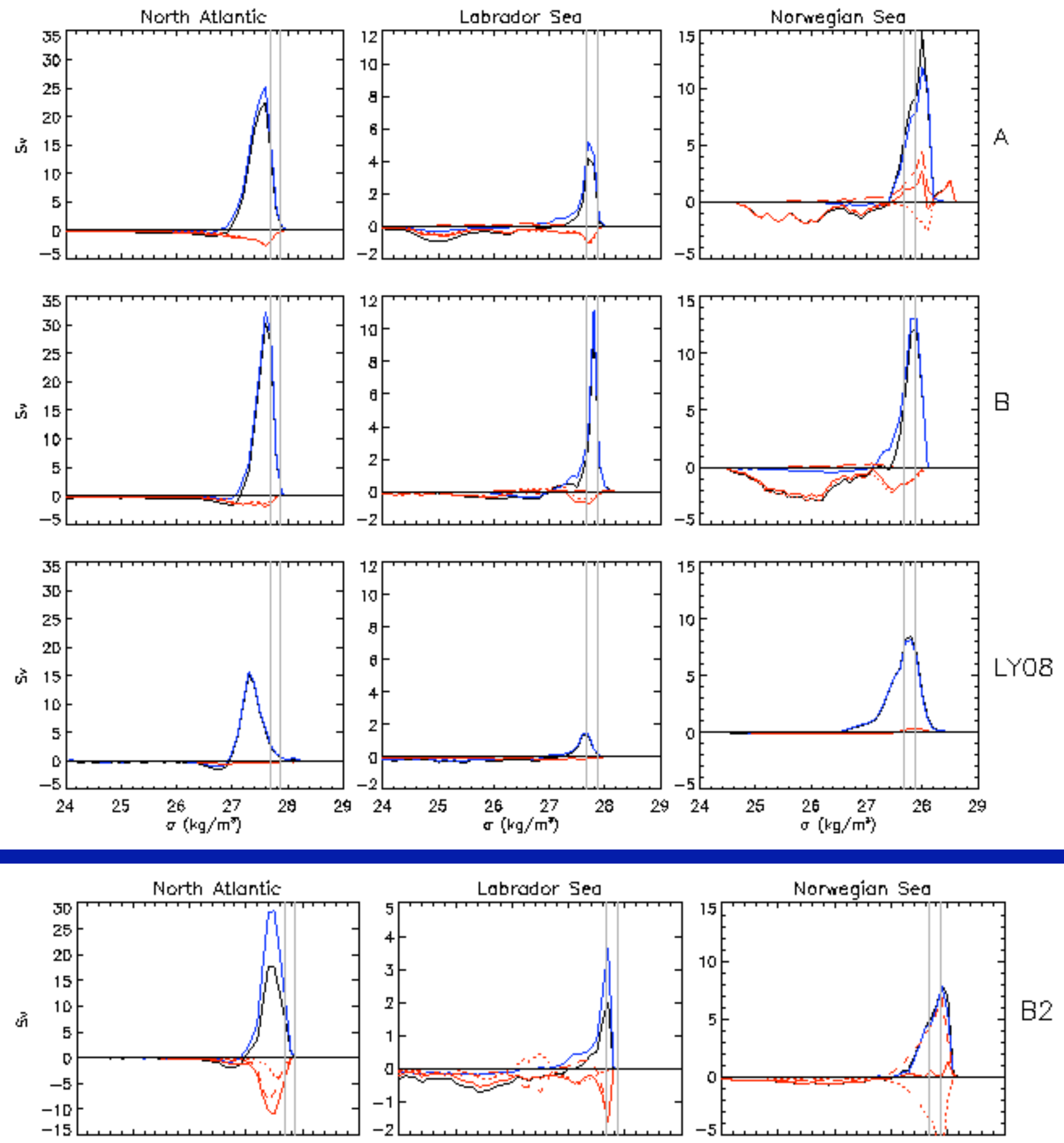


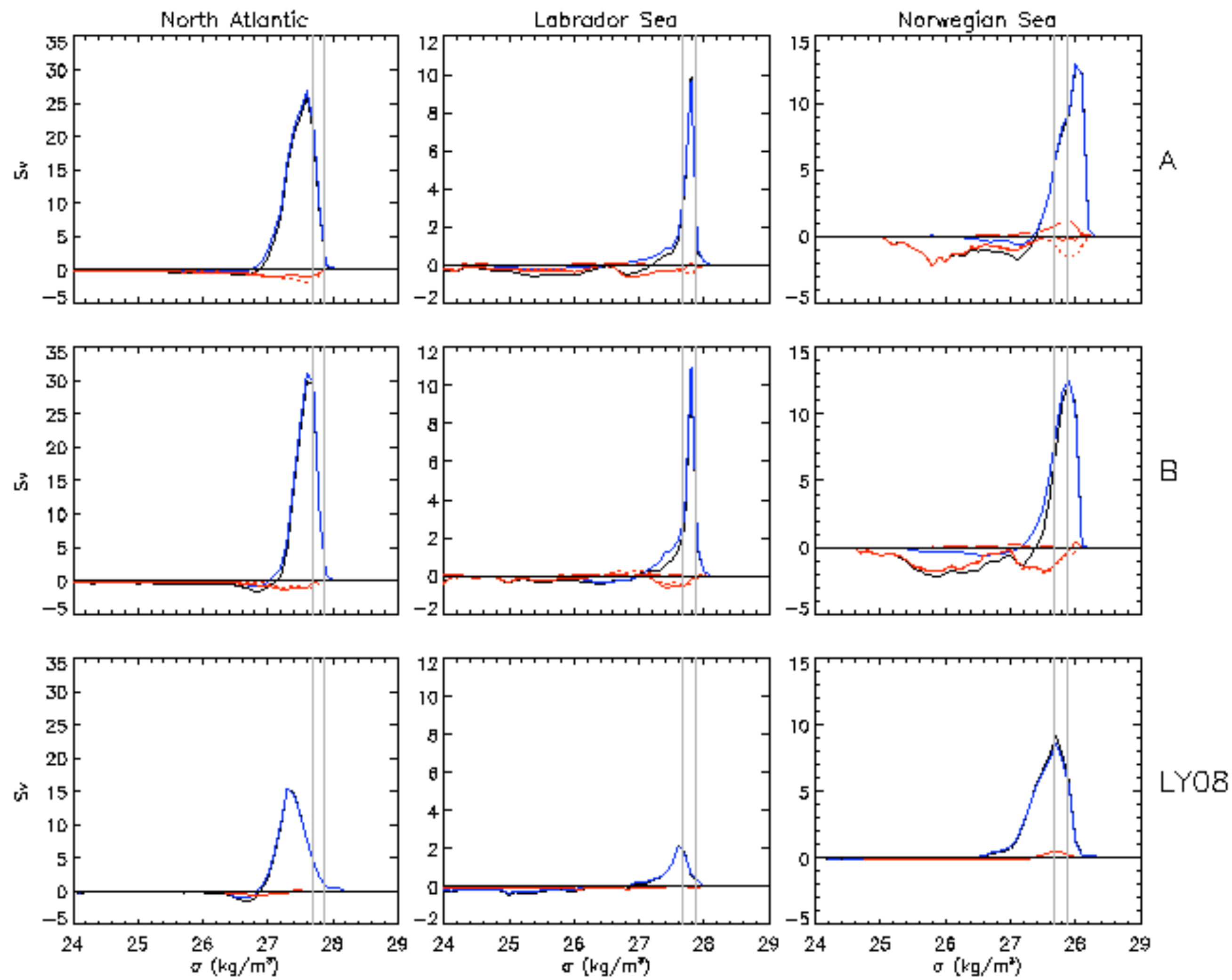
A

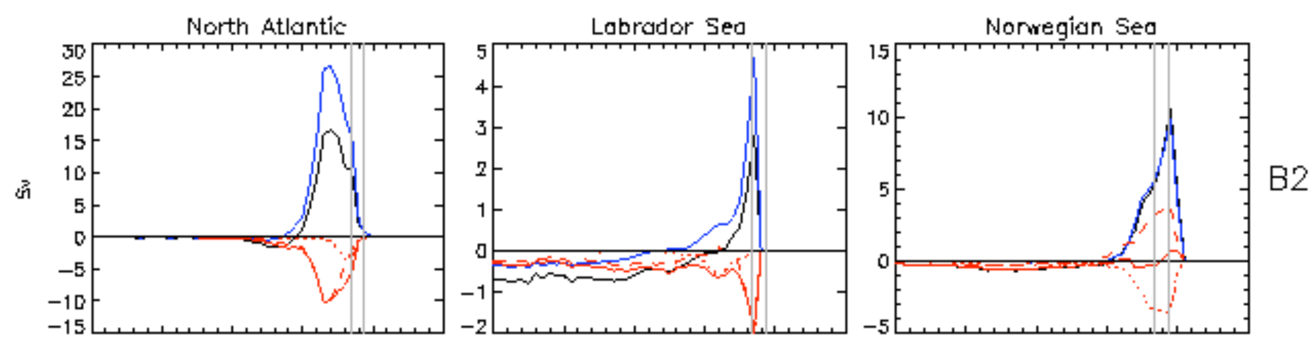


B

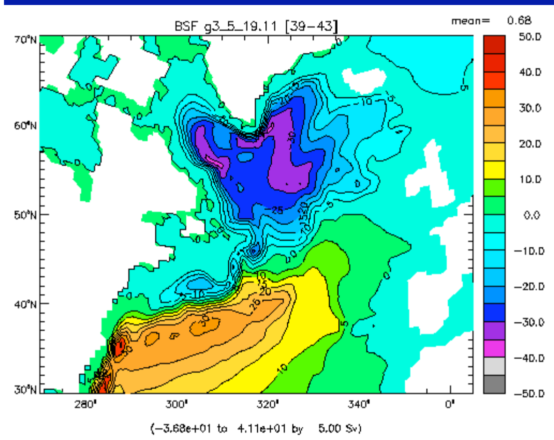


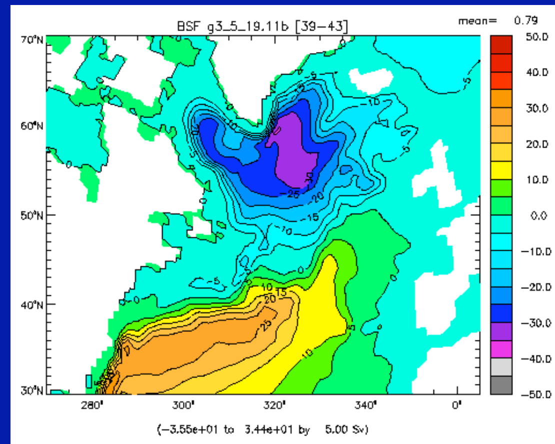

North Atlantic
Labrador Sea
Norwegian Sea
Sv
A
B
LY08
σ (kg/m³)
North Atlantic
Labrador Sea
Norwegian Sea
Sv
B2

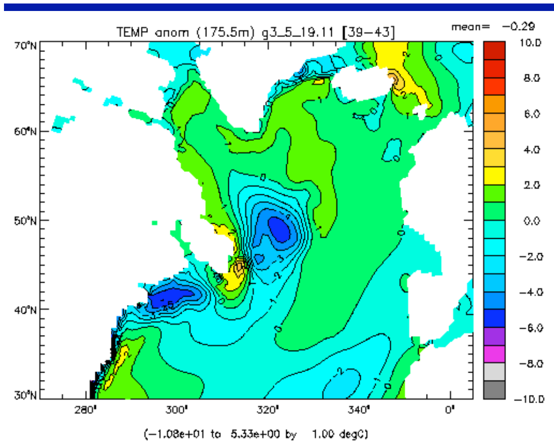

North Atlantic
Labrador Sea
Norwegian Sea
Sv
A
B
LY08
σ (kg/m³)

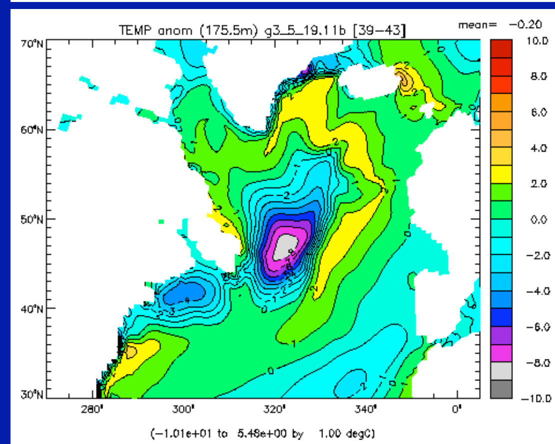

North Atlantic
Labrador Sea
Norwegian Sea
Sv
B2

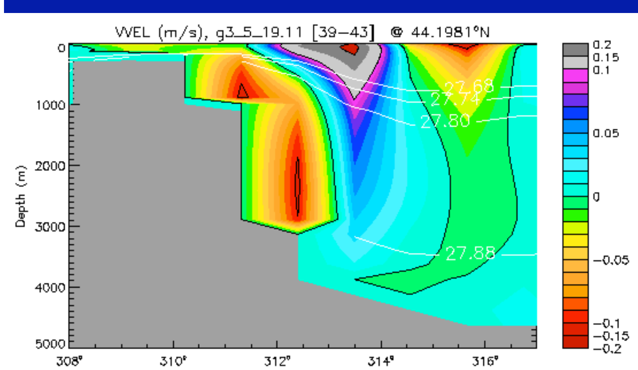
B   B3: NSEF turned OFF

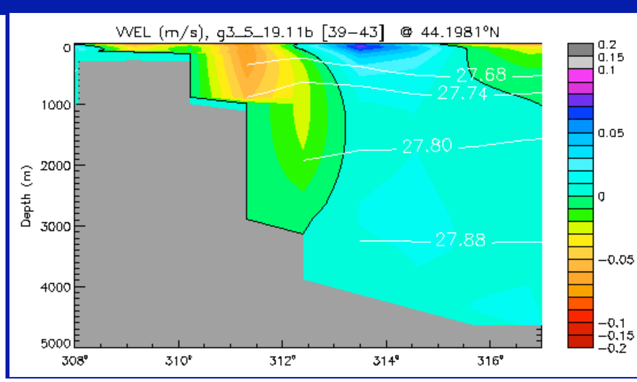






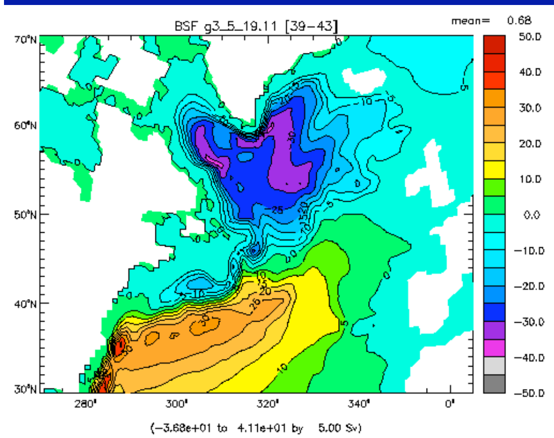


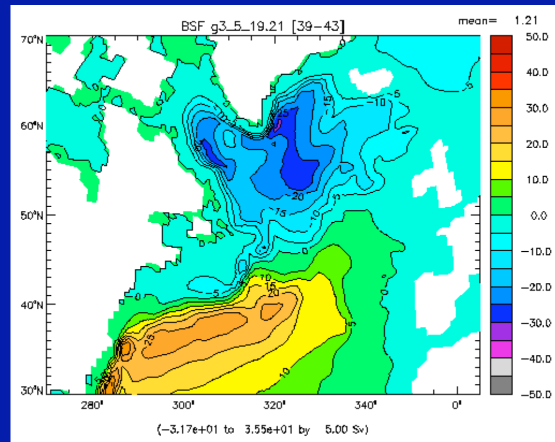


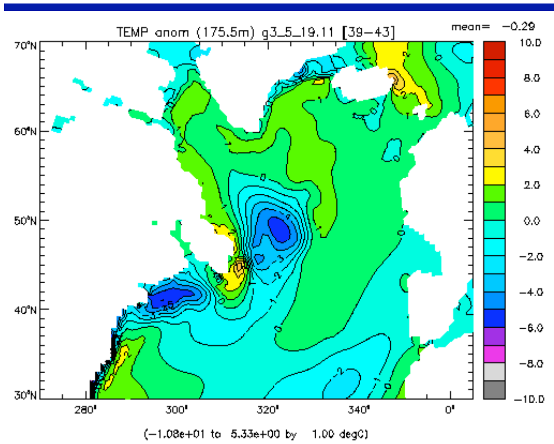


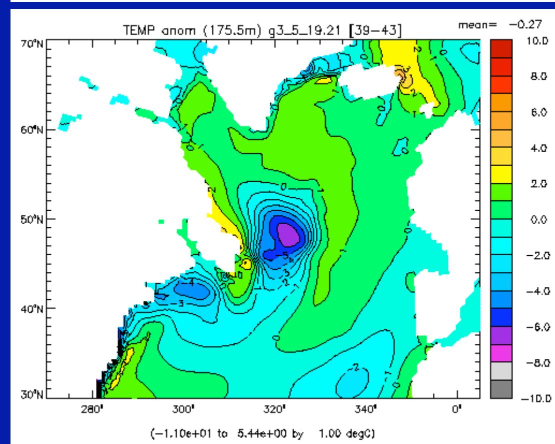
- Weaker subpolar/NRG
- Weaker/lighter DWBC
- very anemic NAC
- Higher T′

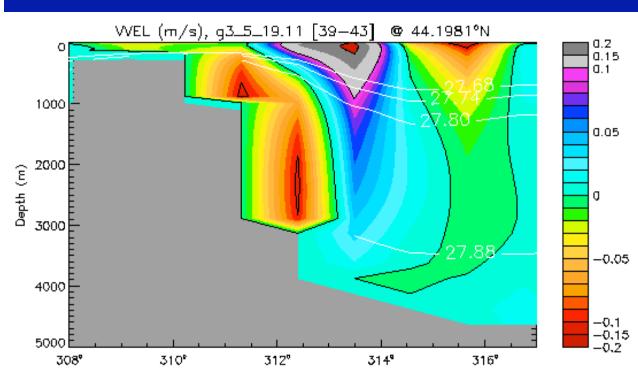
B   B2 Normal Year Forcing

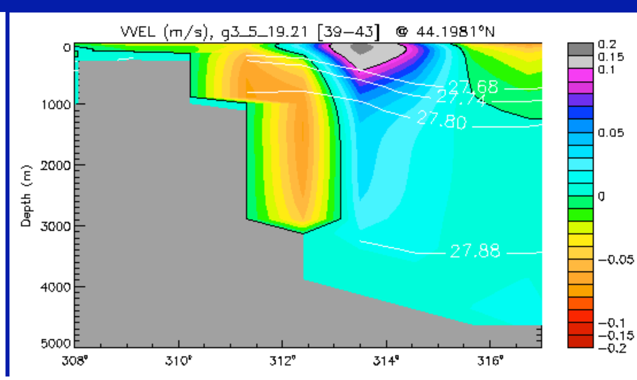






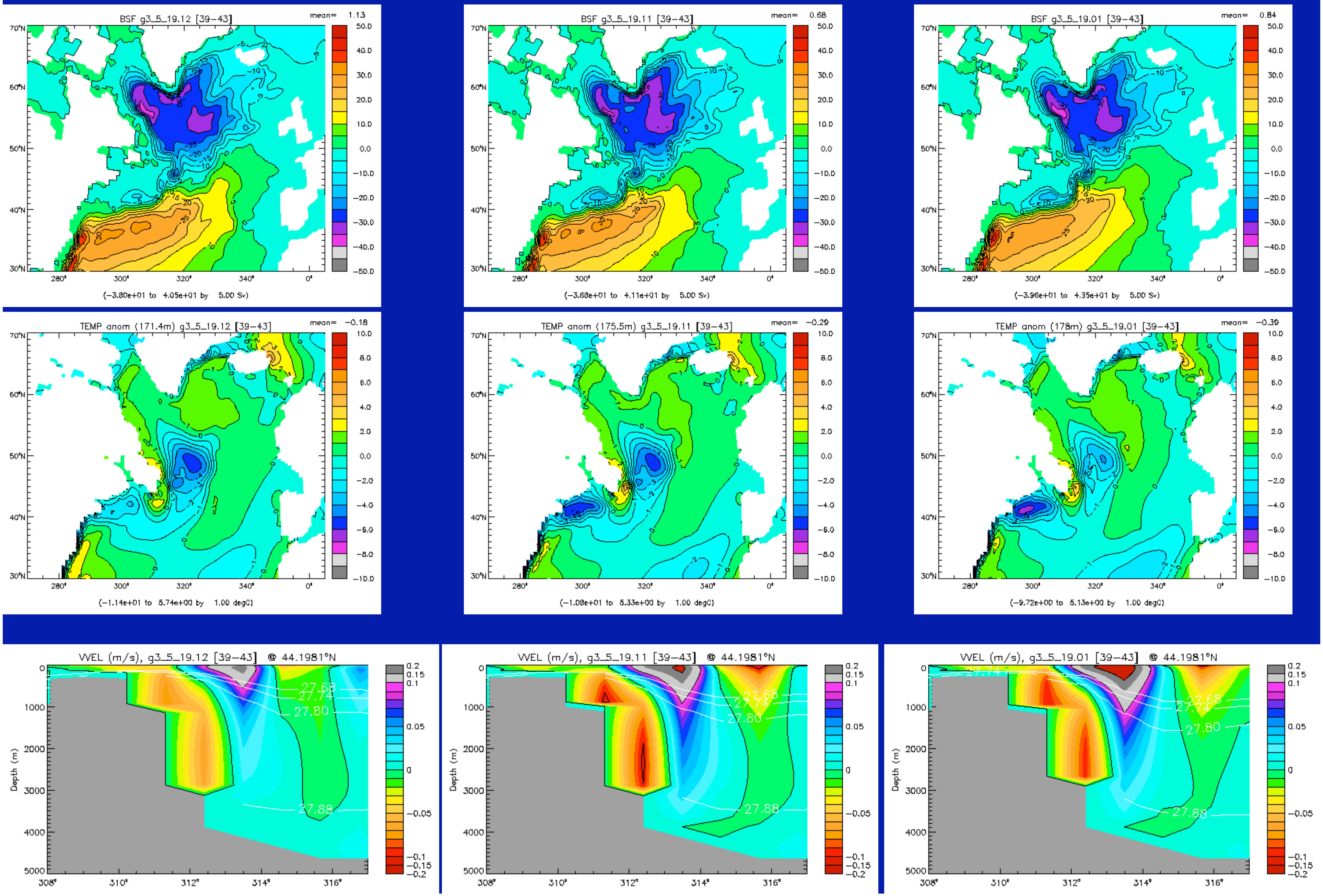






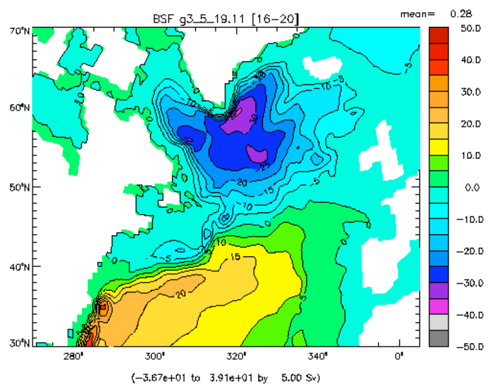
- Weaker subpolar/NRG
- Weaker/lighter DWBC
- Shallow NAC
- Higher T′

B40: 40 verticallevels | B | B100: 100 vertical levels

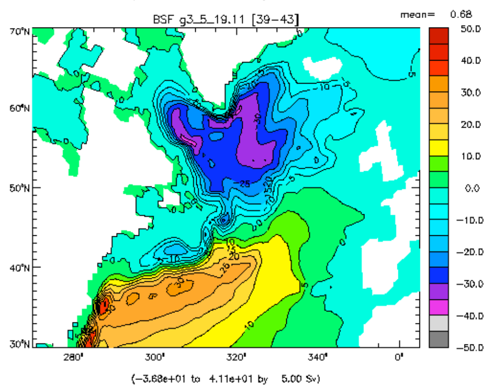


BSF

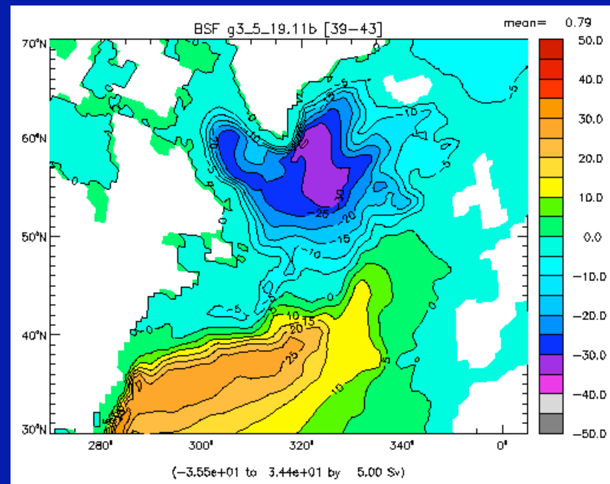
G



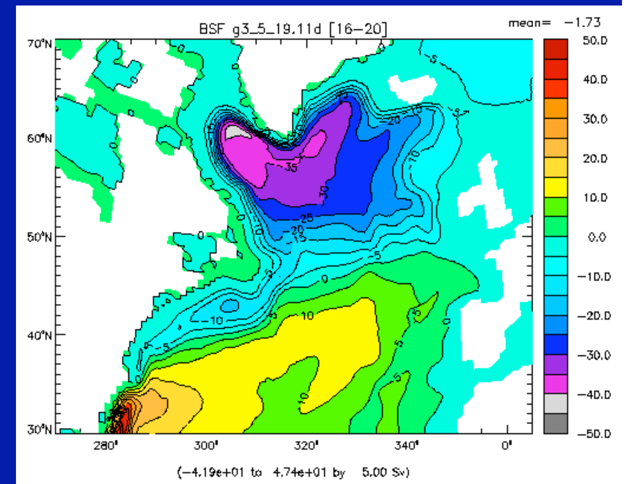
G*



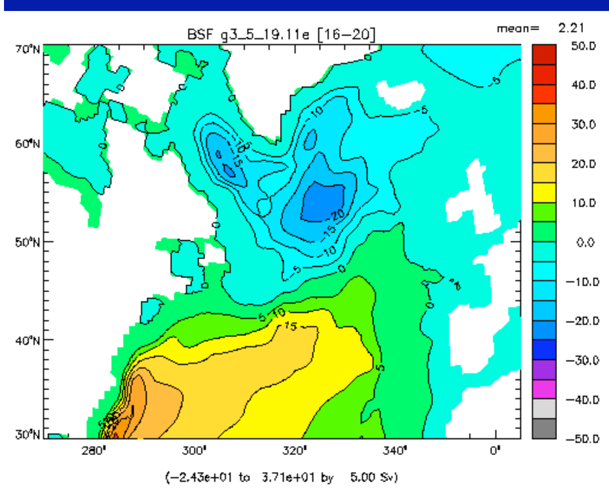
G_nsef*



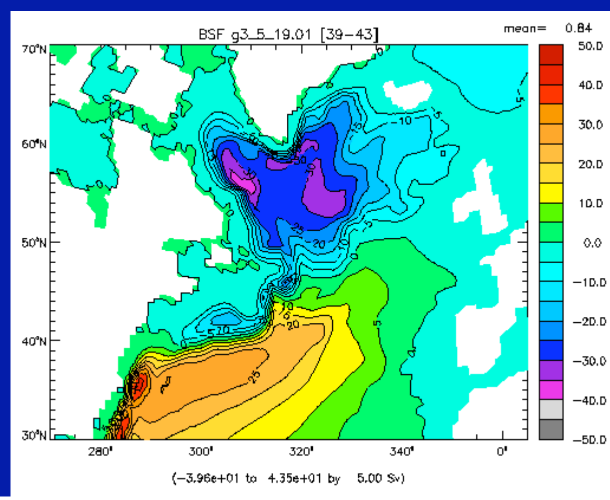
G_kmt



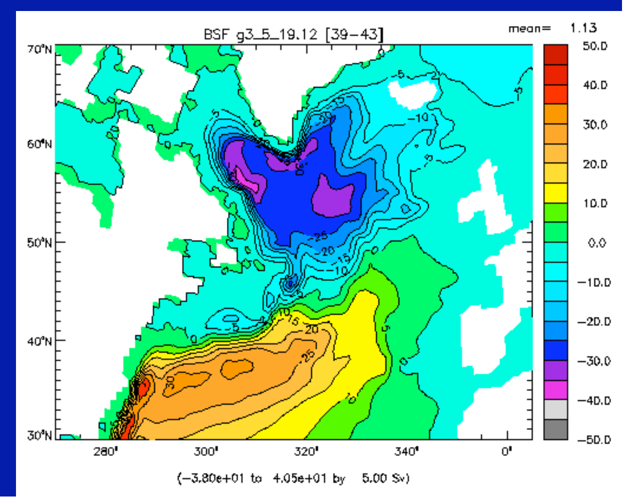
G_visc



G_100*

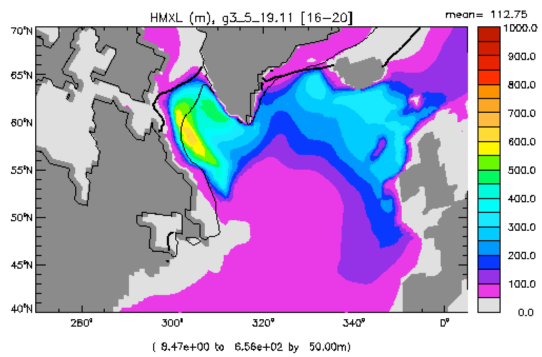


G_40*

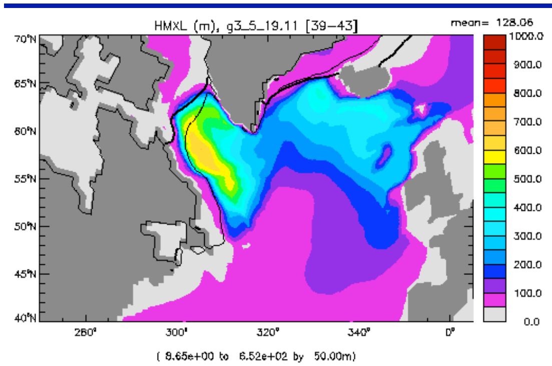


MLD

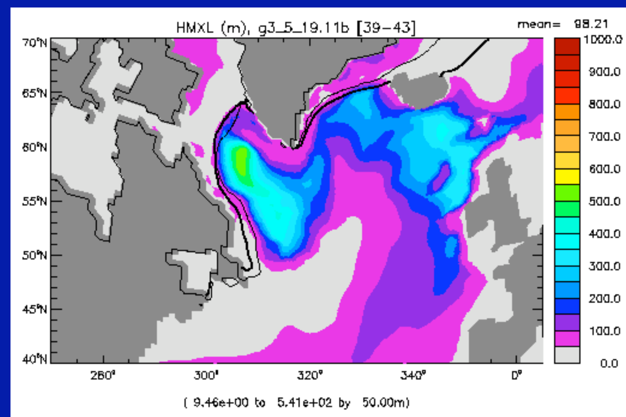
G



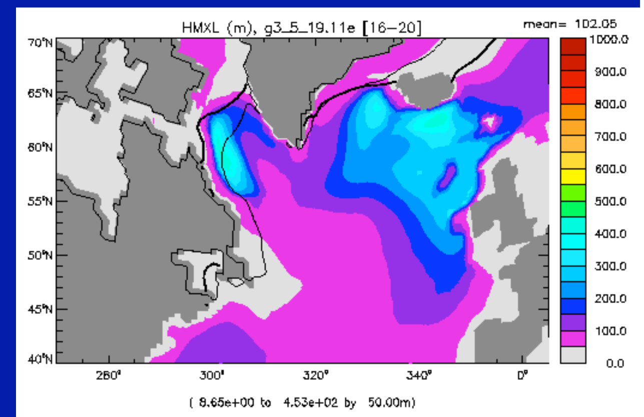
G*



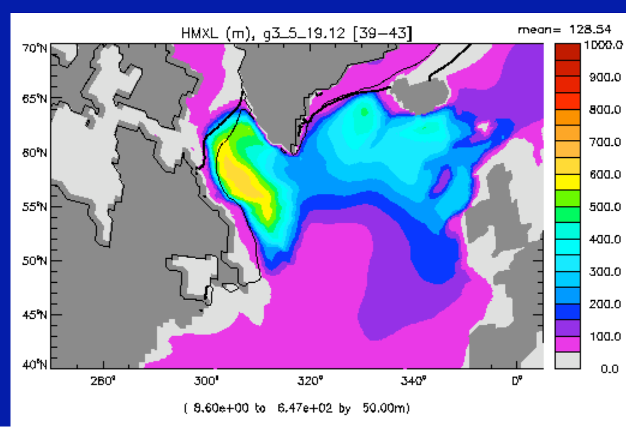
G_nsef*



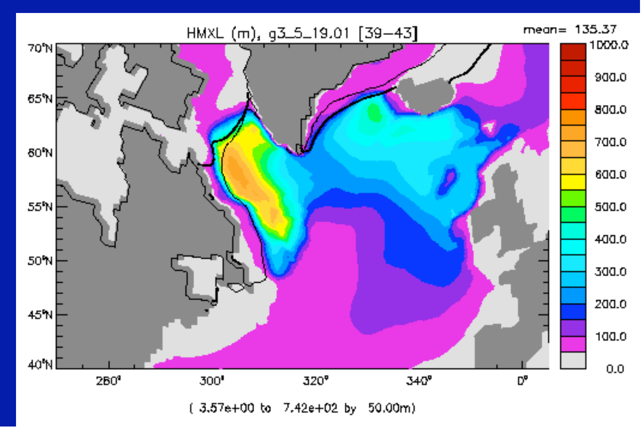
G_visc



G_40*

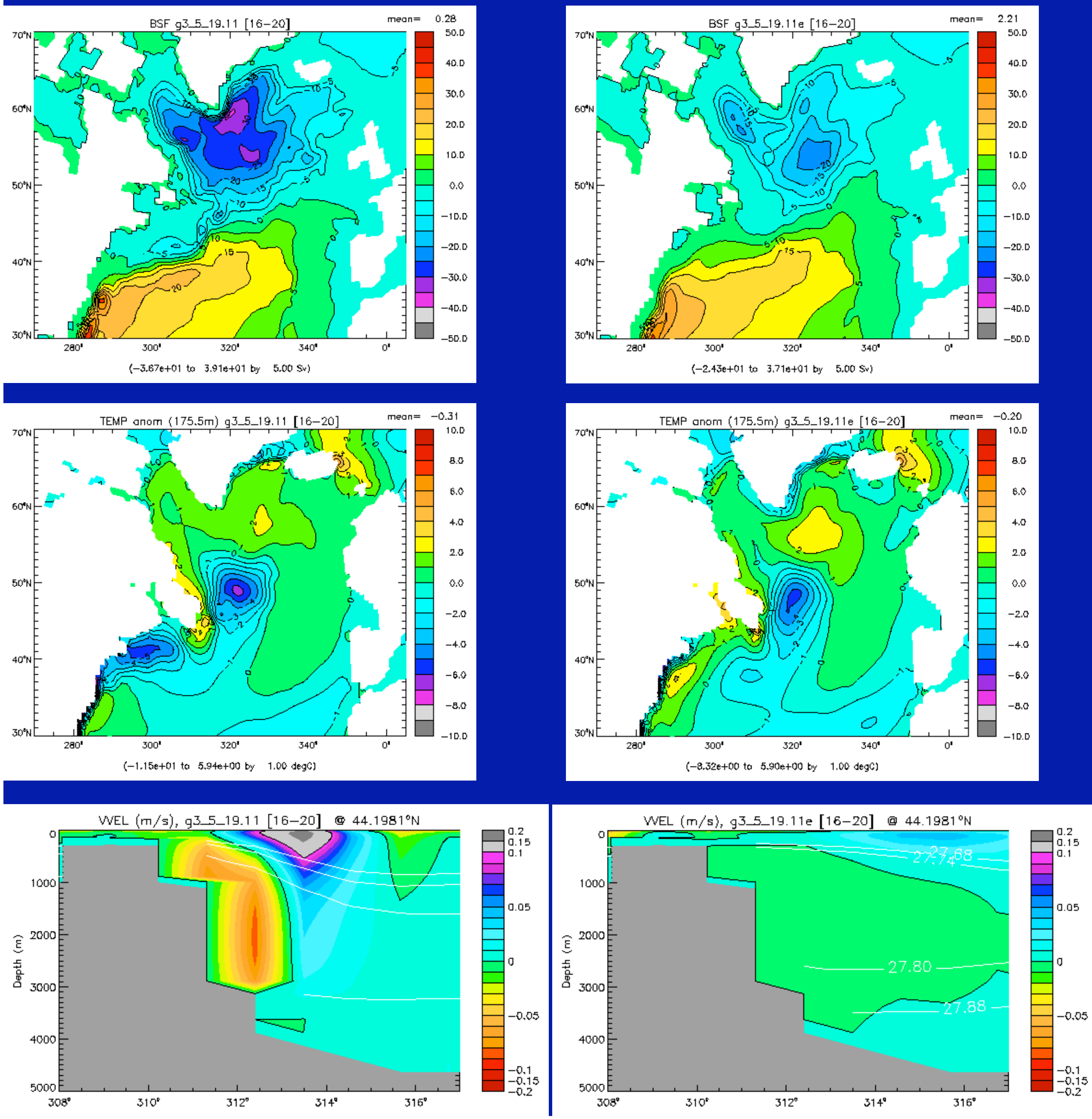


G_100*



G

G_visc: high viscosity



- Dramatic reduction of gyre strengths
- GS fails to separate
- DWBC nonexistent
- Low T′ for the wrong reason