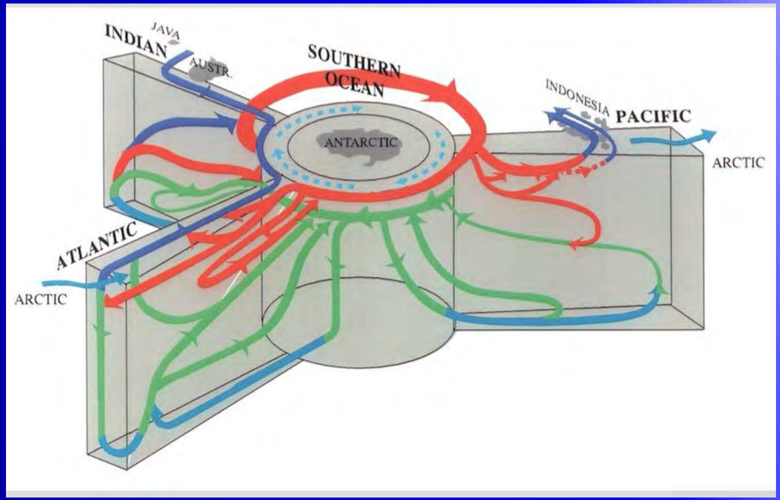
3-dimensional analysis of mixing and overturning in AMOC

Peter Rhines[†] with Xiaobiao Xu[☽]
Eric Chassignet[☽]

in memory of our friend and collegue
Bill Schmitz*

[†] University of Washington
[☽] COAPS, Florida State University
[☀] WHOI Emeritus. Bill passed away in December 2016



The MOC undergoes episodes of mixing on its long journey from warm to cold latitudes and return.

These are often coordinated by the principal wind-forced gyres, which are sources of strong variability in time

New observations of the geography of deep mixing can be compared with models…but it's 3-dimensional

red: warm waters flowing northward in Atlantic

black: deep dense waters flowing southward

purple: thin surface layer of cold, low salinity water flowing south from sources in the Pacific and Arctic

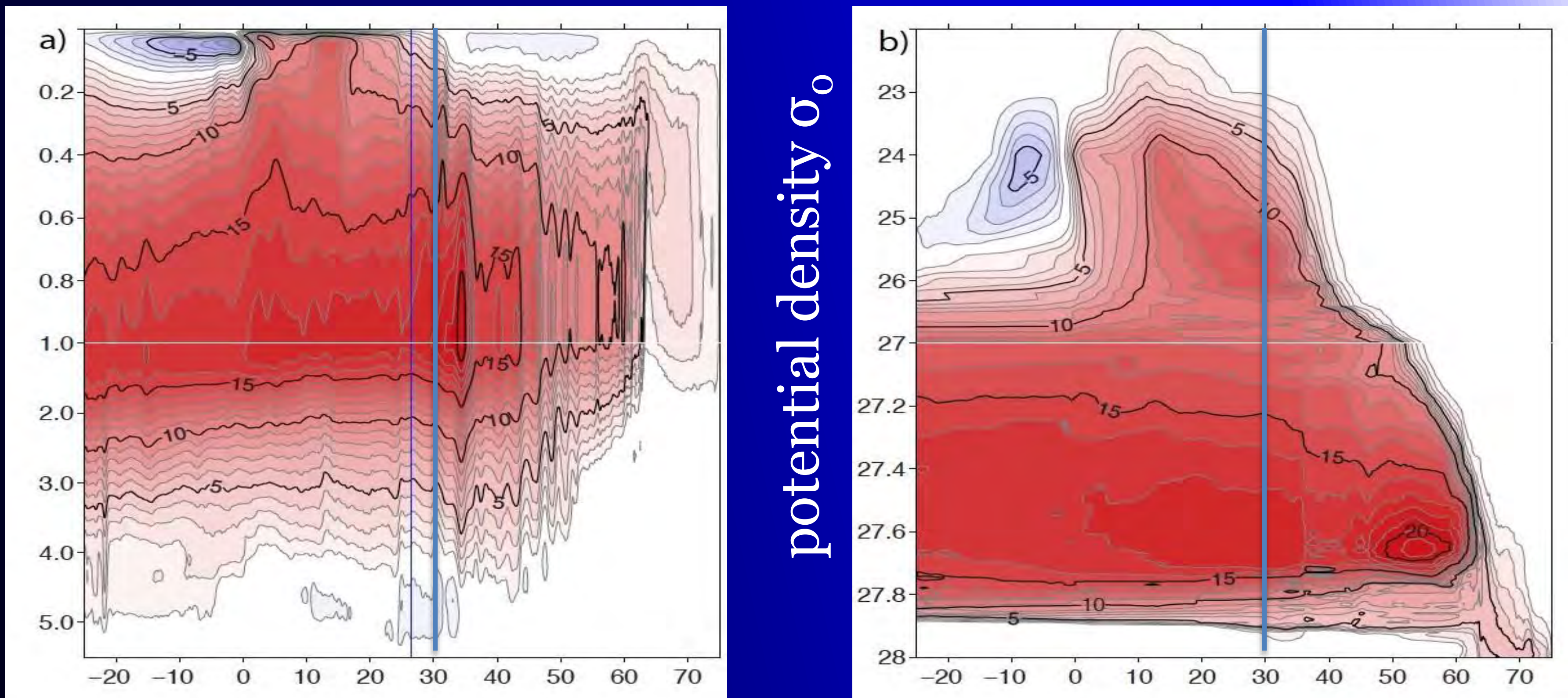
AMOC:Atlantic meridional overturning streamfunction

$\psi_z(y,z)$ $\psi_\sigma(y,\sigma)$

dynamical v,w velocity: connected by Sverdrup vorticity balance $\beta v = f\partial w/\partial z$

diapycnal velocity w_d water-mass transformation

depth (km)

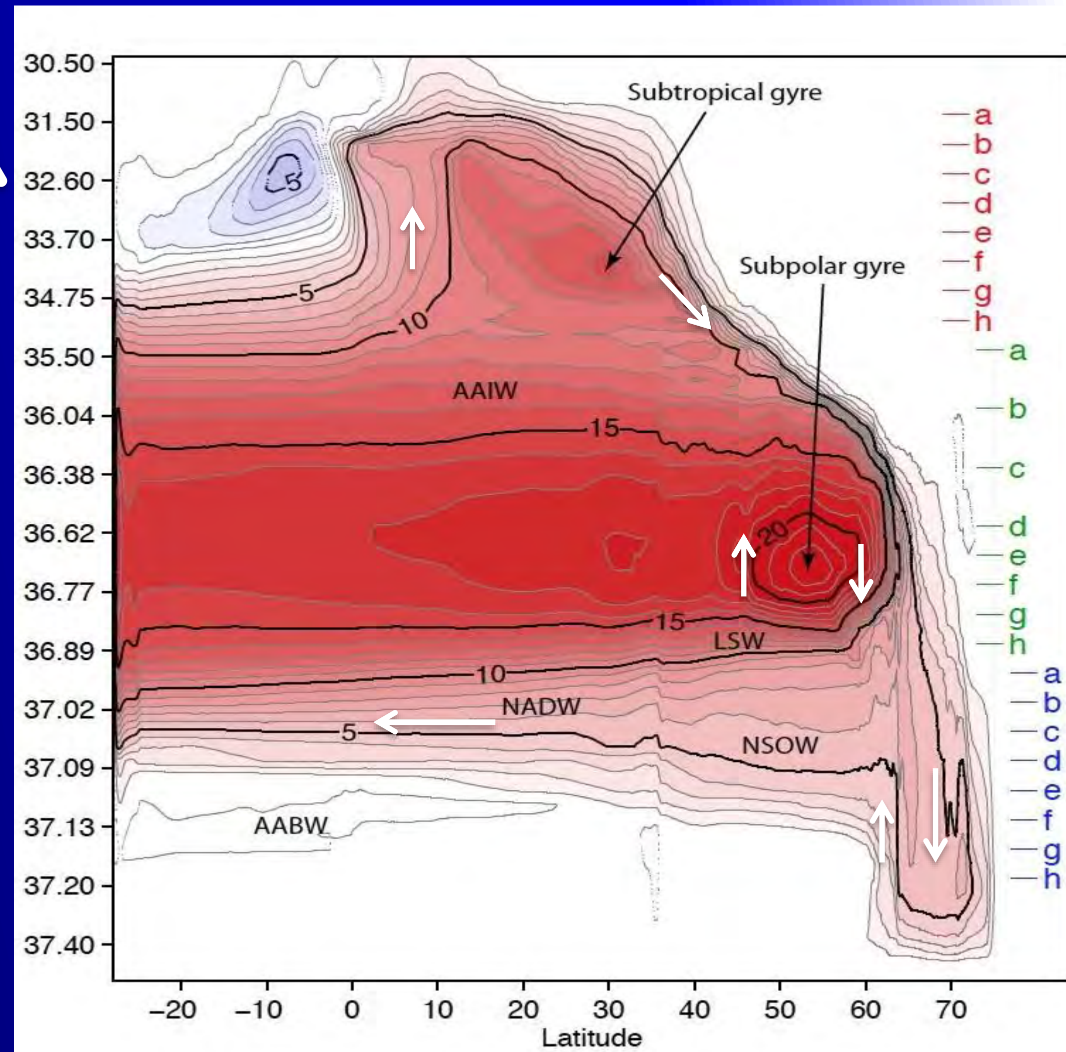


potential density σ_0

latitude

....zonally integrated meridional velocity, including bolus eddy flux, and velocity normal to isopycnal surfaces, W_d

σ_2



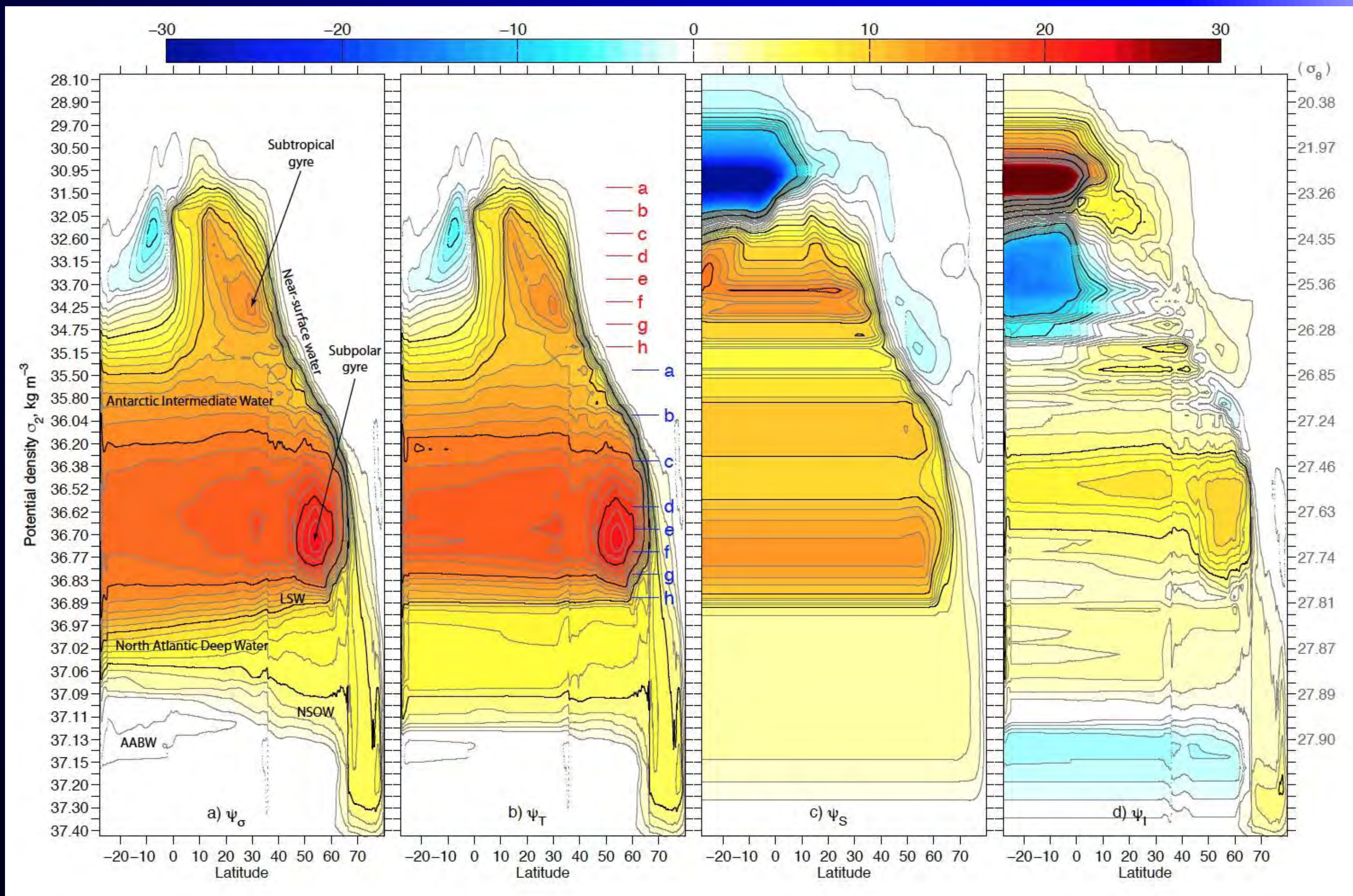
30^0S

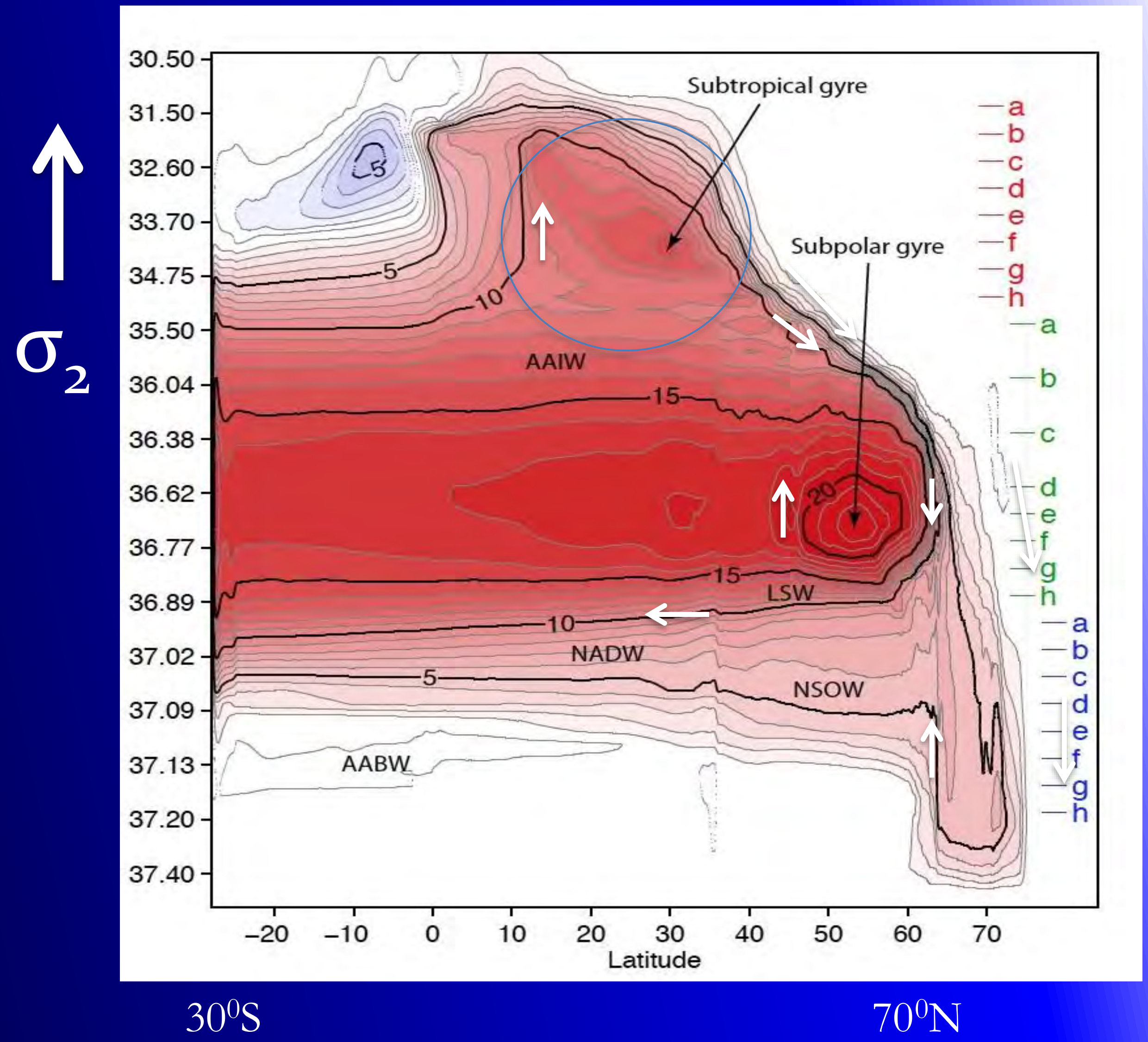
70^0N

HYCOM 1/12^o x 32L
domain: 30S to 80N
ocean only, forced by climatological mean with annual cycle, analyzed for years 16-20 (NCEP reanalysis + annual cycle): see *Xu et al. JGR 2013, 2014…)*

ψ_σ $\psi_T = \psi_S + \psi_I$

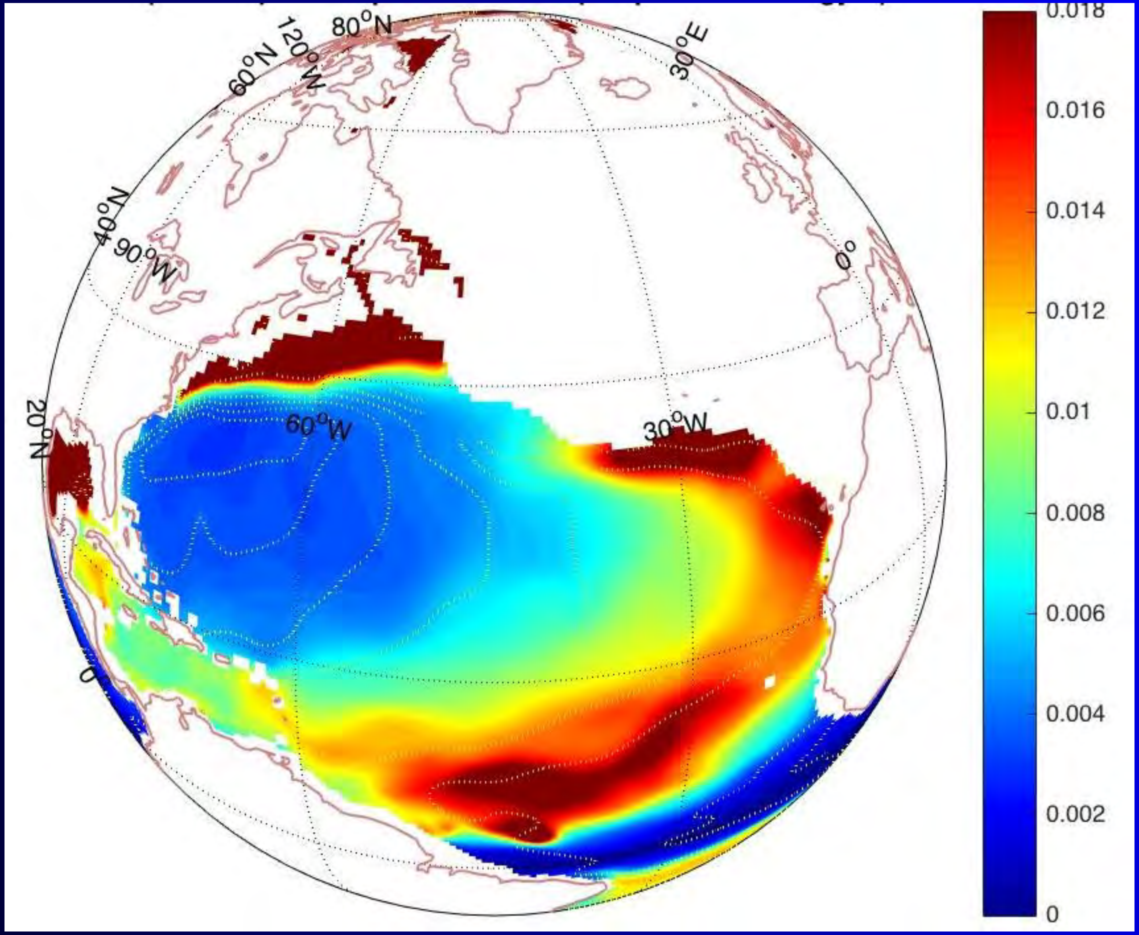
volume transport streamfunction | corrected for adiabatic drift | atmos/ocean forced WMT (Walin, Speer-Tziperman) | internal mixing WMT





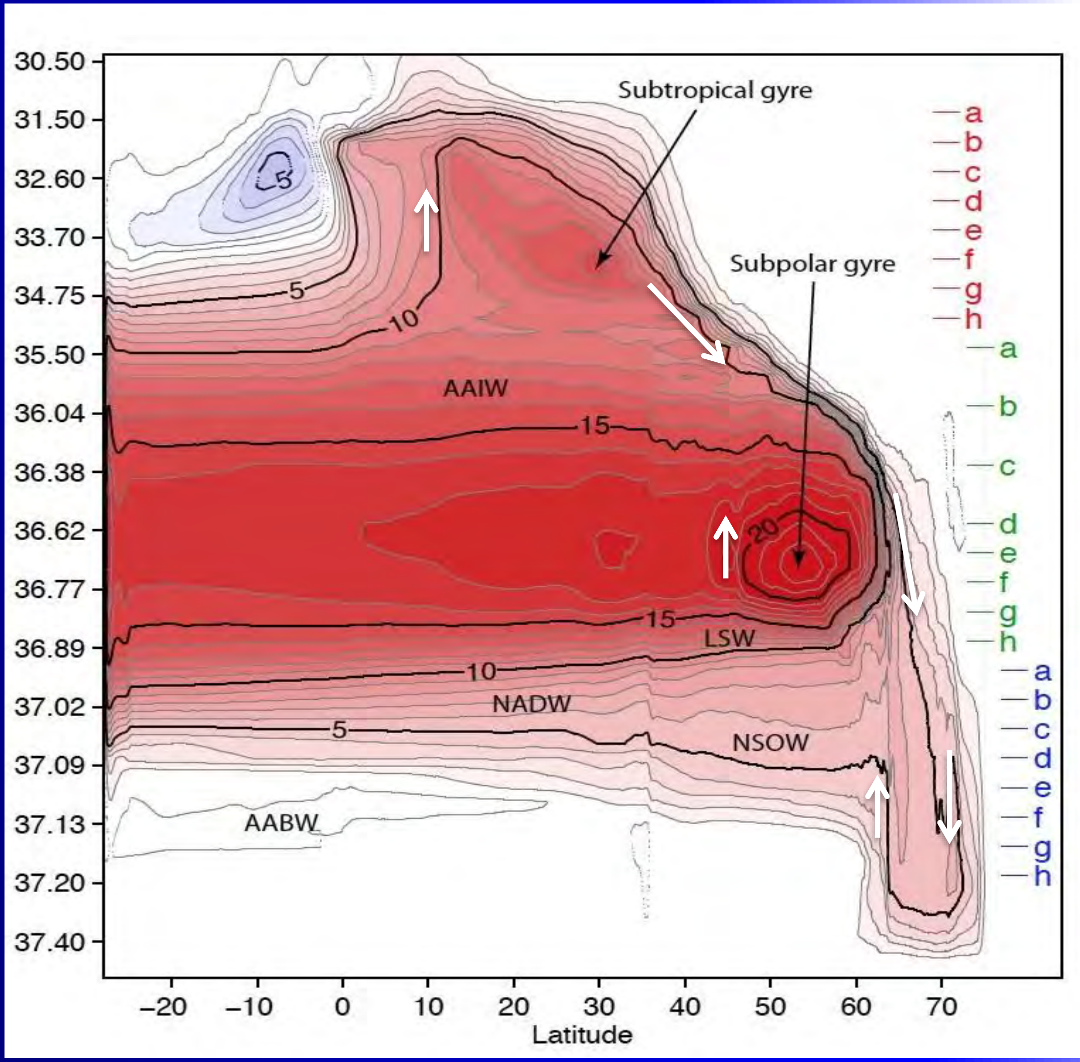
vertical velocity shows diapycnal density mixing/advection at each latitude

Potential vorticity f/h_i on the $\sigma_\theta = 26.4$ potential density surface (ARGO-MIMOC hydrography; h_i is thickness of i^{th} layer)



"vertical" velocity shows diapycnal density mixing/advection at each latitude.

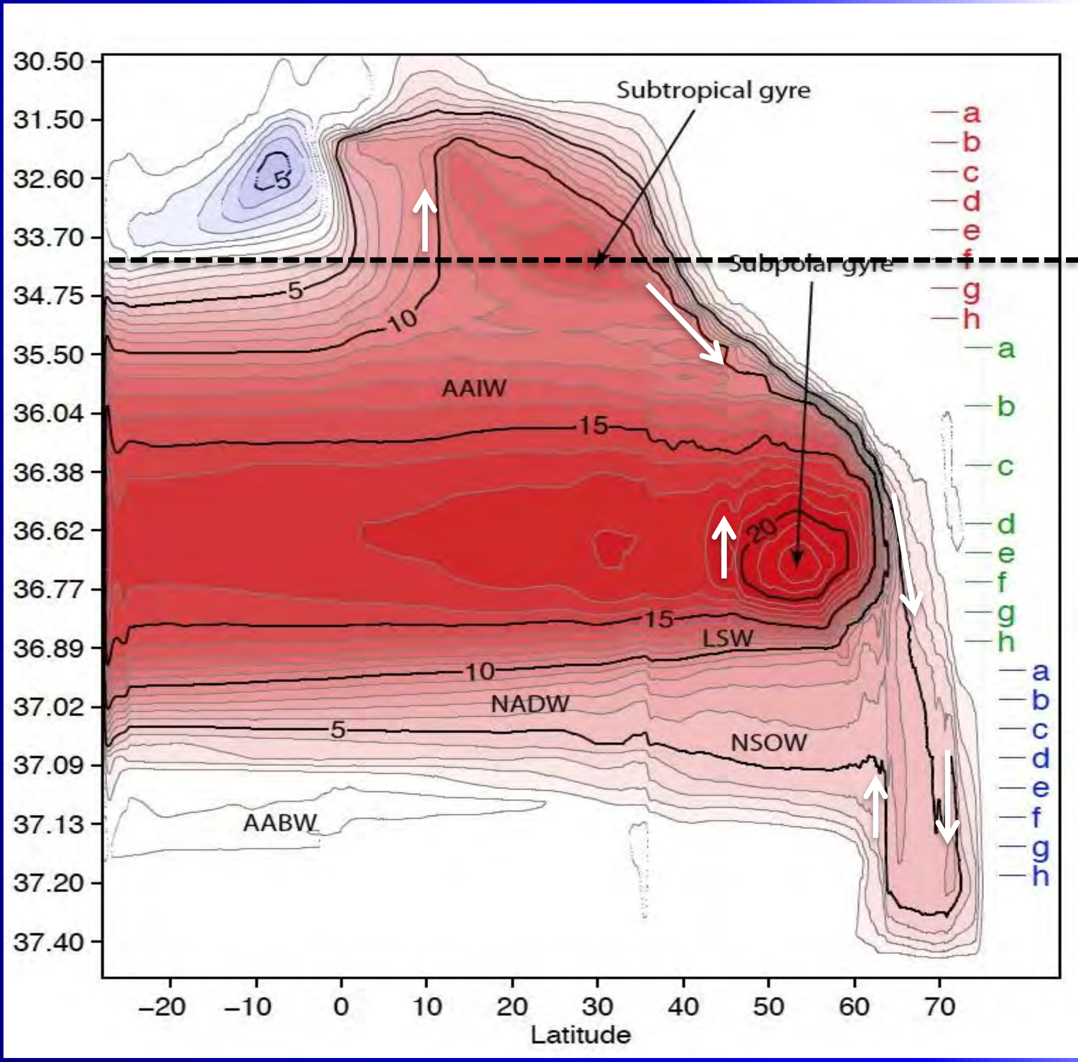
σ_2



30⁰S 70⁰N

Note smooth near-surface transition between subtropics and subpolar latitudes where water parcels change density in mixed layer, forced by atmosphere “vertical” velocity shows diapycnal density mixing/advection at each latitude.

σ_2



30⁰S 70⁰N

Note smooth near-surface transition between subtropics and subpolar latitudes where water parcels change density in mixed layer, forced by atmosphere

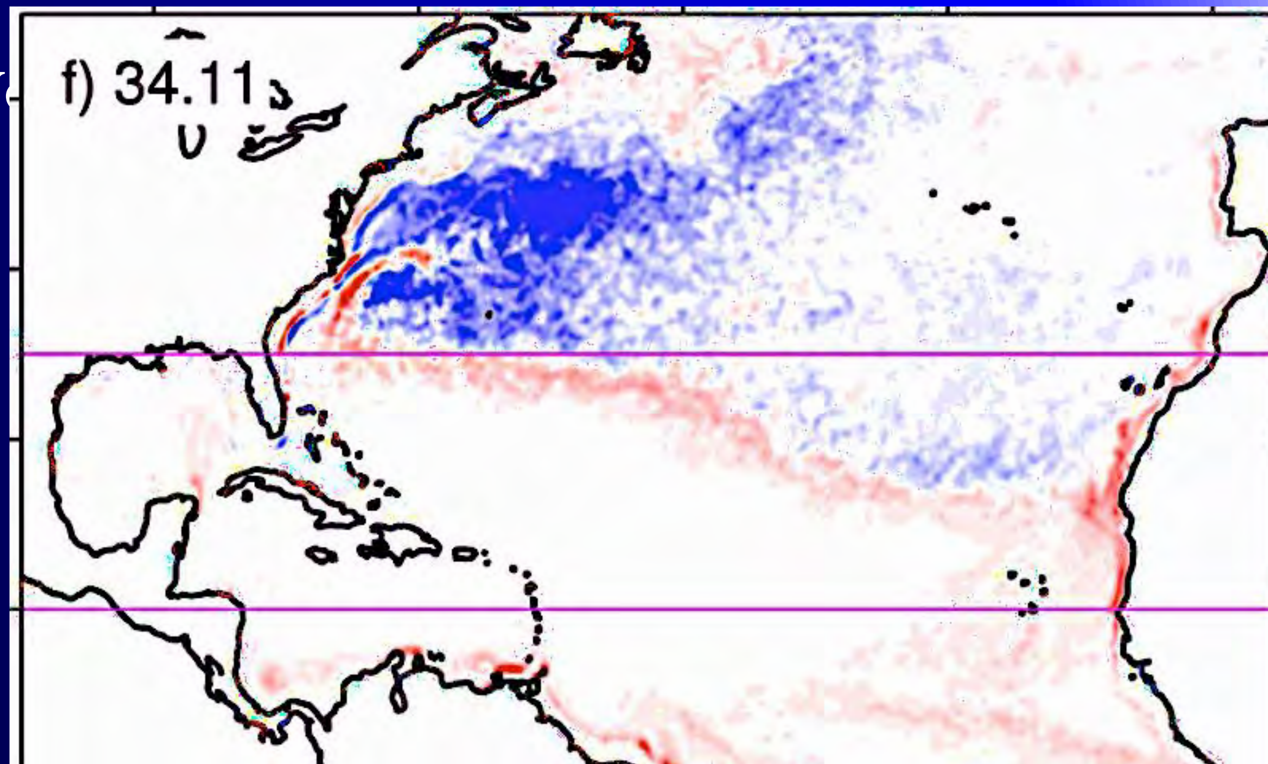
Further chasing the geography of mixing and WMT, consider the diapycnal velocity, W_d, in the subtropics

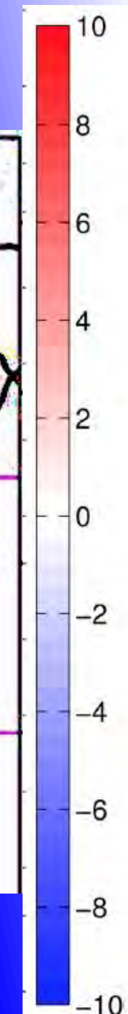
blue: downward W_d
red: upward W_d

Total mean diapycnal velocity W_d 10^{-6} m sec^{-1} on $\sigma = 34.11$ (potential density referenced to 2 km) is in upper 200 m of water column

blue = downward W
(cooling)
red = upward Wd
(warming)

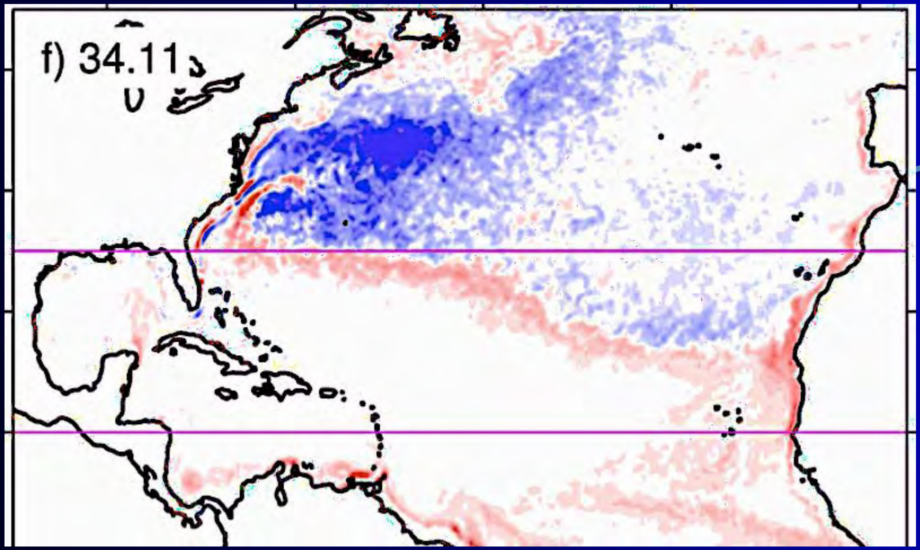
Subtropical
Mode Water,
Gulf Stream,
North Atlantic
Current





Blue isopycnal downwelling Wd...cooling of Gulf Stream, Subtropical Mode Water (18 Degree Water) convection

Red upwelling : seasonal restratification

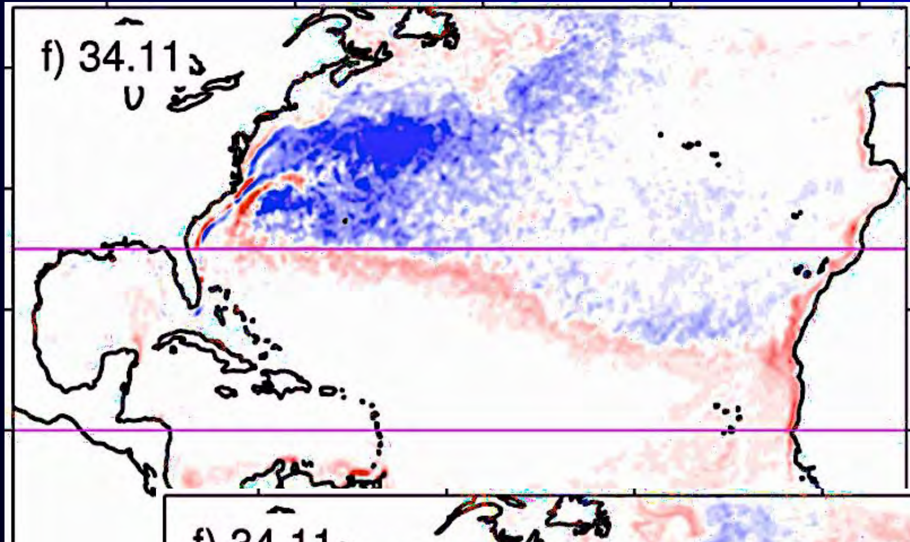


Total diapycnal velocity W_d

blue = downward
red = upward $\sigma_o = 25.7$

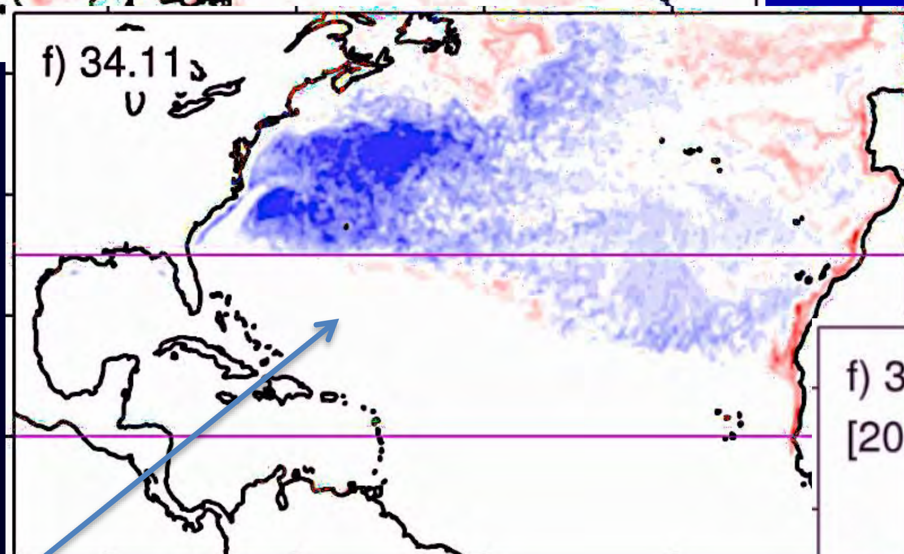
cooling of the
Subtropical Mode Water,
Gulf Stream,
North Atlantic Current

Total diapycnal velocity W_d

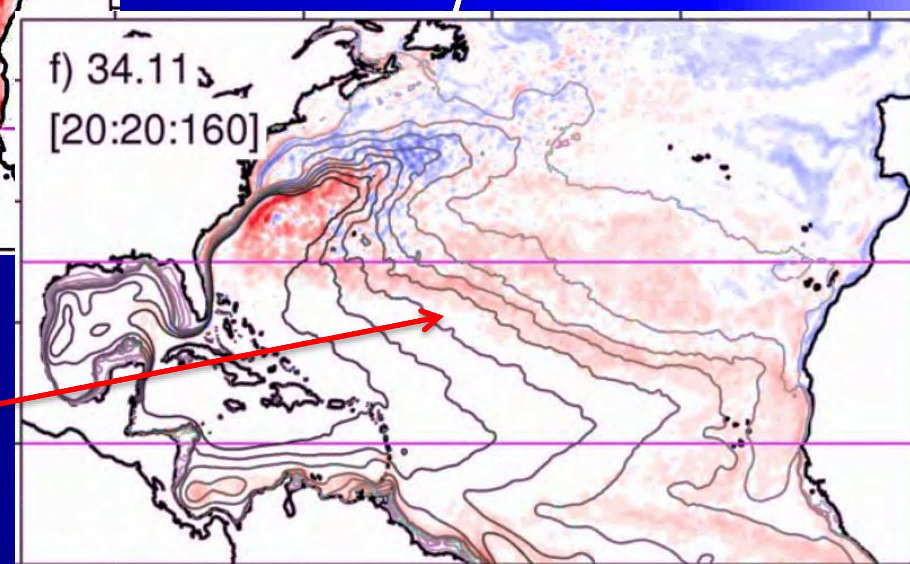


blue = downward
red = upward $\sigma_0 = 25.7$

= Wd induced directly by air-sea buoyancy flux

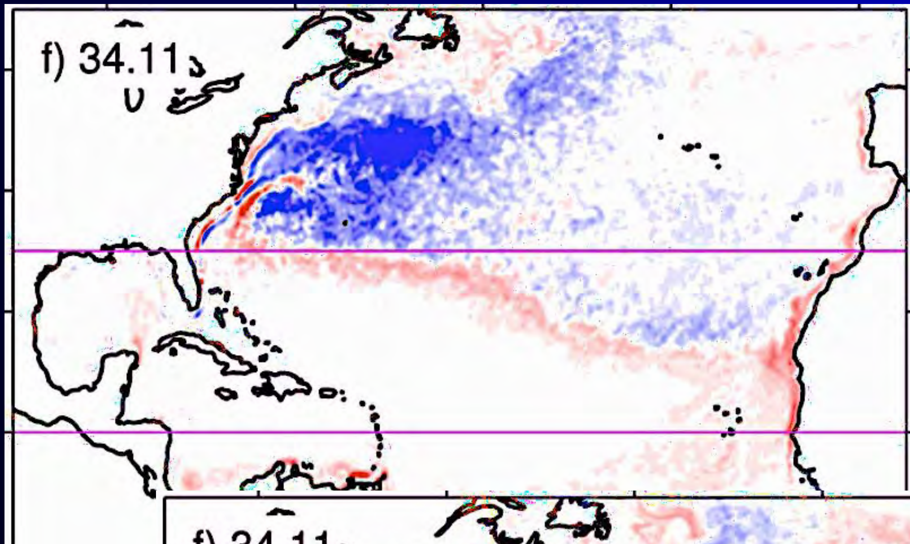


+ Wd due to internal mixing



Cooling of the Subtropical Mode Water,
Gulf Stream,
North Atlantic Current

Warming during spring restratification and through Ekman northward transport



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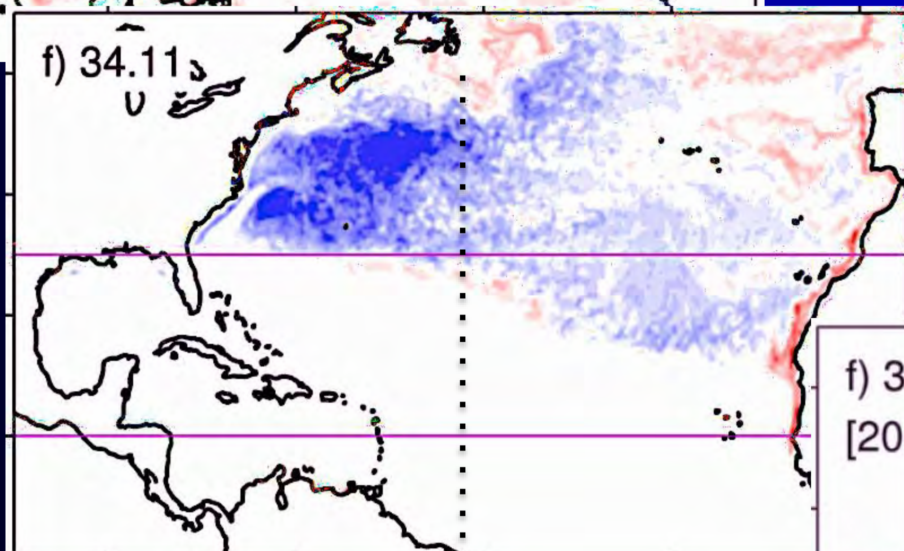
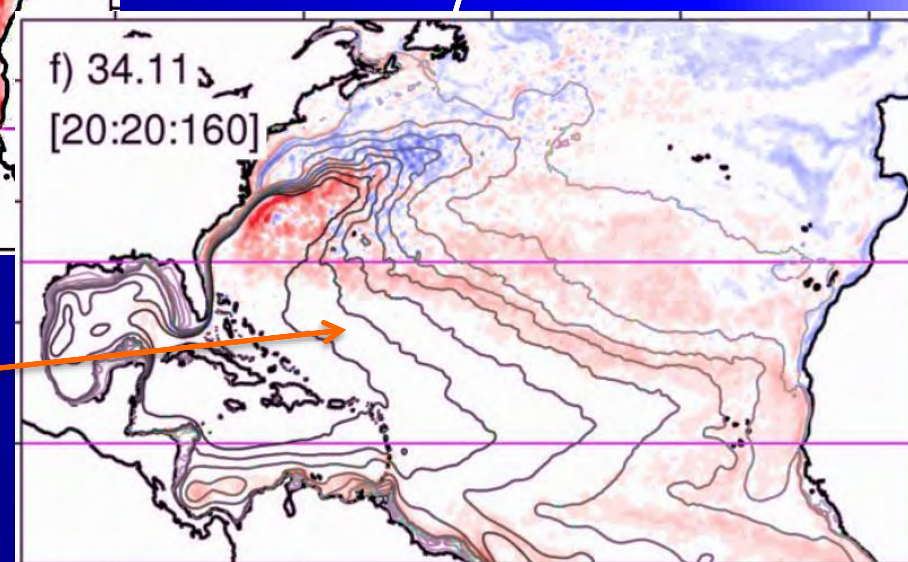
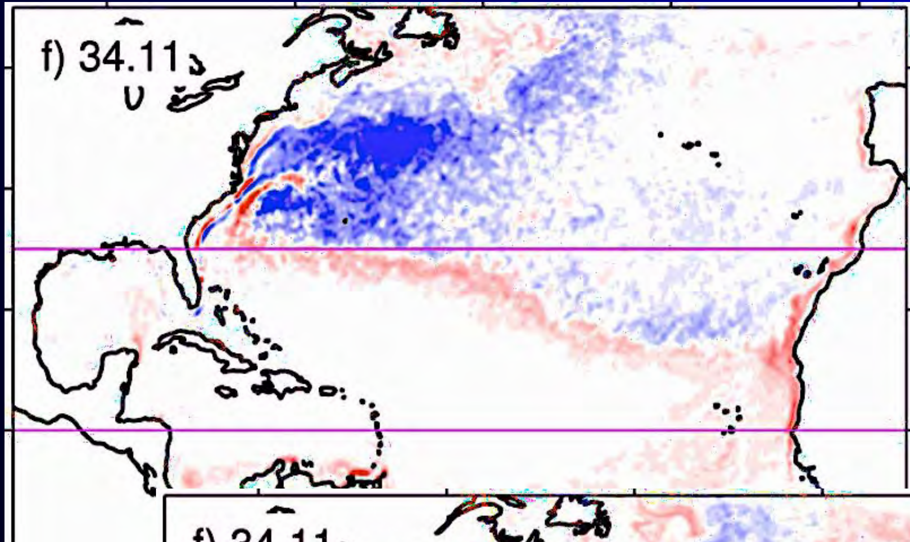


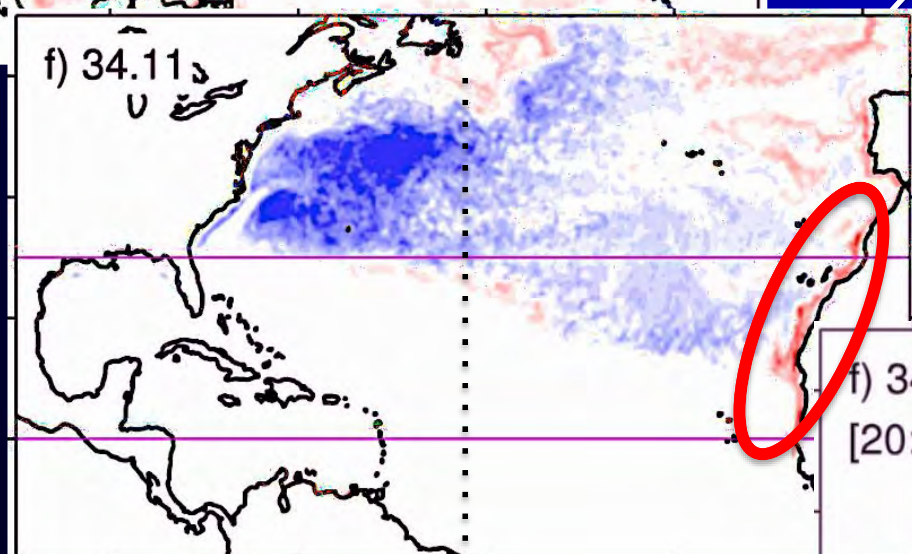
+ Wd due to internal mixing



Black contours are annual mean depth of this density surface. Its outcrop moves north in summer as it restrataifes, and south in winter as it cools/convects. Ekman trnnsport and pumping also affects Wd



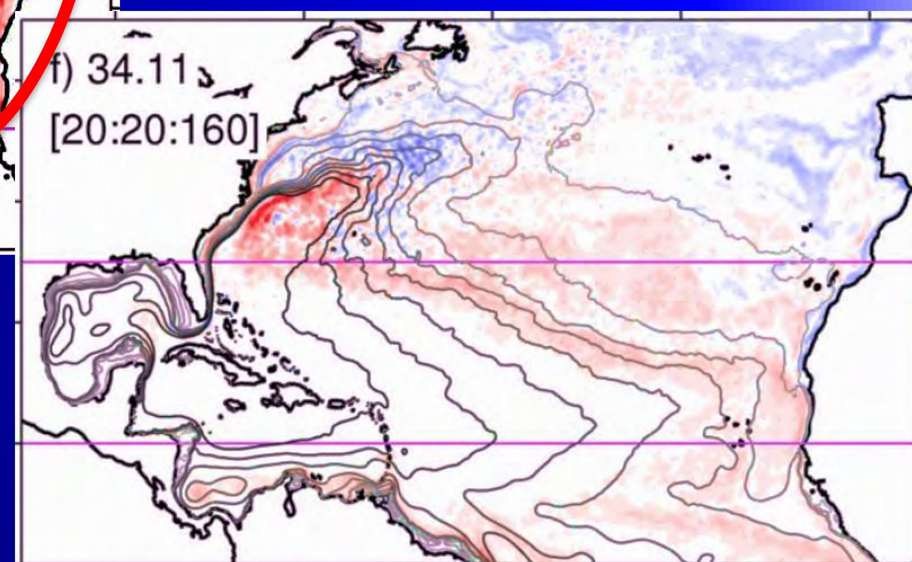
Total diapycnal velocity W_d



= Wd induced directly by air-sea buoyancy flux

+ Wd due to internal mixing

coastal upwelling off west Africa is cold, hence warmed/upwelled diapycnally



The pattern of upwelling/warming in the north and downwelling/cooling in the south for the surface-forced Wd is largely due to seasonal migration of the outcrop line…in winter it is in the south, cooling, while in summer it is warming in the north.

Seasonal variation of diapycnal velocity in subtropics (subtropical mode water … 18 –degree water)

WOCE section A20 (52W)

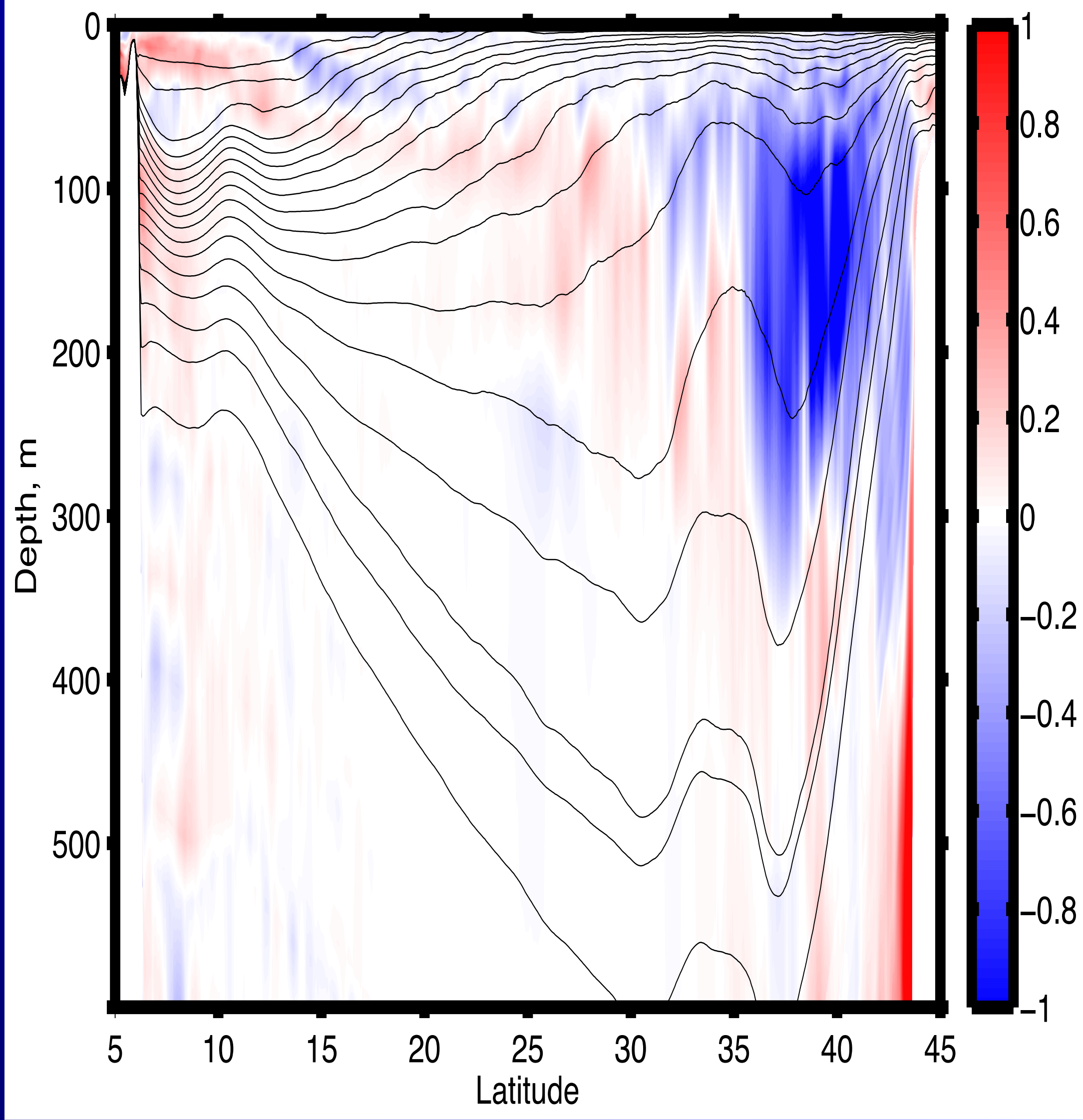
Annual mean diapycnal transformation along 54W longitude

Subtropical Mode Water formation

('18 degree Water' of Val Worthington)

Wd 10^{-5} m sec^{-1}

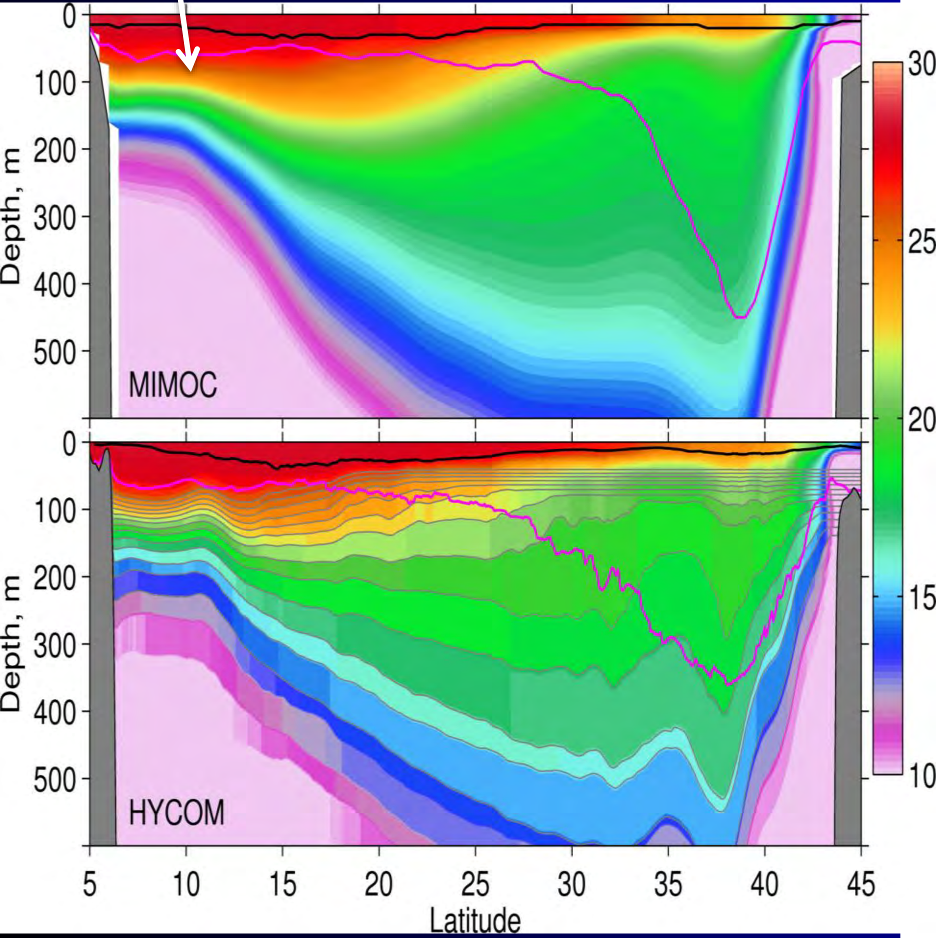
diapycnal velocity blue=down, red= up so, blue is where cooling occurs, red is where warming (by mixing usually) occurs



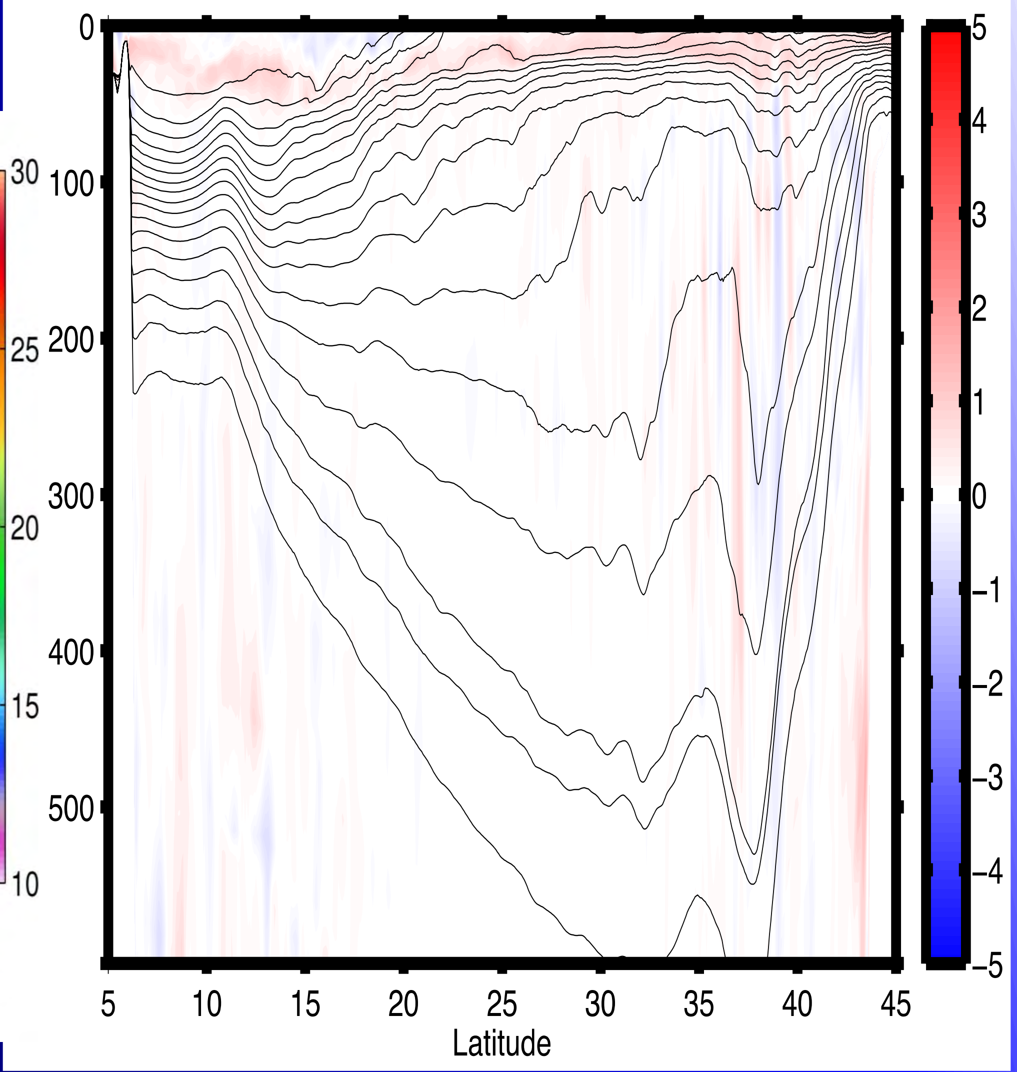
MIMOC-ARGO observations ~2007-2011 Schmidko et al. 2013 JGR

07

Temperature/mixed layer depth

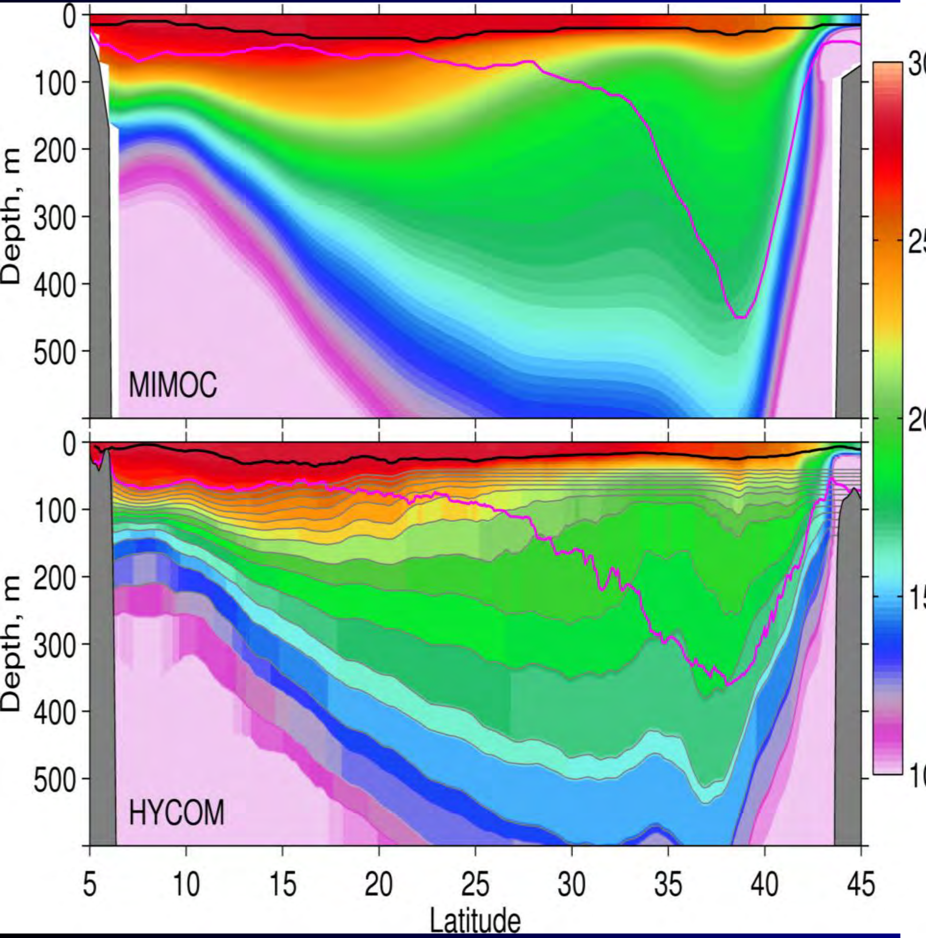


Diapycnal transformation

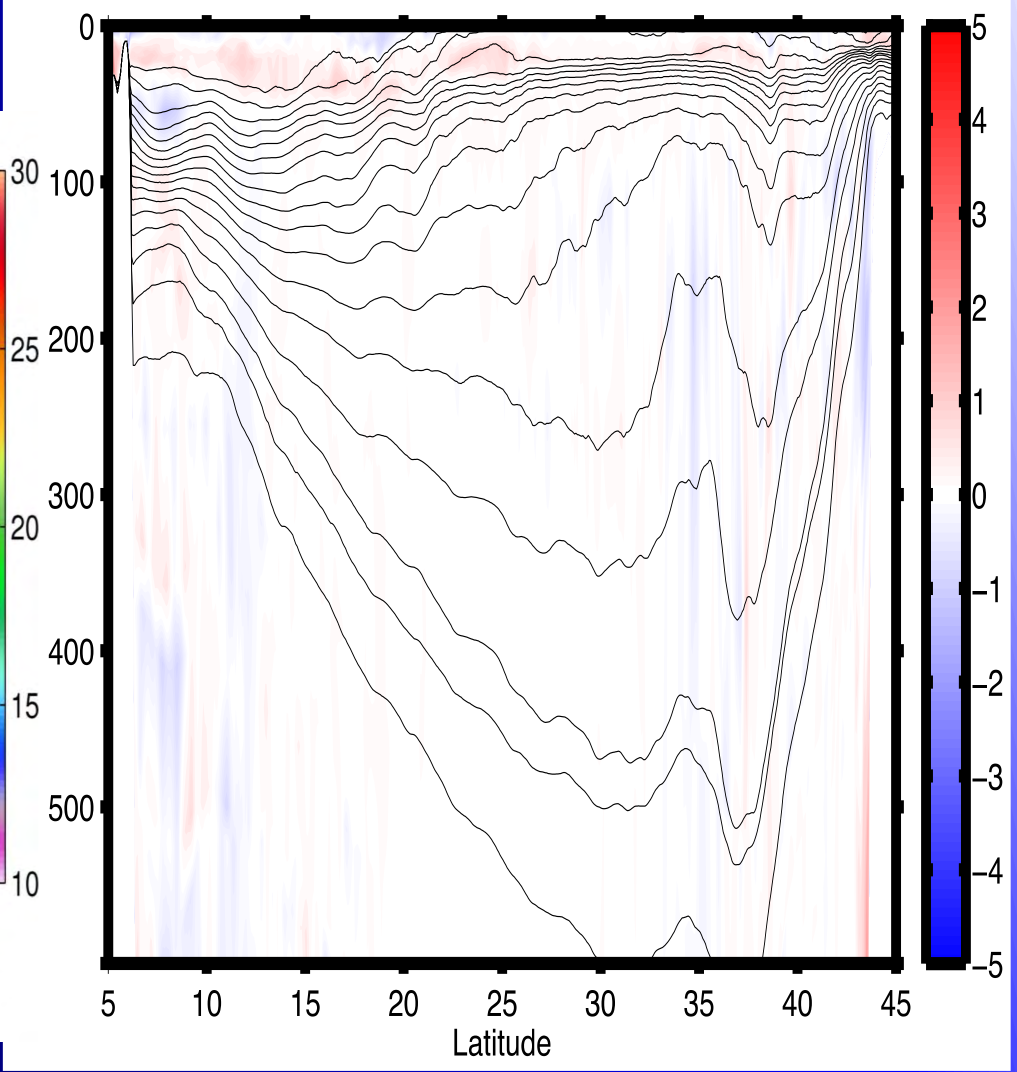


08

Temperature/mixed layer depth

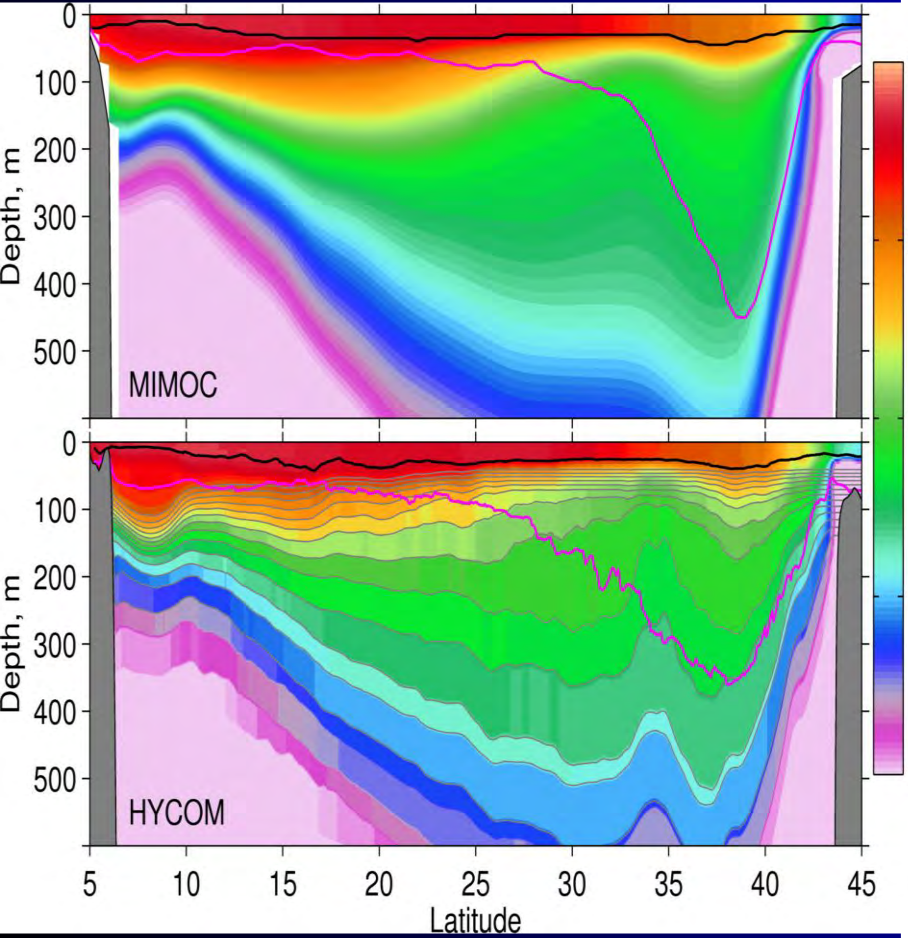


Diapycnal transformation

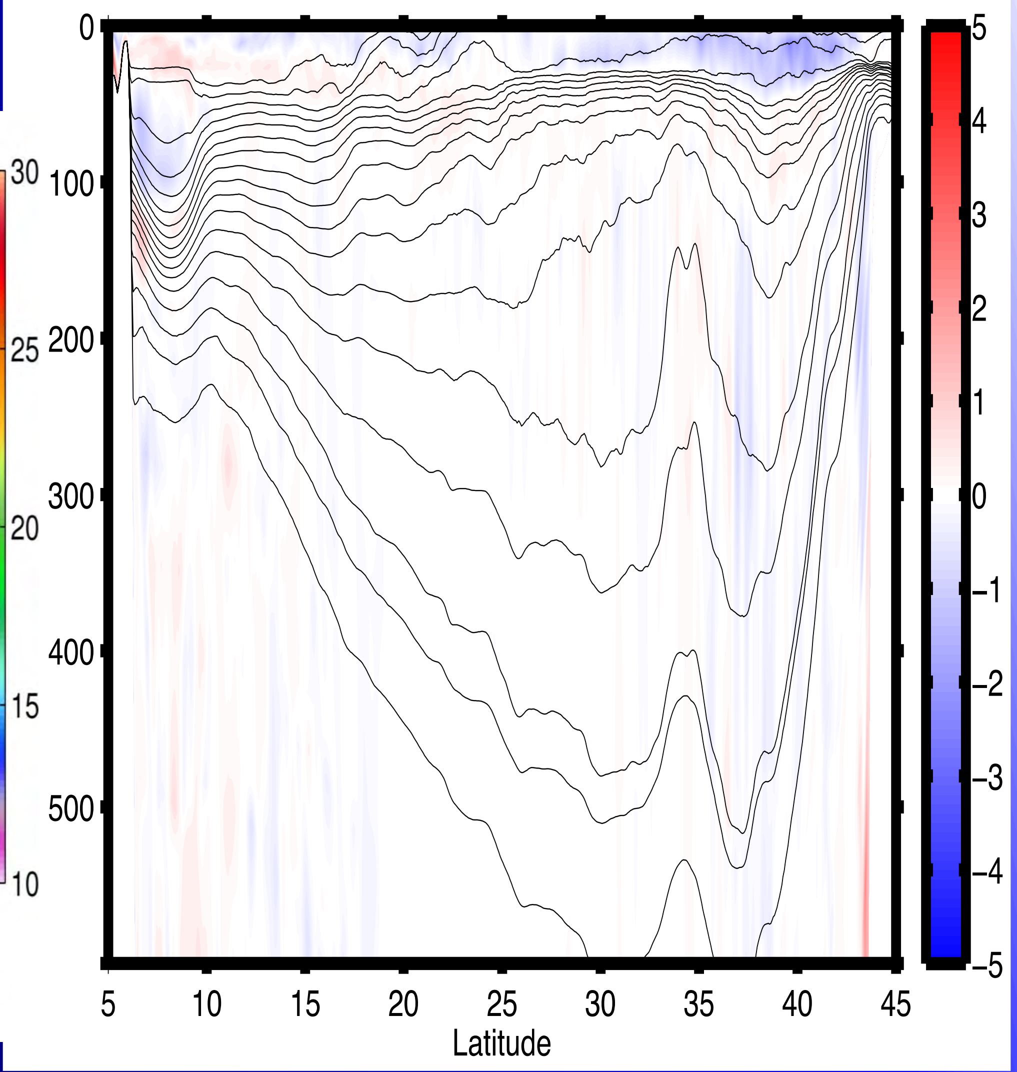


09

Temperature/mixed layer depth



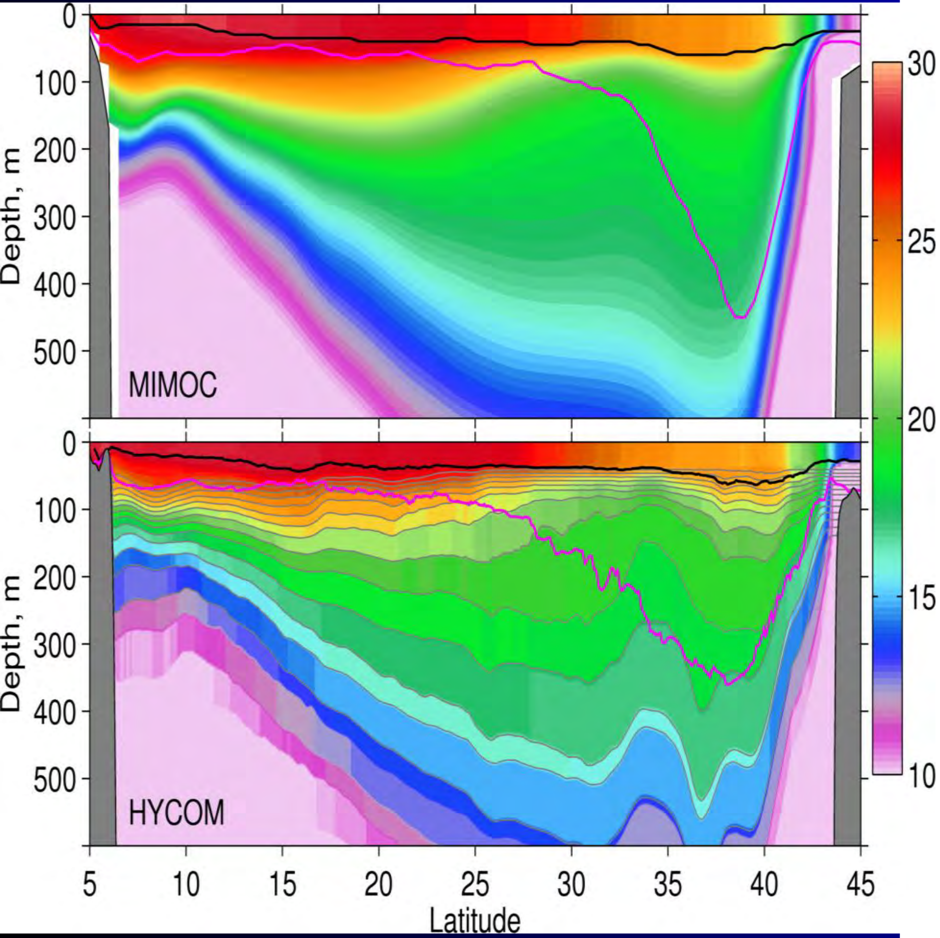
Diapycnal transformation

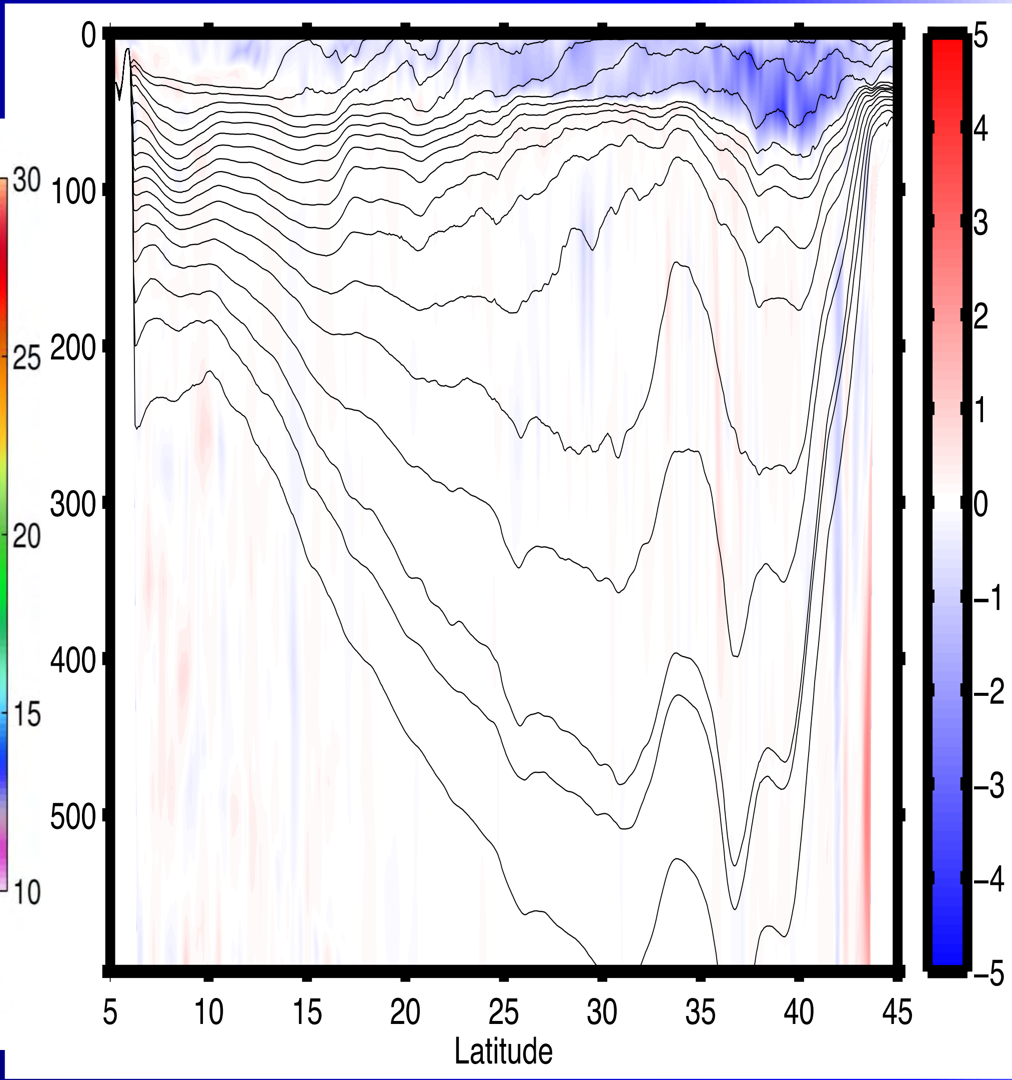


10

Diapycnal transformation

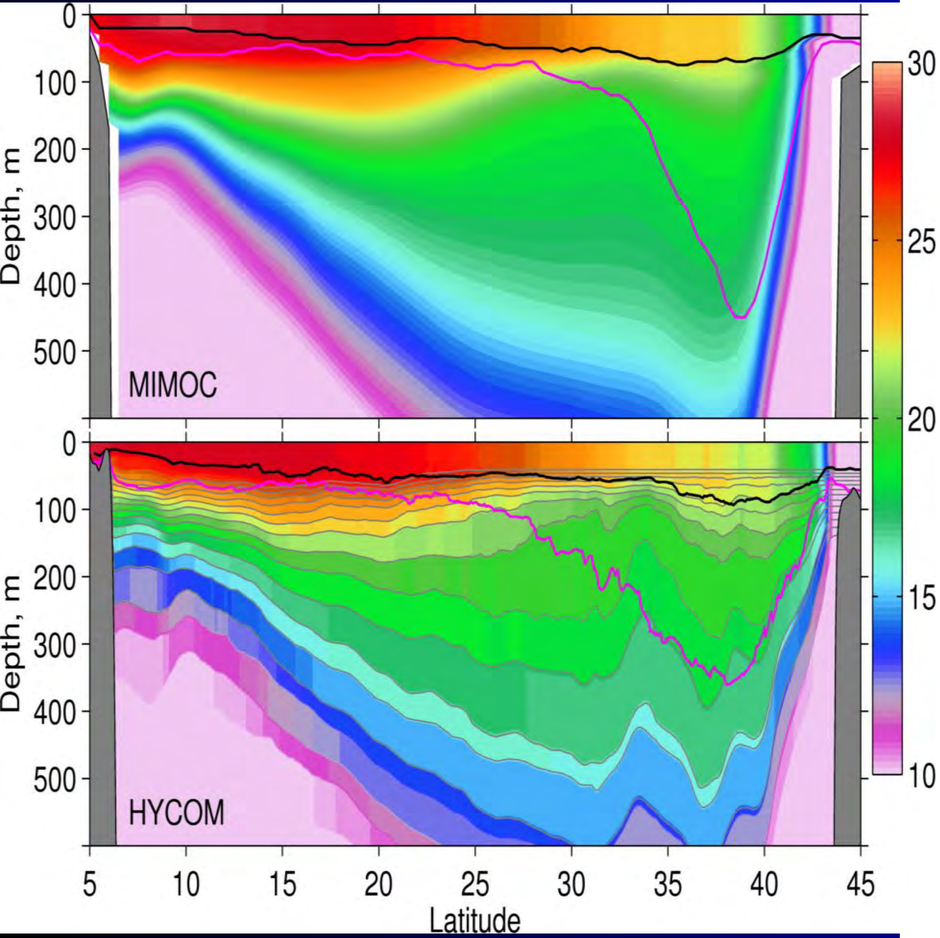
Temperature/mixed layer depth



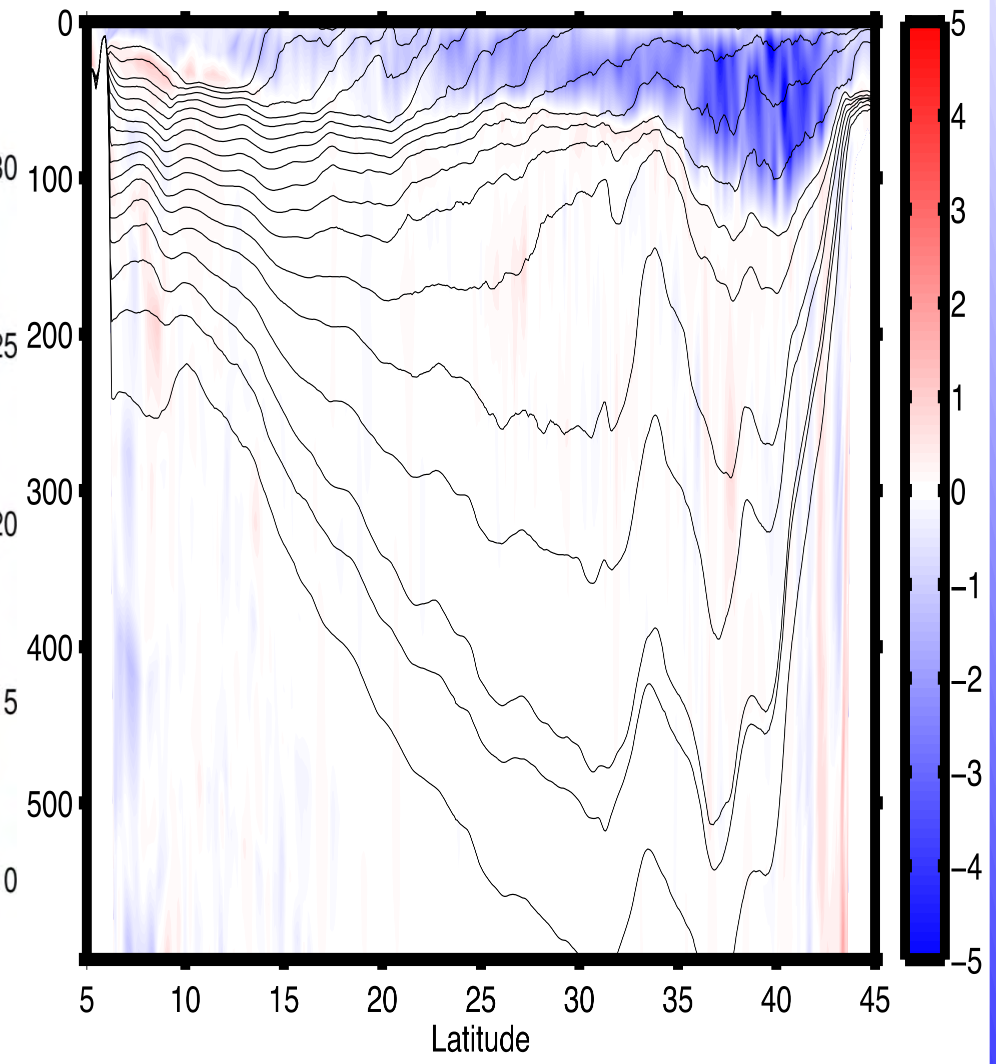


11

Temperature/mixed layer depth



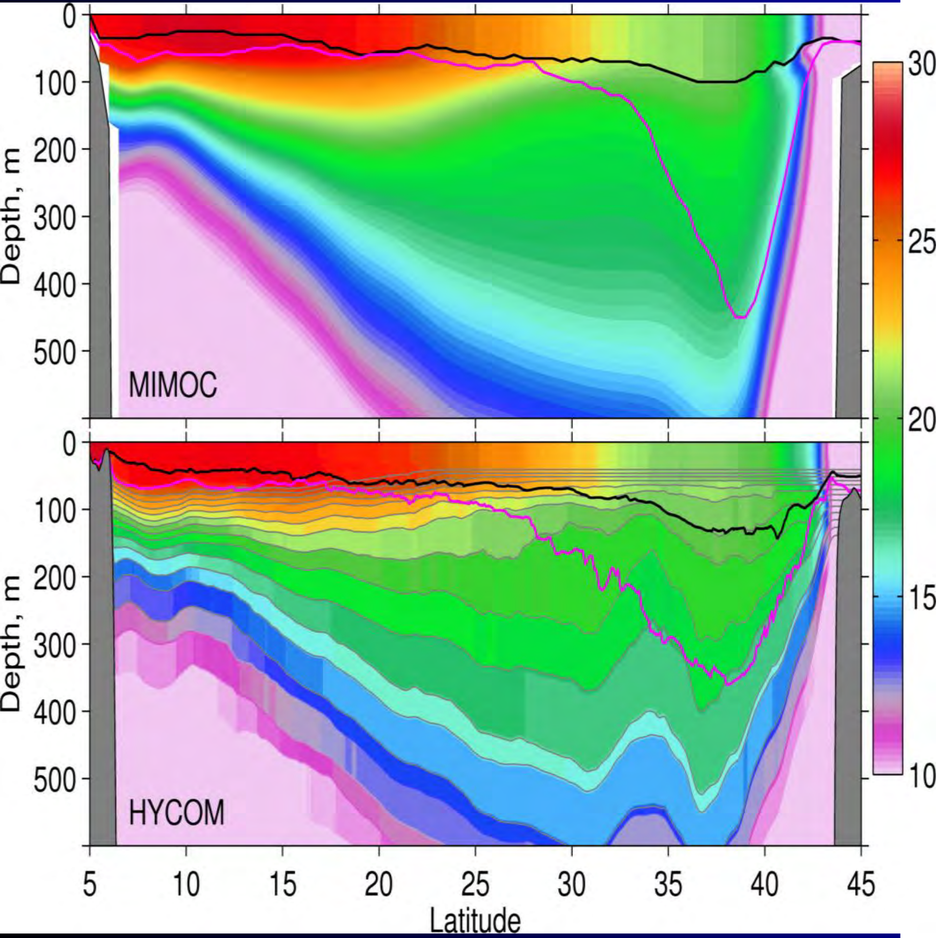
Diapycnal transformation

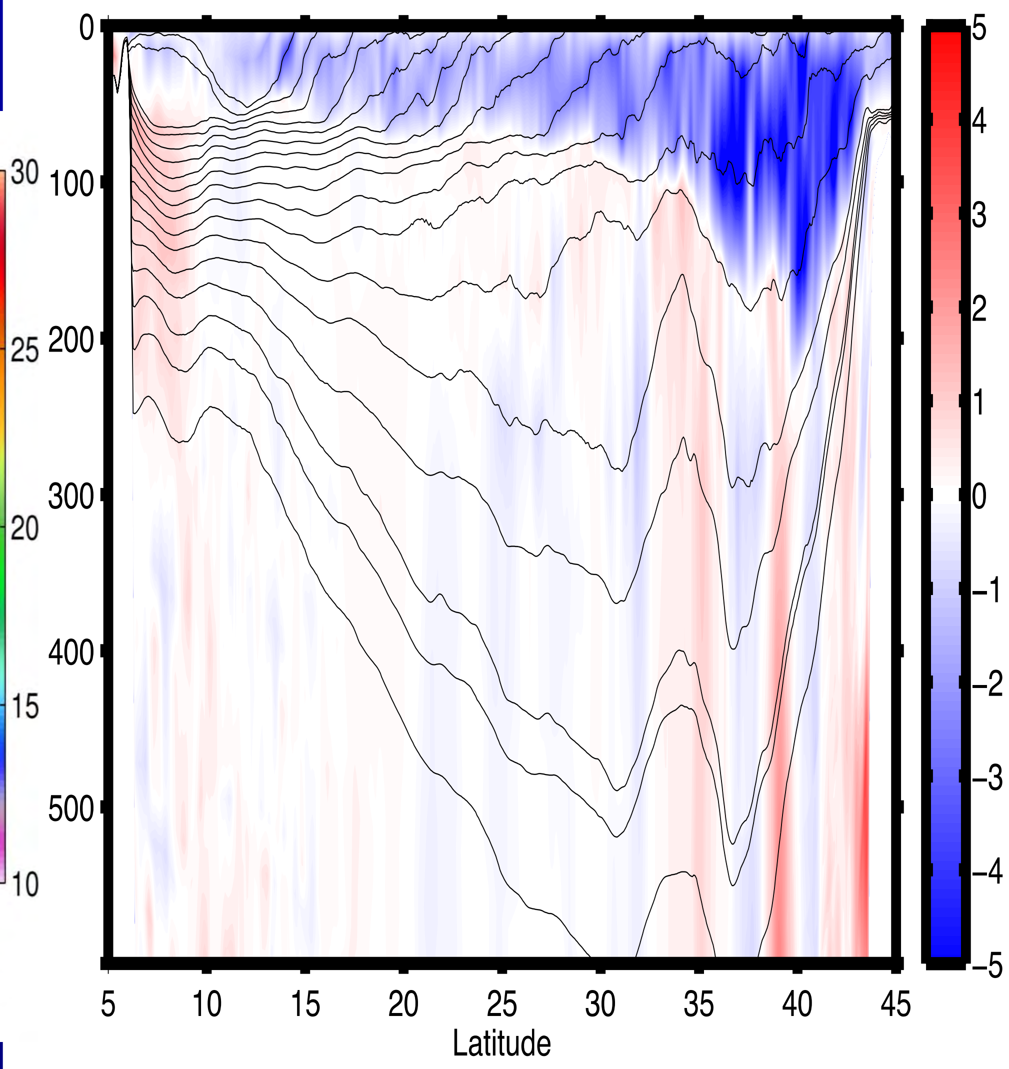


12

Diapycnal velocity 10^{-6} m sec^{-1}

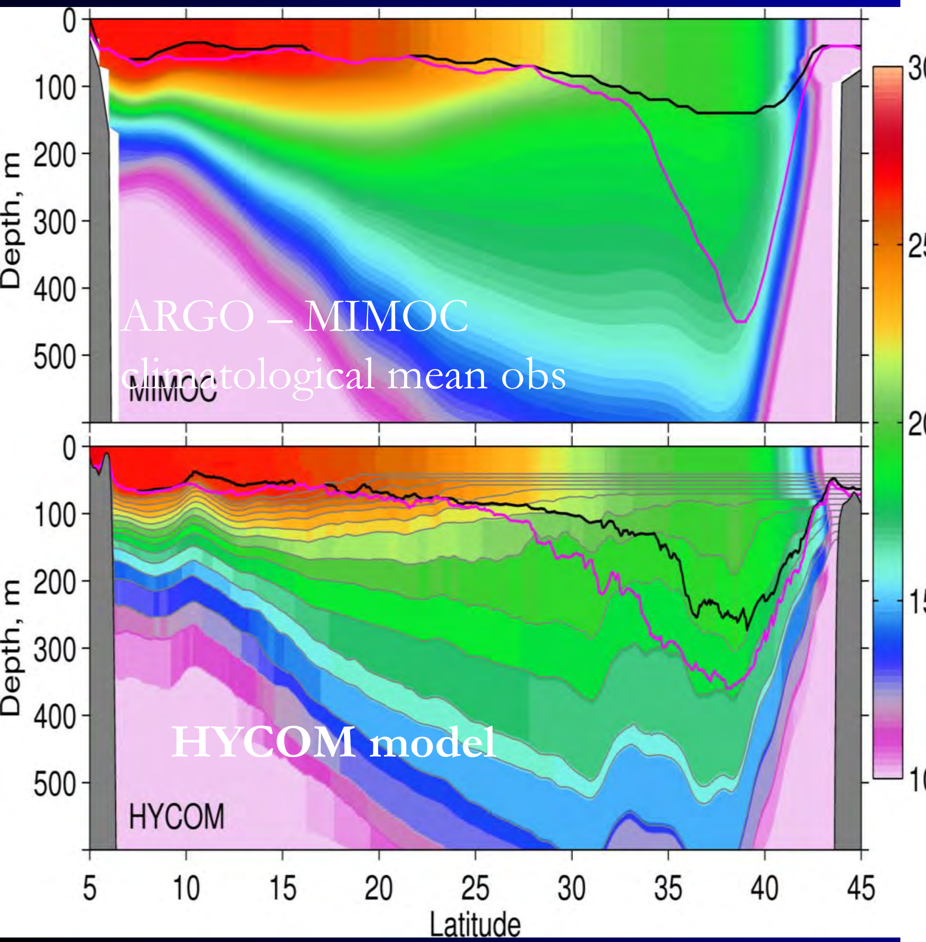
Temperature/mixed layer depth



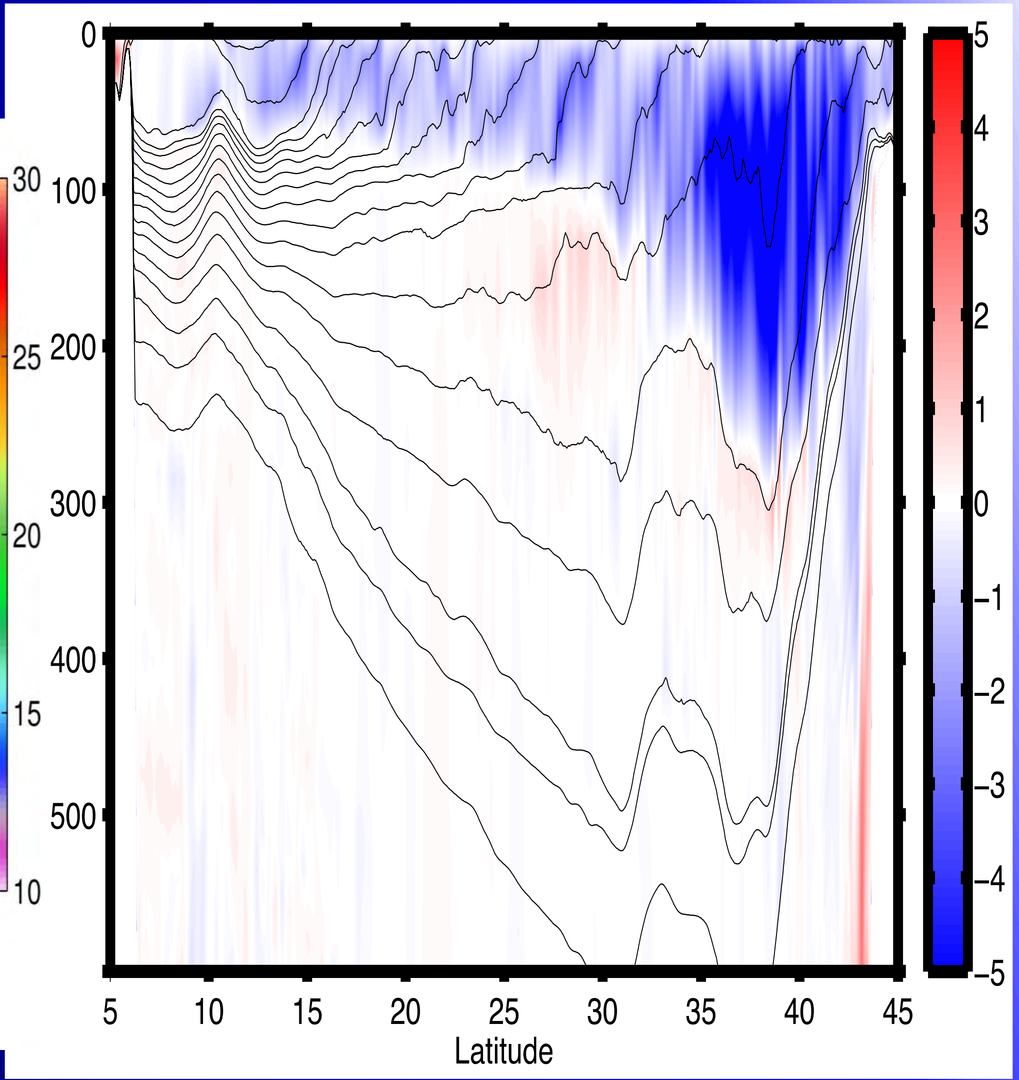


01 (January)

Temperature/mixed layer depth

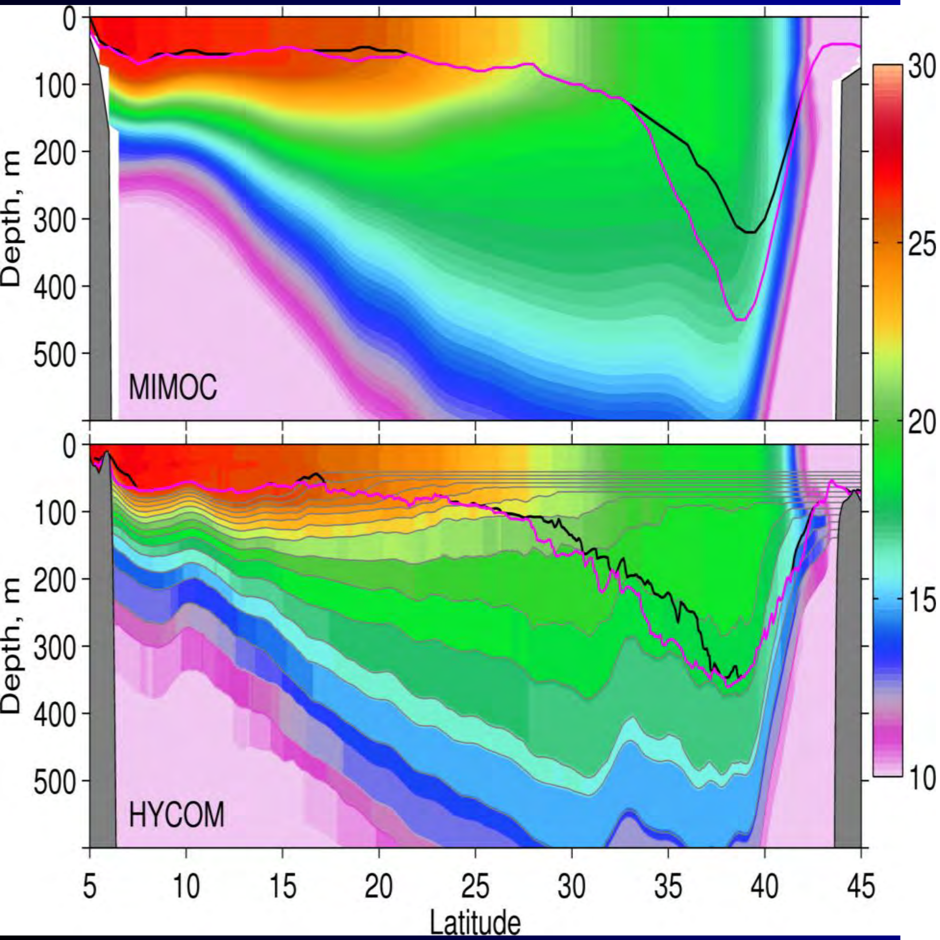


Diapycnal transformation

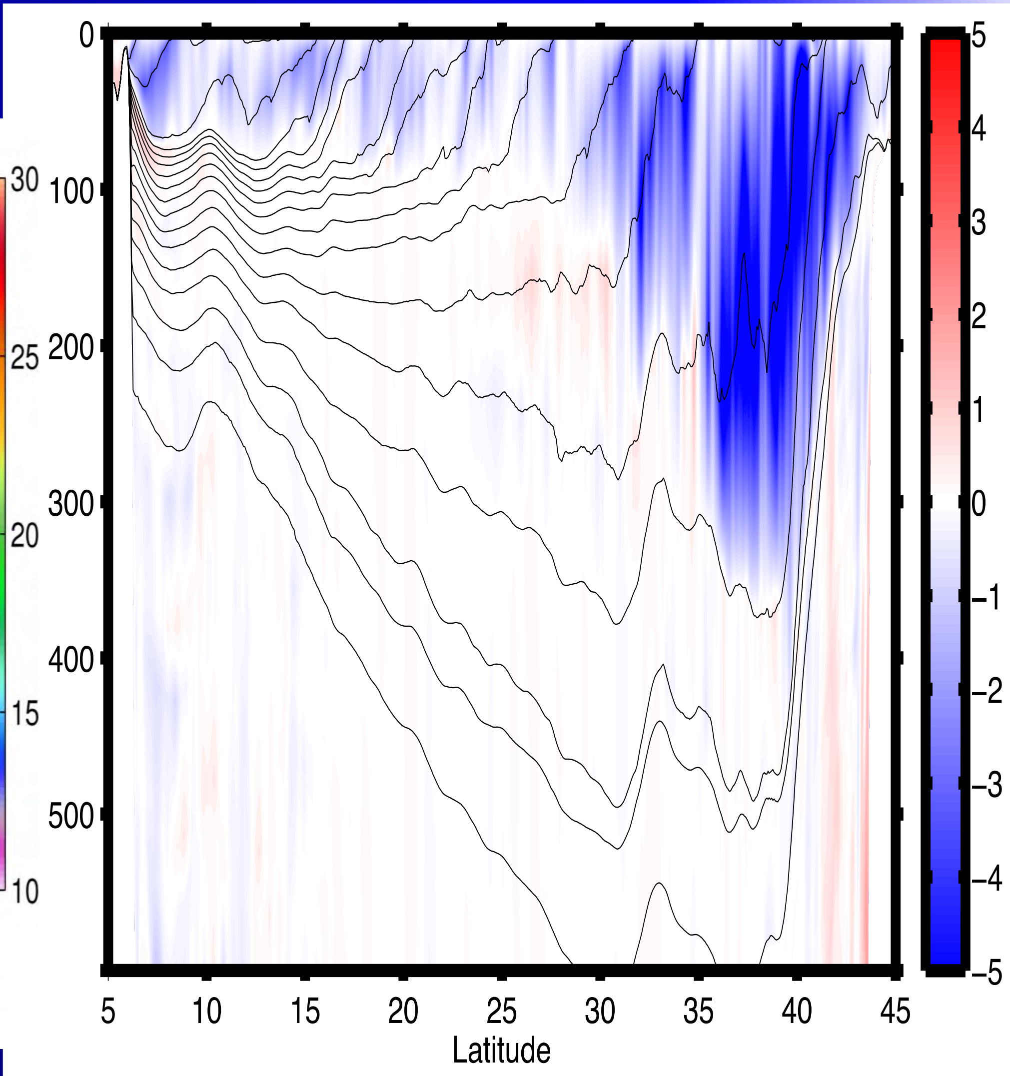


02…strongest cooling in February

Temperature/mixed layer depth

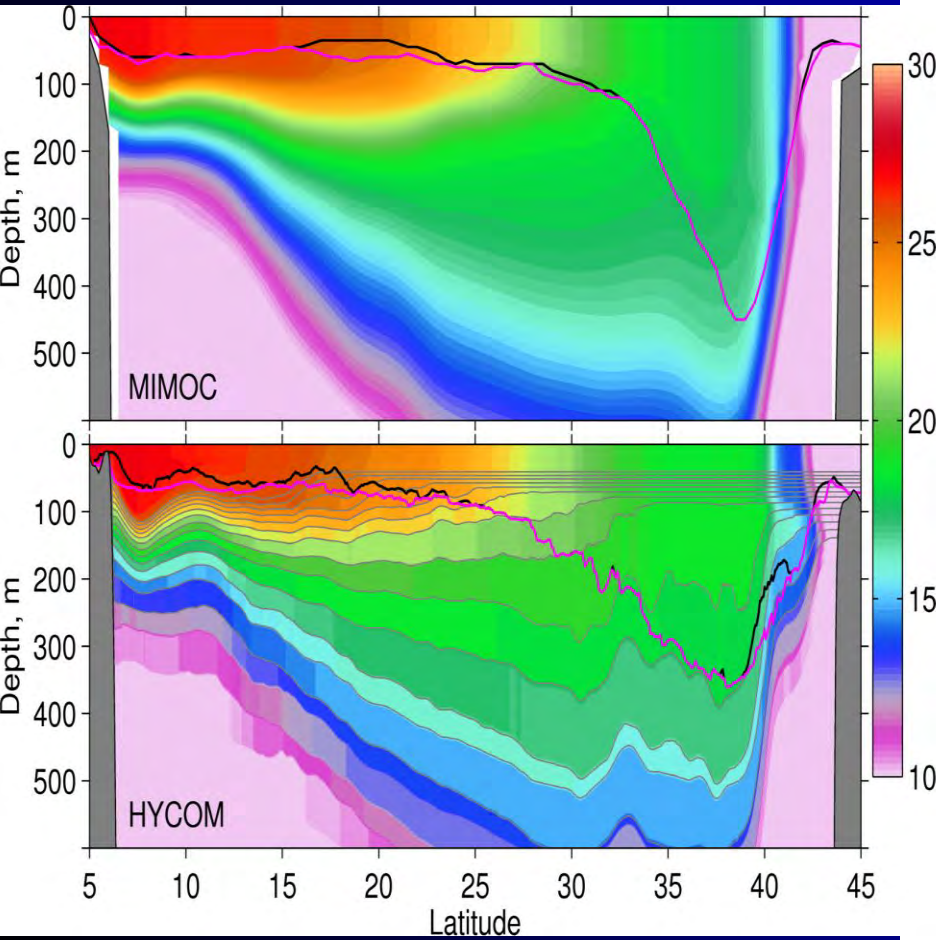


Diapycnal transformation

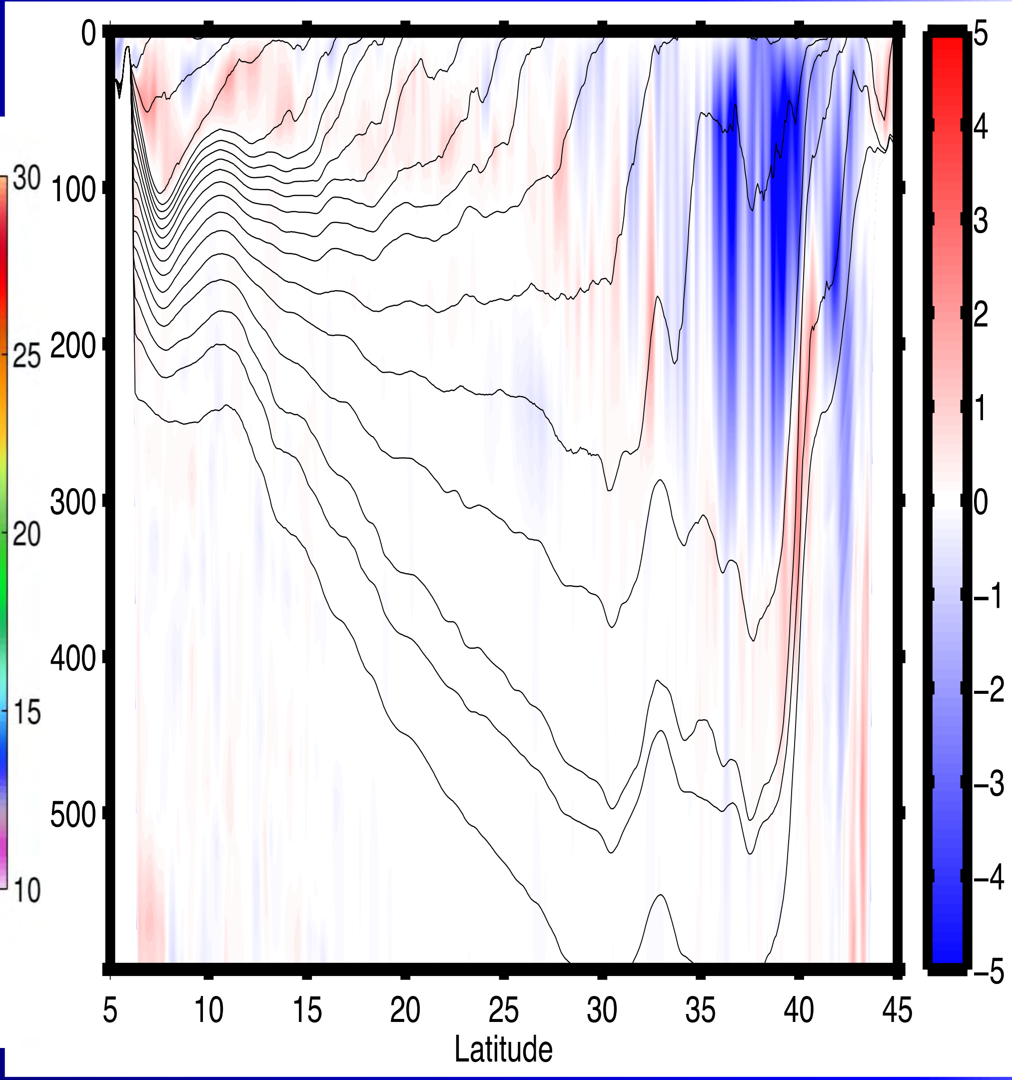


03

Temperature/mixed layer depth



Diapycnal transformation

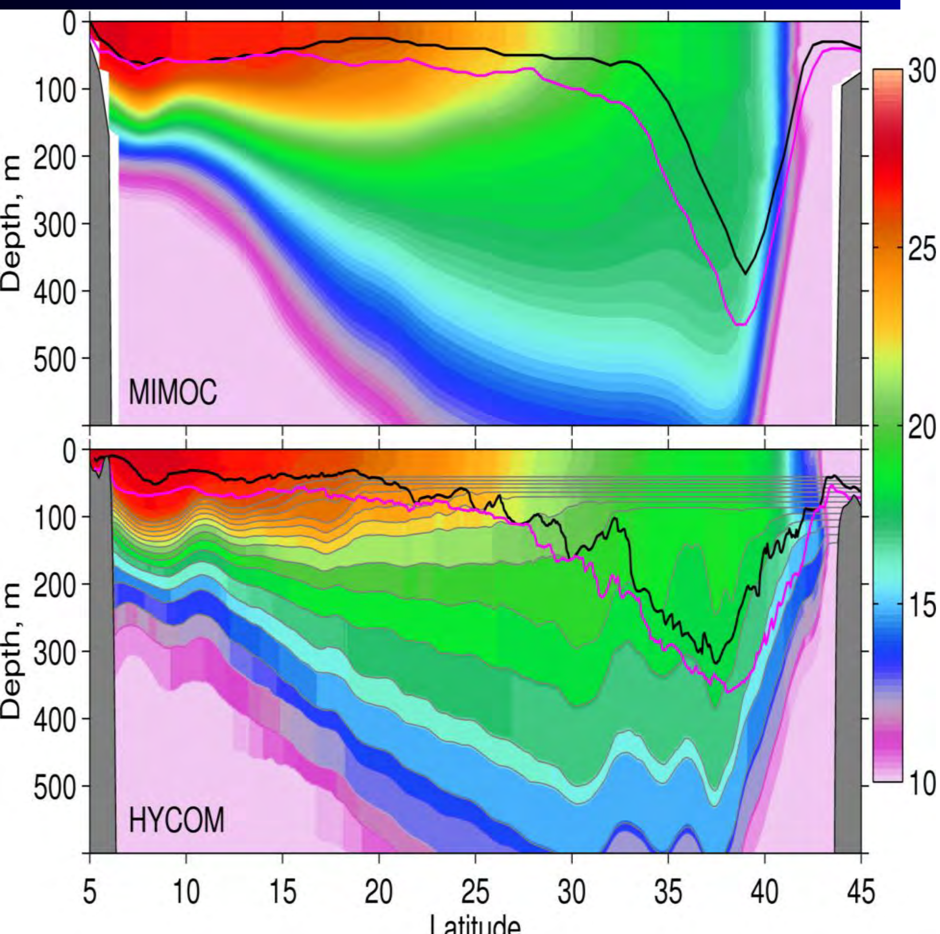


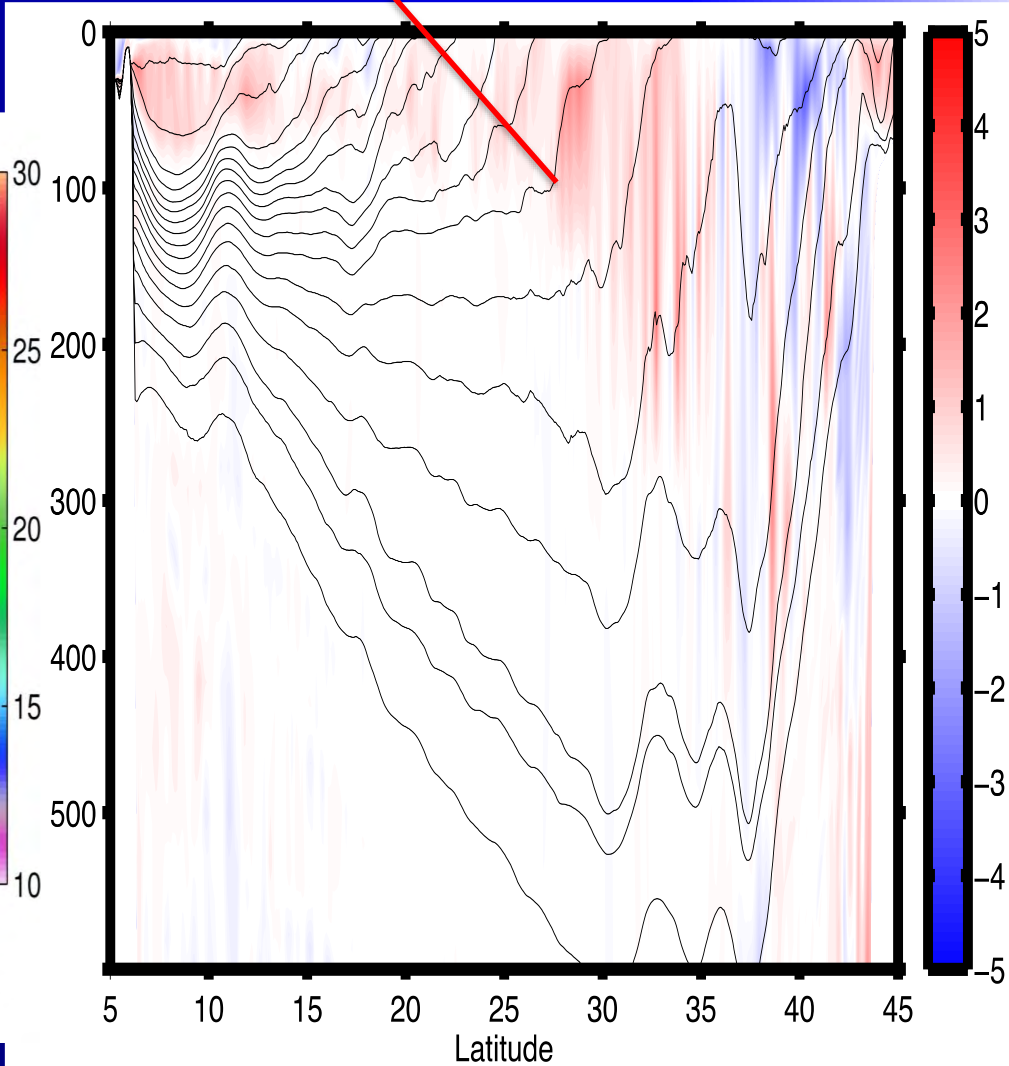
04

restratification where isopycnals slope steeply: horizontal eddy mixing + parameterized horizontal diffusion $\kappa = 30\ m^2\ sec^{-1}$

Diapycnal transformation

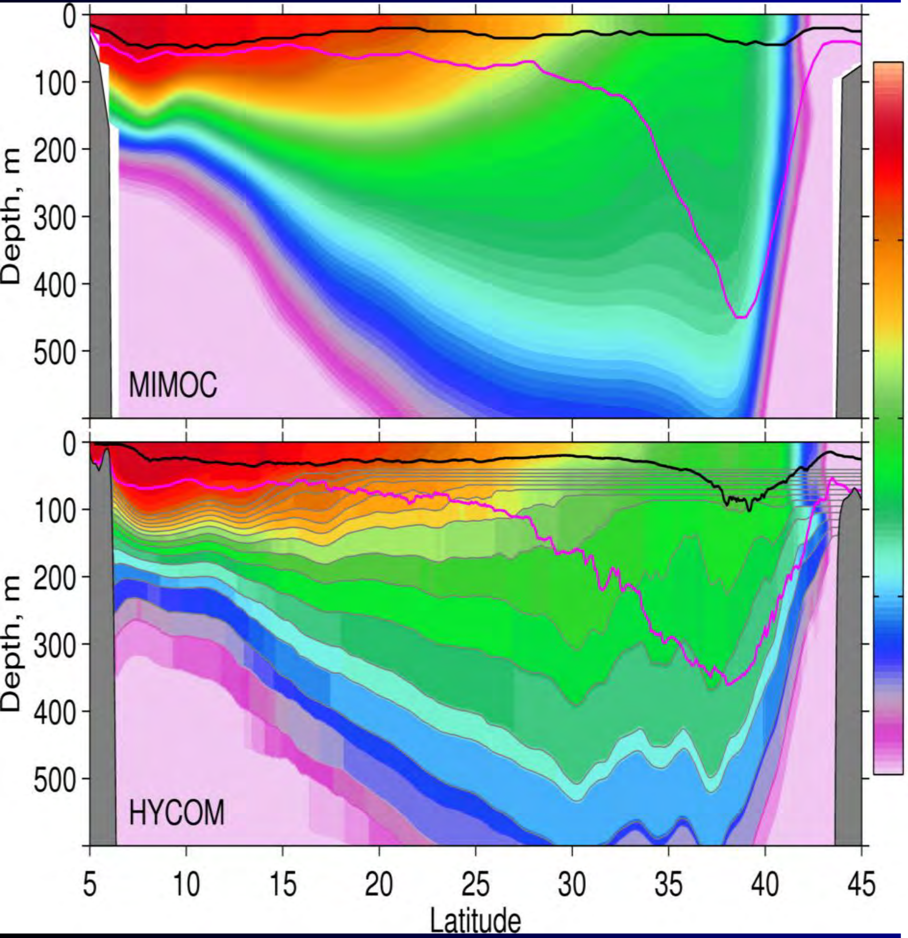
Temperature/mixed layer depth



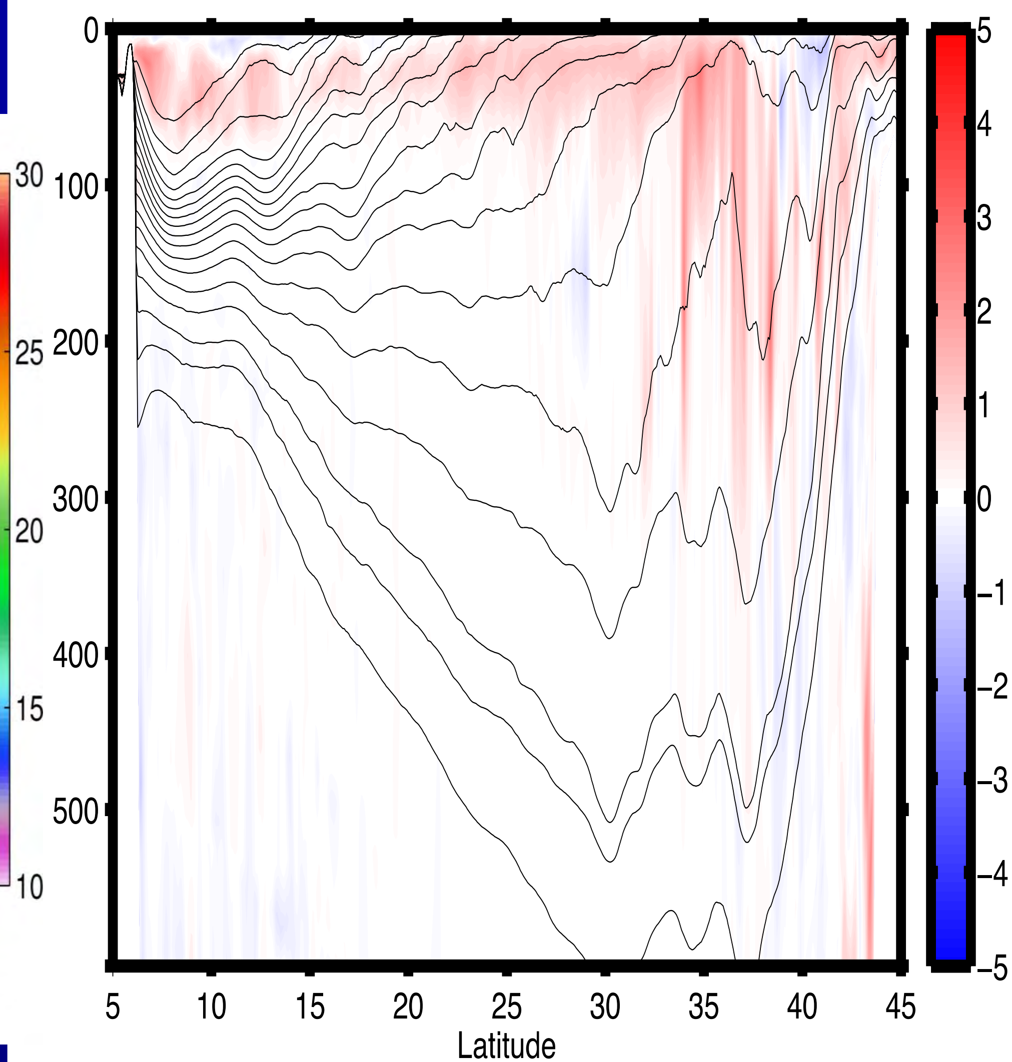


05

Temperature/mixed layer depth

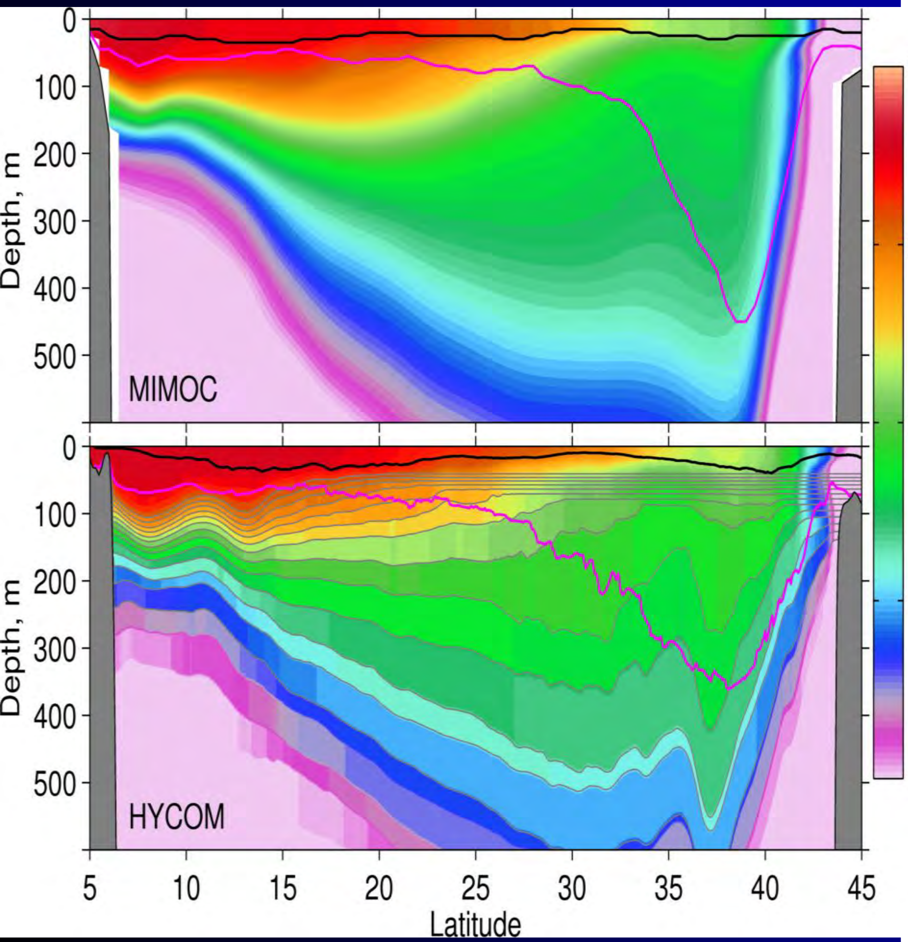


Diapycnal transformation

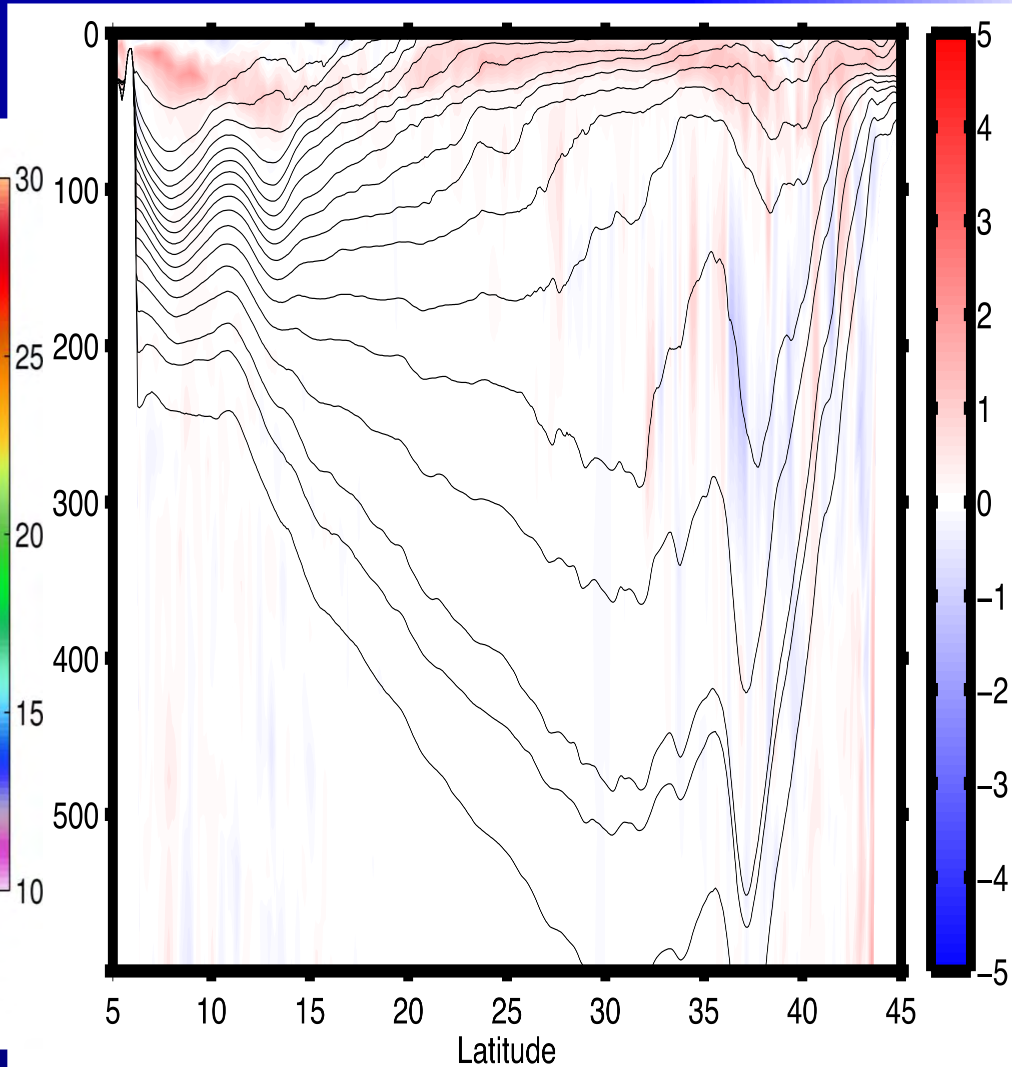


06

Temperature/mixed layer depth

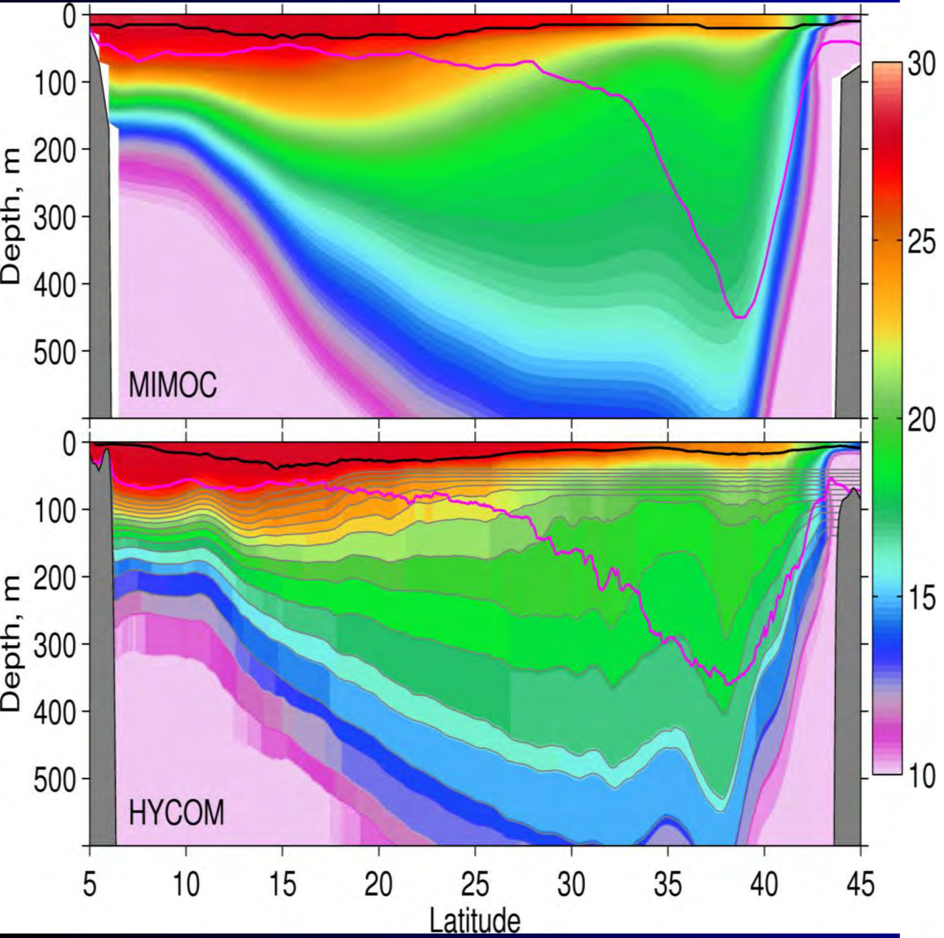


Diapycnal transformation

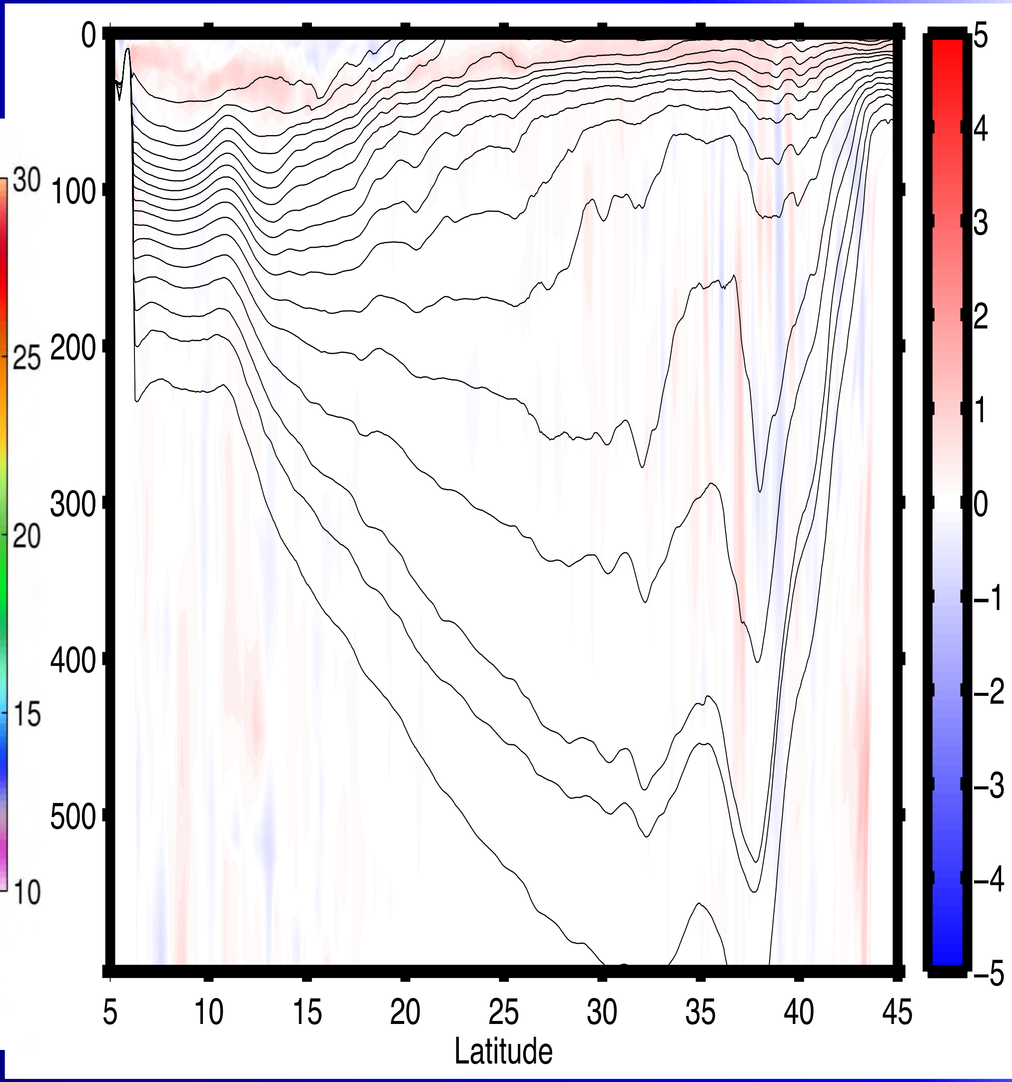


07

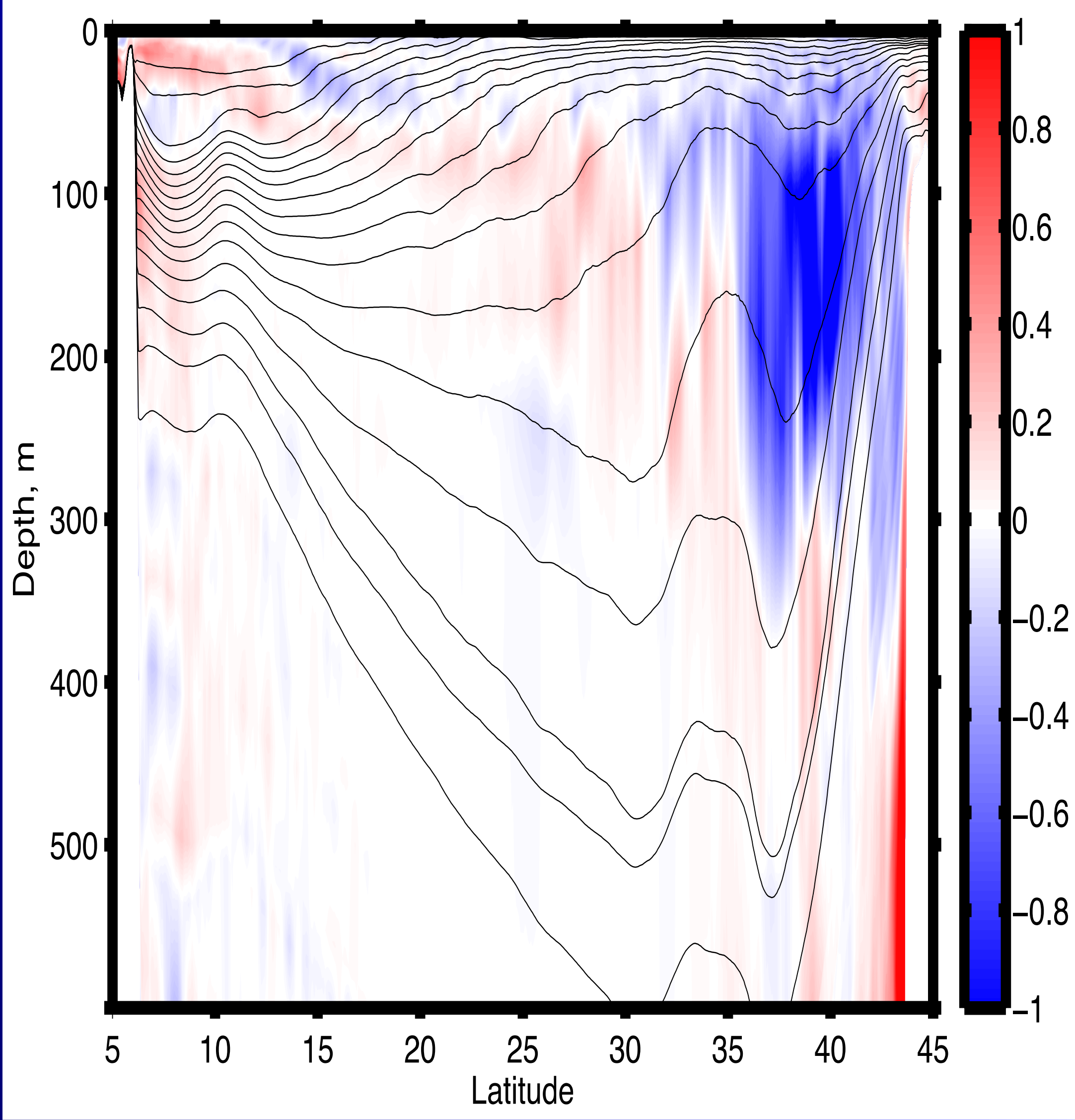
Temperature/mixed layer depth



Diapycnal transformation

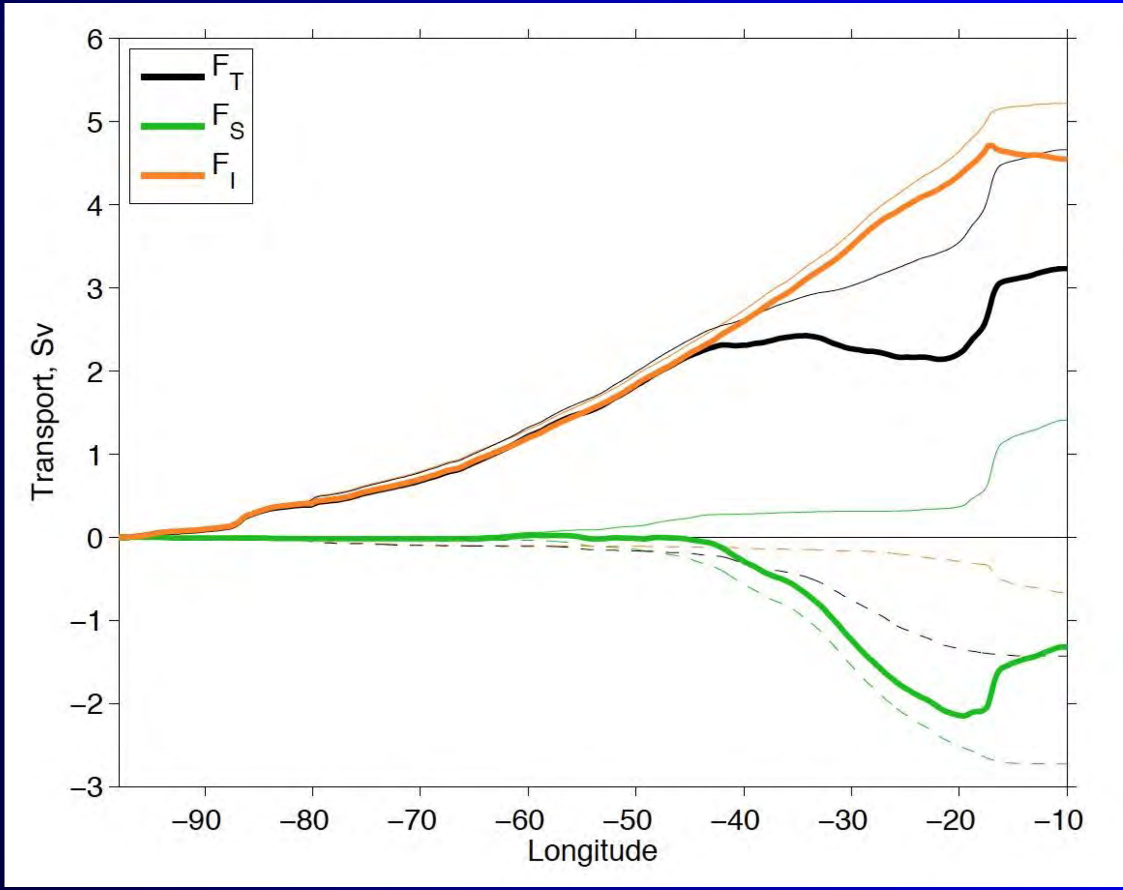


diapycnal velocity blue=down, red= up
so, blue is where cooling occurs, red
is where warming (by mixing usually)
occurs



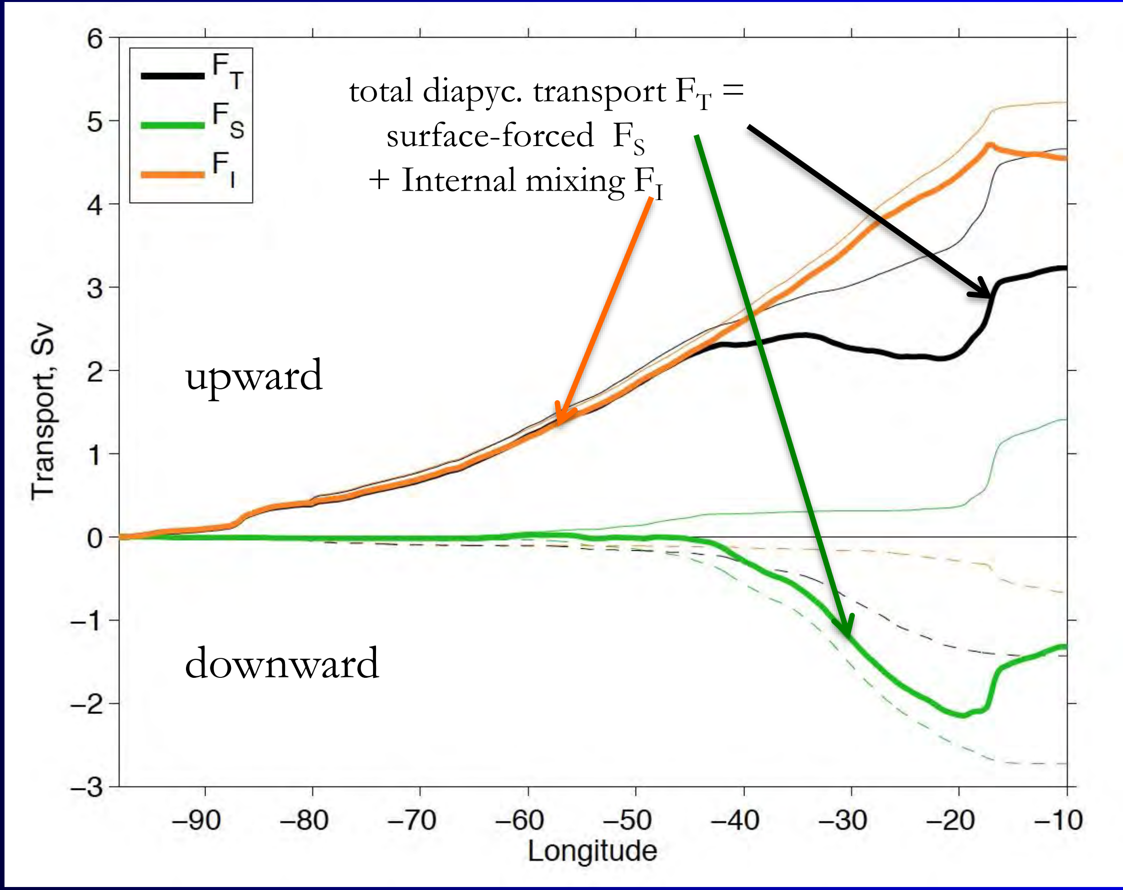
Annual mean diapycnal transformation Wd 10^{-5} m sec^{-1}

Integrate the diapycnal upwelling/downwelling between 15N and 30N, eastward across the basin



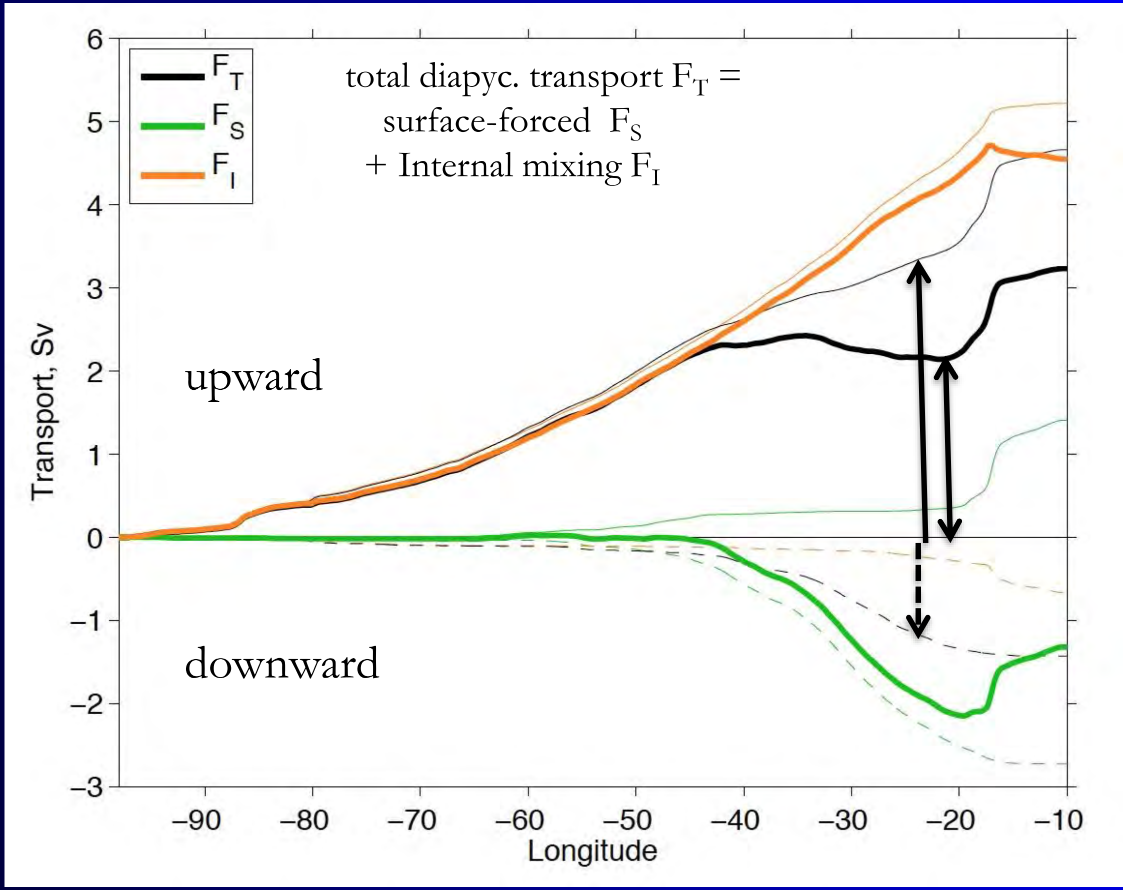
Eastward accumulation of the modeled total (FT , black, in Sv), surface-forced (FS, green), and interior mixing induced (FI , orange) transformations across σ_2 = 34.11 kg m^{-3} *integrated over the latitude band 15-30N.*

Integrate the diapycnal upwelling/downwelling between 15N and 30N, eastward across the basin



Eastward accumulation of the modeled total (FT , black), surface-forced (FS, green), and interior mixing induced (FI , orange) transformations across 2 of 34.11 kg m^{-3} for the latitude band 15-30N. Thin lines are upward (solid) and downward (dashed) contributions before summing: these express east-west overturning cells.

3-dimensional transformation is significantly stronger than zonally-integrated, two-dimensional representations of the meridional overturning streamfunction, by 50% in the southern subtropical North Atlantic and 60% in the westernsubpolar North Atlantic.



The zonal integrated Wd (to 25W) = 2.1 Sv is 3.3 Sv upward minus
1.2 Sv downward
This is ~ 50% larger overturning than seen in AMOC streamfunction

Eastward accumulation of the modeled total (FT , black), surface-forced (FS, green), and interior mixing induced (FI , orange) transformations across 2 of 34.11 kg m^{-3} for the latitude band 15-30N. Thin lines are upward (solid) and downward (dashed) contributions before summing: these express east-west overturning cells.

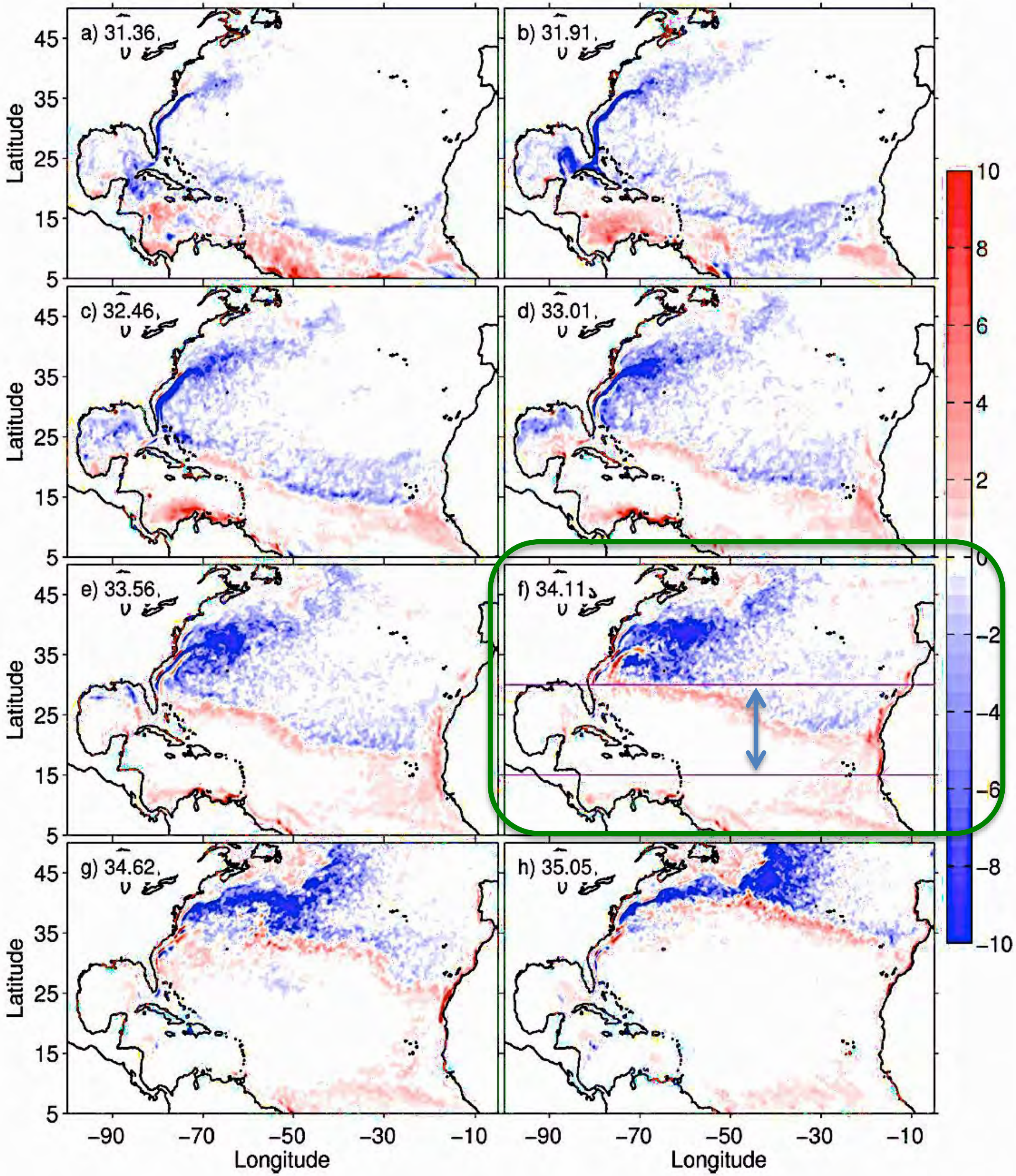
Total diapycnal velocity, Wd

annual mean

blue = down (cooling/evap))

red = up (warming, precip)

Panels a –h at densities marked on AMOC stream function, slide 4 with red letters



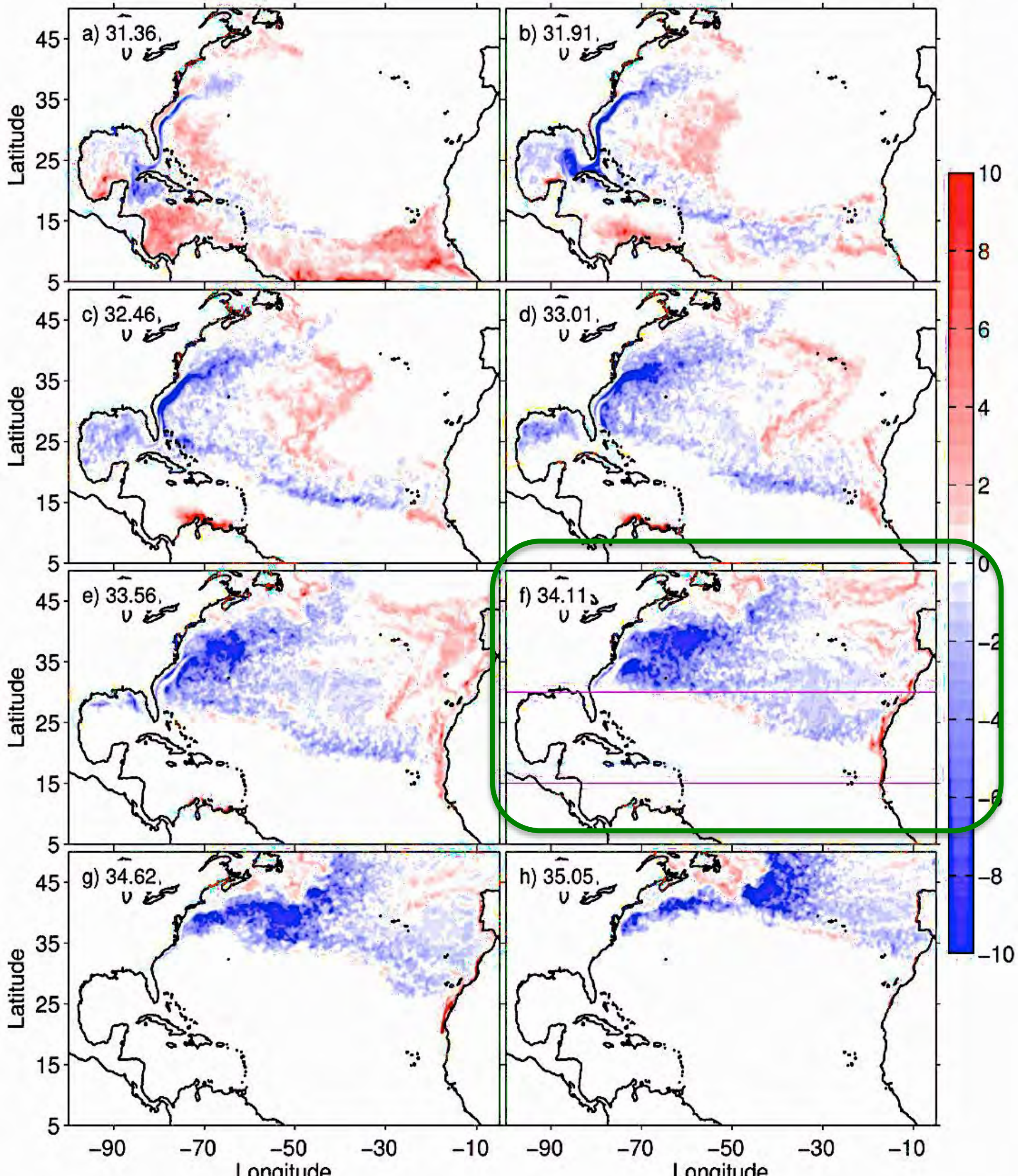
25.0

25.7

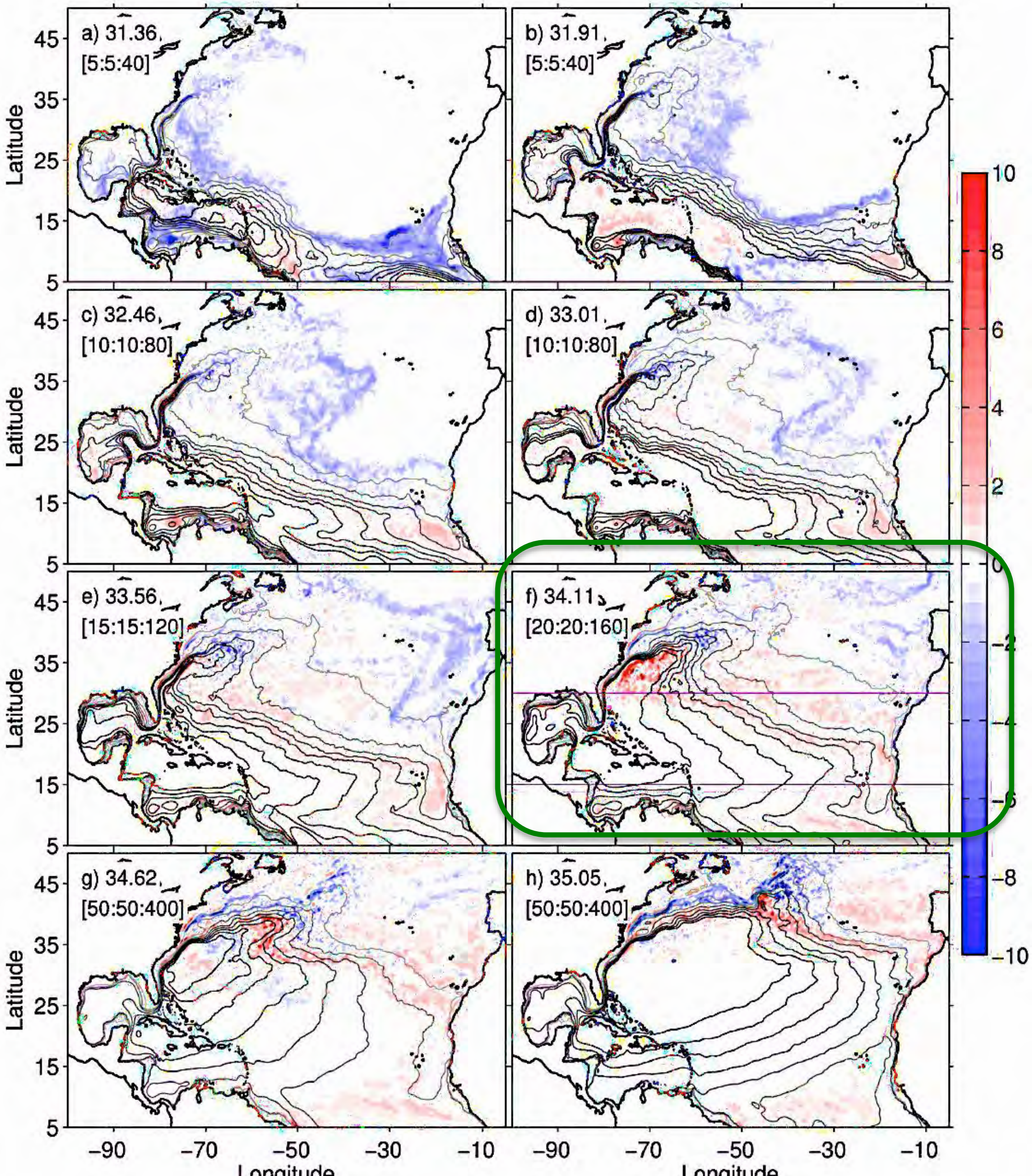
26.5

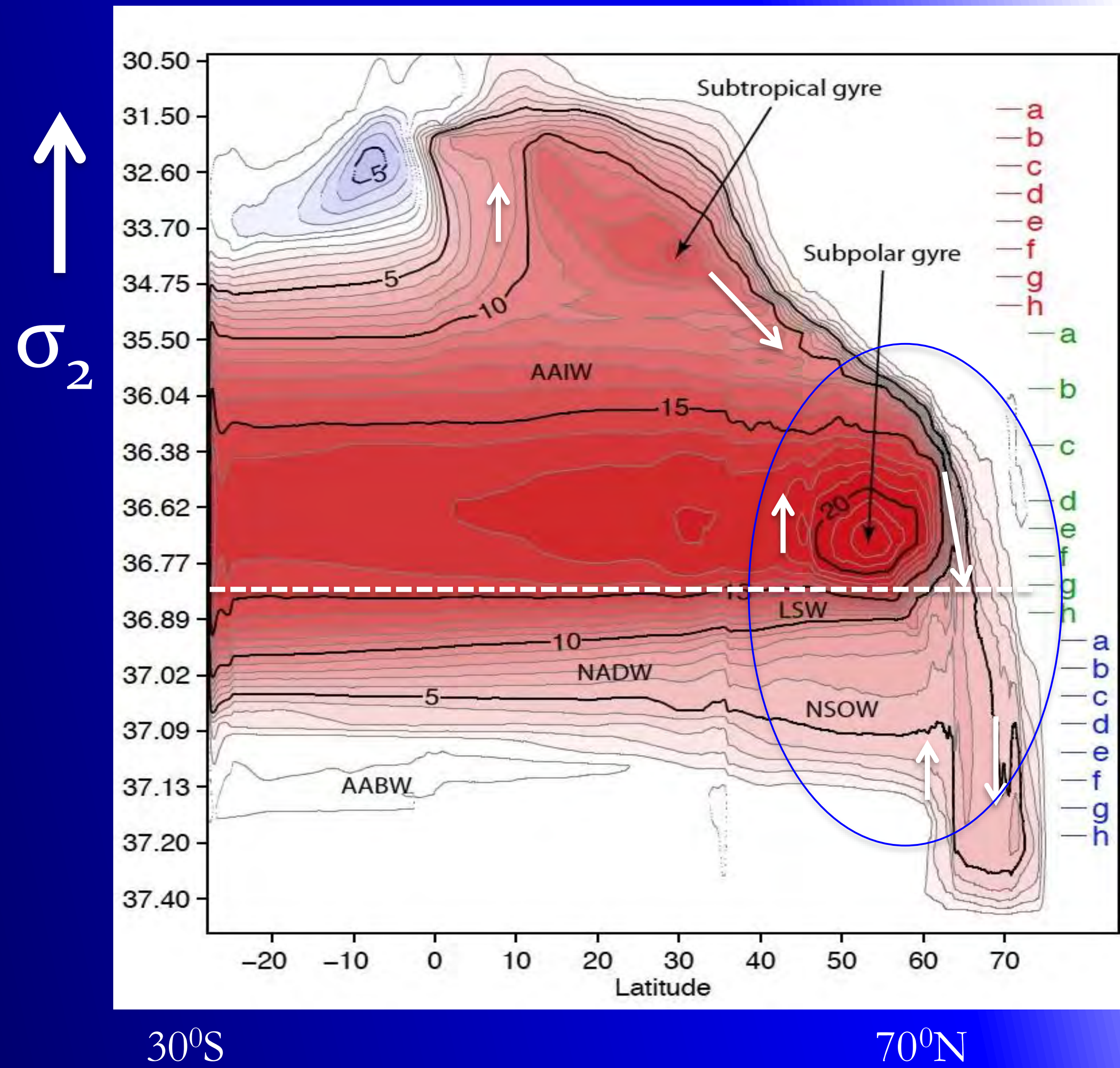
Surface forced Wd

by air/sea buoyancy flux



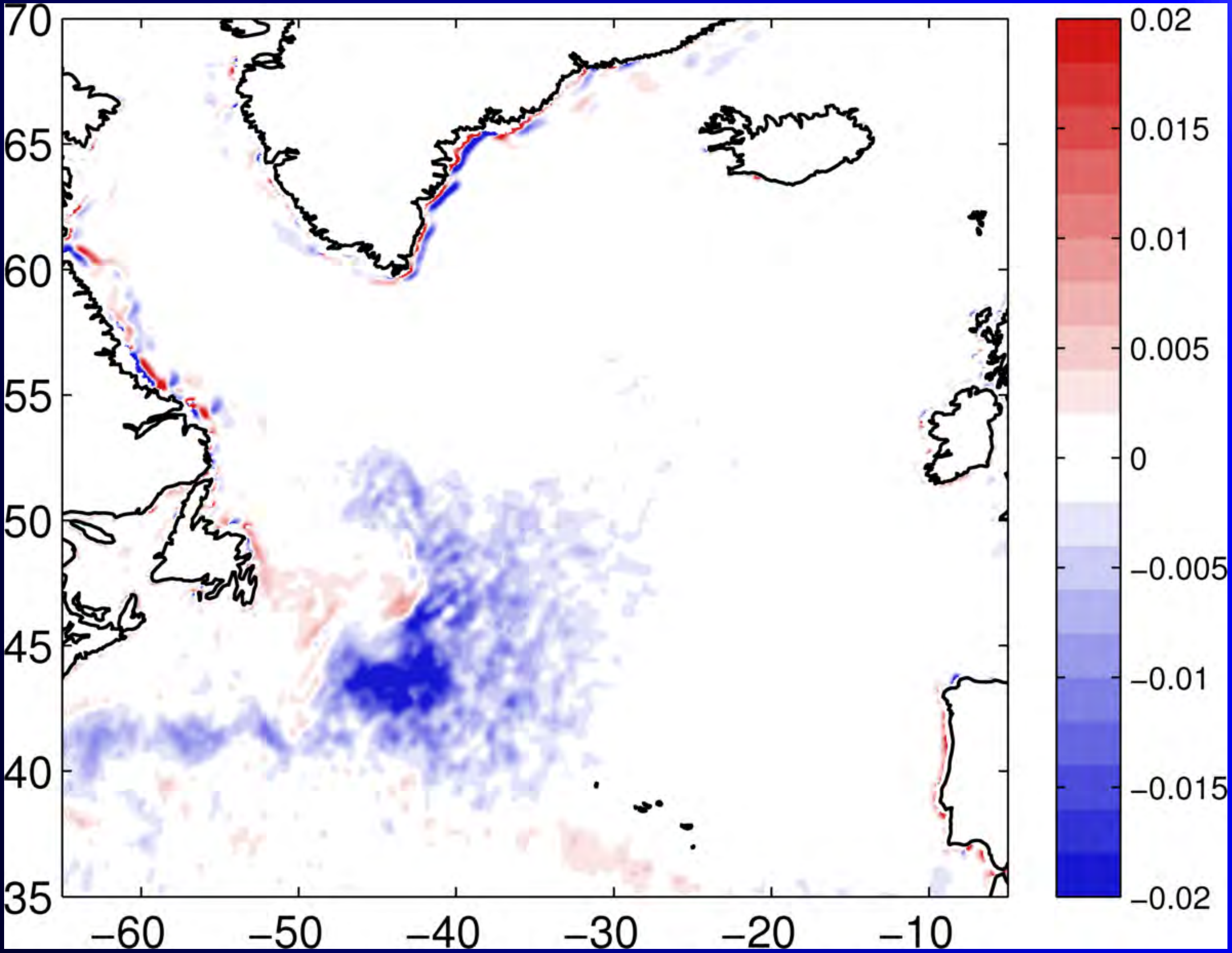
Wd due to sub-mixed layer mixing



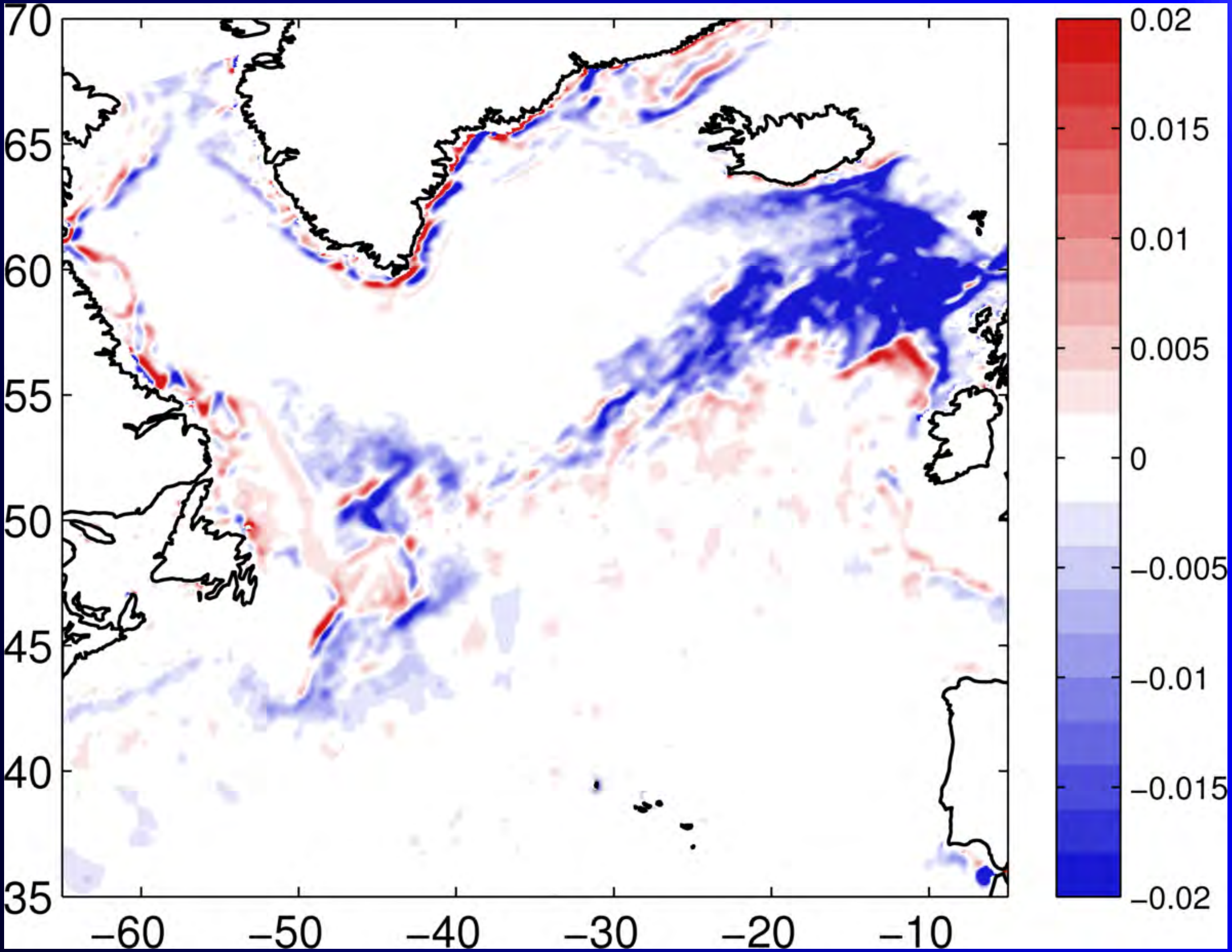


vertical velocity shows diapycnal density mixing/advection at each latitude

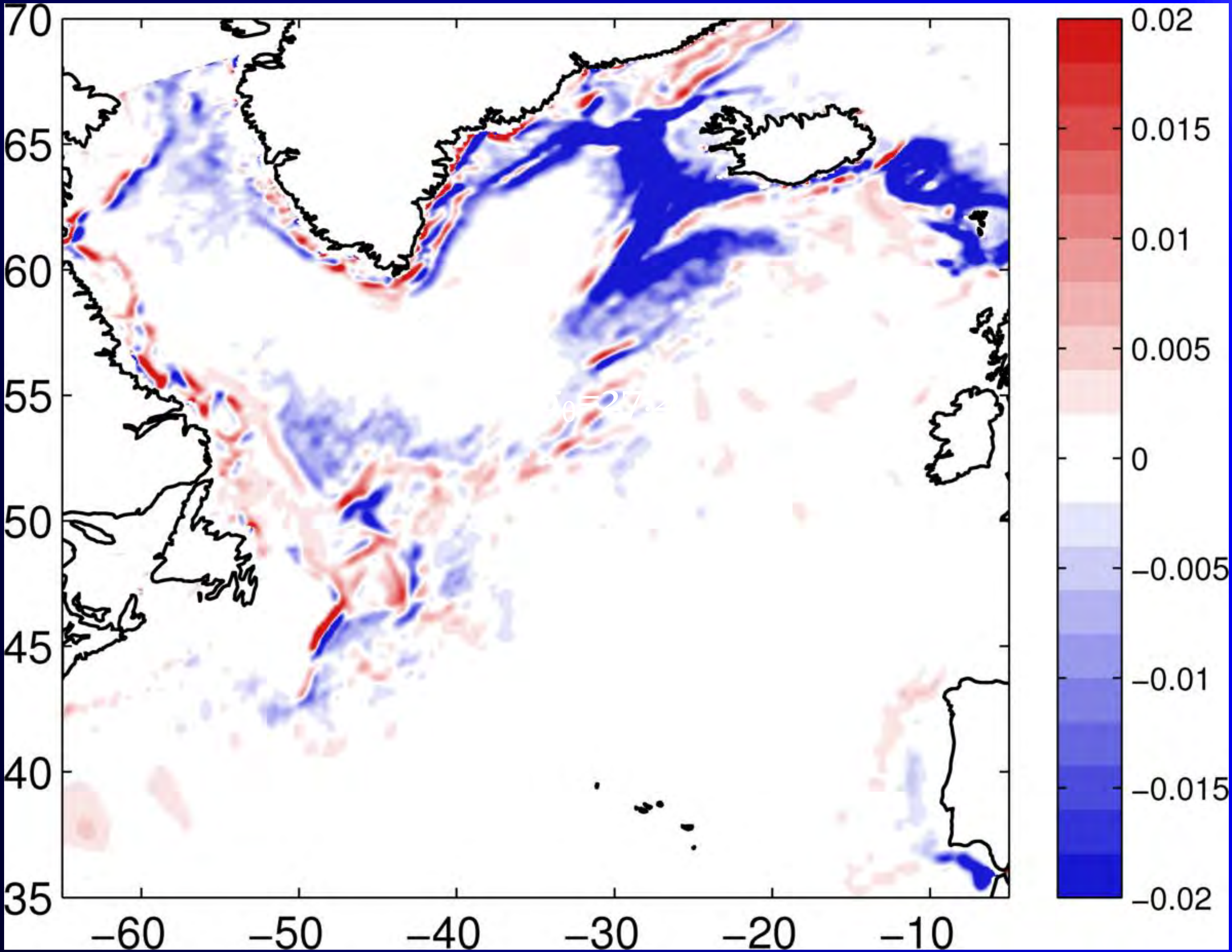
Subpolar gyre: diapycnal velocity Wd on σ_θ=26.5 (blue=downward; red=upward



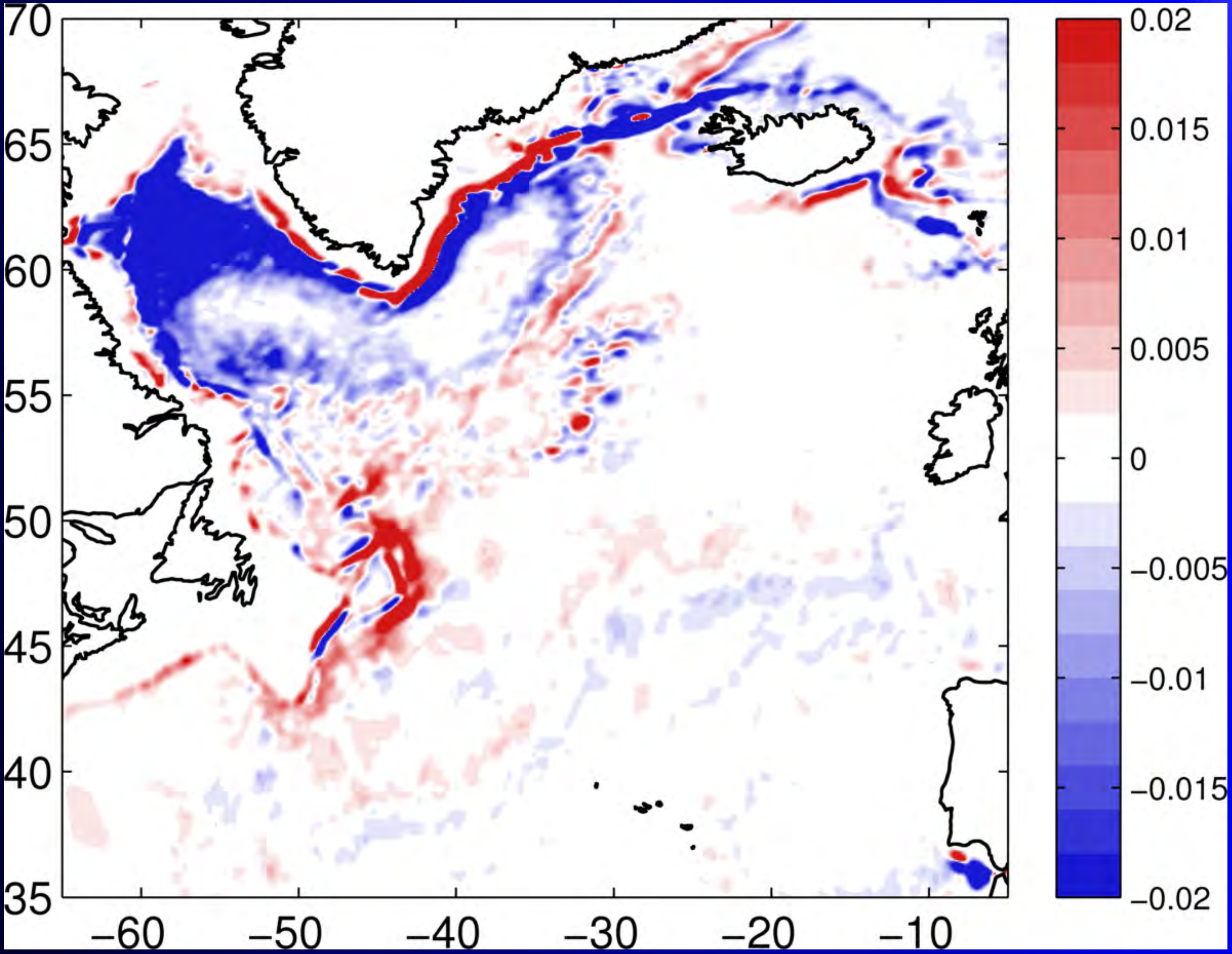
σ_θ=27.25



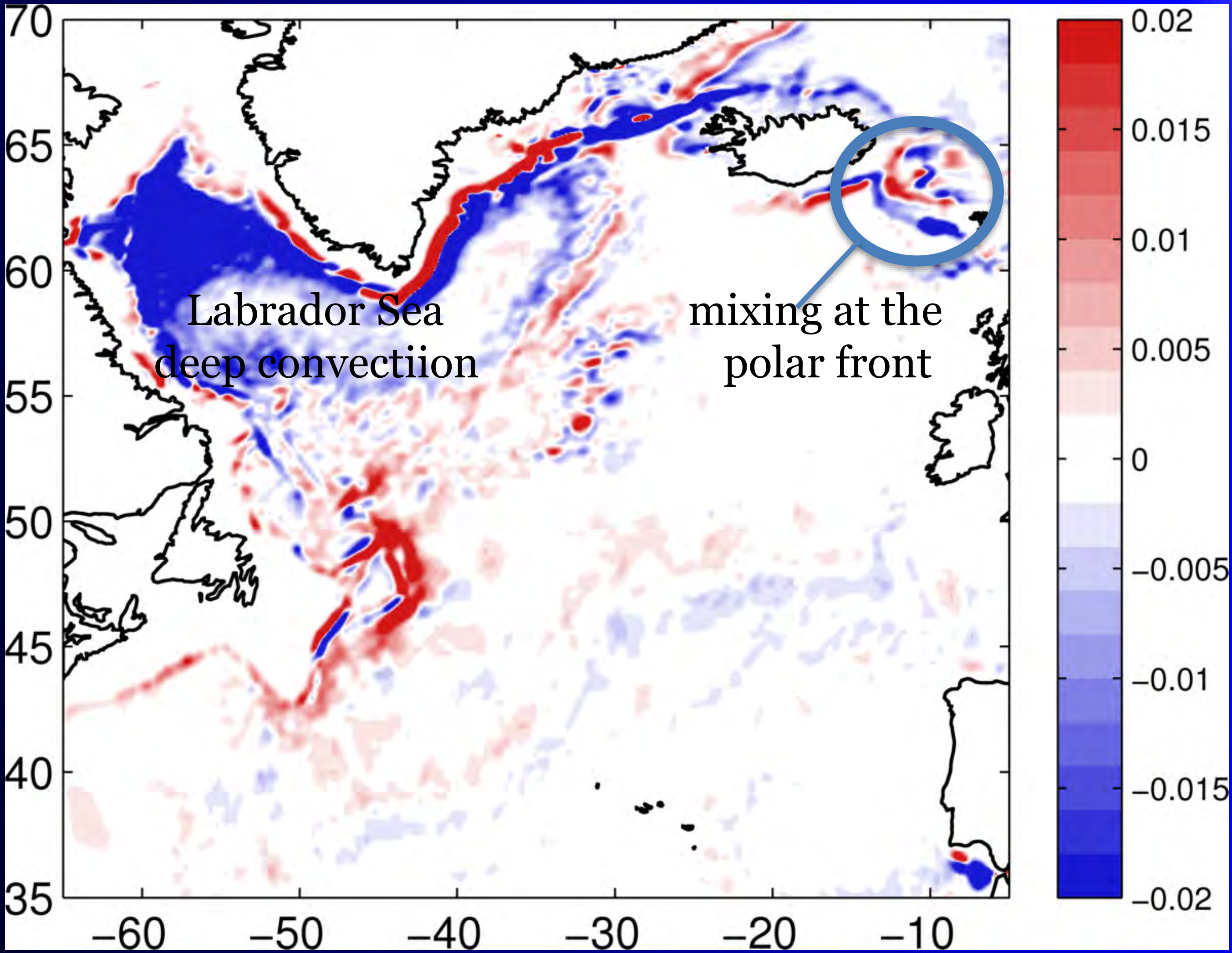
σ_θ=27.45



σ_θ=27.68

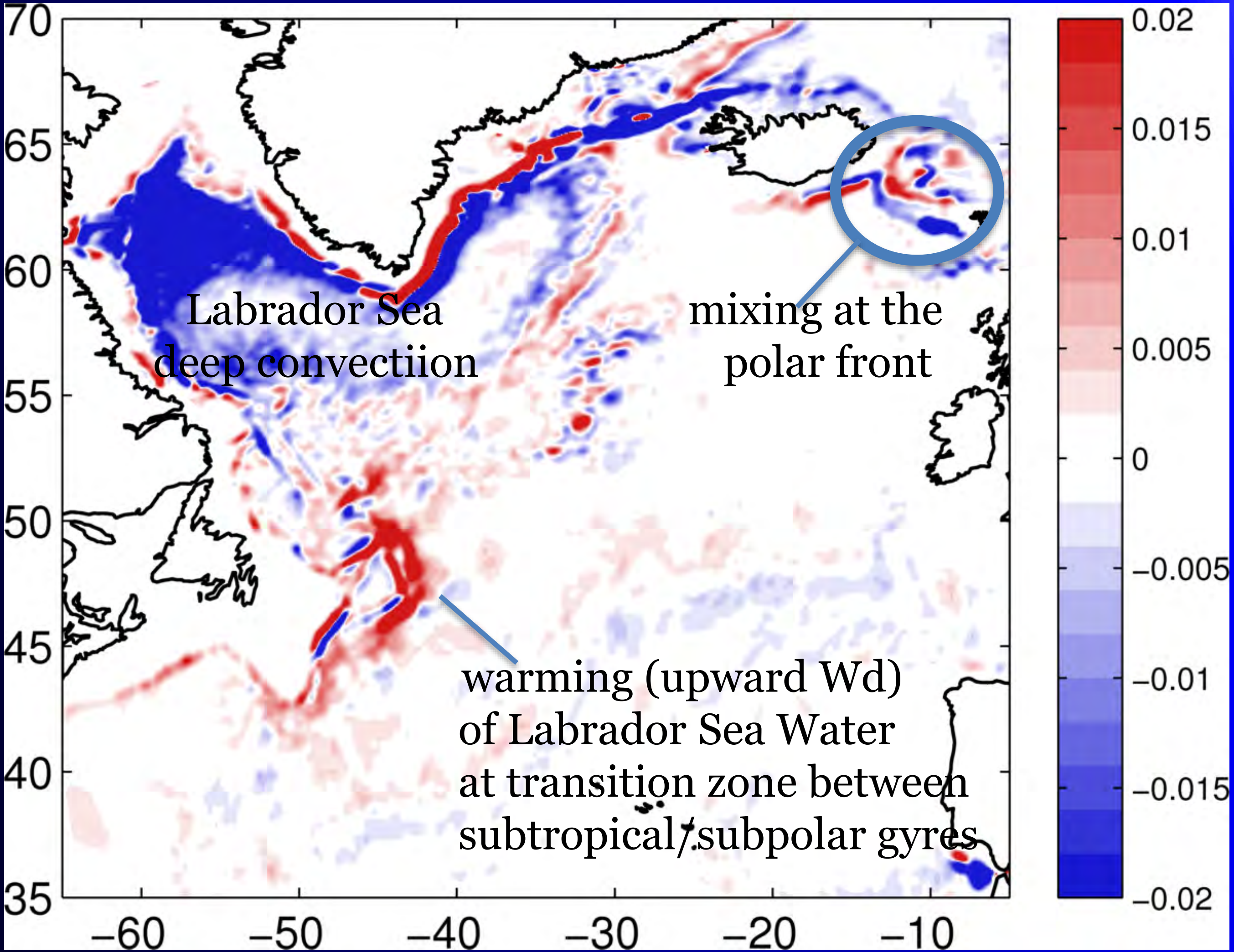


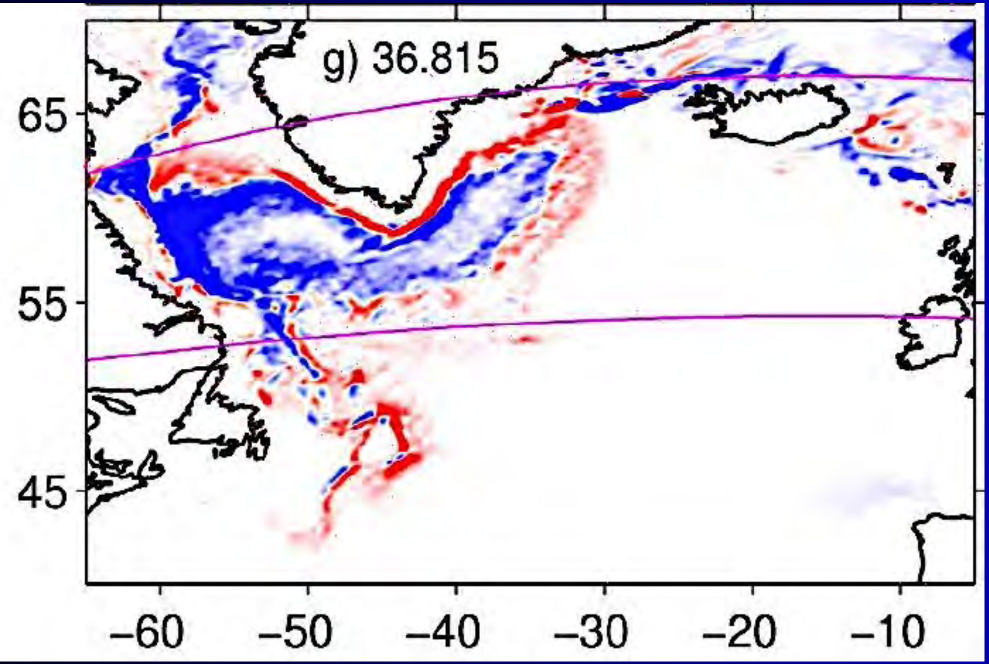
σ_θ=27.68



Wd (10^{-3} m sec^{-1})

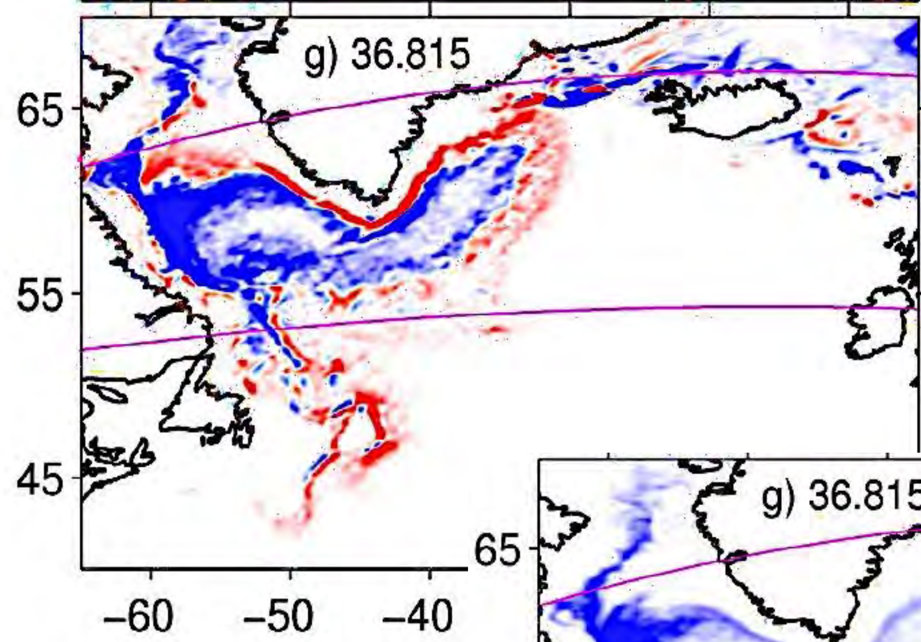
σ_θ=27.68





Labrador Sea Water,
Irminger Basin

blue: downward W_d
red: upward W_d

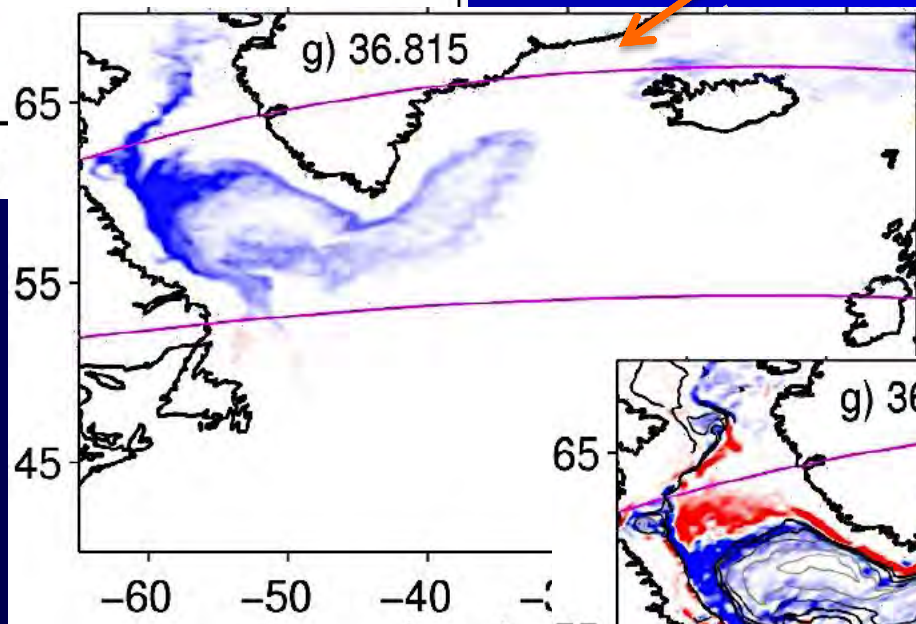


Total diapycnal velocity =

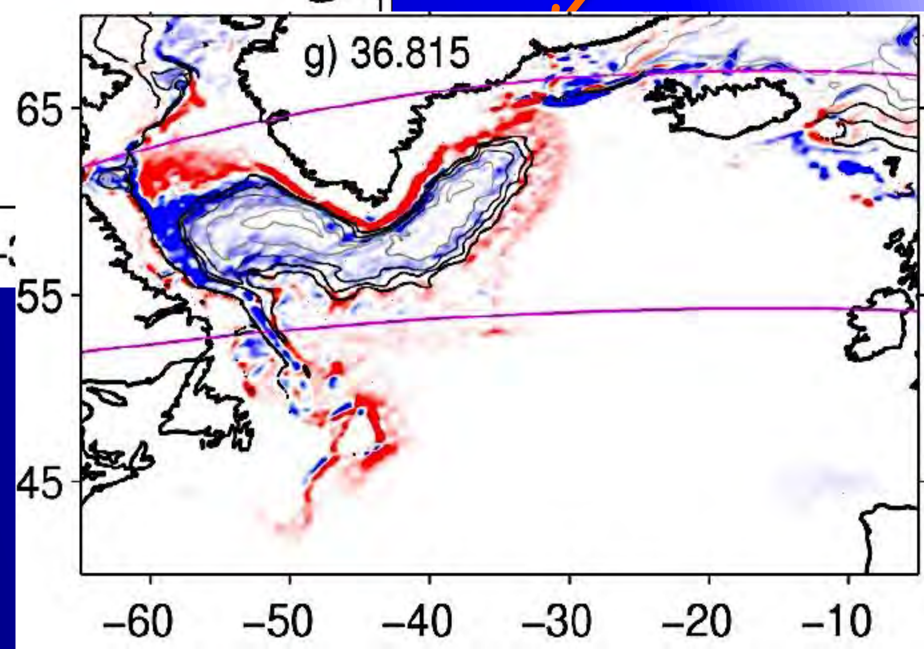
red = upward

blue = downward

part induced by air-sea flux



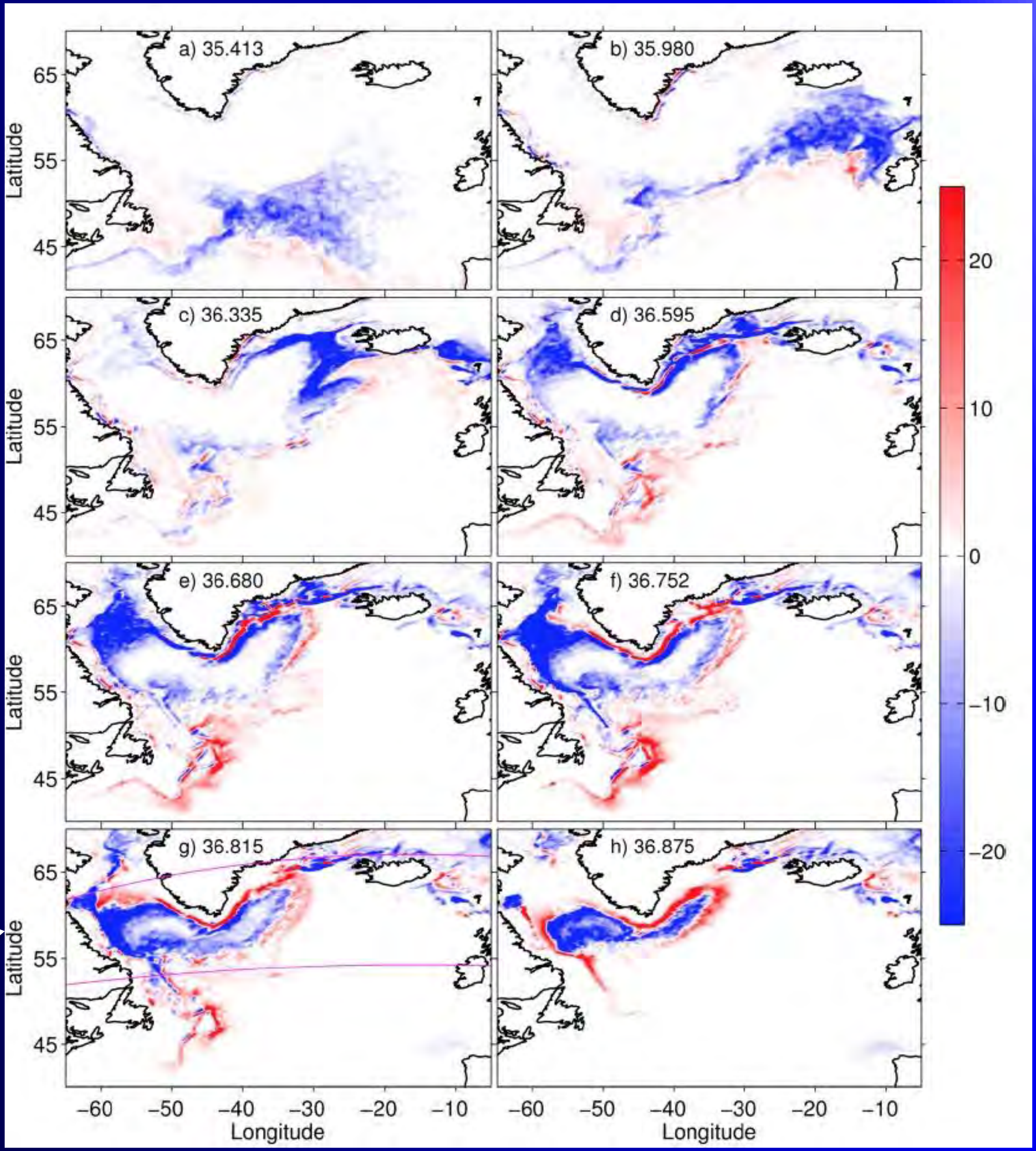
+ part due to internal mixing



Subpolar Atlantic

Total mean diapycnal velocity (10^{-6} m sec^{-1})

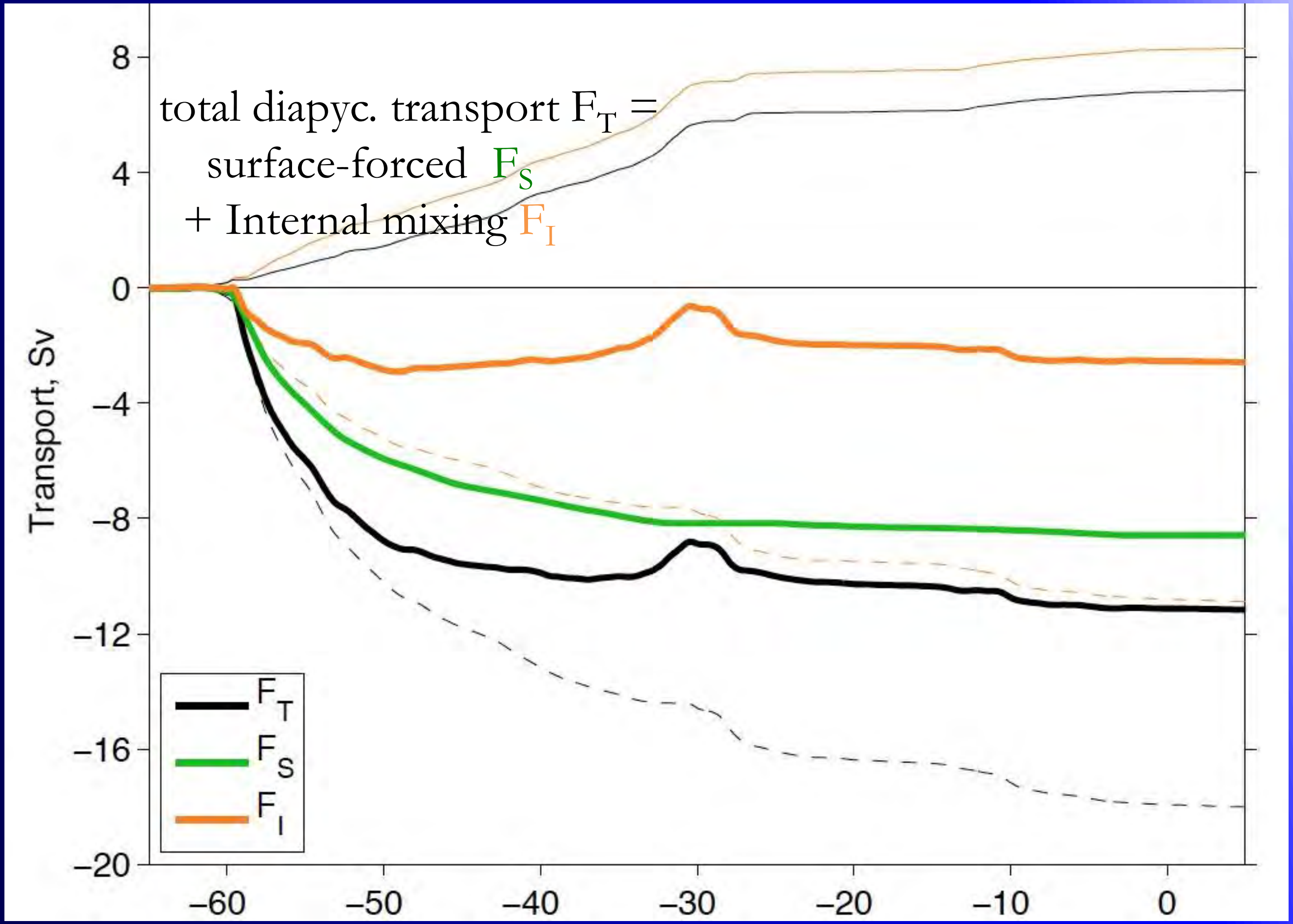
36.815



Integrate the diapycnal upwelling/downwelling between 15N and 30N, eastward across the basin

thin lines show the upwelling (solid) and downwelling (dashed) components of the accumulated diapycnal velocity Wd

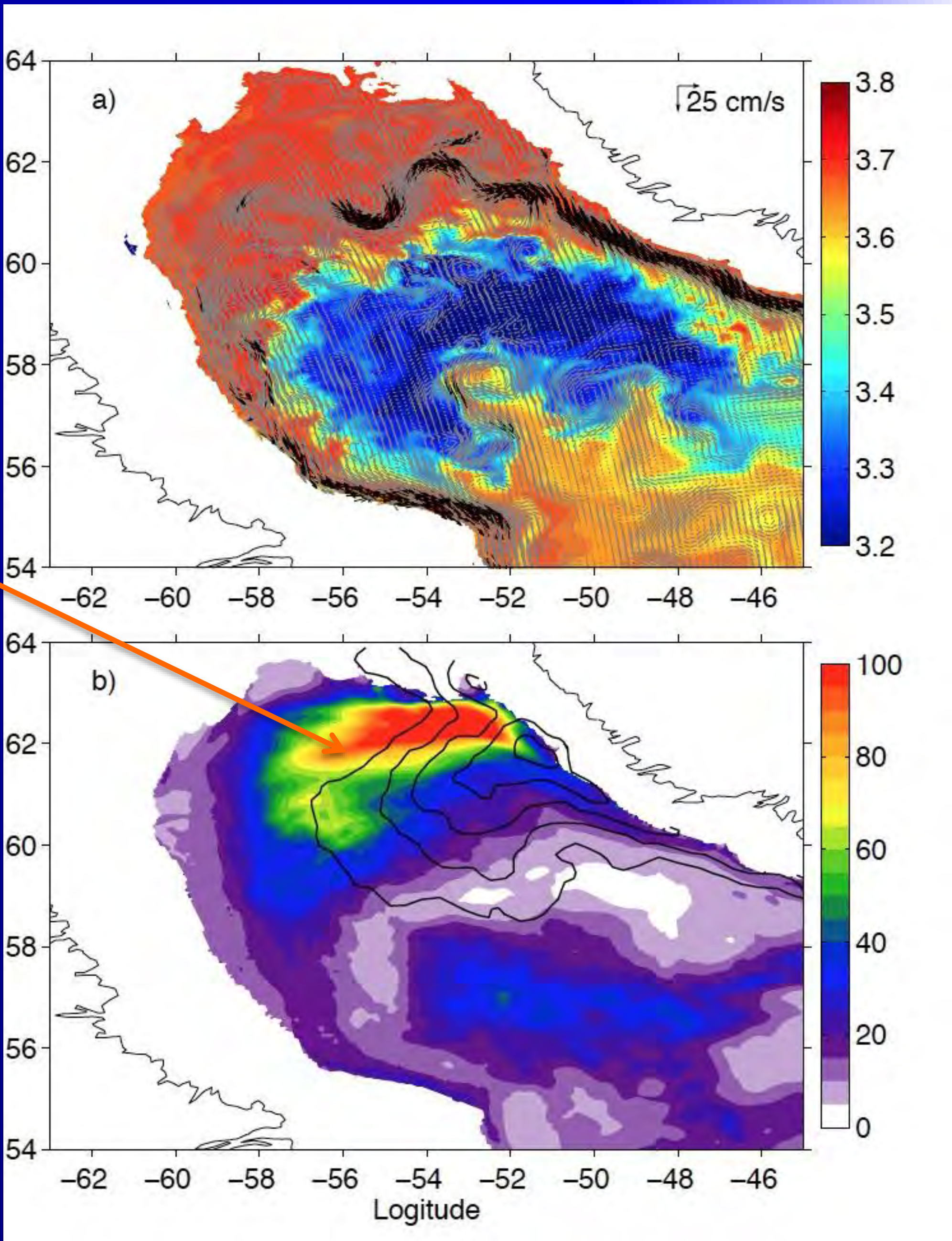
'Ribbons' of Wd at fronts and boundary currents and spring restratification dominate the overturning.



Across the basin, within these two 'latitude' there are ~12 Sv downward transformation (surface forcing contributes ~9Sv). Within the Labrador Sea and Irminger Sea (west of 30W), downward tranformation is about 14 Sv and upward transformation is 6 Sv . 3D upwelling/downwelling is 60% greater than in AMOC streamfunction ψ_σ .

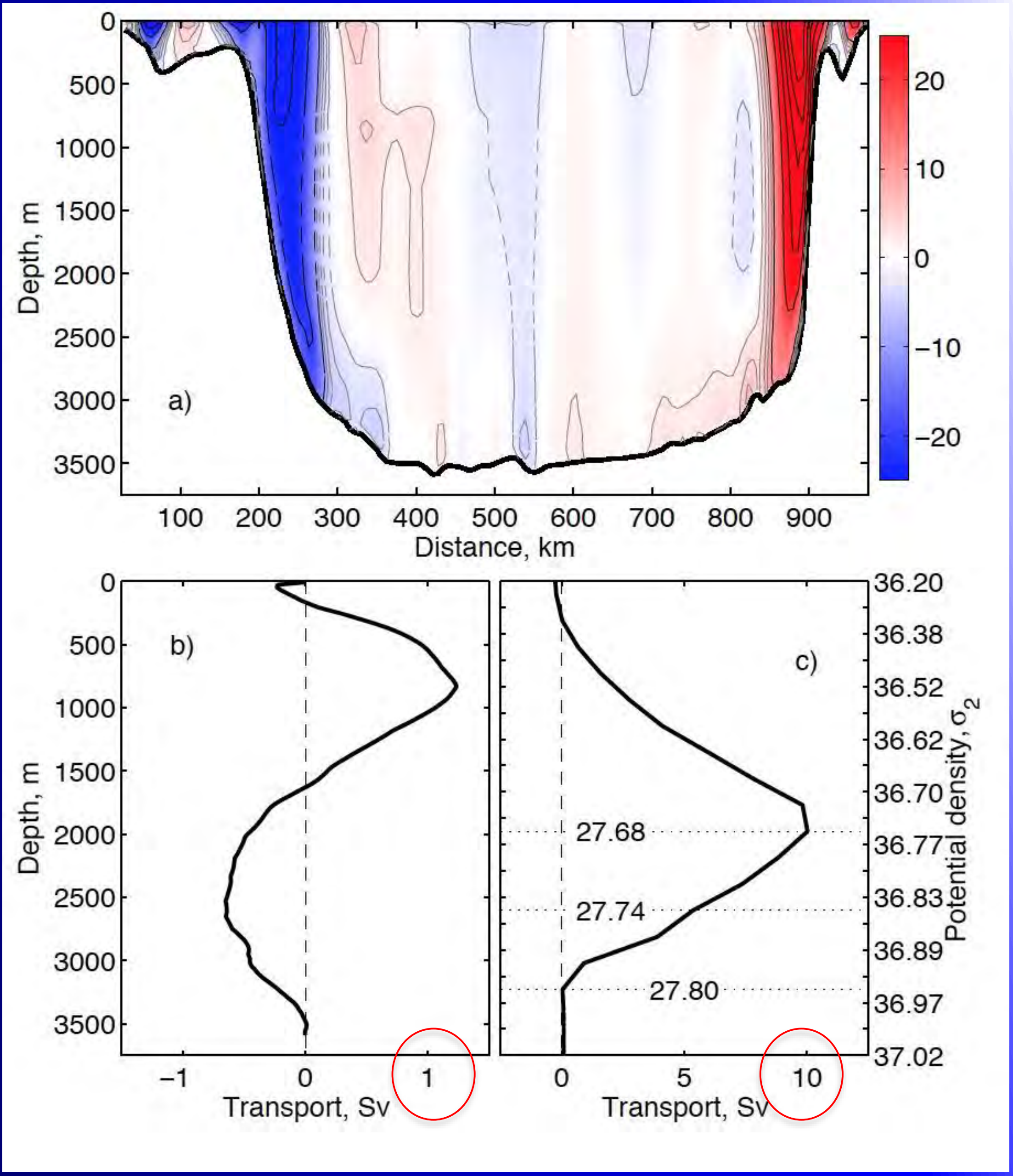
snapshot of 800m depth pot. temperature in late winter: Labrador Sea. Restratfication (upward Wd, warming) by mesoscale eddy mixing eddies from the west Greenland boundary current and from mid-basin instability

Surface eddy kinetic energy, annual mean (HYCOM model in colors; observed in black contours) (*Lilly et al., Prog In Oceanogr. 2003)*

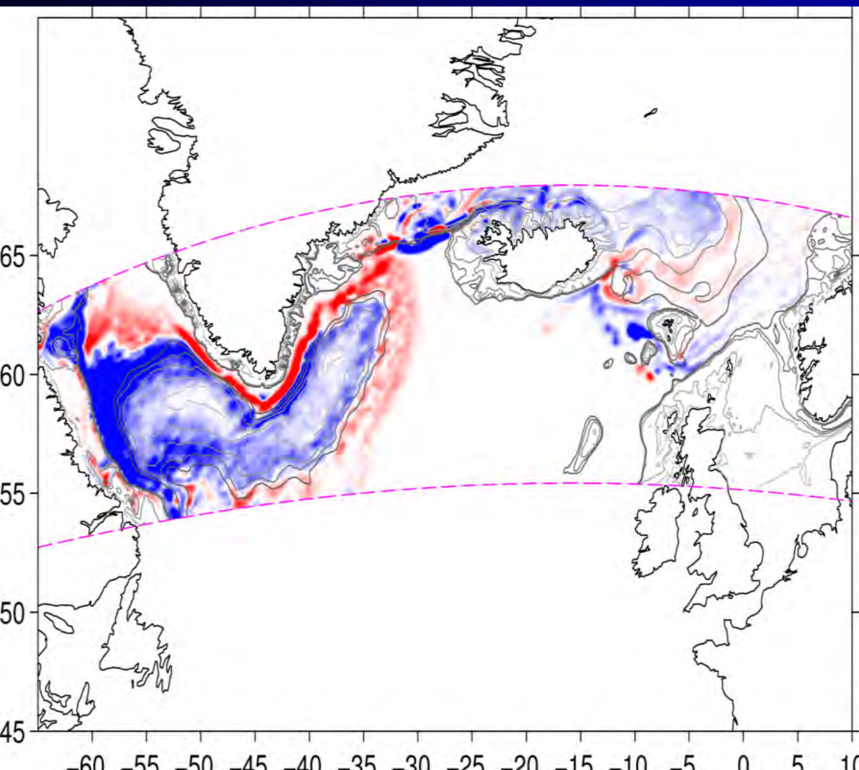


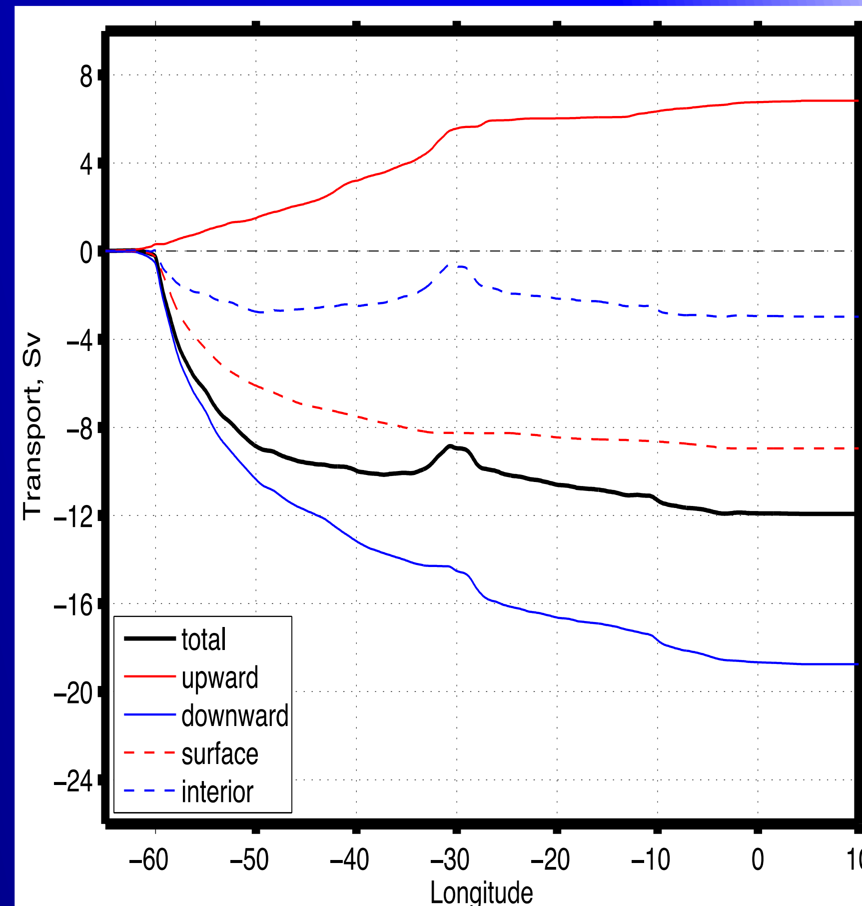
normal velocity section across Labrador Sea (WOCE AR7W)

Section integrated overturning stream-functions: ψ_z and ψ_σ
Cooling/mixing of Irminger Water boundary current occurs at nearly constant z



3-dimensional upwelling/downwelling is about 60% stronger than that in the zonally integrated overturning streamfunction
K=46; sigma2=36.815





Across the basin, within these two 'latitude' there are ~12 Sv downward transformation (with surface forcing contributes ~9Sv). Within the Labrador Sea and Irminger Sea (west of 30W), the downward tranformation is about 14 Sv and upward transformation of 6 Sv …

Why is all this 3D structure of mixing/upwelling important?

o Water-mass transformation (WMT) analysis shows the upwelling/downwelling and transport of water masses, without canceling out east-west overturning cells

o AMOC index (maximum of overturning streamfunction) is shared between hemispheric and local gyre-scale overturning cells

o Thermodynamic interaction of AMOC with wind-spun gyres and Ekman pumping is in 3D; *Marshall, Jamous & Nilsson 1999 DSR; Xu, Rhines & Chassignet JClimate 2016)*

o Diapycnal mixing and isopyncal eddy stirring are both demonstrably important, yet lost in zonally averaged AMOC (=>θ/S/transport analysis)

o NADW is layered with distinct water-masses: LSW, ISOW, DSOW. Its contribution to meridonal transports of heat, salt, tracers involves 3D upwelling/downwelling.

o Climate response to NAO: *Delworth & Zeng 2016* in which Labrador Sea convcction, with strong decadal variablity (North Atlantic Oscillation) accelerates AMOC, *warms* SST, and through ice melt warms the atmosphere.

o Dilution of deep dense AMOC branches as they flow Equatorward is mapped (*Xu, Rhines, Chassignet JPO 2015)*

{JPO paper under review: download at www.ocean.washington.edu/research/gfd}

talk ended

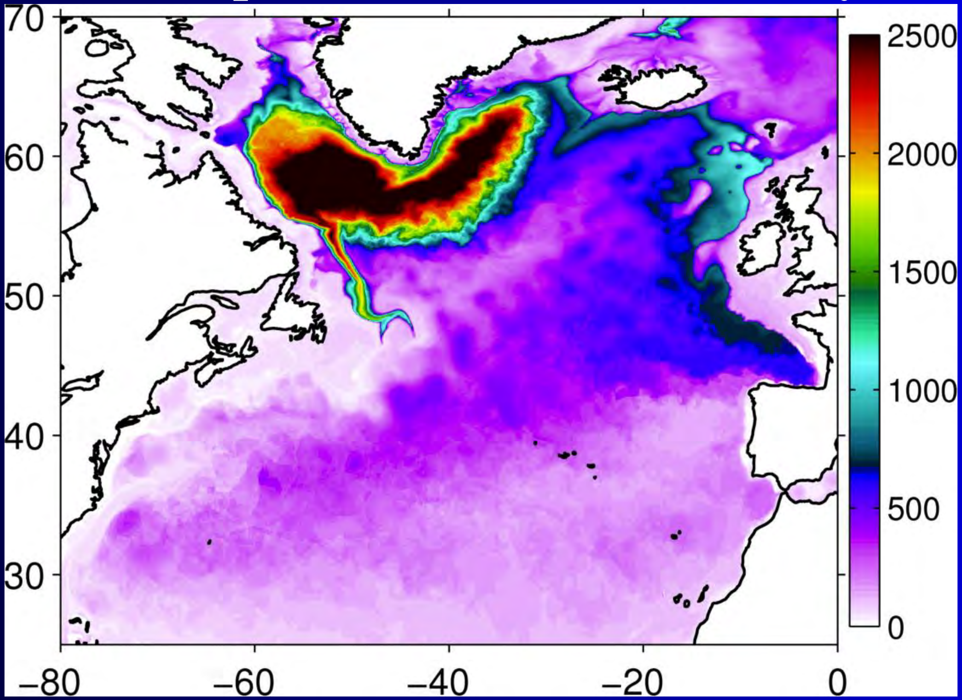
supplementary slides follow;

JPO paper posted at

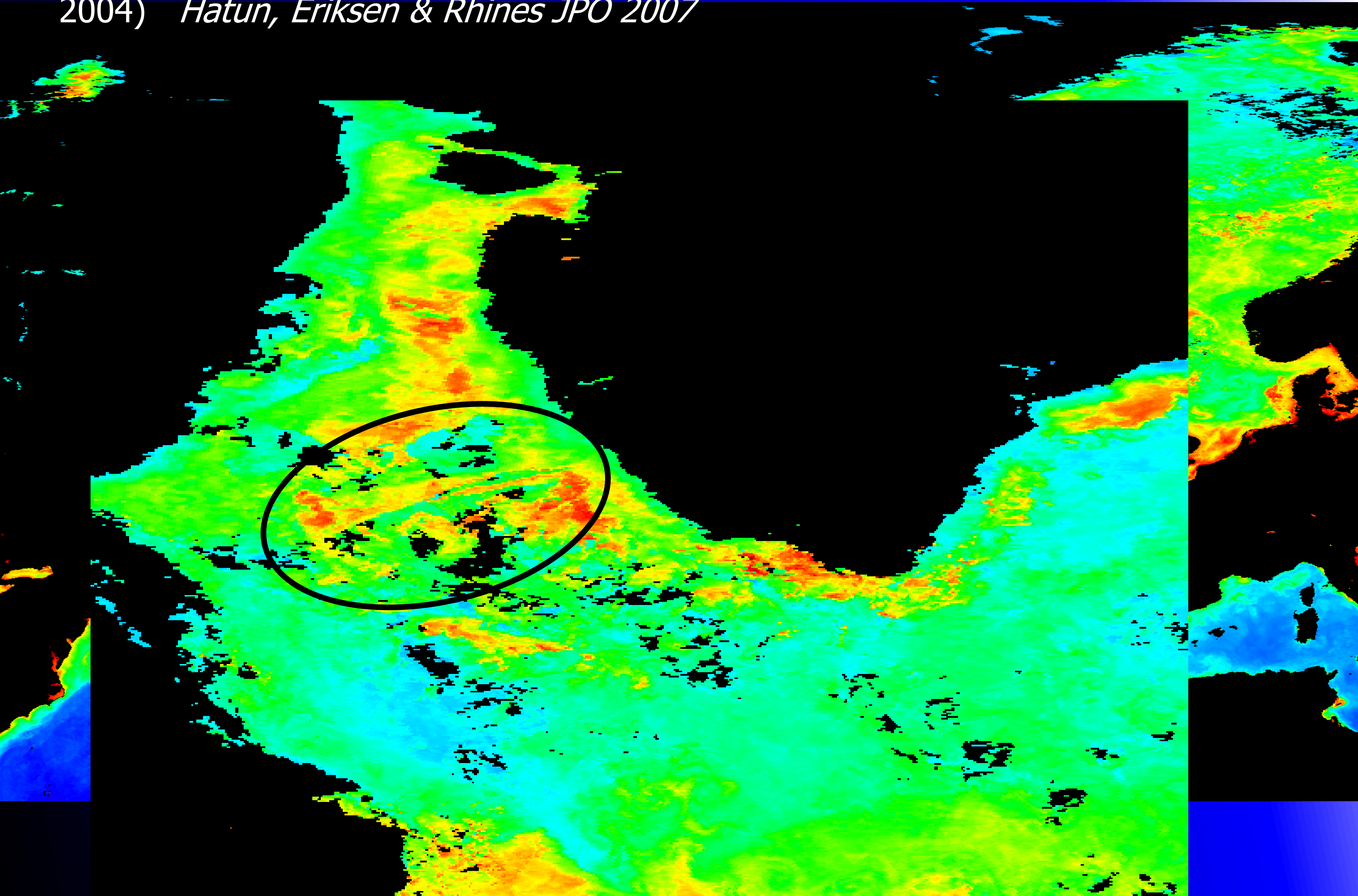
www.ocean.washington.edu/research/gfd

Mixed layer depth in March: HYCOM simulation
it is too extensive and too deep, owing to missing advection of buoyant low-salinity water from Arctic, which narrows the spatial window for deep convection. The entry of that buoyant fresh water from the west Greenland boundary current is observed by *Seagliders: Hatun, Eriksen & Rhines 2007 JPO* and is visible in satellite ocean color imagery (next slide). This effect of Arctic outflow and Greenland ice-melt is missing from most ocean models...including our HYCOM simulation which has no active ice model. This may explain in part our 10 Sv of diapycnal Labrador Sea Water production compared with ~ 2 Sv found by Pickart and Spall.

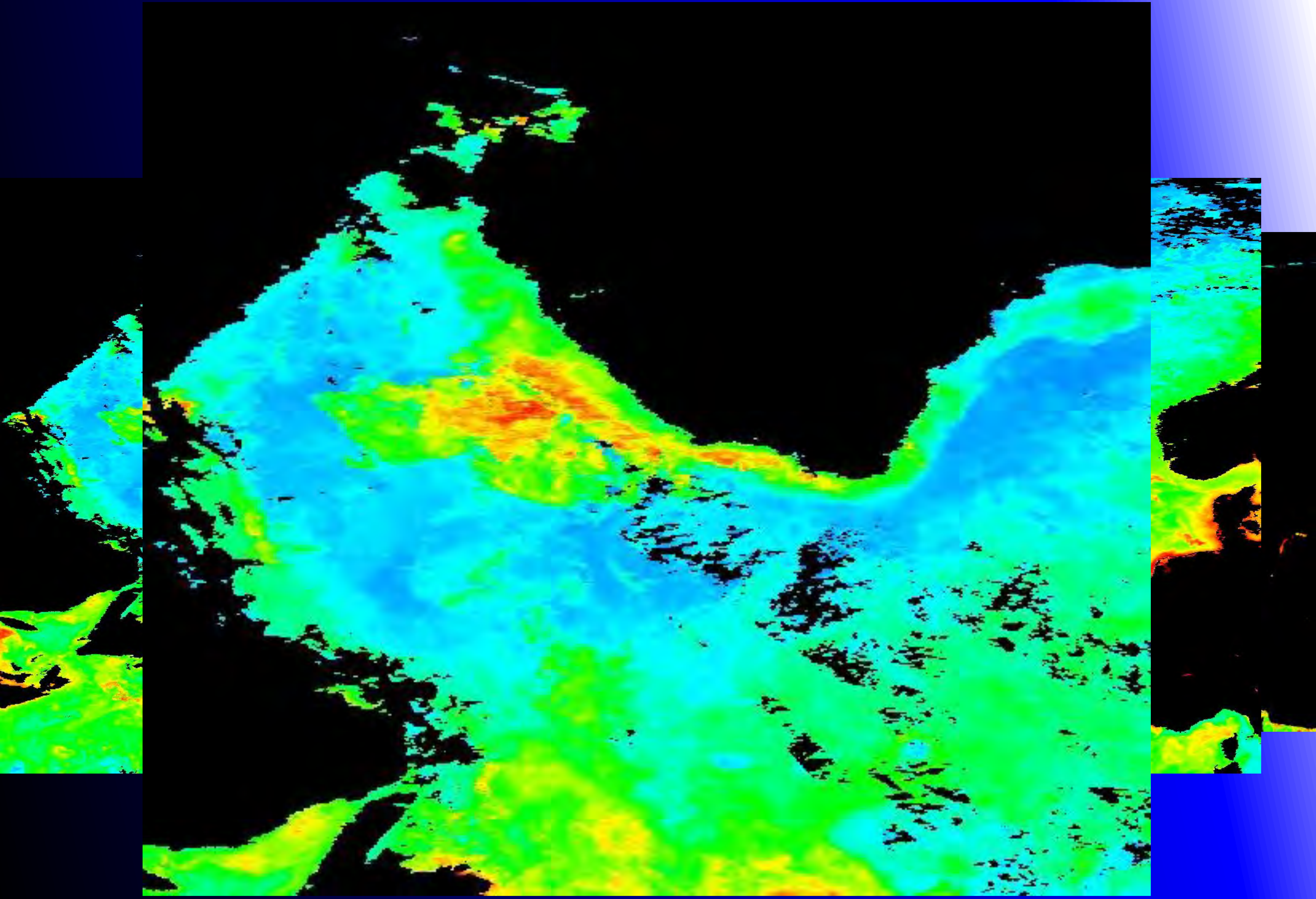
March model mixed layer depth



The buoyant low-salinity Greenland waters reaching out over the Labrador Sea are seen in strong primary productivity in spring…as seen in SeaWIFS ocean color (May 2004) *Hatun, Eriksen & Rhines JPO 2007*



2005 days 91-120



Garrett, Speer & Tragou 1995 JPO

The Walin-Speer-Tziperman surface forced overturning circulation is greatly altered by mixing within and below the mixed layer

A is the lateral advection normal to the outcropped density surface. D is diapycnal mixing of buoyancy. σ is potential density. F is the air/sea buoyancy forcing Bo multiplied by the outcrop window size dS, F = - Bo dS/dσ

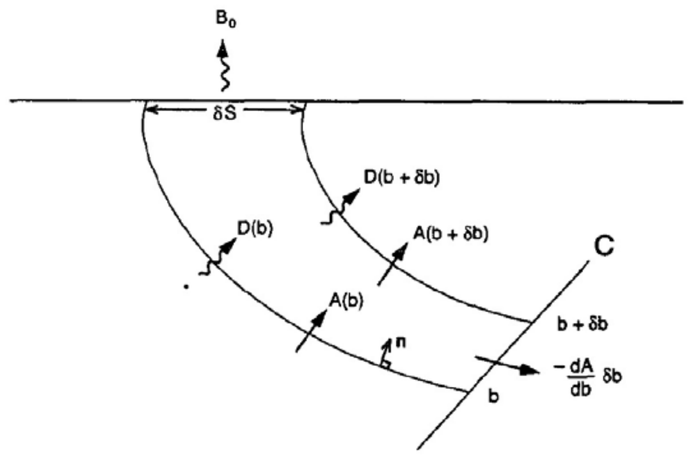
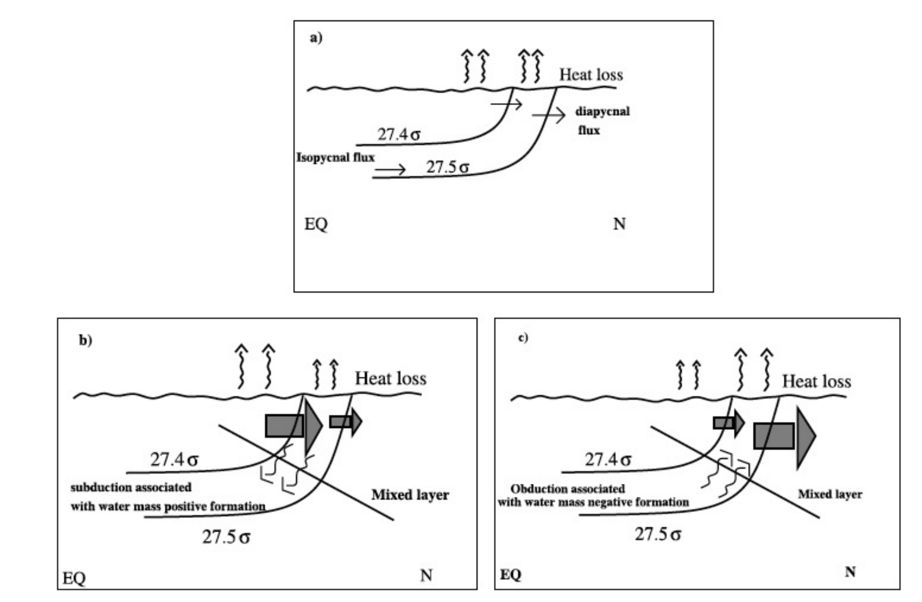


FIG. 1. Schematic of the surface outcropping of isopycnals with buoyancy b and $b + \delta b$. The sea surface area between the two isopycnals is δS, and the spatially averaged rate of surface buoyancy loss there is B_0. The location of the bounding control surface C is arbitrary.

$$A = F - \frac{\partial D}{\partial \sigma}$$

Brambilla, Talley & Robbins 2008 map the integrand of the surface-flux forced circulation in the subpolar Atlantic, from reanalysis estimates of air-sea buoyancy flux alone.



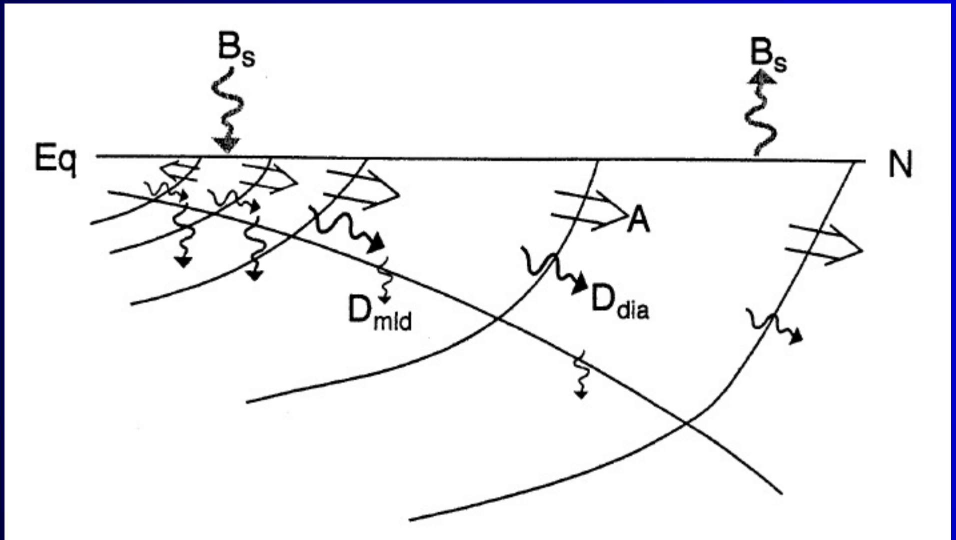
Garrett Speer and Tragou JPO 1995: lateral mixing in ML (mixed layer) and mixing at the ML base and below ML makes WMT unequal to the balancing horizontal circulation and subduction.

Garrett & Tandon DSR 1998, Tandon & Zahariev JPO 2001: time-dependence (diurnal, seasonal) and mixed-layer entrainment change the relationship of air/sea buoyancy flux Bo to overturning circulation and subduction.

Marshall, Jamous & Nilsson DSR 1999

is a precursor to our work, combining Ekman pumping with thermodynamic forcing at the surface and mixing at the base of the mixed layer. Lateral subuction where the Ekman transport encounters outcropping density surfaces is important.

For modern work see *Thomas & Joyce JPO 2000, Joyce, Thomas, Dewar & Girton DSR 2013* who show that along-front wind stress over the Gulf Stream creates Subtropical Mode Water (18 Degree Water) south of the Stream:



Here below is the set of maps for the whole range of densities of the Labrador Sea Water overturning cell. Notice that it upwells in 40-50N, where the Gulf Stream feeds the North Atlantic Current as well as recirculating to the south.

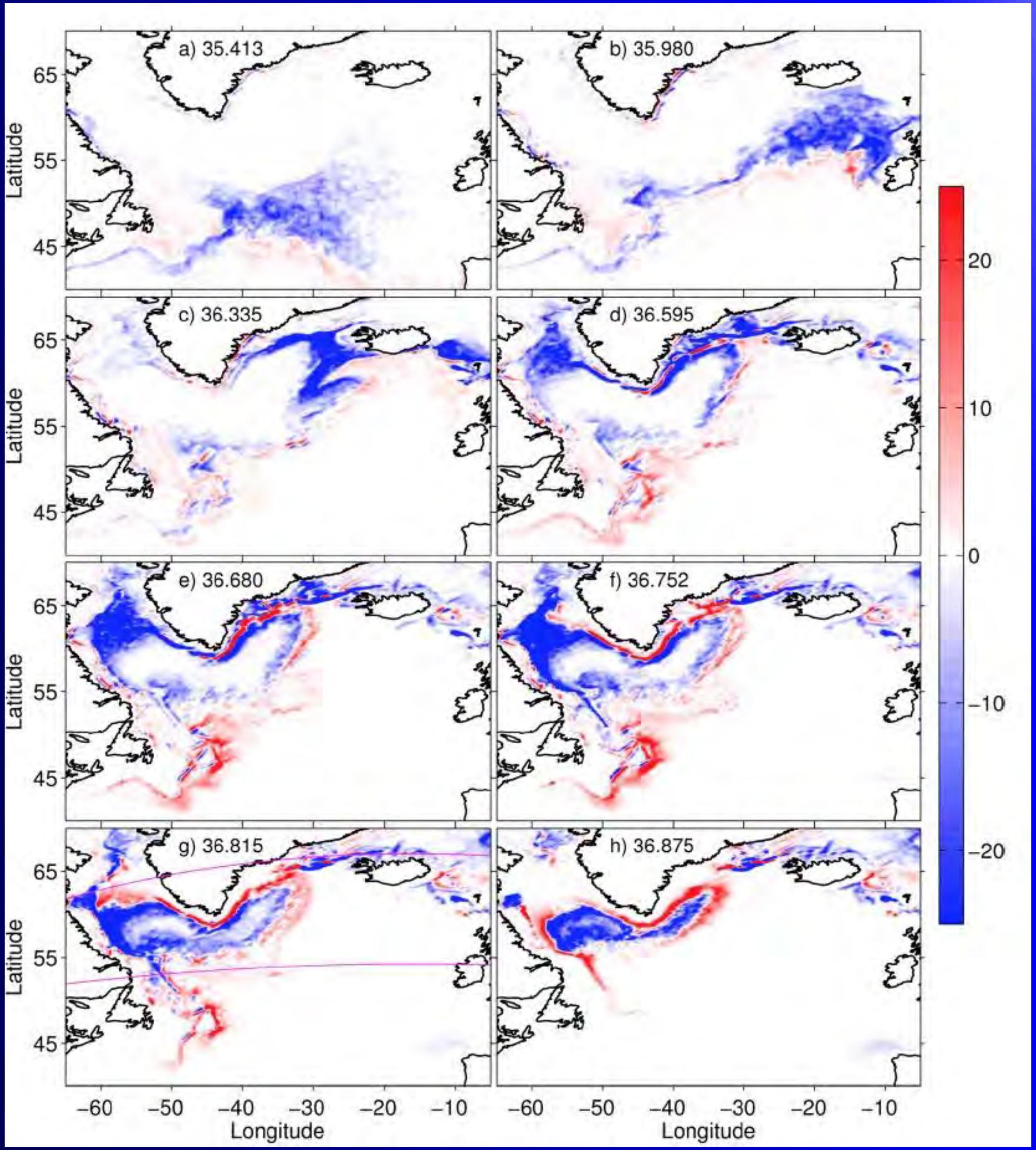
This 'transition zone' between subtropics and subpolar latitudes is the site of diapycnal upwelling (warming) of the 5 to 10 Sv of Labrador Sea Water flowing south, close to the N. Atlantic boundary current overhead. *Lumpkin, Speer & Koltermann JPO 2008* analyze 4 repeat east-west sections (WOCE AR19) in this region, to give this transport estimate.

We focus on this in our JPO paper submitted in Oct 2017.

Subpolar Atlantic

Total upwelling/ downwelling maps for sequence of density surfaces shown on the AMOC streamfunction plot (green a – h)

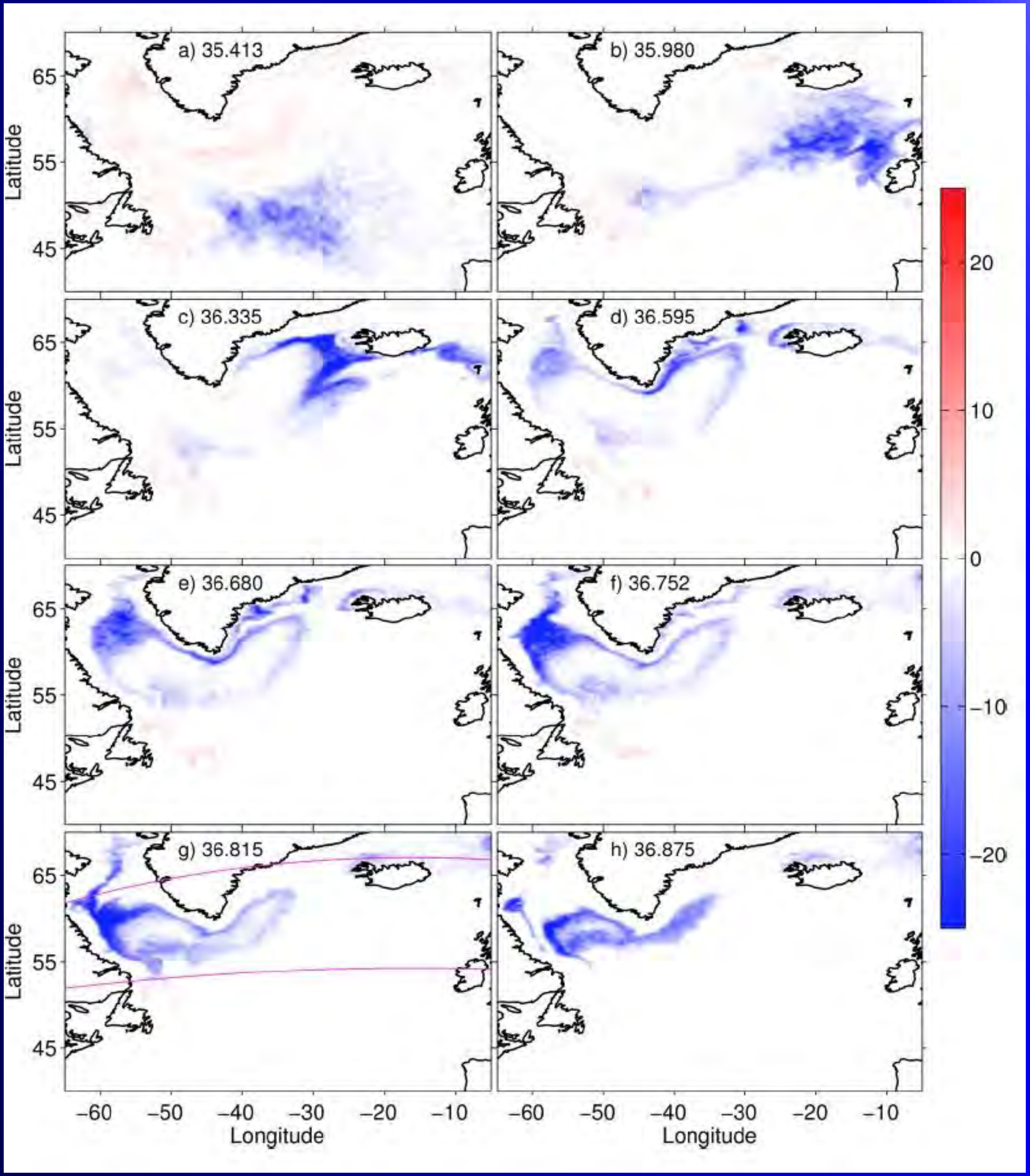
Total mean diapycnal velocity Wd (10^{-6} m sec^{-1})



Subpolar Atlantic

Air-sea buoyancy flux forced component

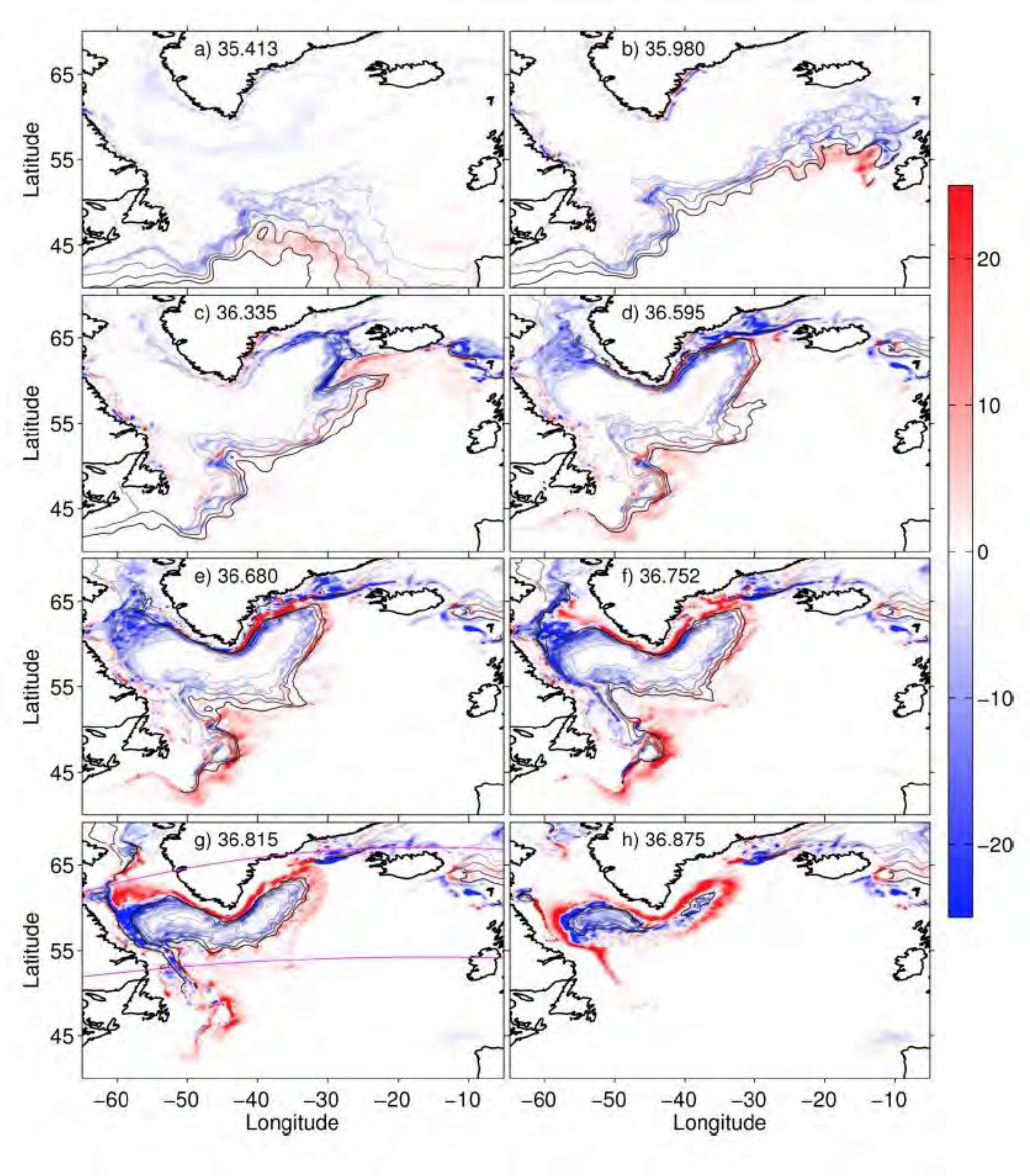
diapycnal velocity Wd (10^{-6} m sec^{-1})



Subpolar Atlantic

Subsurface mixing induced component

diapycnal velocity Wd (10^{-6} m sec^{-1})



Spall JPO 2010

Used simple basin model to explore how a Labrador Sea-like region is cooled by the atmosphere working on a warm inflowing boundary current. He sees an overturning circulation confined very near the coast, and eddy flux to the basin interior, rather like our simulations.

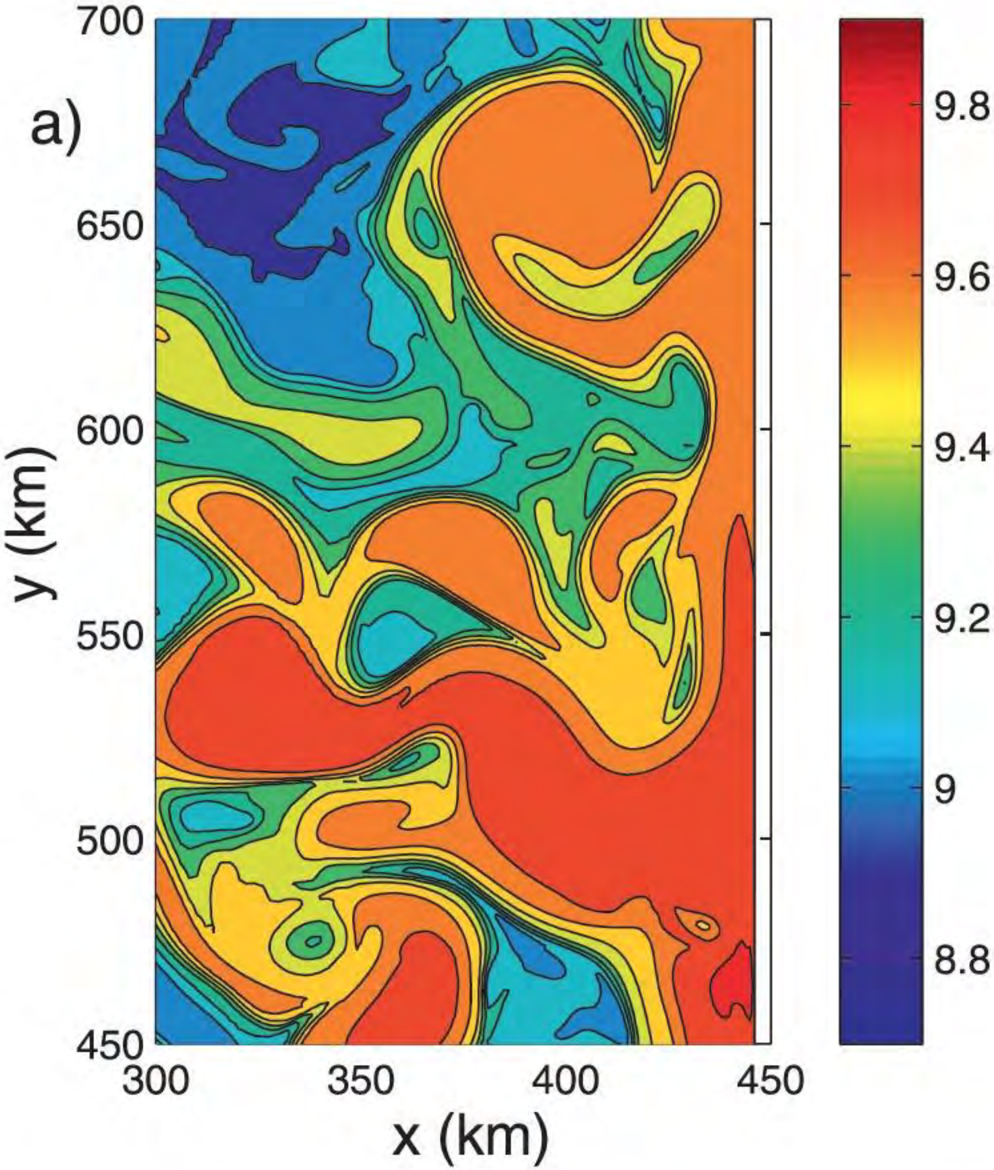
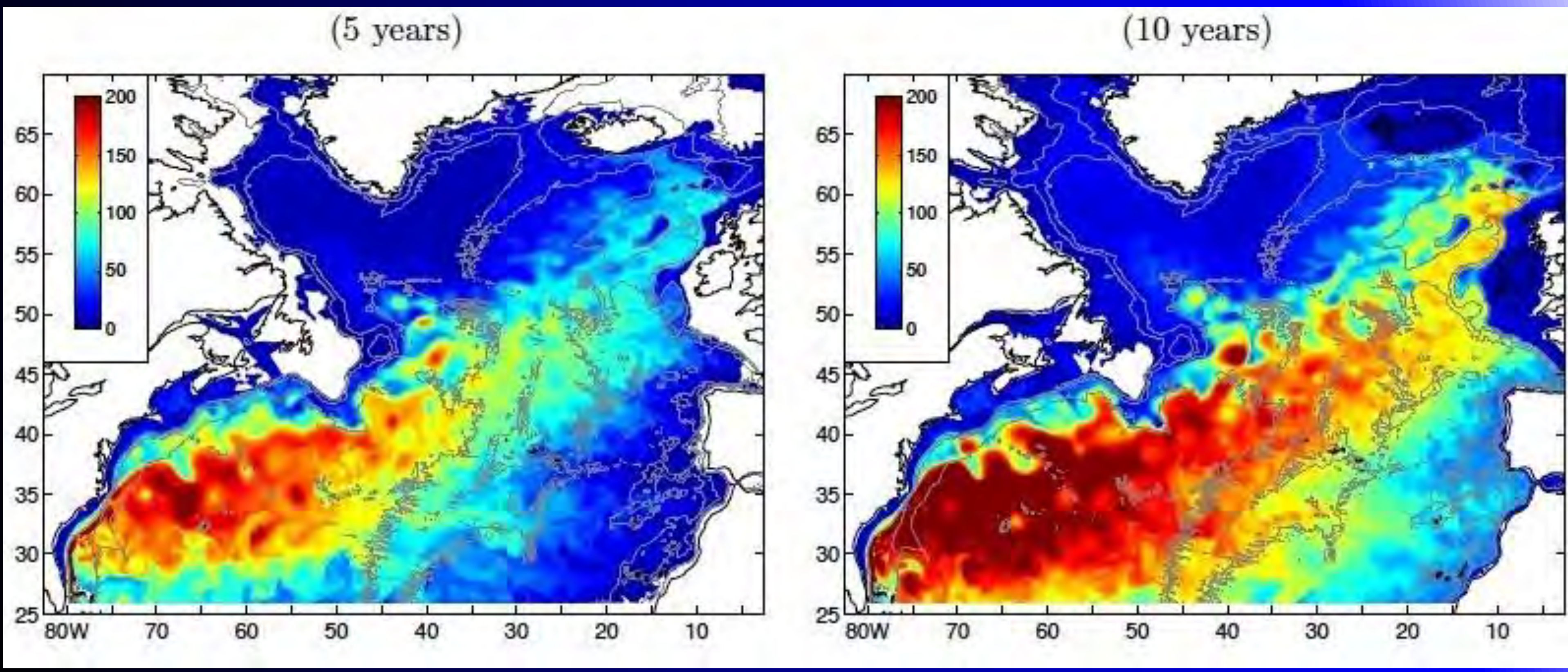


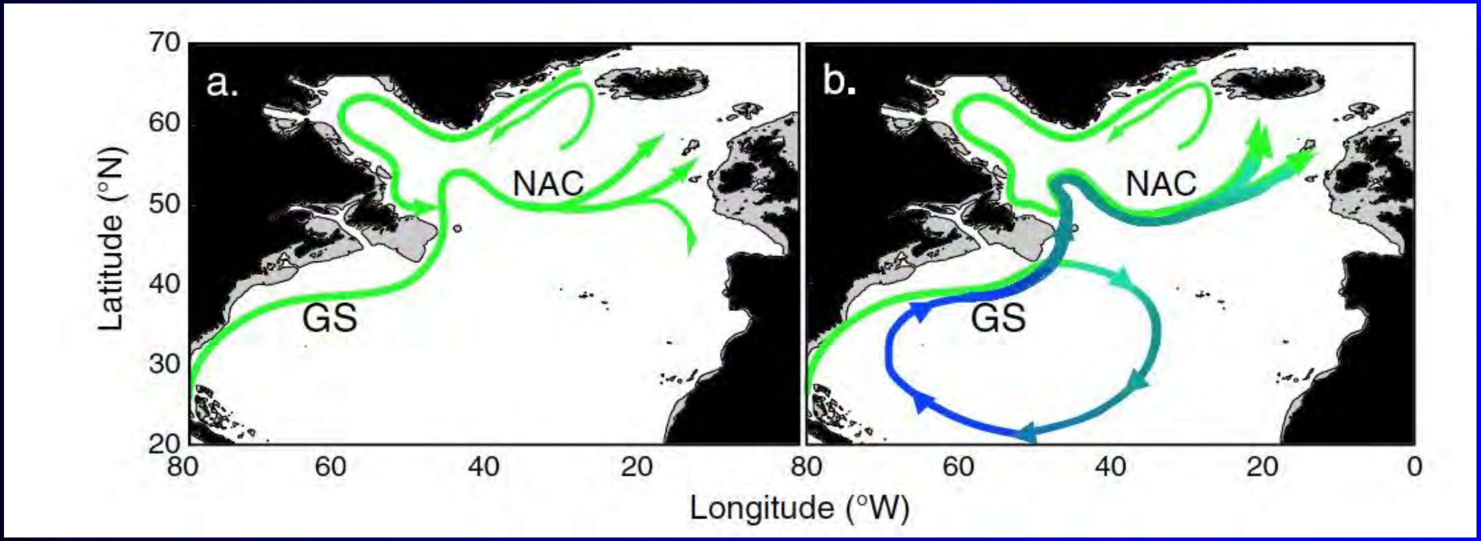
FIG. 6. Snapshot at 50-m depth near the eastern bou
(b) relative vorticity divided by the Coriolis parameter (c
by large, warm, anticyclonic eddies surrounded by narro

HYCOM model: tracer injected steadily in boundary current (in Florida Straits) at thermocline depth (Xu Xiaobiao, FSU, private communication)

PV is a dynamically active tracer, but it pays to look at many different passive tracers in these flows. Note how rapidly the tracer fills out the subtropical gyre in the 5 yr and 10 yr snapshots



One pathway (of ~ 3) for warm branch MOC flow from subtropics to subpolar gyre extends deep (~800-1000m) and involves recirculation in the subtropics, with mixing by Subtropical Mode Water cooling.



Burkholder & Lozier, GRL 2014

John Smith's ocean: Iodine-129 tracer inject by nuclear reprocessing plants at Sellafield England and La Hague, France.

jgr 2008 *Env Fluid Mech 2009*

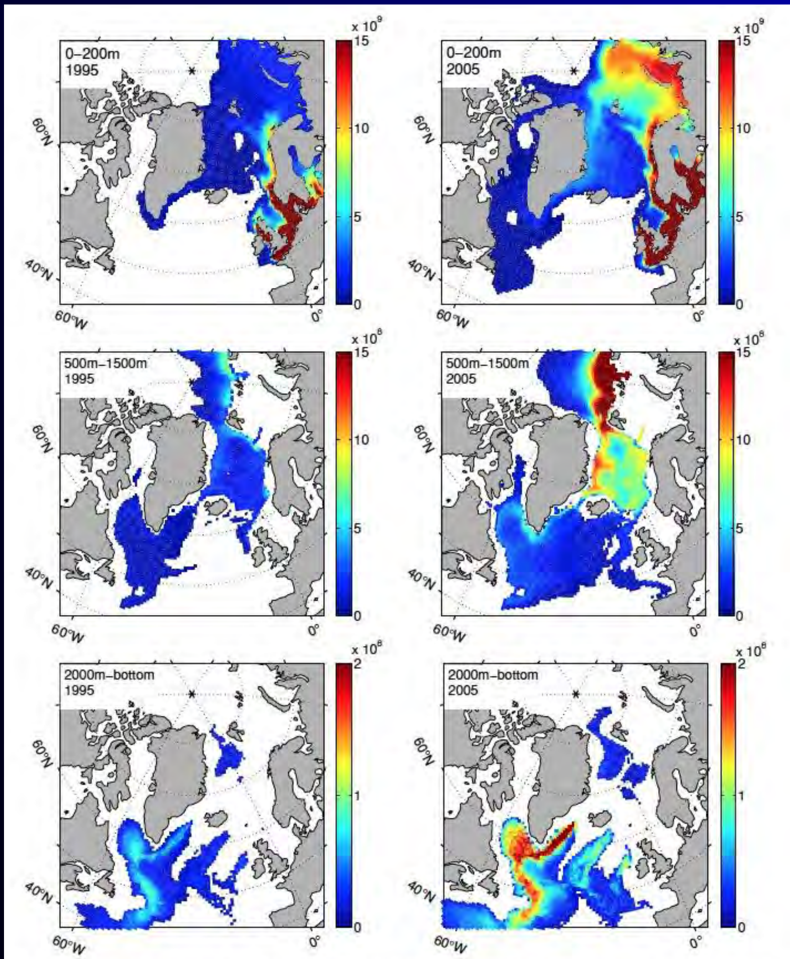


Fig. 3 Simulated concentration of ^{129}I (atoms l^{-1}) from Sellafield and La Hague in 1995 and 2005 averaged over the upper 200 m, for intermediate waters between 500 and 1,500 m, and for deep waters below 2,000 m, see text labels in each subfigure for depth bin and sampled year. Note the different legend scale. ^{129}I concentration less than 10^7 atoms l^{-1} is set to zero

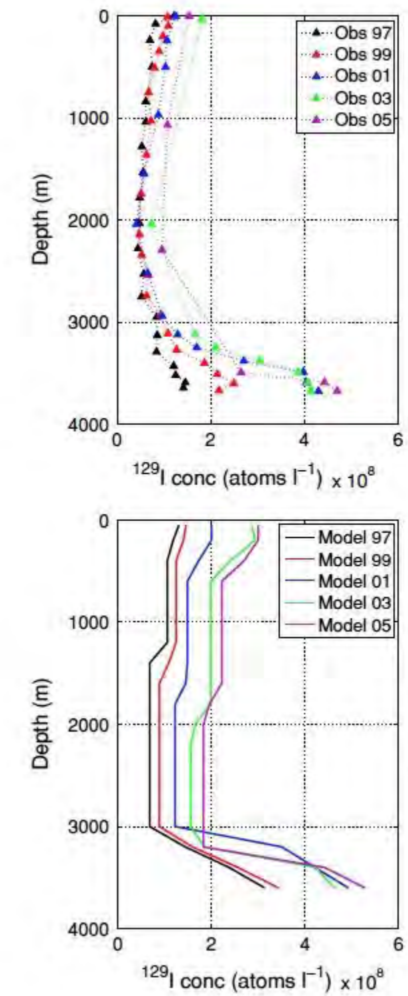
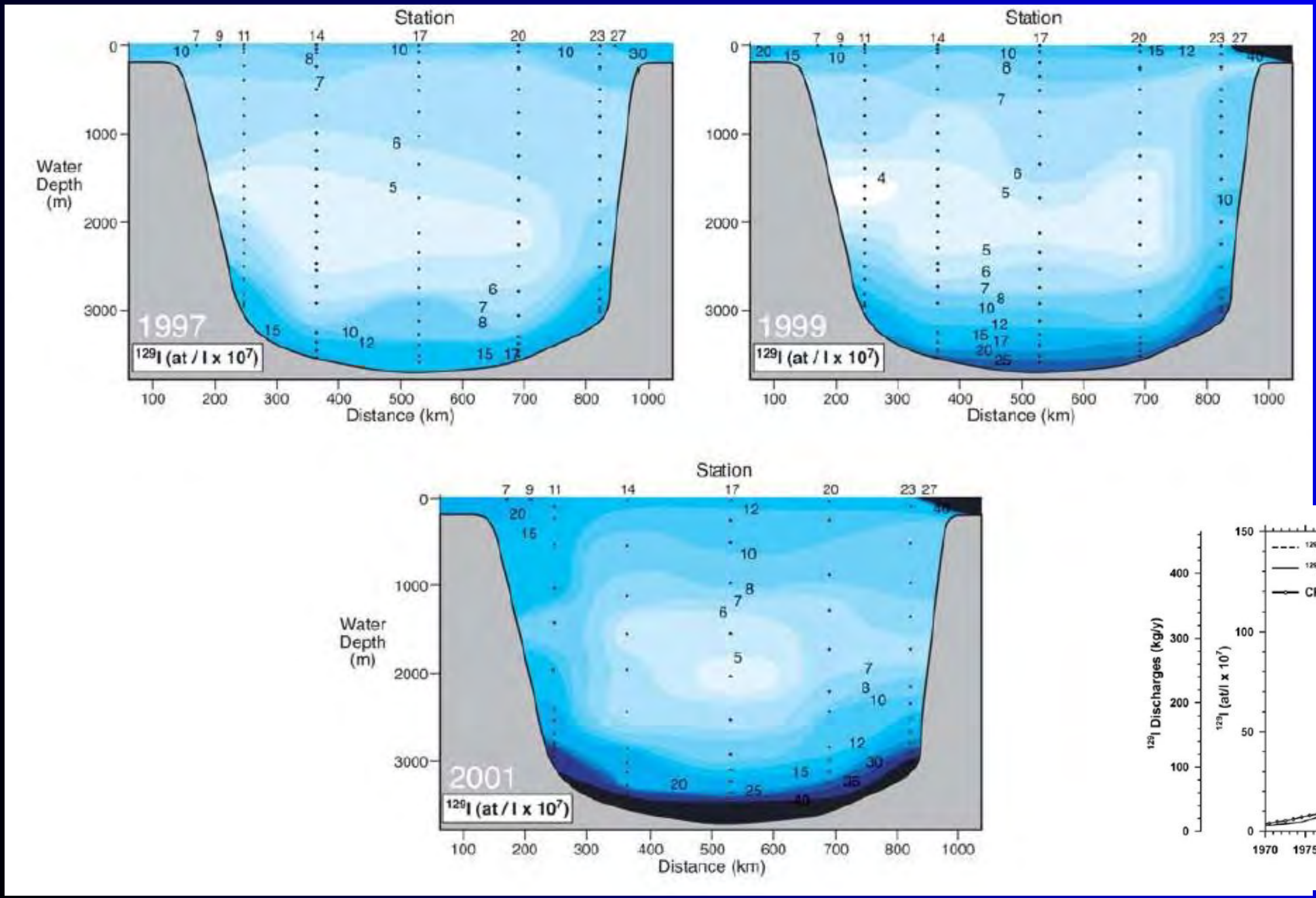
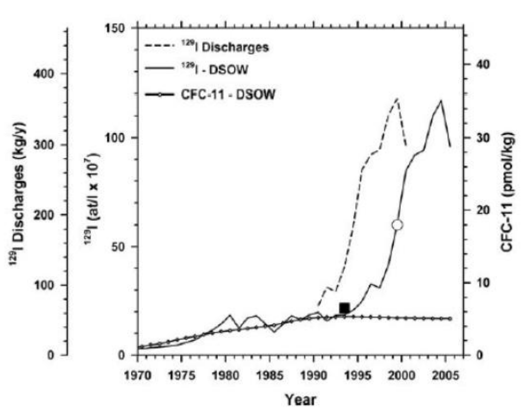


Fig. 7 Concentration and age of ^{129}I at station 17 on the
in 1997, 1999, 2001, 2003 and 2005. The observed valu
et al. [43], the values from 2003 and 2005 are unpublishe
interpolated to constant z-levels with 200 m resolution

Iodine-129 transient tracer arriving in the central Labrador Sea. *Smith, J. et al. JGR 2005*

transit time ~ 3-5 years from Europe to Iceland Sea/Denmark Strait + 0.4-2.6 years to reach deep Labrador Sea





Iodine 129 plume in NADW has reached the subtropical Atlantic both in deep western boundary current and in the interior pathway southeast of Bermuda !

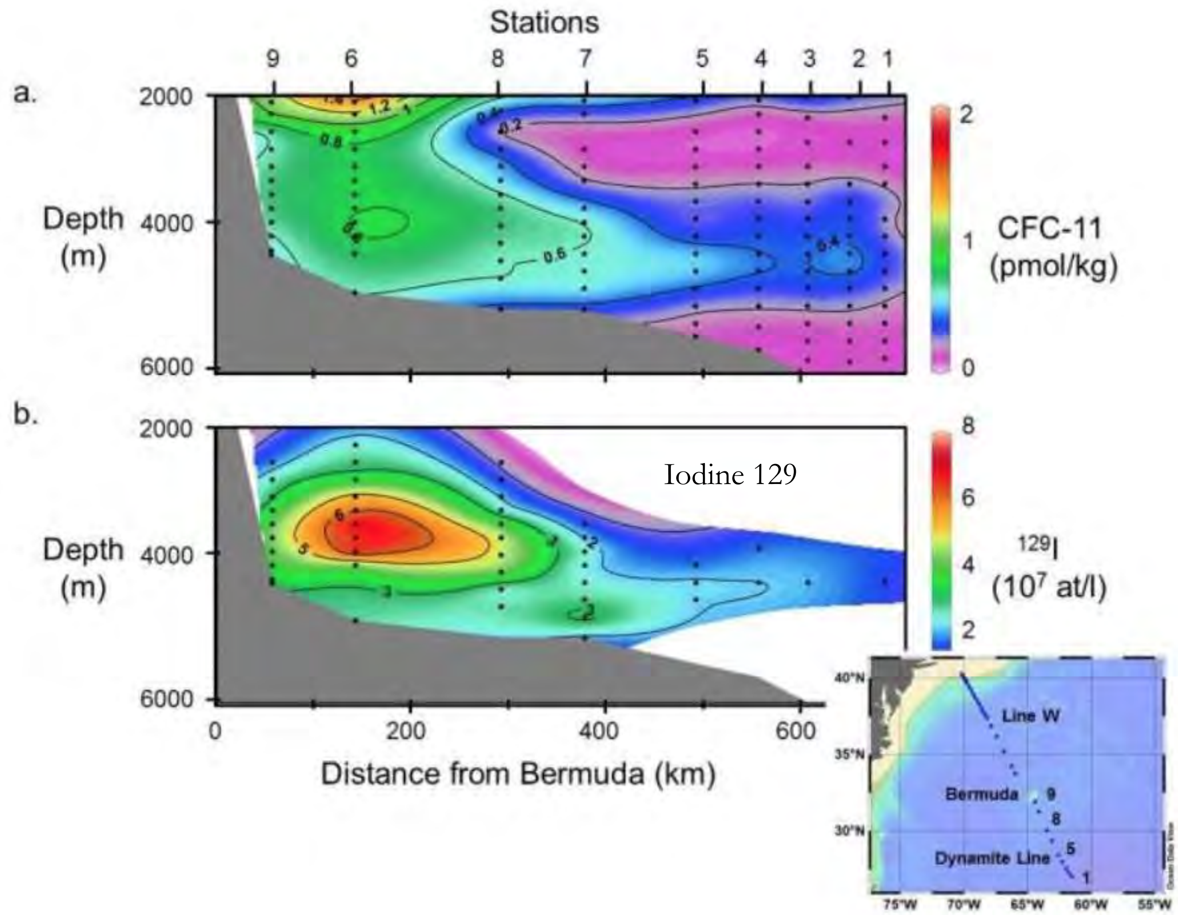
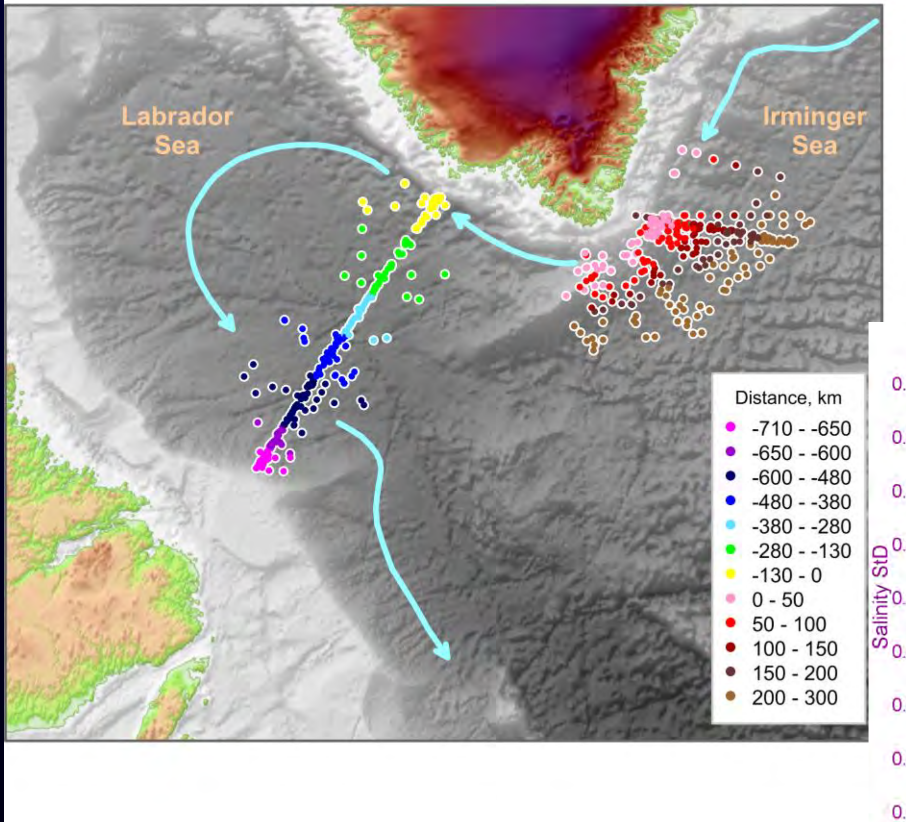


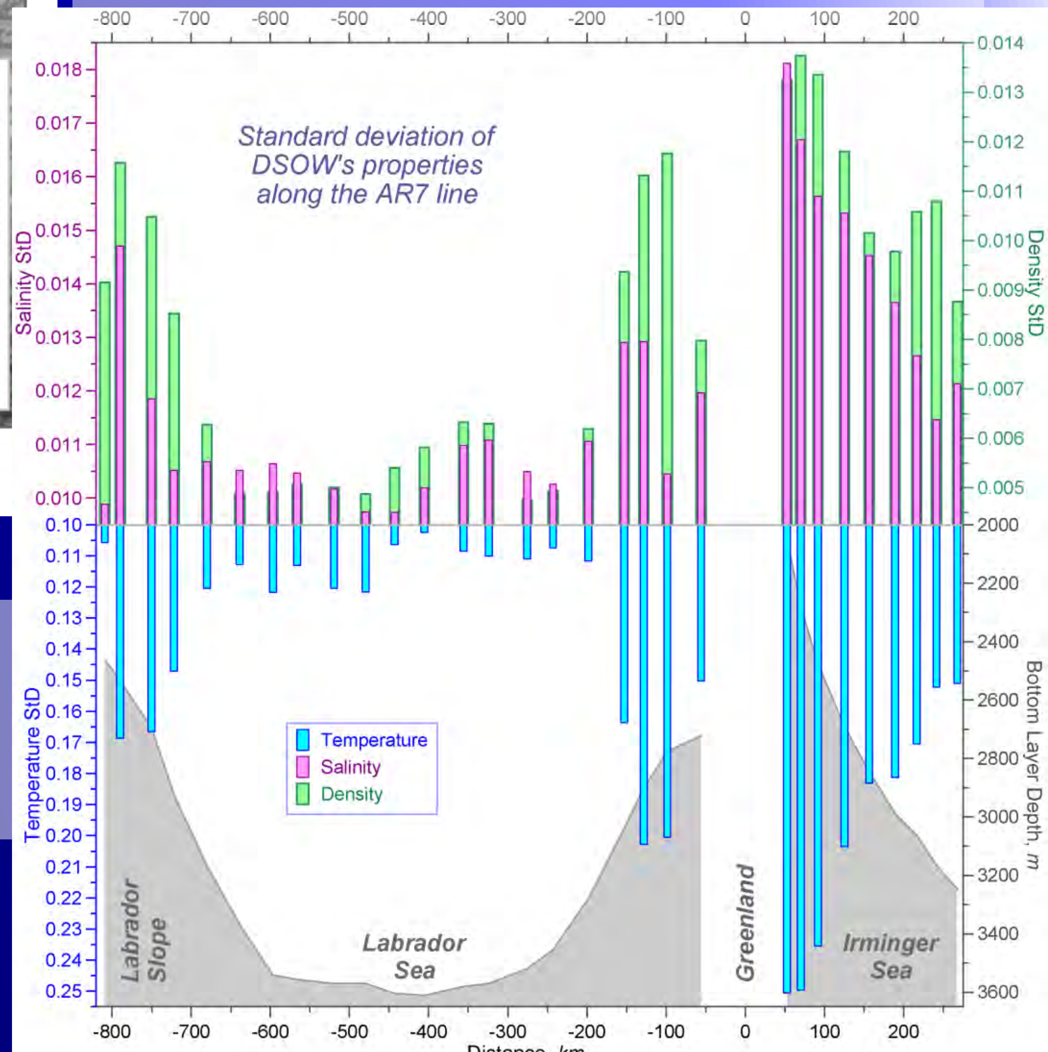
Figure 7. Upper panel (a): CFC-11 section on Dynamite Line extending southward from Bermuda over Bermuda Rise. Lower panel (b): ^{129}I section on Dynamite Line. Inset shows positions of Dynamite Line stations and Line W relative to Bermuda. Core of DSOW that has separated from DWBC and been transported through interior pathways over Bermuda Rise is delineated by tracer maxima adjacent to southern Bermuda slope.

DSOW stats

DSOW was defined as a near-bottom 100 m layer.

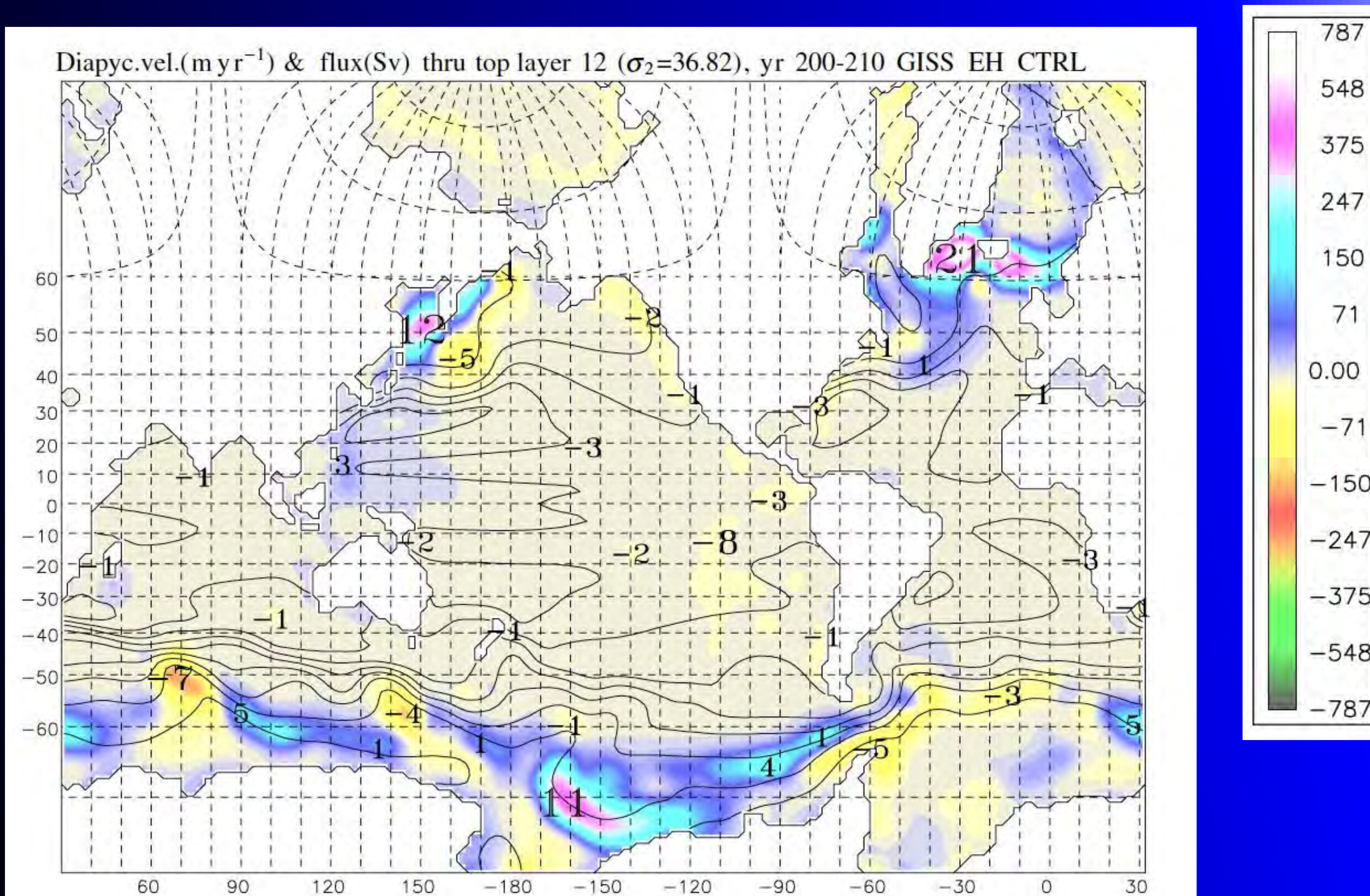
An iterative polynomial model was used to separate spatial and temporal variability of DSOW





Low-cost Monitoring of the lowest limb of the North Atlantic Overturning

Sun & Bleck 2006 Ocean Mod.
Diapycnal upwelling on $\sigma_2 = 36.82$ (m yr^{-1})

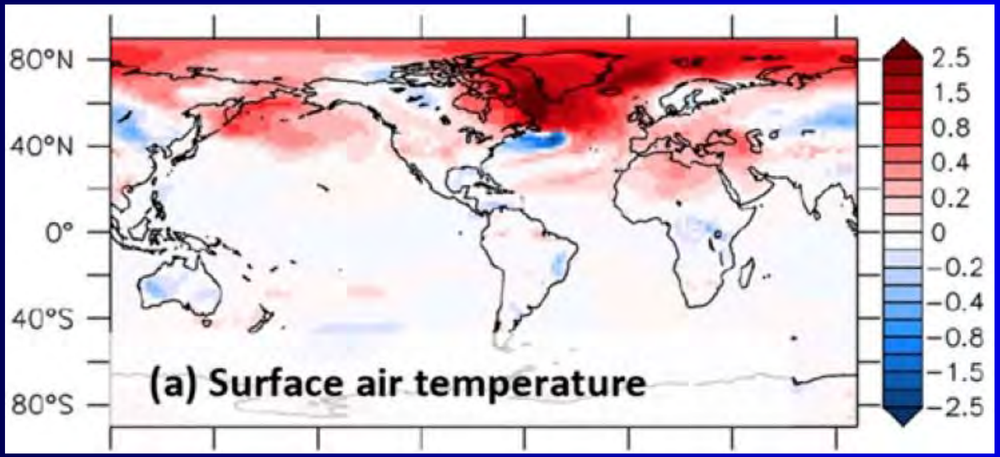


One of the reasons 3-dimensional analysis of upwelling/downwelling is important:

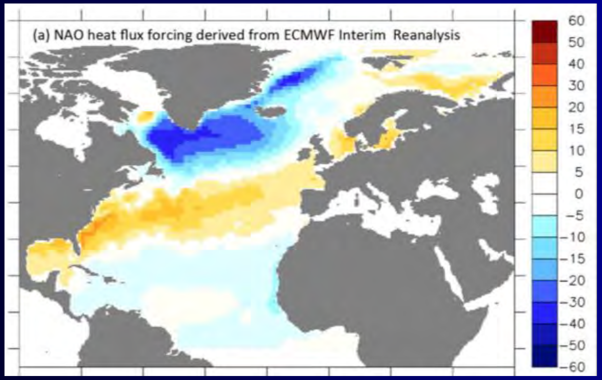
warming of atmosphere by a 20 yr timescale anomaly of positive NAO

(=strong atmospheric *cooling* of subpolar Atlantic, Labrador Sea Water produced,which accelerates AMOC's warm northward circulation, melts ice,changes albedo) *Delworth & Zeng JClim 2016*

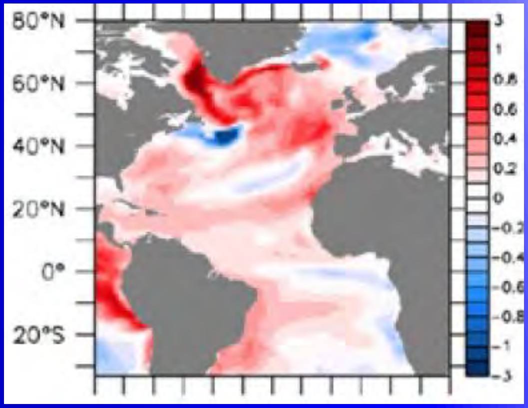
air temperature anomaly following NAO oscillating with 20-year period (cold NAO+ phase excites warming of both SST and surface air temp.



air/sea heat flux anomaly



SST anomaly 9 yrs after sudden NAO shift to positive phase (cold forcing of ocean)



The warming shown by Delworth & Zeng resembles the 1996-2010 warming of the subpolar Atlantic, one of about 3 dramatic warming events since 1900 (in 1930s-40s, 1960s, 2000s) . It was deep-reaching, advected from the subtropics (not just due to warm atmosphere above).

Häkkinen & Rhines JGR 2013: anomalous heat content 0-700m 1993:1997 vs 2007:2011 and anomalous AVISO altimetric surface currents (*left panel)* : weakened subpolar gyre circulation, strengthened North Atlantic Current; (*righthand panels*): pot. temperature sections at 48N and 25W showing deep penetration of warm anomalies

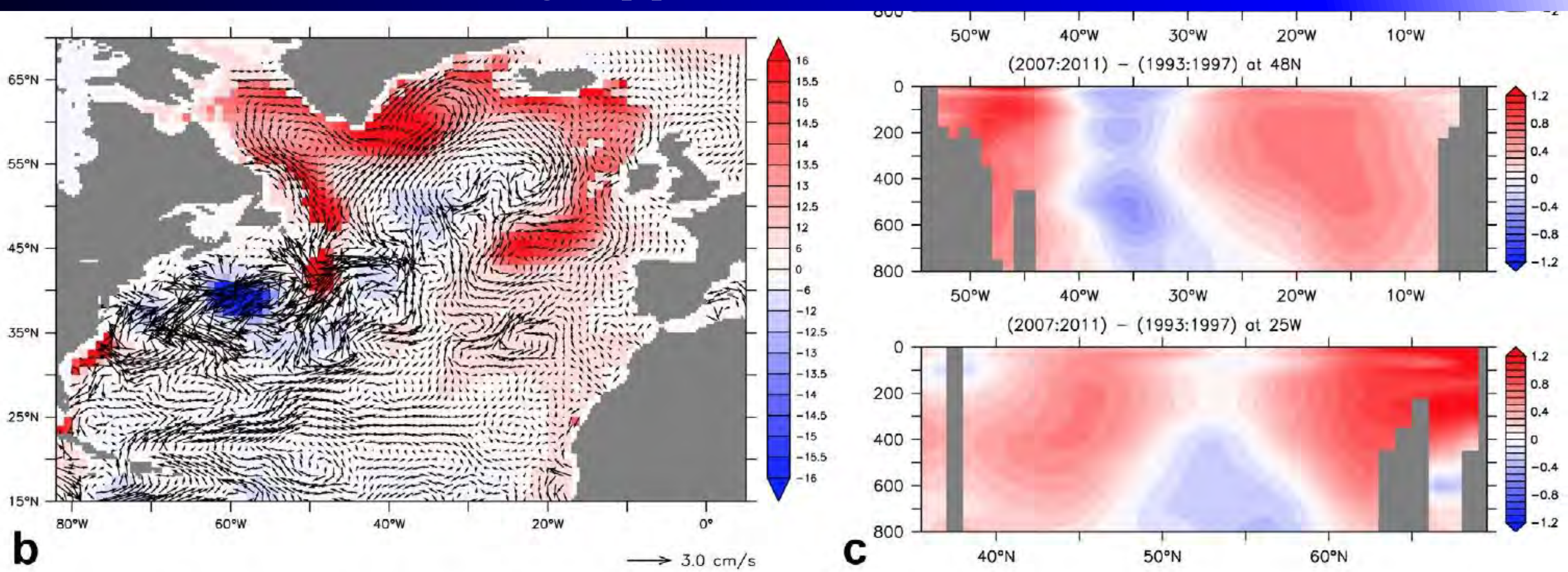
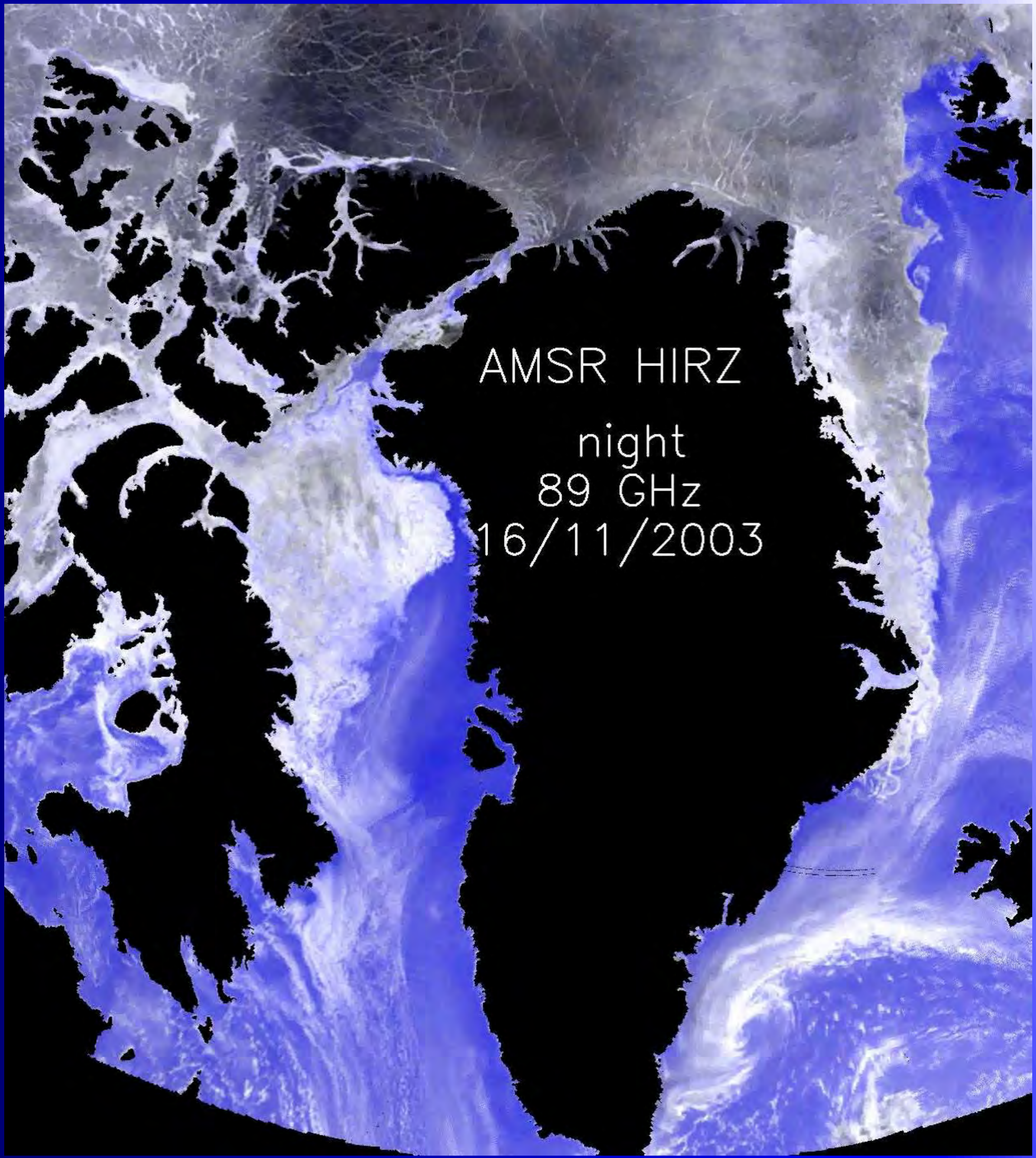


Figure 6. NODC 700 m OHC change from 1993–1997 to 2007–2011 mapped against the time-mean surface currents from AVISO. Magnitude of the thick vectors is twice the scaling of the thin vectors. NODC 700 m OHC change from 1993–1997 to 2007–2011 mapped against the surface current anomalies from MEaSUREs project. NODC pentadal temperature data (top) 1993–1997 and (middle) 2007–2011 at 48°N. Isotherms of 13°C, 12.5°C, 12°C, 11°C, and 10°C are plotted to highlight the spatial changes. Temperature differences at 48°N and 25°W are shown in the bottom figures. Salinity variability is positively correlated with this temperature variability, yet with much less effect on density.

We've learned a lot about the HYCOM high-res model from this work… and a bit about the ocean. The model's Labrador Sea convects much to widely, for lack of the resistance to convection provided by the shallow low-salinity surface layer streaming out of the Arctic…. we had already seen this with 2 ½ years Seaglider deployments in Labrador Sea (*Hatun et al. JPO 2007),* and then 3 years along the Iceland-Scotland Ridge (*Beaird et al. 2013, 2014, 2016)*.



END WEBINAR