Overturning circulations, high-latitude ocean climate from above and below: satellite altimetry and Seagliders

P.B. Rhines, *with*
Charlie Eriksen, Sirpa Häkkinen

Kyoto FDEPS lectures 4-7 xi 2007
Dynamics of oceans and atmospheres

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University of Washington

DAY 4

- 1. rotating, stratified fluids: oceans and atmospheres
  - vorticity: a vector-tracer in classical homogeneous fluids
- geostrophic adjustment, thermal wind
- 2. wave dynamics: fundamentals, group velocity, energetics, ray theory
- potential vorticity (PV)
  - vortex stretching, Prandtl's ratio, geography of PV
- 3. Rossby waves
- 4. instability => geostrophic turbulence; subtropical gyres: dynamics, jets and gyres, topography effects
- 5. Case study of topographic effect on atmospheric circulation: Greenland and Atlantic storm track.
- 6. Teaching young undergraduates about the global environment?
- 7. Seminar: subpolar climate dynamics observed from above and below: meridional overturning circulations (MOCs) altimetry and Seagliders

Some ‘burning’ questions for which we thought we knew the answers:

(i) What drives the global meridional overturning circulation (MOC) of the oceans --- buoyancy or mechanical mixing induced by winds and tides?

(ii) Is high-latitude sinking and the deep, cold branch of the MOC a dominant member of the meridional heat and fresh-water transport?

(iii) Does the ocean circulation substantially warm western Europe?

More generally, does heat transport by oceanic general circulation affect atmospheric climate?

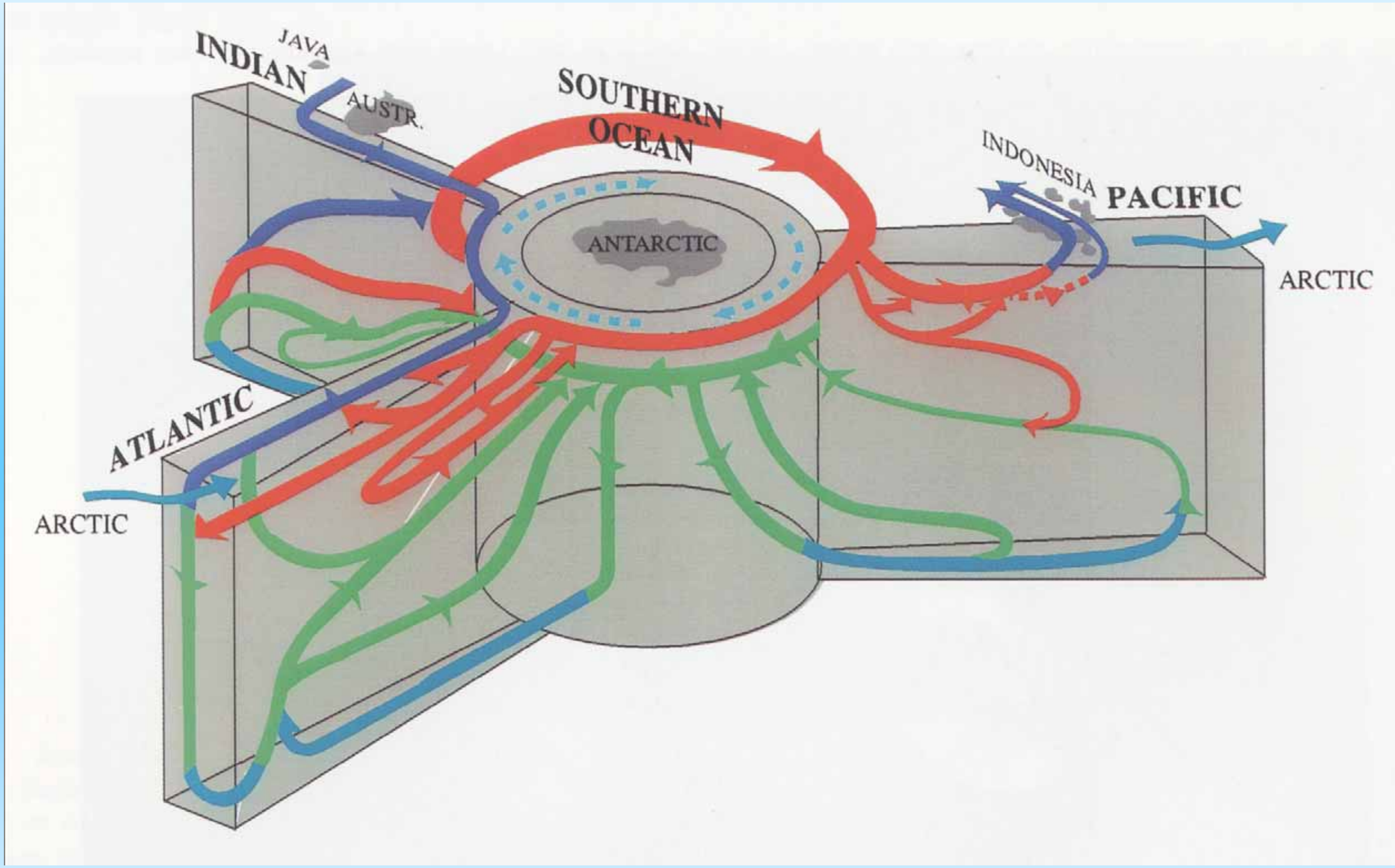
(iv) What are the paths of upwelling of deep waters in the global oceanic MOC?

(v) Where are the crucial sites for convection and water-mass transformation ?

(vi) How does wind-driven circulation interact with buoyancy-driven MOC overturning?

(vi) What is the quantitative rate of water-mass production for the several components of the North Atlantic DeepWater (for example, Labrador Sea Water), and how are they altered before being ‘delivered’ to the global MOC?

(vii) How do convection and mixing drive diffusive overturning at many scales, reaching to the distant circulation.


JAVA
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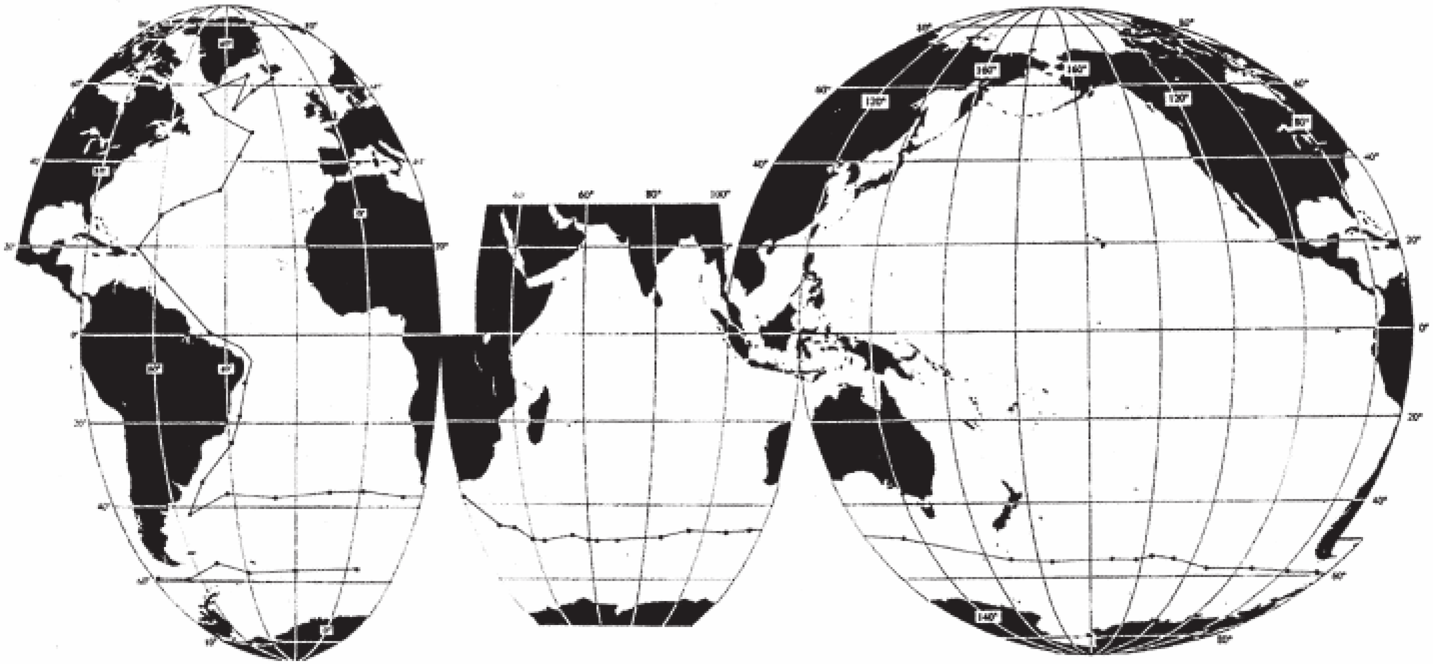
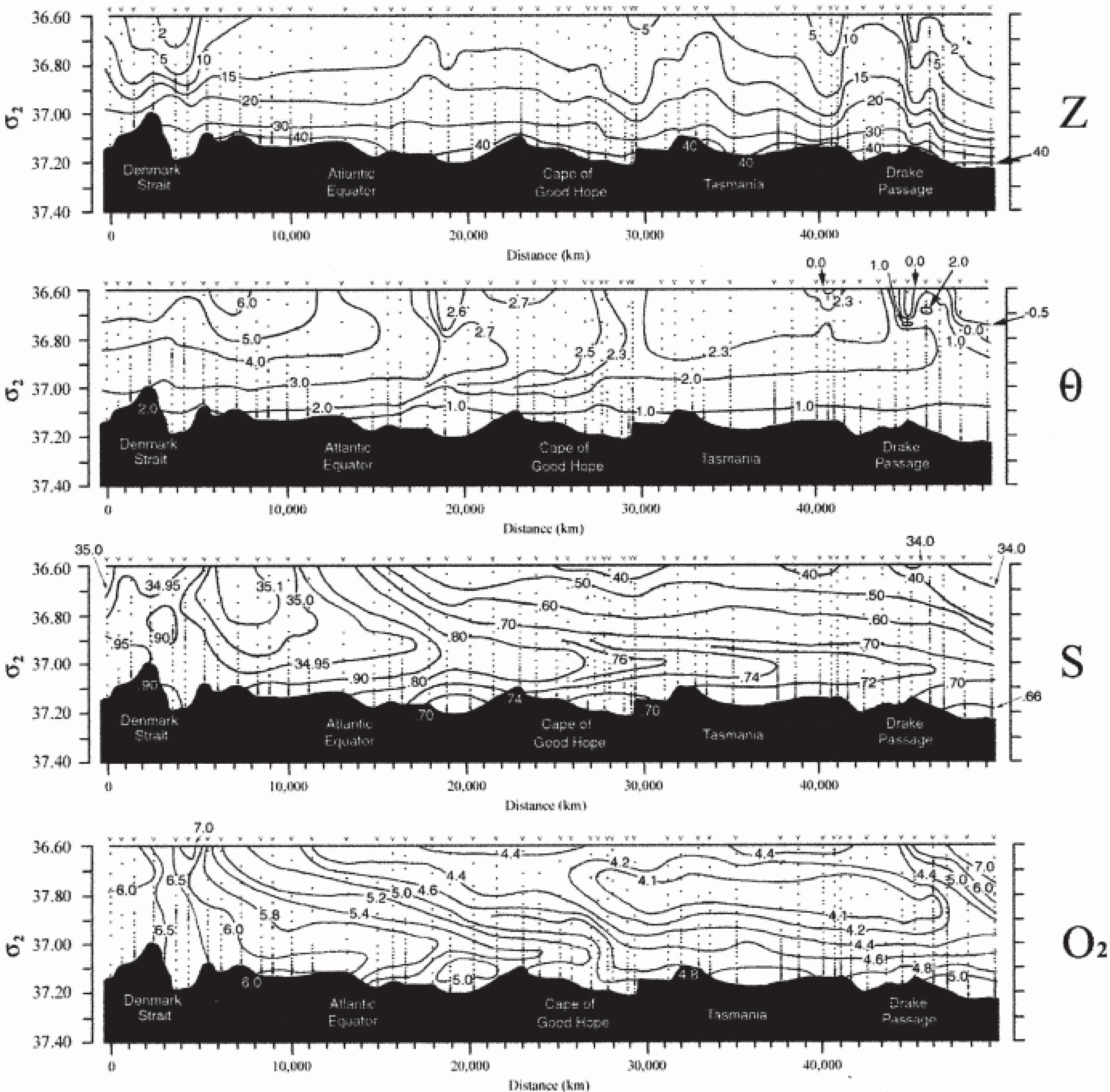


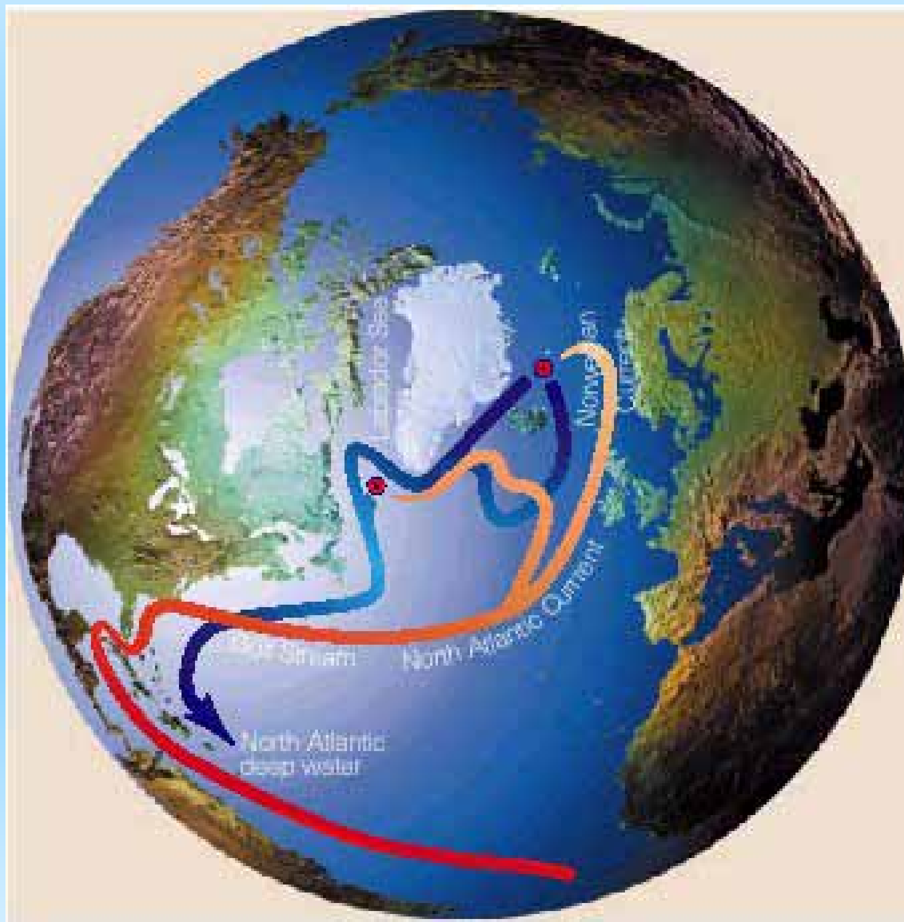
Figure 1. Path of the vertical section from the North Atlantic through the Indian and Pacific oceans and Drake Passage, returning to the Atlantic.

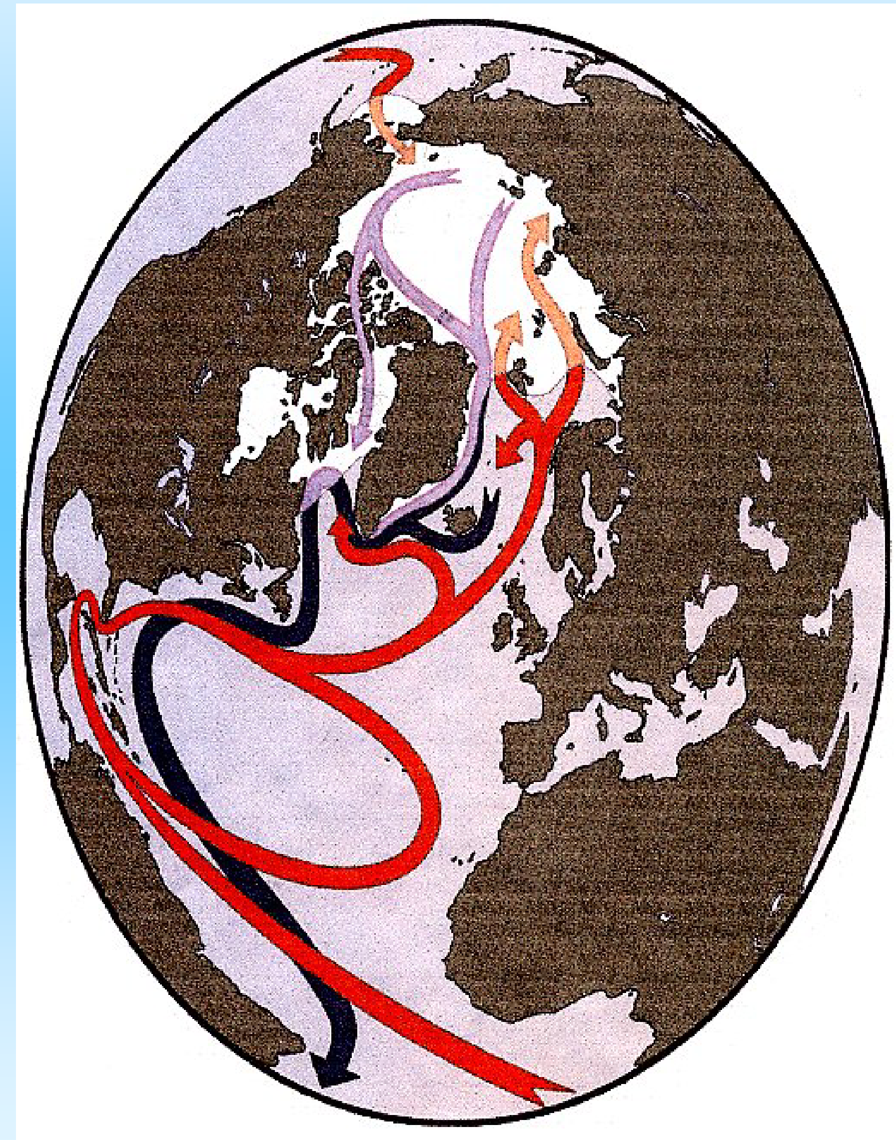
Reid, J Marine Res 2005



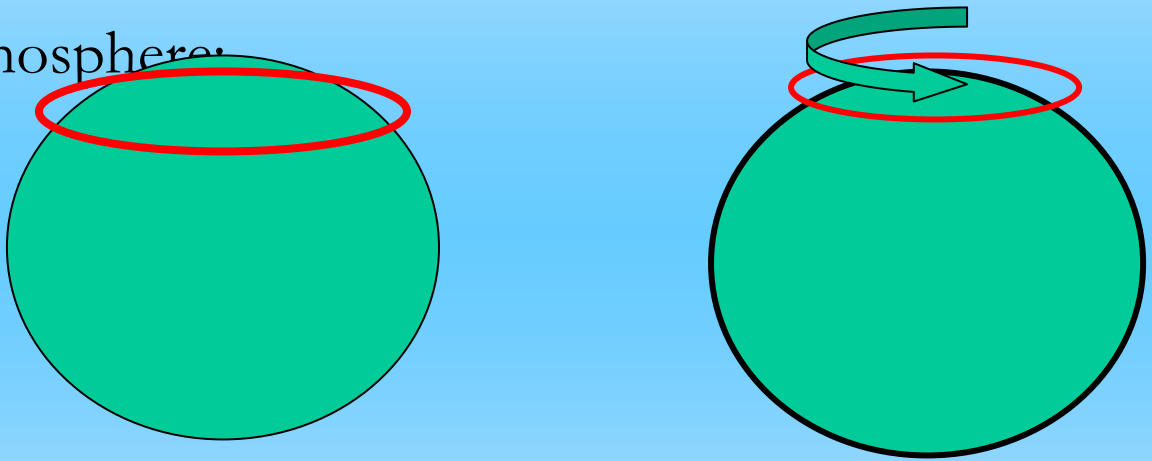
Reid, JMR 2005

Oceanic overturning circulations: coexisting with ‘horizontal gyres of wind-forced circulation





- MOCs have an easier time in the oceans than in the atmosphere:



a ring of air moved 1000 km north gains westerly velocity of 100 m sec^{-1} There is not enough energy available to utilize this mode: the Hadley cell is limited in north-south extent. Forces (eddy momentum flux from PV stirring) and non-symmetric circulation are required to support extensive meridional excursion.

Stationary and transient waves or bottom topography all allow poleward heat flux with small or zero Eulerian v-velocity, as in simple annulus experiment. Note significance of Rossby radius (NH/f where H = vertical scale of motion) the scale at which baroclinic APE ~ KE

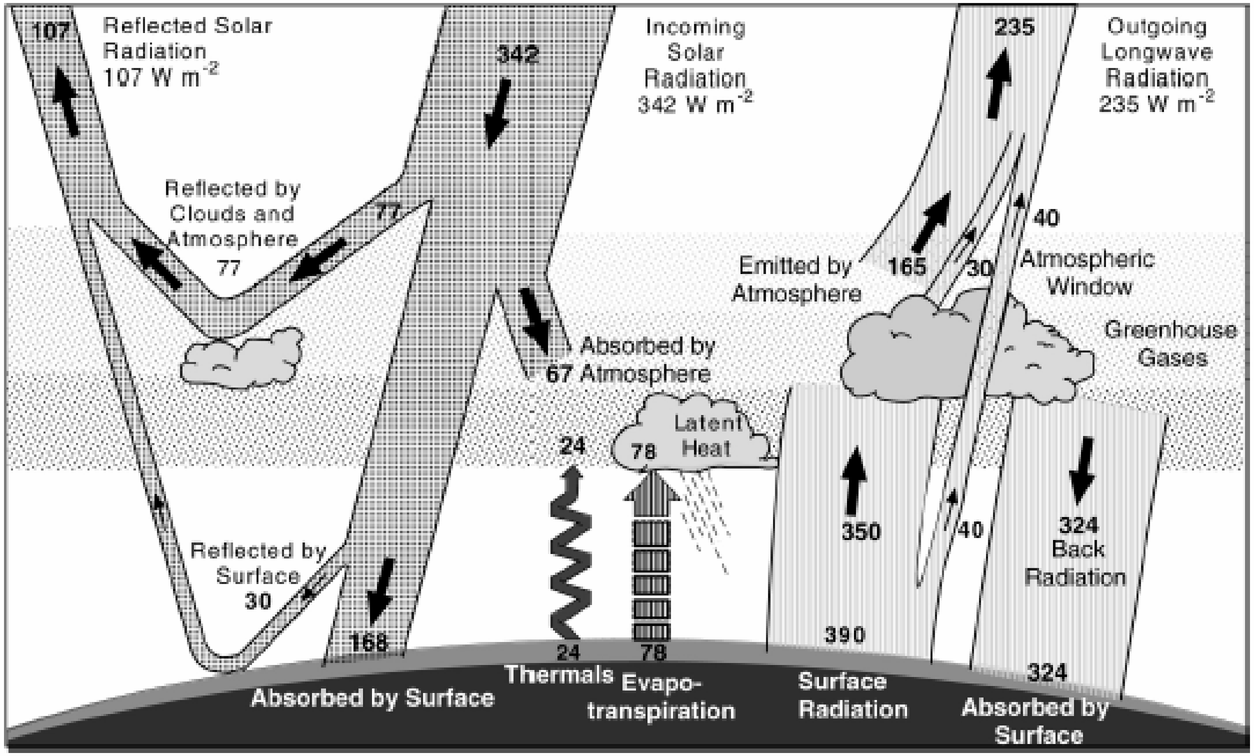


Figure 1. The earth's radiation balance. The net incoming solar radiation of 342 W m^{-2} is partially reflected by clouds and the atmosphere or at the surface, but 49% is absorbed by the surface. Some of that heat is returned to the atmosphere as sensible heating and most as evapotranspiration that is realized as latent heat in precipitation. The rest is radiated as thermal infrared radiation and most of that is absorbed by the atmosphere and re-emitted both upwards and downwards, producing a greenhouse effect, as the radiation lost to space comes from cloud tops and parts of the atmosphere much colder than the surface. From Kiehl and Trenberth (1997).

(31%)

consider the differences between tropics and Arctic…(a)at 60N latitude the sunshine incident per unit area is 50% of the full intensity with the sun overhead; (b) the albedo (whiteness) is greater

source: IPCC-01 / TRENBERTH

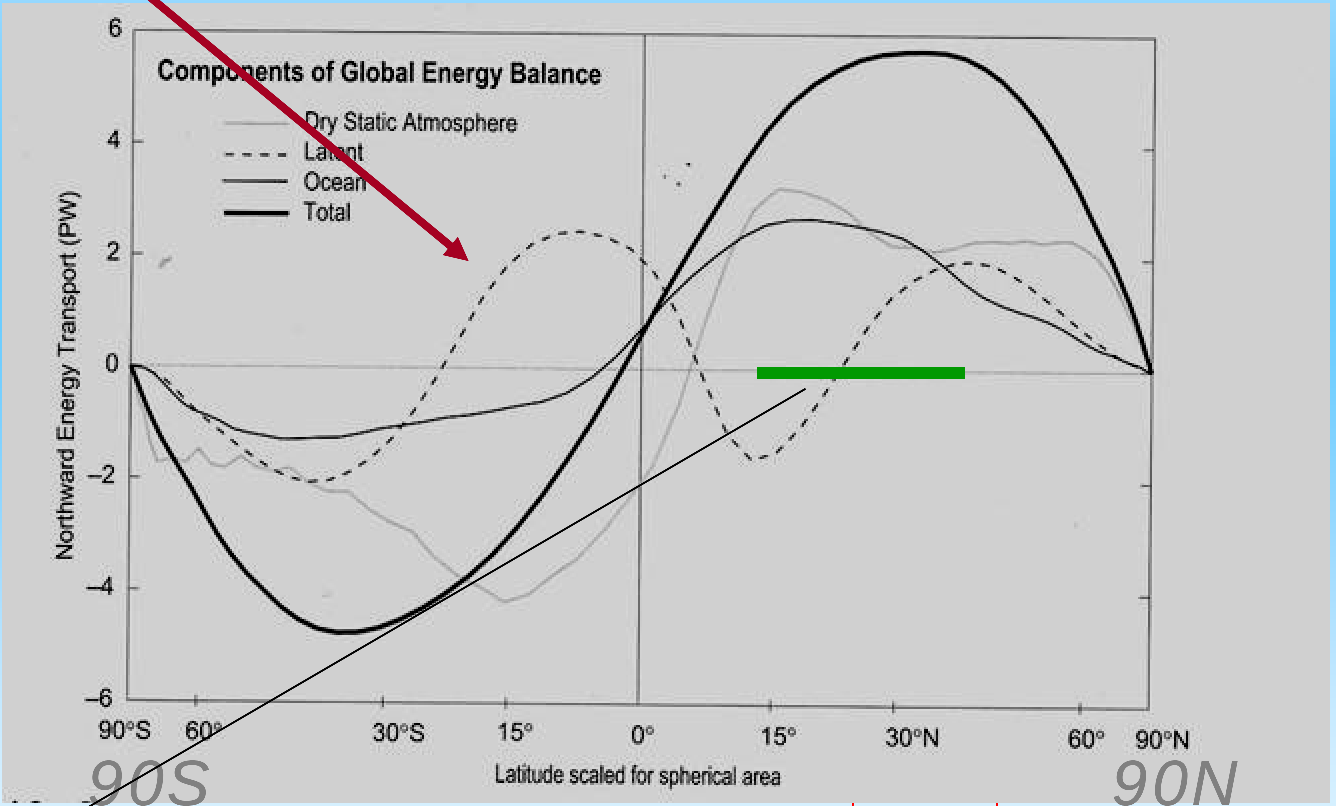
Is the ocean MOC important to atmospheric climate?

Global meridional heat transport divides roughly equally into 3 modes:

1. atmosphere (dry static energy) $c_pT + \Phi$ *(Bryden & Imawaki 2002)*
2. ocean (sensible heat)
3. joint atmosphere/ocean mode: water vapor/latent heat transport Lq

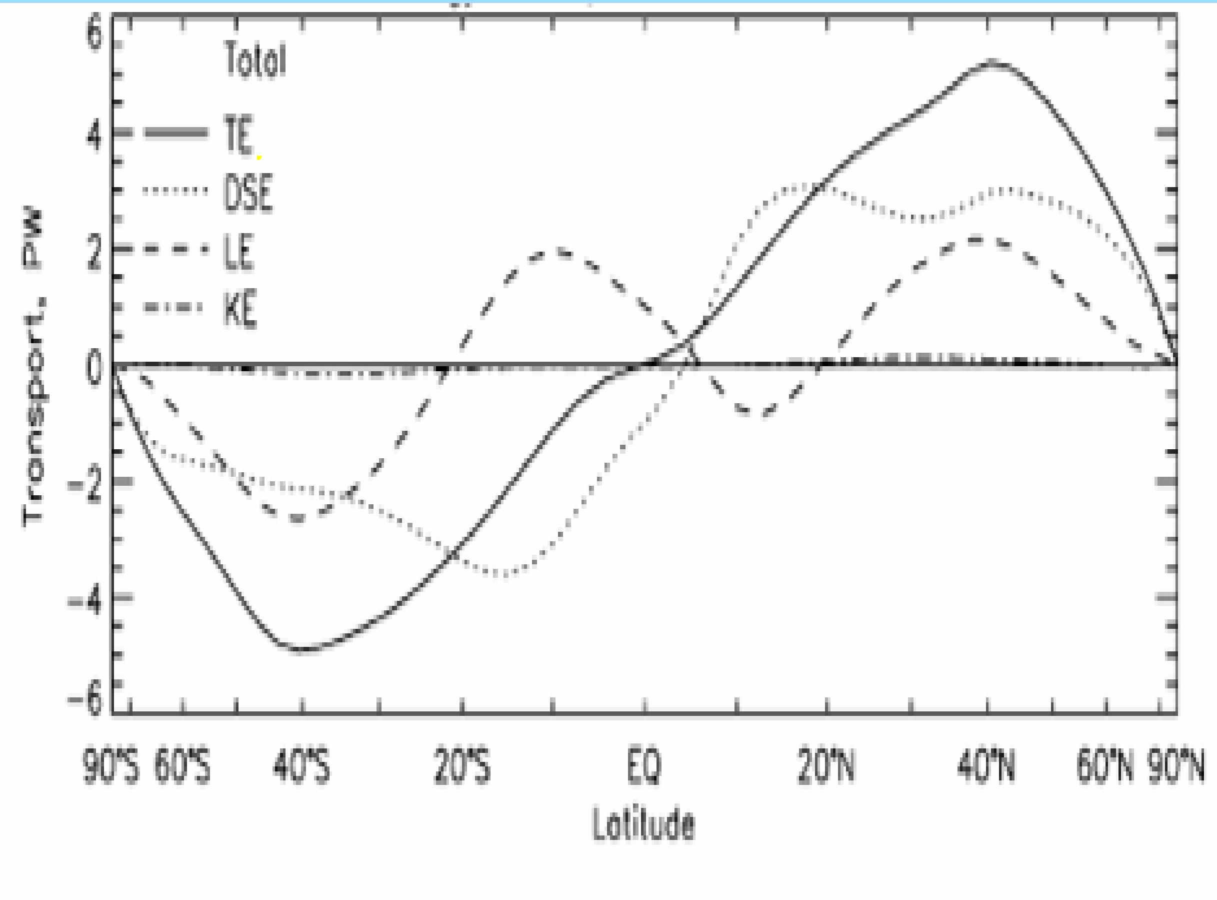
The three modes of poleward transport are comparable in amplitude, and distinct in character (sensible heat flux divergence focused in tropics, latent heat flux divergence focus in the subtropics) (based on Keith (Tellus 1995) climatology, similar to more modern: Trenberth *et al.* J.Clim 2003)

(residual method, TOA radiation 1985-89 and ECMWF/NMC atmos obs: redundant obs (air-sea flux) also available



the northern subtropics show extremely active upward air/

Error est.: ± 9% at mid-latitude; Bryden est 2.0 ±0.42 pW at 24N very similar numbers from Trenberth & Stepaniak,QJRMS 04



- So, ventilation of the tropics by atmosphere + ocean MOC's provides ~ 5 pW (5 x 10^{15} W); distributed over the area of the Earth between 0N and 30N, averages 5 x 10^{15} W/πR^2 =

39 W m^{-2}, delivering the same amount per m^2 to the Earth north of 30N.

Fully as much heat is carried in the atmosphere by 0.8 Sverdrups (megatonnes s^{-1}) moisture flux ~ 2 pW as by dry static energy flux. (using the heat of vaporization, 2.25 MJ kg^{-1})

(It is useful to talk about both oceanic and atmospheric mass (water or air) transports in Sverdrups (Sv):

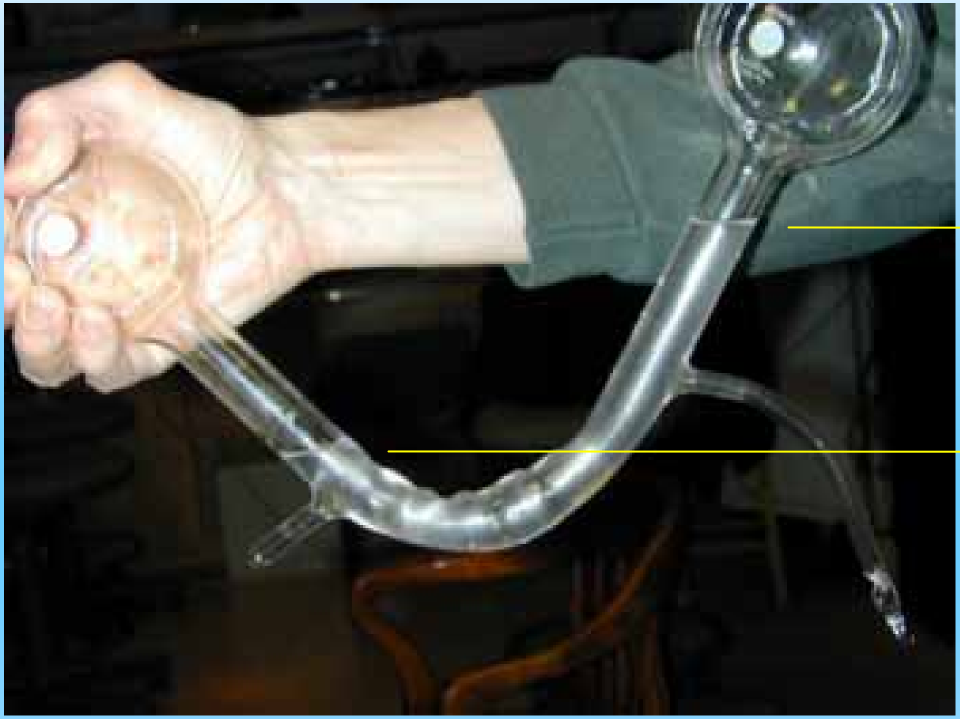
Gulf Stream 30-120 Sv

Antarctic Circumpolar Current~ 180 Sv

Atlantic MOC ~ 16-20 Sv

westerly winds/jet stream ~ 500 Sv

atmospheric MOC ~ 50 -100 Sv



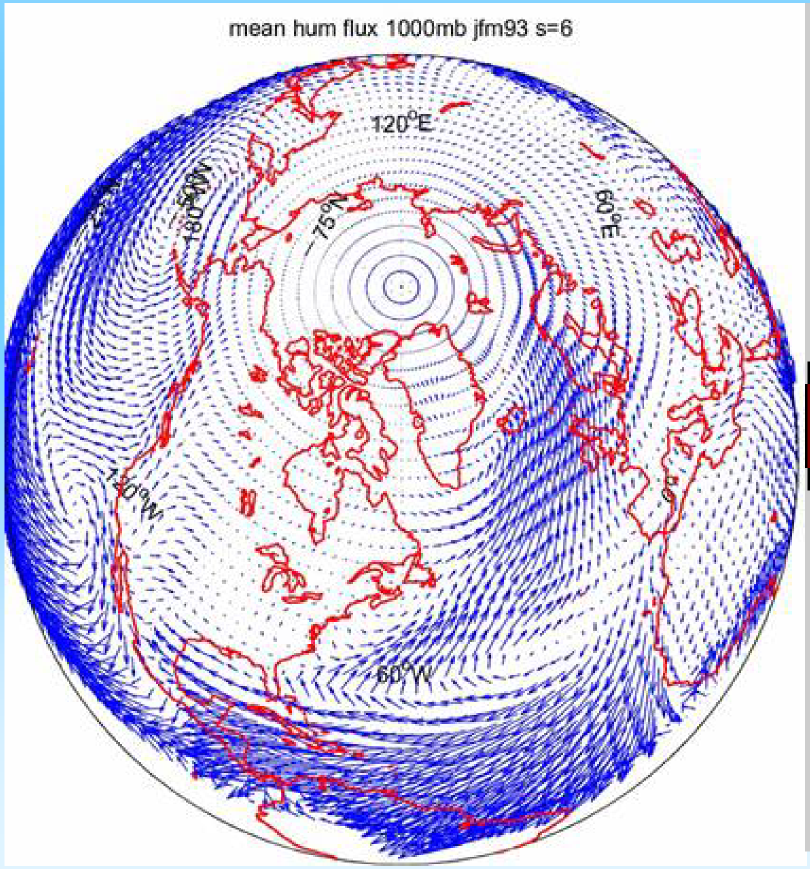
Hydrostatic pressure difference = vapor pressure of water (as a function of temperature

An evacuated glass vessel with water in it illustrates the Clausius-Clapyron relation between vapor pressure of water and temperature. The water is pushed from the vessel in my hand to the ‘cold ball’, and the vapor pressure difference between the two ends is close to the hydrostatic pressure measured by the column’s vertical displacement. One can fill out the curve and see the greater sensitivity (to temperature) of water vapor production at high, ‘tropical’ temperature. This all works because we shake the vessel so that a thin film of water lies under my warm hand. It illustrates a key variable in the climate system.

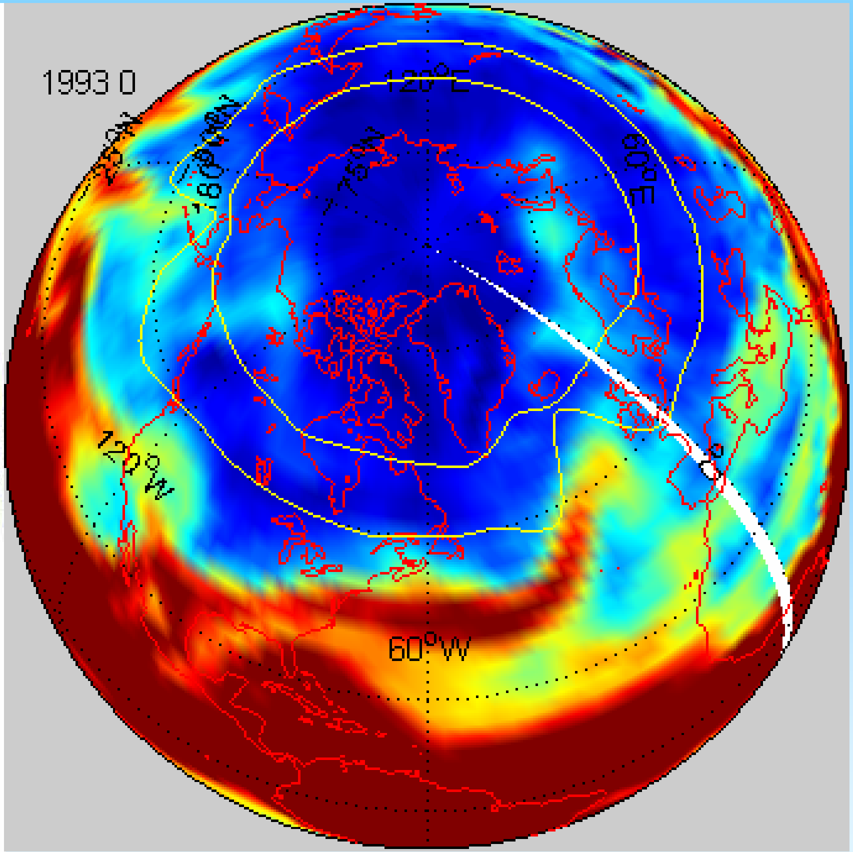
When shaken this water ‘clinks’ like metal,vapor cavities opening up and slamming shut.

Moisture flux during high NAO: concentration in the high-latitude storm tracks of the ~ 2 petawatts of latent heat flux … which is ~0.7 Sverdrup (0.7 megatonnes/sec) of freshwater flux

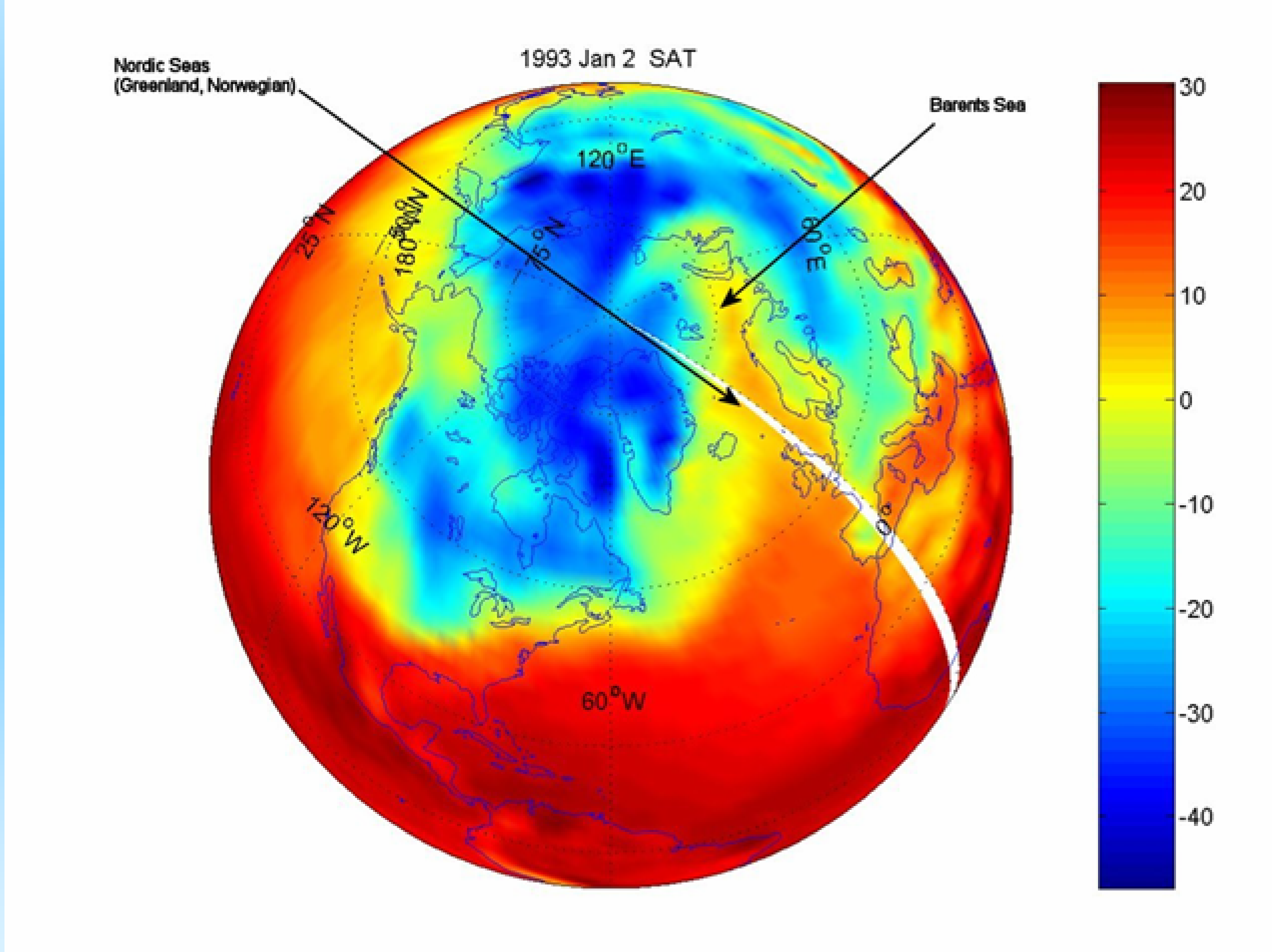
1993 JFM 1000mb moisture flux



1 Jan 1993 velocity column integrated water vapor (red=high, blue=low) and w.v. flux along 50N and 60N (yellow curves)



cold-air outbreaks: a source of deep convection (surface air temperature, 2 Jan 1993)



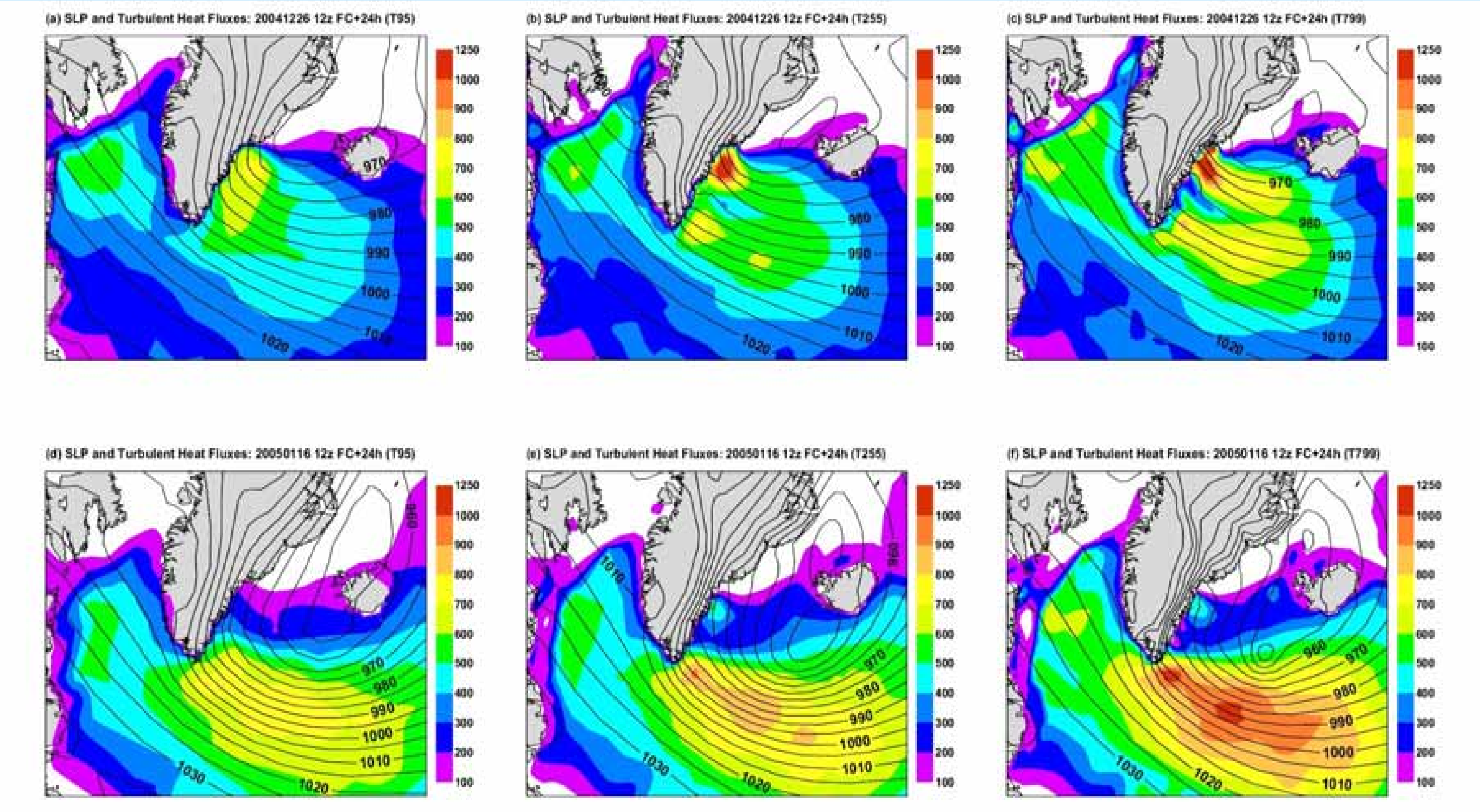
2. *Atmosphere/ocean forcing*

Effect on subpolar gyre of the Atlantic, and Greenland Sea: enhance air/sea heat flux: much intensified at higher model resolution

T95 (210 km grid) T255 T799 (25km grid)

25xii2004

17i2005



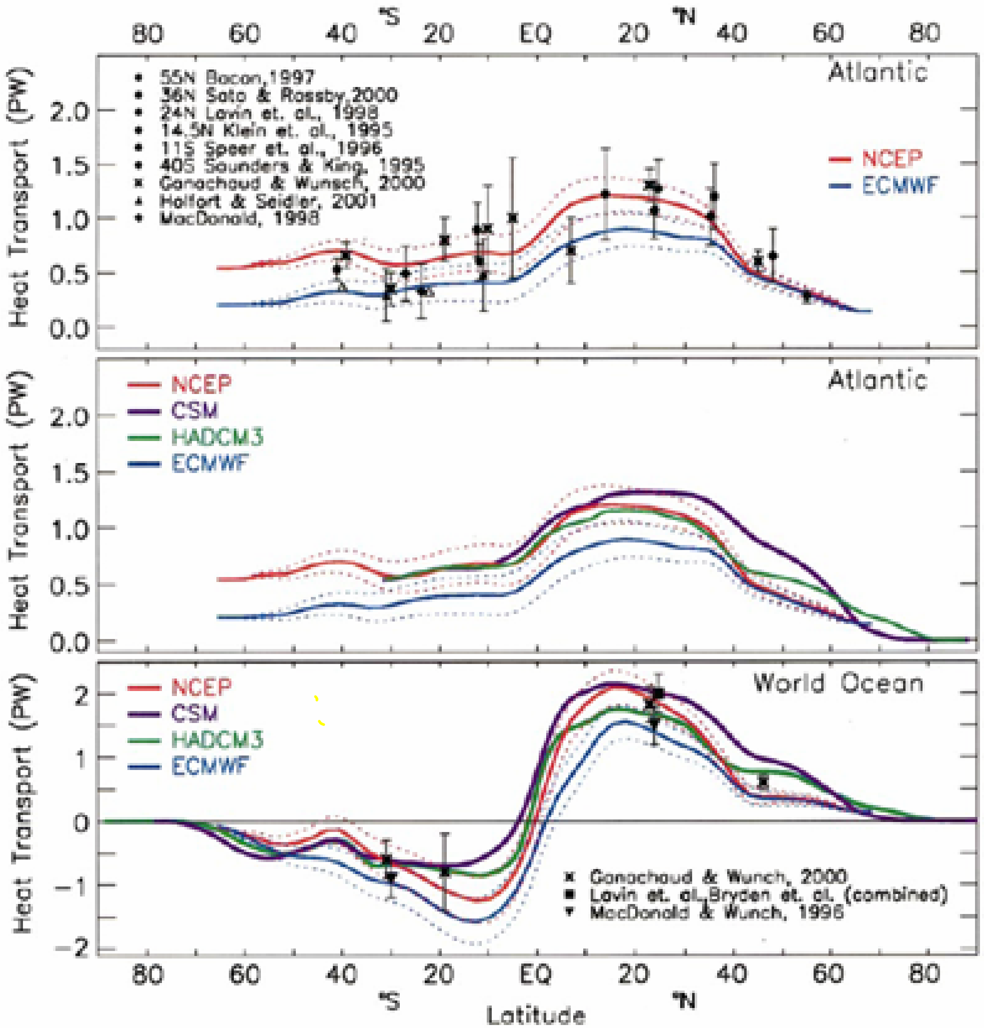


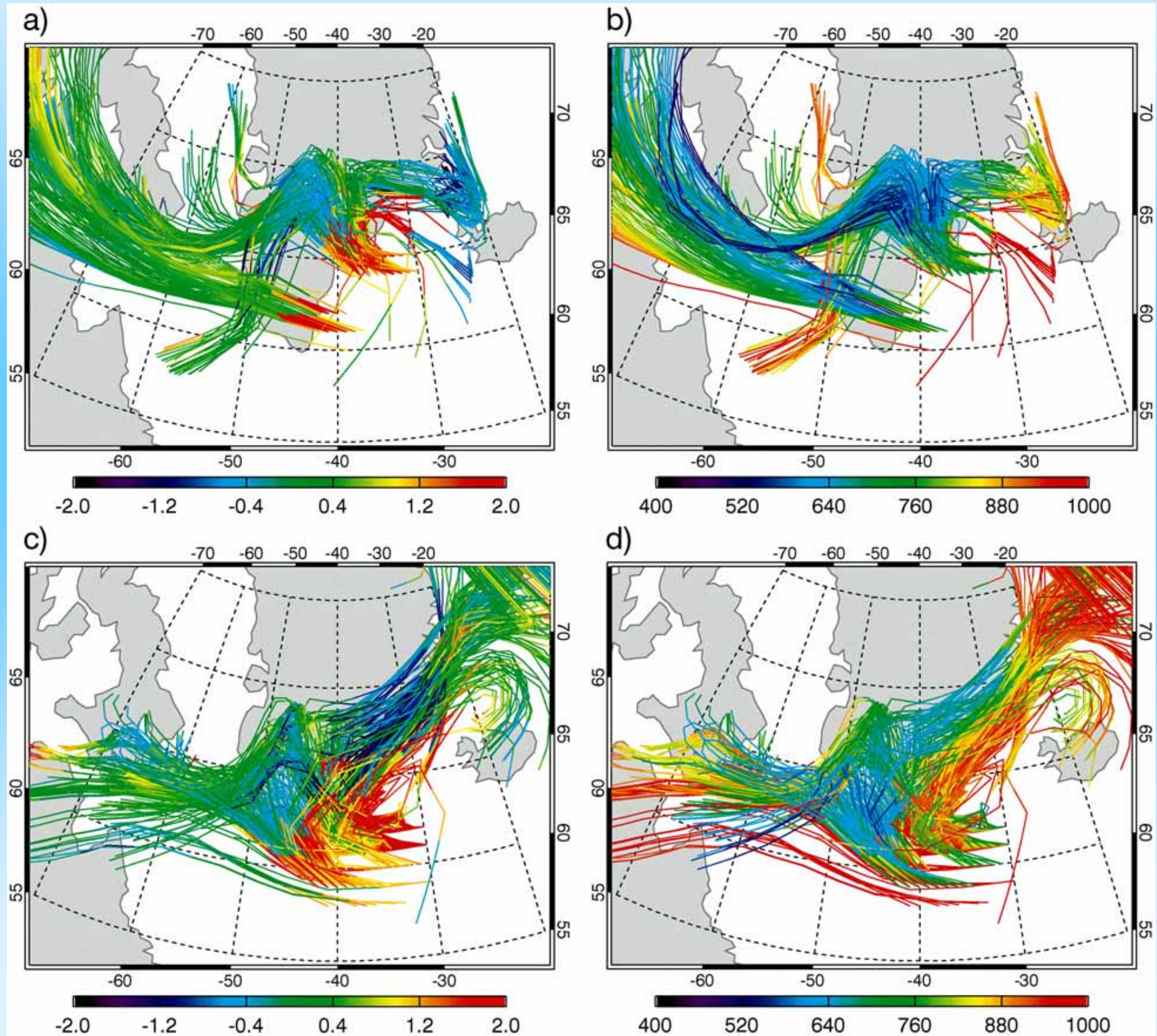
FIG. 6. The northward ocean heat transports from the NCEP-derived and ECMWF-derived products are compared (top) for the Atlantic Ocean with direct ocean estimates from sections, as identified in the key. The dashed curves show the ±1 std err for the derived transports. Where given in the original source, error bars are also plotted and the symbol is solid. Slight offsets in latitude are introduced where overlap would otherwise occur. Several sections are not exactly along a latitude circle, notably those for Bacon (1997) at ~55°N and the Saunders and King (1995) section along 45°S (South America to 10°E) to 35°S (Africa), plotted at 40°S. (middle) Comparison of the derived results with transports from the HADCM3 (years 81–120) and CSM (years 250–299) coupled models for the Atlantic. (bottom) Results for the global ocean along with those from Macdonald and Wunsch (1996) at 24°N and 30°S, and at 24°N the combined Lavin et al. (1998) and Bryden et al. (1991) and for Ganachaud and Wunsch (2000).

Ocean heat transport by MOC
Trenberth & Caron
JClim01

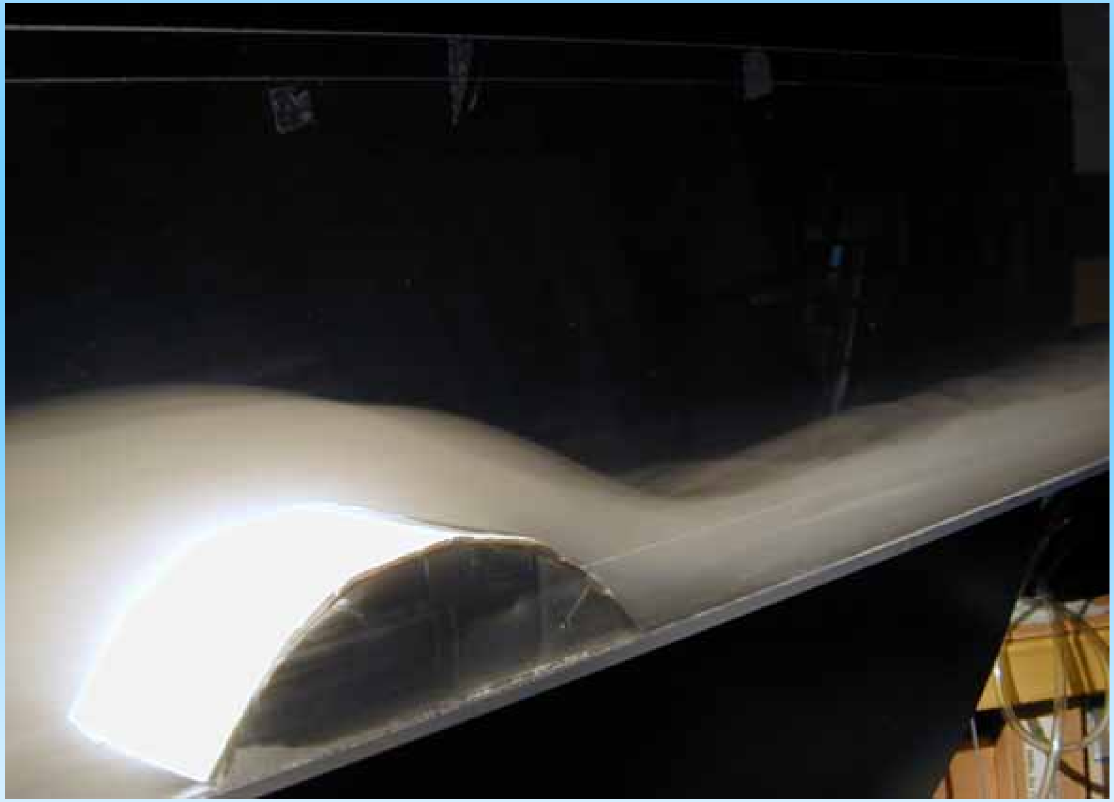
merid. heat transport at 35N: 78% A, 22% O;   18N: 50% A, 50% O vorticity colors | altitude colors

25-27 Dec 04

15-17 Jan 05

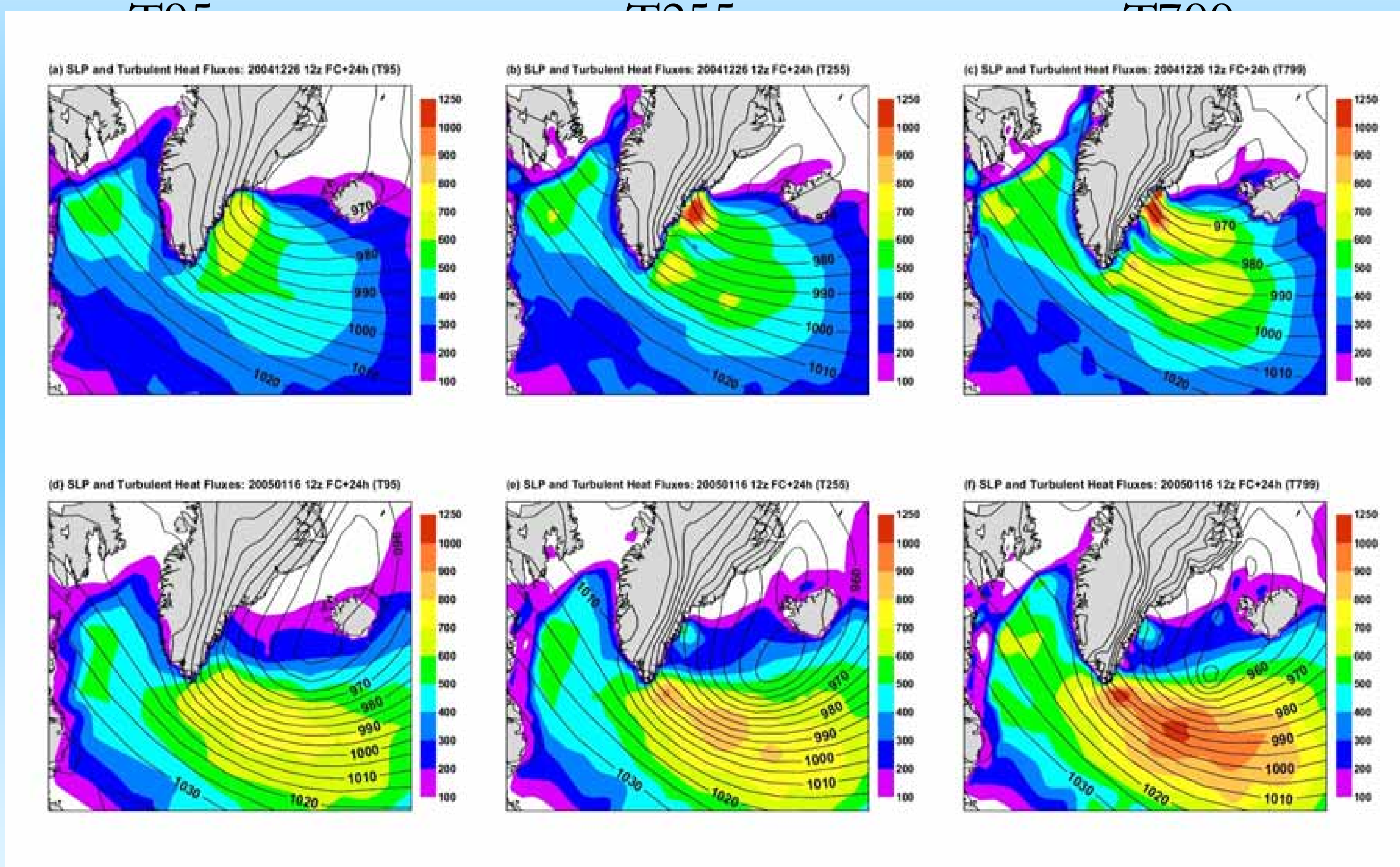


Downslope winds increase wavedrag (by Bernoulli) here in a layer of CO_2



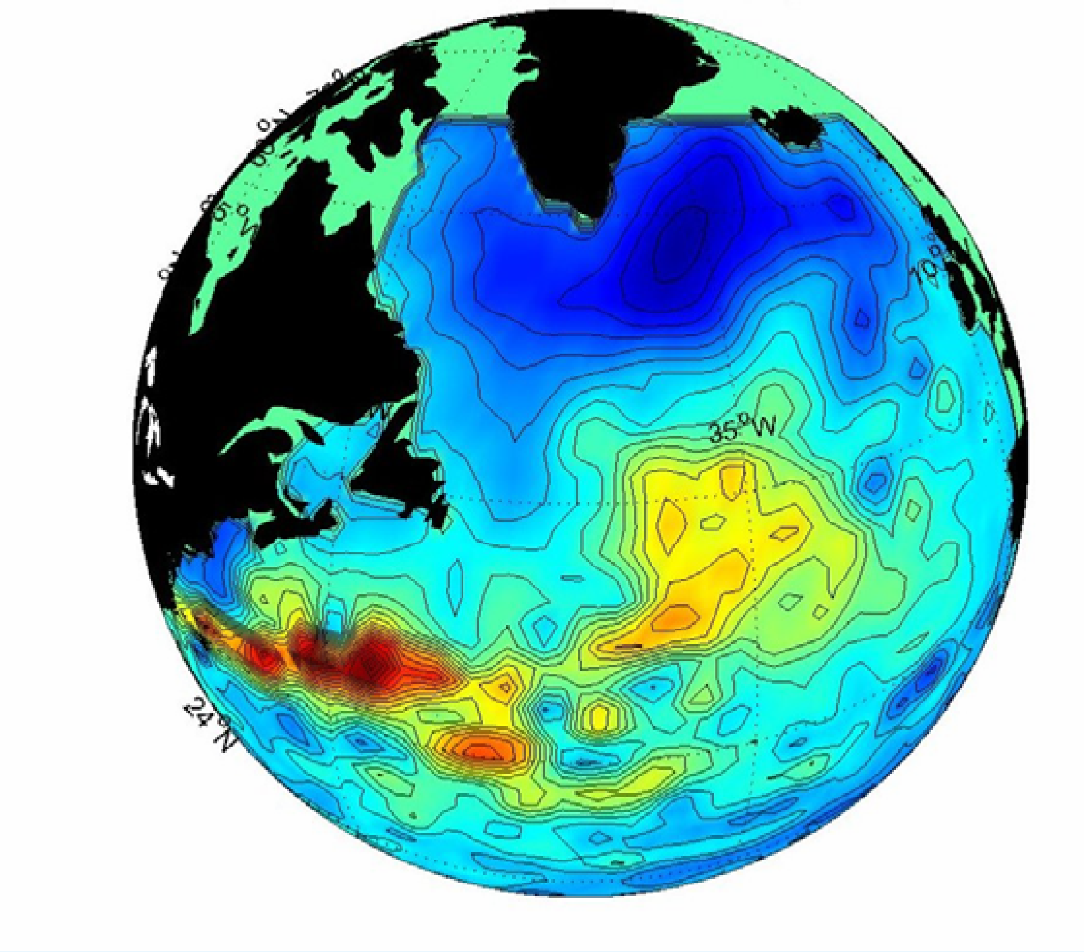
Effect on subpolar gyre of the Atlantic, and Greenland Sea: enhance air/sea heat flux: much intensified at higher model resolution

T95 T255 T799



Principal eof of sea surface elevation, 1992-2006, which is mostly a simple trend, showing deceleration of the subpolar Atlantic gyre over 15 years

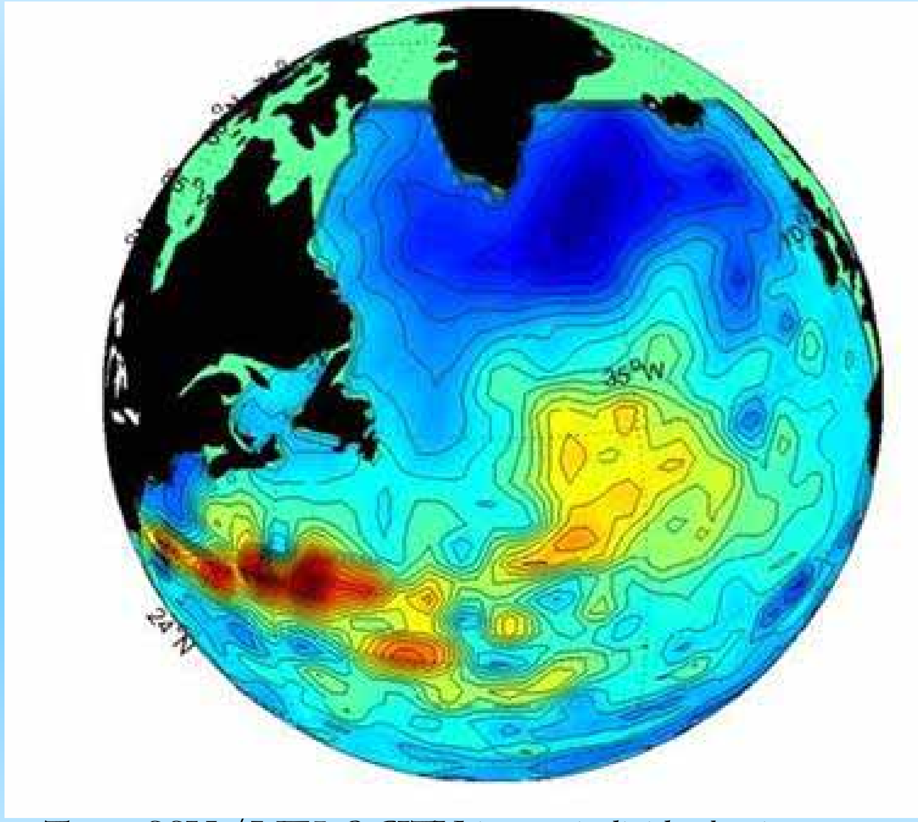
Häkkinen & Rhines 2004 Science

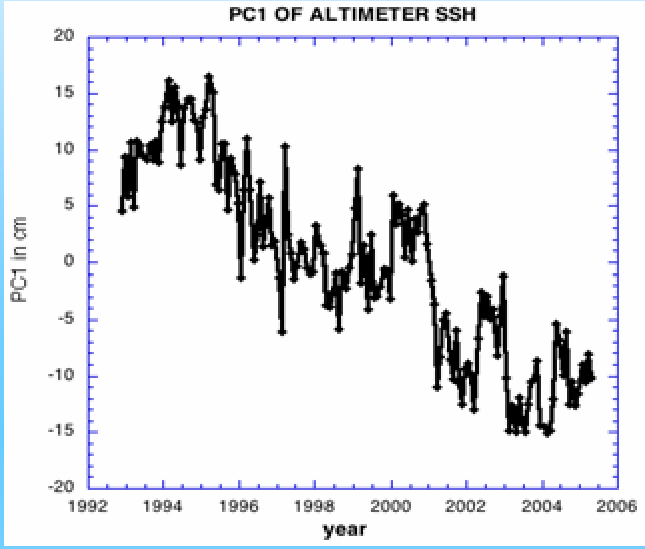


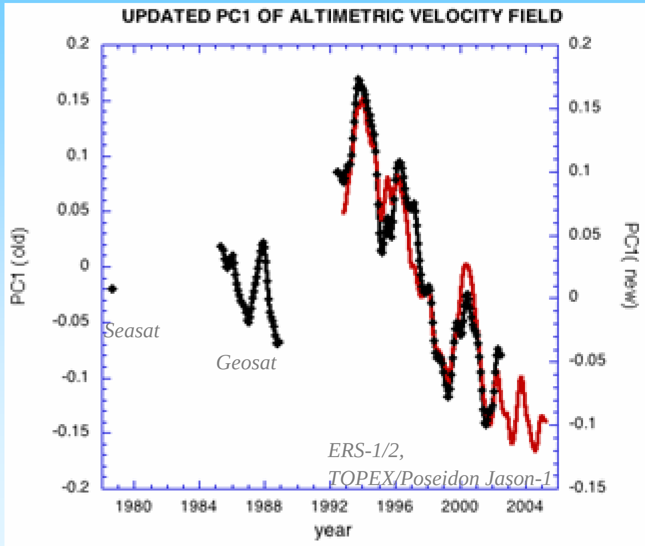
Principal eof of sea surface elevation, 1992-2006, which is mostly a simple trend, showing deceleration of the subpolar Atlantic gyre over 15 years

Häkkinen & Rhines 2004 Science

(update using only TOPEX/Poseidon and Jason-1 data, time period covered: October 1992 to March 2005;

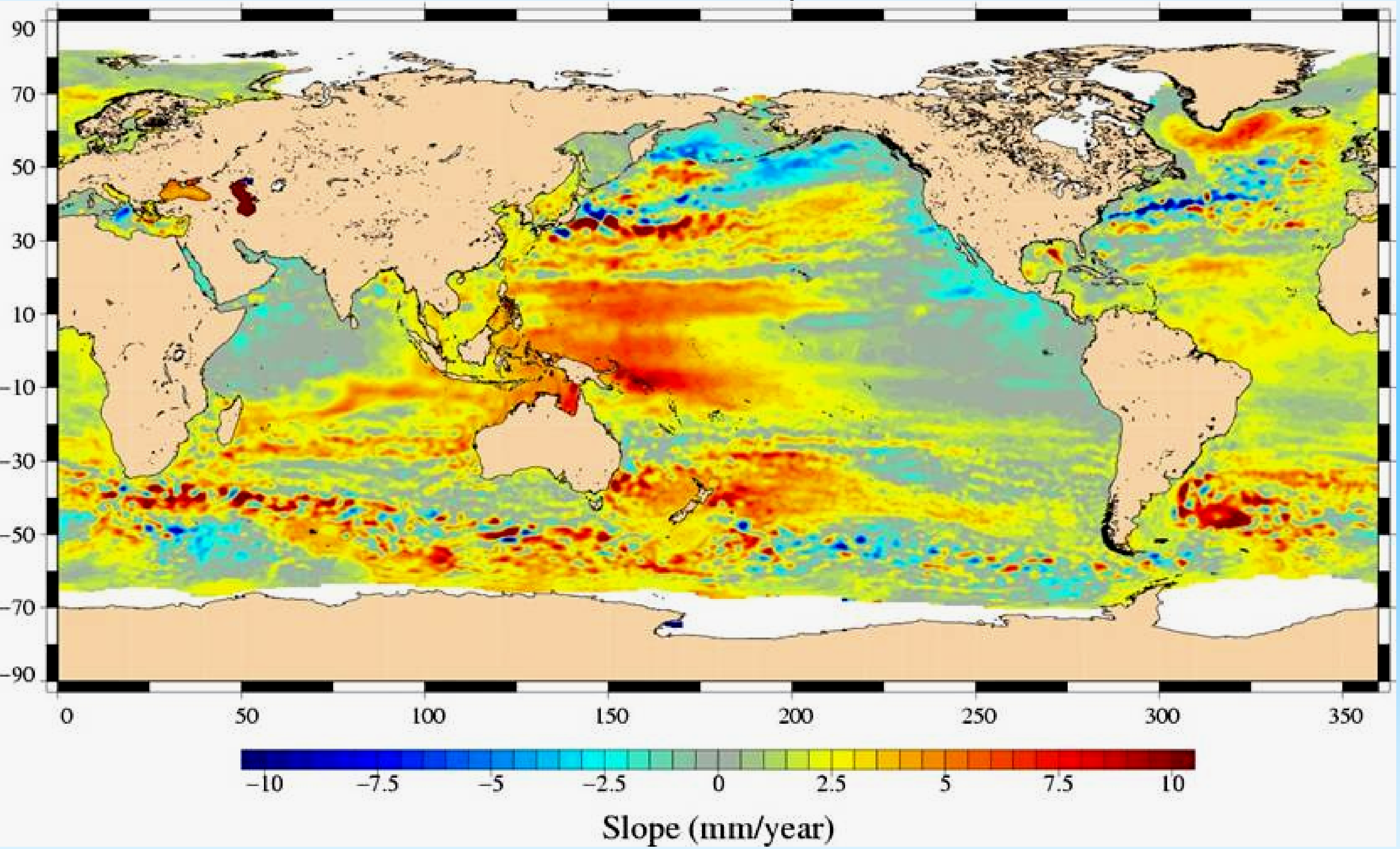






To get SSH / VELOCITY in any individual point one needs to multiply the value of the spatial pattern (left) by the time series value on the right) SSH has units of cm velocities are normalized so they are dimensioless

satellite altimetric height (AH) sea surface trend, 1992-2006



global warming signal + gyre scale dynamics: expansion & acceleration of subtropical gyres, poleward migration of polar fronts; equatorward migration of Gulf Stream, decel of Atl SP gyre, accel of NPac SP gyre

North Atlantic

ALT, 2003/05 – 1993/95

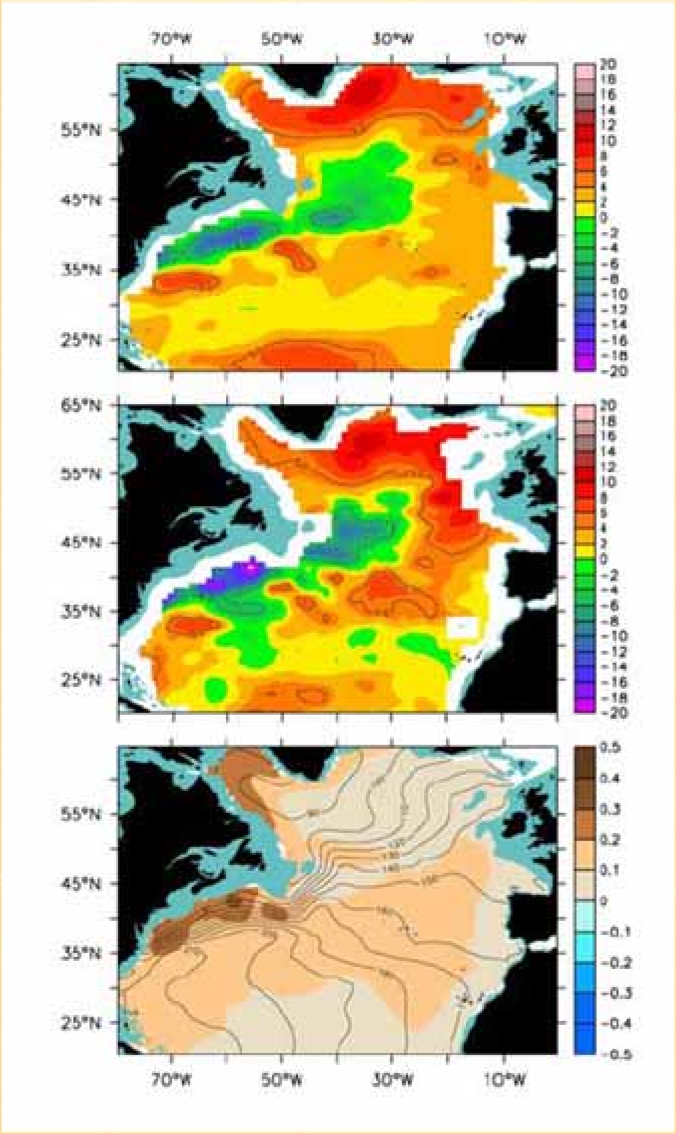
Altimetric surface height trend

Willis-B, SH 0/750 db: 2003/05 – 1993/95

Steric surface height trend

Colors: Argo – WOA01 upper 200 m salinity anomaly

Contours: Argo DH 0/2000 db

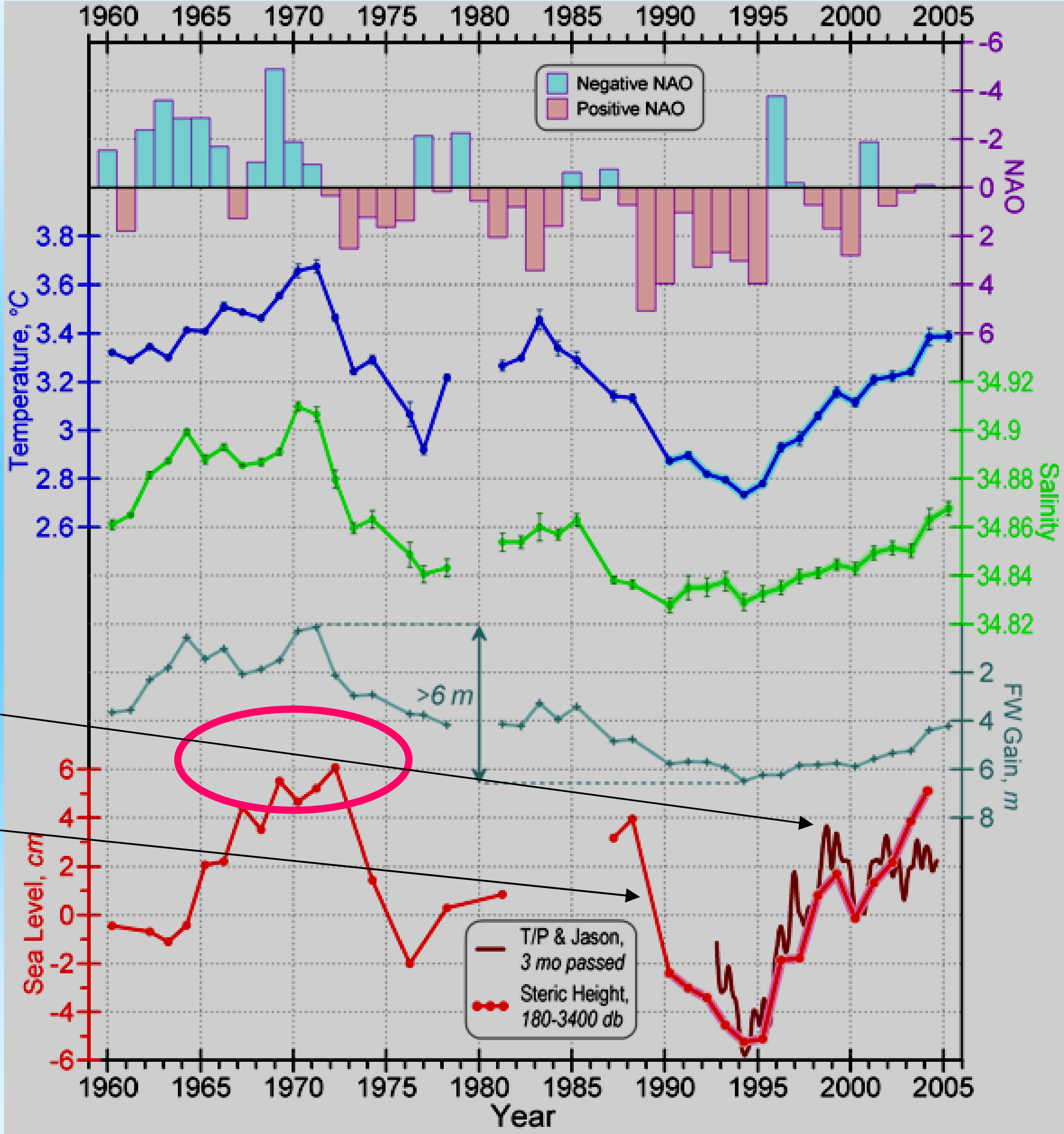


Pattern is similar to North Pacific.

Subpolar gyre decreasing in strength (Hakkinen and Rhines, 2004)

High salinity, reversing the previous decadal freshening (Hatun *et al*, 2005, Peterson *et al*, 2006) is attributed to increased input of subtropical waters.

figure from D. Roemmich (NASA OSTST, Hobart, 2007); Willis, Roemmich & Cornuelle, 2002 JGR

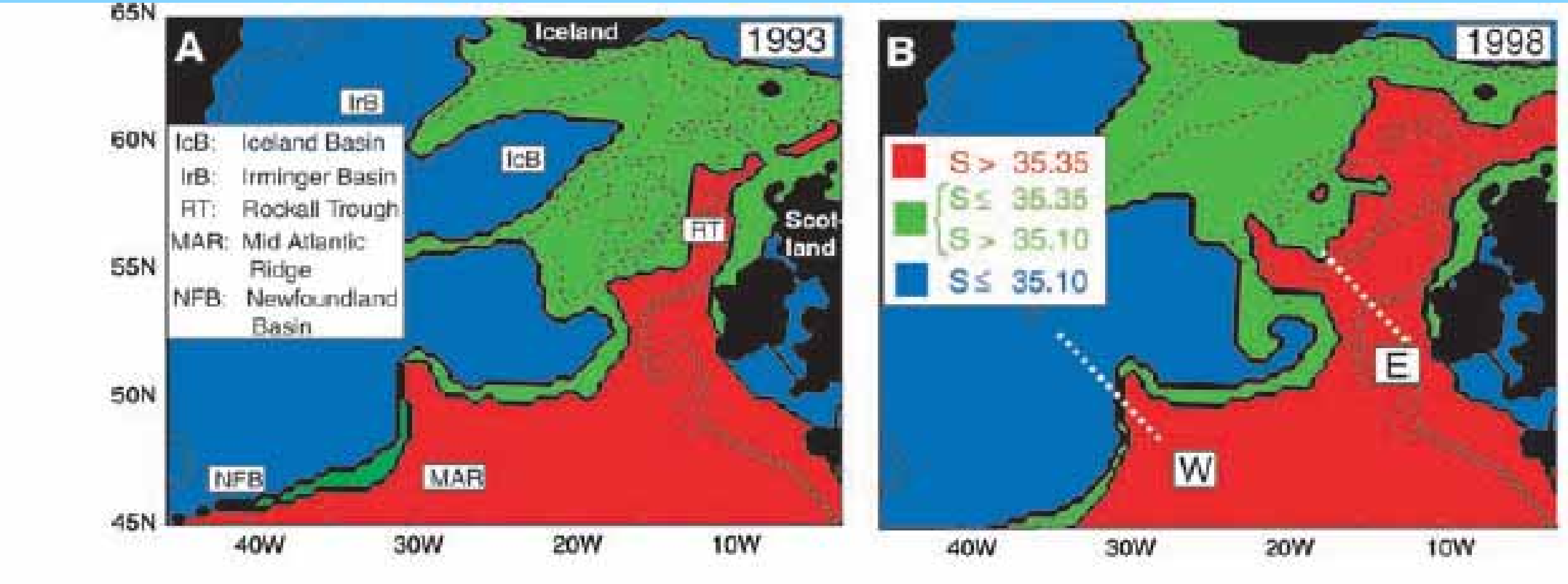


Igor Yashayaev, 2006

altimetric height and steric height: a 2-mode description of the circulation

1960s dynamic-height maximum equal to today's ....GSA.... paradox: the high-latitude world is very barotropic!

accompanying surface SP gyre deceleration is the opening of the eastern Atlantic meridional pathway to stronger advection of subtropical waters by NAC extension (*Hatun et al.Science 2005).*

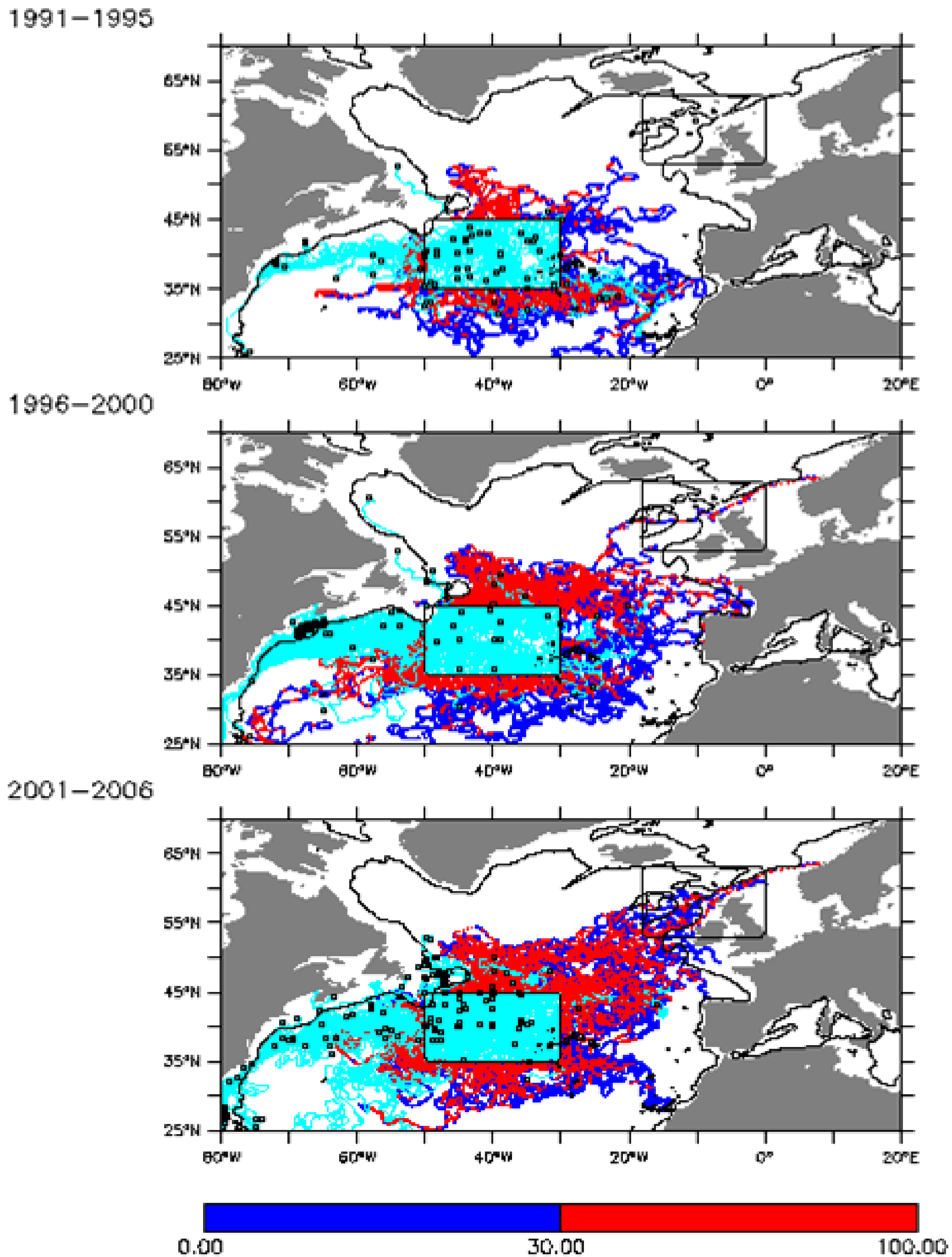


This shift can also be seen with surface drifters….

early
1991-95

middle
1996-2000

late
2001-2006



'departure' Lagrangian-mean flow: drifters released in a subtropical Gulf Stream box (red, blue)

red: speed> 30 cm/sec

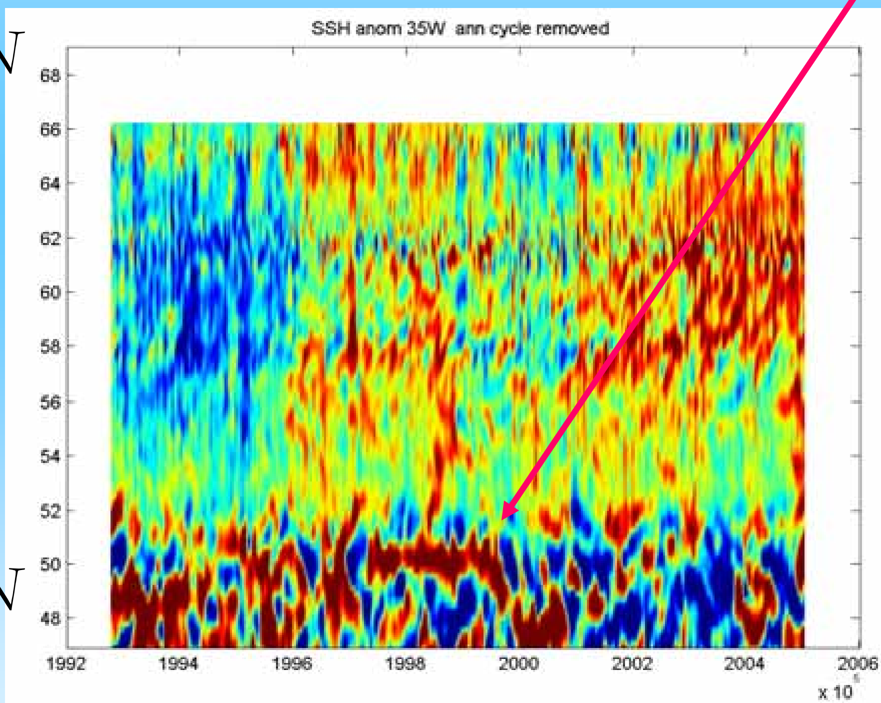
cyan: drifters arriving at box

Häkkinen & Rhines 2007

Sea-surface height anomaly vs. distance and time: subpolar Atlantic

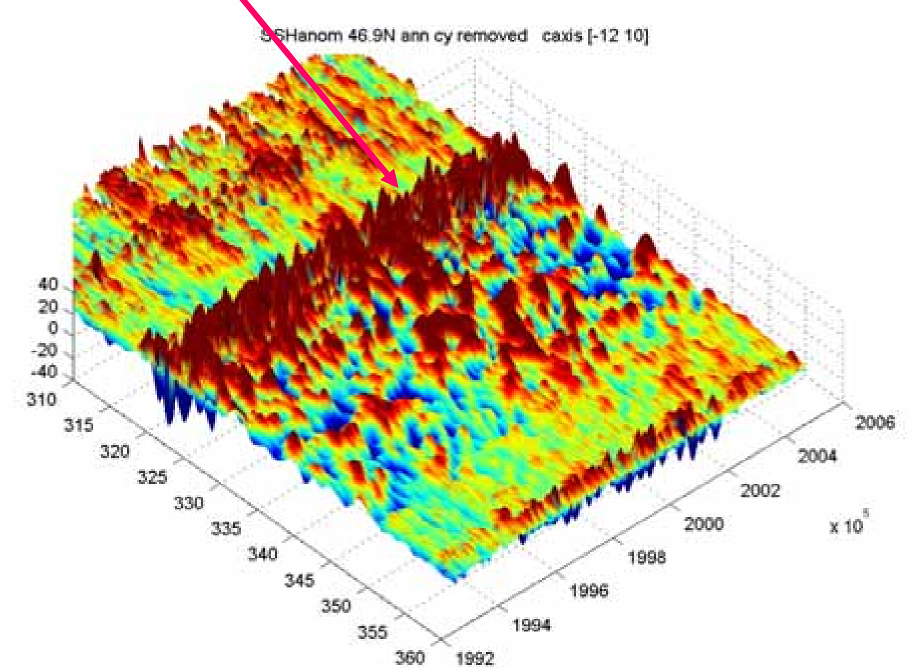
time/latitude at 35W longitude *North Atlantic Current* *time/longitude at 46.9N latitude*

68N

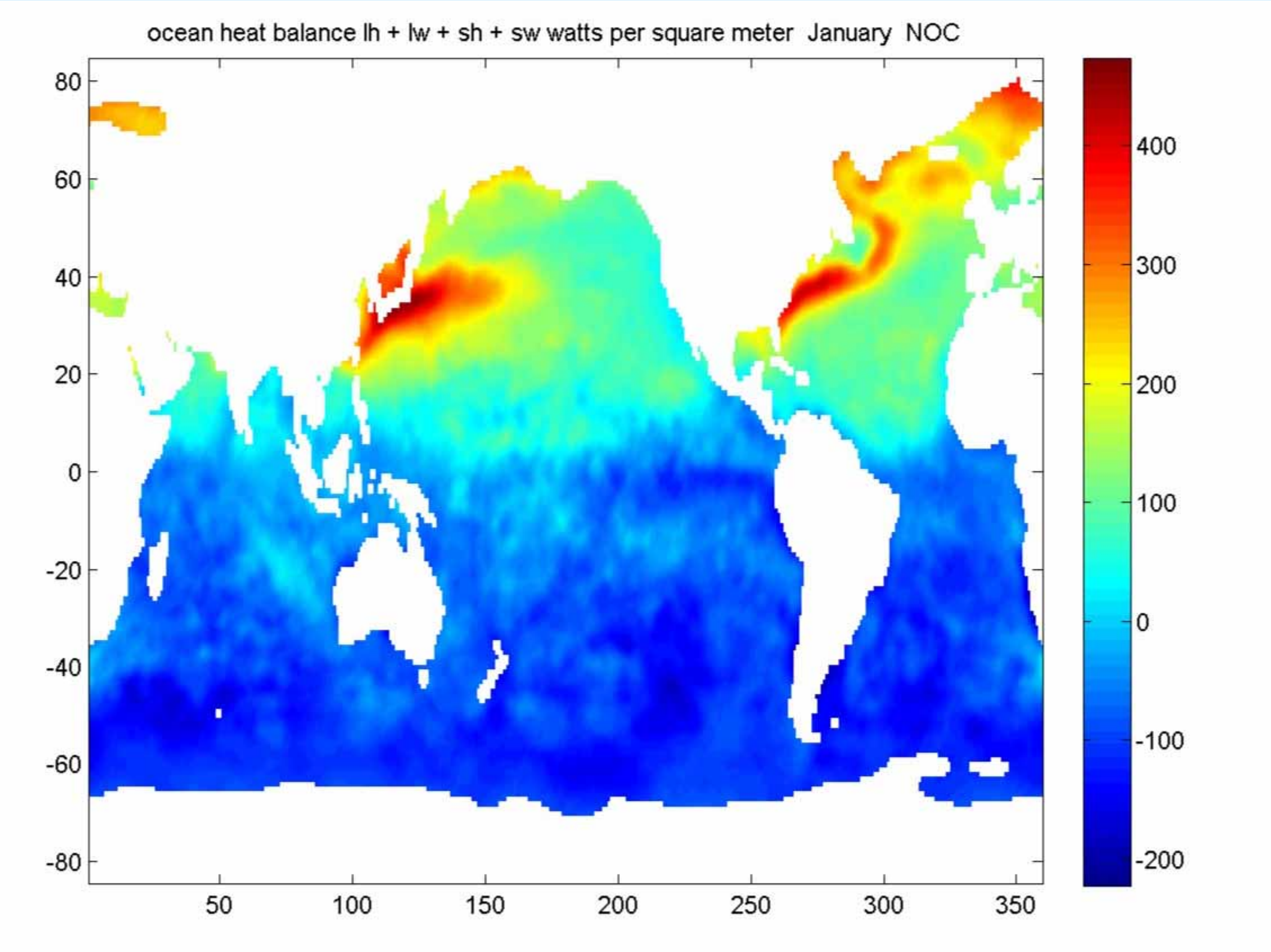


48N

1992 2005

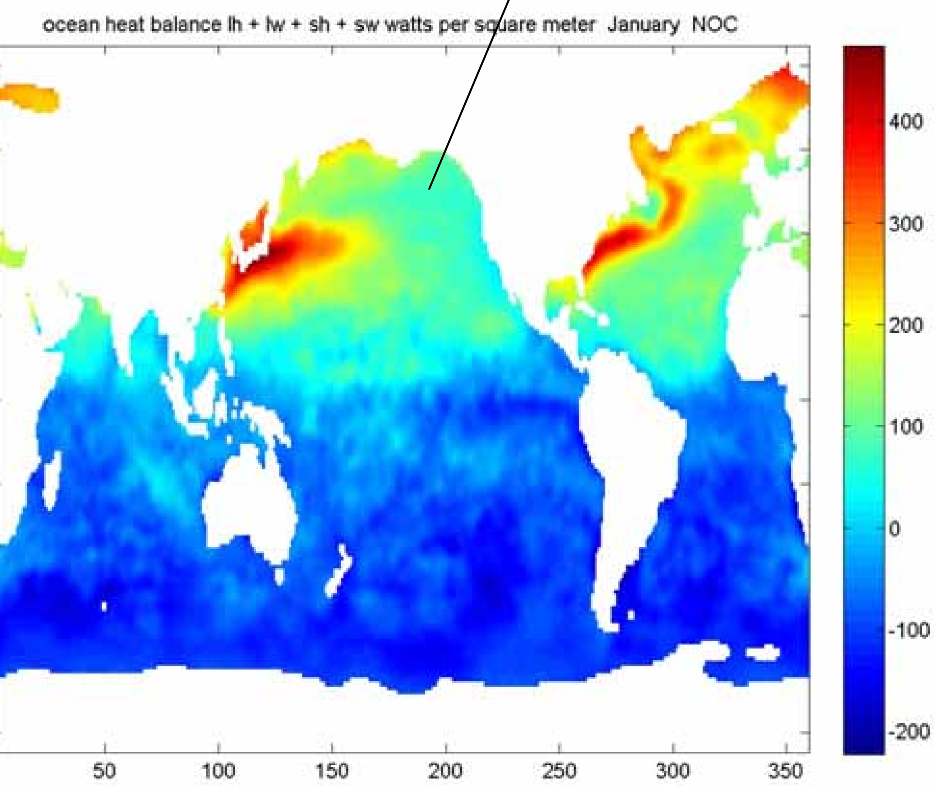


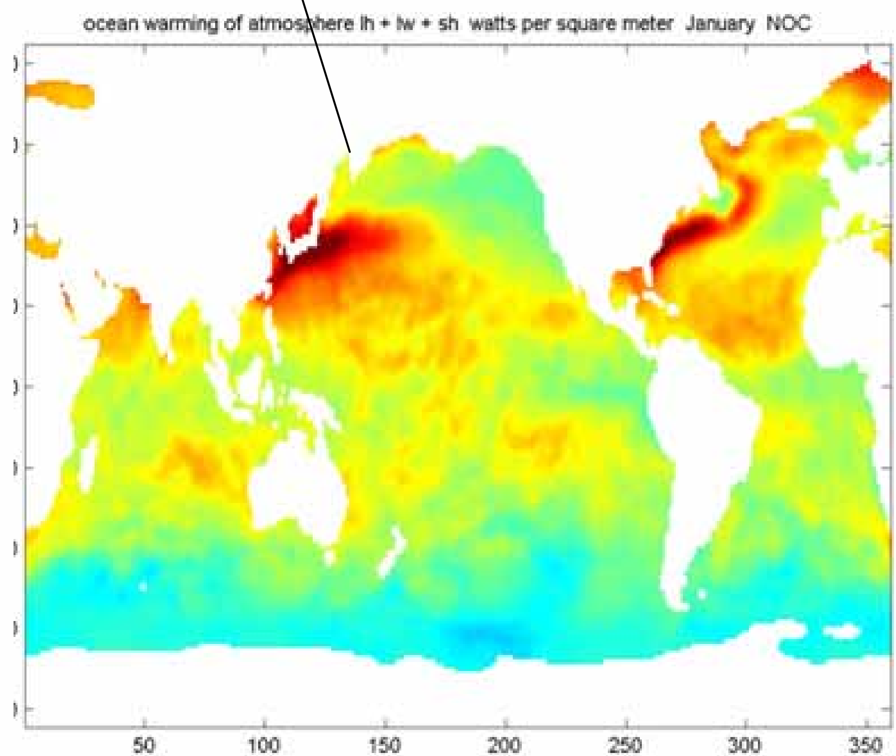
Where is air-sea heat flux most intense? January (W m-2) (SOC/NOC1.1a climatology based on COADS)



The air/sea heat flux seen by the atmosphere (latent+sensible+long-wave rad)

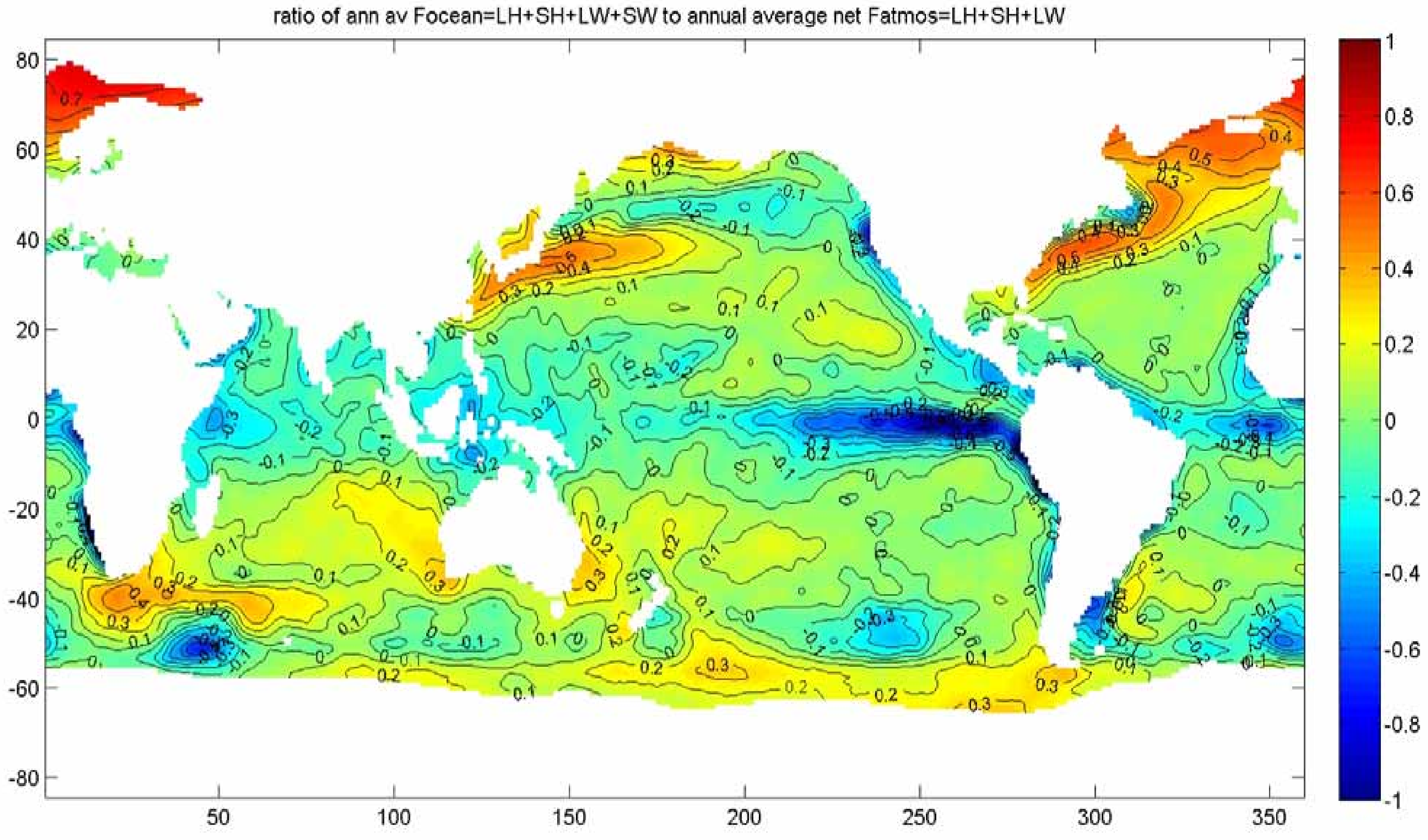
and by the ocean (latent+sensible+long-wave + short wave solar rad)





the sun heats the ocean, but does not cool the atmosphere: so the right-hand figure shows much bigger warming of the atmosphere than the left-hand figure

Annual average ratio of convergence of heat flux by ocean circulation divided by annual average heating of the atmosphere by ocean: (LH+SH+LW+SW)/(LH+SH+LW)



Held et al. (J.Clim.02) 100mb-1000mb diabatic heating for January

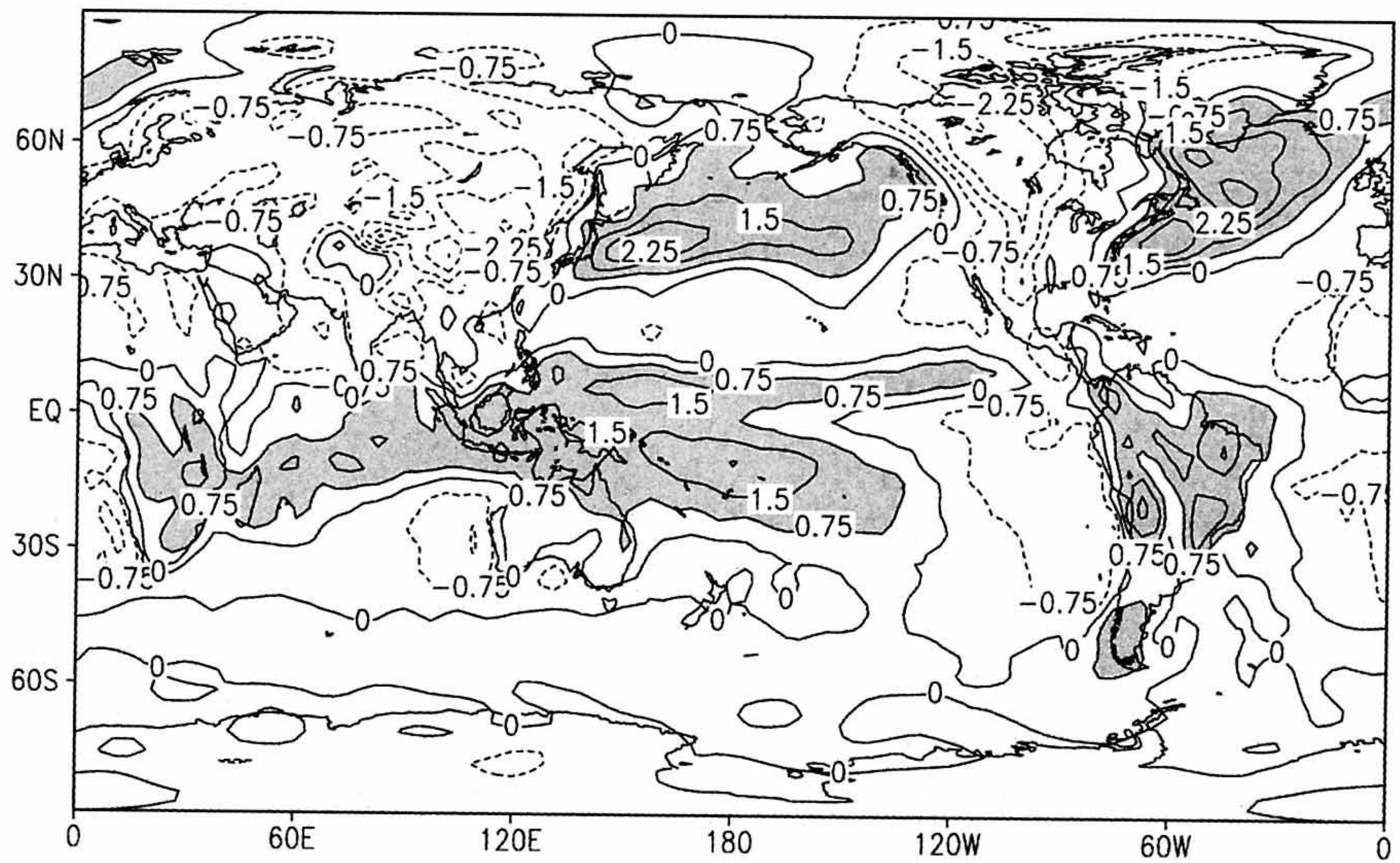


FIG. 8. The column-averaged diabatic heating field in Jan obtained from the NCEP–NCAR reanalysis as described in the appendix. The contour interval is 0.5 K day^{-1}.

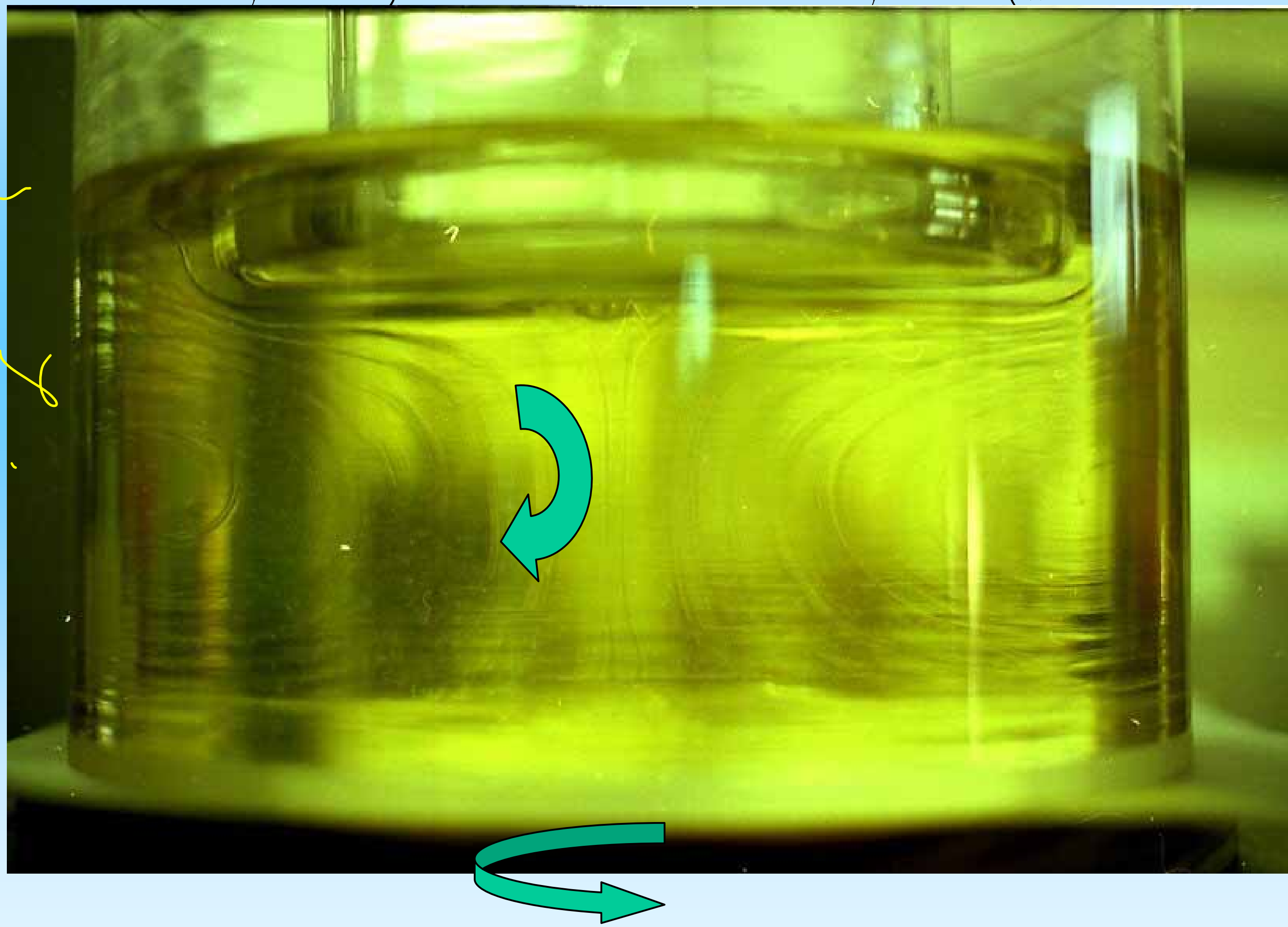
A baroclinic vortex created by injecting water at mid-depth into a stratification

Note purple dye shows azimuthal velocity exists above and below the water mass!

The MOC (meridional circ) drives 3 vortices

viscous overturning in a rotating cylider:
the radial/vertical plane transmits stress from the top plate (which is at rest in the laboratory frame) and the bottom of the cylinder (which is rotating)

The Ekman layers are very thick!



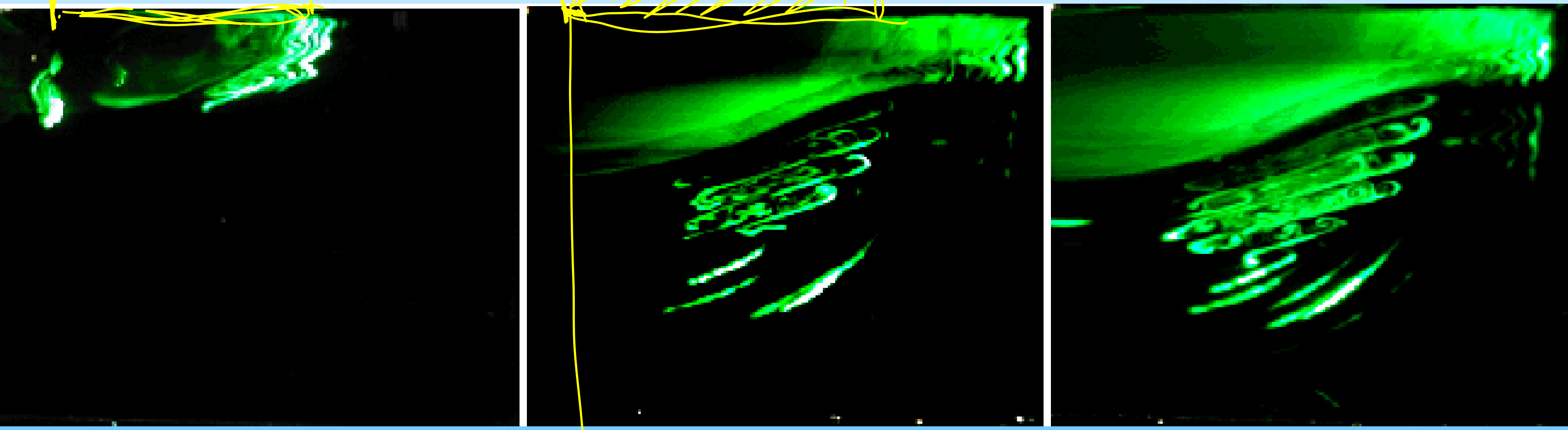
sugar syrup

Overturning cells in an annulus of fluid between concentric cylinders (the inner cyclinder is rotating, the outer cylinder is stationary (Taylor-Couette flow).

The cells transmit torque between the solid cylinders more strongly than would pure viscous diffusion.

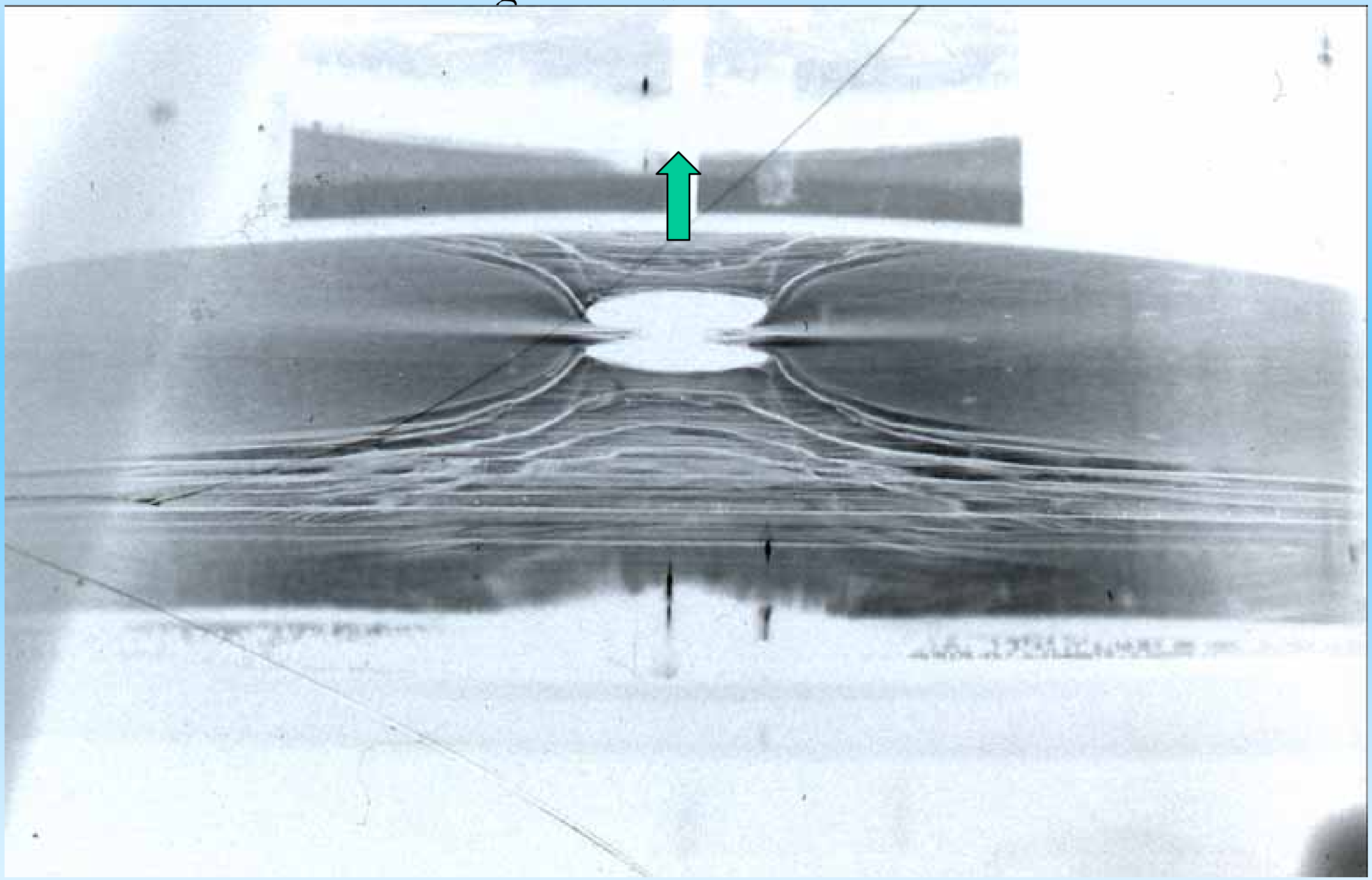
(The same 2D equations govern thermal convection, and the Nusselt number expresses the analogous increase in heat flux above the diffusive rate).

MOCs organized by double diffusion



disk drives an anticyclone (warm eddy) in uniformly stratified fluid

Sink-driven flow in a rotating, stratified fluid: the cyclonic spin of the fluid would be resisted by bottom Ekman friction (and all radial inflow concentrated there in this tornado vortex); However, stable stratification resists and forces continuing MOC within the fluid. The azimuthal velocity

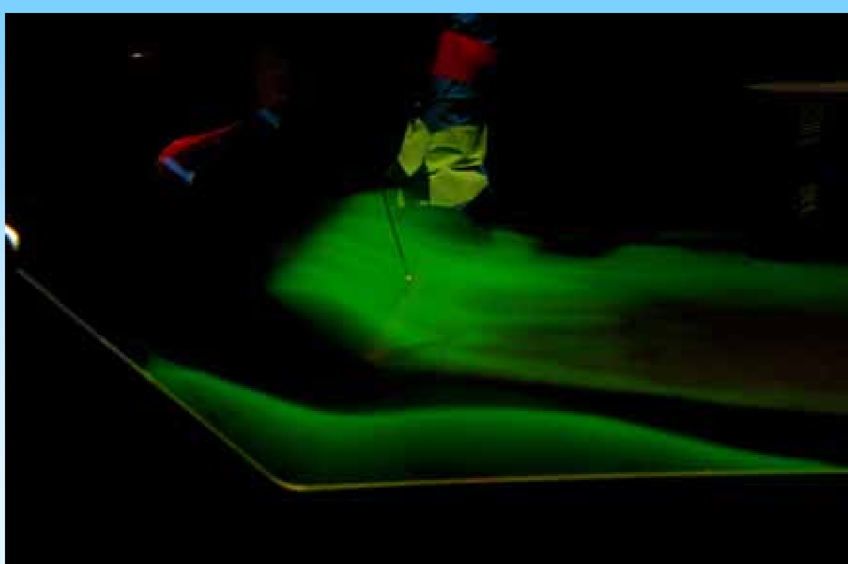


GFD lab, Univ of Washington

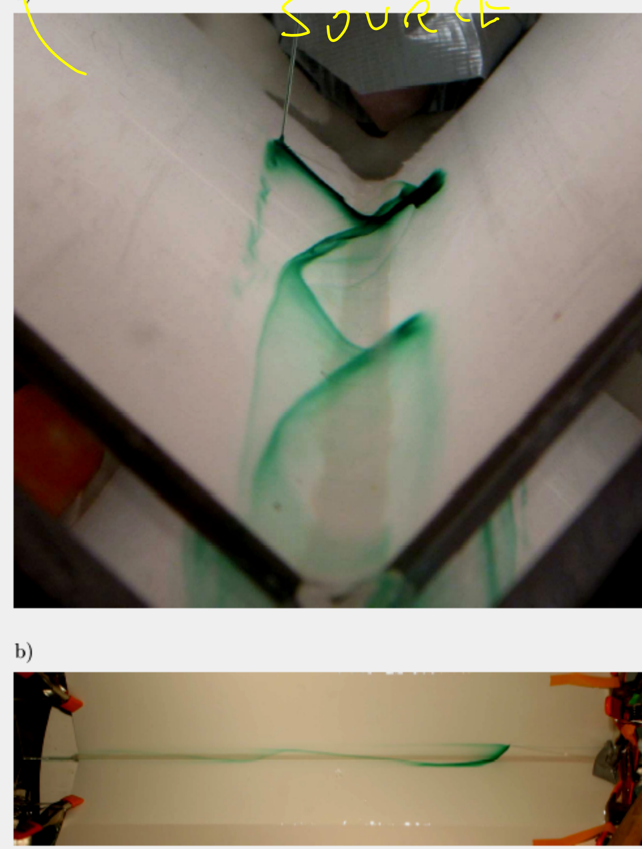
Dense plume flowing down a sloping valley in a rotating fluid (model of dense downslope flows in the Weddell Sea)

Elin Darelius, Univ of Washington GFD lab

particle paths are helical, with Ekman driven meridional overturning transmitting the boundary stress into the fluid. (Looking up the sloping valley)



a)



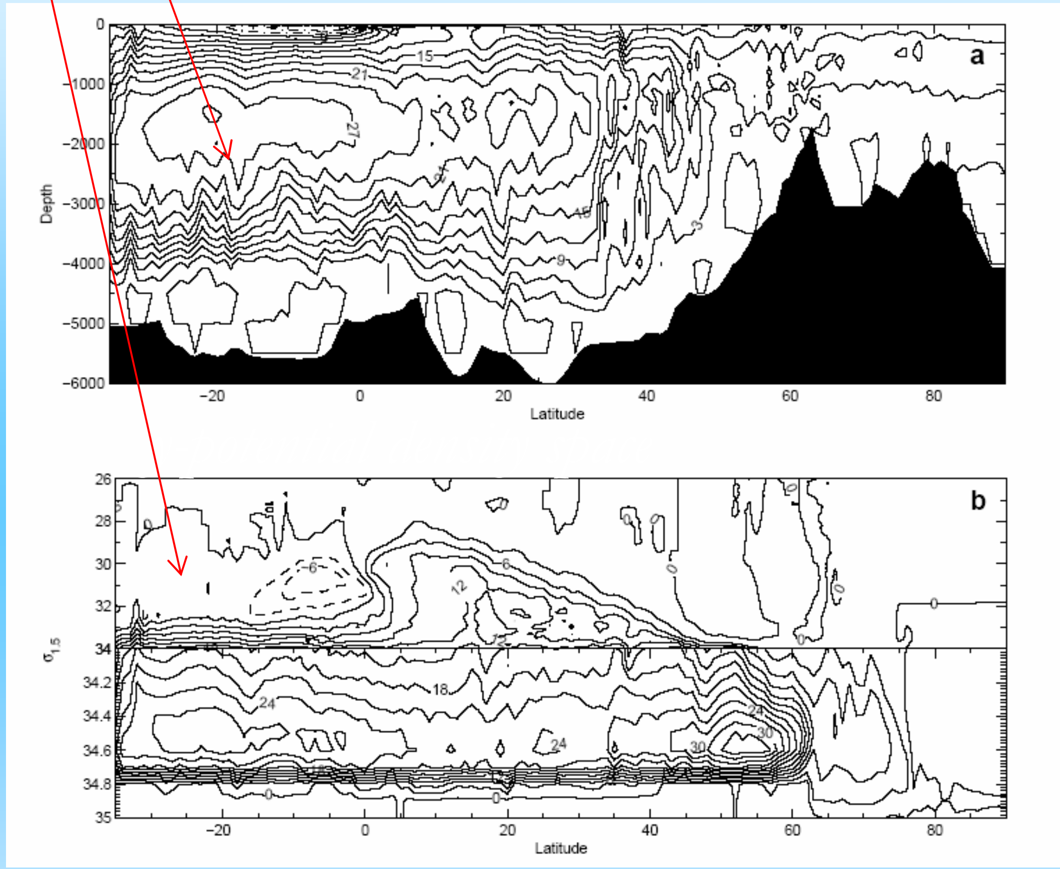
b)

Figure 17: *The "Ekman Helix" traced out by dye injected in the bottom boundary layer seen a) up the canyon and b) from above. The secondary circulation causes a particle to follow a helix like path down the canyon.*

The zonally averaged overturning streamfunction, North Atlantic/Arctic model of Häkkinen driven by NCEP winds and temperatures

$\Psi(y,z)$ *meridional streamfunction x-averaged*

$\Psi(y,\sigma)$ *in density space (σ=potential density)*



35S *90N*

This image of the ocean circulation is the usual output of climate models; many essential processes are made invisible…the east-west detail of the previous slides. These 'details' are likely to be essential to understanding the global ocean transports.

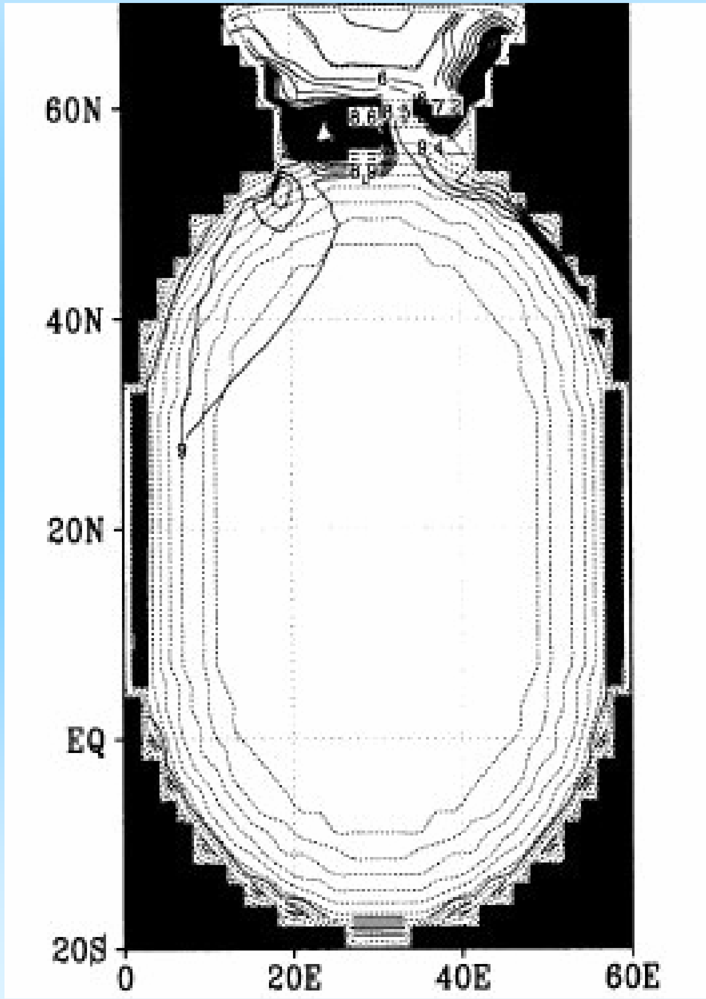
The tendency for dominant sinking south of Greenland in low-resolution climate models is widespread: here in density- latitude space the streamfunction reveals higher latitude sinking and dense overflows.

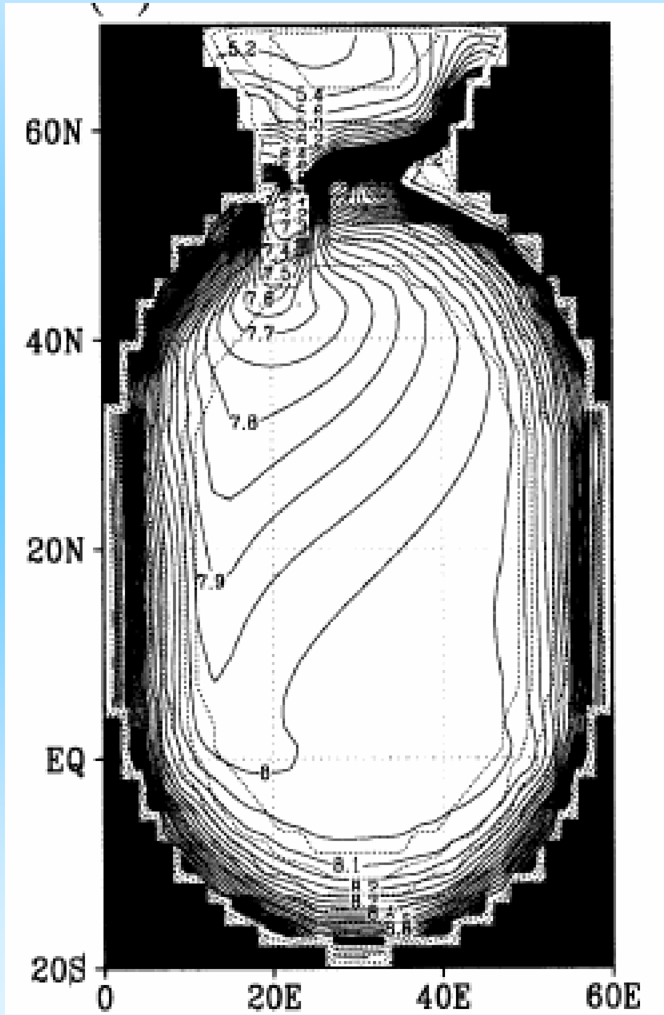
The difference is expected from the east-west tilt of potential density surfaces, so that equal and opposite meridional velocities at the same depth z may have very different densities.

Bailey, Hakkinen, Rhines Climate Dynamics 2005

The sinking region of the deep circulation is not usually correctly resolved in ocean models; here a bottom boundary layer parameterization improves the sinking of dense water

Nakano & Suginahara 2002 JPO

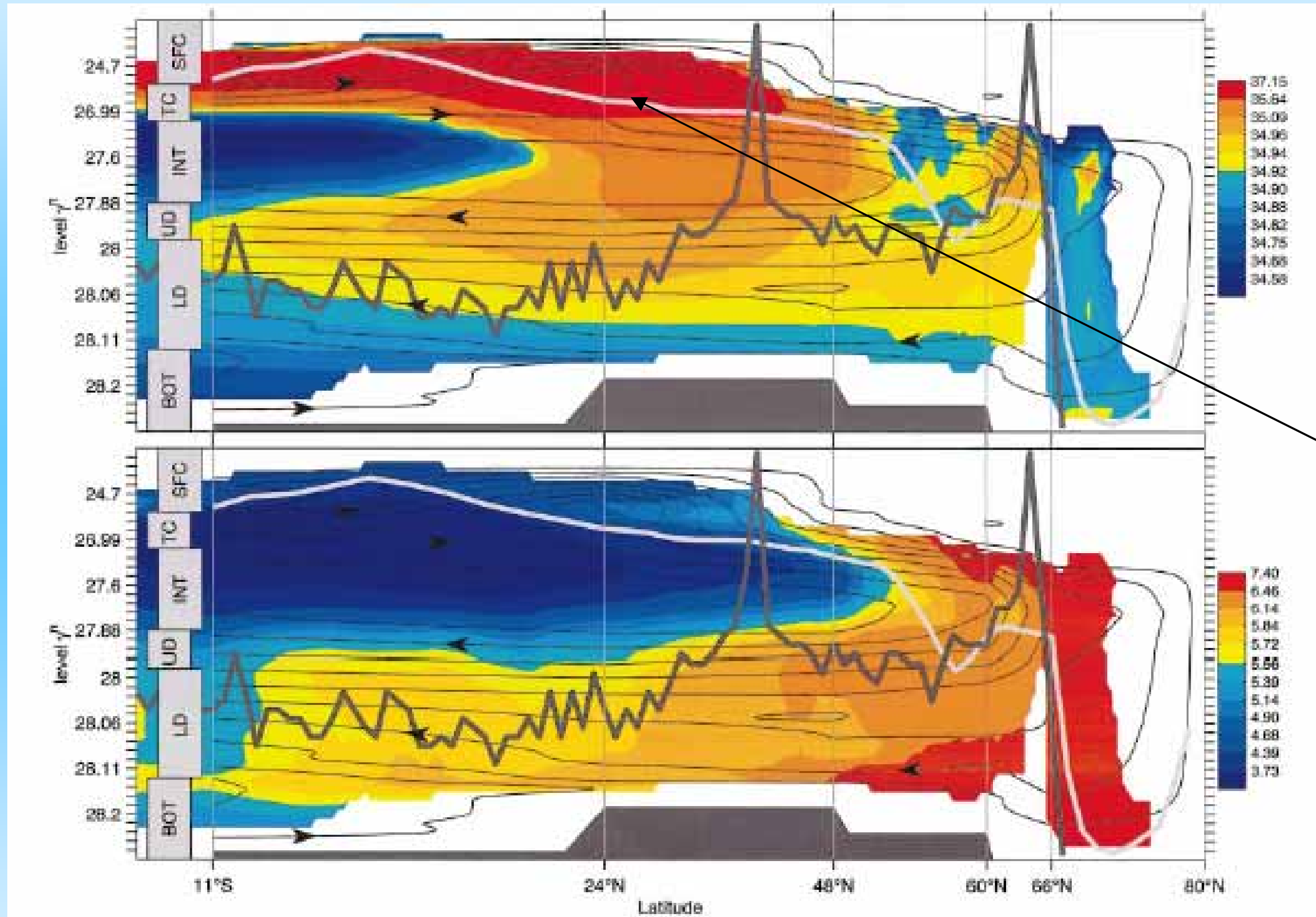




Lumpkin & Speer's JPO 03 discussion of the Atlantic MOC, here plotted against potential density and latitude. Even though we know there is much east-west structure (boundary currents, horizontal gyres as in Reid's maps) the zonally averaged MOC 'looks like' the simple 2-dimensional box models of the circulation

S

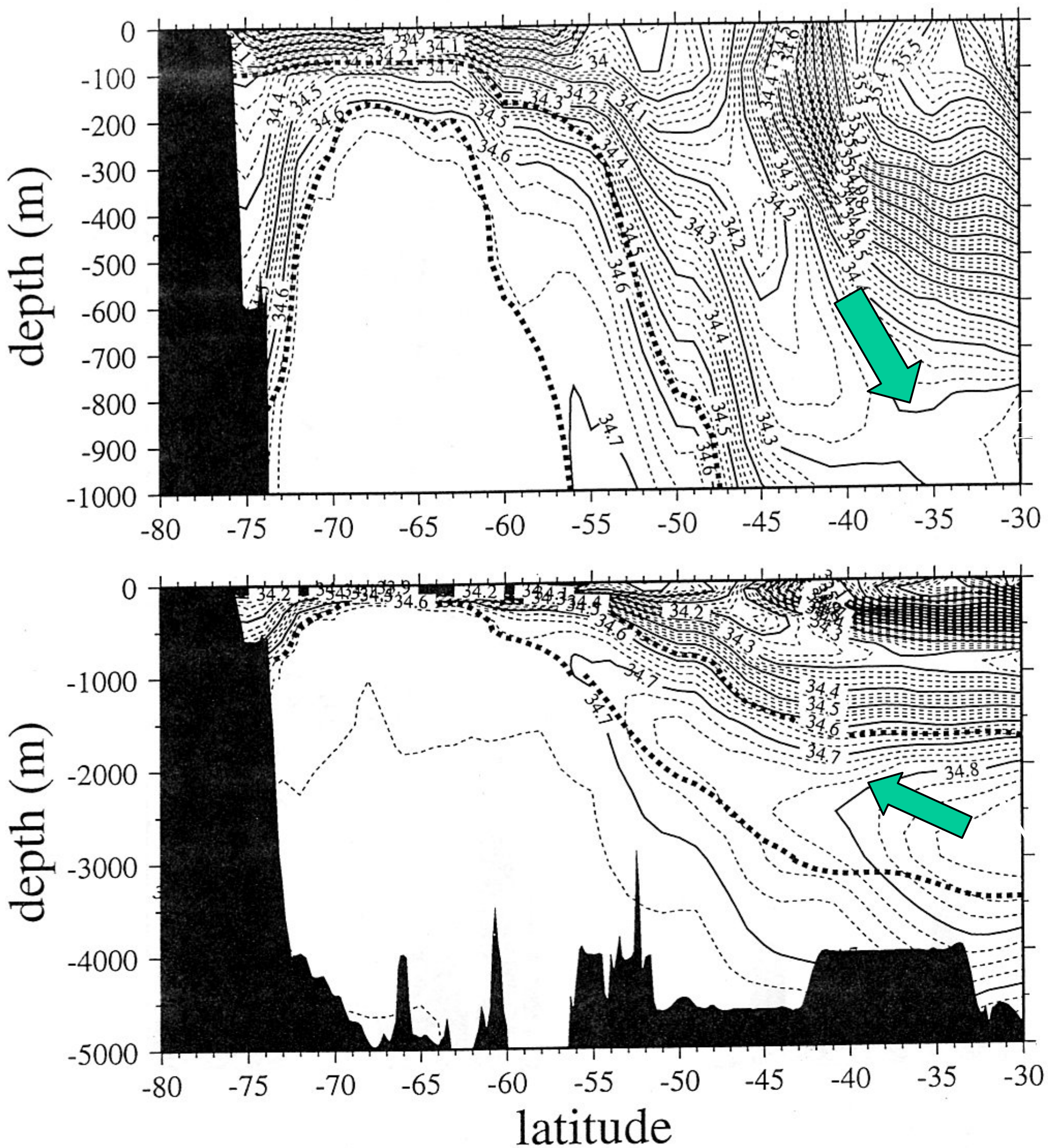
O_2



sea surface

FIG. 9. Side view of the North Atlantic meridional overturning, contoured in 2-Sv intervals, superimposed on zonally averaged (top) salinity and (bottom) oxygen (mL L^{-1}) calculated from climatology (Gouretski and Jancke 1998). Light gray curve: densest outcropping layer, estimated from COADS climatology. Dark gray curve: crest of the Mid-Atlantic Ridge, including the Azores Plateau and Iceland.

Figure 4. Vertical-meridional section of salinity at 24°W in the South Atlantic. Data sources are as in Fig. 2, and the heavy dashed lines are the potential density surfaces highlighted in that figure. The salinity minimum diving down at 52°S and heading north is AAIW. The salinity maximum below that, starting from the South Atlantic and rising and growing weaker into the Weddell Sea is NADW. The highlighted density surfaces were chosen to include this salinity maximum.

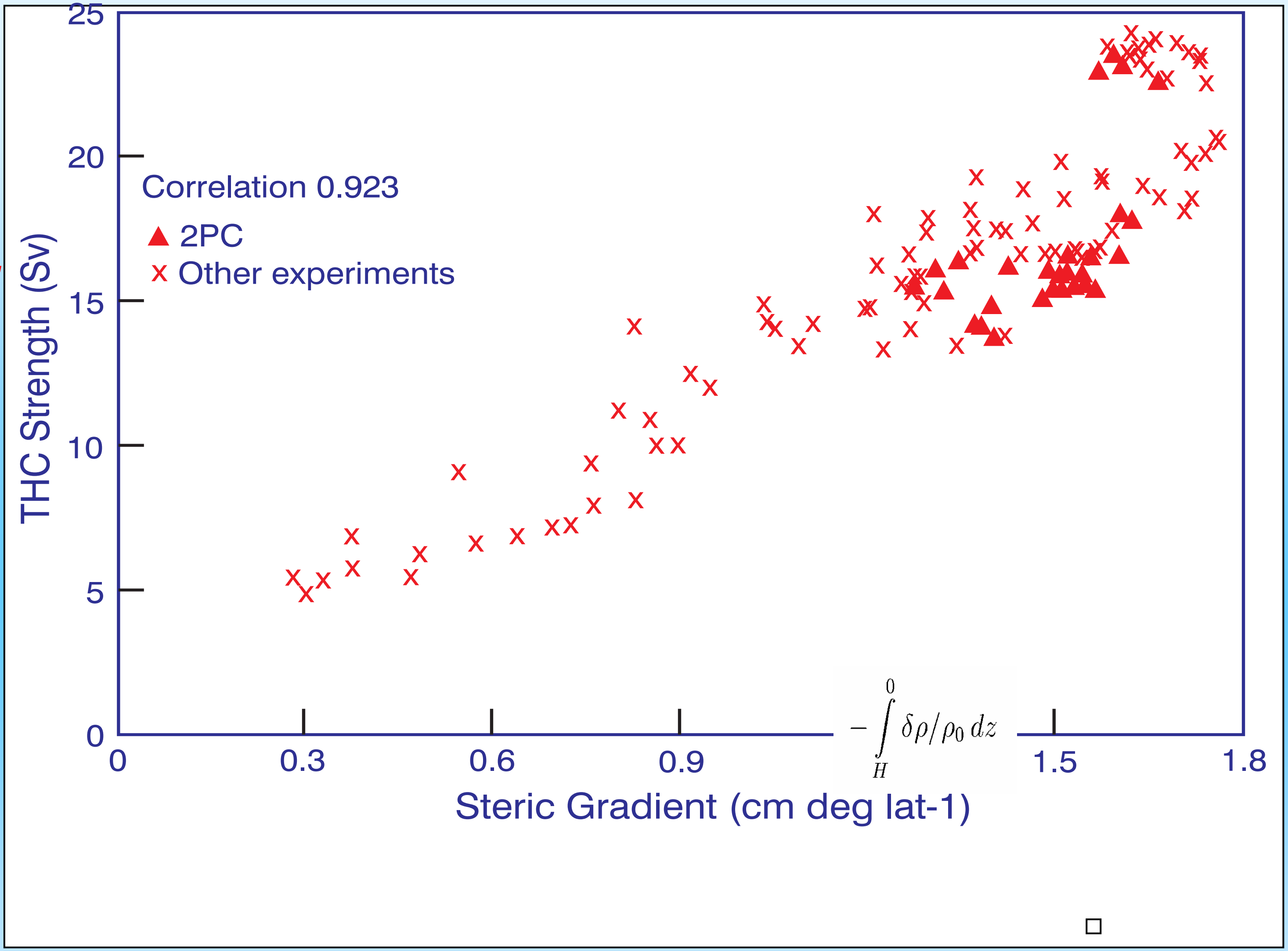


The ACC is the only ocean current with The Problem (how to flow meridionally, given the absolute angular momentum constraint)..yet it has ample topographic bottom slopes to lean on: these clearly balance the zonal wind stress that drives this greatest of all ocean currents

This may be a dominant site of upwelling in the global MOC (with respect z and potential density)

Salinity at 24W longitude

Oceanic meridional overturning strength vs. meridional baroclinic dynamic height gradient in HADCM3



A change in the MOC transport may be associated with some measurable change in the meridional density gradient. HadCM3 finds a very close correlation between Atlantic overturning rate and the S-N gradient of steric height from 30S - 60N through the W Atlantic. But, there is a possible oversensitivity of models to subpolar buoyancy/Labrador Sea.

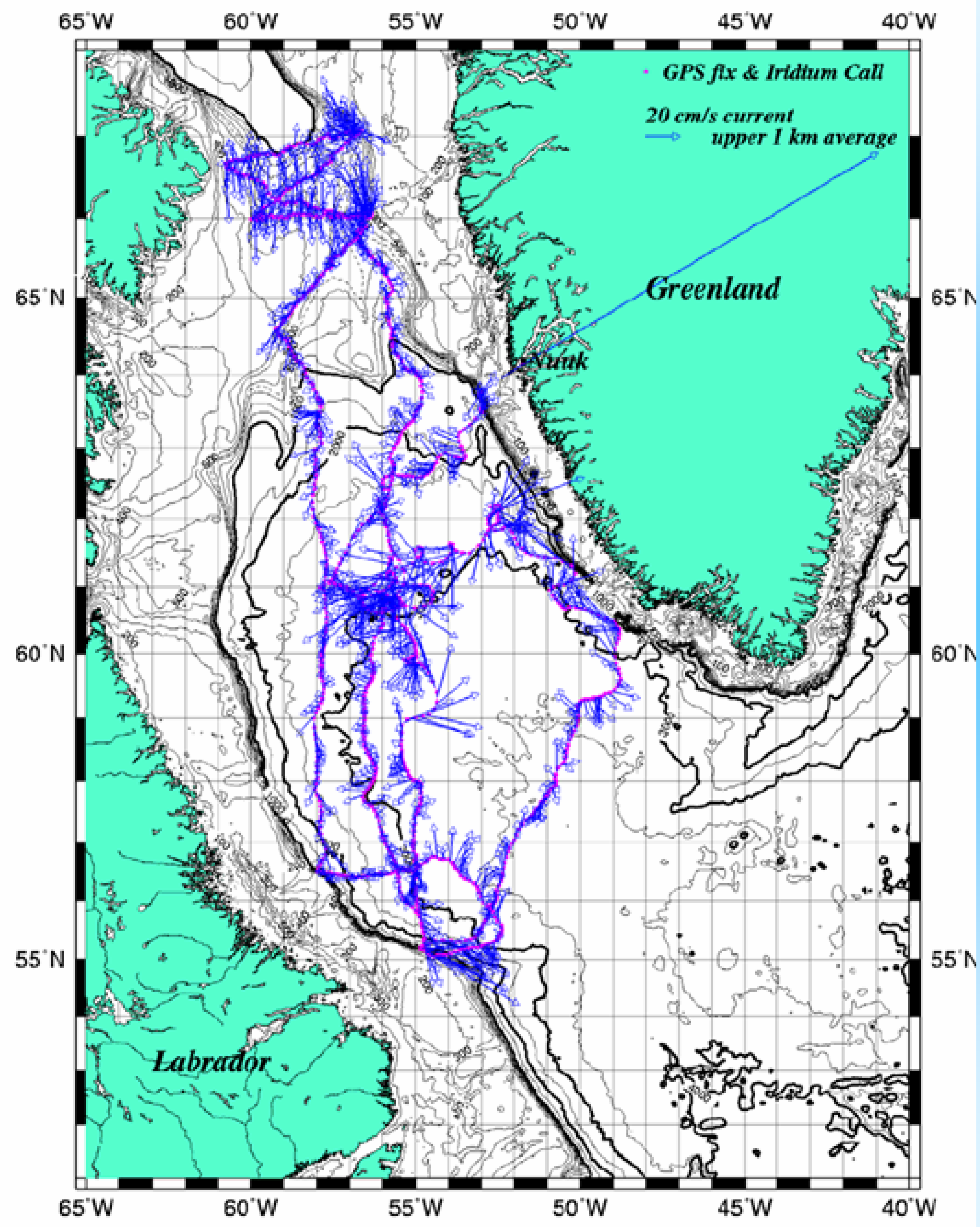
Observations of the MOC in the Labrador Sea andIceland-Scotland Ridge:
Temperature, salinity, oxygen, fluorescence, particle scattering, vertical velocity, depth-avereaged horizontal velocity all for 0.5 Watts power

for publications visit
www.ocean.washington.edu/research/gfd/papers-rhines.html

the classic way to do subpolar hydrography (R/V Knorr, R.Pickart photo)

Charlie Eriksen with a potential customer

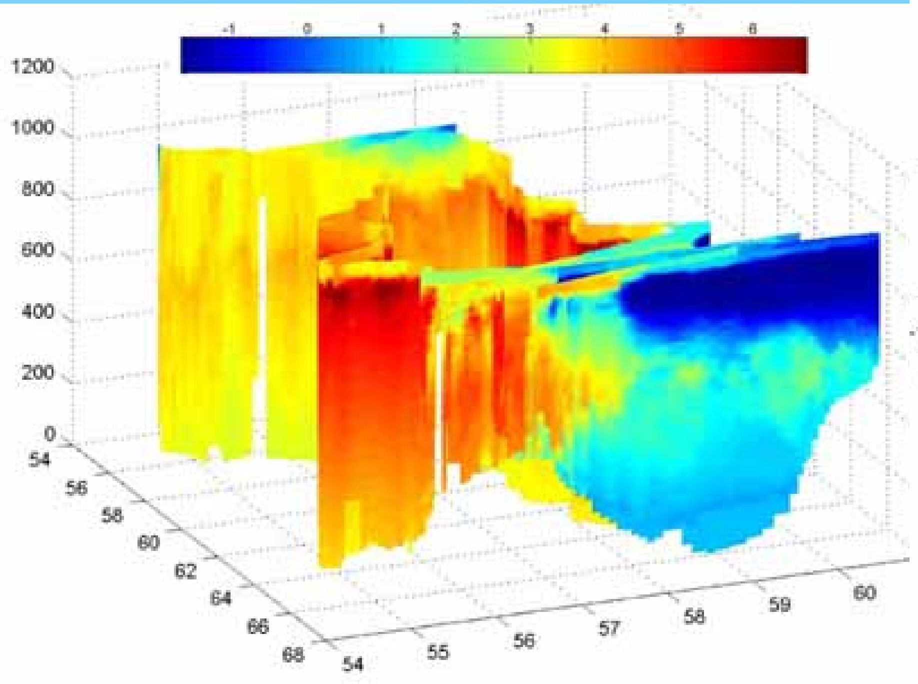
Wait for a nice day and zoom out to deep water…

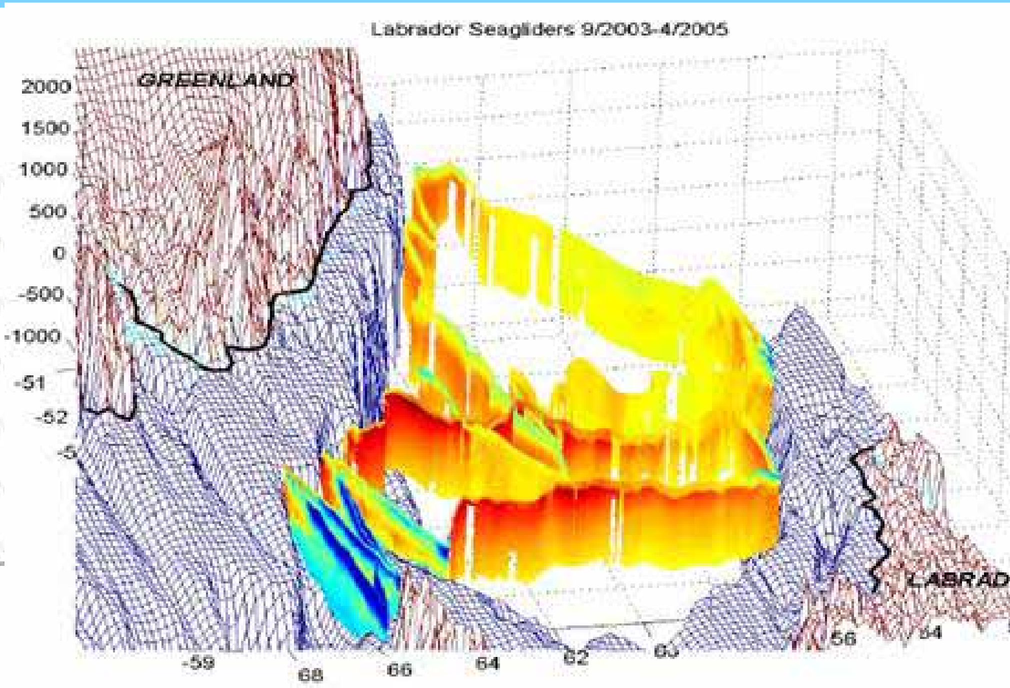


65°W
60°W
55°W
50°W
45°W
40°W
GPS fix & Iridium Call
20 cm/s current
upper 1 km average
Greenland
Nuuk
Labrador
65°N
60°N
55°N

potential temperature along glider tracks: ix2003-iv2005

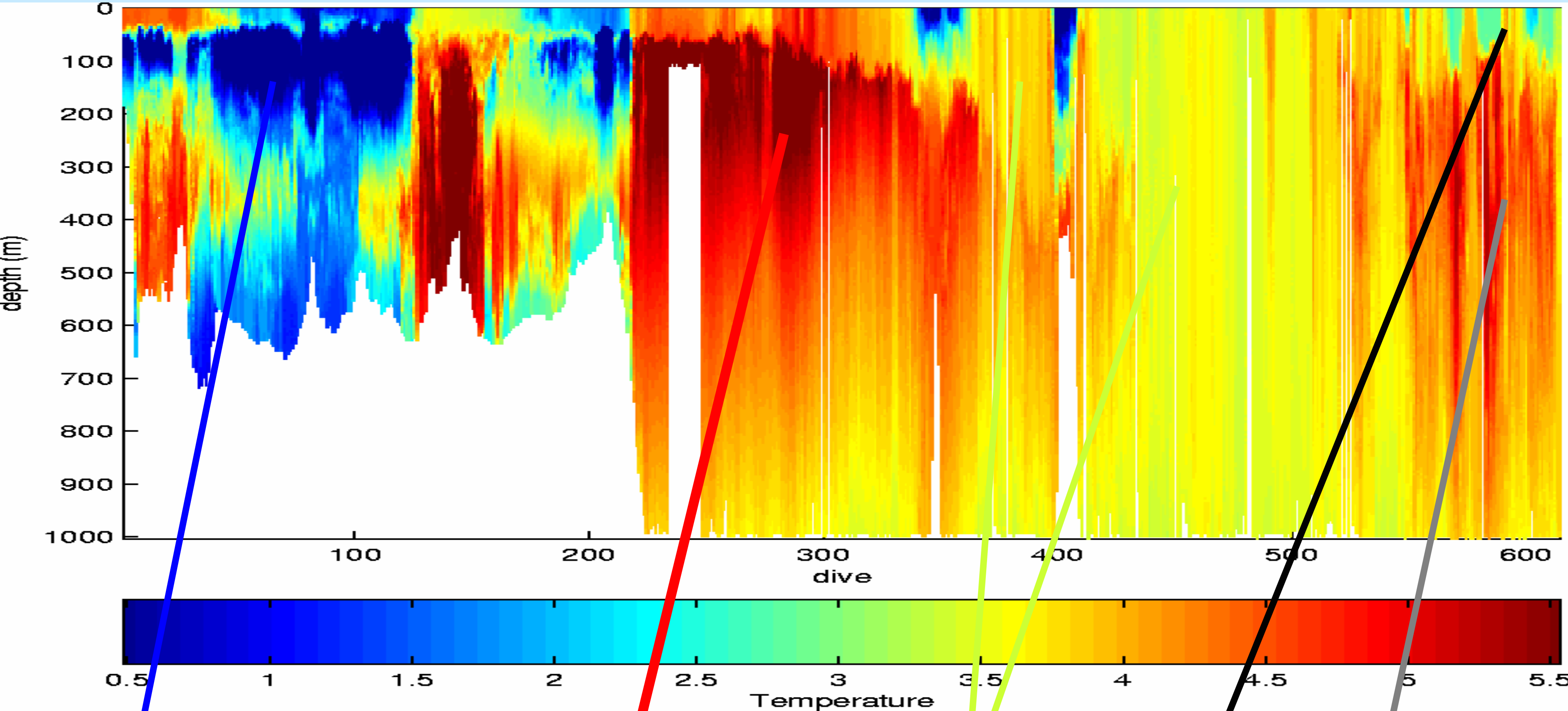
-Arctic waters from Baffin Bay;
-warm Irminger Sea water from boundary current along w. Greenland
-thin, cold, low-salinity surface layer advected over-top of Labrador Sea from Greenland coast





Seaglider ribbon section viewed from NE; *Labrador Sea looking from NW*

The ribbon pulled taut: Seaglider 014: 1200 profiles of temperature, salinity, oxygen, chlorophyll… Oct 04-April 05



Davis Strait cold Arctic waters

Warm Irminger Sea water

winter deep convection

cold,fresh Greenland shelf water

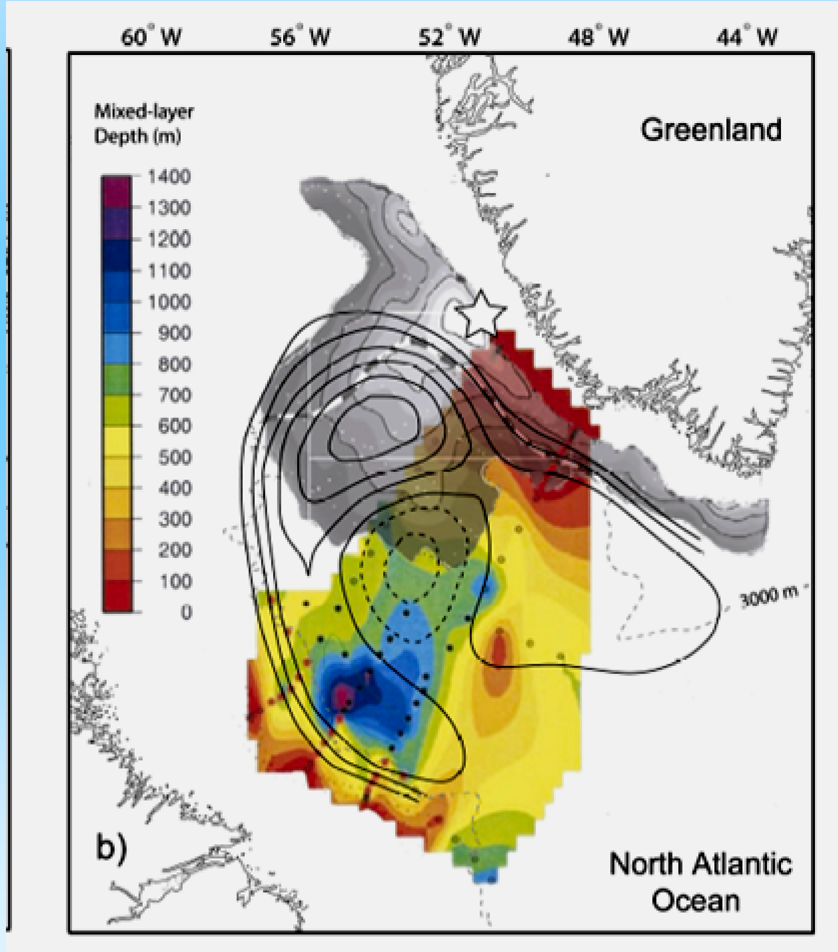
intense fine sructur

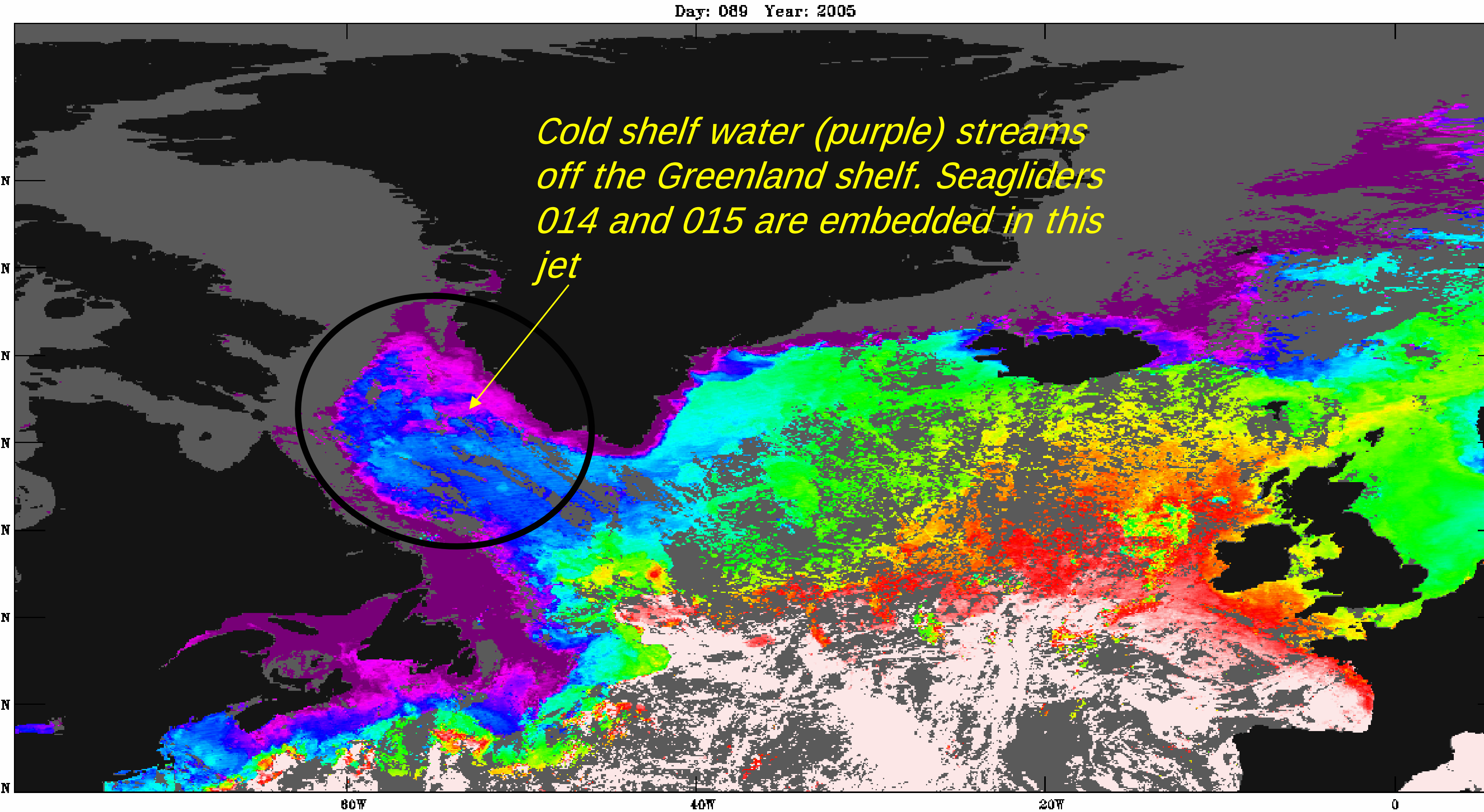
advection of low salinity surface layer off the west Greenland coast shapes both deep convection region, Labrador Sea Water production and primary spring plankton bloom (*Hatun, Eriksen & Rhines 2007 JPO)*

black contours: Lavender ARGO streamfunction

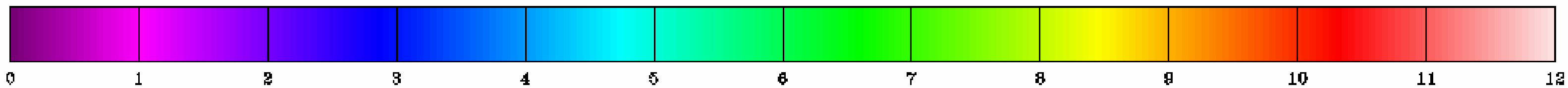
grey shades: altimetric EKE

colors: depth of winter convection in 1968. from Pickart et al. 2002)

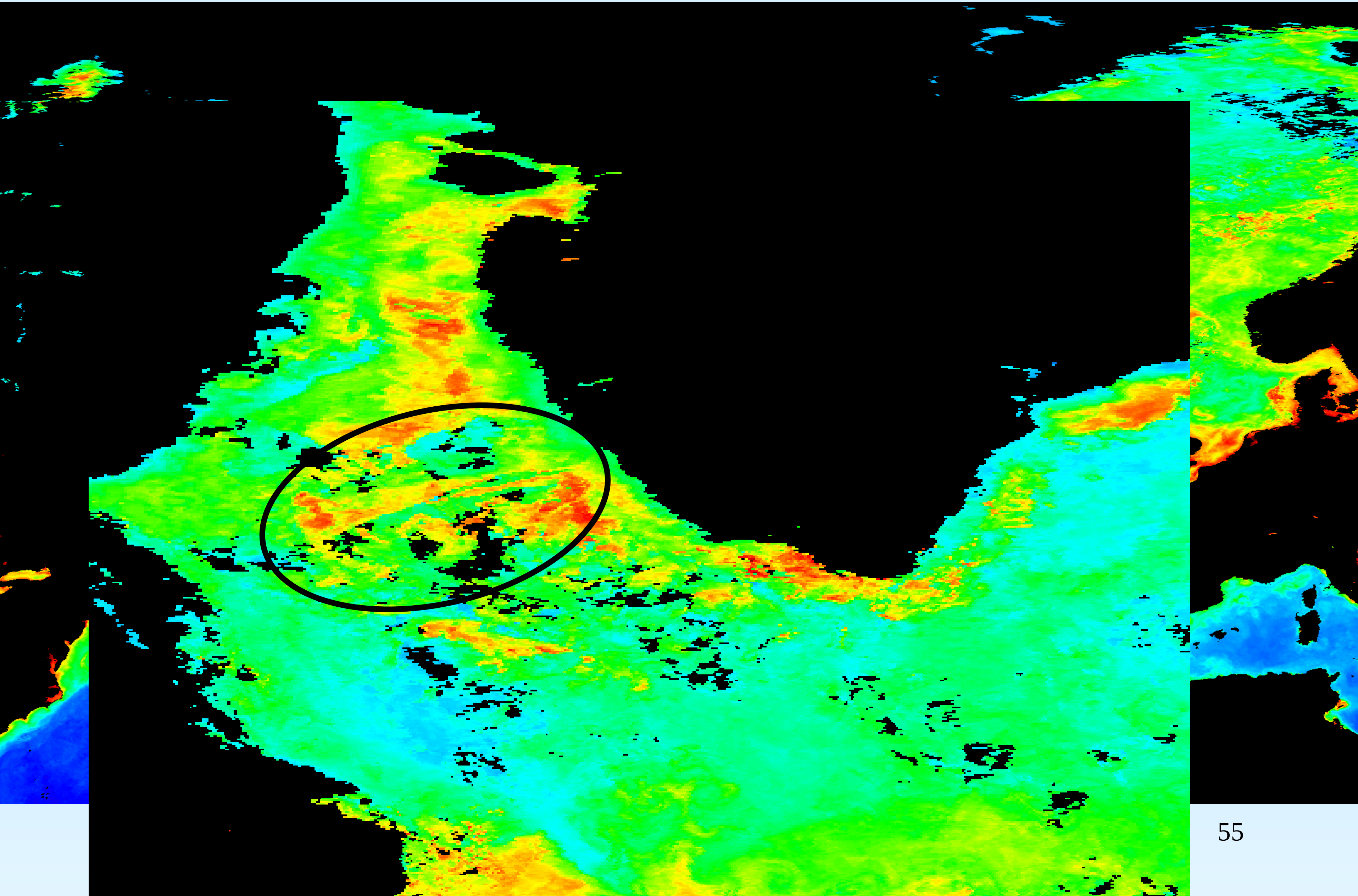




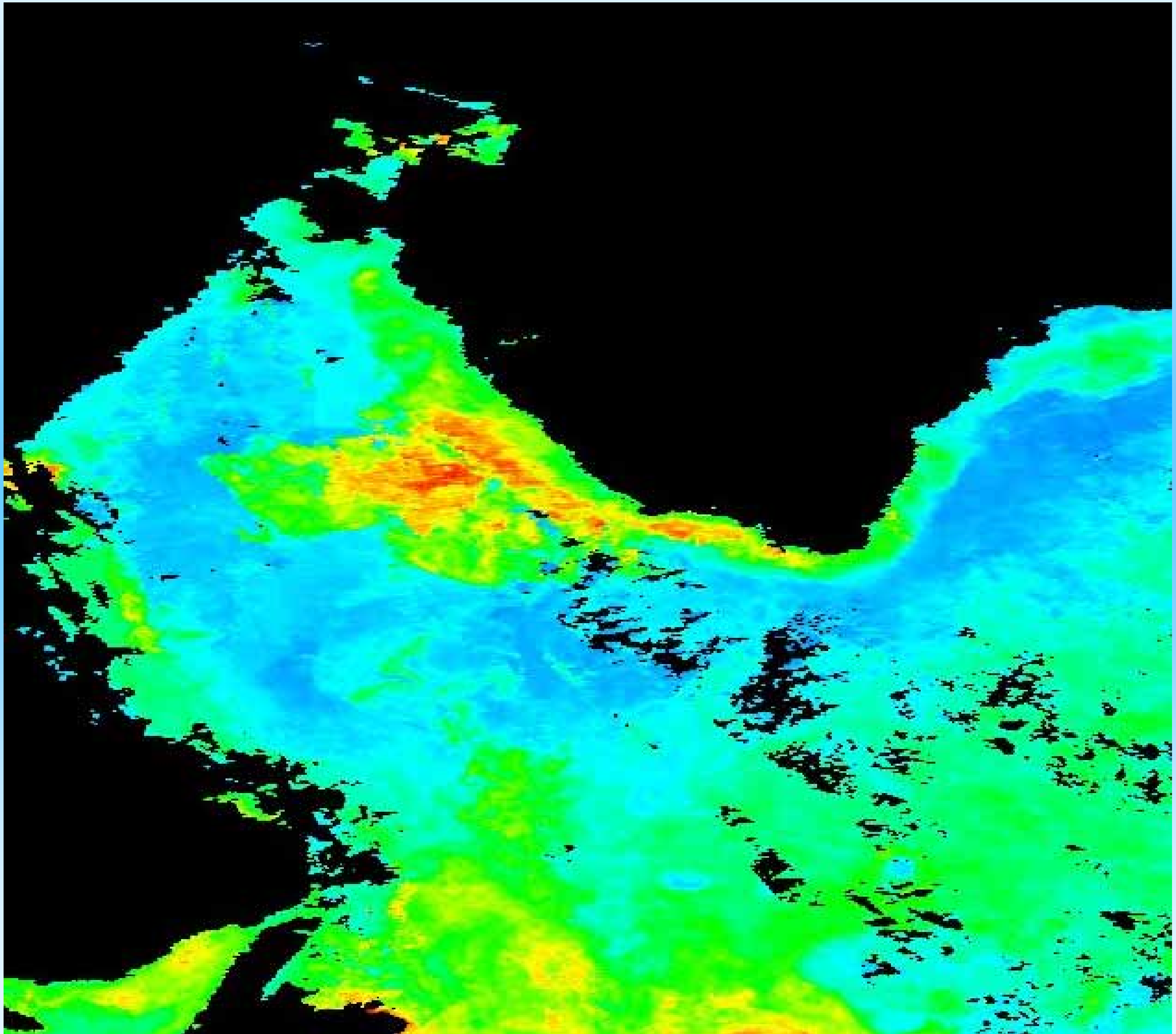
Aqua & Terra satellite SST day 089 05

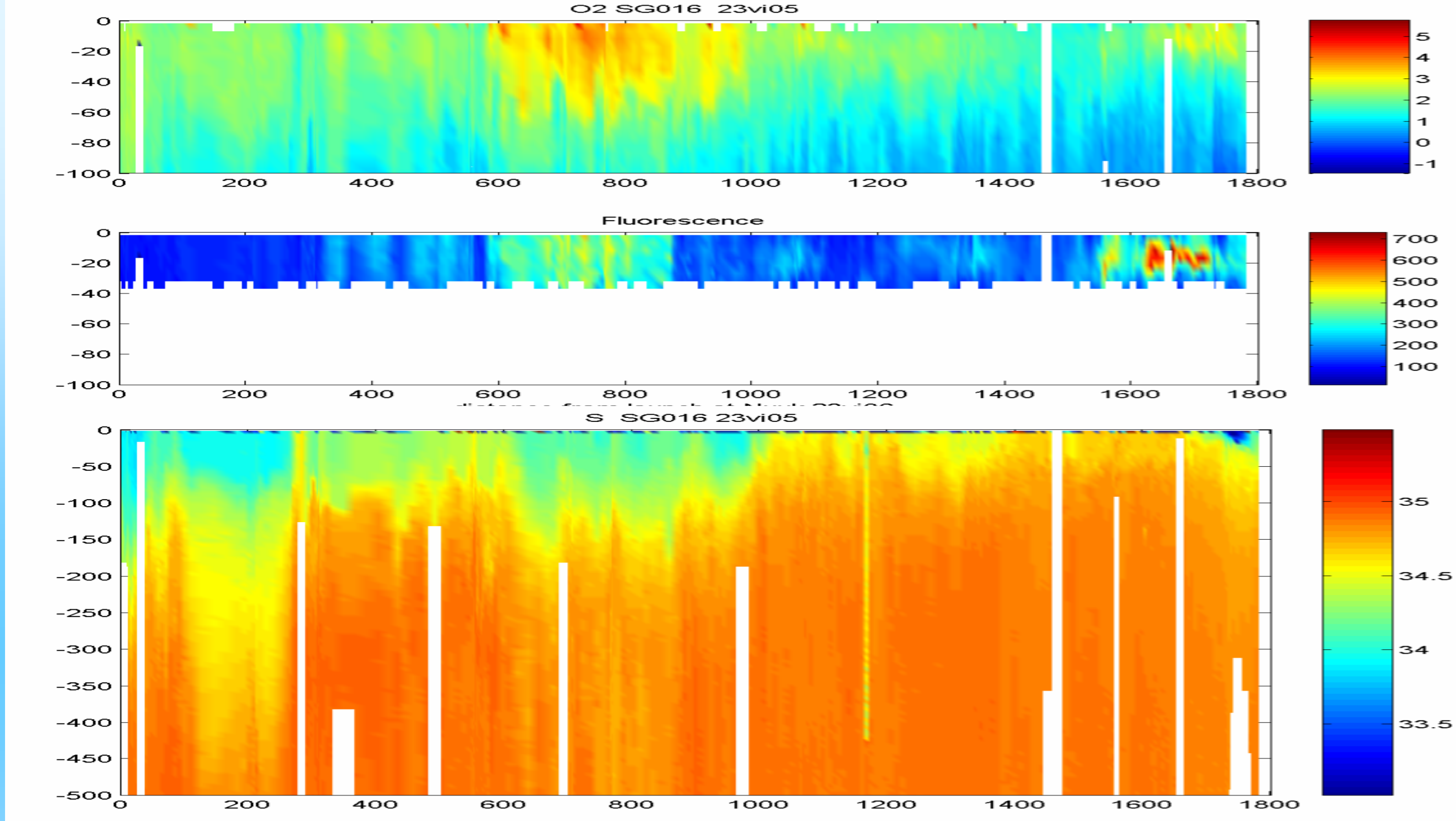


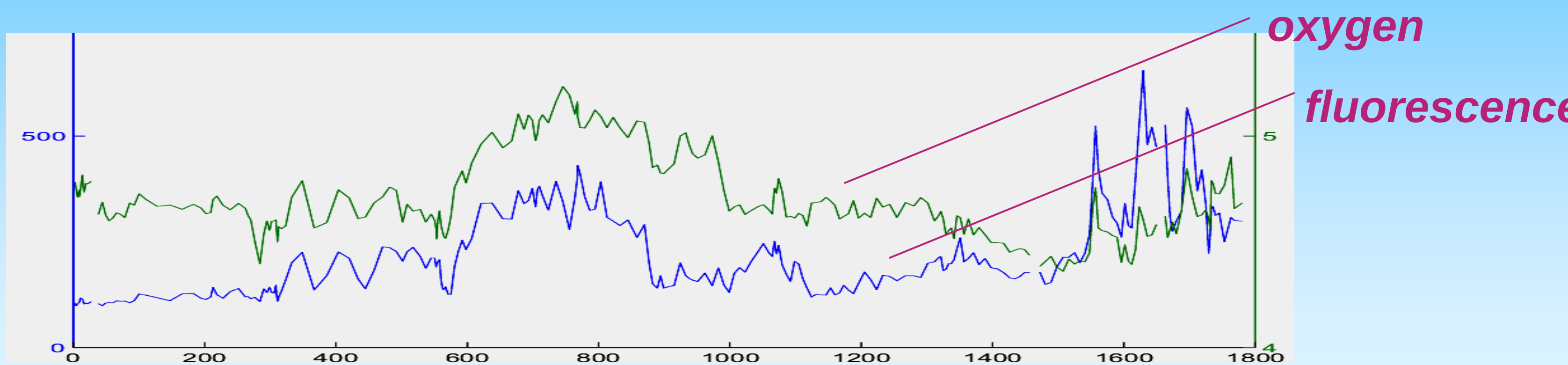
The Greenland waters reaching out over the Labrador Sea also carry strong primary productivity with them…as seen in SeaWIFS ocean color (May 2004)



SeaWiFS ocean color: 2005 days 91-120; two Seagliders pass through this bloom

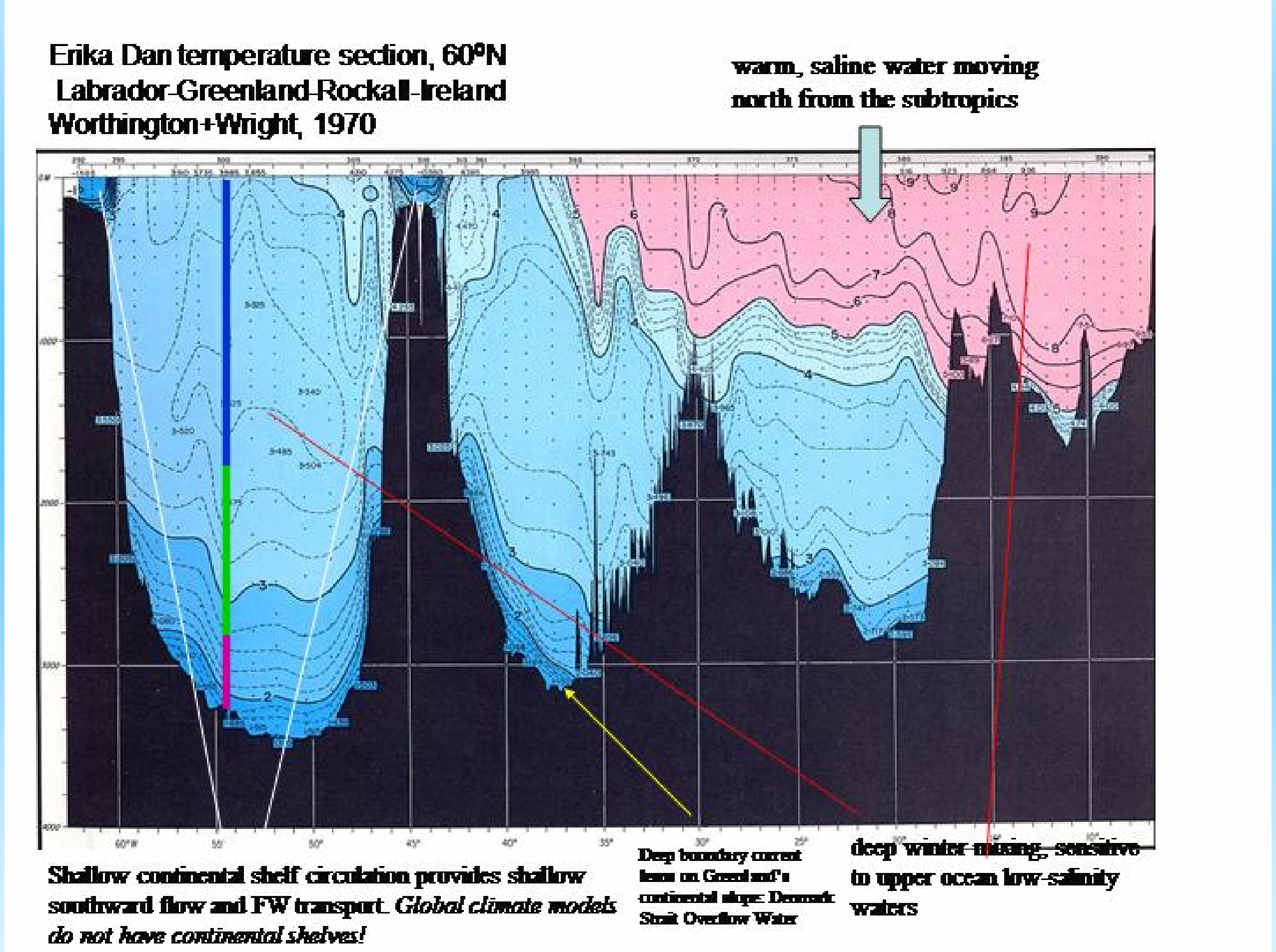






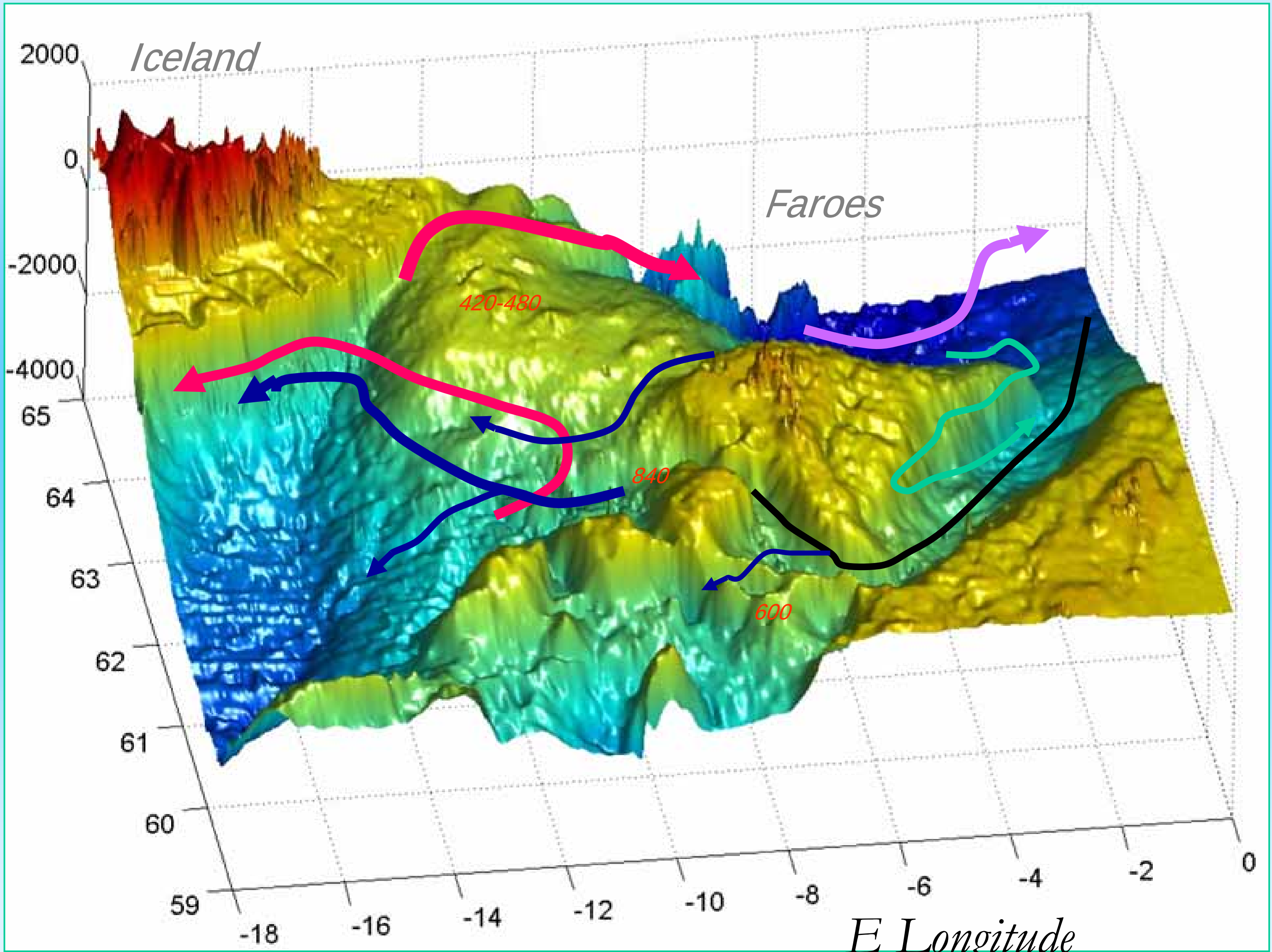
Seaglider 016 spring 2005 1800 km Labrador Sea track

channels and conduits for heat- and fresh-water transport



5. Deep Ocean overturning circulations at the 'headwaters' of the global MOC

exchanges across the Iceland-Faroes-Shetland Ridge and Channel



latitude

E Longitude

B. Hansen, S. Østerhus / Progress in Oceanography 45 (2000) 109–208 121

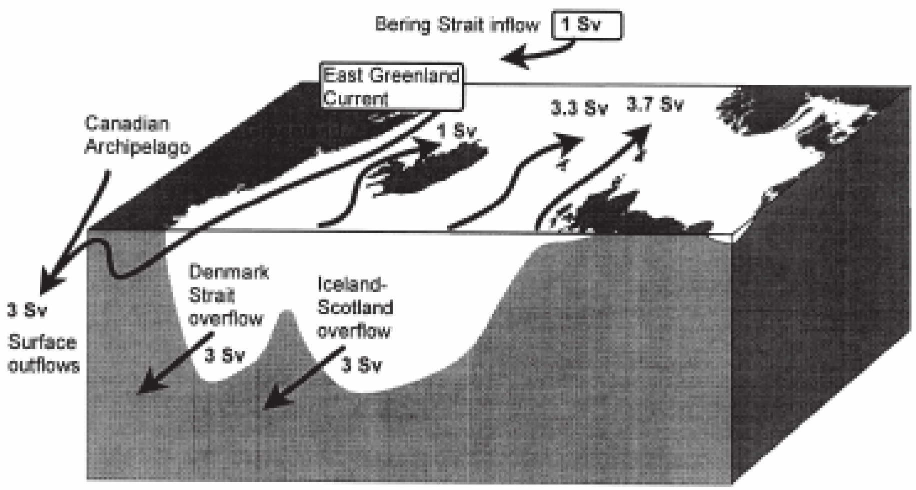


Fig. 8. Preliminary water balance in Sv for the Arctic Mediterranean.

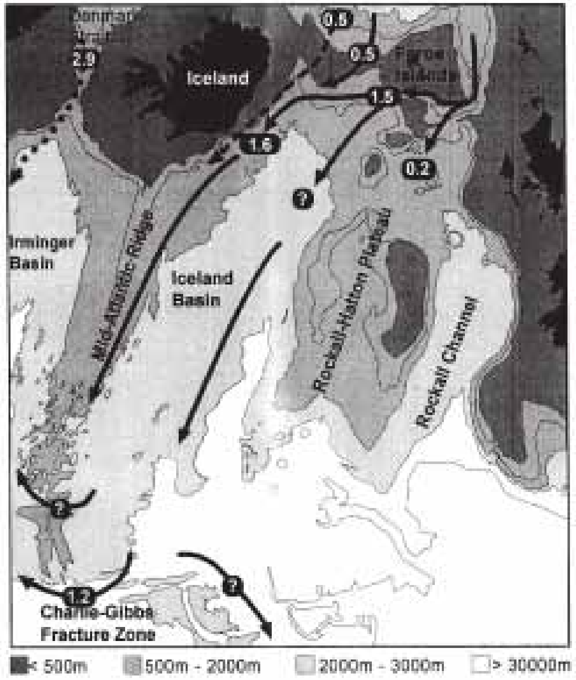


Fig. 54. 'Best' estimates of Iceland–Scotland overflow fluxes (in Sv) in different areas. Continuous arrows indicate flux of NSAIW+NSDW. Dashed arrow indicates flux of MEIW. Also shown by a dotted arrow is the estimated overflow through the Denmark Strait according to Dickson and Brown (1994). Water entrained after the overflow has passed the Greenland–Scotland Ridge is not included in the flux values.

Hansen & Osterhus PiO 2000

Water-mass transformation on Θ/S plane:

Faroe-Bank Channel *Mauritzen et al. 2005 DSR:* mixing downstream of the final sill dilutes the dense cold water, with impact on the global MOC

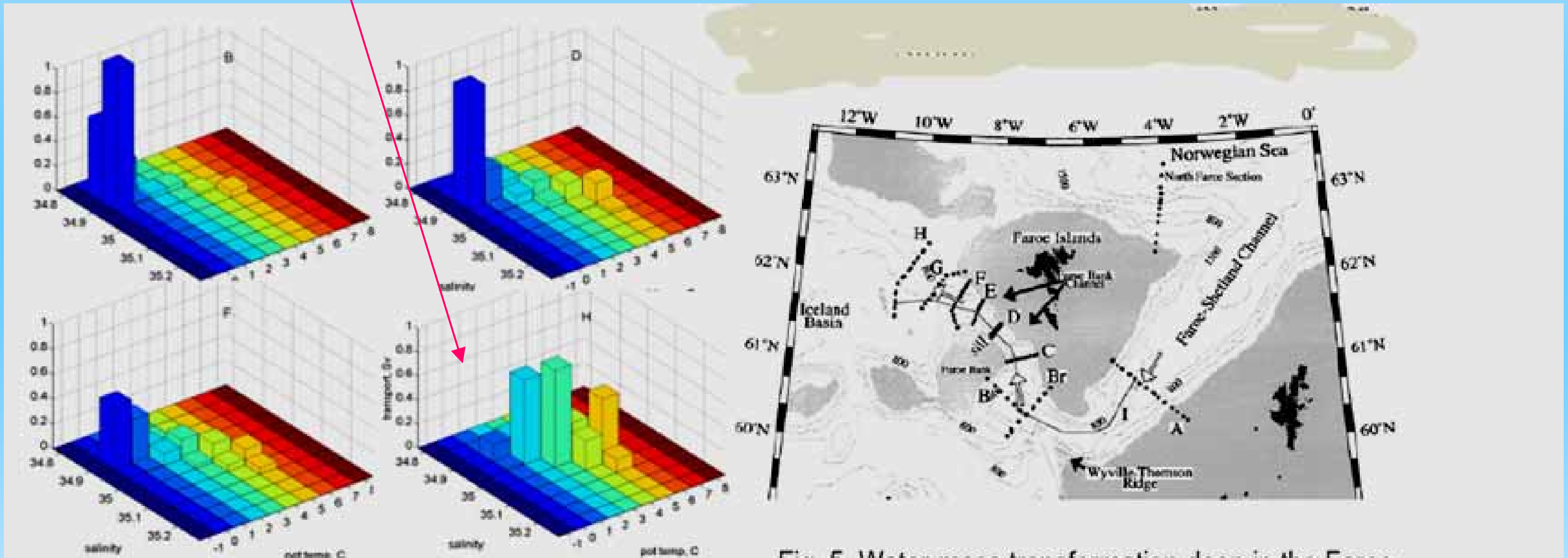
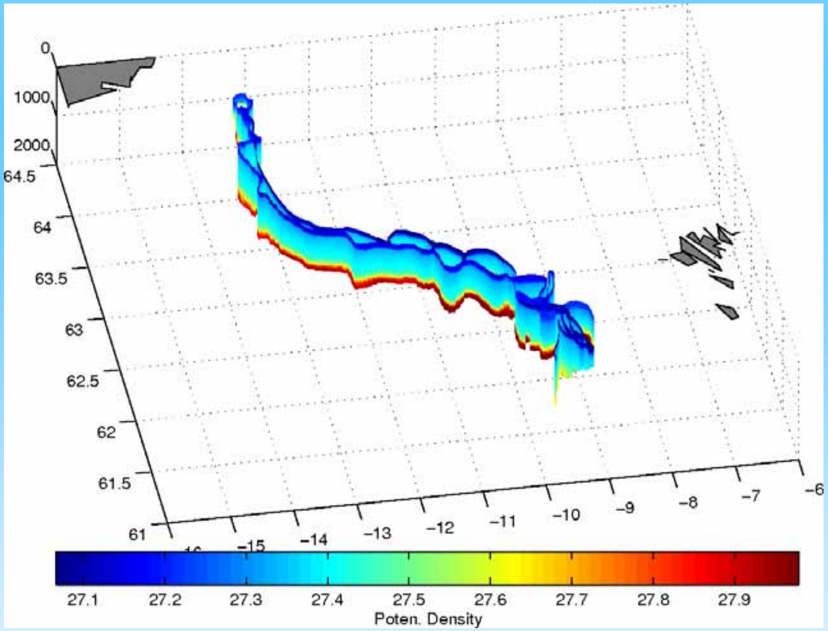
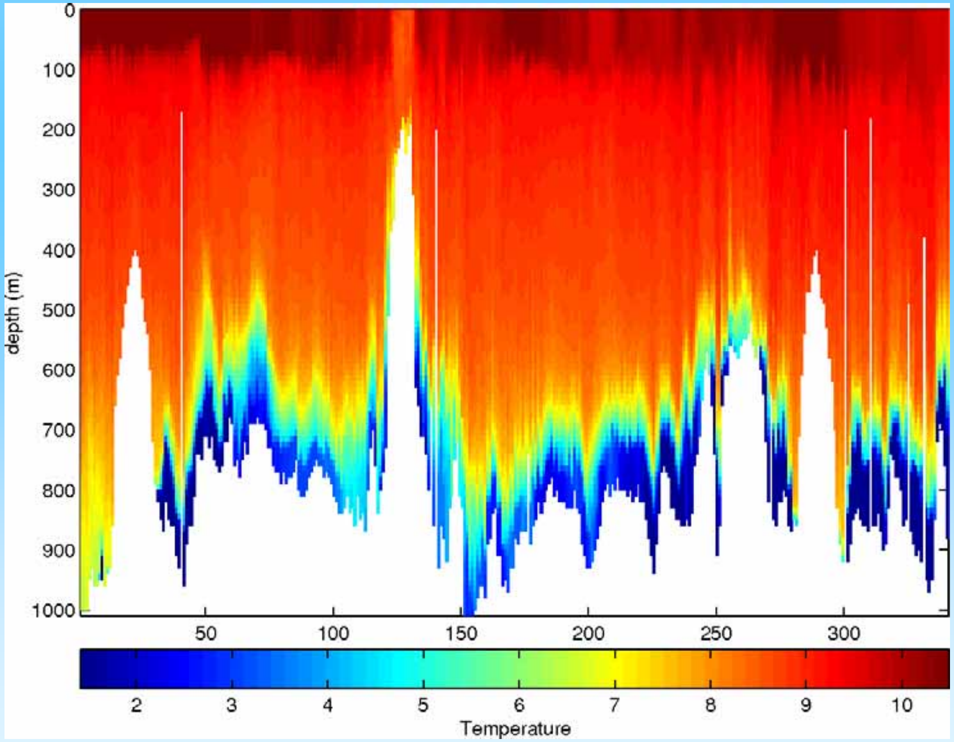


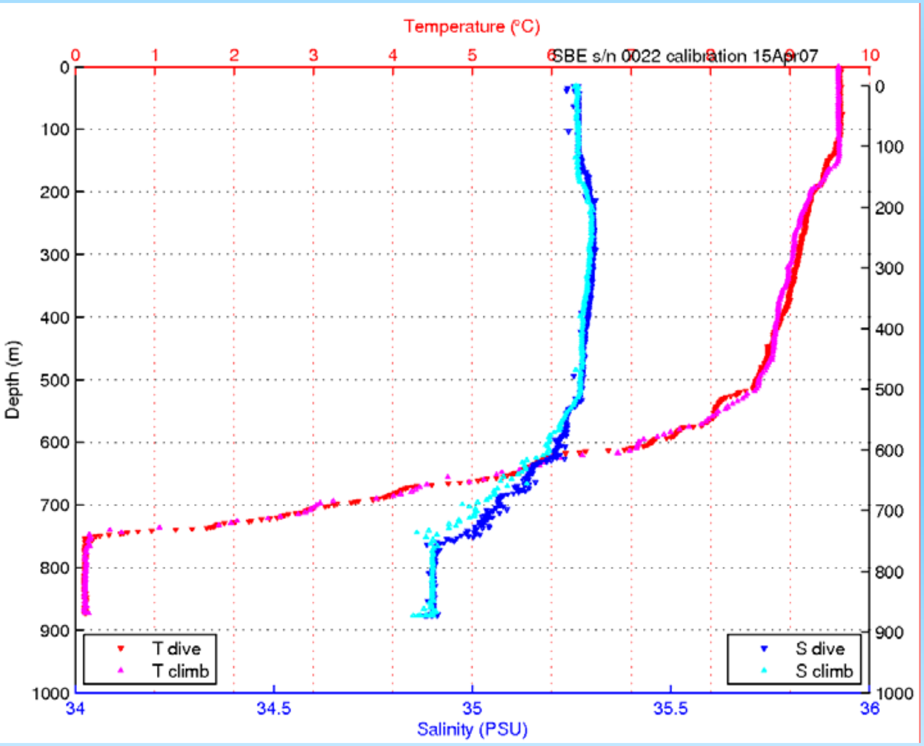
Fig. 5. Water-mass transformation deep in the Faroe-Bank Channel, displayed as transport on the θ/S plane at successive sections from the entry (section B, upper left, westward to sections D, F and finally H at the exit to the IFR, from Mauritzen *et al.*, 2005. The deep overflow mixes to warmer, saltier values downstream in the FBC, emerging much less dense than it enters.

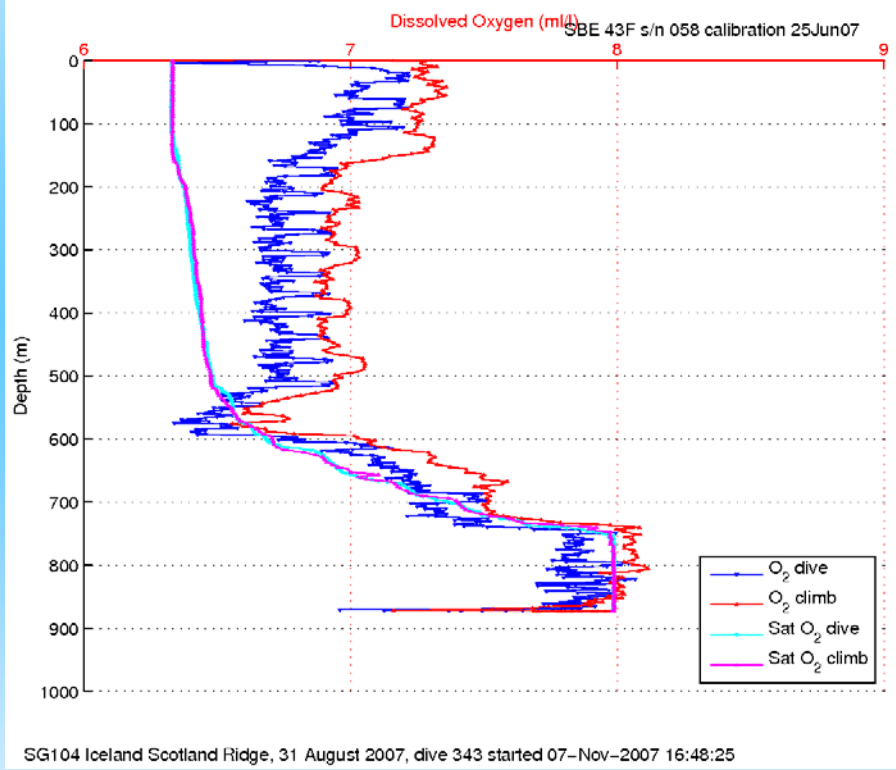
Potential temperature to 7 November 2007 Seaglider 104 Iceland-Faroe Ridge 686 hydrographic profiles during this 3 month mission



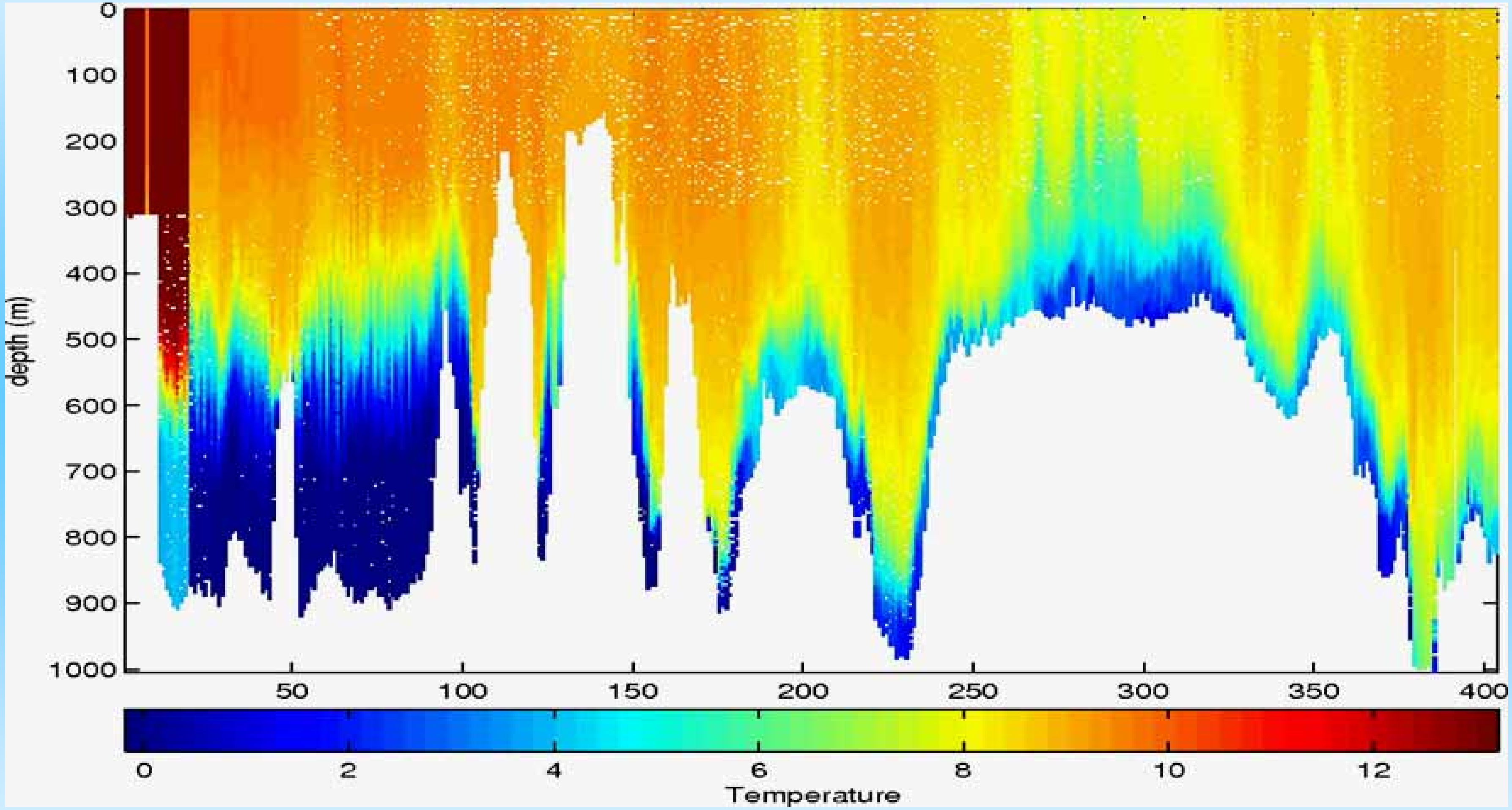


Temperature and dissolved oxygen profiles dive 343 in Faroe Shetland Channel





Temperature section following glider 101 (Nov 2006-March 2007)

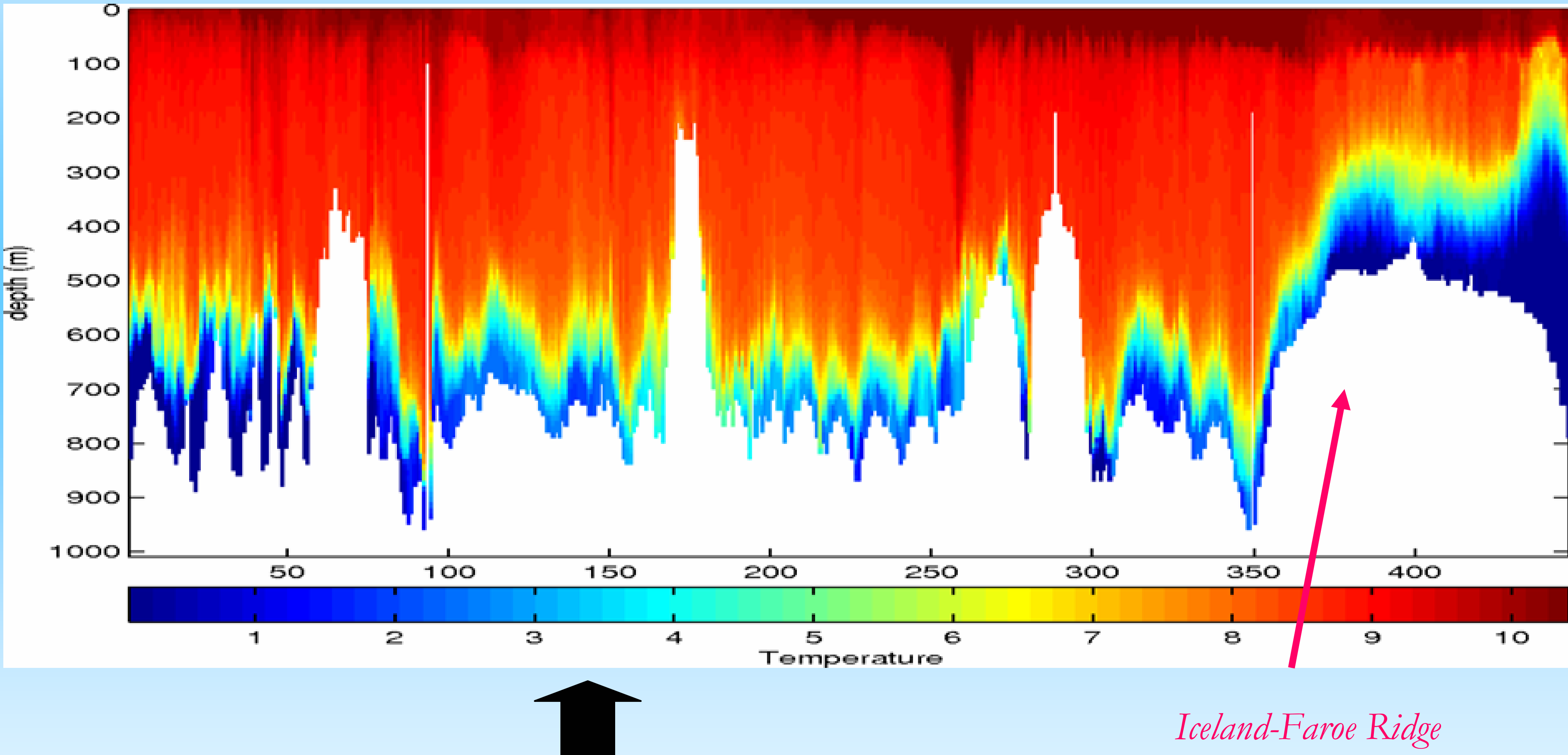


Wyville-Thompson Basin *Iceland-Faroe Ridge*

multiple crossings of Faroe-Bank Channel

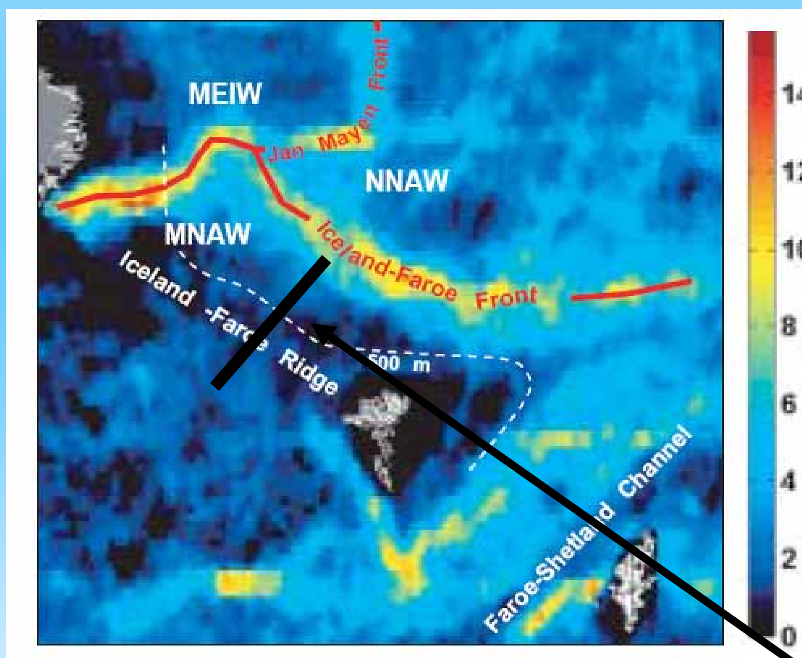
Seaglider 101 9 June-30 Aug 2008: temperature section on south slope of Iceland-Faroe Ridge (plus north-south section at end…like Poseidon section of Meincke, 1976). Thin, cold bottom layer encountered widely

0357Z
31 Aug 07



Patrolling east-west along southern flank of Iceland-Faroe Ridge

Iceland-Faroe Ridge
south <-> north



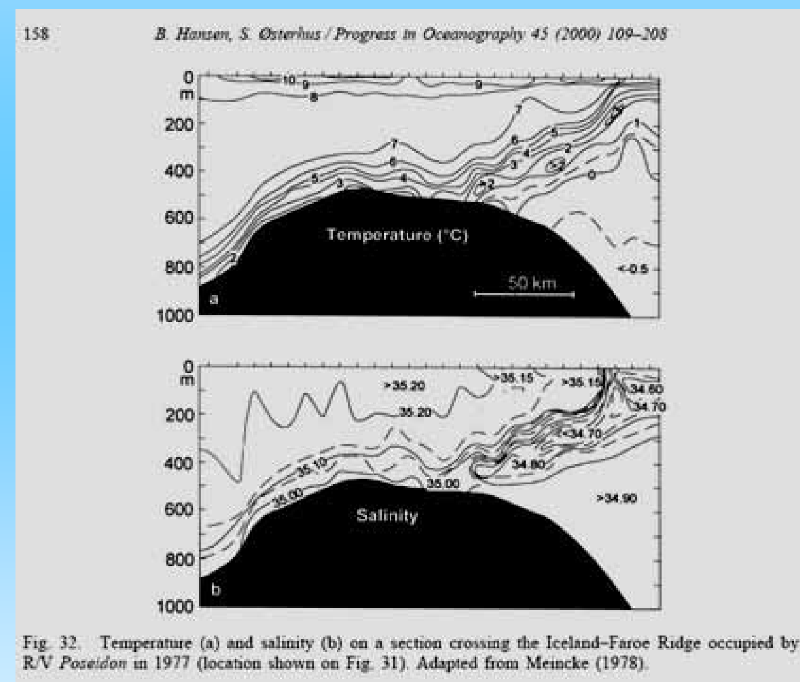

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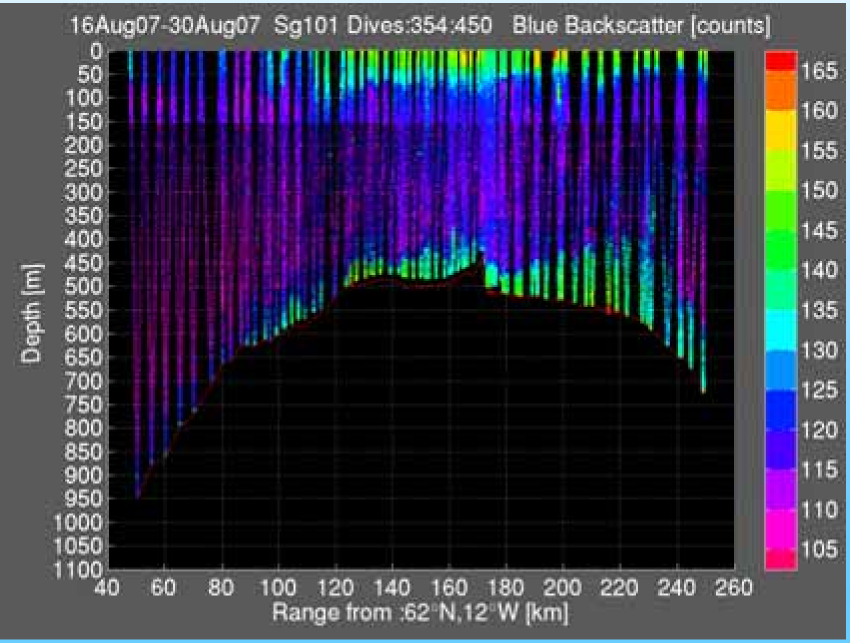
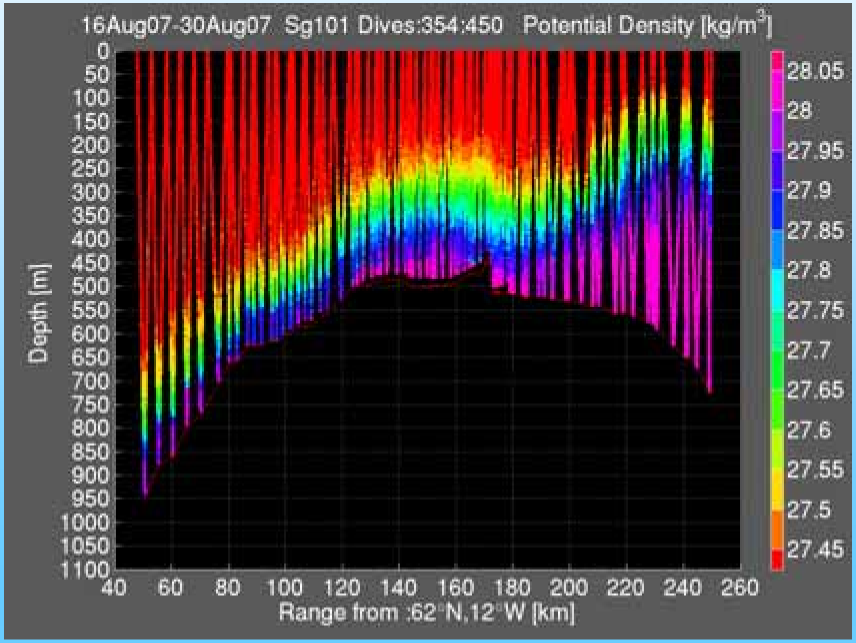
Fig. 32. Temperature (a) and salinity (b) on a section crossing the Iceland–Faroe Ridge occupied by R/V *Poseidon* in 1977 (location shown on Fig. 31). Adapted from Meincke (1978).

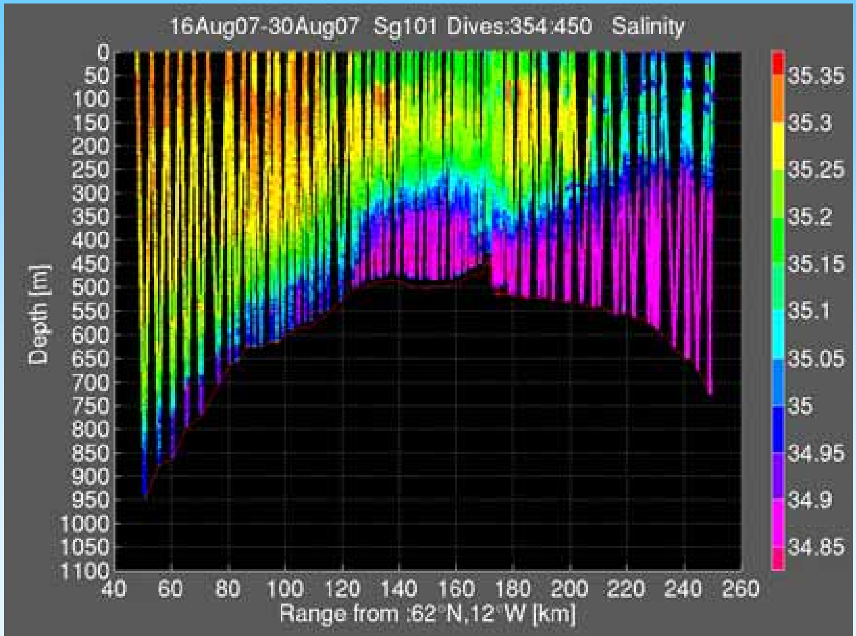
South North

Iceland Faroe Ridge 'Poseidon' 1977 Section (Meincke 1978)

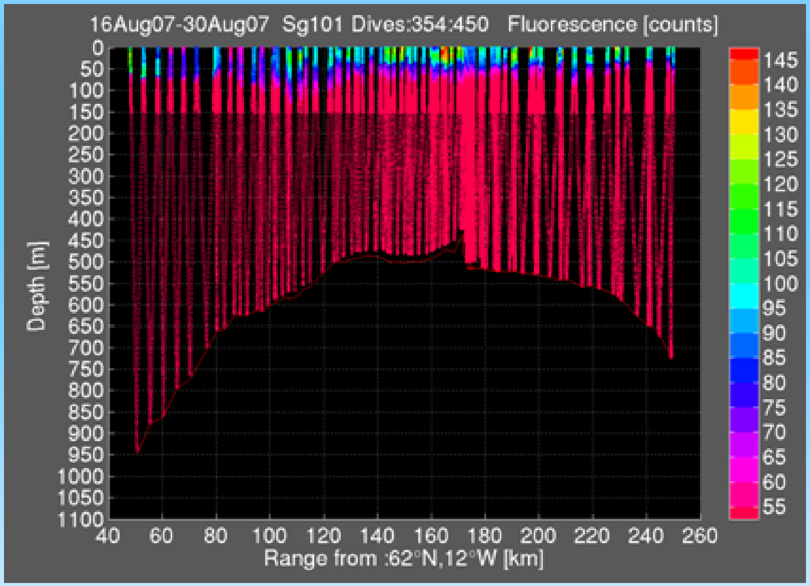


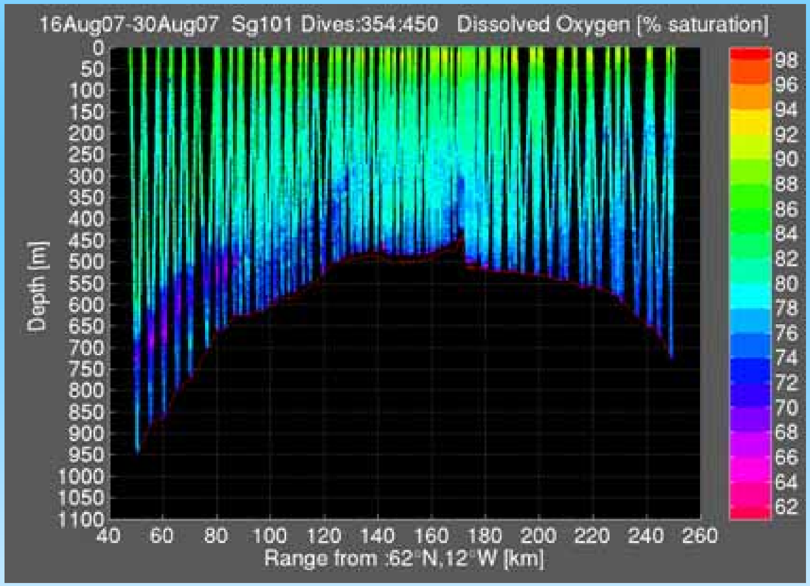


close to the Poseidon section on the previous slide, a Seaglider section…blue-light particle backscatter showing biological activity and potential density, salinity, Iceland-Faroe Ridge, SG101 Aug 2007

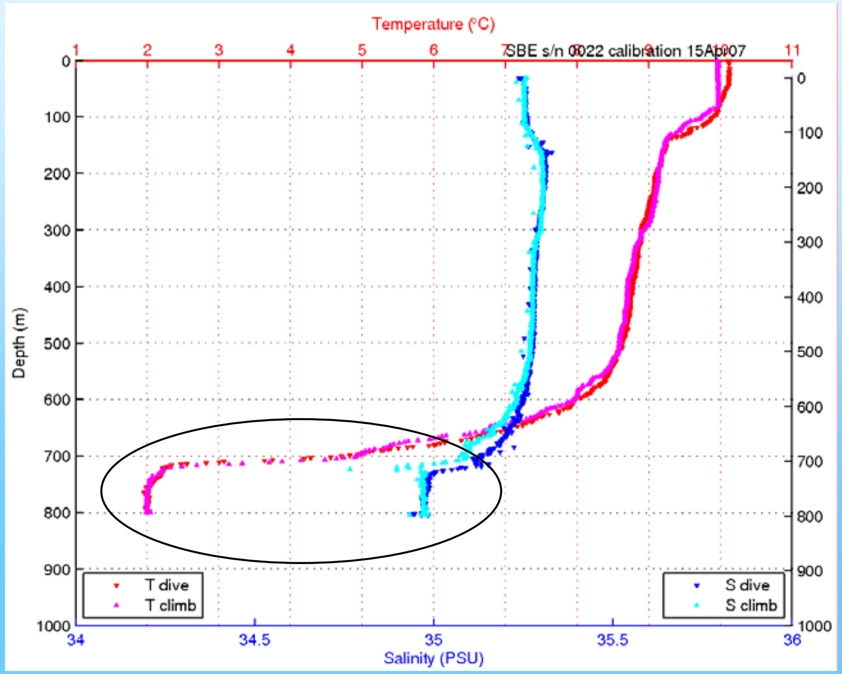


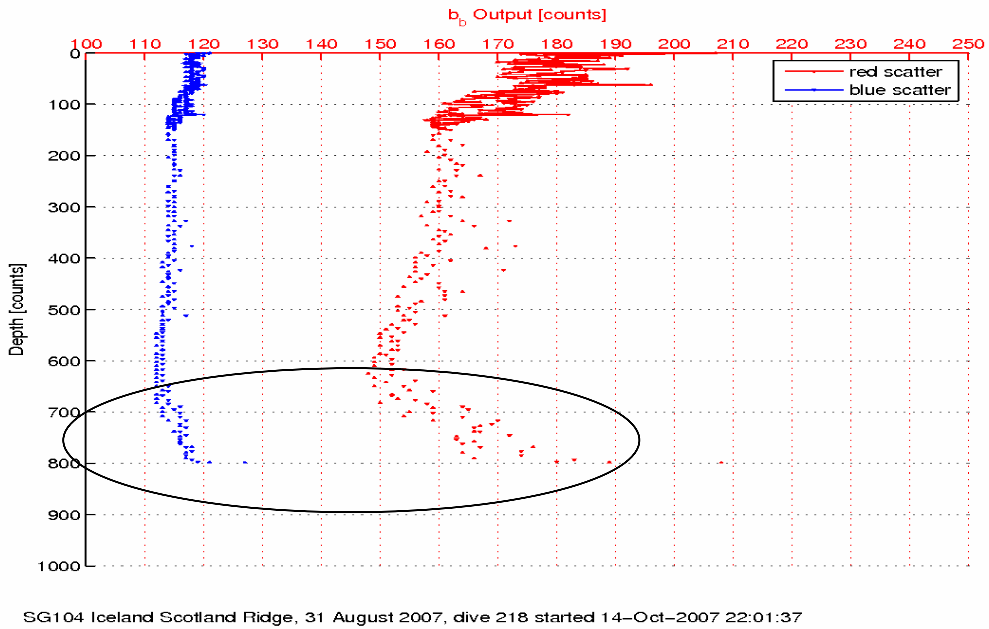
fluorescence and oxygen saturation

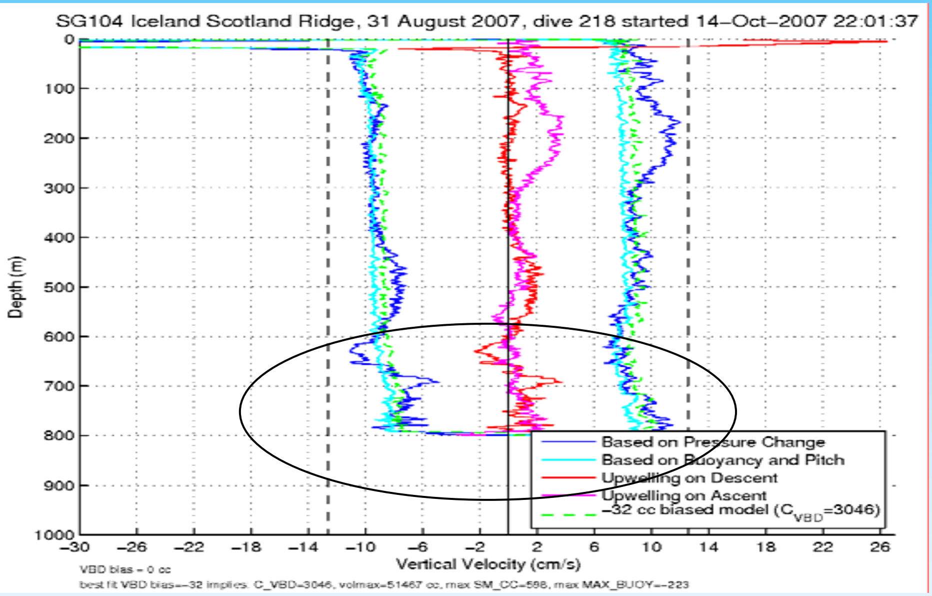


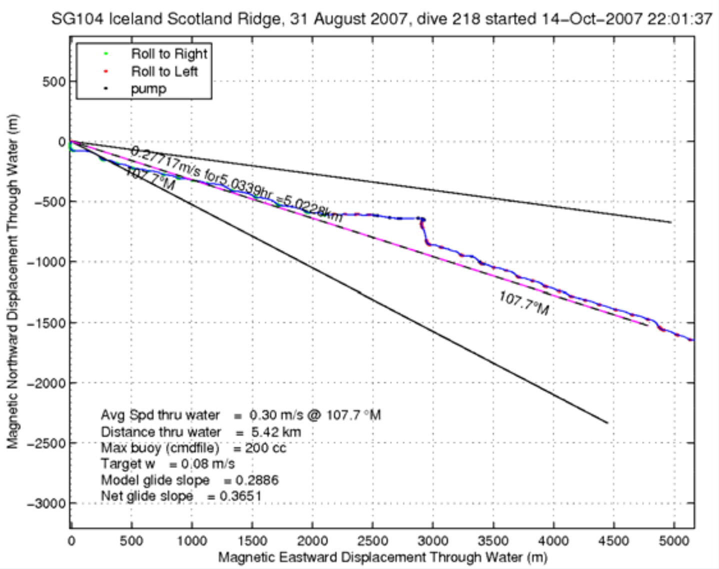


Seaglider 104 dive 218 15 x 2007 Iceland Faroe Ridge

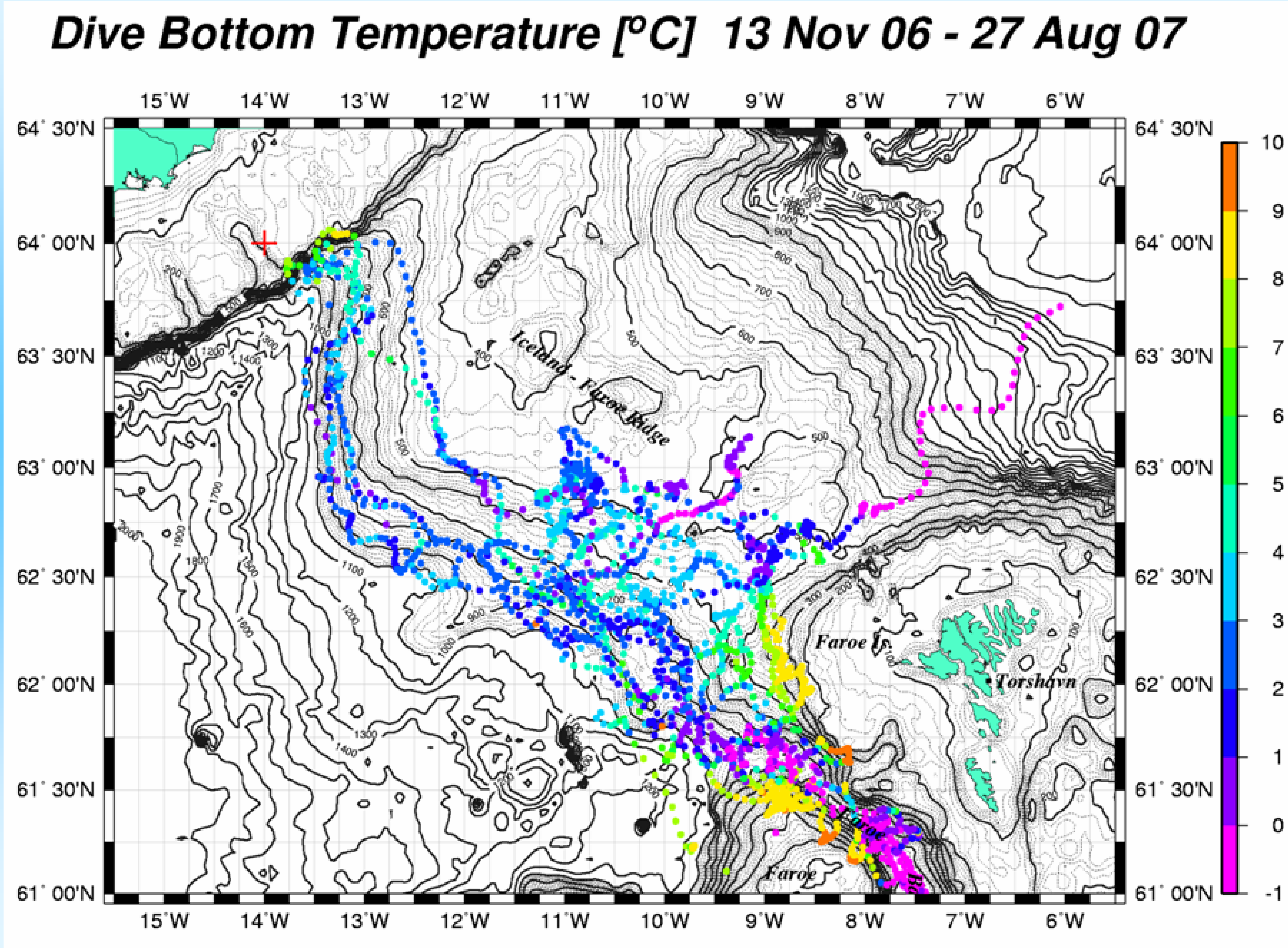








Seeking the cold, thin overflows on the Iceland-Faroe Ridge.



Kyoto FDEPS lectures 4-7 xi 2007

Dynamics of oceans and atmospheres

P.B. Rhines

University of Washington

ALL DAYS

- 1. rotating, stratified fluids: oceans and atmospheres
  - vorticity: a vector-tracer in classical homogeneous fluids
- geostrophic adjustment, thermal wind
- 2. wave dynamics: fundamentals, group velocity, energetics, ray theory
- potential vorticity (PV)
  - vortex stretching, Prandtl's ratio, geography of PV
- 3. Rossby waves
- 4. instability => geostrophic turbulence; subtropical gyres: dynamics, jets and gyres, topography effects
- 5. Case study of topographic effect on atmospheric circulation: Greenland and Atlantic storm track.
- 6. Teaching young undergraduates about the global environment?
- 7. Seminar: subpolar climate dynamics observed from above and below: meridional overturning circulations (MOCs) altimetry and Seagliders

- **FDEPS Lectures, November 2007**
- P.B. Rhines, Oceanography and Atmospheric Sciences, University of Washington
- Rhines@ocean.washington.edu
- www.ocean.washington.edu/research/gfd
-
- These lectures will address the dynamics of oceans and atmospheres, as seen through theory, laboratory simulation and field observation. We will look particularly at high latitudes and climate dynamics of the ocean circulation coupled to the atmospheric storm tracks. We will emphasize the dynamics that is difficult to represent in numerical circulation models. We will discuss properties of oceans and atmospheres that are both fundamental, unsolved questions of physics, and are also important, unsolved problems of global environmental change.
- **Lecture 1**:
- Is the ocean circulation important to global climate ? Does dense water drive the global conveyor circulation? Fundamental questions about oceans and atmospheres that are currently under debate.
-
- The field theory for buoyancy and potential vorticity.
- Basic propagators: Rossby waves and geostrophic adjustment.
- Potential vorticity: inversion and flux.
- **Lecture 2**:
- How do waves and eddies shape the general circulation, gyres and jet streams?
- Almost invisible overturning circulations.
- Lessons from Jupiter and Saturn.
- The peculiar role of mountains, seamounts and continental-slope topography.
- **Lecture 3**:
- Dynamics of ocean gyres and their relation with the global conveyor circulation.
- Water-mass transport, transformation and air-sea exchange of heat and fresh water.
- Ocean overflows and their mixing.
- Decadal trends in the global ocean circulation.
- **Lecture 4**:
- Heat, fresh-water, ice: convection in oceans and atmospheres and the texture of geophysical fluids.
- **Lecture 5**:
- Teaching young students about the global environment using the GFD laboratory: science meets energy and environment in the lives of Arctic natives
- **Seminar**:
- *Exploring high-latitude ocean climate with Seagliders and satellites*

These are unusual times we live in….

- ***Congratulations Nobel Peace Laureates;***

- ***Fundamentals of our basic science of circulation and climate are under debate** (what drives the global oceanic overturning circulation? is the ocean important to climate?...)*

- ***We are about to hit the wall (the exponentials of global change);***

- ***Our science is never far from the public interest…and the public interest is disturbingly remote from the integrity of the biosphere; =>there has never been a more important time to engage in teaching broad environmental science to young people.***

Kelvin waves, inertial waves in shallow rotating fluid