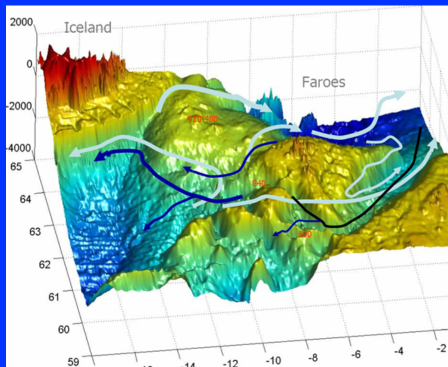
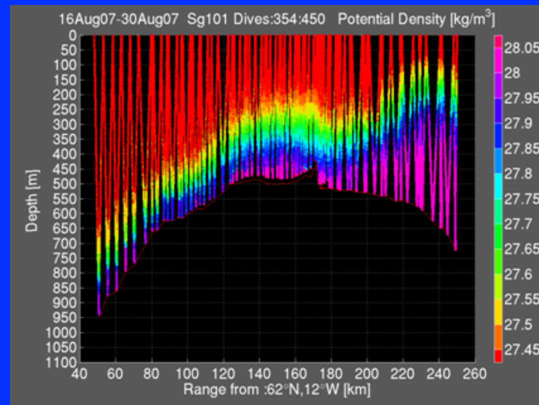
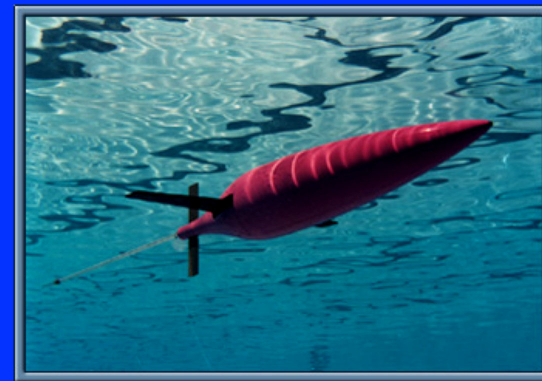
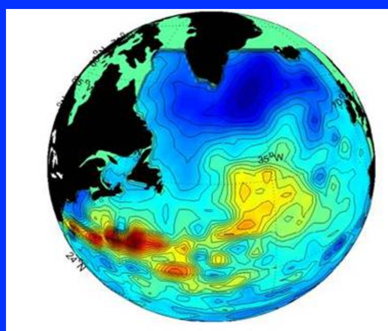
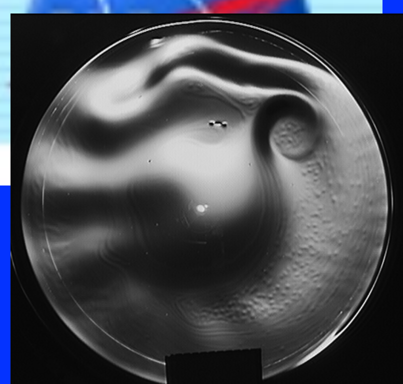










Seaglider encounters with key AMOC processes in the northern Atlantic/ Nordic/Labrador Seas

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

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

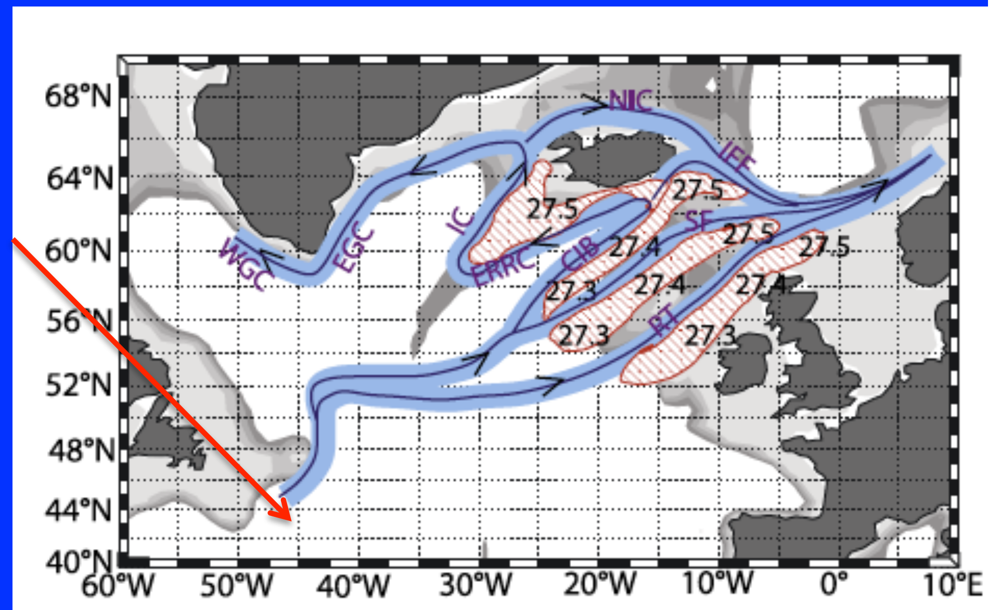
AMOC June 7, 2010

- Northern Atlantic/Labrador/Nordic Seas Seaglider programs
  - Norwegian Current
  - Davis Strait
  - Labrador Sea
  - Iceland-Faroe Ridge / Faroe Bank Channel

Background AMOC decadal variability

UPPER OCEAN BRANCH:

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



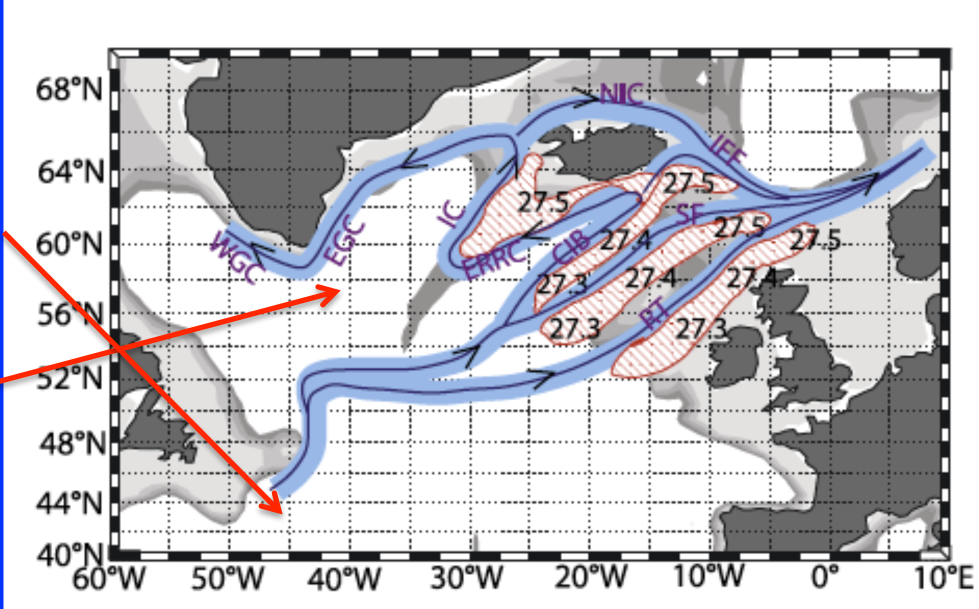
Background AMOC decadal variability

UPPER OCEAN BRANCH:

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

*Deceleration of subpolar gyre from satellite altimetry (1992-2000's)

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



Background AMOC decadal variability

UPPER OCEAN BRANCH:

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

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

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

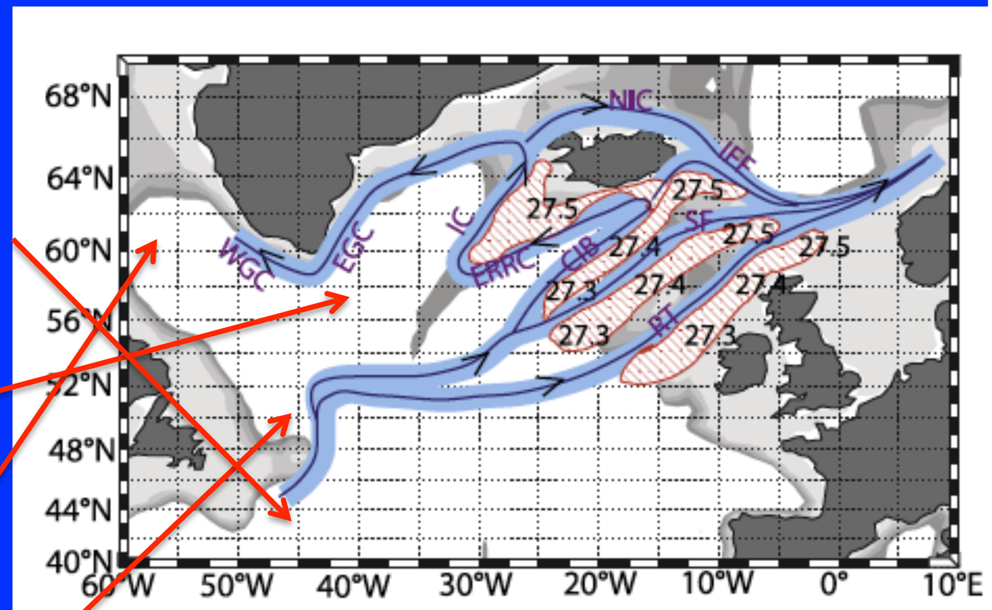
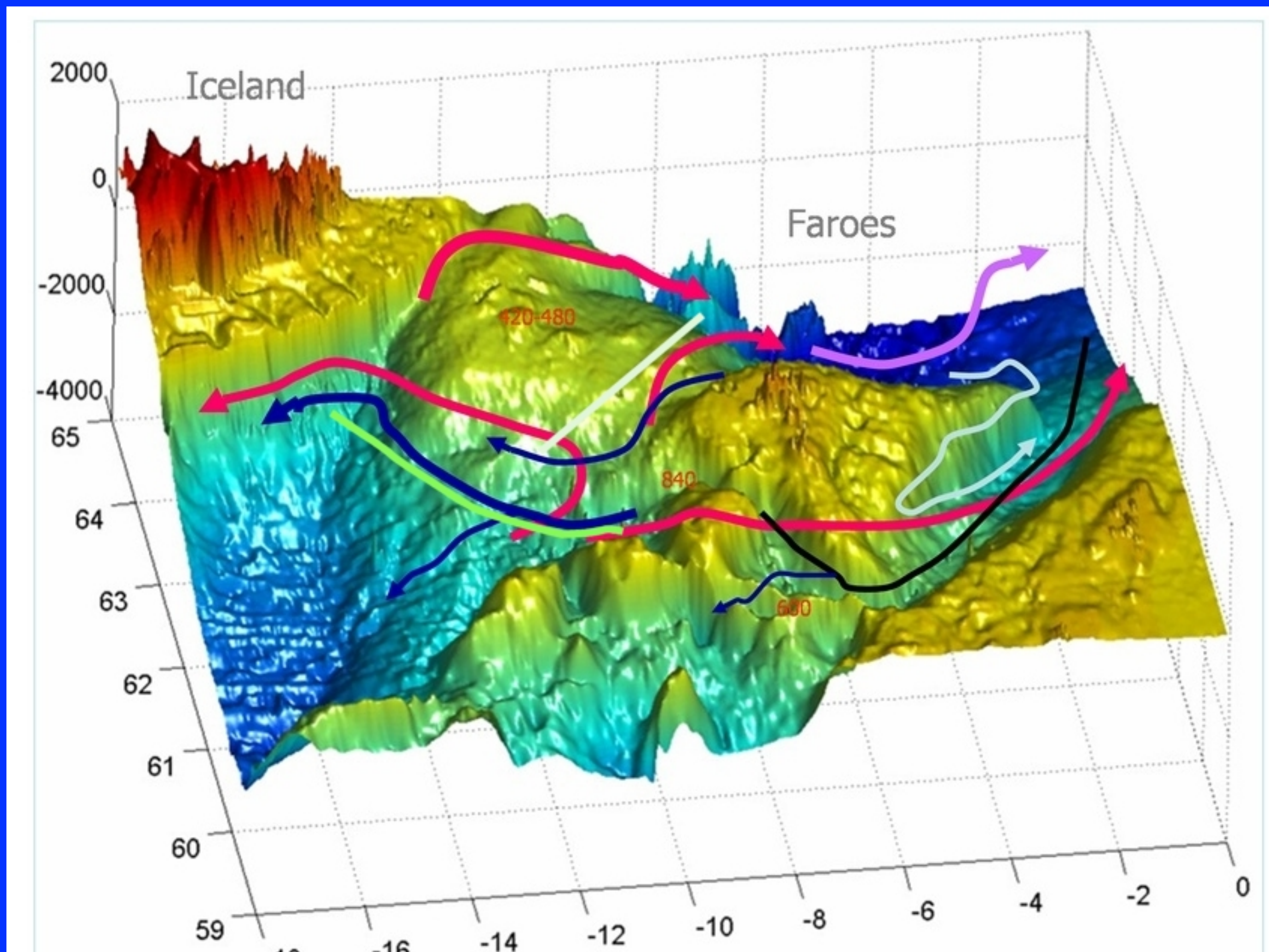
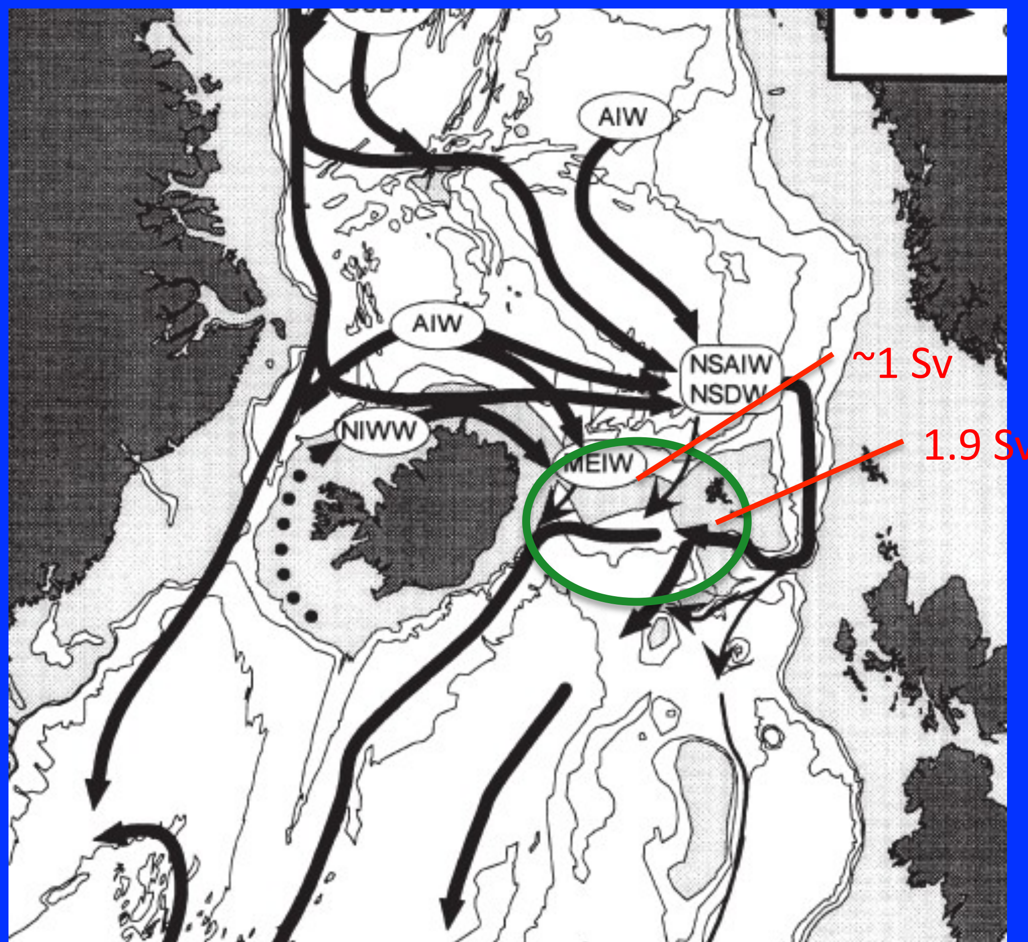


figure: *Brambilla & Talley*, JGR 2008

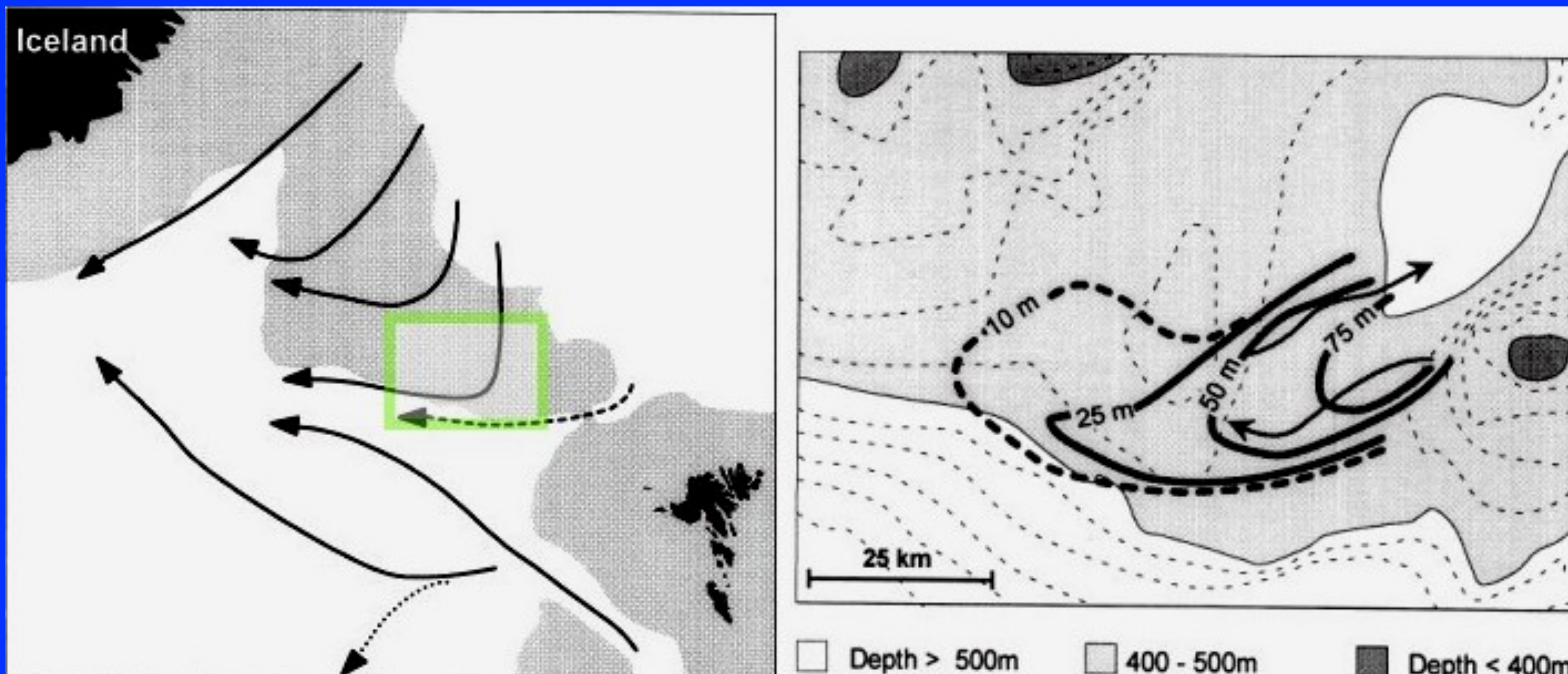
Iceland Faroe Ridge / Faroe Bank Channel



Dense overflow pathways (*Hansen & Osterhus,* PIO 2000)



Overflow ’73 (*Koltermann, Meincke & Muller* 1976 IFM rep.)

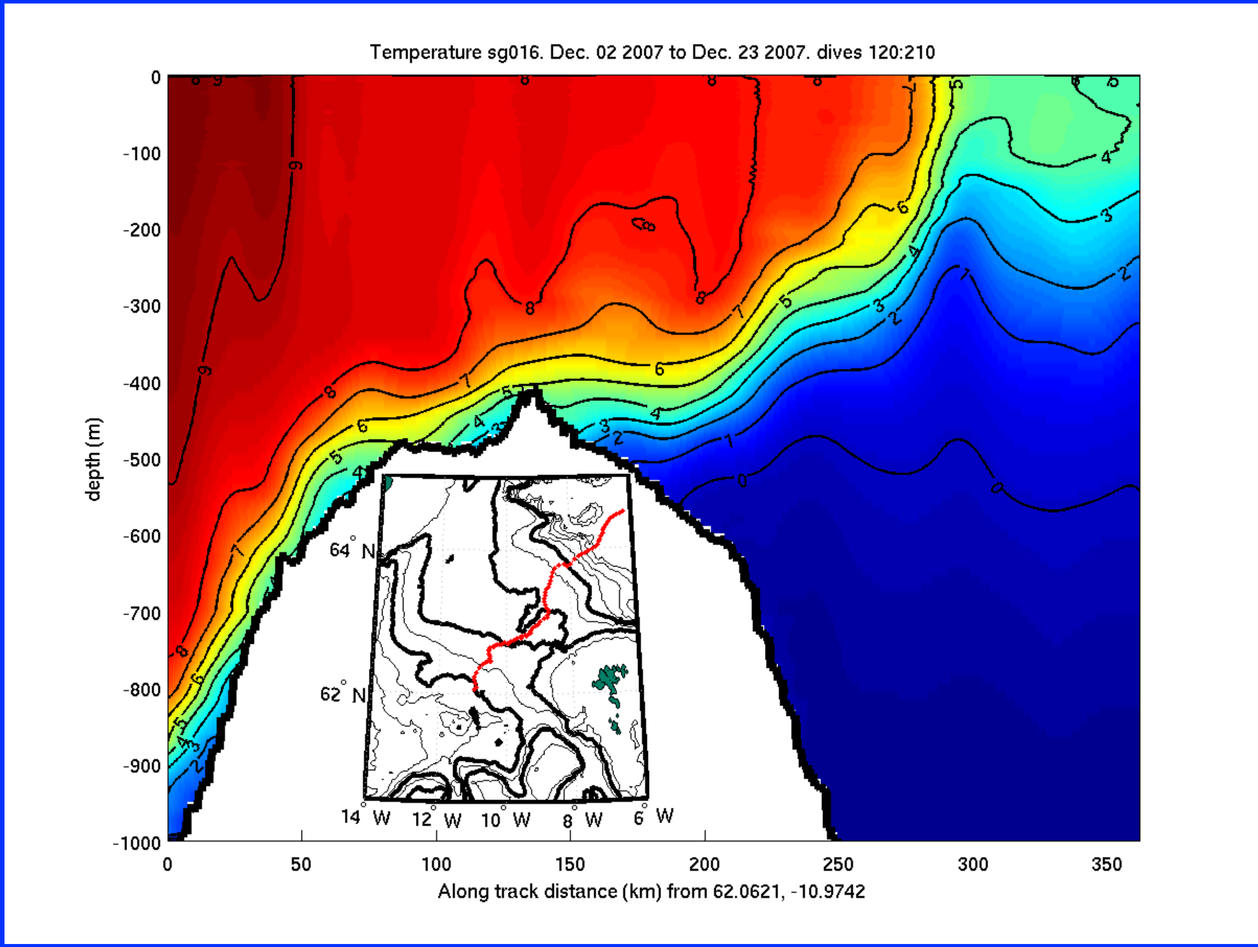


NSF-OCE sponsored Seaglider deployments

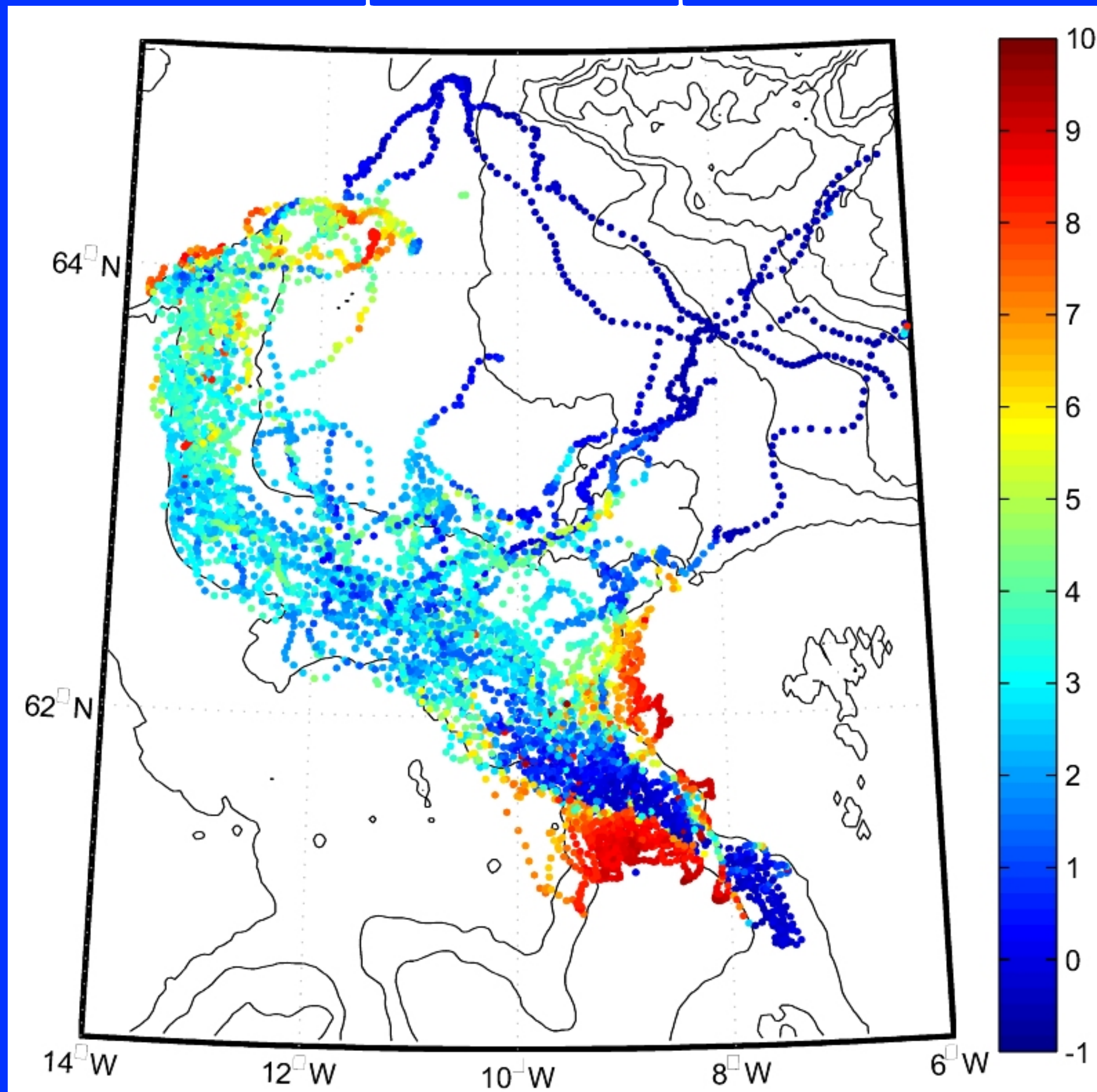
From Nov 2006 to Nov 2009, Seaglider launches from the Faroe Islands returned 23 successful 'cruises' yielding more than 17,000 profiles, mostly full depth: θ, S, p, O_2, fluorescence, red and blue particle backscatter; depth-averaged horizontal velocity, small-scale vertical velocity .

Concentrated on south flank of Ridge and Faroe Bank Channel exit, where the ~ 3 Sv of dense water enters Iceland Basin, eventually producing NorthEast Atlantic Deep Water, a constituent of lower North Atlantic Deep Water with potential density ~ 27.8

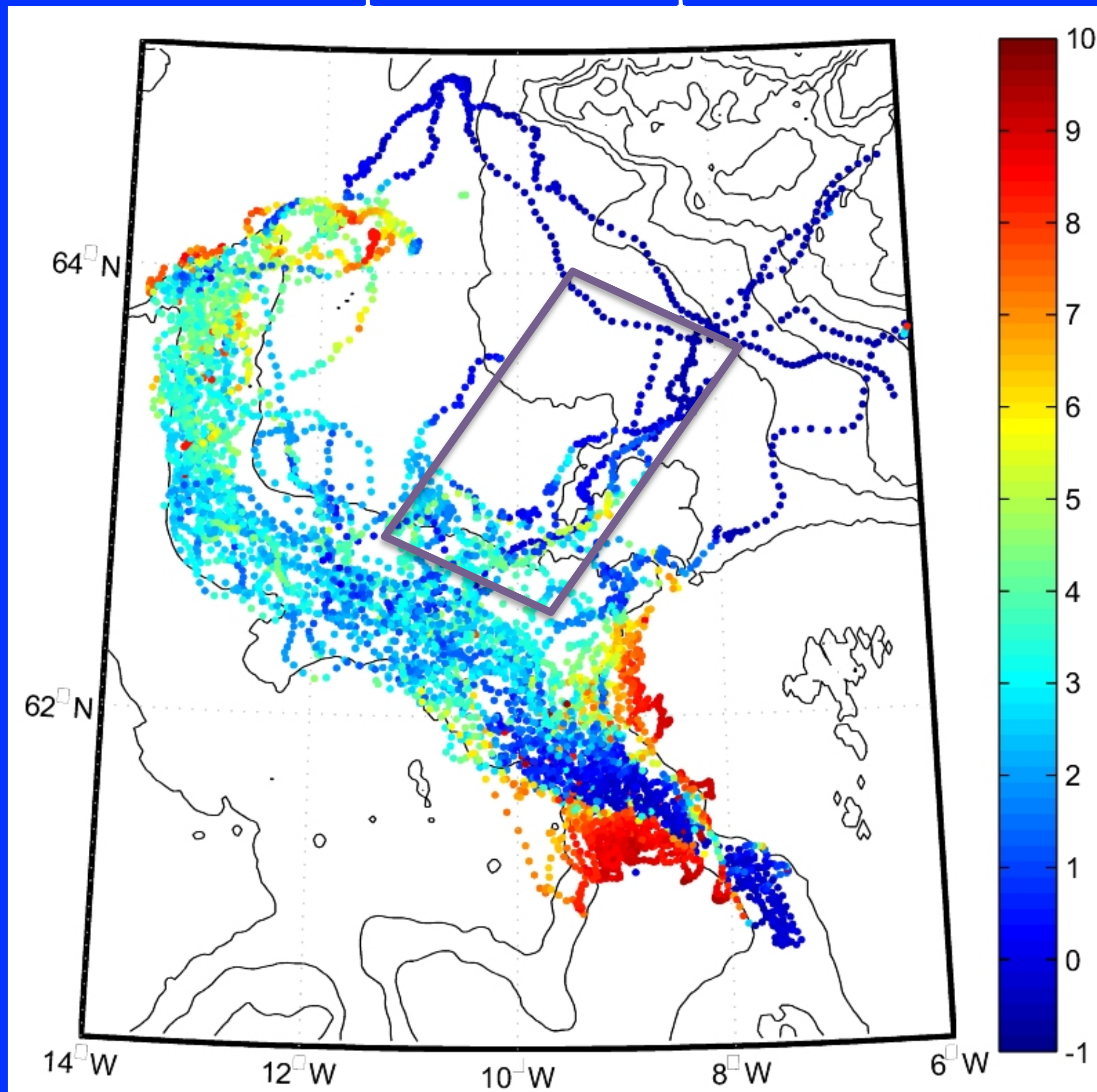
Cross-ridge glider temperature section



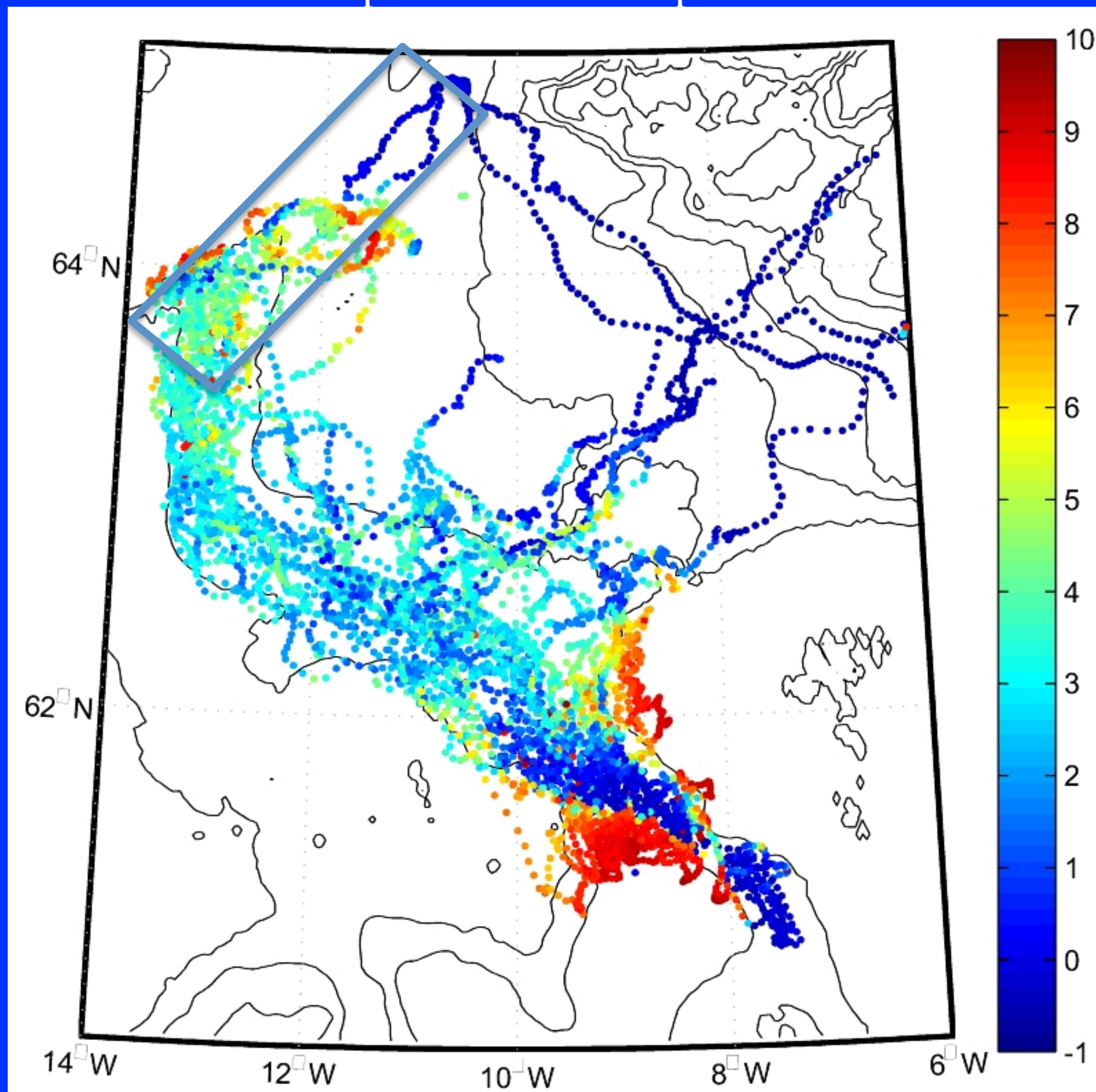
Bottom potential temperature…all



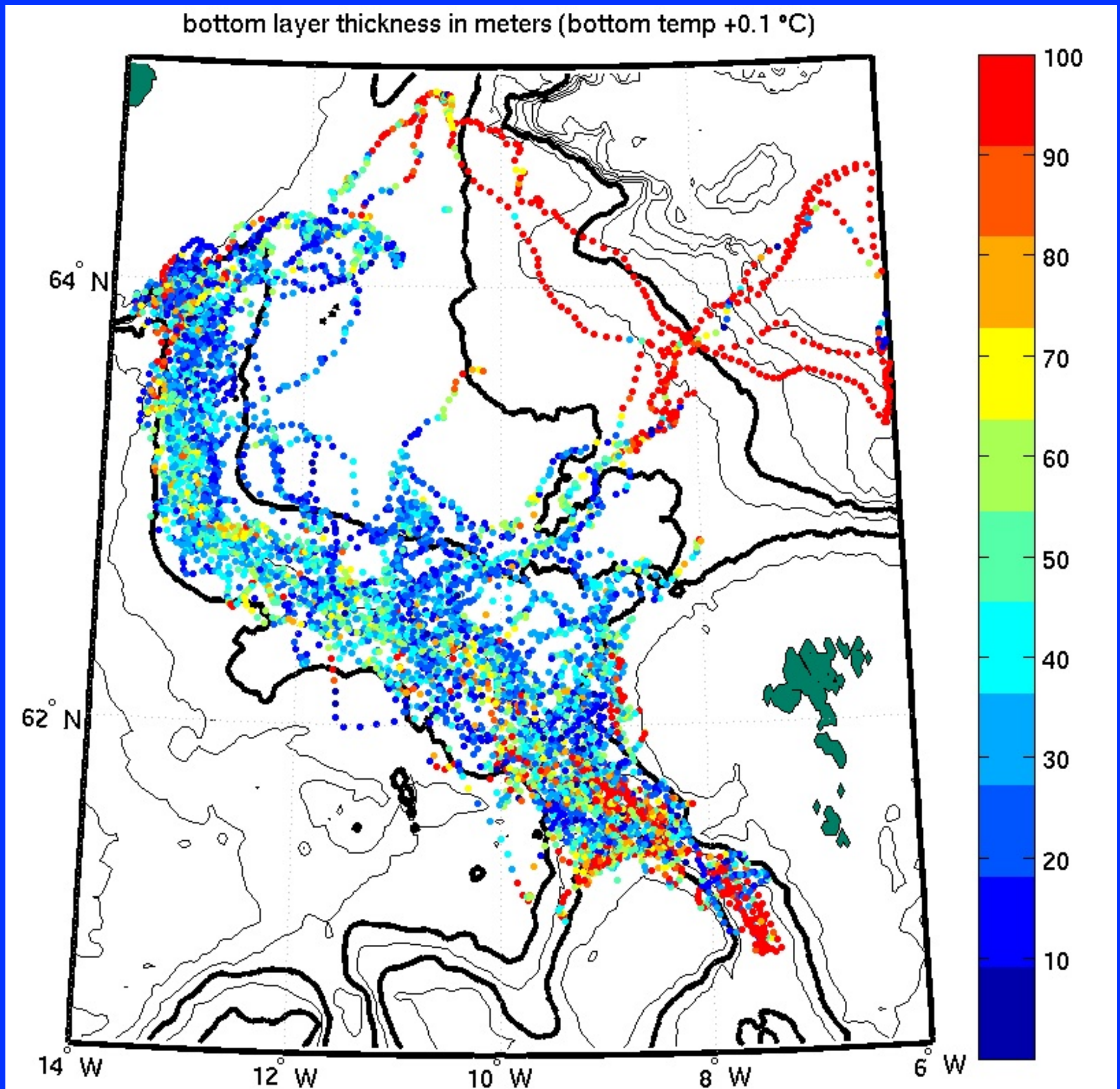
Bottom potential temperature…all



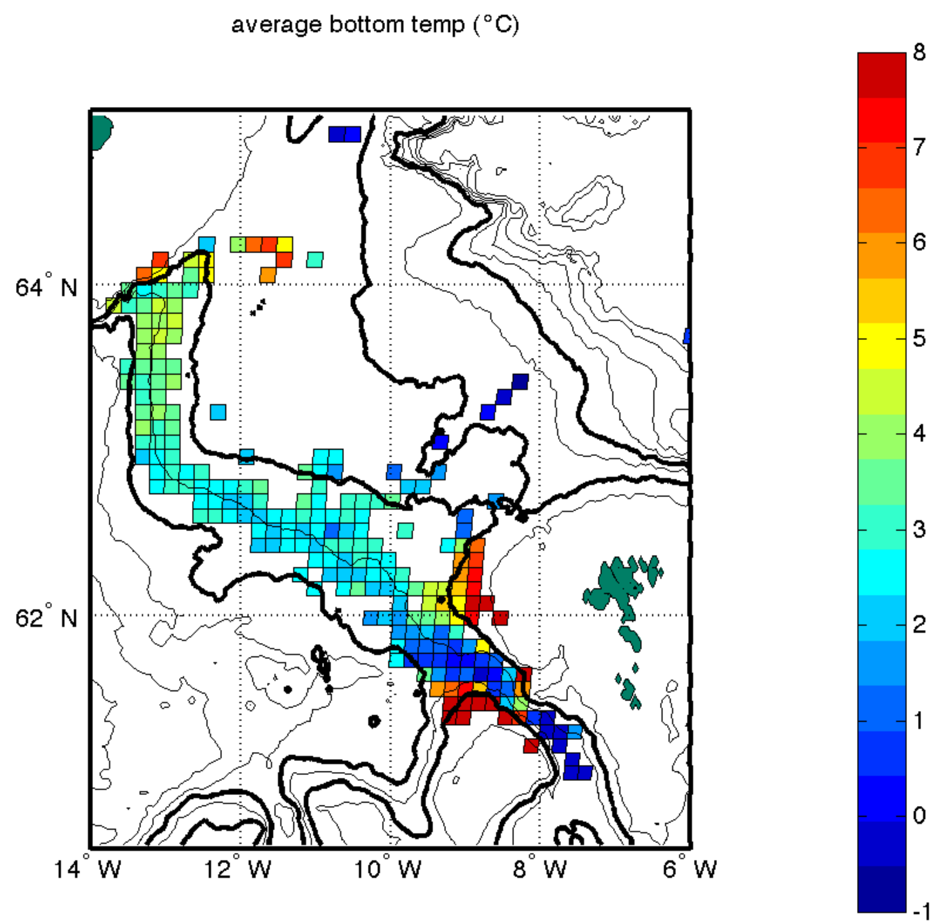
Bottom potential temperature…all



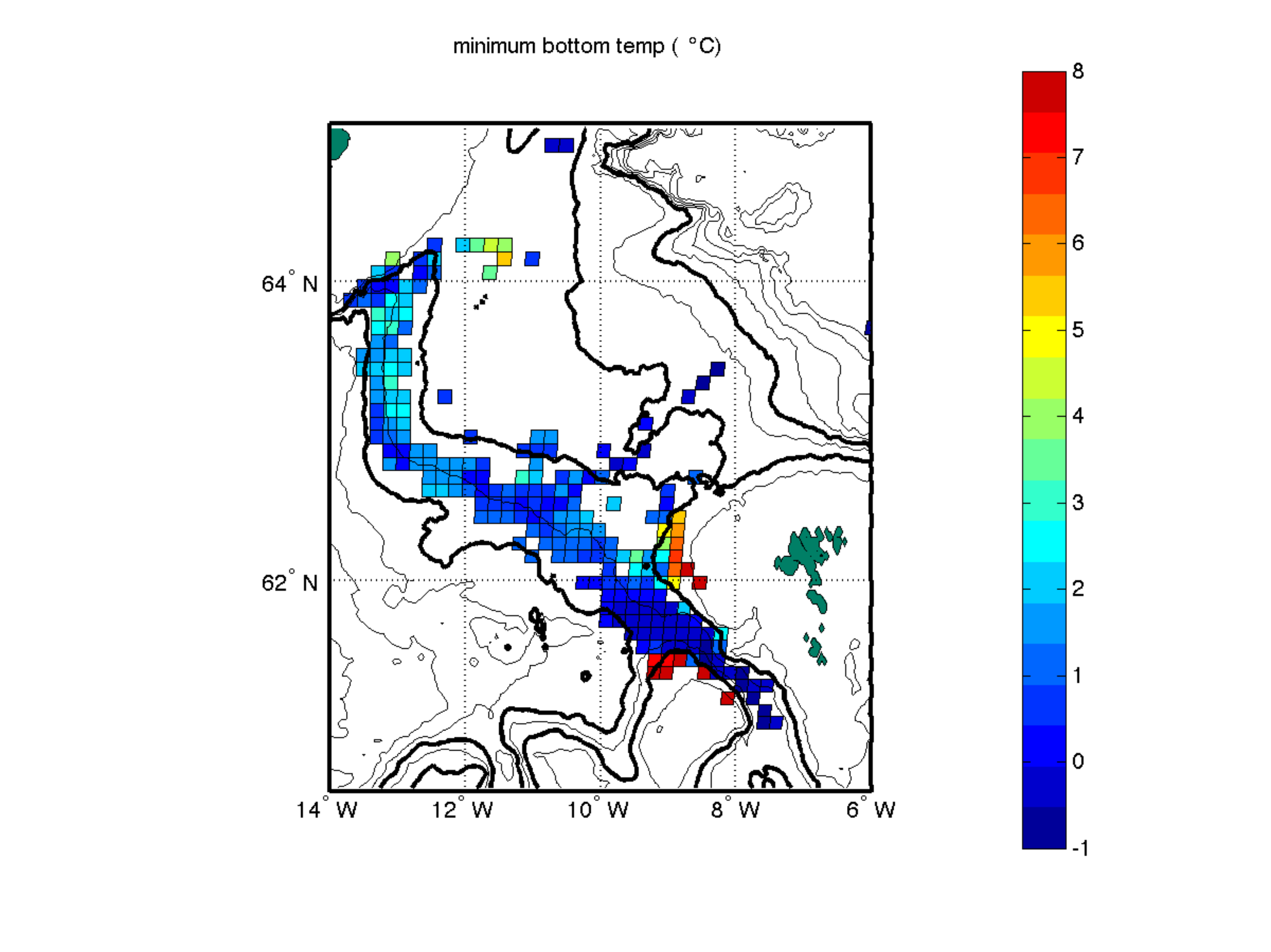
Bottom dense layer thickness



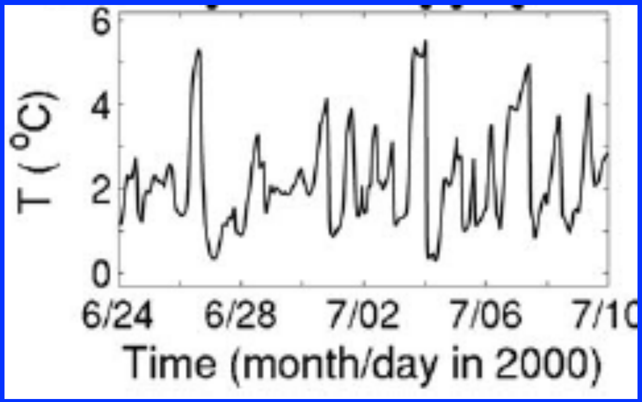
Average bottom pot. temperature



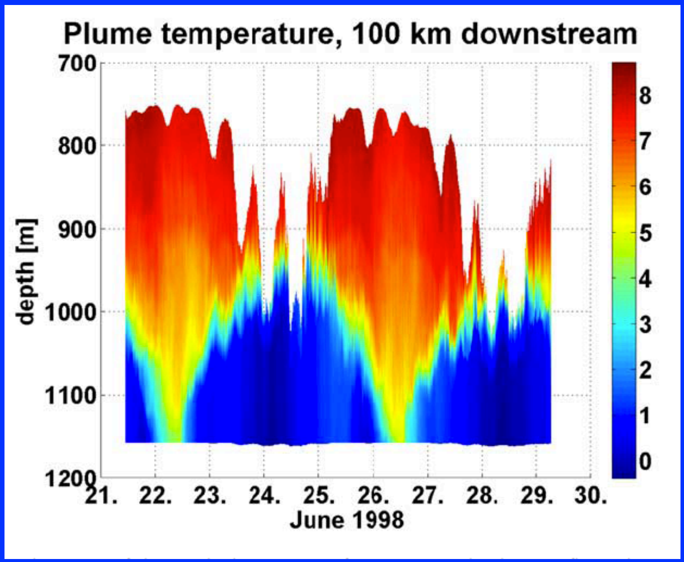
Extreme observed bottom pot. temperature



Moored observations show dense plume variability at 2-5 days near the FBC exit; here we see such variability along the entire 400 km Ridge pathway

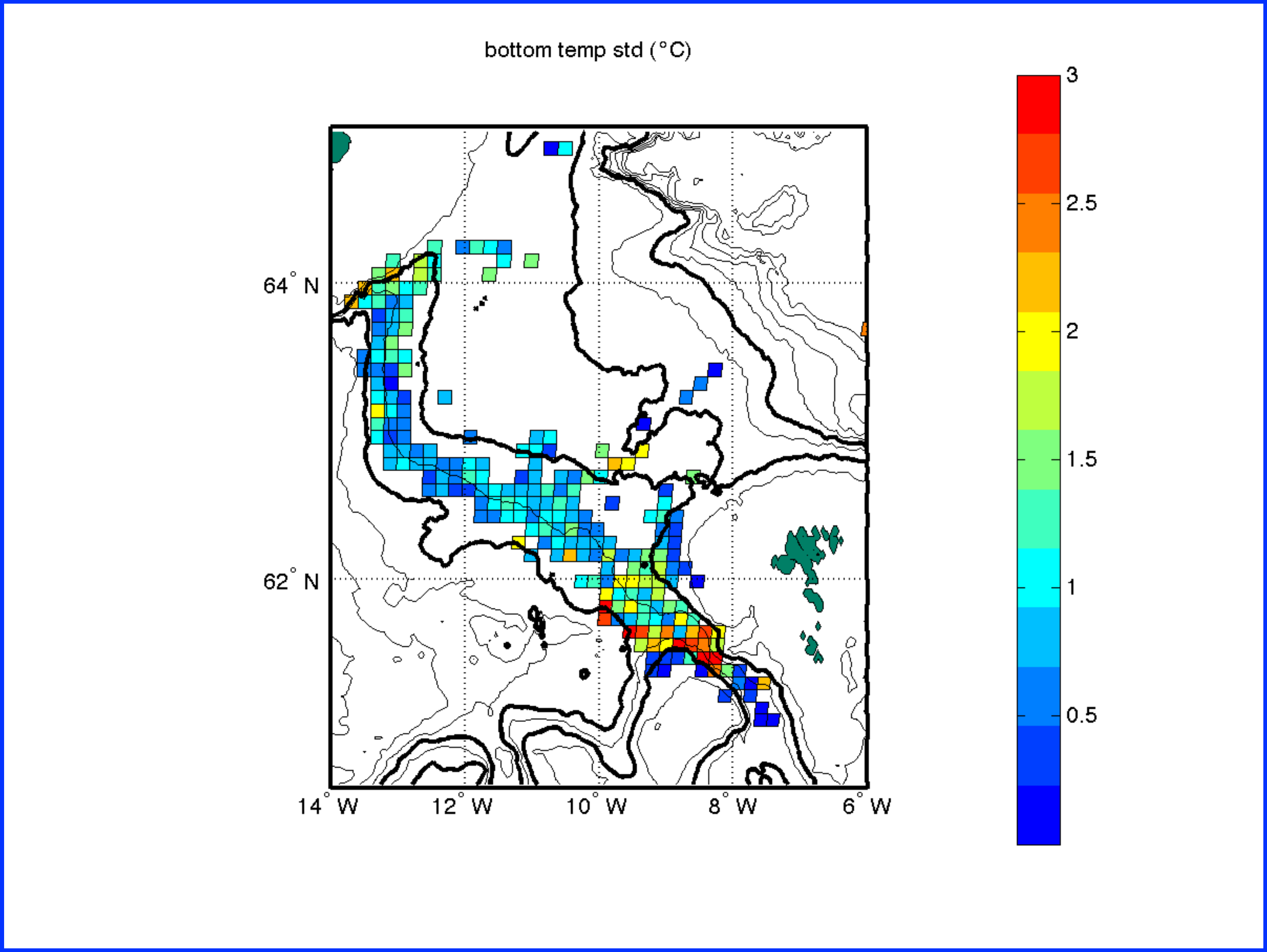


Prater & Rossby JGR 2005

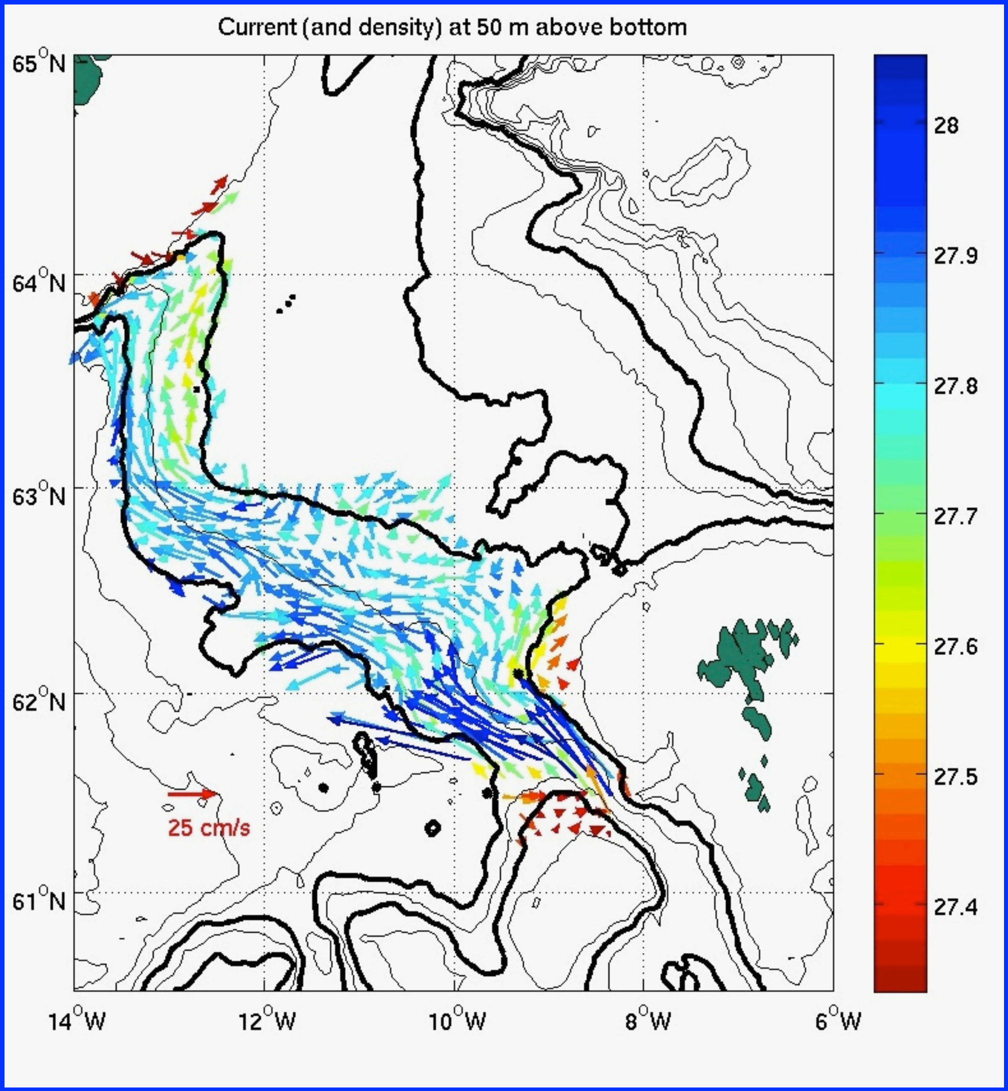


Geyer et al. JGR 2006).

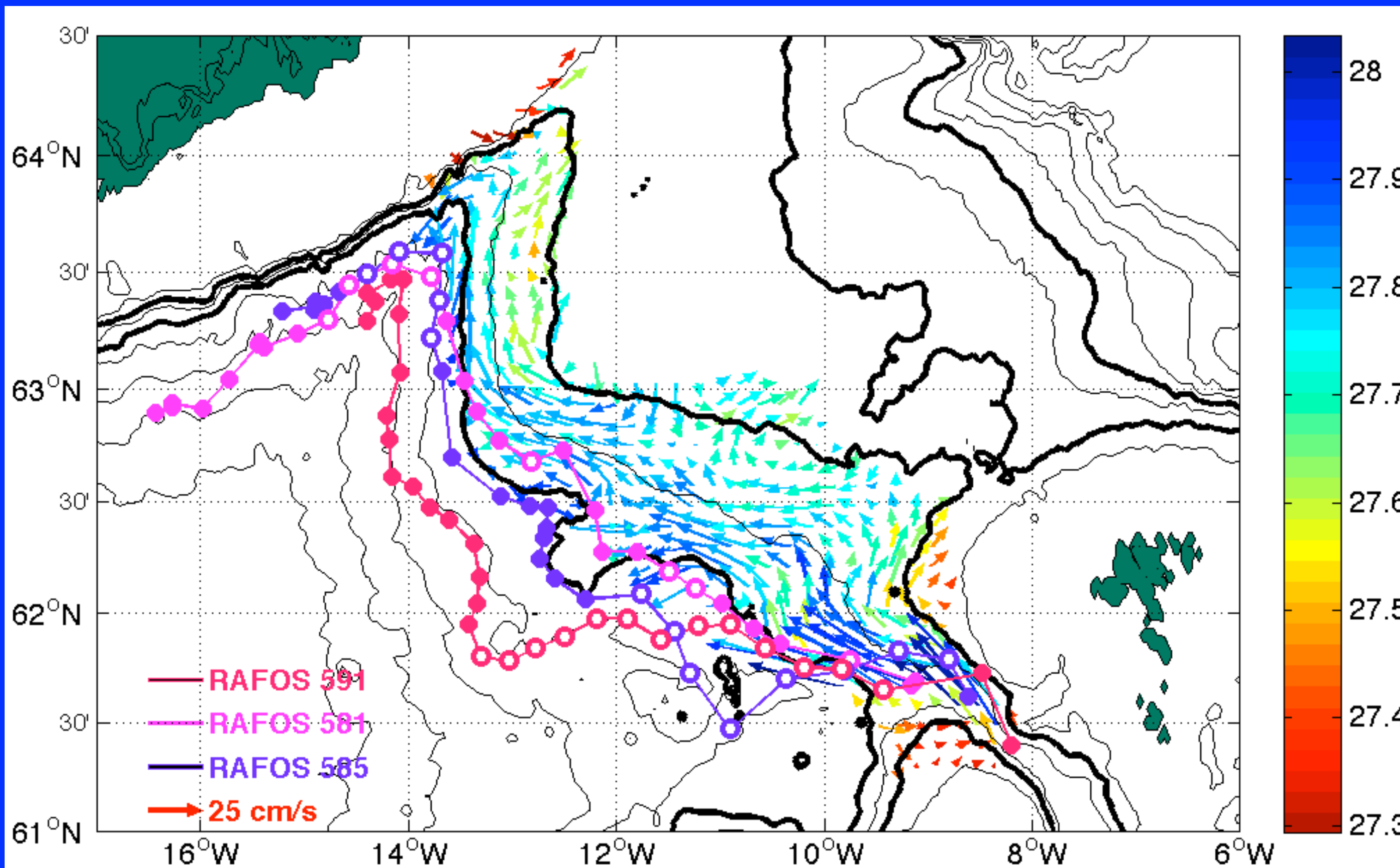
standard dev. of bottom pot temperature

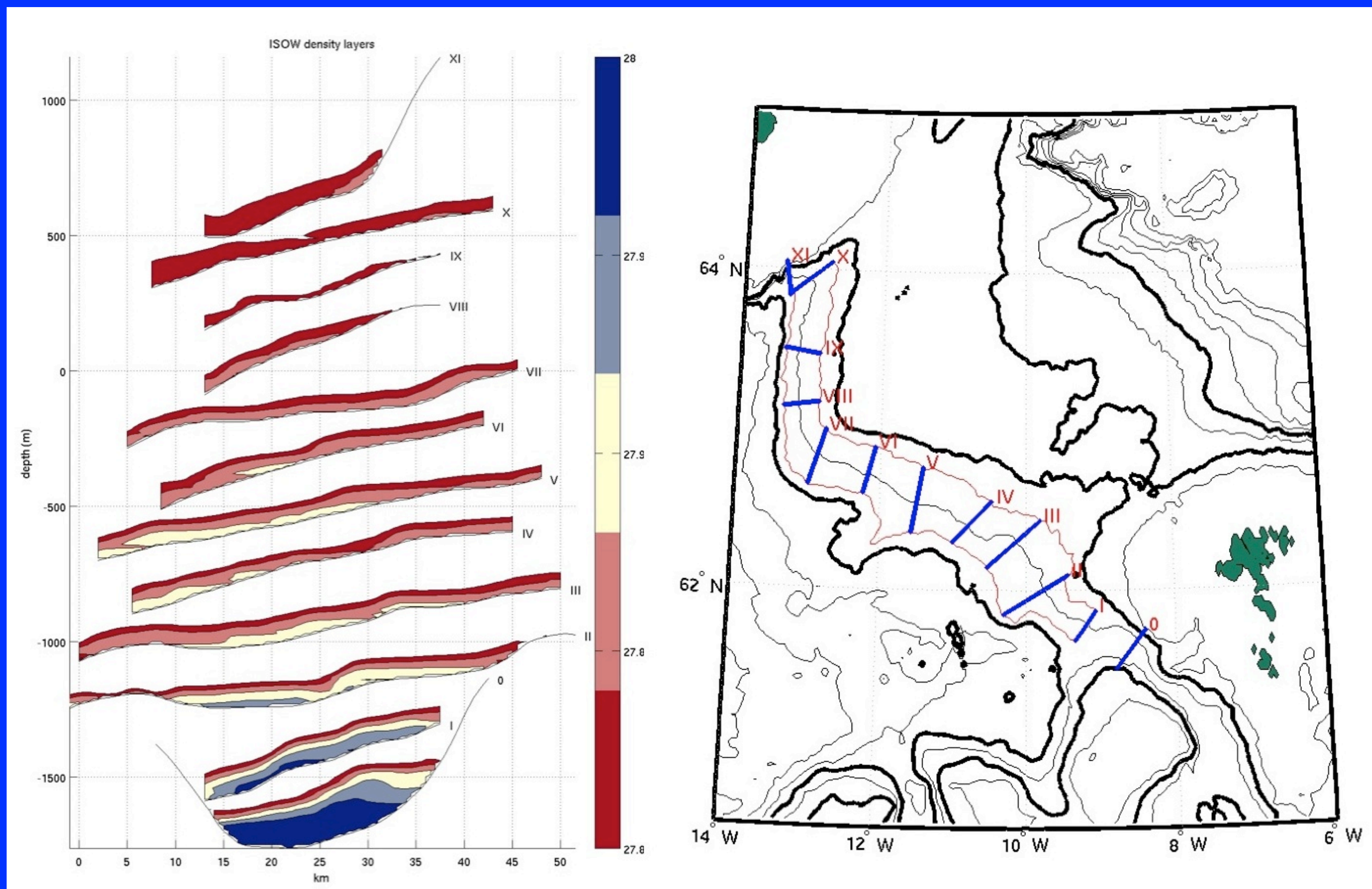


3-year mean current and potential density 50m above bottom (500-1000m) from thermal wind plus glider depth-averaged horizontal velocity



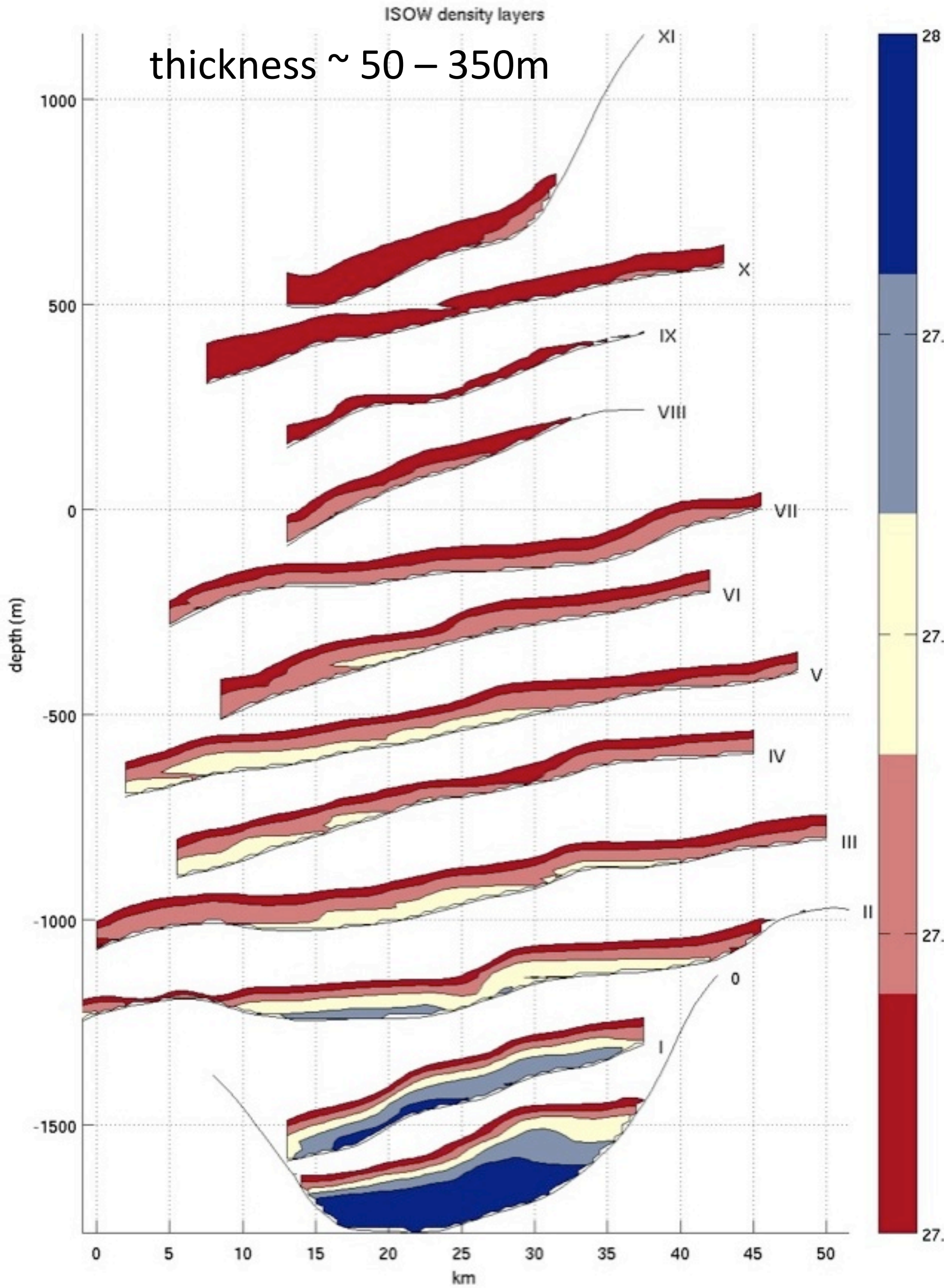
Rossby-Prater bottom RAFOS drifter tracks (JGR 2005)

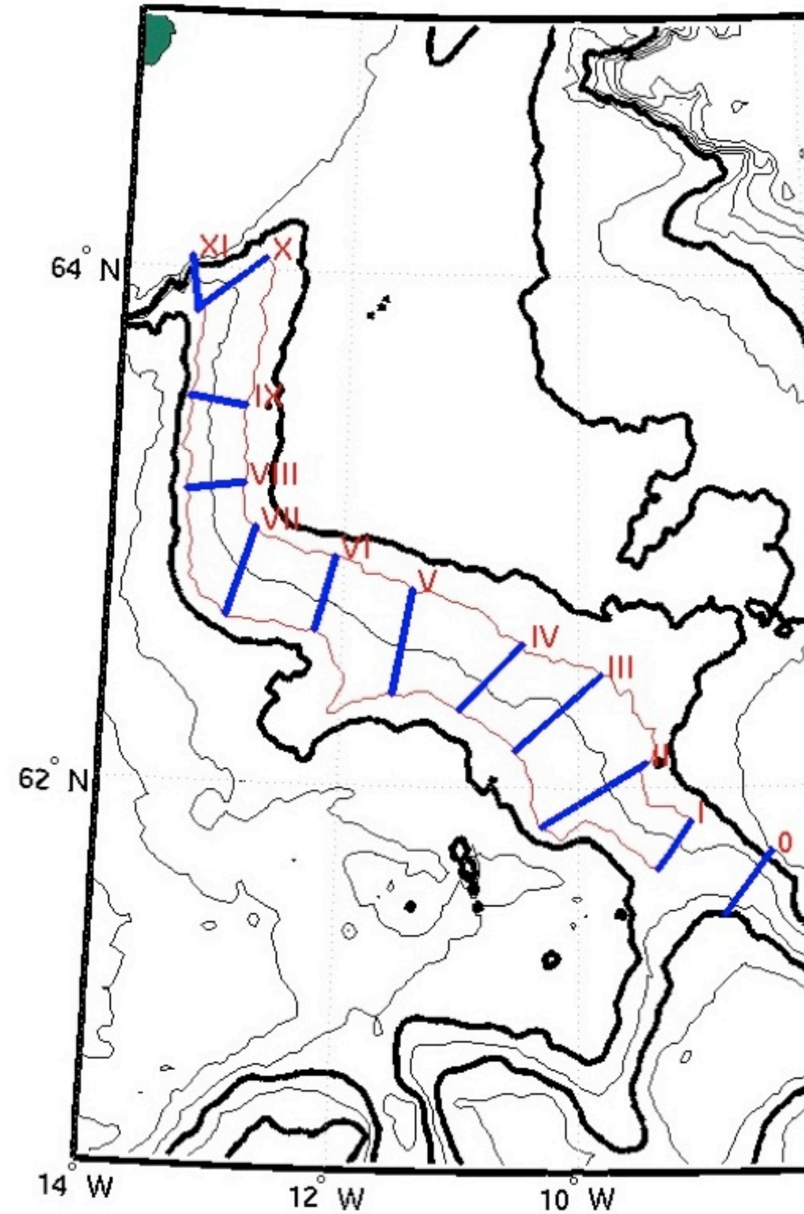


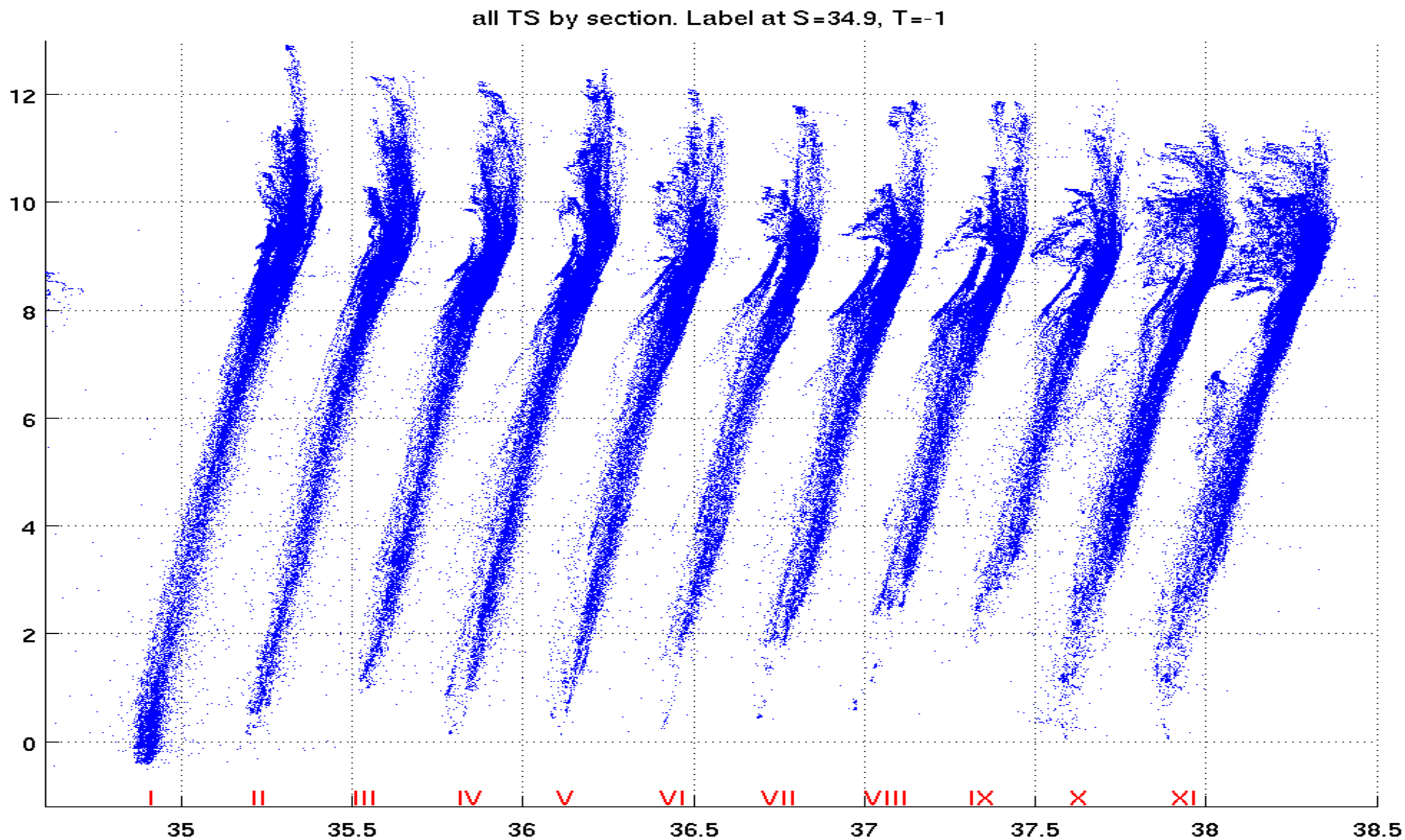


ISOW density layers
depth (m)
km
XI
X
IX
VIII
VII
VI
V
IV
III
II
I
0
28
27.9
27.8
64° N
62° N
14° W
12° W
10° W
8° W
6° W

thickness ~ 50 – 350m



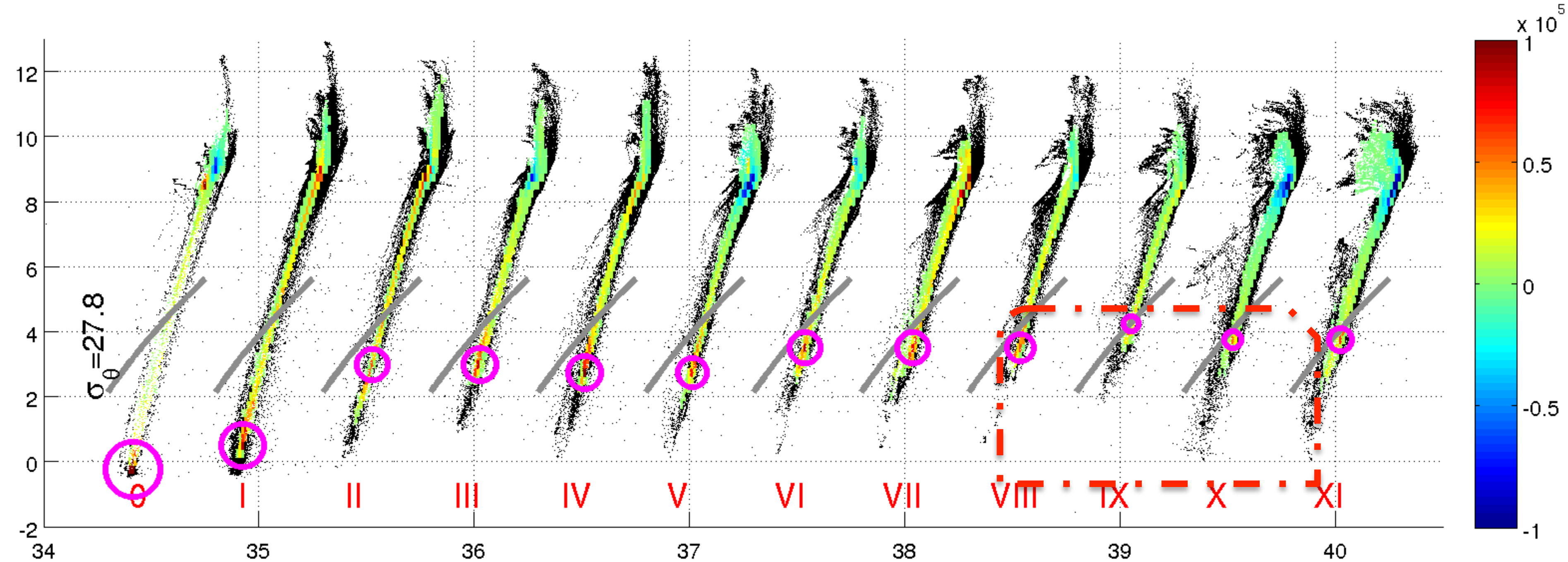




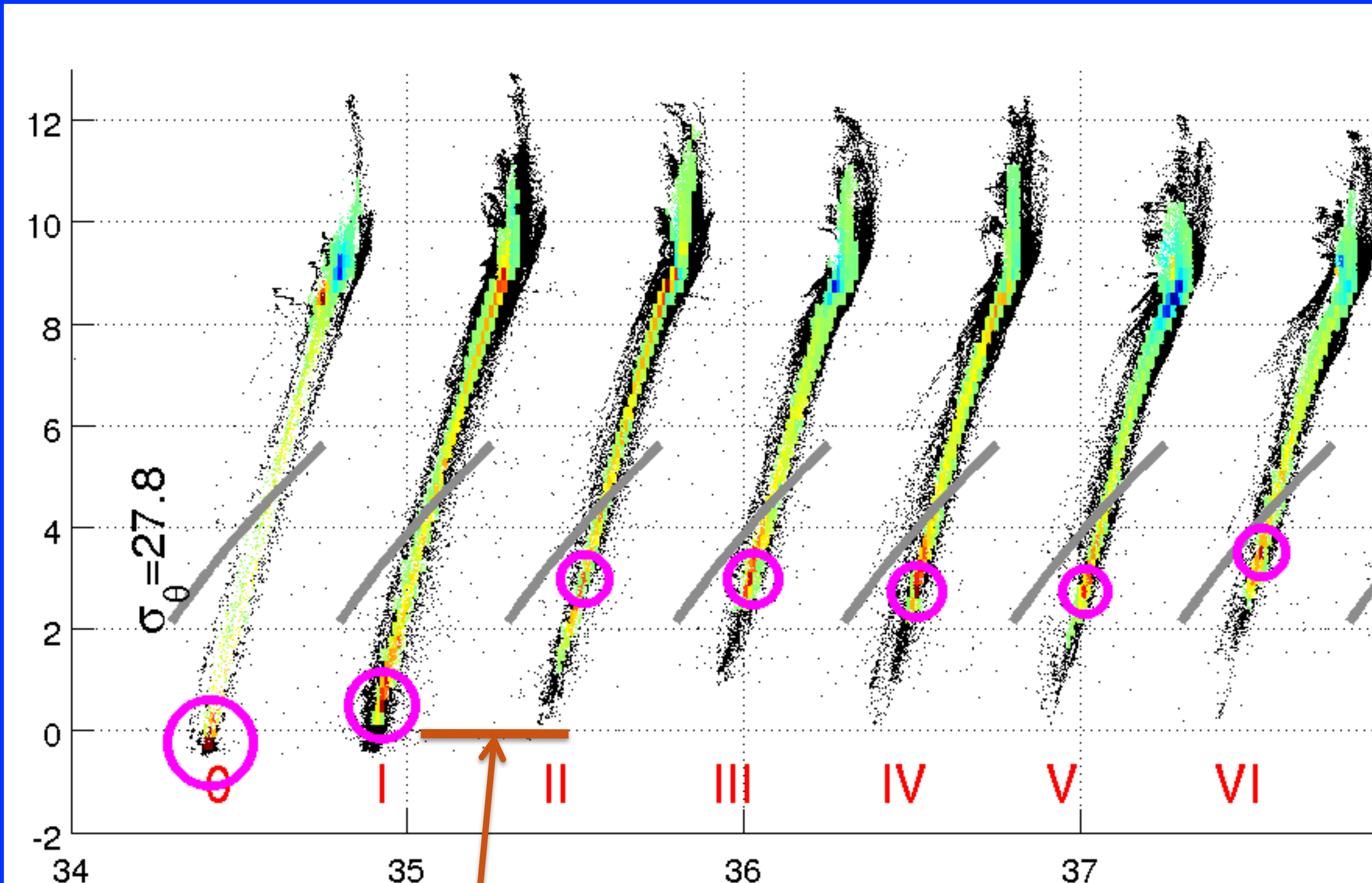
all TS by section. Label at S=34.9, T=-1
12
10
8
6
4
2
0
35
35.5
36
36.5
37
37.5
38
38.5
I
II
III
IV
V
VI
VII
VIII
IX
X
XI

Downstream evolution with transport projected on θ/S

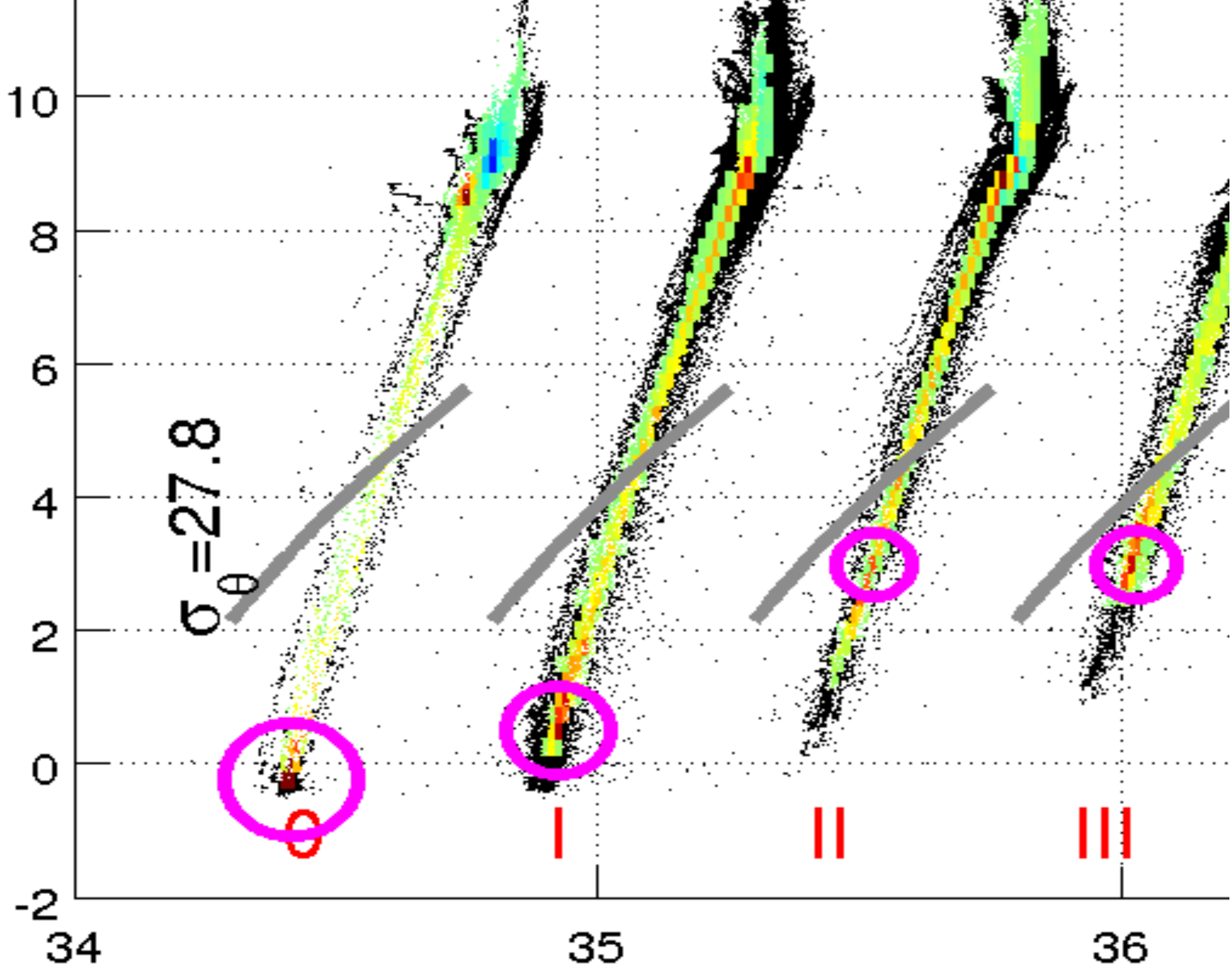
Transport weighted circles



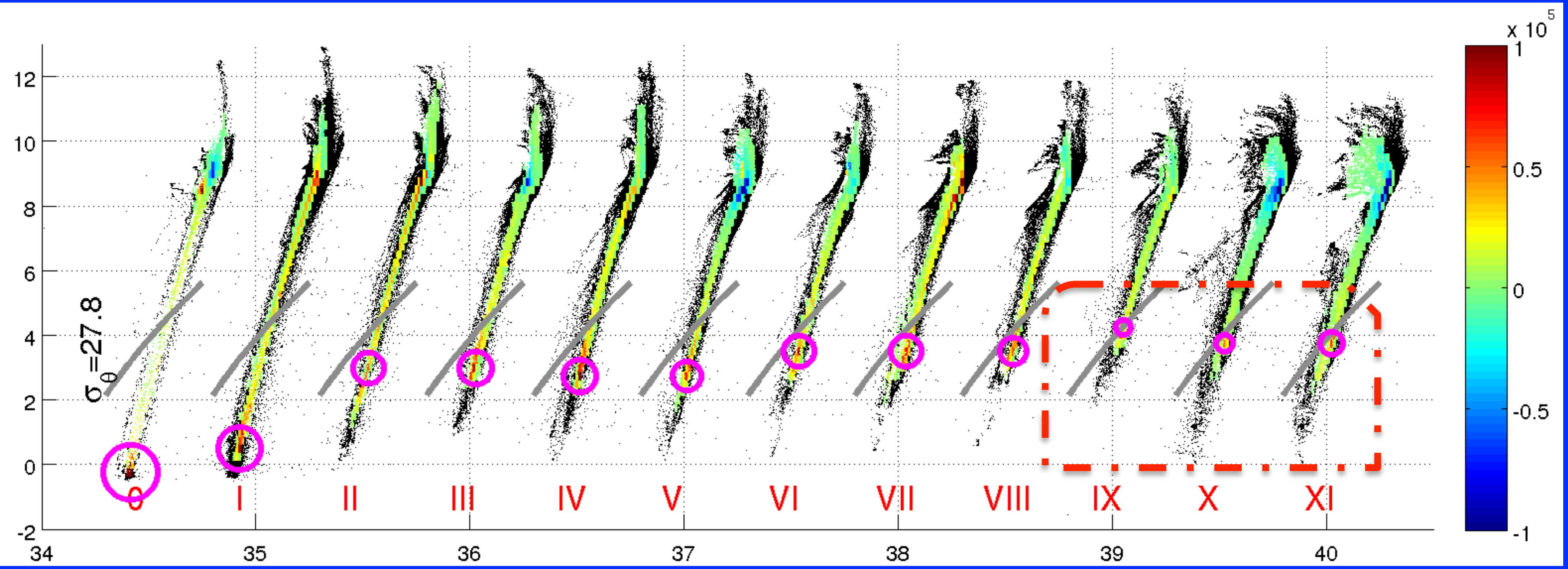
Beaird, Eriksen & Rhines, AGU 2010



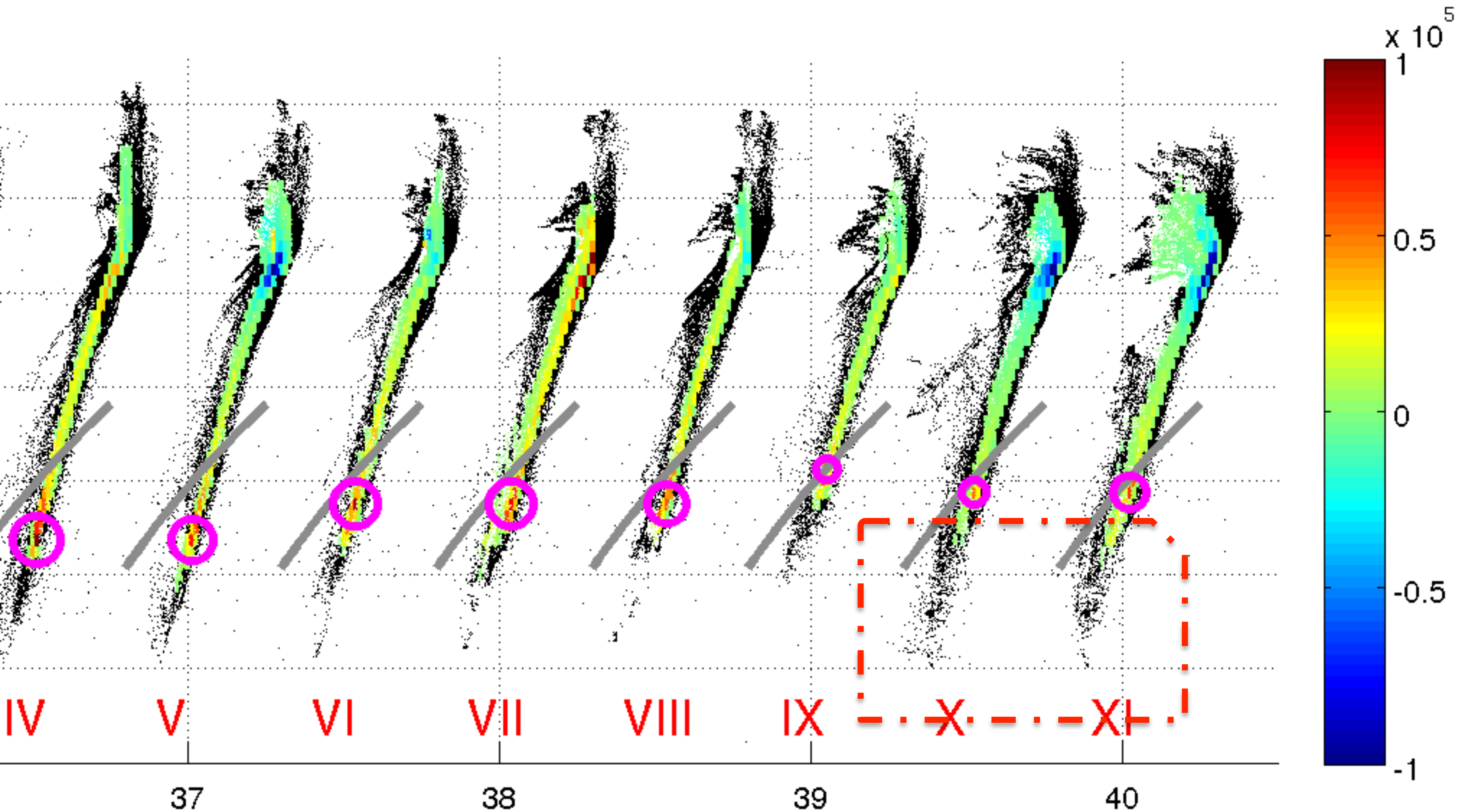
Rapid mixing events in Mauritzen et al. (DSR 2004) FBC cruise occurred here



10
8
6
4
2
0
-2
34
35
36
$\sigma_\theta=27.8$
0
I
II
III

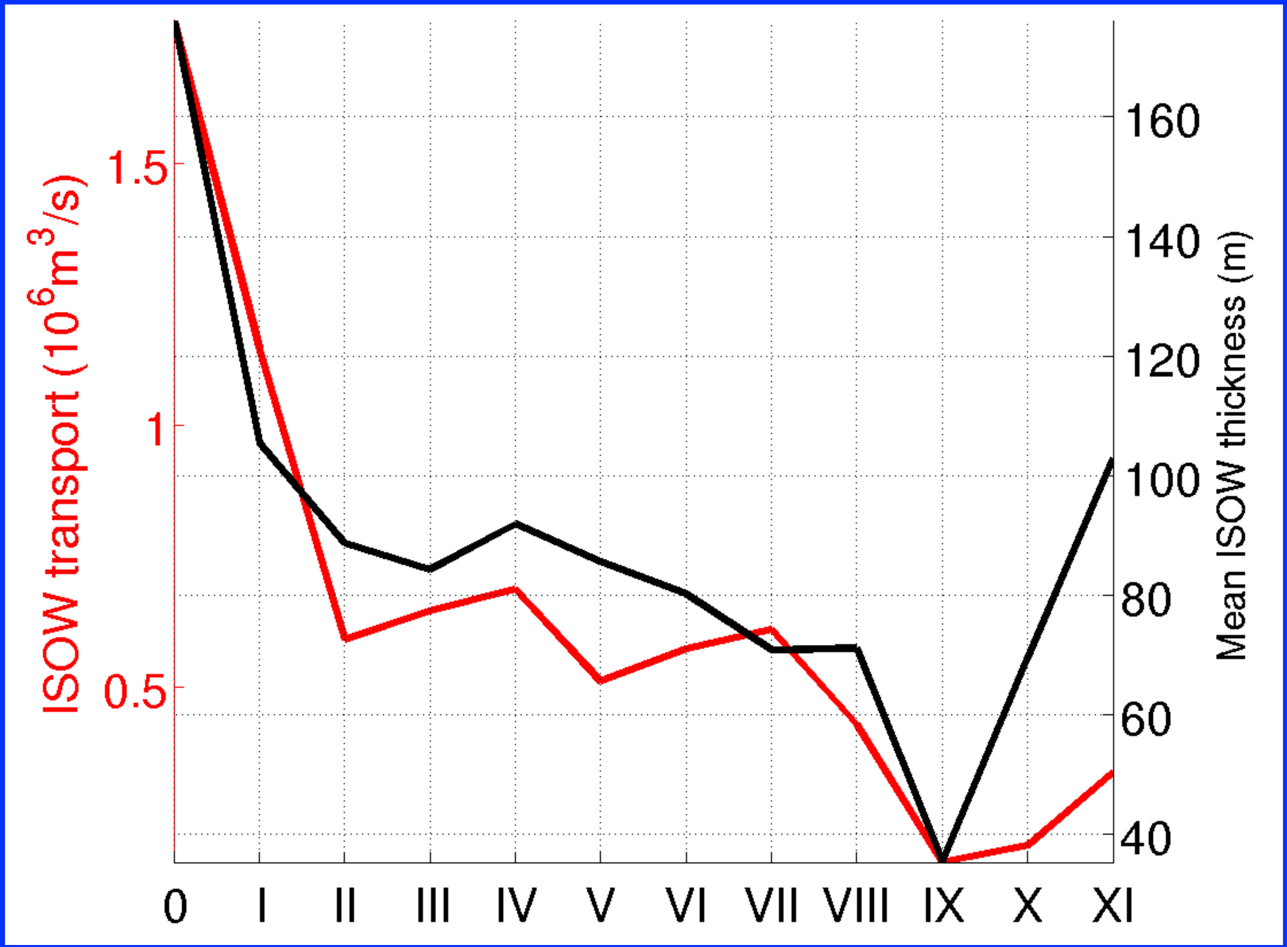


x 10^5
1
0.5
0
-0.5
-1
12
10
8
6
4
2
0
-2
34
35
36
37
38
39
40
σ_θ=27.8
0
I
II
III
IV
V
VI
VII
VIII
IX
X
XI



Note reappearance of dense water near Iceland, overflowing through valley at Iceland slope…but with very small transport

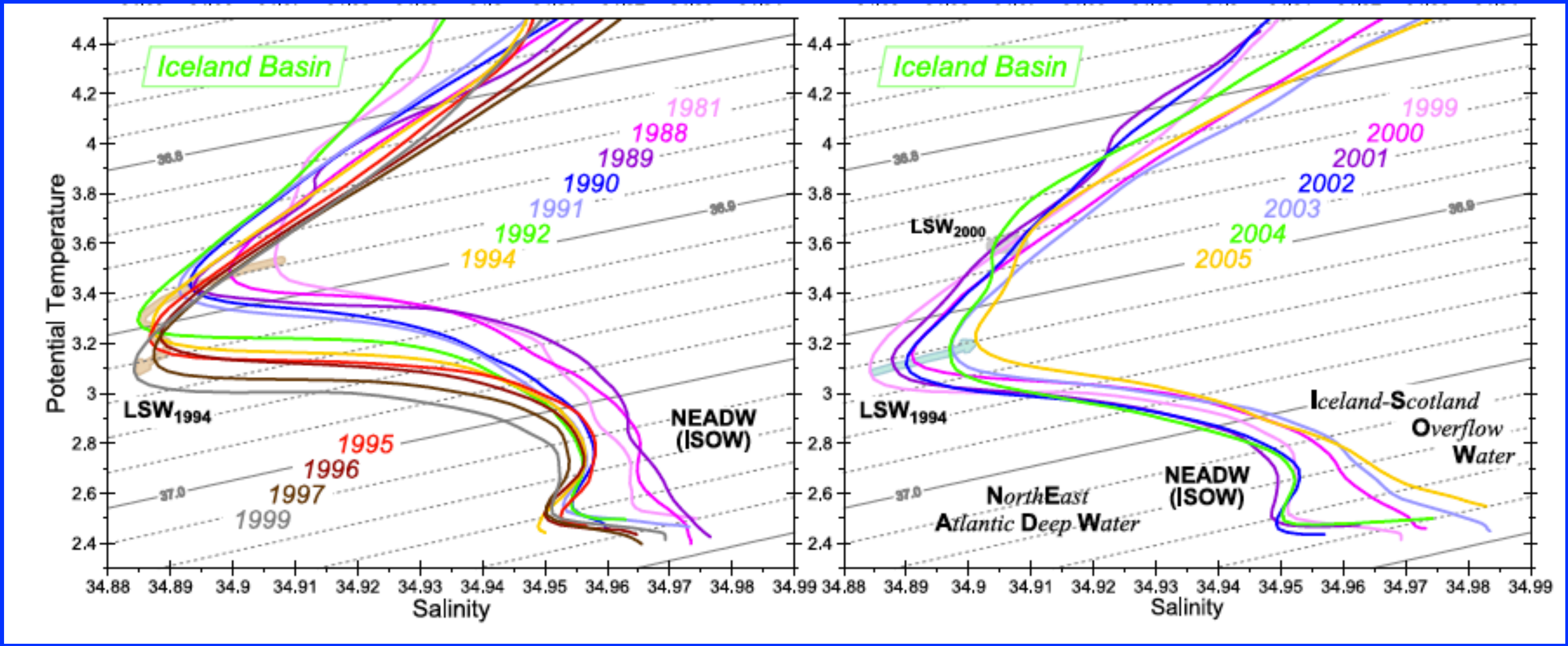
downstream evolution of dense water mean transport (σ > 27.8)



Entrainment appears to have taken the warmer, more saline upper ocean trend into the deepest densest overflows of the northeast Atlantic….the NEADW / ISOW- Yashayaev et al GRL2007: the AMOC really is a triad of fluxes: mass, heat, salt

1981 – 1999

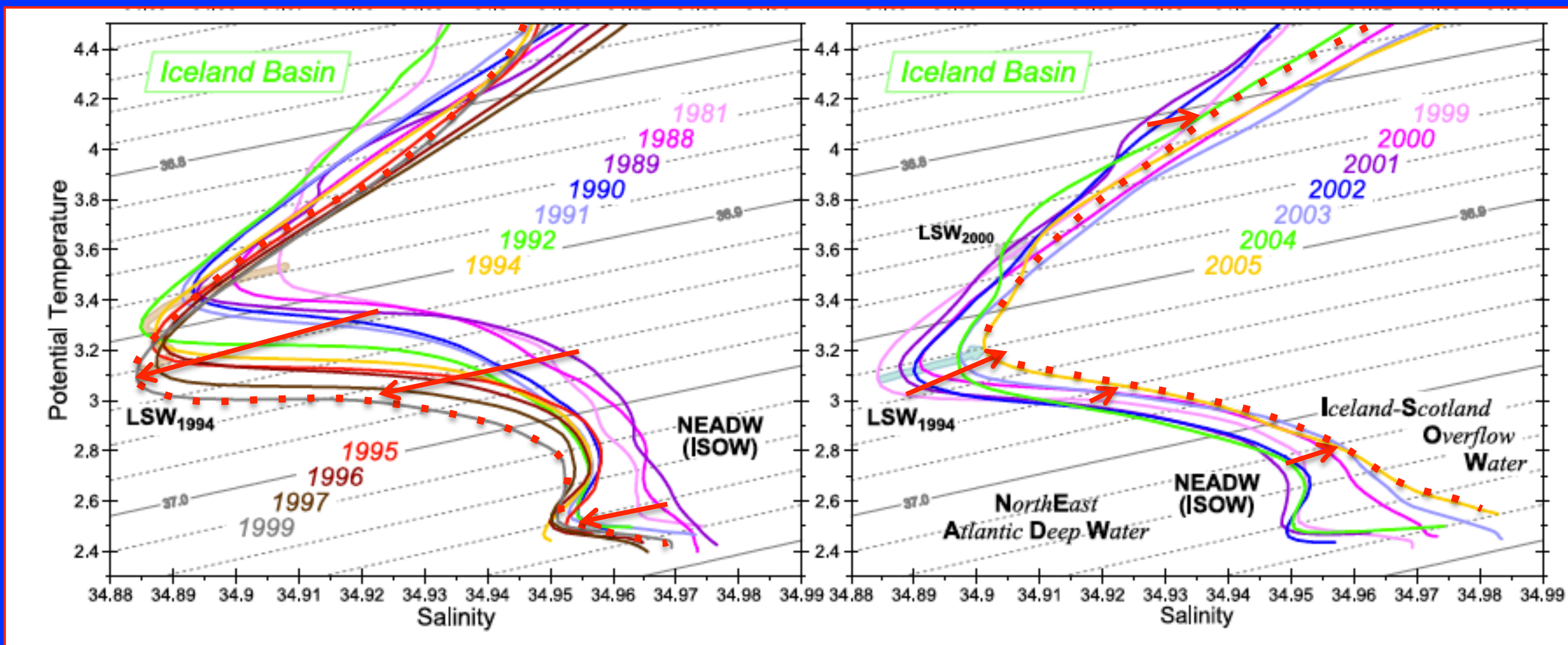
1999-2005



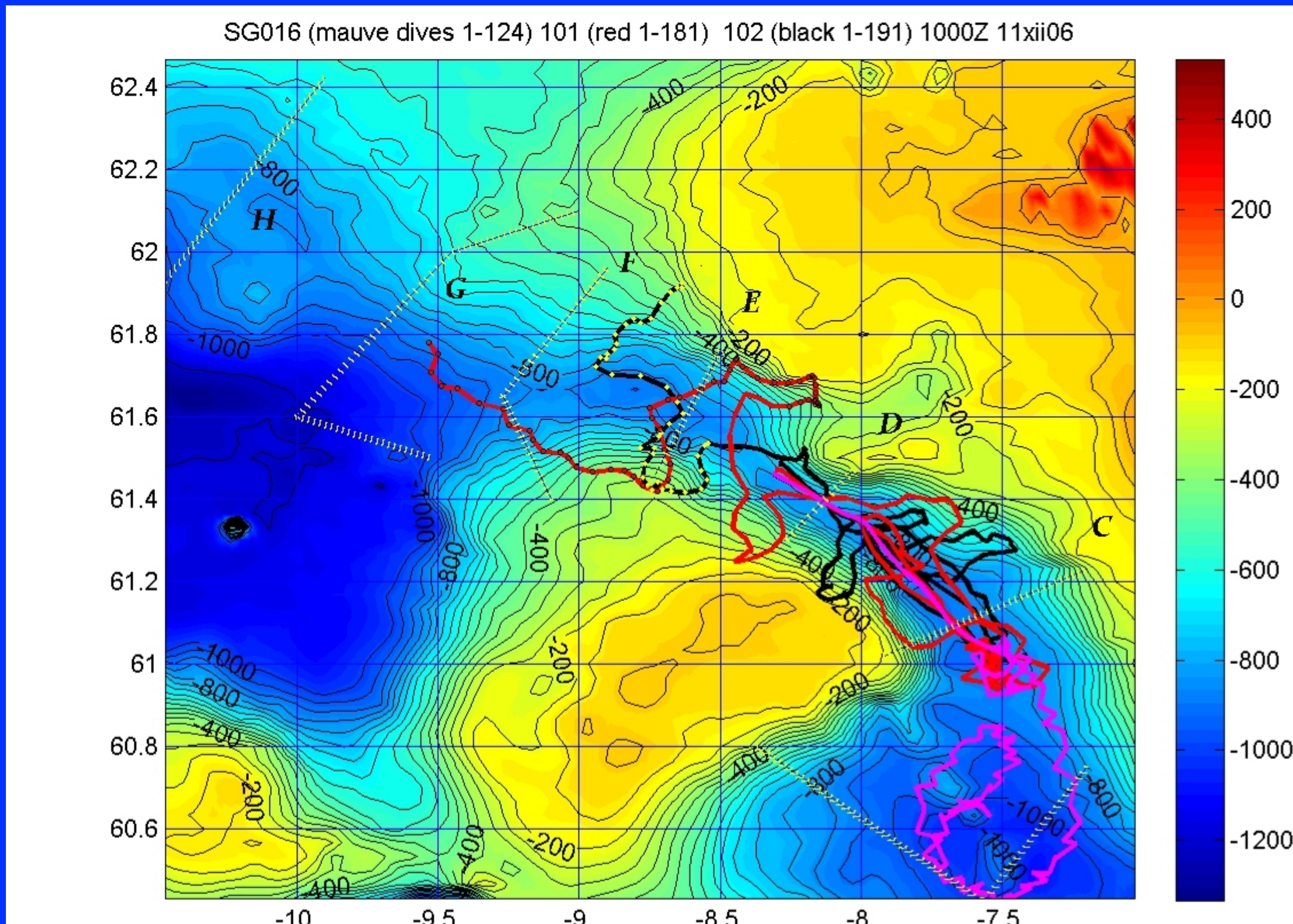
Entrainment appears to have taken the warmer, more saline upper ocean trend into the deepest densest overflows of the northeast Atlantic….the NEADW / ISOW- Yashayaev et al GRL2007: the AMOC really is a triad of fluxes: mass, heat, salt

1981 – 1999 =>fresher ,colder

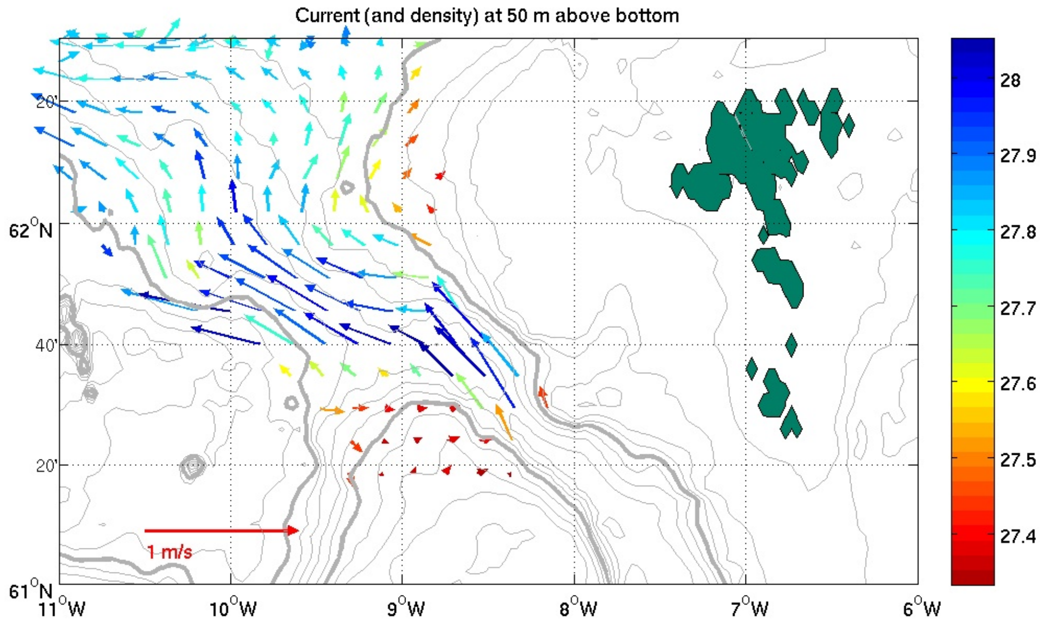
1999-2005 =>saltier, warmer

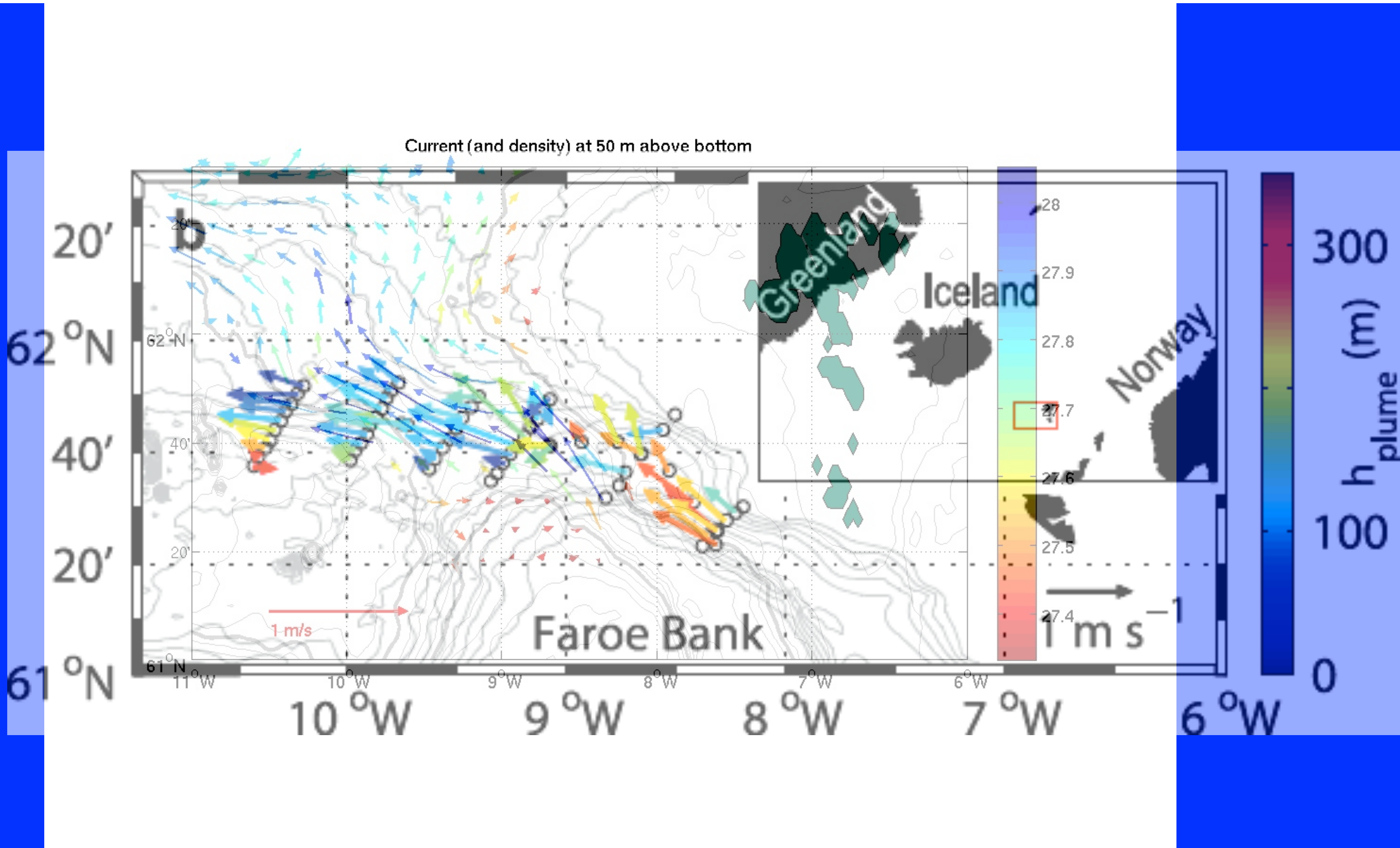


Faroe-Bank Channel outflow and mixing



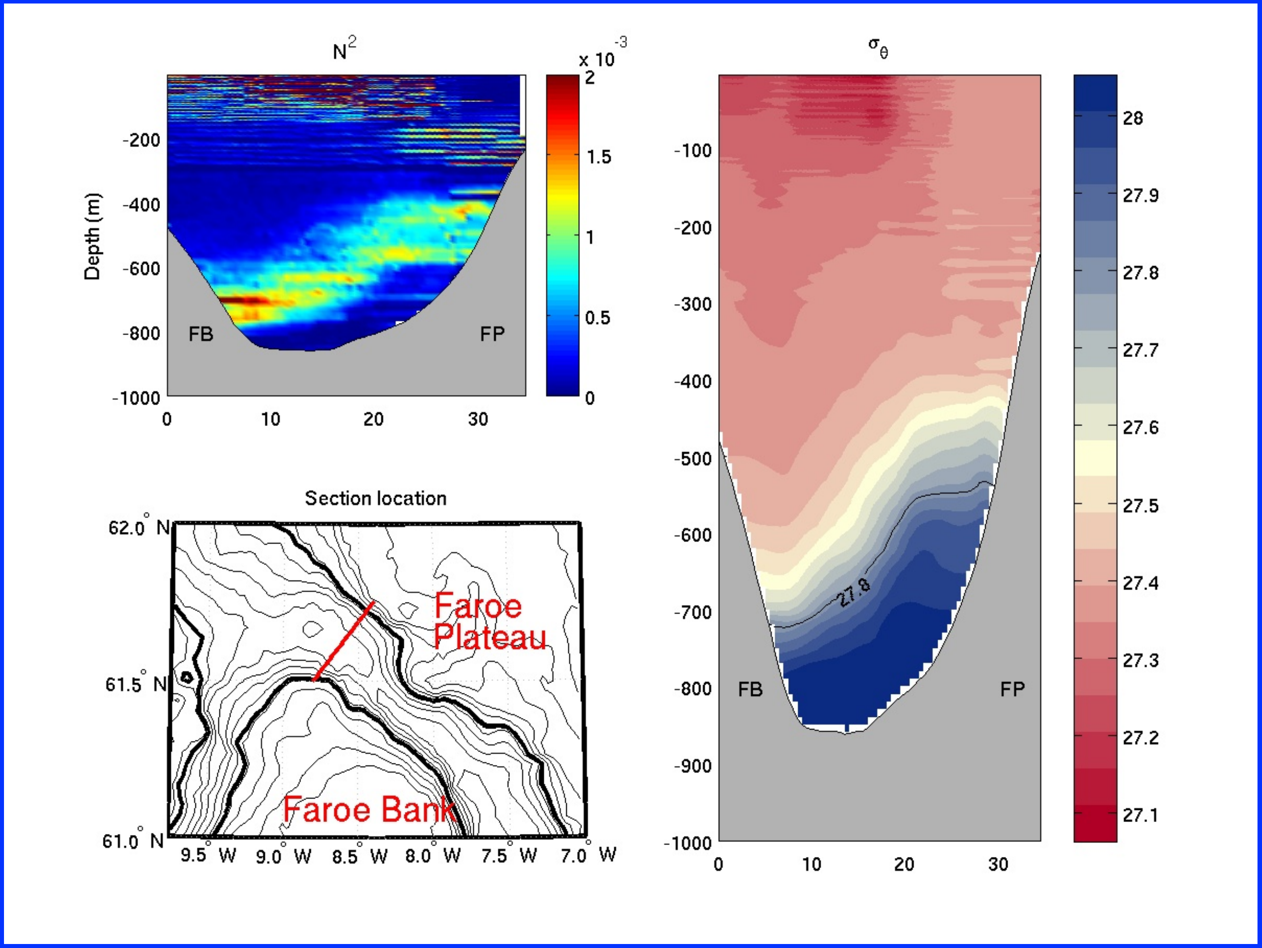
SG016 (mauve dives 1-124) 101 (red 1-181) 102 (black 1-191) 1000Z 11xii06
H
G
F
E
D
C


Current (and density) at 50 m above bottom
20'
62°N
40'
20'
61°N
11°W
10°W
9°W
8°W
7°W
6°W
1 m/s
28
27.9
27.8
27.7
27.6
27.5
27.4



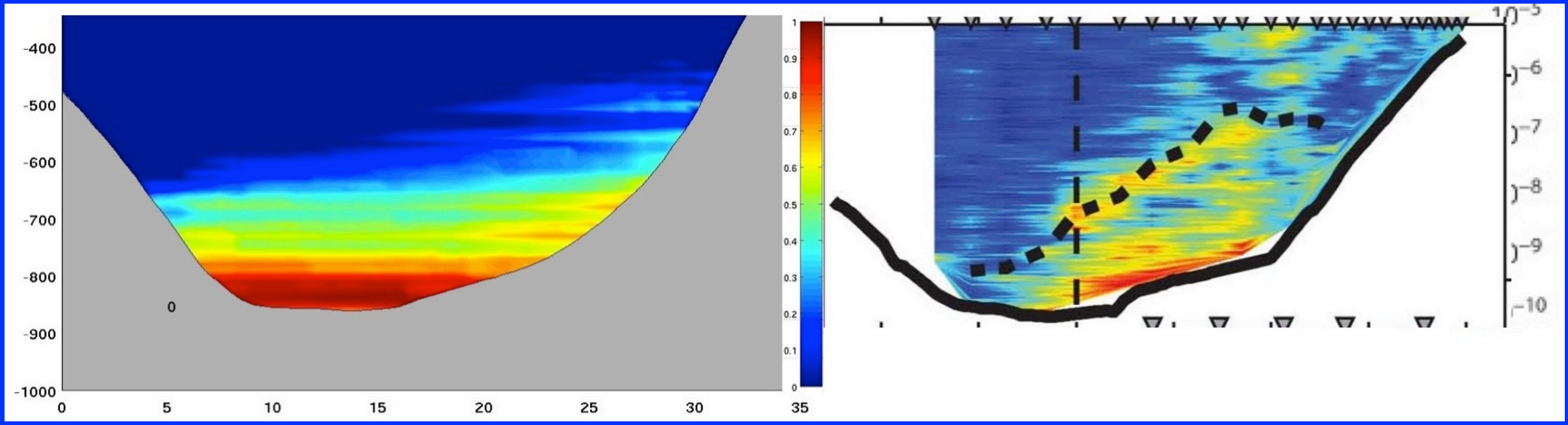
comparing bottom moored adcp velocities (*Fer et al.* 2010) and
3-year mean Seaglider velocity 50m above bottom; max speed ~ 1.35 m sec^{-1}

synthetic mean Seaglider section 10 km downstream of final sill (N^2 and potential density)

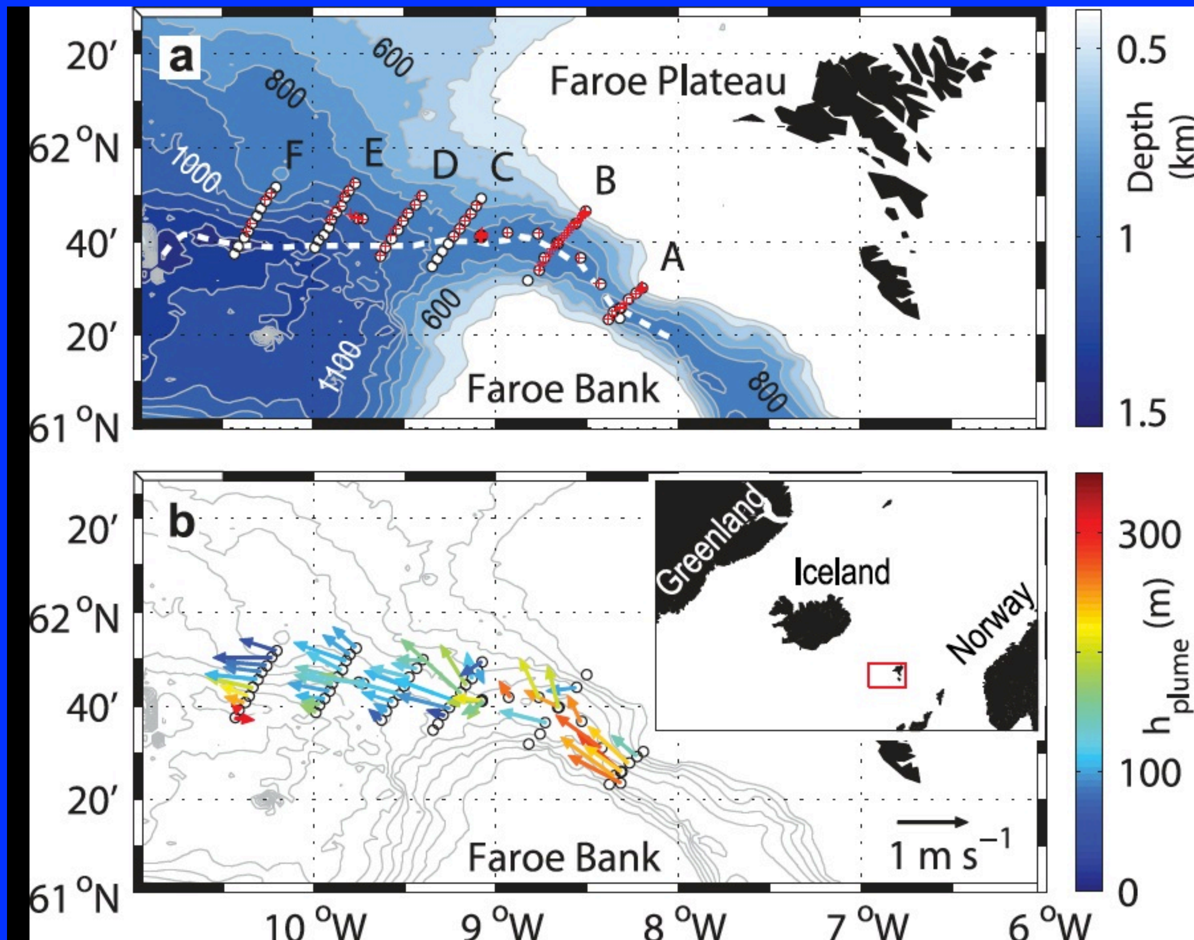


Seaglider vertical velocity variance and turbulence probe KE dissipation (*Fer* et al., GRL 2009)

log <w^2> ε (W kg^{-1})

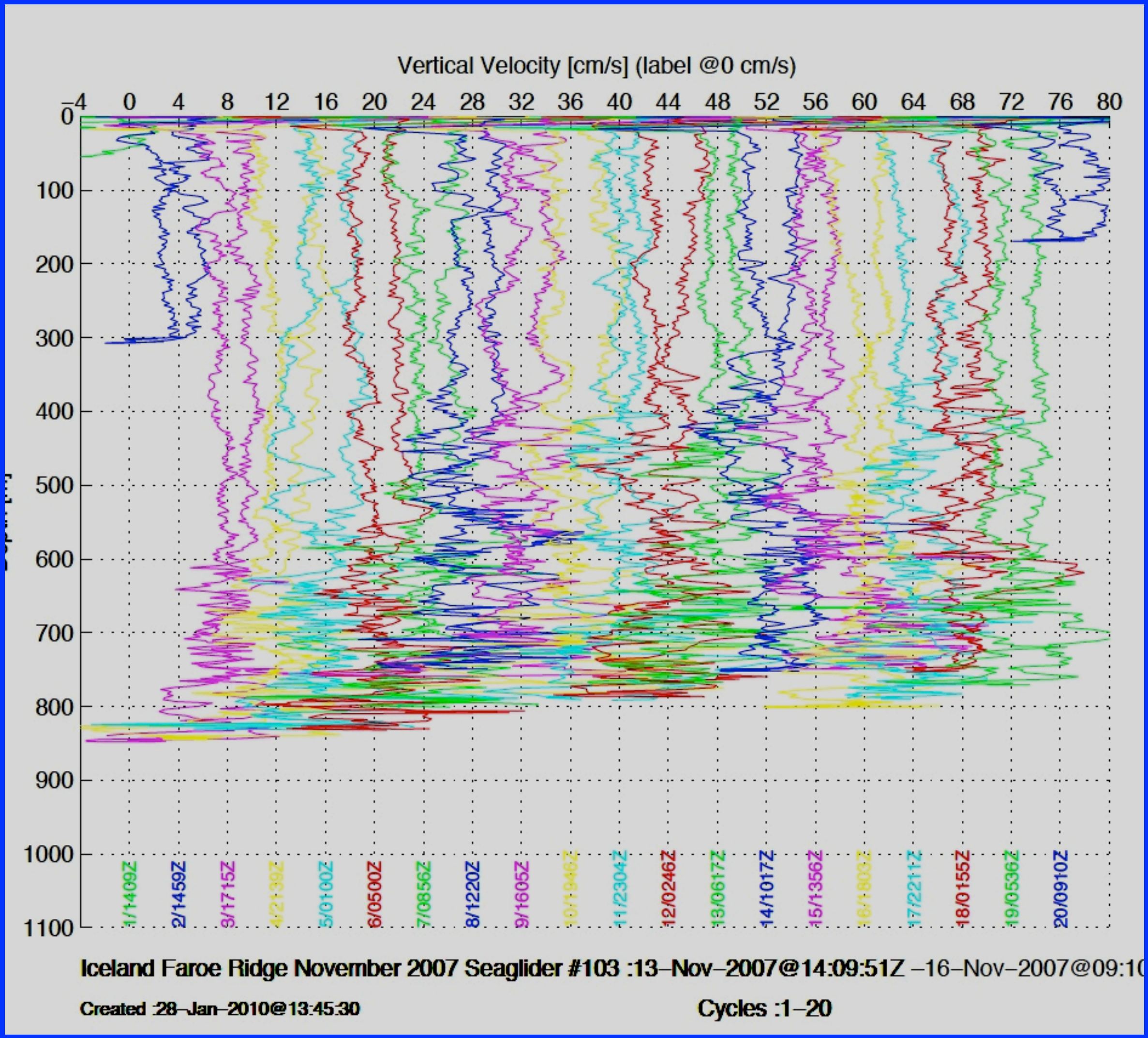


Fer et al. JGR 2010

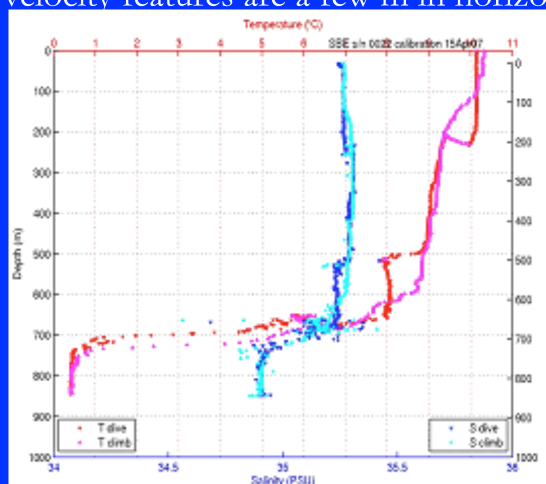


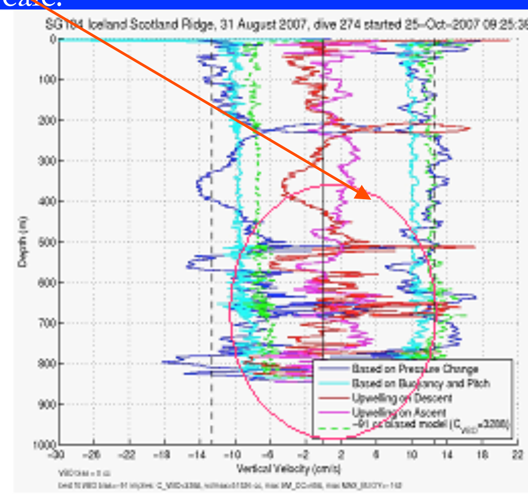
Seaglider vertical velocity and mixing

Vertical velocity profiles at Faroe Bank Channel exit

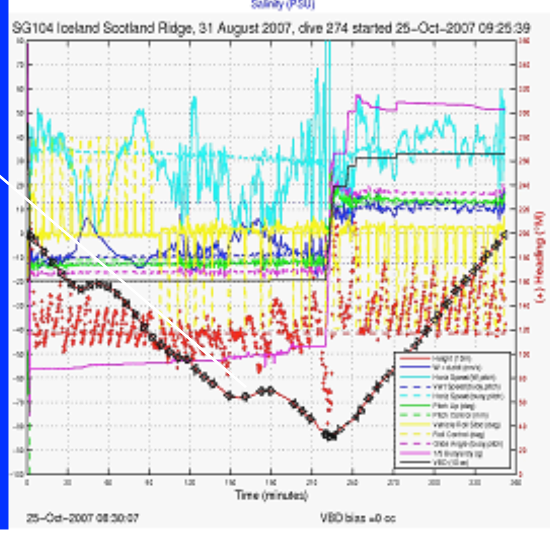


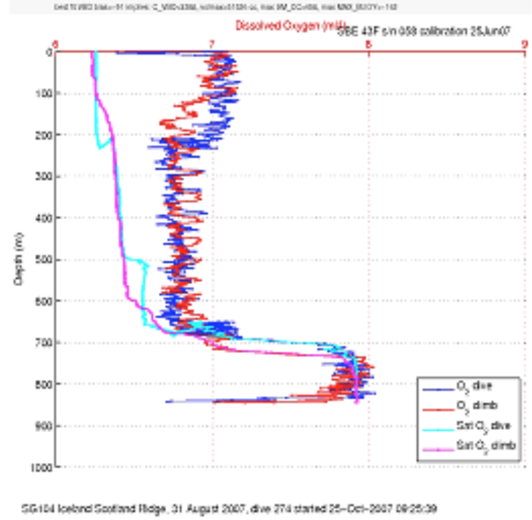
A remarkable image of turbulence and mixing appears in measurements of vertical velocity, in conjunction with hydrography and particle scattering. This is done by comparing the pressure depth with the depth anticipated from glider flight performance (with known pitch angle and buoyancy). Dive 122 of SG104 in August 2007 at the mouth of the Faroe Bank Channel shows extreme vertical velocity in and above the dense plume (here cold, fresh with high oxygen content). The red and hot-pink profiles show the resolved vertical fluid velocity on up- and down dives with amplitude 5 to 10 cm sec-1, from differencing observed fall rate and fall-rate relative to the water (blue curves). Note the up/down trace differences and the long duration (~30min) of some vertical velocity features. The glider depth history (black) further illustrates the up/down drafts. The smallest observable vertical velocity features are a few m in horizotal scale.

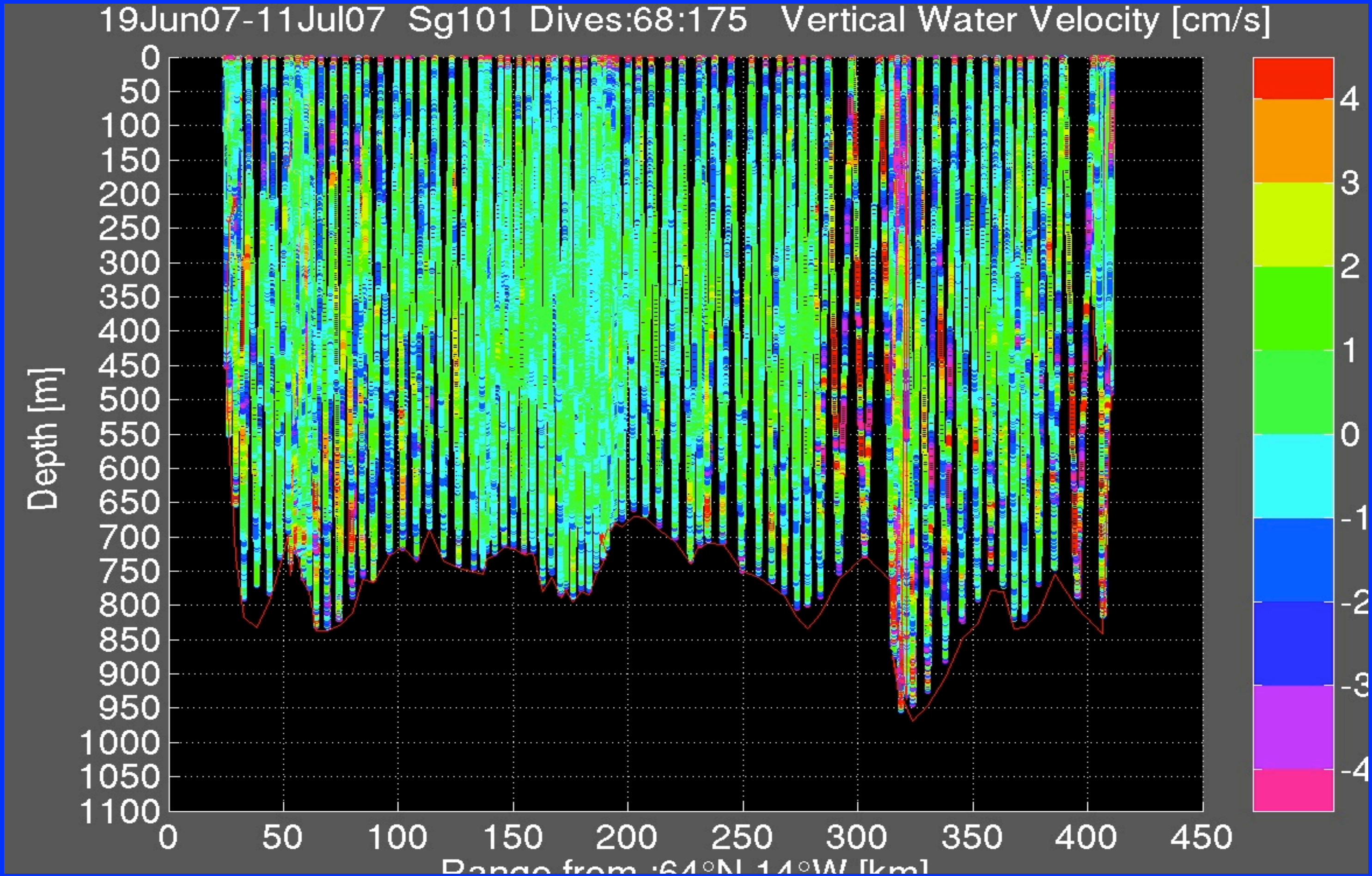


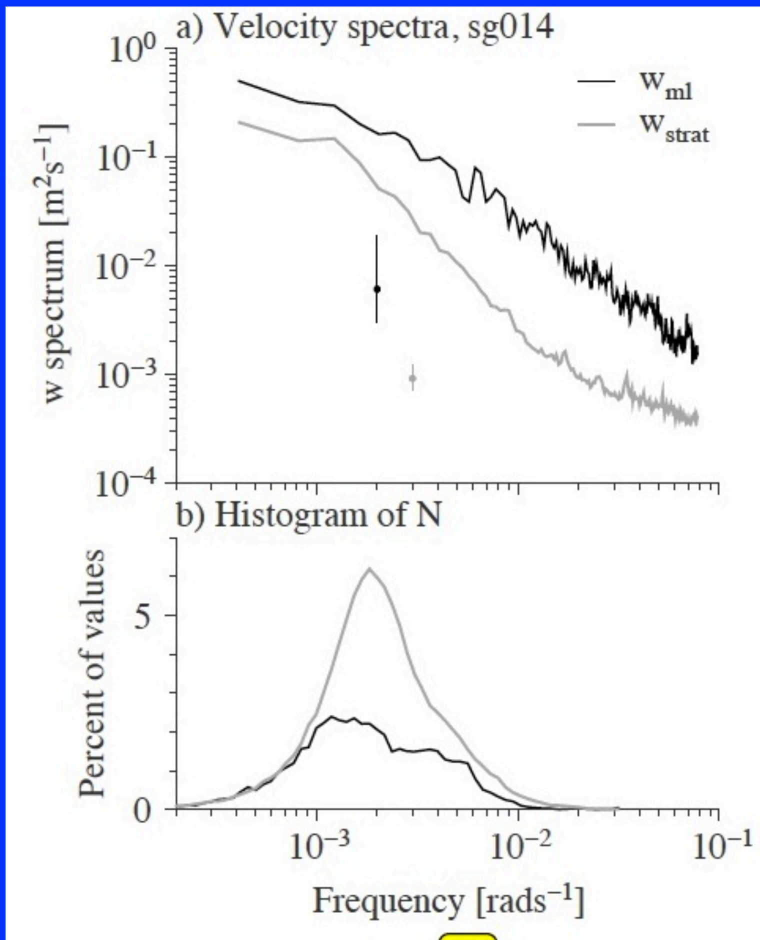


time history of the glider depth

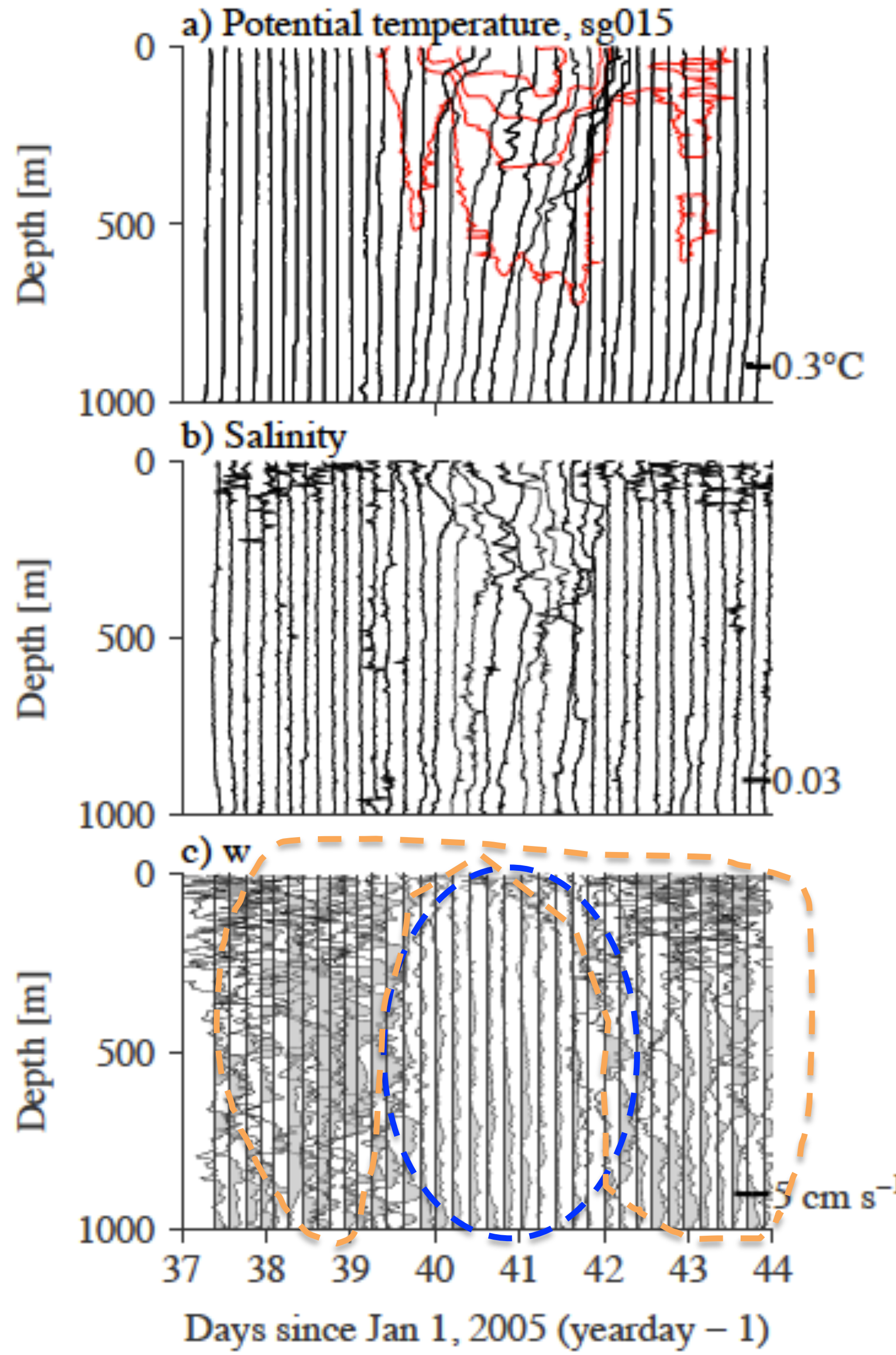





19Jun07-11Jul07 Sg101 Dives:68:175 Vertical Water Velocity [cm/s]
Depth [m]
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
0
50
100
150
200
250
300
350
400
450
4
3
2
1
0
-1
-2
-3
-4



a) Velocity spectra, sg014
w spectrum [m²s⁻¹]
w_{ml}
w_{strat}
b) Histogram of N
Percent of values
Frequency [rads⁻¹]

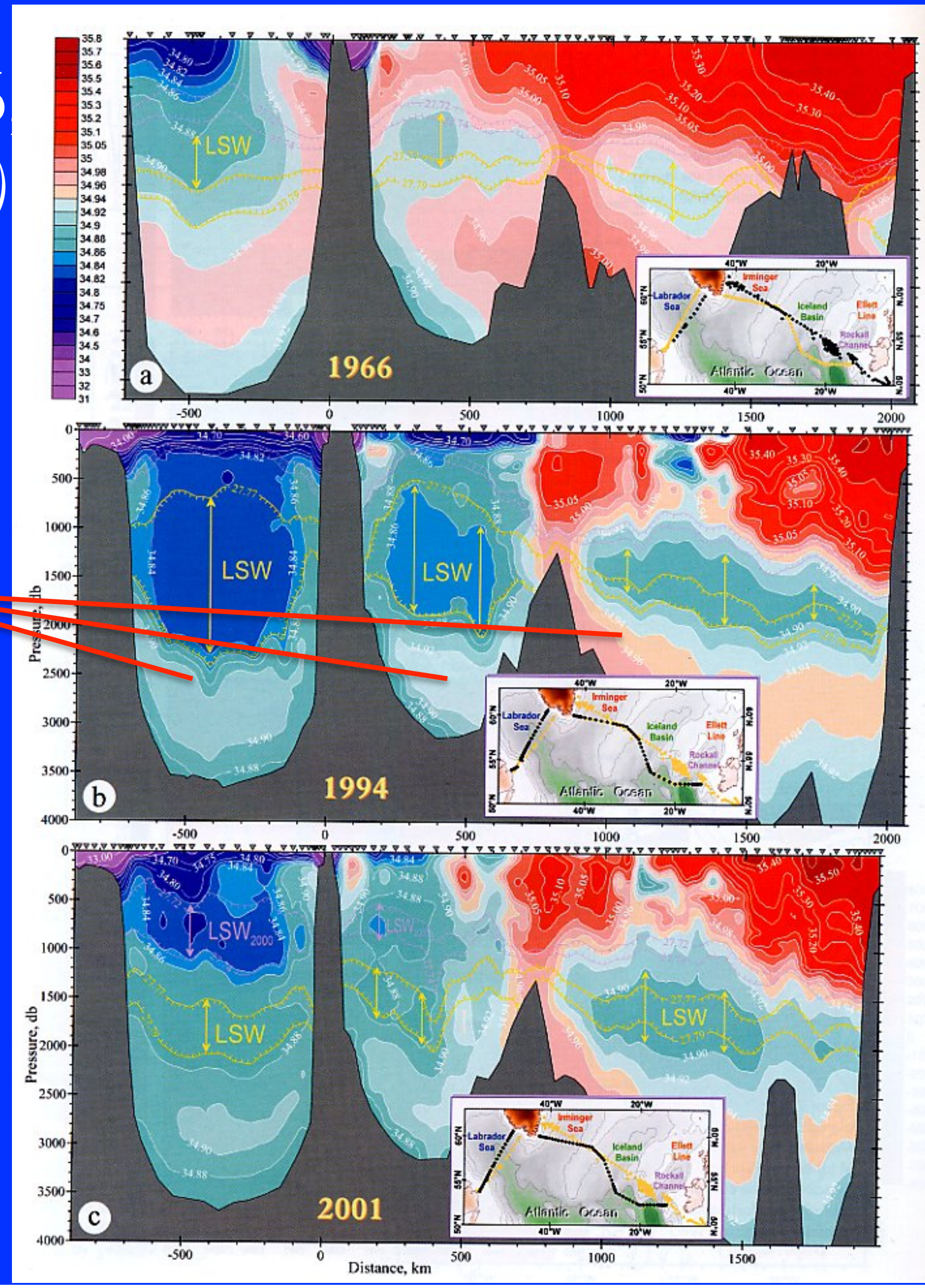


a) Potential temperature, sg015
Depth [m]
0.3°C
b) Salinity
0.03
c) w
5 cm s⁻¹
Days since Jan 1, 2005 (yearday – 1)

Downstream evolution of dense overflows in Iceland Basin

Subpolar salinity: 1966, 1994, 2001 (*Yashayaev*)

ISOW …NEADW settles at about 2500m, joining the cyclonic subpolar gyre, as a 'basement' to Labrador Sea Waterl in the parfait of North Atlantic Deep Water



CFC-12
AR7/W
Labrador Sea

Azetsu-Scott et al. JGR 2003

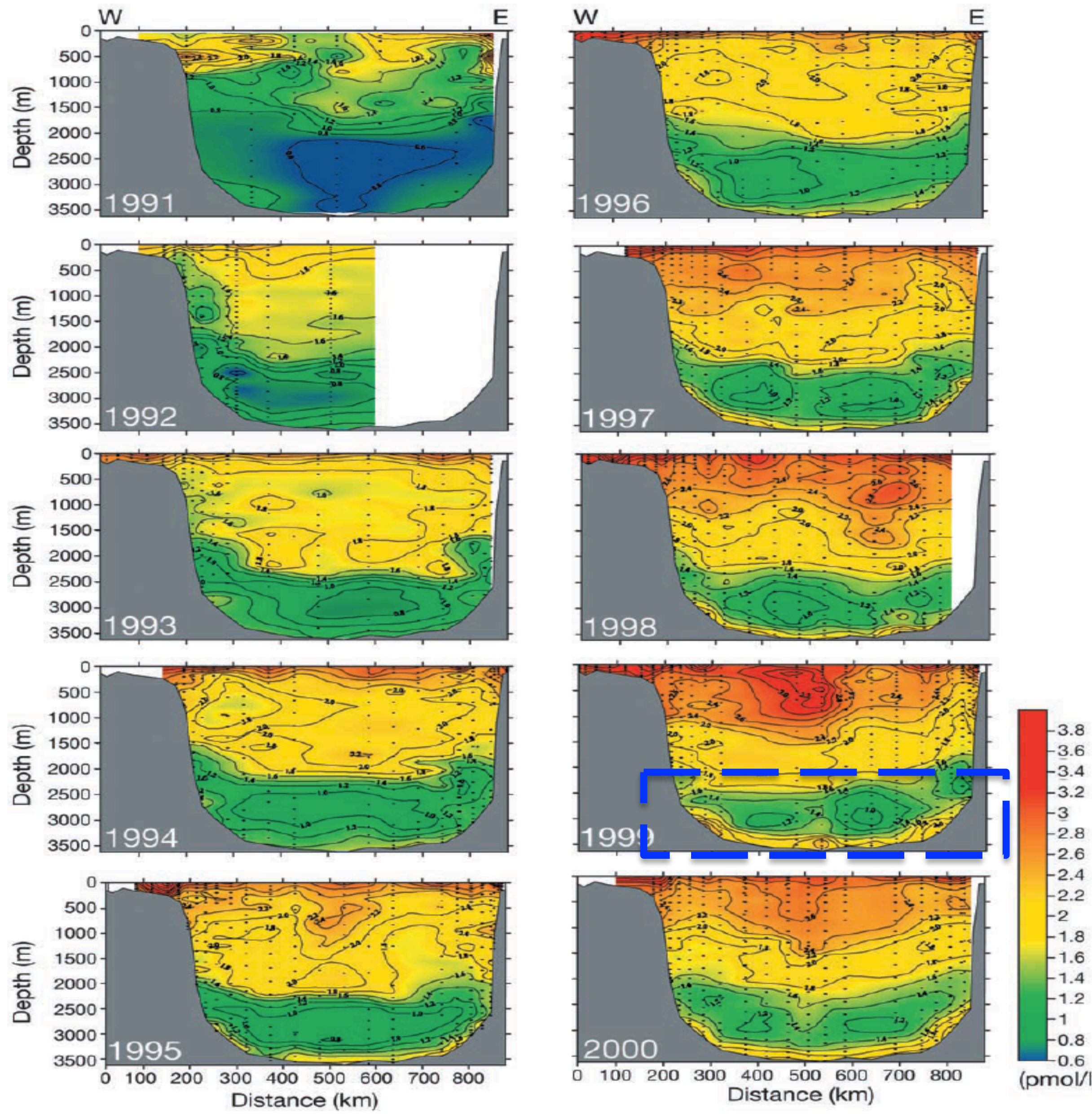
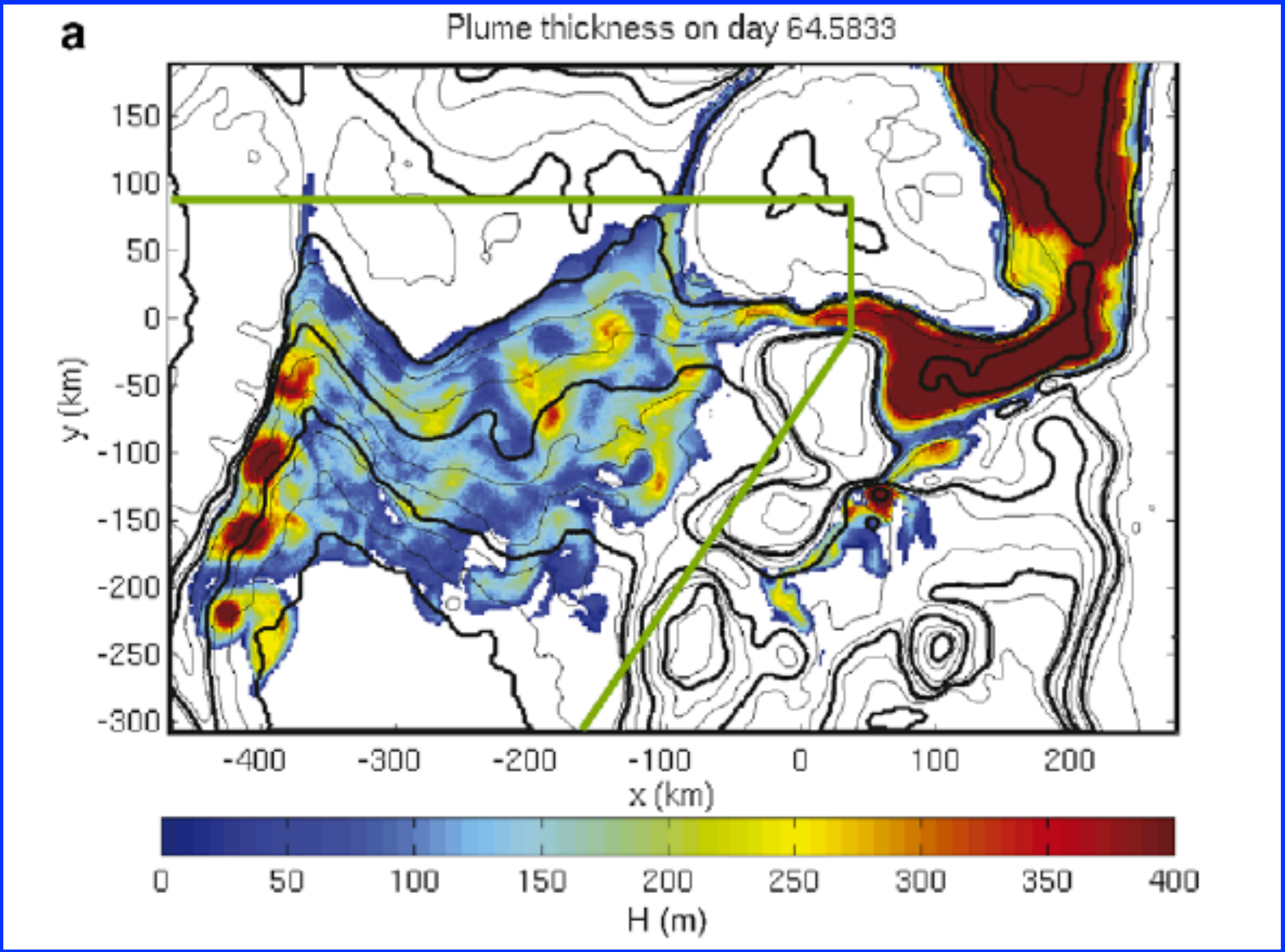


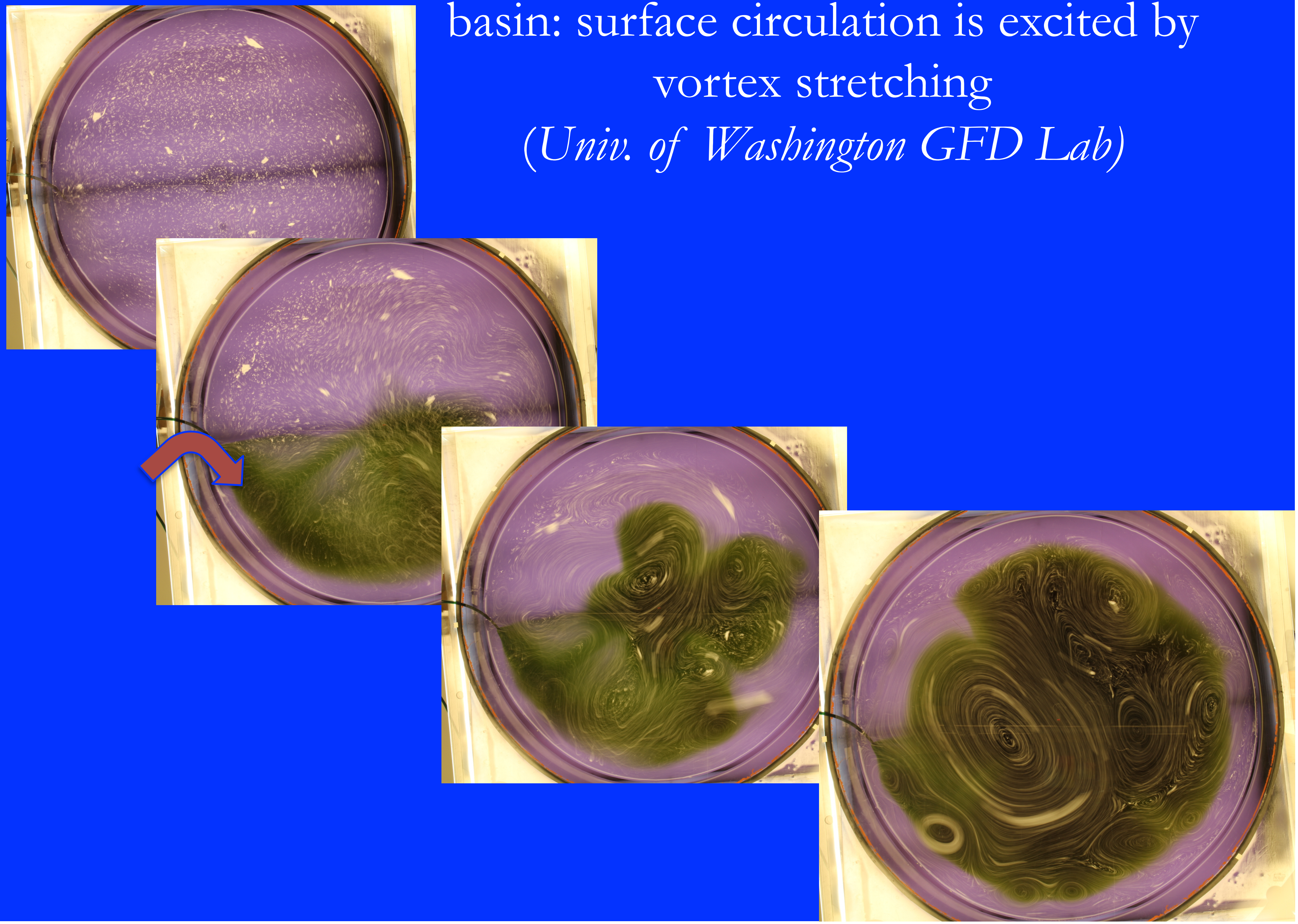
Figure 3. CFC-12 distribution along the WOCE AR7W line from 1991 to 2000. In 1992, measurements were limited to the western half of the AR7W line. Access to the shelf stations depended on the ice conditions and was limited in some years.

Riemenschneider & Legg OM 2007 *MIT* GCM @ 2.5 km x 25m res

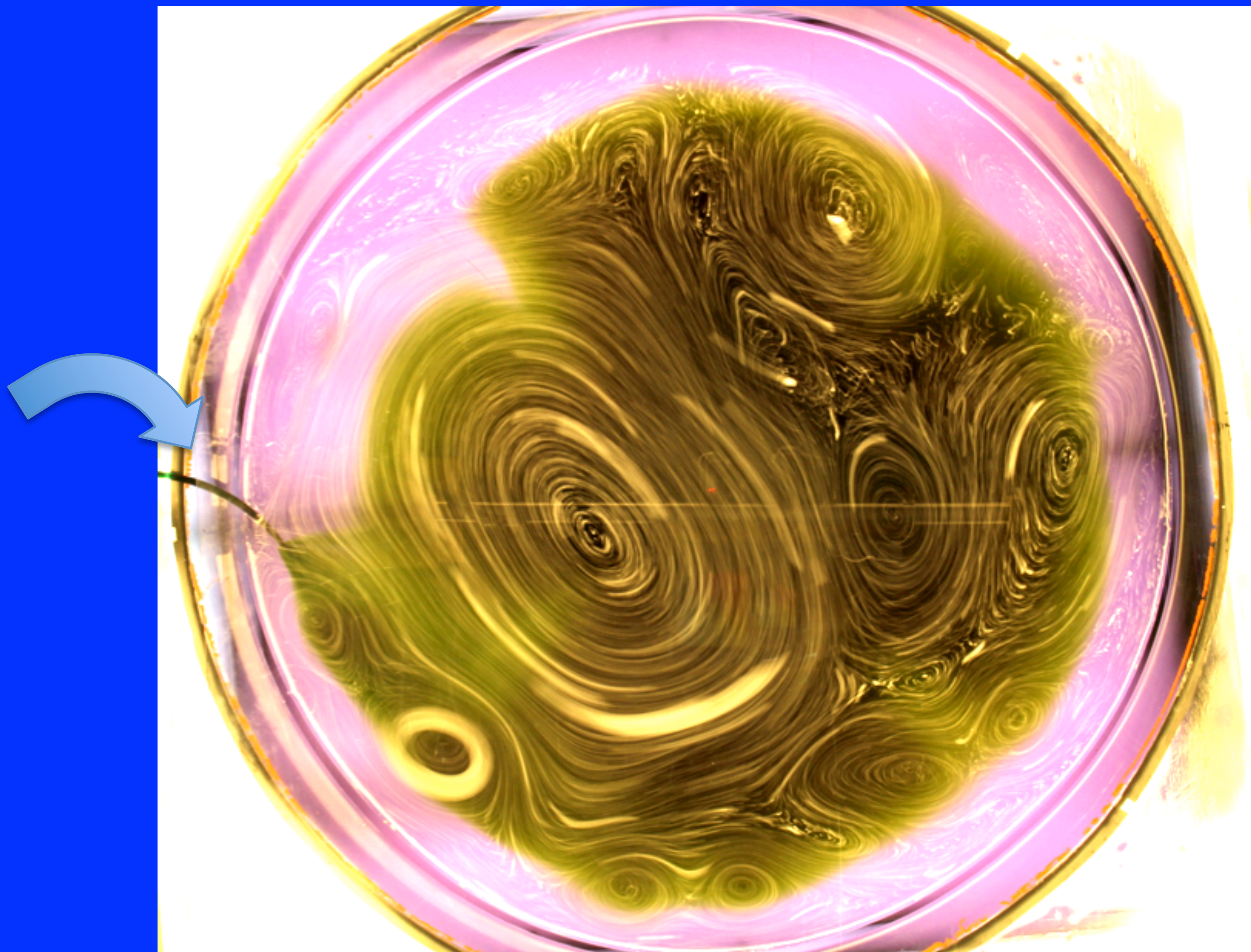


Dense plume entering a bowl-shaped basin: surface circulation is excited by vortex stretching

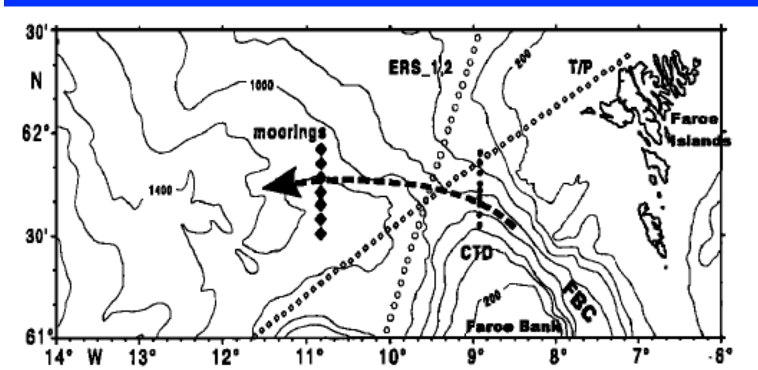
(Univ. of Washington GFD Lab)

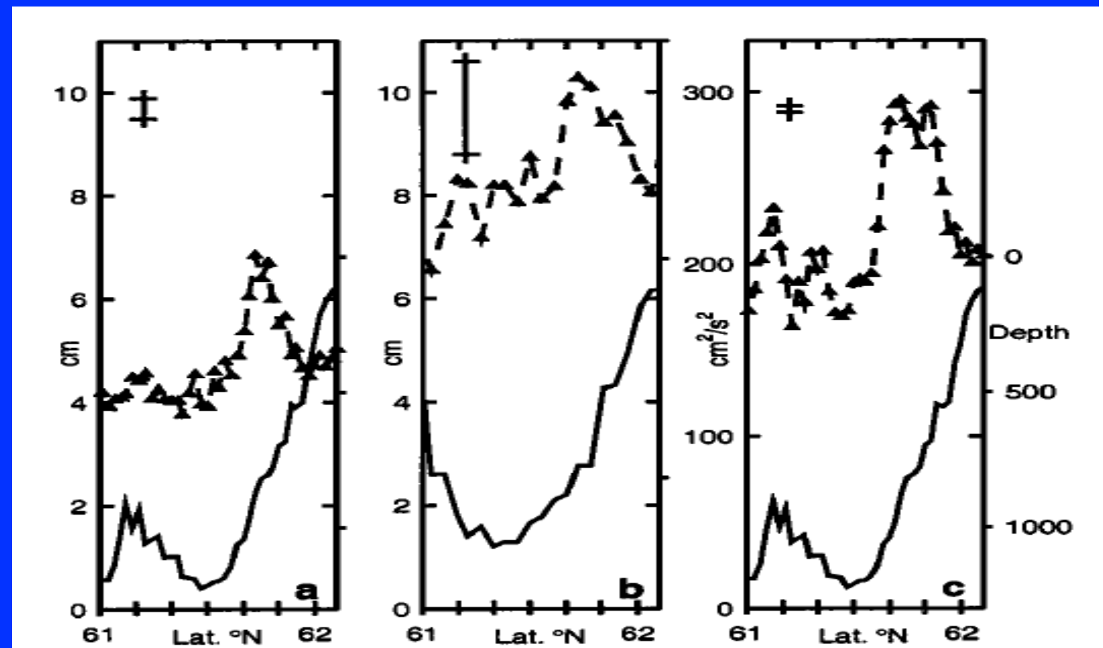


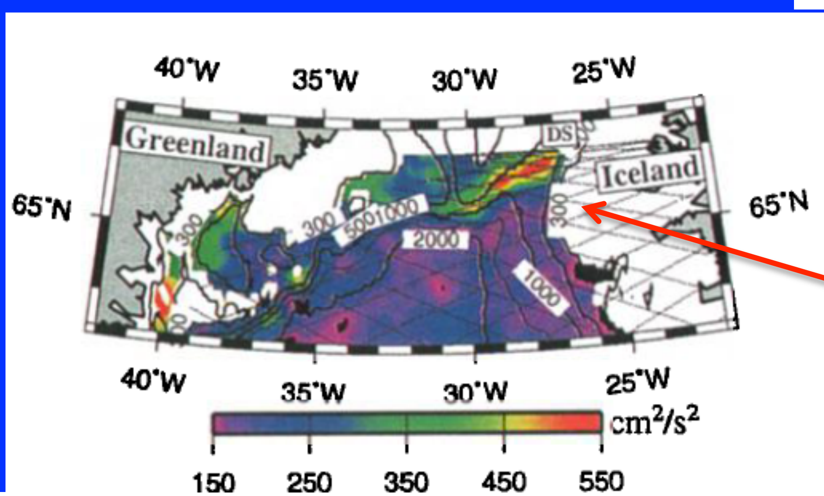
Barotropization is powerful! Even with a thin overflow plume



Altimetric sea-surface height and EKE peak above exiting deep overflow plumes *Høyer & Quadfasel GRL 2001*







var(SSH) Topex/Poseidon

var(SSH) ERS-1

EKE

Faroe Bank Channel

Denmark Strait

Conclusions

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

- The 3-year Seaglider program did not determine quantitatively the passage of dense overflows at the Iceland Faroe Ridge yet it produced

  – The transport (on the θ/S plane) of the dense water layer on the IF Ridge, showing admixing of the IFR overflow and FBC outflow and its severe dilution with distance.
    - near-bottom, & vertical structure of the circulation near the 1000m isobath was estimated over 3 years, showing the dilution of the transport-weighted density, θ,S and decay of transport from ~ 1.5 Sv to less than 0.5 Sv.

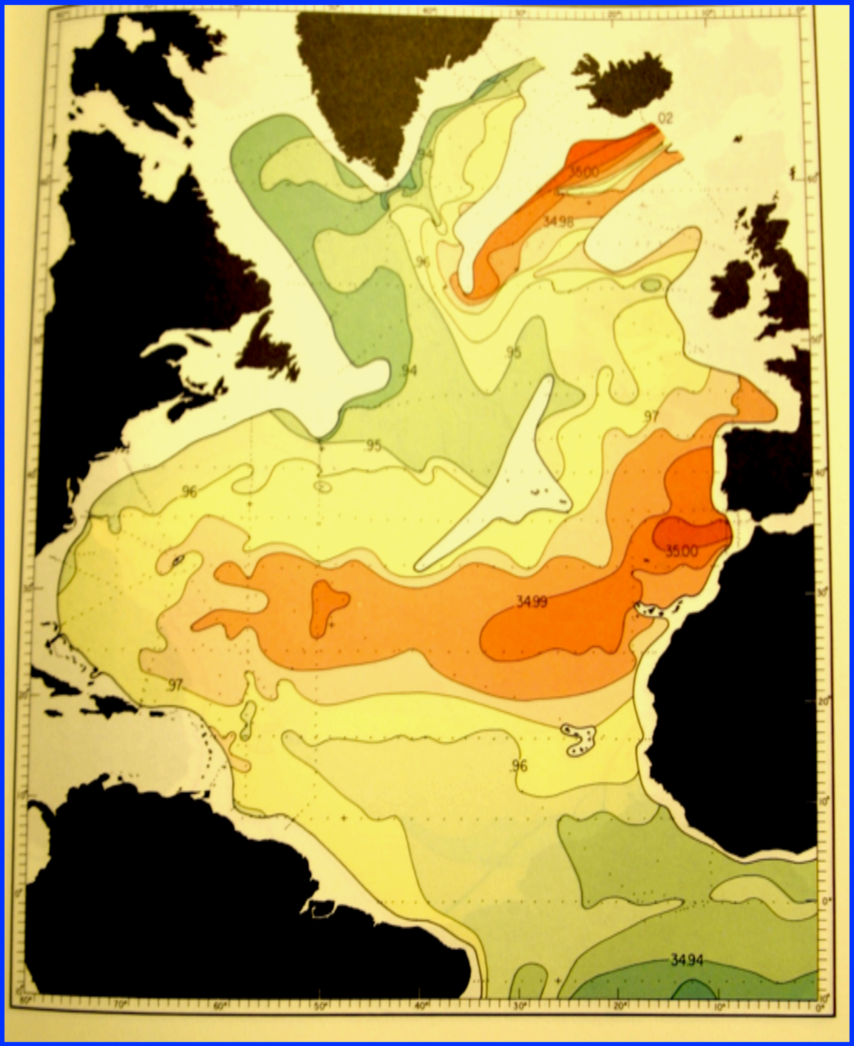
  – The bifurcation of the Faroe Bank Channel outflow was observed, although it will take Deepgliders to follow that (small?) sinking branch to 2500m depth

  – The western IFR overflow pathway near Iceland was found to be very intermittent, unlike the conclusions reached from the 1970s (*Saunders, JPO* 1996).

- Seaglider observations of vertical velocity show a rich geography of mixing and internal waves relevant to the dilution of the dense overflows, as well as in deep convection in Labrador Sea
    - in conjunction with geostrophic velocity, θ, S, turbidity (light scattering) and other tracers. Gliders are being equipped with turbulence probes.
- The depth-averaged Seaglider velocity field including tides is well resolved to roughly 1 cm sec^{-1}, yielding absolute velocity profiles and evidence of strong quasi-barotropic eddies and jets.

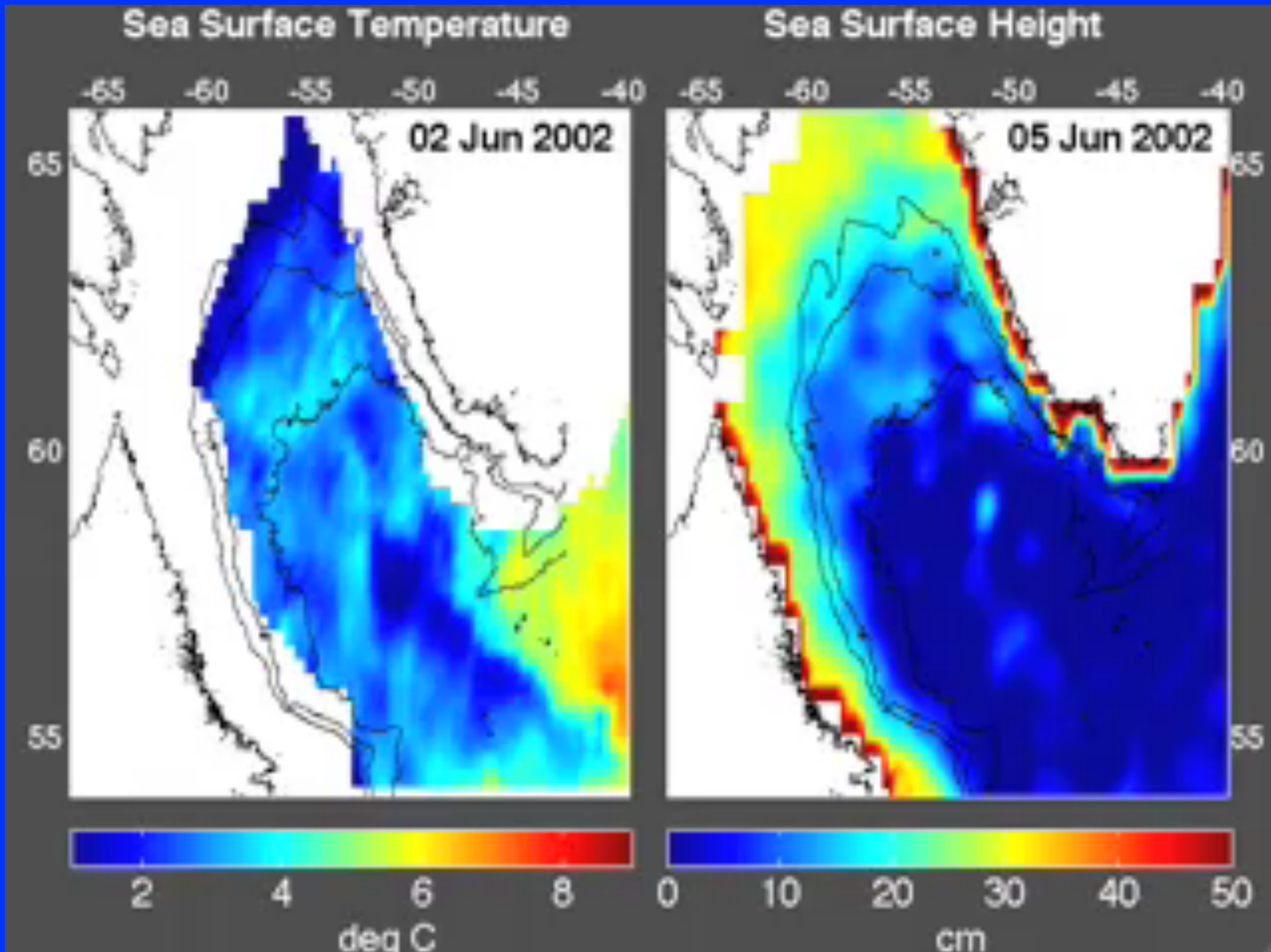
  vortex stretching activates the upper ocean above dense overflow jets.

S on the 3.0C θ surface (*Worthington & Wright atlas)*



Seagliders in the Labrador Sea (2003-2005)

Hatun et al. (JPO 2007), Frajka-Williams et al. (DSR 2009)



Sea Surface Temperature
Sea Surface Height
-65
-60
-55
-50
-45
-40
65
60
55
02 Jun 2002
05 Jun 2002
2
4
6
8
deg C
0
10
20
30
40
50
cm

Frajka-Williams, Rhines & Eriksen, DSR 2009

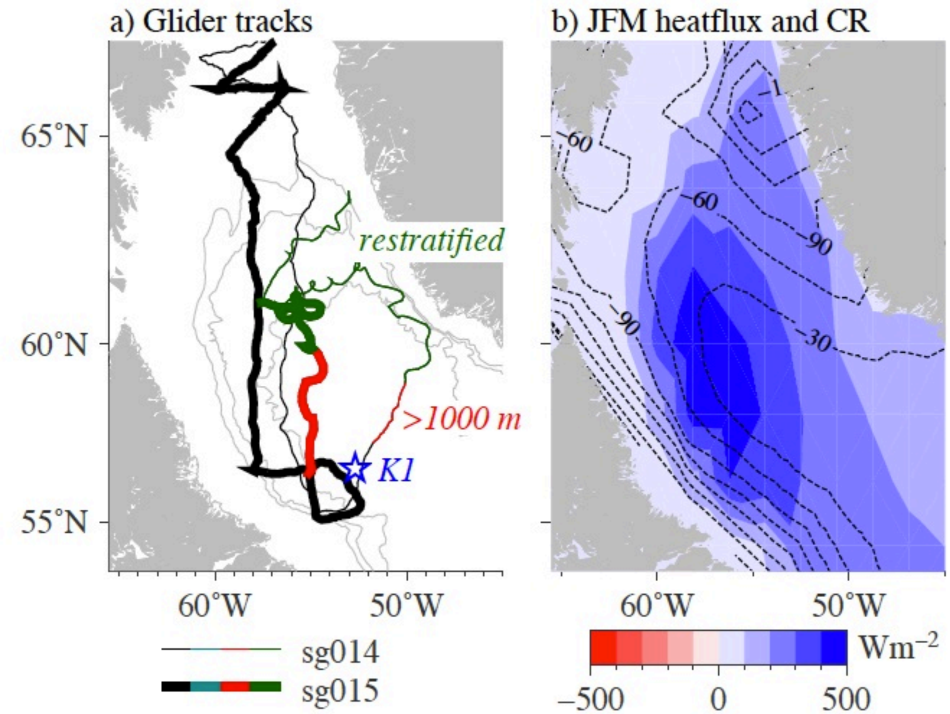
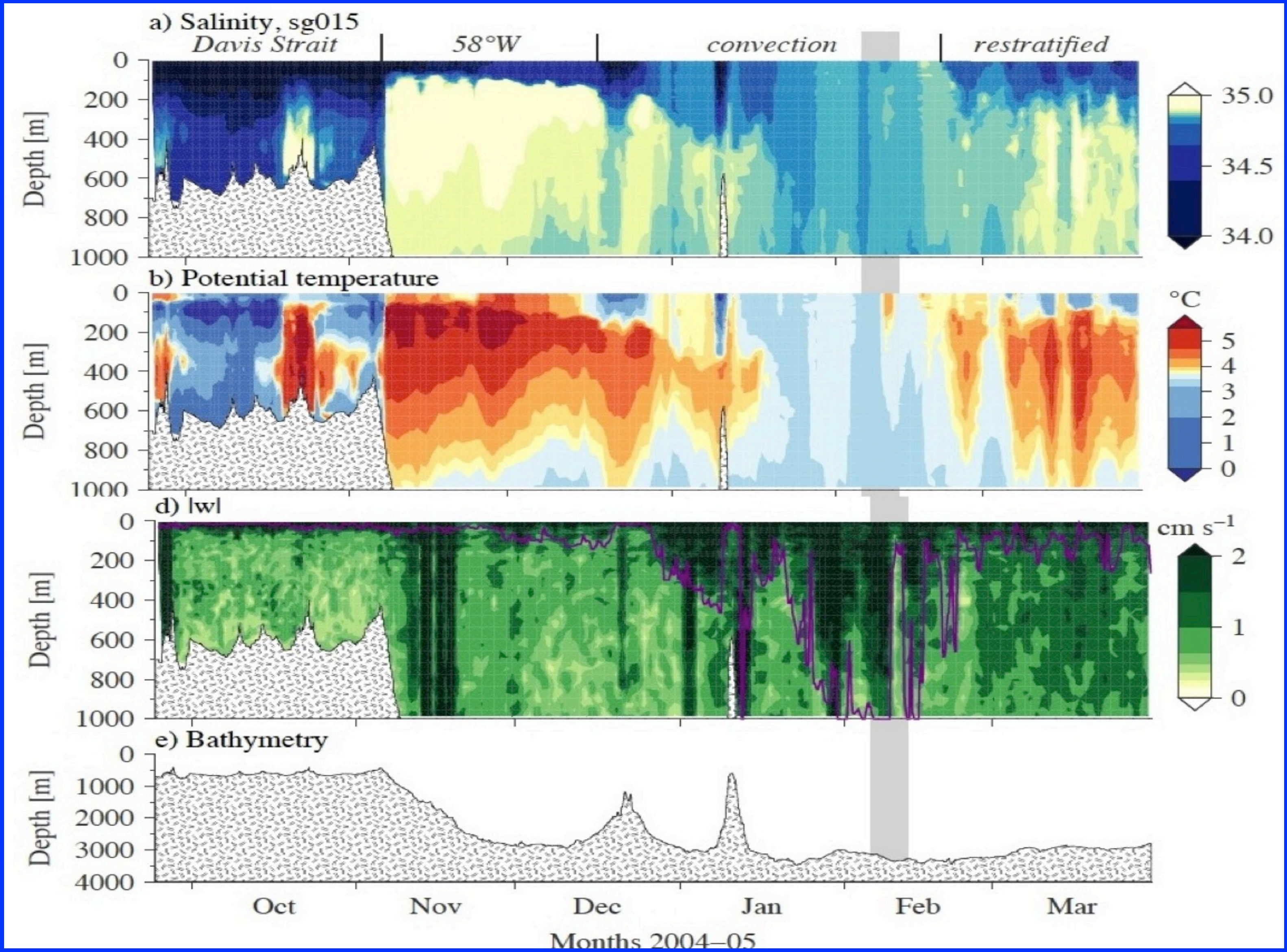
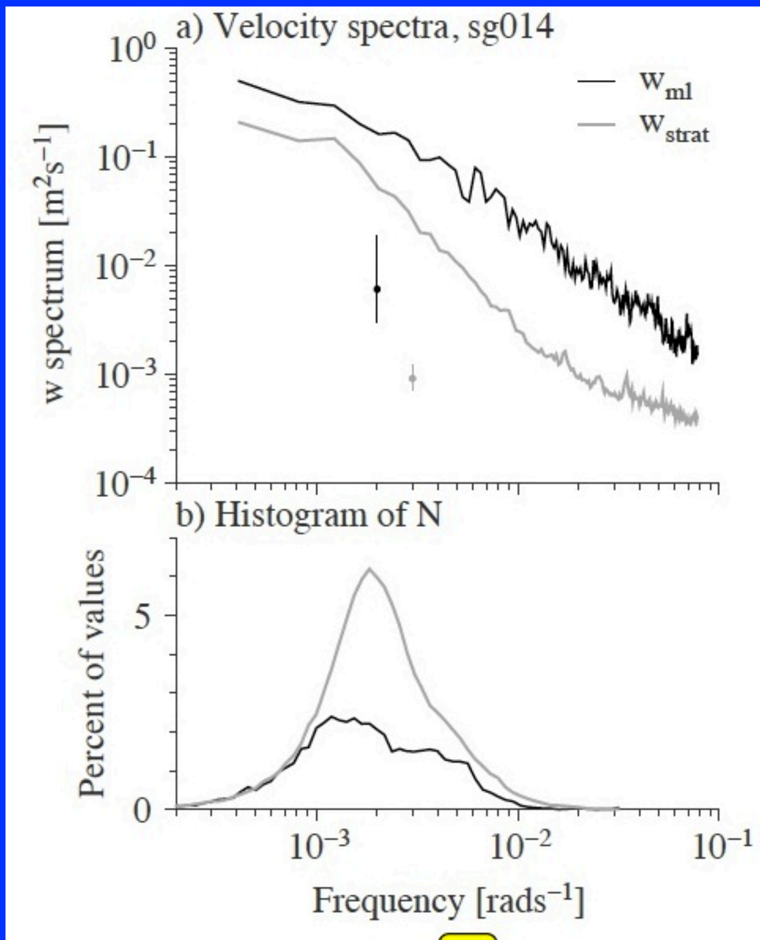
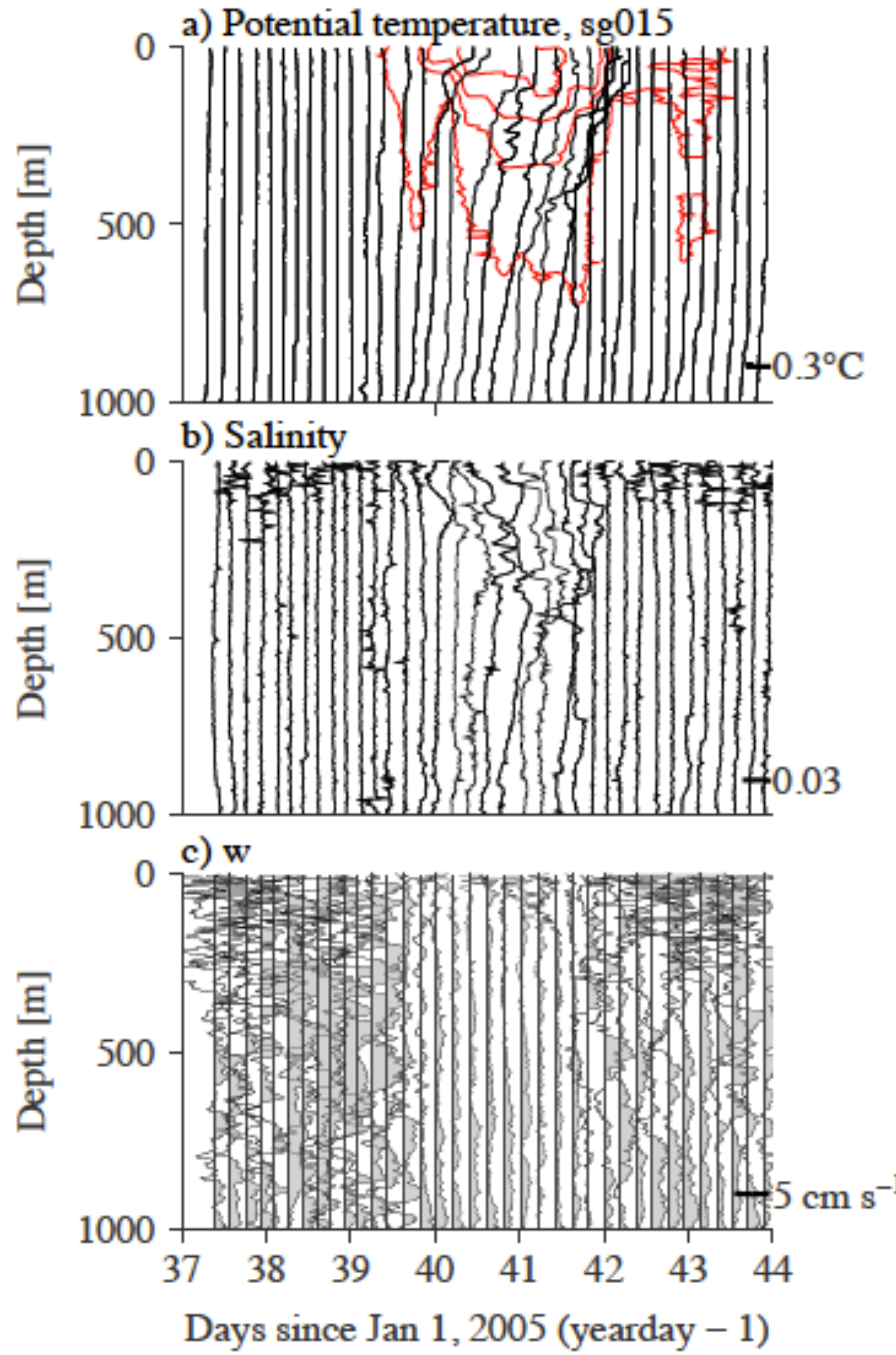


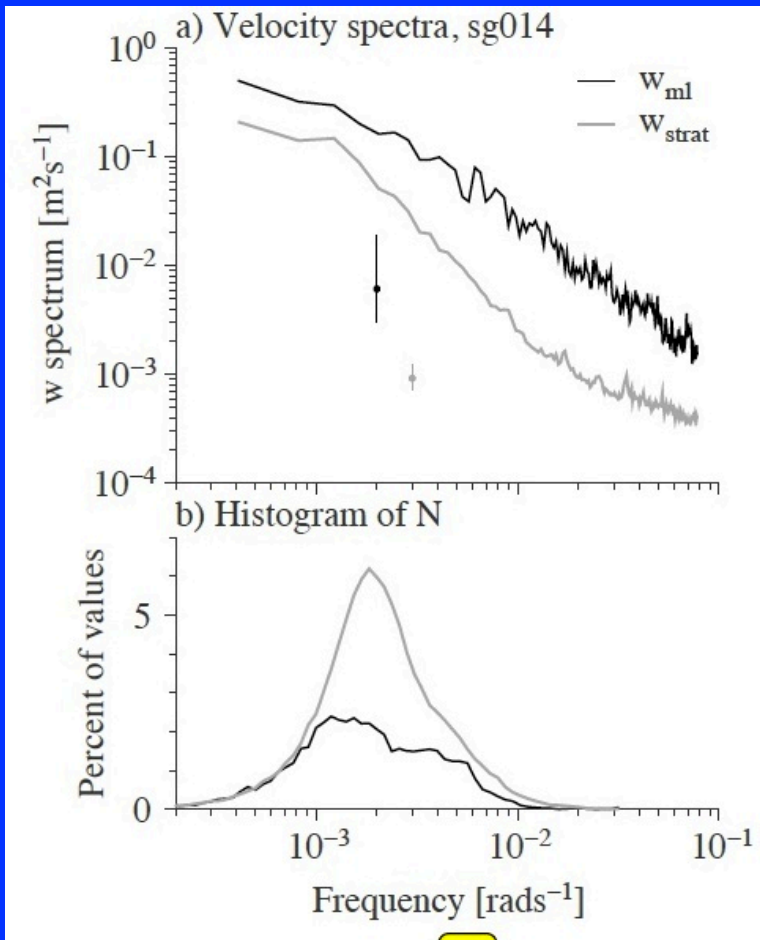
Figure 1: (a) Map of the Labrador Sea with Seaglider tracks, sg014 (thin) and sg015 (thick). Regions with mixed layer depths greater than 1000 m are in red, while the restratified region post-deep convection is in green. (b) Average winter heat fluxes (latent and sensible heat fluxes, net long wave and net short wave radiation) are in blue shading. Greater heat loss to the atmosphere (oceanic cooling) is in more saturated blue. Salinity convection resistance, the surface to 500 m buoyancy anomaly due to salinity variations in March, is contoured in dashed lines. Negative convection resistance indicates haline stratified (relatively fresh water above 500 m as compared to at 500 m). The blue star in (a) indicates the position of the K1 mooring.

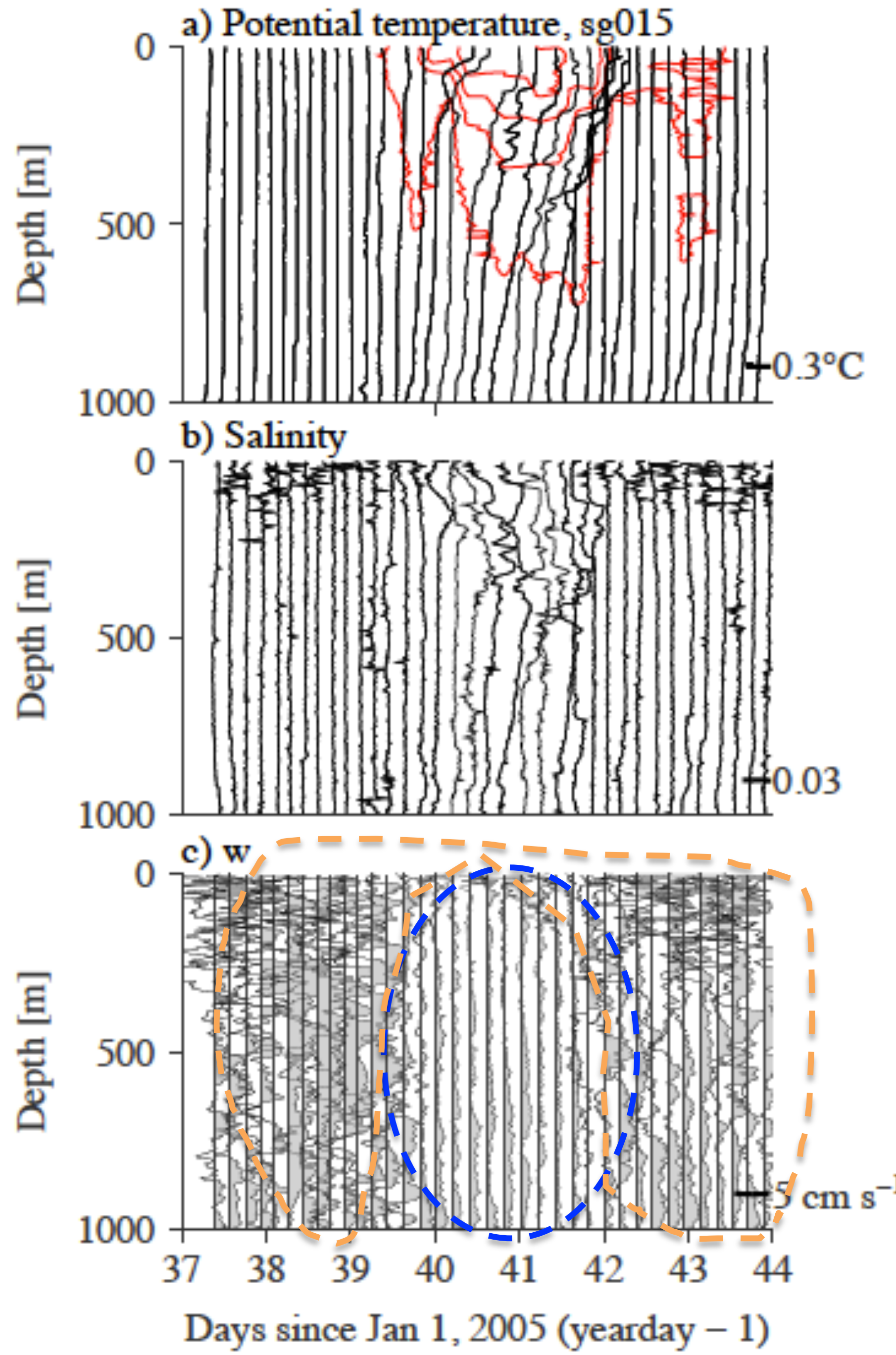
Seaglider S, θ, vertical velocity over about 1500km in Labrador Sea




a) Velocity spectra, sg014
w spectrum [m^{2}s^{-1}]
w_{ml}
w_{strat}
b) Histogram of N
Percent of values
Frequency [rads^{-1}]


a) Potential temperature, sg015
Depth [m]
0.3°C
b) Salinity
0.03
c) w
5 cm s^{-1}
Days since Jan 1, 2005 (yearday − 1)


a) Velocity spectra, sg014
w spectrum [m²s⁻¹]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
w_{ml}
w_{strat}
b) Histogram of N
Percent of values
5
0
10^{-3}
10^{-2}
10^{-1}
Frequency [rads⁻¹]


a) Potential temperature, sg015
Depth [m]
0
500
1000
0.3°C
b) Salinity
0.03
c) w
5 cm s⁻¹
37
38
39
40
41
42
43
44
Days since Jan 1, 2005 (yearday − 1)

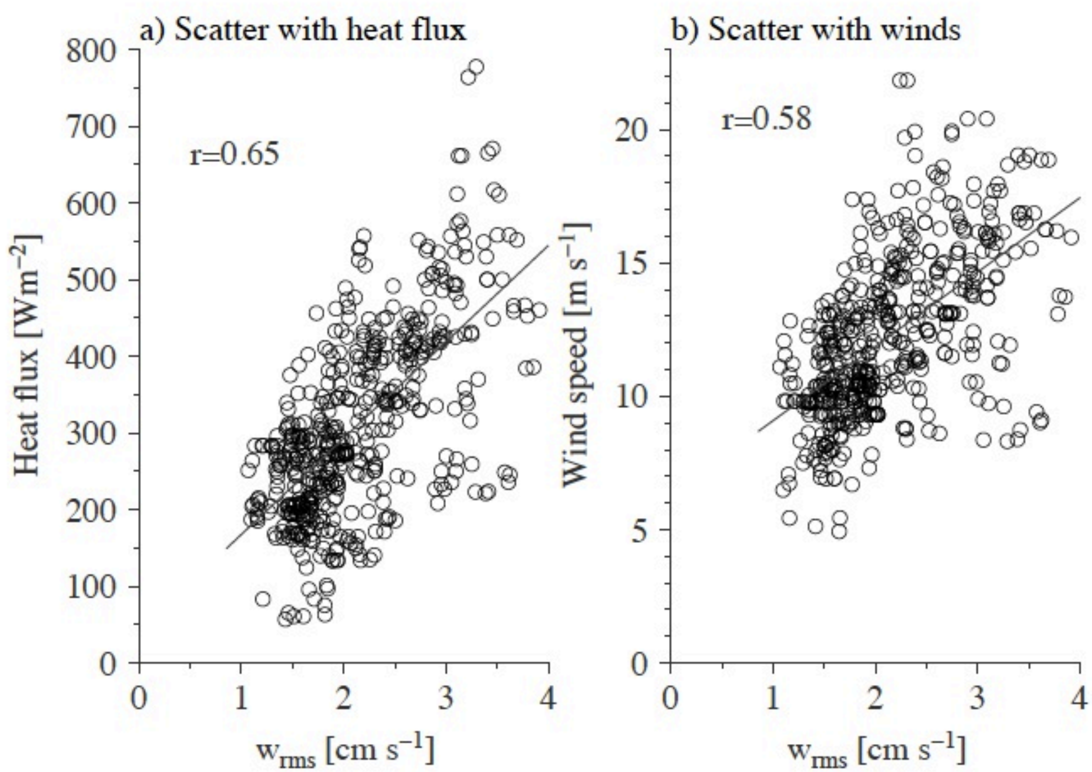


Figure 21: Scatterplots of sg015 w_{rms} on heat flux (a) and wind speed (b) for lagged daily averages.

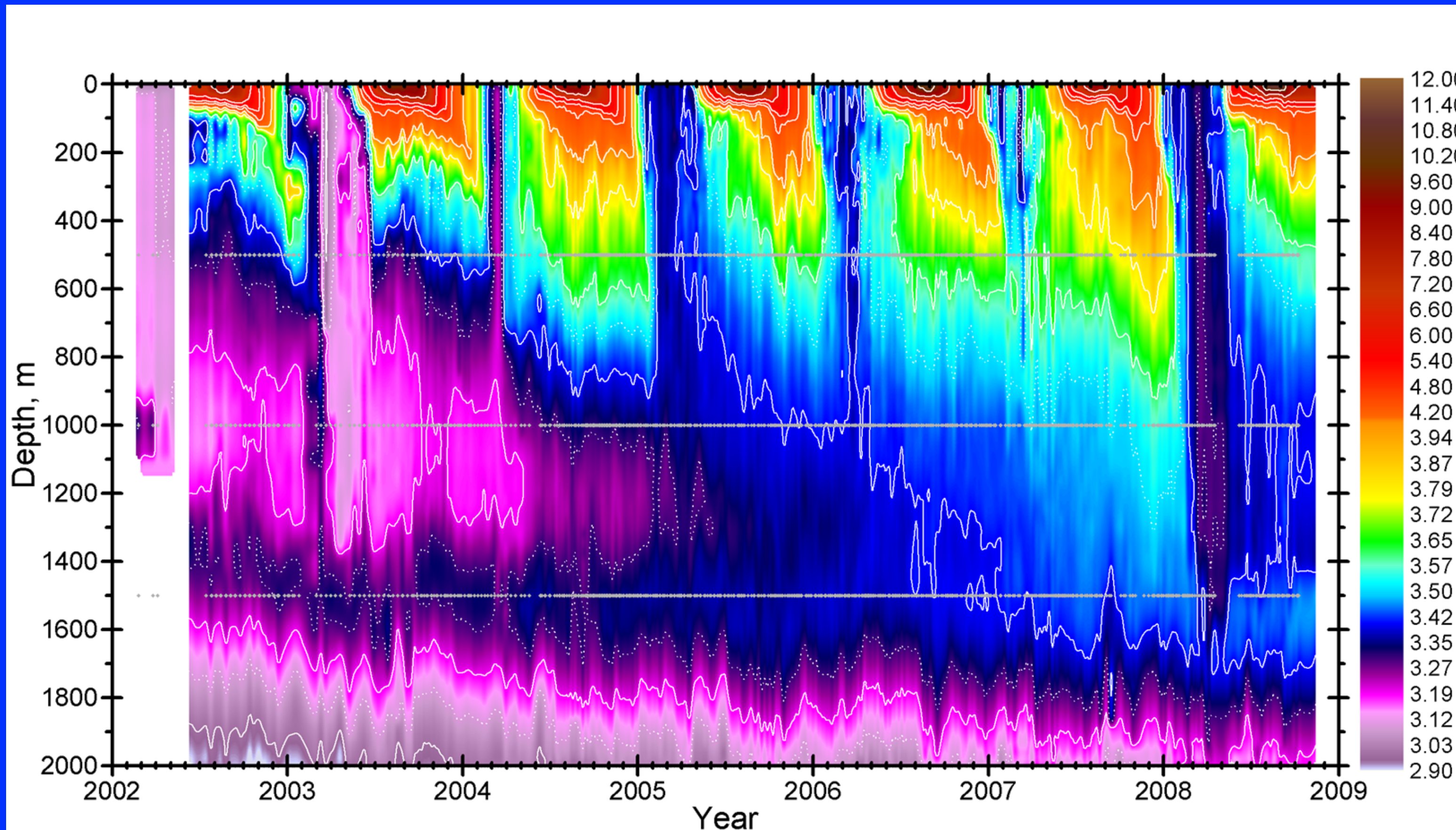
Conclusions

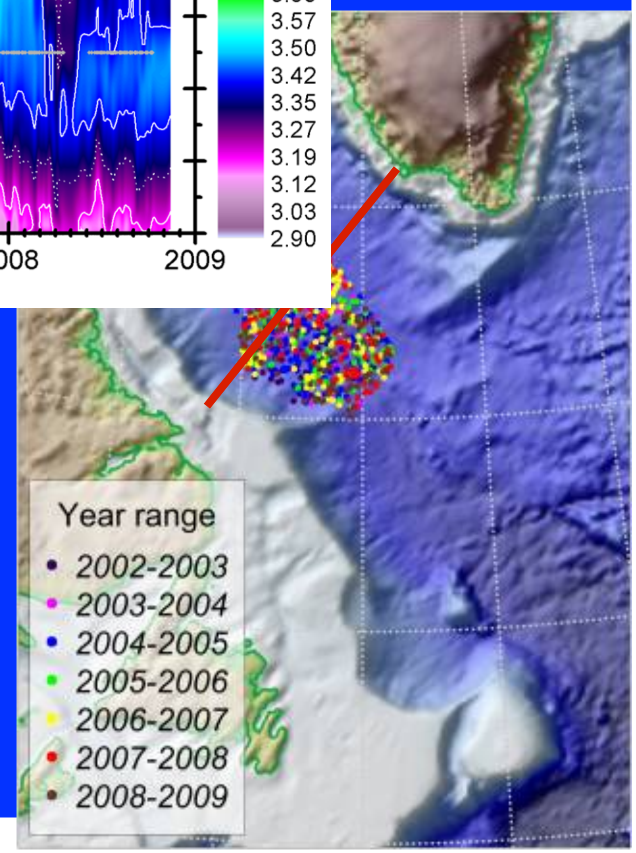
- A statistical approach to dense overflows is needed
    - when they have exited narrow channels: while this is formally 'eddy flux' its evaluation suggests repeated Iceland Basin surveys extending to ~2500m depth.

- The 3-year Seaglider program did not determine quantitatively the passage of dense overflows at the Iceland Faroe Ridge yet it produced
    - The transport (on the θ/S plane) of the dense water layer on the IF Ridge, showing admixing of the IFR overflow and FBC outflow and its severe dilution with distance.
        - near-bottom, & vertical structure of the circulation near the 1000m isobath was estimated over 3 years, showing the dilution of the transport-weighted density, θ,S and decay of transport from ~ 1.5 Sv to less than 0.5 Sv.
    - The bifurcation of the Faroe Bank Channel outflow was observed, although it will take Deepgliders to follow that (small?) sinking branch to 2500m depth
    - The western IFR overflow pathway near Iceland was found to be very intermittent, unlike the conclusions reached from the 1970s (*Saunders, JPO* 1996).

- Seaglider observations of vertical velocity show a rich geography of mixing and internal waves relevant to the dilution of the dense overflows, as well as in deep convection in Labrador Sea
    - in conjunction with geostrophic velocity, θ, S, turbidity (light scattering) and other tracers. Gliders are being equipped with turbulence probes.
- The depth-averaged Seaglider velocity field including tides is well resolved to roughly 1 cm sec^{-1}, yielding absolute velocity profiles and evidence of strong quasi-barotropic eddies and jets.

    vortex stretching activates the upper ocean above dense overflow jets.

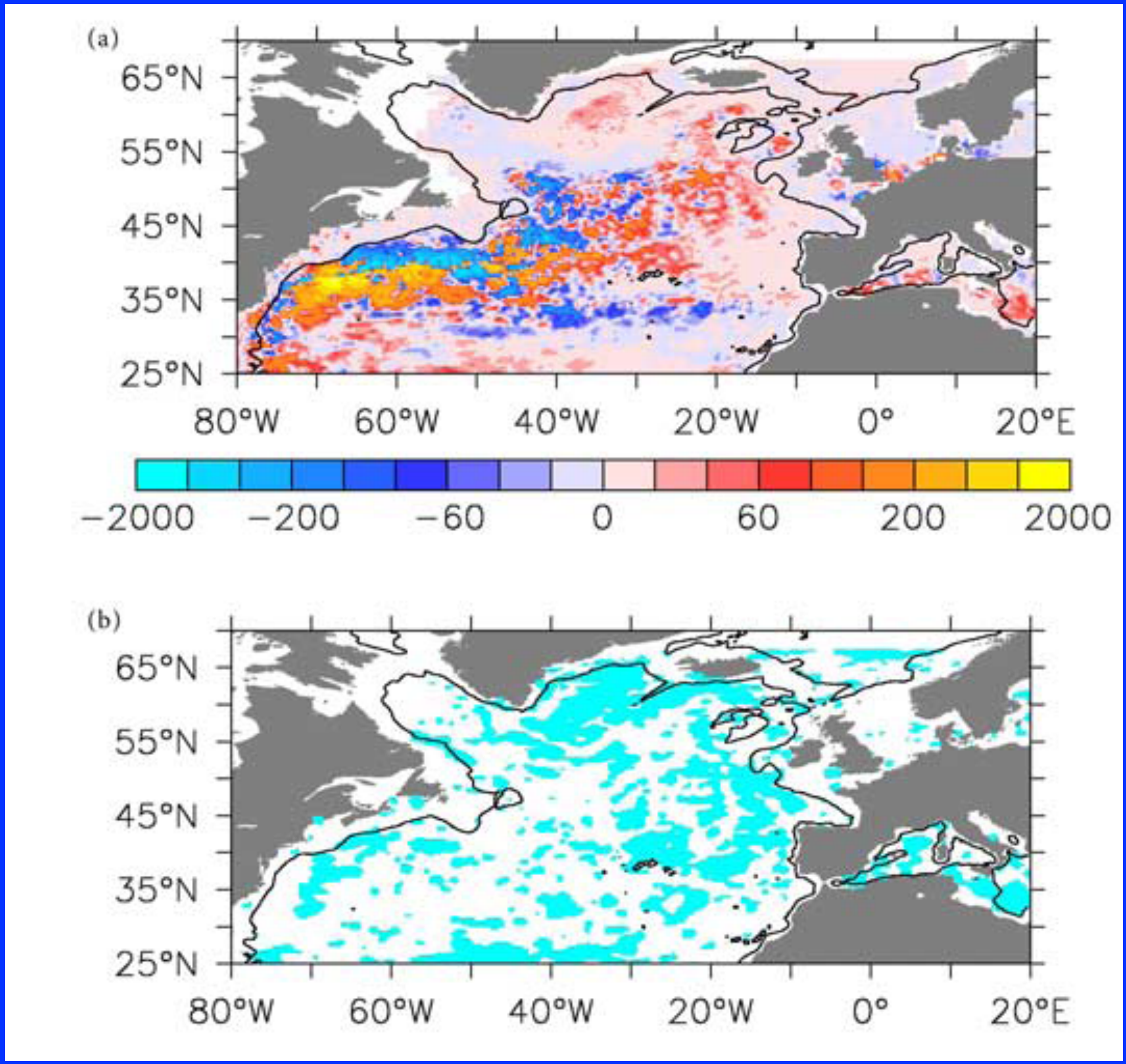




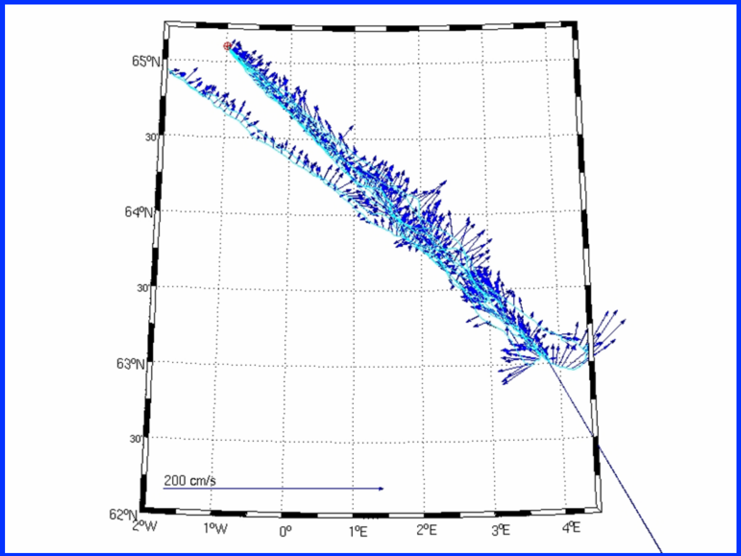
In addition to global scope, there is locally intensive sustained observation, for example as virtual weatherships:

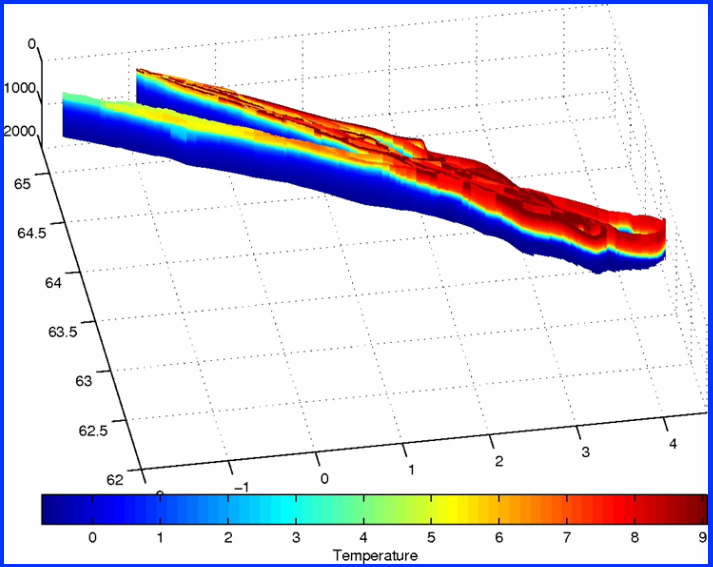
ARGO temperature vs. depth in central Labrador Sea, 2002-2009 (*Yashayaev, 2009*):
(though no meteorology or biology or geochemistry)

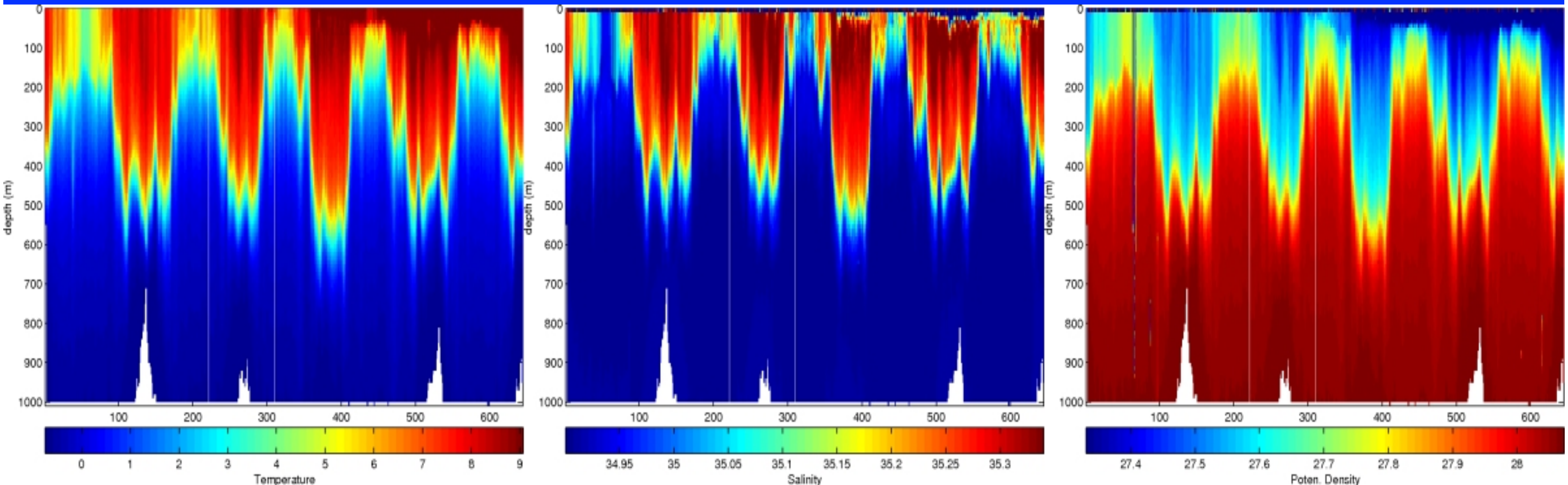
Linear trend in EKE 1992-2006 (high confidence in blue areas)



Svinøy section: 647 dives Jan-August 2009 (Seaglider ER.. extended range… had plenty of battery energy left at end)

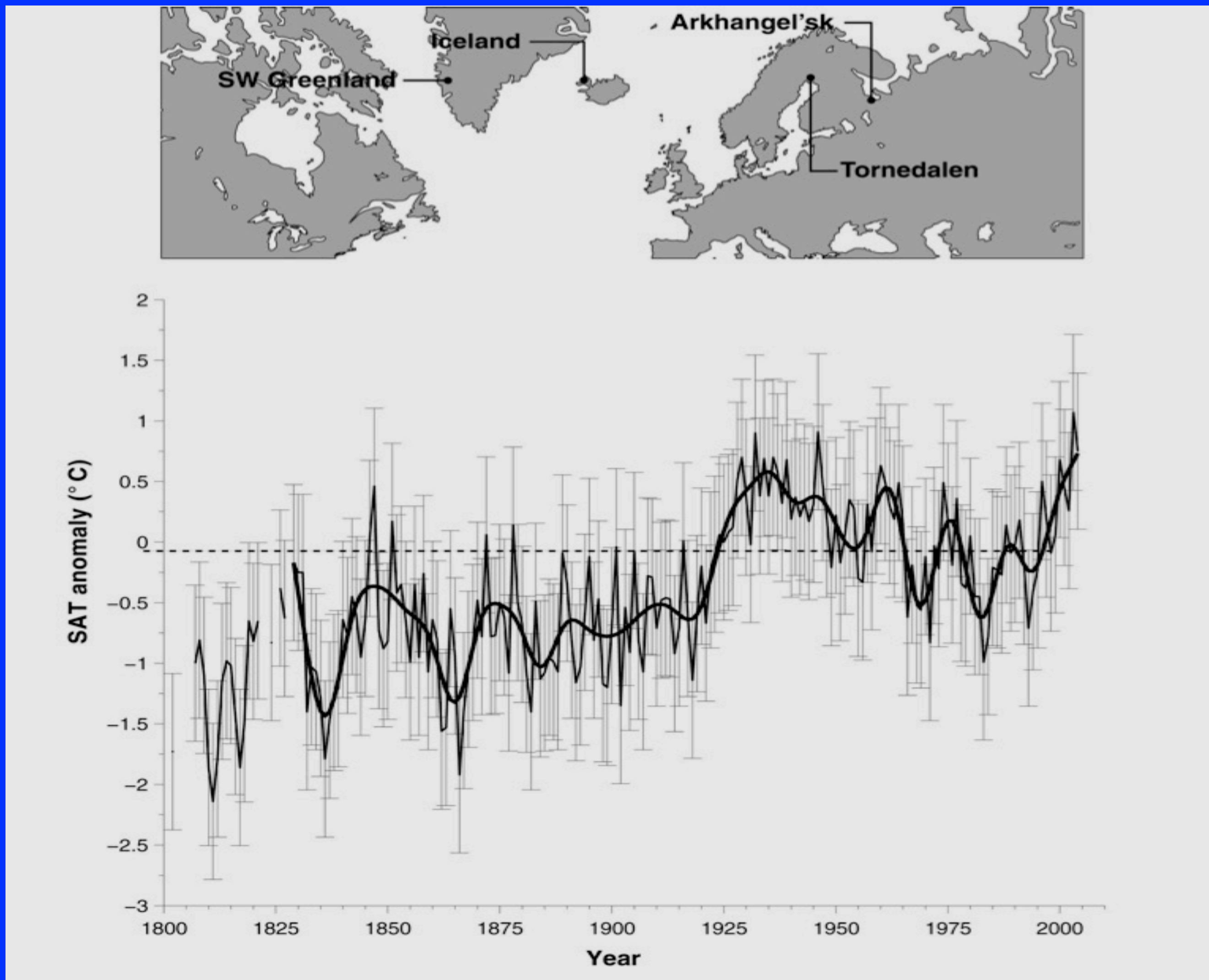






Reconstructed SAT relating to AMV

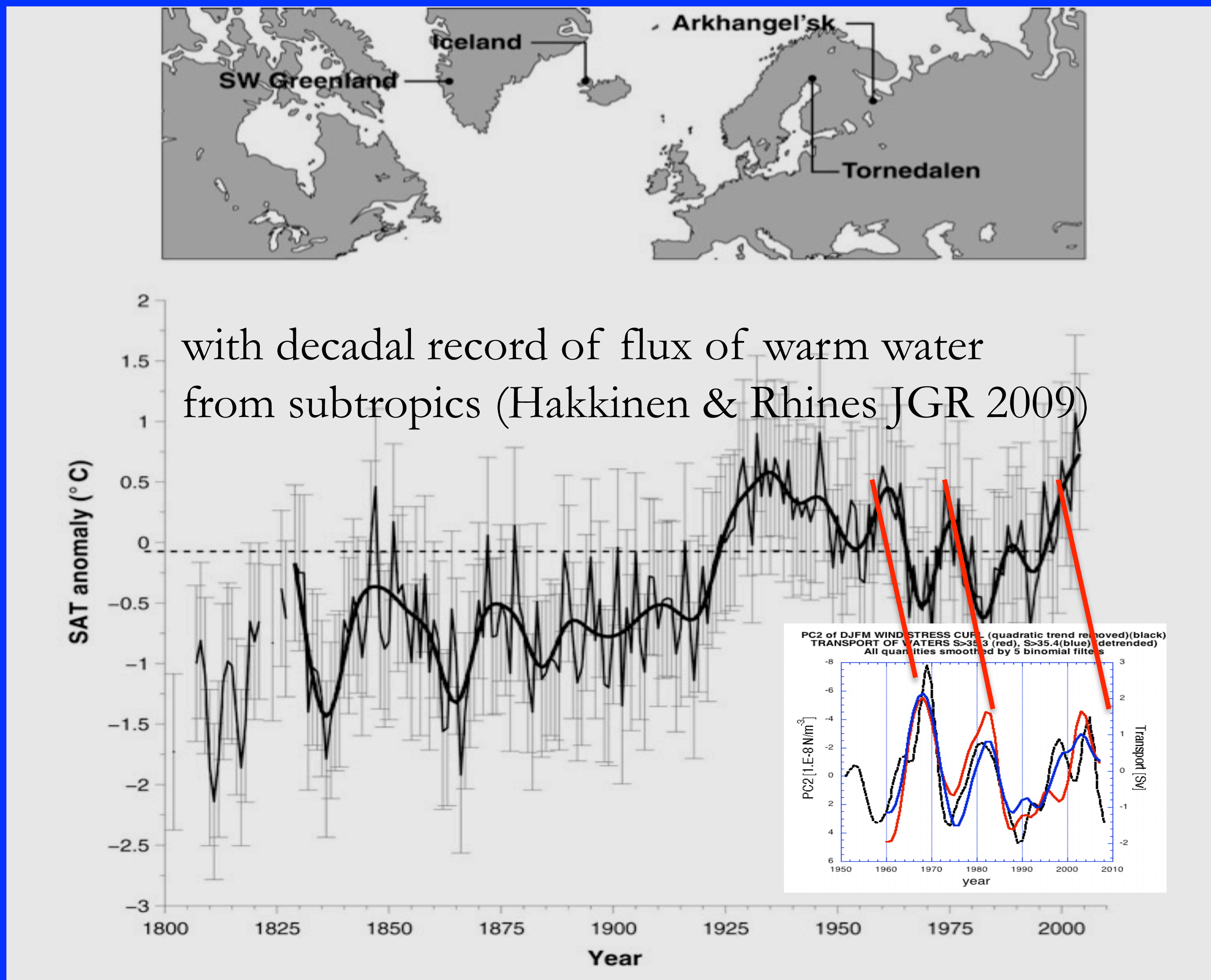
Wood, Overland, Jonsson & Smoliak, JGR subm.



1800 1900 2000

Reconstructed subpolar SAT relating to AMV

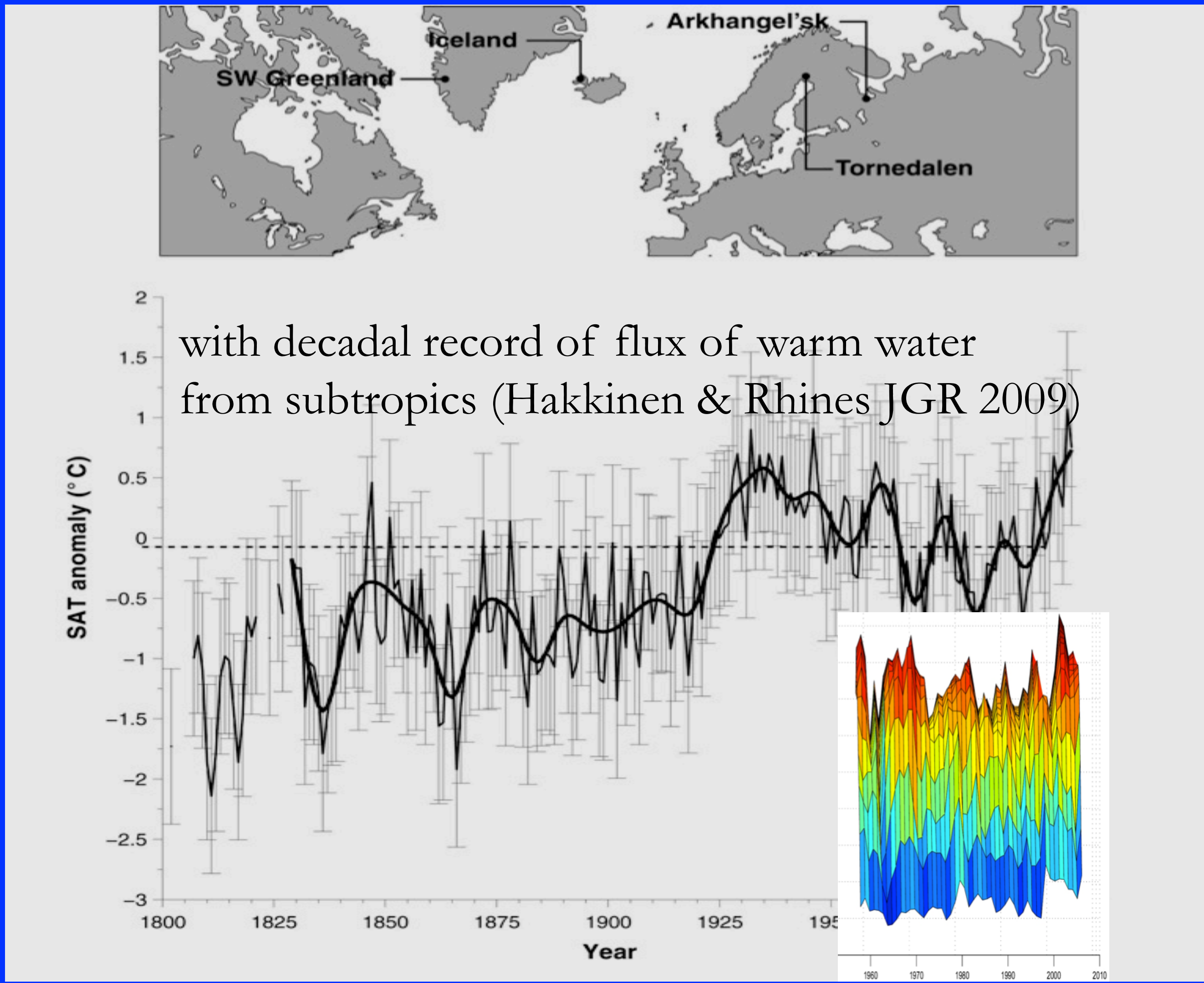
Wood, Overland, Jonsson & Smoliak, JGR subm.



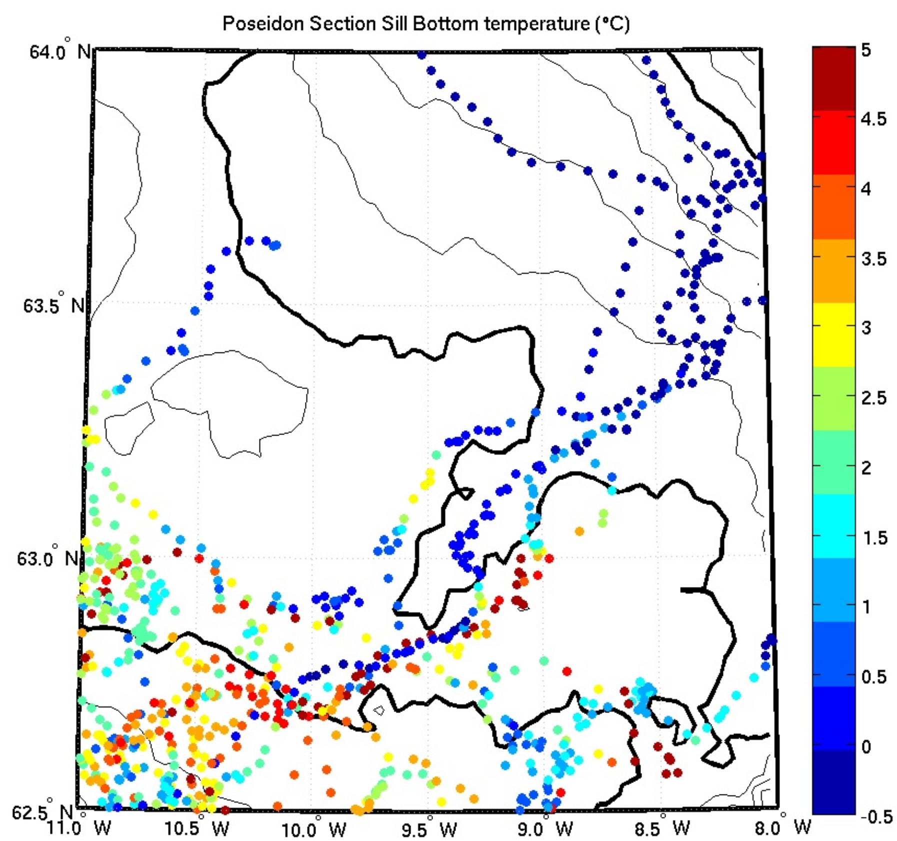
1800 1900 2000

Reconstructed subpolar SAT relating to AMV

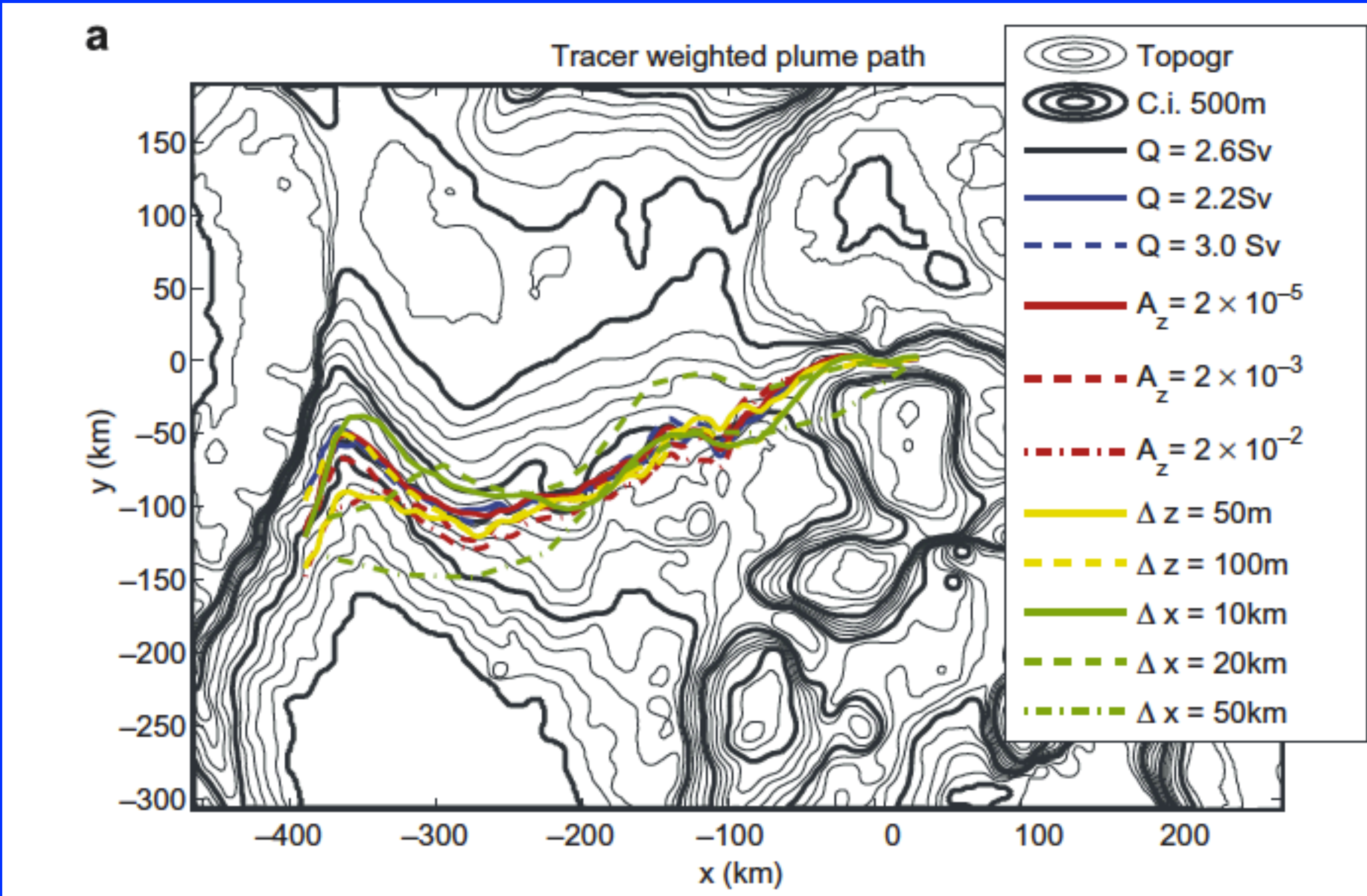
Wood, Overland, Jonsson & Smoliak, JGR subm.



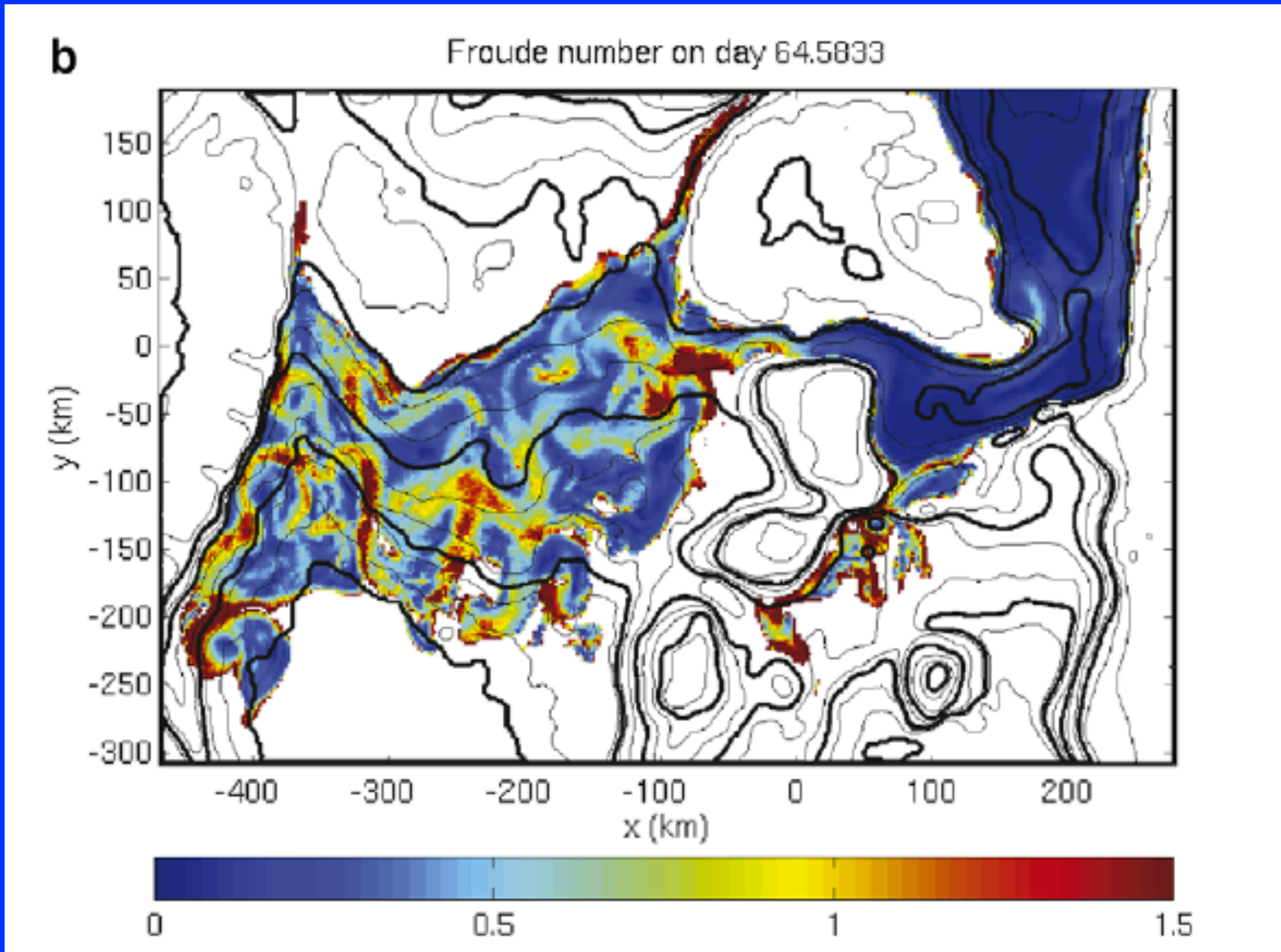
1800 1900 2000



Poseidon Section Sill Bottom temperature (°C)
64.0° N
63.5° N
63.0° N
62.5° N
11.0° W
10.5° W
10.0° W
9.5° W
9.0° W
8.5° W
8.0° W
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5

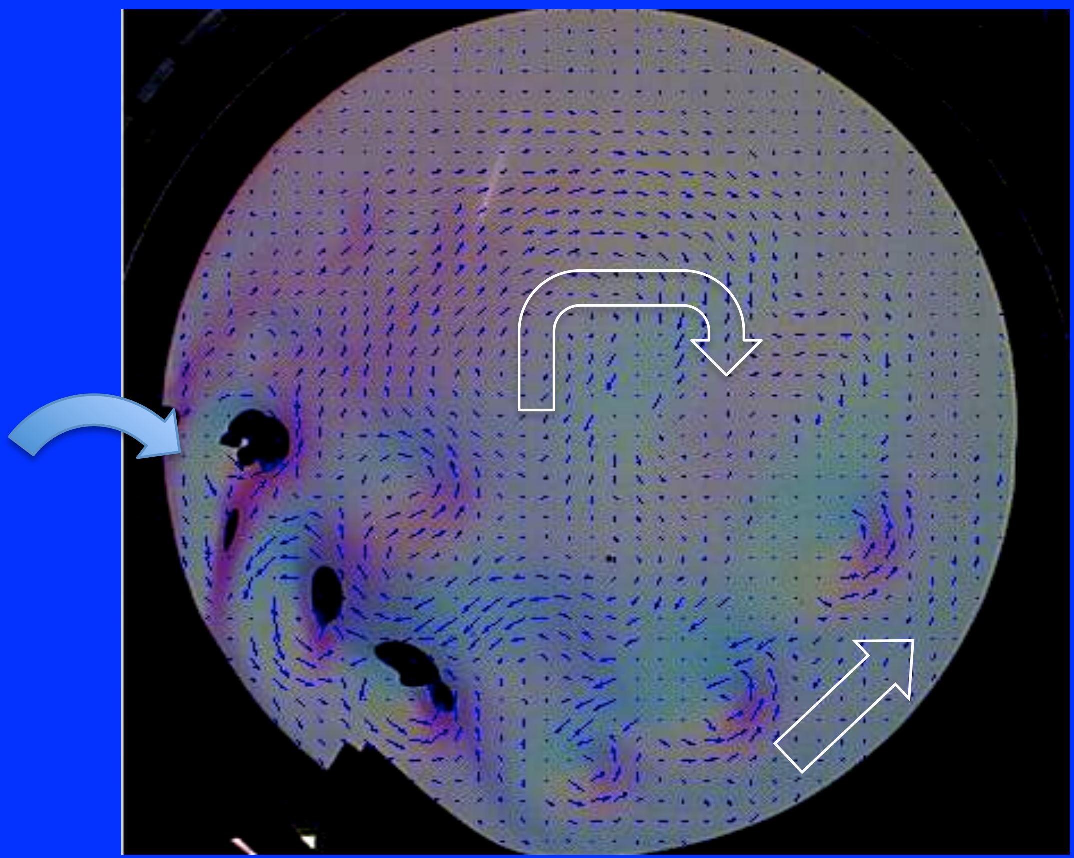


a
Tracer weighted plume path
Topogr
C.i. 500m
Q = 2.6Sv
Q = 2.2Sv
Q = 3.0 Sv
$A_z = 2 \times 10^{-5}$
$A_z = 2 \times 10^{-3}$
$A_z = 2 \times 10^{-2}$
Δ z = 50m
Δ z = 100m
Δ x = 10km
Δ x = 20km
Δ x = 50km
y (km)
150
100
50
0
−50
−100
−150
−200
−250
−300
−400
−300
−200
−100
0
100
200
x (km)



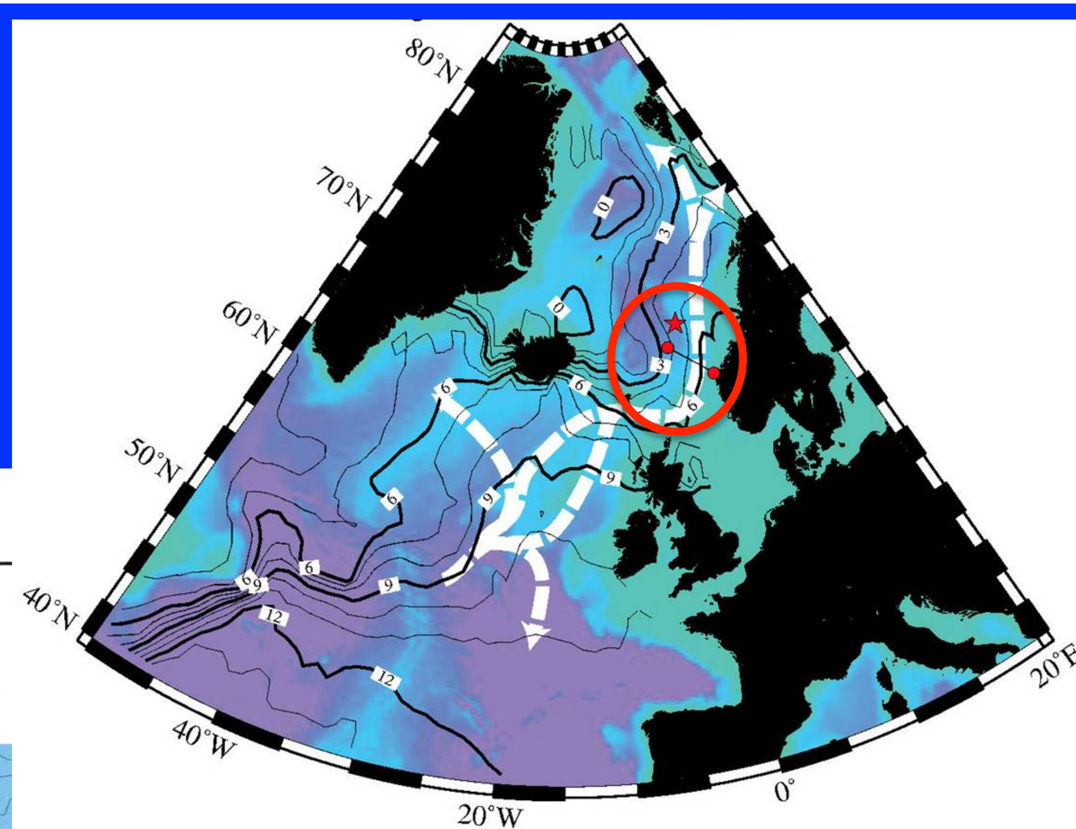
b
Froude number on day 64.5833
150
100
50
0
-50
-100
-150
-200
-250
-300
y (km)
-400
-300
-200
-100
0
100
200
x (km)
0
0.5
1
1.5

Dense source entering a bowl-shaped basin (*Ole Anders Nøst & GFD lab, Univ of Washington*): surface signature viewed with optical altimetry. The plume separates into two components, a thin downslope flow and a train of cyclonic eddies



Transformation of the Norwegian Atlantic Current- Glider Surveys at OWS Mike & Svinoy

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



K.A. Orvik et al. / Deep-Sea Research I 48 (2001) 937–957

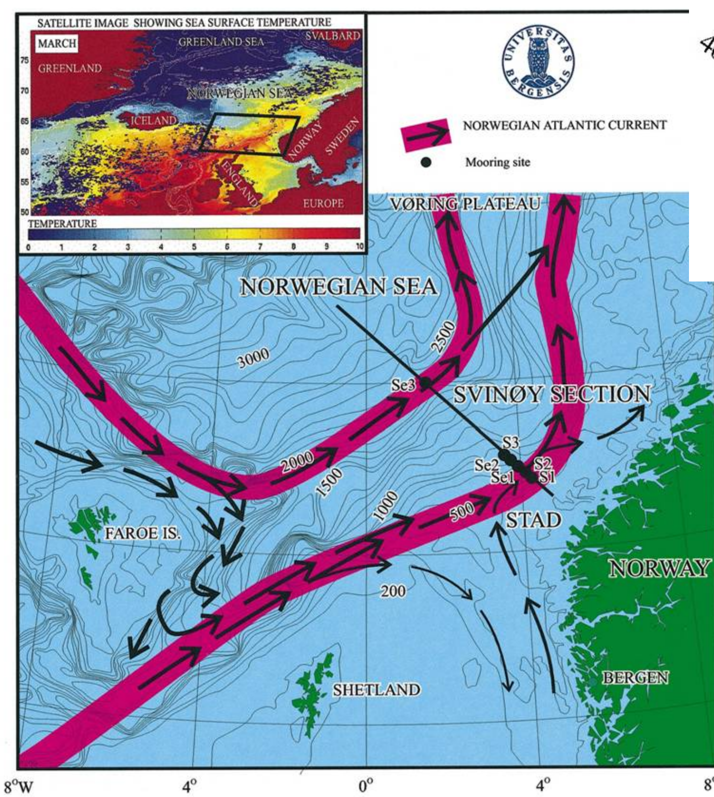
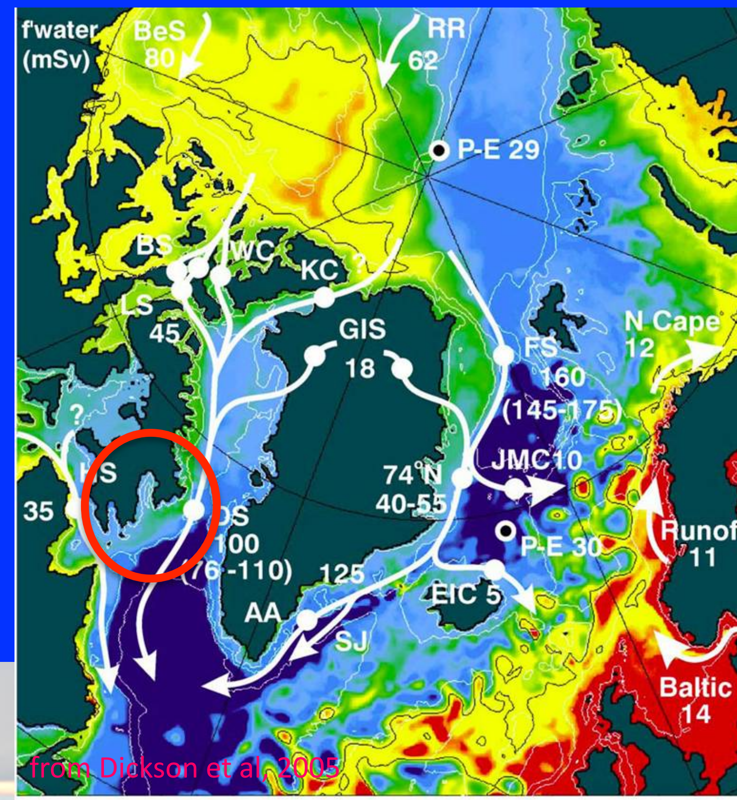


Fig. 1. Schematic of surface currents showing the Atlantic inflow to the Norwegian Sea and the sea surface temperature from an AVHHR image in March. The Svinøy section with mooring sites is indicated as a full line.

Hoydalsvik, Mauritzen, Lee, Hansen and Orvik

ASOF: Arctic Gateways: Davis Strait Transports and Fluxes

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



Fisheries and Oceans Canada Pêches et Océans Canada

Bedford Institute of Oceanography

Lee, Petrie, Gobat, Moritz and Azetsu-Scott

Background AMOC decadal variability

UPPER OCEAN BRANCH:

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

*Deceleration of sfc gyre from altimetrty

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

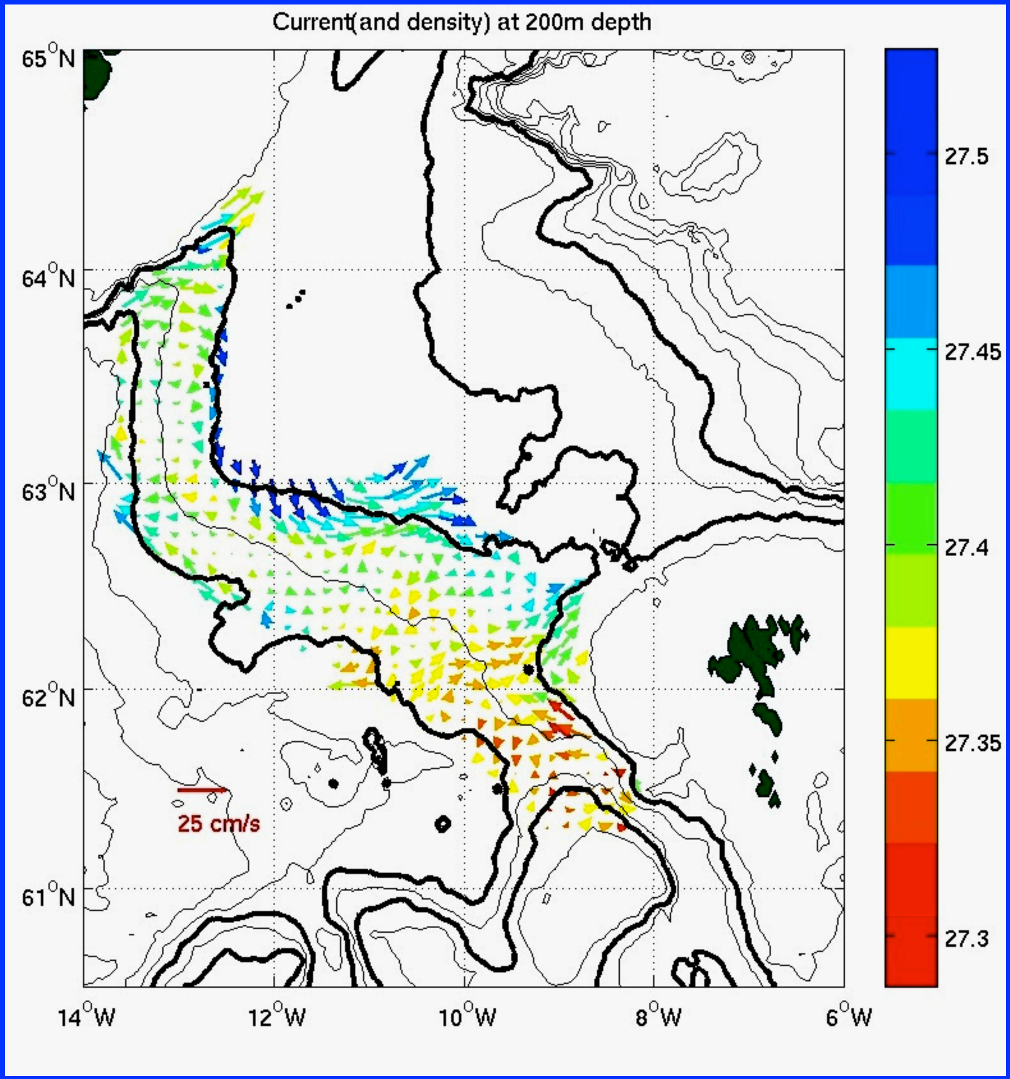
* Fresh Water invasions control deep convection in Labrador Sea: sensitive to E and W Greenland coastal currents and NAC's 'NW Corner': retention in subpolar gyre

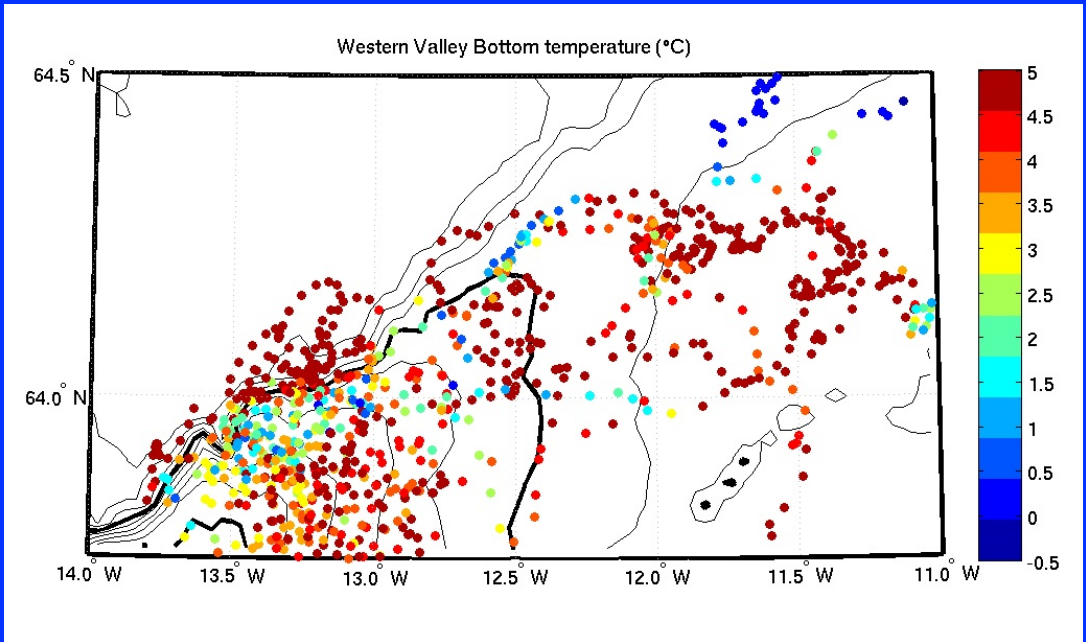
DEEP OCEAN BRANCH:

- More variability in Θ/S than in volume transport
- Substantial overflow at Iceland-Faroe Ridge largely unassessed
- Downslope evolution of Faroe-Bank Channel outflow involves bifurcation and fragmentation of dense plume

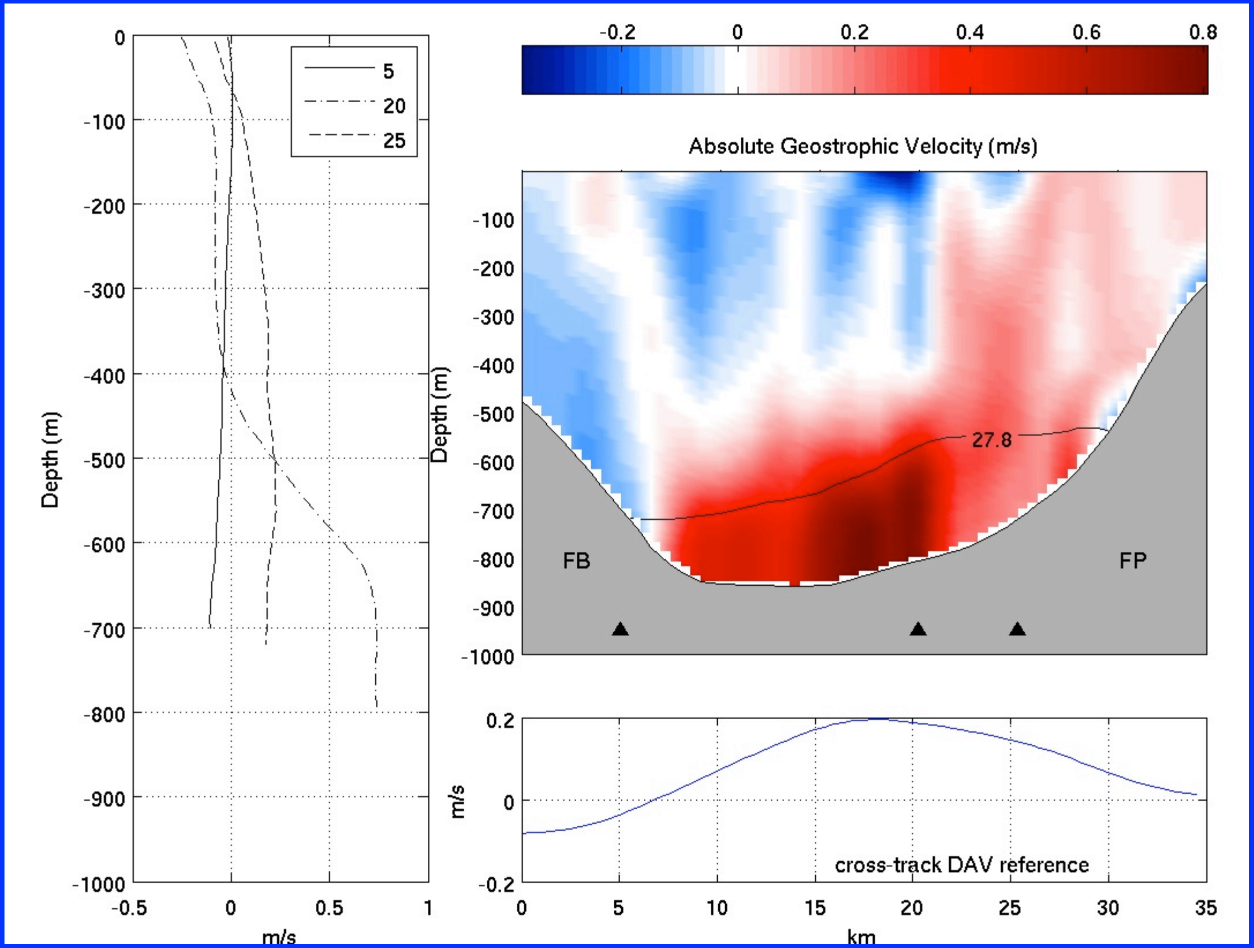
- I. Dense overflow water on the south flank of the Iceland Faroe Ridge: two sources

200m mean currents and density

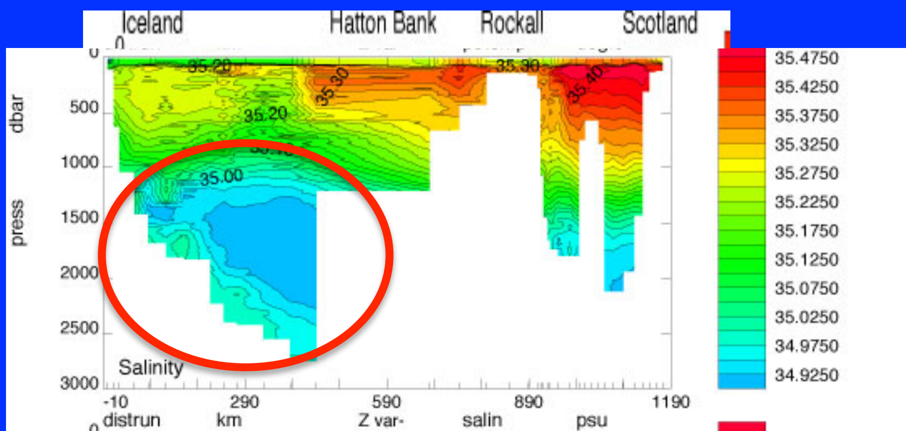


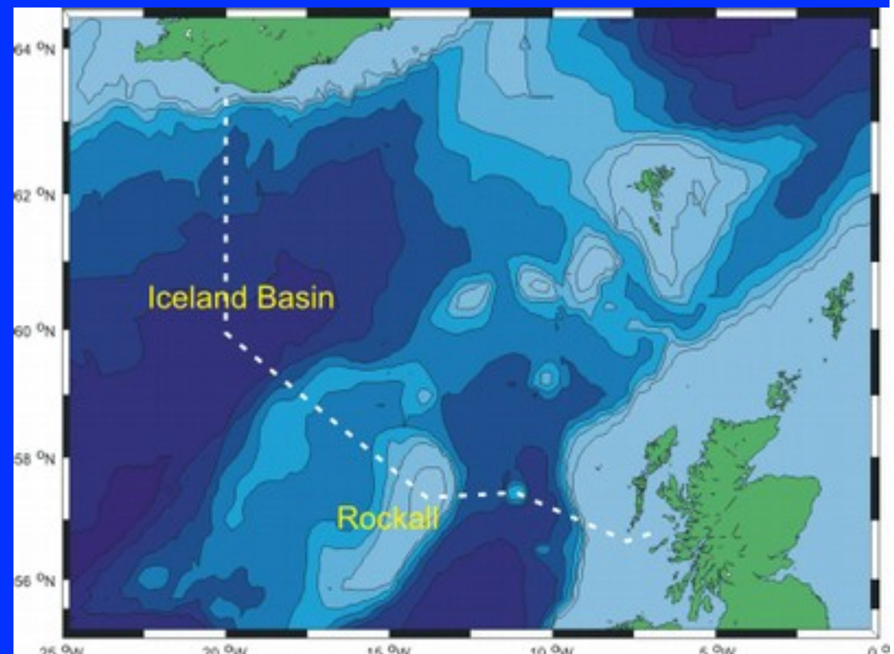


Western Valley Bottom temperature (°C)
64.5° N
64.0° N
14.0° W
13.5° W
13.0° W
12.5° W
12.0° W
11.5° W
11.0° W
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5

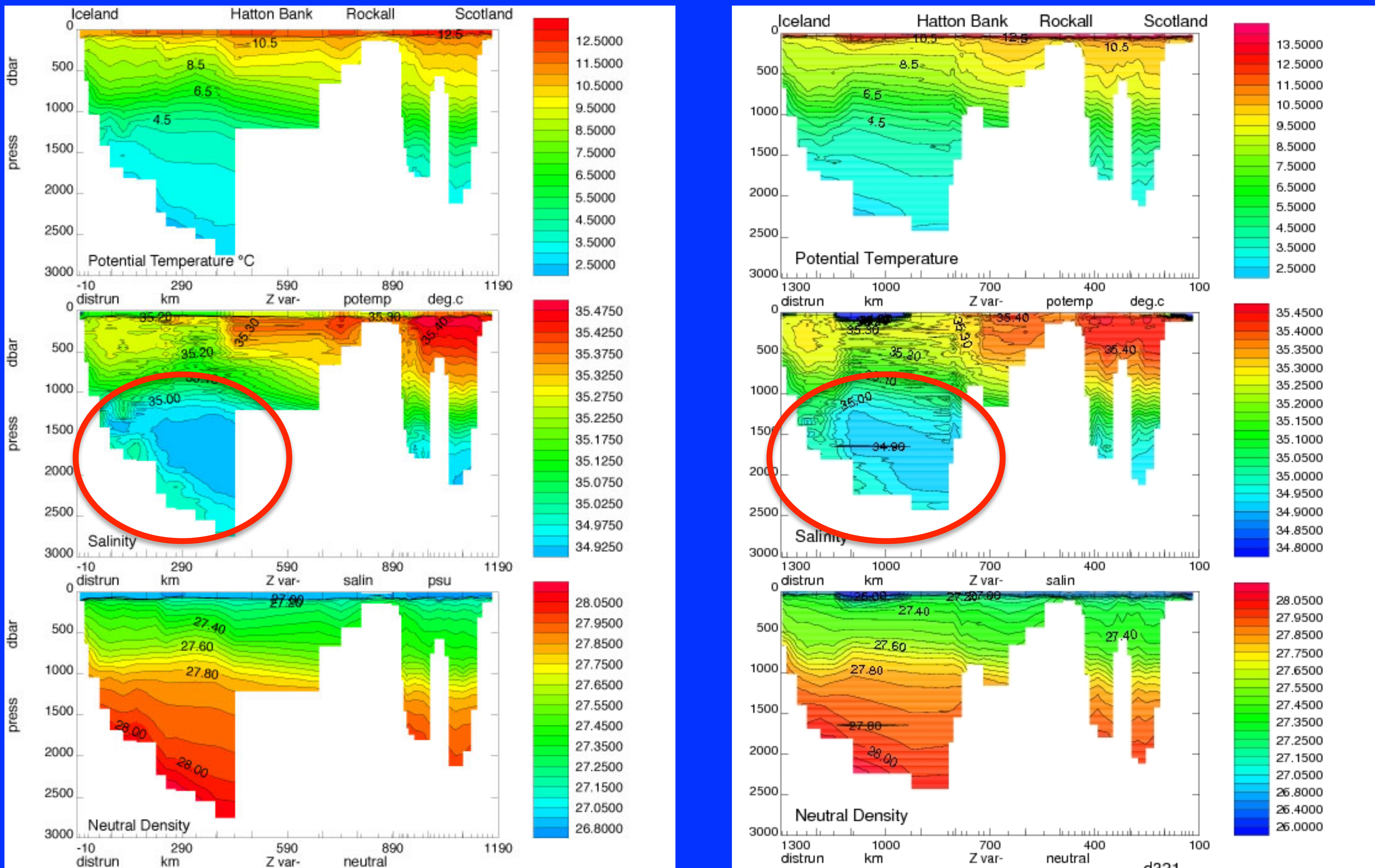


5
20
25
Depth (m)
m/s
Absolute Geostrophic Velocity (m/s)
27.8
FB
FP
Depth (m)
km
cross-track DAV reference





2006 Extended Ellet Line



2006 Extended Ellet Line 2007