Measuring poleward volume and heat fluxes
(with Charlie Flagg, SBU)

The focus of this talk will be to show how working with merchant marine vessels one can measure poleward fluxes in the ocean directly. Hull-mounted acoustic Doppler current profilers (ADCP) scan currents and XBTs deployed along the same route map temperature. Integrals of velocity and its product with temperature yield volume and temperature flux.

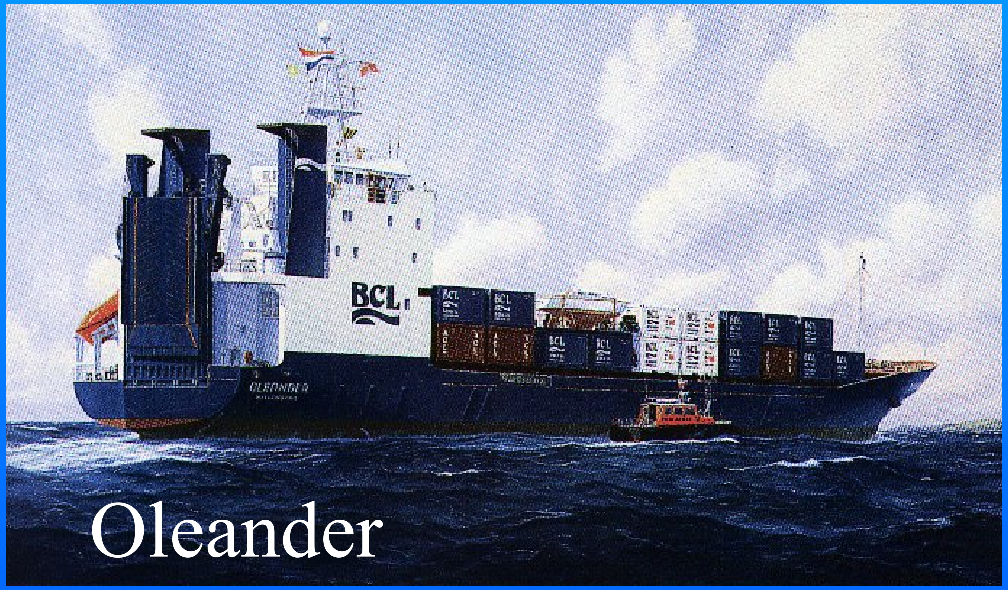
Three vessels in the North Atlantic operate ADCPs: the Oleander operating between New Jersey and Bermuda, the Nuka Arctica between Cape Farewell and Scotland, and the Norröna between Iceland and Scotland. All take XBTs. I will give a brief overview of our work and where we stand today with respect to these objectives.

Nuka Arctica

2

3

Norröna



Oleander

1

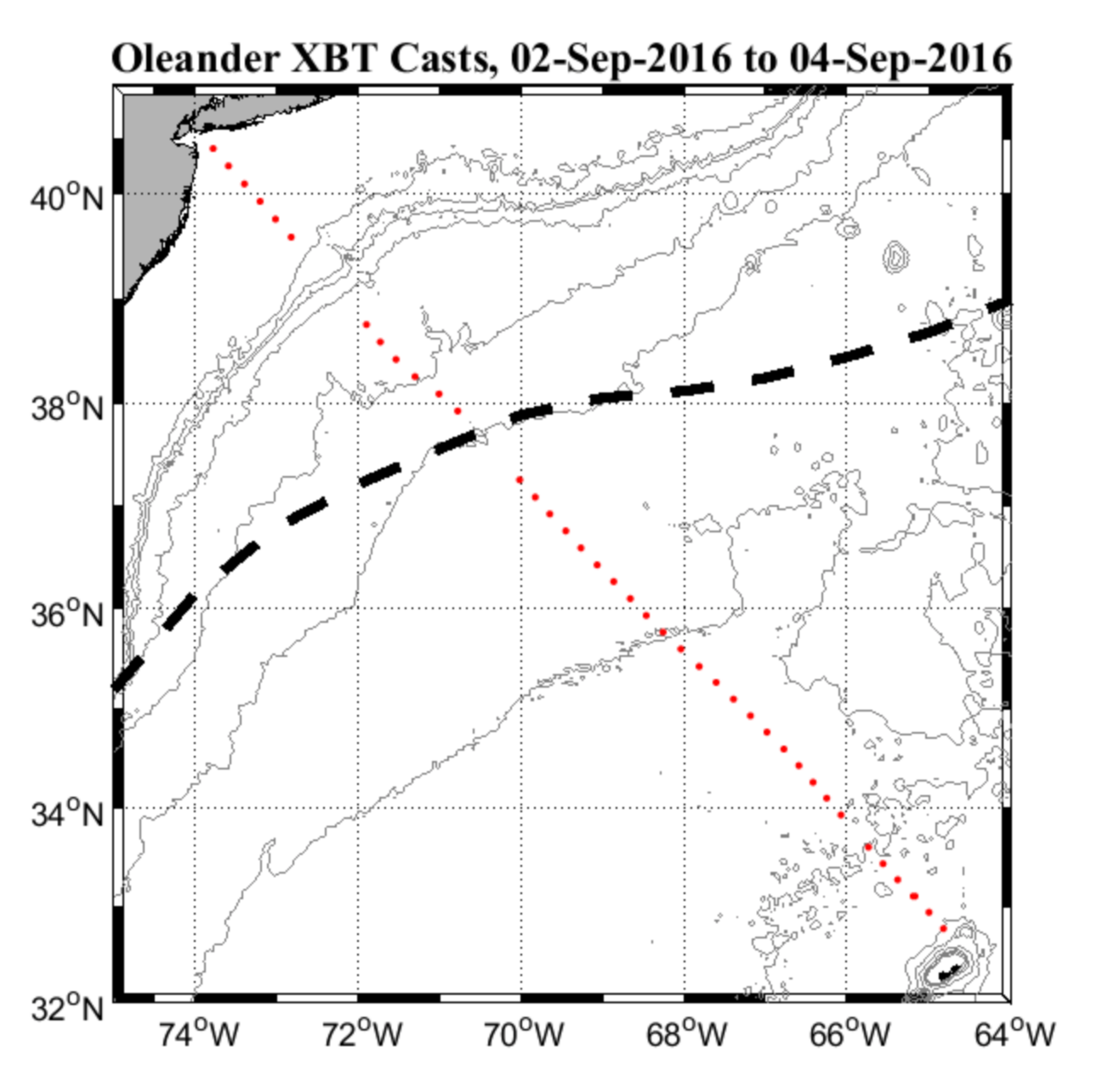

Explorer of the Seas


Laurence M. Gould

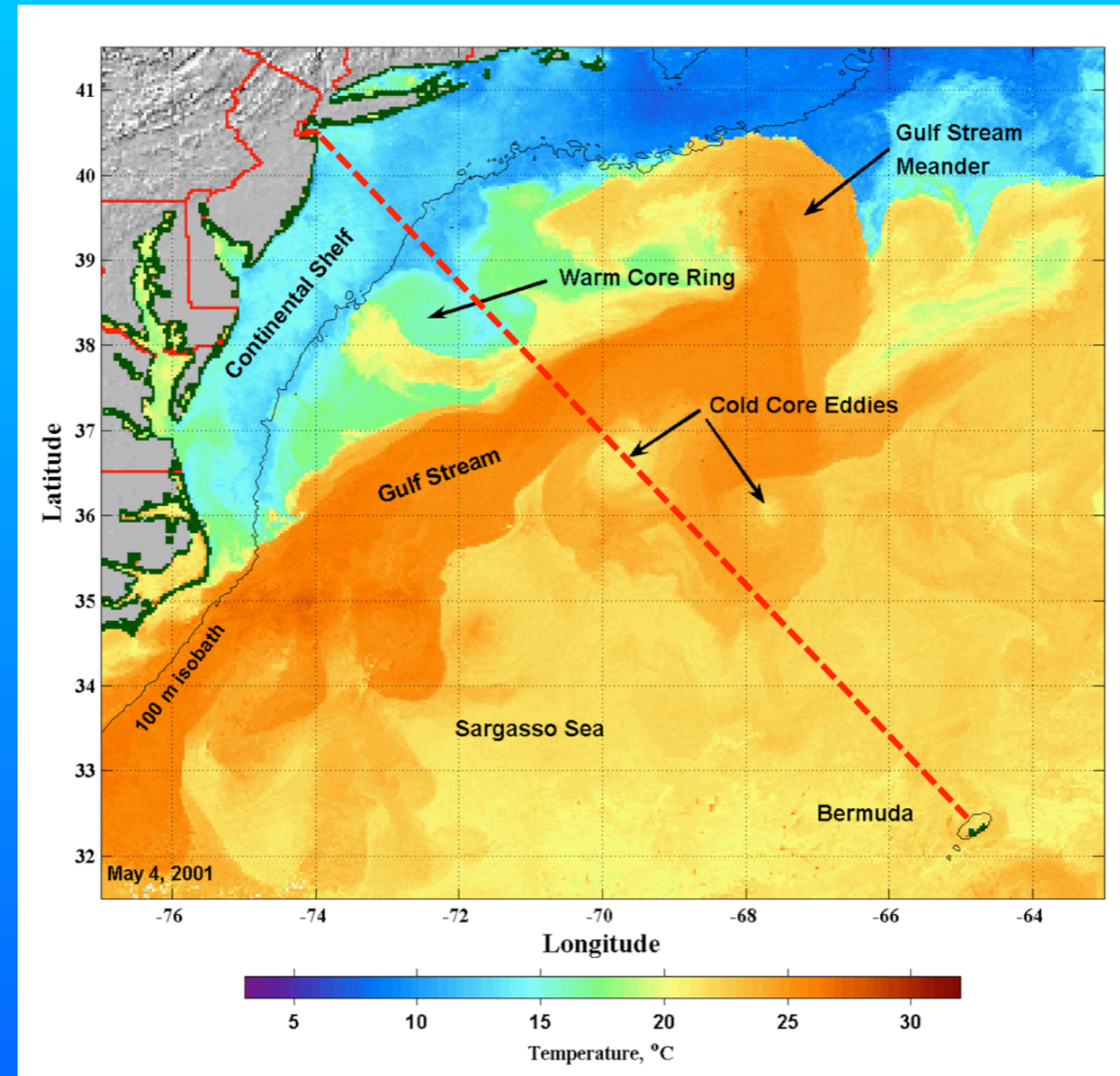
ADCP-equipped vessels in repeat service

Weekly service Bermuda-New Jersey. 118 m long, 5 m draft, 16 Kt.

XBT operations on monthly basis since 1977 across the shelf and to the GS (T-7s). Gradual expansion to include the GS, AXIS operation since 2012. All data are forwarded to NOAA in near-realtime and are also posted at oleander.bios.edu (it links to Flagg’s website).



NOAA also took a number of high-resolution XBT sections in the 1970s from a cruise ship in regular service. These were each described in excellent reports.

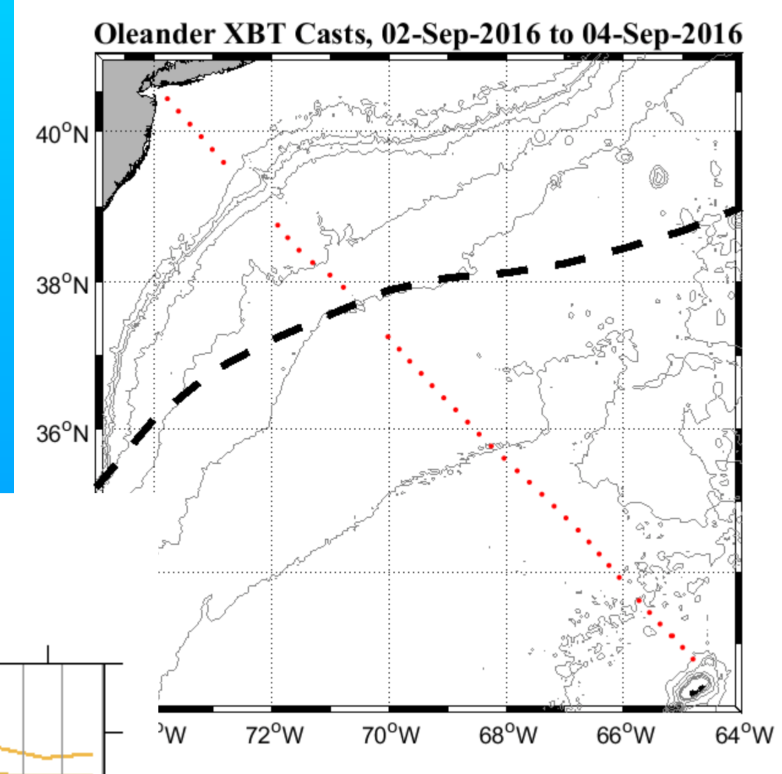


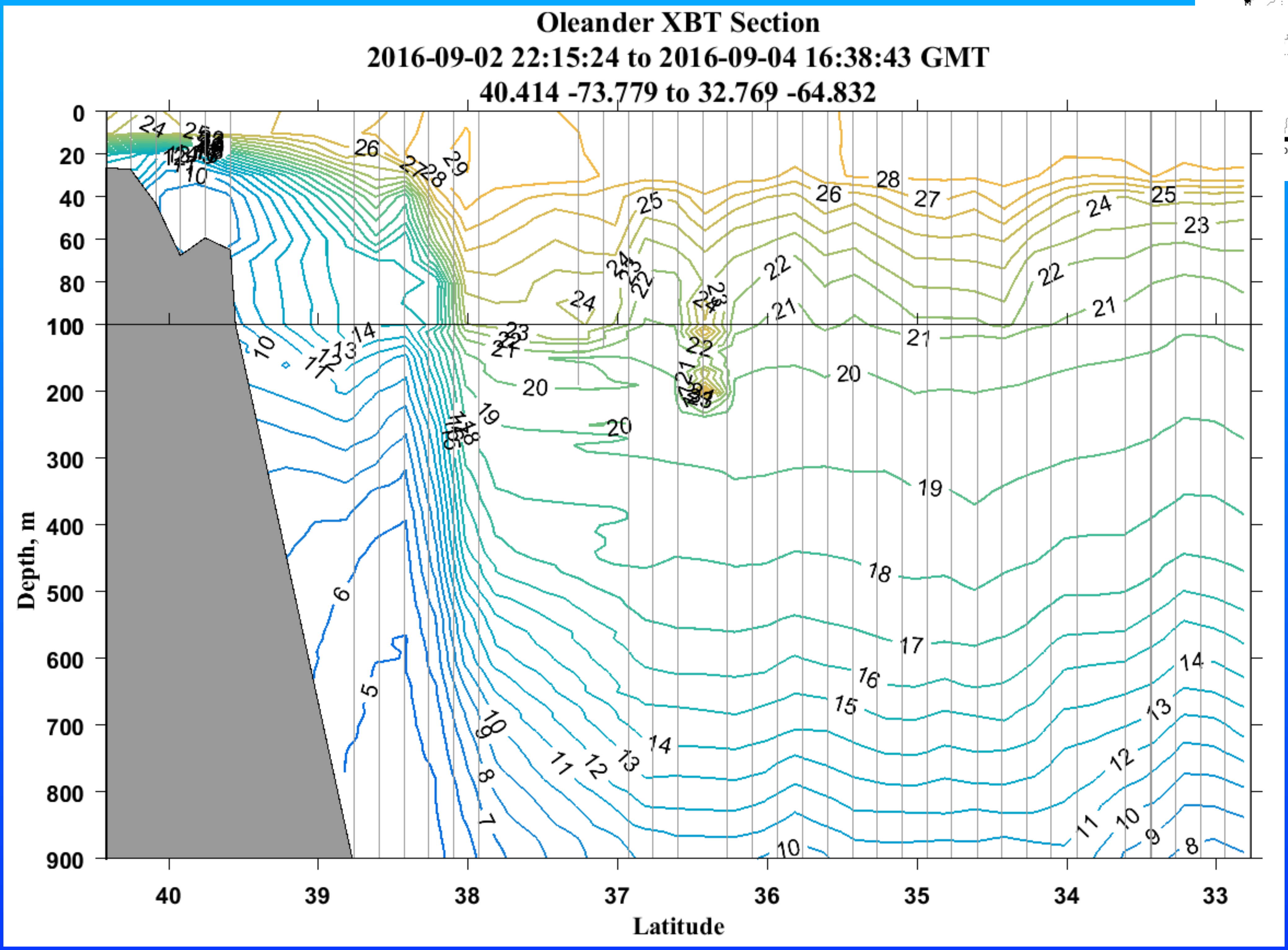
Weekly service Bermuda-New Jersey
118 m long, 5 m draft, 16 Kt.

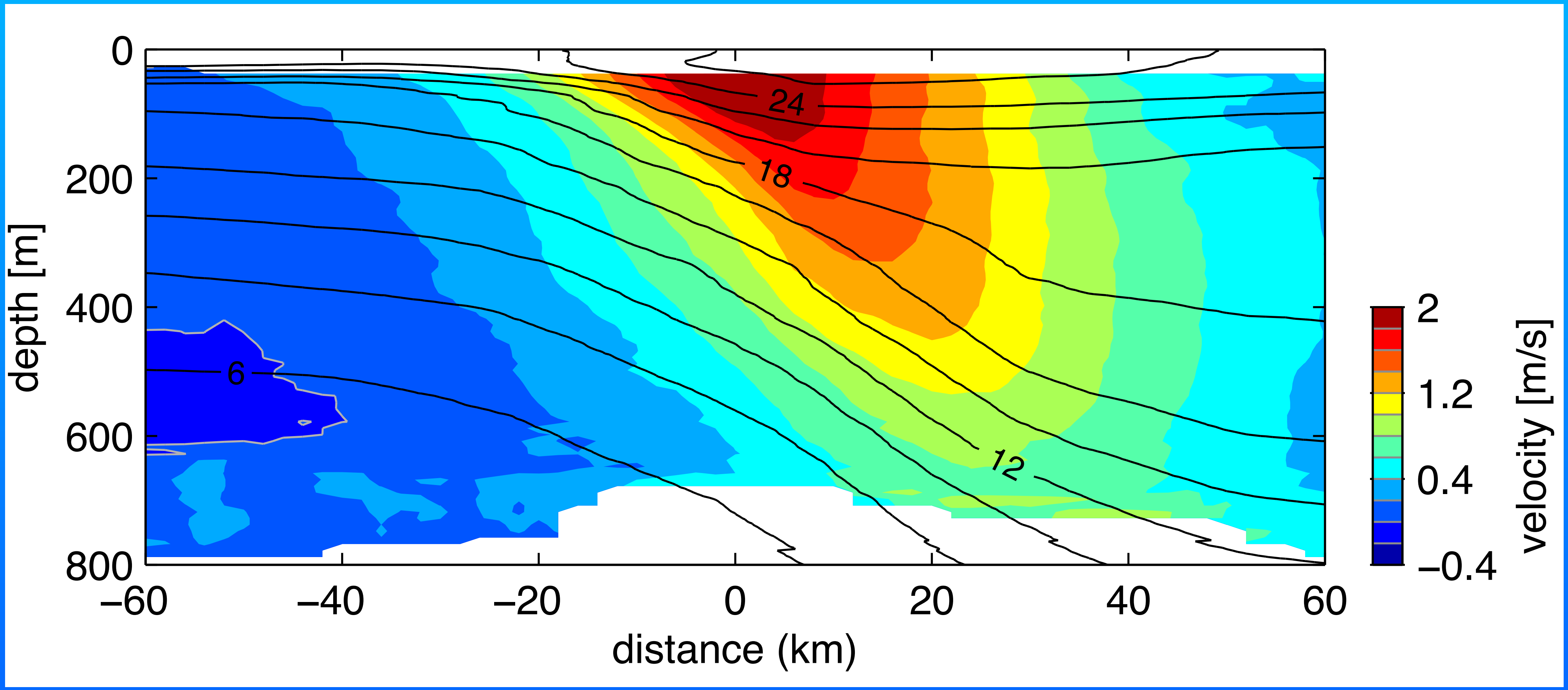
ADCP operations are continuing:
150 kHz 1992-2004 (8 m x 2 km)
75 kHz 2005-present (16 m x 2 km)
Measurement accuracy ±0.01 m s^{-1}

Data transferred by 4G in port (NJ), processed at URI and posted at our new website: oleander.bios.edu

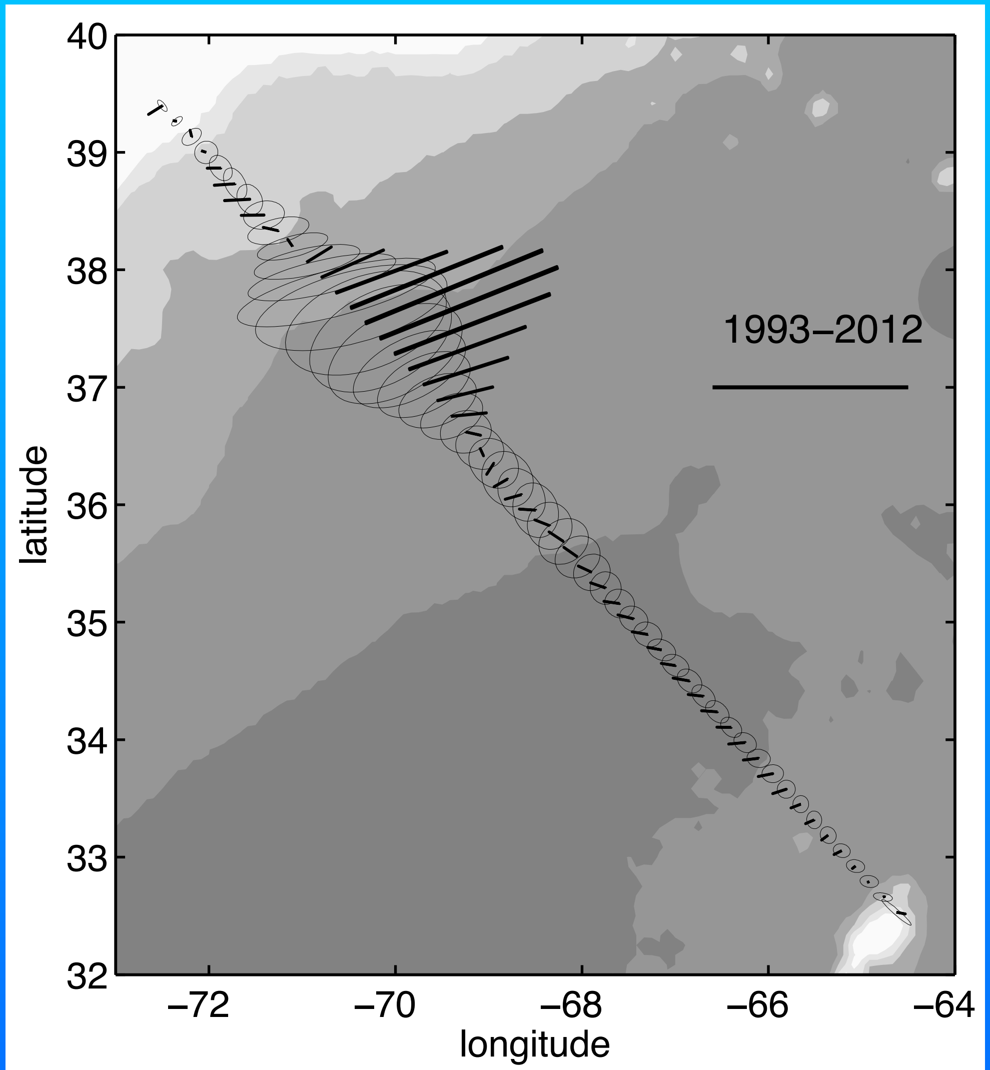
Oleander: The most recent XBT section

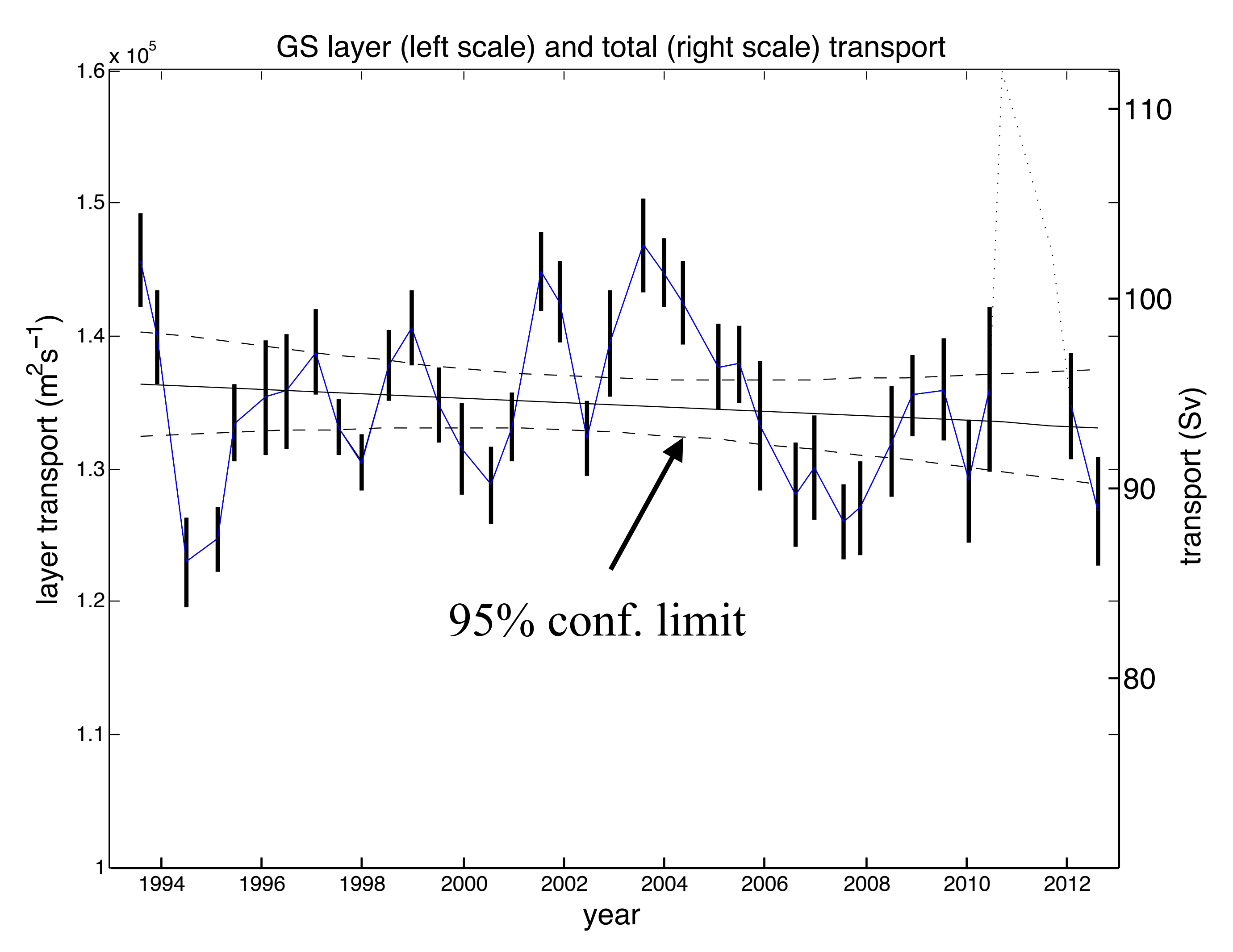






Mean temperature from XBTs and downstream velocity from 75 kHz ADCP in stream coordinates. Simultaneous measurement of v and T can be used to examine for example the potential vorticity structure of the GS. Another unexplored question might be eddy temperature fluxes.





20 year mean and variance at
50 m depth.

The bar corresponds to 1 ms $^{-1}$ and 0.5 m^2s^{-2}

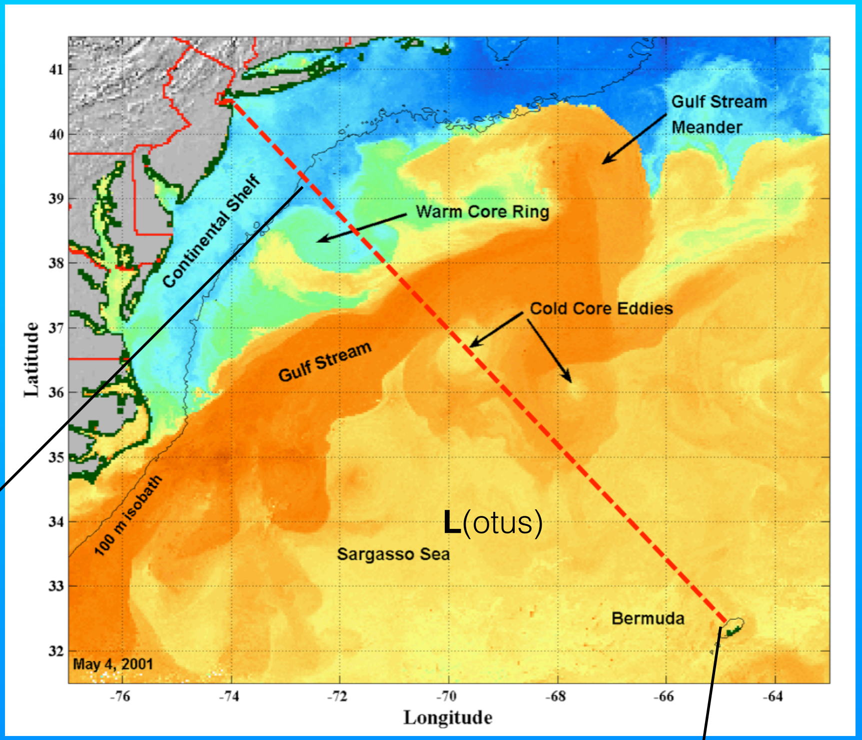
Annually averaged layer transport stepped every half year.

Right axis: 0–2000 m transport

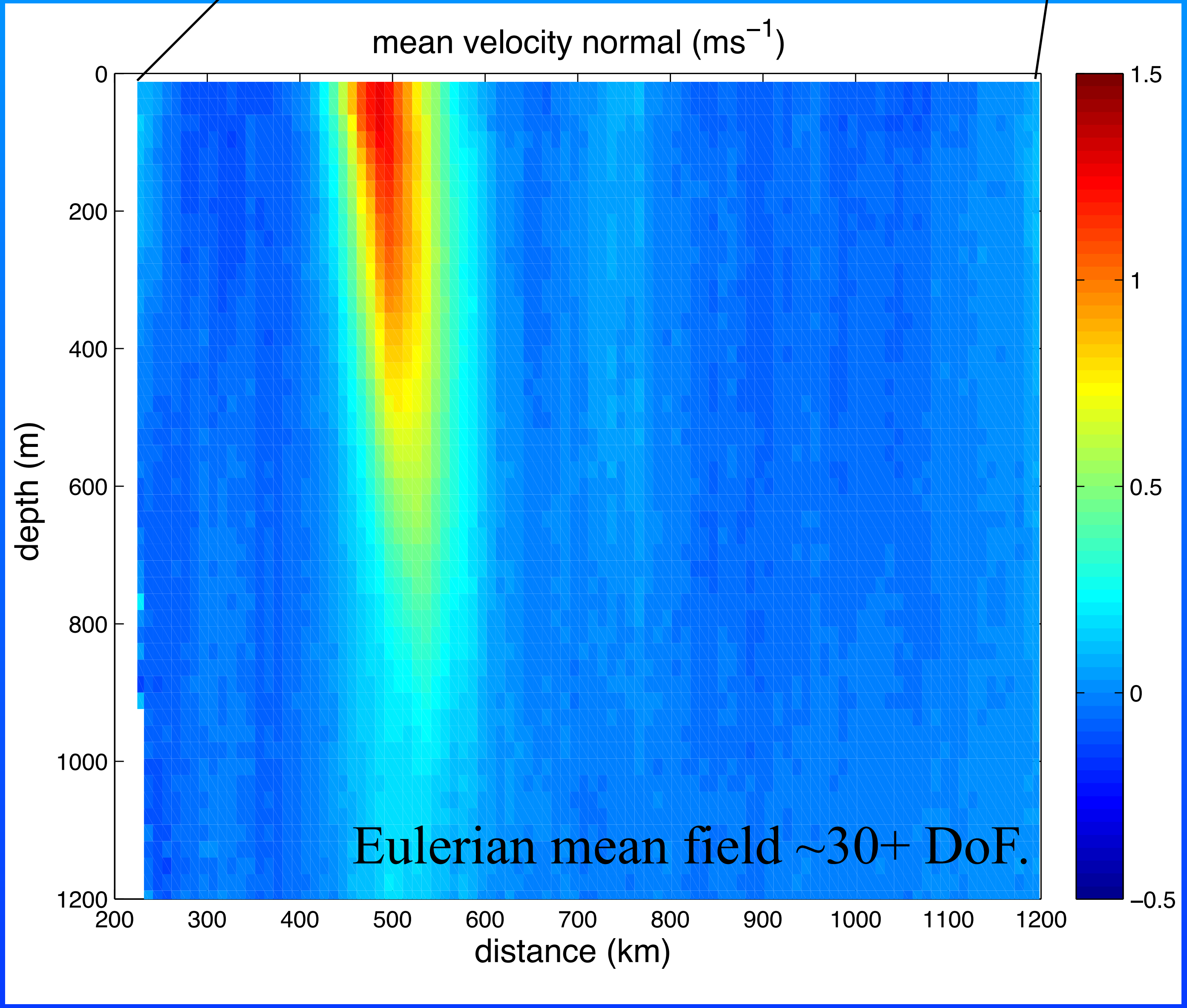
standard deviation of annual averages = 4.5%

These variations have yet to be studied, but surely are mostly wind-driven.

A long-term objective of the Oleander project is to put its findings into the larger context of the MOC and heat flux at this latitude.



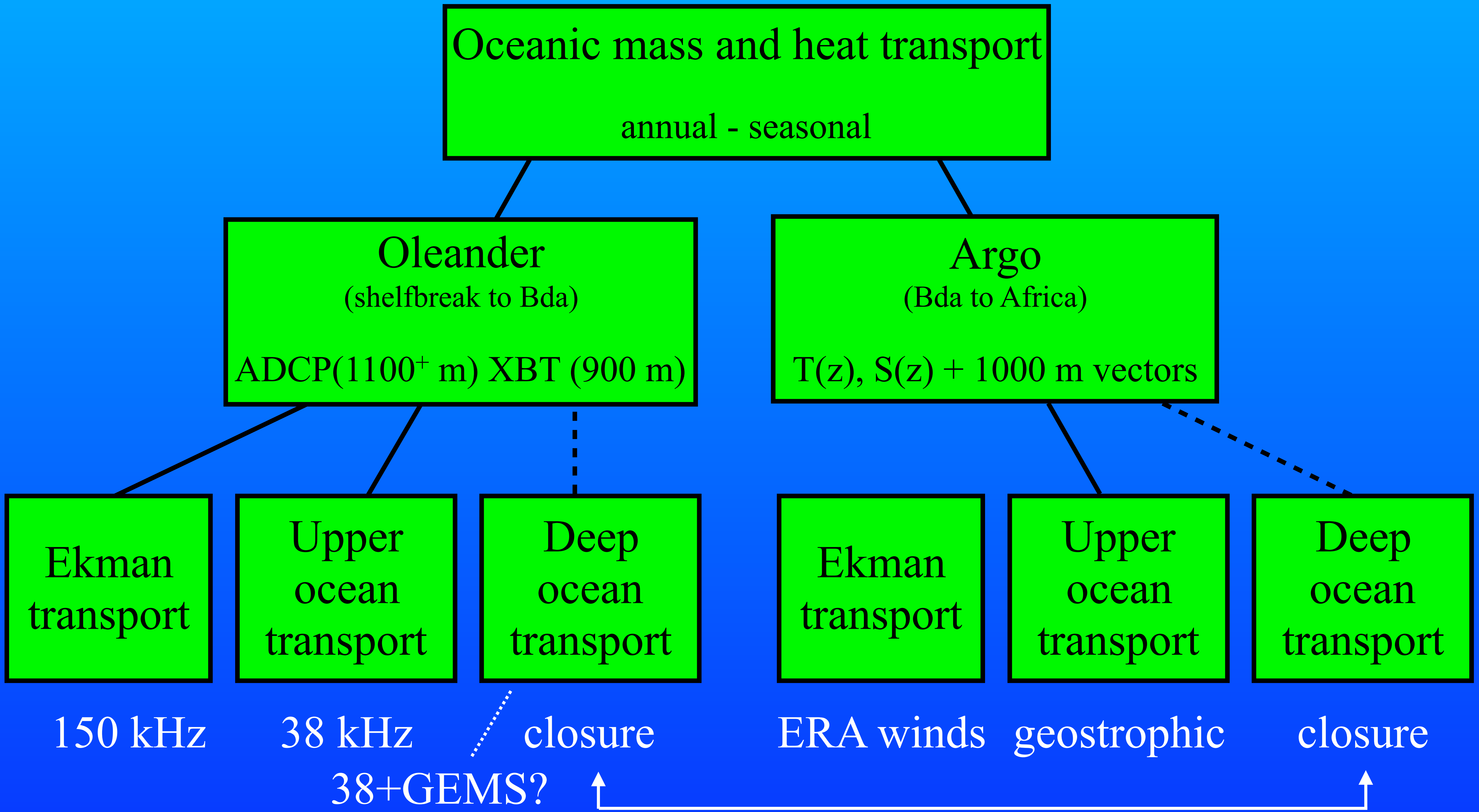
We will soon instrument a new Oleander with 2 ADCPs, 150 kHz to scan the shelf and surface waters and a 38 kHz to reach deep. This slide shows mean field between NJ and Bermuda with a 38 on the Ex-Seas. Sustained profiling to these depths opens up new possibilities.



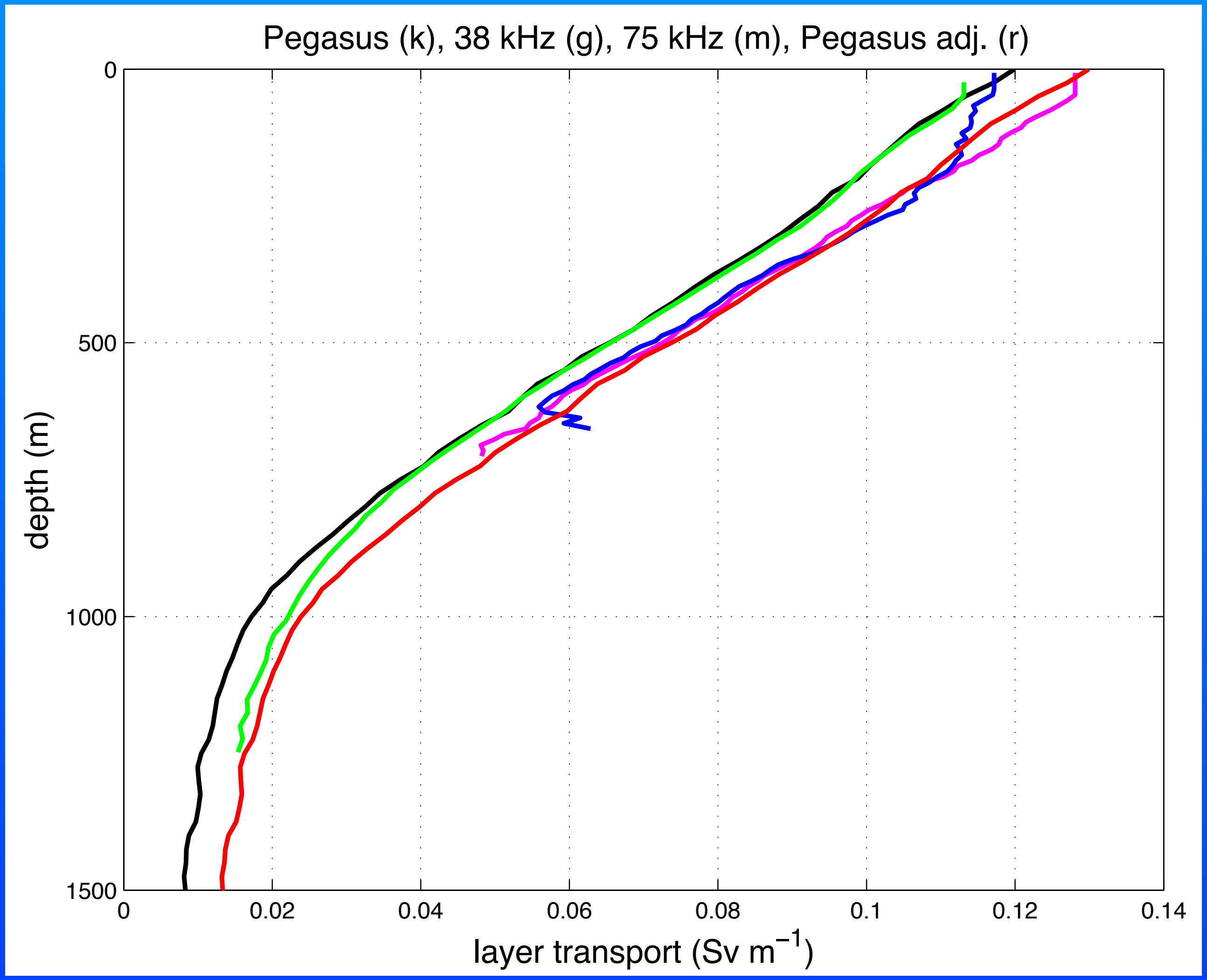
The following slides show a first attempt with existing data:

Heat flux: $$Q = \rho C_P \int_A (\theta v)\, dA$$

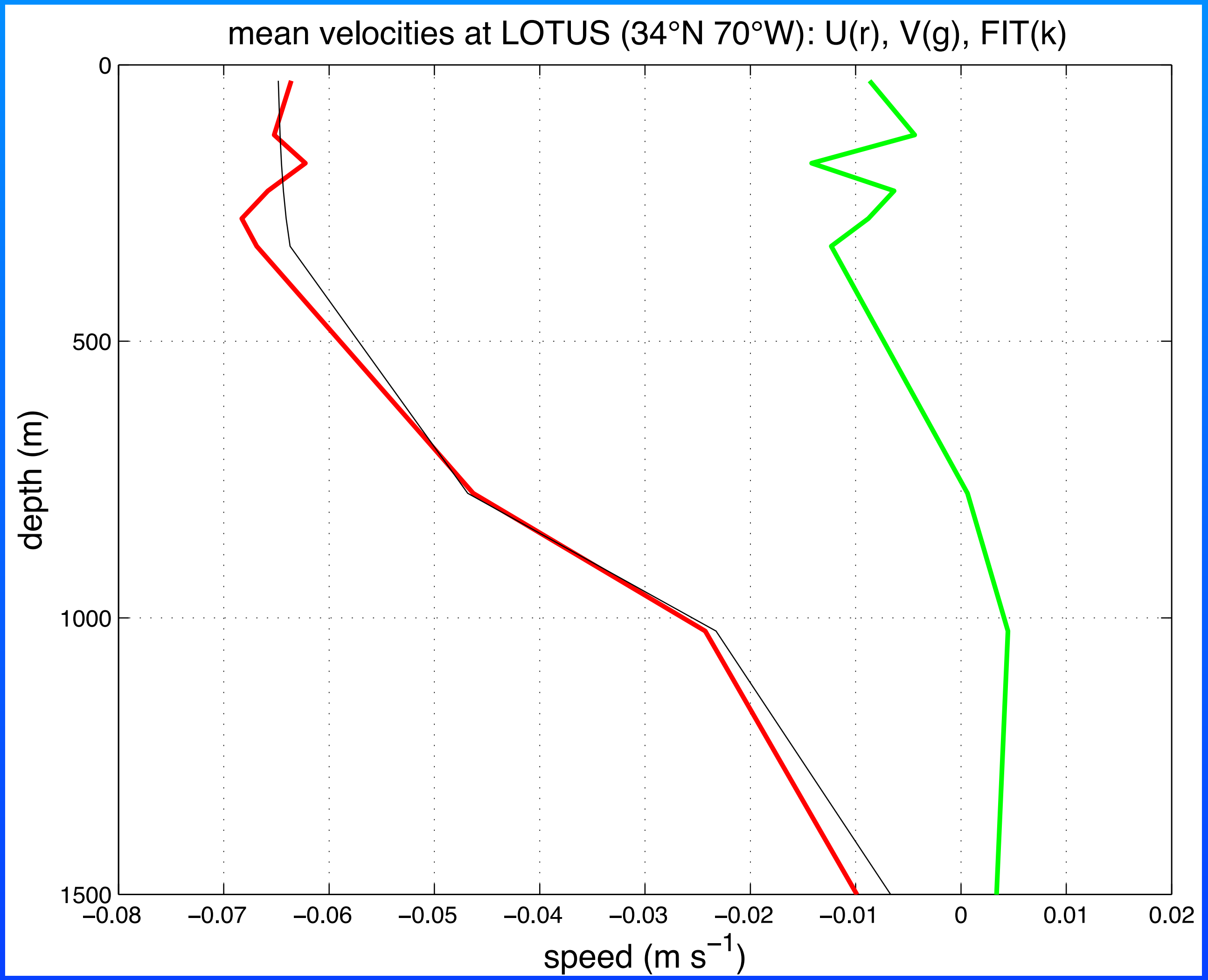
Mass flux: $$M = \rho \int_A v\, dA = 0$$



First, ADCP data to 600 m (b), the 1980-1983 Pegasus profiles (k), and the ExSeas ADCP data to 1200 m (g). For exploratory purposes the red line serves as a best estimate of mean transport in the Gulf Stream.

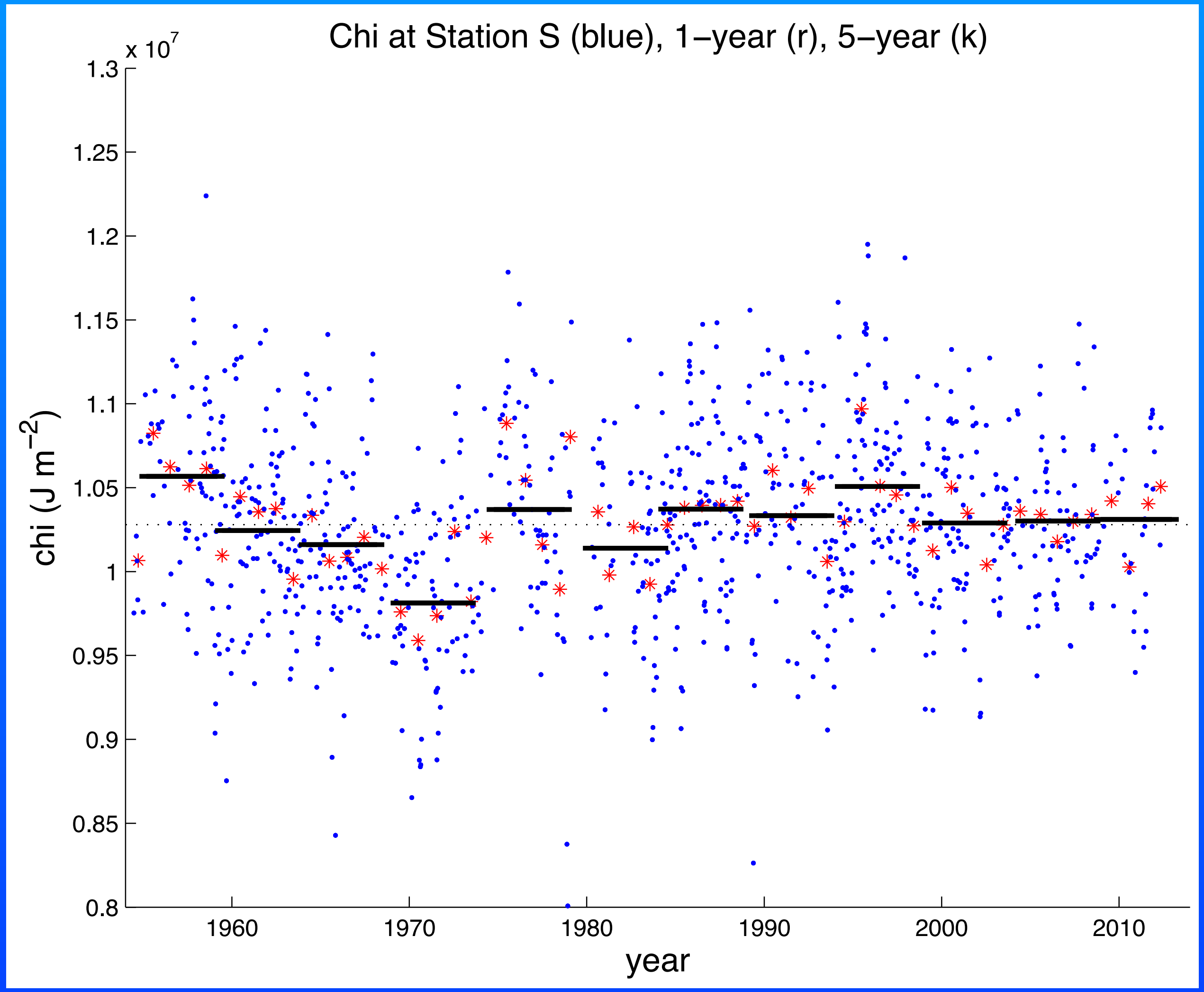


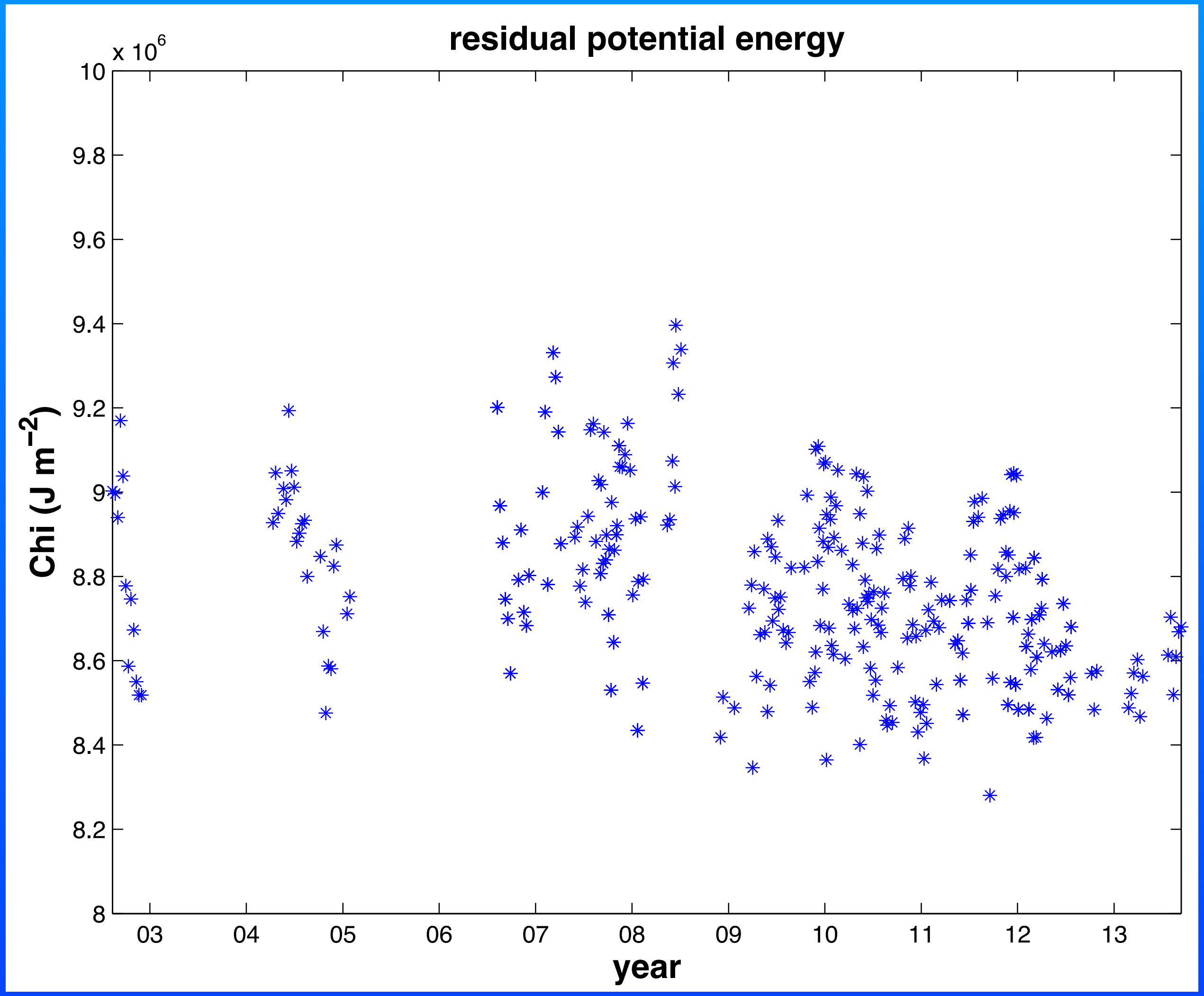
Second, <u>, <v> at the LOTUS site 34°N 70°W (1 year avg.) Black line is a tanh(z) fit to <u> sampled at the same depths. It agrees well with the Oleander in the Sargasso Sea and serves as our estimate of mean flow in this region.



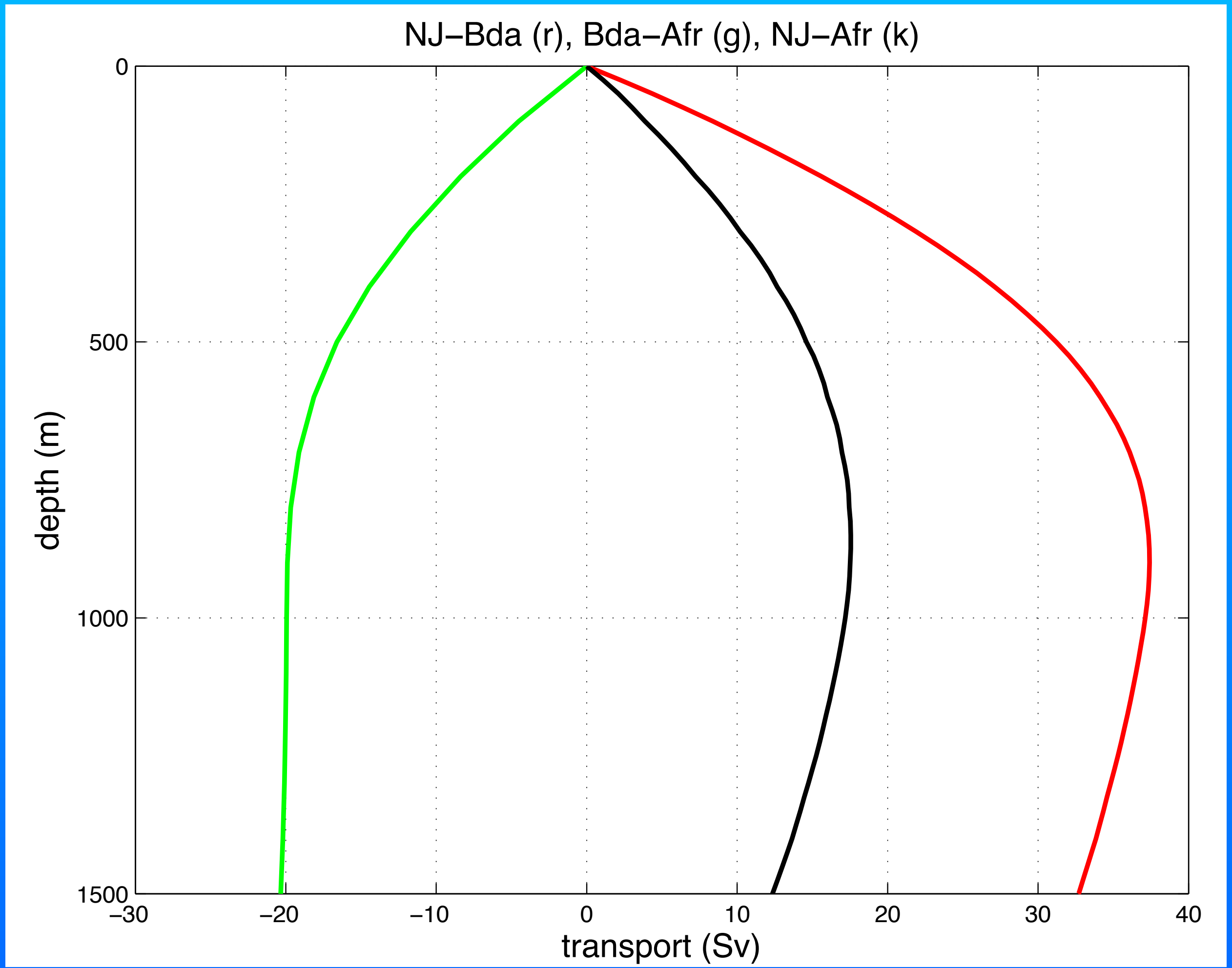
Third, baroclinic transport between Bermuda and North Africa (32°N) can be estimated from the potential energy (χ) difference between the two ends: Station S: χ = 1.028e7 (5.4% std, 2.7% (1-year), 1.9% (5-year). Eastern end: χ = 8.77e6 Jm^{-2} (2.4% std). Between 2007 and 2013 there is also a 4.3% drop.

The difference in χ/f = 19.6 Sv (sfc to 1000 m).



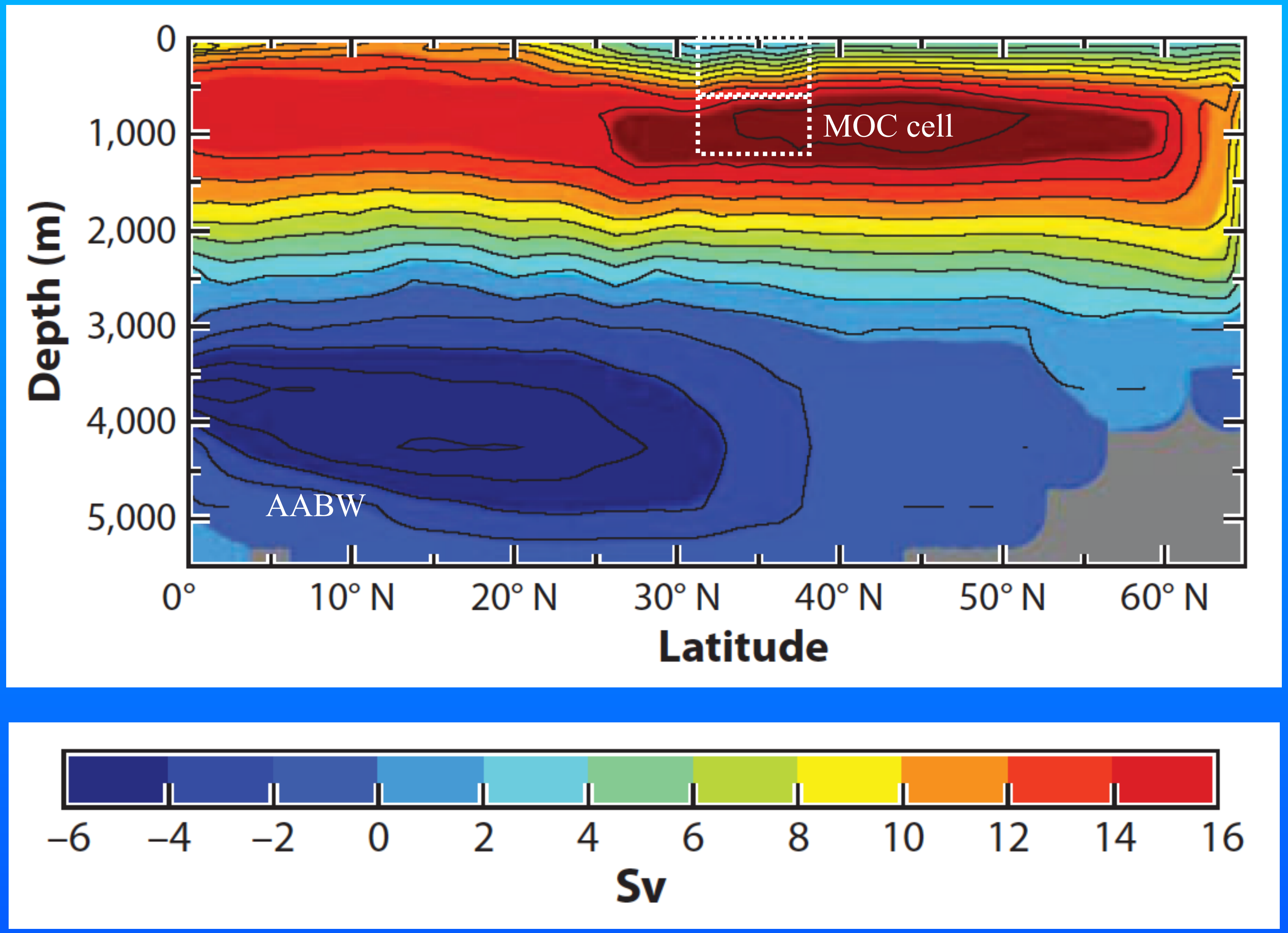


Summing the subsets we get the following profiles:



NJ-Bda cumulative transport to 1500 m (r); note 37.4 Sv max at 900 m depth (this is well within reach of the 38 kHz ADCP). The 20 Sv Bda-Africa baroclinic Sverdrup flow (g) is referenced to 0 at 1000 m (no barotropic field). The 32°N section is close to wind-stress minimum so little Ekman transport. The ocean-wide sum (k) has a maximum (17.5 Sv) at about 860 m.

To put these exploratory results into a larger frame we can use the mean MOC from HadCM3 coupled oc-atm model:



Bingham et al. 2007

The dashed boxes show the Oleander route in the MOC plane:

To 600 m
(75 kHz, present)

To 1200 m
(38 kHz, future)

Even though this is only an exercise, both the maximum of the MOC and its depth ~900 m depth accord well with this model study.

Oleander summary:

XBTs (monthly) since 1977 and the full section since 2008.
ADCP (150 kHz) 1992-2004
ADCP (75 kHz) 2005-present
ADCP (38 kHz) starting 2018

Products:
Shelf warming (Forsyth et al., 2015)
Seasonal cycles
Gulf Stream thermal, velocity and vorticity structure
Dynamics of the Gulf Stream, rings and eddies
Transports
Comparisons with altimetry
MOC and heat fluxes (future)

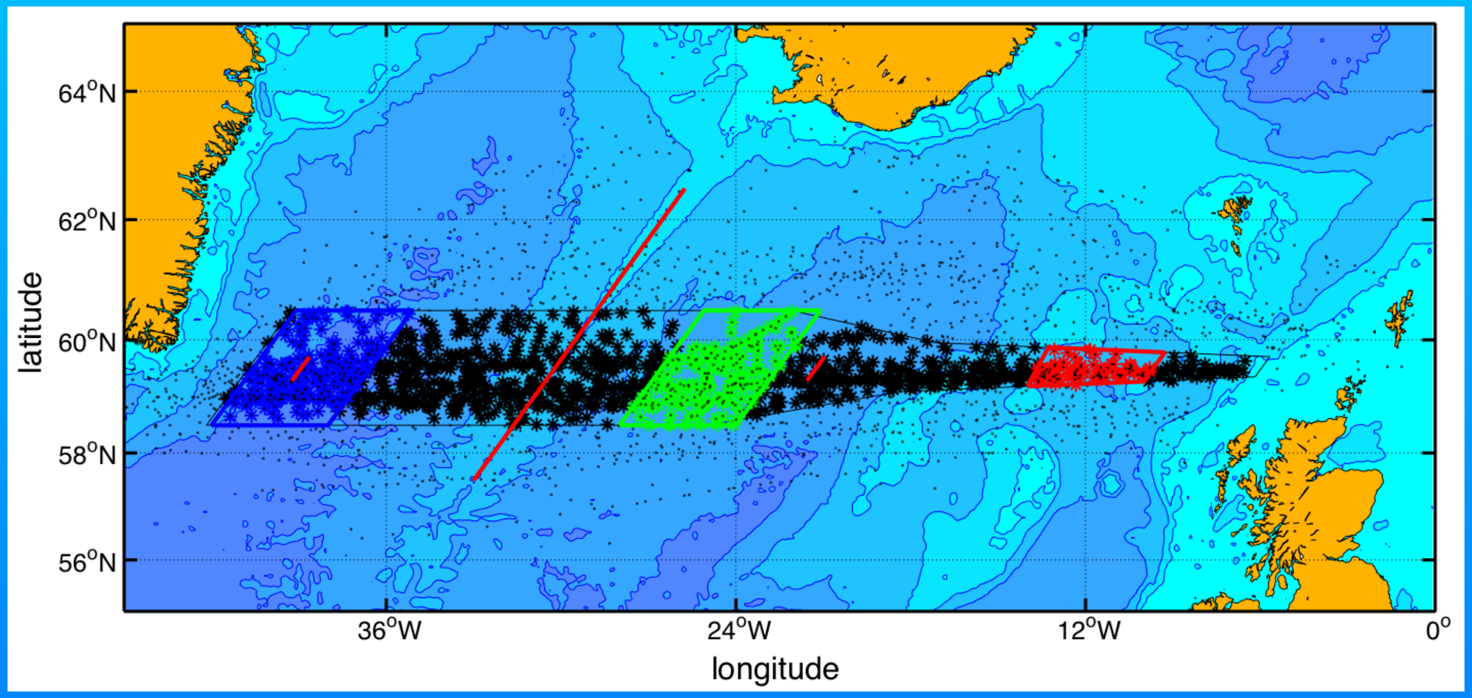
The Nuka Arctica and its forerunners have a history of observation which might be interesting to learn more about. Rawinsondes for the Danish Met Office, and XBTs for a period in the mid-1980s and continuously since 2001.

The largest annual variations occur in the Iceland Basin:

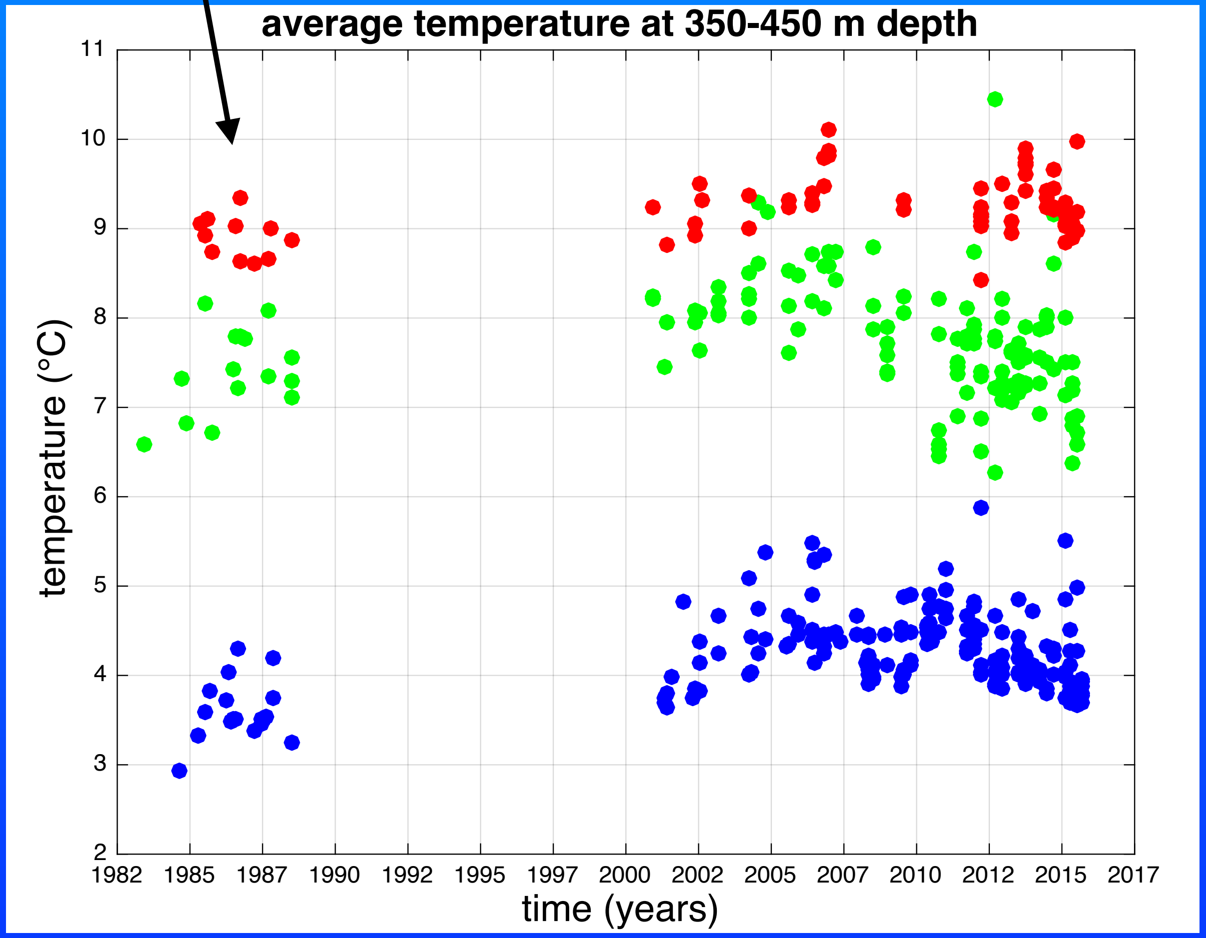
3- week service Greenland to Denmark. 7 m draft, 16 Kt.

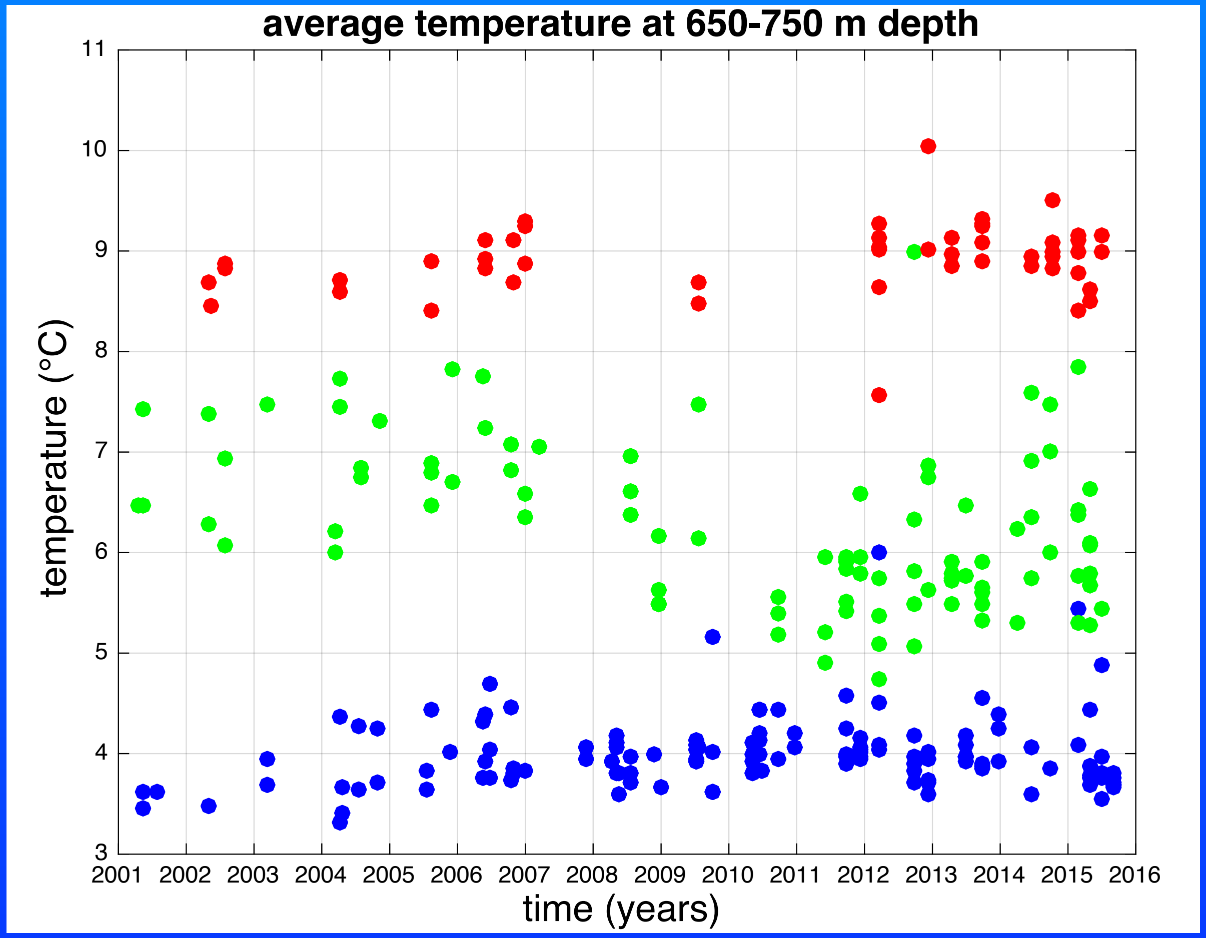
150 kHx ADCP 1999-2002 (400 m)
75 kHz ADCP 2012-present (800 m)

Average temperature from XBT profiles in 3 regions

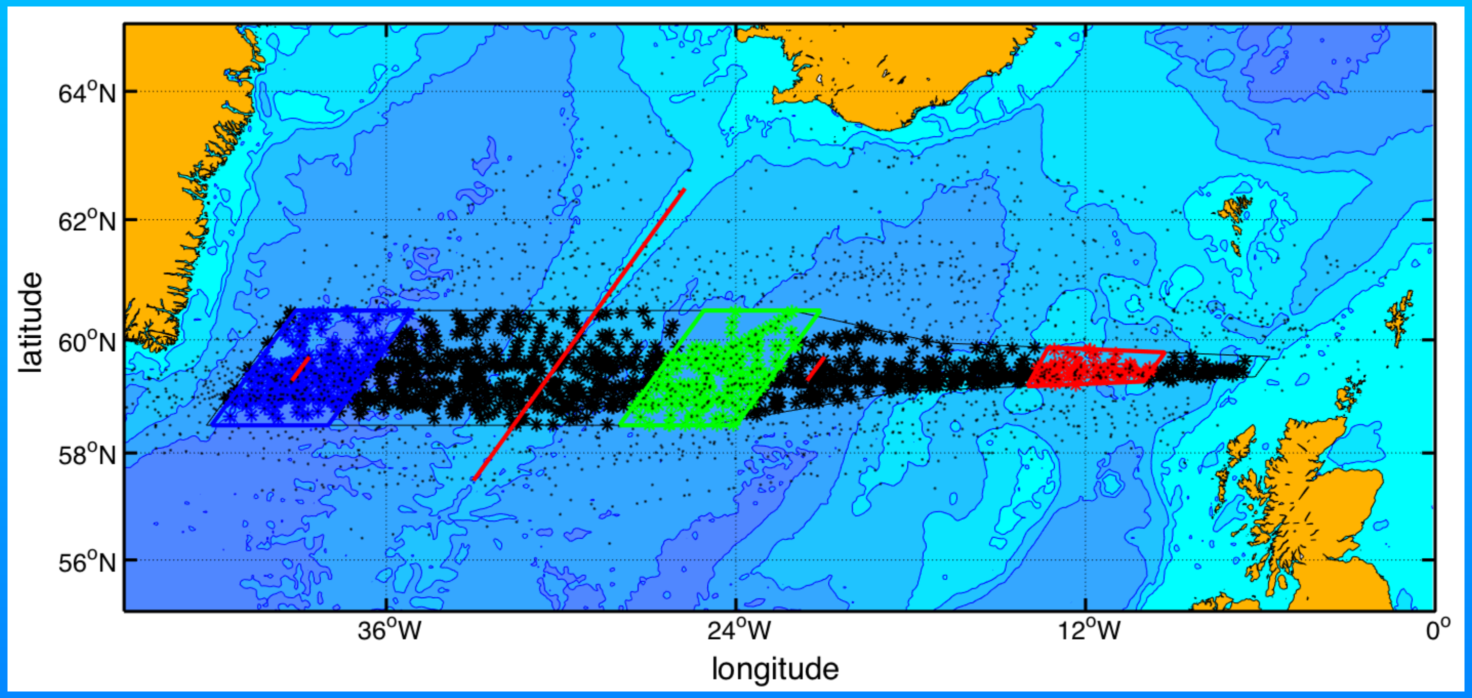


Nivi Ituk XBTs

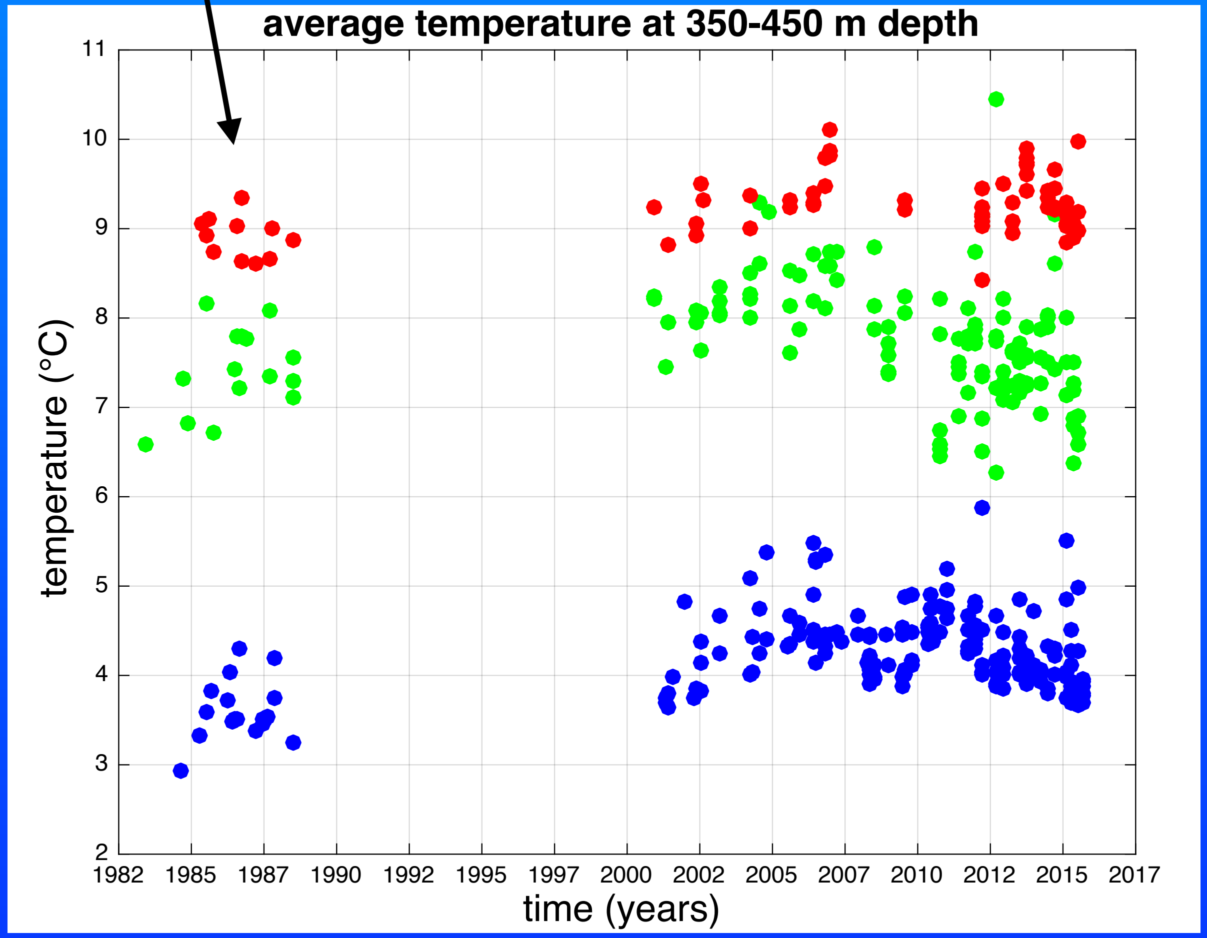


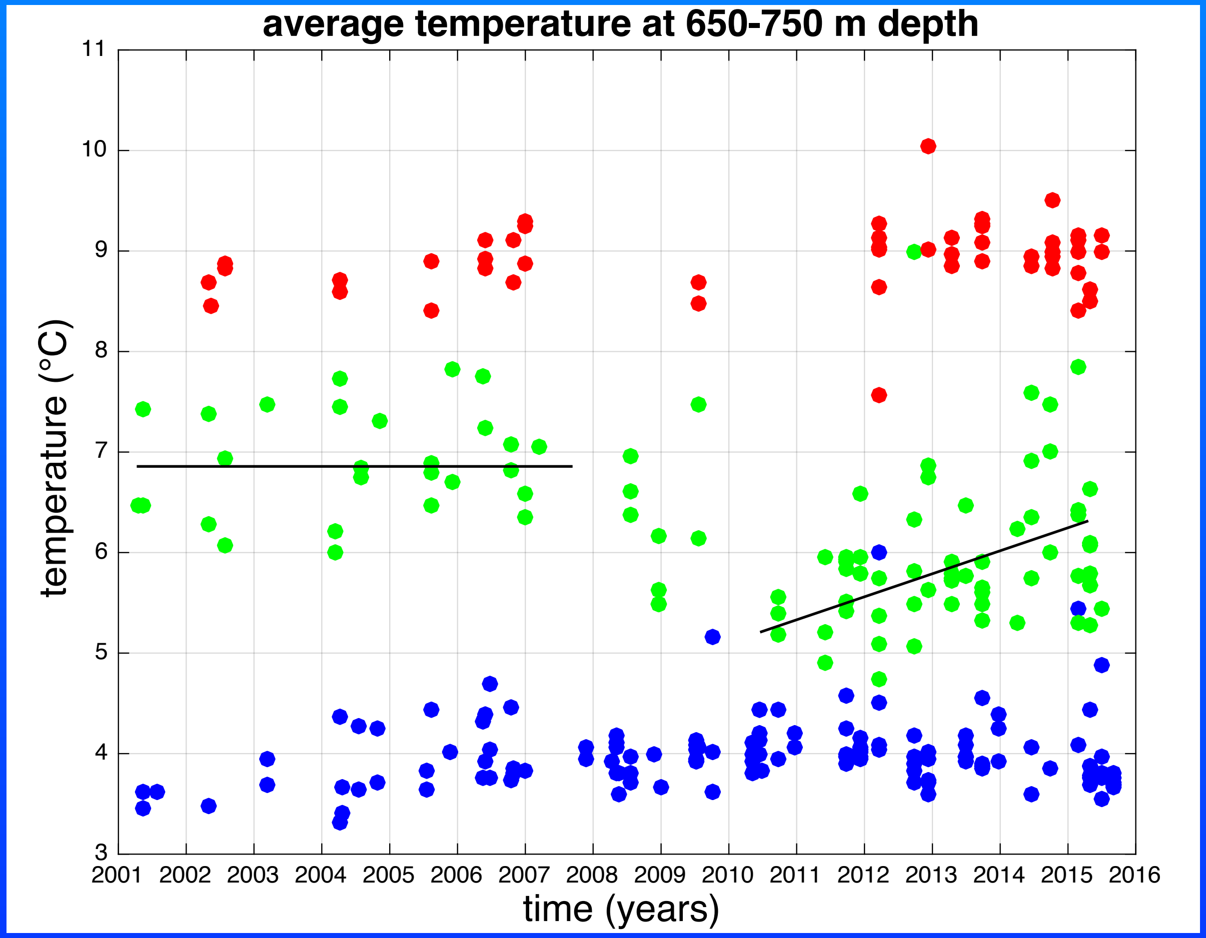


Average temperature from XBT profiles in 3 regions

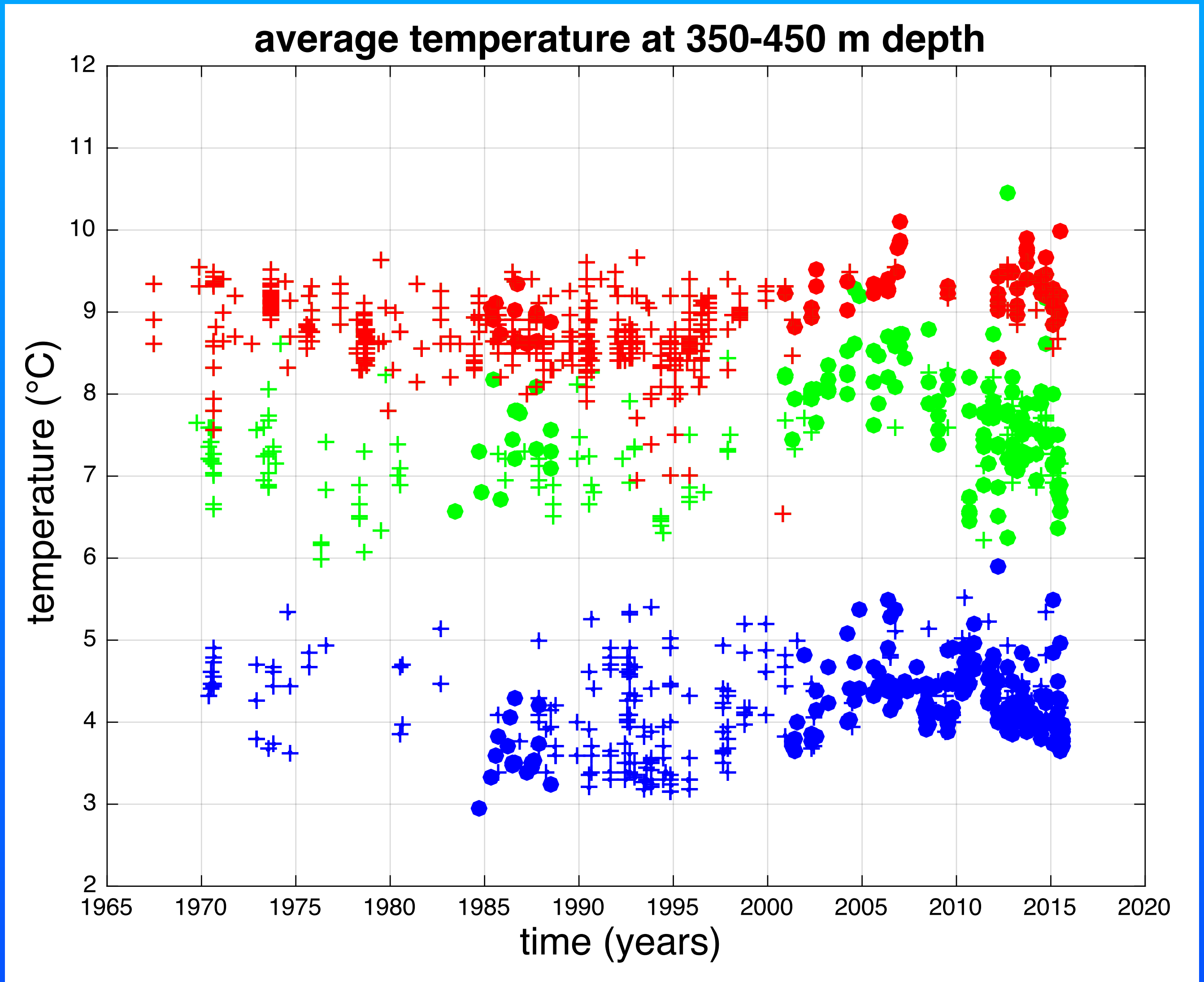


Nivi Ituk XBTs

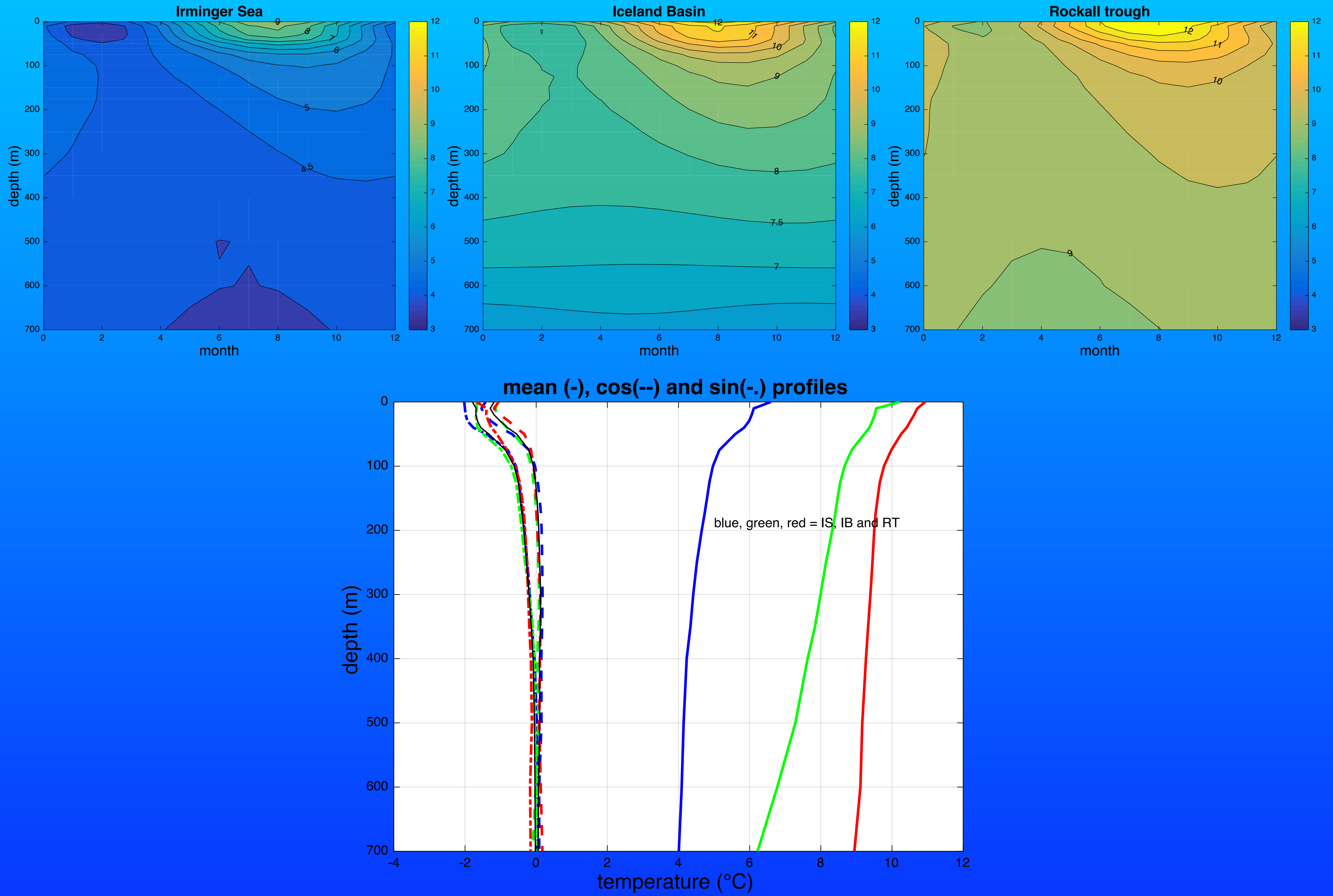




Looking back even further in time:

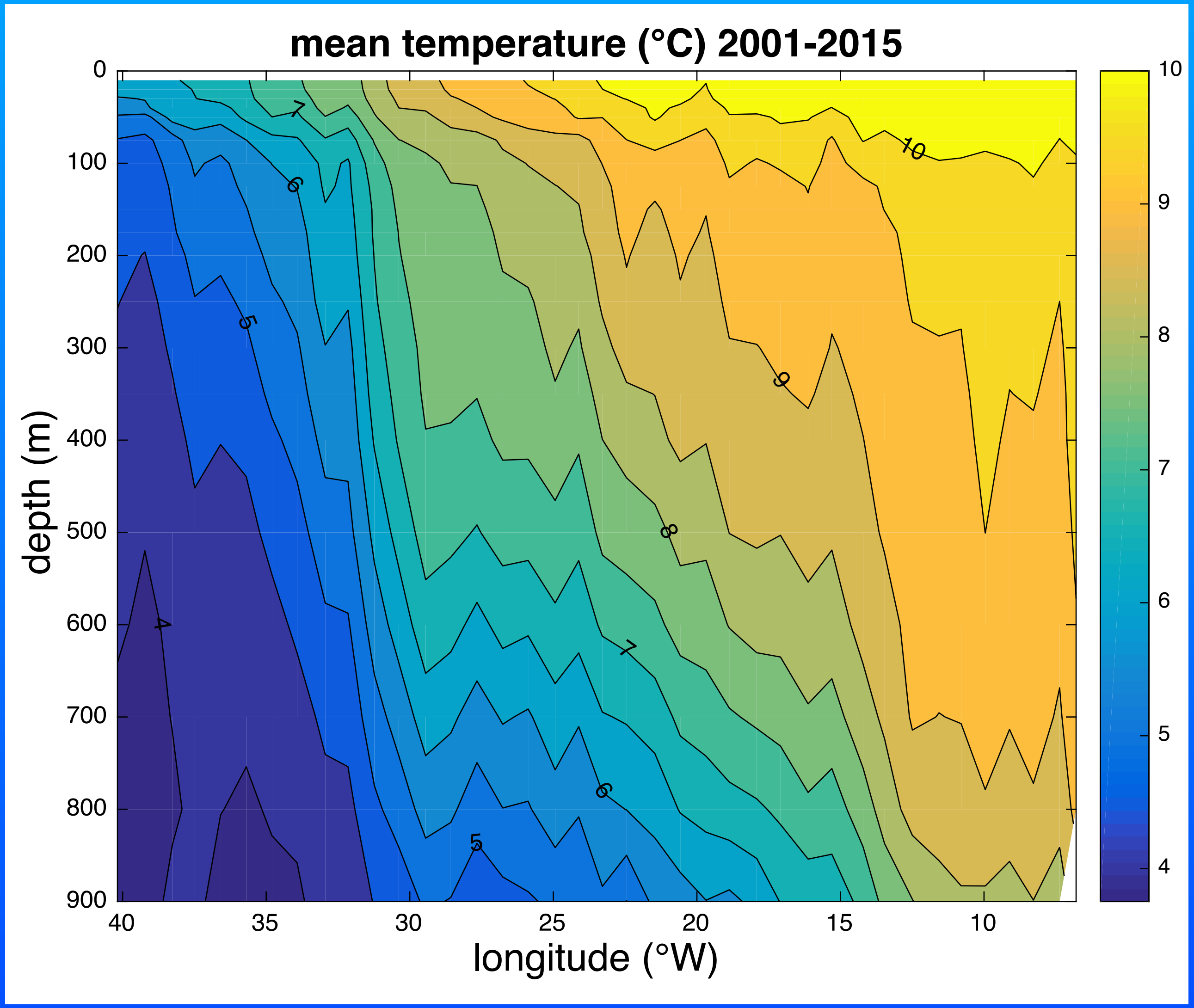


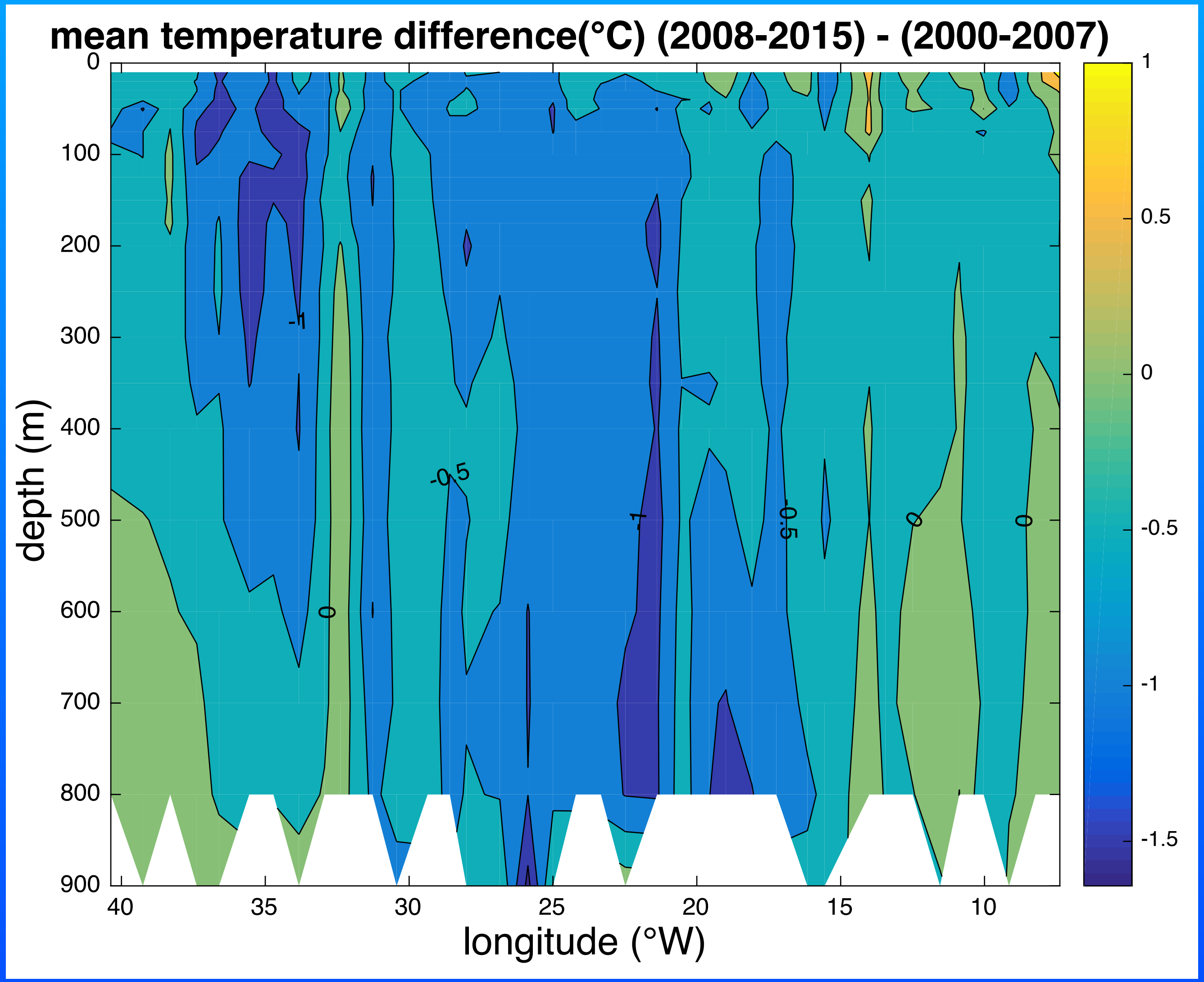
seasonal cycle of temperature



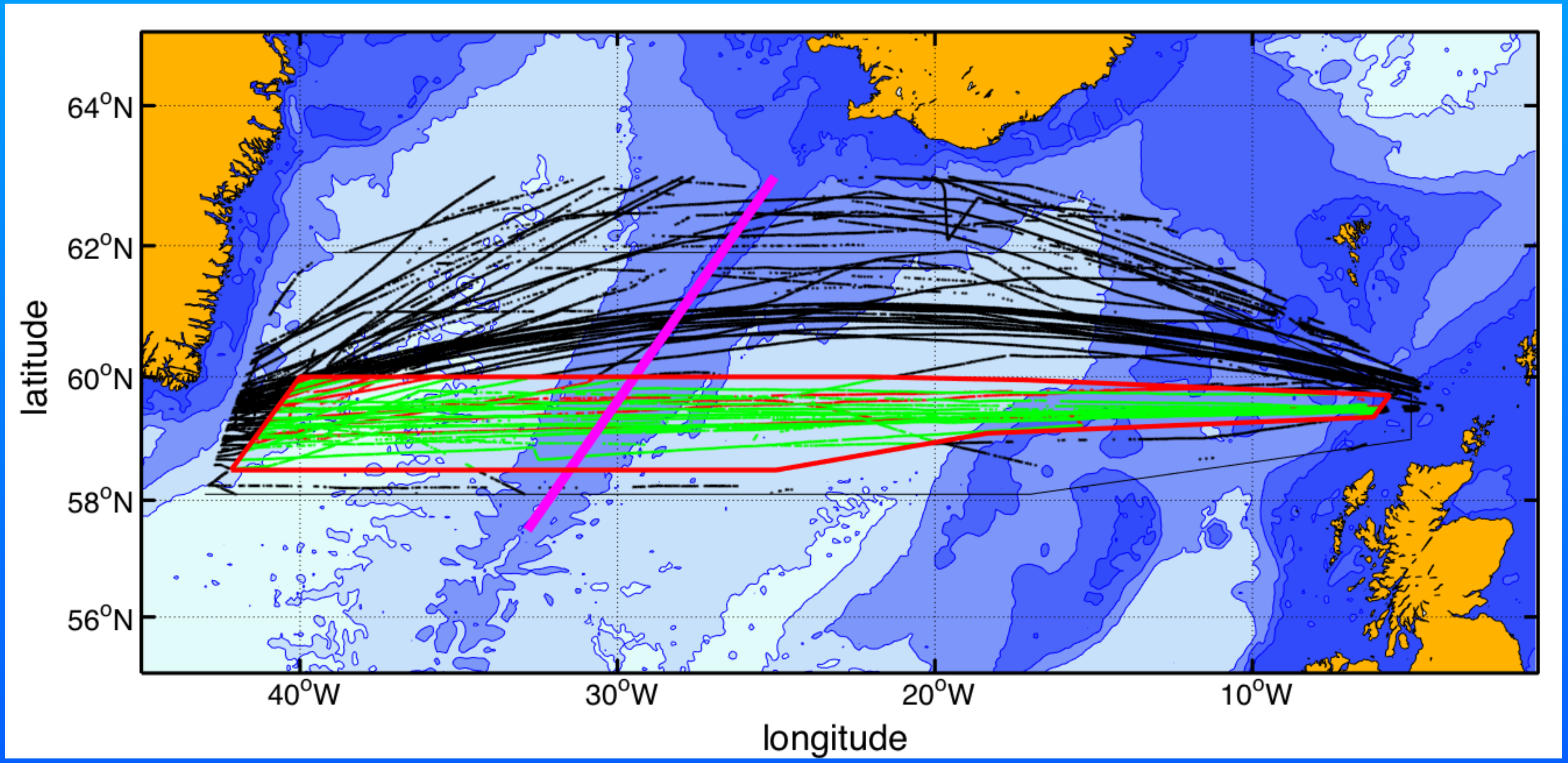
De-seasoned mean temperature 2001-2015 along 59.5°N

Mean temperature difference (2008-2015) - (2001-2007)





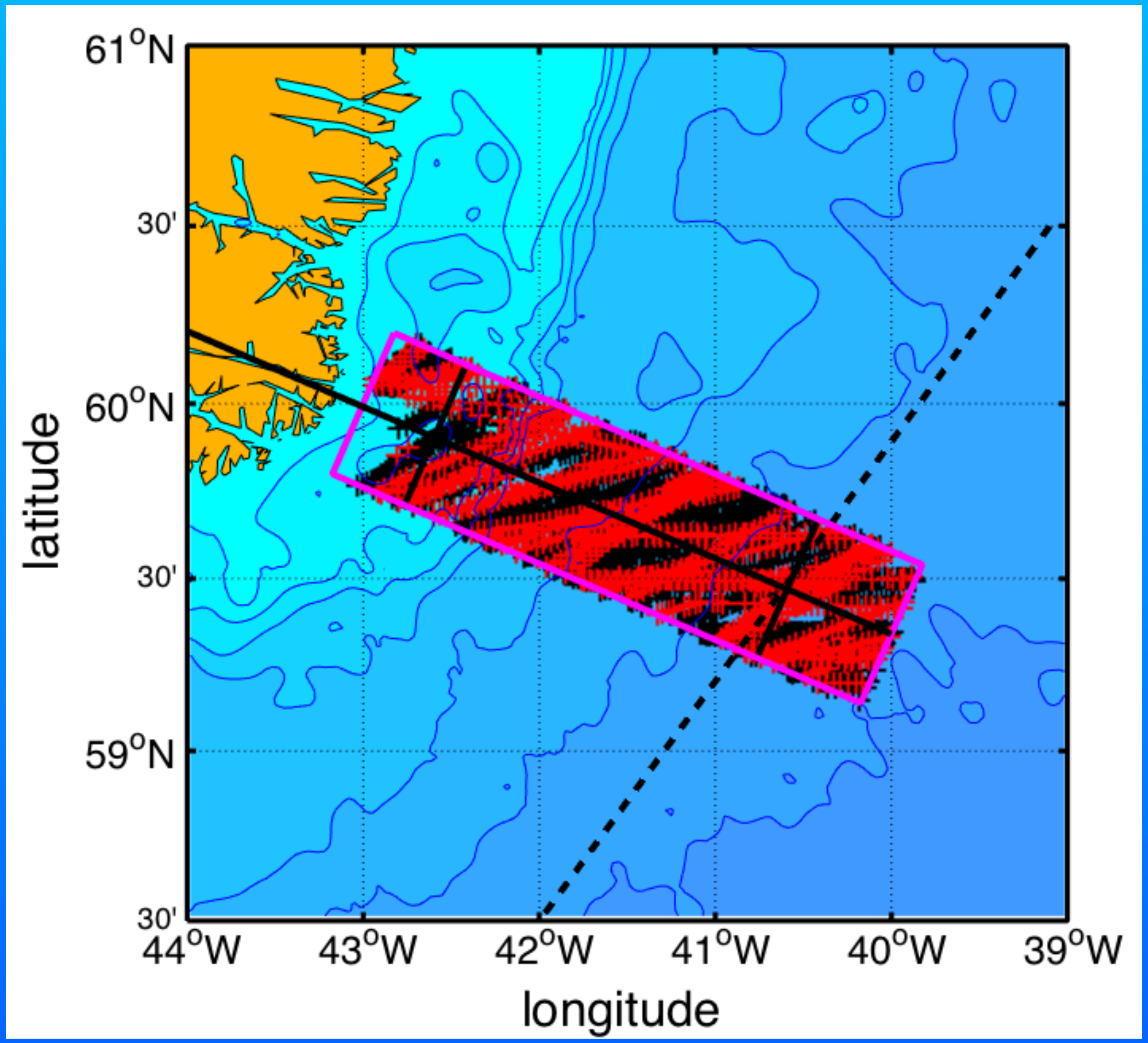
The Nuka Arctica has also been operating an ADCP in two periods.

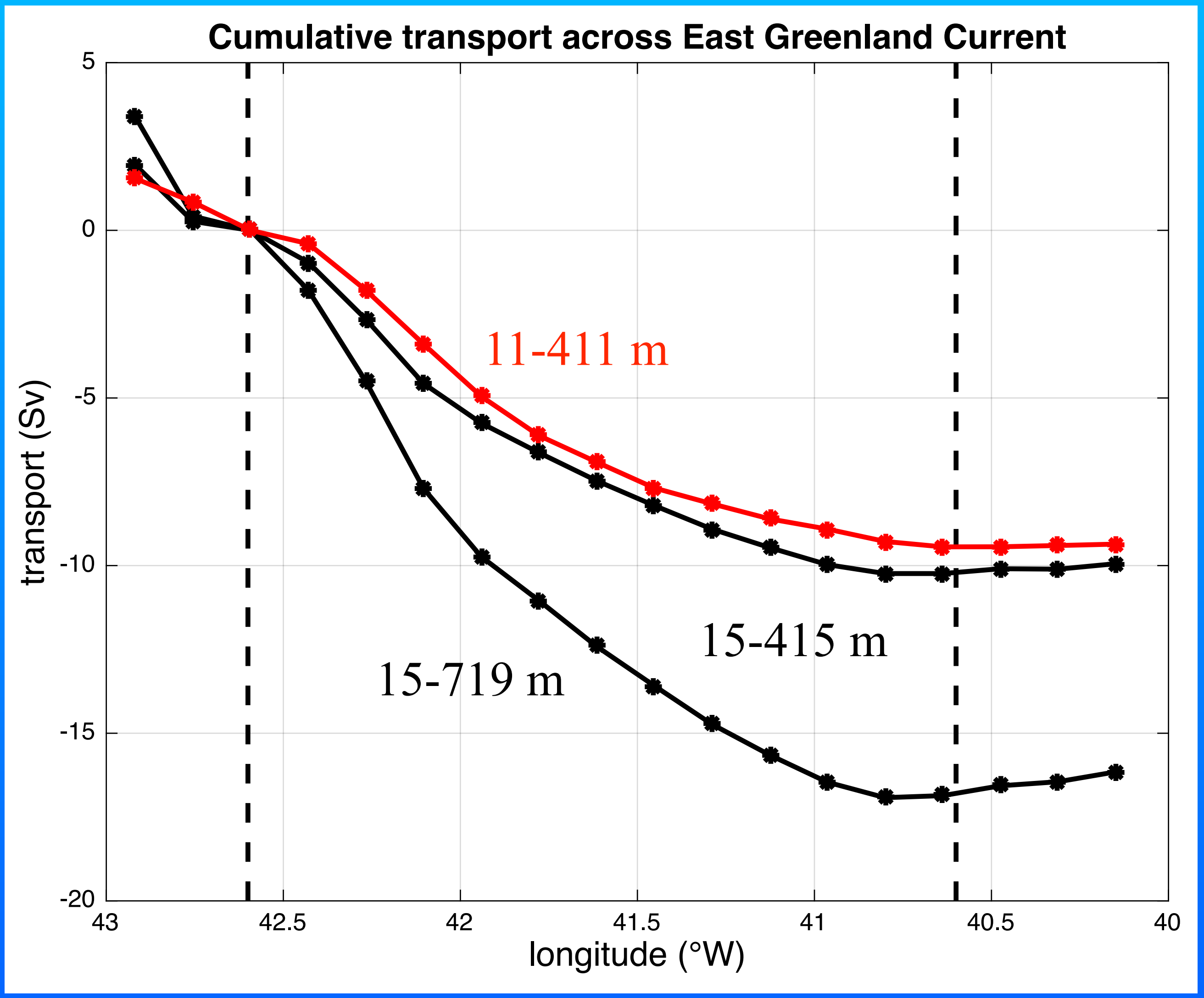


Bogi Hansen, Martin Mork, myself, Hilding Sundkvist contributed to an ADCP program (150 kHz) that operated between 1999-2002. Program restarted with a 75 kHz ADCP in late 2012 and is ongoing.

We use the ADCP from Greenland to Scotland to get volume fluxes:

We first consider transits in the EGC:



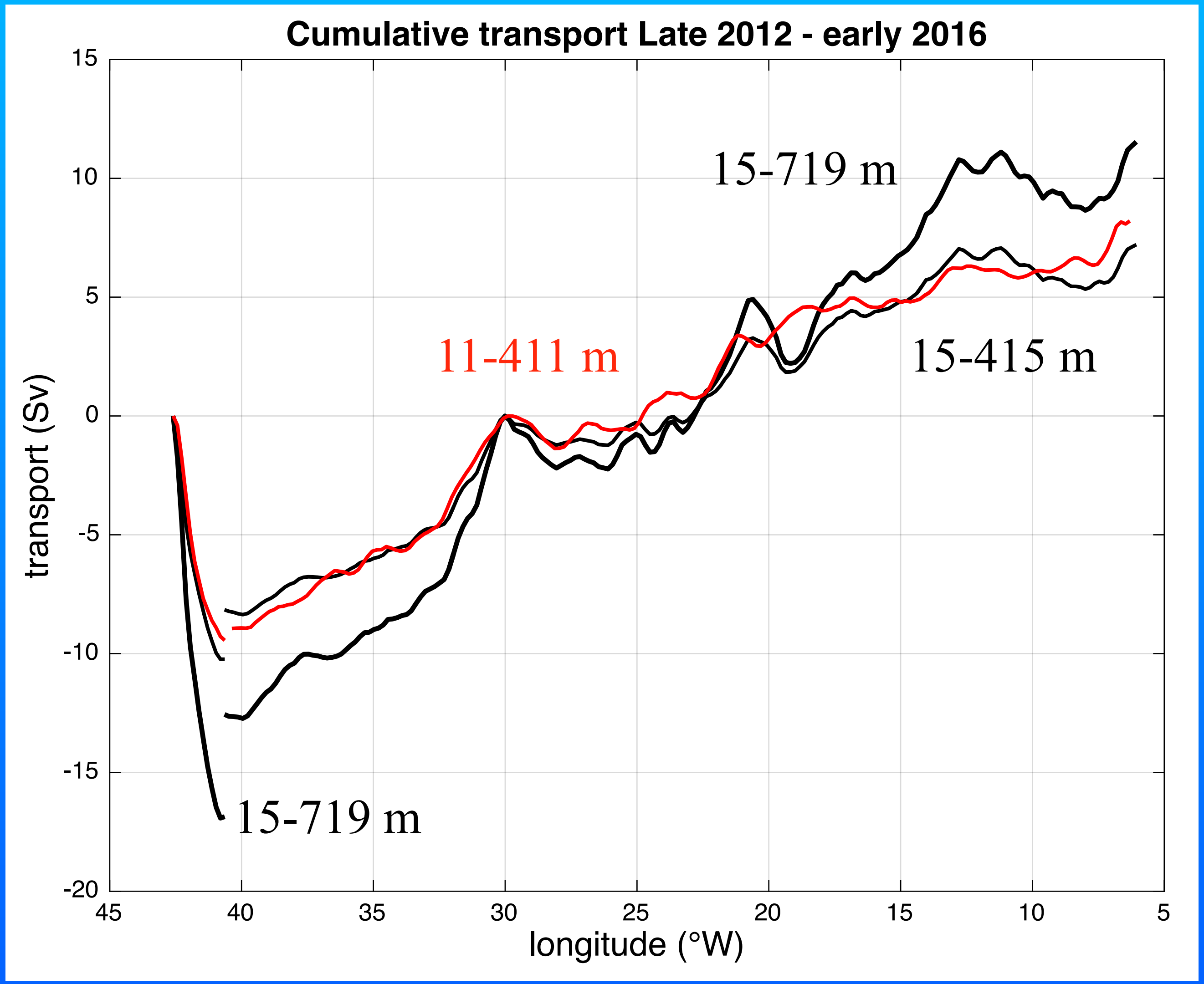


red: 1999-2002; black: 2012-2016

Both west and eastbound transits are used to construct mean velocity in EGC. It appears that the EGC has changed hardly at all between the two epochs.

We then consider the entire zonal section:

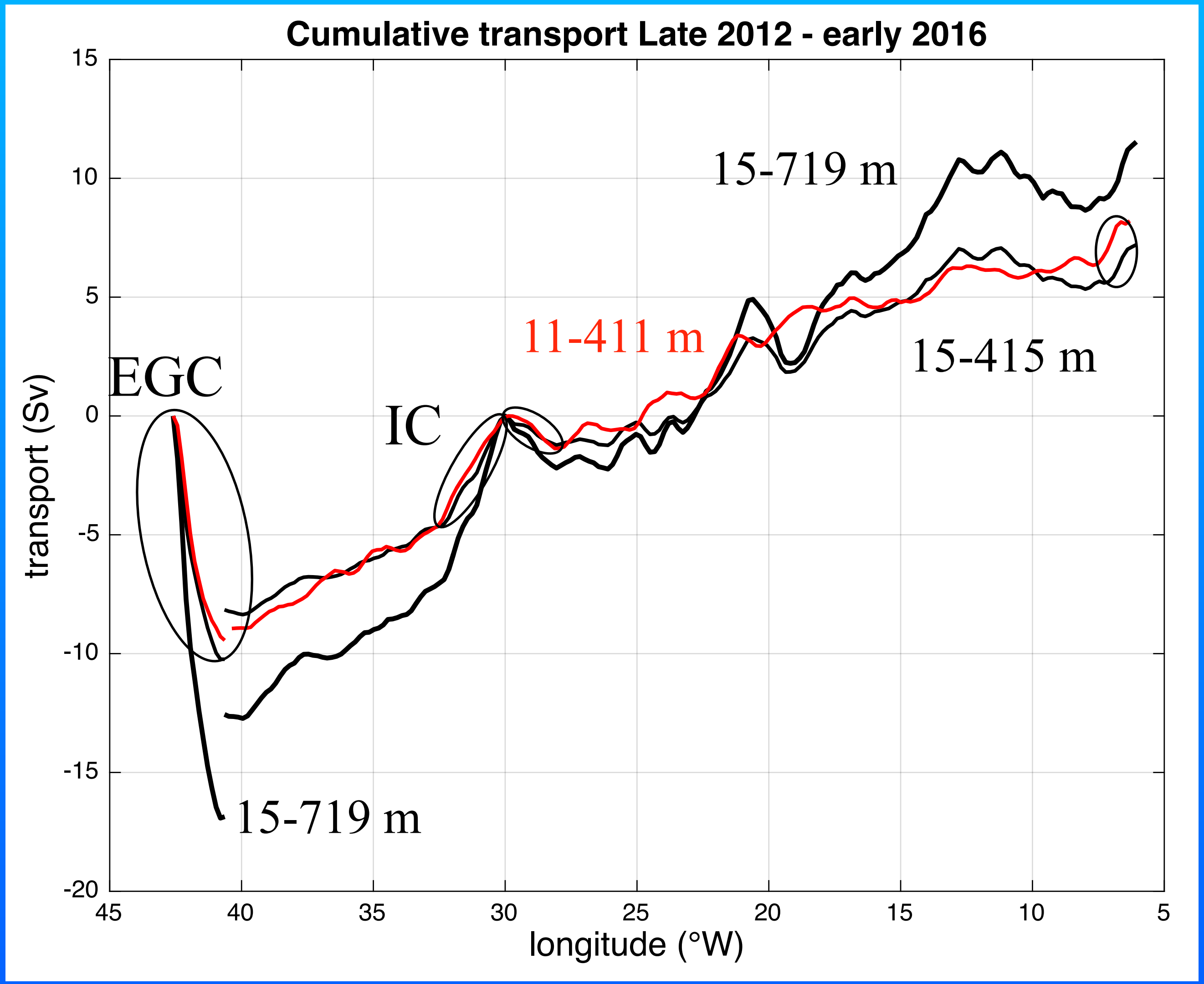
red: 1999-2002
black: 2012-2016



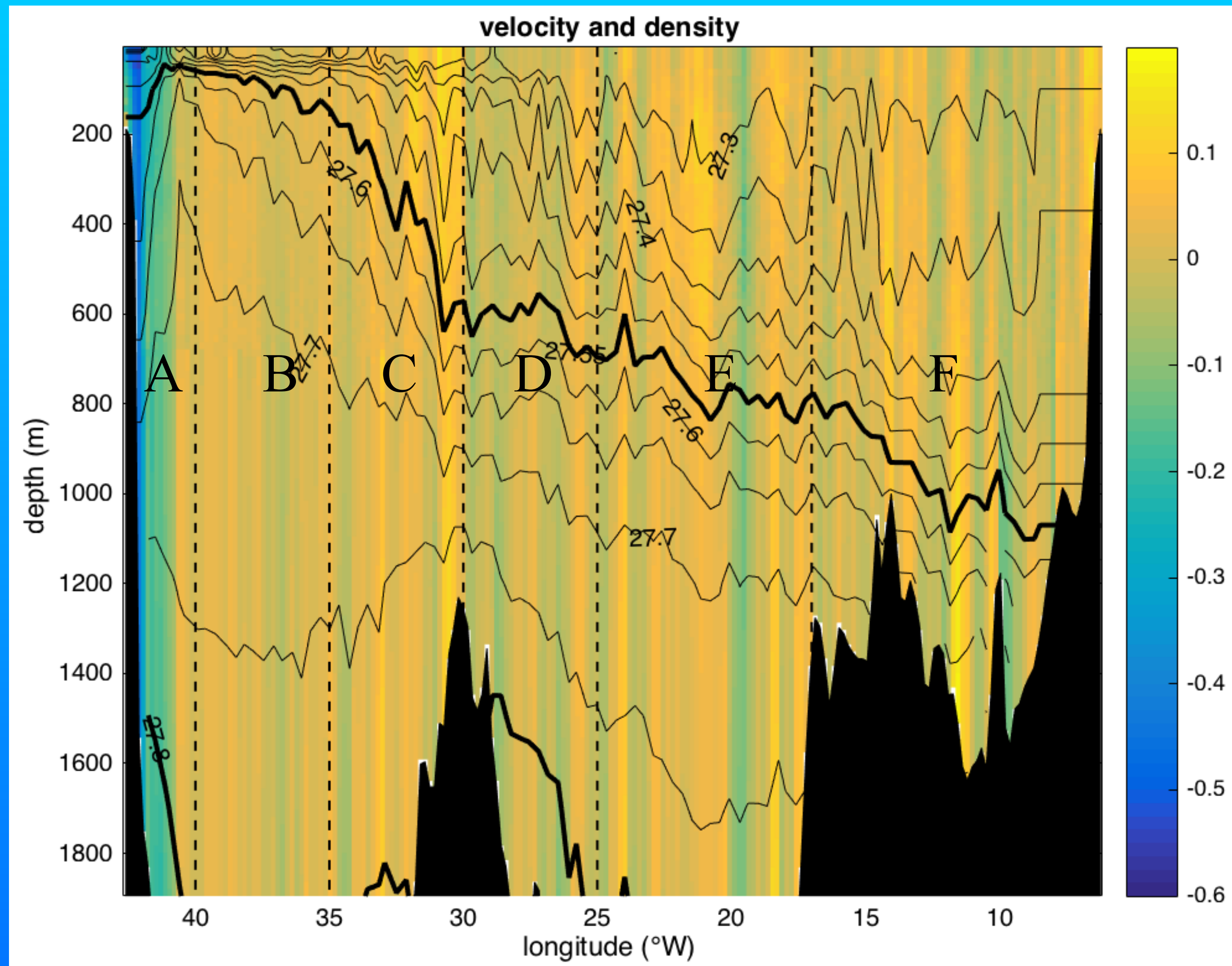
This figure shows integral of transport relative to mid-Atlantic ridge (30°W). The red and black curves are virtually identical, especially for flow along topography (boundary and ridge currents):

We then consider the entire zonal section:

red: 1999-2002
black: 2012-2016



This figure shows integral of transport relative to mid-Atlantic ridge (30°W). The red and black curves are virtually identical, especially for flow along topography (boundary and ridge currents).
These independent ADCP integrals yield very similar fluxes.



ADCP to 700 m

Argo ext. to 1900 m

WOA ext. to bottom

Revised Sept. 12

layer	A	B	C	D	E	F	sum	
<27.55	-3.5 -84	0.4 10	6.1 175	-0.1 1	7.3 250	5.0 172	15.1 524	Sv TW
27.55-27.80	-24.0 -364	5.3 87	8.3 144	-2.8 -48	3.9 74	-0.4 23	-9.7 -84	Sv TW
> 27.80							-7* ~-84*	Sv TW

* Separate integration using WOA for the deepest layer

layer	A	B	C	D	E	F	sum	
<27.55	-5.4	0.9	5.6	-0.9	6.0	10.4	16.6	Sv
27.55- 27.80	-16.4	5.0	6.4	-4.5	5.3	1.0	-3.2	Sv
> 27.80	-10.6	1.0	0.0	-4.0	0.3	-	-13.3	Sv

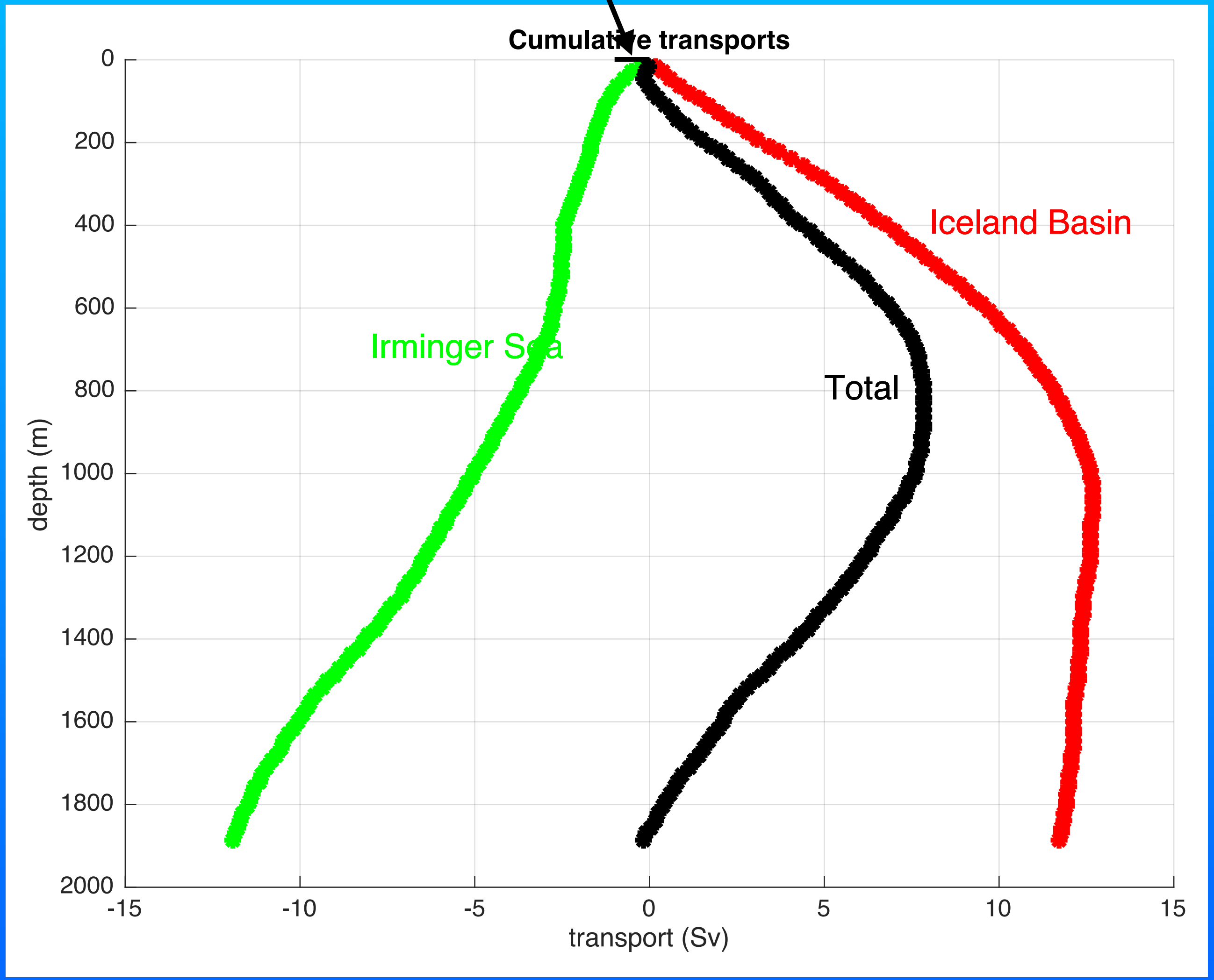
Sarafanov et al., 2012

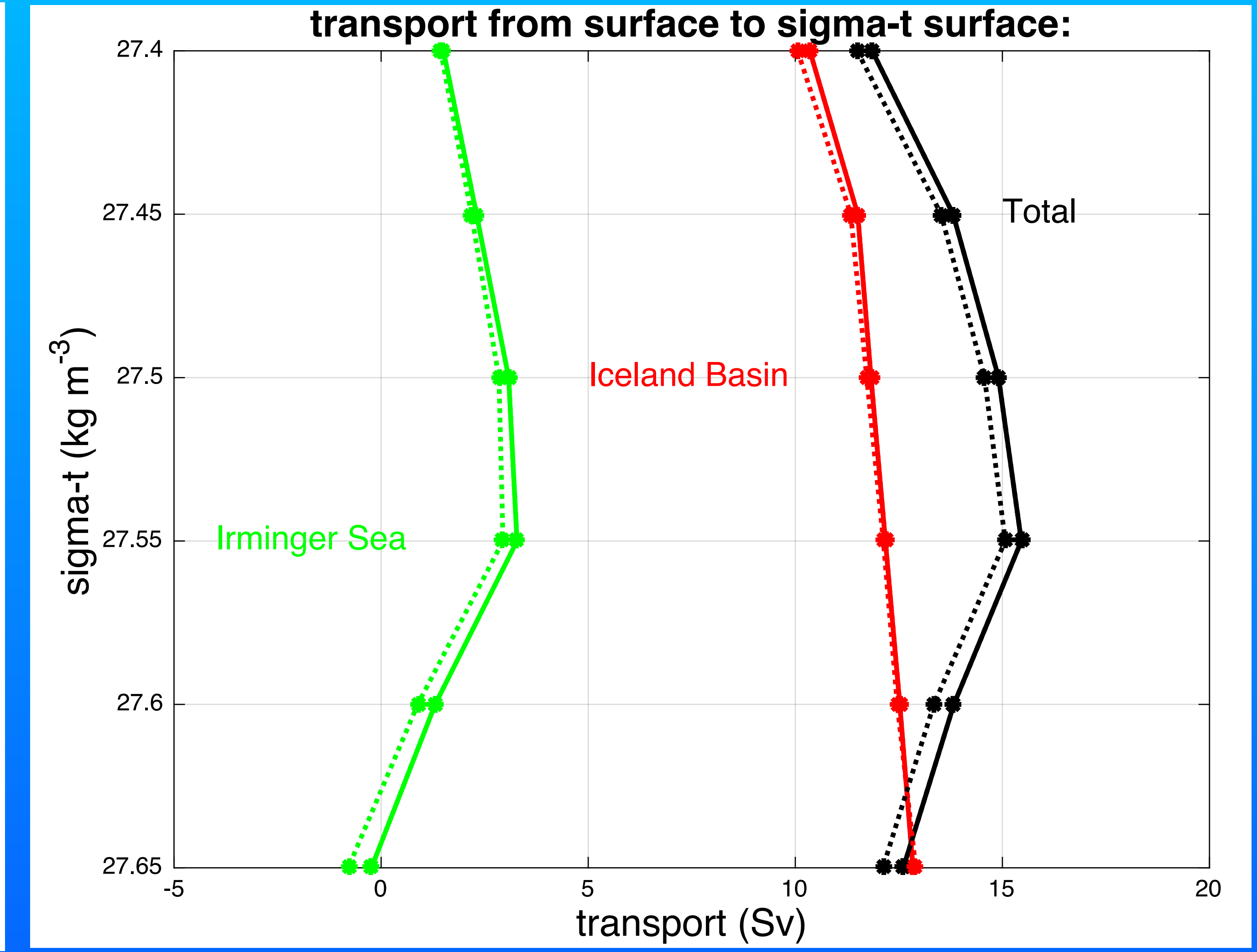
Net: -1.6 Sv; 356 TW

layer	A	B	C	D	E	F	sum	
<27.55	-3.5 -84	0.4 10	6.1 175	-0.1 1	7.3 250	5.0 172	15.1 524	Sv TW
27.55- 27.80	-24.0 -364	5.3 87	8.3 144	-2.8 -48	3.9 74	-0.4 23	-9.7 -84	Sv TW
> 27.80							-7* ~-84*	Sv TW

* Separate integration using WOA for the deepest layer

Ekman layer transport from ADCP



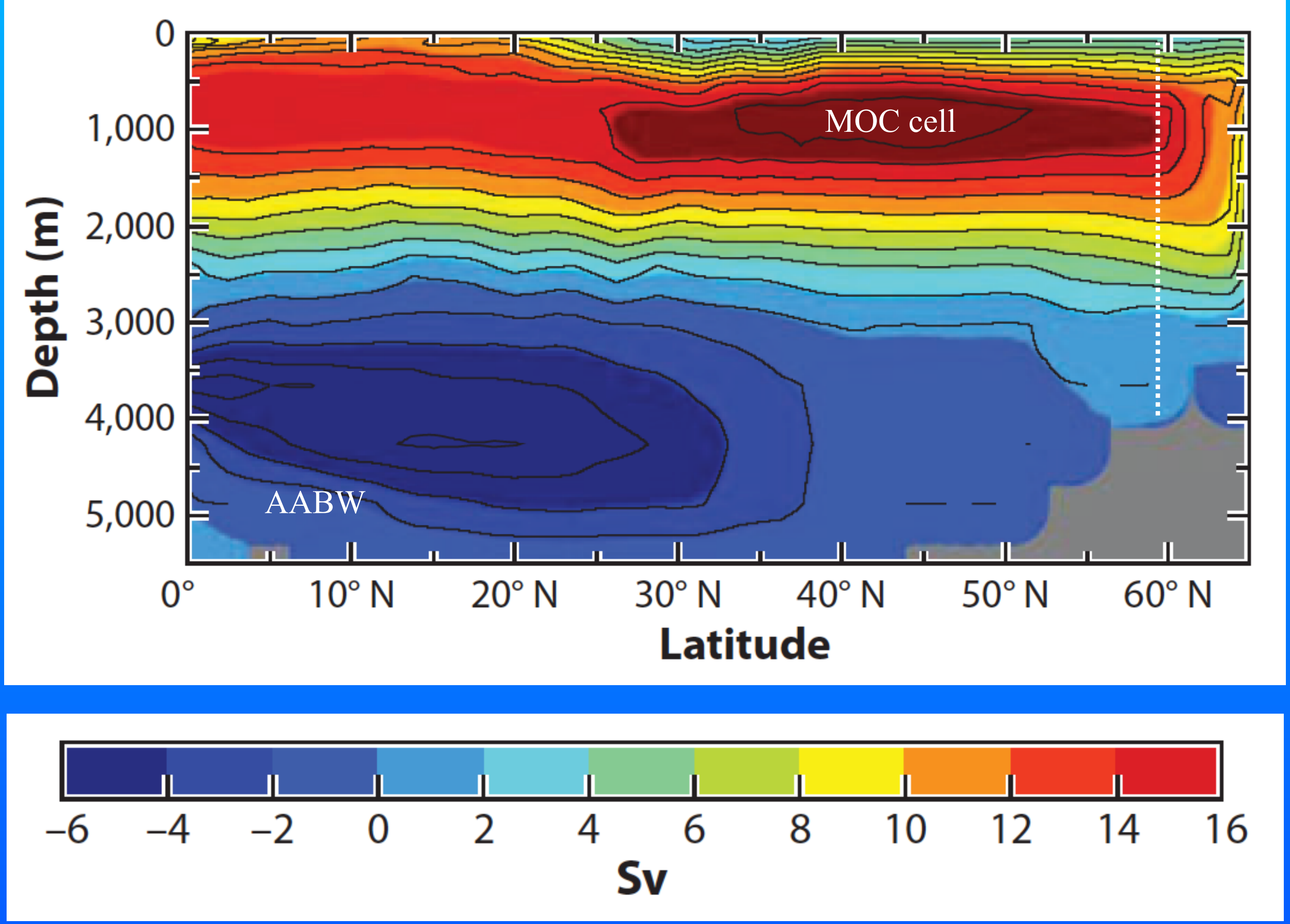


mean of seasonally averaged ADCP data

solid lines: simple data average
dashed lines: pre-averaged seasons

This is work still in development and uncertainty estimates are not yet final, but based on two completely independent ADCP data sets should be O(1) Sv.

To put the Nuka Arctica estimate into a larger frame we use the same mean MOC from HadCM3 coupled oc-atm model:



Bingham et al. 2007

The 8 Sv maximum at 800-900 m depth differs from the model estimate of ~16 Sv.

Nuka Arctica summary:

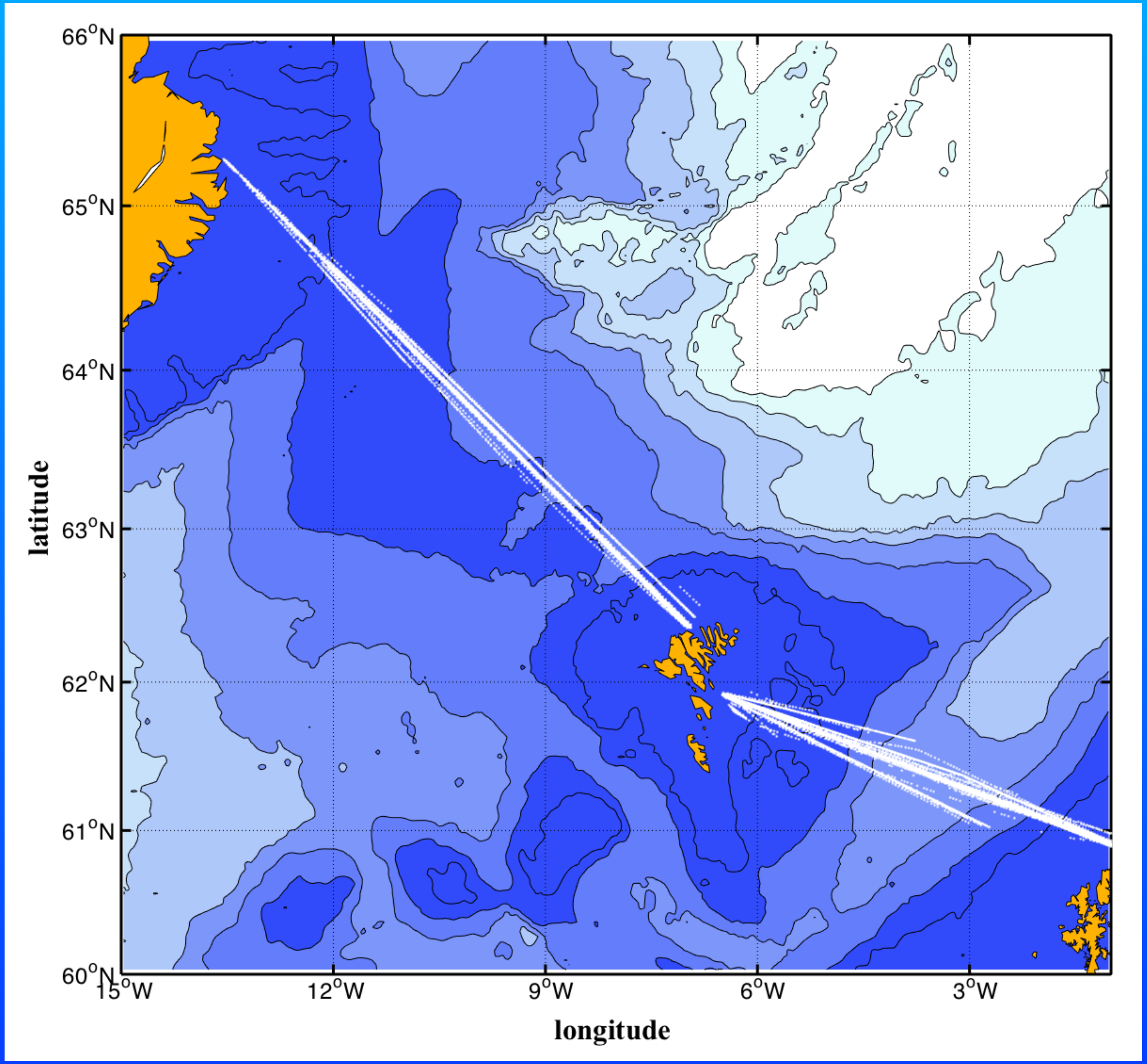
XBTs continuous since late 2000.
ADCP (150 kHz) 1999-2002
ADCP (75 kHz) late 2012-present

Products:
Biggest temperature changes in Iceland Basin
Max MOC and heat transport between Cape Farewell and Scotland =15(σ)/8(z) Sv, 356 TW (prov. est.)

Mean velocity and EKE fields along 59.5°N.
(data also for West Greenland and North Sea)

Future studies might include role of the Banks in steering flow. What about the PRIME eddy - appears to be much stronger in recent data set?

We have been operating a 75 kHz ADCP on the high-seas ferry Norröna since 2008.

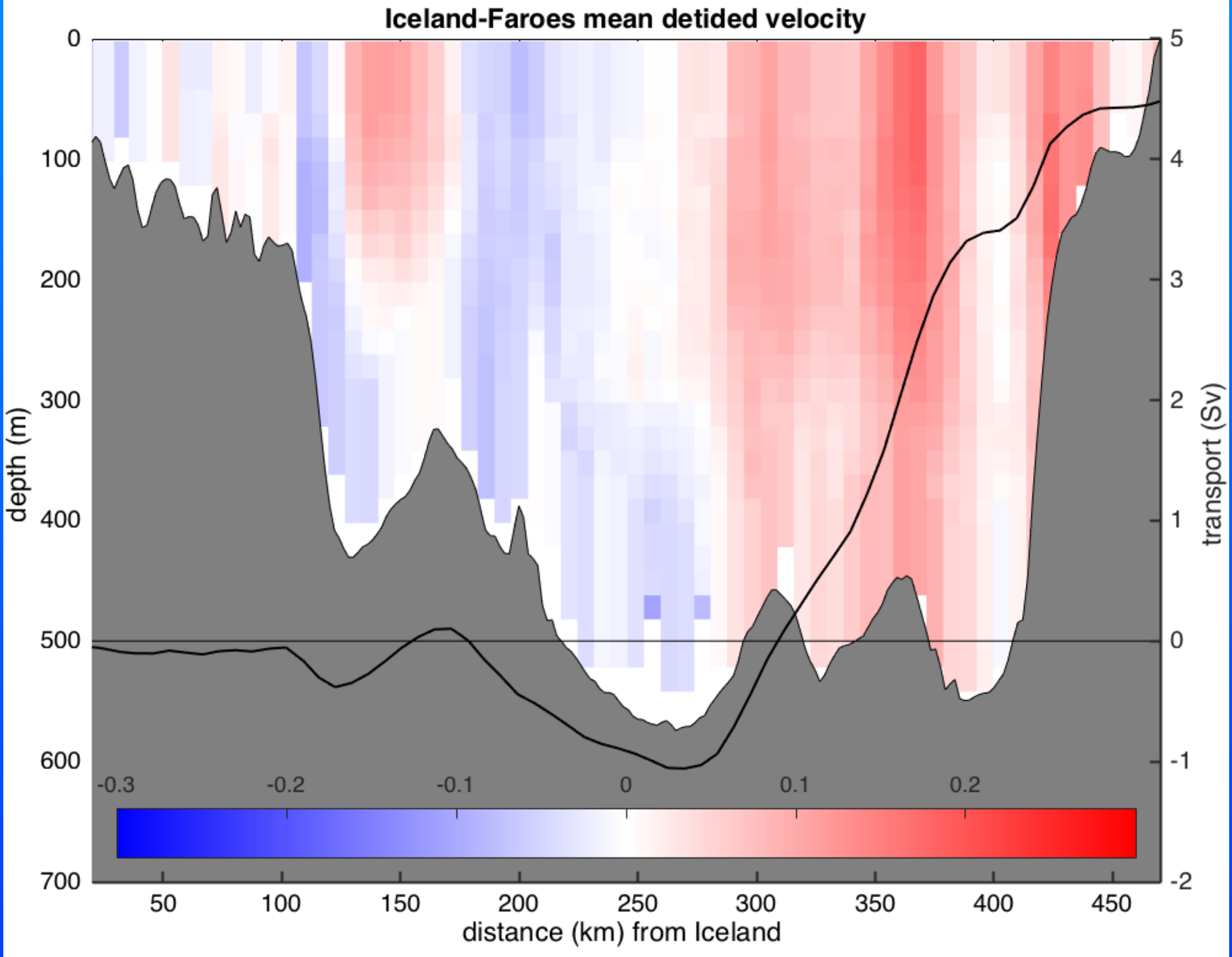


16 m x 2.4 km 'bin' size. Vessel makes a complete round-trip each week. Severe bubble problems limit good data for Iceland section to summer only.

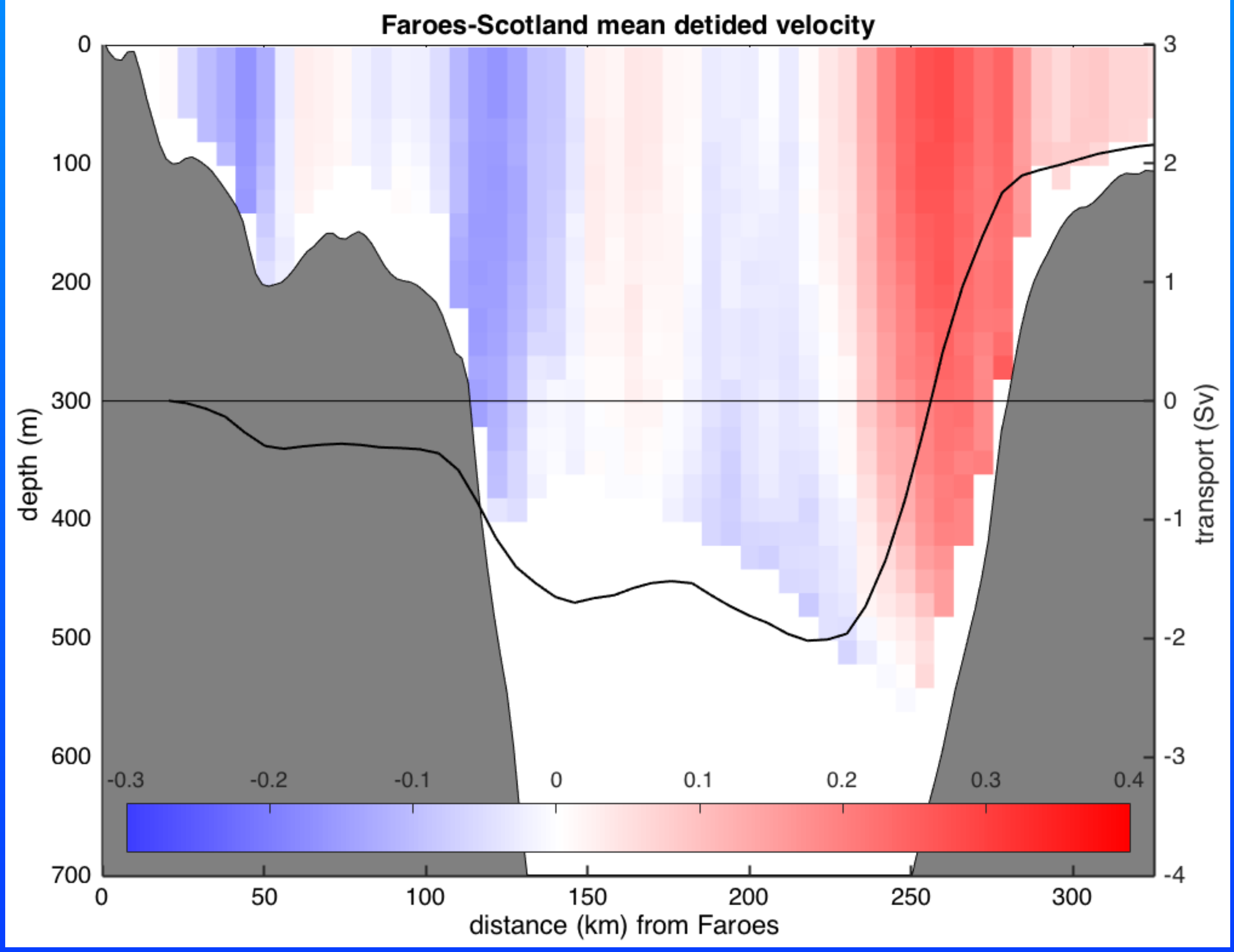
Better, but only limited winter data in FSC.

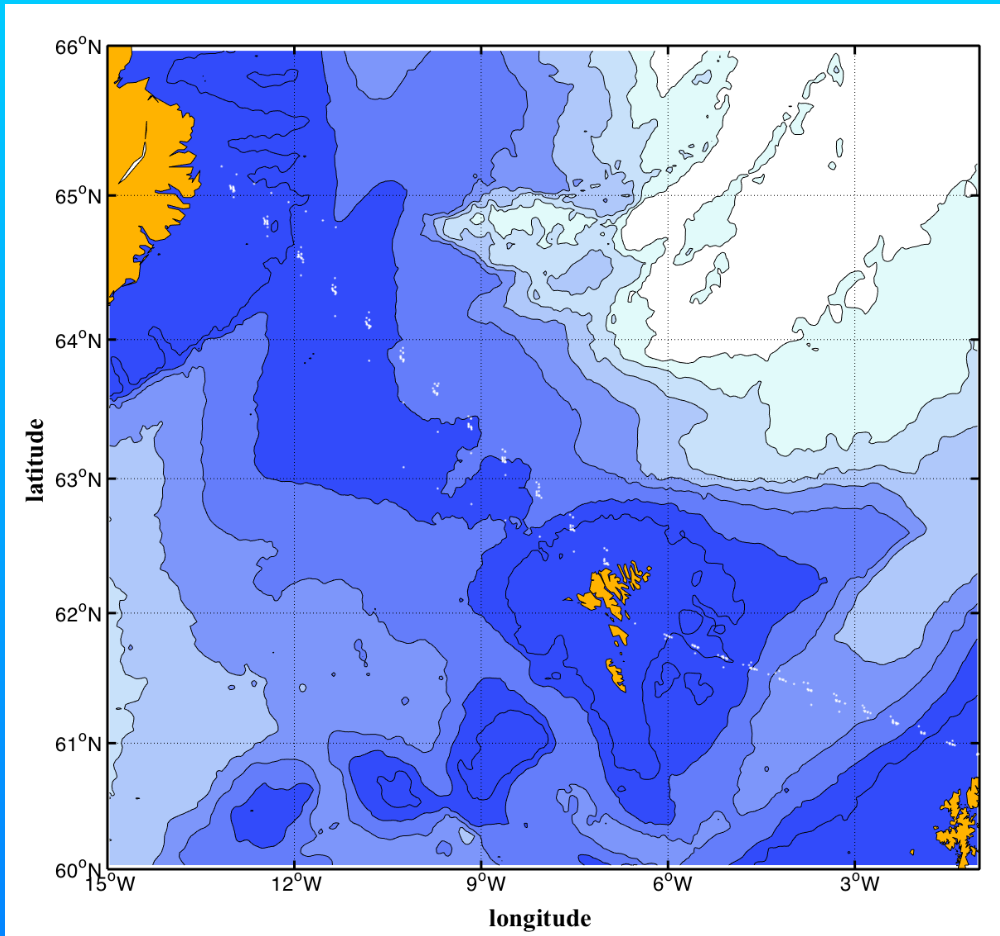
As in other studies all velocity data have been decided.
Velocity has also been de-seasoned for FSC but not IFR.
Better, but only limited winter data for FSC.
Figures show average velocity normal to ship track (m s^{-1}).
Black line = transport integral (right side scale).

IFR



FSC

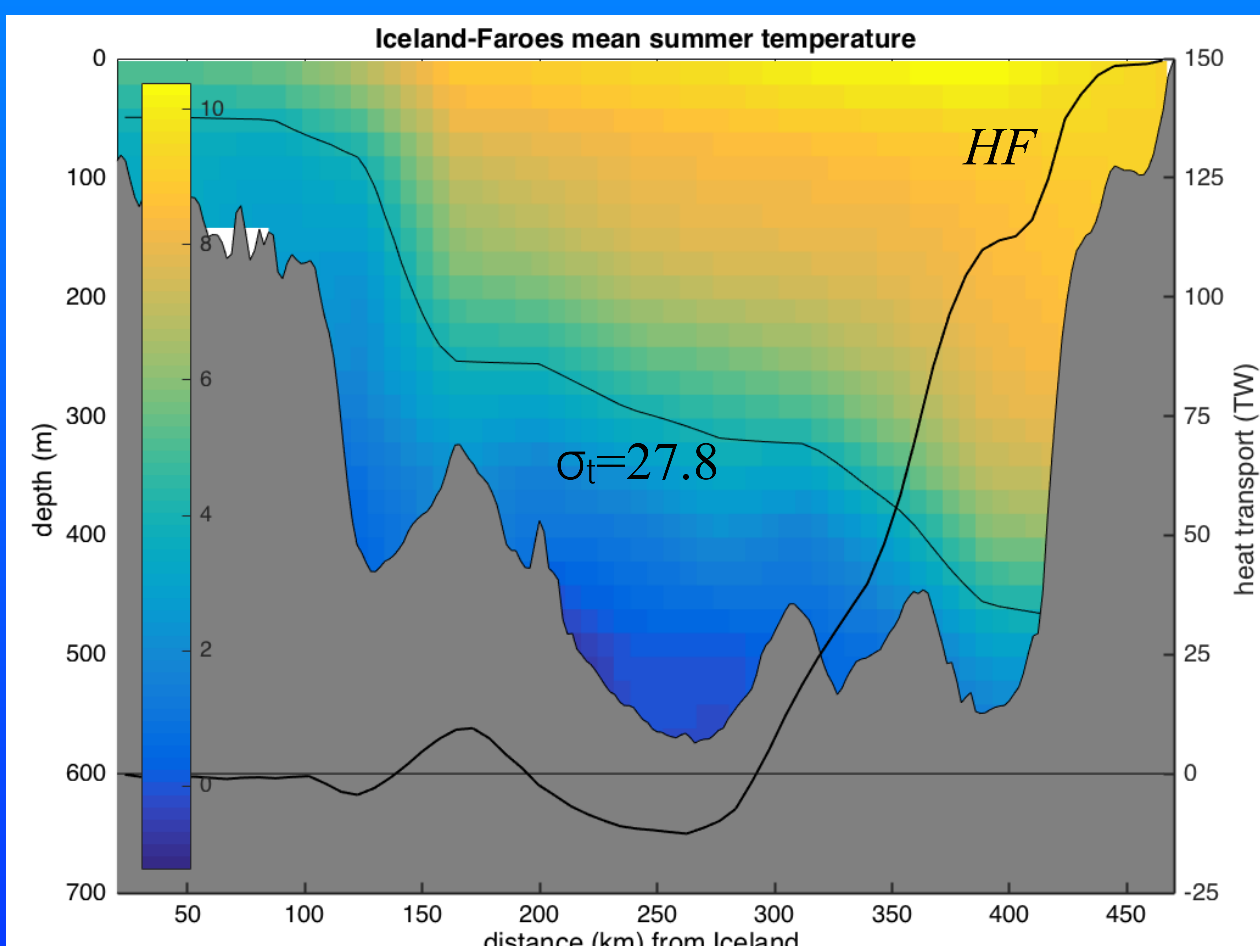


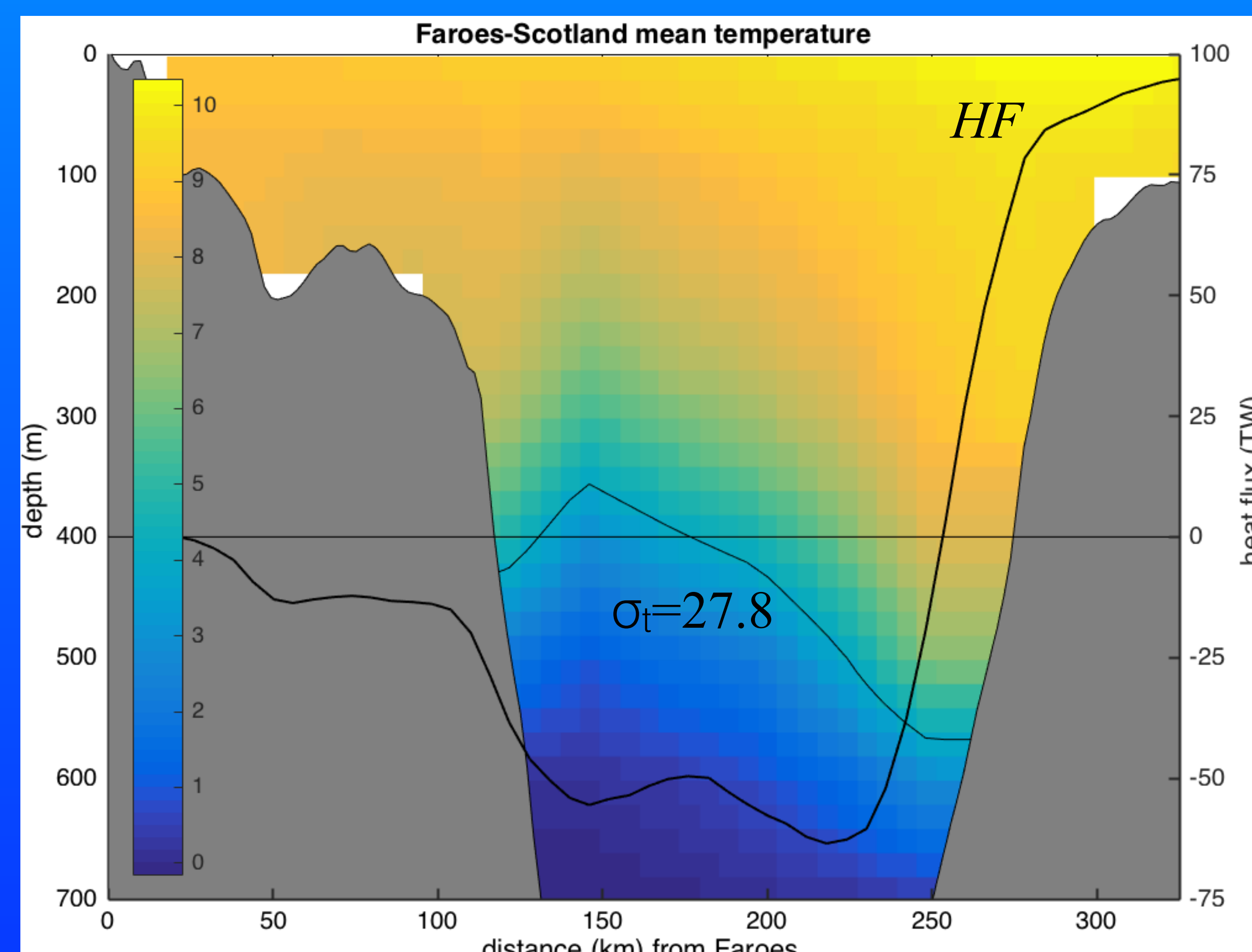


Mean temperature fields from 2+ years of monthly XBT sampling (white dots). Product of mean velocity and temperature give us the mean heat flux integral:

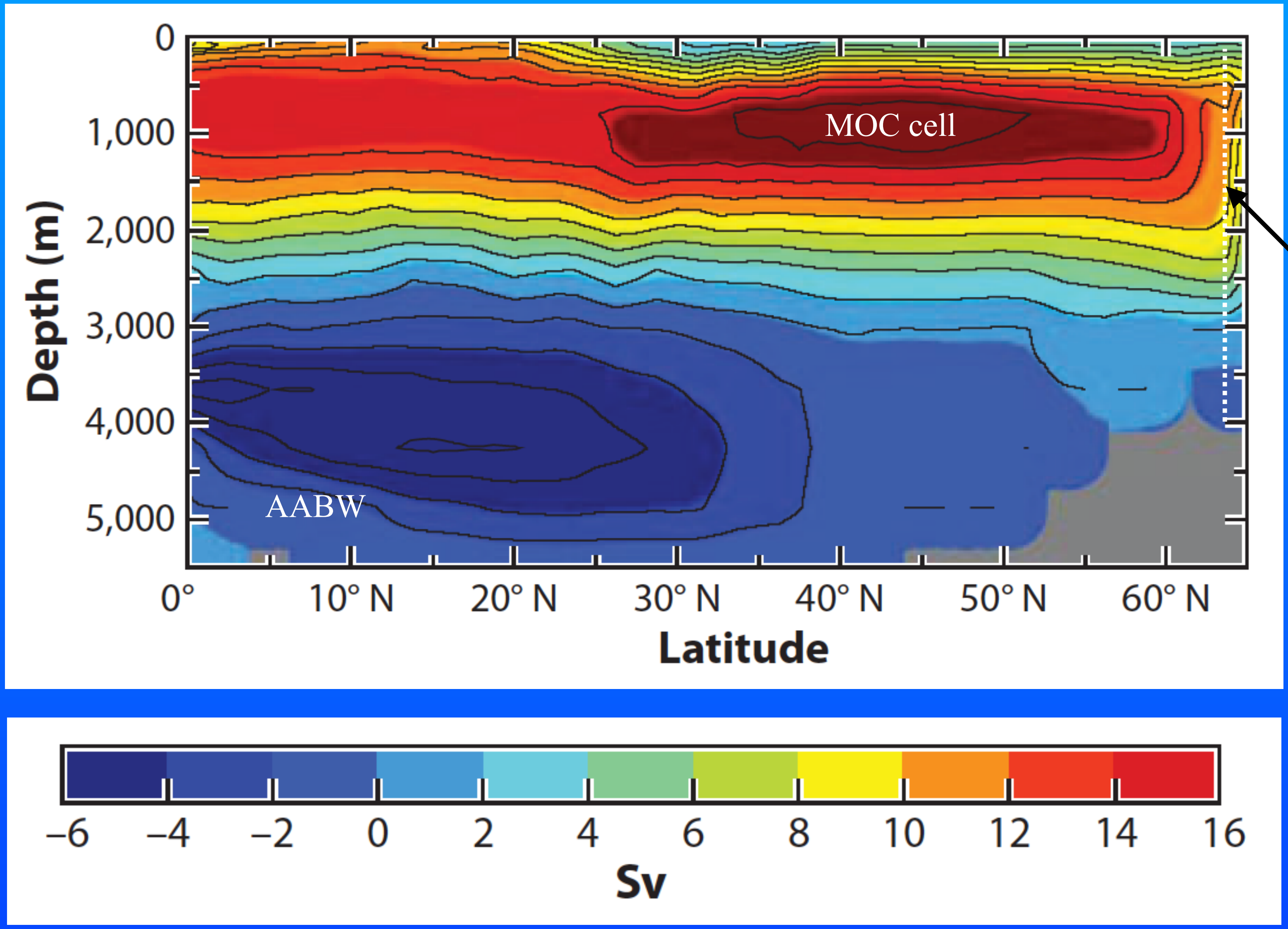
$$HF = \rho C_p \iint v_n T \, dx \, dz$$

thick black line (right side scale). The by far dominant source of uncertainty is velocity.





The volume and heat fluxes can be combined with flows in Denmark St to give a total exchange of mass and heat between the NE Atlantic and Nordic Seas. Our working estimate of these are 5.4± Sv and 228± TW. To put these estimate into a larger frame we use the same mean MOC from HadCM3 coupled oc-atm model:



Bingham et al. 2007

As with the Nuka Arctica the model shows a much larger MOC, but being at the northern model limit may make comparison uncertain.

Norröna summary:

XBT sections monthy since late 2013 (AXIS).
ADCP (75 kHz) 2008-present

Products:
Large variations in transport in the FSC. Overall mean value for volume transport and heat flux between NE Atlantic and Nordic Seas = 5.4± Sv and 228± TW. Monitoring the Nordic Seas contribution to the MOC is greatly facilitated at this ‘coke-point’.

The main point of this survey has been to show how helpful the merchant marine can be to extend our observational capabilities. In addition to ongoing XBT, TSG, CO_2, and CPR programs, the examples discussed here show how we can add the direct measurement of ocean currents to the suite of observables.

Vessels in repeat traffic provide us with high-resolution scans. They do not give us time series as we know them, but through repeat sampling we build an ensemble of observations that provide the needed degrees of freedom to determine temperature fields, currents, their seasonal variations, and if maintained for long enough inter-annual variability.

Thank you!