Variability in the Deep Circulation of the North Atlantic Ocean

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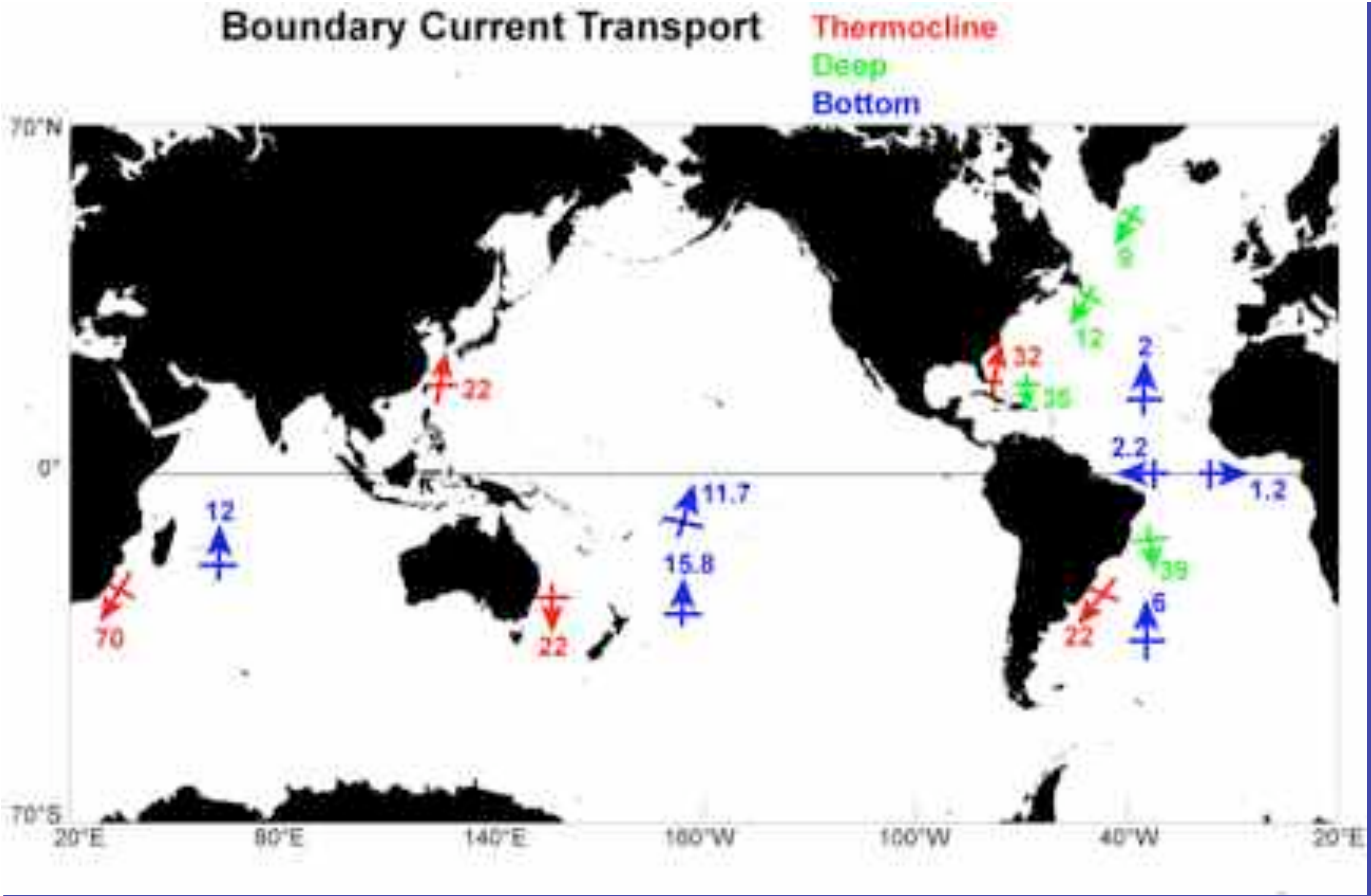
Strong ocean currents primarily occur near the western boundary of the ocean, both in the upper thermocline(above 1000 m depth) and in the deep ocean.

Upper ocean currents like the Gulf Stream are well known. Here I will concentrate on the deep currents in the North Atlantic Ocean and their variability.

There was a major effort during the World Ocean Circulation Experiment during 1990 – 2000 to measure the strength and structure of western boundary currents throughout the world ocean, many for the first time.

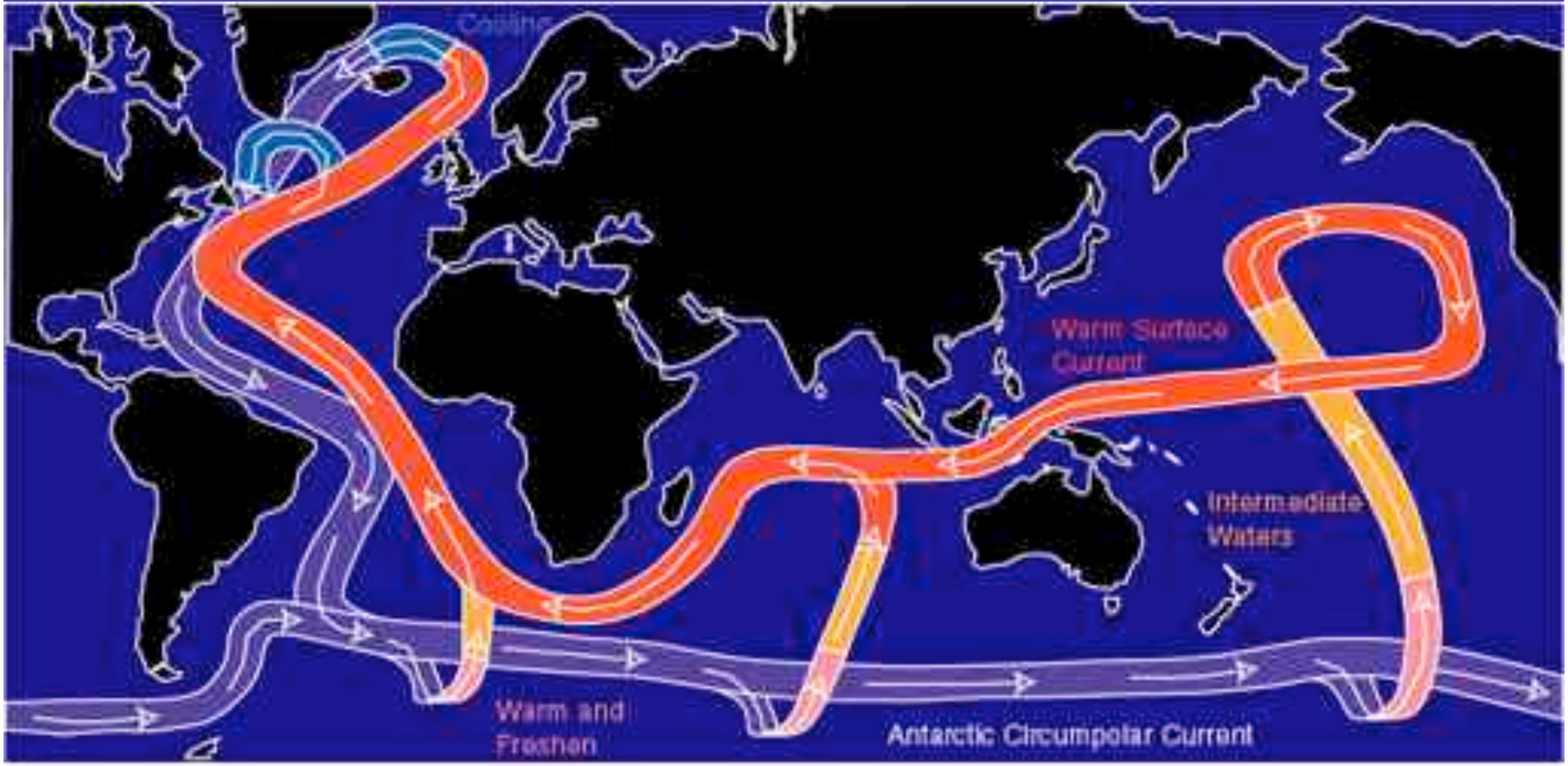


Summary of Boundary Current Transports measured during WOCE

With a paleo perspective outlined in Prof. Bard’s opening lecture, we will focus on the North Atlantic, primarily at 26°N to discuss the issues:

Boundary Current Transport
Boundary Current Variability
Recirculation
Overall Net Transport
Stability of the deep circulation

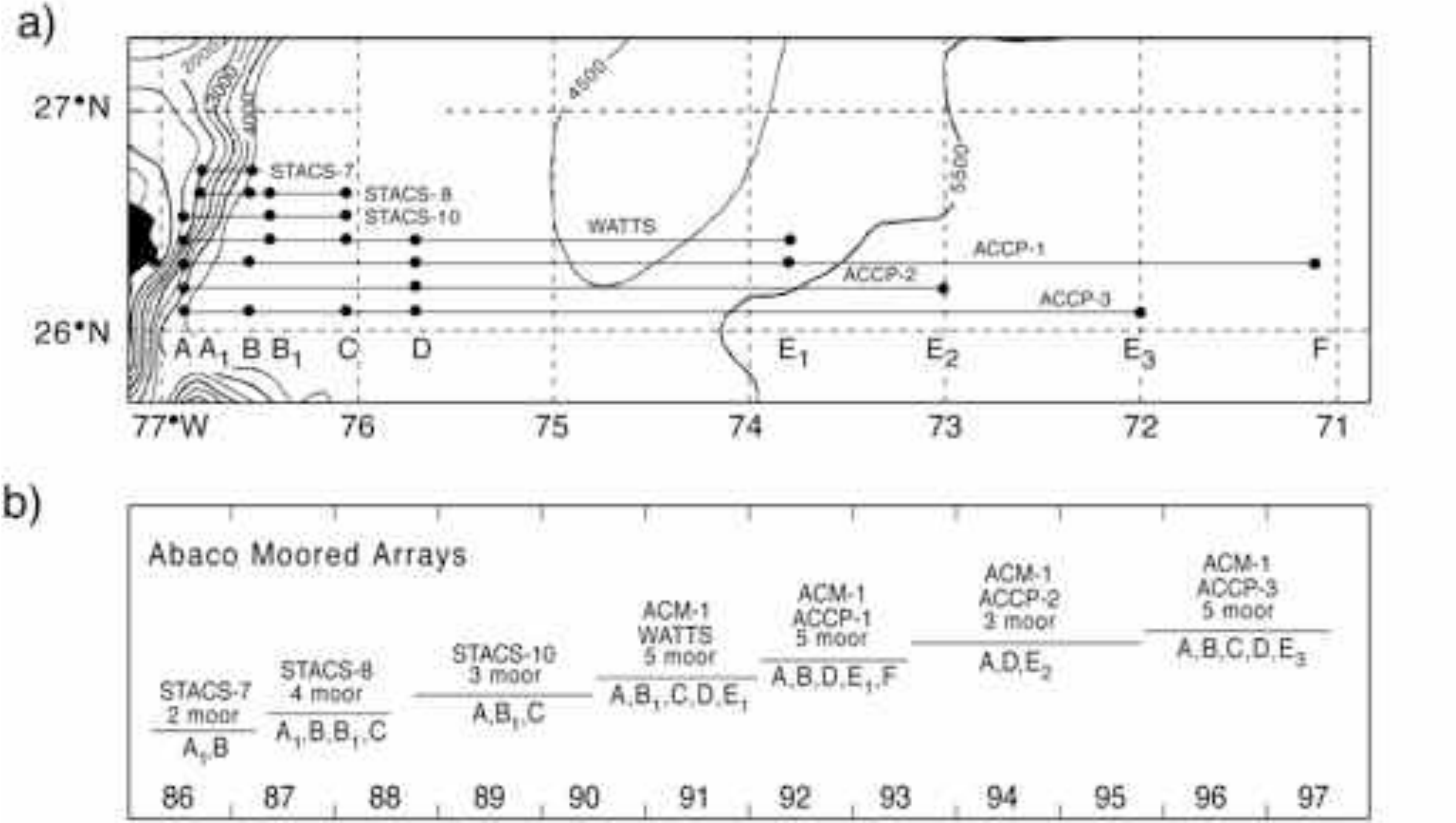
Sometimes the circulation is simplified into a Conveyor Belt



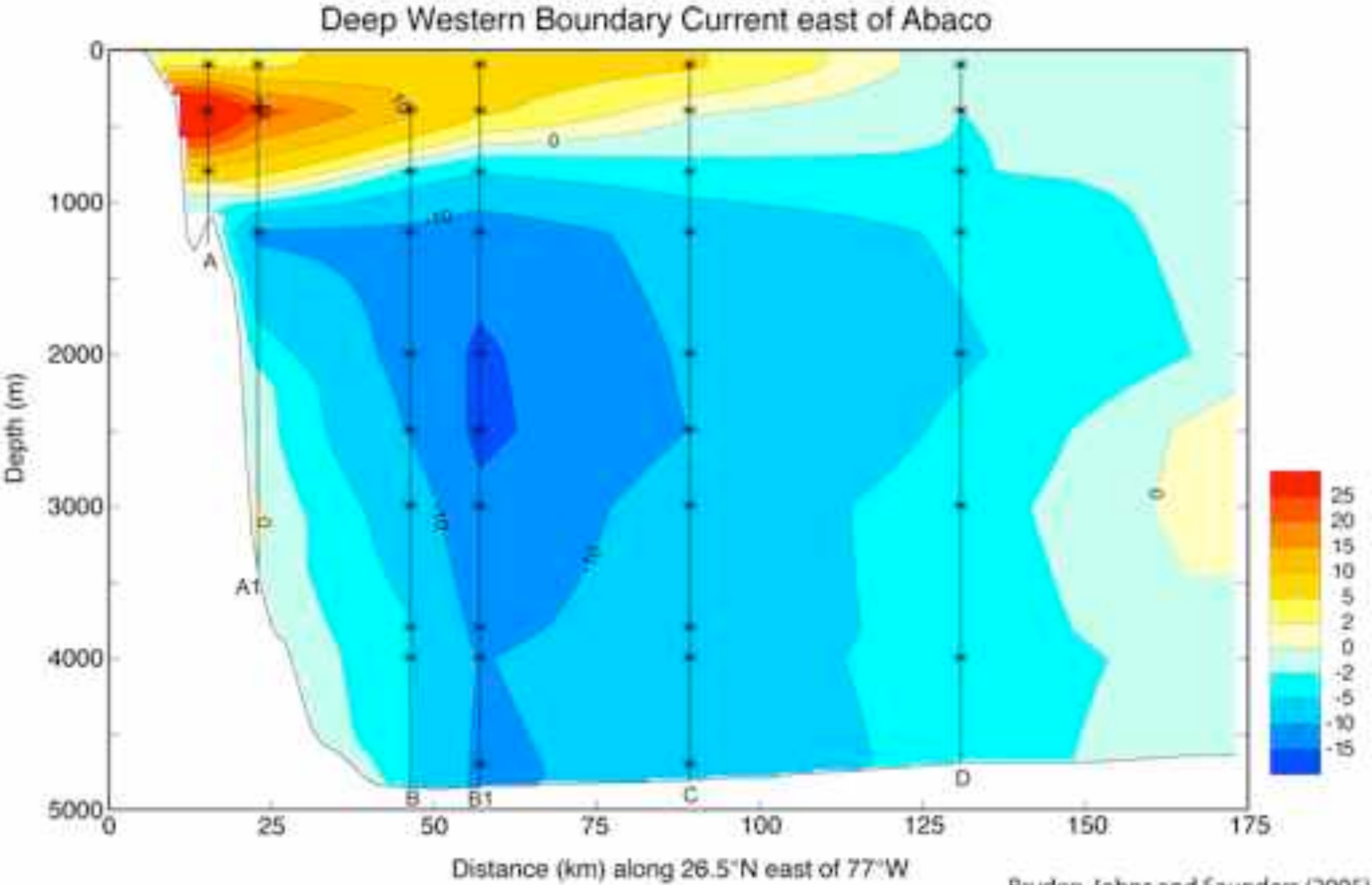
Thermohaline Conveyor Belt (after Doos and Webb)

t96g_ocean/thermohaline2

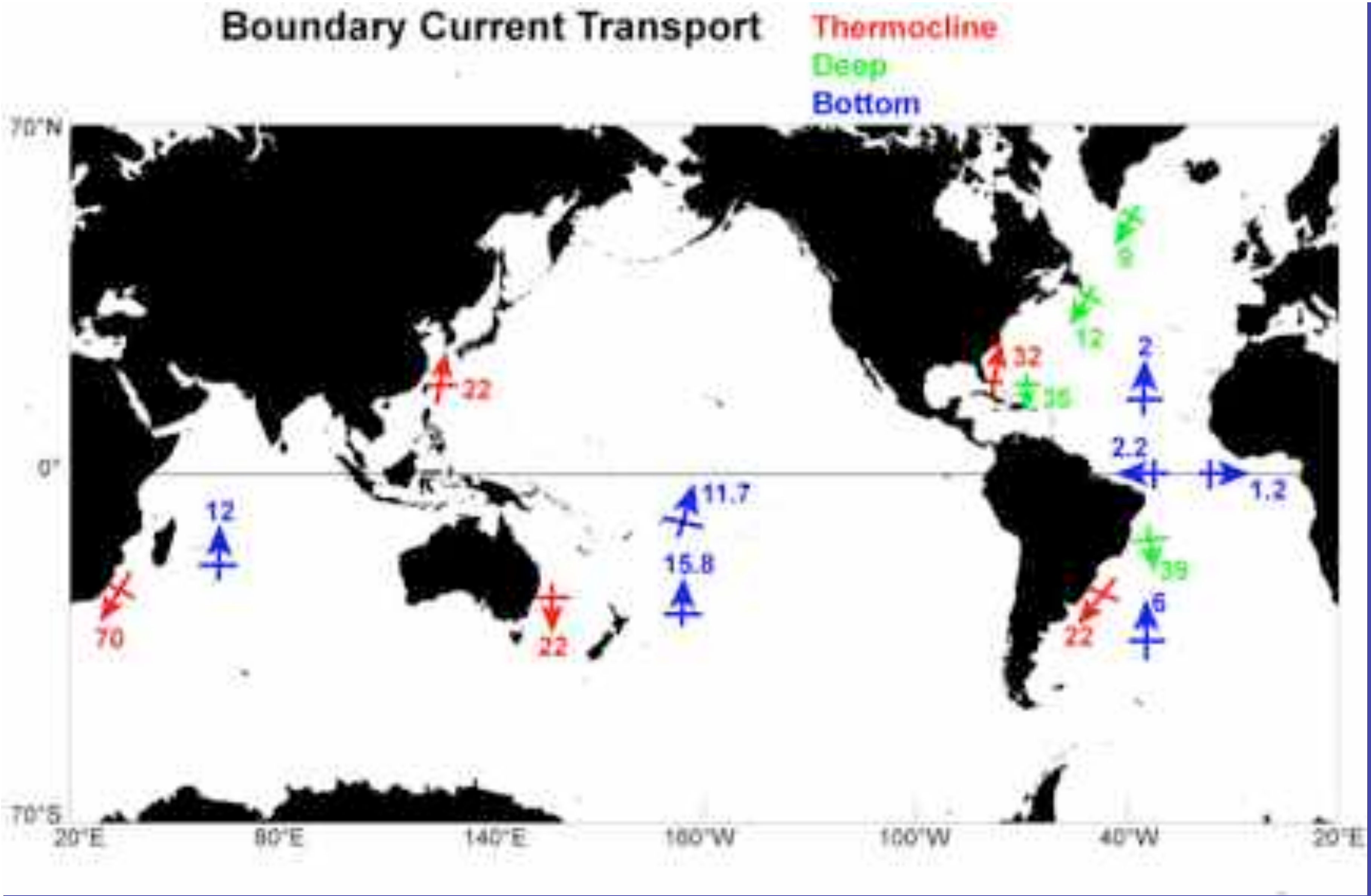
Boundary Current Arrays just west of Bahama Islands 1986-1997



Structure of Deep Western boundary Current at 26.5°N from Abaco arrays (1987-1998)



Bryden, Johns and Saunders (2005)



Summary of Boundary Current Transports measured during WOCE

The southward deep western boundary current at 26°N has a larger transport than the famous Gulf Stream at the same latitude!

What sets the size of the deep western boundary current (DWBC) transport?

Why does the DWBC transport in the Atlantic increase southwards? Dynamical arguments by Stommel and Arons suggest the DWBC transport should decrease away from its source.

Boundary Current Variability

During 2 time periods the deep (below 800m) instruments on all moorings A,B,C, D worked so we can examine the variability in the boundary current structure and transport

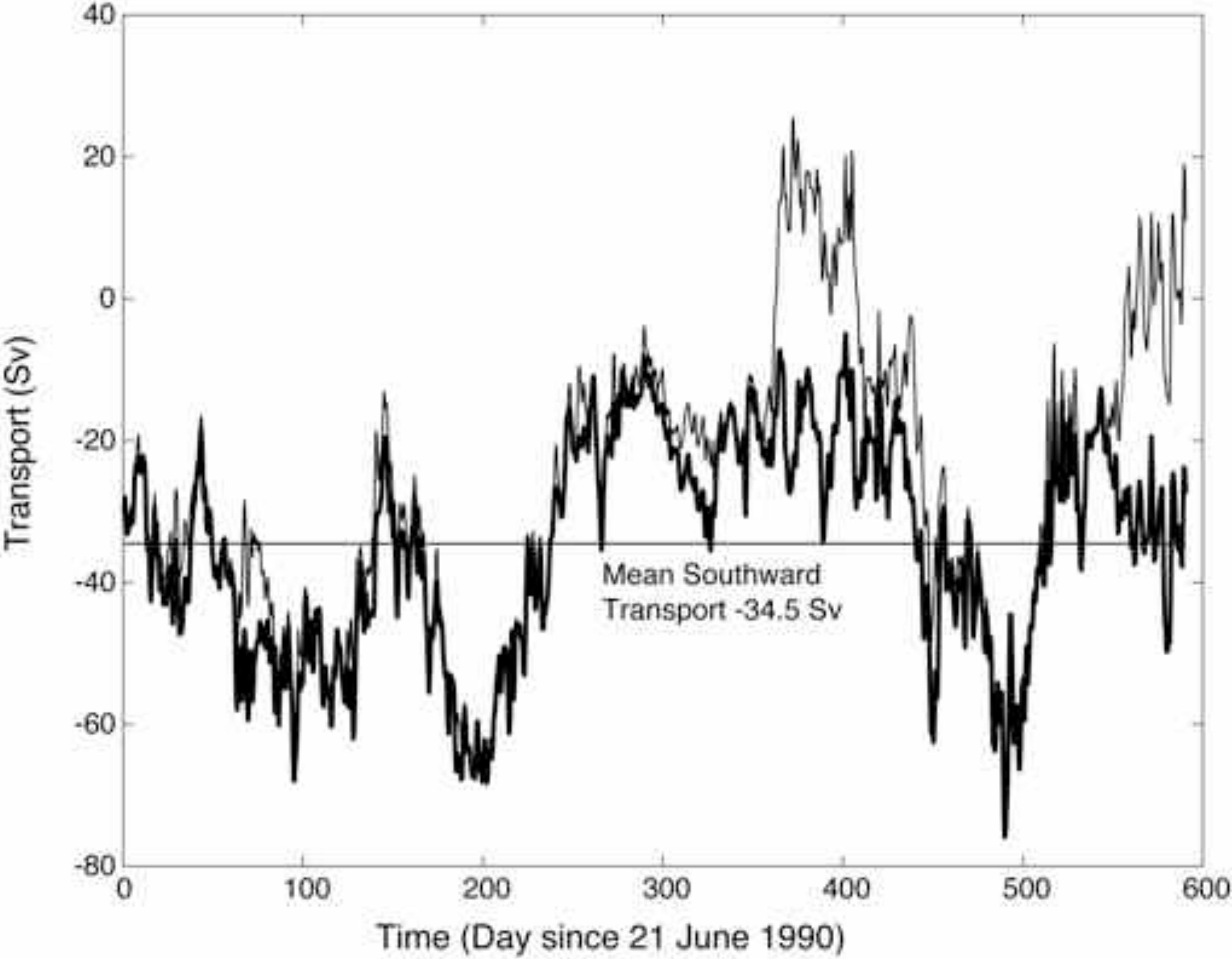
Movie in Firefox

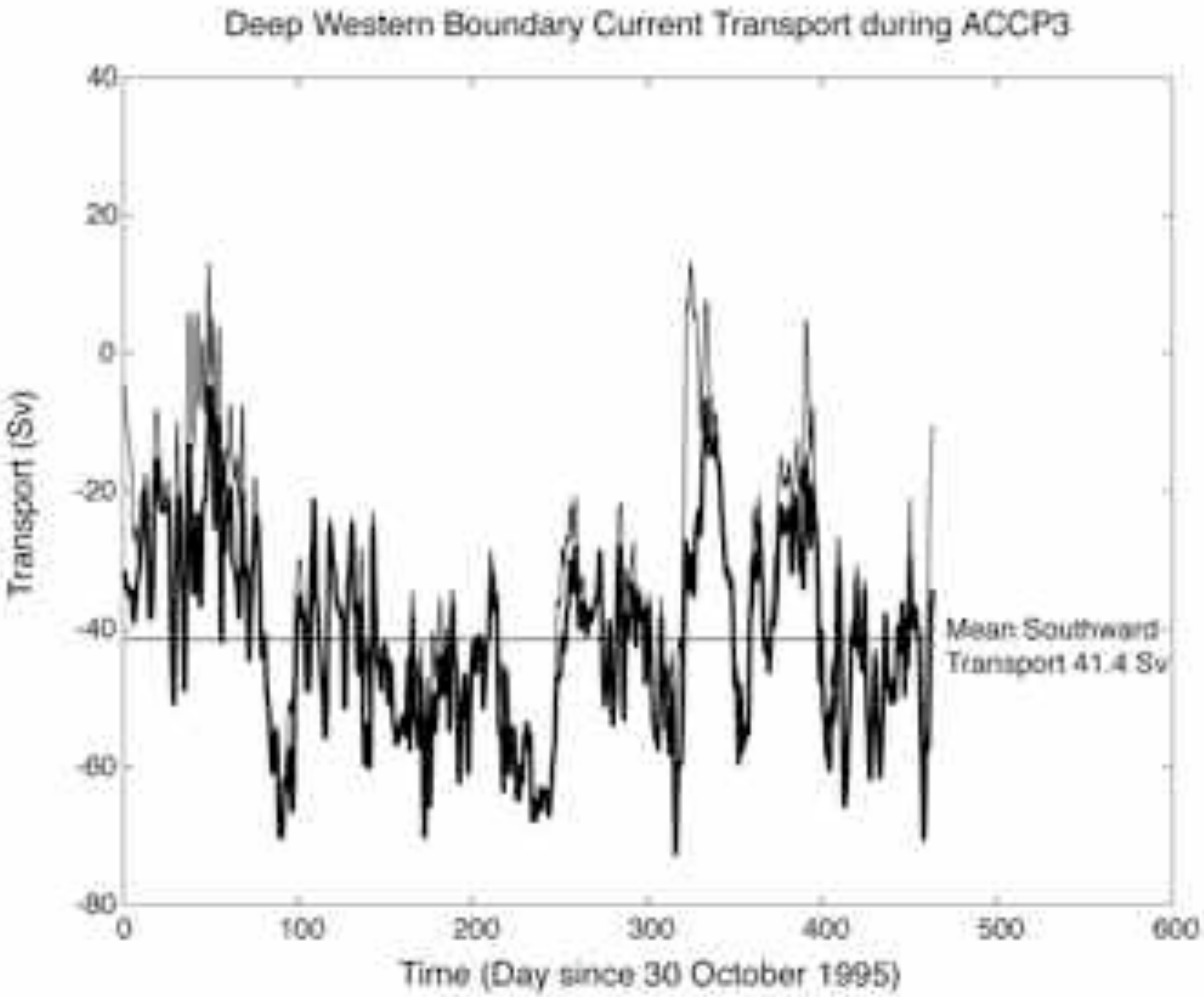
Note the Pulsing and the Offshore Meandering

We do not know what causes the variability:

Natural instabilities?
Westward propagating eddies impacting the boundary region?
Southward propagating continental slope waves?
Variability in source waters?

Deep Western Boundary Current Transport during WATTS




Deep Western Boundary Current Transport during ACCP3
Transport (Sv)
40
20
0
-20
-40
-60
-80
0
100
200
300
400
500
600
Time (Day since 30 October 1995)
Mean Southward
Transport 41.4 Sv

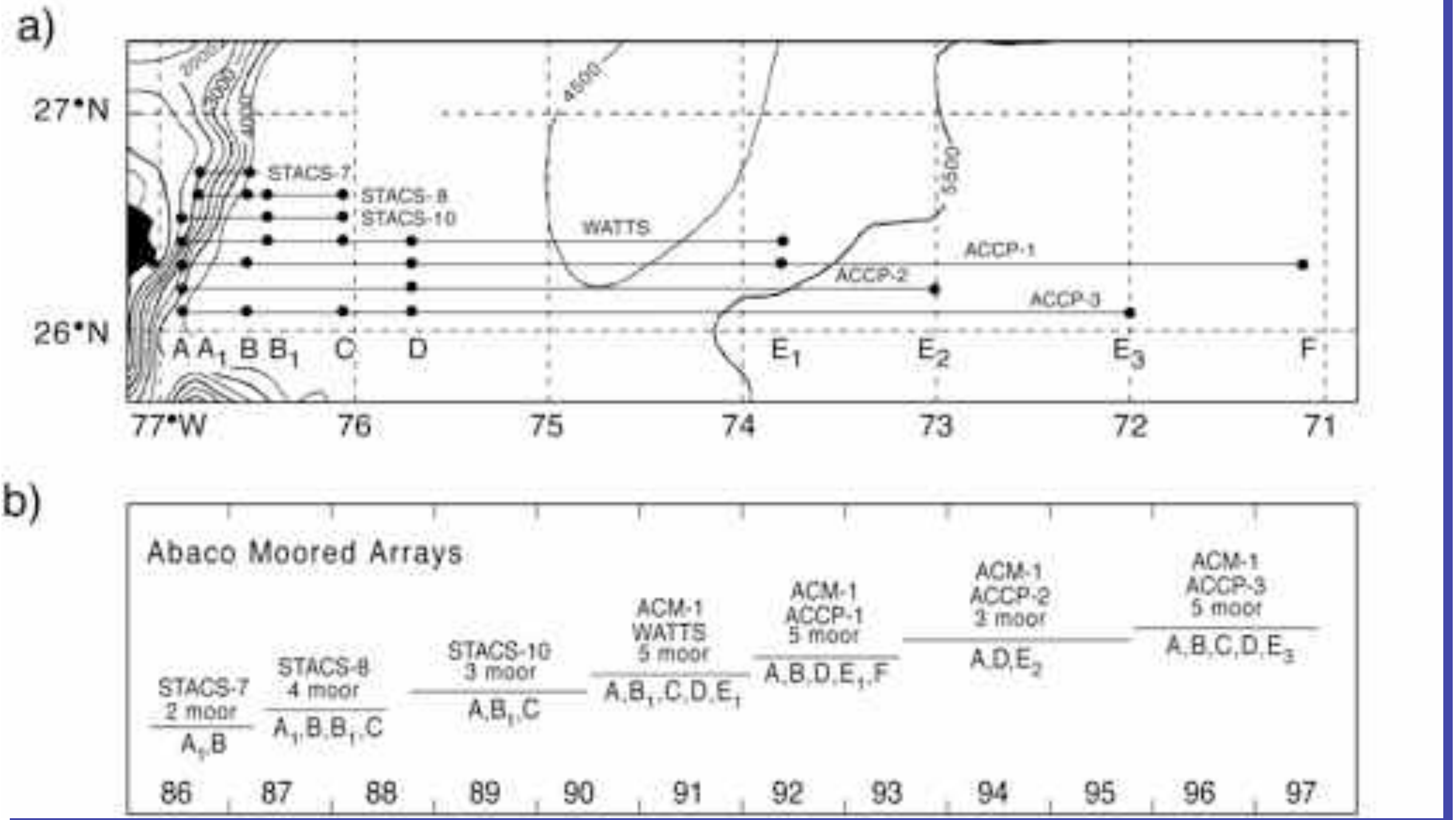
We do not understand the causes of the variability in the deep western boundary current transport:

There is no obvious seasonal cycle
How much of the variability is caused by offshore meandering versus pulsing in place?
Is it related to Gulf Stream transport? To wind stress curl? To NAO?
Are longer term variations related to variations in northern overflow strength?

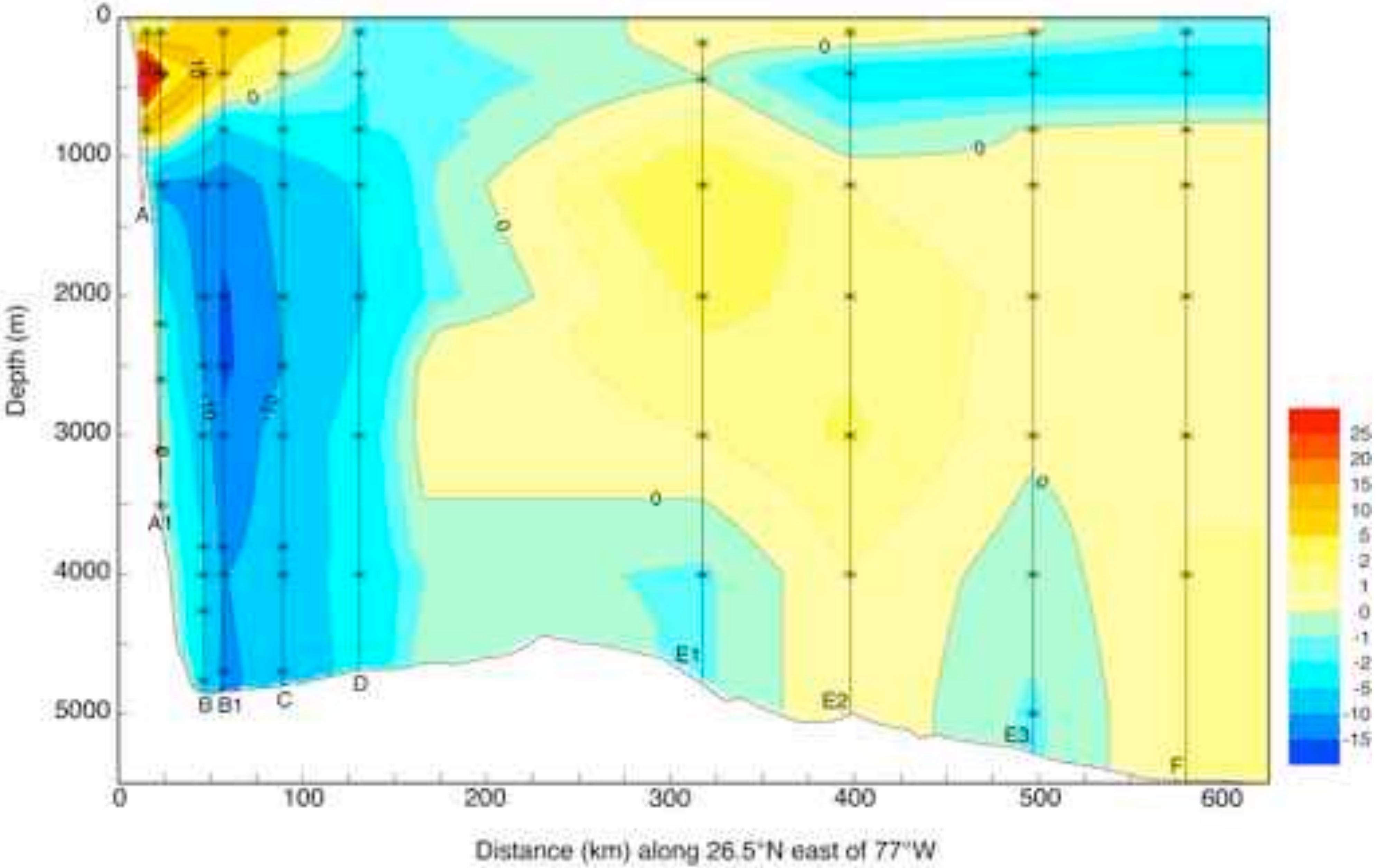
Recirculation

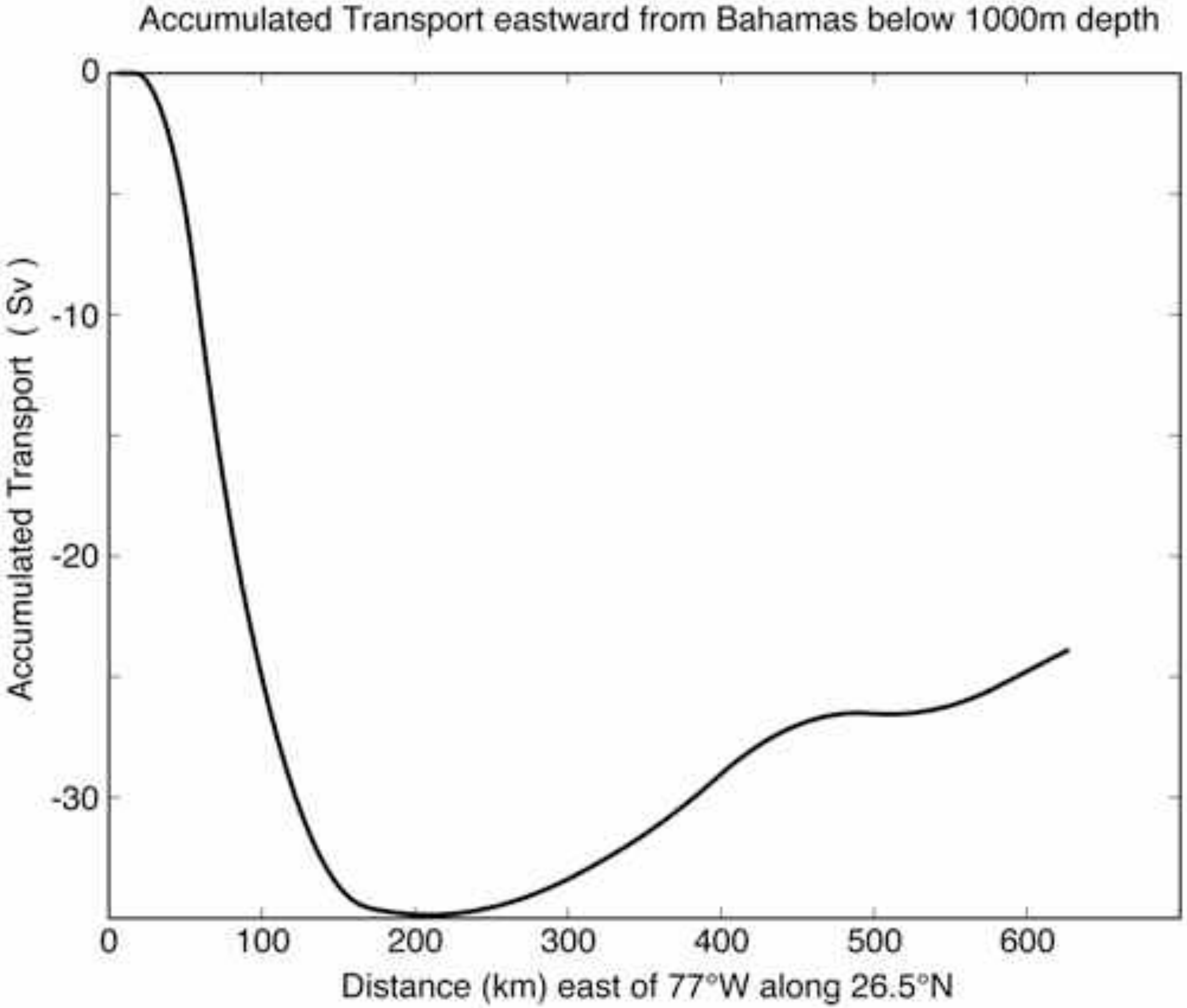
Some of the southward transport recirculates back northward offshore of the boundary current. A major effort was made with the Abaco arrays to extend the observations seaward to measure the northward recirculation. By and large these extensions failed to resolve the recirculation.

Boundary Current Arrays just west of Bahama Islands 1986-1997



Meridional Velocity in the Western Boundary Current system east of Abaco




Accumulated Transport eastward from Bahamas below 1000m depth
Accumulated Transport (Sv)
0
-10
-20
-30
0
100
200
300
400
500
600
Distance (km) east of 77°W along 26.5°N

What sets the size of the deep western boundary current (DWBC) transport?

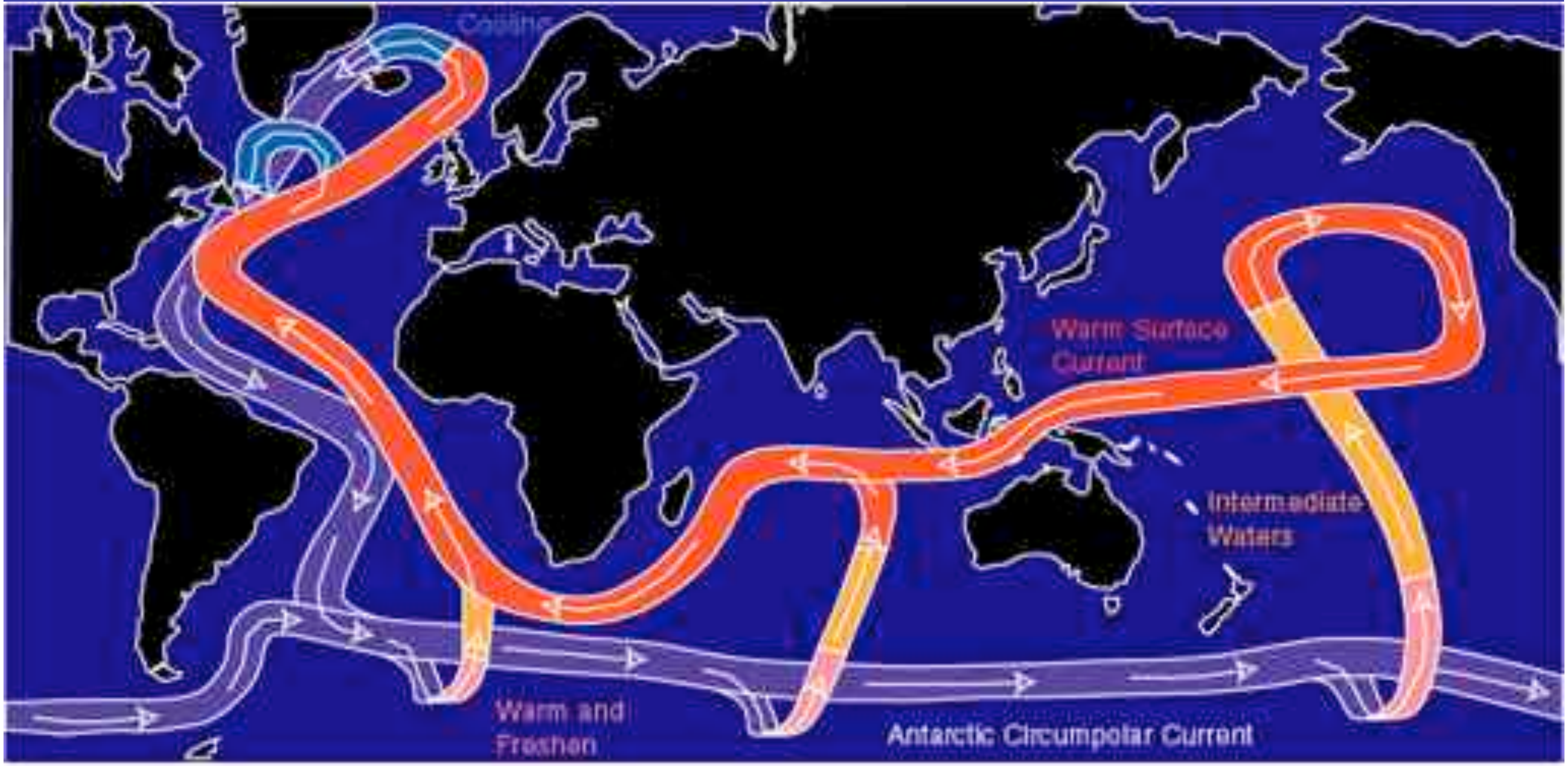
The southward boundary current transport is much larger than the net amount of water flowing southward.

Why?

How much of the southward flow recirculates northward?

How far offshore does the northward recirculation extend?

In terms of the global thermohaline circulation, we are interested in the net southward flow through the Atlantic Ocean.



Thermohaline Conveyor Belt (after Doos and Webb)

t96g_ocean/thermohaline2

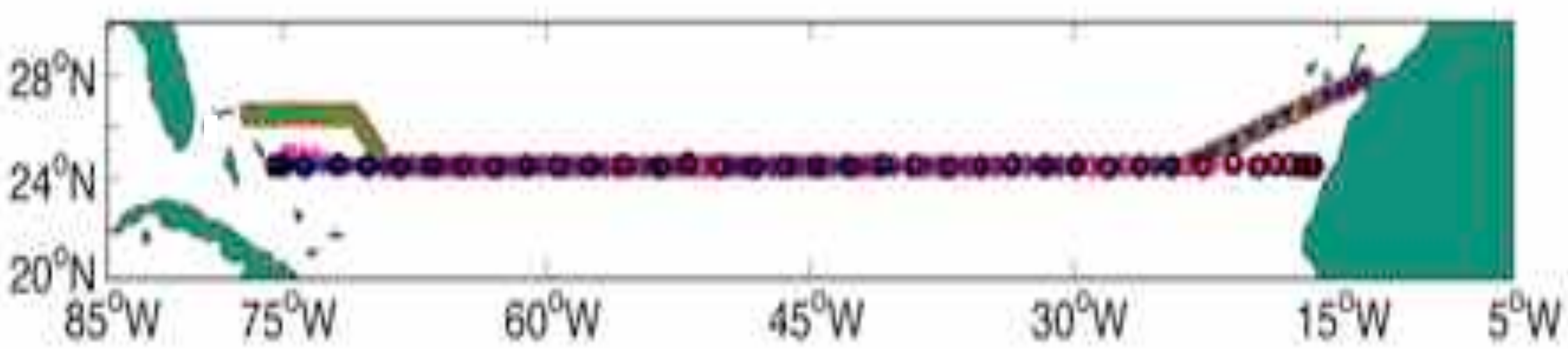
Overall Net Transport

To address the net flow, hydrographic sections have been made to define the vertical structure of the meridional currents averaged across the basin.

The Conveyor Belt schematic is in fact based on estimates of the thermohaline circulation derived from hydrographic sections.

Traditional Monitoring of Mid-Ocean Circulation

Six Hydrographic Sections at 25ºN
1957, 1981, 1992, 1998, 2004, 2010



Hydrographic station locations of the 1957 (o), 1981 (x), 1992 (+), 1998 (+) and 2004 (o) transatlantic cruises. Shaded regions are above sea level.

Make a zonal, transocean section of hydrographic stations measuring temperature and salinity from top to bottom

Calculate geostrophic current profiles, adjust reference velocity to balance mass

Quantify the net flow of water as a function of depth or water mass type

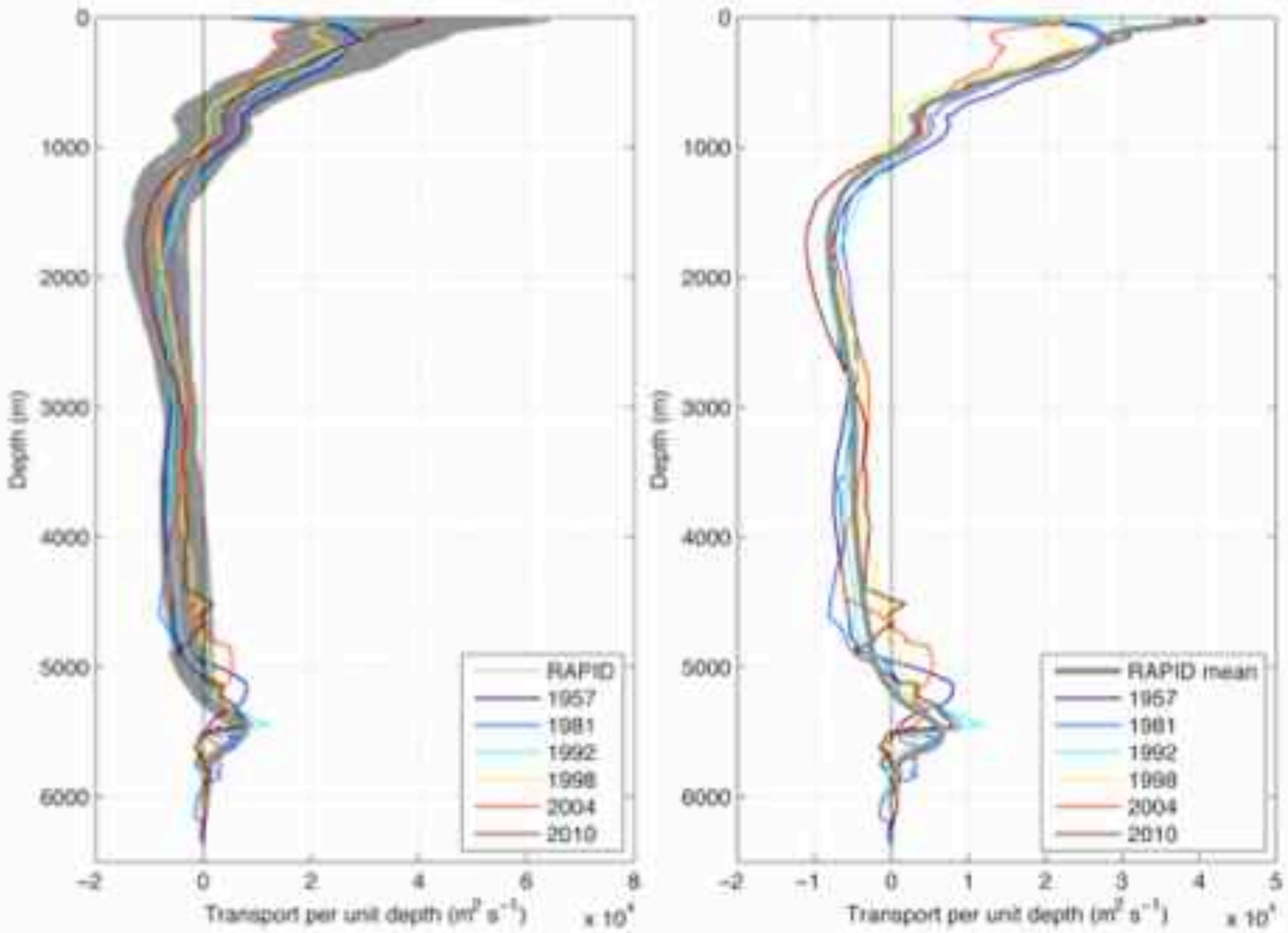
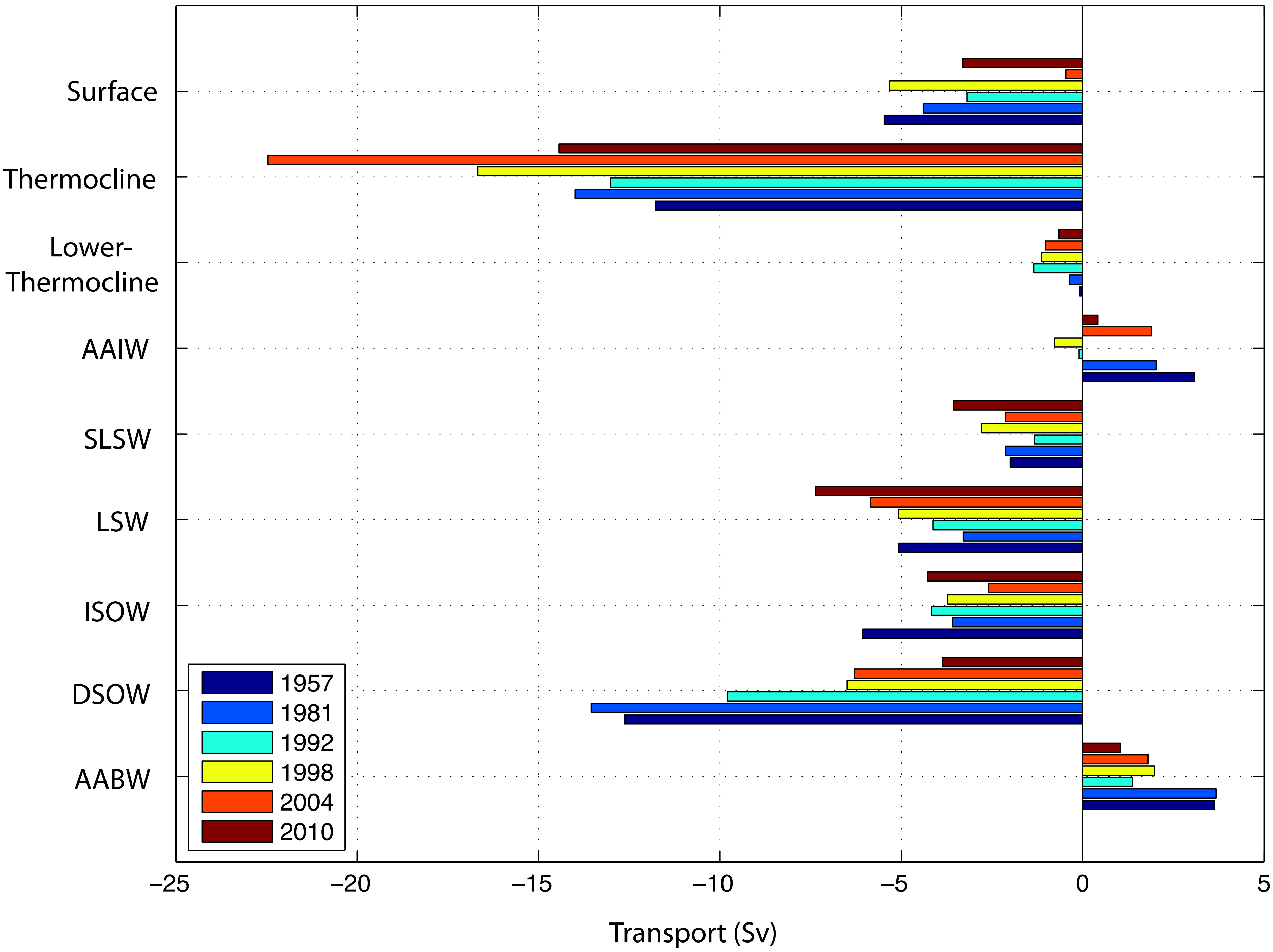


Fig. 5. Profiles of total transport per unit depth (excluding mean surface Ekman transport) for the 6 hydrographic section and 5 years of Rapid-WATCH data (April 2004–April 2009). Rapid-WATCH data are shown in grey, the grey envelope in the left plot comprises 3562 Rapid profiles (available twice daily for 5 years) whilst the grey line in the right plot shows the mean of these profiles. All profiles use long-term mean Florida Straits and Ekman transport, thus variability represents only that associated with changes in mid-ocean vertical transport structure.


Surface
Thermocline
Lower-Thermocline
AAIW
SLSW
LSW
ISOW
DSOW
AABW
1957
1981
1992
1998
2004
2010
–25
–20
–15
–10
–5
0
5
Transport (Sv)

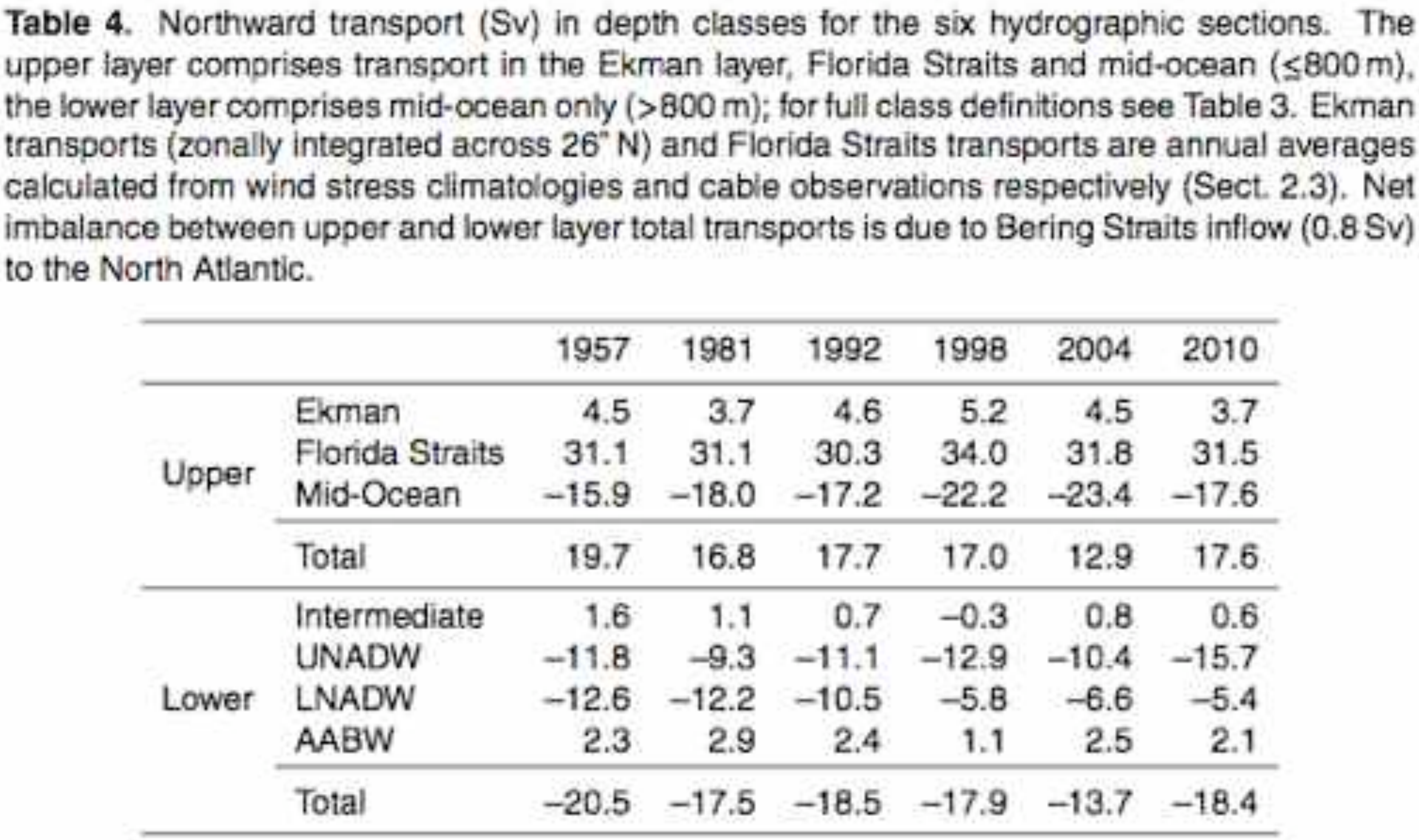
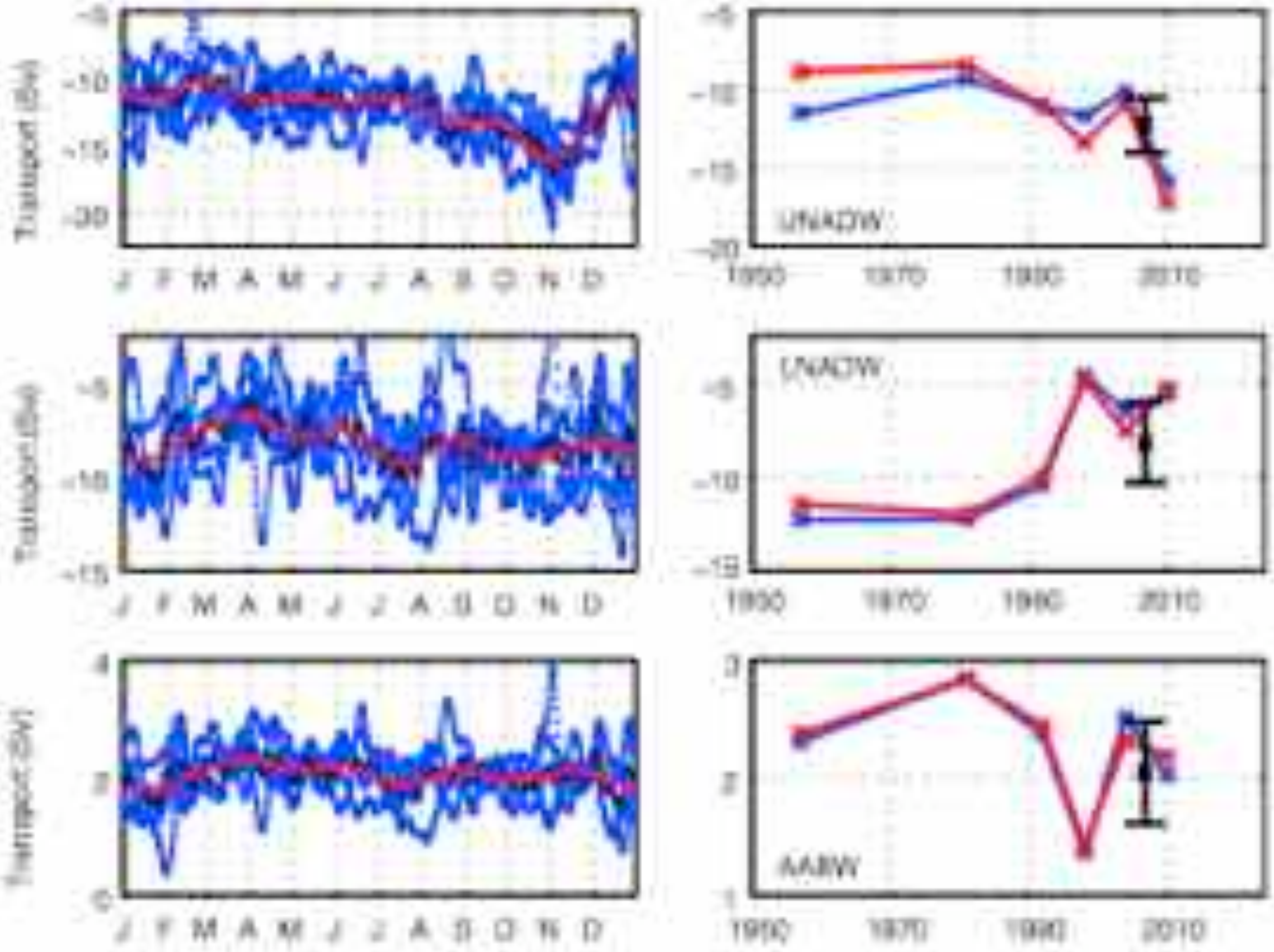


Table 4. Northward transport (Sv) in depth classes for the six hydrographic sections. The upper layer comprises transport in the Ekman layer, Florida Straits and mid-ocean (≤800 m), the lower layer comprises mid-ocean only (>800 m); for full class definitions see Table 3. Ekman transports (zonally integrated across 26° N) and Florida Straits transports are annual averages calculated from wind stress climatologies and cable observations respectively (Sect. 2.3). Net imbalance between upper and lower layer total transports is due to Bering Straits inflow (0.8 Sv) to the North Atlantic.

		1957	1981	1992	1998	2004	2010
Upper	Ekman	4.5	3.7	4.6	5.2	4.5	3.7
	Florida Straits	31.1	31.1	30.3	34.0	31.8	31.5
	Mid-Ocean	–15.9	–18.0	–17.2	–22.2	–23.4	–17.6
	Total	19.7	16.8	17.7	17.0	12.9	17.6
Lower	Intermediate	1.6	1.1	0.7	–0.3	0.8	0.6
	UNADW	–11.8	–9.3	–11.1	–12.9	–10.4	–15.7
	LNADW	–12.6	–12.2	–10.5	–5.8	–6.6	–5.4
	AABW	2.3	2.9	2.4	1.1	2.5	2.1
	Total	–20.5	–17.5	–18.5	–17.9	–13.7	–18.4



Transport (Sv)
-5
-10
-15
-20
J F M A M J J A S O N D
-5
-10
-15
-20
1950
1970
1990
2010
UNADW
Transport (Sv)
-5
-10
-15
LNADW
4
2
0
3
2
1
AABW

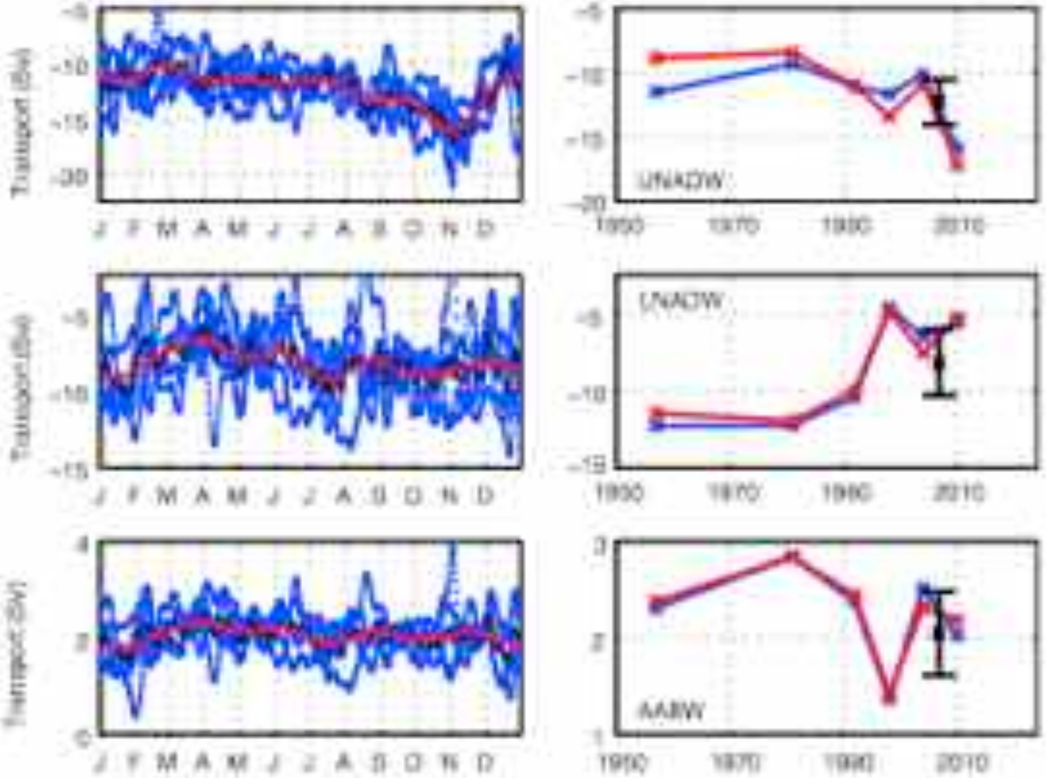


Fig. 8. Left column, seasonal transport cycles (red lines) calculated in depth classes given in Table 3 for five years of Rapid-WATCH data (2004–2009). Blue lines denote each year of data overlaid (10-day low-pass filtered), fine black lines show the 5-year mean of each twice daily value (i.e. all January 1st's, all January 2nd's etc) which are then 60-day low-pass filtered to obtain the seasonal cycle (red lines). Right column, lines denote mid-ocean transport for the 6 hydrographic sections with (red) and without (blue) adjustment for seasonal anomalies. Black bars denote the mean of the Rapid-WATCH data ±1 std. dev. of the de-trended and de-seasonalised 5-year timeseries.

On the basis of 6 hydrographic sections along 26°N, it appears that the net southward flow of Lower North Atlantic Deep Water has decreased from the classical value of 12 Sv (Schmitz and McCartney,1993) to about 6 Sv.

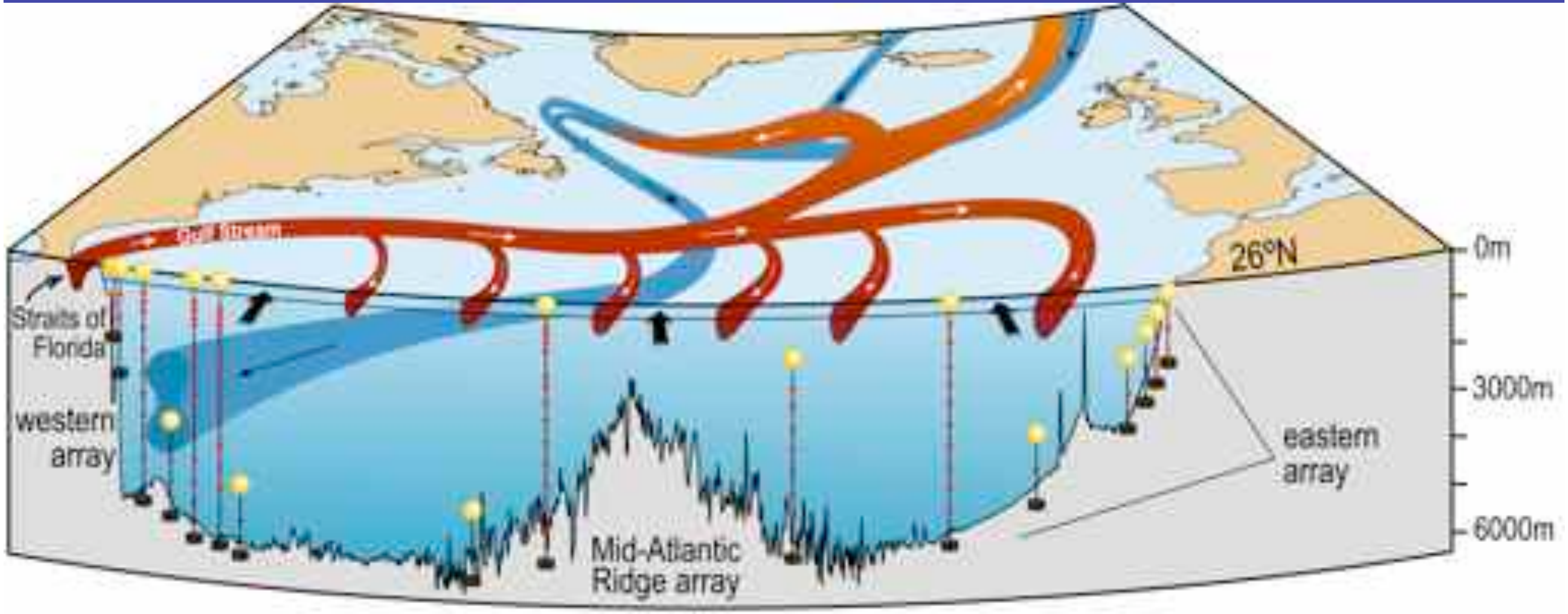
The southward flow of Upper North Atlantic Deep Water appears reasonably steady at 11 Sv but with an increase in the most recent 2010 section to 16 Sv.

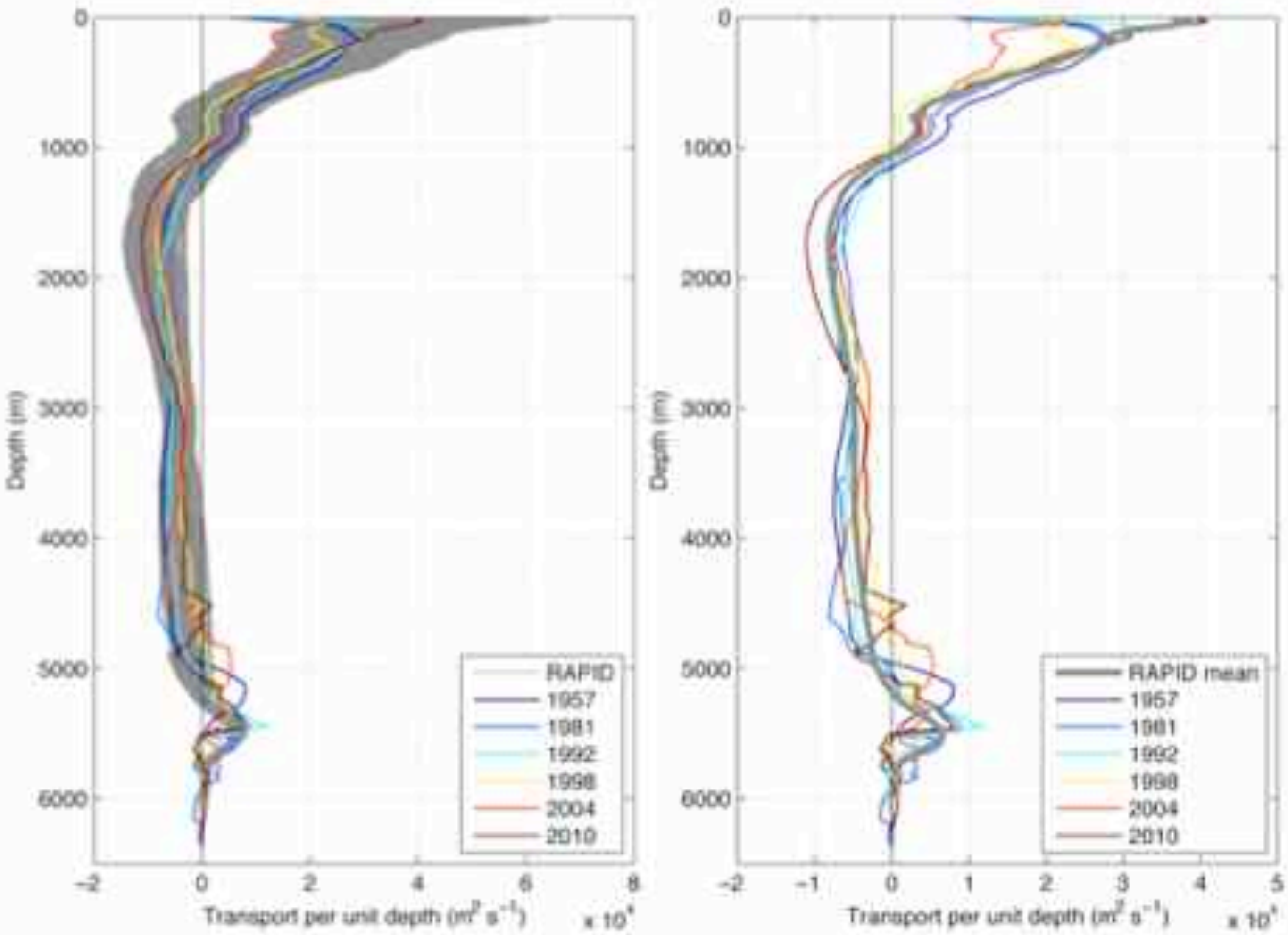
Stability of the deep circulation

We have been monitoring the Atlantic Meridional Overturning Circulation (AMOC) since 2004 with the Rapid array of moored instruments acorss the Atlantic Ocean at 26°N.

Effectively, the array represents a continuous hydrographic section to define the structure and variability of the meridional flow on a basin-scale basis.

Schematic of North Atlantic circulation with Rapid monitoring array at 26°N





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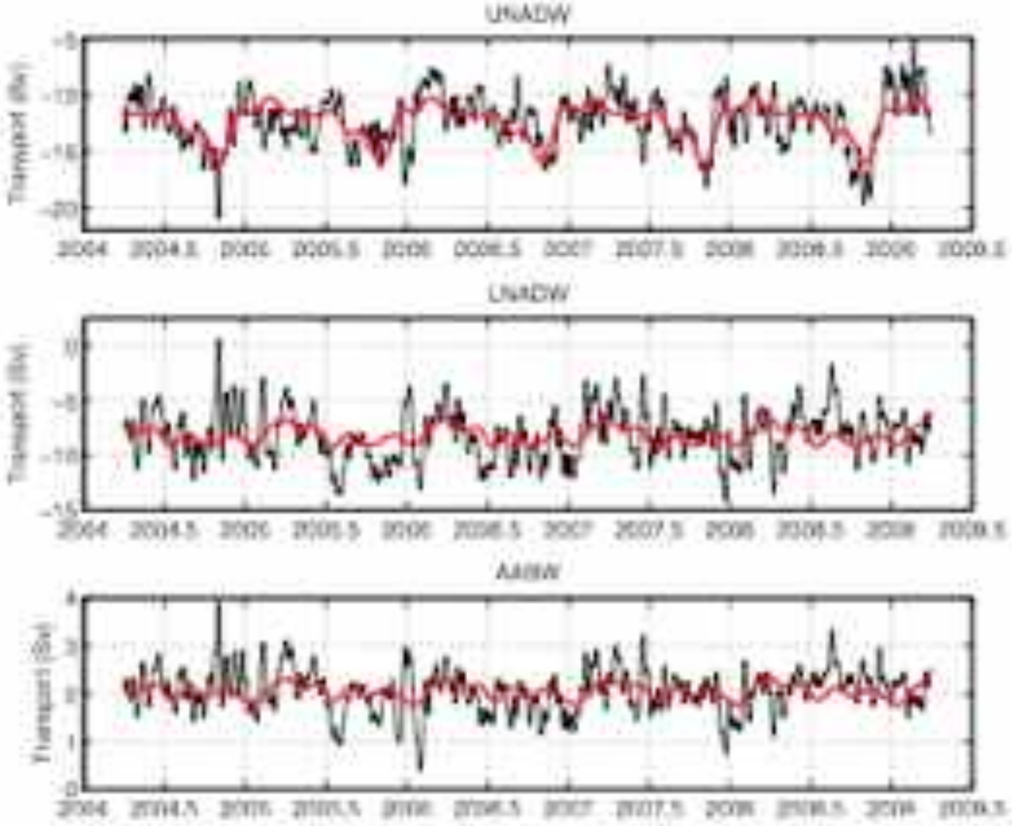
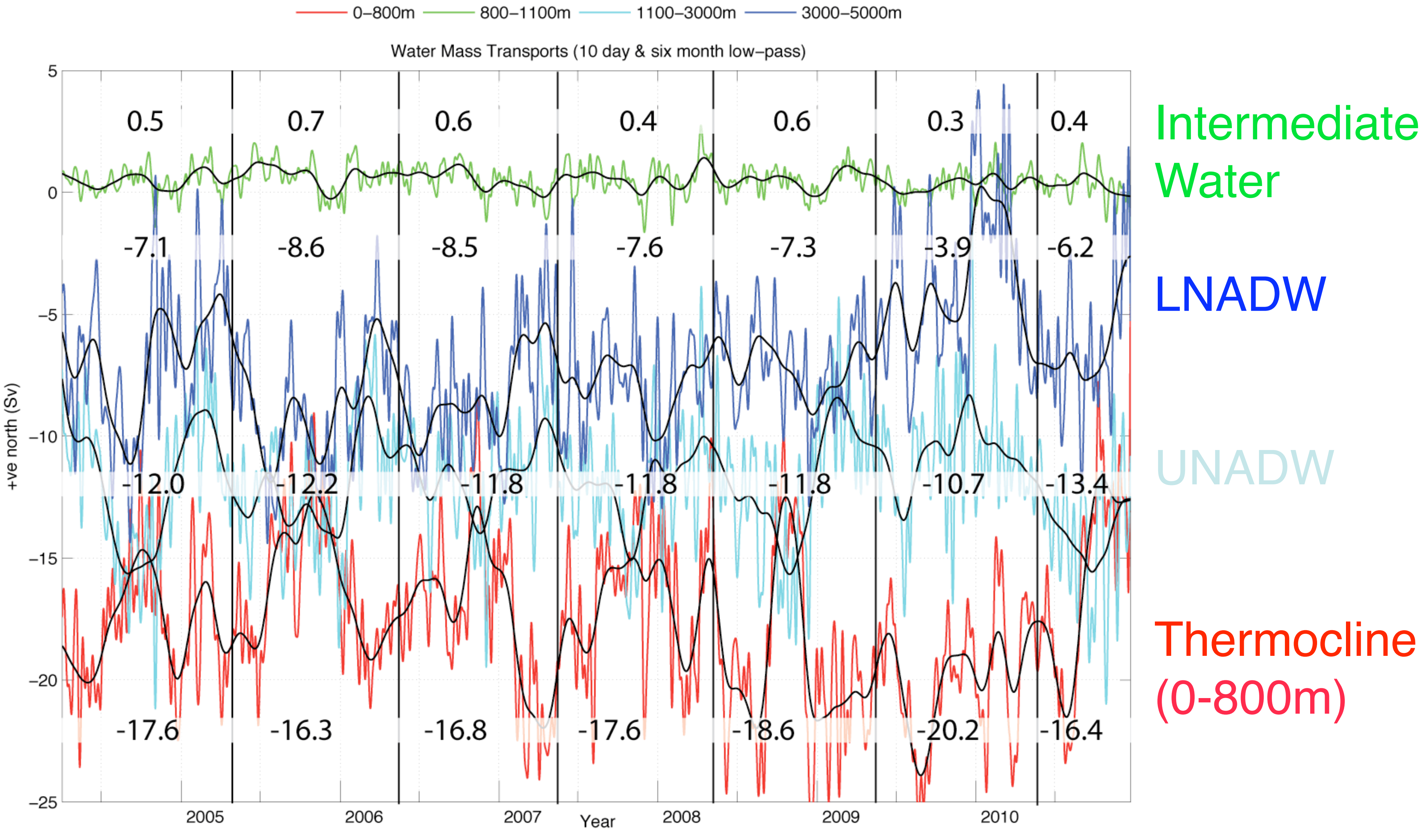


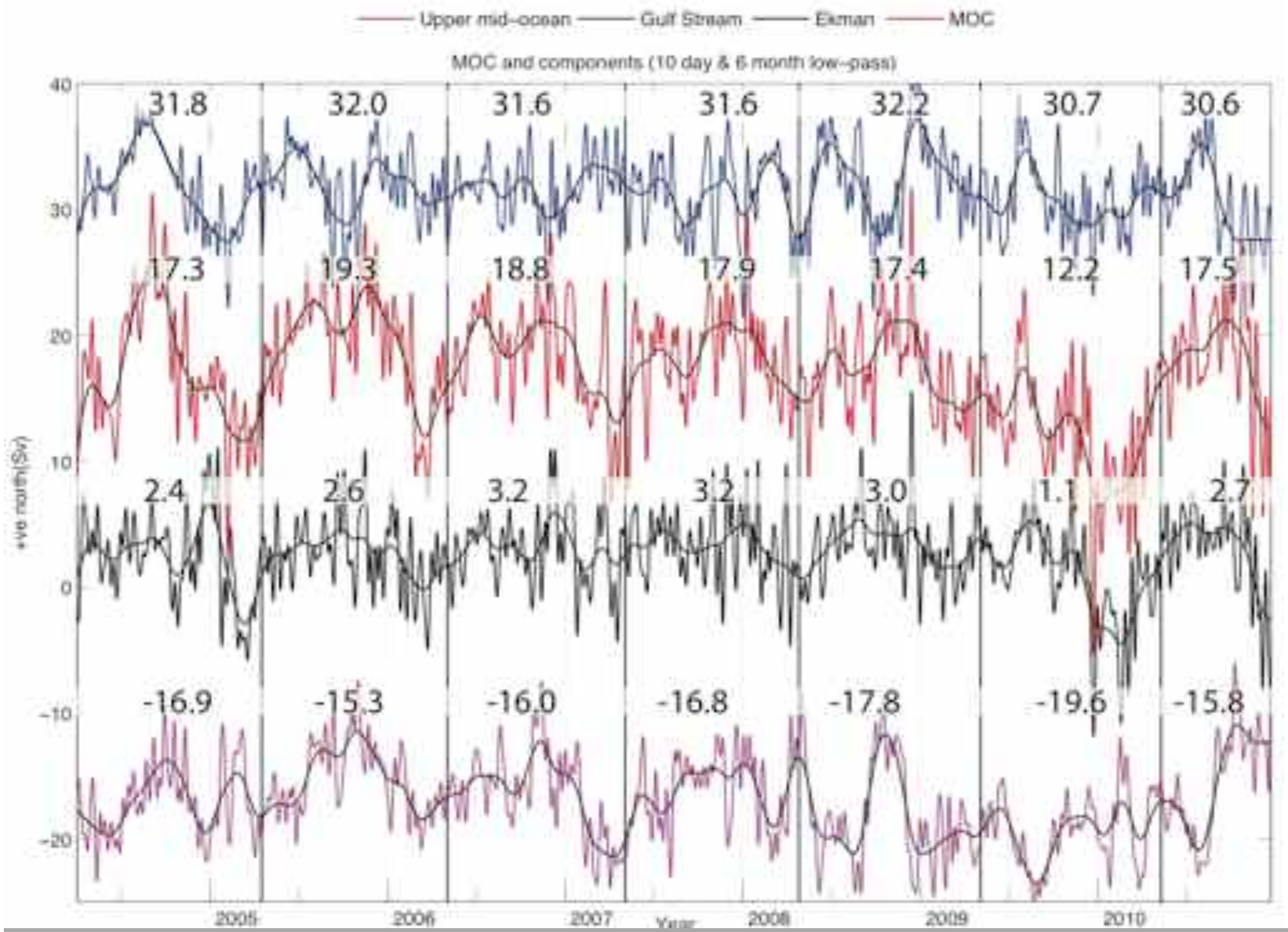
Fig. 7. April 2004–April 2009 Rapid-WATCH transport timeseries at 26° N (black) with the mean seasonal cycle overlaid (red). Mid-ocean timeseries are calculated using time-mean Ekman and Florida Straits transports (to isolate mid-ocean variability). Seasonal cycles are calculated from the 5-year mean of each twice daily value (i.e. all January 1st's, all January 2nd's etc) which are then 60-day low-pass filtered to obtain the seasonal cycle.

No trends immediately strike you in UNADW, LNADW or AABW transports: LNADW is consistently about 7 Sv, there is more variability in UNADW

Water Mass Layer Transports (10-day & 3-month, low-pass filtered) April 2004 to Dec 22nd 2010



Gulf Stream, MOC, Ekman & Upper Mid-Ocean Transports (10-day & 3-month, low-pass filtered) April 2004 to Dec 22nd 2010



Gulf Stream

MOC

Ekman

Mid-Ocean Recirculation

- MOC timeseries and related data products are available from www.noc.soton.ac.uk/rpdmoc
- Data from individual instruments are available from www.bodc.ac.uk

The AMOC stopped for a brief period during 2010;

On a year-long average basis, the AMOC was 30% lower during 2009-2010;

The net southward transport of Lower North Atlantic Deep Water appears to be only half its classical value;

and

The net southward flow of Lower North Atlantic Deep Water has stopped on several occasions.

Could the AMOC stop? Is the present AMOC capable of being in an off state?

Stability of the deep circulation

According to work by Dijkstra (2007) and Drijfhout et al. (2010), the freshwater transport across the southern boundary of the Atlantic Ocean associated with the meridional overturning circulation determines whether the AMOC exhibits multiple equilibria in a wide class of models. They define a quanitity called Mov salinity transport (really the freshwater transport associated with the overturning) as:

$$\mathrm{Mov} = -\,(1/\langle \underline{S} \rangle)\ \int \rho \langle v \rangle(z) \langle S \rangle(z)\, L(z)\, dz$$

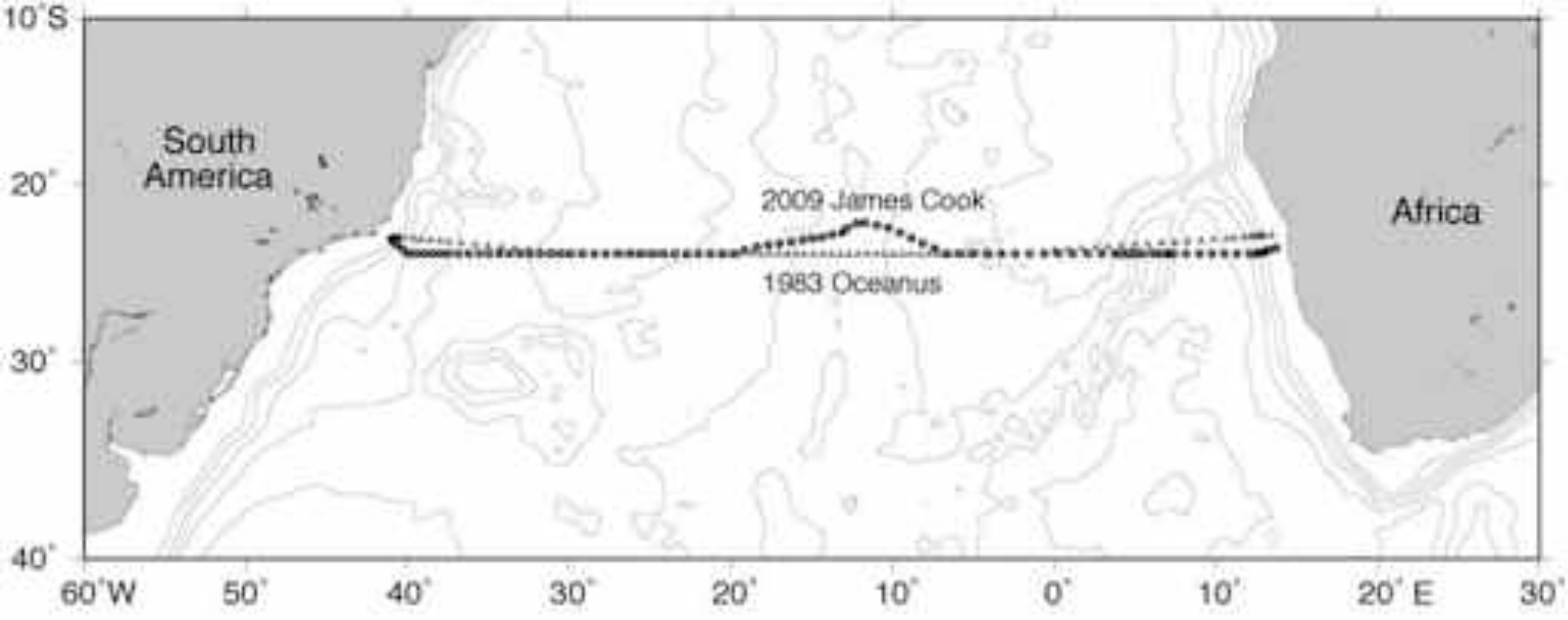
Where $\langle \underline{S} \rangle$ is the section-averaged salinity and $\langle \underline{v} \rangle$ and $\langle \underline{S} \rangle$ are zonally averaged baroclinic velocity and salinity and L is the width of the section.

If Mov is negative, that is the overturning circulation transports freshwater southward, then the theory suggests the MOC is in a state of multiple equilibria, capable of switching from on to off.

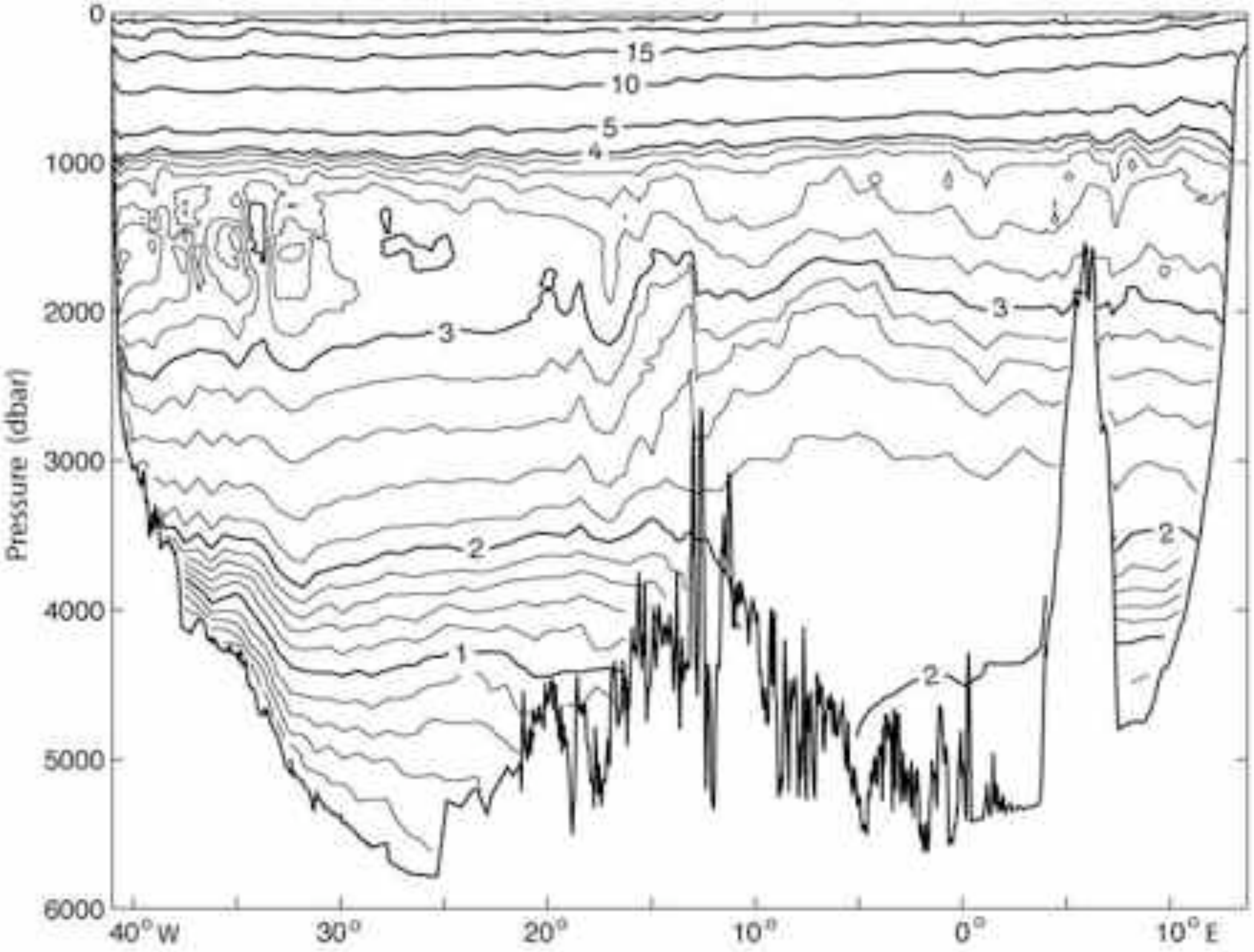
To determine the Mov salinity transport, we made a transatlantic hydrographic section along 24°S during 2009 on board RRS James Cook.

We also examine an earlier 24°S section made in 1983 on board R/V Oceanus.

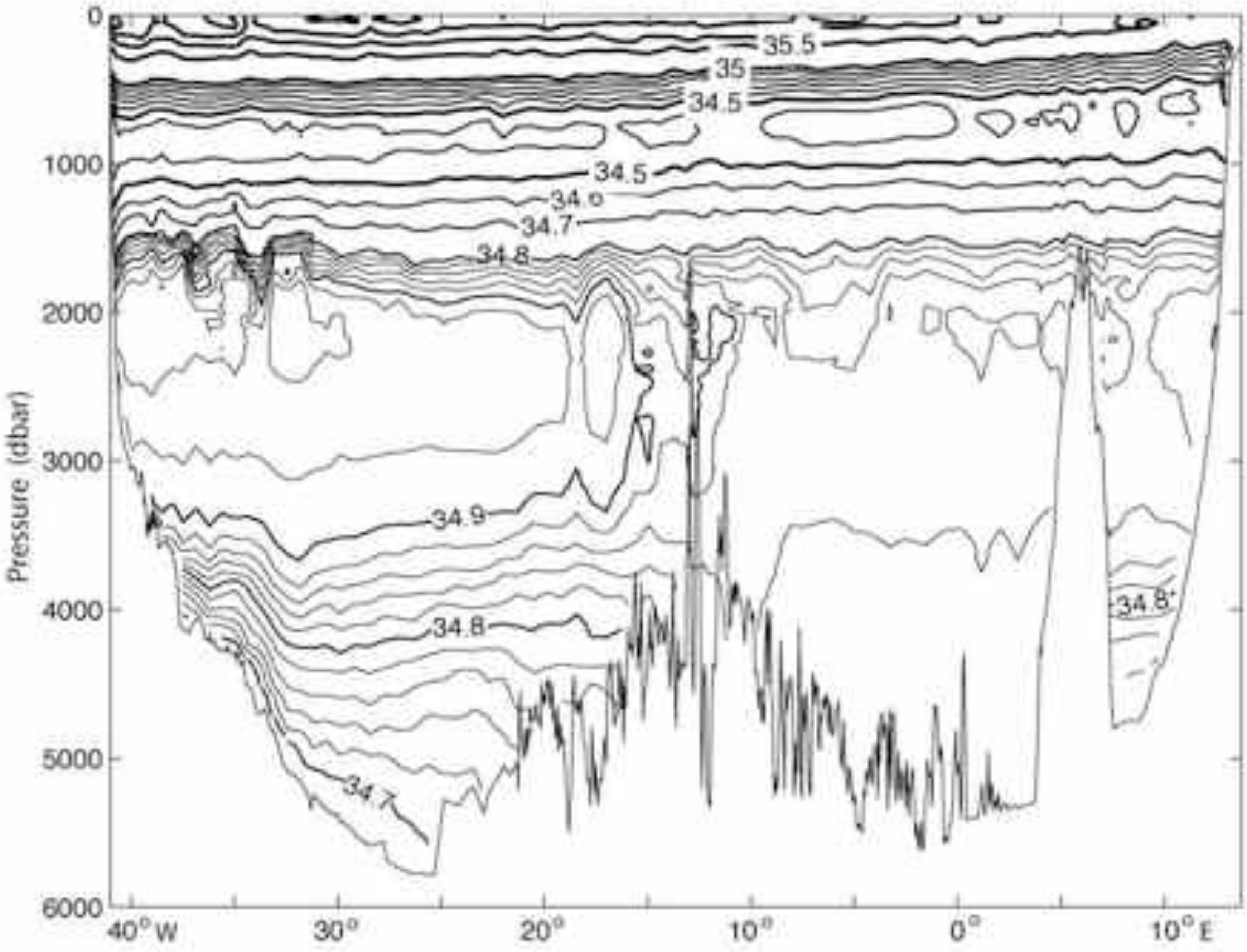
Transatlantic Hydrographic Sections along 24°S



2009 James Cook 24°S Potential Temperature



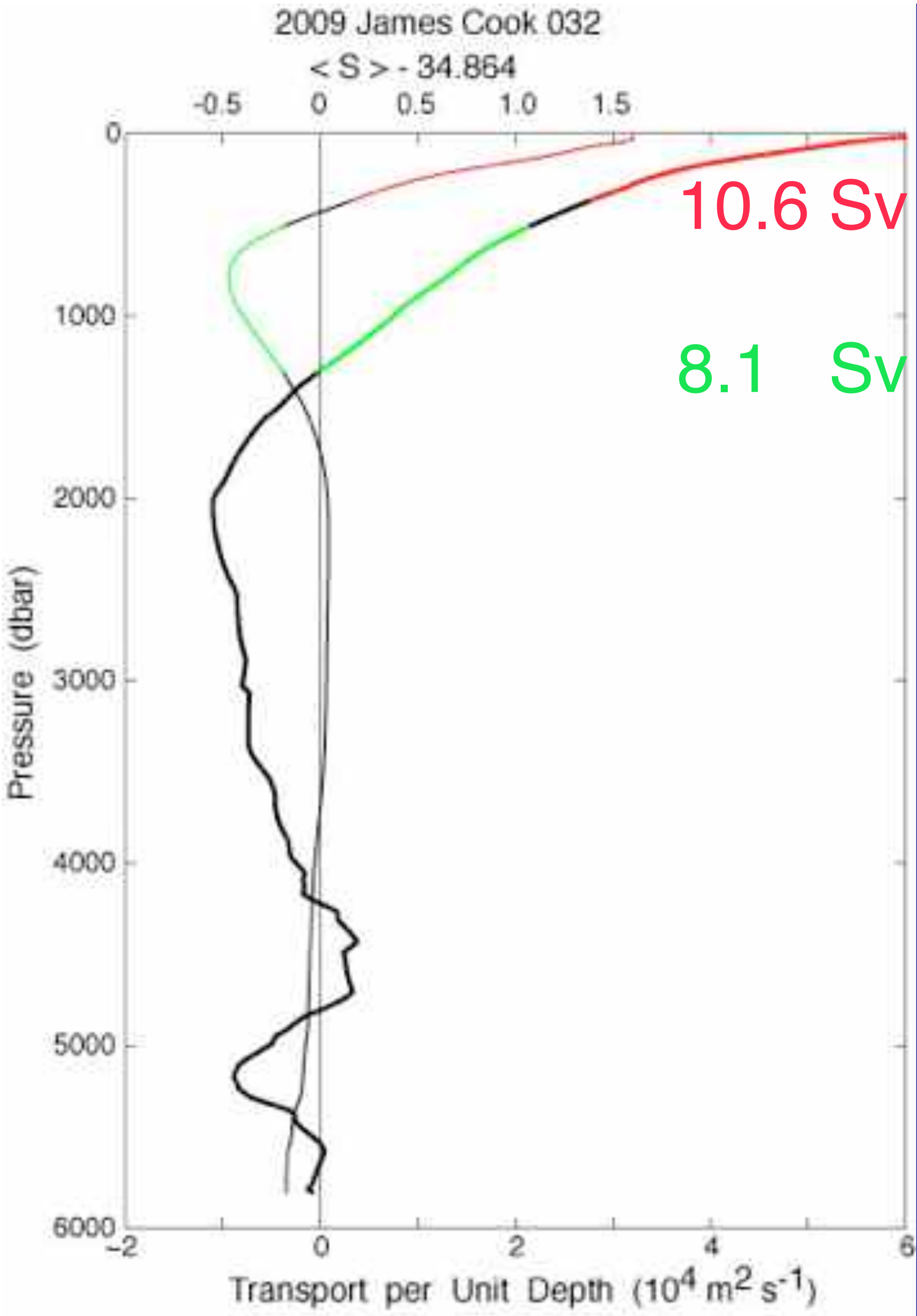
2009 James Cook 24°S Salinity



The traditional view is that the Atlantic is an evaporative basin. In the Atlantic thermohaline circulation, northward flow of relatively fresh Antarctic Intermediate Water (AAIW) is transformed in the North Atlantic via evaporation into saltier North Atlantic Deep Water which is then exported southward out of the Atlantic. Thus the North Atlantic imports freshwater that is then evaporated.

We test this view by examining the salinity of the northward and southward flowing waters at 24°S.

Northward Upper Transport



10.6 Sv Salty Thermocline Flow

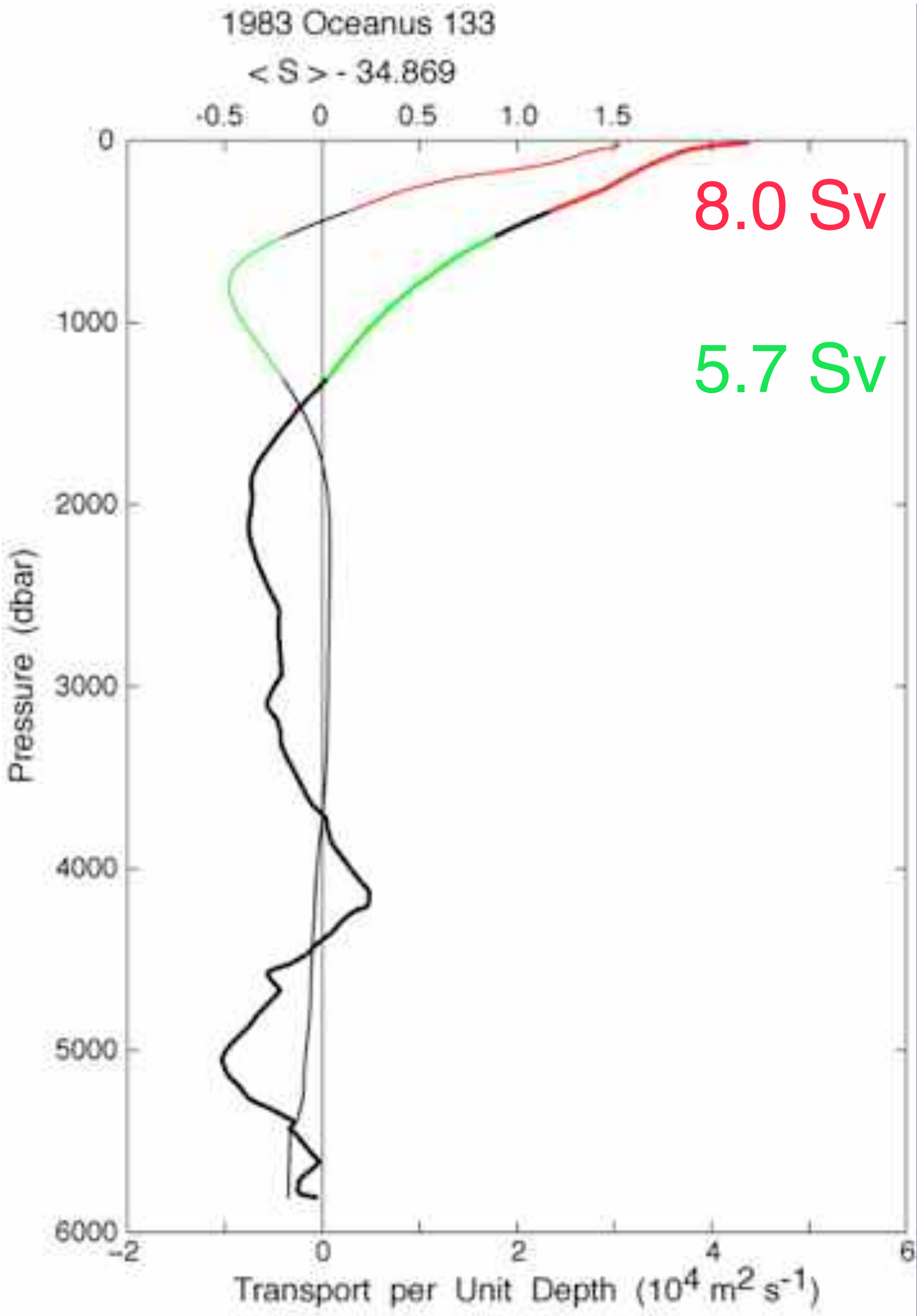
$S > 35$

8.1 Sv Fresh Intermediate Water

$S < 34.68$

James Cook 2009

Northward Upper Transport



8.0 Sv Salty Thermocline Flow

$S > 35$

5.7 Sv Fresh Intermediate Water

$S < 34.68$

Oceanus 1983

Freshwater Transport Convergences for the Atlantic basin bounded by 24°S, Bering Straits, America and Africa-Europe-Asia

	2009 *James Cook*	1983 *Oceanus*
Net Evaporation	0.04 Sv	0.17 Sv

Overall, there is a small northward freshwater flux across 24°S resulting from the salty southward Ekman and Brazil Current transports.

In terms of Mov which is the freshwater transport associated with the thermohaline circulation

$$\mathrm{Mov} = -\,(1/\langle \underline{S} \rangle)\int \rho \langle v \rangle(z) \langle S \rangle(z)\, L(z)\, dz$$

in units of Sv psu or 10^9 kg s^{-1}

Mov	-0.13	-0.09

The overturning circulation transports freshwater southward!

Note the small net evaporation over the Atlantic basin

- Models are generally forced with about 1 Sv Net Evaporation
- Analysis of transatlantic sections at 30°S and 45°S estimate net evaporation over the basin of -0.02 Sv to 0.1 Sv (Saunders and King 1995; Weijer et al., 1999; McDonagh and King 2005)

Mov salt flux is definitely negative

- Upper layer northward flow across 24°S is saltier than the southward deep water return flow of North Atlantic Deep Water
- Waters flowing northward are salty (S > 35‰)upper thermocline waters (58% of northward transport) and fresher (S < 34.68‰) intermediate waters (42% of transport) for both the James Cook and Oceanus sections.

The present Atlantic Meridional Overturning Circulation is capable of Multiple Equilibria and it could shutdown

High salinity flow from the Indian Ocean is the dominant source for northward return flow through the South Atlantic with a transport of 8 to 11 Sv.

Low Salinity AAIW also flows northward with a transport of 6 to 8 Sv.

Warm Water Pathway represents the majority of the return flow for the Atlantic meridional overturning circulation.