

Monitoring the AMOC

Advanced Methods in Oceanography

Lecture 3

For the end of the the lectures you should be able to...

- Describe the consequences of AMOC slowdown
- Describe and derive the state-of-the-art method for monitoring the AMOC
- Describe the current changes in the AMOC.

Monitoring the AMOC

- What is the AMOC?
 - Description
 - Impact on Climate
- Monitoring the AMOC
 - Theory
 - Application
- Current AMOC changes

What is the AMOC?

Origin of the concept:

- 1.Theory* – Stommel (A survey of ocean current theory, Deep-Sea Res, 1958)
- 2.Observations* – Gordon (Interocean exchange of thermocline water, JGR, 1986)
- 3.Paleoclimate* – Broecker (The great ocean conveyor, Oceanography, 1991)

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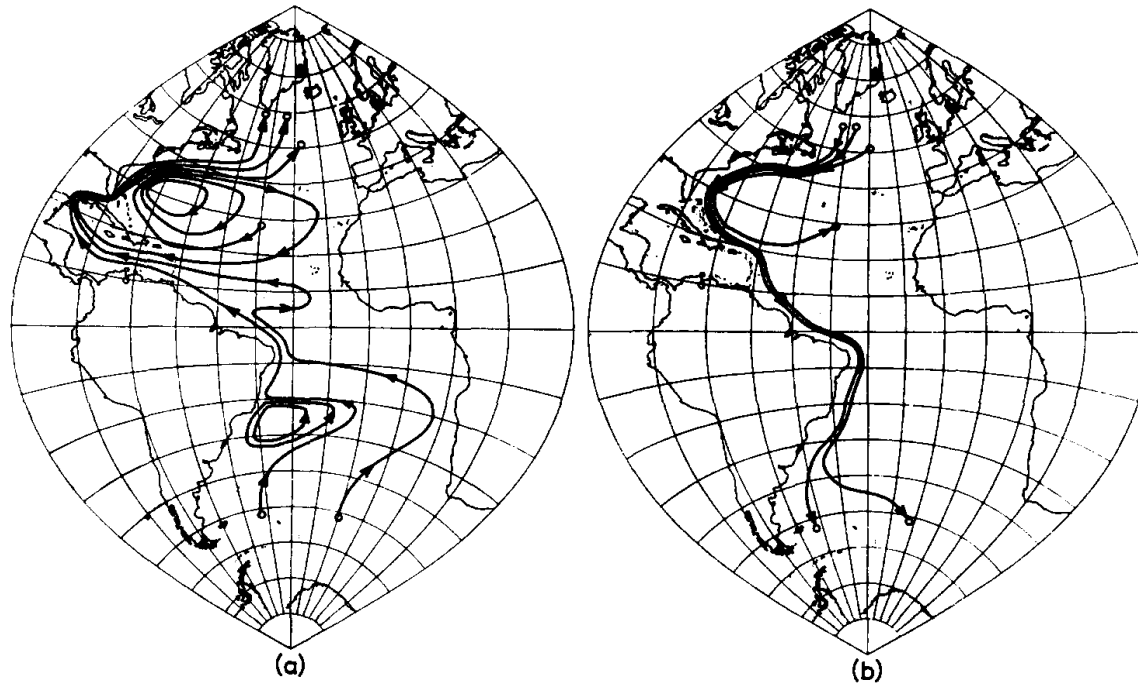


Fig. 10. A similar interpretation of the total transports in the surface layer (a) and bottom layer (b) but drawn on a chart of the Atlantic Ocean. Points of sinking and upwelling across the level surface are indicated by the little circles.

What is the AMOC?

Origin of the concept:

2. *Observations* – Gordon (Interocean exchange of thermocline water, JGR, 1986)

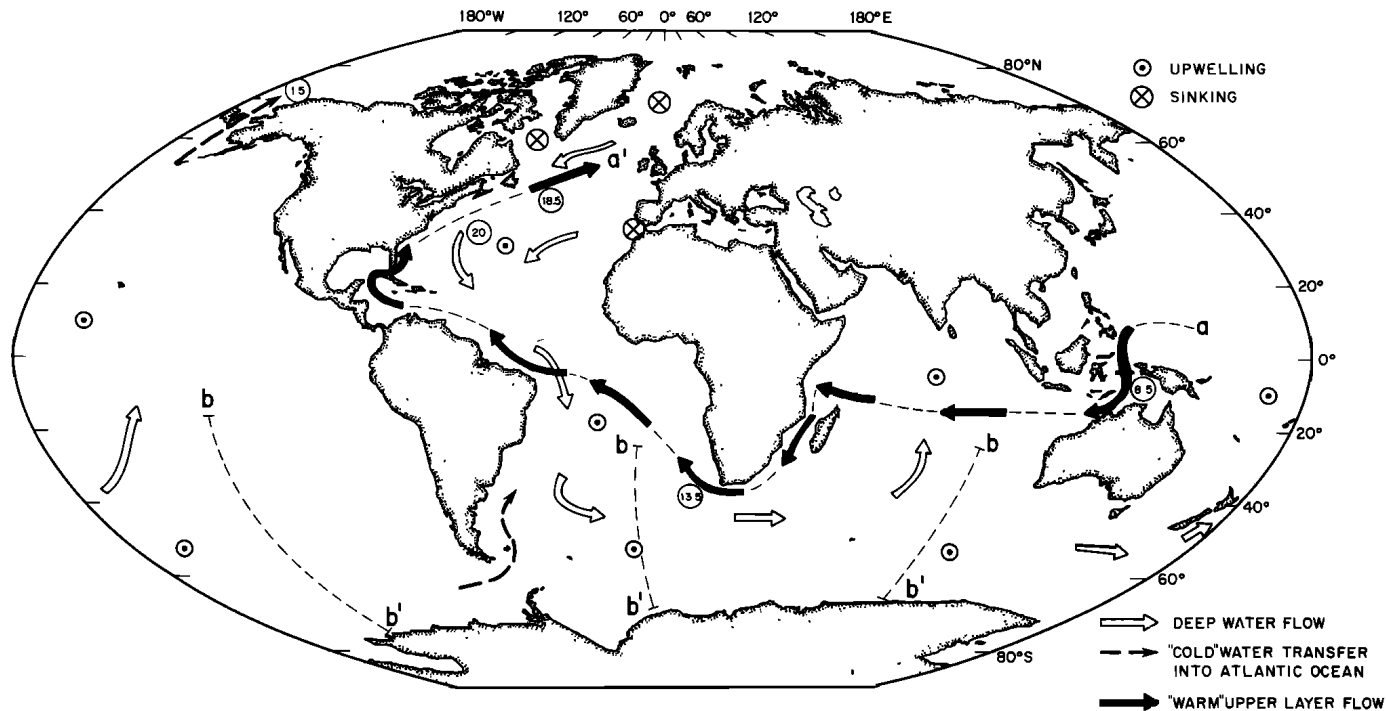


Fig. 2a. Global structure of the thermohaline circulation cell associated with NADW production. The warm water route, shown by the solid arrows, marks the proposed path for return of upper layer water to the northern North Atlantic as is required to maintain continuity with the formation and export of NADW. The circled values are volume flux in $10^6 \text{ m}^3/\text{s}$ which are expected for uniform upwelling of NADW with a production rate of $20 \times 10^6 \text{ m}^3/\text{s}$. These values assume that the return within the cold water route, via the Drake Passage, is of minor significance.

What is the AMOC?

Origin of the concept:

3. *Paleoclimate* – Broecker (The great ocean conveyor, Oceanography, 1991)

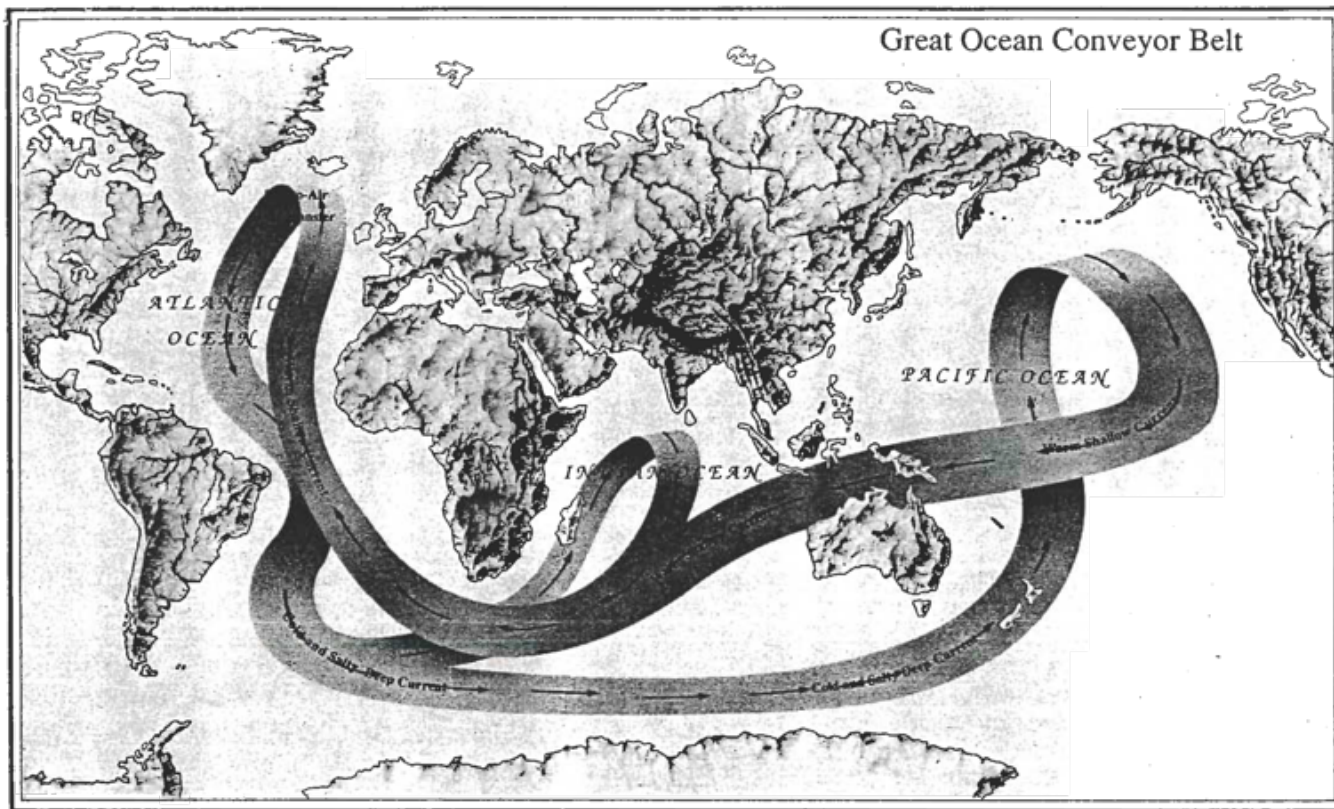
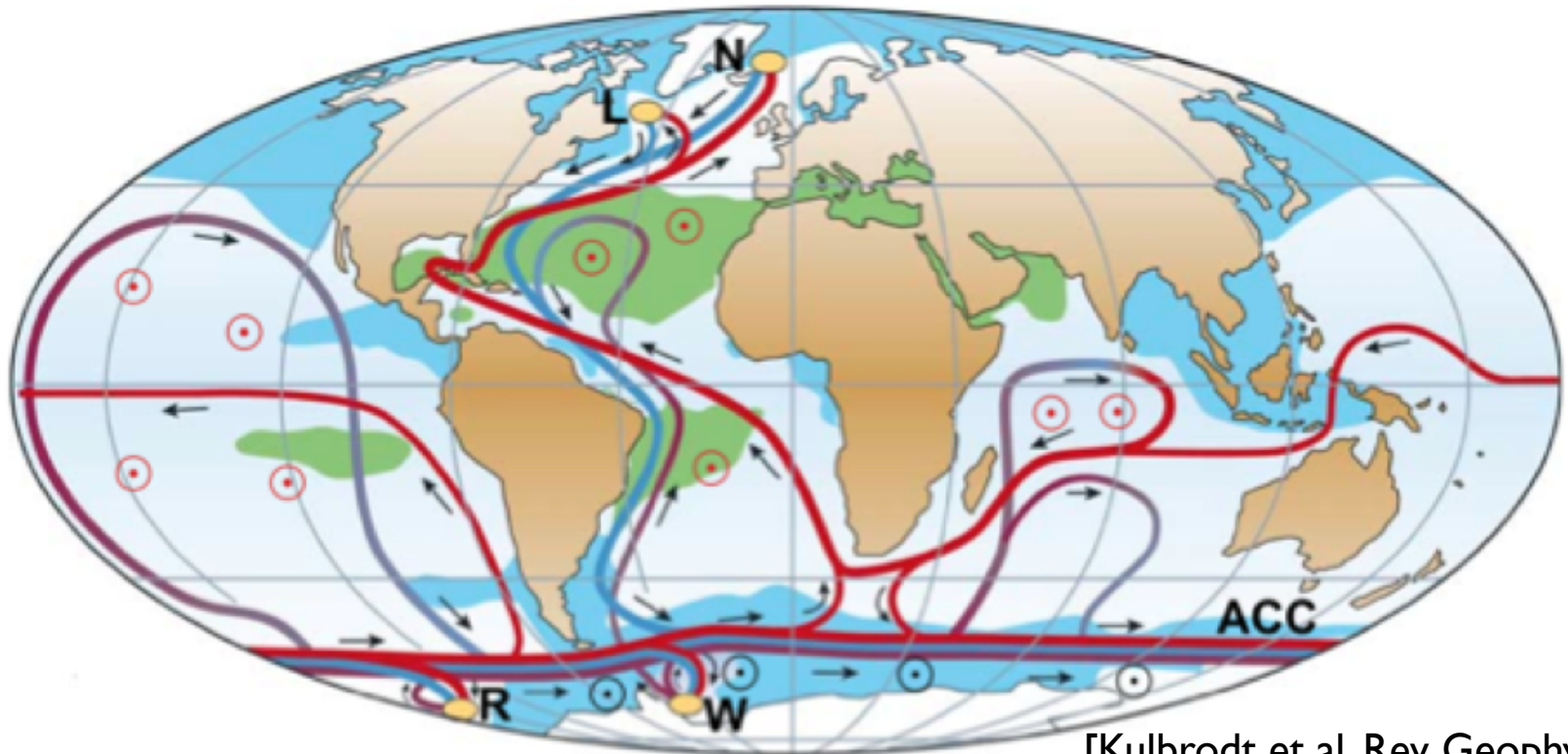


Fig. 1: The great ocean conveyor logo (Broecker, 1987). (Illustration by Joe Le Monnier, Natural History Magazine.)

What is the AMOC?

A more accurate/state-of-the-art vision:



[Kulbrodt et al, Rev Geophys, 2007]

- Surface flow
- Deep flow
- Bottom flow
- Deep Water Formation

- ⊙ Wind-driven upwelling
- ⊙ Mixing-driven upwelling
- Salinity > 36 ‰
- Salinity < 34 ‰

- L Labrador Sea
- N Nordic Seas
- W Weddell Sea
- R Ross Sea

What is the AMOC?

Definition:

How could you define the Atlantic Meridional Overturning Circulation?

What is the AMOC?

Definition:

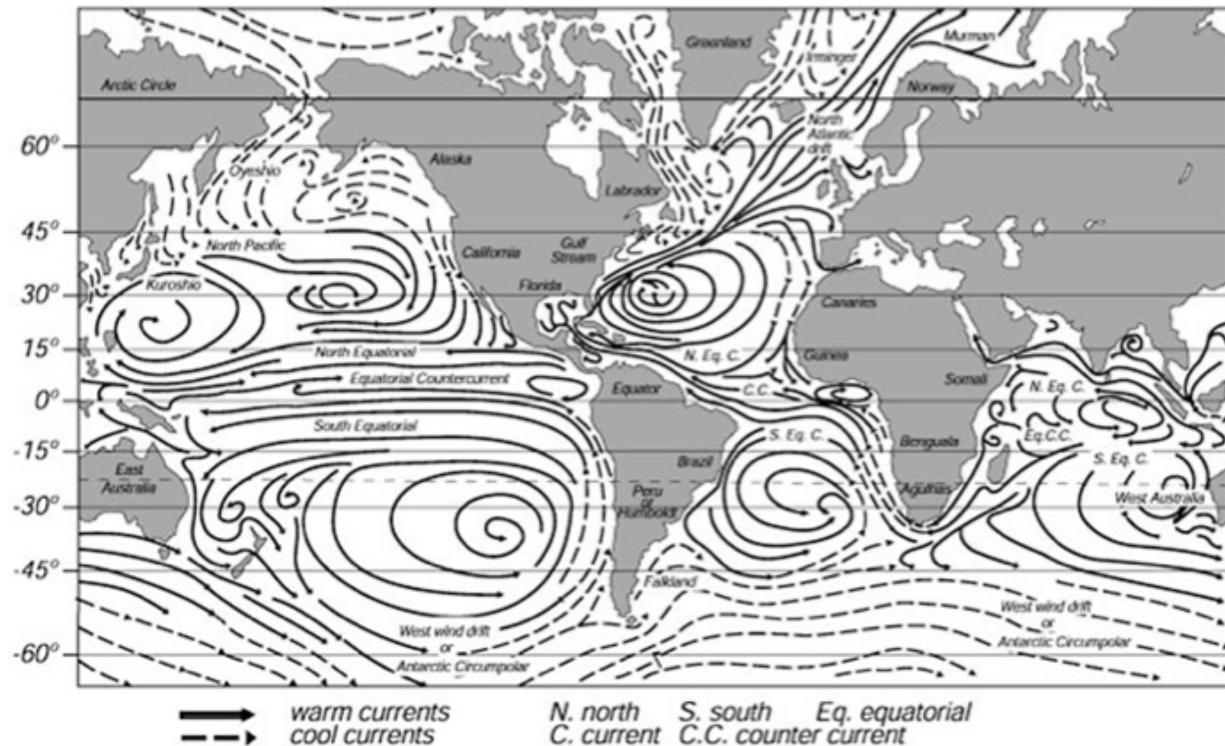
How could you define the Atlantic Meridional Overturning Circulation?

I suggest: the *Residual of the the Zonally-averaged Ocean Circulation*

Because of the wind stress the circulation is primarily horizontal:

- Up to to in 30 Sv in Gyre and
- 125 Sv in ACC

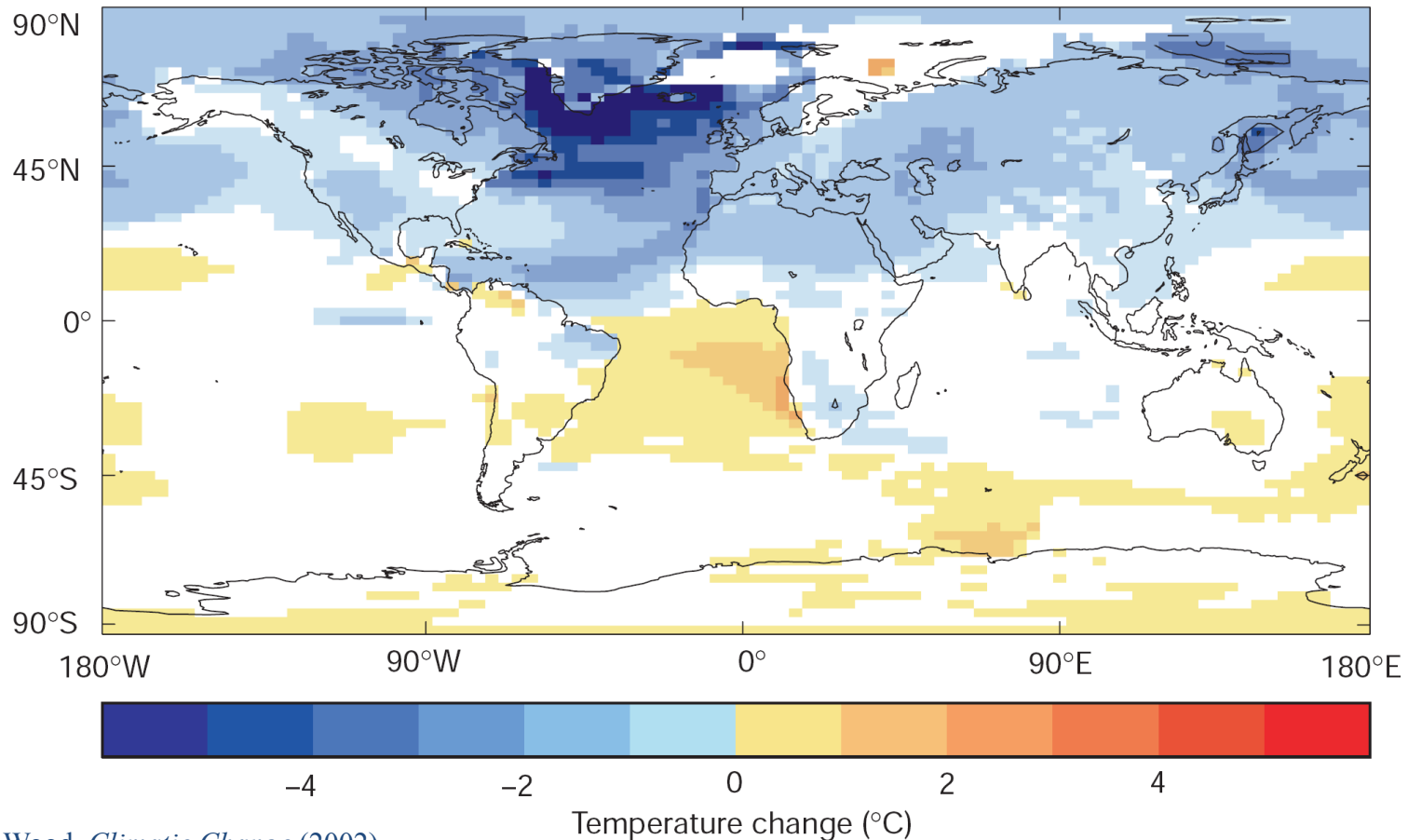
This should be compared with ~18 Sv for the AMOC



What is the AMOC?

Consequence:

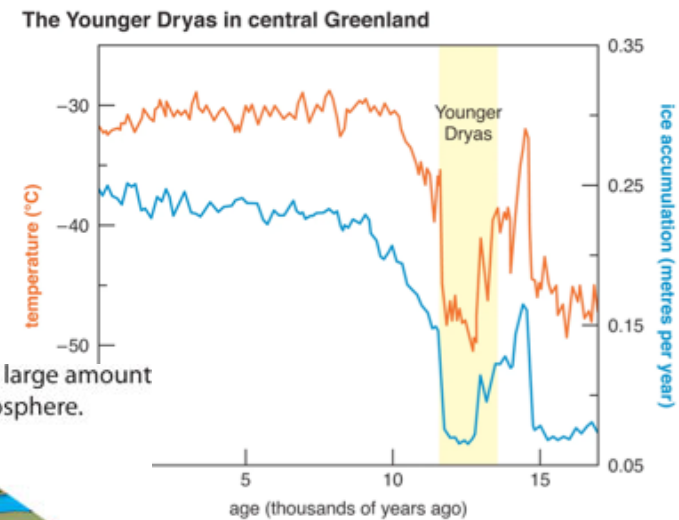
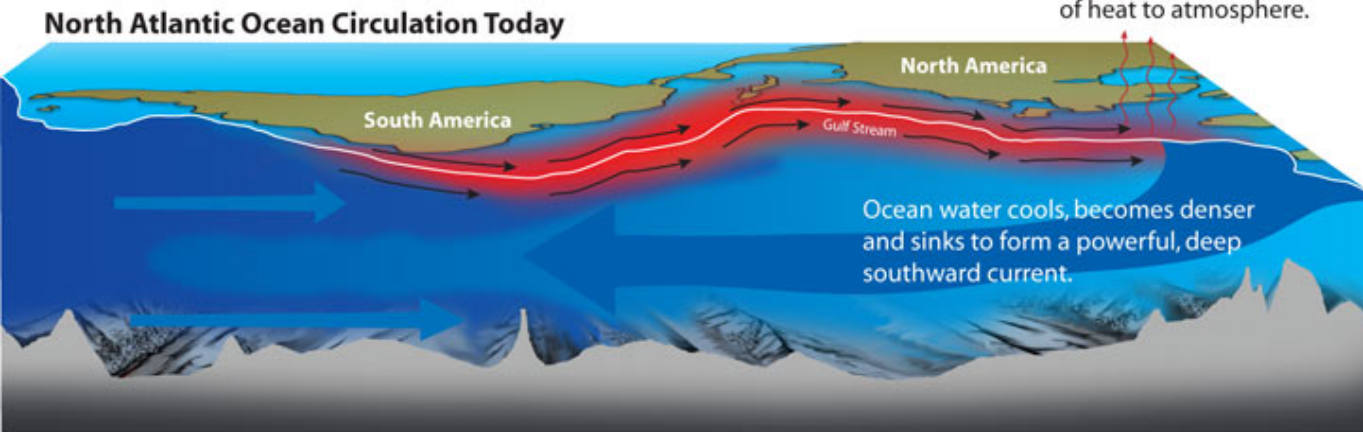
- SAT anomaly 10-20 yr after a forced AMOC shutdown:
 - A large cooling appears all over the Northern hemisphere
 - Europe is cooled by 1-2 K where British and Irish Islands is cooled by 2-4 K



What is the AMOC?

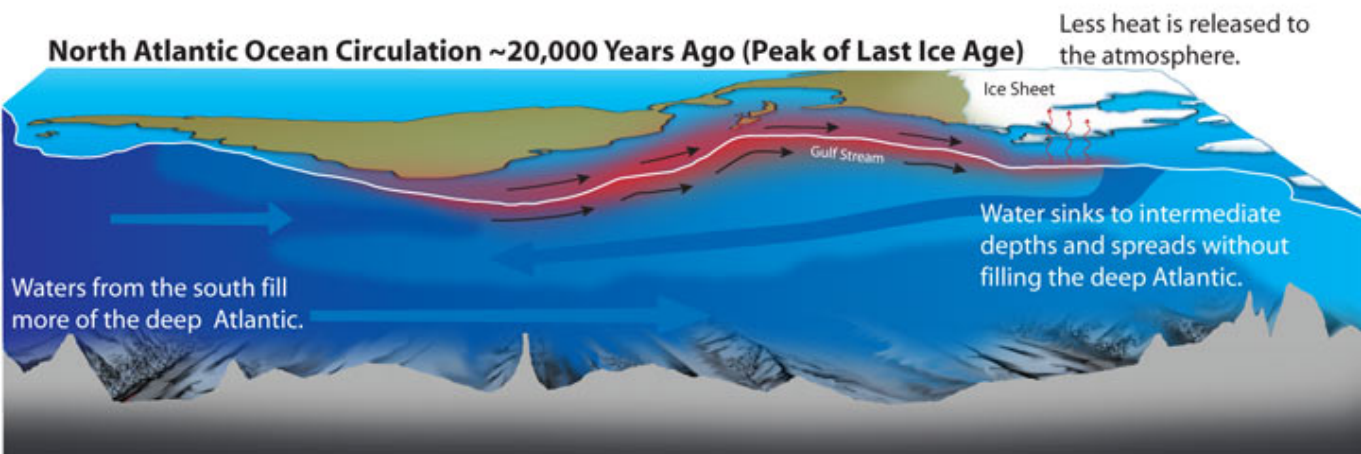
Consequence:

➤ Younger Dryas Events



(source: Lamont-Doherty Earth Obs., 2002)

Warm phase



Cold phase

Slowdown of the AMOC could cool the Northern North Atl.!

McManus et al. (2004)

What is the AMOC?

Summary:

The Atlantic Meridional Overturning Circulation

- It is a Global Scale Circulation;
- With a maximum of ~ 18 Sv;
- It is a residual of the intense horizontal flow after zonal averaging;
- Because of its heat transport (baroclinic circulation through a thermally stratified ocean) it has potentially important consequence on climate.

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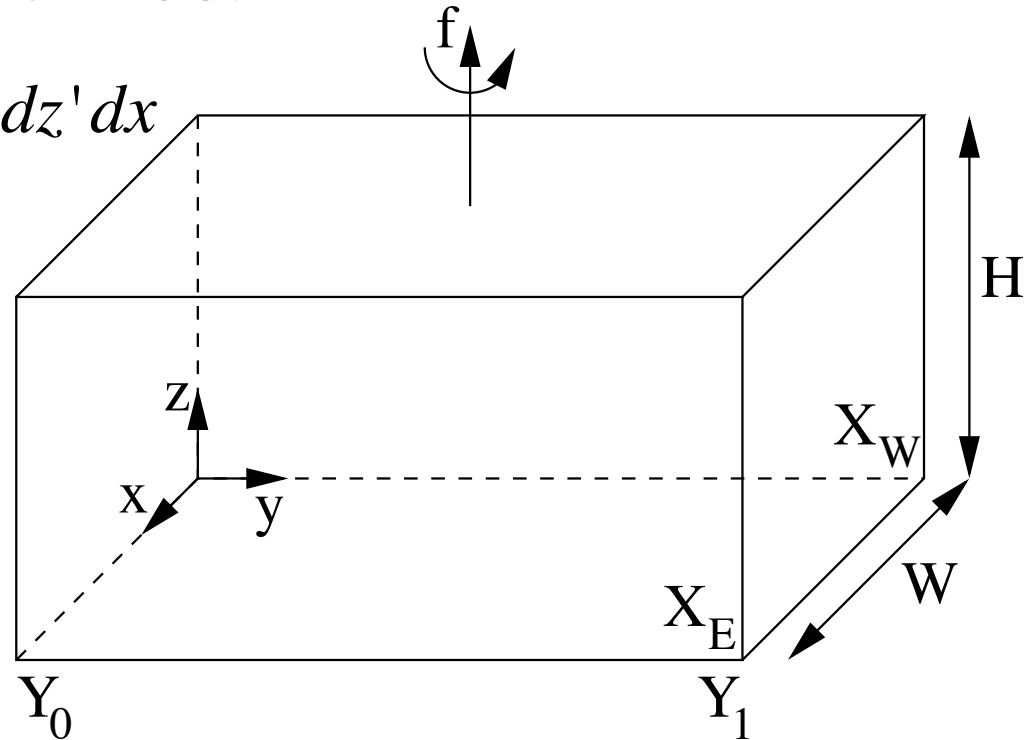
How to mathematically defined the AMOC?

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How to mathematically defined the AMOC?

$$\psi(y, z) = - \iint_{\substack{z'=[-H, z], \\ x=[X_W, X_E]}} v(x, y, z') dz' dx$$

What can we learn from equations on ψ ?



How would you monitor the AMOC? [Discussion in small groups]

- *Why? How?*

Design an efficient monitoring system for the AMOC

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Summary

- We can determine the AMOC if we know:
 - East and West boundary density and
 - the surface wind stress
- Shortcoming:
 - We have a flat bottom ocean → Role of the topography?

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Application to numerical model:

We will investigate the role of Topography through experiments B and D

TABLE 1. Configurations for experiments

Name	Model	Topography
B	MIT	No
D	OCCAM	Yes

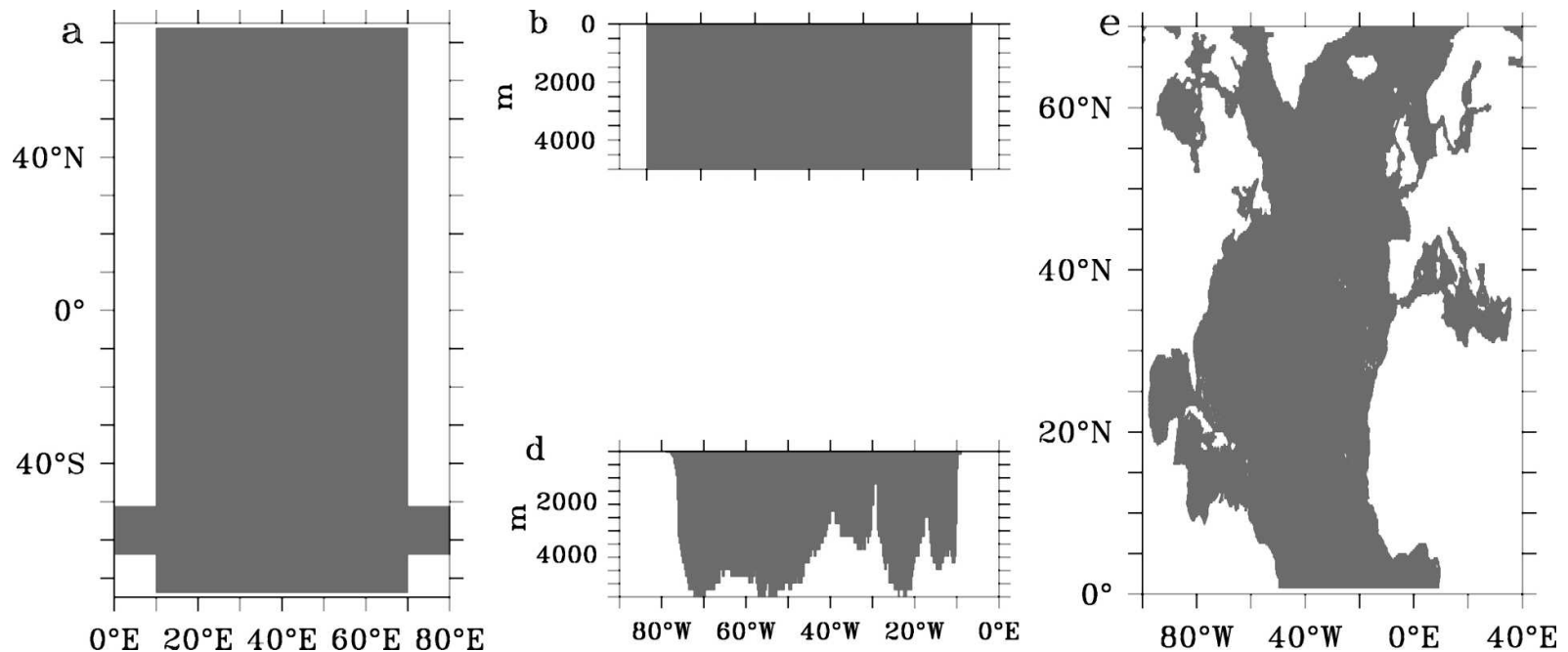
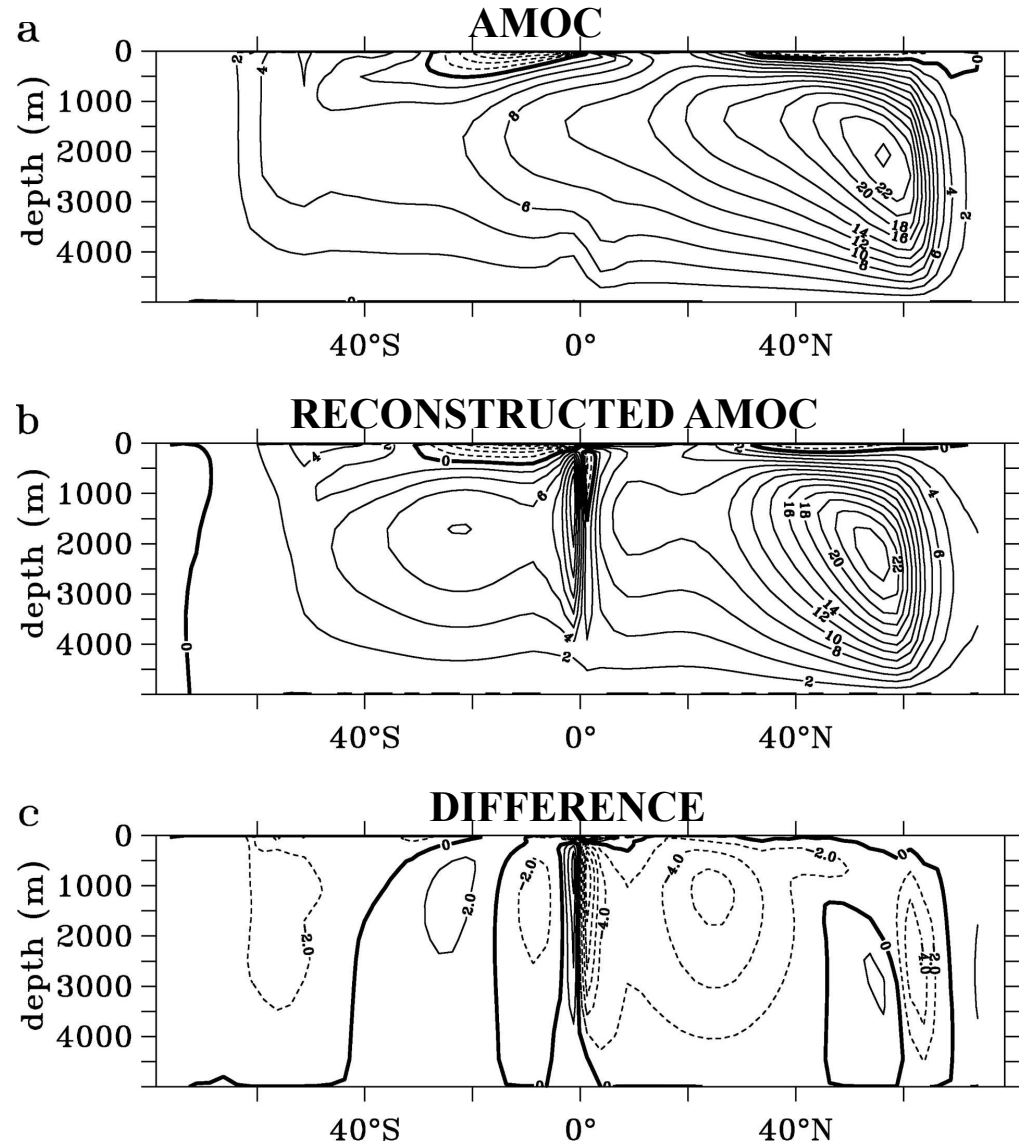


FIG. 1. (a)–(c) Model geometries for the idealized runs (b) without topography. (d), (e) Eddy-permitting model (OCCAM). In the present study we only consider a North Atlantic domain extending from the equator to 70°N. As an illustration (d) shows the topography at 40°N.

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Application to numerical model:
Flat Bottom application (Exp B)

- Except in the equatorial region the circulation is well represented
- In the location of the maximum overturning the error is only a couple of Sv vs 20 Sv for the mean (*i.e.* $\sim 10\%$)



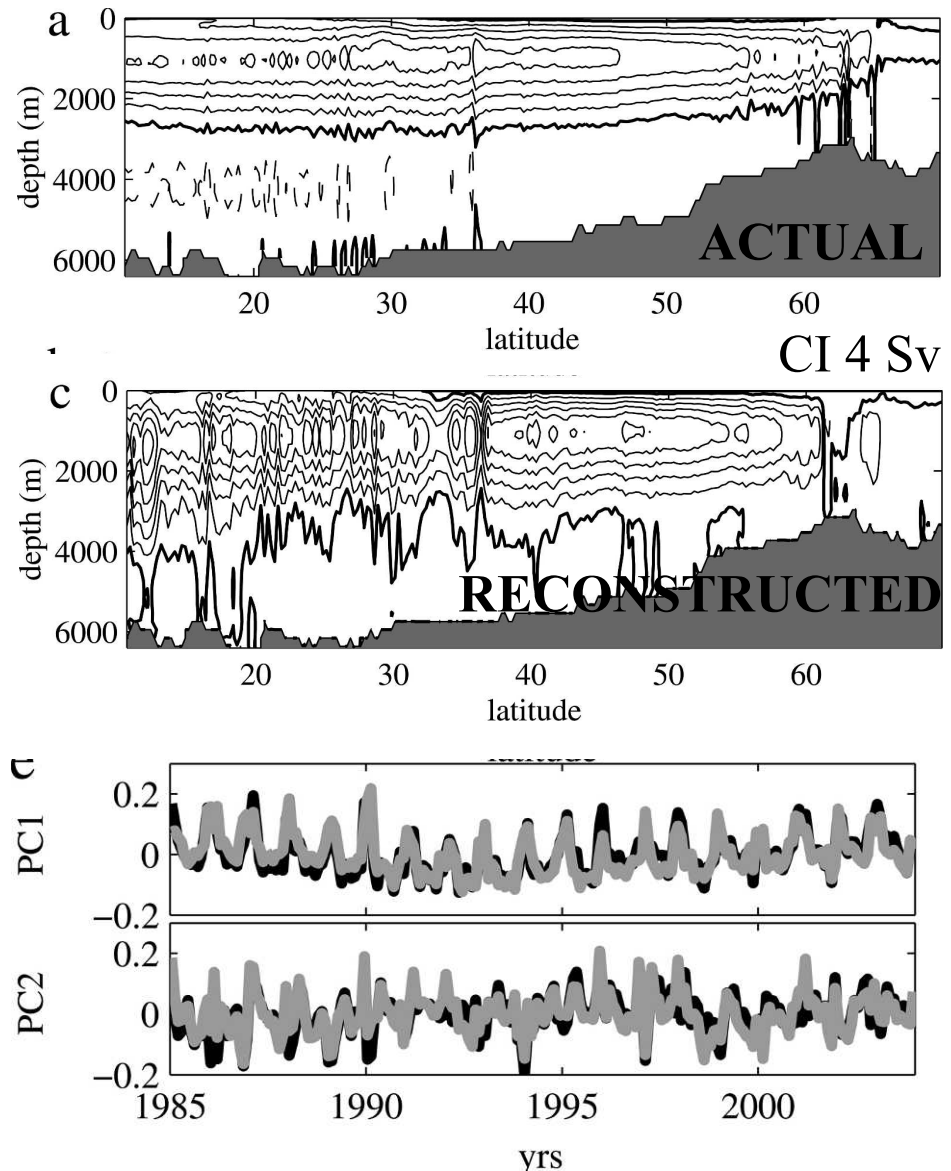
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Application to numerical model:
With Topography

- The qualitative accuracy seem ok, except in the equatorial region the circulation is well represented
- However the error is up to 8 Sv, *i.e.* ~50% of the mean

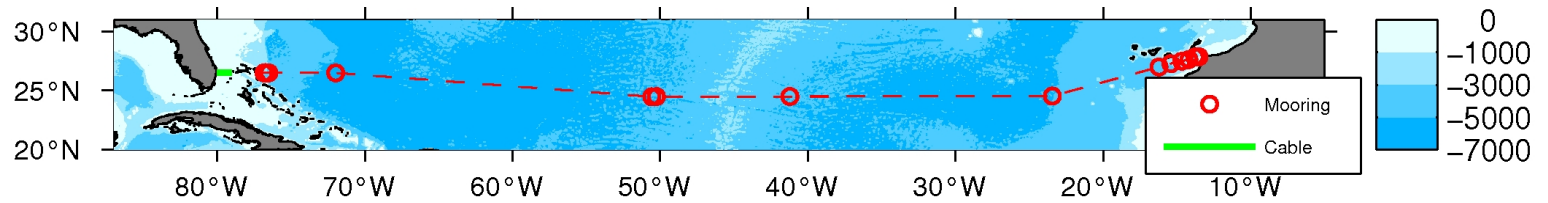
$$w|_{z=-H} \neq 0$$

- The mean is ~wrong but the variability seems accurate!



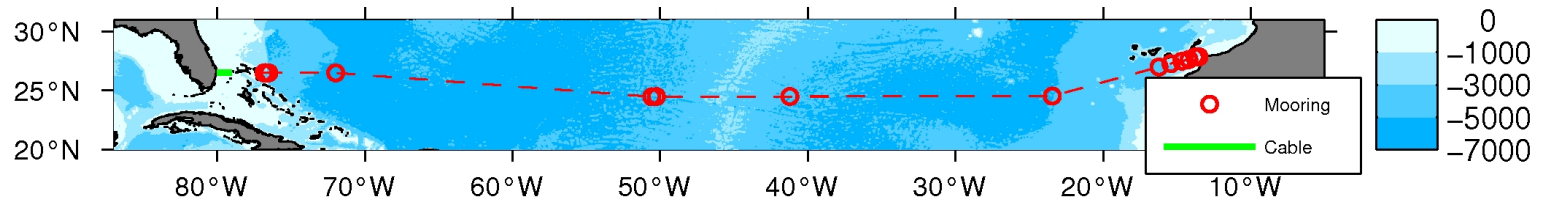
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Application to an *in situ* monitoring system: RAPID



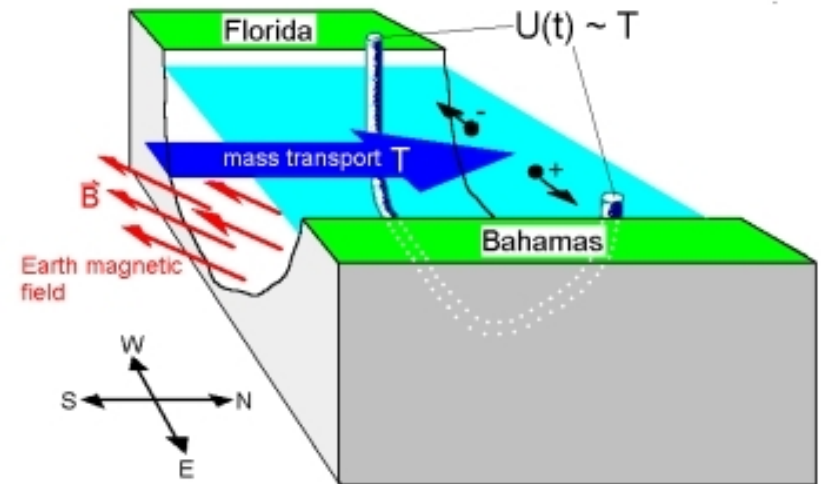
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Application to an *in situ* monitoring system: RAPID



The choice of 26°N:

1. Cable measurements of the Gulf Stream run by NOAA since 1982
1. Previous hydrographic sections (Lecture 1)



Maxwell–Faraday equation
(Faraday's law of induction)

$$\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Time-varying magnetic field is always accompanied by a spatially-varying electric field

- Direct current meter measurements near the Bahamas
- Array focused on boundaries and near topography—more complicated than simple square channel

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Application to an *in situ* monitoring system: RAPID

- **Hardware: The mooring**

Deploying several instruments on a mooring, we can determine the variability of the vertical structure

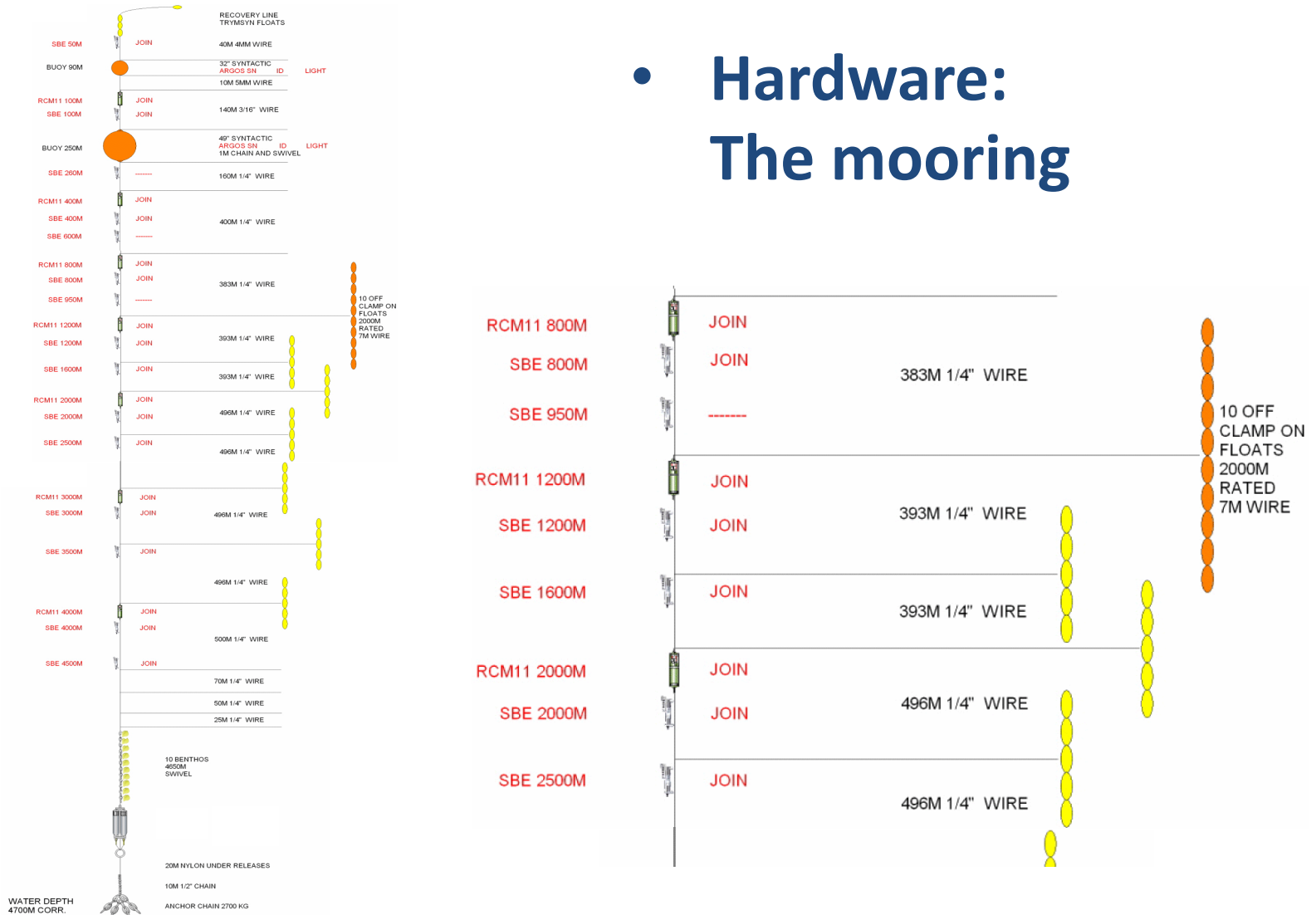


water depth ~5km

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Application to an *in situ* monitoring system: RAPID

- Hardware:
The mooring



water depth ~5km

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Application to an *in situ* monitoring system: RAPID



water depth ~5km

Knorr 2011, WB



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Application to an *in situ* monitoring system: RAPID



- MicroCATS measure conductivity, temperature, depth

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Application to an *in situ* monitoring system: RAPID

- Current meters measure velocity



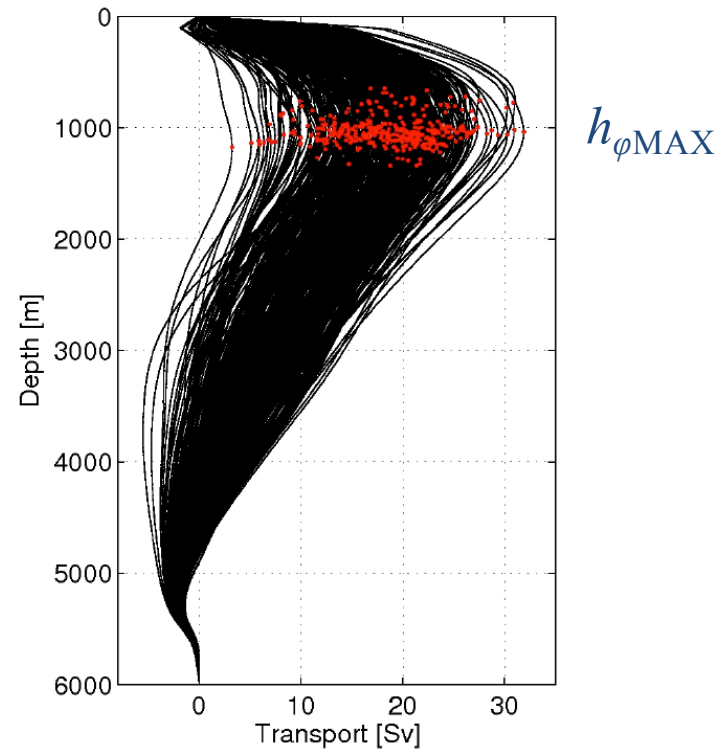
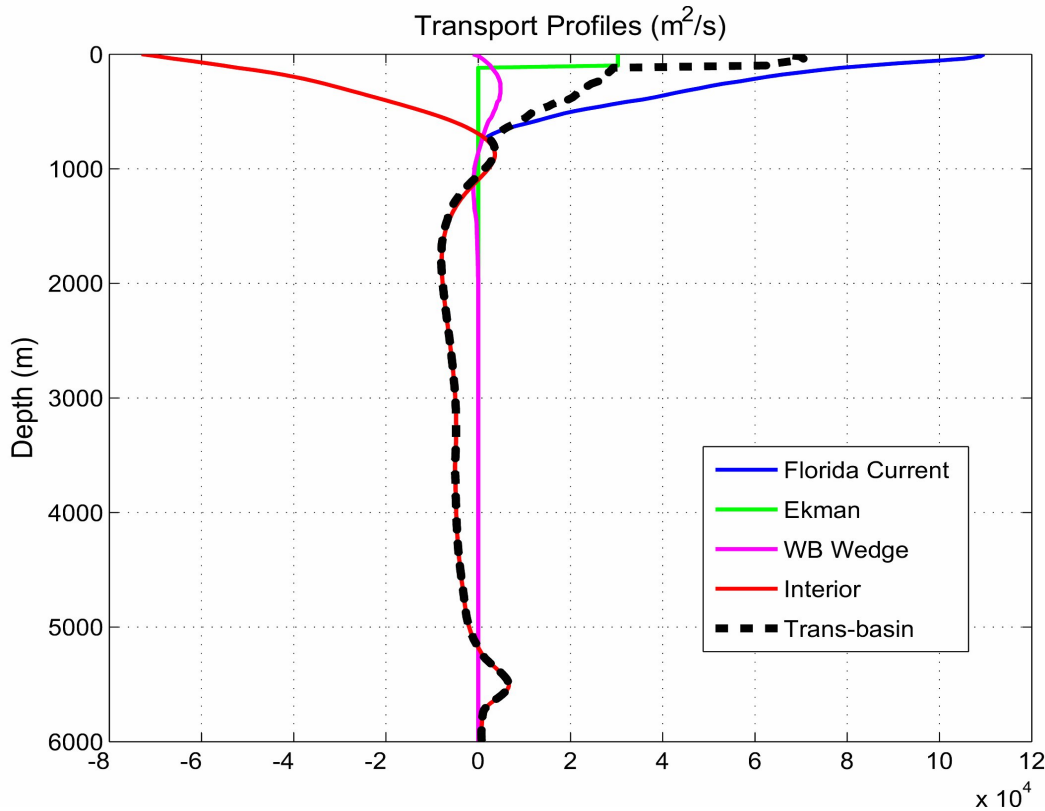
Water depth:
~5km

WATER DEPTH
4700M CORR.



Monitoring the AMOC

Application to an *in situ* monitoring system: RAPID



The AMOC:

$$\varphi_{\text{MAX}}(t) = \int_{h_{\varphi\text{MAX}}}^0 T_{\text{AMOC}}(z, t) dz$$

Here $h_{\varphi\text{MAX}} = 1000$ m is set for the entire analysis...

This is a significant shortcoming!

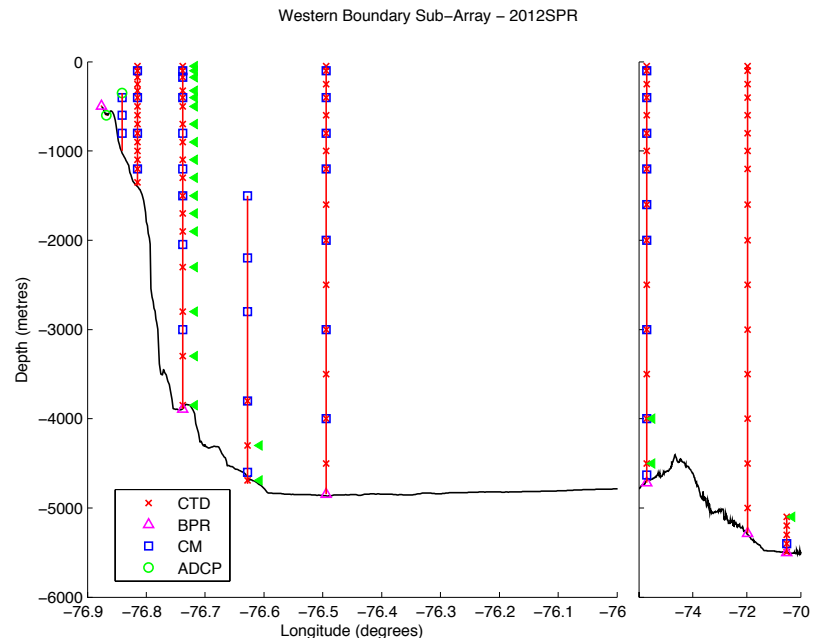
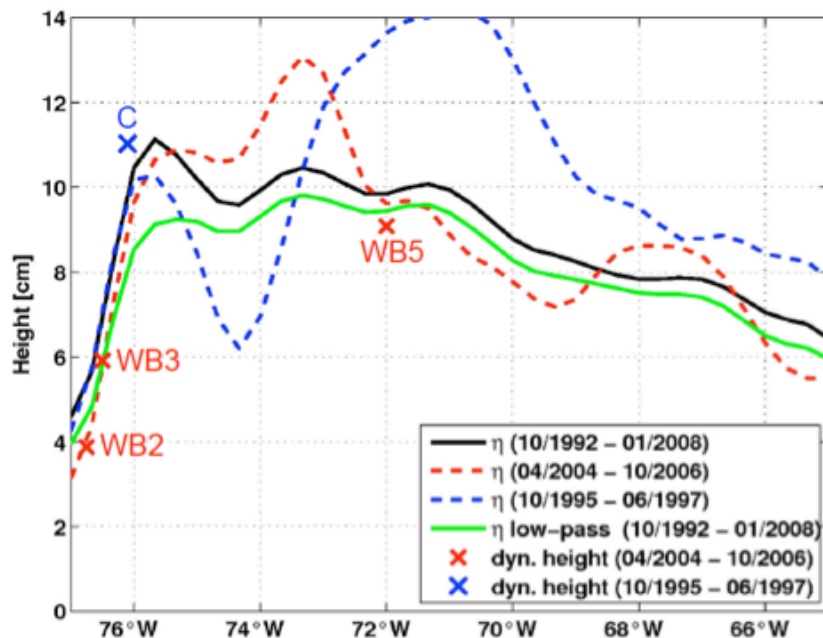
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Application to an *in situ* monitoring system: RAPID

By construction Rapid suffers from a potential major issue.

T_{INT} is virtually only controlled by $\rho|_{East}$ and $\rho|_{West}$

Measurements errors at the boundaries strongly impact the accuracy of T_{INT}



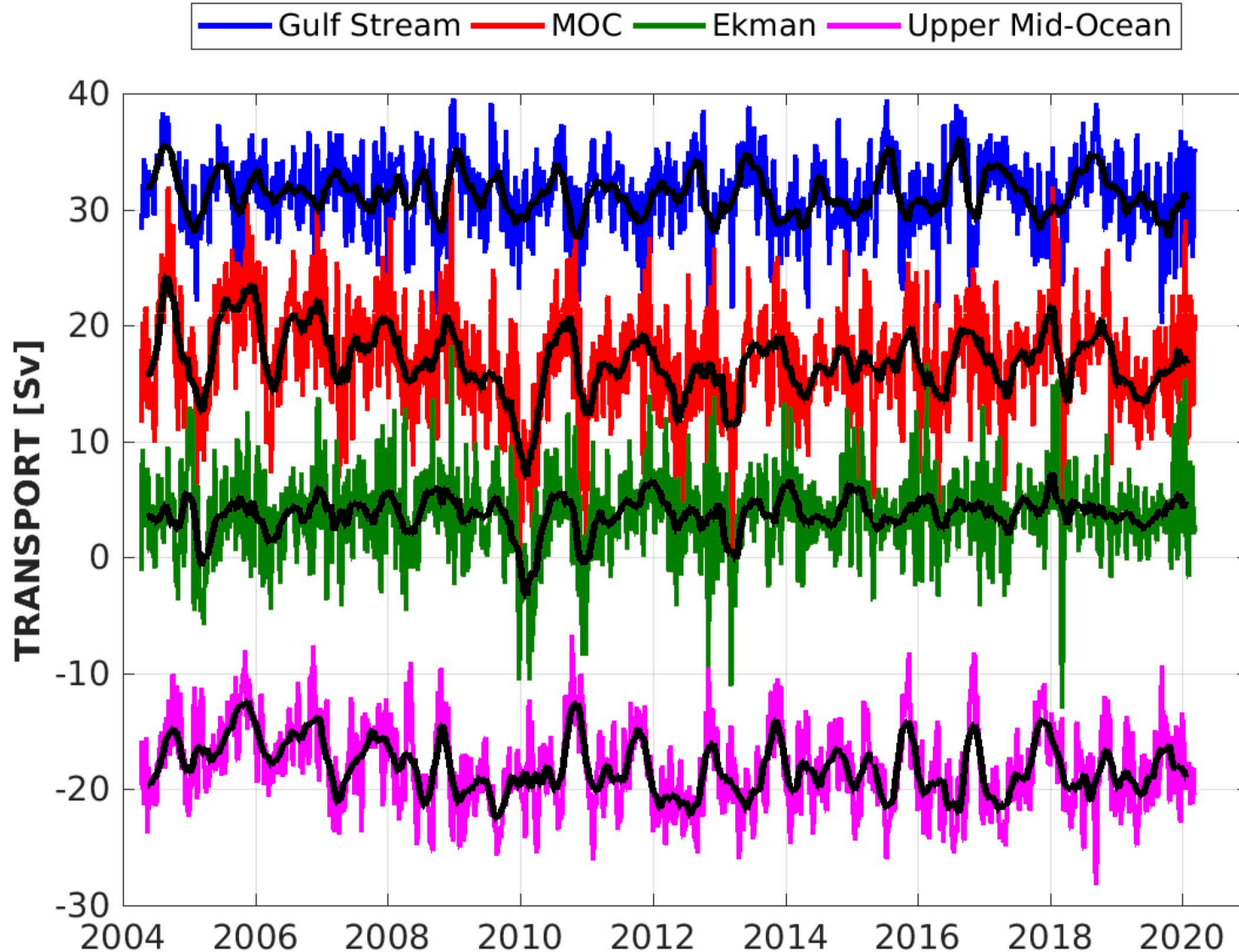
Kanzow et al (JPO, 2009)

Importance of sampling accurately the boundary:

- SSH variability decreases towards close to the western boundary
- We measure a small variance of 4 Sv compared to the interior.
- Measuring away-from coast could over-estimate the actual variability of T_{INT}

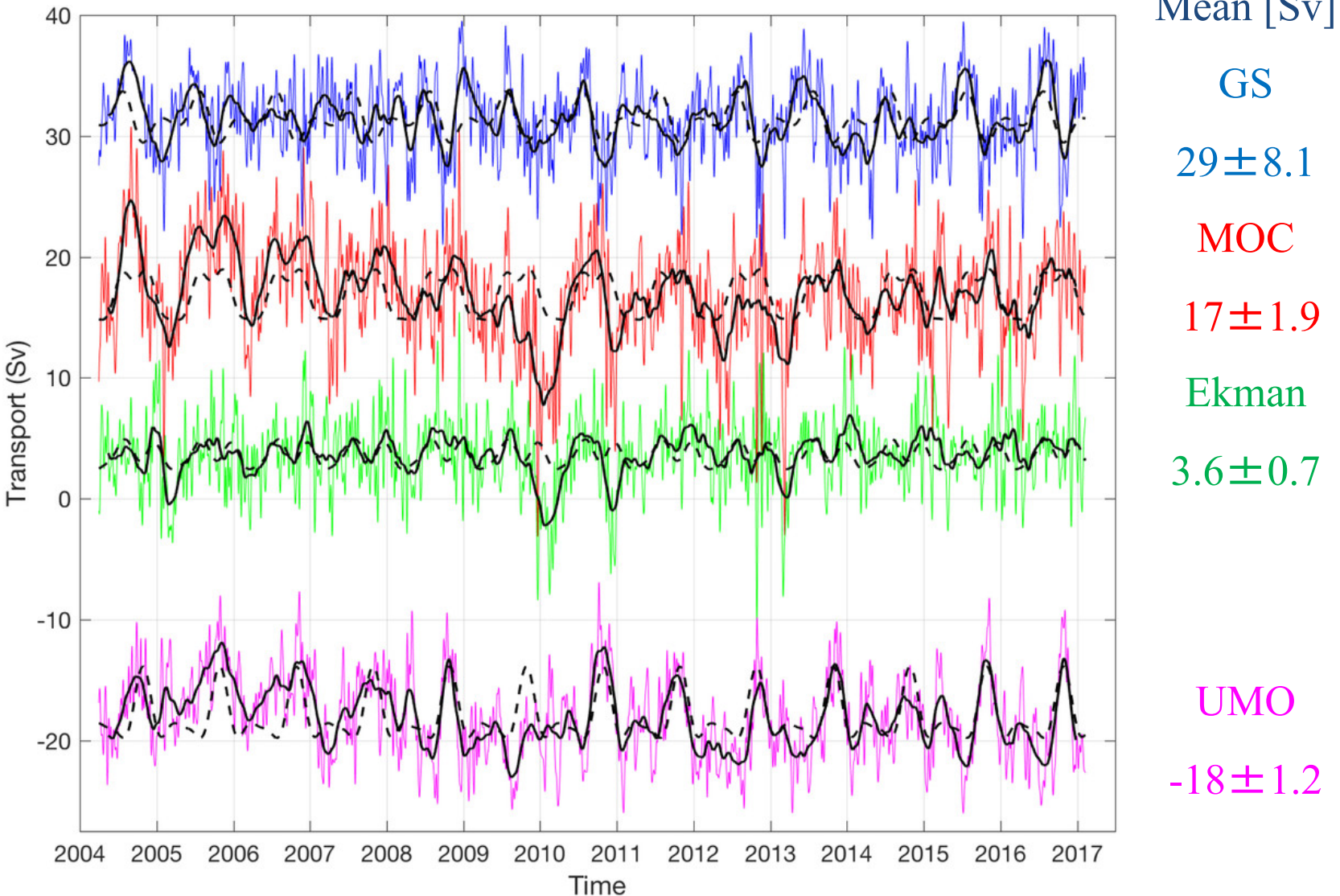
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Results from an *in situ* monitoring system: RAPID



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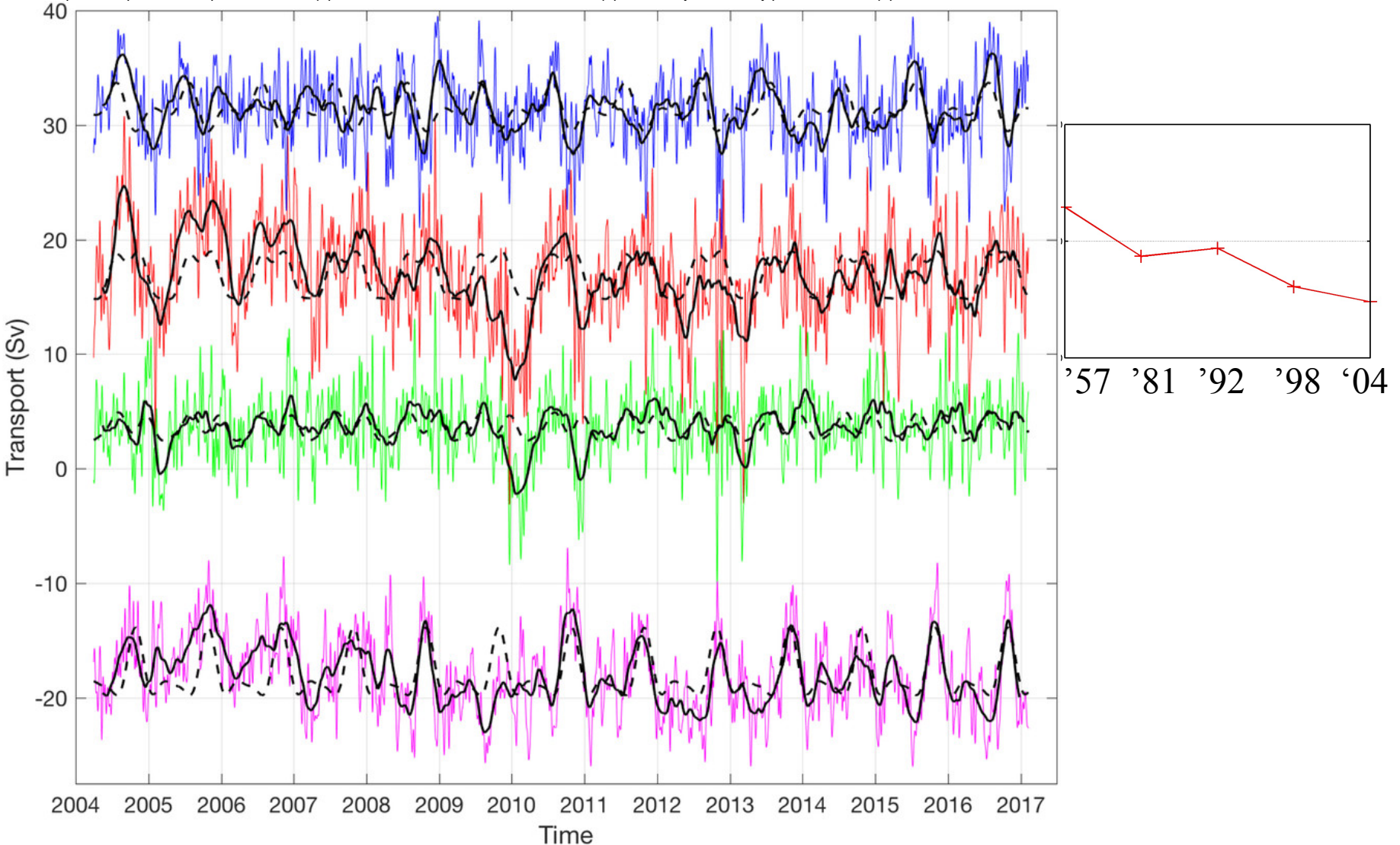
Results from an *in situ* monitoring system: RAPID



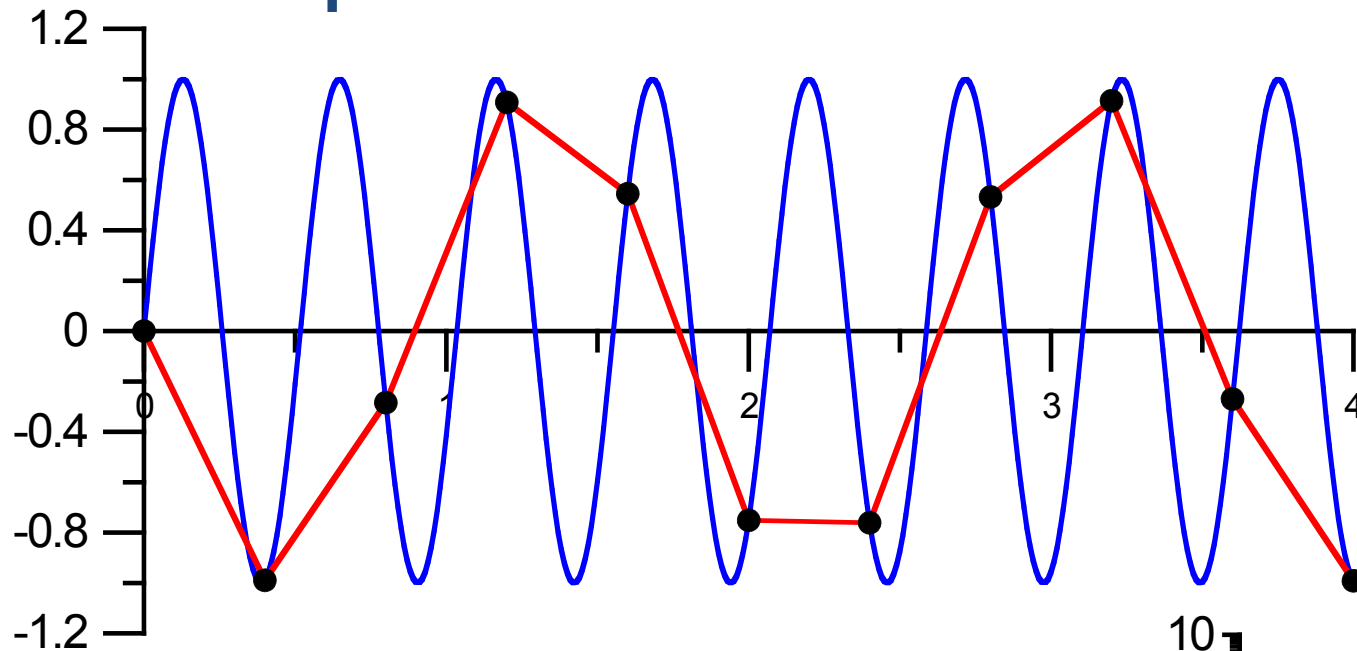
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Results from an *in situ* monitoring system: RAPID

Bryden, H. L., H. Longworth and S. Cunningham (2005), Slowing of the Atlantic meridional



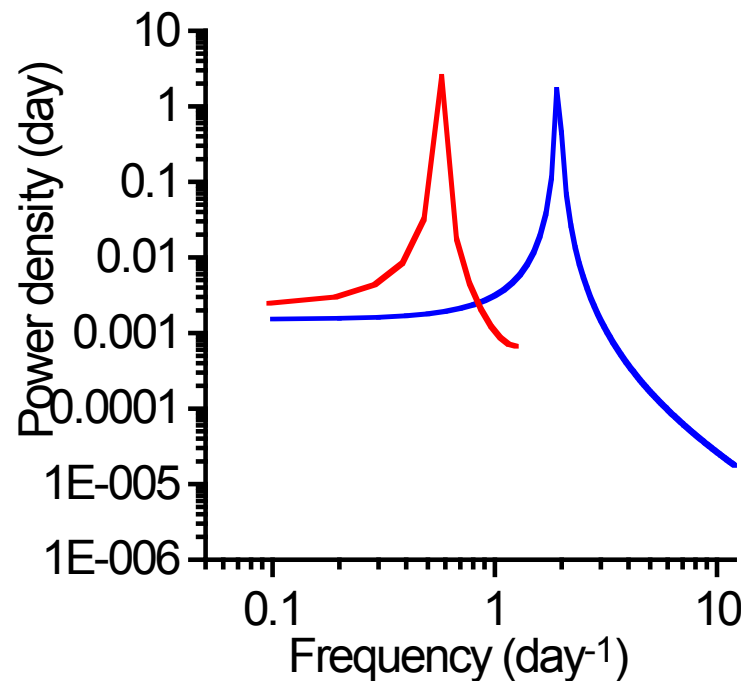
The problem of timescales: Again !



Aliasing a signal:

Blue line = well-resolved

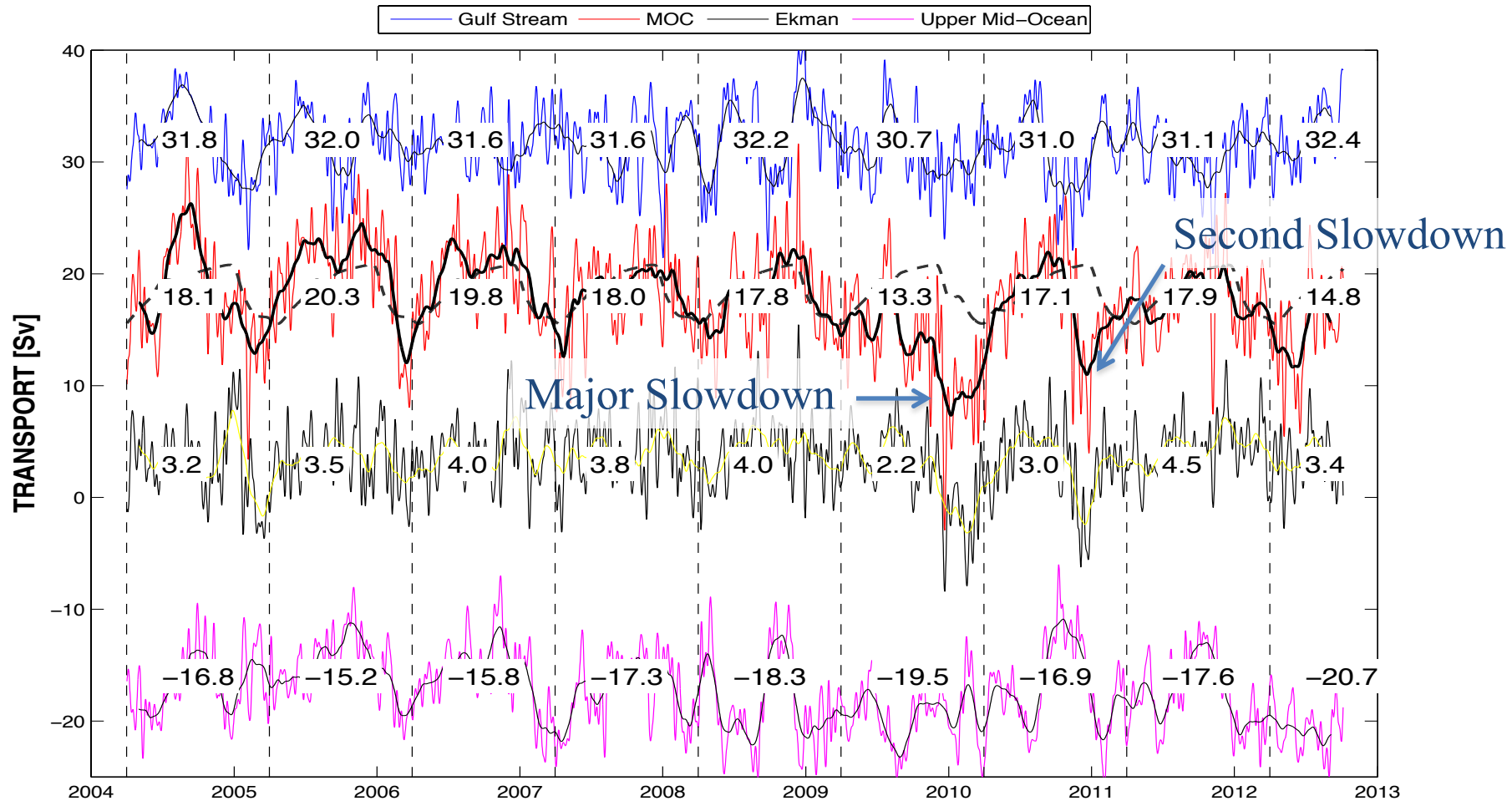
Red line = poorly resolved →
apparent existence of low frequency
signal



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Results from an *in situ* monitoring system: RAPID

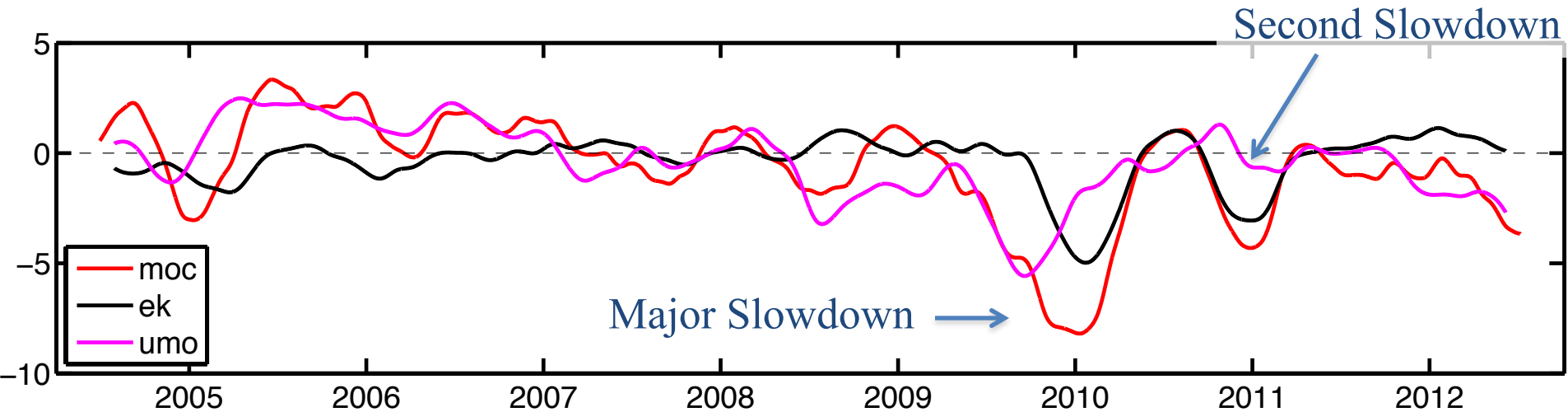
The 2009/10 events:



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Results from an *in situ* monitoring system: RAPID

The 2009/10 events:



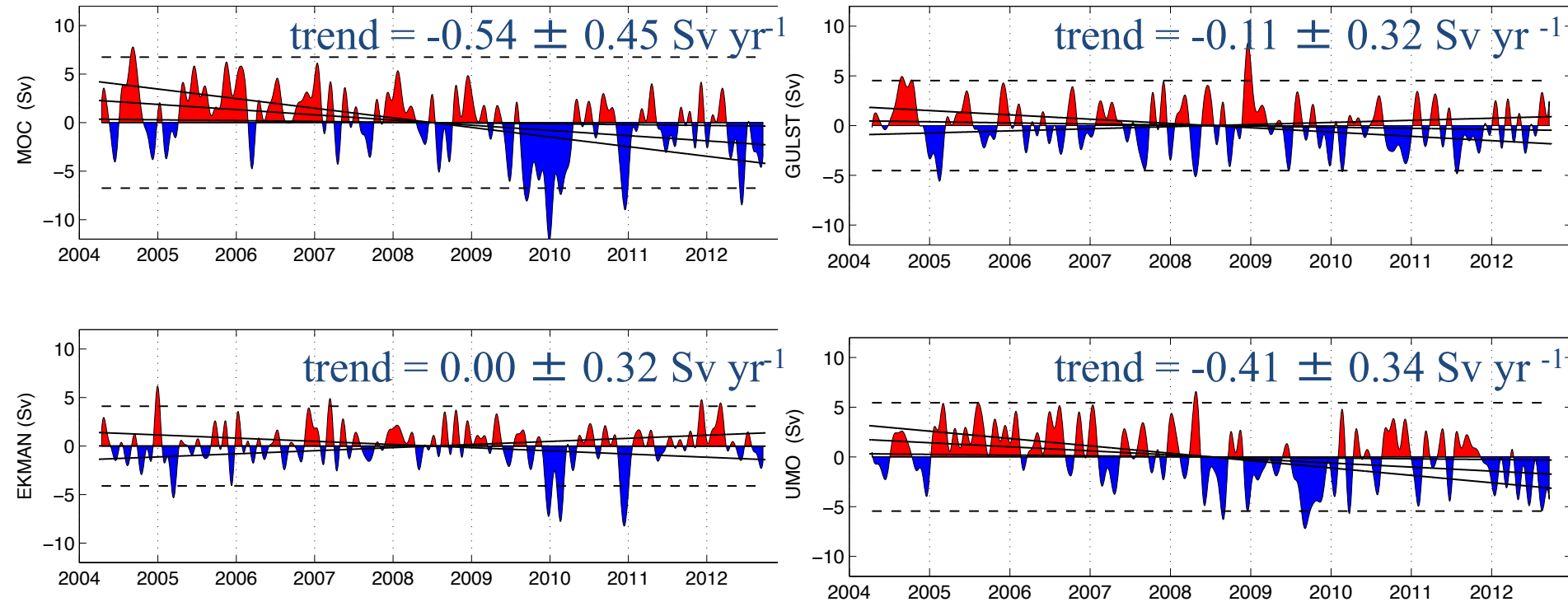
Seasonal cycle was removed, and data smoothed with 180-day filter

- 2009 event is linked to an anomalous UMO (*i.e.* East-West density difference) and Ekman (wind change)
- 2010 is primarily due to an anomalous Ekman
- The 2009 event corresponds to a reduction of ~50% and 2010 – ~25%

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Results from an *in situ* monitoring system: RAPID

The long term trend:



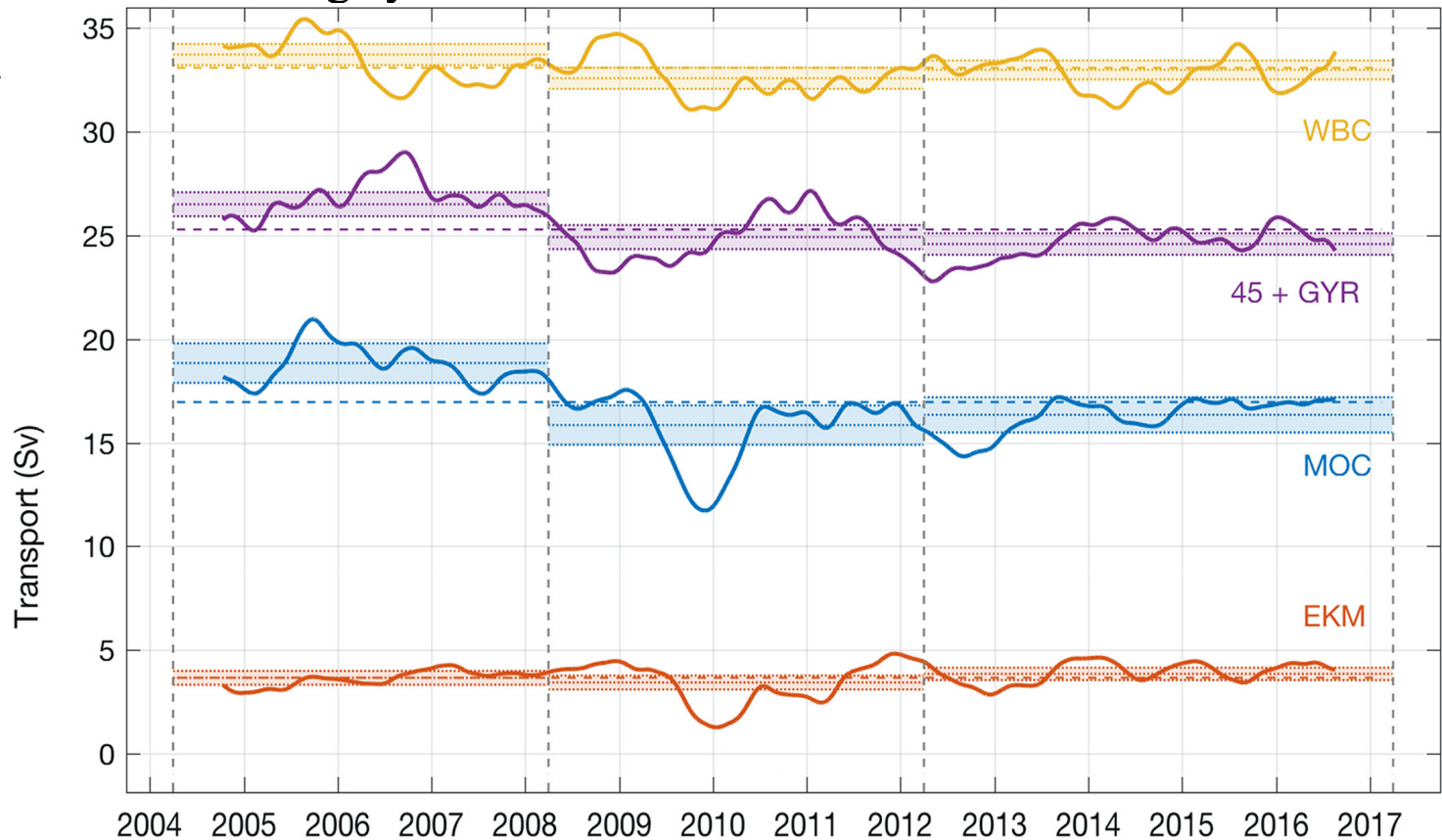
Anomalies (positive is northward) relative to mean annual cycle. A 45-day low-pass filter was applied to each time series.

- The data suggests a slowdown of the AMOC by $\sim 0.5 \text{ Sv yr}^{-1}$;
- It is linked to a slow down of the UMO term (East-West density differences);
- Even without the 2009 events the slowdown is visible in the UMO term.

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Results from an *in situ* monitoring system: RAPID

The regime shift:



Anomalies (positive is northward) relative to mean annual cycle. Low-pass filter was applied to each time series. 45 Sv is added to GYR

- The data suggests a regime shift post 2008 of $\sim 3 \text{ Sv}$;
- It is linked to GYR and WBC.
- There is arguably a second regime change post 2012.

Monitoring the AMOC

Summary:

We have

- Discussed the importance of the AMOC
 - Describing the AMOC
 - Describing its impact
- Derived the principle of Rapid monitoring system
 - This gives theoretical grounds to the monitoring system
 - And highlights its limits
- Described the *in situ* application of RAPID and the monitoring subtleties
 - The direct Gulf-stream measurement through telephonic cable at 26°N
 - The importance of boundaries measurement
- Discussed three noticeable features monitored through RAPID
 - The 2009/2010 slowdown events of up to ~50% of the mean
 - The long term trend of $-0.54 \pm 0.45 \text{ Sv yr}^{-1}$
 - Possible regime shift post 2008 of ~3 Sv