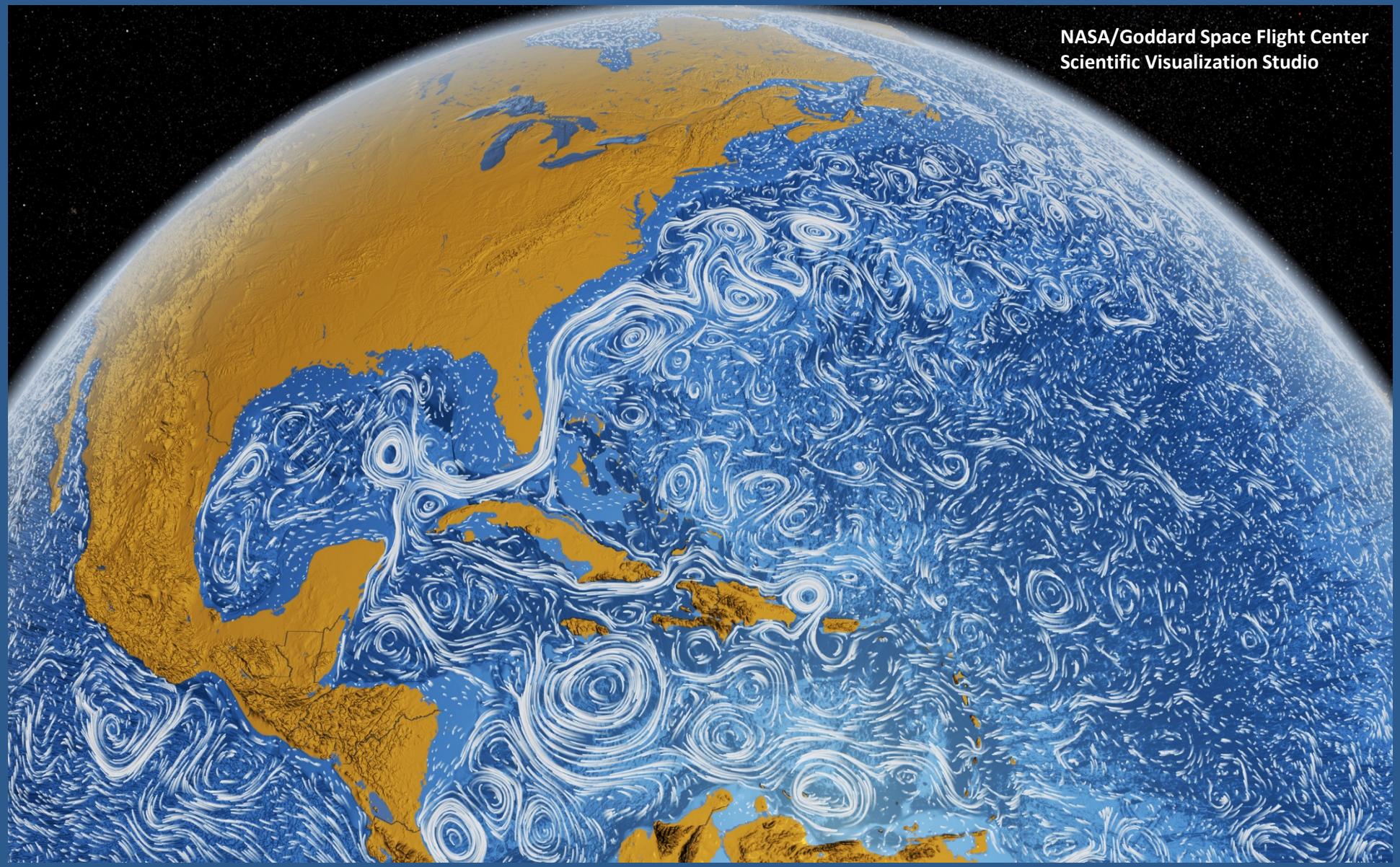
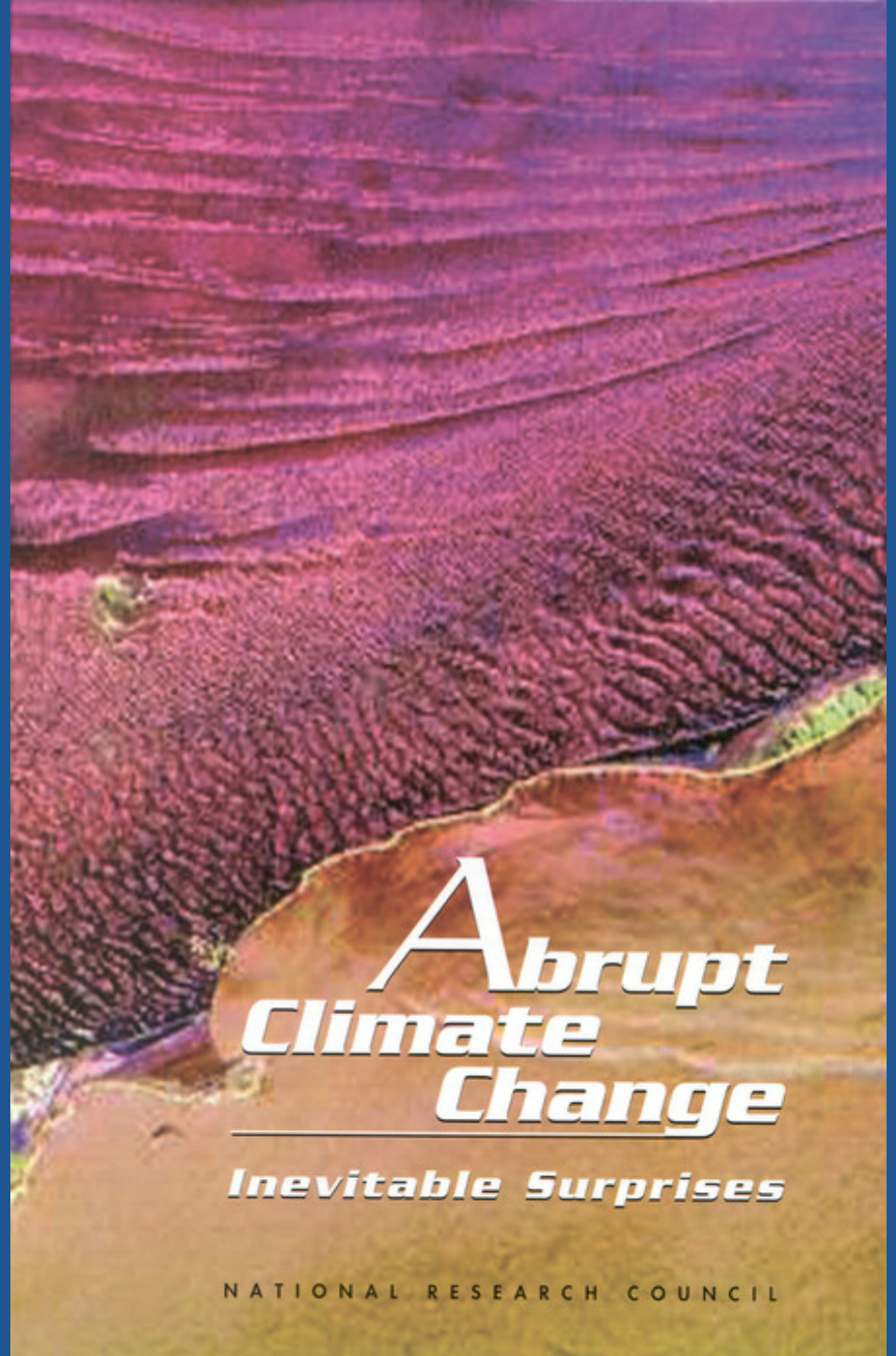
# Convergent and divergent views of the AMOC: a look past and ahead




Susan Lozier, Duke University

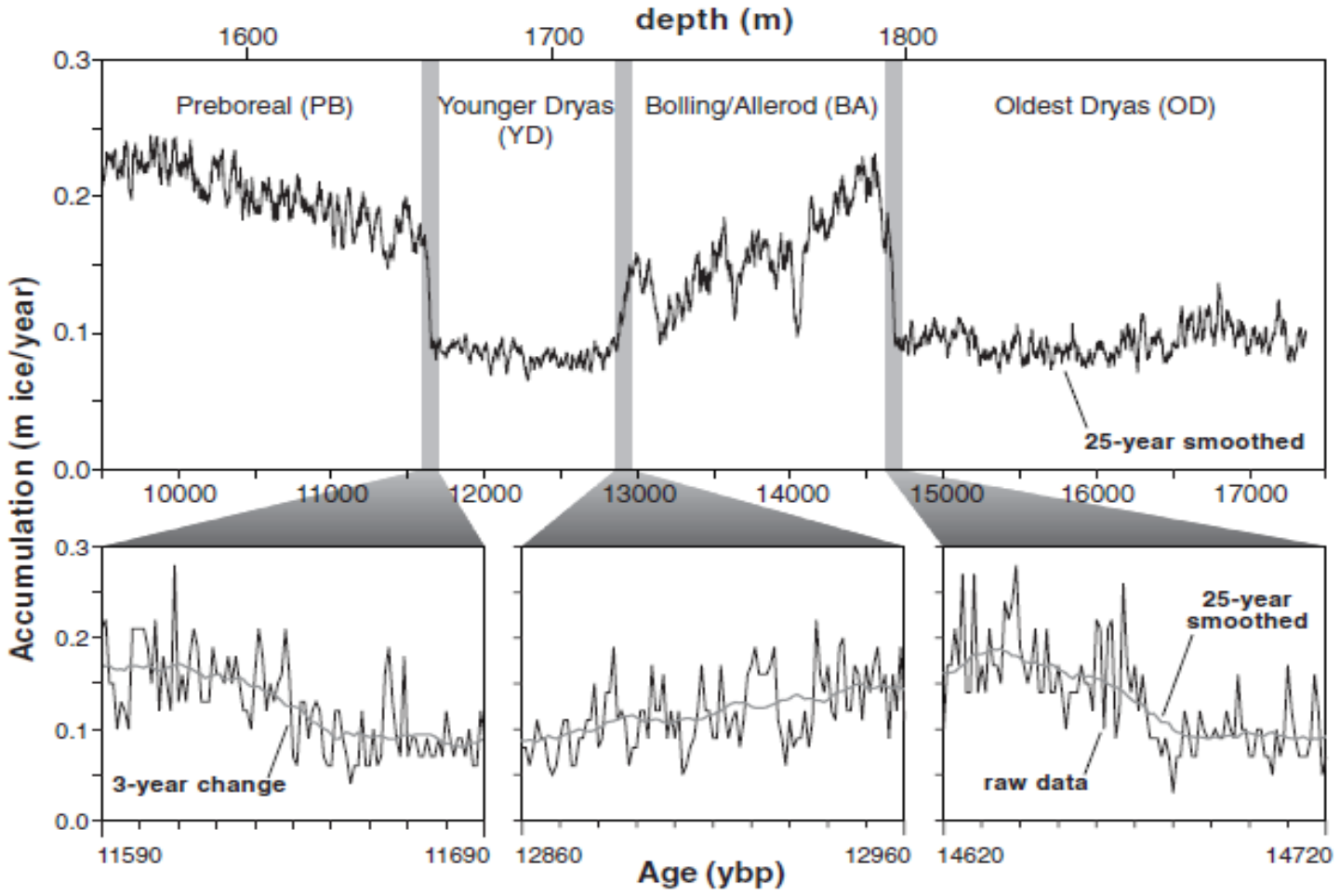
2018 International AMOC Science Meeting




**"The climate record for the past 100,000 years clearly indicates that the climate system has undergone periodic--and often extreme--shifts, sometimes in as little as a decade or less."**

**Published 2002**

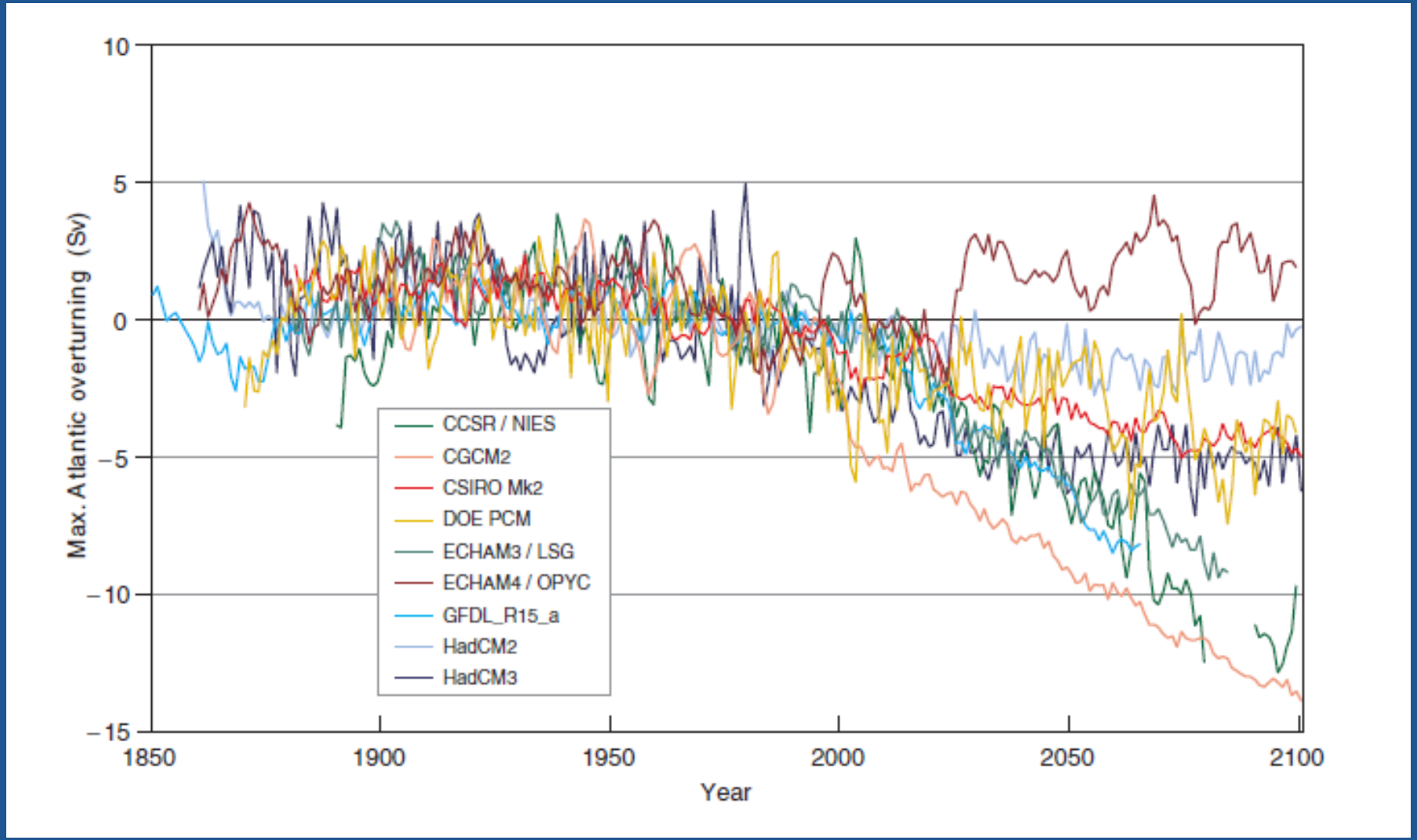
# Accumulation of ice in Greenland



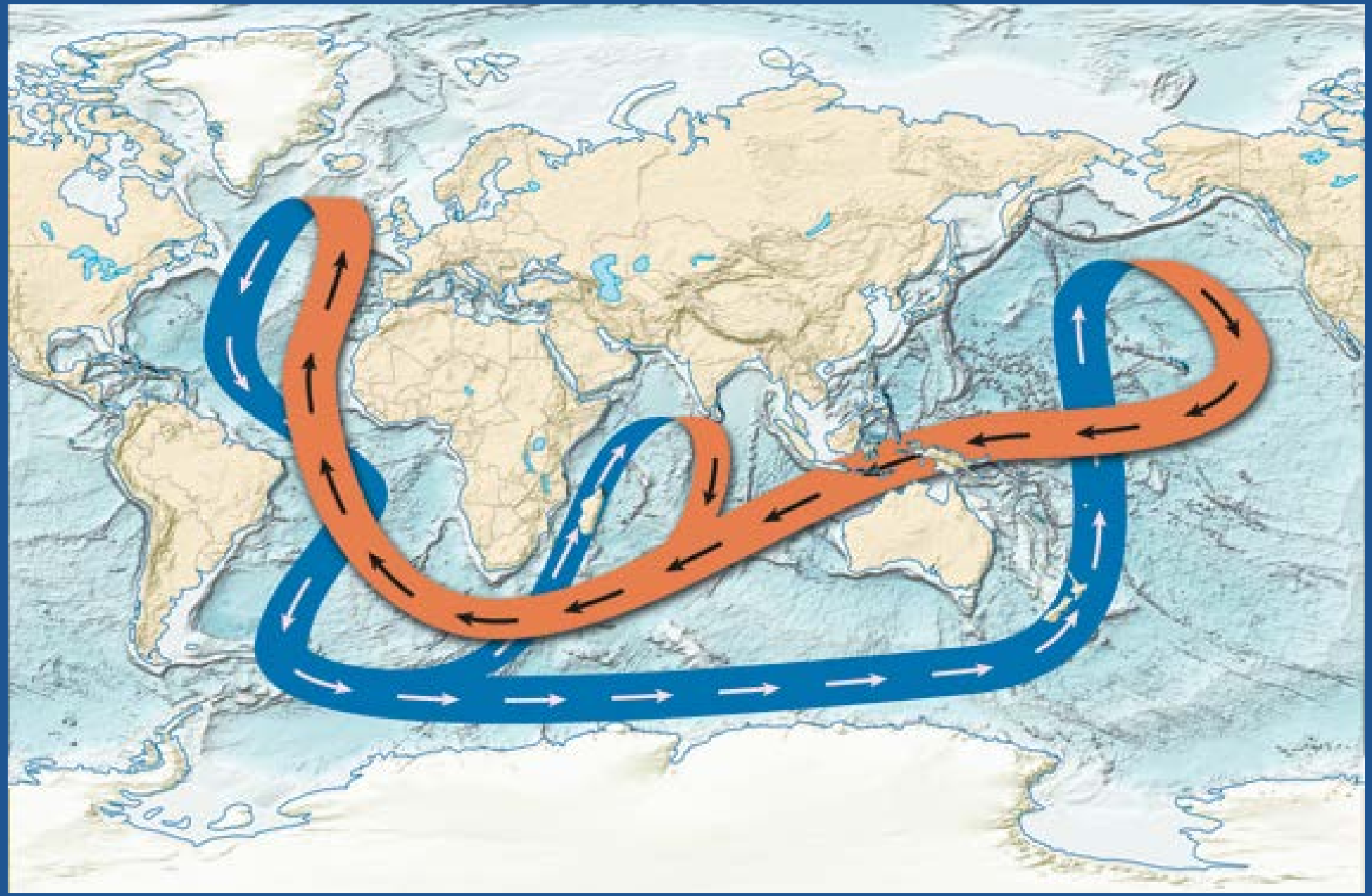

NRC 2002; modified from Alley et al. 1993

Start and end of Younger Dryas are marked by abrupt change.

# AMOC Projections from the 2001 IPCC WG1 2001 Report




AMOC change (Sv) relative to the 1961-1990 mean; future forcing scenario IS92a.



**The global ocean conveyor belt**

**Adapted from Broecker 1987**

# Consensus view in 2002

- There is a meridionally coherent AMOC with coherent variability.
- Quantification of AMOC transport is roughly achieved by summing the volume of the deep water components: LSW, ISOW and DSOW.
- Lower limb of the AMOC is contained within the Deep Western Boundary Current.
- The AMOC is variable on time scales from years to millennia.
- AMOC variability is driven by deep water mass variability in the Labrador and Nordic Seas.
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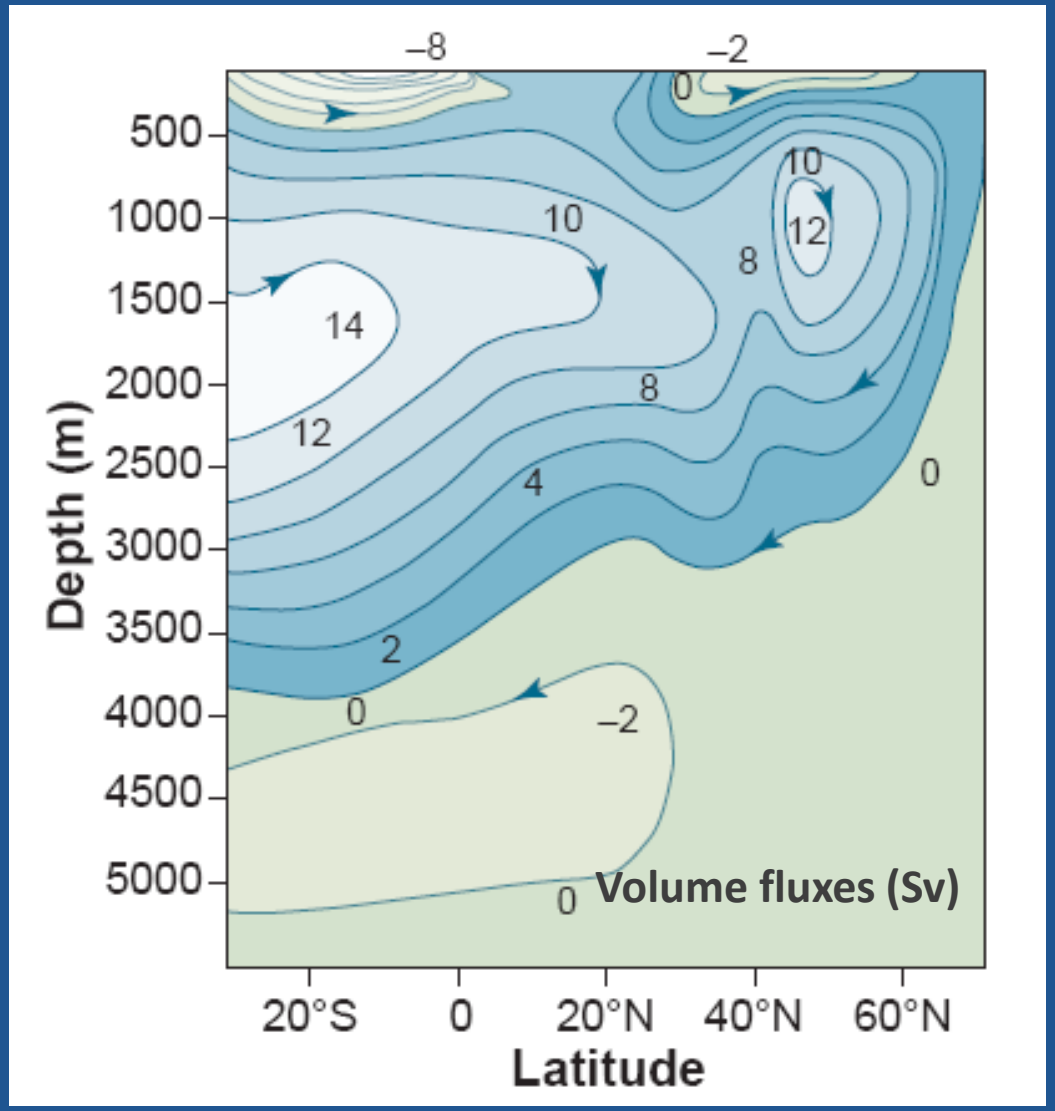
# Meridional Overturning Circulation (MOC)




Wunsch (2002)

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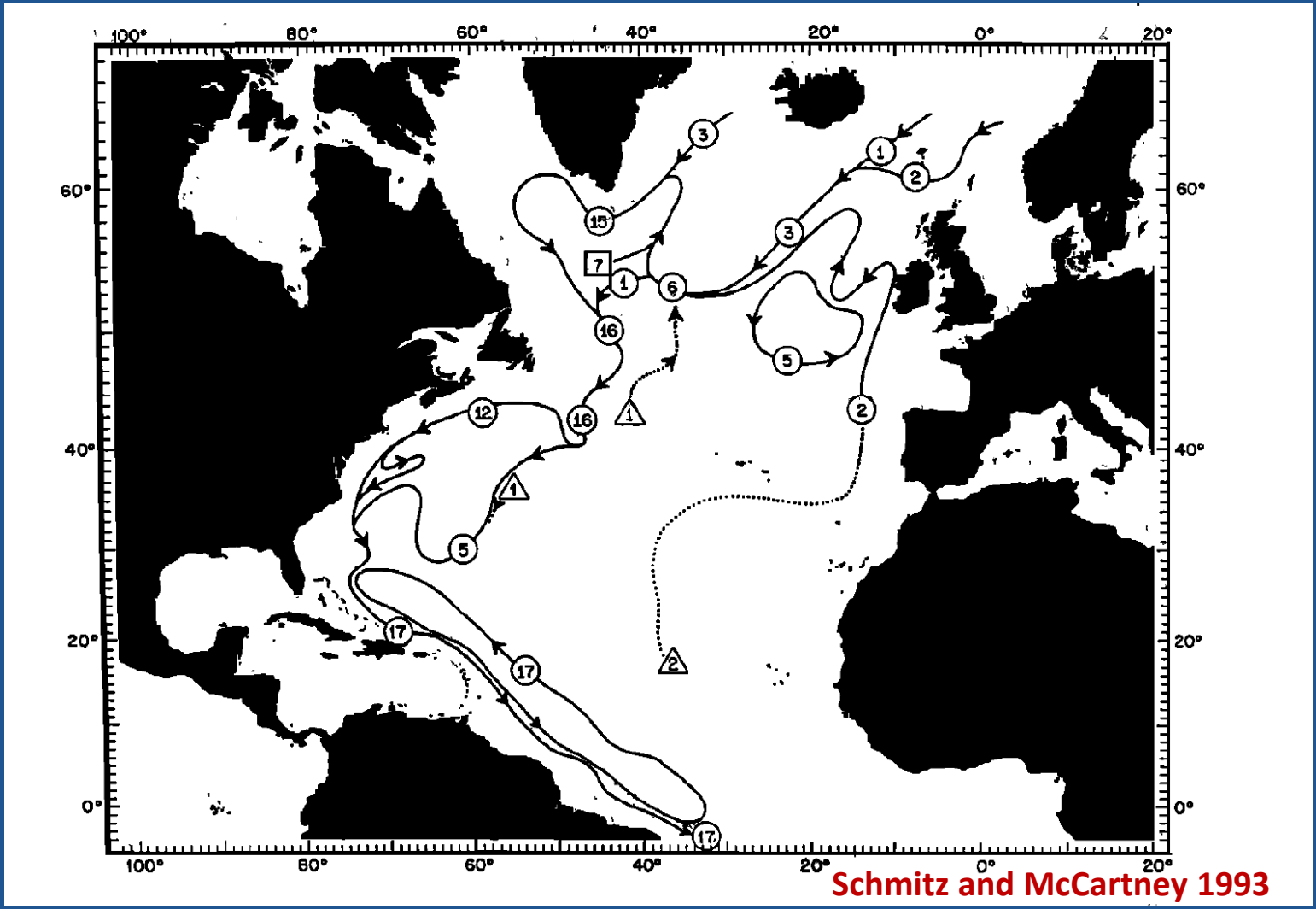
# Circulation schematic for deep flows between 1.8 and 4°C.




Transports are in Sv, squares showing sinking and triangles show upwelling.

# Consensus view in 2002

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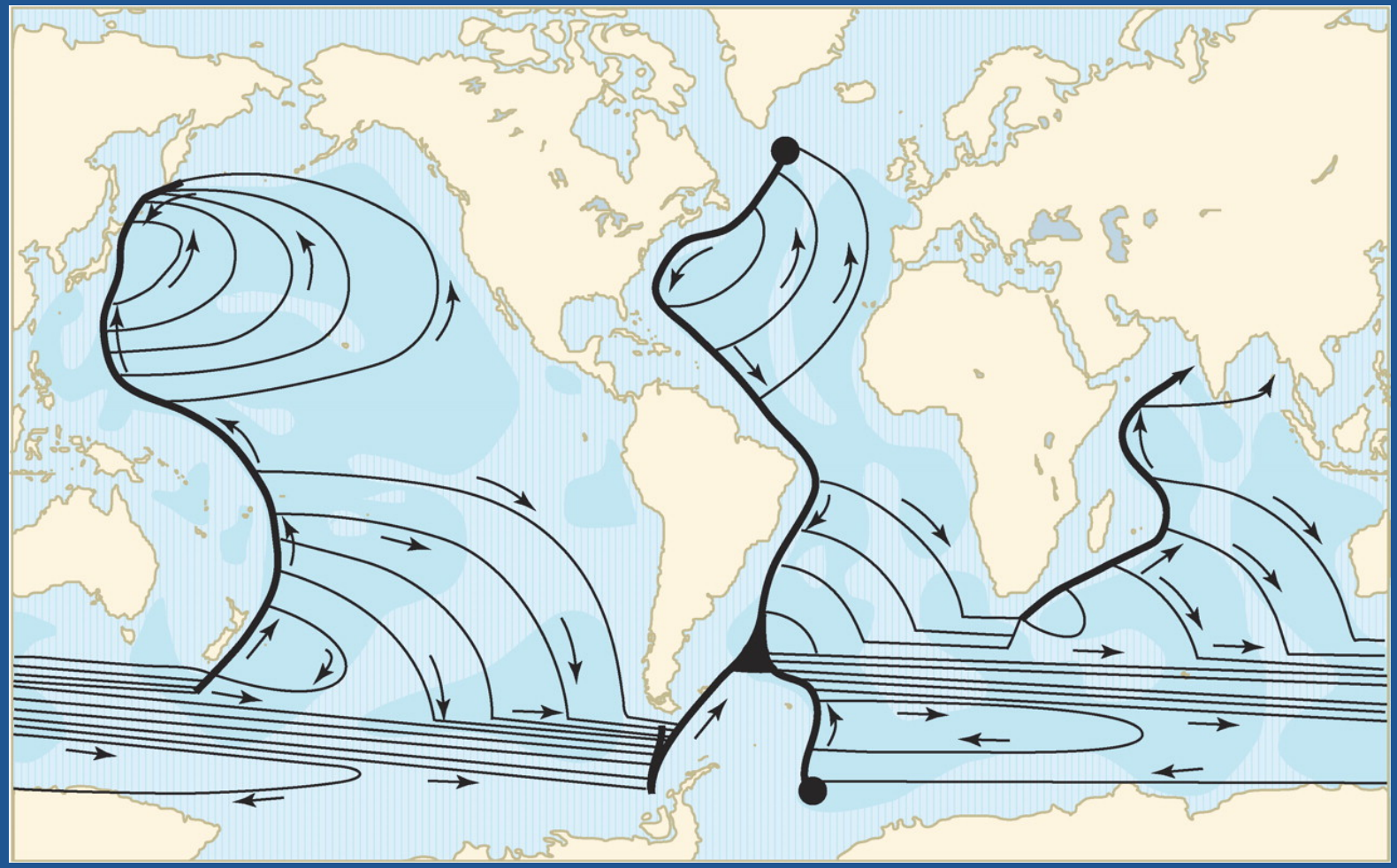
# Deep Western Boundary Current as Conduit



Stommel 1958

# Consensus view in 2002

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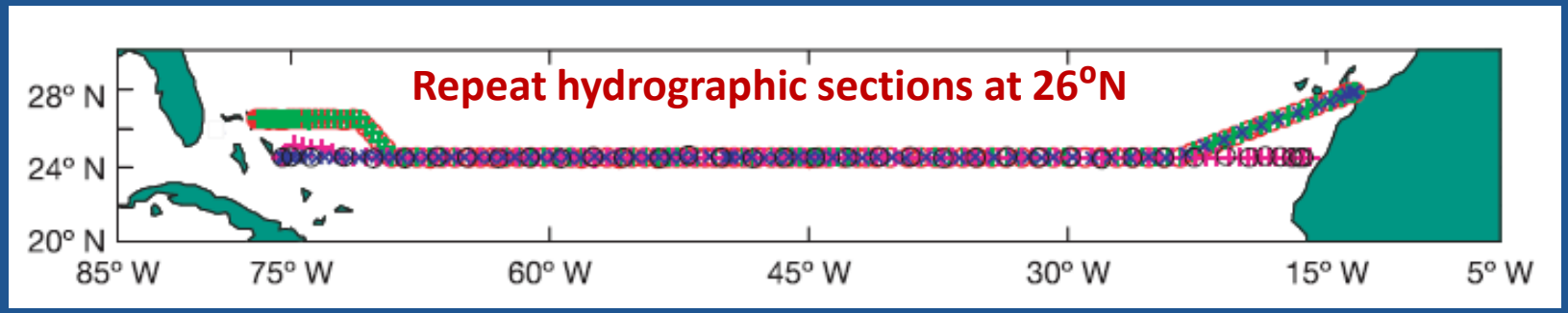
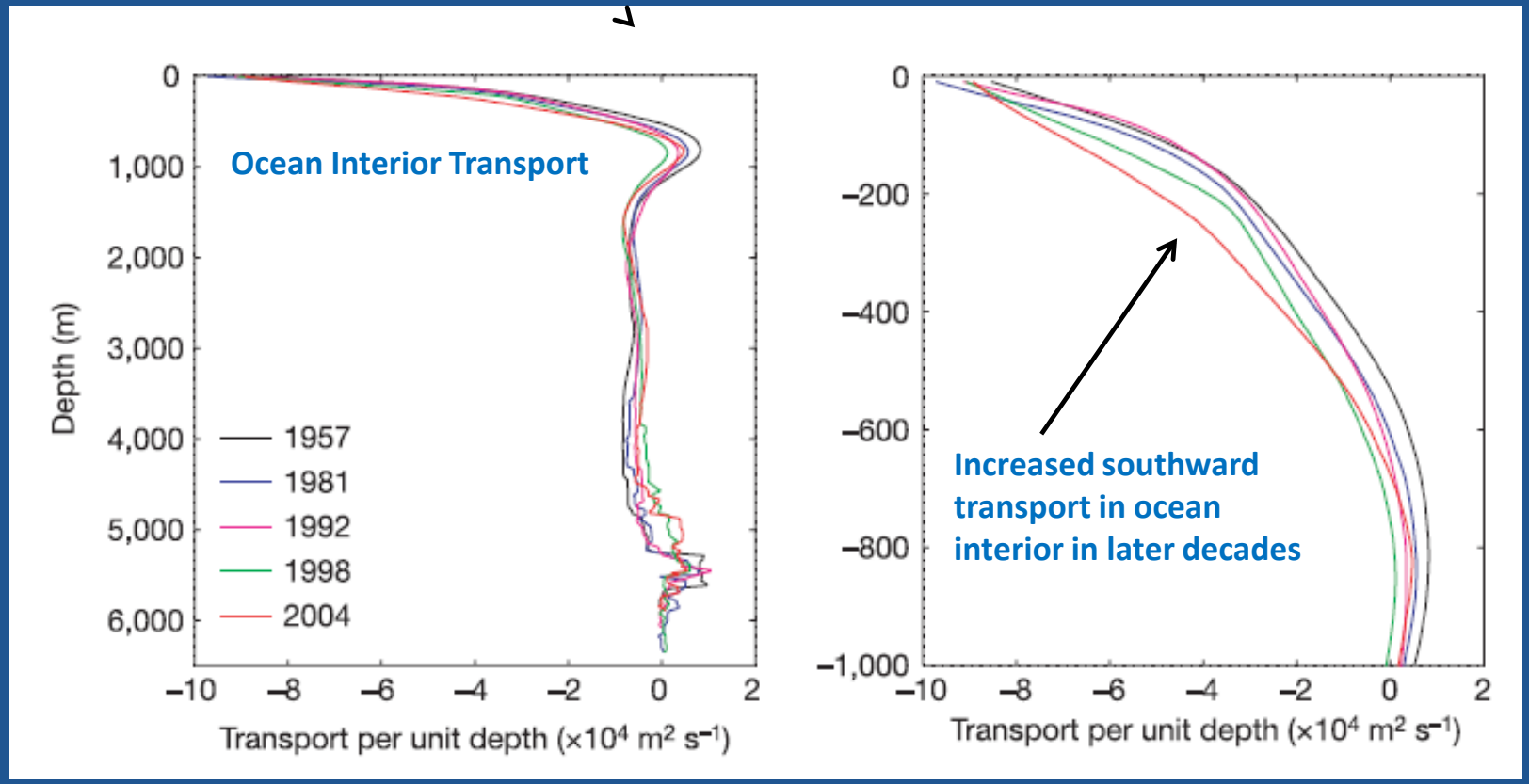
# Synoptic sections used to assess decadal variability and long-term trends




Bryden et al. (2005)

# Consensus view in 2002

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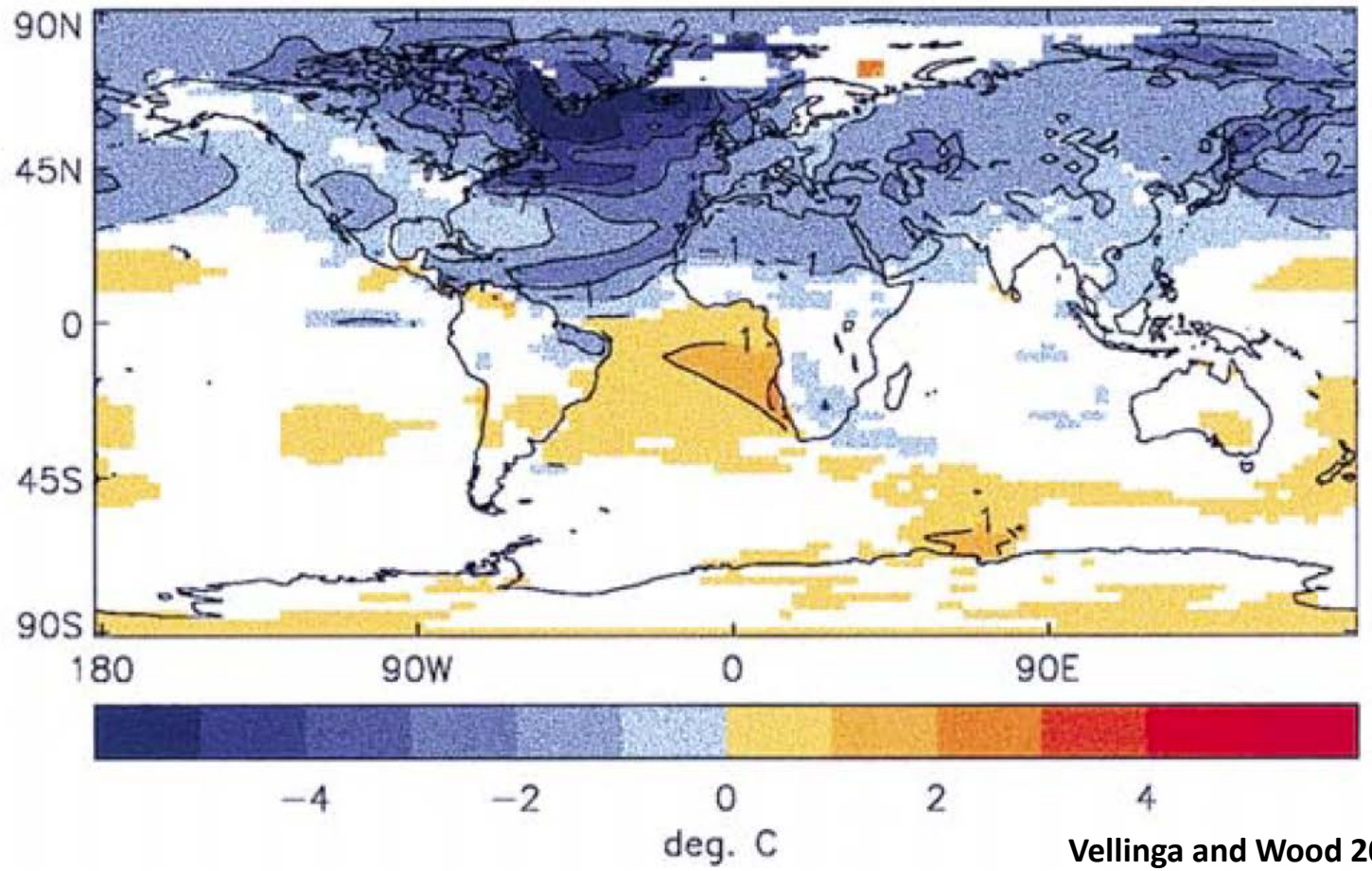
# Modeled SAT response to decrease in deep water formation




Vellinga and Wood 2002

**SAT anomaly 20-30 years after THC collapse in HadCM3.**

**Perturbation: Salinity increase of ~2 psu for upper 800 m of North Atlantic.**

**In large part, the main question about the AMOC in the early part of this century was whether it was changing, and if so, by how much and how fast.**

**Yet, open questions were plenty:**

- **What is the current state of the AMOC?**
- **How has the AMOC varied in the past on interannual to centennial time scales?**
- **What governs AMOC changes?**
- **Is the AMOC predictable on 10-100 year timescales?**
- **What are the impacts of AMOC variability and change?**

**2007 US AMOC Implementation Report**

# Oceanographers went to work

## Design and implementation of an AMOC monitoring system

*Trans-basin arrays:* OSNAP, RAPID-MOCHA, MOVE, 11°S, SAMBA

*Alternate observational estimates:* Bottom pressure (RAPID-WAVE); DWBC arrays (53N, 47N and Line W); satellite-based approaches using altimetry and gravimetry; satellite-based measures plus hydrography; RAFOS floats

## Assessment of AMOC's role in climate

High resolution and coupled atmosphere-ocean modeling studies; Reanalysis studies; paleo reconstructions; paleo modeling

## Assessment of AMOC mechanisms, variability and predictability

High resolution and coupled atmosphere-ocean modeling studies; Reanalysis studies; decadal prediction studies; paleo reconstructions; paleo modeling

**So:**

**17 years after the IPCC 2001 report,**

**16 years after the 2002 NRC report,**

**14 years after RAPID-MOCHA launch,**

**14 years after *The Day After Tomorrow***

**11 years after US AMOC program start**

# What *do* we know about the AMOC?

# Revisit: consensus view in 2002

- There is a meridionally coherent AMOC with coherent variability.
- Quantification of AMOC transport is roughly achieved by summing the volume of the deep water components: LSW, ISOW and DSOW.
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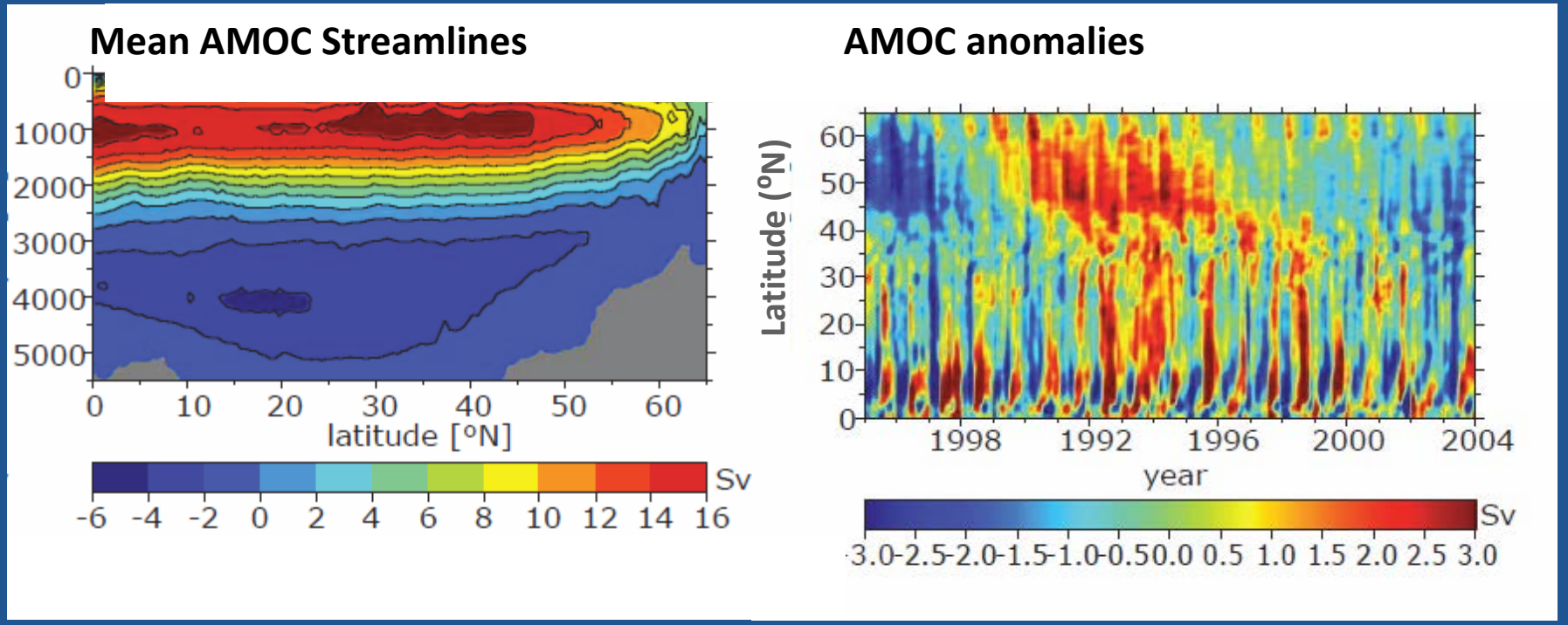
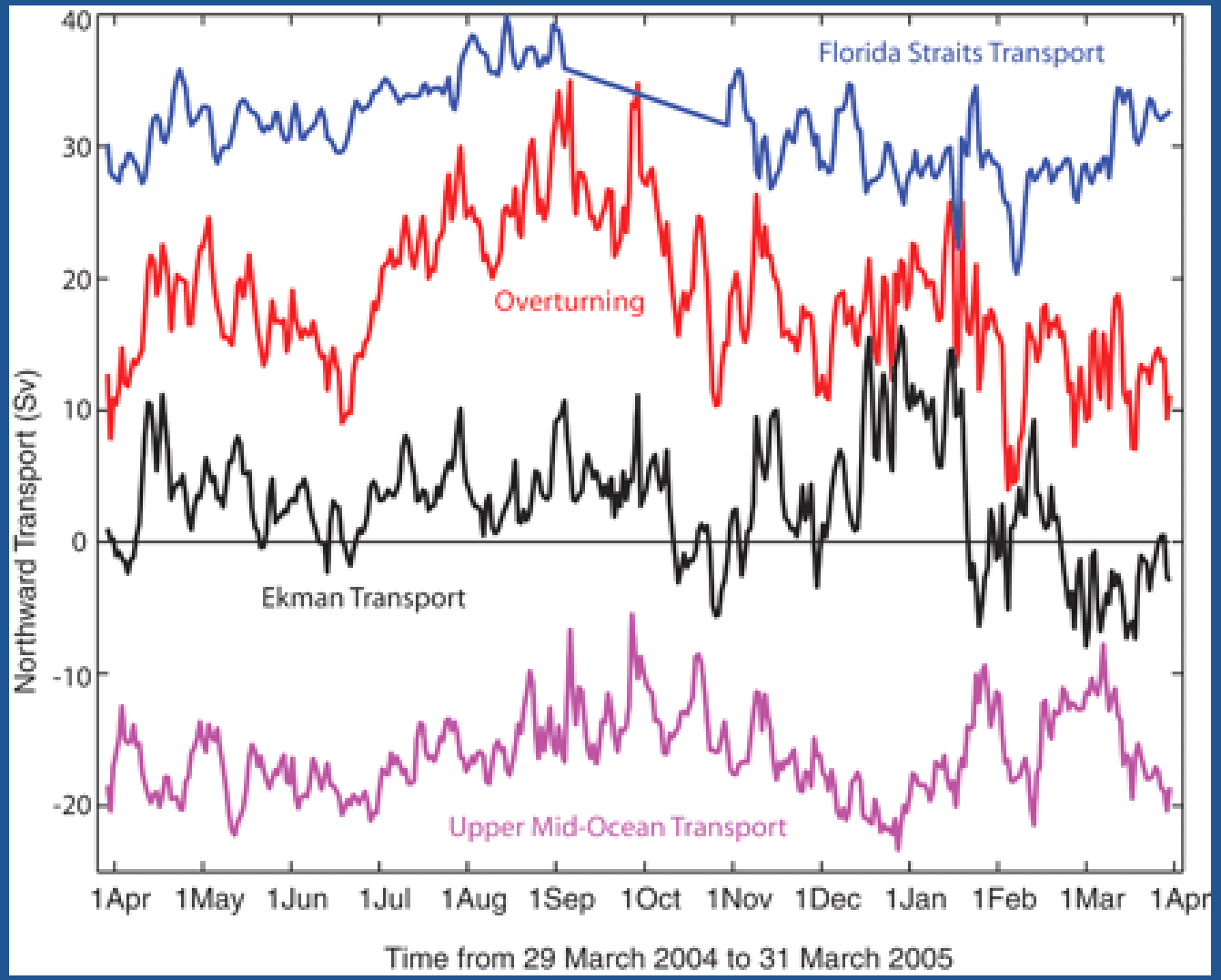
# Meridional coherence of AMOC anomalies




Bingham et al. 2007

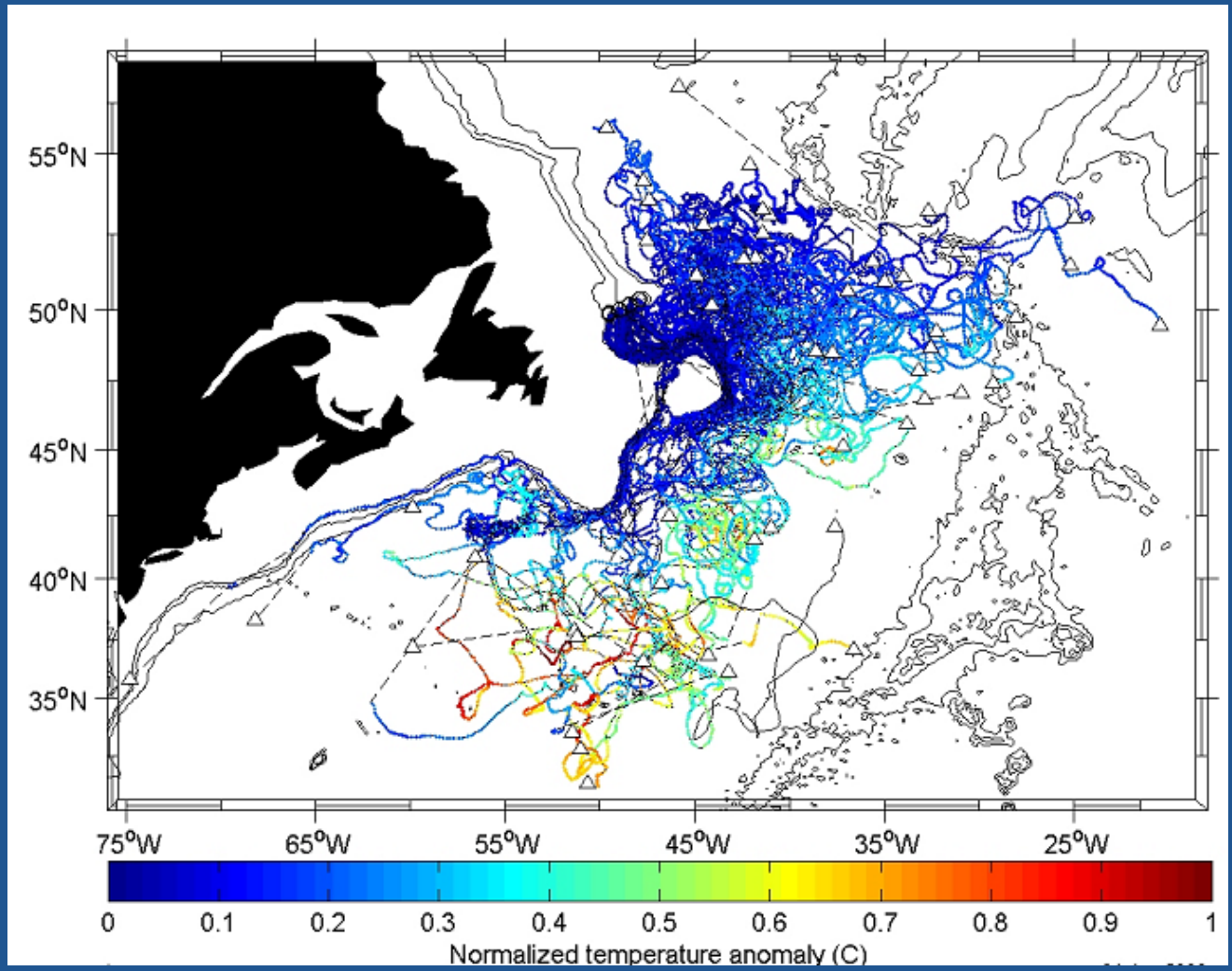
# Temporal Variability of the Atlantic Meridional Overturning Circulation at 26°N




Cunningham et al. 2007

Maximum northward transport of upper-layer waters on each day

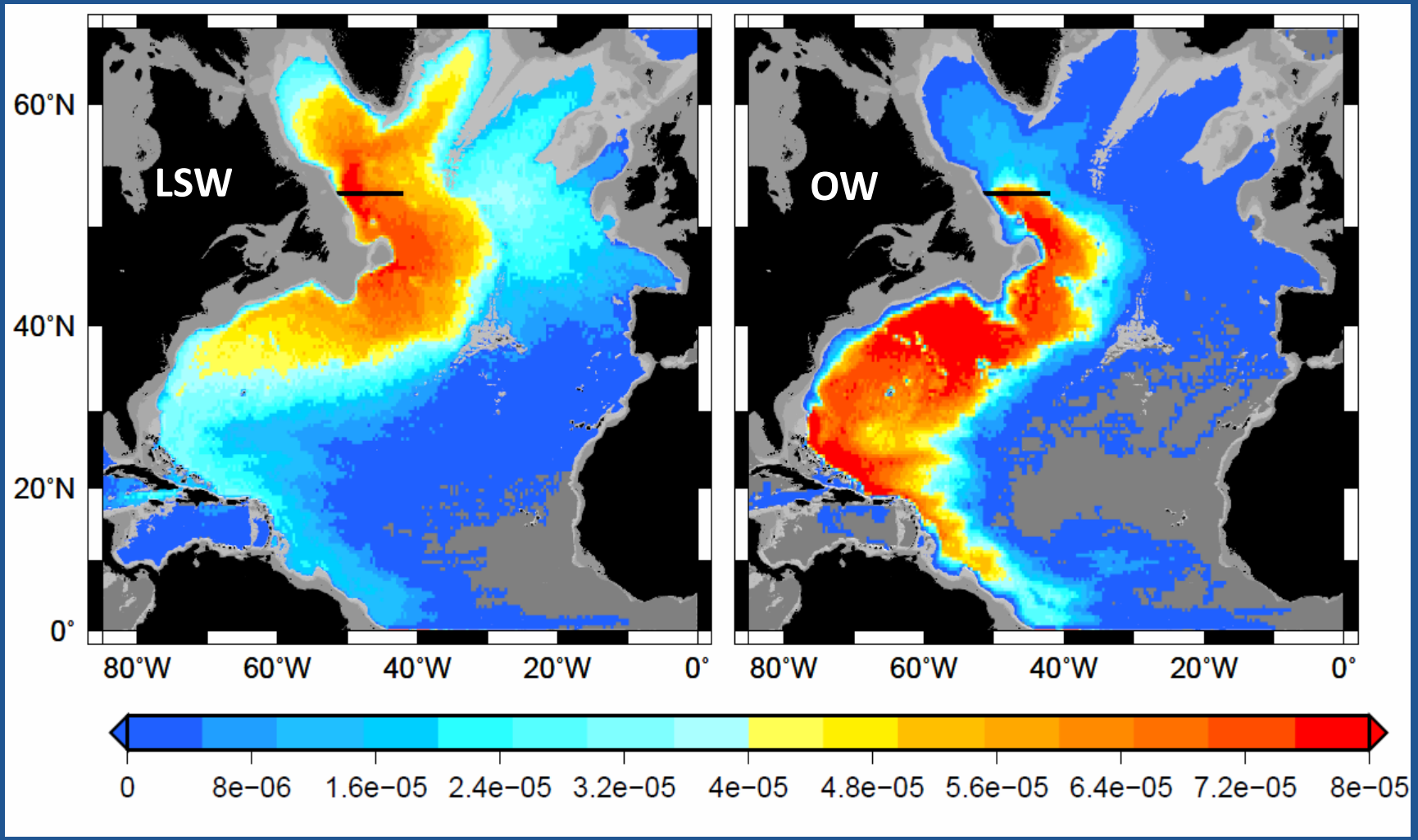
# Lower Limb Subpolar to Subtropical Pathways




**Trajectories of RAFOS floats deployed in the Lab Sea from 2003-2006 and tracked for 2 years.**

**Bower et al. 2009**

# Modeled spread of Labrador Sea Water and Overflow Waters

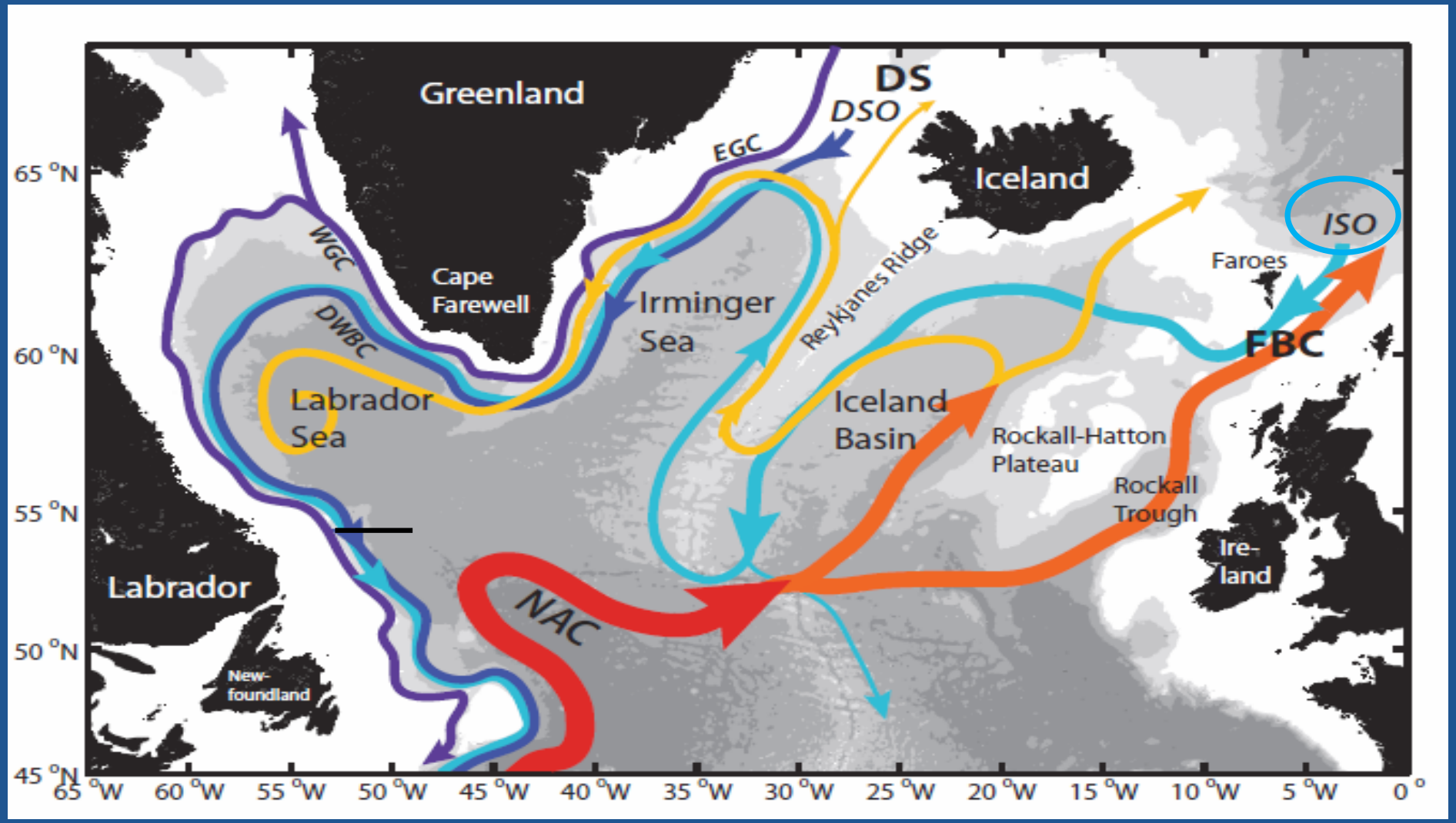



Probability map constructed from 50-year trajectories

LSW: Labrador Sea Water; OW: Overflow Water

Lozier et al. 2013

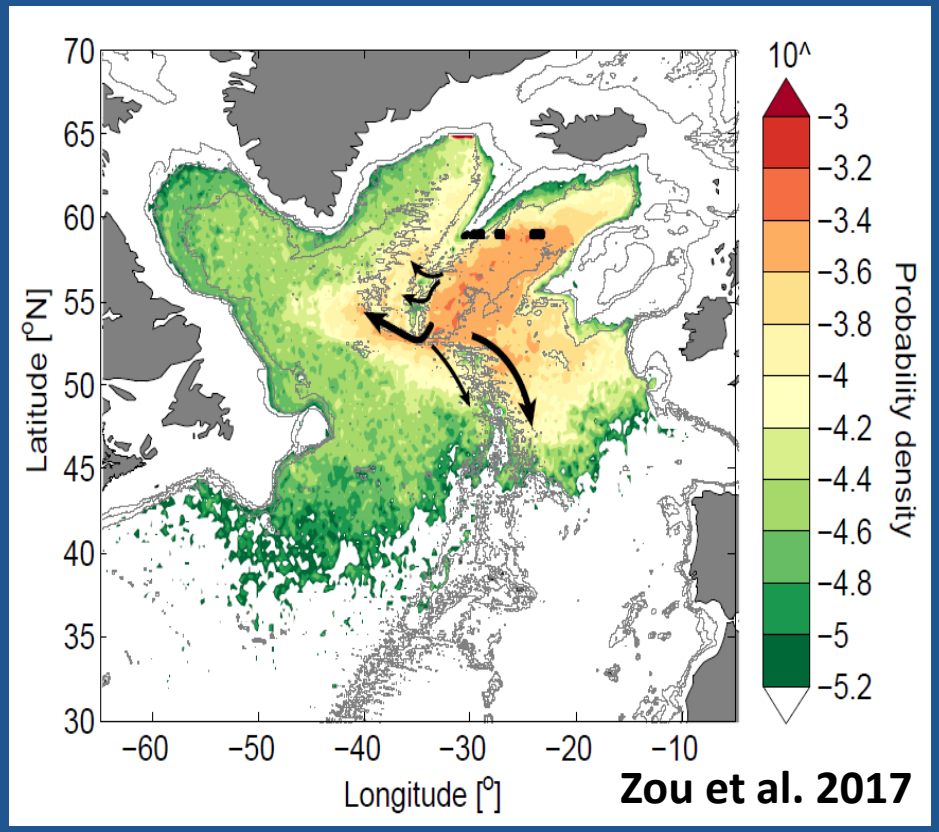
# Lower Limb of the Overturning: Arctic Overflow Water Pathways




Schematic credit: H. Furey, WHOI

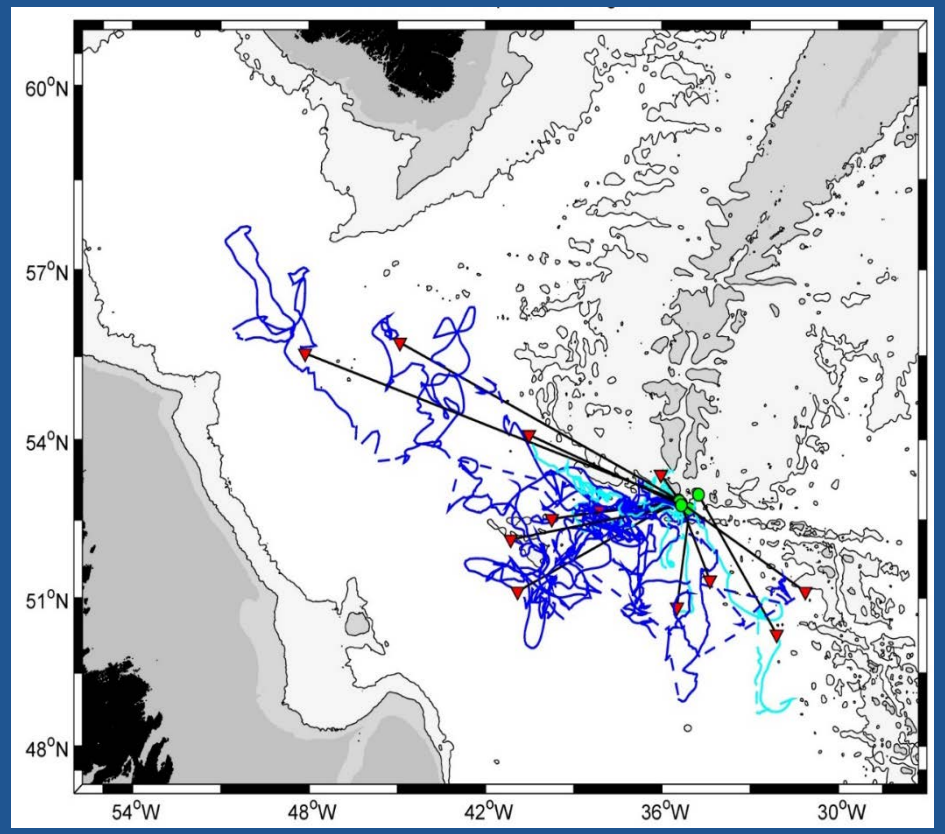
## Traditional View

# Probability map of e-floats launched in ISOW




Trajectories integrated for 10 yrs after release at 59°N in velocity cores in Iceland basin. Black dots: launch locations for e-floats.

# Early results from OSNAP floats launched in ISOW




9 floats released in CGFZ in 2014; 3 floats released in Iceland Basin in 2015 and 2016. Cyan indicates tracks < 2 years; tracking is preliminary.

# Consensus view in 2018

- There is ***not*** a meridionally coherent MOC on interannual to decadal time scales. There is *likely* a coherent MOC on multi-decadal to longer time scales.

- The lower limb of the AMOC is ***not*** solely contained within the Deep Western Boundary Current. LSW and OW have interior pathways.

- The MOC is variable on time scales from ***intraseasonal*** to millennial time scales. Wind and buoyancy forcing contribute to MOC variability.

# Also a consensus in 2018

- **Progressive decline in the AMOC is *expected* due to diminishment of deep water formation.**
- **Anthropogenic $CO_2$ at depth in the North Atlantic is attributable to AMOC.**
- **SST variability impacts continental precipitation, hurricane activity, regional to global climate, etc.**

# Still a consensus view in 2018?

- Quantification of AMOC transport is achieved by summing the volume of the deep water components: LSW, ISOW and DSOW.

- AMOC variability on decadal to millennial time scales is driven by deep water mass variability in the Nordic Seas and at high latitudes in the North Atlantic.

- Low-frequency SST variability is driven by AMOC changes.

**Q1:** If I know how much water comes over the Greenland-Scotland Ridge and how much deep water is formed in the Labrador Sea, I have a pretty good estimate for the mean AMOC in the subtropical North Atlantic.

**Choices:** Strongly agree, Agree, Neutral, Disagree, Strongly disagree

**Q2:** On time scales ranging from decades to millennia, AMOC variability is driven by deep water mass variability in the Labrador and Nordic Seas.

**Choices**: Strongly agree, Agree, Neutral, Disagree, Strongly disagree

**Q3:** Low-frequency SST variability in the North Atlantic is primarily driven by:

**Choices:** The atmosphere, the AMOC, the ocean but not necessarily the AMOC, both the ocean and the atmosphere, I am the last person to be voting on this question.

# Points of divergence in 2018

- Efficacy of AMOC proxies, e.g. LSW volume and thickness, Lab Sea density, DWBC transport, Gulf Stream position; subpolar temperature.
- Whether the warm water or cold water pathway feeds the AMOC upper limb in the South Atlantic.
- Connection between AMOC changes and D-O events.
- Whether the ‘cold blob’ is indicative of a long-term AMOC decrease.
- AMOC’s importance to Gulf Stream variability and sea level rise.
- Whether we are *currently* observing the AMOC’s long-term decline.

**Q4:** **The AMOC is *currently* in a state of long-term decline.**

**Choices**: **Strongly agree, Agree, Neutral, Disagree, Strongly disagree**

**Q5:** **The cold blob is an indicator of the AMOC's 20$^{th}$ century decline.**

**Choices**: **Strongly agree, Agree, Neutral, Disagree, Strongly disagree**

**Q6:** AMOC variability controls D-O events.

**Choices**: Strongly agree, Agree, Neutral, Disagree, I don't know what D-O events are.

# Grading our progress

*From the US AMOC 2007 Implementation Report:*

**What is the current state of the AMOC?**

**How has the AMOC varied in the past on interannual to centennial time scales?**

**What governs AMOC changes?**

**Is the AMOC predictable on 10-100 year timescales?**

**What are the impacts of AMOC variability and change?**

**Q7:** How well do we know the current state of the AMOC?

**Choices**: Completely, Moderately well, so-so, barely, not at all

**Q8:** How well do we know how the AMOC varied in the past on interannual to centennial time scales?

**Choices**: Completely, Moderately well, so-so, barely, not at all

**Q9: How well do we understand what governs AMOC changes?**

**Choices: Completely, Moderately well, so-so, barely, not at all**

**Q10: Do we understand AMOC predictability on 10-100 year timescales?**

**Choices: Completely, Moderately well, so-so, barely, not at all**

**Q11: How well do we understand the impacts of AMOC variability and change?**

**Choices: Completely, Moderately well, so-so, barely, not at all**

# A look past

***How much of what we have learned about the AMOC in the modern world is relevant for the interpretation of paleo signals?***

- **DWBC is not the sole pathway for UNADW and LNADW.**
- **DWBC transports are not clearly linked to the AMOC.**
- **Overturning in density space can differ widely from that in depth space; transformation in temperature and/or salinity space overestimates AMOC.**
- **Wind forcing contributes to AMOC variability, perhaps even on decadal scales. Relatedly, subpolar and subtropical AMOC estimates may differ.**
- **Ocean contributions to heat content and/or SST variability are not restricted to the AMOC. Same applies to bottom properties.**

# A look ahead

*Where does the community head from here?*

- A focus on AMOC should shift to a focus on carbon, freshwater and heat uptake, transport and storage. This focus should involve a measure of the AMOC since it impacts MHT, MFT and carbon uptake.

- A *cost-effective* long-term monitoring system should be designed to measure the MOC. Choices will need to be made.

- North Atlantic observing systems should build out capacity to measure carbon uptake and storage.

- Attribution studies are critical, as are predictability studies. Again, here a focus on carbon, heat and freshwater is warranted. Efficacy of models is a critical issue.

# Moving forward

**Q12: Should we use only high resolution models for AMOC studies?**

**Choices: Duh, Probably, Neutral, Of course not**

# Moving forward

**Q13: Are we over-measuring the AMOC?**

**Choices: Most definitely, Sort of, Neutral, We don't know yet, We are under-measuring the AMOC.**

# Moving forward

**Q14: What is the most important quantity we should be observing to make progress on the AMOC?**

**In your own (few) words….**