AMOC 2010 Annual Meeting

June 7-9, 2010

Conrad Hotel, Miami FL

Attendance: ≈ 80

Focus:

1. **P.I. updates on funded research**
2. **Plenary talks and discussion groups:**

   - What have we learned in the last 5 years?

   - Define gaps and near-term priorities for coordinated research

AMOC Program Lead P.I.'s

Molly Baringer (NOAA.AOML)
Amy Bower (WHOI)
James Carton (U. Maryland)
Ping Chang (Texas A&M)
Ruth Curry (WHOI)
Tom Delworth (GFDL)
Kathleen Donohue (URI)
George Halliwell (NOAA/AOML)
Gordon Hamilton (U. Miami)
Bill Johns (U. Miami)
Terry Joyce (WHOI)
Igor Kamenkovich (U. Miami)
Kathy Kelly (U. Washington)
Craig Lee (U. Washington)
Tong Lee (JPL)
Jonathan Lilly (NWRA)
Timothy Liu (JPL)
Susan Lozier (Duke)
Jay McCreary (SOEST/IPRC)
Vikram Mehta (CRCES)
Chris Meinen (NOAA/AOML)
Peter Minnett (U. Miami)
Peter Rhines (U. Washington)
Uwe Send (Scripps)
C.K. Shum (OSU)
Fiamma Straneo (WHOI)
John Toole (WHOI)
Josh Willis (JPL)
Carl Wunsch (MIT)
Xiao-Hai Yan (U. Delaware)
Jiayan Yang (WHOI)
Gokhan Danabasoglu (NCAR)
Mike McPhaden (NOAA/PMEL)
Young-Oh Kwon (WHOI)
Patrick Heimback (MIT)
Shenfu Dong (NOAA/AOML)

AGENDA

Sessions:

1. Use of existing observations to characterize the variability and structure of the AMOC

2. Impact of existing measurements on constraining AMOC state estimations and an evaluation of the need and strategy for enhancing the current AMOC observing system

3. Examination of the role of AMOC variability on the climate system

4. The predictability of AMOC.

Plenary (invited) presentations:

Bill Johns:
Progress in characterizing AMOC structure and variability from observations

Tom Delworth: *Simulating the AMOC, its climatic impacts, and its predictability in coupled models*

Gokhan Danabasoglu:
AMOC Variability Mechanisms, Their Robustness, and Impacts of Model Configurations

Yochanan Kushir: *The Role of AMOC Variability in Climate*

Carl Wunsch:
Existing and Potential North Atlantic Circulation Estimates: Where do we go from here?

Progress in Characterizing AMOC Structure and Variability from Observations

Bill Johns

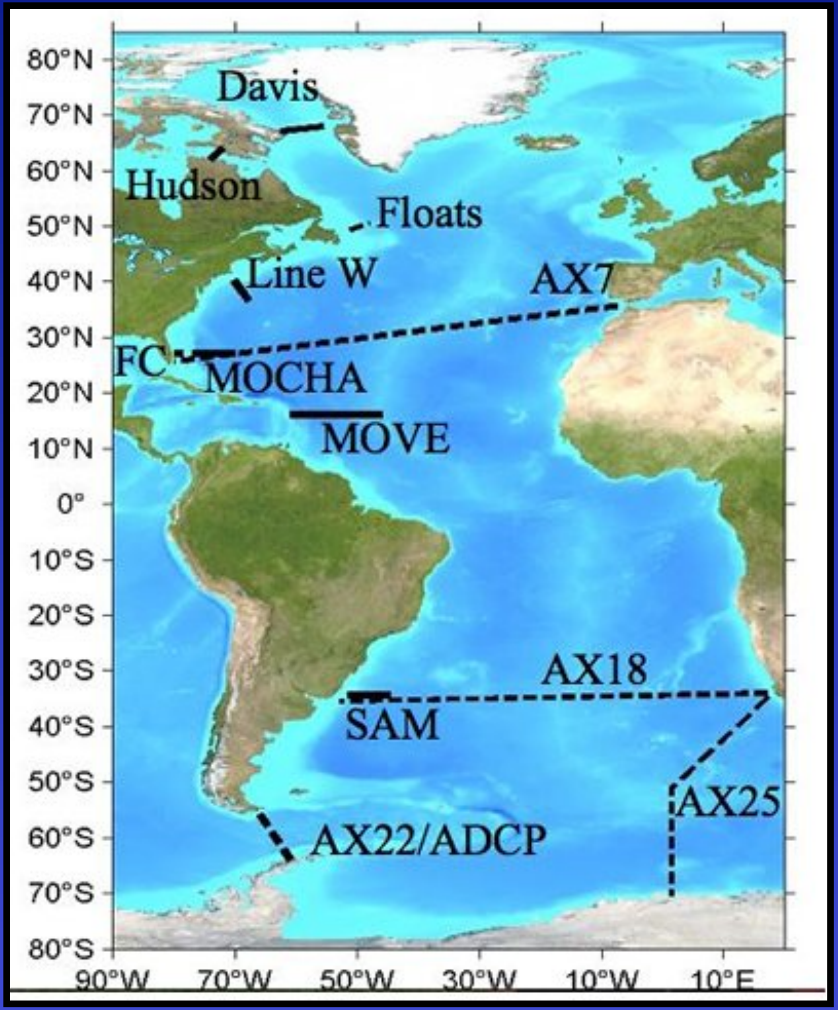
RSMAS, University of Miami, Miami FL

Outline:

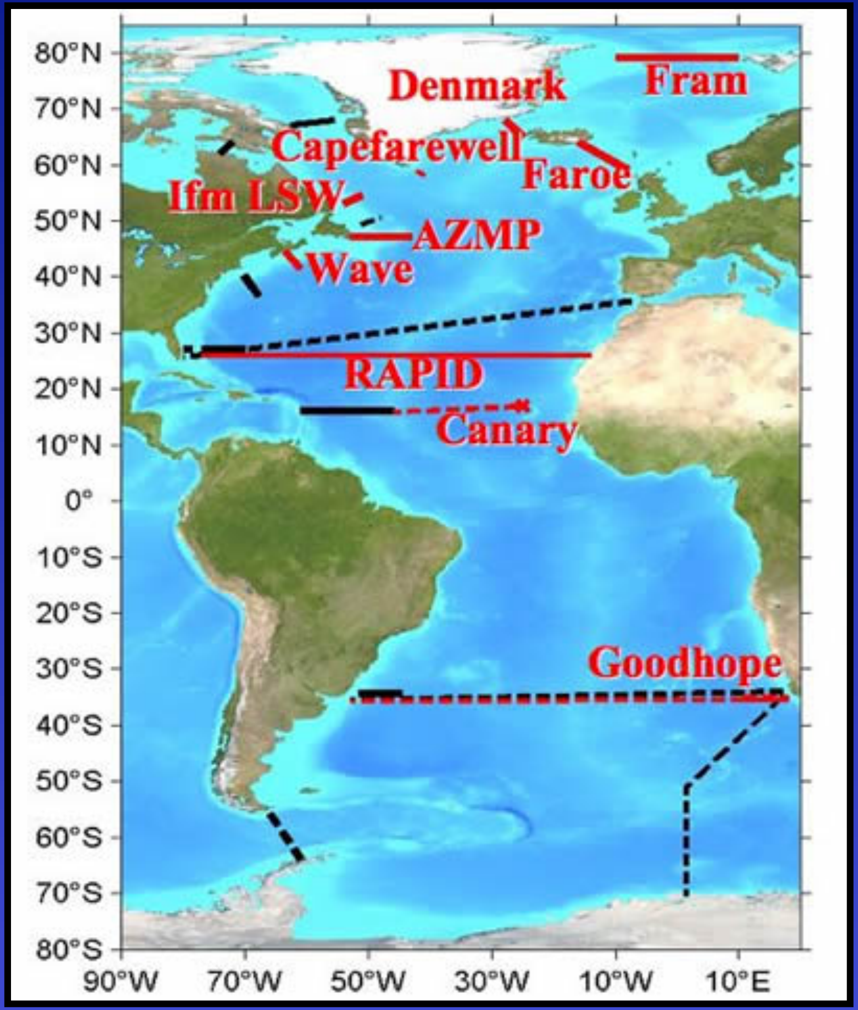
1. An AMOC tour from the subpolar gyre to the South Atlantic
2. How to move forward in directly observing the AMOC
3. What have we learned in the last ~5 years?

AMOC Observational Network

U.S. Programs



International Programs

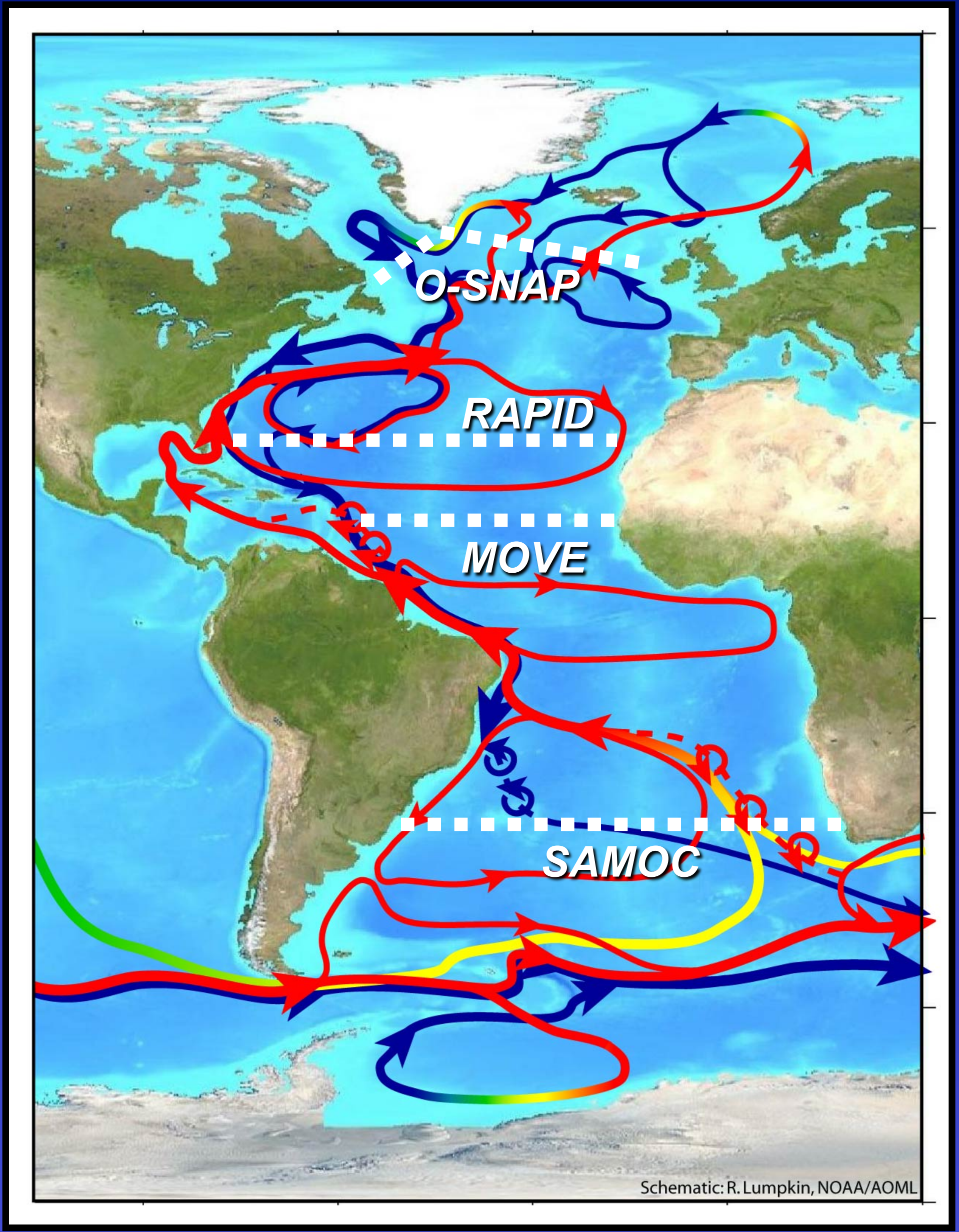


AMOC Monitoring Strategy

Establish discrete set of trans-basin arrays (moorings + autonomous profiling) for continuous AMOC estimates

Value:

- ***Accurate*** multi-year mean AMOC estimates, for comparison with future (and past) AMOC states
- ***Understanding*** of processes underlying short-term (intraseasonal to annual) variability
- ***Benchmarks*** for evaluation of modeled AMOC variability (GCMs, data synthesis models)



What have we learned in the past ~5 years?

1. Increasing evidence that overflows are stable (over the modern record, last 50 yrs). *-> Denmark Strait and Iceland-Faroes Ridge monitoring remains challenging.*

2. Mean transport of ISOW/DSOW at Cape Farewell appears to be ~9 Sv (*not 13 Sv*). Varies by ±30% on decadal timescales.
   -> Entrainment variability? LSW "blocking" at Gibbs?

3. LSW production can be temporally monitored by transient tracers. Mean LSW production 7.6-8.9 Sv (1970-97). Cycling between cLSW/uLSW, w/ link to NAO forcing. *-> How to monitor going forward (SF_6)? Pathways of export to the subtropics?*

4. LSW makes up *nearly half* of the deep limb of the AMOC.
   48ºN: LSW: 7.1 Sv; DSOW/ISOW: 9.1 Sv.
   26ºN: LSW: 8.2 Sv; DSOW/ISOW (minus AABW): 10.2 Sv.
   -> How are variations in LSW production reflected in export to subtropics? Modulating/buffering processes?

What have we learned in the past ~5 years (continued)?

1. Large short-term (intraseasonal to annual) MOC variability in subtropics. Ekman forcing dominates at intraseasonal; geostropic variability dominates on longer time scales (annual+). Annual MOC cycle documented and its fundamental mechanism explained.

2. AMOC snapshots derived from single hydrographic sections can be subject to considerable aliasing. The interior baroclinic flow cannot be assumed steady. The Bryden (2005) “trend” can be largely explained by seasonal aliasing.

3. MOC strength is fairly uniform throughout the basin. (16-18 Sv). Minor “internal” closure. *-> How does the partitioning of internal components vary? uLSW/CLSW? Agulhas leakage vs. AAIW?*

4. Complex NADW transformation processes in the S. Atlantic. DWBC eddies; interior pathways -> eastern boundary “DWBC”. Significant upward shift in mean density of NADW limb. *-> Equatorial mixing/ deep jets?*

Atlantic Variability, Climate Impacts, and Issues for AMOC Predictions

T. Delworth, Shaoqing Zhang, A. Rosati

1. Observed Atlantic variability and climatic impacts
2. Issues in decadal prediction, including the AMOC
3. Influence of observing systems on characterizing and predicting the AMOC
4. Summary

US AMOC Science Team Meeting June, 2010

Summary and Discussion

1. Atlantic SST variability has a rich spectrum with clear climatic impacts. This motivates attempts to understand the relationship of the AMOC to that variability, and to predict AMOC variations.

2. The use of ideal twin experiments, in concert with coupled assimilation system, allows an assessment of the potential of various observing systems to observe and predict the AMOC.

3. Model results suggest that the ARGO network is crucial to most faithful representation of AMOC in model analysis.

4. Predictability experiments show use of ARGO network plus atmospheric analysis provides the most skillful AMOC prediction (skill for AMOC is 78% with ARGO versus 60% without). Inclusion of changing radiative forcing tends to increase skill on longer time scale.

5. These experiments DO NOT take into account model bias, which is a formidable challenge. Anomaly initialization is an alternate strategy for prediction.

6. GFDL decadal prediction efforts using observed data are ongoing using ensemble coupled assimilation system and GFDL CM2.1 model.

Opportunities and Challenges

1. The causes of Atlantic decadal and multidecadal SST variations are not well understood. What role for the AMOC?

2. Enhanced focus on annually resolved proxy indicators could pay large dividends in better characterizing Atlantic variability.

3. It is crucial to maintain an adequate and stable observing network.

4. Model biases remain a critical problem for coupled models.

5. IPCC AR5 has a substantial focus on near-term predictions using initialized models – great opportunity for analysis of AMOC and predictability.

AMOC MULTI-DECADAL VARIABILITY: MECHANISMS, THEIR ROBUSTNESS, AND IMPACTS OF MODEL CONFIGURATIONS

Gokhan Danabasoglu and Steve Yeager
National Center for Atmospheric Research

Proposed AMOC variability mechanisms

1. Damped ocean-only mode, excited by atmospheric noise: Delworth et al. (1993), Griffies & Tziperman (1995), Delworth and Greatbatch (2000), Dai et al. (2005), Dong and Sutton (2005)

2. Internal mode, zonally propagating subpolar temperature anomalies: TeRaa and Dijkstra (2002, 2003), Zhu and Jungclaus (2008)

3. Arctic/Atlantic freshwater flux: Delworth et al. (1997), Jungclaus et al. (2005), Oka et al. (2006), Hawkins and Sutton (2007)

4. Fully coupled mode, basin-wide/tropics: Vellinga and Wu (2004)

5. Southern Ocean influence: (a) Winds: Delworth and Zeng (2008); (b) Freshwater flux: Saenko et al. (2003); (c) Dynamic signals from Agulhas leakage: Biastoch et al. (2008)

SUMMARY – WHAT HAVE WE LEARNED IN THE LAST 5 YEARS? (CGCM view)

- AMOC variability and predictability are (perhaps) more complicated than originally thought.
- Proposed variability mechanisms are not (really) robust across different models.
- Unresolved processes, e.g., mesoscale eddies, Nordic Sea overflows, oceanic mixing, appear to influence AMOC significantly.
- AMOC variability in CCSM4 is muted compared to that of CCSM3 and preliminary results indicate influence of overflows and a different mechanism than in CCSM3.

Key observational priorities listed in the AMOC 2009 report will be certainly helpful in discriminating against some of the proposed mechanisms.

The Role of AMOC Variability in Climate

(AMOC-SST association and the Atmospheric Response)

Yochanan Kushnir

Mingafng Ting, Naomi Naik, Cuihua Li, In-Sik Kang*,

Richard Seager, & M. Cane

Cooperative Institute for Climate Applications and Research

Lamont-Doherty Earth Observatory

Columbia University | Earth Institute

* *On sabbatical from Seoul National University*

2010 U.S. AMOC Annual Meeting / June 2010, Miami

Outline

- The relationship between AMOC variability and SST
- Observed and modeled impact of AMOC-related Atlantic SST variability on climate
- Mechanisms of atmospheric response to AMOC variability

Summary: AMOC-AMV

- AMOC variability leads to low-frequency changes in SST with a spatially coherent pattern (AMV), that is well simulated in forced and unforced coupled model:
  - The regions where the signal is large (and significant) are also strongly affected by high-frequency atmospheric forcing*.
  - There is no agreement between models and observations regarding the time scale of the variability.
  - The temporal relation AMOC-AMV is not uniform across models.
  - All these detracts from the ability to use SST for monitoring AMOC change (though it is a good diagnostic tool).

** Recent studies show that such high-frequency perturbations can lead to rapid growth of multi-decadal AMOC perturbations*

Summary: AMV impact

- AMV affects climate in and around the Atlantic Basin:
  - The impact of AMV is caused mainly by related changes in the north tropical Atlantic (NTA) SST.
  - Within the Atlantic and the surrounding land masses, models (coupled and uncoupled) simulated the observed AMV impact quite

Where Do We Go From Here?

AMOC June 2010 Miami

Carl Wunsch
MIT

One of the major difficulties in formulating a scientific plan for understanding the climate system is the huge variety of possibilities and interests, such as changes in heat content, salinity, meridional enthalpy transports, carbon uptake and transports, sea surface temperature, …. on time scales of years, decades, centuries,….., dynamics versus kinematics.

How do you get a focus? A particular problem for designing observing systems.

A suggestion:

A Strawman Proposal

Agree on a goal: US east coast sea level trend to be predicted to 15 years with an accuracy equivalent to 0.3mm/y. (Almost all physical processes show up in sea level and/or are affected by sea level.) Altimeter sets of a nominal accuracy goal.

Design an observing system that would be capable of that accuracy.

Develop the models capable of that accuracy.

Formulate a requirement on meteorological reanalyses capable of that accuracy.

Construct a coupled atmosphere-ocean-sea ice-land ice model formally capable of prediction from a known initial state.

Many people will not find this a compelling goal---but it does provide a framework incorporating almost all imaginable ones related to the ocean circulation. A 15-year time scale is humanly accessible.
It involves several other communities. Is that a bad thing?

Discussion Group Summaries:

1. Characterizing AMOC variability and structure using observations
2. Impact of observations on constraining AMOC; model-based assessment of observing systems
3. Climate impacts of the AMOC
4. Mechanisms and Predictability of the AMOC

Observational Discussion Group

Discussion leads: Susan Lozier and Josh Willis

Identification of gaps

- What is the response of MOC to variation in deep water formation rates (convective + overflow)?
- What is connectivity of AMOC from latitude to latitude?
- What mechanism communicates signals meridionally?
- How does Arctic variability relate to AMOC variability?
- How does Aghulas leakage impact AMOC variability?
- Can we devise a long-term strategy for observing coherent modes of interannual/decadal variability?
- Are we prepared to observe and document anthropogenically-forced AMOC changes?
- Must occupy complete subpolar sections for 10+ years to relate MOC to water mass formation

Near term foci:

Implement enhanced AMOC observing systems in the South Atlantic and Subpolar North Atlantic

- SAMOC
- O-SNAP

Results of AMOC Observing System Workshops:

1. Subpolar North Atlantic Workshop
   April 14-16, Duke University,
   Organizer: Susan Lozier

2. South Atlantic MOC Workshop (SAMOC3)
   May 11-13, DHN, Niteroi, Rio de Janeiro
   Organizers: Silvia Garzoli, Edmo Campos,
   Alberto Piola and Sabrina Speich

Observational Subpolar North Atlantic Program (working acronym:"O-SNAP")

Overall Goal:

"To quantify the large-scale, low-frequency, full water-column net fluxes of mass, heat and fresh water associated with the meridional overturning circulation in the subpolar North Atlantic."

Questions to address:

a. Can the overturning circulation be meaningfully related to the production of deep water masses?

b. What is the relative contribution of the horizontal versus overturning circulation to the net poleward heat transport? How does this relationship differ in depth-space versus density-space?

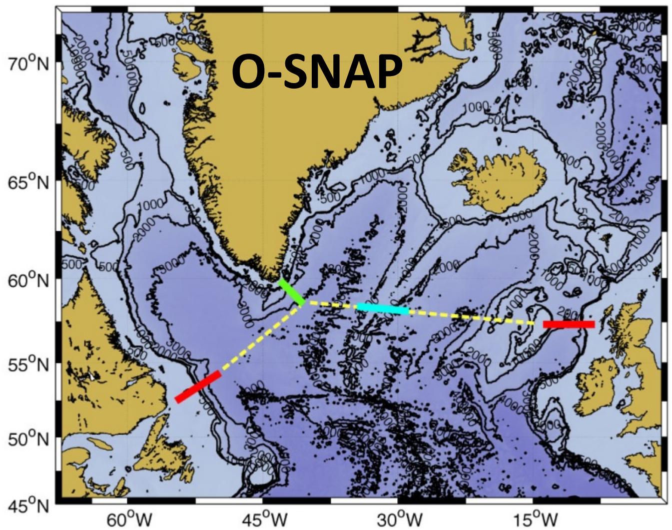
c. What is the relative contribution to the AMOC from water mass transformation in the Labrador/Irminger Seas versus the Nordic Seas?

Questions to address, continued

d. To what degree does the high-latitude water mass transformation occur in the boundary current system versus the interior basin?

e. What controls the partitioning of heat transported into the subpolar North Atlantic versus the Nordic Seas/Arctic?

f. What are the dominant pathways of the upper and lower limbs of the AMOC that connect the subpolar and subtropical regions?



Red lines: Boundary monitoring partially implemented. The two red lines are (i) the German Labrador Sea Exit array, which would need to be extended both to near-surface and inshore on the shelf, and (ii) the Ellett Line, which needs improved temporal and spatial measurement density.

- *Green line*: Location of the UK DWBC and French EGC arrays, in the water between 2004-2008.

- *Blue line*: Approximate location of a possible Mid-Atlantic Ridge array.

- *Yellow lines*: Ocean regions to be monitored by "soft" arrays, comprising of a mixture of gliders, floats, possibly deep T/S moorings, BPRs and bottom current meters.

O-SNAP linkages

1. International linkages and collaborations are essential for this work.
2. Strong interdisciplinary linkage with biogeochemists and biologists is being nurtured, particularly with the US/Canada/BASIN program.
3. Modeling efforts to guide the optimization of a long-term observing system; to aid our interpretation of those observations; and to advance our nascent mechanistic understanding of the AMOC are needed.
4. Observations (Eulerian, Lagrangian, satellite-based, etc. that provide connectivity from subpolar North Atlantic, subtropical North Atlantic and subtropical South Atlantic MOC measures are needed.

SAMOC 3

Niteroi, Rio de Janeiro, May 11, 12, 13, 2010

Organized by: Edmo Campos, Silvia Garzoli, Alberto Piola and Sabrina Speich

About 30 participants from Argentina, Brazil, France, the Netherlands, Russia, South Africa, the UK, Uruguay and the US

Funded by NOAA/CPO, US CLIVAR, IFREMER, Brazilian Navy And Brazilian Science Council

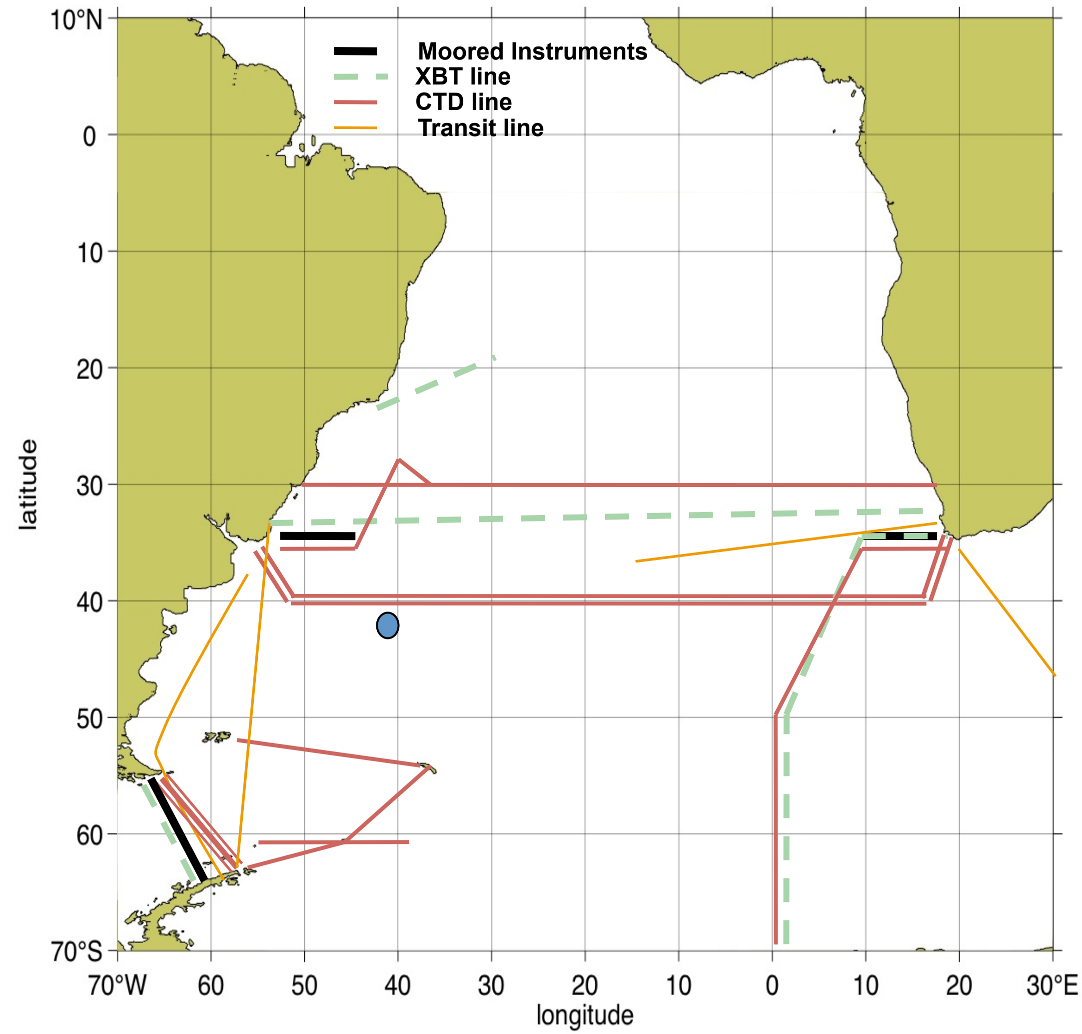
Main Objective:

• To gather international experts to design the basis for an observational program for the Meridional Overturning Circulation in the South Atlantic.

Goals:

• To discuss how present observations may contribute to estimate the meridional fluxes of mass, heat and freshwater;
• How the observational array ought to be upgraded to better capture these fluxes and their variability, and
• How to transition from an initial observational array to a long-term sustained program.

For that purpose it was necessary to determine ***what*** *parameters should be observed,* ***where*** *the observations are needed,* ***who*** *will be interested in carrying them out,* ***how*** *to observed them – what are the best possible observation strategies, and* ***when*** *will the participants aim to begin*. The workshop also aimed to foster international cooperation, which is of crucial importance to fulfill these objectives.



	Dates	Institution	POC
AX18 35°S	Quarterly	AOML/SHN	Baringer, Troisi
AX97 22°S	Quarterly	FURG/AOML	Mata, Goni
AX25 GoodHope line	Dec 2010, February 2011	UCT/AOML	Ansorge/Garzoli
AX22 Drake Passage (includes SADCP) RV Gould	Bi-monthly	SIO	Sprintall
CLIVAR repeat Hydro. 30°S. CTD/LDCP, CO_2. CfC, ph, He/Tr, nutrients.	March May 2011	AOML/PMEL	Baringer
GoodHope line. RV Vavilov	Oct-10	Shirshov/IFREMER	Gladyshev, Speich
Cape Town-Montevideo, 40°S. RRS Discovery	October-November 2010	NOCS	Mills
Vema Channel Session and SAM region. CTD/LDCP. RV Akademik Ioffe	Nov-10		Zavialov
Drake Passage	Nov-10	Shirshov	Gladyshev
Drake Passage. cDrake	November 2010 and 2011	URI/SIO	Chereskin
Drake Passage RRS J.C.Ross	Dec-10	NOCS	King
DIMES (west of Drake) RV James Cook	12/1/2010 and February 2012	NOCS/BAS	Meredith/Naveira Garabato
Scotia Sea & Transits Malvinas, S. Georgia, S. Orkney, and Antarctic Peninsula SADCP, TSG. RV Vavilov	November 2010 and March 2011		Gladyshev
Orkney Passage. RRS J.C. Ross	Apr-11	BAS	Abrahamsen
Cape Town to Gough Island	Sep-10	UCT	Ansorge
Cape Town to Marion Island	Apr-11	UCT	Ansorge
Drake Passage and Antarctica Peninsula. RV Puerto Deseado	December 2010 and March 2011	SHN	Troisi
Transit Brazil-Antarctica	October and March 2010	Brazil	Garcia
SAM. CPIES/PIES. 34.5°S South Western Atlantic		AOML/SHN	Meinen, Troisi
GoodHope. CPIES		Ifremer	Speich
GoodHope line. Tall moorings		AWI	
GoodHope line PIES		AWI	Boeble
cDrake PIES/CPIES		URI/SIO	Chereskin
OOI		WHOI/SIO	Send

What: *parameters should be observed,* :

- Meridional heat transport
- Water-mass exchanges through the choke points (Drake, S. of Africa)
(which is already happening via related programs)
- T, S, velocity & bottom pressure along sections as possible
- Absolute boundary current measurements (particularly DWBC)

Where: *are the observations needed* : Nominally 35°S

Who: *will be interested in carrying them out* : Everyone attending

How: *to observe them, what are the best possible observation strategies* :

- Full depth hydrographic line
- Instrument a line at nominally 35°S

Model evaluation & mooring system design studies ongoing

When: 2012+

Discussion Group 2:

Impact of observations on constraining AMOC; model based assessment of observing systems

Discussion lead: Tony Lee

Specific near term foci:

- Complete observing system evaluation for subpolar N. Atlantic and S. Atlantic
- Quantify impact of deep measurements in the interior North Atlantic (deep ARGO, full depth gliders)
- Develop observing systems capable of examining meridonal coherence of the AMOC and associated elements, including forcing functions.
- Developing plans for putting judicious posterior error estimates on AMOC strength and variability estimates derived from ocean state estimation models.
- Develop coordinated activity (including model development and observing system sensitivity studies) to examine special physics region such as high-latitude sinking regions.
- Develop coordinated activity to examine water-mass transformation associated with AMOC and related air-sea interaction using modeling and assimilation systems.
- Understand the reasons for differences - or biases- in the relationship between model MOC intensity and MHT in available models, as compared to observations.
- Evaluate robustness of AMOC fingerprint in different models and consistency with observed fingerprint.

Discussion Group 3:

Climate Impacts of the AMOC

Discussion lead: Yochanon Kushnir

Near term priorities:

- Understanding the link between AMOC and SST variability: The most important near term goal in this area is to study and understand better the interaction between AMOC and upper ocean properties, particularly temperature/SST but also salinity. It is important to study the mechanisms of AMOC's influence on the latter but also the role of upper ocean anomalies on generating (predictable) AMOC variability. There is a need to determine the phase relationships between the overturning circulation, the strength of the horizontal gyres, and the subsequent impact on SST.

- Robustness of AMOC/AMV impacts and connecting impact studies to societal needs: While the the number of studies on AMOC/AMV impact on world (particularly Northern Hemisphere) climate, has increased and broadened, more should be done to establish the robustness of these links, understanding their cause, and comparing them to other long-term changes in climate, forced and natural. It is important to link these impact studies to societal needs and if relevant to actual sectoral decision (e.g., in water resources, coastal infrastructure, health, and ocean resource management). This will help focus impact research and lead to tangible benefits from AMOC research.

- Strengthen links to other related CLIVAR/WCRP activities: This will raise the profile of our PIs' work and help in exchange of important information and stimulate progress. This goal can be achieved through U.S. CLIVAR, the International CLIVAR Atlantic Implementation Panel, and through communication with individual program committees, nationally and internationally.

Discussion Group 4:

Mechanisms and Predictability of AMOC

Discussion lead: Gokhan Danabasoglu

Specific near-term, high priority goals/coordinated activity:

- Study AMOC and NHT relationships in models (forward, assimilation, eddy-permitting) in comparison with the RAPID data

- Inter-comparison of near-term prediction experiments (AR5) to investigate robustness of model simulations

- Inter-comparison of hindcast ocean-only and ocean-ice coupled simulations forced with the CORE-II inter-annual data sets to assess the robustness of model simulations under specified forcing

- Need new observations & synthesis of existing observations to discriminate against proposed mechanisms, including synthesis of proxy data

Specific near-term, high priority goals (continued):

- Impact of model biases, e.g., Gulf Stream and North Atlantic Current paths, on AMOC variability and predictability

- Focus studies between modeling groups for mechanisms (focus needs to be identified, e.g., convection, overflows, ….)

- Identify "best" initialization practices for decadal prediction simulations (unclear if this can be accomplished????)

- Investigate impacts of high resolution (0.1^{o}) on AMOC variability

- Identify standard metrics (CLIVAR DVWG?)

AMOC Program next steps:

- AMOC P.I.'s team up to produce proposals to accomplish near-term goals (with external/international collaboration, as appropriate)
- Re-evaluation of AMOC Task Teams; engage new science team membership/leadership
- Appoint AMOC executive committee (science team chair, task team chairs, and U.S. Clivar rep. (Legler) to facilitate communications/coordination with other programs and U.S./international funding agencies
- Next meeting: joint with RAPID international conference, 12-15 July, 2011, Bristol, UK.

Progress in Characterizing AMOC Structure and Variability from Observations

Bill Johns

RSMAS, University of Miami, Miami FL

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AMOC Observational Network

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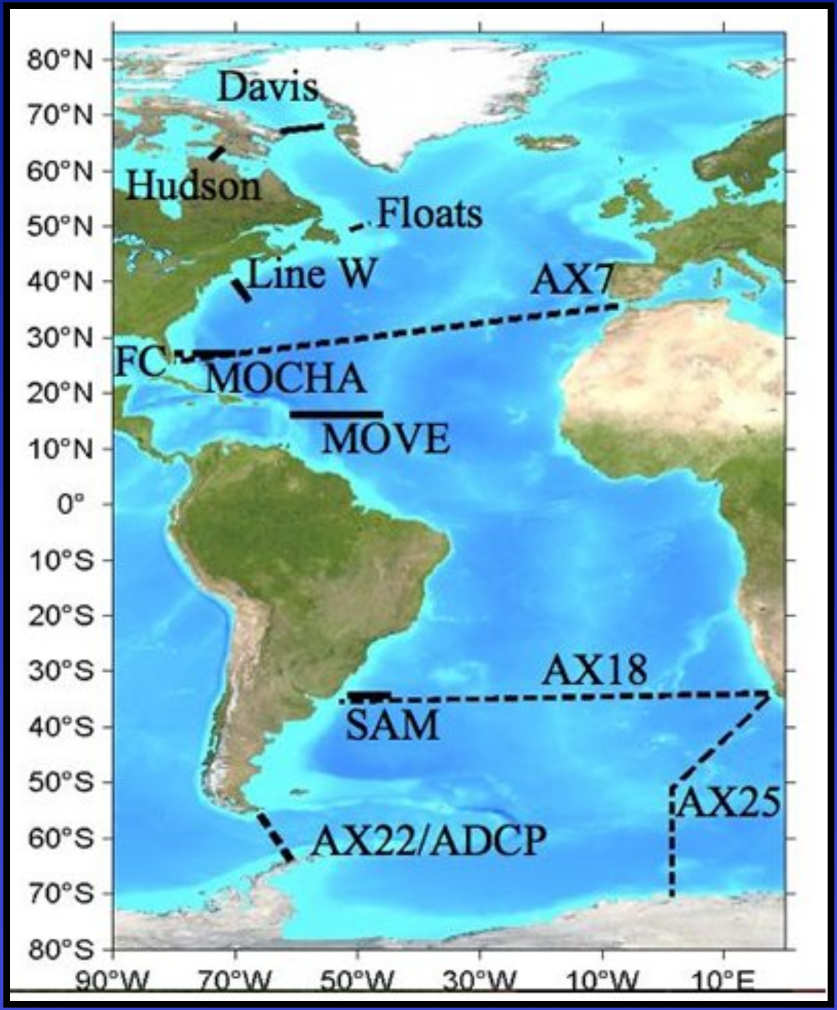
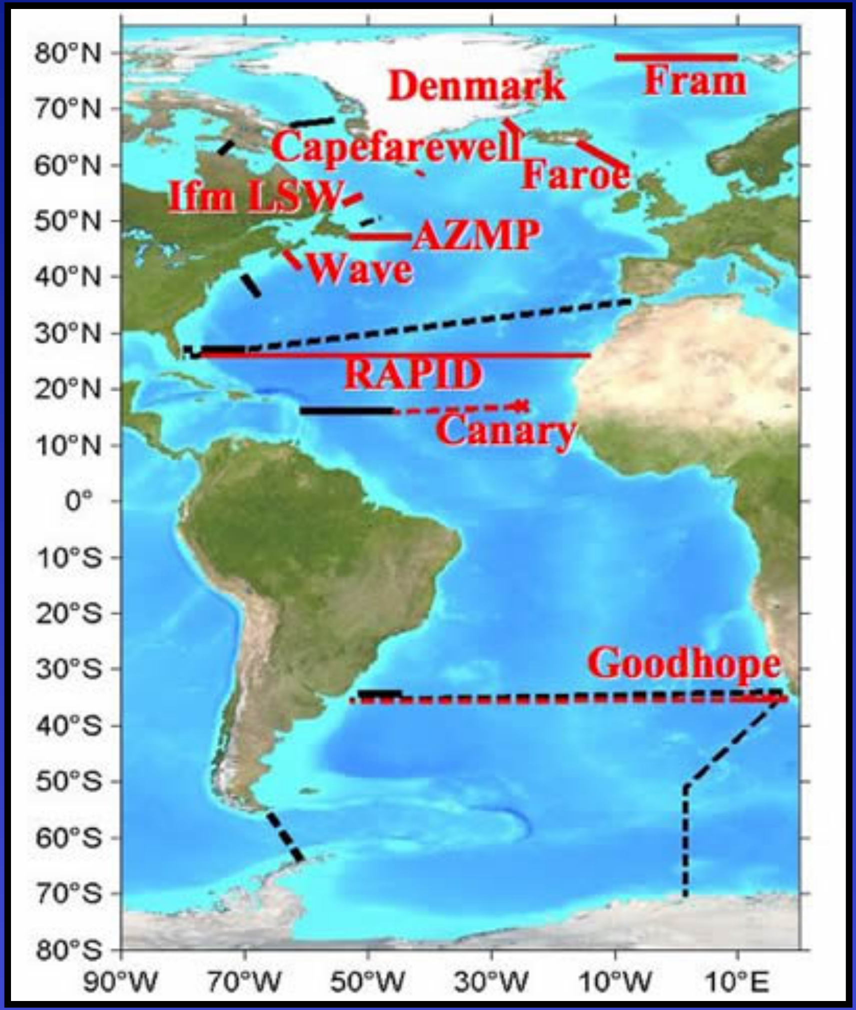
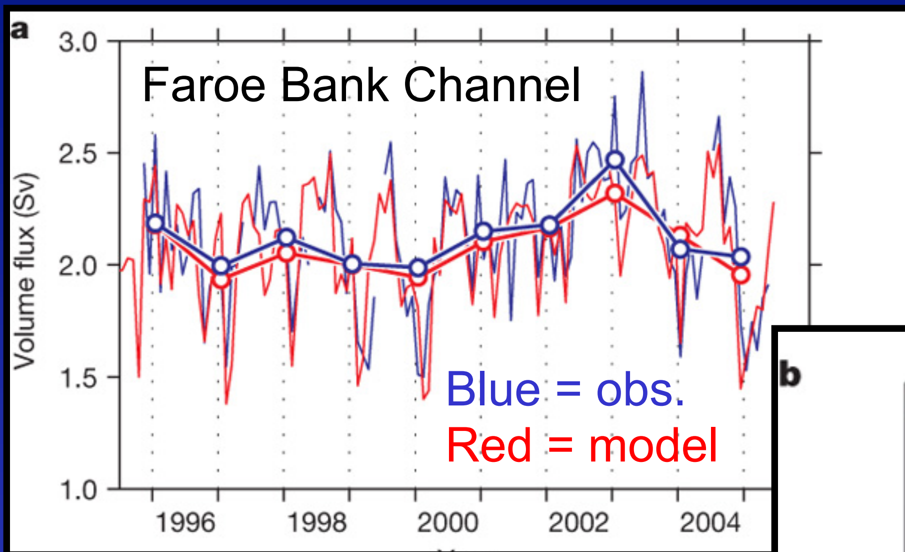


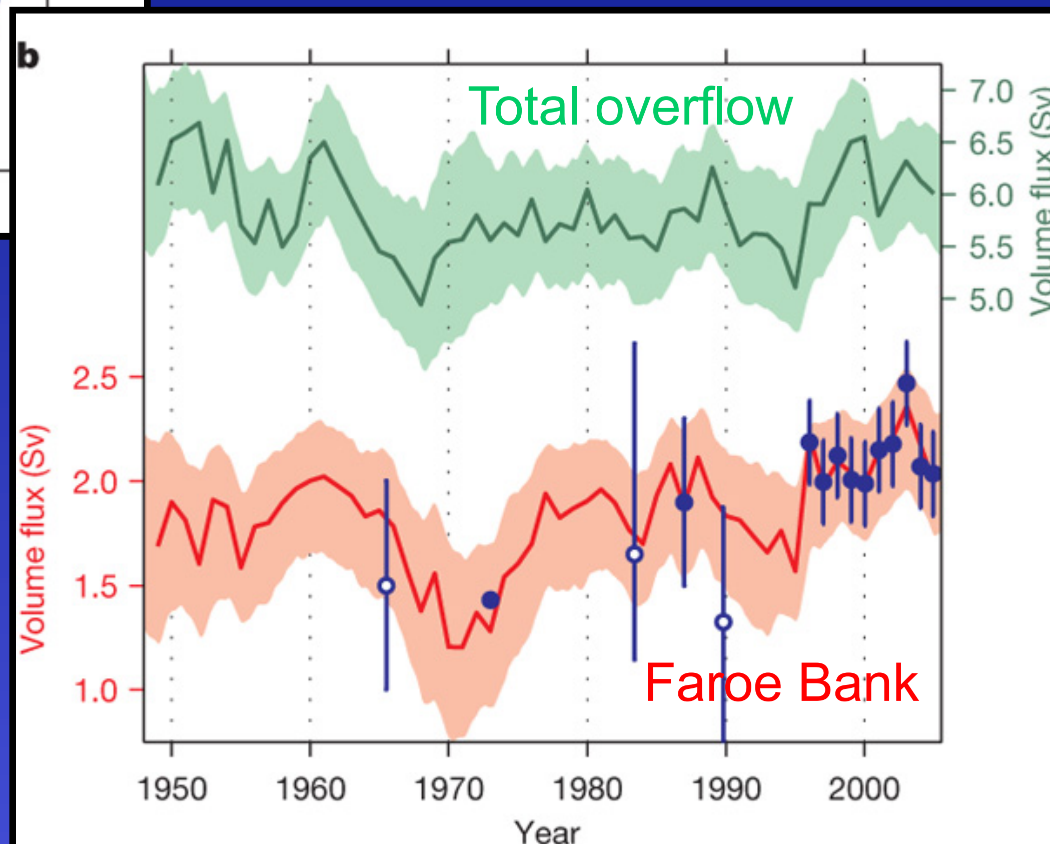
International Programs



Nordic Seas Overflows

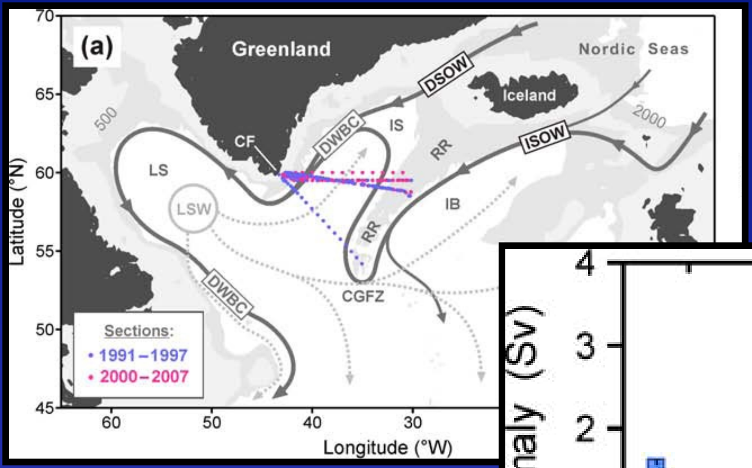


Olsen et al. (2008)

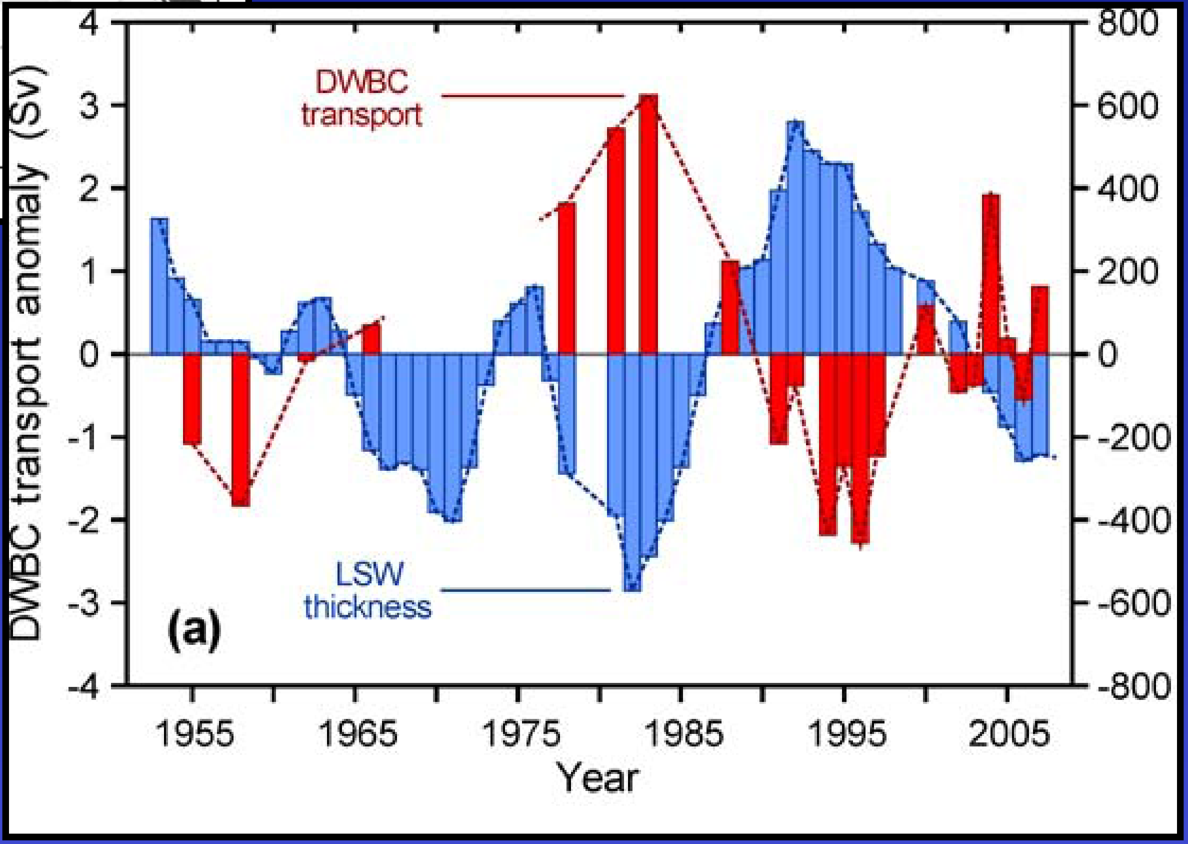


Model hindcast of Faroe Bank overflow during the observational record (top), and for the last 50 years (right). Total Nordic Sea overflow shown in green (right).

Historical DWBC Measurements at Cape Farewell (updated)

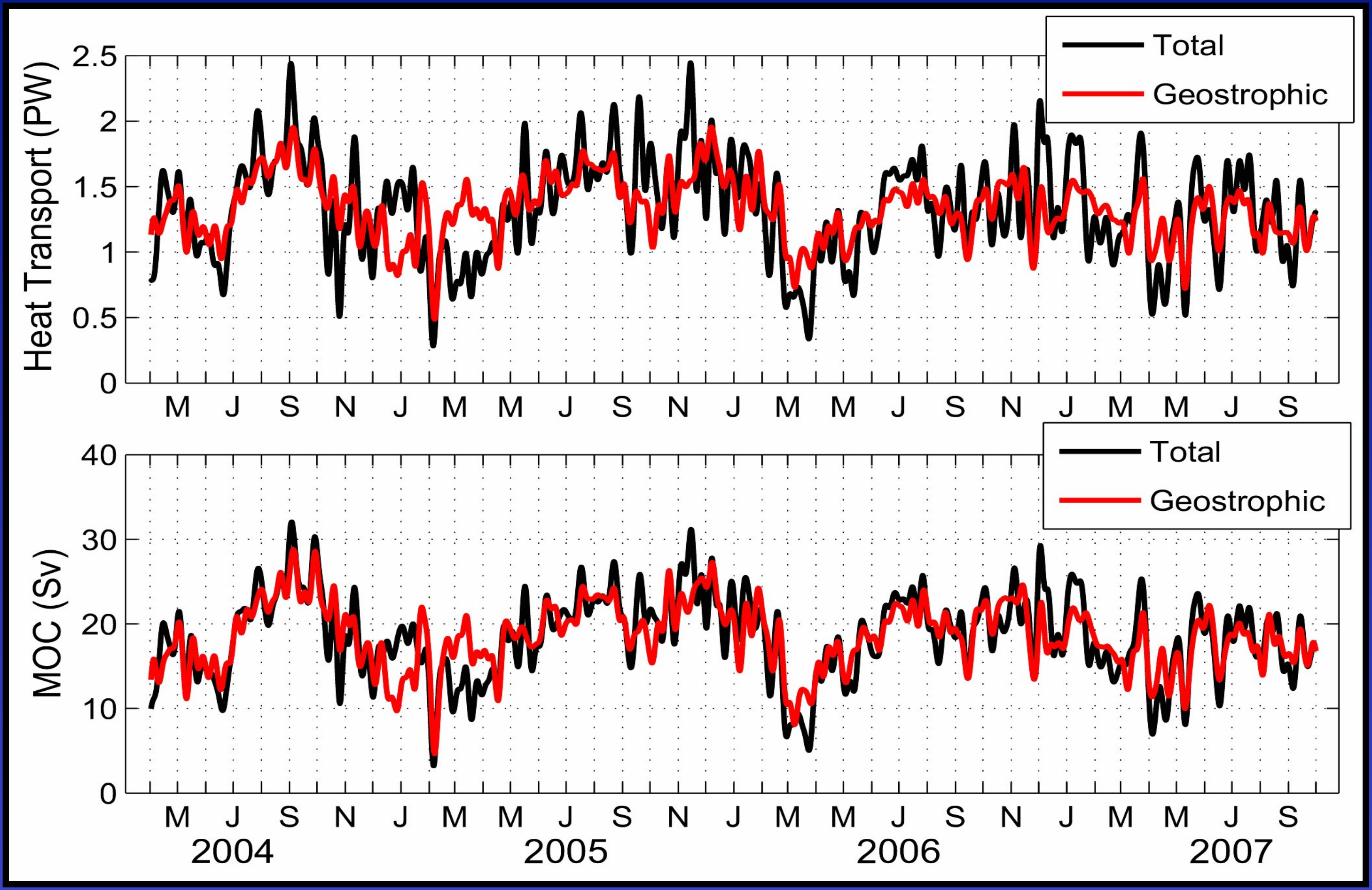


Sarafanov et al. (2009)



Cape Farewell DWBC baroclinic transport anomaly vs. Labrador Sea Water thickness

RAPID-MOCHA Array at 26.5ºN
MOC and Heat Transport Variability



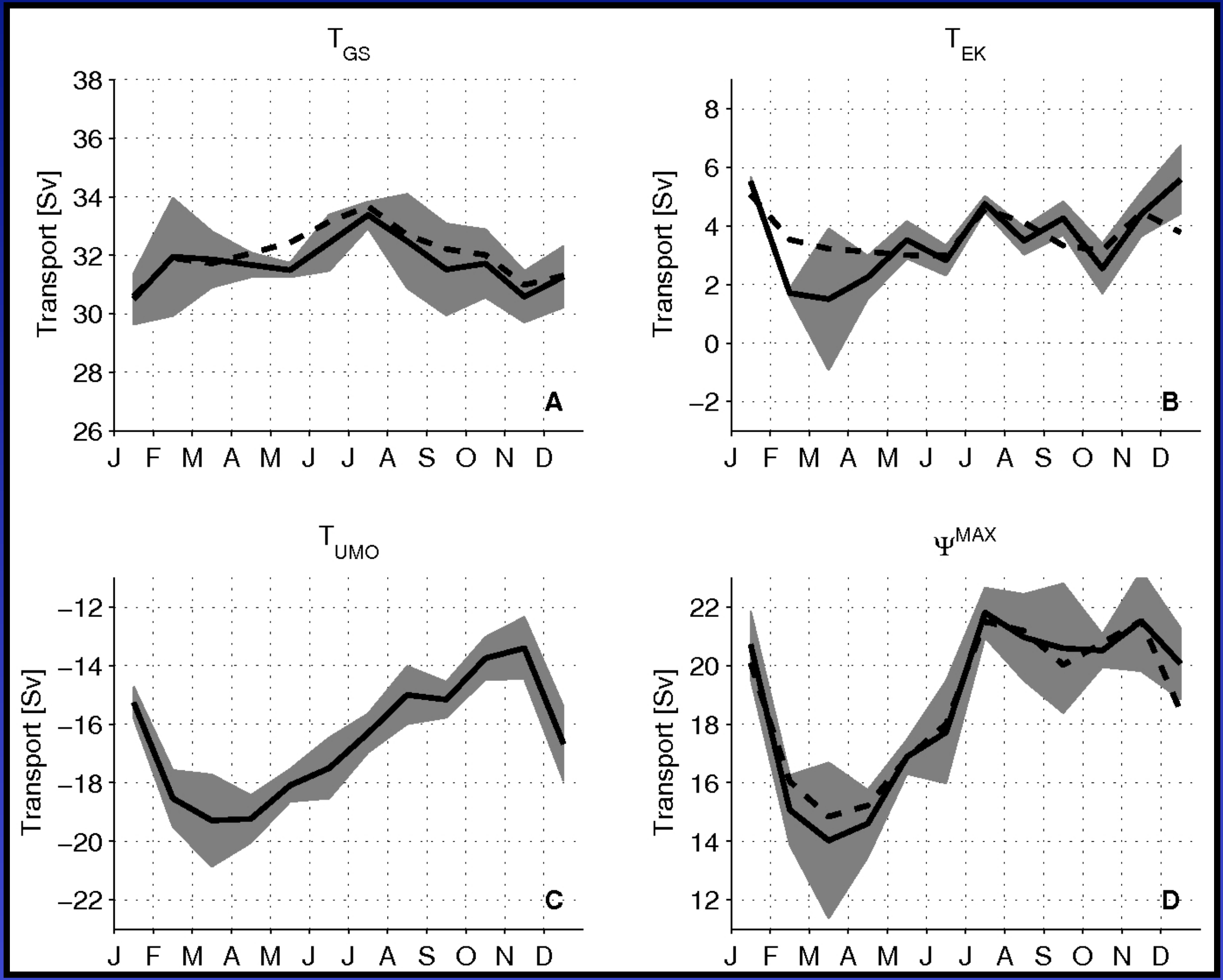
3.5 year mean MOC: 18.5 ± 4.9 (3.8*) Sv (σ_{err} = 2.1 Sv)

mean MHT: 1.33 ± 0.40 (0.24*) PW (σ_{err} = 0.12 PW)

*with contribution by Ekman transport variability removed

AMOC seasonal cycle at 26.5ºN

AMOC seasonal cycle and seasonal contributions to upper ocean part of AMOC cell

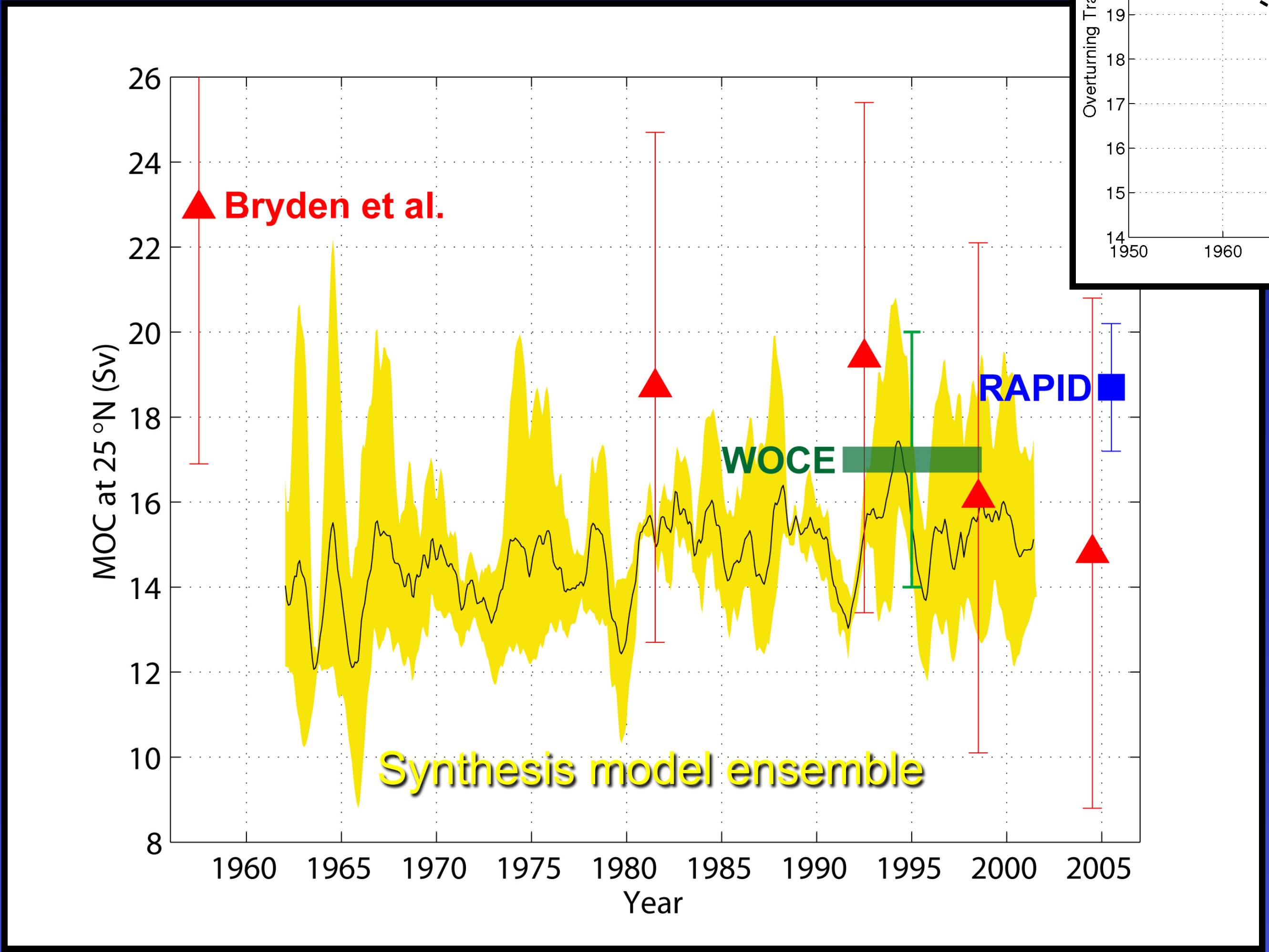


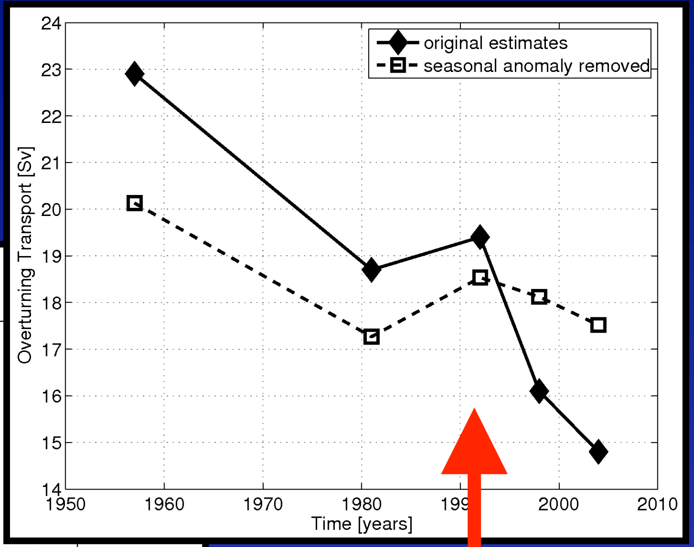
The interior transport (T_{UMO}) cycle can be explained by linear, forced Rossby wave response to wind stress curl, contained mostly in eastern basin

Kanzow et al. (2010)

26.5ºN in perspective

CCSP (2008): Abrupt Climate Change



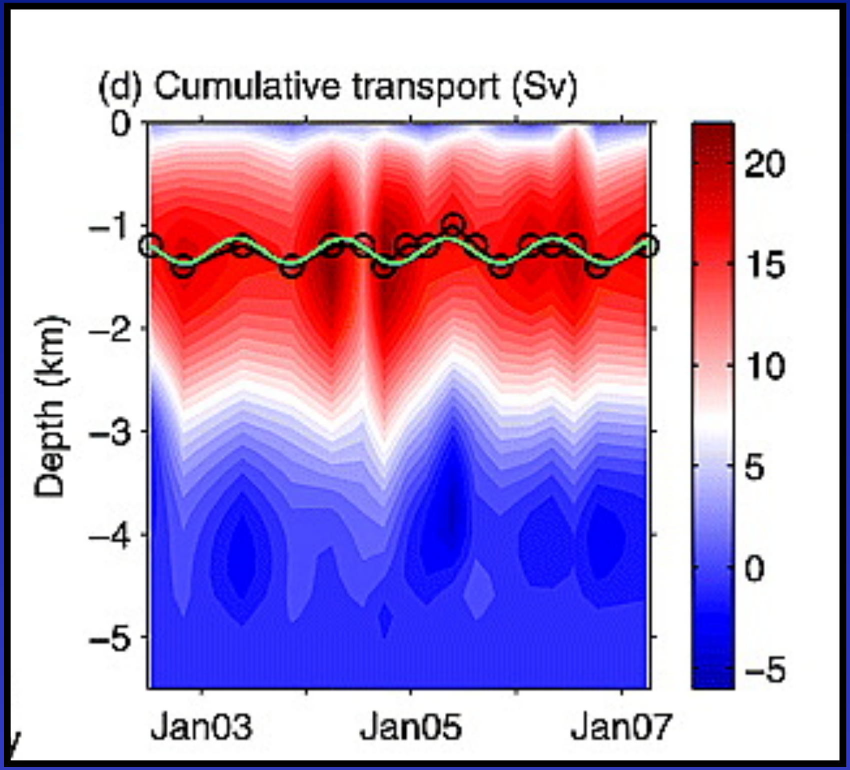


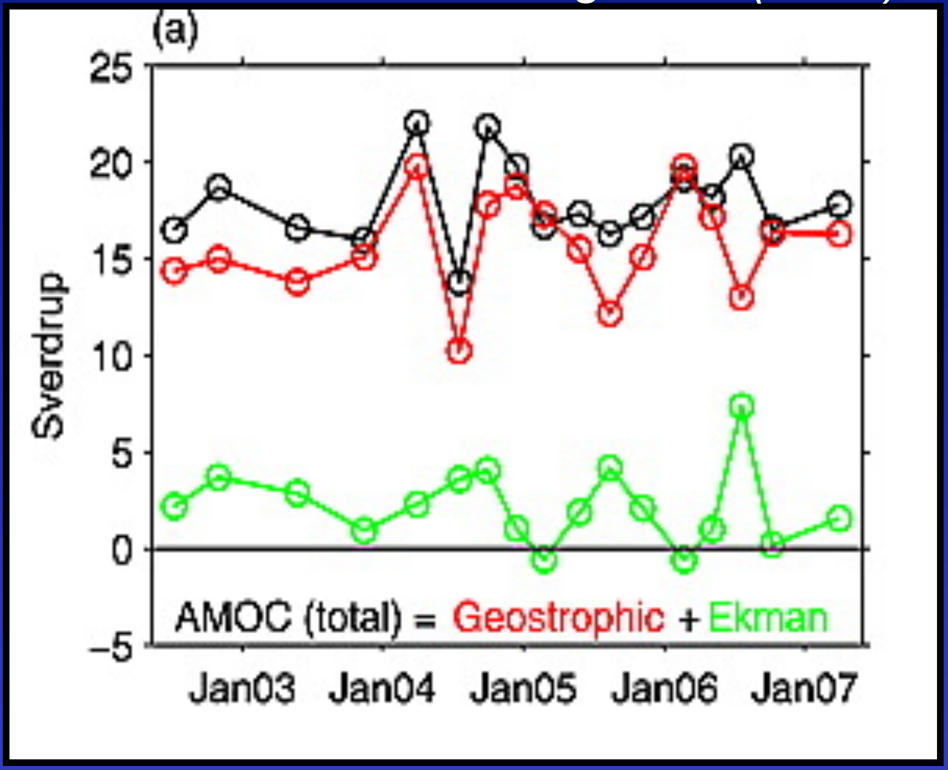
Bryden (2005) MOC values after application of seasonal correction

Kanzow et al. (2010)

South Atlantic (35ºS)

Dong et al. (2009)





17 transects (2002-2007):

Mean MOC: 17.9 ± 2.2 Sv

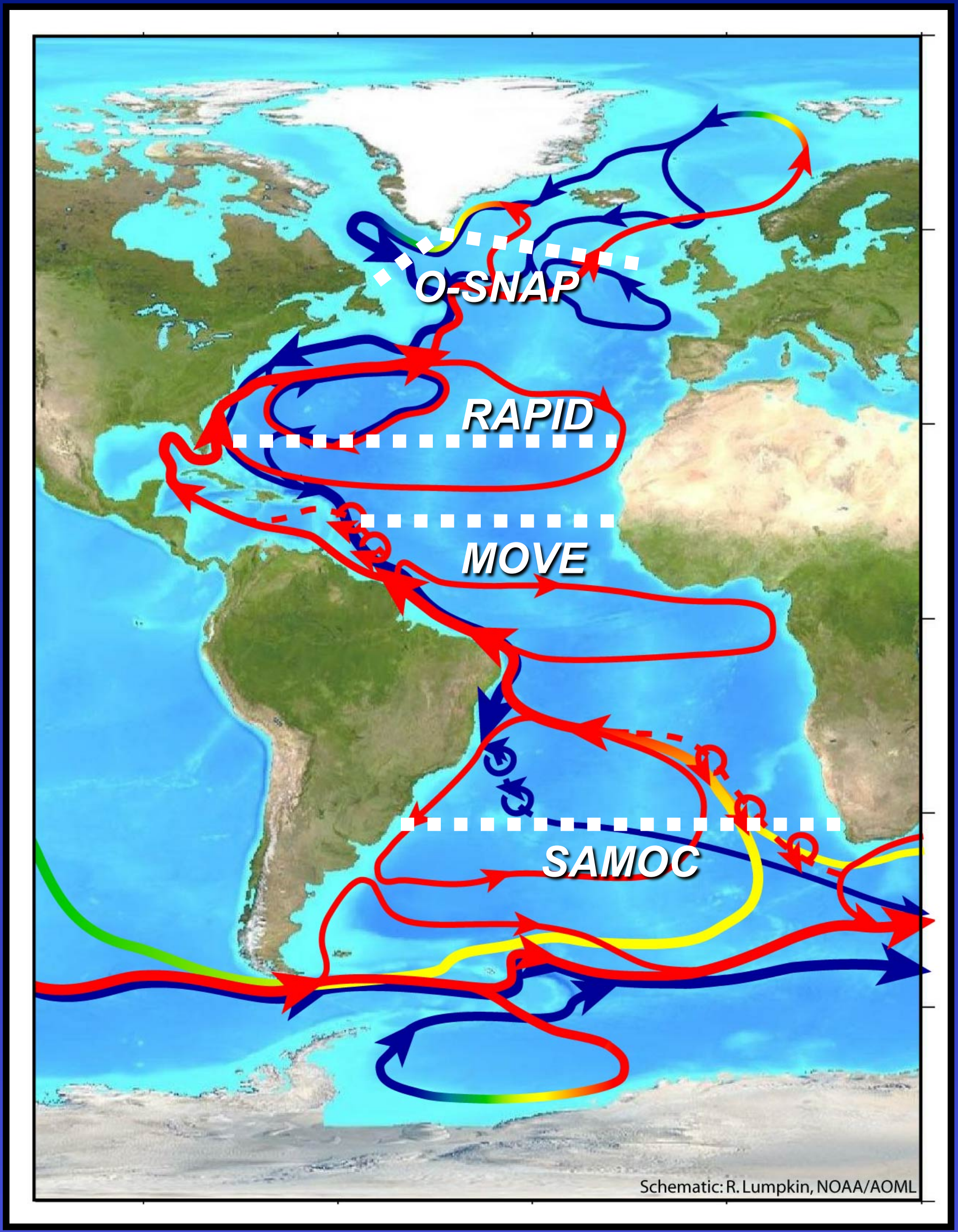
Mean MHT: 0.55 ± 0.14 PW

AMOC Monitoring Strategy

Establish discrete set of trans-basin arrays (moorings + autonomous profiling) for continuous AMOC estimates

Value:

- ***Accurate*** multi-year mean AMOC estimates, for comparison with future (and past) AMOC states
- ***Understanding*** of processes underlying short-term (intraseasonal to annual) variability
- ***Benchmarks*** for evaluation of modeled AMOC variability (GCMs, data synthesis models)



What have we learned in the past ~5 years?

1. Increasing evidence that overflows are stable (over the modern record, last 50 yrs). *-> Denmark Strait and Iceland-Faroes Ridge monitoring remains challenging.*

2. Mean transport of ISOW/DSOW at Cape Farewell appears to be ~9 Sv (*not 13 Sv*). Varies by ±30% on decadal timescales.
-> Entrainment variability? LSW "blocking" at Gibbs?

3. LSW production can be temporally monitored by transient tracers. Mean LSW production 7.6-8.9 Sv (1970-97). Cycling between cLSW/uLSW, w/ link to NAO forcing. *-> How to monitor going forward (SF_6)? Pathways of export to the subtropics?*

4. LSW makes up *nearly half* of the deep limb of the AMOC.
48ºN: LSW: 7.1 Sv; DSOW/ISOW: 9.1 Sv.
26ºN: LSW: 8.2 Sv; DSOW/ISOW (minus AABW): 10.2 Sv.
-> How are variations in LSW production reflected in export to subtropics? Modulating/buffering processes?

What have we learned in the past ~5 years (continued)?

1. Large short-term (intraseasonal to annual) MOC variability in subtropics. Ekman forcing dominates at intraseasonal; geostropic variability dominates on longer time scales (annual+). Annual MOC cycle documented and its fundamental mechanism explained.

2. AMOC snapshots derived from single hydrographic sections can be subject to considerable aliasing. The interior baroclinic flow cannot be assumed steady. The Bryden (2005) "trend" can be largely explained by seasonal aliasing.

3. MOC strength is fairly uniform throughout the basin. (16-18 Sv). Minor "internal" closure. *-> How does the partitioning of internal components vary? uLSW/CLSW? Agulhas leakage vs. AAIW?*

4. Complex NADW transformation processes in the S. Atlantic. DWBC eddies; interior pathways -> eastern boundary "DWBC". Significant upward shift in mean density of NADW limb. *-> Equatorial mixing/ deep jets?*

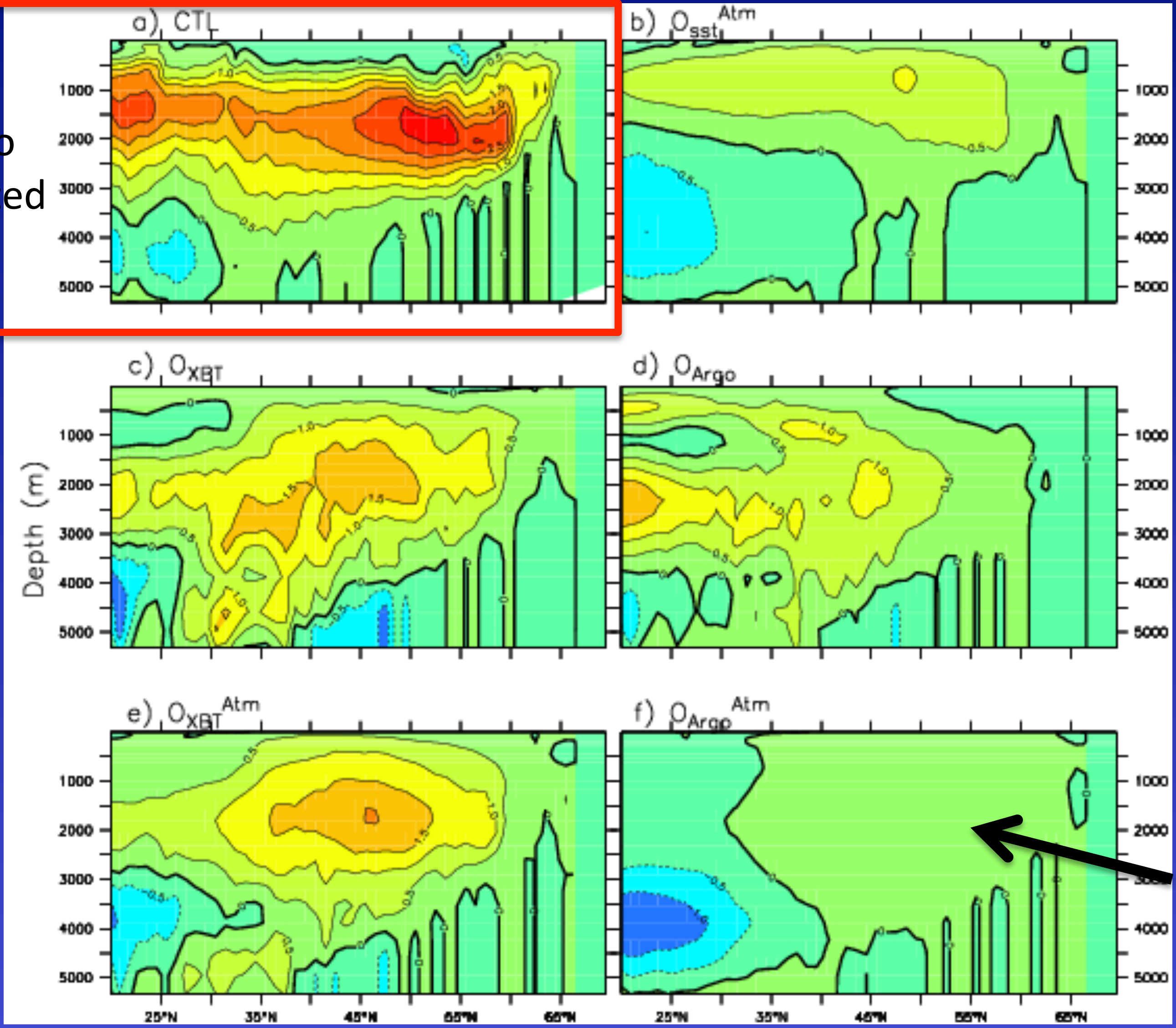
Atlantic Variability, Climate Impacts, and Issues for AMOC Predictions

T. Delworth, Shaoqing Zhang, A. Rosati

1. Observed Atlantic variability and climatic impacts
2. Issues in decadal prediction, including the AMOC
3. Influence of observing systems on characterizing and predicting the AMOC
4. Summary

Recovery of "true" spatial pattern of AMOC as a function of observing system

" Worst case" (no assimilated data)

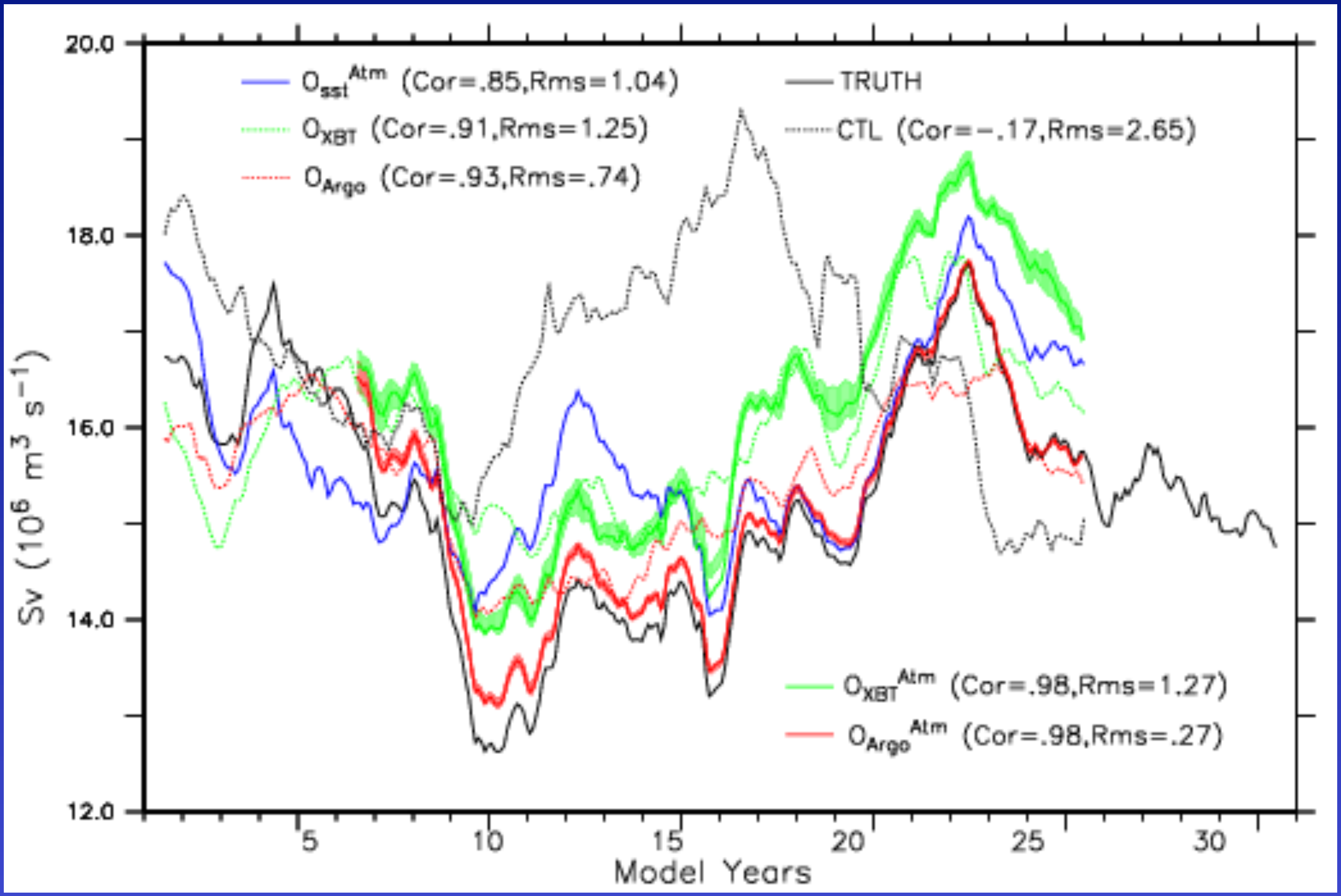


Other panels show difference between assimilated AMOC and "truth" as a function of observing system

"BEST"
(Argo plus atmosphere temp and winds)

Ability to represent AMOC in models is a function of observing system

- Use of ARGO plus atmospheric temperature and winds performs best



Zhang et al, accepted

Summary and Discussion

1. Atlantic SST variability has a rich spectrum with clear climatic impacts. This motivates attempts to understand the relationship of the AMOC to that variability, and to predict AMOC variations.

2. The use of ideal twin experiments, in concert with coupled assimilation system, allows an assessment of the potential of various observing systems to observe and predict the AMOC.

3. Model results suggest that the ARGO network is crucial to most faithful representation of AMOC in model analysis.

4. Predictability experiments show use of ARGO network plus atmospheric analysis provides the most skillful AMOC prediction (skill for AMOC is 78% with ARGO versus 60% without). Inclusion of changing radiative forcing tends to increase skill on longer time scale.

5. These experiments DO NOT take into account model bias, which is a formidable challenge. Anomaly initialization is an alternate strategy for prediction.

6. GFDL decadal prediction efforts using observed data are ongoing using ensemble coupled assimilation system and GFDL CM2.1 model.

Opportunities and Challenges

1. The causes of Atlantic decadal and multidecadal SST variations are not well understood. What role for the AMOC?

2. Enhanced focus on annually resolved proxy indicators could pay large dividends in better characterizing Atlantic variability.

3. It is crucial to maintain an adequate and stable observing network.

4. Model biases remain a critical problem for coupled models.

5. IPCC AR5 has a substantial focus on near-term predictions using initialized models – great opportunity for analysis of AMOC and predictability.

AMOC MULTI-DECADAL VARIABILITY: MECHANISMS, THEIR ROBUSTNESS, AND IMPACTS OF MODEL CONFIGURATIONS

Gokhan Danabasoglu and Steve Yeager
National Center for Atmospheric Research

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Proposed AMOC variability mechanisms

1. Damped ocean-only mode, excited by atmospheric noise: Delworth et al. (1993), Griffies & Tziperman (1995), Delworth and Greatbatch (2000), Dai et al. (2005), Dong and Sutton (2005)

2. Internal mode, zonally propagating subpolar temperature anomalies: TeRaa and Dijkstra (2002, 2003), Zhu and Jungclaus (2008)

3. Arctic/Atlantic freshwater flux: Delworth et al. (1997), Jungclaus et al. (2005), Oka et al. (2006), Hawkins and Sutton (2007)

4. Fully coupled mode, basin-wide/tropics: Vellinga and Wu (2004)

5. Southern Ocean influence: (a) Winds: Delworth and Zeng (2008); (b) Freshwater flux: Saenko et al. (2003); (c) Dynamic signals from Agulhas leakage: Biastoch et al. (2008)

Damped Ocean-only mode, forced by stochastic atmosphere

Delworth et al. (1993): GFDL R15 coupled model, 40-80 yr period

weak AMOC

↓

reduced heat transport

↓

cold, dense pool in middle North Atlantic

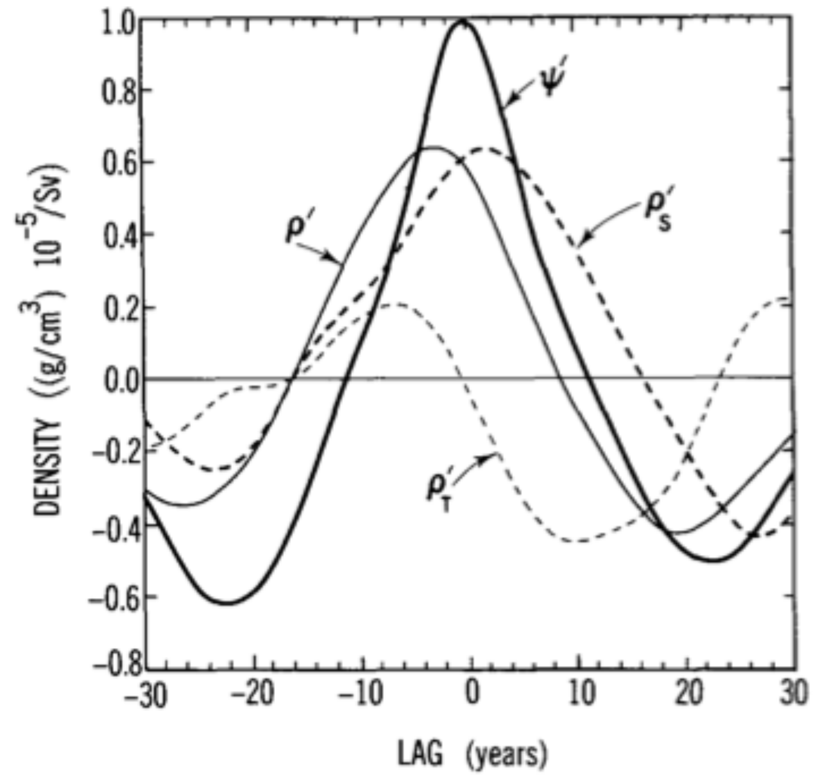
↓

T anomalies generate cyclonic gyre circulation

↓

anomalous circulation transports S into the sinking region → S, density, and AMOC all increase

$AMOC_{max}$ vs density regressions



Coupled ocean-atmosphere mode, basin-wide (HadCM3, 90 yr)

Vellinga & Wu (2004): Involves large scale air-sea interaction

AMOC + → increased NHT → generates cross Equatorial SST gradient

→ northward ITCZ shift → increased rainfall and FW flux into the ocean

→ surface salinity decreases → low salinities advected north into sinking regions → AMOC -

SUMMARY – WHAT HAVE WE LEARNED IN THE LAST 5 YEARS? (CGCM view)

- AMOC variability and predictability are (perhaps) more complicated than originally thought.
- Proposed variability mechanisms are not (really) robust across different models.
- Unresolved processes, e.g., mesoscale eddies, Nordic Sea overflows, oceanic mixing, appear to influence AMOC significantly.
- AMOC variability in CCSM4 is muted compared to that of CCSM3 and preliminary results indicate influence of overflows and a different mechanism than in CCSM3.

Key observational priorities listed in the AMOC 2009 report will be certainly helpful in discriminating against some of the proposed mechanisms.

The Role of AMOC Variability in Climate

(AMOC-SST association and the Atmospheric Response)

Yochanan Kushnir

Mingafng Ting, Naomi Naik, Cuihua Li, In-Sik Kang*,

Richard Seager, & M. Cane

Cooperative Institute for Climate Applications and Research

Lamont-Doherty Earth Observatory

Columbia University | Earth Institute

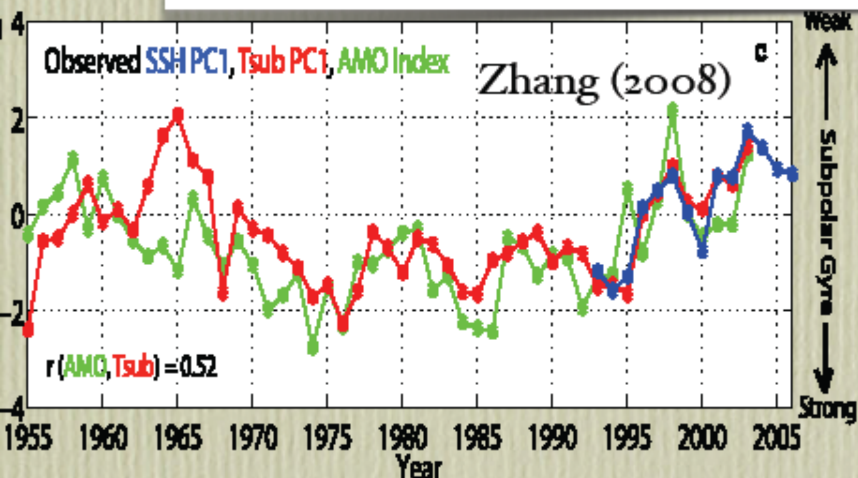
*On sabbatical from Seoul National University

2010 U.S. AMOC Annual Meeting / June 2010, Miami

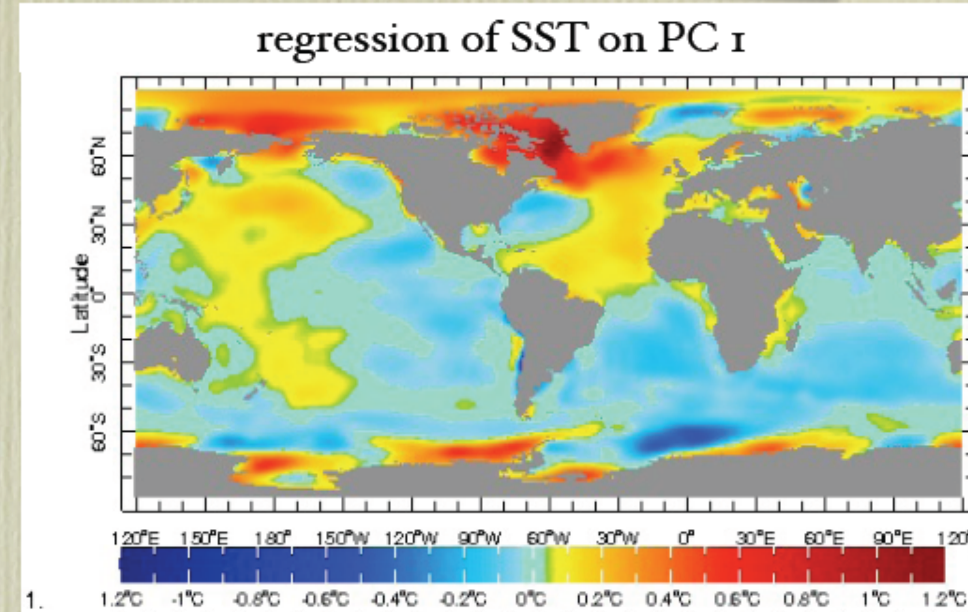
Outline

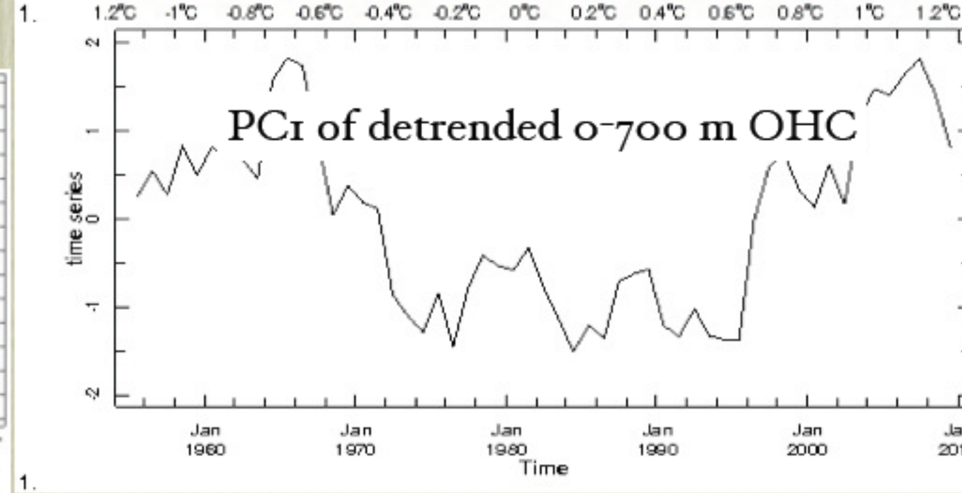
- The relationship between AMOC variability and SST
- Observed and modeled impact of AMOC-related Atlantic SST variability on climate
- Mechanisms of atmospheric response to AMOC variability

AMOC and SST Variability - 4

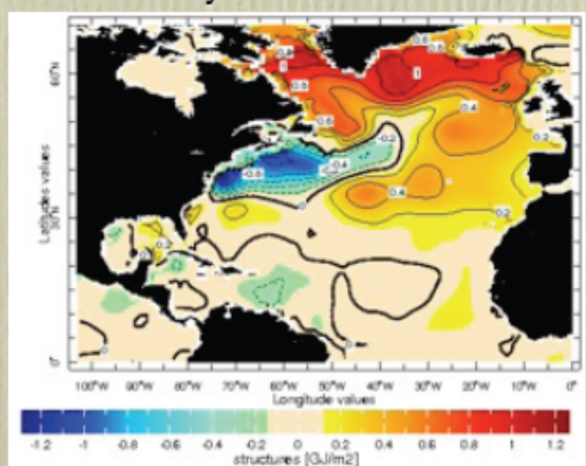


By studying obs and model output, *Zhang (2008)* showed that EOF 1 of 400m ocean temperature provides an *in-phase* proxy for AMOC variability

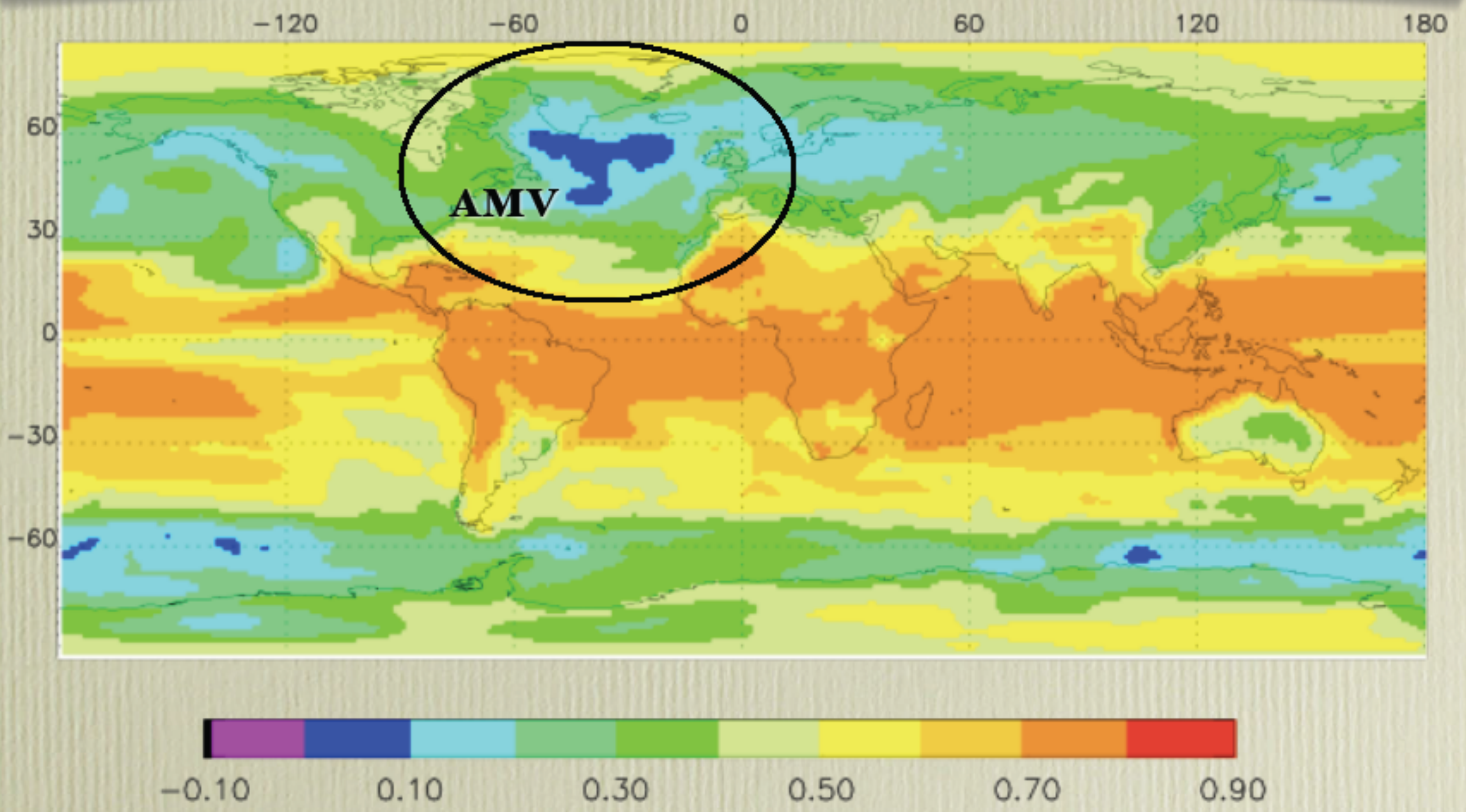




Leading EOF of detrended 0-700 m OHC (GJ/m²)



Forced & Natural Variability



Ting et al. (2009): Ratio of externally-forced to total variance of decadal surface temperature variability in CMIP3 models. Results are based on 6 model ensemble with ≥ 4 realizations each.

Summary: AMOC-AMV

- AMOC variability leads to low-frequency changes in SST with a spatially coherent pattern (AMV), that is well simulated in forced and unforced coupled model:
  - The regions where the signal is large (and significant) are also strongly affected by high-frequency atmospheric forcing*.
  - There is no agreement between models and observations regarding the time scale of the variability.
  - The temporal relation AMOC-AMV is not uniform across models.
  - All these detracts from the ability to use SST for monitoring AMOC change (though it is a good diagnostic tool).

** Recent studies show that such high-frequency perturbations can lead to rapid growth of multi-decadal AMOC perturbations*

Summary: AMV impact

- AMV affects climate in and around the Atlantic Basin:
  - The impact of AMV is caused mainly by related changes in the north tropical Atlantic (NTA) SST.
  - Within the Atlantic and the surrounding land masses, models (coupled and uncoupled) simulated the observed AMV impact quite

Where Do We Go From Here?

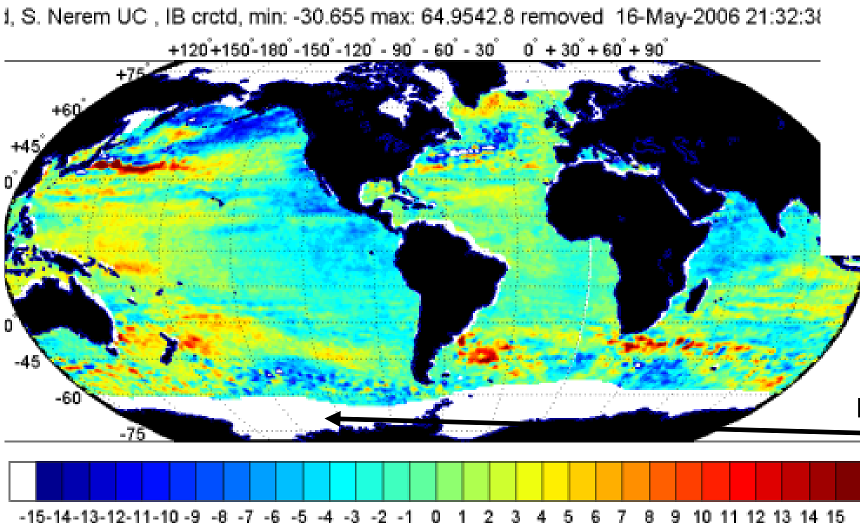
AMOC June 2010 Miami

Carl Wunsch
MIT

One of the major difficulties in formulating a scientific plan for understanding the climate system is the huge variety of possibilities and interests, such as changes in heat content, salinity, meridional enthalpy transports, carbon uptake and transports, sea surface temperature, …. on time scales of years, decades, centuries,…., dynamics versus kinematics.

How do you get a focus? A particular problem for designing observing systems.

A suggestion:



no data

mm/y

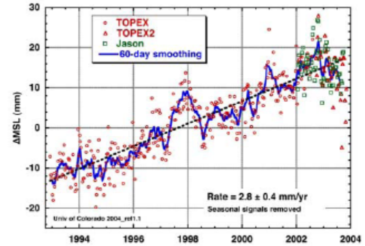


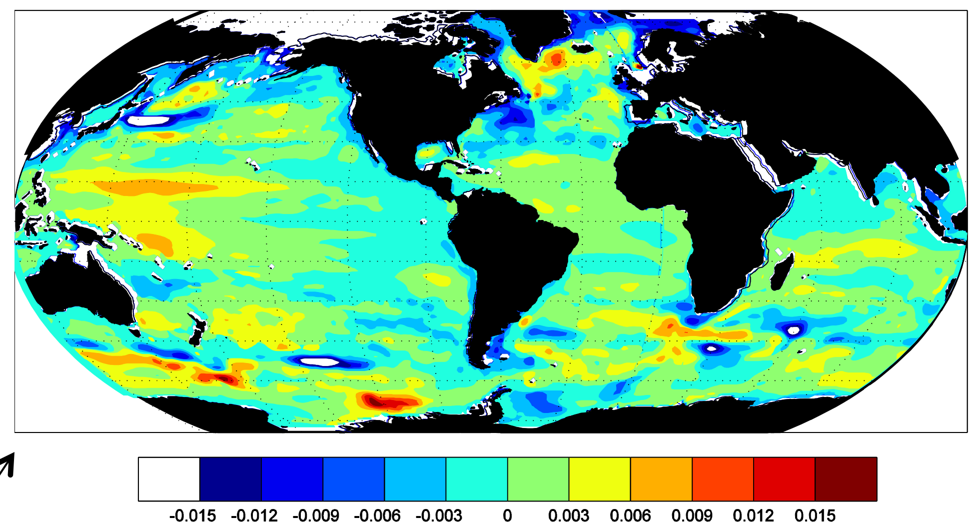
Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the altimeter data, and seasonal variations have been removed.

global mean. alt. alone
Nerem & Cazenave, 2004

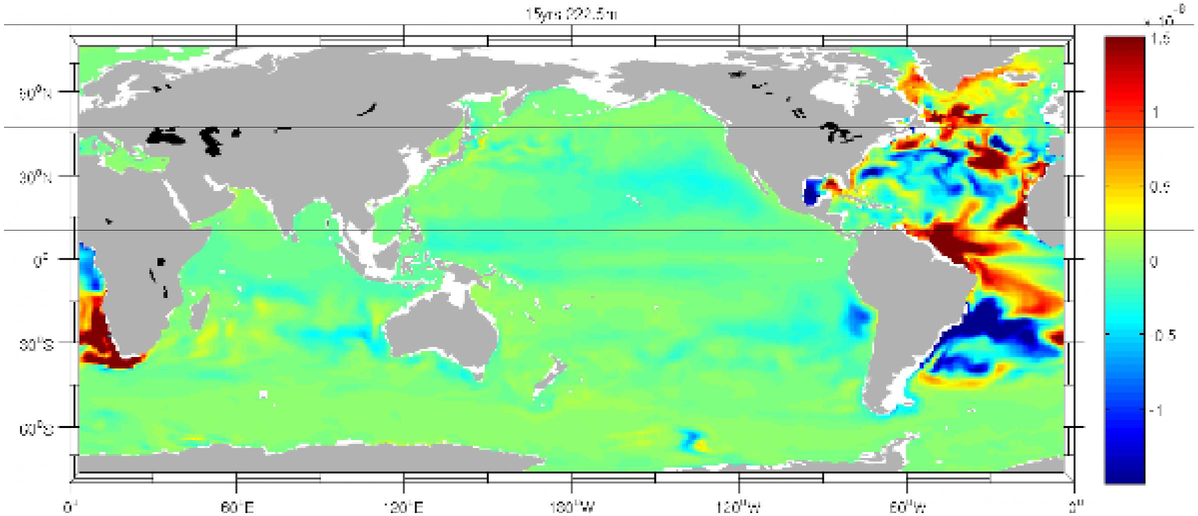
What controls regional sea level change?

Directly measured by a satellite. Note how complicated the pattern is. The global mean value is estimated as about 2.8mm/y +/-0.3mm/y

According to Peltier (1991) should add another 0.33mm/y for post-glacial rebound



ECCO-GODAE version 3.73 (more complete sea ice model)



Sea level change sensitivity, western N. Atlantic (US east coast) from (normalized) temperature changes 15 years previously (P. Heimbach from ECCO v3.73)

Normalization is by the expected errors in the measurements.

Clearly, forecasting and understanding of change involve the ocean and atmospheric states over long times

A Strawman Proposal

Agree on a goal: US east coast sea level trend to be predicted to 15 years with an accuracy equivalent to 0.3mm/y. (Almost all physical processes show up in sea level and/or are affected by sea level.) Altimeter sets of a nominal accuracy goal.

Design an observing system that would be capable of that accuracy.

Develop the models capable of that accuracy.

Formulate a requirement on meteorological reanalyses capable of that accuracy.

Construct a coupled atmosphere-ocean-sea ice-land ice model formally capable of prediction from a known initial state.

Many people will not find this a compelling goal---but it does provide a framework incorporating almost all imaginable ones related to the ocean circulation. A 15-year time scale is humanly accessible.
It involves several other communities. Is that a bad thing?

Discussion Group Summaries:

1. Characterizing AMOC variability and structure using observations

2. Impact of observations on constraining AMOC; model-based assessment of observing systems

3. Climate impacts of the AMOC

4. Mechanisms and Predictability of the AMOC

Observational Discussion Group

Discussion leads: Susan Lozier
and Josh Willis

Identification of gaps

- What is the response of MOC to variation in deep water formation rates (convective + overflow)?
- What is connectivity of AMOC from latitude to latitude?
- What mechanism communicates signals meridionally?
- How does Arctic variability relate to AMOC variability?
- How does Aghulas leakage impact AMOC variability?
- Can we devise a long-term strategy for observing coherent modes of interannual/decadal variability?
- Are we prepared to observe and document anthropogenically-forced AMOC changes?
- Must occupy complete subpolar sections for 10+ years to relate MOC to water mass formation

Near term foci:

Implement enhanced AMOC observing systems in the South Atlantic and Subpolar North Atlantic

- SAMOC
- O-SNAP

Results of AMOC Observing System Workshops:

1. Subpolar North Atlantic Workshop
   April 14-16, Duke University,
   Organizer: Susan Lozier

2. South Atlantic MOC Workshop (SAMOC3)
   May 11-13, DHN, Niteroi, Rio de Janeiro
   Organizers: Silvia Garzoli, Edmo Campos

Observational Subpolar North Atlantic Program (working acronym: "O-SNAP")

Overall Goal:
"To quantify the large-scale, low-frequency, full water-column net fluxes of mass, heat and fresh water associated with the meridional overturning circulation in the subpolar North Atlantic."

Questions to address:

a. Can the overturning circulation be meaningfully related to the production of deep water masses?

b. What is the relative contribution of the horizontal versus overturning circulation to the net poleward heat transport? How does this relationship differ in depth-space versus density-space?

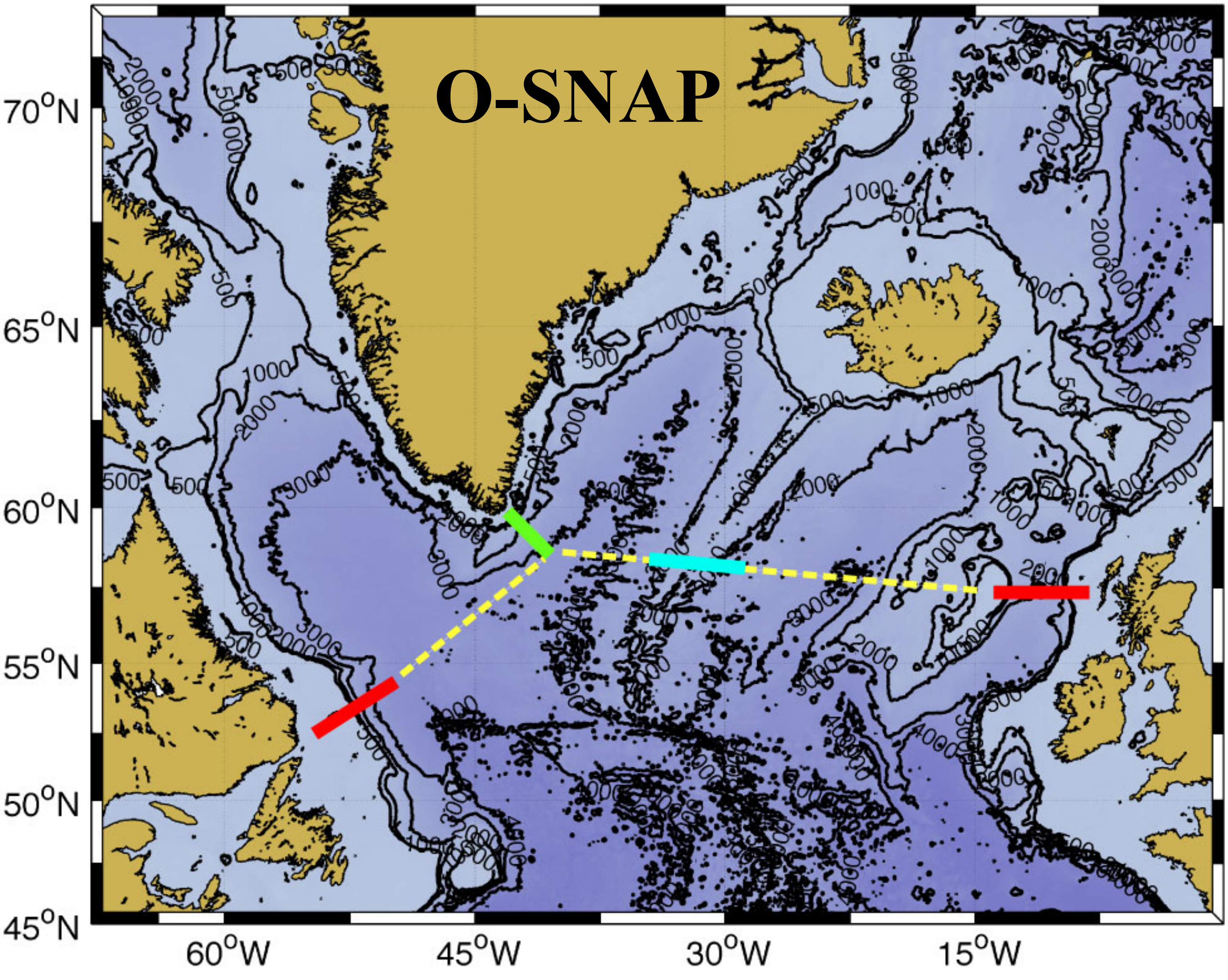
c. What is the relative contribution to the AMOC from water mass transformation in the Labrador/Irminger Seas versus the Nordic Seas?

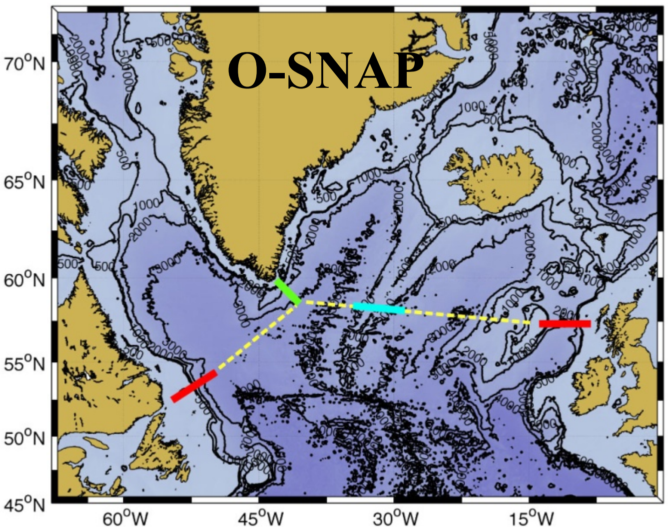
Questions to address, continued

d. To what degree does the high-latitude water mass transformation occur in the boundary current system versus the interior basin?

e. What controls the partitioning of heat transported into the subpolar North Atlantic versus the Nordic Seas/Arctic?

f. What are the dominant pathways of the upper and lower limbs of the AMOC that connect the subpolar and subtropical regions?


O-SNAP
70°N
65°N
60°N
55°N
50°N
45°N
60°W
45°W
30°W
15°W



Red lines: Boundary monitoring partially implemented. The two red lines are (i) the German Labrador Sea Exit array, which would need to be extended both to near-surface and inshore on the shelf, and (ii) the Ellett Line, which needs improved temporal and spatial measurement density.

- *Green line*: Location of the UK DWBC and French EGC arrays, in the water between 2004-2008.

- *Blue line*: Approximate location of a possible Mid-Atlantic Ridge array.

- *Yellow lines*: Ocean regions to be monitored by "soft" arrays, comprising of a mixture of gliders, floats, possibly deep T/S moorings, BPRs and bottom current meters.

O-SNAP linkages

1. International linkages and collaborations are essential for this work.
2. Strong interdisciplinary linkage with biogeochemists and biologists is being nurtured, particularly with the US/Canada/ BASIN program.
3. Modeling efforts to guide the optimization of a long-term observing system; to aid our interpretation of those observations; and to advance our nascent mechanistic understanding of the AMOC are needed.
4. Observations (Eulerian, Lagrangian, satellite-based, etc. that provide connectivity from subpolar North Atlantic, subtropical North Atlantic and subtropical South Atlantic MOC measures are needed.

SAMOC 3

Niteroi, Rio de Janeiro, May 11, 12, 13, 2010

Main Objective:

• To gather international experts to design the basis for an observational program for the Meridional Overturning Circulation in the South Atlantic.

Goals:

• To discuss how present observations may contribute to estimate the meridional fluxes of mass, heat and freshwater;
• How the observational array ought to be upgraded to better capture these fluxes and their variability, and
• How to transition from an initial observational array to a long-term sustained program.

For that purpose it was necessary to determine ***what*** *parameters should be observed,* ***where*** *the observations are needed,* ***who*** *will be interested in carrying them out,* ***how*** *to observed them – what are the best possible observation strategies, and* ***when*** *will the participants aim to begin*. The workshop also aimed to foster international cooperation, which is of crucial importance to fulfill these objectives.

Convenors:
Edmo Campos, Silvia Garzoli, Alberto Piola, Sabrina Speich

Attendees:
Povl Abrahamsen
Isabelle Ansorge
José Azevedo
Molly Baringer
Andre Barreto
Guilherme Castelao
Luiz Antonio Barreto de Castro
Henk Dijkstra
Sybren Drijfhout
Shenfu Dong
Kathy Donohue
Mariana Fernandez
Antonio Fetter
Carlos Garcia
Sergey Gladyshev
Bill Johns
Jose A M Lima
Chris Meinen
Raquel L Mello
Frederico A S Nogueira
Afonso M Paiva
Renellys C. Perez
Steve Piotrowicz
Chris Reason
Martin Saraceno
Alexey Sokov
Janet Sprintall
Ariel Troisi
Domingos Urbano
Peter Zavialov

Agenda

Day 1: Tuesday May 11

Sabrina Speich: The Indian Atlantic connection. Results from the GoodHope (France, South Africa, Russia, US)

Janet Sprintall: The Pacific-Atlantic Connection: Drake Passage Measurement programs.

Molly Baringer: Meridional exchanges of fluxes. Observational studies and results from AOML and collaborators from Argentina and Brazil.

Edmo Campos: Brazilian Modeling and Observational Projects

Joel Hirschi MOC related activities at NOC (presented by **Povl Abrahamsen**):

Brian King : NOCS UK: initial results and future plans (presented by **Povl Abrahamsen**)

Henk Dijkstra: A scalar indicator of the stability of the Atlantic Meridional Overturning Circulation

Sybren Drijfhout: Why 30°S is the best location to monitor the stability of the THC? KNMI models

Renellys Perez: Model analysis for experiment design in NOAA

Povl Abrahamsen: Model analysis for experiment design in UK

Sergey Gladyshev: Russian field program in the South Atlantic in 2009 – 2010

Peter Zavialov: "Physical Oceanography at Shirshov Institute, and selected results on South Atlantic".

Shenfu Dong: How satellites observations can be used to monitor AMOC components.

Domingos Urbano: Modeling the Earth System at INPE

Day 2: Wednesday May 12

Andre Barreto: Mar-Eco South Atlantic

Mariana Fernandez: Pre-operational modeling of the Rio de la Plata- Rio Uruguay system.

Presented by Ariel Troisi: Ocean Observatory Initiative by Weller and Cowles

Presented by Alberto Piola: Monitoring the formation rate of NADW components using tracer inventories by Rana Fine

Infrastructure availability in the South Atlantic:

Edmo Campos University of Sao Paulo

Carlos Garcia, Fund. Univ. Rio Grande

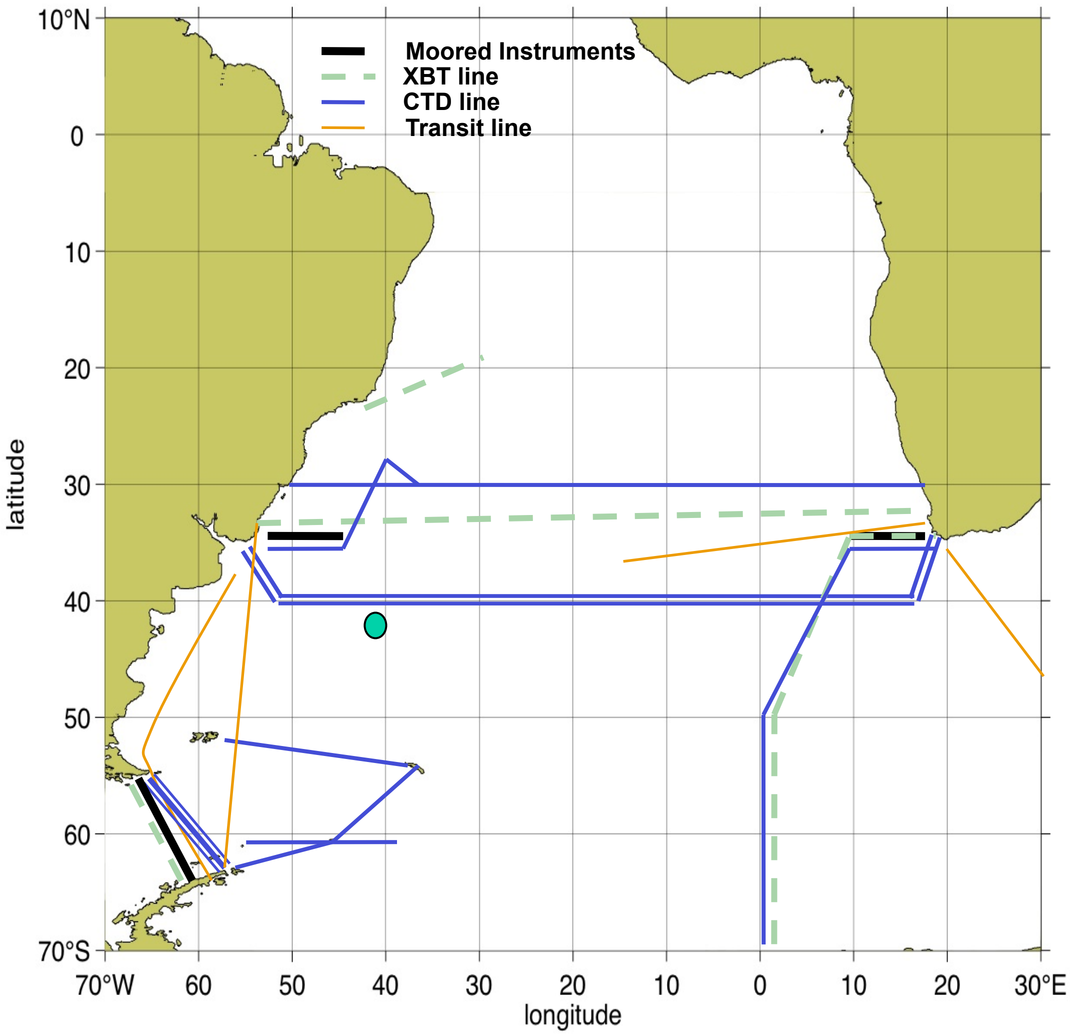
Ariel Troisi (SHN, Argentine Navy)

Isabelle Ansorge (Univ. Cape Town, South Africa)

Peter Zavialov (Russia)

Plenary discussions on Infrastructure and Data sharing

Steve Piotrowicz: Data shearing policies



	Dates	Institution	POC
AX18 35°S	Quarterly	AOML/SHN	Baringer, Troisi
AX97 22°S	Quarterly	FURG/AOML	Mata, Goni
AX25 GoodHope line	Dec 2010, February 2011	UCT/AOML	Ansorge/Garzoli
AX22 Drake Passage (includes SADCP) RV Gould	Bi-monthly	SIO	Sprintall
CLIVAR repeat Hydro. 30°S. CTD/LDCP, CO_2. CfC, ph, He/Tr, nutrients.	March May 2011	AOML/PMEL	Baringer
GoodHope line. RV Vavilov	Oct-10	Shirshov/IFREMER	Gladyshev, Speich
Cape Town-Montevideo, 40°S. RRS Discovery	October-November 2010	NOCS	Mills
Vema Channel Session and SAM region. CTD/LDCP. RV Akademik Ioffe	Nov-10		Zavialov
Drake Passage	Nov-10	Shirshov	Gladyshev
Drake Passage. cDrake	November 2010 and 2011	URI/SIO	Chereskin
Drake Passage RRS J.C.Ross	Dec-10	NOCS	King
DIMES (west of Drake) RV James Cook	12/1/2010 and February 2012	NOCS/BAS	Meredith/Naveira Garabato
Scotia Sea & Transits Malvinas, S. Georgia, S. Orkney, and Antarctic Peninsula SADCP, TSG. RV Vavilov	November 2010 and March 2011		Gladyshev
Orkney Passage. RRS J.C. Ross	Apr-11	BAS	Abrahamsen
Cape Town to Gough Island	Sep-10	UCT	Ansorge
Cape Town to Marion Island	Apr-11	UCT	Ansorge
Drake Passage and Antarctica Peninsula. RV Puerto Deseado	December 2010 and March 2011	SHN	Troisi
Transit Brazil-Antarctica	October and March 2010	Brazil	Garcia
SAM. CPIES/PIES. 34.5°S South Western Atlantic		AOML/SHN	Meinen, Troisi
GoodHope. CPIES		Ifremer	Speich
GoodHope line. Tall moorings		AWI	
GoodHope line PIES		AWI	Boeble
cDrake PIES/CPIES		URI/SIO	Chereskin
OOI		WHOI/SIO	Send

What: *parameters should be observed,* :

• Meridional heat transport

• Water-mass exchanges through the choke points (Drake, S. of Africa) (which is already happening via related programs)

• T, S, velocity & bottom pressure along sections as possible

• Absolute boundary current measurements (particularly DWBC)

Where: *are the observations needed* : Nominally 35°S

Who: *will be interested in carrying them out* : Everyone attending

How: *to observed them, what are the best possible observation strategies* :

• Full depth hydrographic line

• Instrument a line at nominally 35°S

Model evaluation & mooring system design studies ongoing

When: 2012+

Discussion Group 2:

Impact of observations on constraining AMOC; model based assessment of observing systems

Discussion lead: Tony Lee

Specific near term foci:

- Complete observing system evaluation for subpolar N. Atlantic and S. Atlantic
- Quantify impact of deep measurements in the interior North Atlantic (deep ARGO, full depth gliders)
- Develop observing systems capable of examining meridonal coherence of the AMOC and associated elements, including forcing functions.
- Developing plans for putting judicious posterior error estimates on AMOC strength and variability estimates derived from ocean state estimation models.
- Develop coordinated activity (including model development and observing system sensitivity studies) to examine special physics region such as high-latitude sinking regions.
- Develop coordinated activity to examine water-mass transformation associated with AMOC and related air-sea interaction using modeling and assimilation systems.
- Understand the reasons for differences - or biases- in the relationship between model MOC intensity and MHT in available models, as compared to observations.
- Evaluate robustness of AMOC fingerprint in different models and consistency with observed fingerprint.

Discussion Group 3:

Climate Impacts of the AMOC

Discussion lead: Yochanon Kushnir

Near term priorities:

- Understanding the link between AMOC and SST variability: The most important near term goal in this area is to study and understand better the interaction between AMOC and upper ocean properties, particularly temperature/SST but also salinity. It is important to study the mechanisms of AMOC's influence on the latter but also the role of upper ocean anomalies on generating (predictable) AMOC variability. There is a need to determine the phase relationships between the overturning circulation, the strength of the horizontal gyres, and the subsequent impact on SST.

- Robustness of AMOC/AMV impacts and connecting impact studies to societal needs: While the the number of studies on AMOC/AMV impact on world (particularly Northern Hemisphere) climate, has increased and broadened, more should be done to establish the robustness of these links, understanding their cause, and comparing them to other long-term changes in climate, forced and natural. It is important to link these impact studies to societal needs and if relevant to actual sectoral decision (e.g., in water resources, coastal infrastructure, health, and ocean resource management). This will help focus impact research and lead to tangible benefits from AMOC research.

- Strengthen links to other related CLIVAR/WCRP activities: This will raise the profile of our PIs' work and help in exchange of important information and stimulate progress. This goal can be achieved through U.S. CLIVAR, the International CLIVAR Atlantic Implementation Panel, and through communication with individual program committees, nationally and internationally.

Discussion Group 4:

Mechanisms and Predictability of AMOC

Discussion lead: Gokhan Danabasoglu

Specific near-term, high priority goals/coordinated activity:

- Study AMOC and NHT relationships in models (forward, assimilation, eddy-permitting) in comparison with the RAPID data

- Inter-comparison of near-term prediction experiments (AR5) to investigate robustness of model simulations

- Inter-comparison of hindcast ocean-only and ocean-ice coupled simulations forced with the CORE-II inter-annual data sets to assess the robustness of model simulations under specified forcing

- Need new observations & synthesis of existing observations to discriminate against proposed mechanisms, including synthesis of proxy data

Specific near-term, high priority goals (continued):

- Impact of model biases, e.g., Gulf Stream and North Atlantic Current paths, on AMOC variability and predictability

- Focus studies between modeling groups for mechanisms (focus needs to be identified, e.g., convection, overflows, ….)

- Identify “best” initialization practices for decadal prediction simulations (unclear if this can be accomplished????)

- Investigate impacts of high resolution (0.1°) on AMOC variability

- Identify standard metrics (CLIVAR DVWG?)

AMOC Program next steps:

- AMOC P.I.'s team up to produce proposals to accomplish near-term goals (with external/international collaboration, as appropriate)
- Re-evaluation of AMOC Task Teams; engage new science team membership/leadership
- Appoint AMOC executive committee (science team chair, task team chairs, and U.S. Clivar rep. (Legler)) to facilitate communications/coordination with other programs and U.S./international funding agencies
- Next meeting: joint with RAPID international conference, 12-15 July, 2011, Bristol, UK.