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Satellites and state estimates in the context of AMOC studies

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Guiding questions

- What comprises the current AMOC observing system?
- Main limitations of the current AMOC observing system in meeting the goals of
  - measuring the overturning in the Atlantic basin?
  - gaining a mechanistic understanding of AMOC variability?
- What component(s) should be added to address the above limitations?
- Which elements of the Atlantic circulation does the observing system constrain, and how well do these in turn constrain climate-specific metrics?
- To what extent do satellite data complement the existing and planned in-situ observing system(s)? Complementary role of model/data synthesis and state estimation systems?

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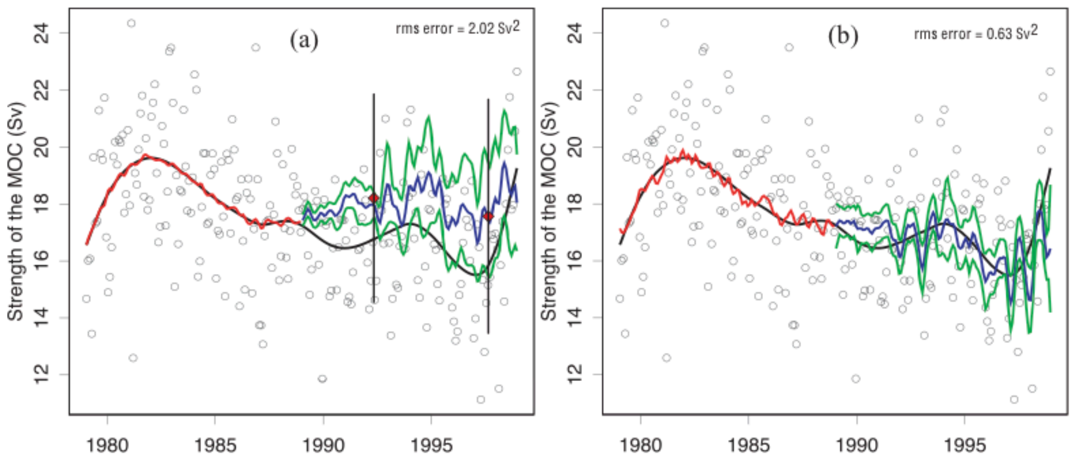
Main general points

- Satellites can help in constraining direct measurements of line transports but their main strengths lie in their basin/global scale coverage
- As such, satellites provide a broader context in which line AMOC transport measurements can be interpreted and deliver essential information on other relevant climate metrics (large-scale SST, heat content, etc.)
- Model/data synthesis and state estimation systems provide an optimal platform for data fusion and time-space interpolation consistent with basic dynamics and conservation principles
- Such systems also add many other capabilities to studies of the AMOC (e.g., connections to global phenomenology, sensitivity to different parameters, observational strategies and design, predictability and prediction, etc.)
- Future plans should consider potential of new satellite systems (SWOT, new gravity, SSS) and improved state estimates of the NA/global ocean and consider AMOC transports in the broadest climate variability context

The view from space…

- Scatterometer winds can yield Ekman component
- Difficult to estimate geostrophic transports from only altimeter sea level data (e.g., Hirschi et al. 2009, Lorbacher et al. 2010)

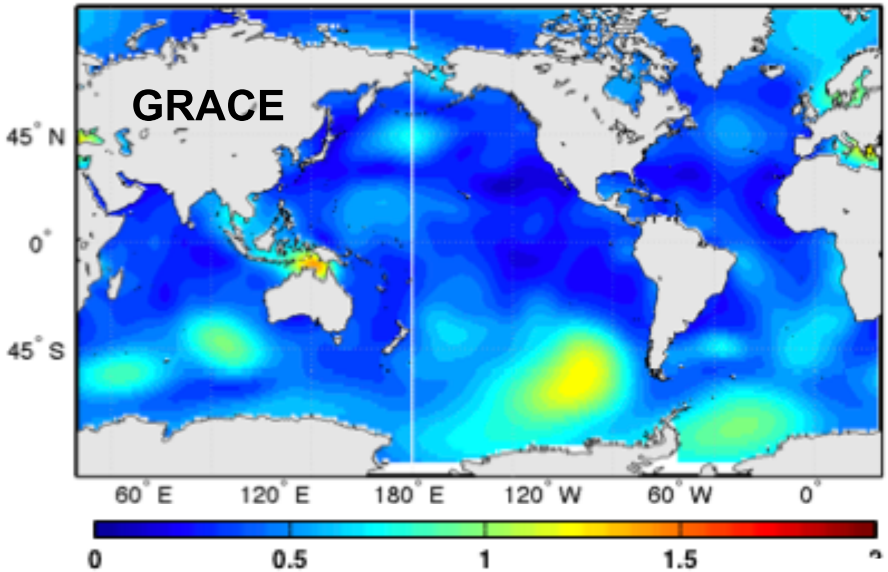


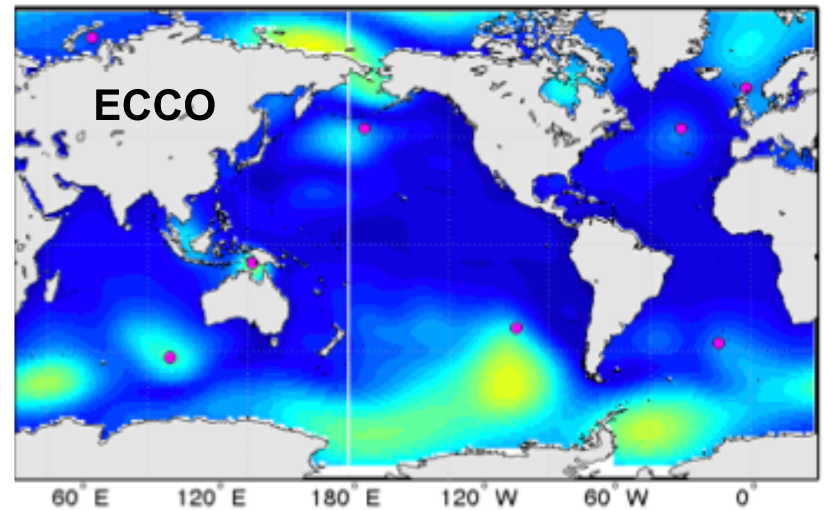
Cromwell et al. (2007, Ocean Sci.)

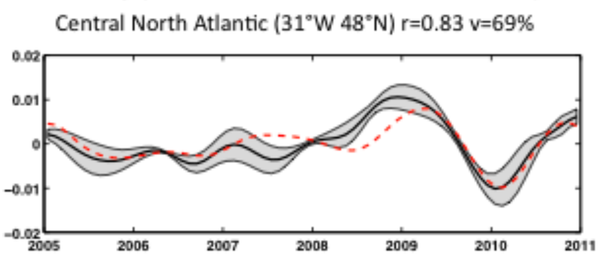
- Complicated regression (NAO, local and basin sea level and bottom pressure patterns)
- Bottom pressure data helpful but not currently available at sufficient resolution

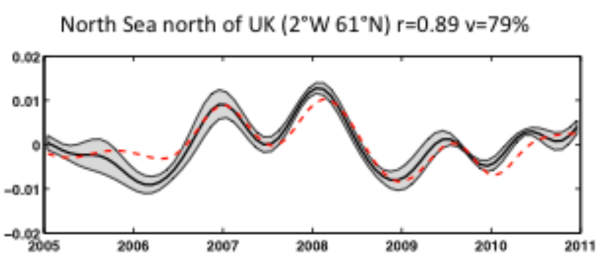
Bottom pressure/GRACE

Standard deviation (cm; interannual timescales only)

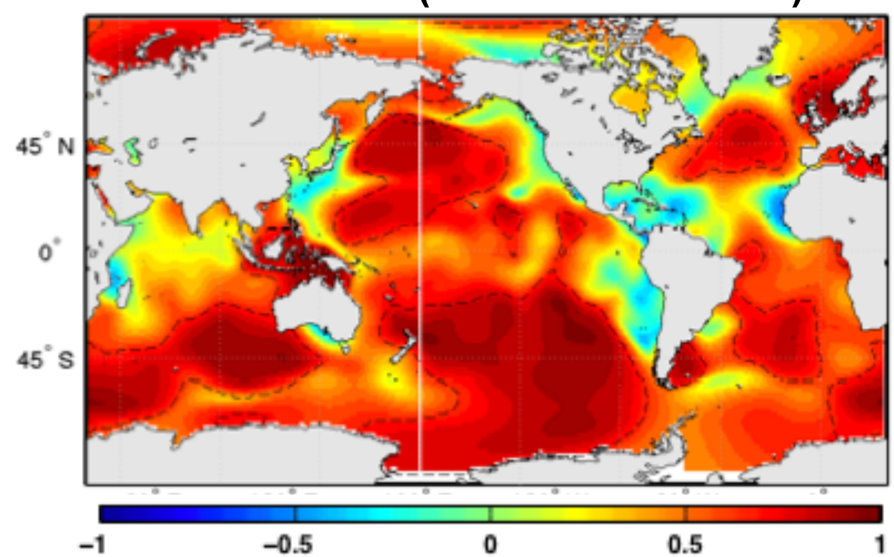








Correlation (GRACE vs. ECCO)



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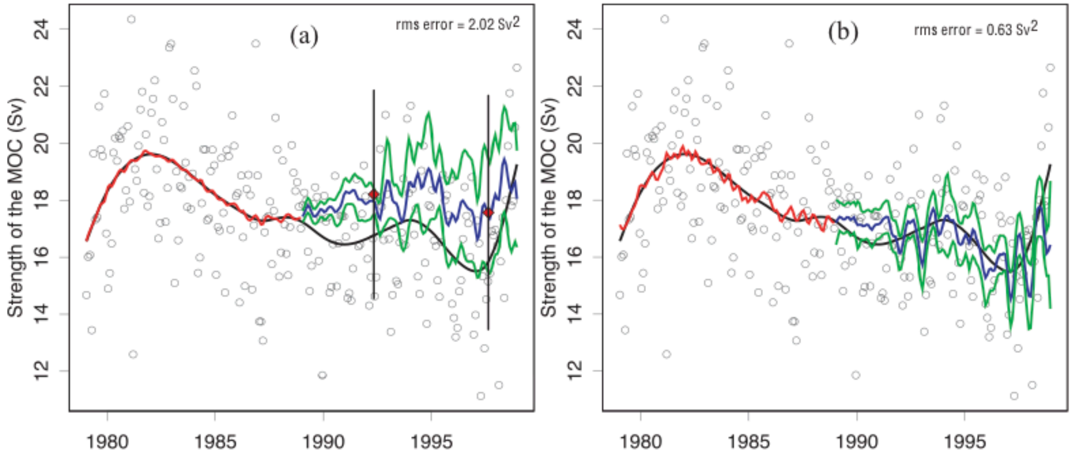

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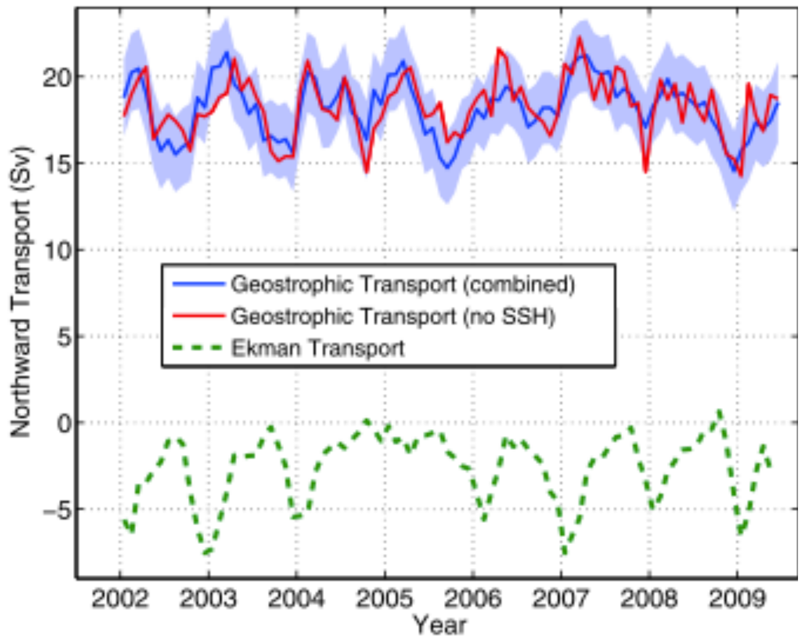
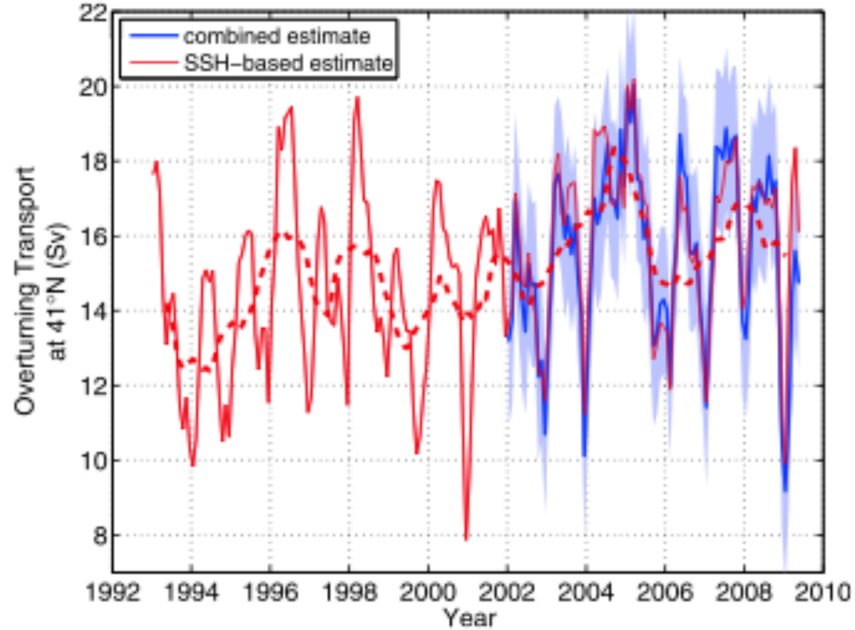
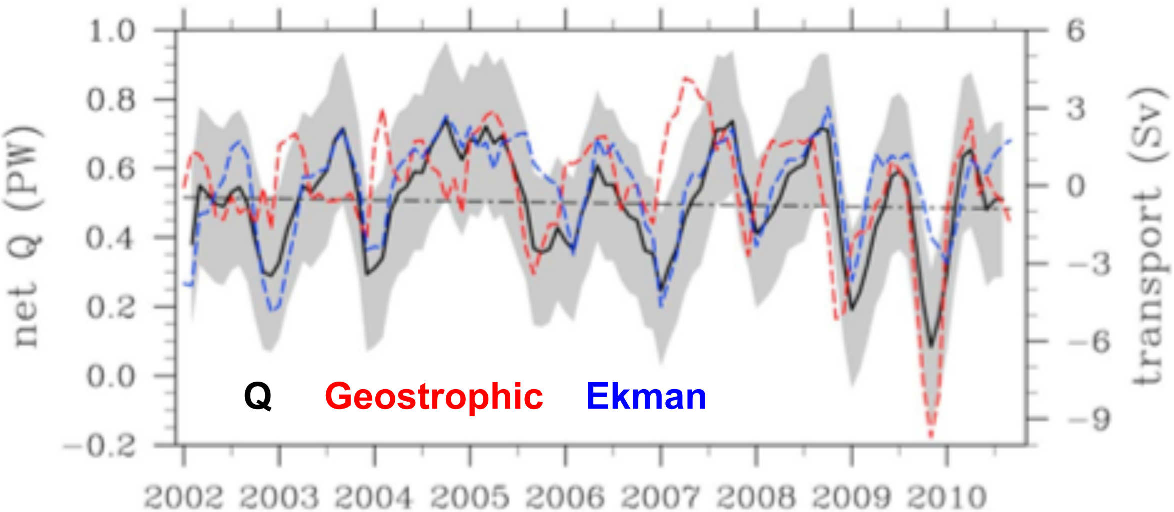
Complementing in situ data





Willis (2010, GRL)



Satellite data can be combined with in situ measurements for calculation of AMOC volume and heat transports (example at 41N)

Hobbs and Willis (2012, JGR)

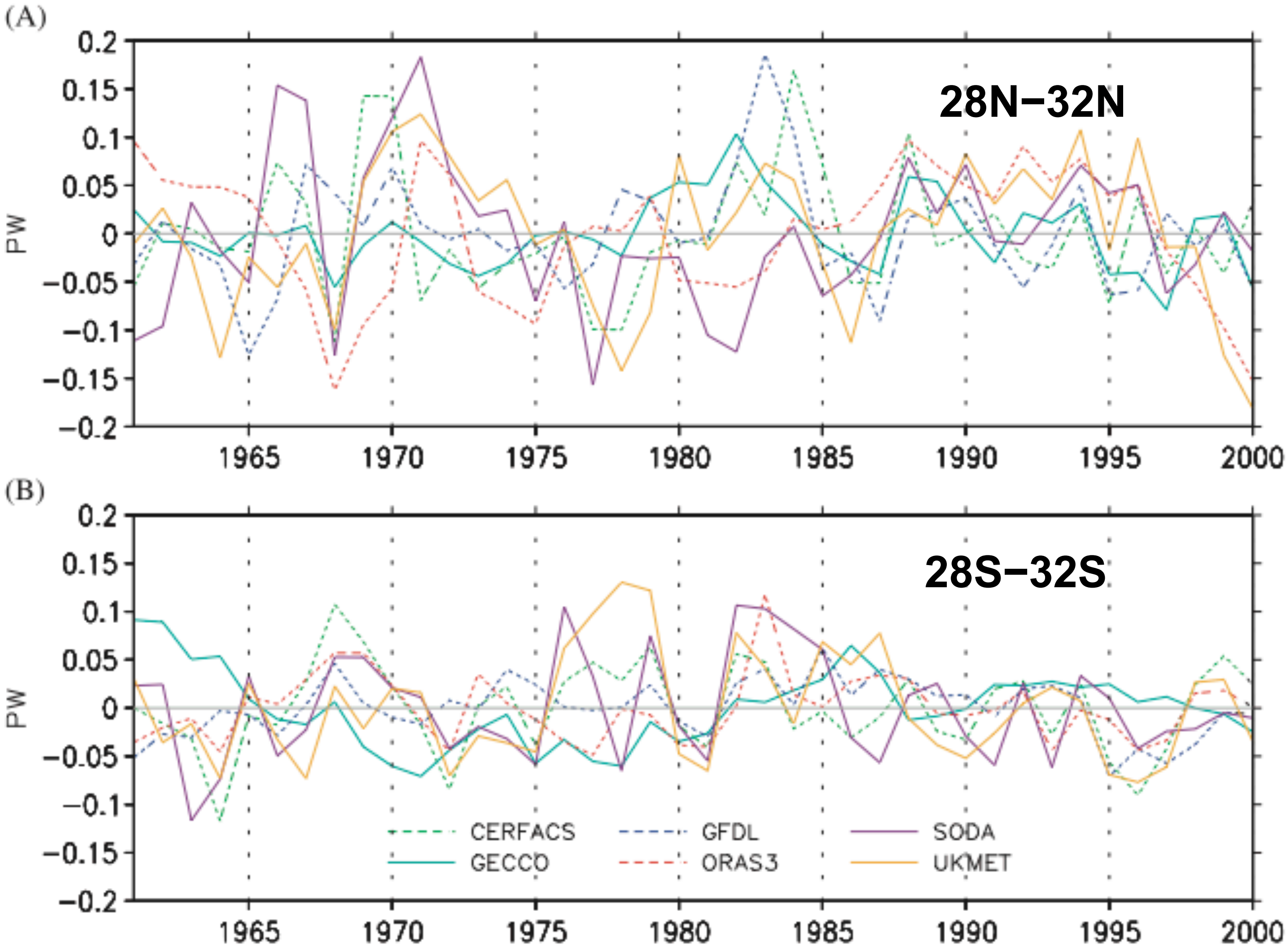
A few words on satellite data

- **Sea level/various (mature technology, operational, several different missions over the next 5 years, much higher resolution SWOT launch at the end of the decade)…surface pressure gradients, geostrophic flows, heat content and other subsurface information,…**
- **Bottom pressure/GRACE (continued improvements in data quality expected, potential for data gap in the future, GRACE Follow-On to fly in 2017, laser ranging system planned with potential 10-fold increase in accuracy)…bottom pressure gradients, deep variability, heat content,…**
- **SST/various (continuing high resolution coverage on basin scales)… air-sea fluxes, air-sea coupling, upper ocean heat content,…**
- **Winds/various (mixture of active/passive systems, operational ASCAT-A/B, well complemented by available atmospheric analyses and merged products like CCMP)…Ekman transports, surface forcing,…**
- **SSS/Aquarius/SMOS (relatively new and experimental, intended accuracies of 0.2 psu for monthly estimates on ~100 km scales)…air-sea fluxes, convection, heat and freshwater content,…**

A role for state estimation

- A platform for synthesis of widely different (space-based and in situ) observations in a dynamically consistent framework
- Providing fully 3-D estimates of the variable North Atlantic and global circulations and diagnostics of relevant property budgets (heat, freshwater) for interpretation of AMOC behavior
- Essential for a mechanistic understanding of the AMOC, regarding its dynamics, forcing mechanisms, relation to heat content and other climate metrics
- Useful for determining AMOC sensitivities to various parameters, value of different observational constraints, and optimal observing system design
- Essential for studies of the coupled atmosphere-ocean system and its predictability and the development of forecasting capabilities

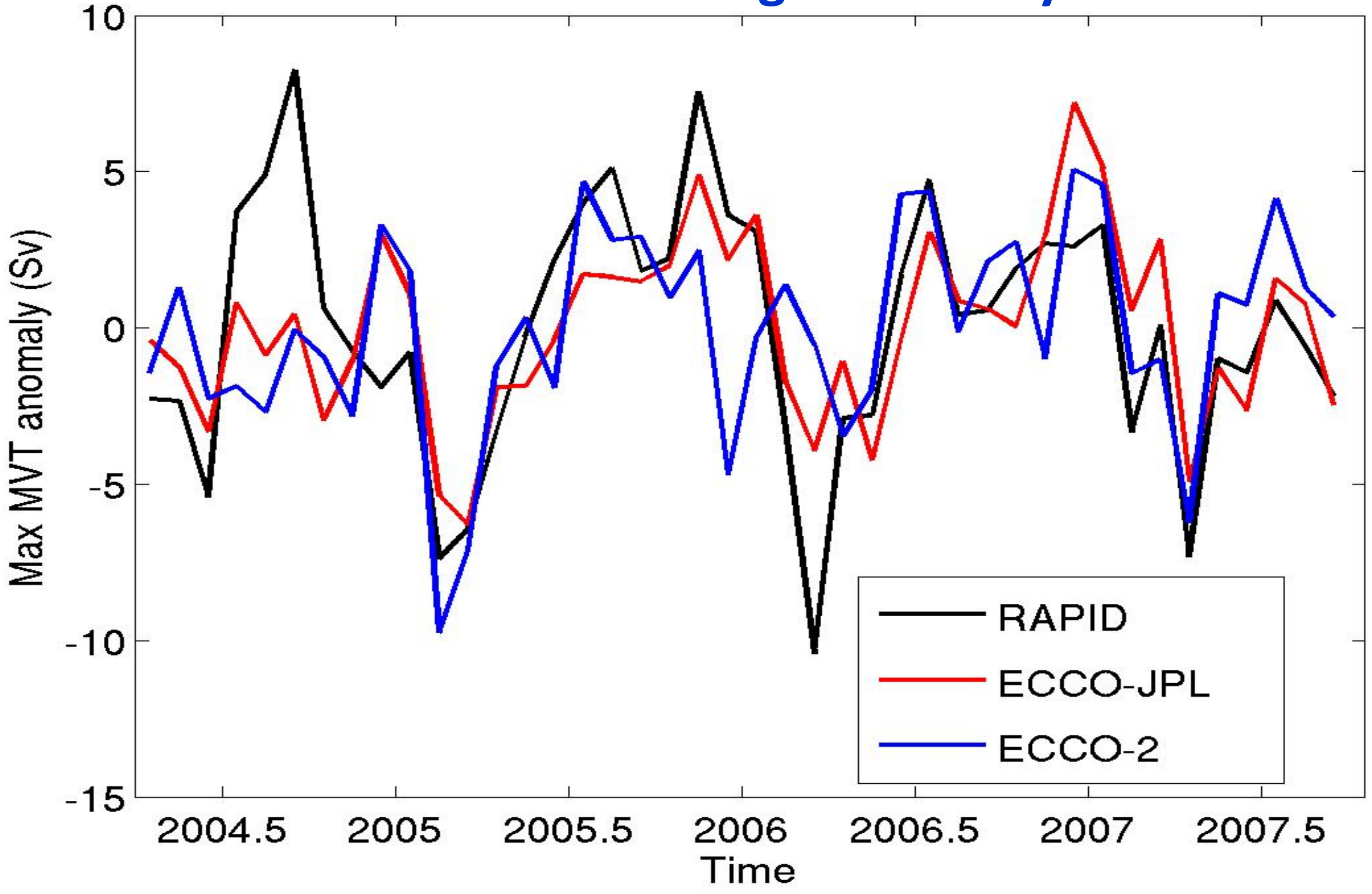
Estimates of heat transport anomalies



(Munoz et al., 2011, DSR)

Reproducing AMOC transports (I)

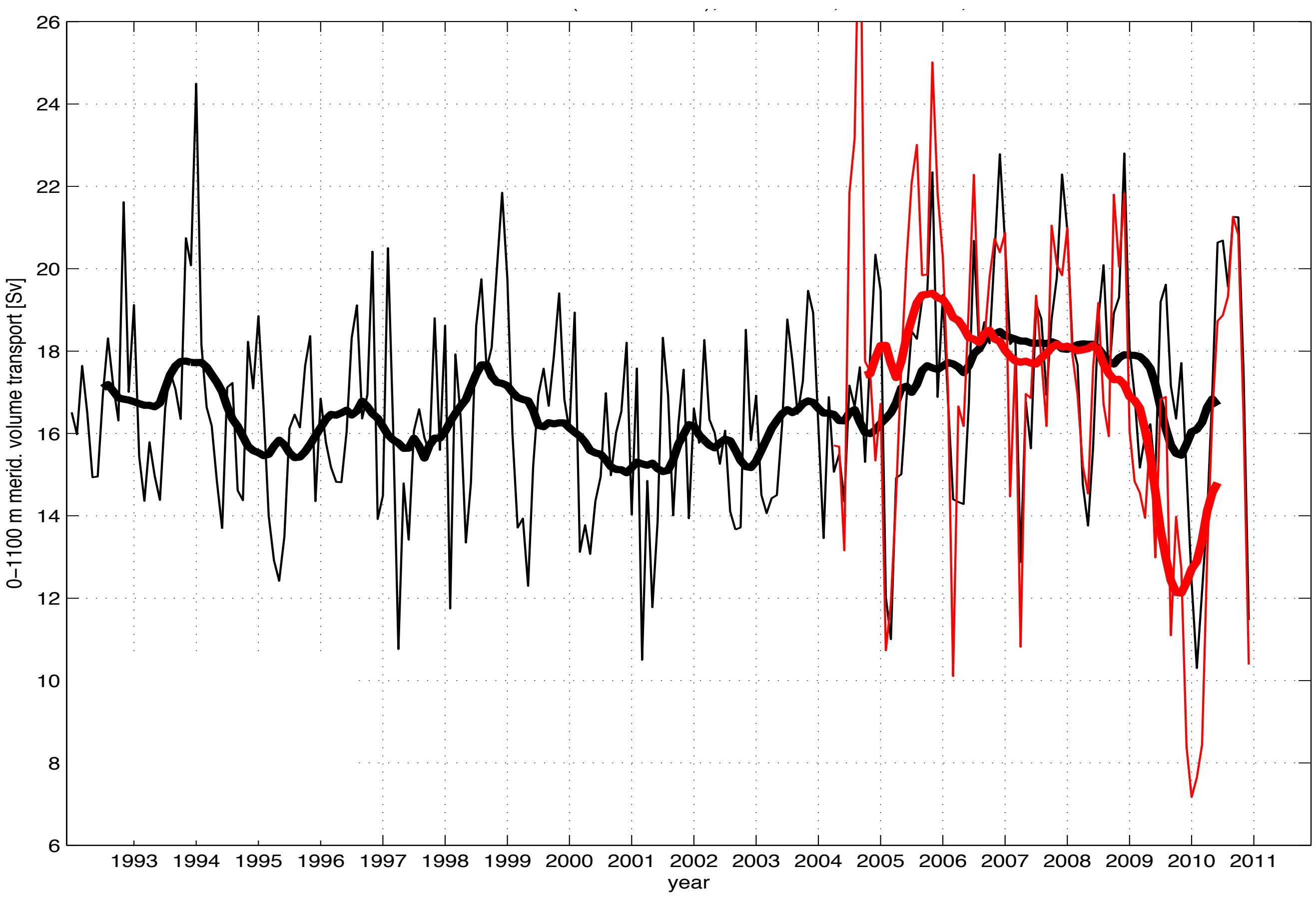
AMOC strength anomaly



(from T. Lee, JPL)

Reproducing AMOC transports (II)

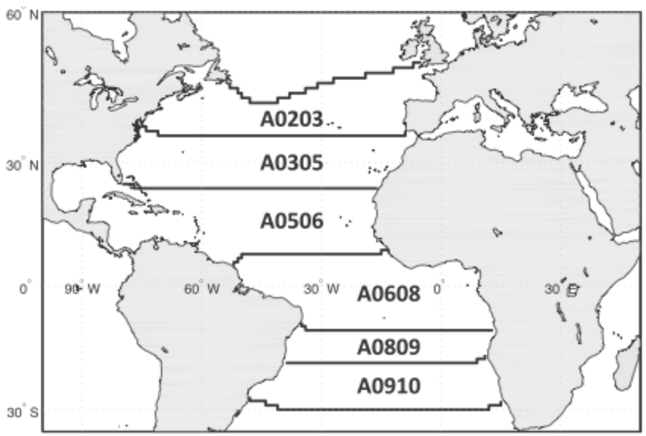
- Preliminary estimate from ongoing optimization using latest ECCO version 4 system (does not use RAPID nor Florida Straits transport data as constraints)

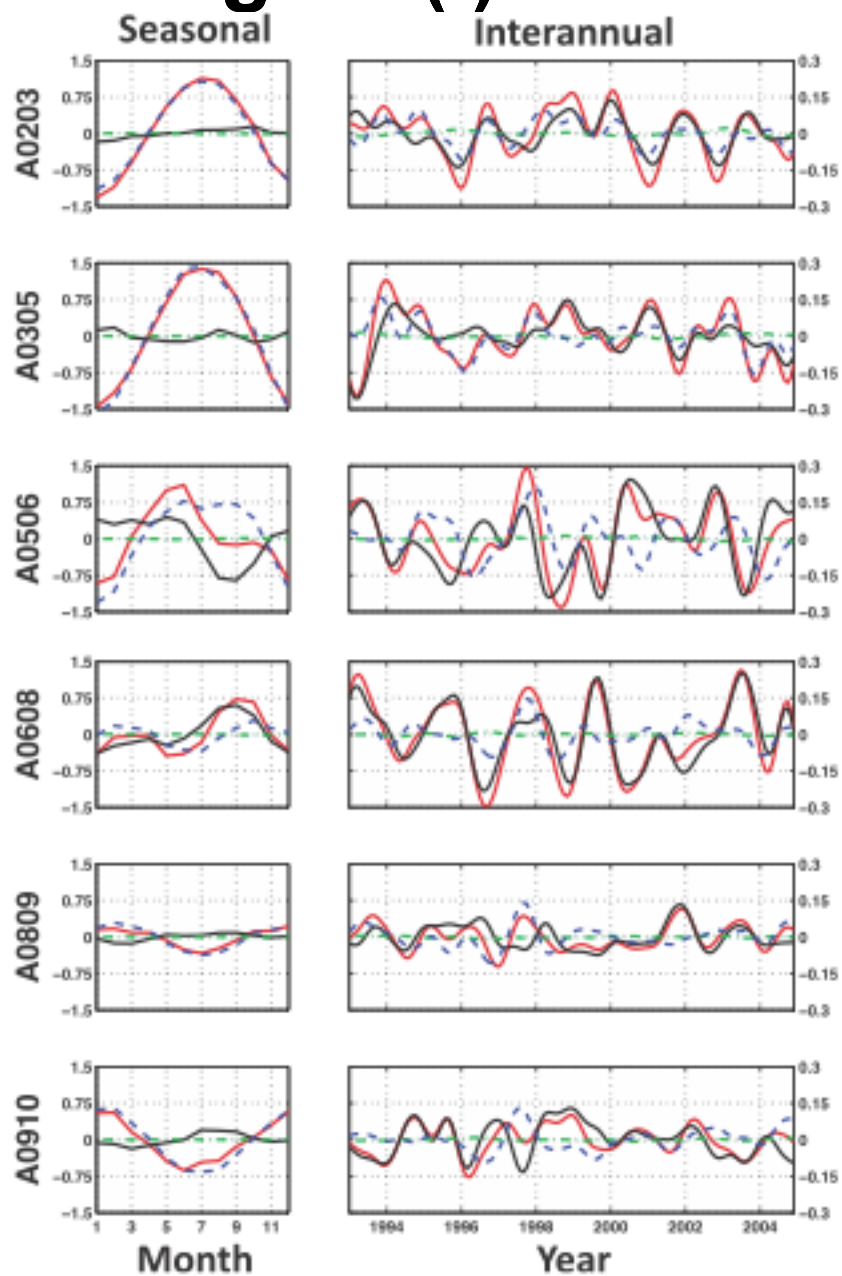


(from P. Heimbach, MIT)

Heat budgets (I)

Upper ocean budgets (0-1000 m)





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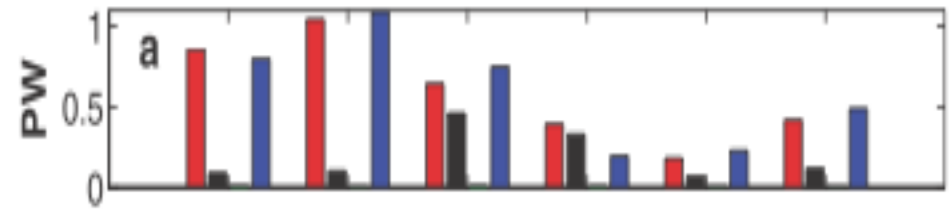
$$H = A + \Delta + \Theta$$

- Heat storage rate H (red)
- Advection A (black)
- Diffusion D (green)
- Surface exchange Q (blue)

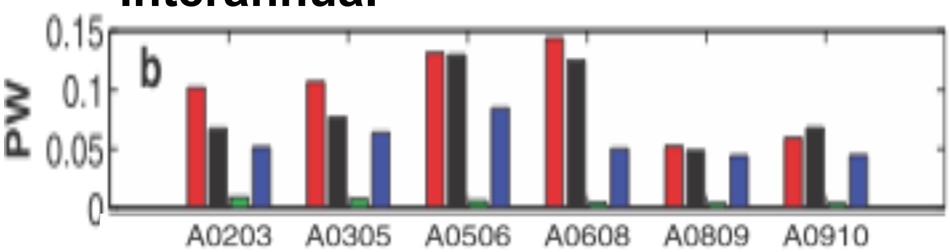
Piecuch & Ponte (2012, JClim)

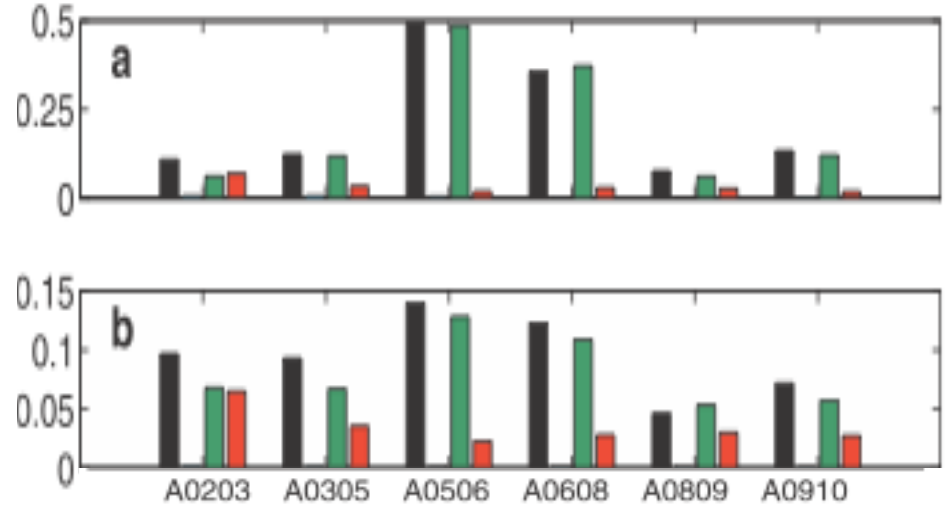
Heat budgets (II)

Seasonal



Interannual





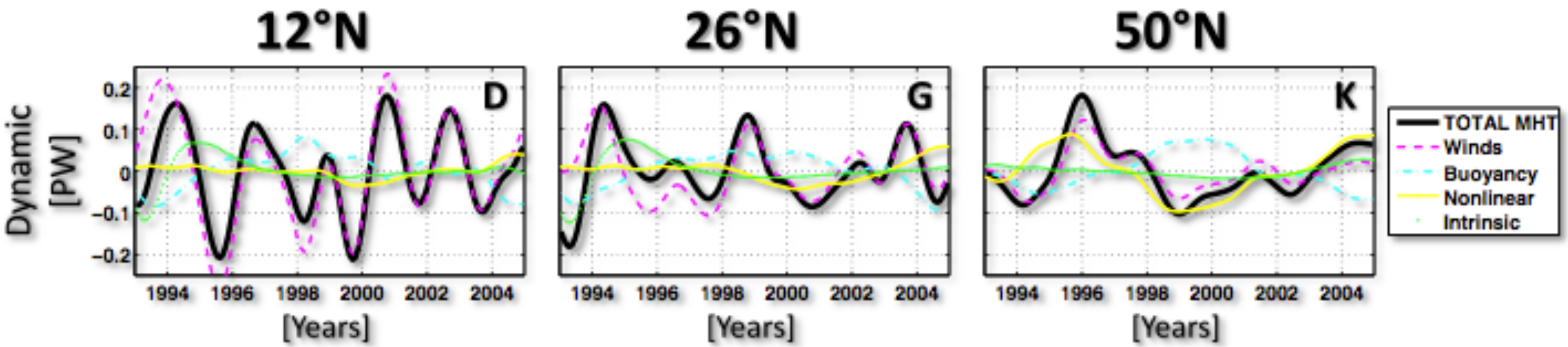
- Heat storage rate H (red)
- Advection A (black)
- Diffusion D (green)
- Surface exchange Q (blue)

- Total advection A (black)
- Zonally asymmetric (orange)
- Zonally symmetric baroclinic (green)

Piecuch & Ponte (2012, JClim)

Exploring forcing mechanisms

- Solutions under different forcing can be used to assess their importance for driving heat transport variability (case shown is for interannual anomalies, for more details see poster by Piecuch)

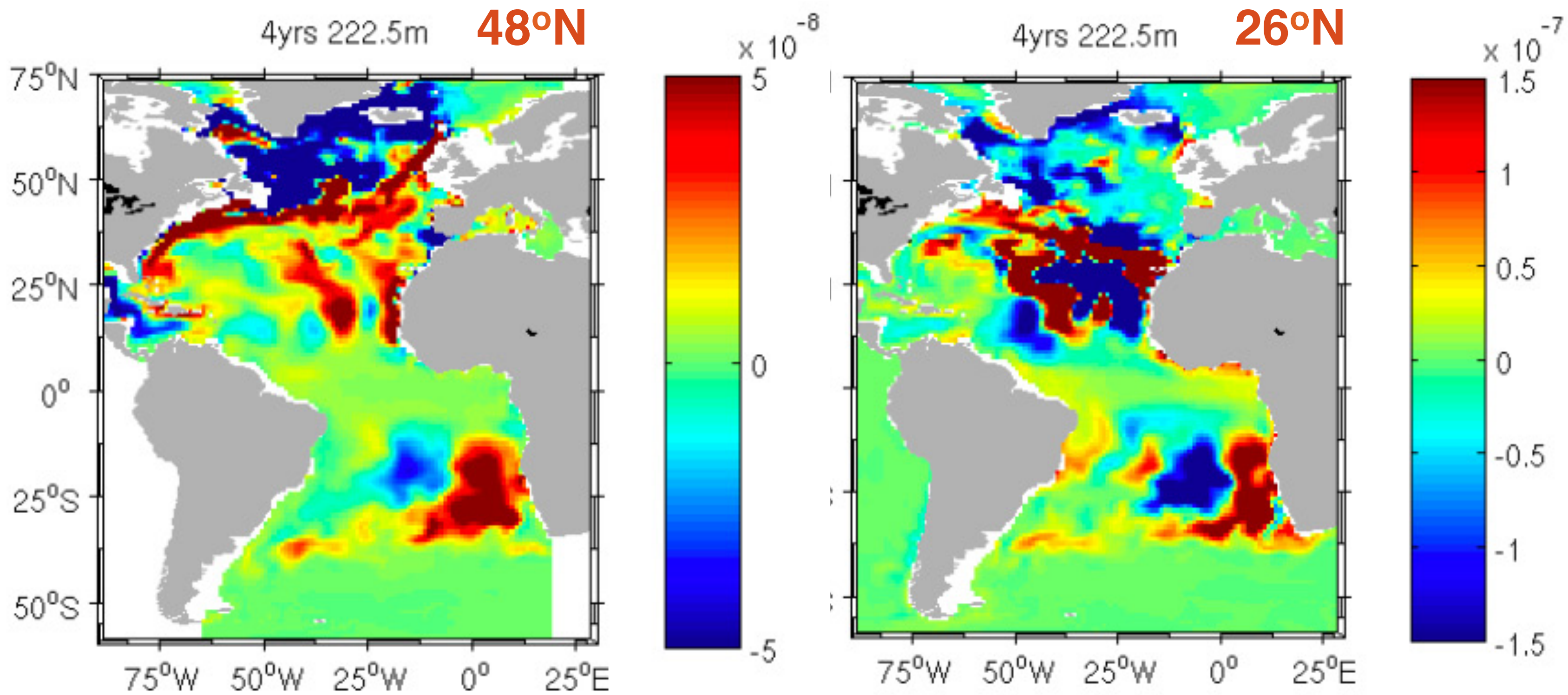


- Total heat transport anomalies are the sum of wind- and buoyancy-driven components plus other nonlinear terms (intrinsic variability or nonseparable joints effects of wind and buoyancy)

- Winds most important forcing at 12N, 26N but buoyancy and other effects not negligible at all latitudes

Exploring AMOC sensitivities

- **Sensitivity of AMOC transports to various parameters such as upper ocean temperature (inferable from adjoint formalism used in state estimates)**

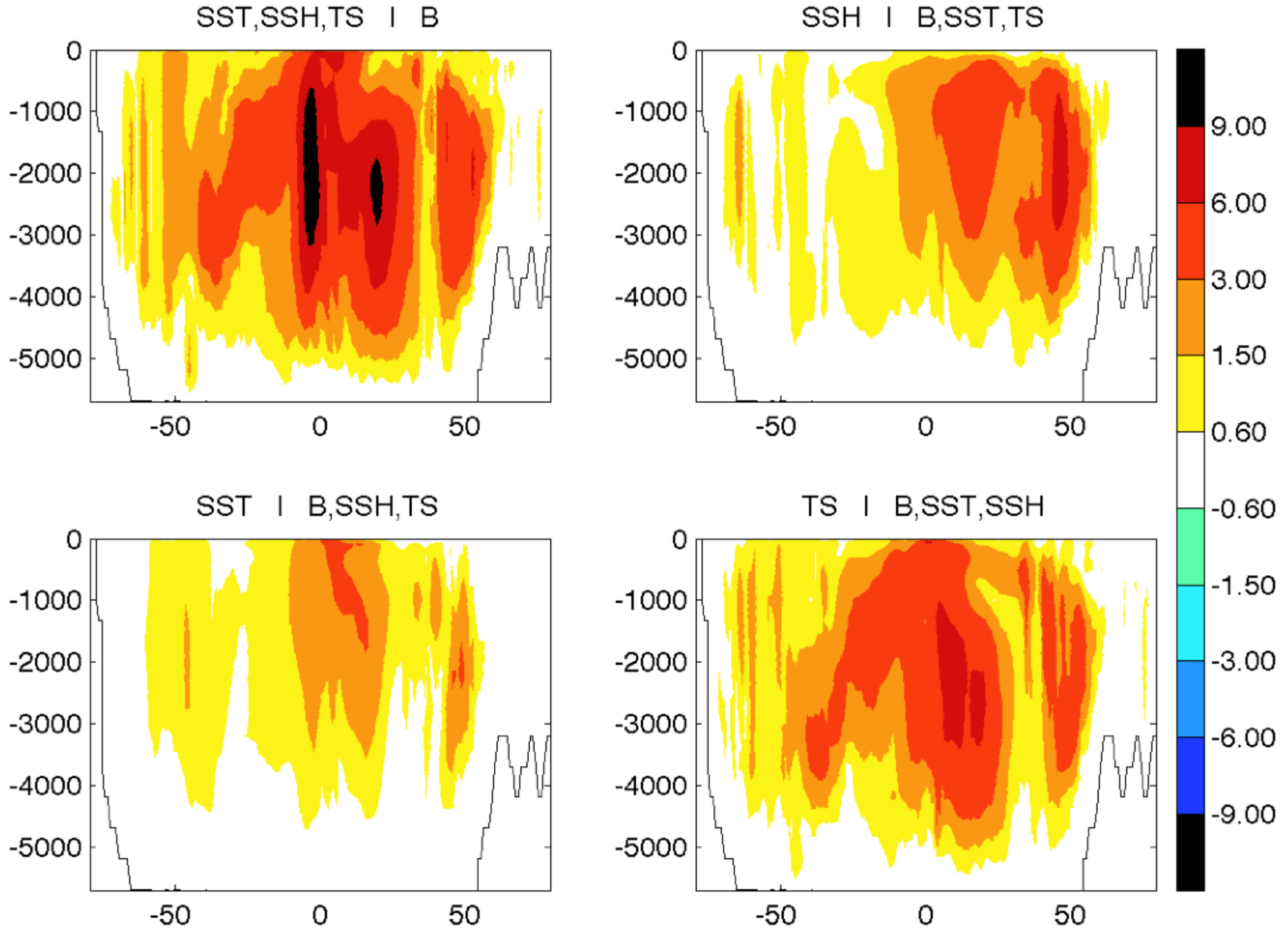


- **Sensitivities provide insight on different mechanisms affecting AMOC at different latitudes, local vs. remote influences, global connections, etc.**

Heimbach et al. (2011, DSR)

Assessing data impacts (I)

- Testing effects of various data constraints on MOC estimates

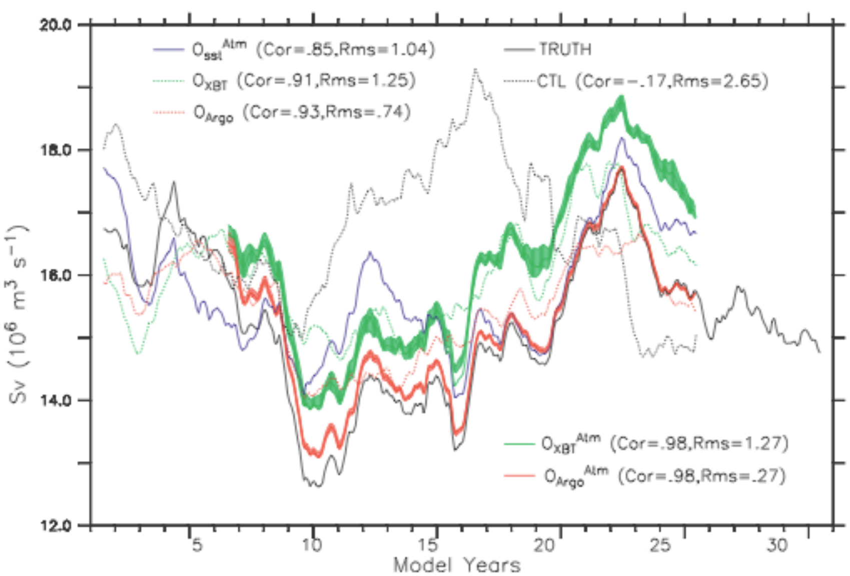


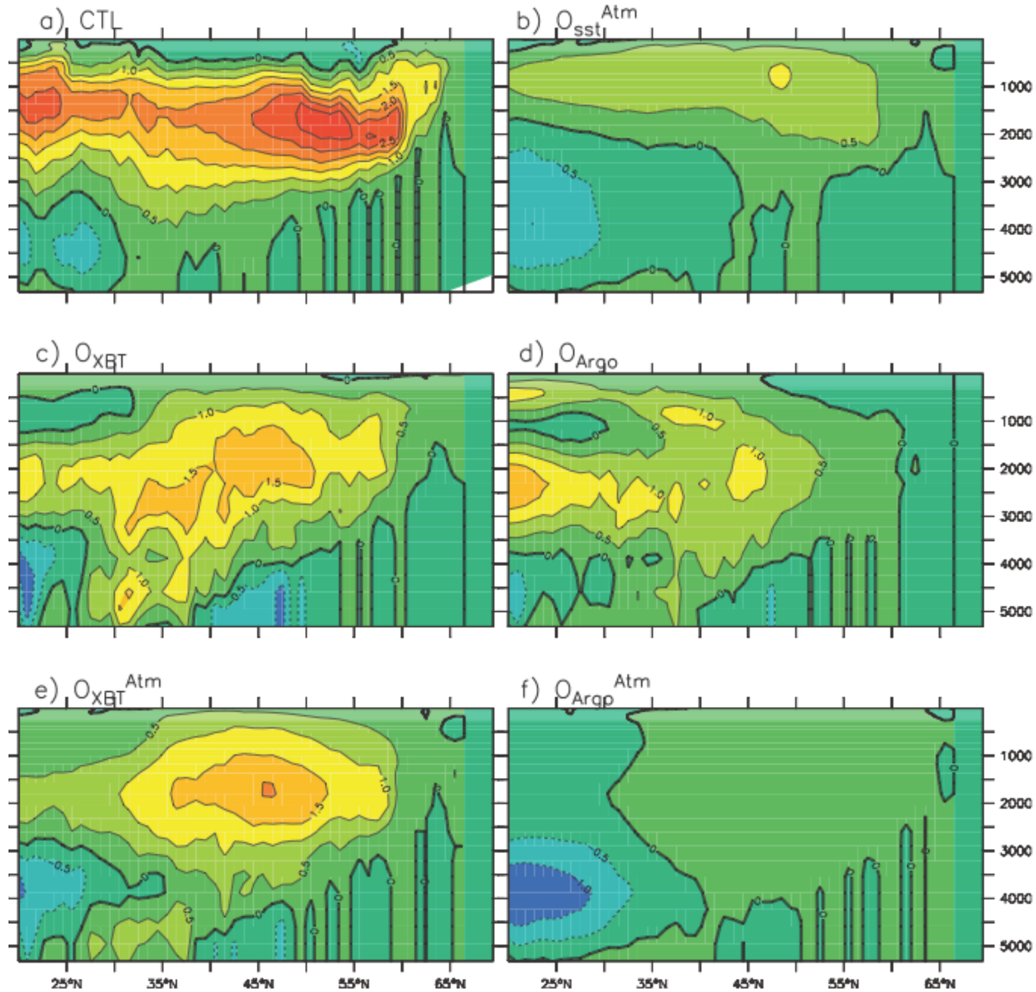
- Large impact of modern datasets
- Similar changes from altimetry and Argo
- Satellite effects not restricted to surface
- Modest impact of SST

B: baseline **SSH**: altimetry **TS**: Argo **SST**: satellite SST

Forget et al. (in preparation)

Assessing data impacts (II)





- Large errors when only XBT type network available

- Well-constrained atmospheric forcing important

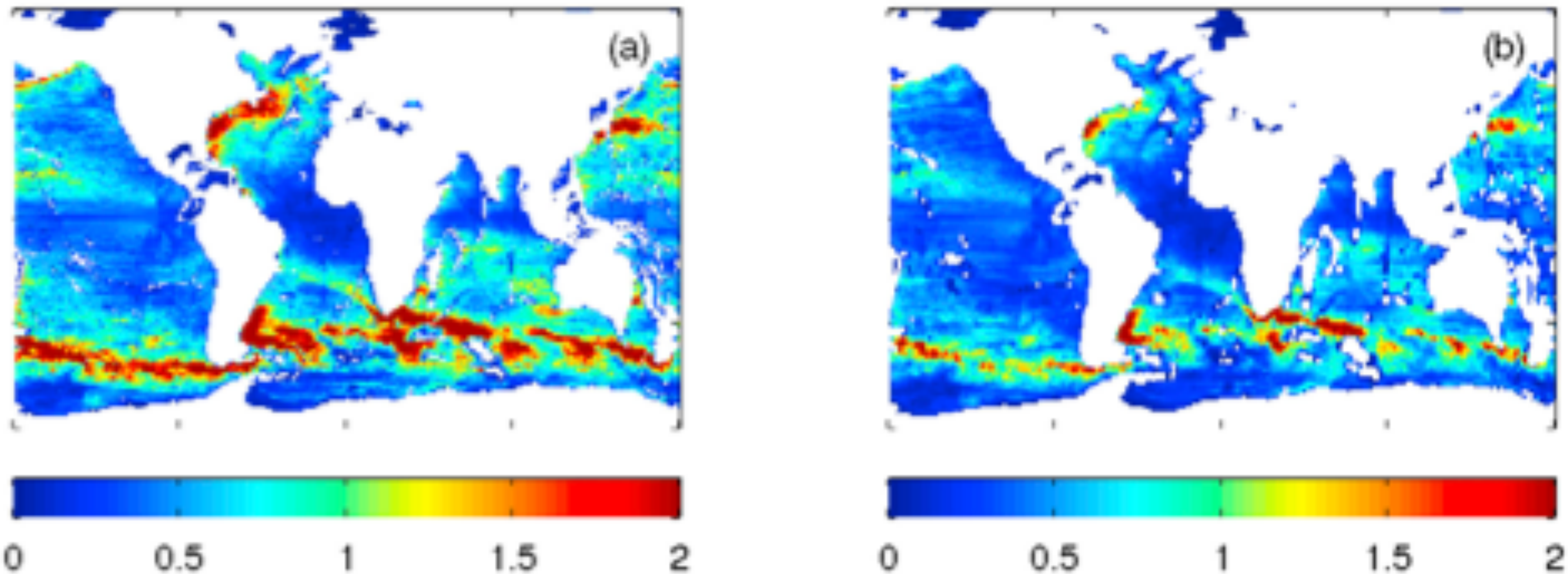
XBT: hydrography prior to Argo

Zhang et al. (2010, JClim)

Deep density field

Standard deviation of steric height (depth < 1800 m) with seasonal cycle and trend removed based on ECCO2 estimate

¼ x ¼ degree **2 x 2 degree**



Substantial signals possible, mostly thermal in nature, and with large effects from eddies

Ponte (2012, GRL)

General considerations

- Systematic evaluation of state estimates in the North Atlantic with focus on recent decades (model and data errors, differences in assimilating methodologies, provision of uncertainty estimates)
- Exploration of available state estimates for dynamical inference of AMOC and related climate variability (important to have dynamically consistent estimates with no hidden sources of heat, freshwater, momentum, and appropriate for closed property budgets)
- Assessment of current data capabilities and possible new datasets (deep ocean T and S, bottom pressure) for an improved observing system
- Development of next generation state estimates with a role for eddies and improved resolution of boundary and high latitude processes (convection, sea ice, overflows) with a dedicated focus on AMOC and related issues
- Ultimate challenge of coupled (air-sea-ice) estimation with balanced fluxes across all interfaces and dynamically consistent evolution of all climate metrics