Climate Observing Systems for the Intermediate & Deep Ocean

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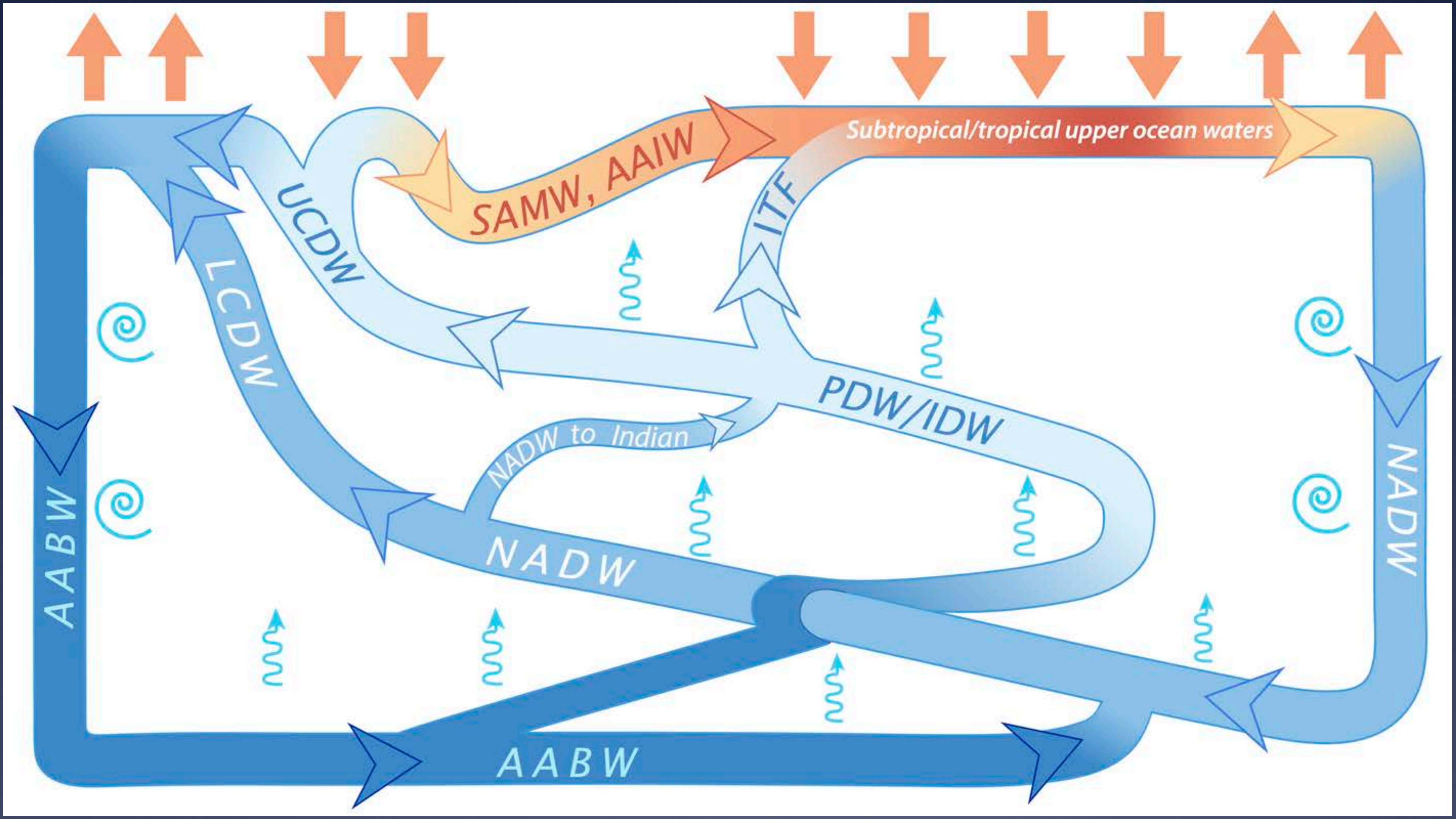
- Introduction
- GO-SHIP
- Argo & Deep Argo
- Moorings & Deep Gliders
- Satellite measurements
- CLIVAR Variations (2017) **15***(2)*

Introduction

- MOC
- NADW & AABW
- Ocean Heat Content

Meridional Overturning Circulation

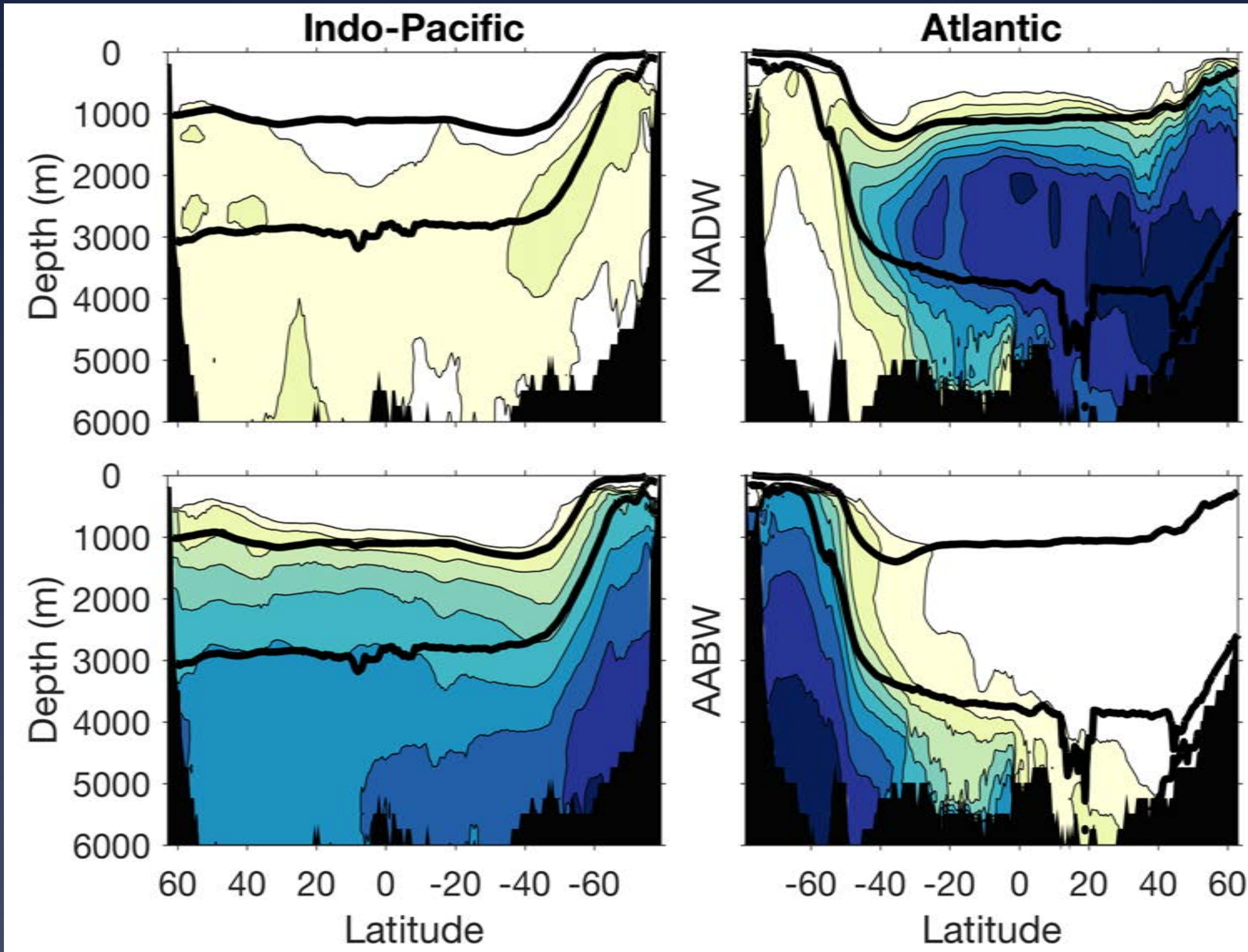
(modified from Talley, 2013)



- AABW & NADW both formed at rates of about 15 x 10^6 m^3 s^{-1}
- Changes in formation rates & water properties can warm deep ocean

AABW & NADW Concentrations

(based on Johnson 2008)



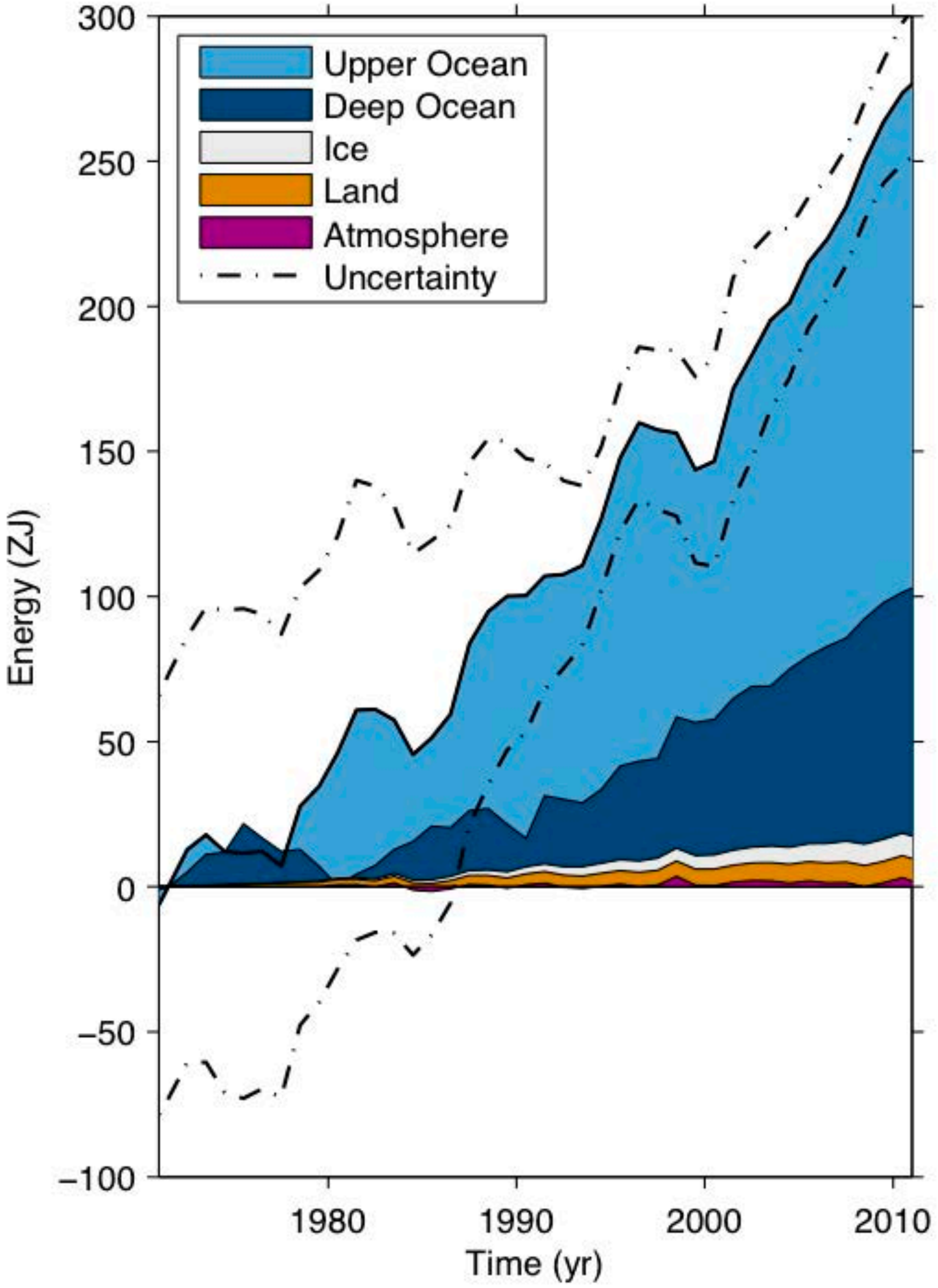
- AABW volume about twice that of NADW
- Filling times centuries to a milennium, timescale for climate adjustment

Thermal Energy Storage

(IPCC, 2013)

Observational Assessment:

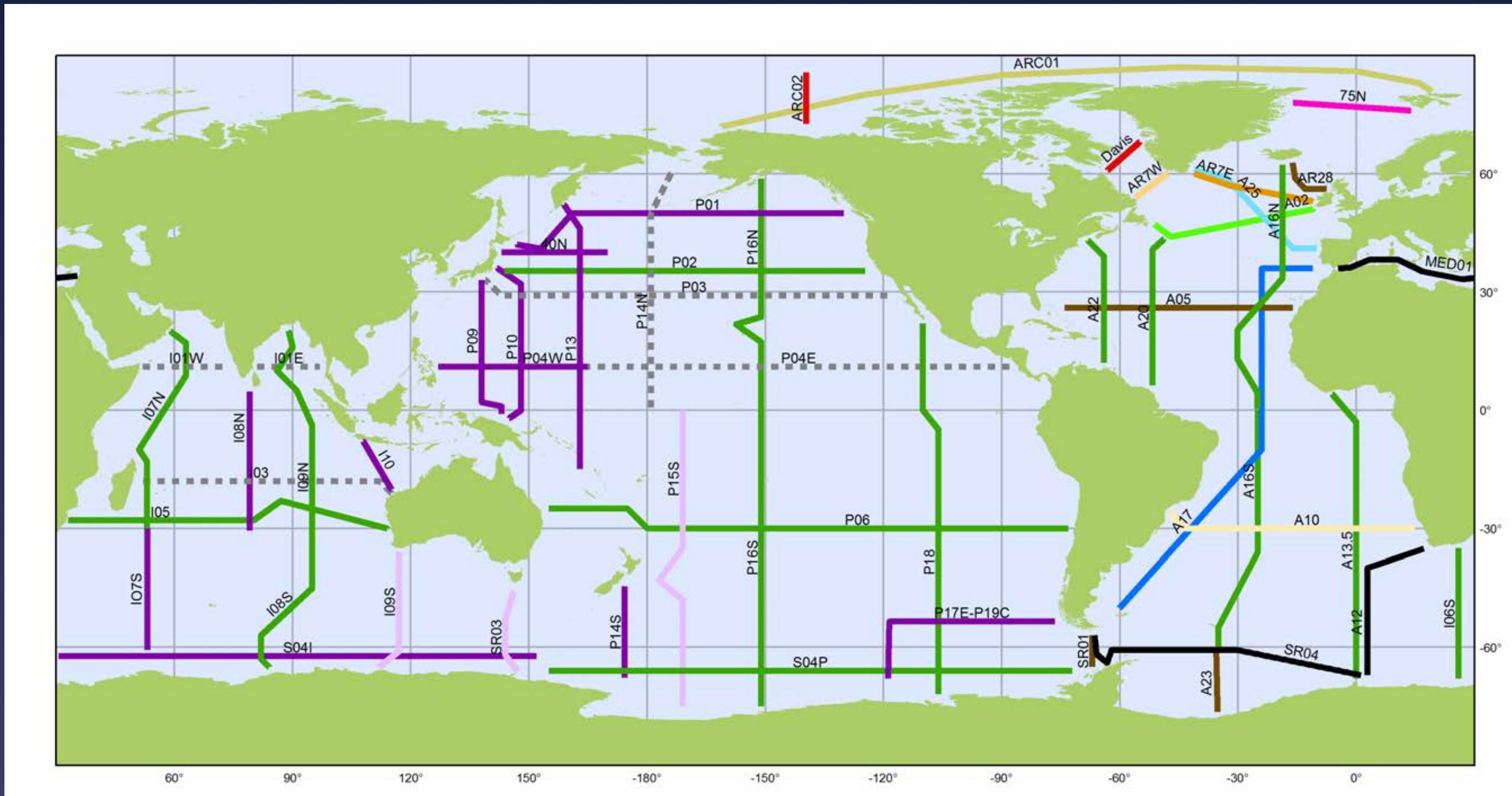
- 0.4 W m^{-2} 1971-2010
  - Ocean 93%
  - Ice melt 3%
  - Land 3%
  - Atmosphere 1%
- 0.5 W m^{-2} 1993-2010
- Sparser observations make uncertainties larger earlier in time.



GO-SHIP

- Decadal Surveys
- Deep Ocean Warming
- Carbon Uptake
- (Oxygen & Nutrient Changes)

GO-SHIP



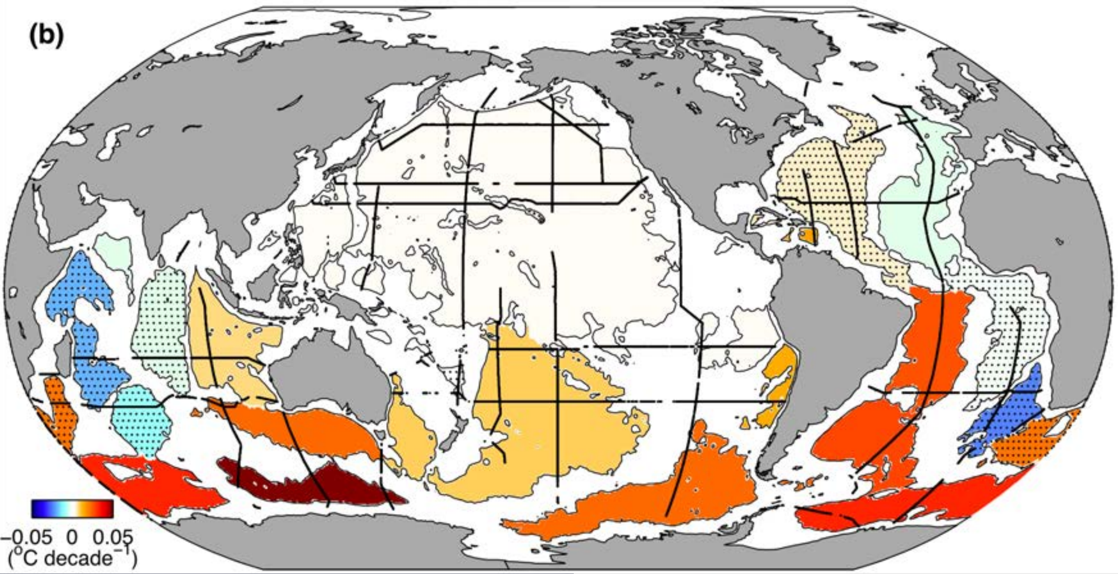
•Global Decadal Revisits of Key Full-Depth, Transoceanic Hydrographic Sections

•High Accuracy, Many essential ocean variables (Temperature, Salinity, Velocity, Oxygen, Nutrients, Carbon, Transient Tracers)

•Provides traceable calibration data for autonomous platforms (Argo floats, Gliders)

•Measures quantities that autonomous platforms cannot

•Provides deployment opportunities for autonomous platforms.

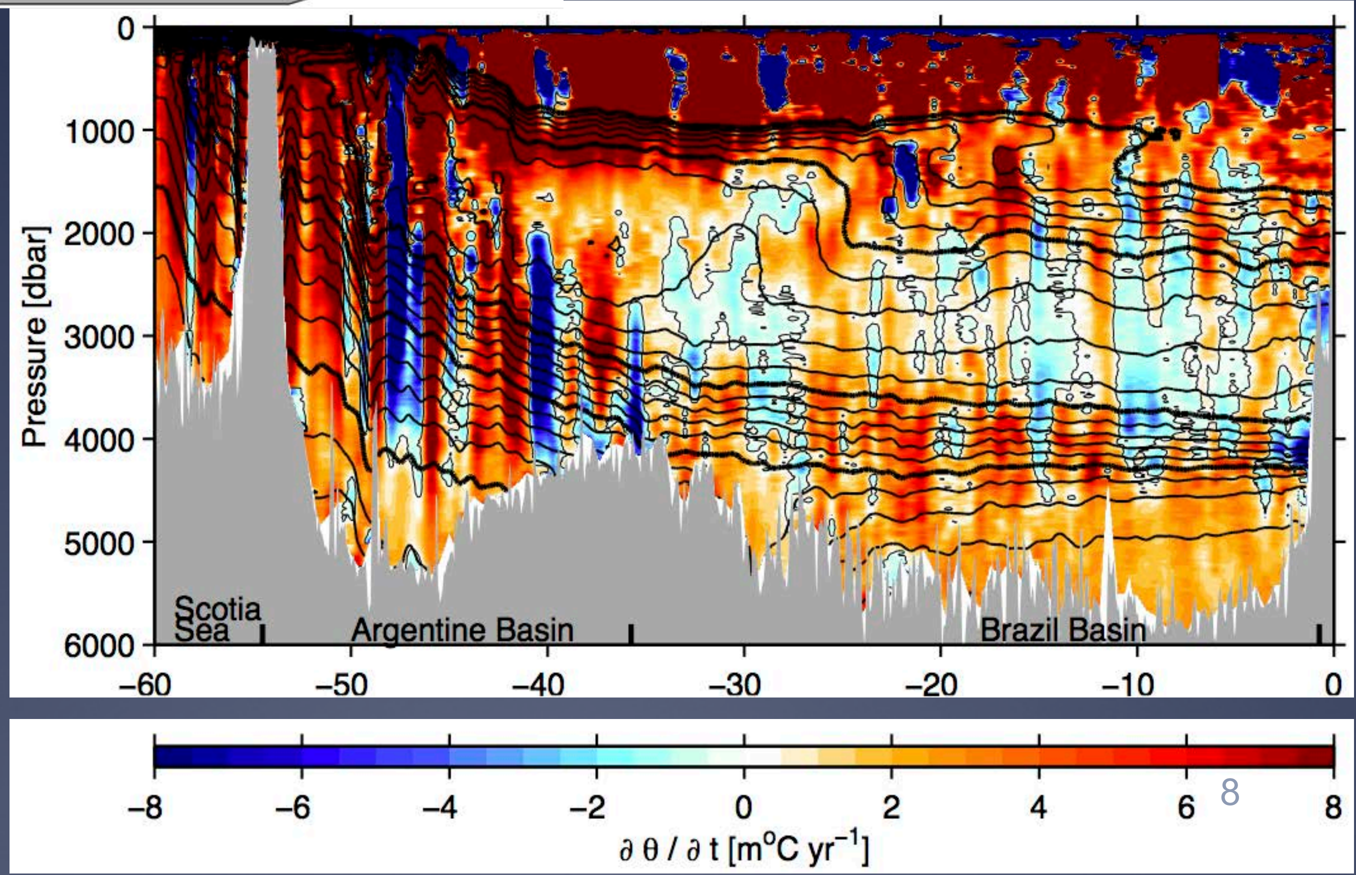


Observed Deep Ocean Warming

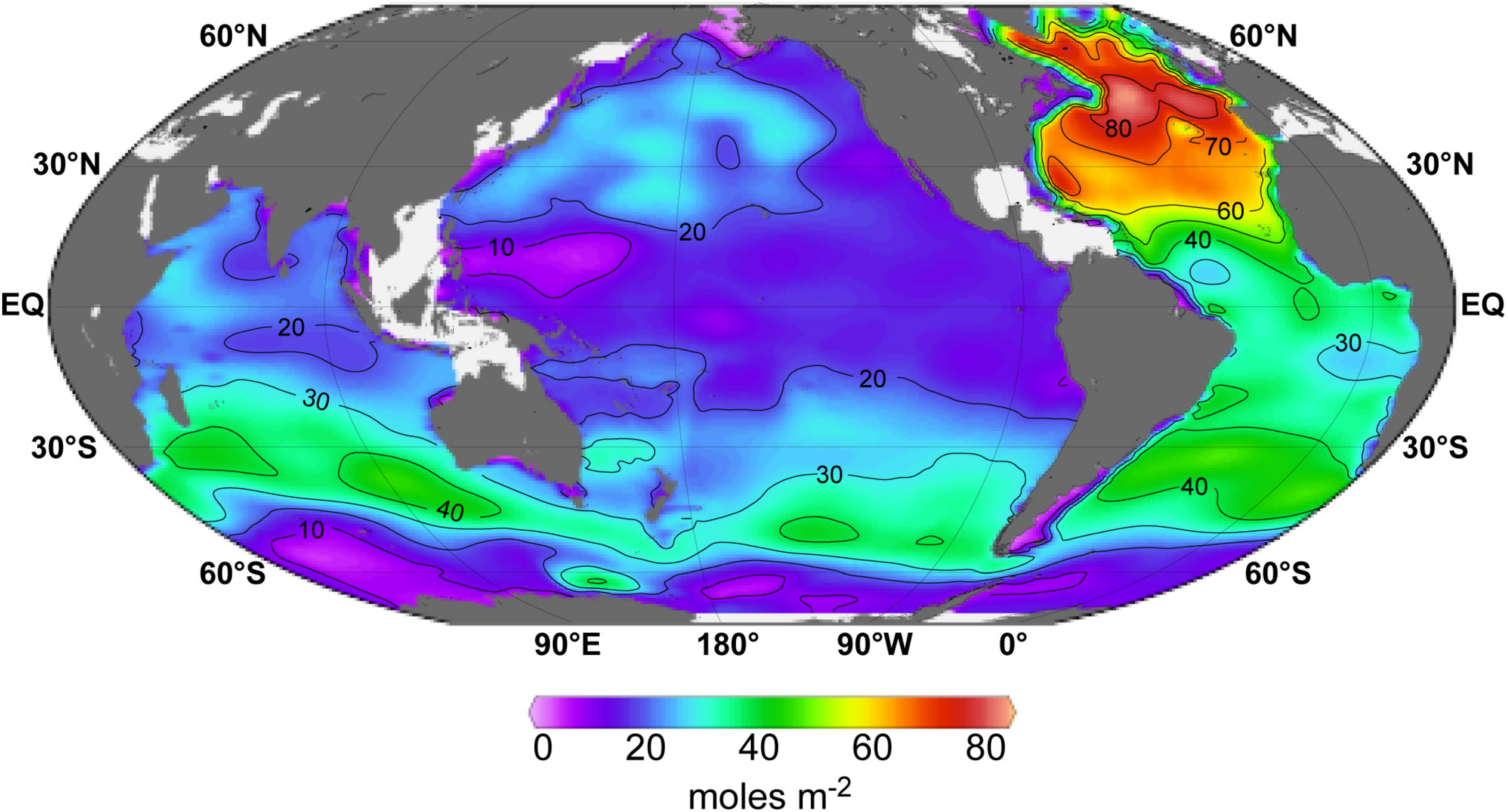
- Sparse decadal ship surveys
- Revealing deep ocean warming
- Qualitative assessment

After Purkey & Johnson (2010)

Example:
S. Atlantic
1989–2014
(Johnson et al. 2015)



Ocean Carbon Inventories



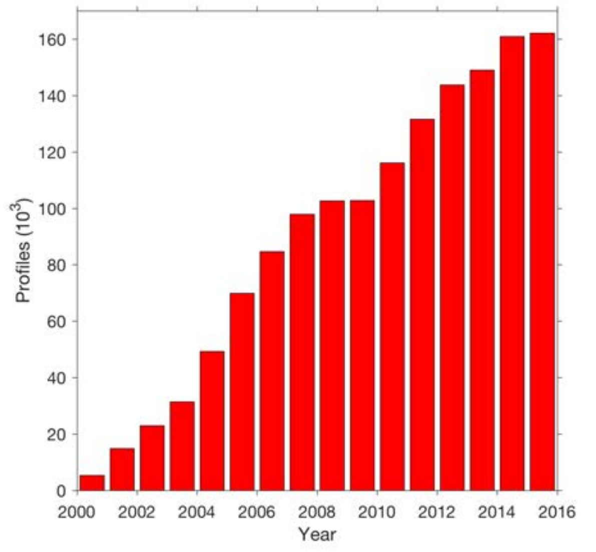
- Sabine et al. (2004)
- Global, high-quality, decadal repeats of carbon system parameters
- Oxygen, nutrients, & transient tracers distinguish natural & anthropogenic signals

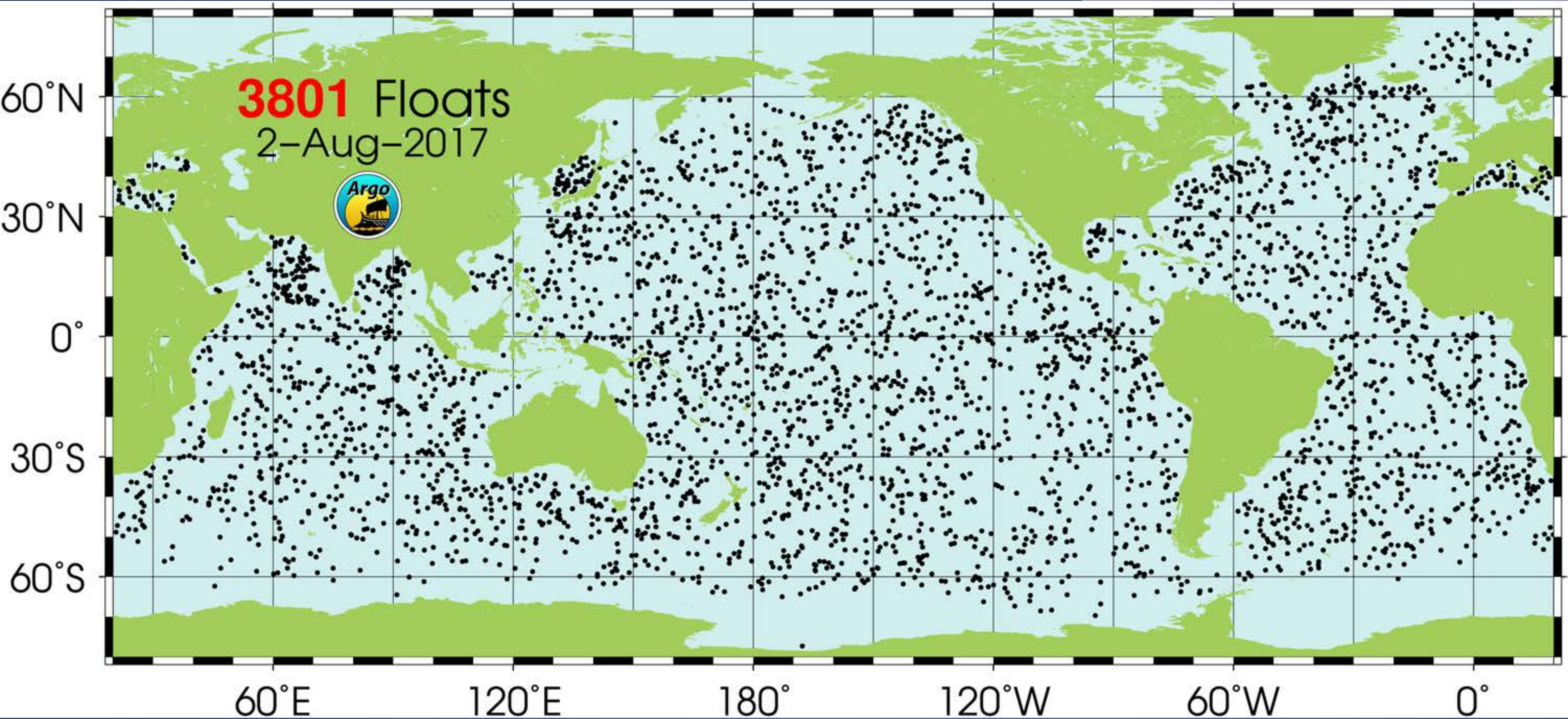
Argo & Deep Argo

- Argo
  - Ramp-up
  - Decadal EEI Uncertainty reduced
  - Interannual EEI variations measured
- Deep Argo
  - Plans
  - Impact
  - Status

Argo

- •Year-Round, High-Quality temperature & salinity data
- •Publically available in near real-time
- •Started in 2000
- •Achieved near global coverage circa 2005
- •Upper 2 km of ocean sampled

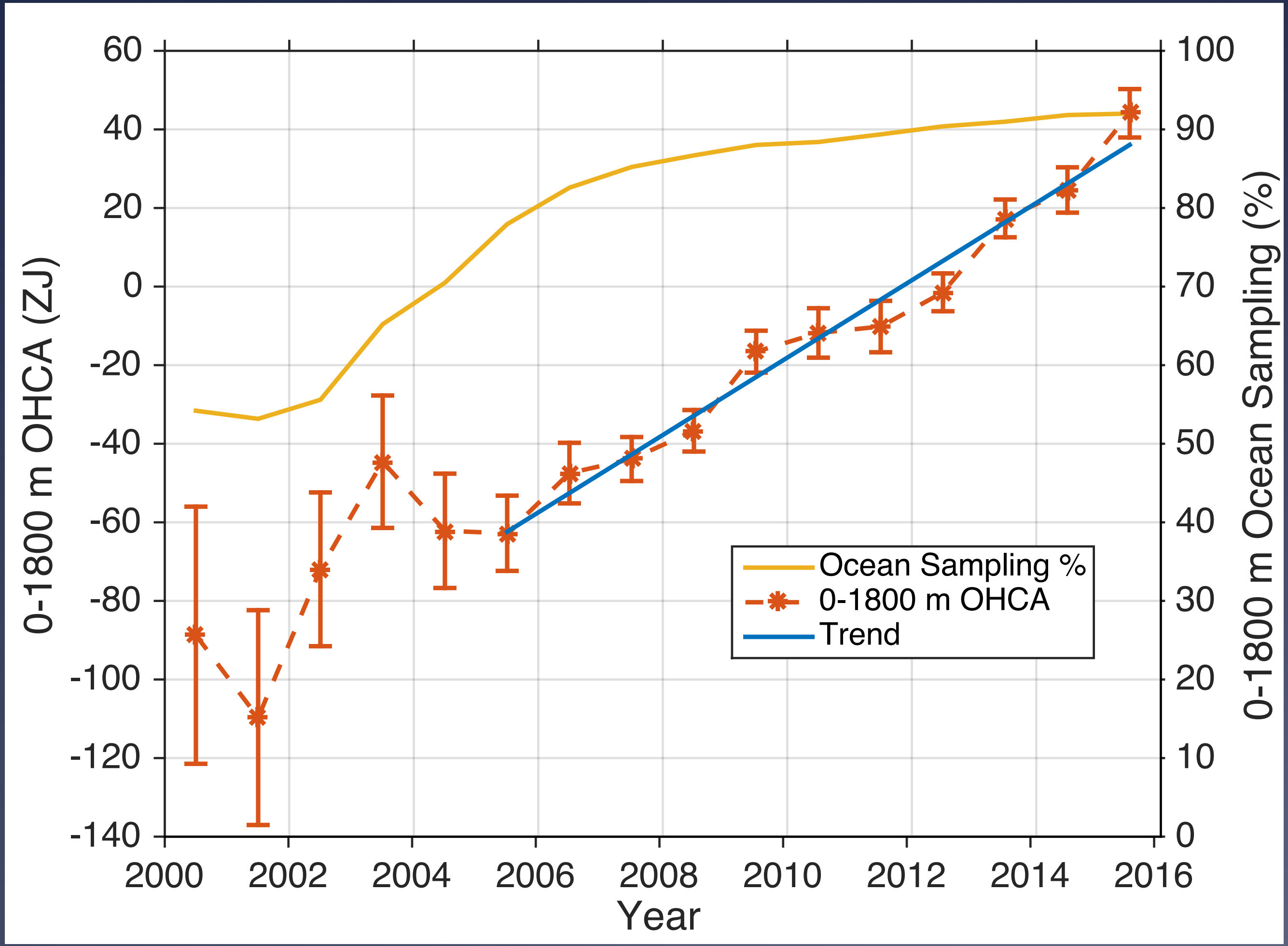




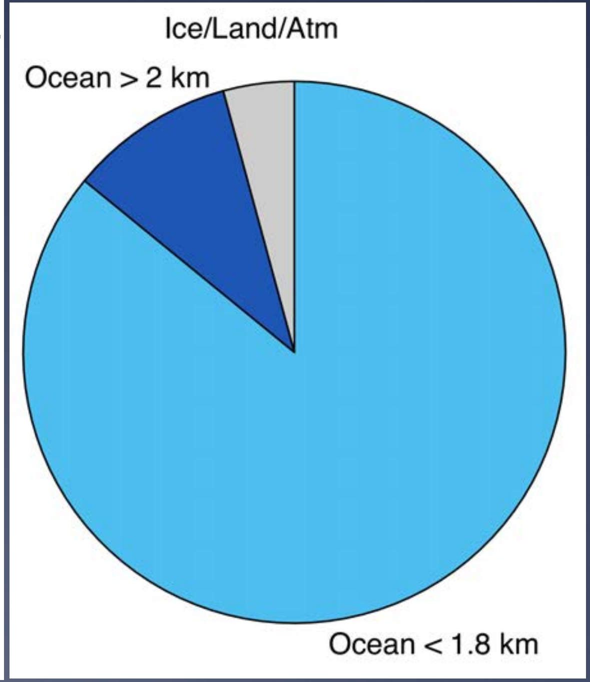
Argo & Ocean Energy Storage

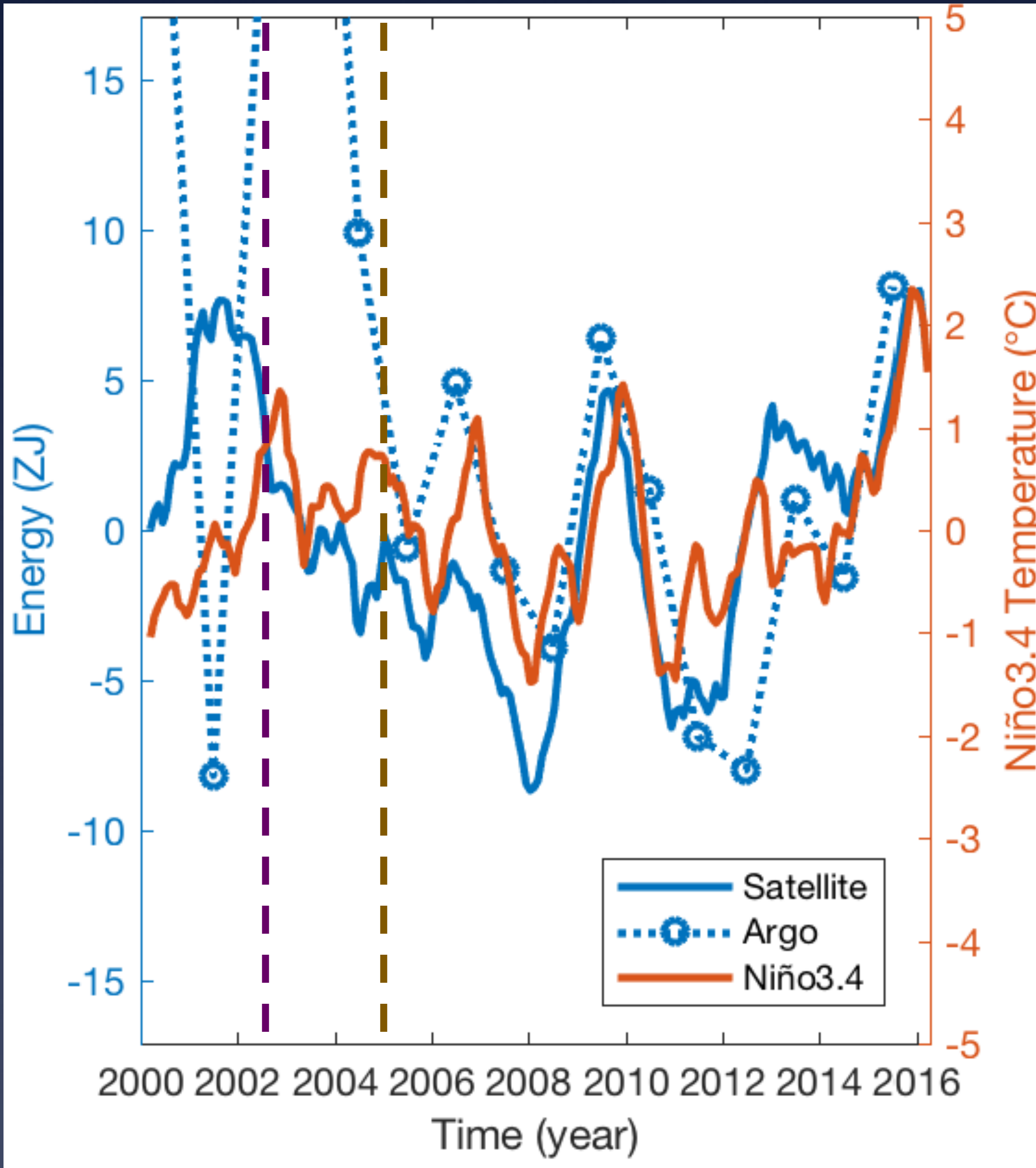
After Johnson et al. (2016)

• *Total Trend 2005.5–2015.5: 0.71±0.10 W m^{-2}*



- Argo ***nails*** global energy storage trend
- Argo ***anchors*** satellite energy flux observations
- Deep (> 2 km) Ocean 2nd largest contribution
- Year-to-year signals emerging…CERES?





Energy Storage & El Niño

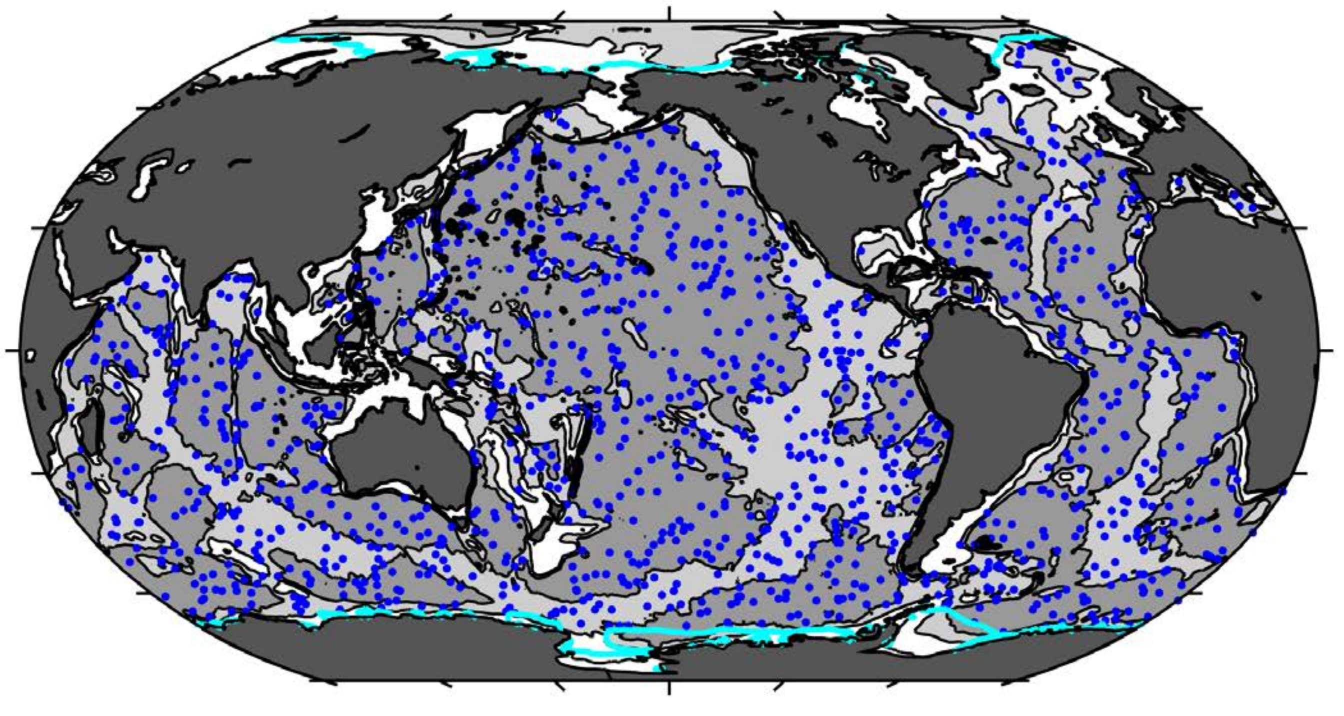
(Johnson & Birnbaum, 2017)
doi:10.1002/2016GL071767

- July 2002 (purple vertical dashes) when 2nd satellite came online)
- 2005 (brown vertical dashes) when Argo -> global
- El Niño modulates GMST & Ocean Heat Storage Variations
- CERES & Argo Interannual Energy Storage Anomalies Agree!

Informing Deep Argo array design using Argo and full-depth hydrographic section data

(Johnson, Lyman, & Purkey; 2015)

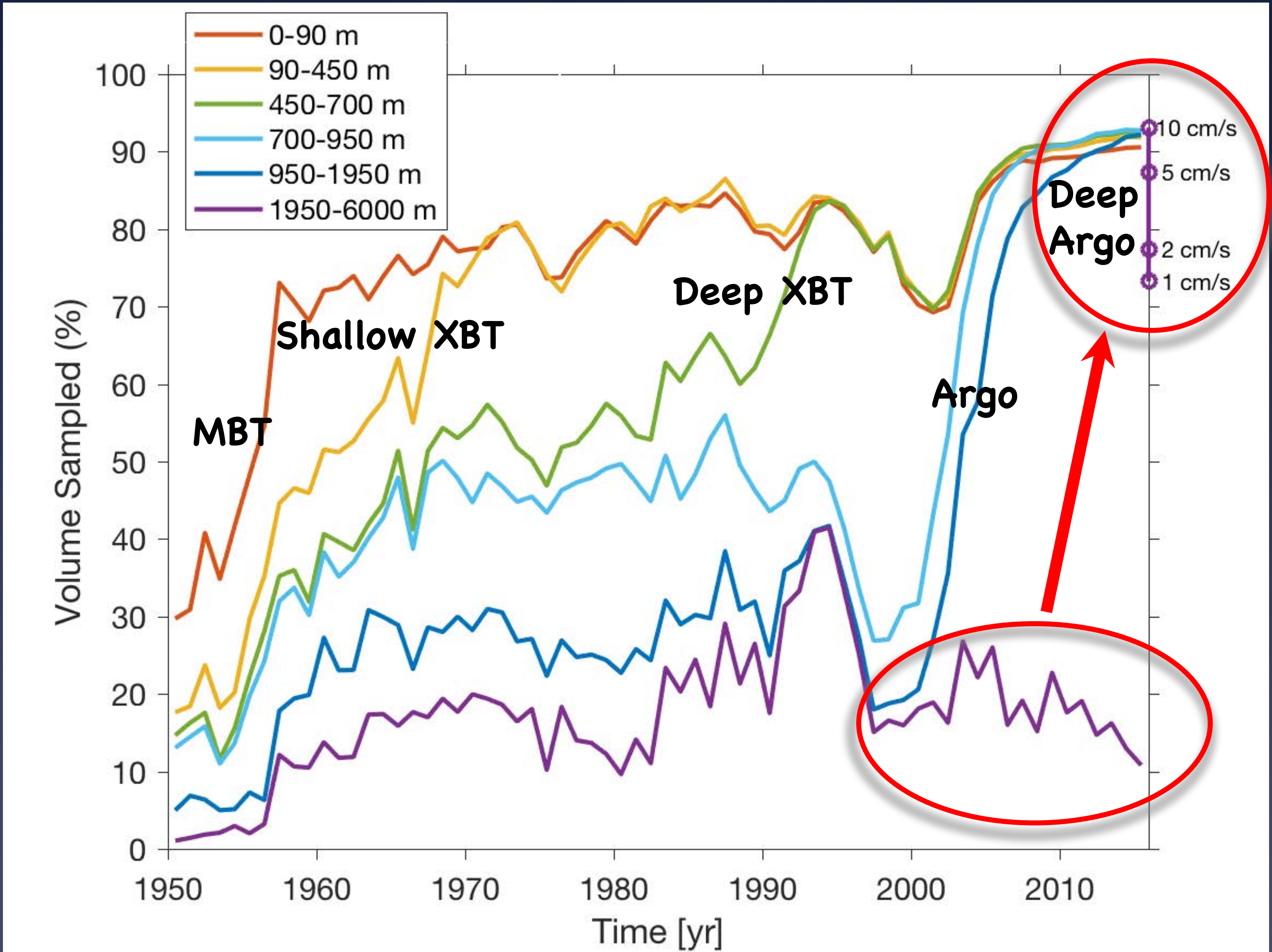
doi:10.1175/JTECH-D-15-0139.1



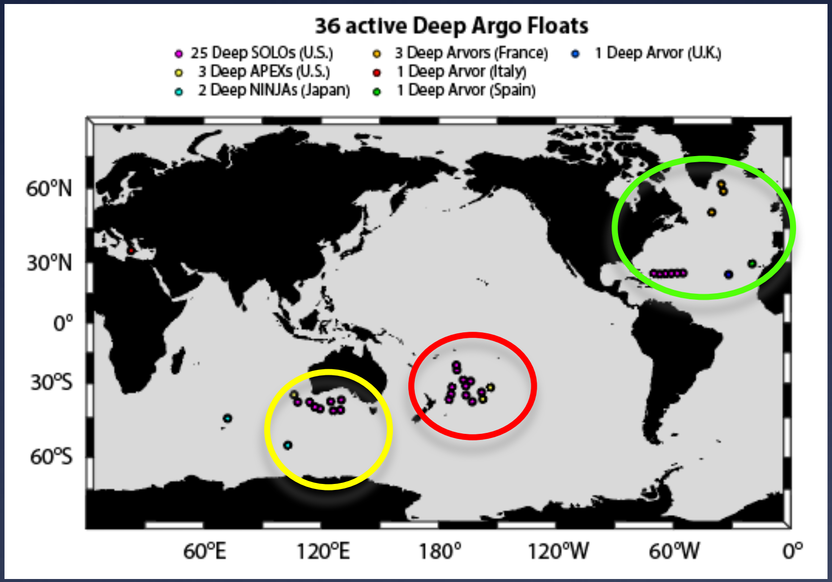
- 1228 floats
- 15-day cycles
- 0-6000 m high-quality profiles

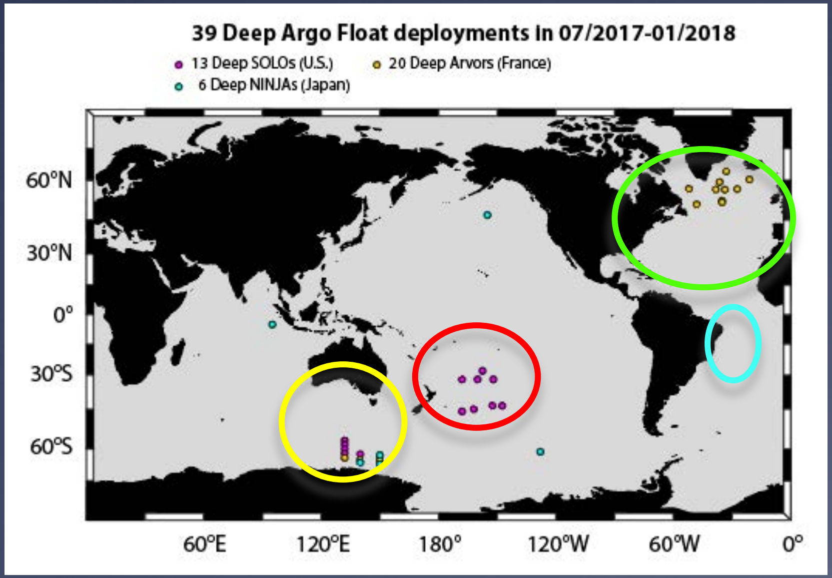
Pilot arrays deployed/planned

Ocean Sampling: Deep Argo Impact



Deep Argo Status





- Implementation phase: regional pilot arrays
- Technical capability for floats and CTDs
- Feasibility of large-scale arrays
- Scientific value of systematic observations

75 Deep Argo floats – 4 pilot arrays in regions of significant deep ocean warming signal and near deep water mass formation

North Atlantic Basin (28 floats)

Southwest Pacific Basin (21 floats)

South Australian and Australian Antarctic Basin (21 floats)

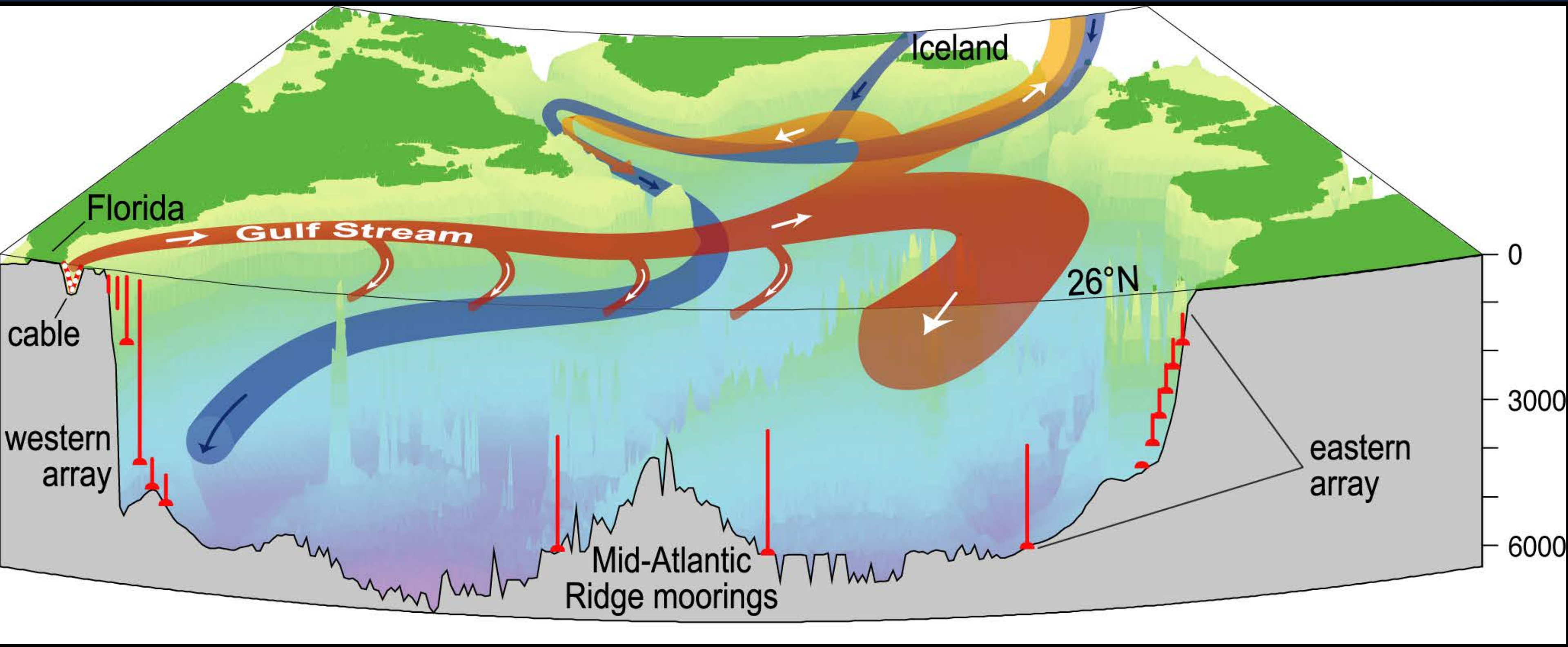
Brazil Basin (28+ floats)

Global implementation of Deep Argo could start in 2-3 years

Moorings & Deep Gliders

- Rapid/MOCHA/WBTS
  - MOC/MHT Time-Series
- Ocean Sites
  - Deep T/S time-series
- Deep Gliders
  - Boundary current sampling

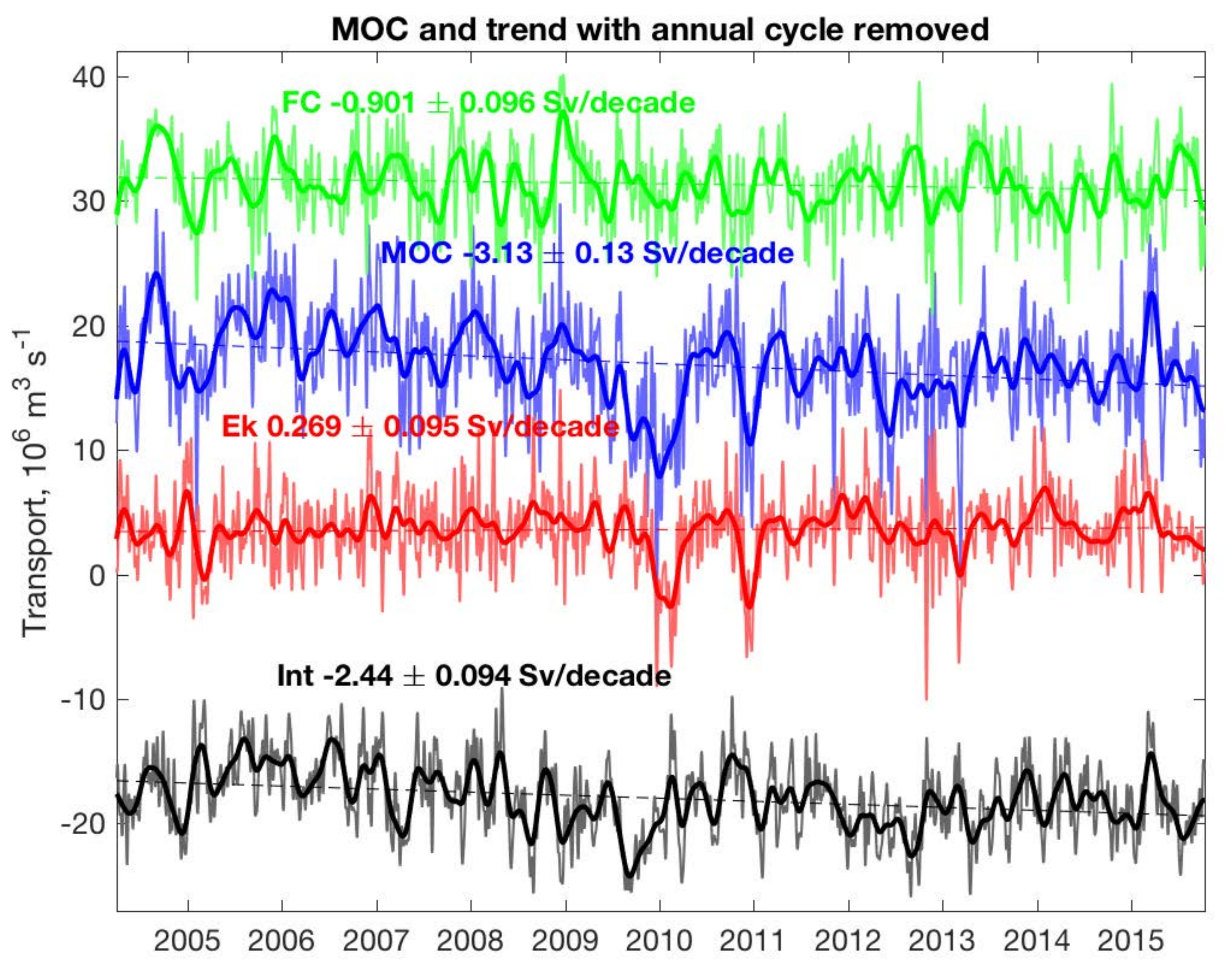
Rapid/MOCHA/WBTS Array



Measurement components:

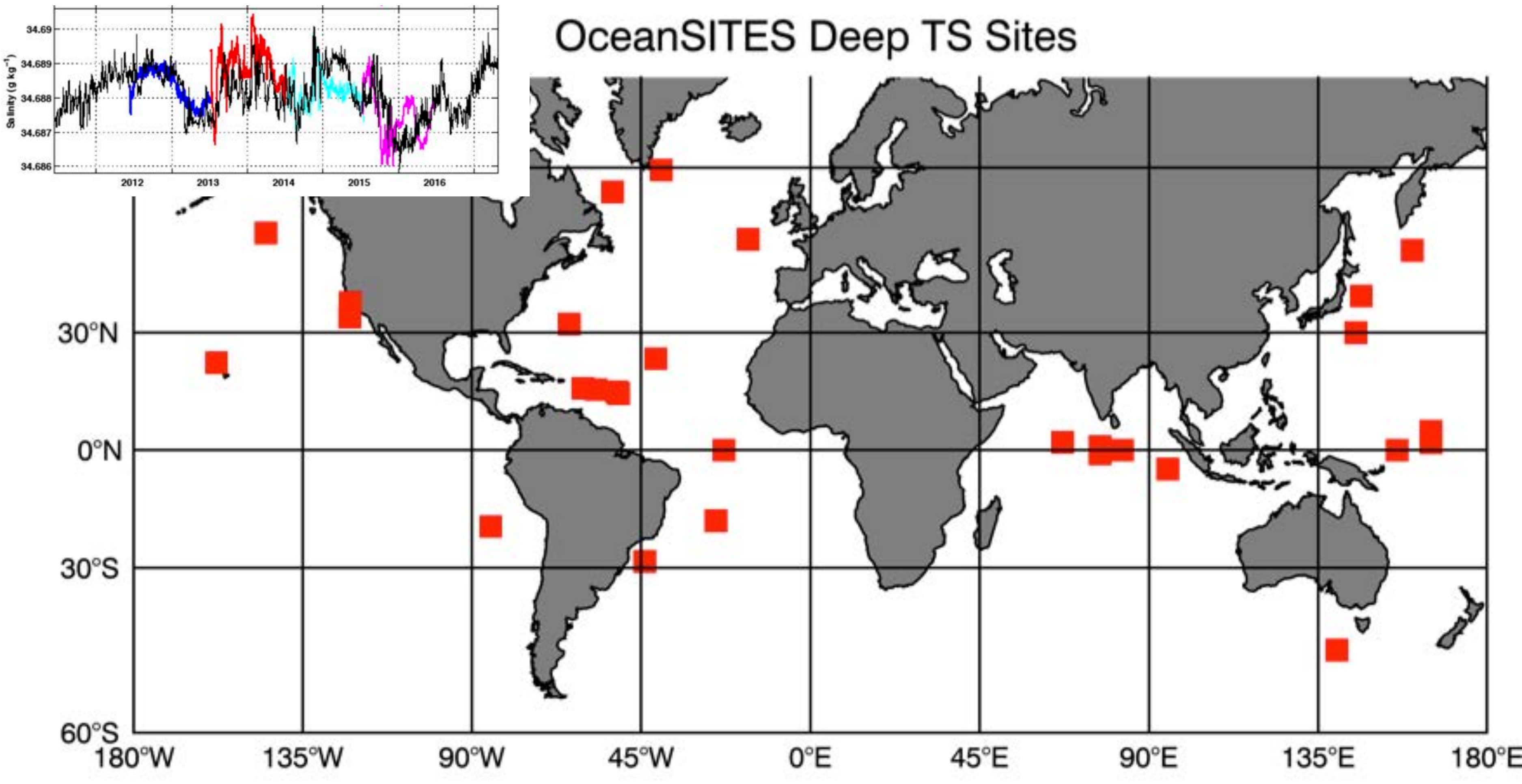
- Gulf Stream - telephone cable
- Ekman - scatterometer
- Mid-ocean - density, current meters

Rapid/MOCHA/WBTS Array



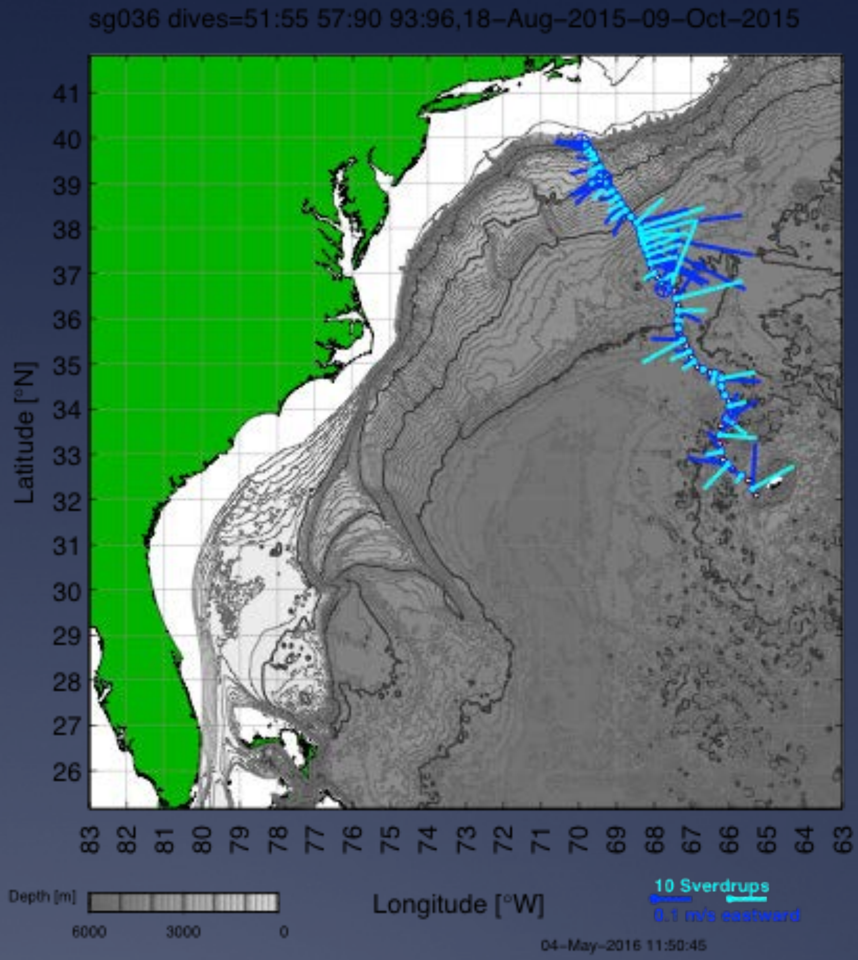
Baringer et al. (2017)

Ocean Sites Deep T-S



- Geographically distributed Deep T-S time-series
- e.g HOT salinity inset 2011-2017

Deep Gliders

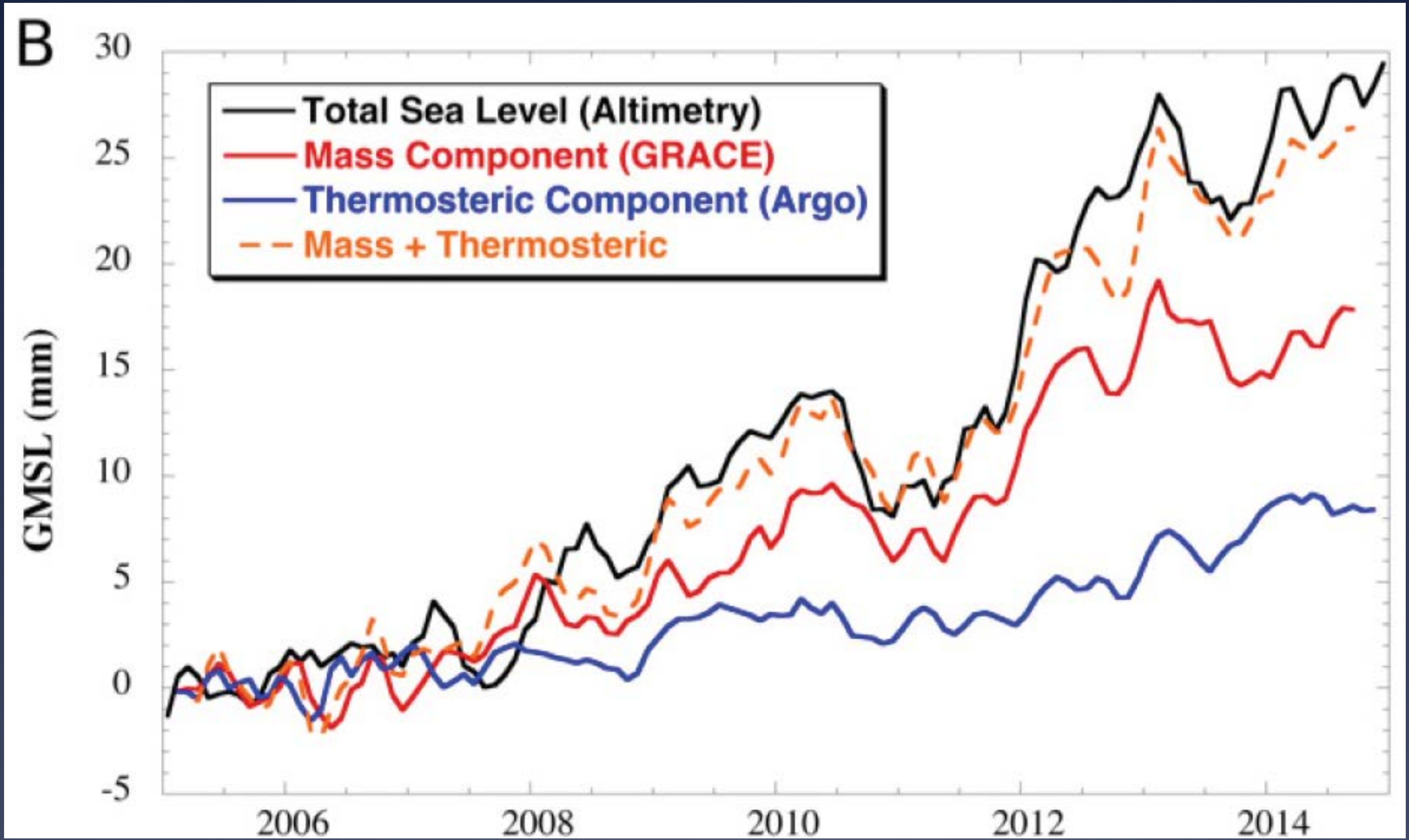


- Deployable from small boats
- Full-depth, closely spaced boundary current sampling

Satellites

- Altimetry & Gravimetry
  - Sea Level Budgets (with Argo)
  - Deep Ocean transports (GRACE)

Global Sea Level Budget

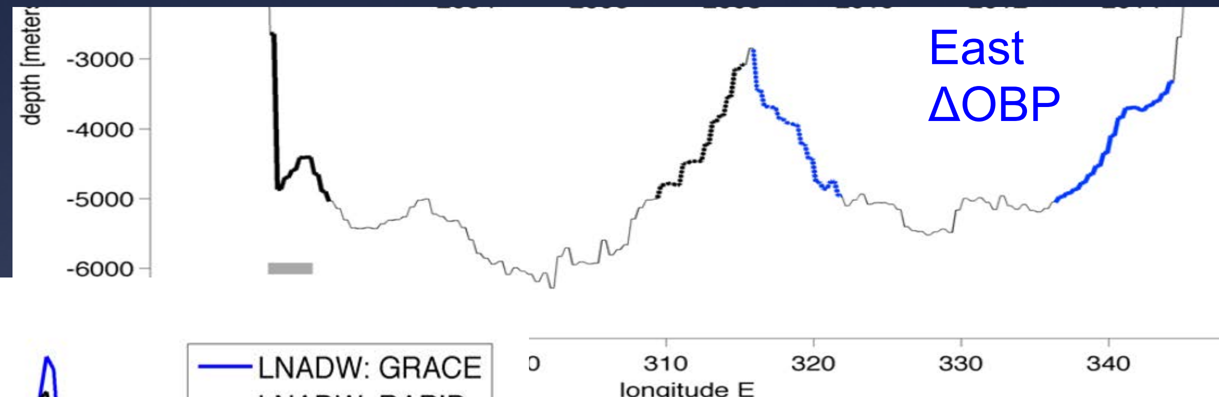


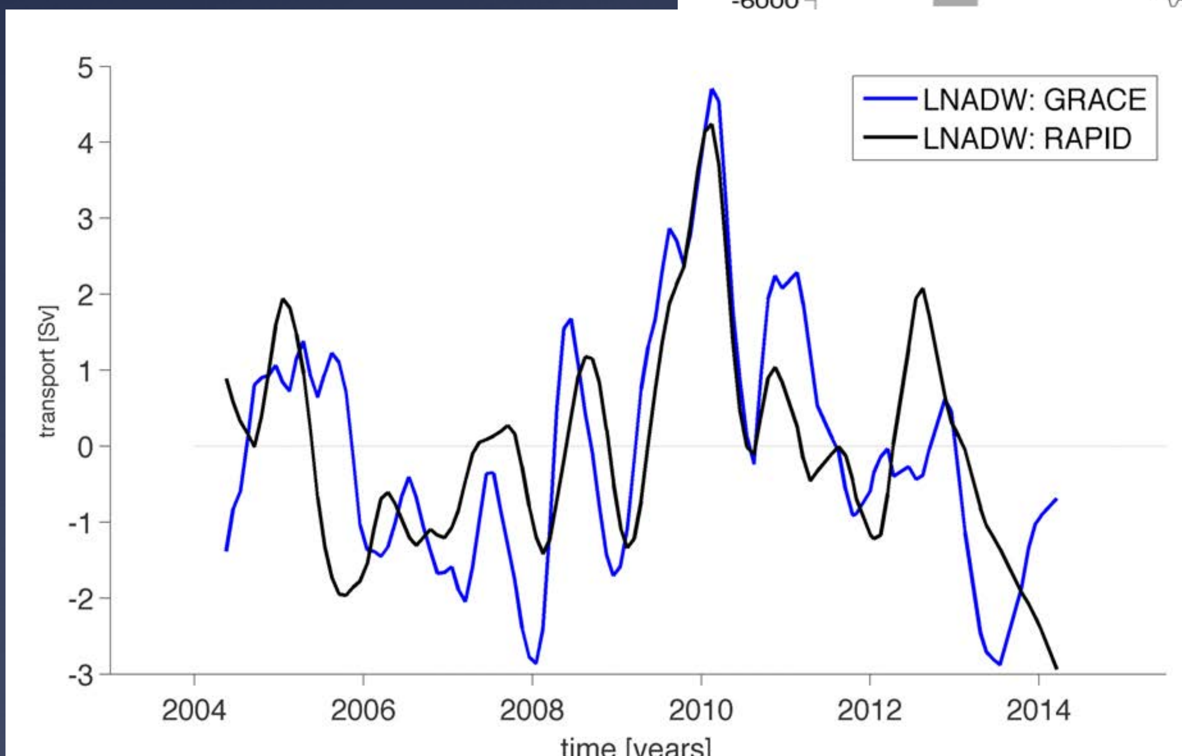
- Very good agreement between altimetry, gravimetry, and in-situ (Argo) data
- Missing deep ocean warming (thermal expansion smaller in cold water)

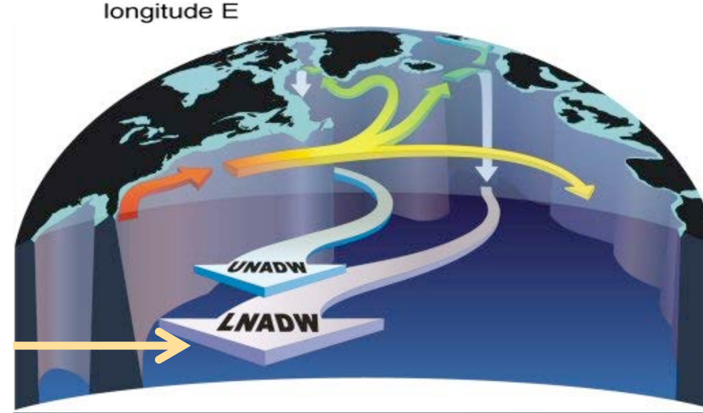
Rapid/MOCHA & GRACE LNADW

Lower North Atlantic Deep Water time series:

- GRACE correlation with RAPID/MOCHA: **R=0.7**
- Estimated error: +/- 1.1 Sv







Landerer et al. (2015)

Conclusions

- GO-SHIP: Sparse decadal global coverage
  - EOVs unmeasured/unmeasurable by Argo
  - Full depth not yet measured by Argo
  - Provides highest accuracy calibration data & deployment opportunities for Argo/Gliders
  - Global class vessel retirements looming issue
- Argo: Upper 2 km T&S
  - US constant dollar funding since 2003 a threat
  - Deep Argo now feasible (subject to funding)
  - BGC now feasible (subject to funding)
- Moorings (Rapid/MOCHA, OceanSites, etc)
  - Provide time-series in key locations (MOC & T-S)
- Deep gliders could be valuable in boundary currents
- Satellites (Altimetry & Gravity) provide Sea Level and Ocean Bottom Pressure information.