Ocean Warming: Anchoring Earth's Energy Imbalance

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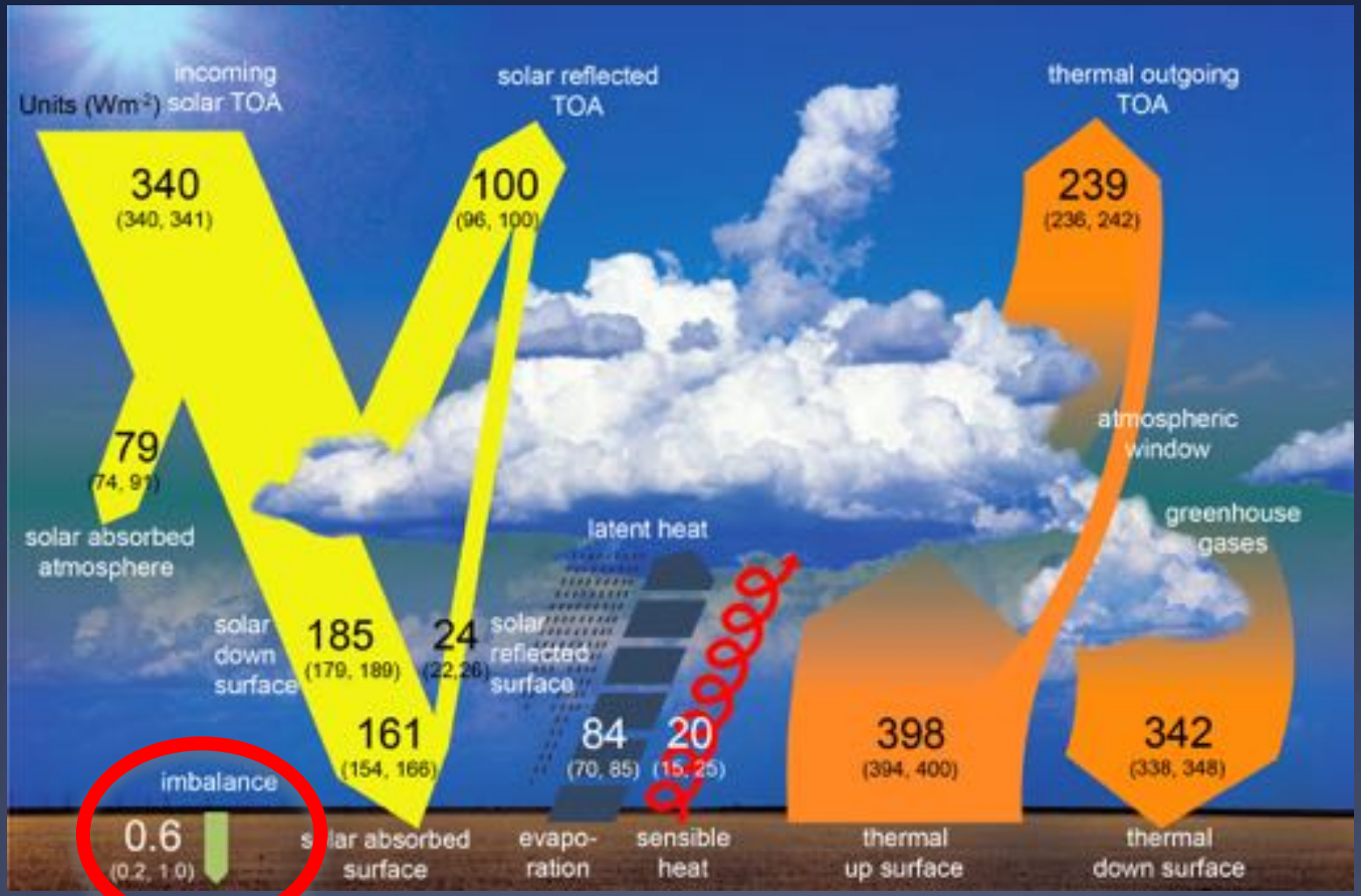
- Global Energy Flows & Thermal Energy Storage Estimates
- Ocean Heat Content Dirty Laundry
- The Argo Revolution
- CERES-In Situ Comparison of Earth's Energy Uptake
- (Deep Argo Advertisement)

Global Energy Flows, Thermal Energy Storage, & Ocean Heat Content Estimates

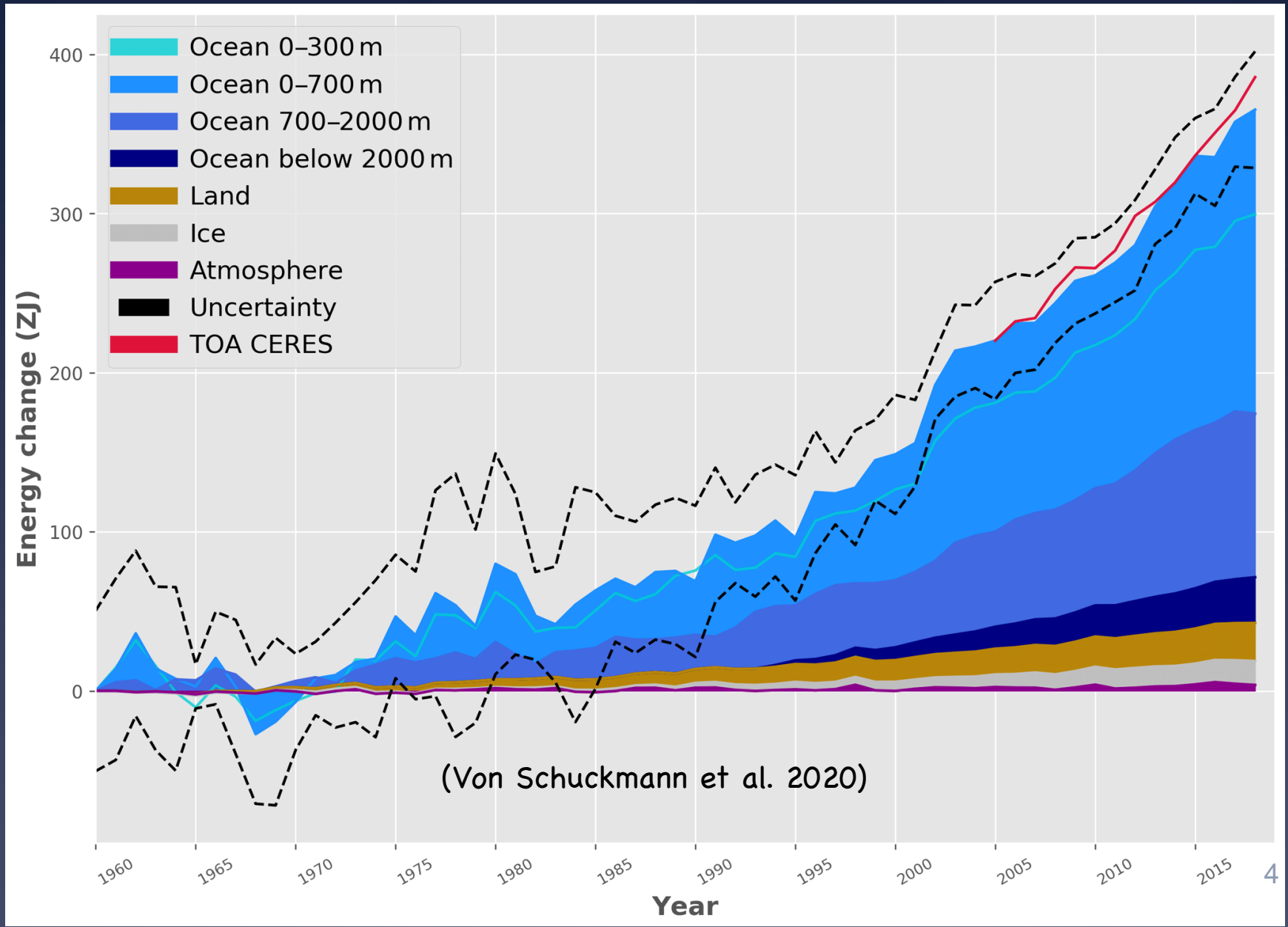
Global Energy Flows

(IPCC, 2013)

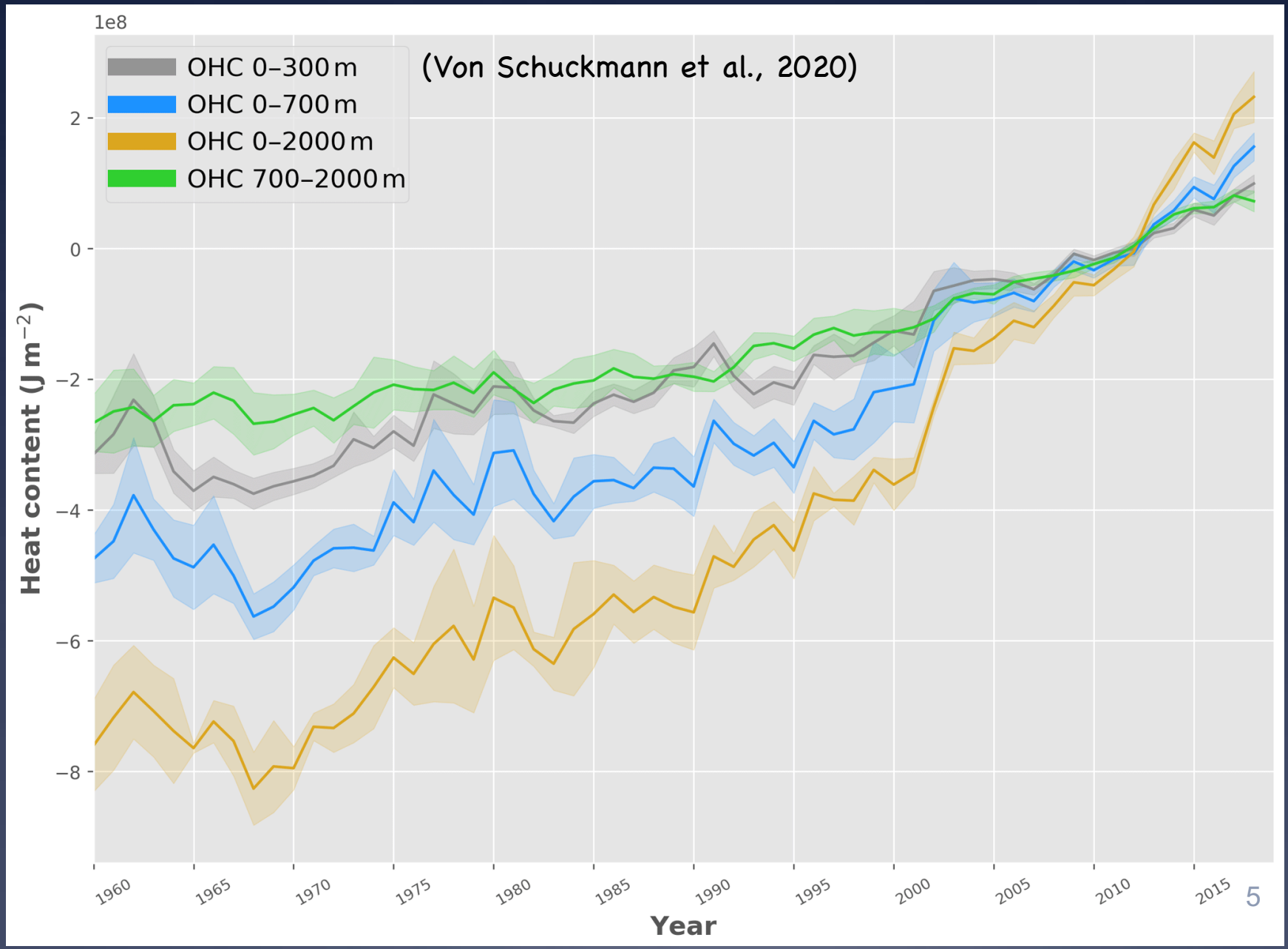


- Imbalance of ~0.6 W m^{-2} (not into corn fields though – ***into the ocean!***)
- Small difference of big numbers – measuring storage change robust?

Thermal Energy Storage

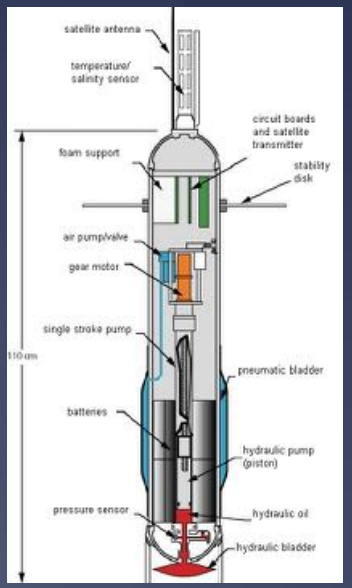


Ocean Heat Content Estimate Spread



Ocean Heat Content Dirty Laundry: Changing Instrumentation, XBT Biases, & Sparse Historical Sampling

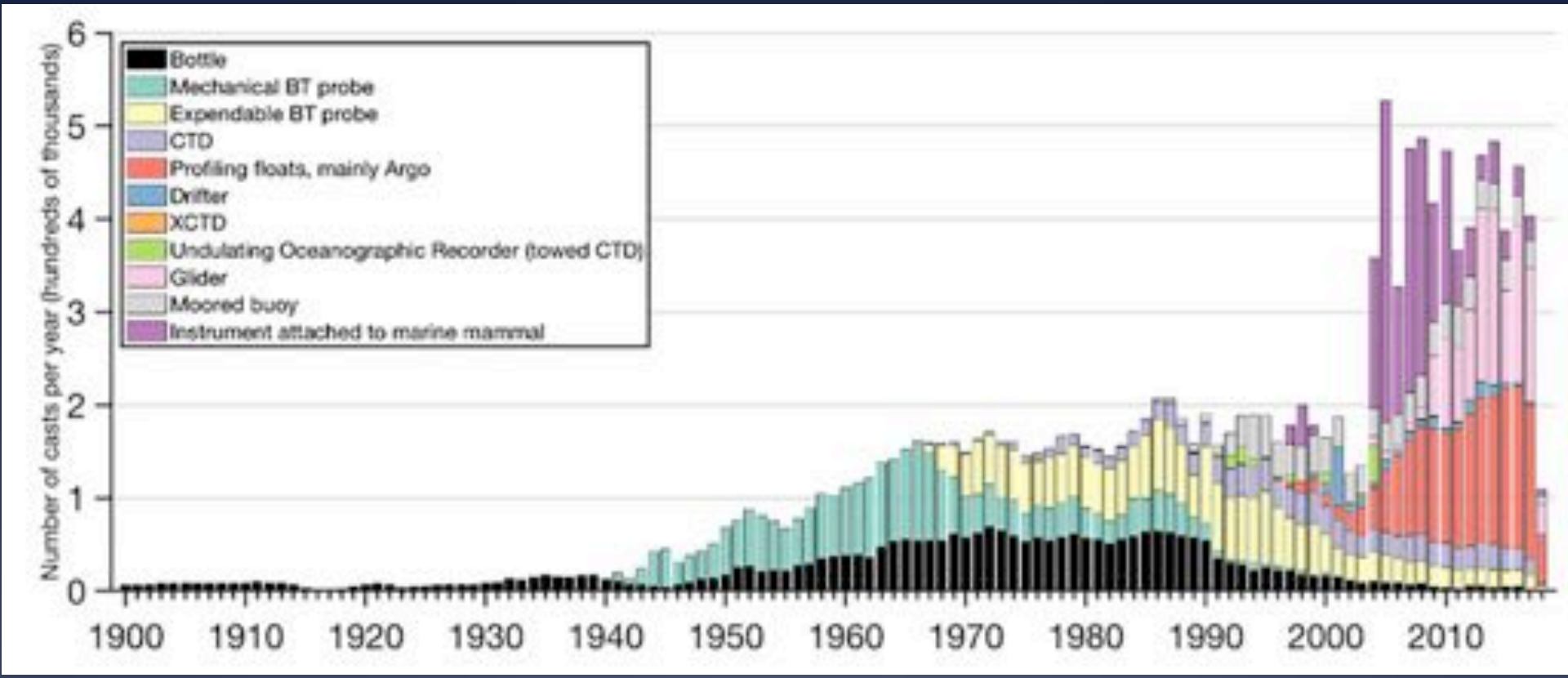
MBT, 1938: ±0.1ºC, ±1% z, < 300 m. XBT, 1966: ±0.1ºC, ±2% z, 400 & 750 m.



Reversing Therm., 1900: ±0.01ºC, ±1% z, btm. Argo, 2000: ±0.01ºC, 0.1% z, 2000 m.
CTD, 1961: Accuracy by mid-1980s ±0.002ºC, ±0.05% z, 6000 m.

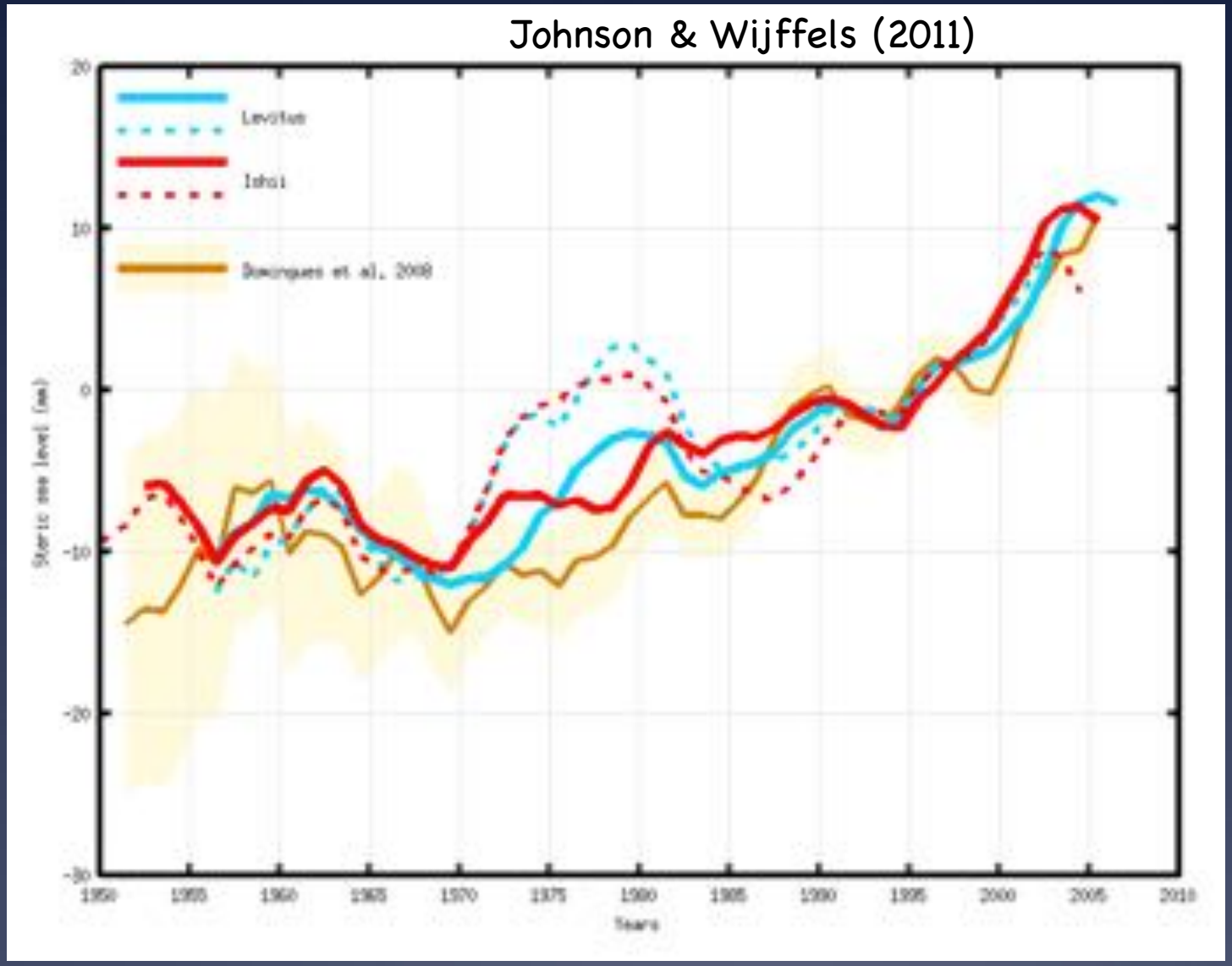
Changing Ocean Instrumentation

(Meyssignac et al. 2019)



- Bottle, CTD, & profiling float data good & widely distributed
- Glider, moored buoy, & marine mammal data often localized
- XBT & MBT data shallow, low accuracy, & have *bias* issues.

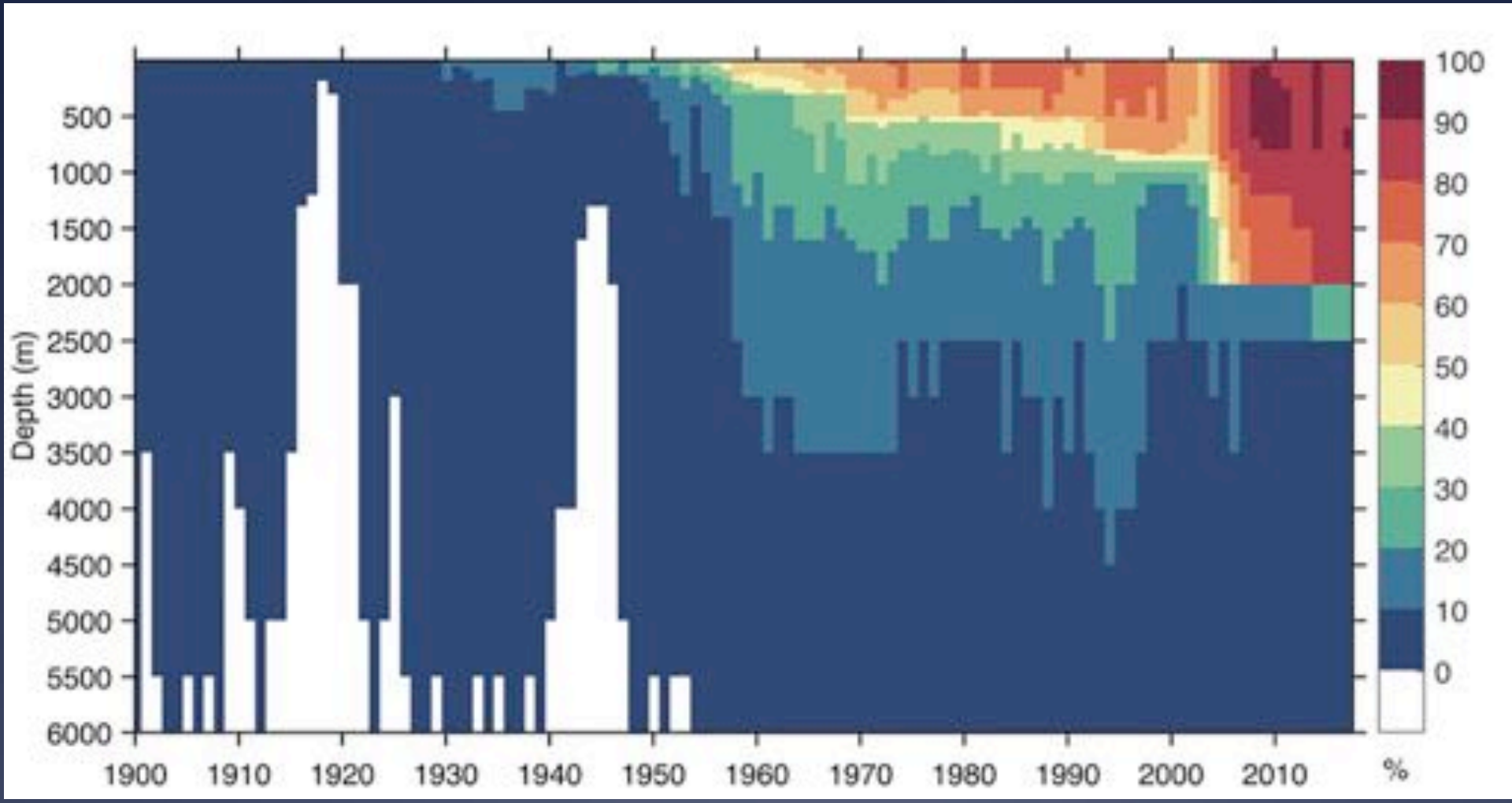
Ocean Heat Content & Instrument Biases



- XBT bias corrections greatly reduced mid-1980s spurious ocean warming
- Large (sampling) uncertainties before circa 1970.

Changing Ocean Sampling

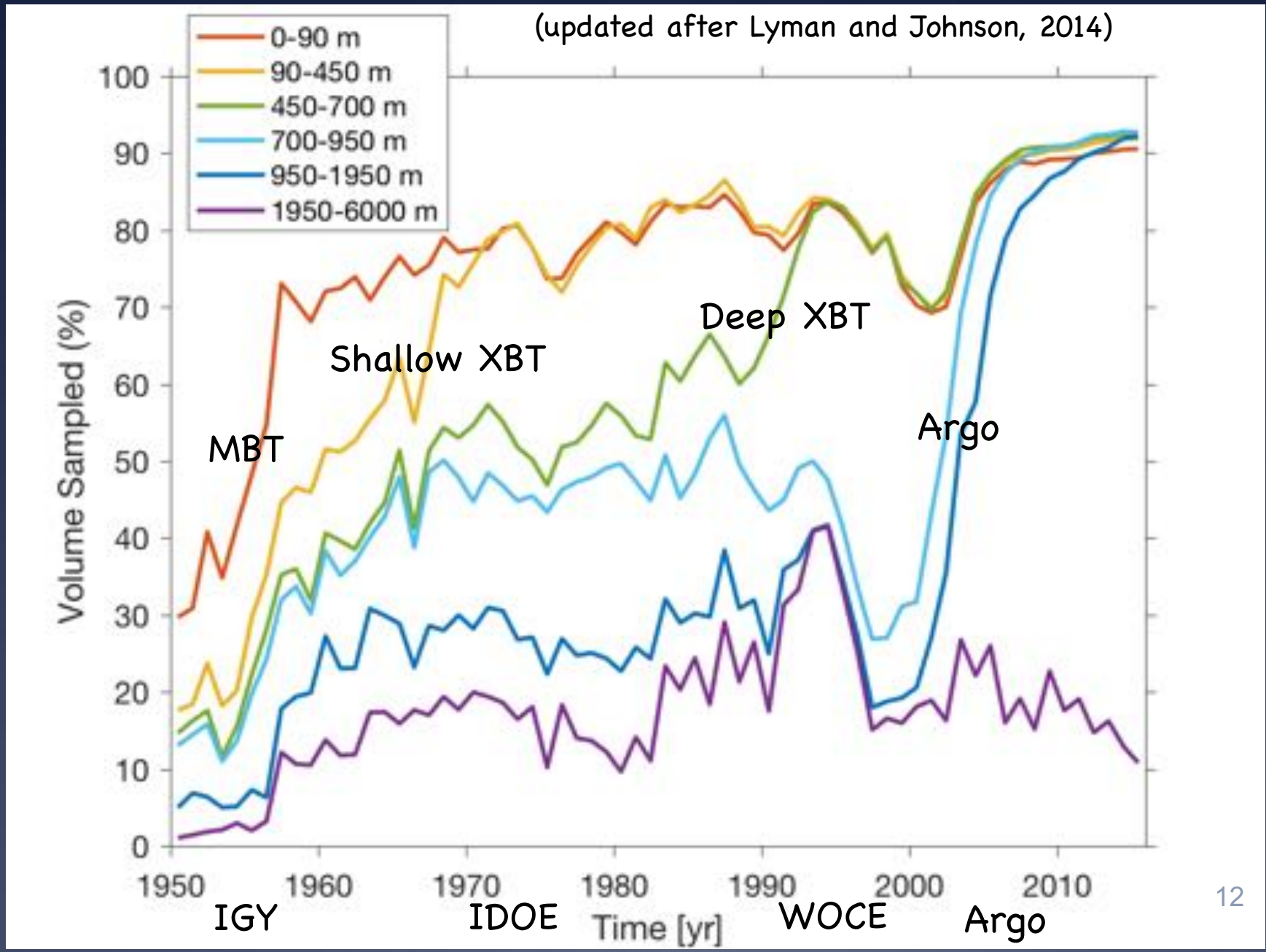
(Meyssignac et al. 2019)



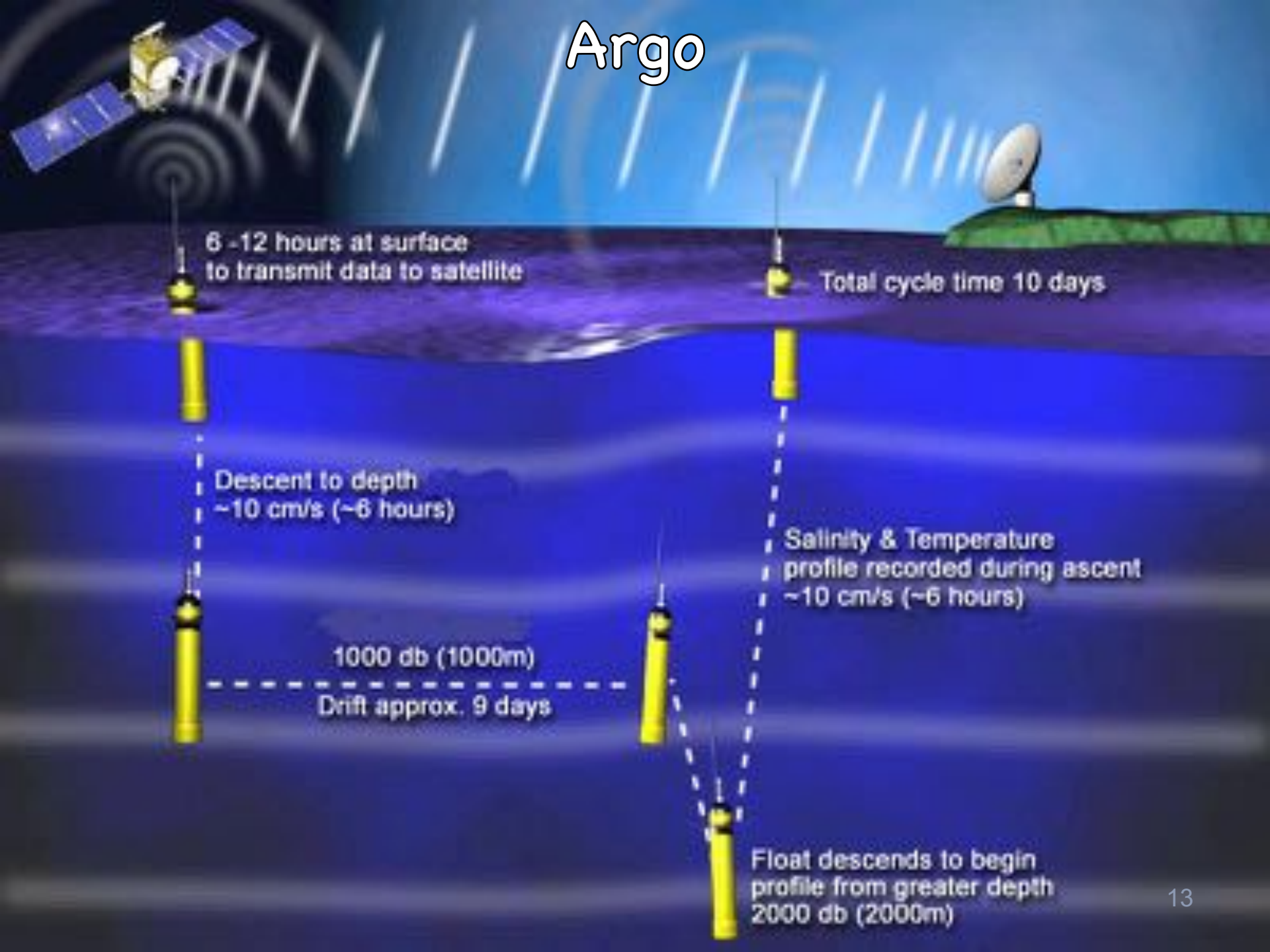
- Percentage of annual ocean coverage in 3° x 3° bins
- 0-2000 m really only covered since 2005 (Argo)

The Argo Revolution for Ocean Temperature and Salinity Data

Global Fraction of Ocean Sampled

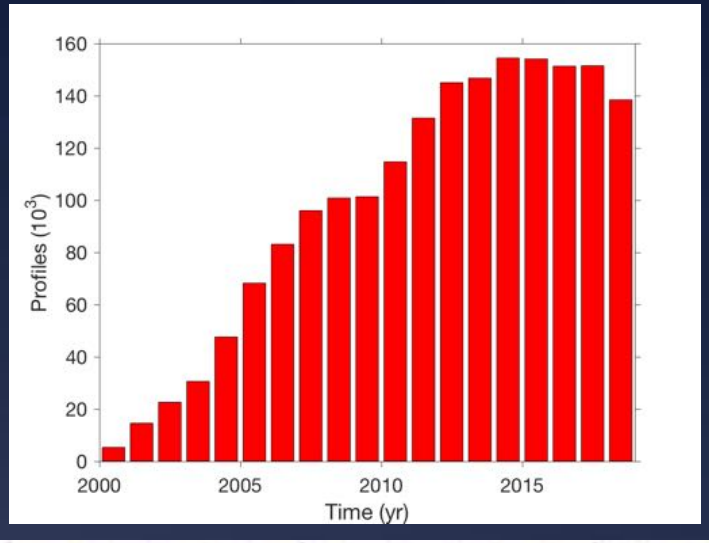


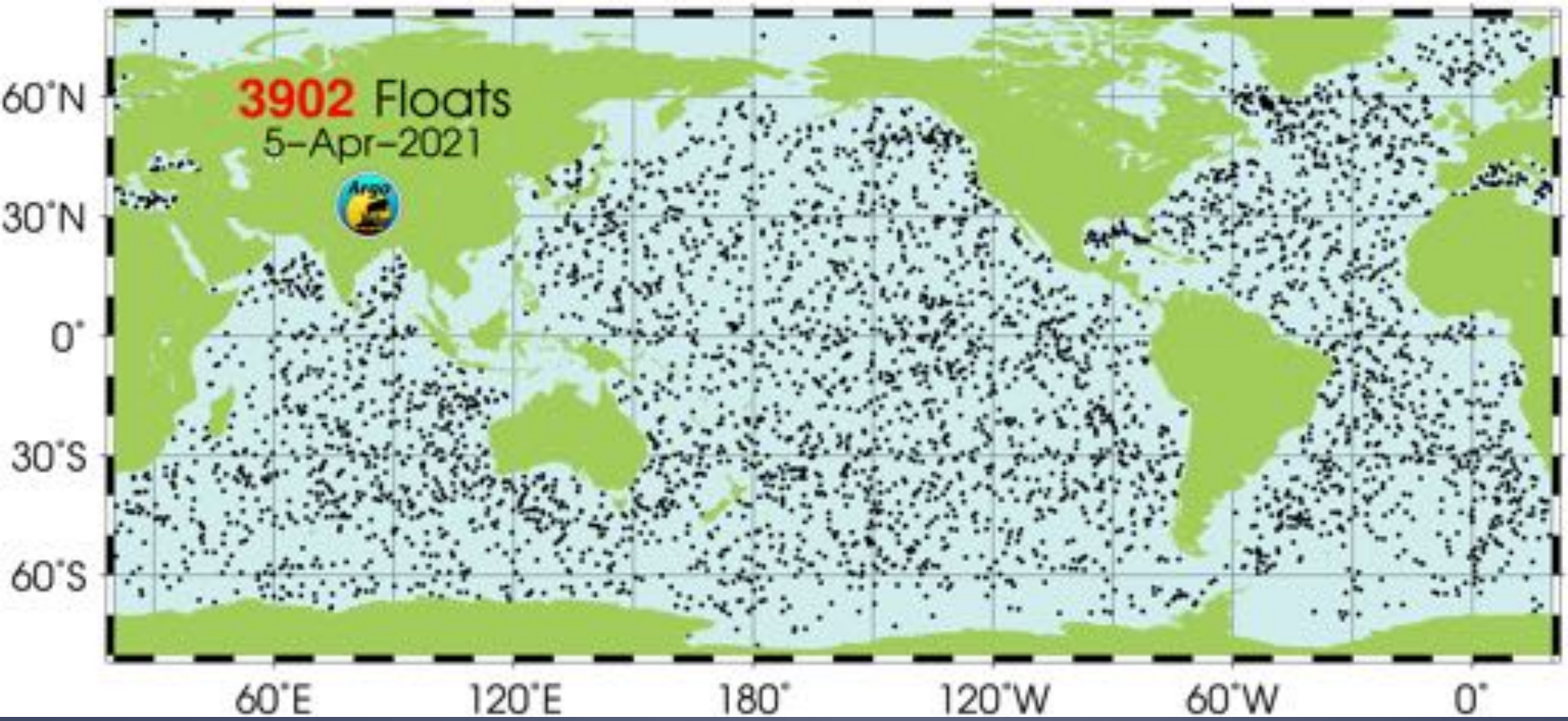
Argo


6 -12 hours at surface
to transmit data to satellite
Total cycle time 10 days
Descent to depth
~10 cm/s (~6 hours)
Salinity & Temperature
profile recorded during ascent
~10 cm/s (~6 hours)
1000 db (1000m)
Drift approx. 9 days
Float descends to begin
profile from greater depth
2000 db (2000m)

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

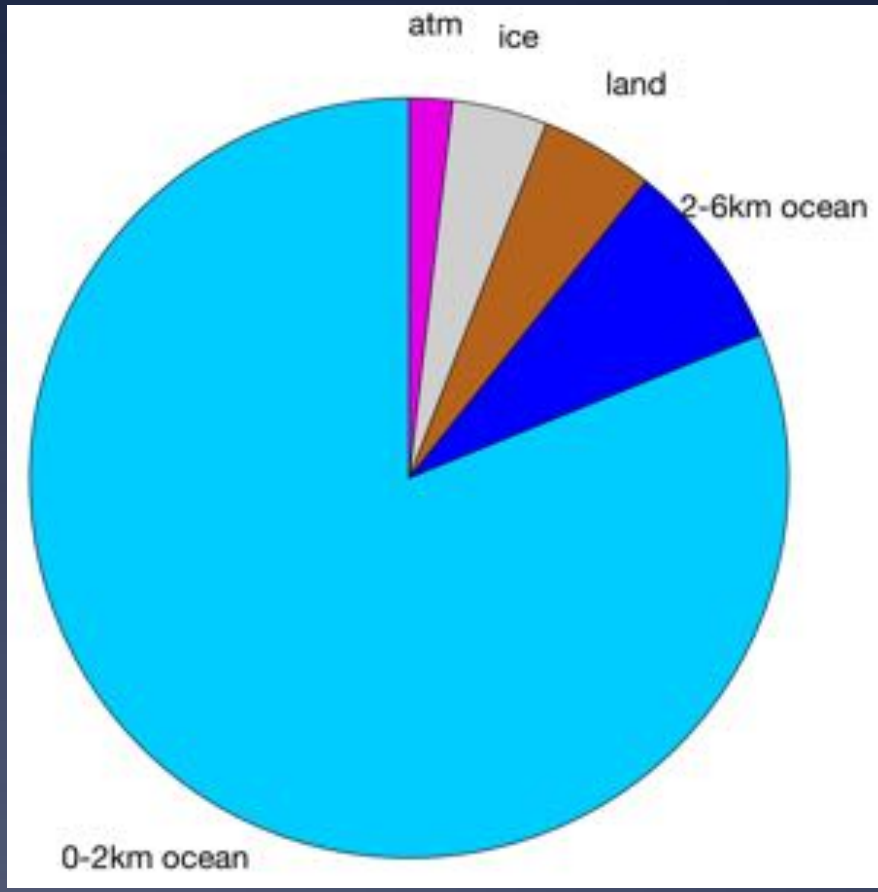




CERES-In Situ Comparison of Earth's Energy Uptake

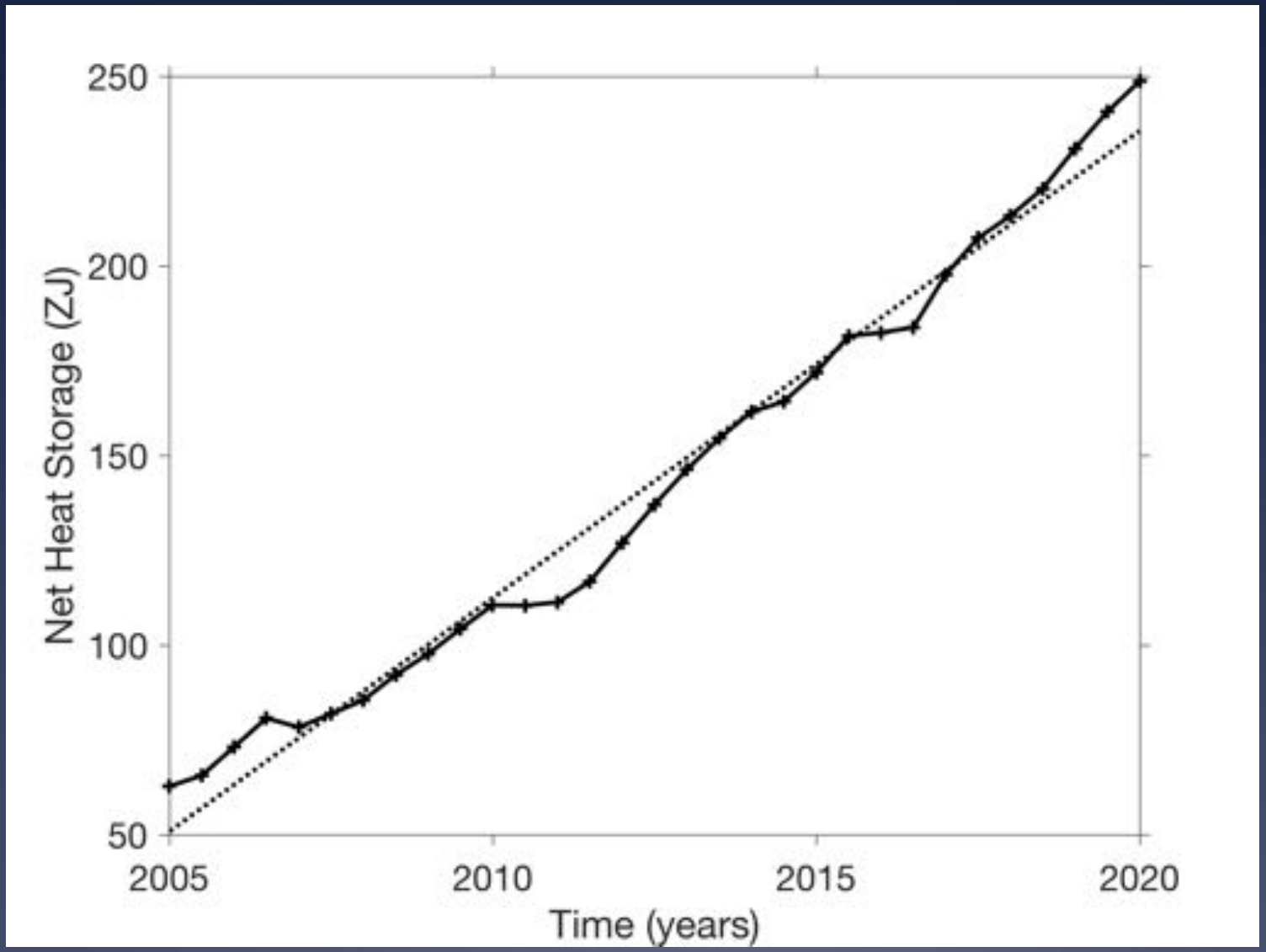
Thermal Energy Storage

- In situ observational anchor (trends):
  - Ocean 0–2 km:
  0.62±0.05 W m^{-2} (2005–2019)
  - Ocean 2–6 km:
  0.062±0.038 W m^{-2} (1992–2011)
  - Land:
  0.037±0.004 W m^{-2} (2005–2018)
  - Ice:
  0.031±0.006 W m^{-2} (2005–2016)
  - Atmosphere:
  0.014±0.009 W m^{-2} (2005–2018)
- Net trend: 0.77±0.06 W m^{-2} (2005 to 2019)



In situ "Anchor"

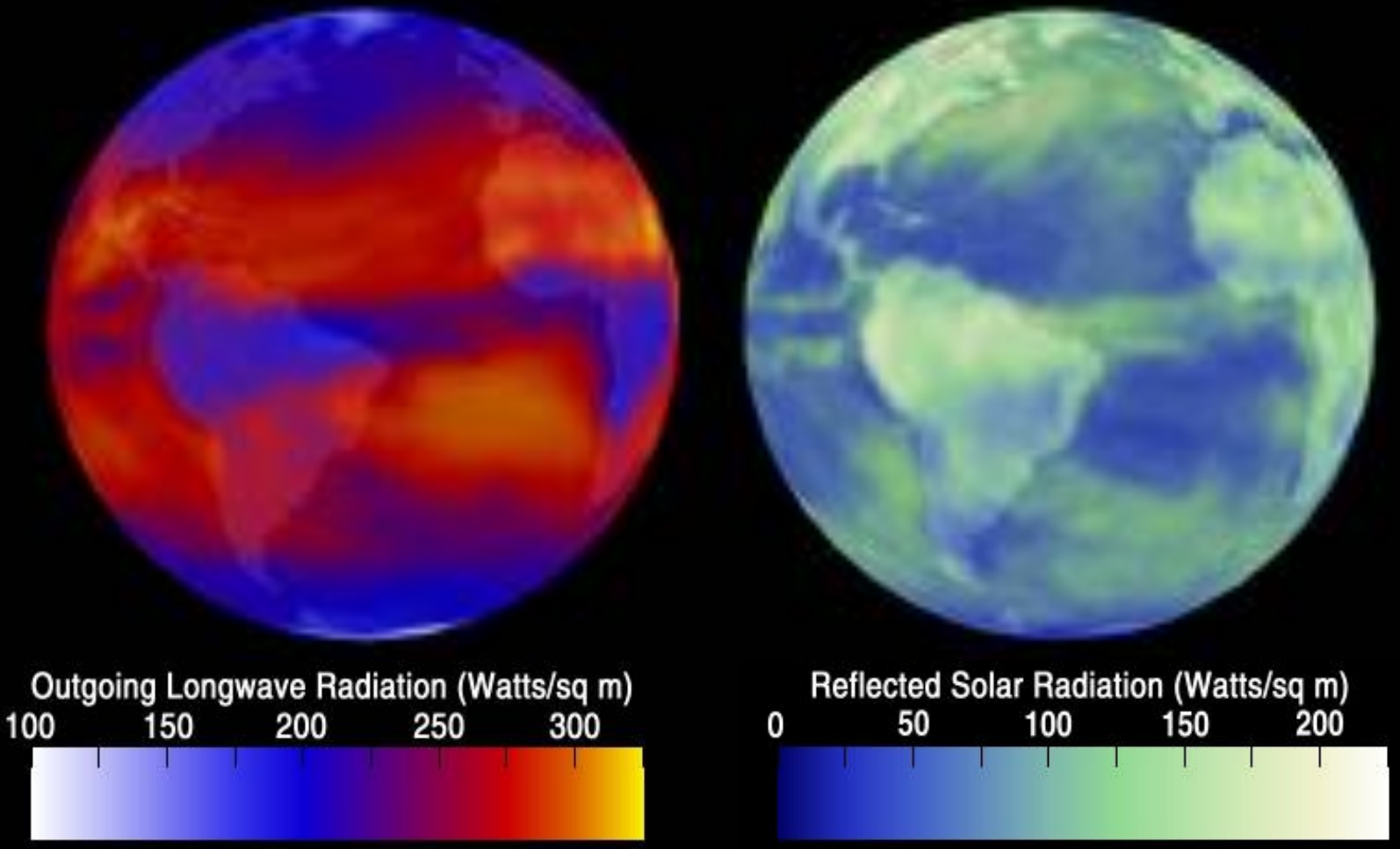
After Loeb et al. (submitted)



- Trend: 0.77 W m^{-2} with acceleration evident

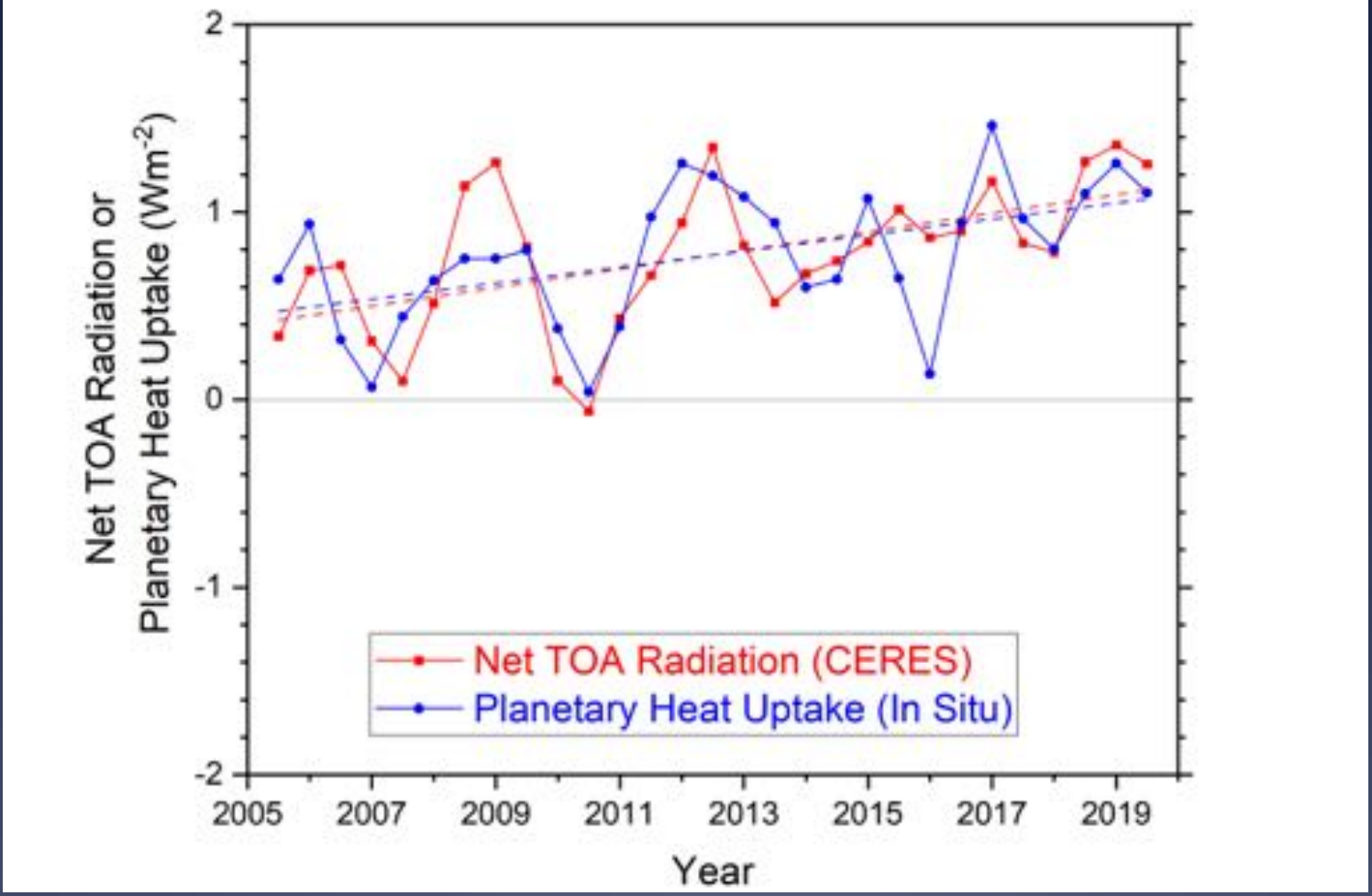
CERES

Satellite Top-of-Atmosphere (TOA) energy fluxes
Precise, but requires in situ anchor for accuracy



Earth's Energy Uptake Variations

After Loeb et al. (submitted)



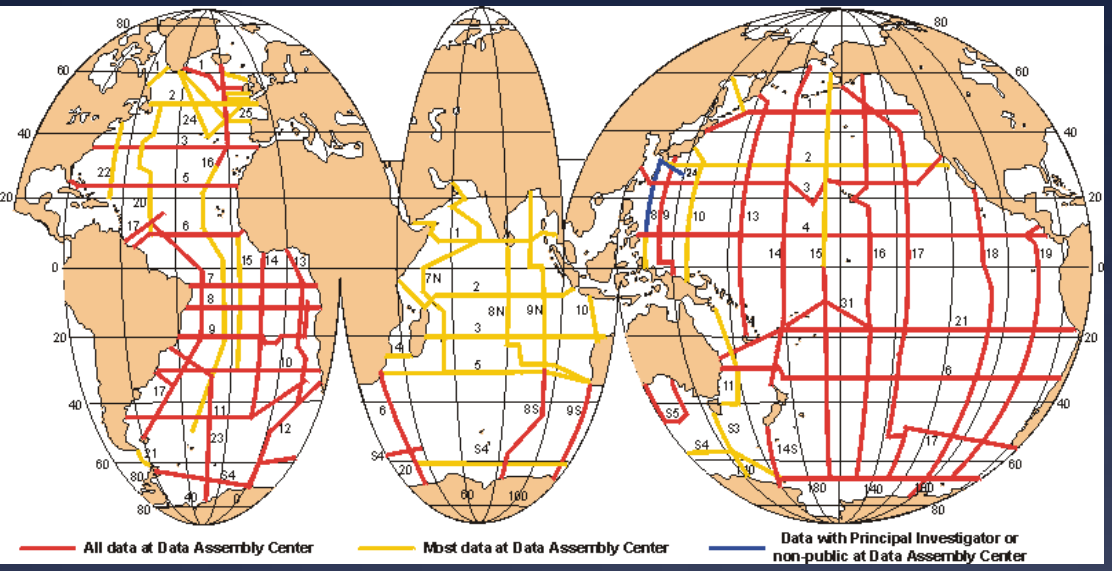
- In Situ 0.43±0.40 W m^{-2} $decade^{-1}$; CERES 0.50±0.47 W m^{-2} $decade^{-1}$
- Correlation coefficient 0.70

Conclusions

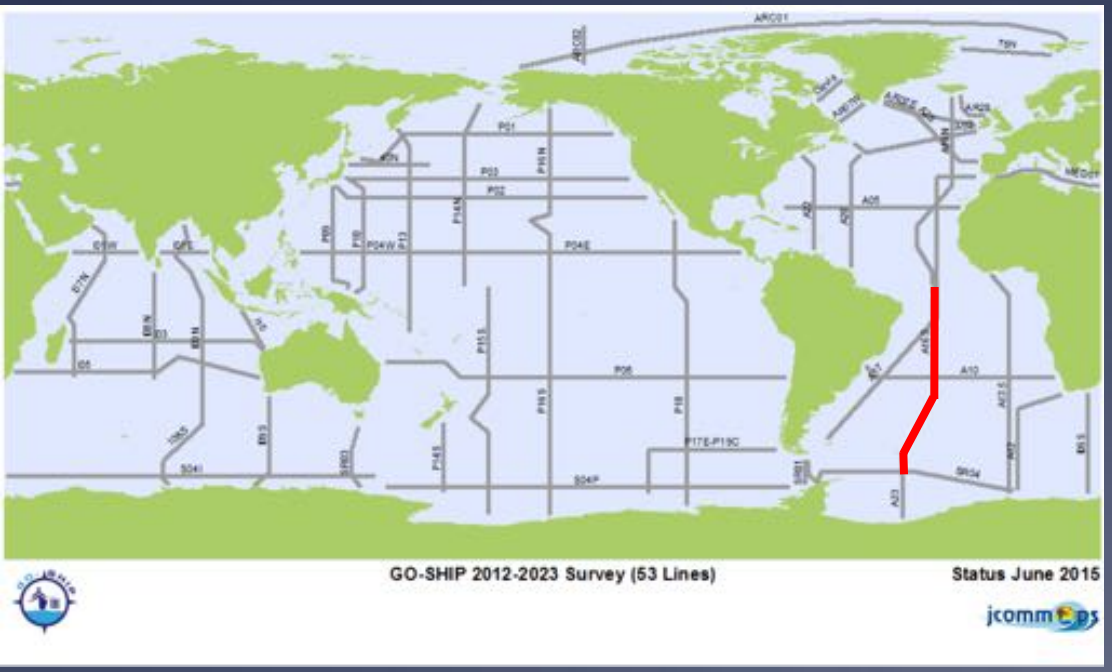
- Earth's Energy Imbalance is a (relatively) small difference of big numbers
- Best quantified by changes in reservoirs of heat (9/10ths ocean warming)
- Sparse sampling and instrument biases are issues for global ocean heat content estimates in the pre-Argo record
- About 15 years of Argo data greatly reduces ocean heat storage uncertainties on annual time scales
- Two complementary but independent measurement systems (CERES and Argo) show correlated interannual variations in Earth's energy storage!
- They both find a statistically significant, and similar acceleration in the warming rate, with approximate doubling from 2005–2019.

Deep Argo

Deep Ocean Sampling: WOCE & GO-SHIP



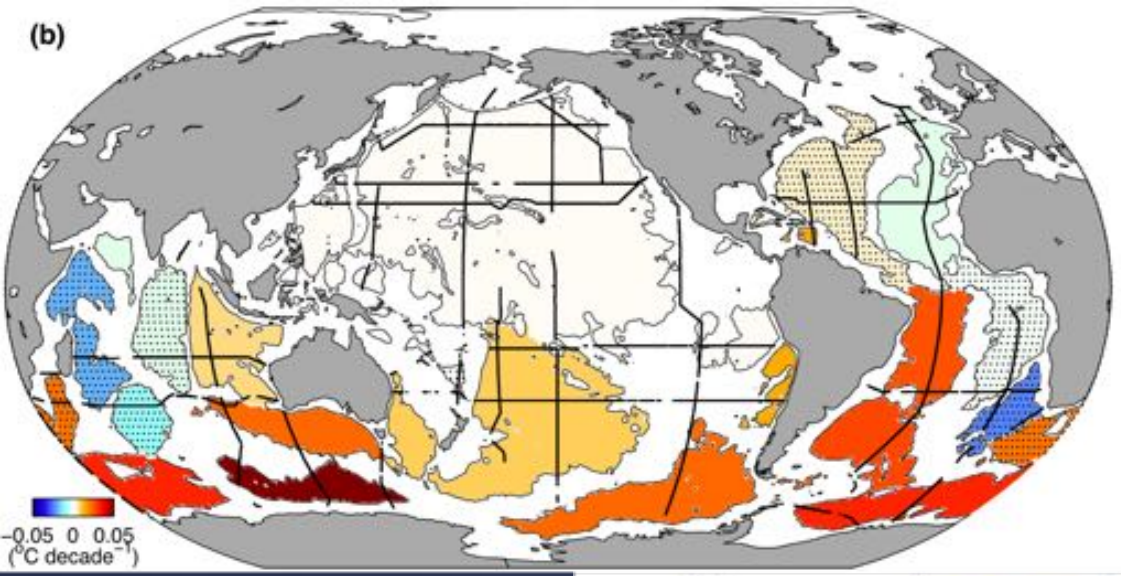
- WOCE: 1990s accurate ocean climate baseline
- Monumental int'l effort
- Full depth, transocean
- Temp. ±0.002° C
- Salinity ±0.003 PSS-78
- Many other parameters



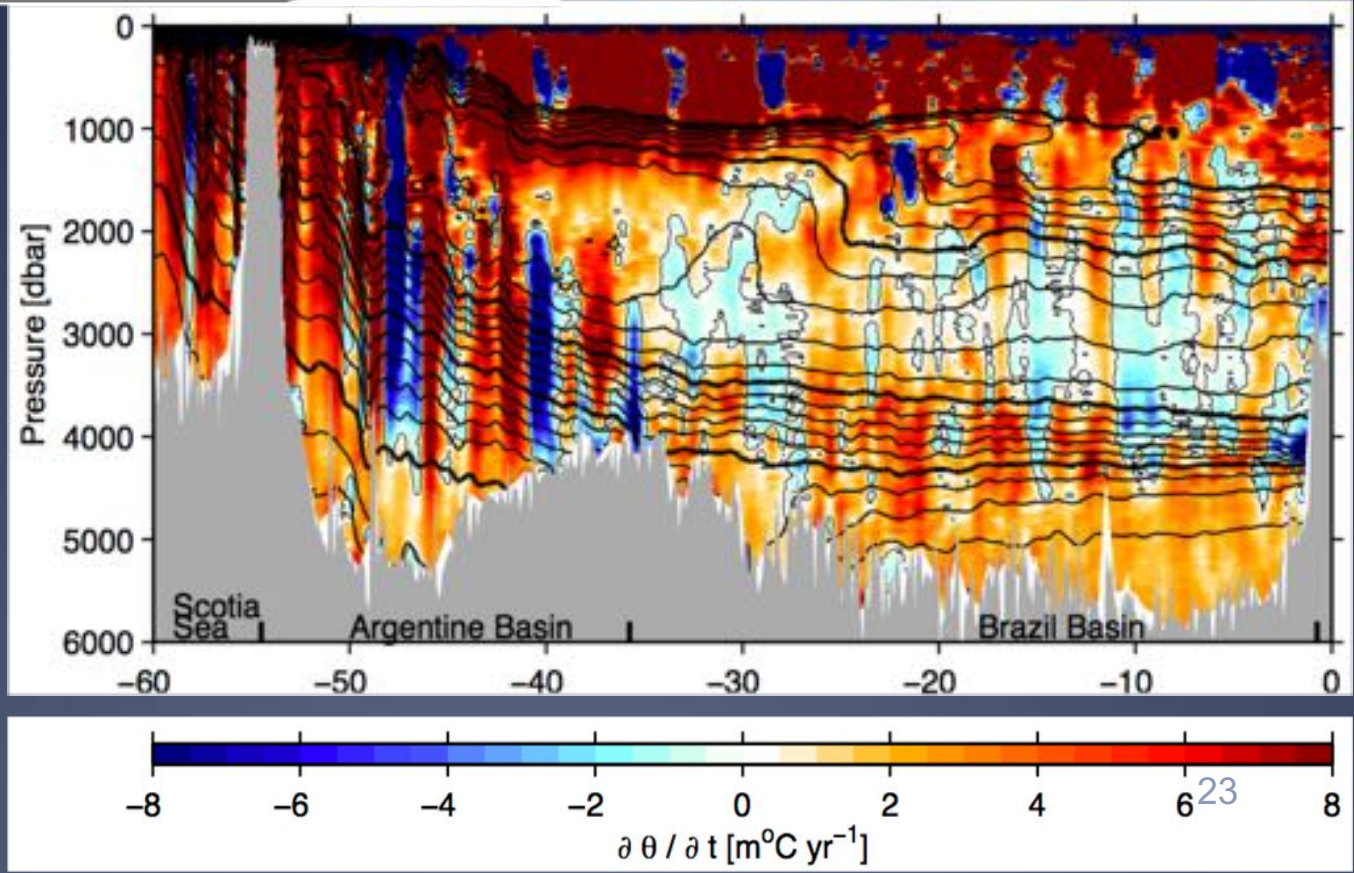
- Decadal resurveys:
- CLIVAR/CO_2(1999–2012)
- GO-SHIP (2012–2023)
- Key sections cross major deep basins
- T ±0.001° C
- S ±0.003
- Ongoing effort

Observed Deep Ocean Warming

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



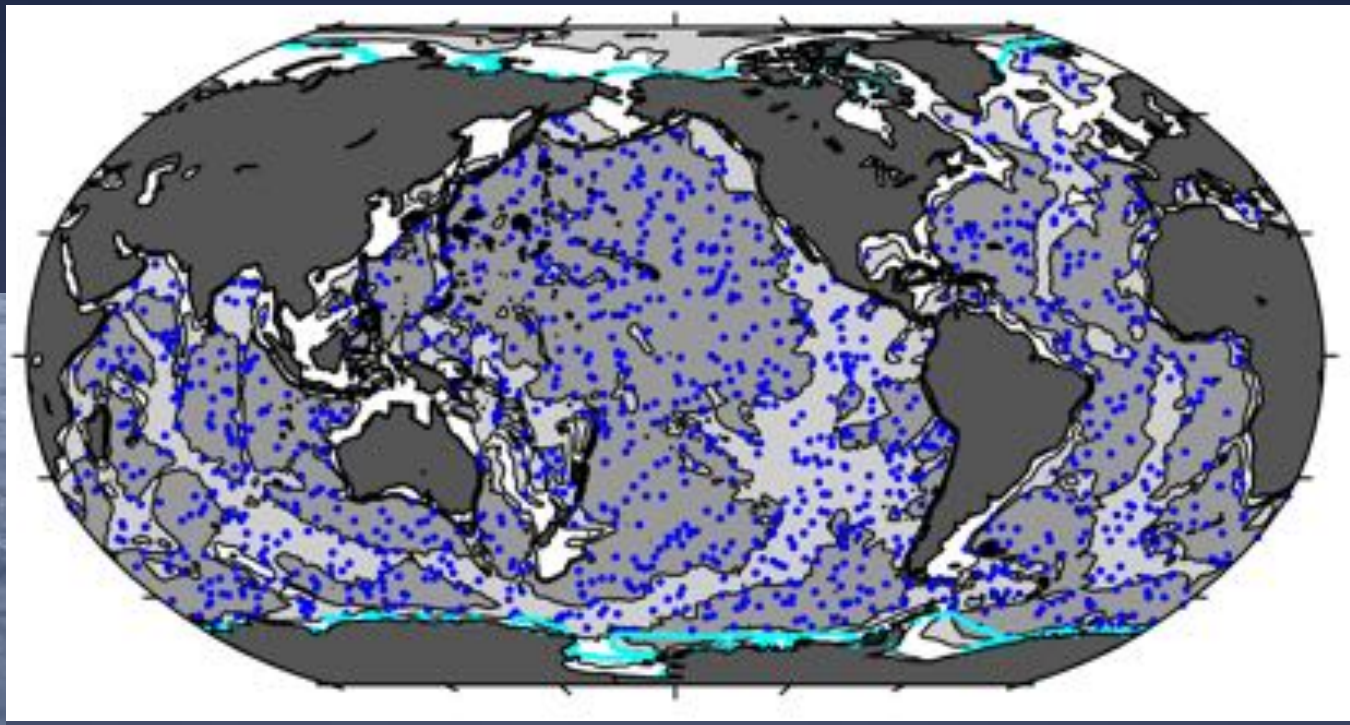
After Purkey & Johnson (2010)



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

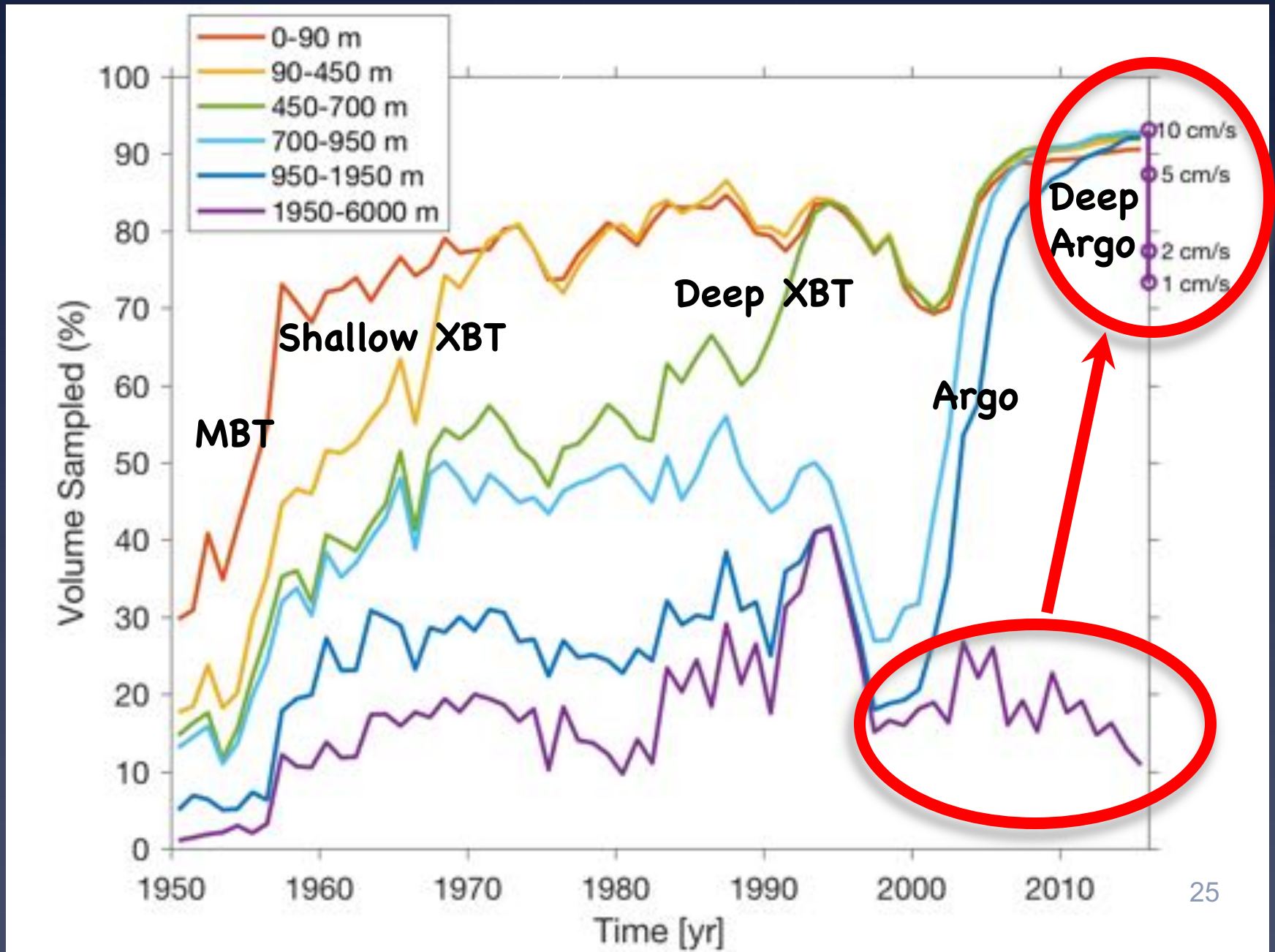
Informing Deep Argo array design using Argo and full-depth hydrographic section data

(Johnson, Lyman, & Purkey; 2015)
doi:10.1175/JTECH-D-15-0139.1

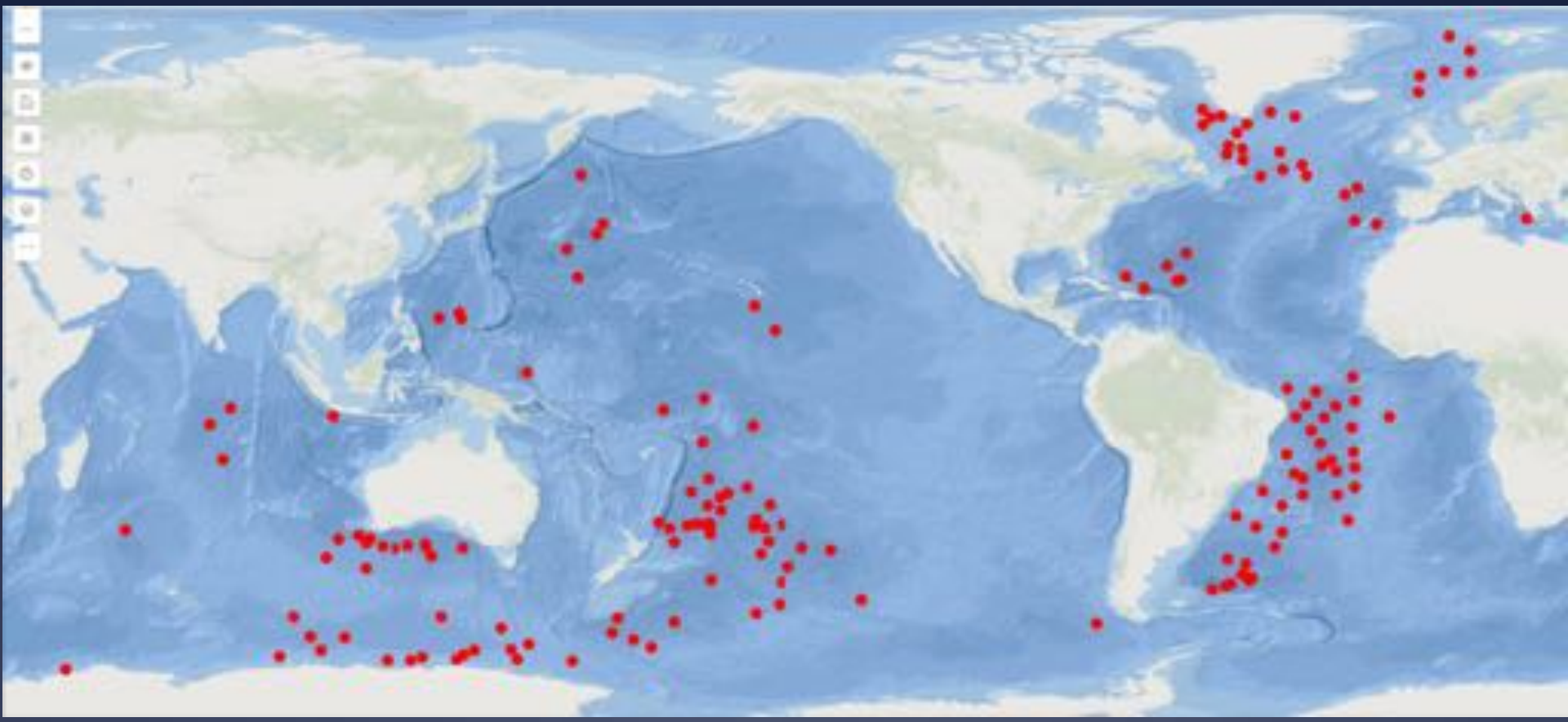


- 1228 floats
- 10-day cycles
- 0-6000 m high-quality profiles
- Reduce uncertainties of decadal heat gain over ***5-fold***
- Allow continual assessments of deep ocean changes

Ocean Sampling: Deep Argo Impact



Deep Argo Status: March 2021



- 162 Deep floats operational in regional pilot arrays
- Still working to raise funding for a global array