The Deep Ocean's Contribution to the Warming Hiatus

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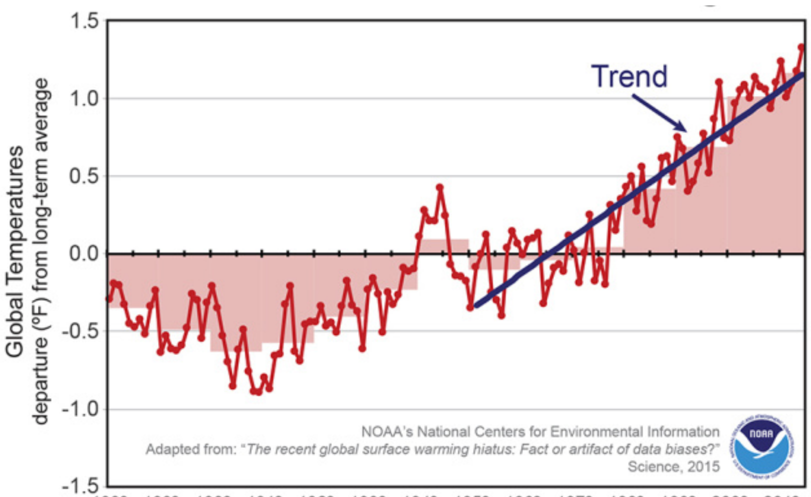
Outline:

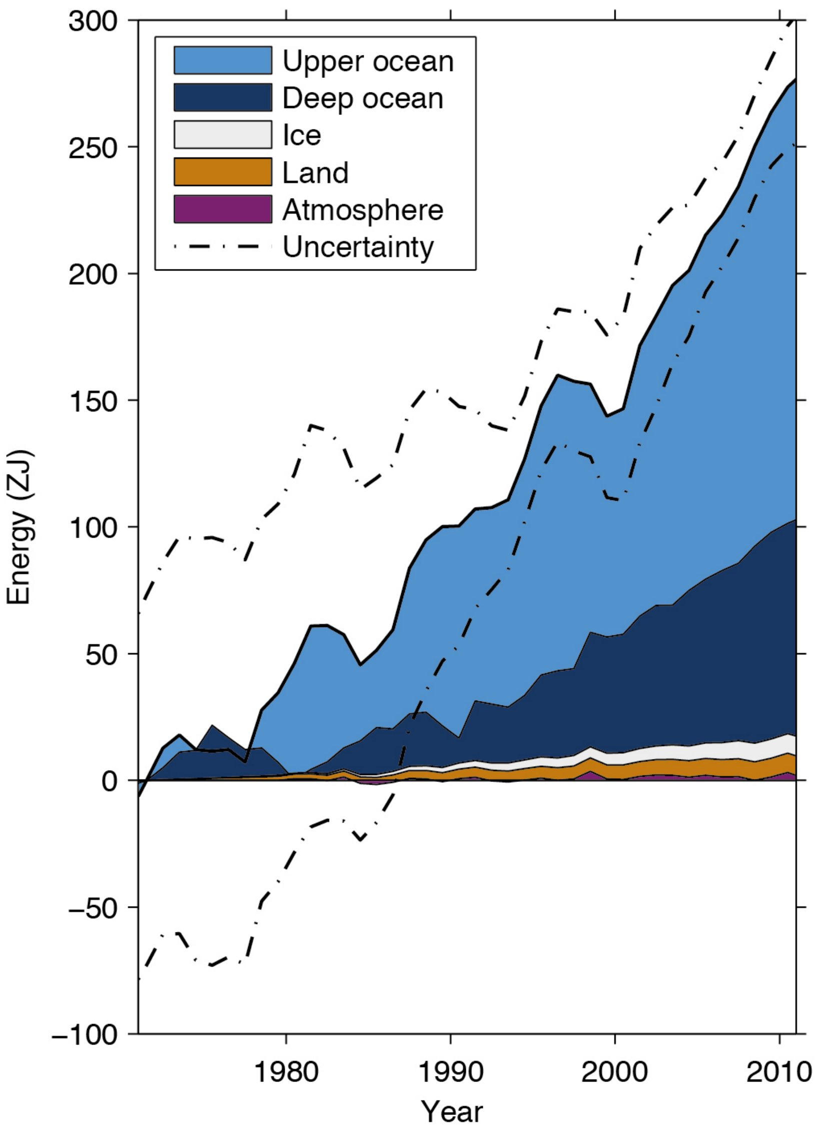
- How we know what we know: deep ocean data
- Deep ocean temperature trends since the 1990s
- The deep ocean does not appear to be contributing to the recent warming hiatus

Introduction: Global heat budget



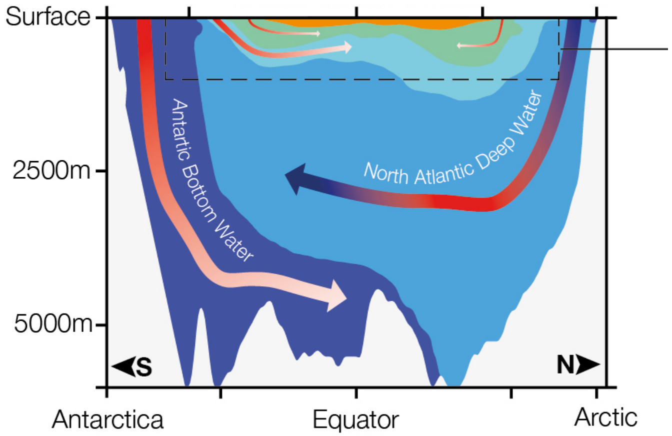
Contrary to much recent discussion, the latest corrected analysis shows that the rate of global warming has continued, and there has been no slow down.

- The global mean surface temperature trend has slowed since the early 2000s, often referred to as a 'Warming Hiatus'
- 93% of the anthropogenic warming goes into the ocean
- Therefore, accurately quantifying total ocean heat content is important for monitoring the global heat budget



(Rhein et al. 2013)

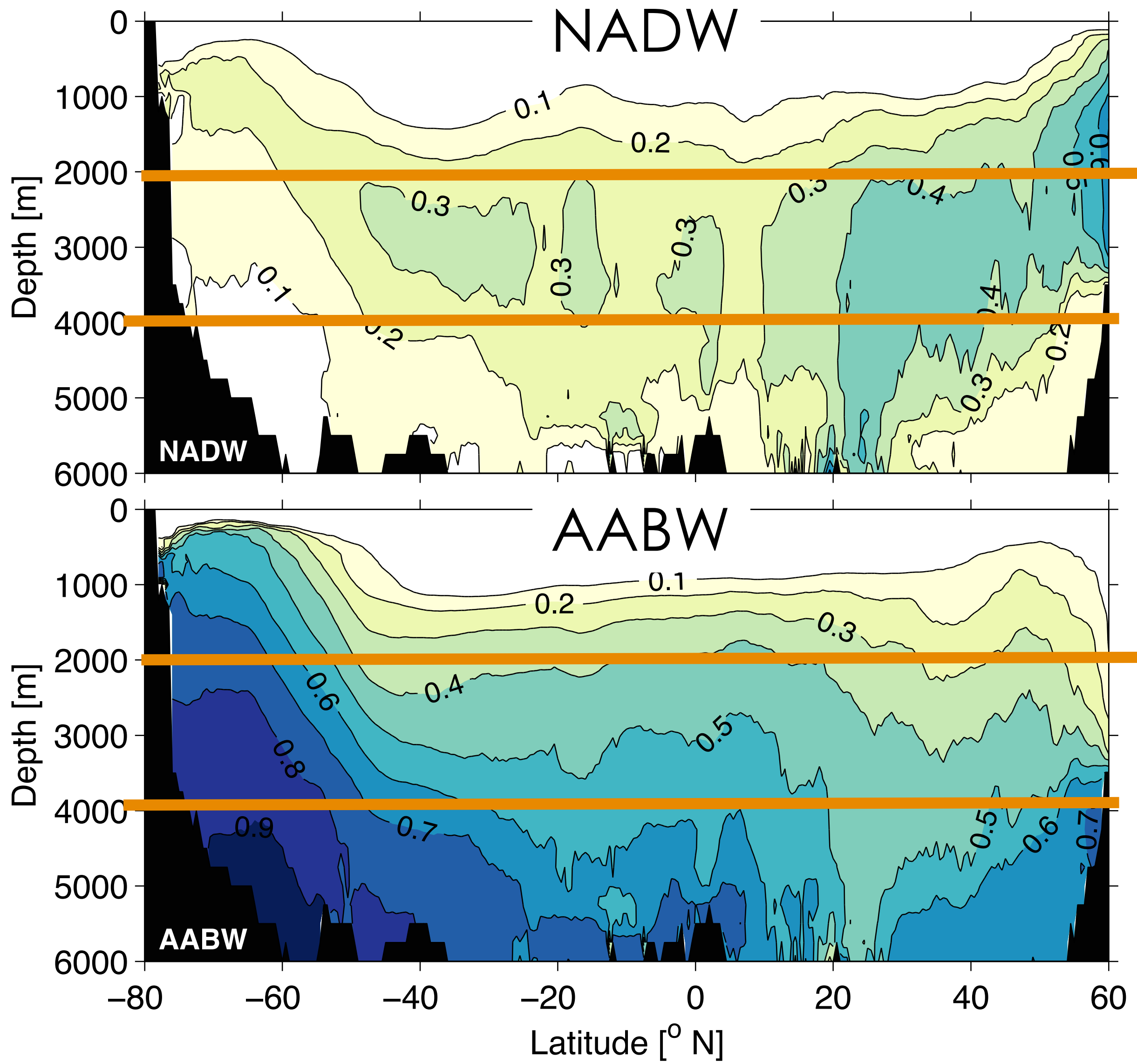
Introduction: The deep and abyssal ocean



(Rhein et al. 2013)

- The deep (below 2000m) and abyssal (below 4000m) are filled with dense waters formed at high latitudes

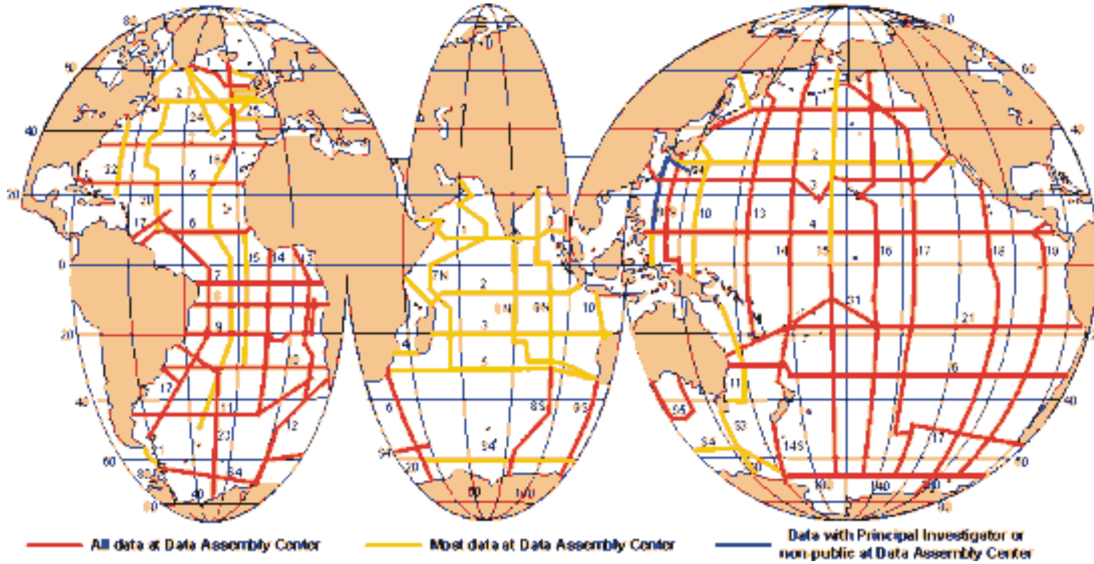
- Climatology shows filled by two water masses: North Atlantic Deep Water and Antarctic Bottom Water

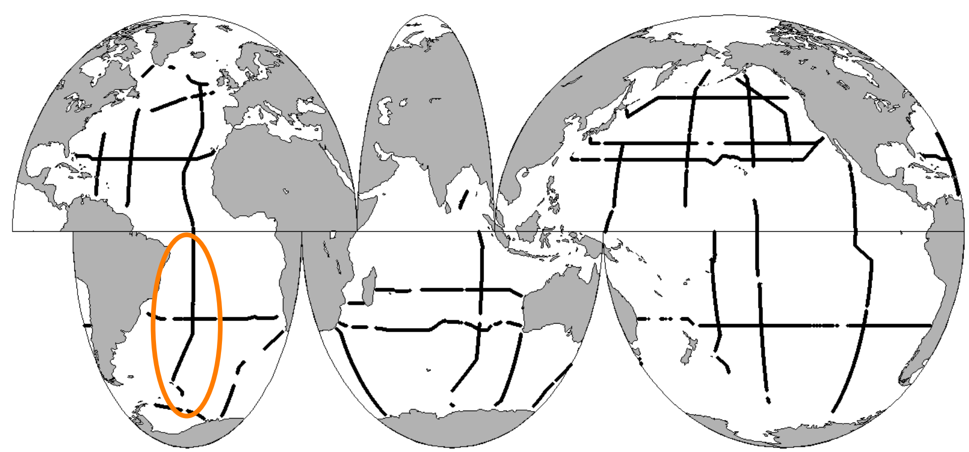


(Johnson, 2008)

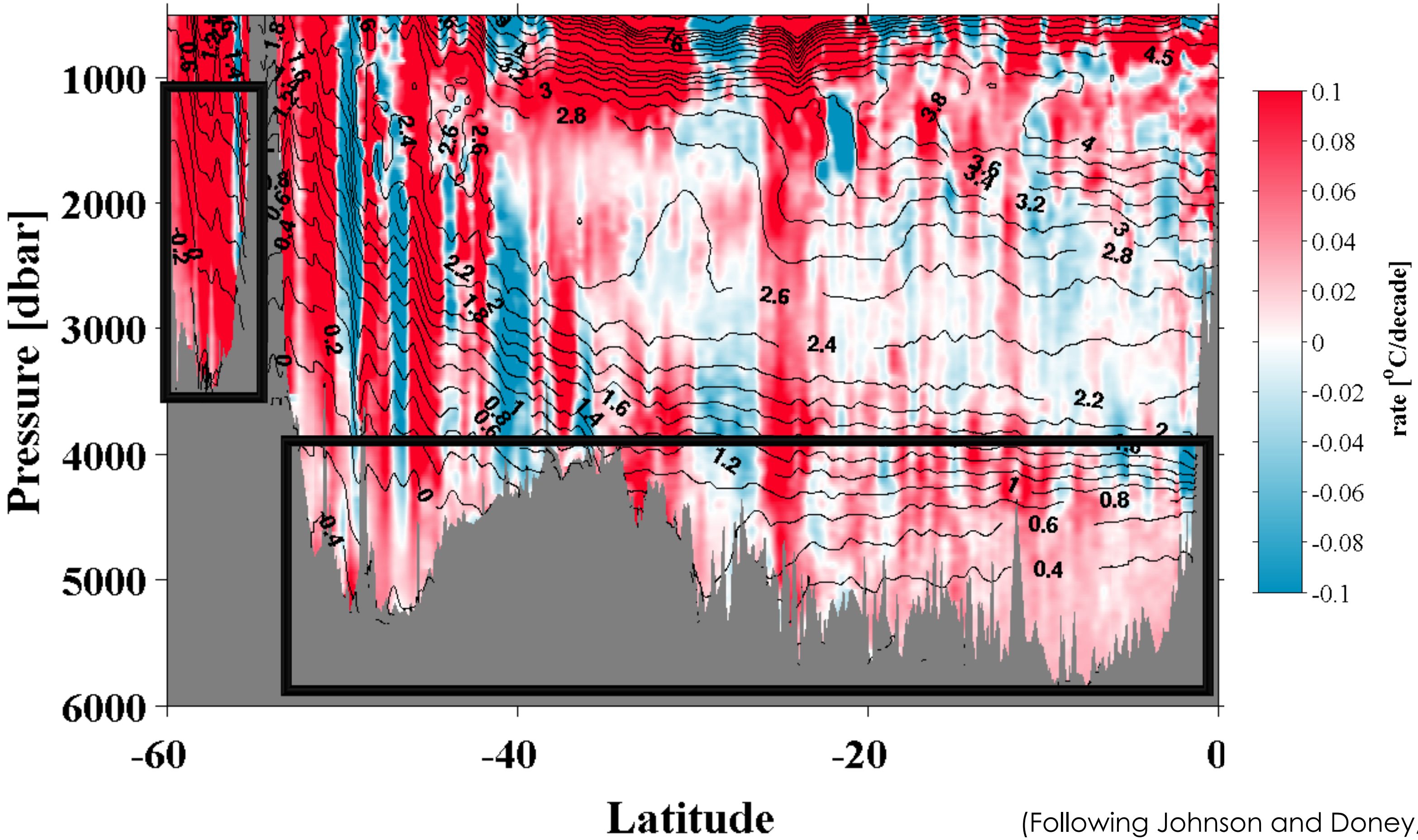
Deep ocean data: Go-Ship

- Deep ocean observations are mostly limited to ship based hydrography work
- World Ocean Circulation Experiment (WOCE):
  - Full depth, highly accurate temperature (0.001 °C) and salinity (0.003), bottom to top oceanographic survey in the1990s
- Go-Ship: CLIVAR and CO_2 repeat hydrography:
  - Repeated a key subset of these sections allowing for estimates of deep changes in temperature/ salinity in time





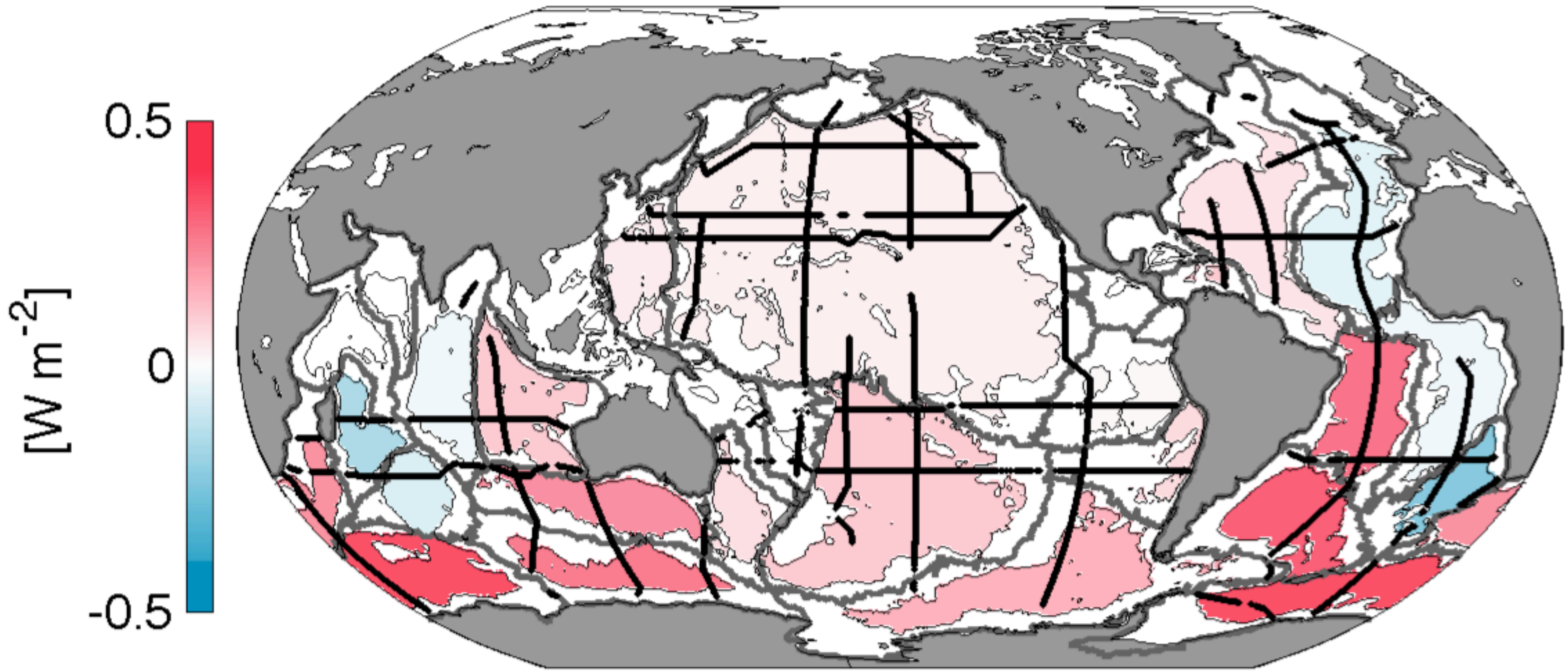
Deep ocean trends: A16S



(Following Johnson and Doney, 2006)

- Repeat sections show warming (red) throughout the deep Southern Ocean and abyssal global ocean
- E.g. Difference in temperature along A16 between 1989/1995 and 2005/2003

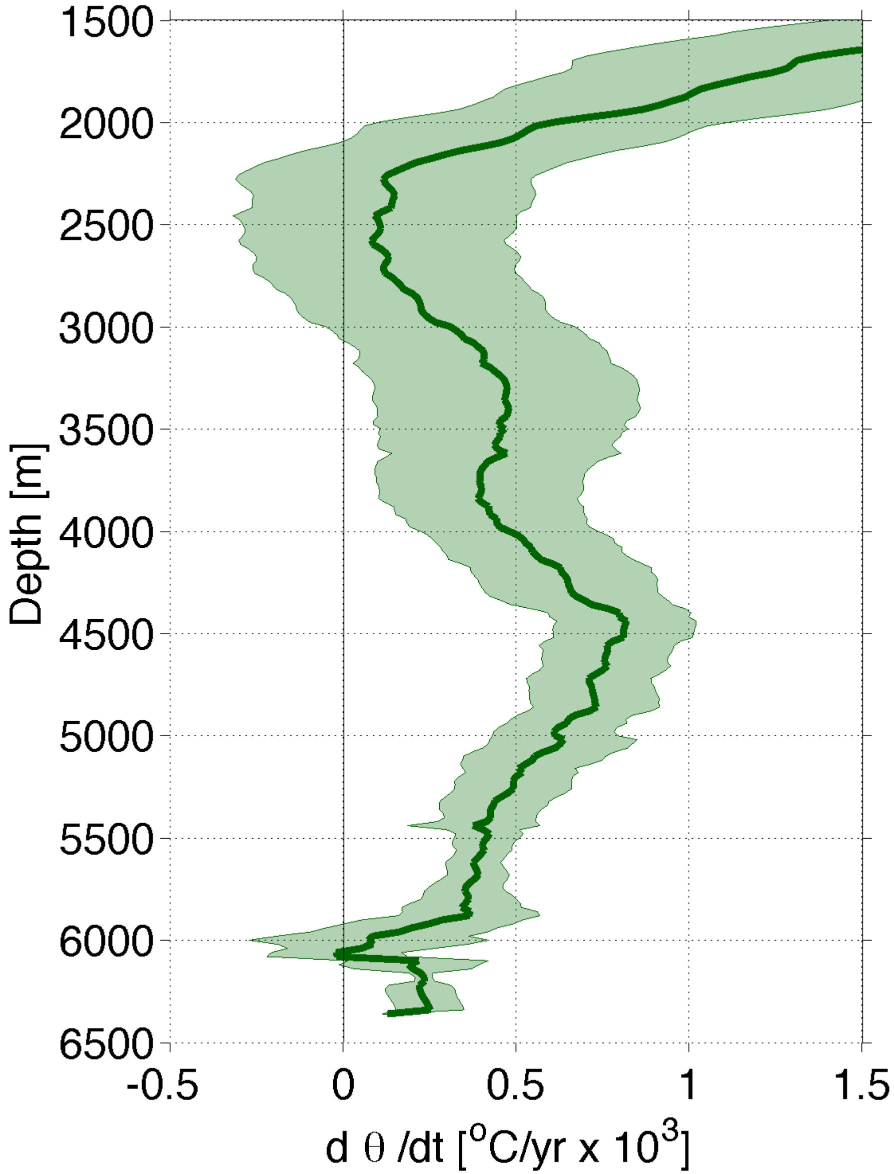
Deep ocean warming trends: 1992-2005



(Purkey & Johnson 2010)

- Using all repeat sections within a basin, find basin mean temperature trend below 4000 m centered between 1992 and 2005
- Most trends are significant at the 95% confidence level
- Southern intensified warming, with a weak, but detectable, warming signal to the north

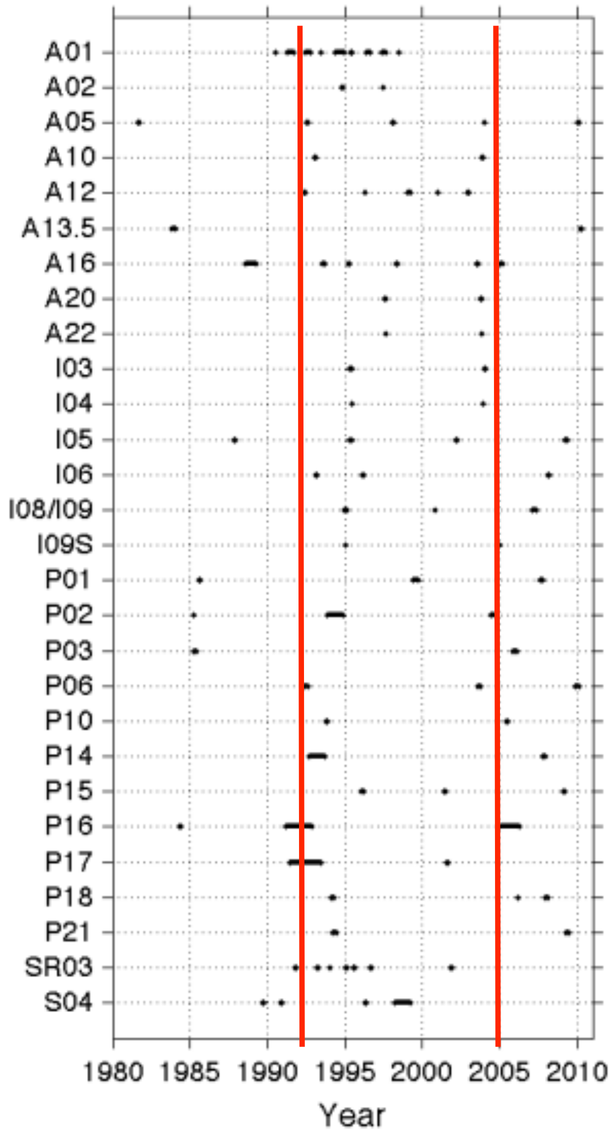
Deep ocean warming trends: 1992-2005



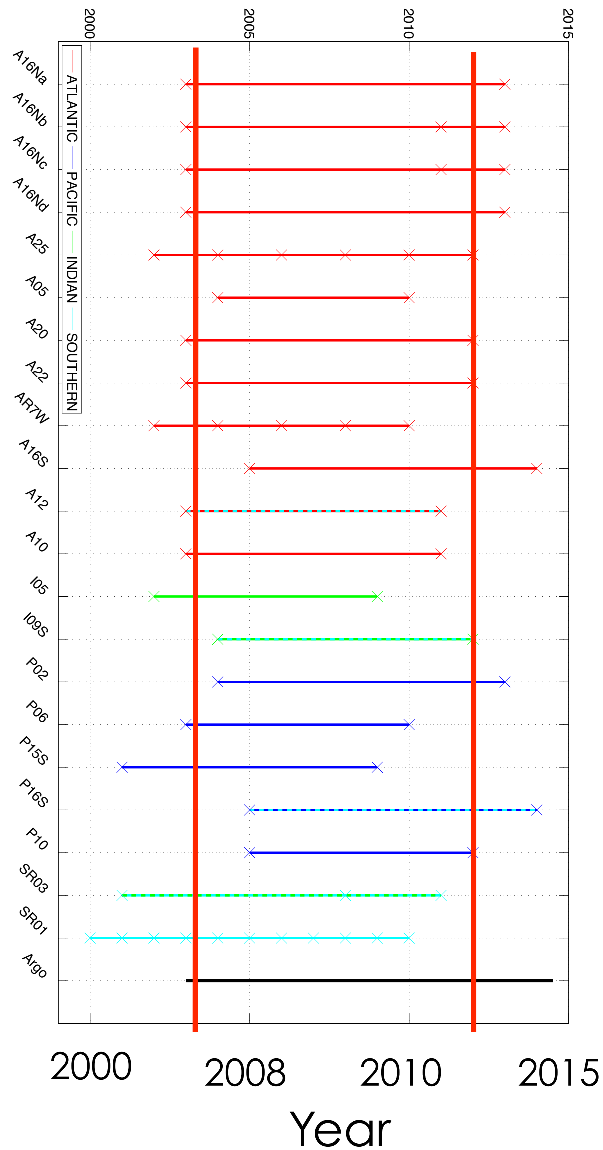
- The abyssal ocean is warming below 4000 m at an average rate 5 °mC decade^{-1}
- The Southern Ocean is warming much faster through out the water column, at a mean rate of 30 °mC decade^{-1} below 1000 m
- Warming accounts for an increase in ocean heat storage of 0.027 W m^{-2} below 4000 m and 0.07 W m below 2000 m

(Purkey & Johnson 2010)

Temporal variability: The warming hiatus



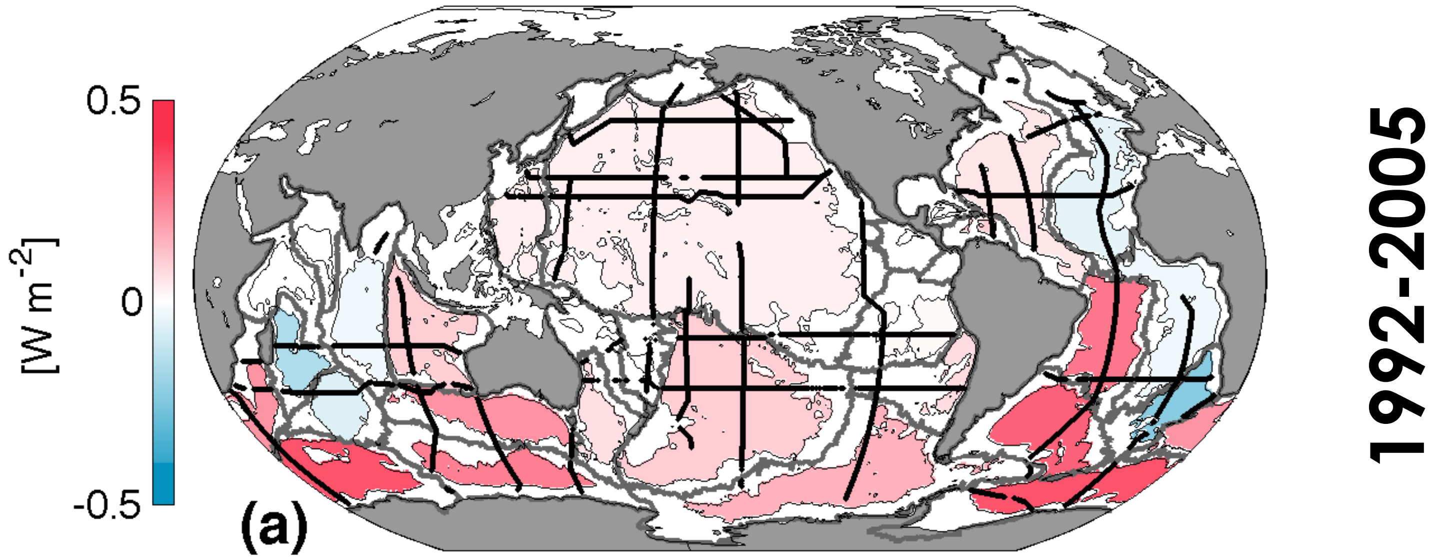
(Purkey and Johnson 2010)



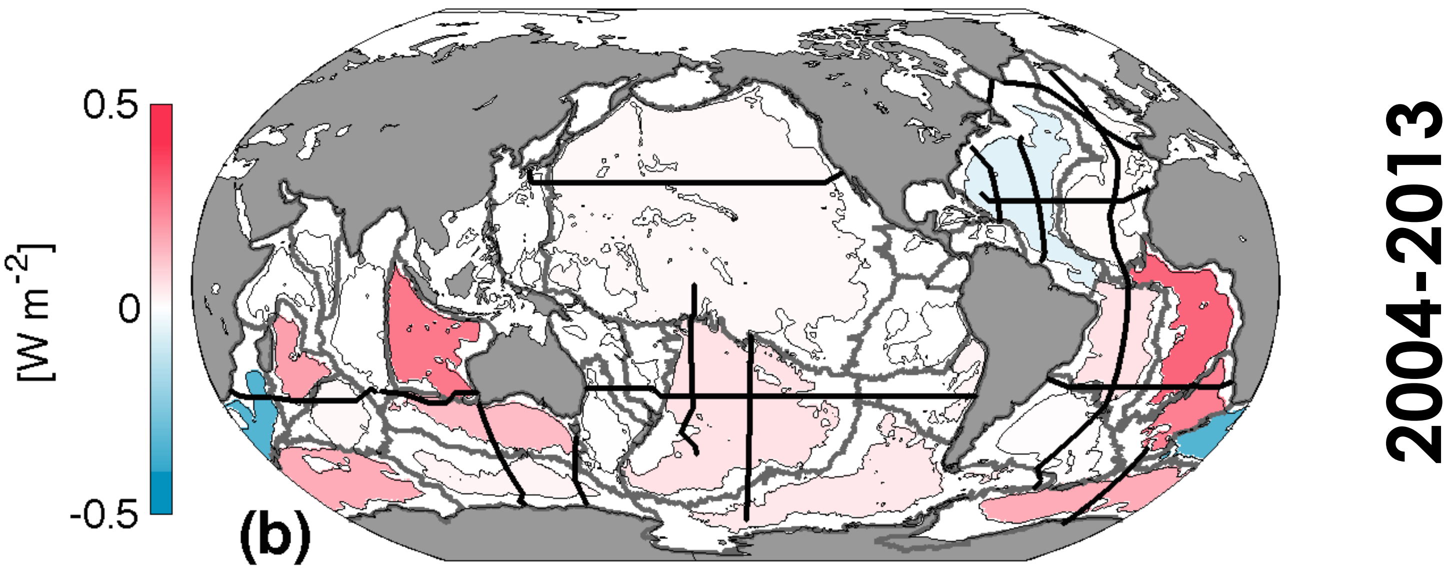
(Desbruyeres et al, *in prep*)

- Sparse temporal coverage allows for linear trends at best, centered between1992 and 2005
- Using only the most recent data, can compare data collected between 1981-2010 period (centered between 1993-2005) to data collected between 2001-2015 period (centered between 2004-2013)

Temporal variability: The warming hiatus

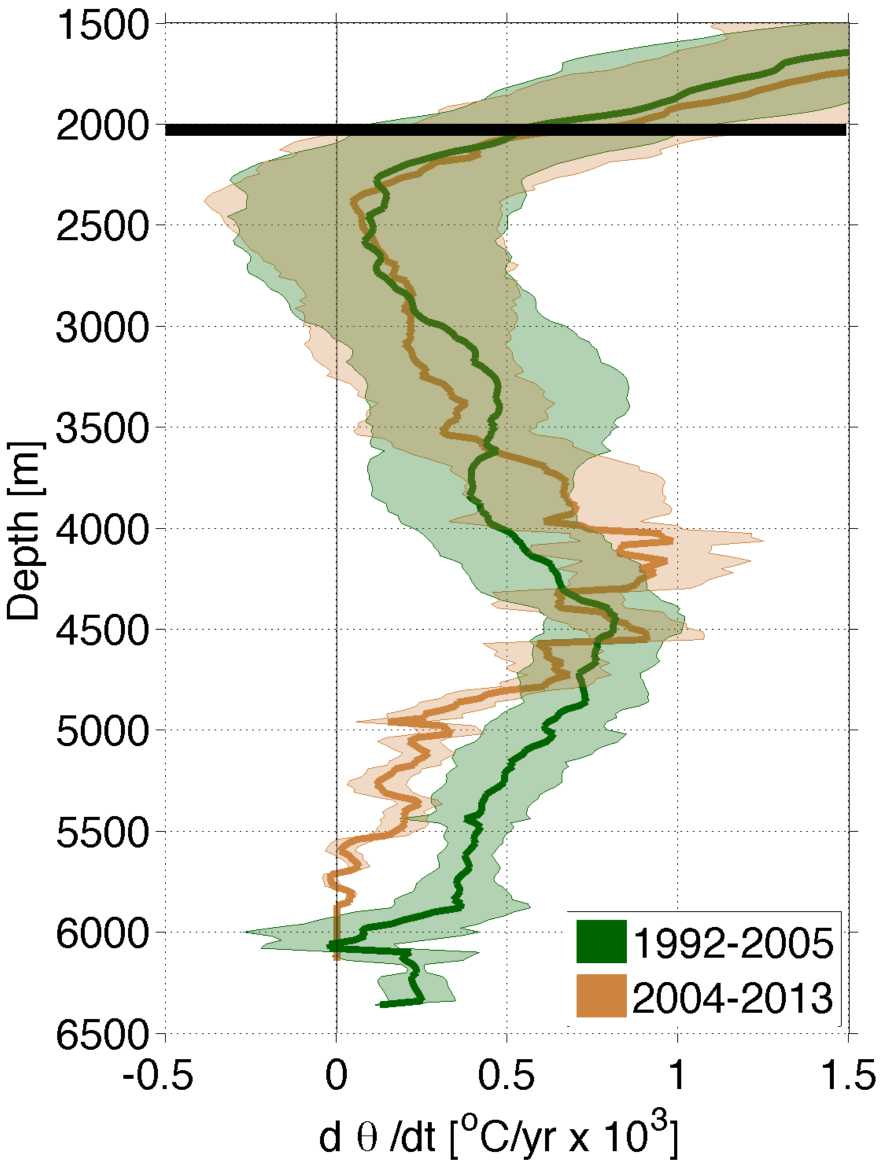


(Purkey and Johnson 2010)



(Desbruyeres et al, *in prep*)

Temporal variability: The warming hiatus

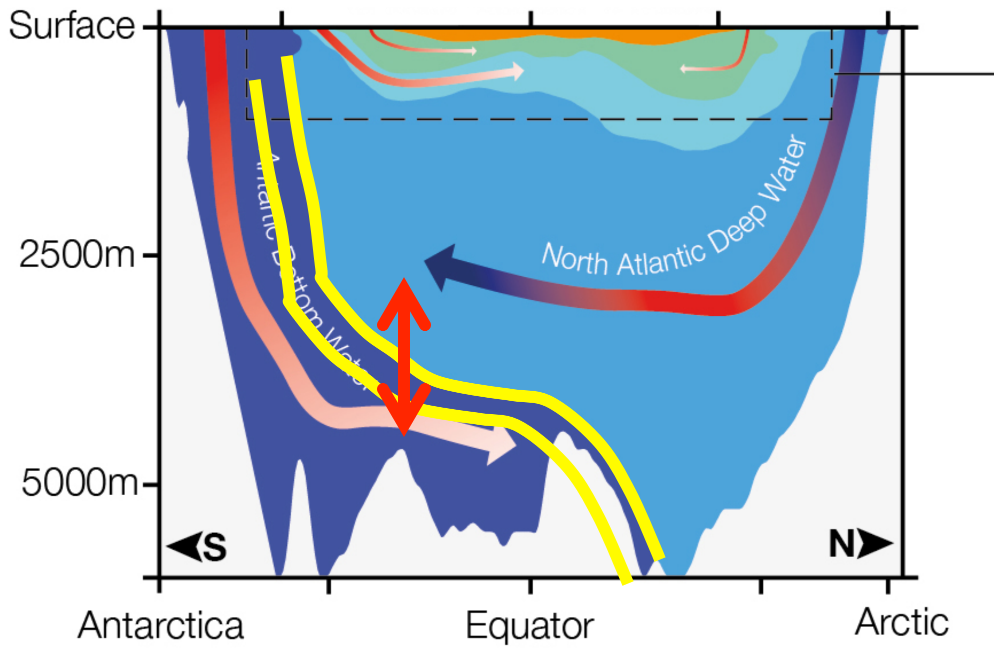


(Purkey and Johnson 2010 and Desbruyeres et al, *in prep)*

- The global mean warming rate [°C/yr]: 1992-2005 vs 2004-2013
- Abyssal ocean warming rate over the 1990s – 2000s has decreased between 2000s–2010s
- Both periods show the deep ocean heat content below 2000 m is increasing at a rate of 0.07 ± 0.06 W m^{-2}
- No evidence of an increase in the rate of deep warming over the hiatus period

Temporal variability: Cause?

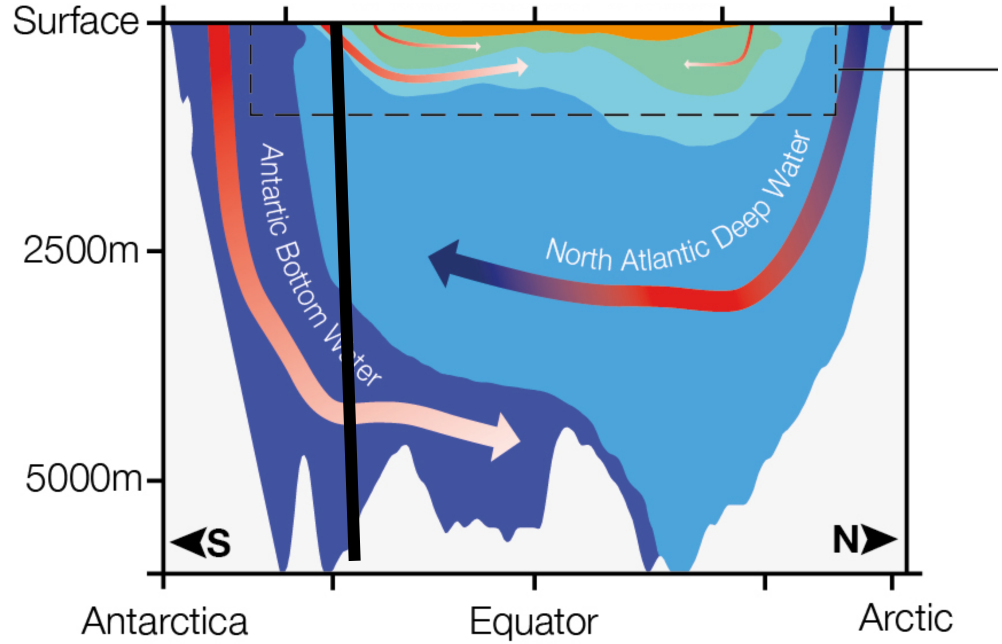
- Deep ocean heat content can be change either by advection or by isotherm heave



(Rhein et al. 2013)

Temporal variability: Cause?

- Deep ocean heat content can be change either by advection or by isotherm heave
- Observations show deep ocean warming is driven primarily by isotherm heave



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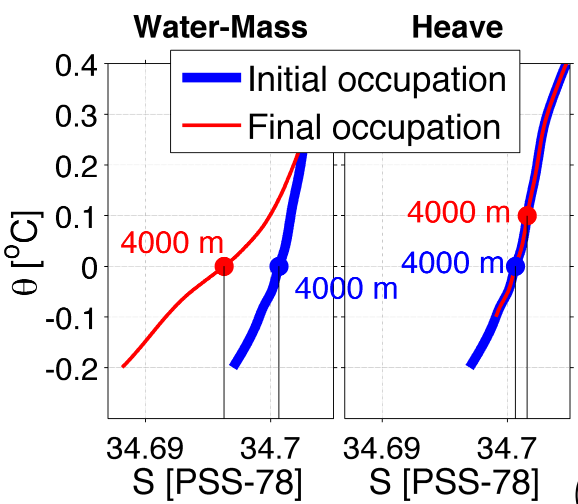
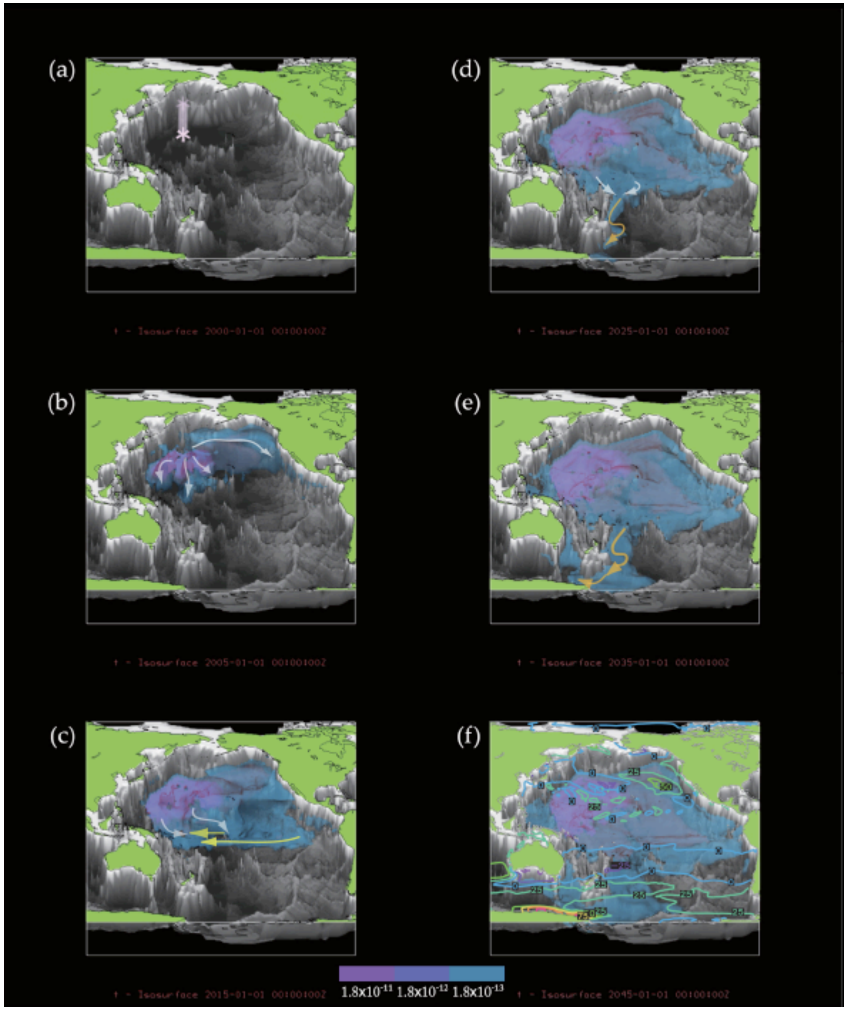


(Purkey & Johnson 2013)

Temporal variability: Cause?

- Deep ocean heat content can be change either by advection or by isotherm heave
- Observations show deep ocean warming is driven primarily by isotherm heave
- Isotherm heave, driven by a reduction in bottom volume, is communicated around the global oceans via Kelvin and Rossby waves on decade time scales



(Masuda et al 2010)

Conclusions

- The deep ocean has been warming, contributing ~10% to the total ocean heat content with some interdecadal variability
- Detecting interdecadal variability is limited owing to sparse temporal coverage
- However, no evidence of an increase in the rate of deep (below 2000 m) warming over the hiatus period
- To resolve the deep ocean heat content on decadal time scales, need a deep observing system such as Deep Argo Array