Observing the ocean below 2 km: Why and How?

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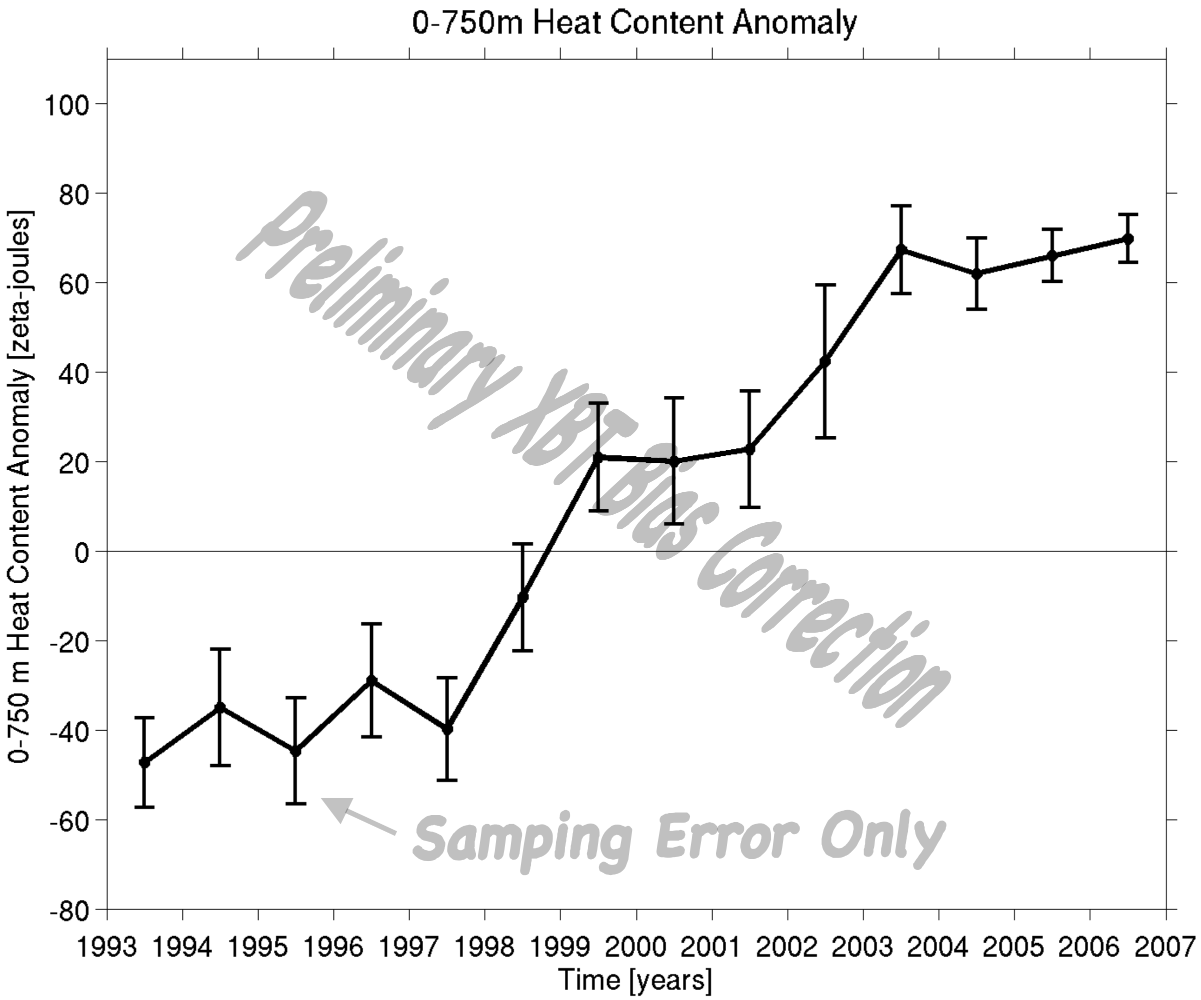
- Why?
    - Ocean Heat Content Budgets
    - Sea Level Budgets
    - Abrupt Change Detection

- Ocean heat content perspective
    - Arguments for an abyssal signal
    - Evidence of abyssal signals
        - N. Atlantic
        - S. Atlantic
        - N. Pacific
    - Abyssal ocean & global heat budget

- How?
    - Augmenting the deep ocean observing system

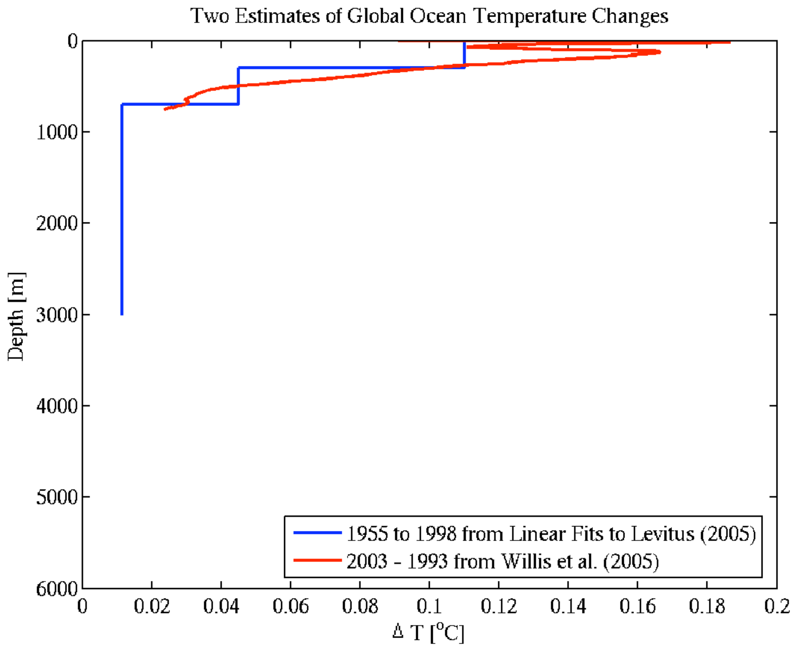
Upper Ocean Heat Content



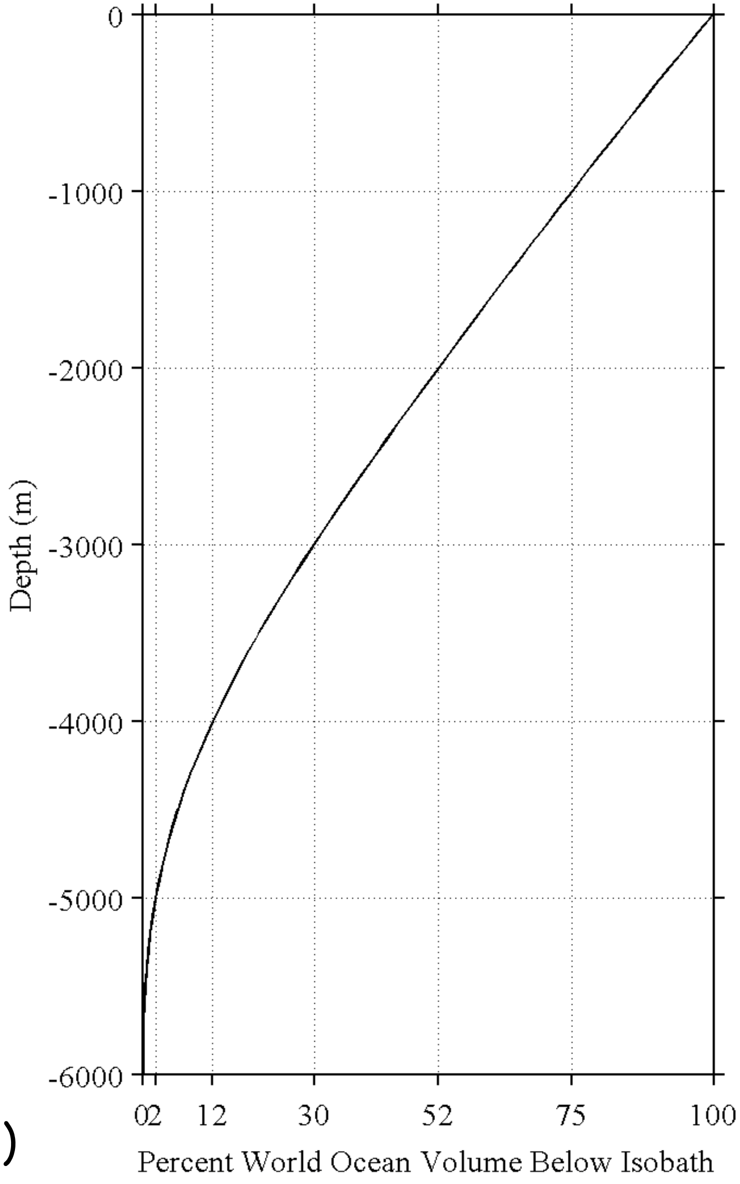
- Global heat budget
- Vital climate diagnostic (Hansen et al., 2005)
- Ocean 85% global budget (Levitus et al., 2005)
- Upper ocean best measured
- Upper ocean dominant?
- Close global budgets for
    - Heat
    - Sea Level
- Abyss important?

Surface Intensification?

- Global data analyses suggest it:
    - Levitus et al. (2005)
    - Willis et al. (2005)

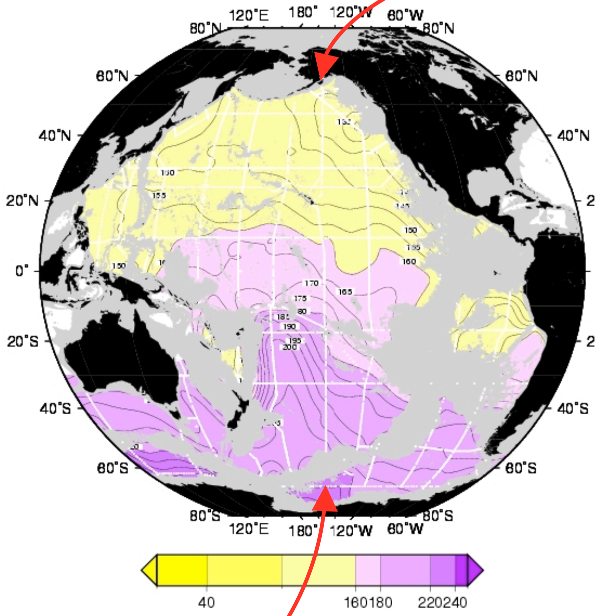


- How a swamp ocean would look
- Limited data ∴ analysis > 3000 m
- Abyssal ventilation?
- 81% ocean below 750 m (XBT)
- 52% below 2000 m (Argo)
- 30% below 3000 m (Deepest global estimates)



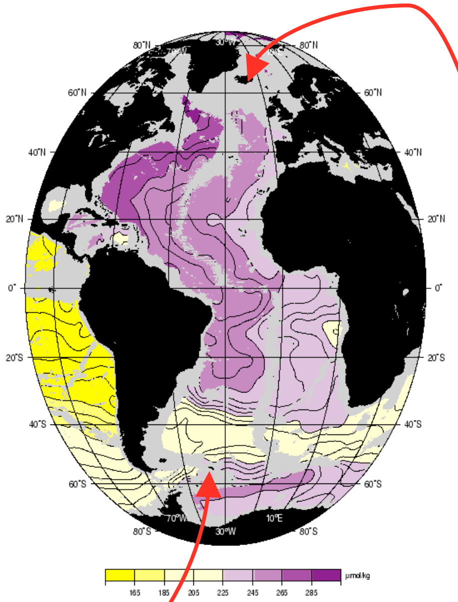
Why an Abyssal Signal?

4000 dbar

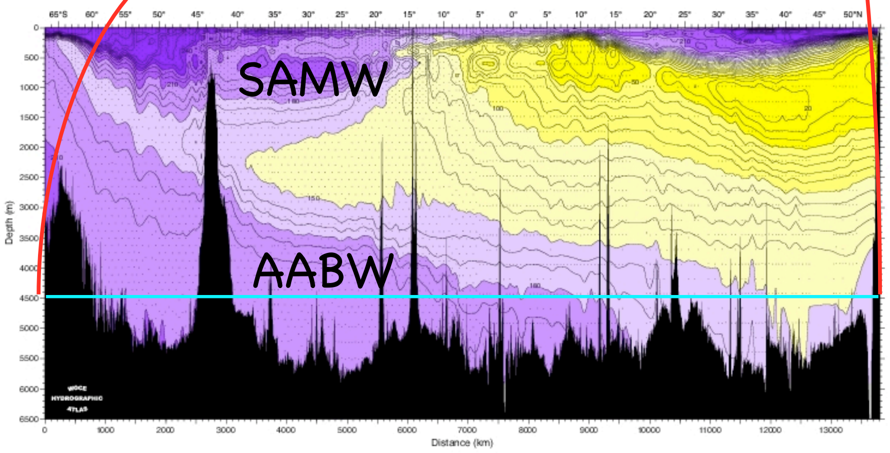


- Oxygen (WOCE)
  - Talley
  - Koltermann et al.
- Purple O_2-rich
  - "Ventilated"
- Yellow O_2-poor
  - "Old"

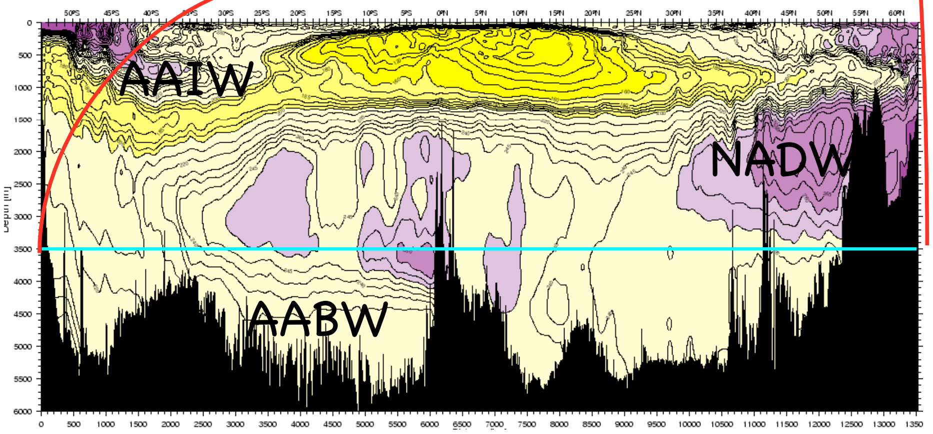
3500 dbar



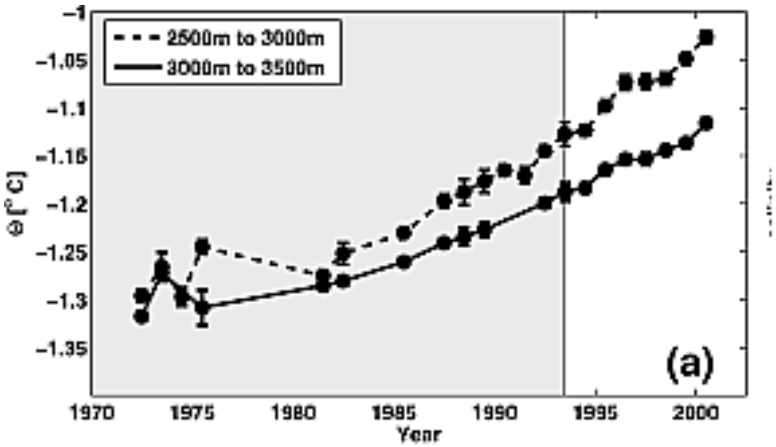
WOCE P16 150°W



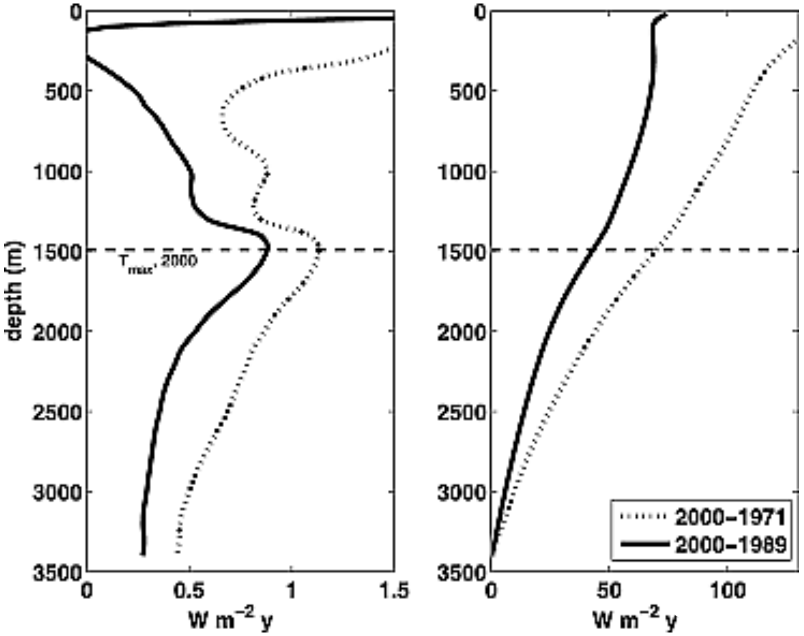
WOCE A16 ~20°W

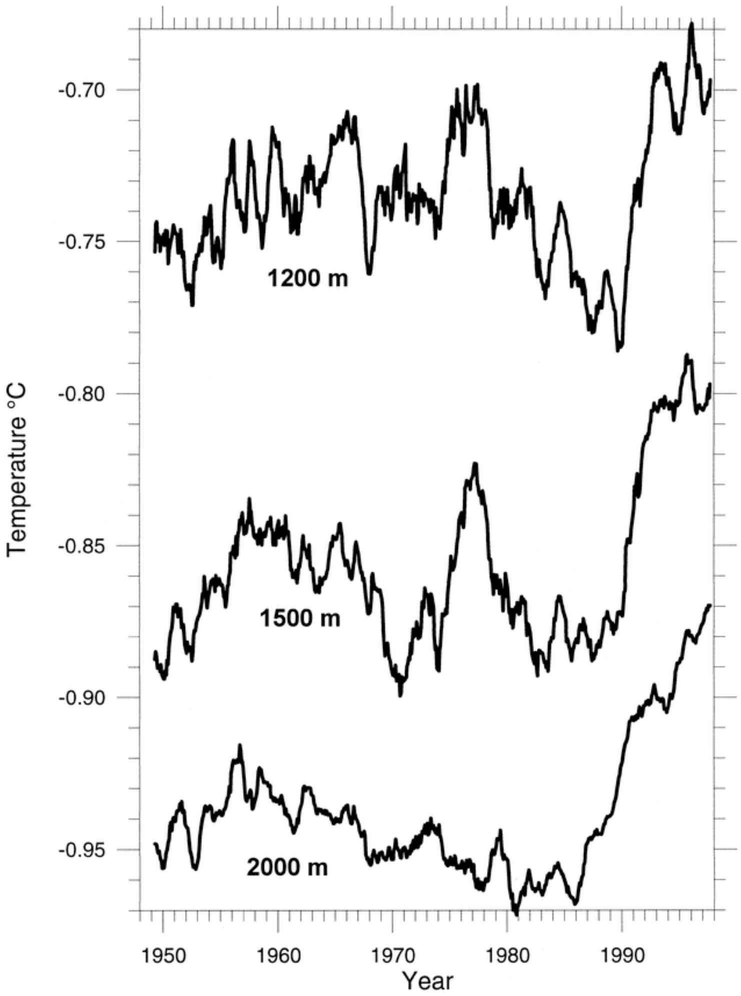


North Atlantic Changes



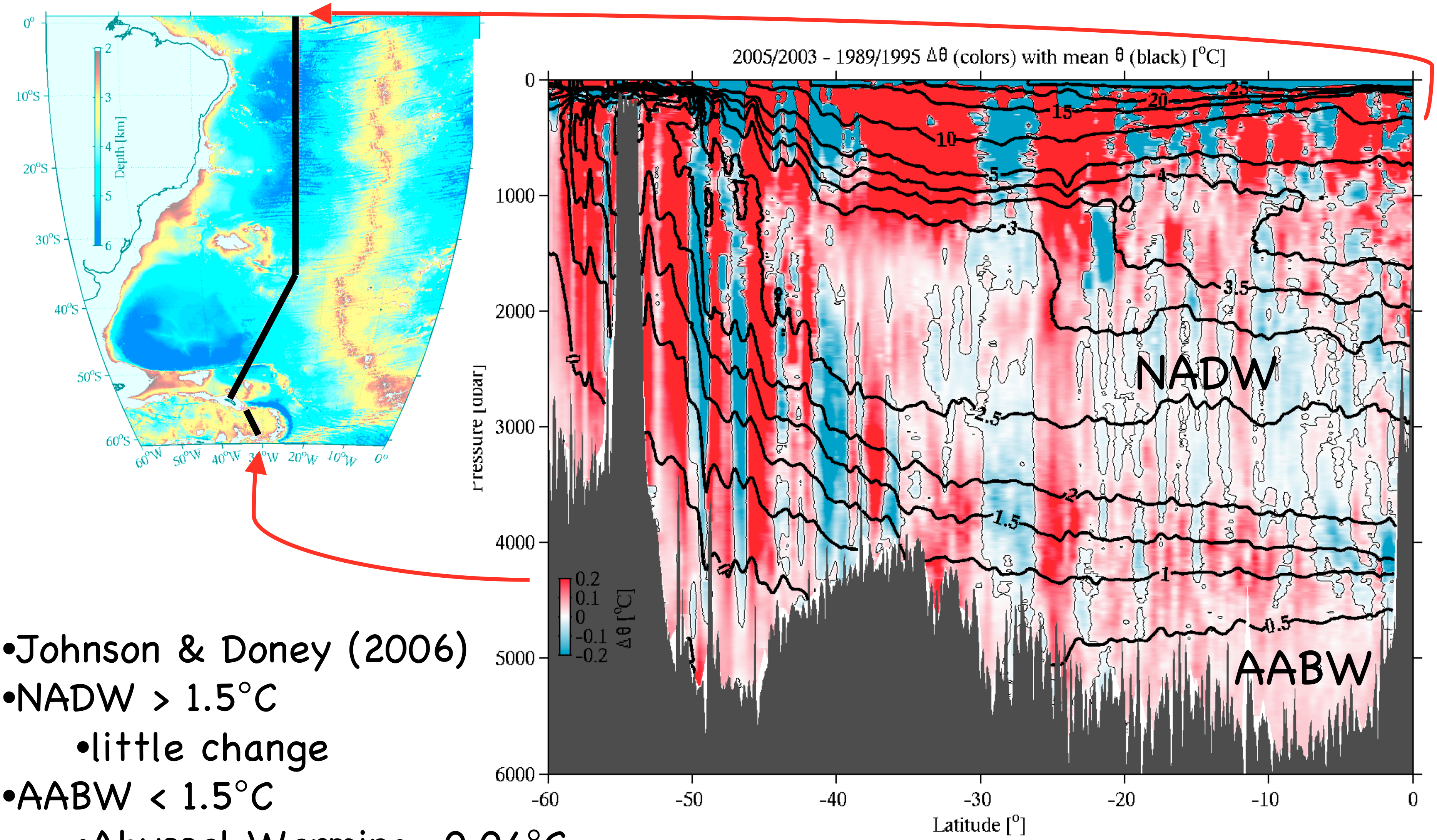
- Greenland Sea (Karstensen et al., 2005)
- ~0.2°C deep & bottom water changes
- ~4 W m^{-2} locally





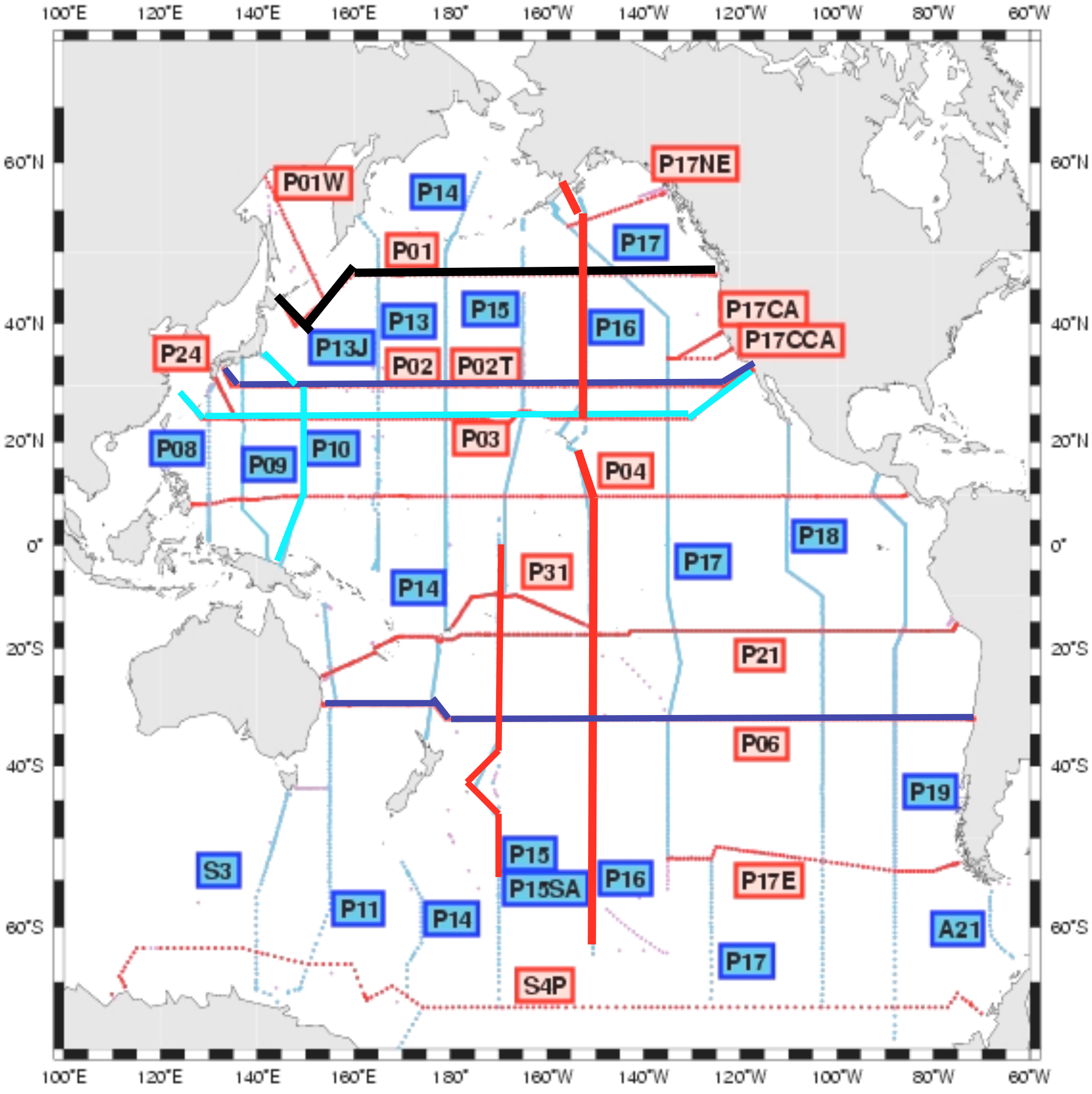
- Norwegian Sea (Østerhus and Gammeslrød, 1999)
- < 0.1°C deep changes
- ~ 1 W m^{-2} locally

S Atlantic 2005/2003 - 1989/1995 θ



- Johnson & Doney (2006)
- NADW > 1.5°C
  - little change
- AABW < 1.5°C
  - Abyssal Warming ~0.04°C
  - Below 3000 m: ~0.5 W m^{-2}

Pacific Abyssal Temperature Changes



Johnson et al. (2007)

150°W: 2006/5 – 1992/1

(& 1984)

170°W: 2001 – 1996

Kawano et al. (2006)

30°N: 2004 – 1994

32°S: 2003 – 1992

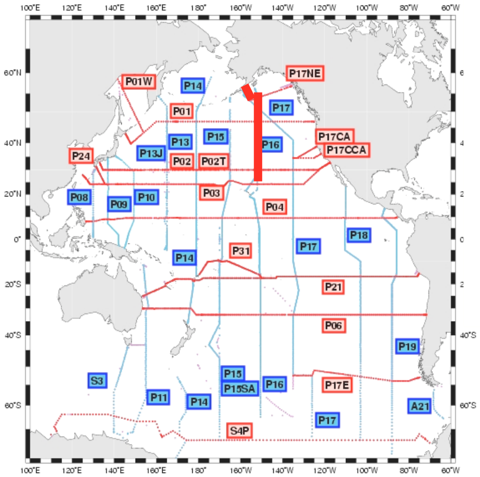
150°E: 2005 – 1993

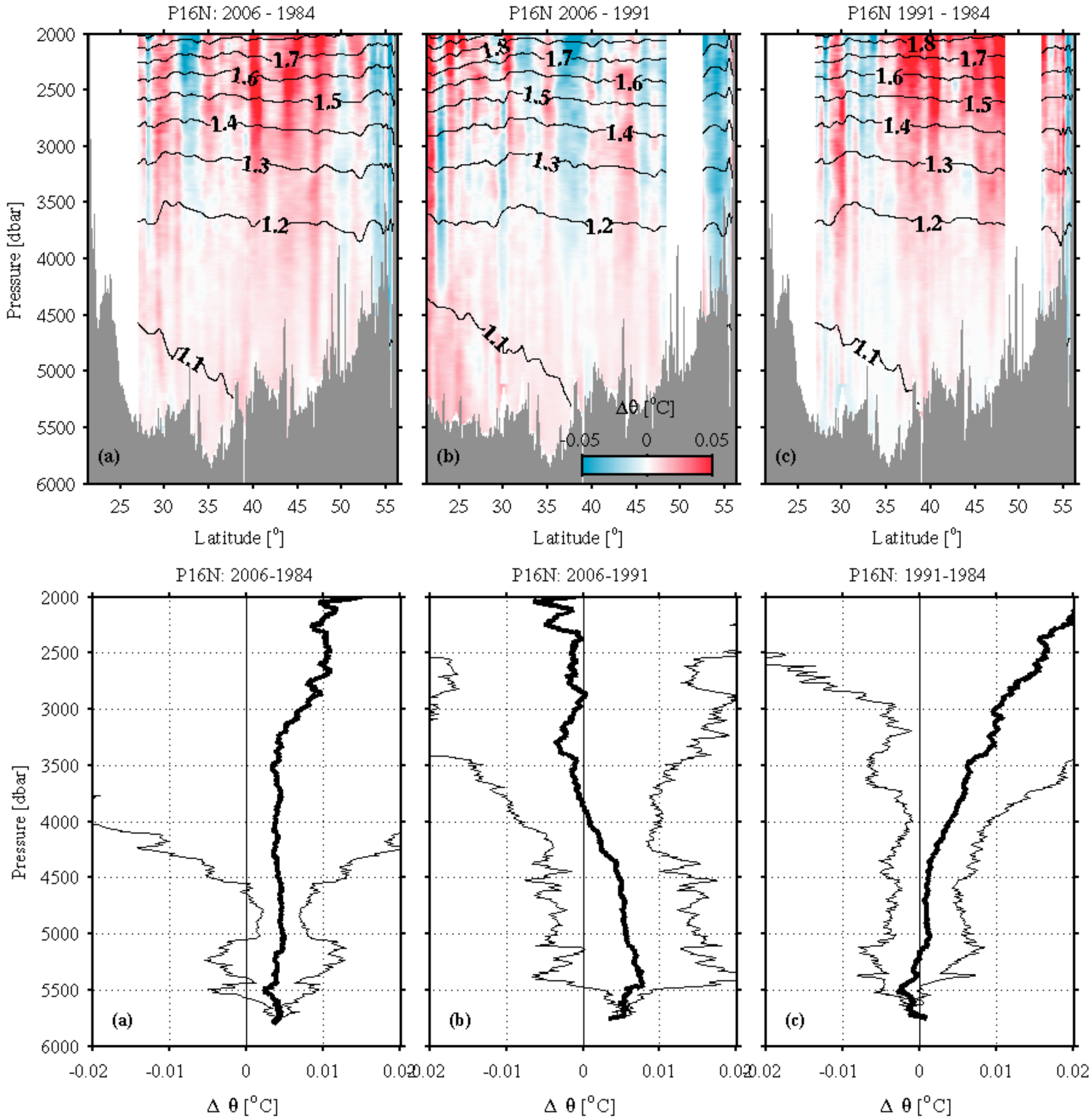
24°N: 2005 – 1985

Fukasawa et al. (2004)

47°N: 1999 – 1985

150°W: 2006, 1991 & 1984





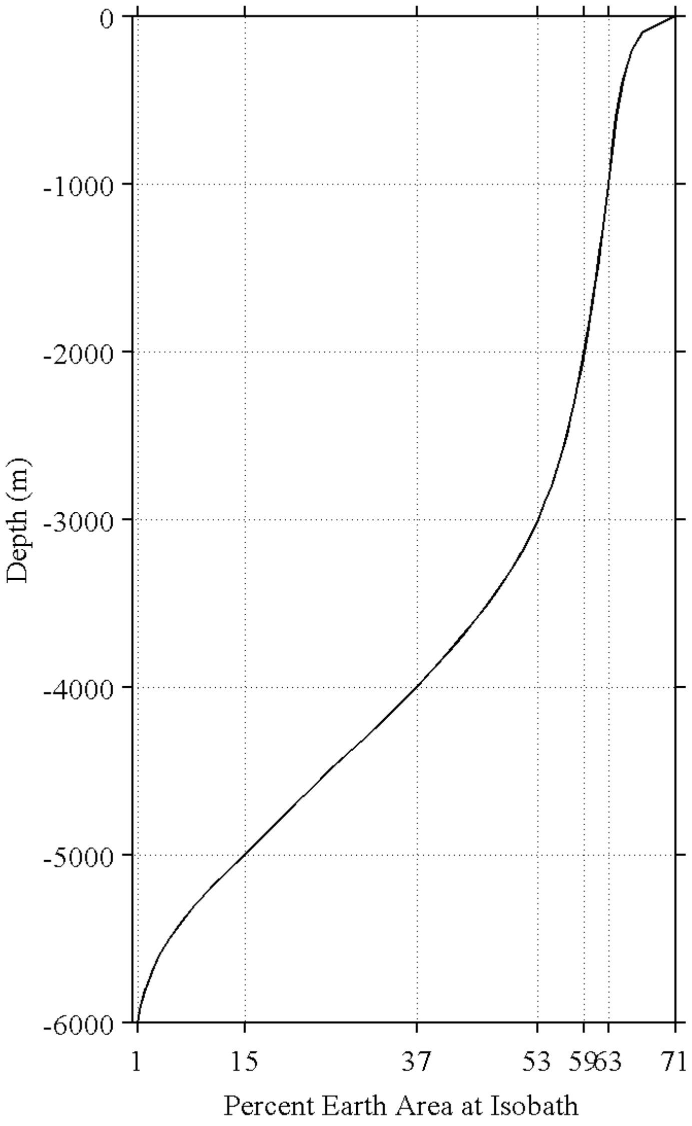
0.005°C abyssal warming 2006-1991

None for 1991-1984

Starts ~3500 dbar

Significant at 95% CI in places

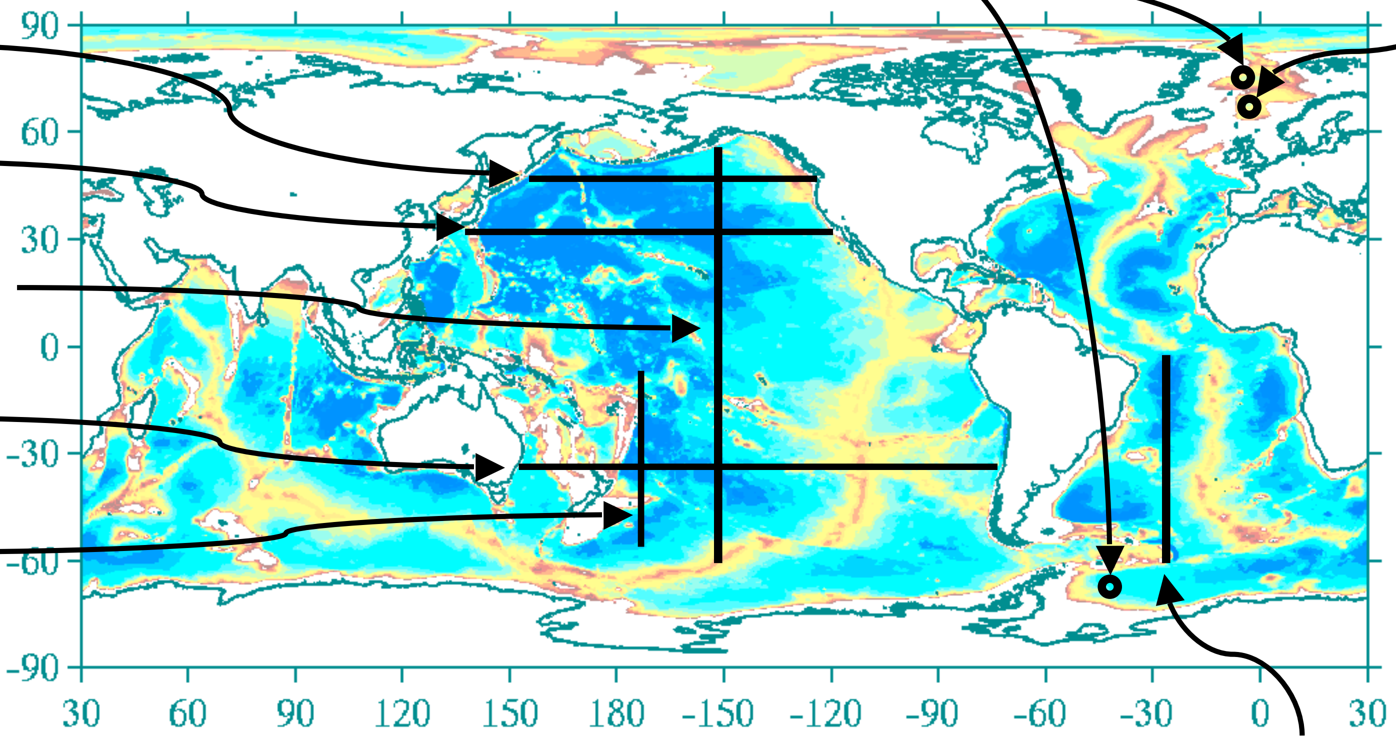
Abyssal Heat Content & Hypsometry



$$\Delta Q(p) = \left\langle \rho c_p (T_f - T_i)/(t_f - t_i) \right\rangle_x$$

- Global heat budgets W m^{-2} over entire Earth surface
- Ocean @ surface covers 71% of Earth
- Ocean @ 3000 m covers 53% of Earth
- Apply fraction of global ocean coverage to section depth averages
- Integrate result from 3000 m to bottom
- Done for estimates made here
- Interior basin estimates
    - S. Atlantic
    - Pacific

Summary: Abyssal Heat Content Changes



(4) W m^{-2}

(1) W m^{-2}

0.01 W m^{-2}

0.02 W m^{-2}

0.02 W m^{-2} (N)
0.04 W m^{-2} (S)

0.02 W m^{-2}

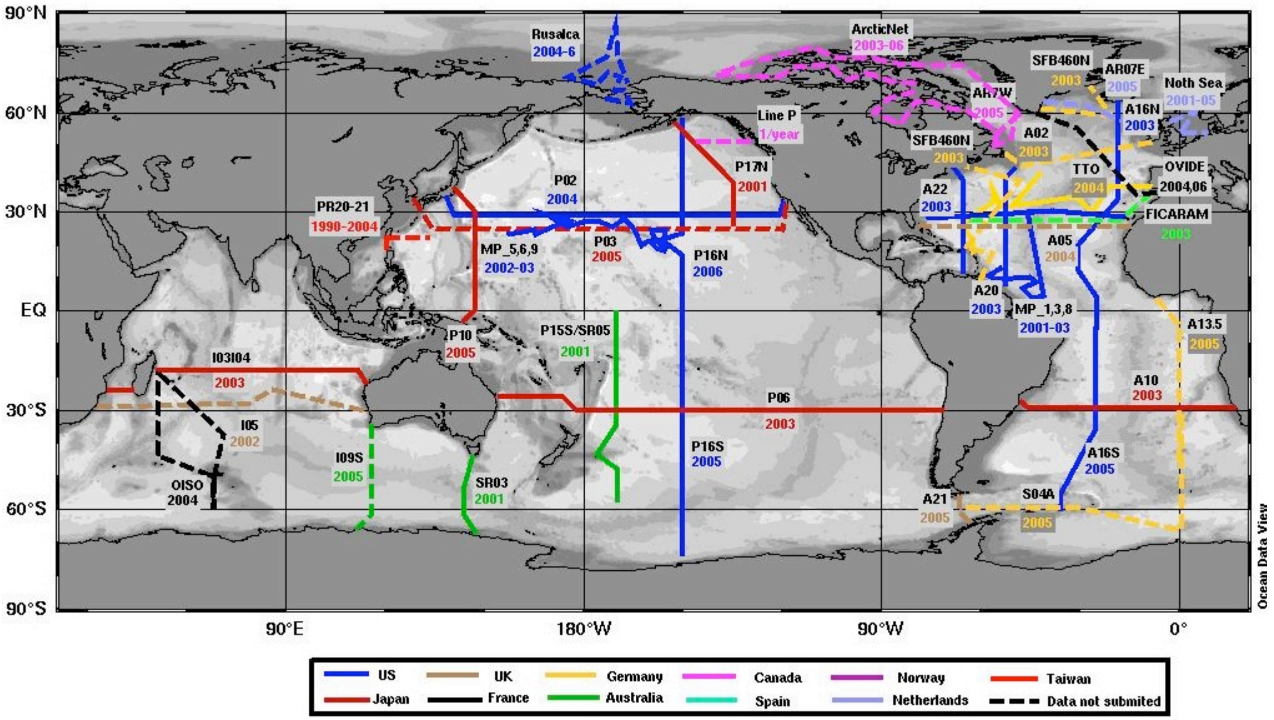
0.06 W m^{-2}

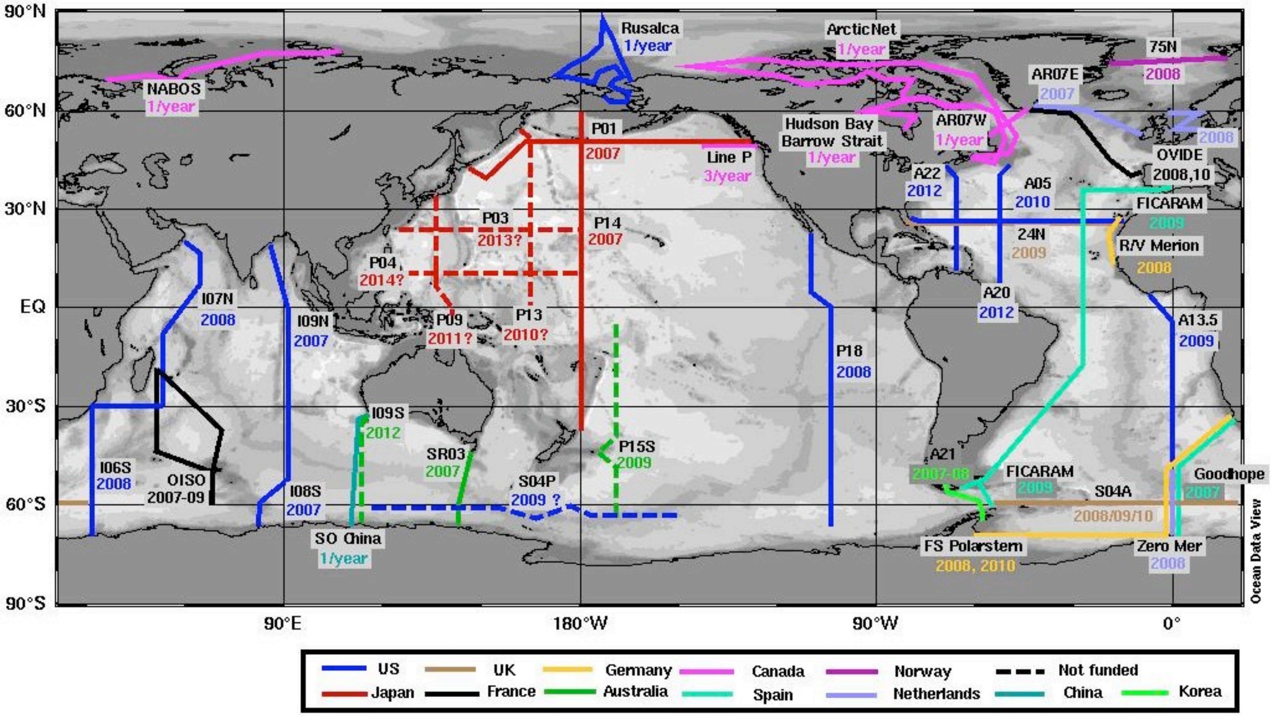
0.2 W m^{-2}

- Abyssal waters: small horizontal & vertical gradients
- Allows detection of very small interior temperature changes
- Small changes found over large areas (entire basins) & depth ranges (km's)
- Significant relative to decadal upper ocean? (~0.6 W m^{-2} last decade)
- Near source regions 1 to 4 W m^{-2} (not hypsometry corrected)
- Basin interiors 0.01 - 0.2 W m^{-2} (hypsometry corrected)
    - Larger areas e.g. S. Atlantic, Pacific
    - Closer to source, the larger the heat gain

Repeat Hydrography

- Zonal Subtropical
- Meridional Deep Basin
- Bottom Water Outflow

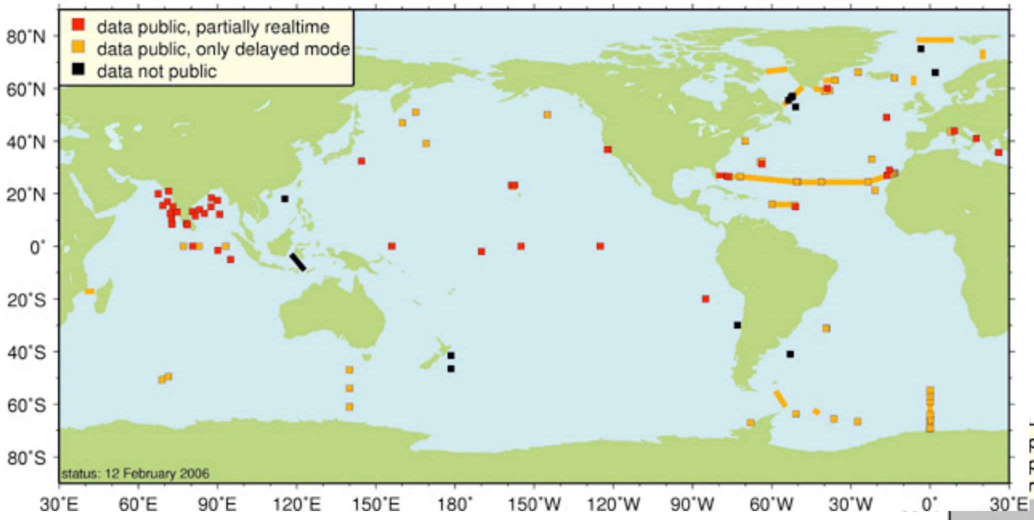




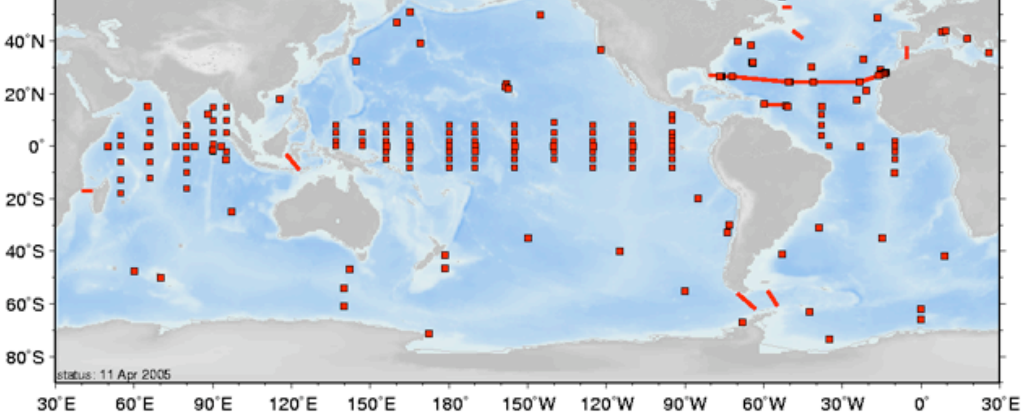
- Excellent vertical
- Excellent horizontal
- Decadal intervals
- Far between sections
- Logistical impediments
  - W. Indian Ocean
  - Southern Ocean
    - Ross Sea
    - Adelie Land

Augmenting the deep ocean observing system

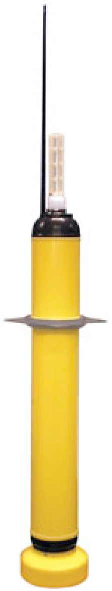
OceanSITES – current

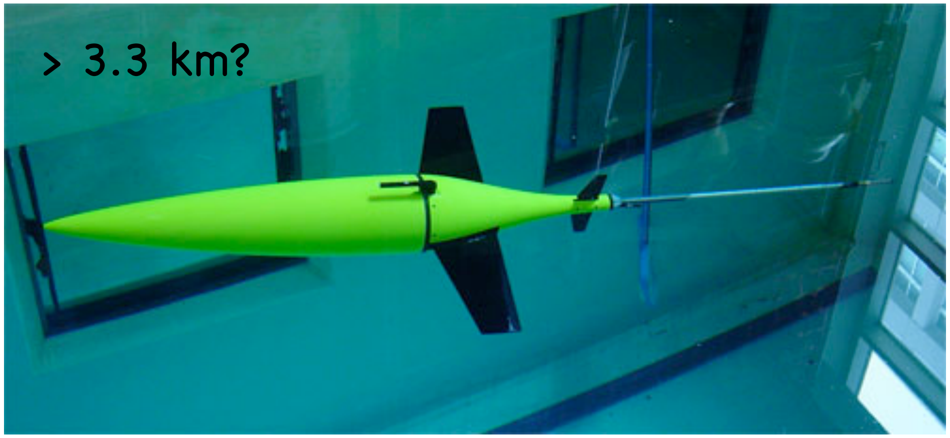


OceanSITES – vision



- Continue Repeat Hydrography
  - Decadal intervals
  - All deep basins
  - Deep outflow regions
- Augment abyssal time-series
  - Ocean Sites
  - Alongside Tsunameters?
- Develop Autonomous instruments
  - UW's Deepglider
    - (currently 3.3 km)
  - Floats
    - Currently 2 km
    - 3-km under development

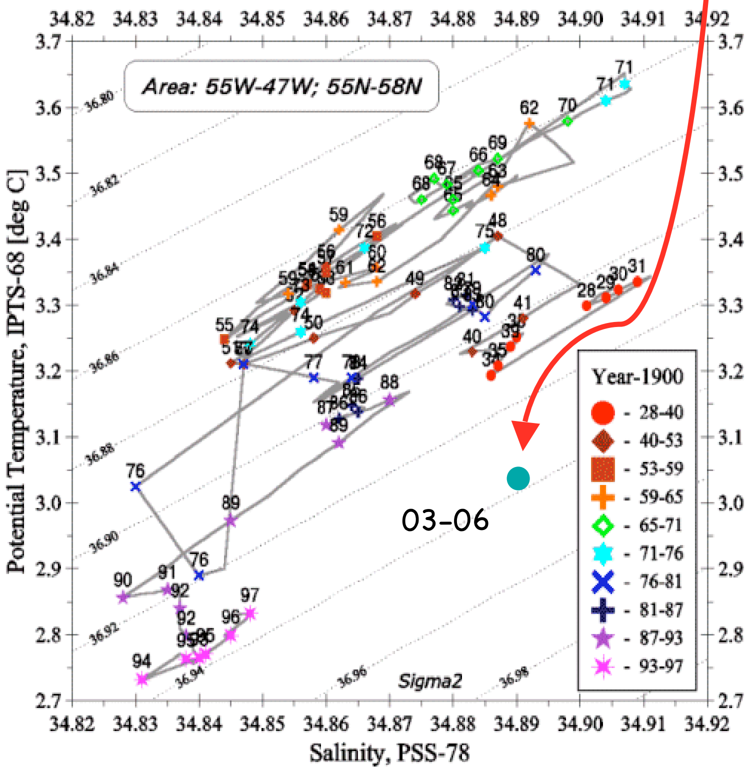


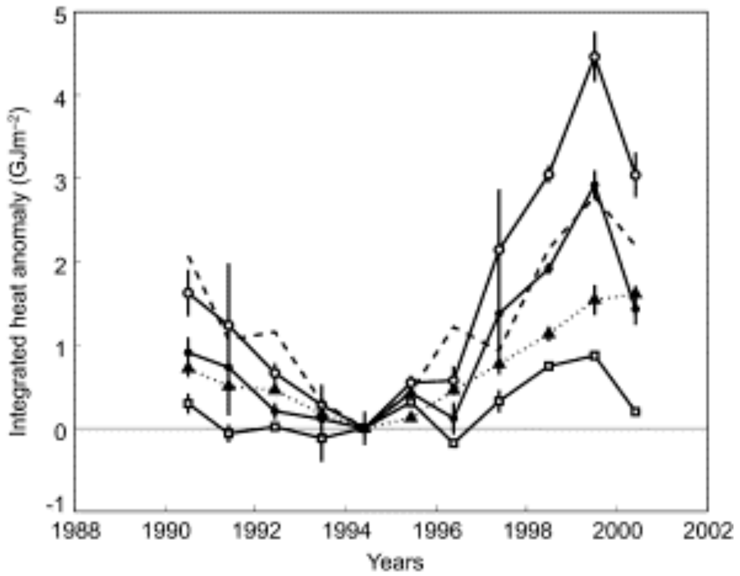


> 3.3 km?

More North Atlantic Changes

- Labrador Sea Water (Yashayaev et al.)
- Large interdecadal T-S variations
- Warmer and saltier since 1994
- DWBC spreads lagged signal into N. Atlantic (Molinari et al., 1998; Curry et al. 1998)

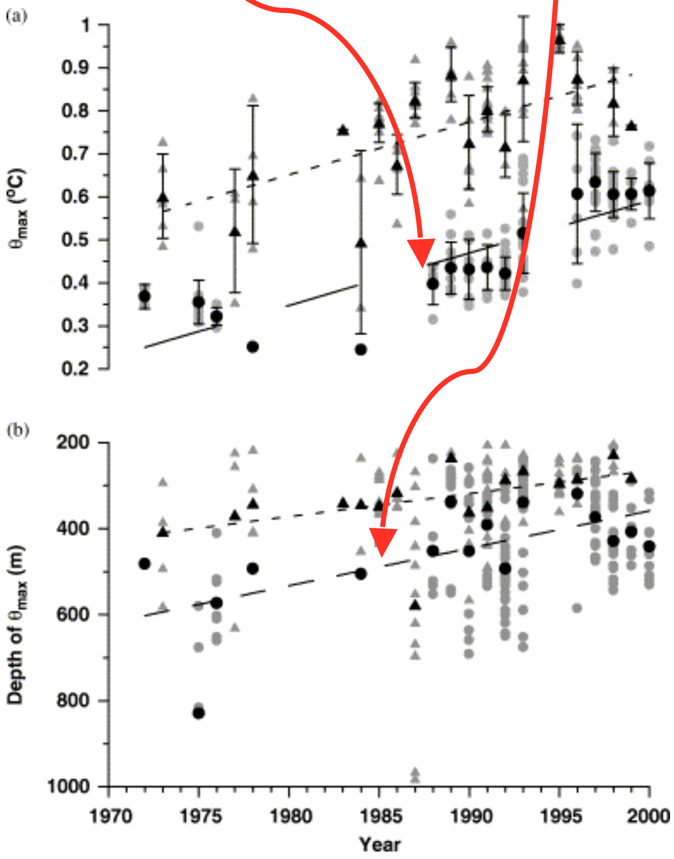




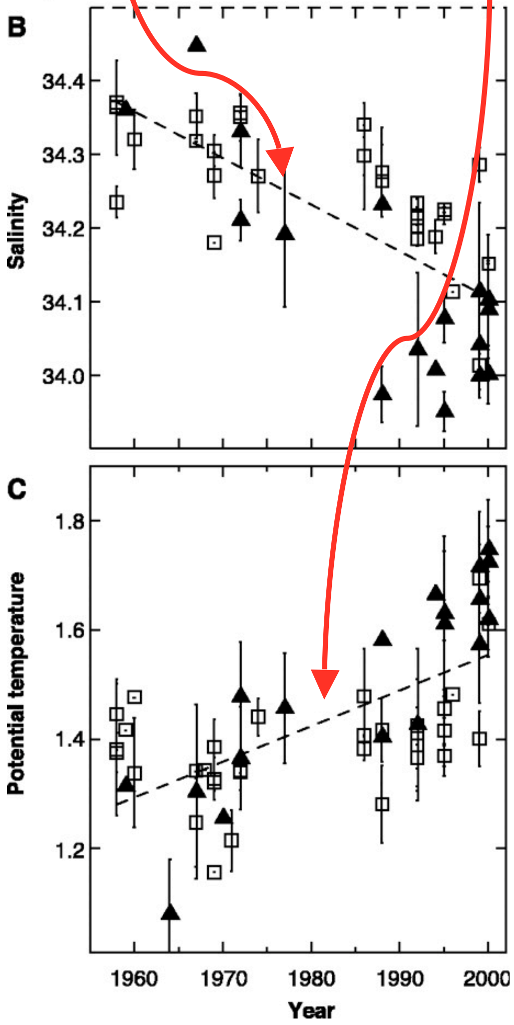
- 0-2000 dbar heat inventories (Lazier et al., 2002)
- '90-94 -> 13 W m^{-2} loss
- '94-99 -> 28 W m^{-2} gain
- Local air-sea flux anomalies
- NAO

Southern Ocean Changes

- Shallow Weddell Sea (Robertson et al., 2002):
  - T-max Warmer
  - T-max Shallower
- Late 1990's reversal (Fahrbach et al. 2004)



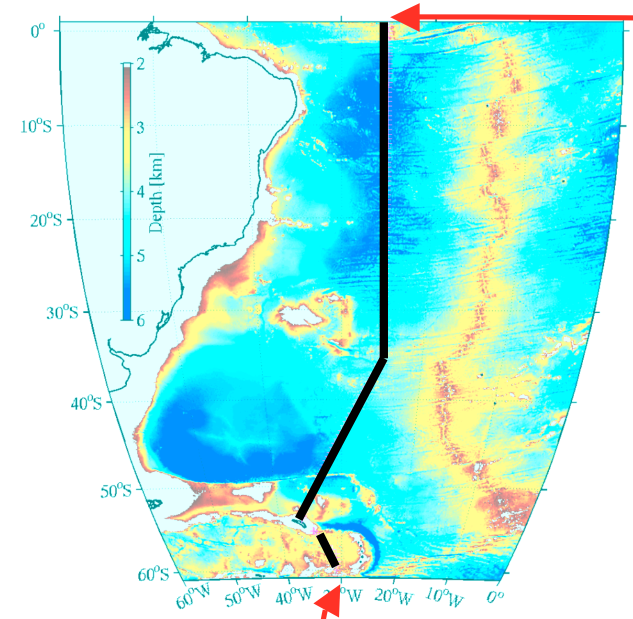
- Shallow Ross Sea (Jacobs, 2002):
  - T-min Fresher
  - T-max Warmer

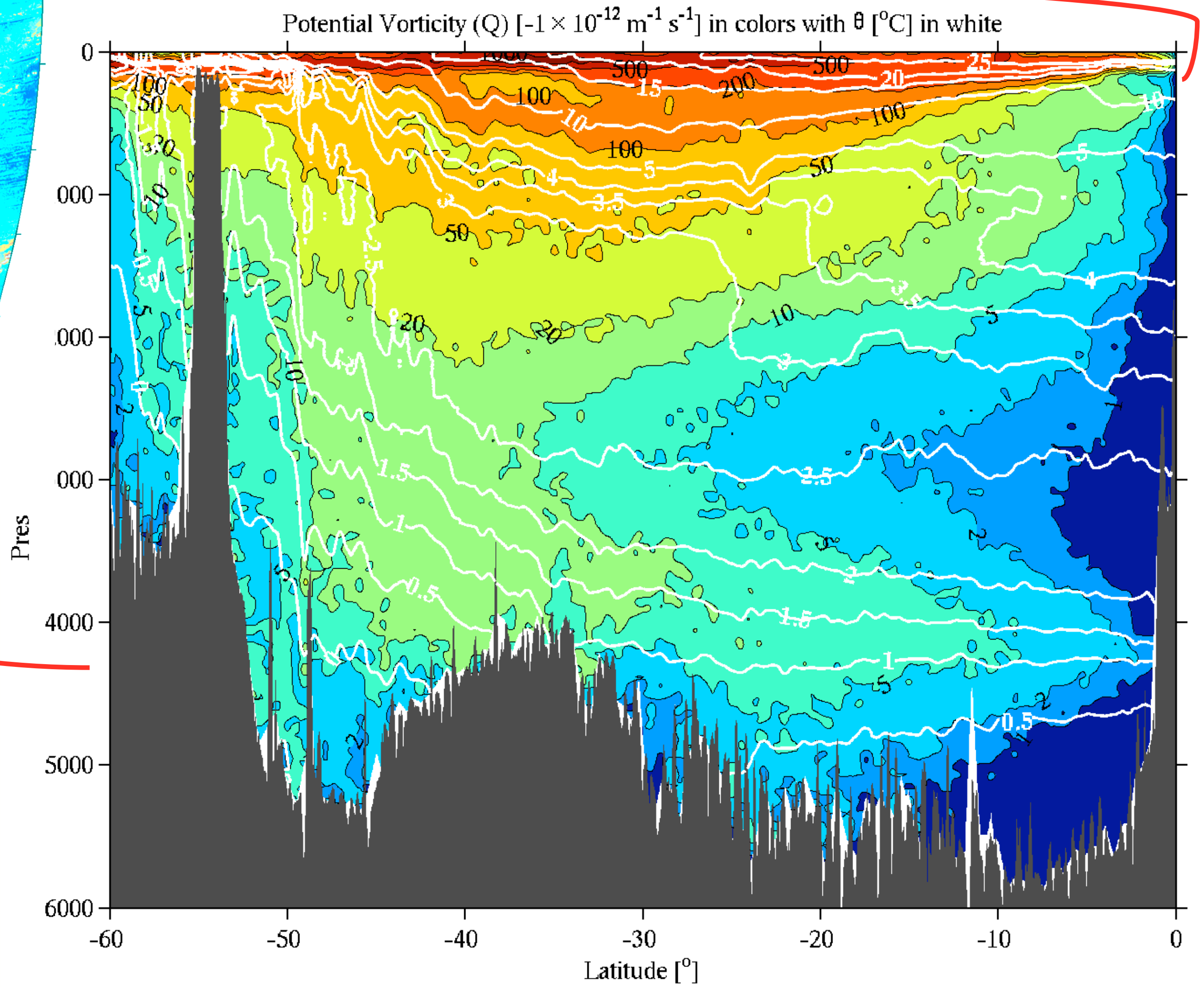


- Weddell Sea
- ~4 W m^{-2} long-term (Smelsrud, 2005)
- Warmer Bottom Water (Fahrbach et al., 2004)

- Downstream of Ross Sea: Cooler & Fresher Bottom Water (Whitworth, 2002)

S Atlantic 2005&1989: Potential Vorticity



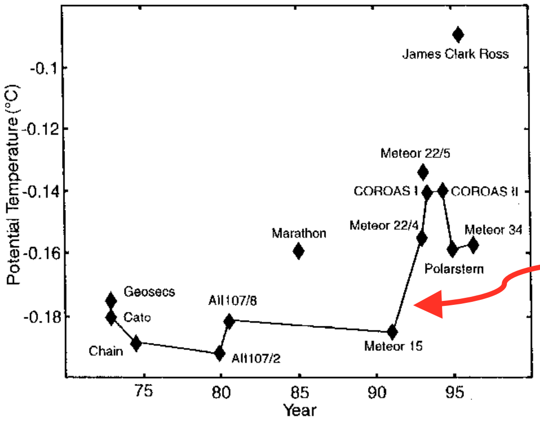


NADW ≈ 2.5°C

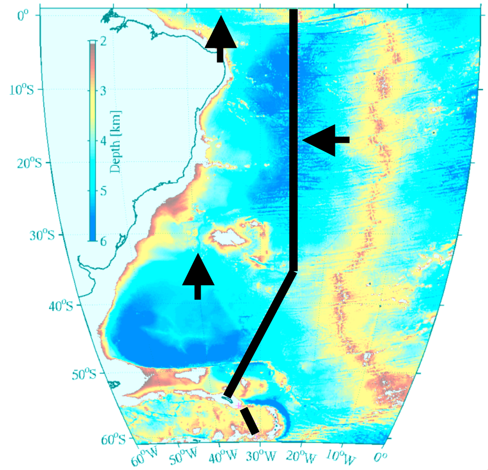
- Low Q

- Boundary ≈ 1.5°C
  - High Q
- AABW < 1.5°C
  - Low Q

2005 - 1989 Brazil Basin Δθ

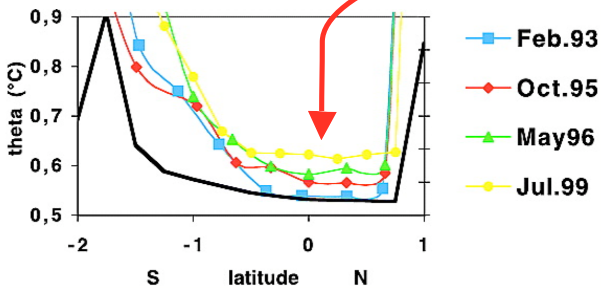


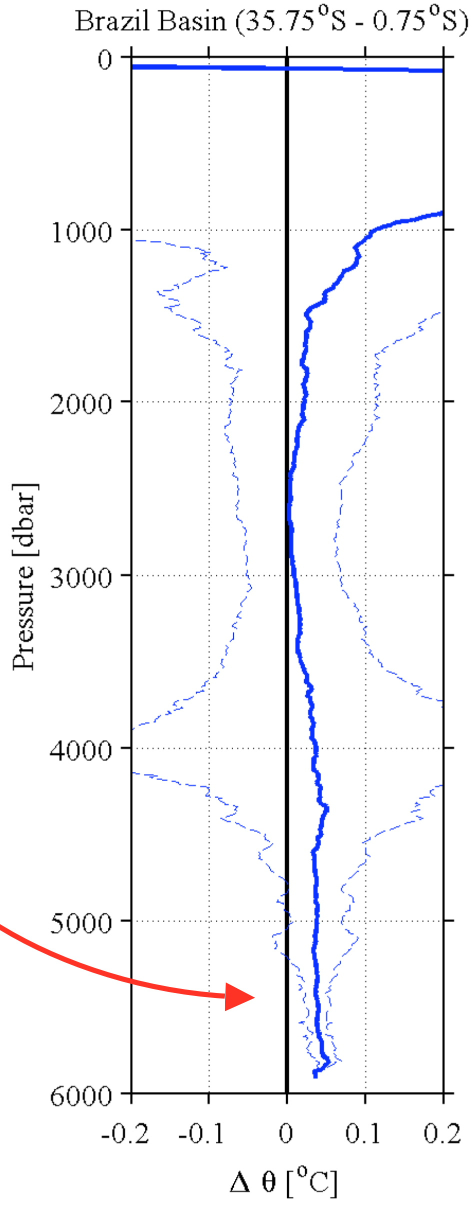
- Vema Channel near 32°S (Hogg & Zenk, 1997)
- 1992 warming
- ~0.03°C



- Brazil Basin Interior (Johnson &Doney, 2006)
- 2005-1989 warming
- ~0.04°C

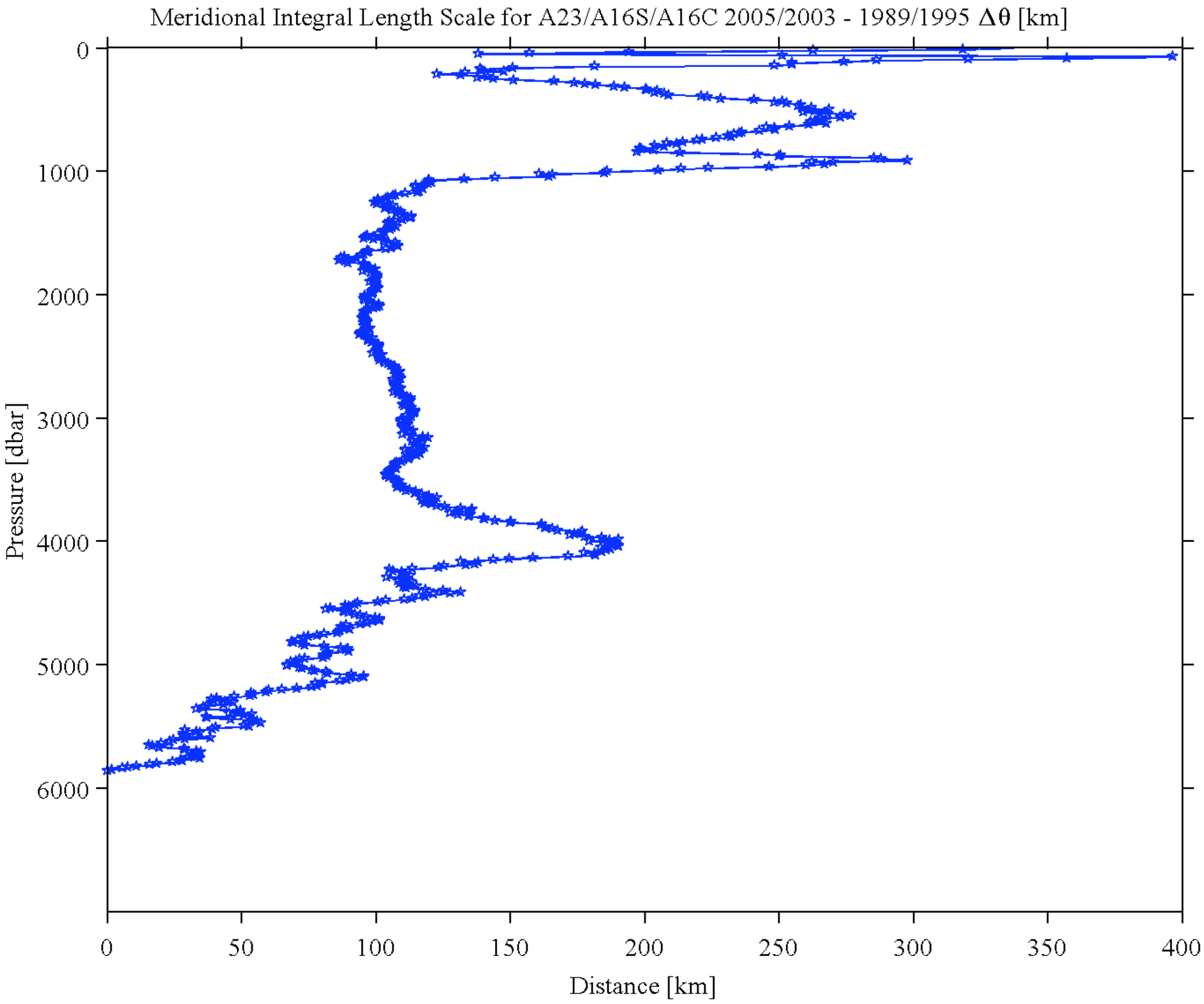
- Equator at 35°W (Andrie et al., 2003)
- 1990's Bottom warming
- < 0.1°C

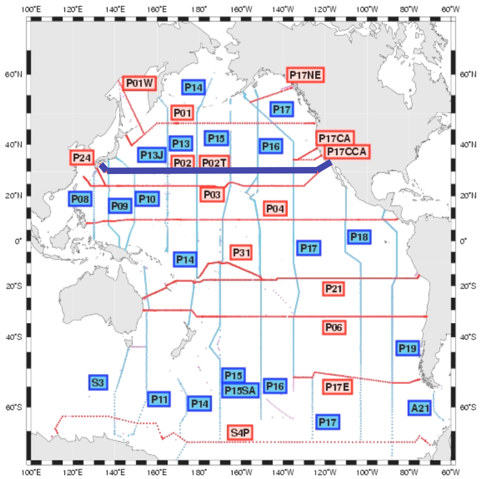




Degrees of Freedom For 95% CI

- Grid each section θ on pressure
- Calculate gridded 2005 -1989 for each pressure
- Detrend result vs. latitude
- Calculate autocorrelation
- Integrate out to first zero-crossing
- 2x result meridional integral length scale
- DOF = Length/Scale
    - Longest shallow
    - Shorter deep
    - Benthic (4000 dbar) thermocline local max





30°N: 2004 - 1993/1994

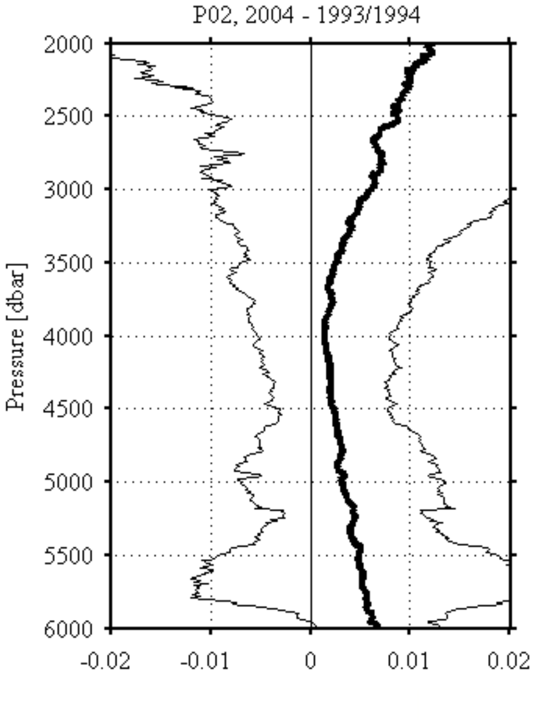
Kawano et al. (2006)

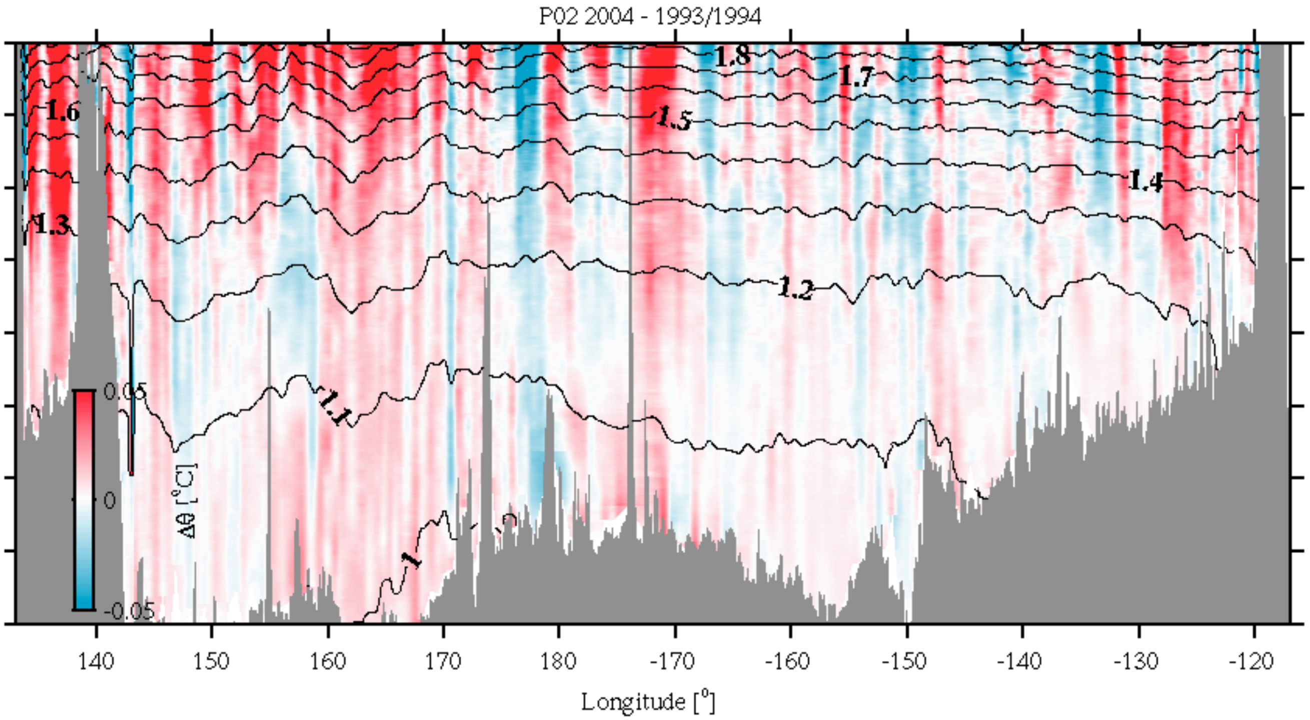
> 0.005°C abyssal warming

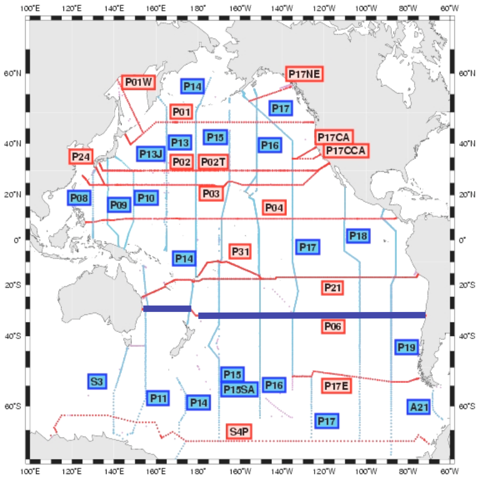
Coldest, weakest stratified waters warm

Starts at 4000 dbar

Significant at 95% CI near 6000 dbar


P02, 2004 - 1993/1994


P02 2004 - 1993/1994



32°S: 2003 - 1992

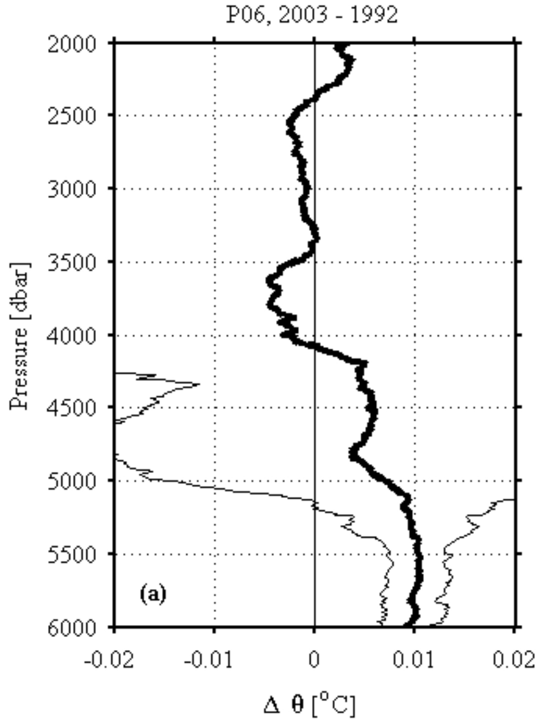
Kawano et al. (2006)

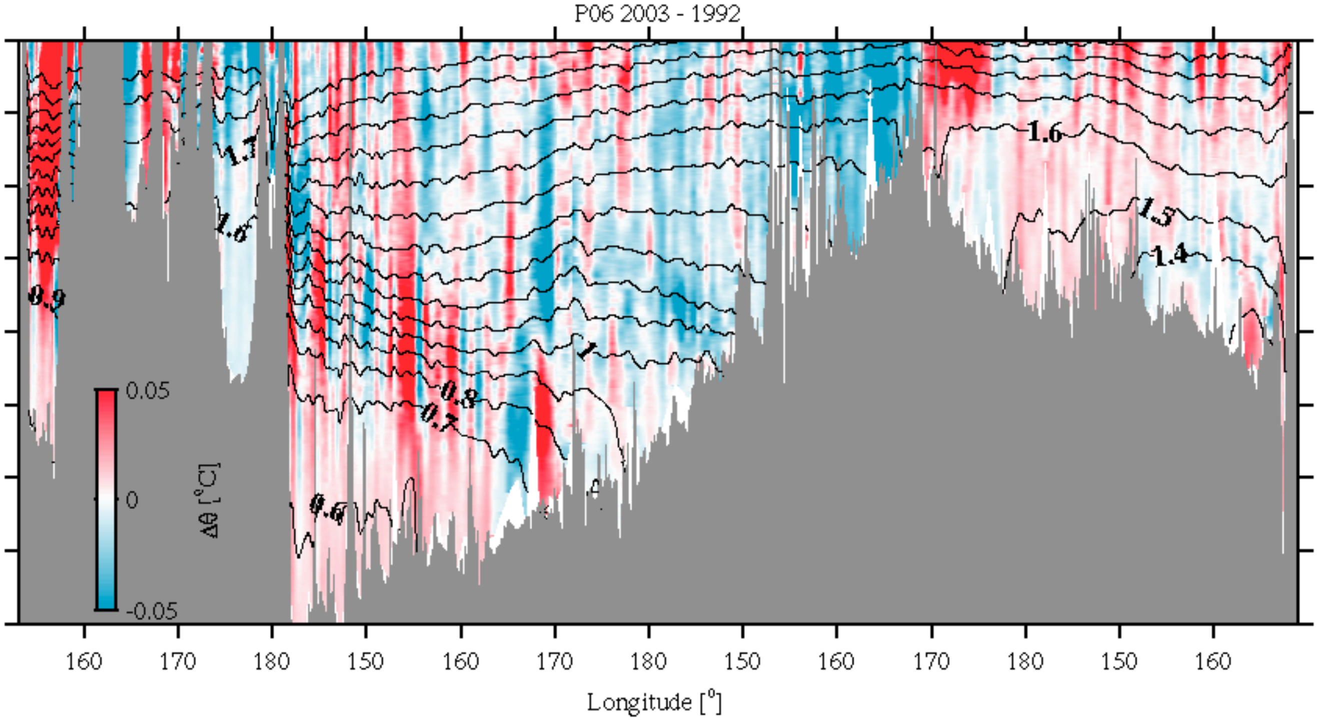
0.010°C abyssal warming

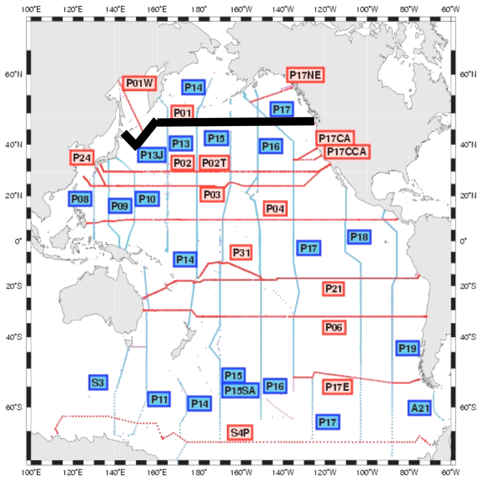
Coldest, weakest stratified waters warm

Starts at 4000 dbar

Significant at 95% CI below 5000 dbar







47°N: 1999 - 1985

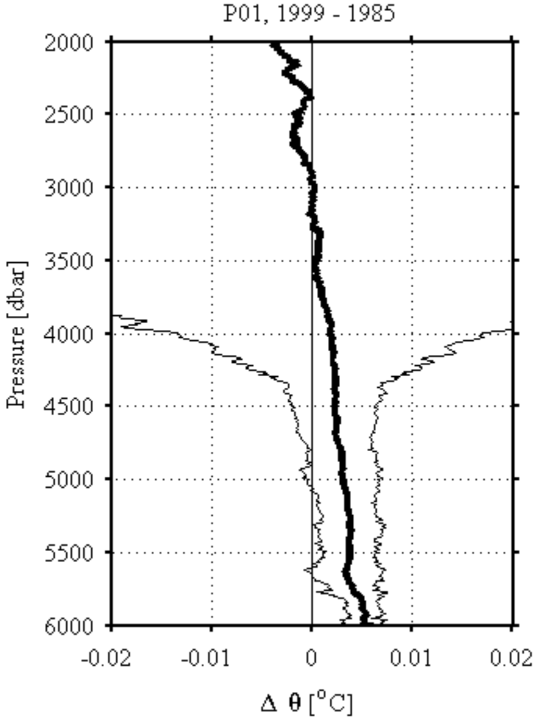
Fukasawa et al. (2004)

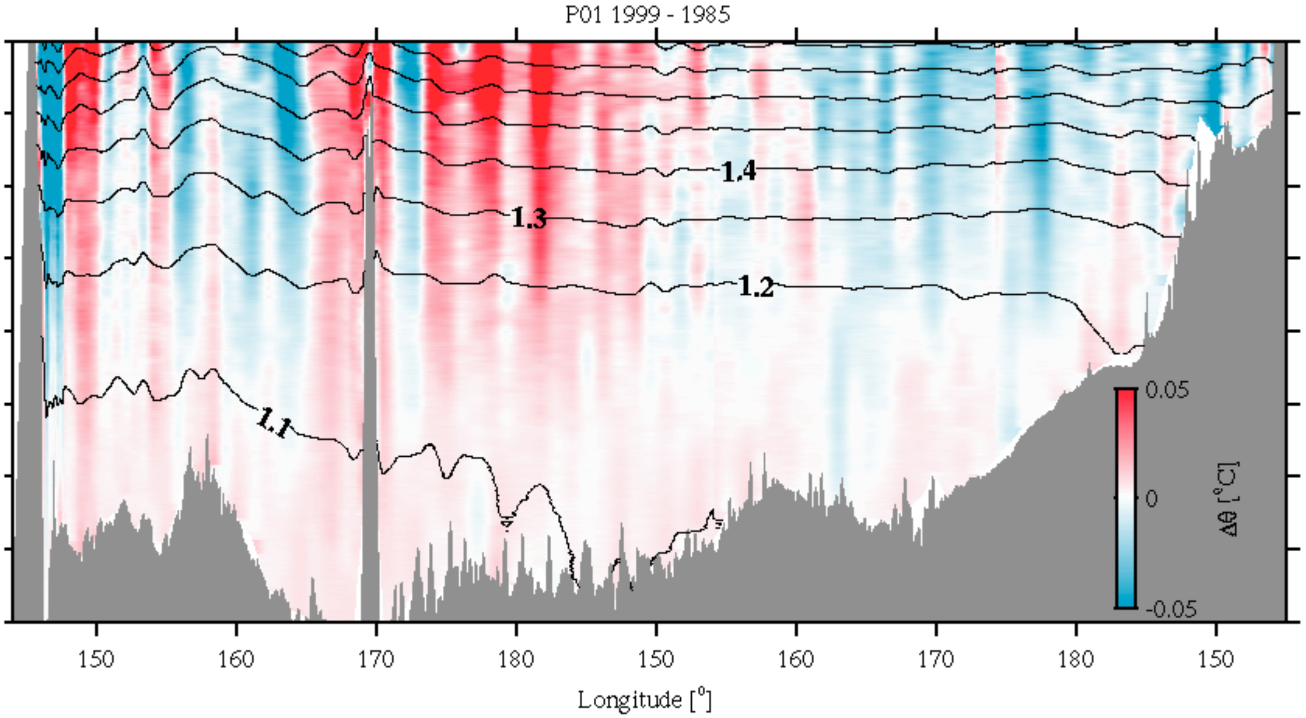
0.005°C abyssal warming

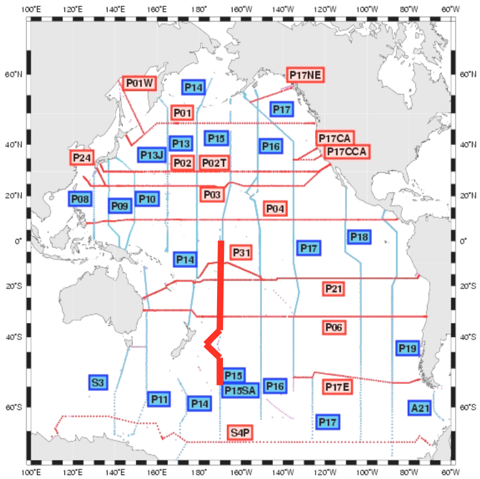
Coldest, weakest stratified waters warm

Starts at 3500 dbar

Significant at 95% CI below 4500 dbar







170°W: 2001 - 1996

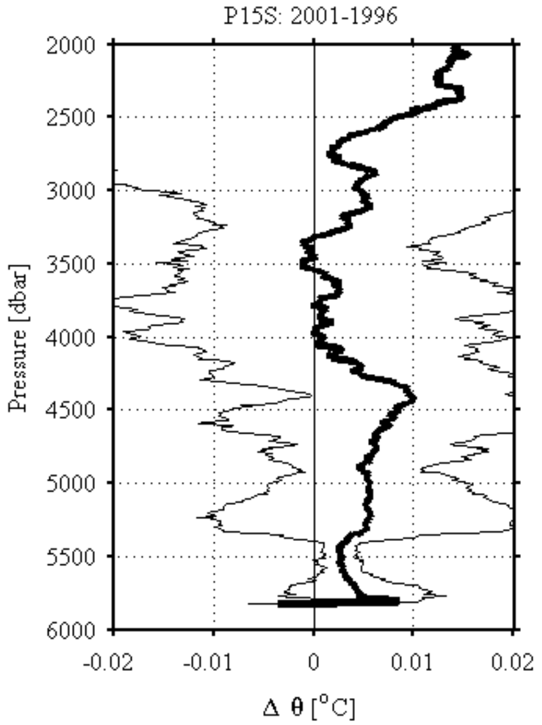
Only 5-year time interval

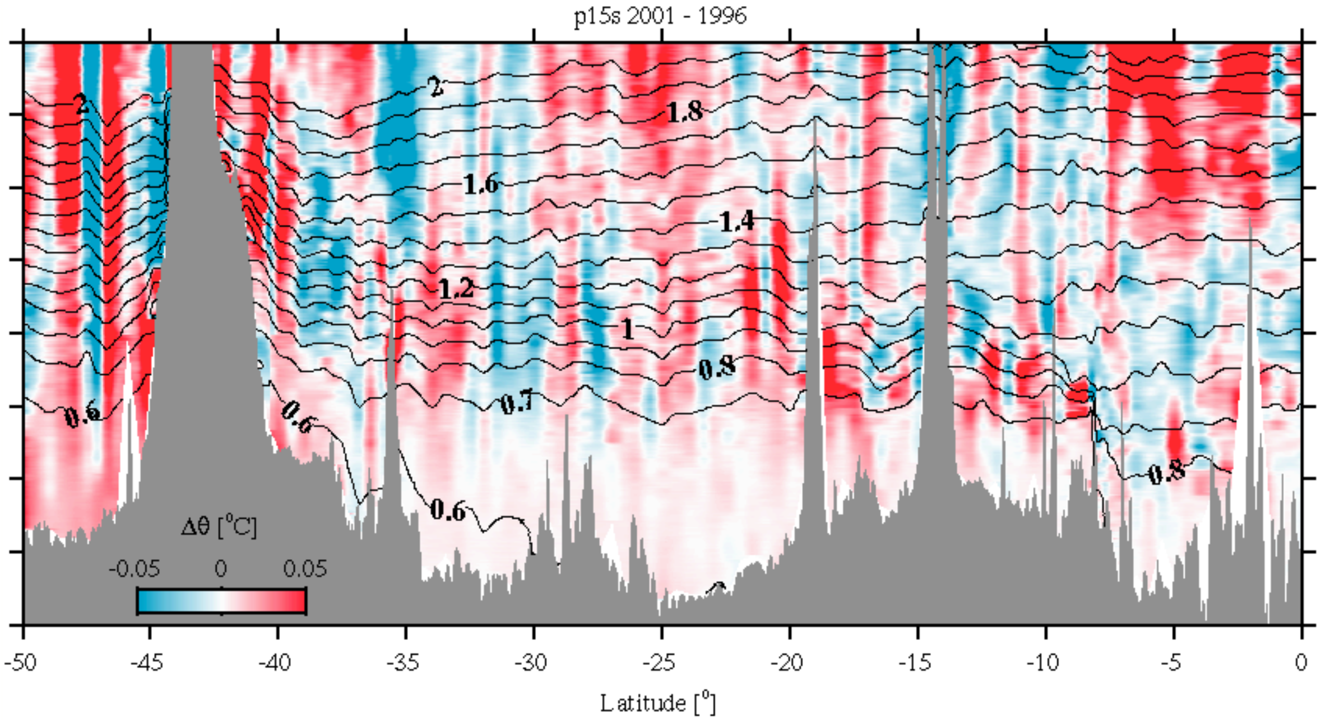
0.005 to 0.010°C abyssal warming

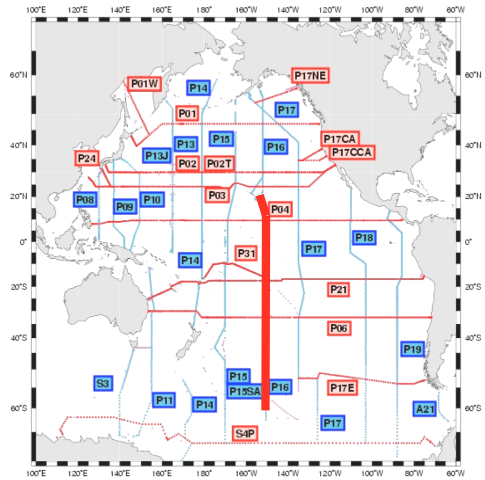
Starts at 3500 dbar

Significant at 95% CI below 4000 dbar

Warming strongest in the south







150°W: 2006/2005-1992/1991

0.005 to 0.010°C abyssal warming

Coldest, weakest stratified waters warm in all basins

Starts at 3000 dbar

Near significant at 95% CI below 4000 dbar