Southern Ocean Hydrography and Circulation: Warming of Global Abyssal and Deep Southern Ocean Waters Between the 1990s and 2000s

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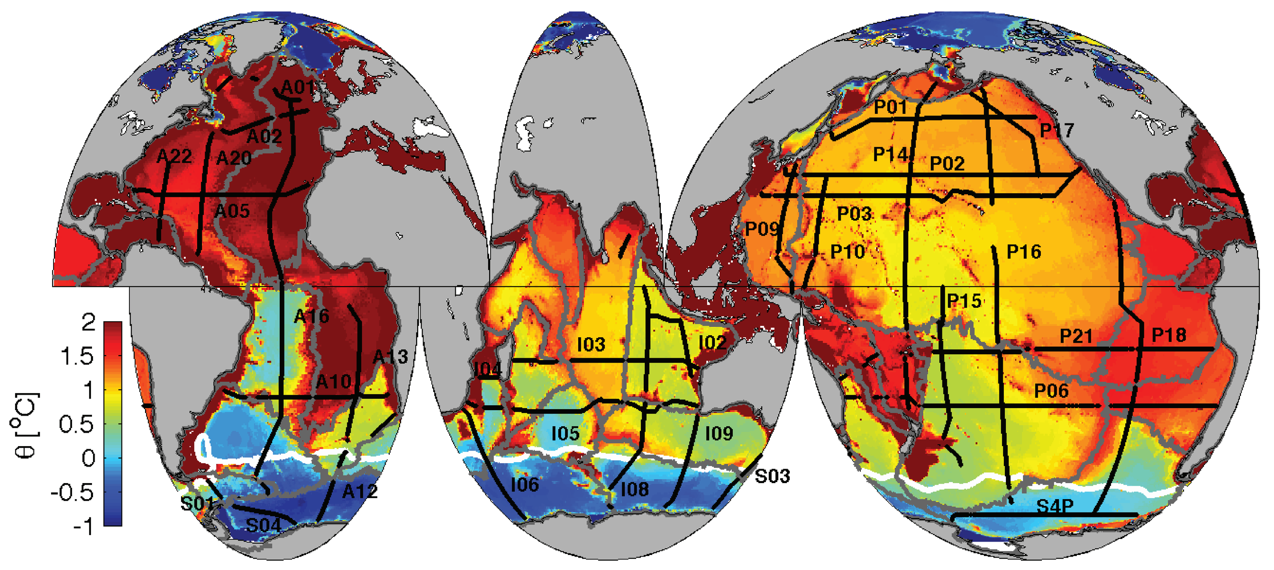
1. Introduction

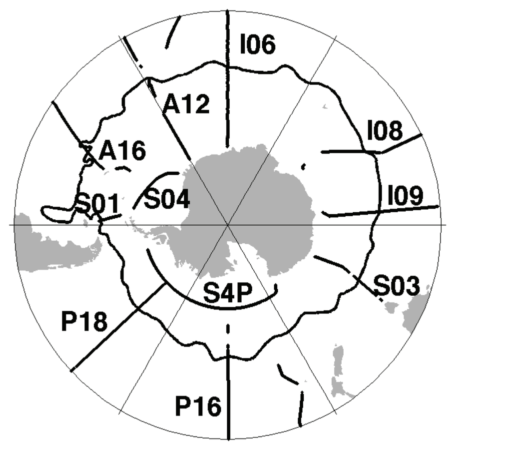
- The upper oceans absorb most of the energy from anthropogenic warming.
- This warming accounts for about half the sea level rise of 3.1 mm yr^{-1} between 1993 and 2003.
- We assess recent warming of the abyss and quantify its role in global heat and sea level budgets (Purkey and Johnson 2010).
- We quantify a volume loss within deep temperature classes and estimate the implied slowdown of the lower limb of the Meridional Overturning Circulation (MOC; Purkey and Johnson *in prep*).

2. Data

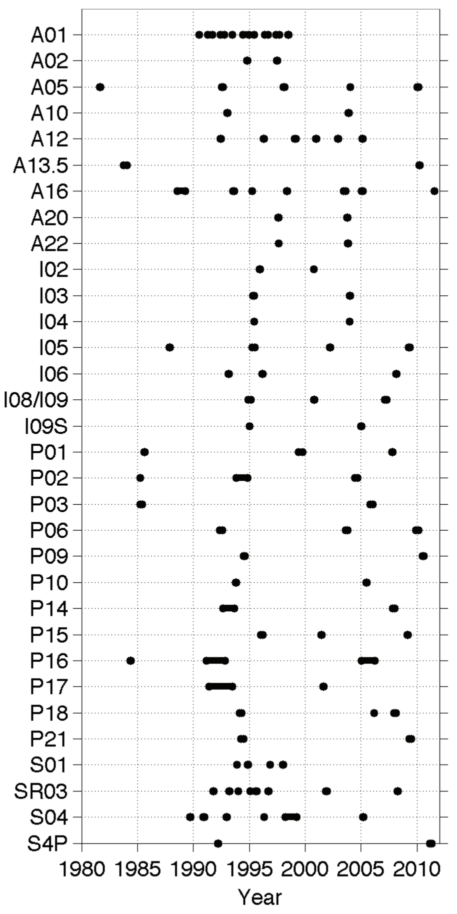
- We use 32 full-depth, high-quality hydrographic sections occupied two or more times between 1980 and 2011 (below). Tracklines of repeated sections (black lines) with World Ocean Circulation Experiment (WOCE) designators noted adjacent.



- We divide the world ocean (above) into 33 deep basins (gray lines) based on topography and bottom potential temperature (θ; colors).
- We also separately analyze the Southern Ocean using the SubAntarctic Front (SAF; white line above; Orsi et al. 1995) as a dynamical northern bounary.
- Eleven repeated tracklines (below) extend into the Southern Ocean south of the SAF (curved line).



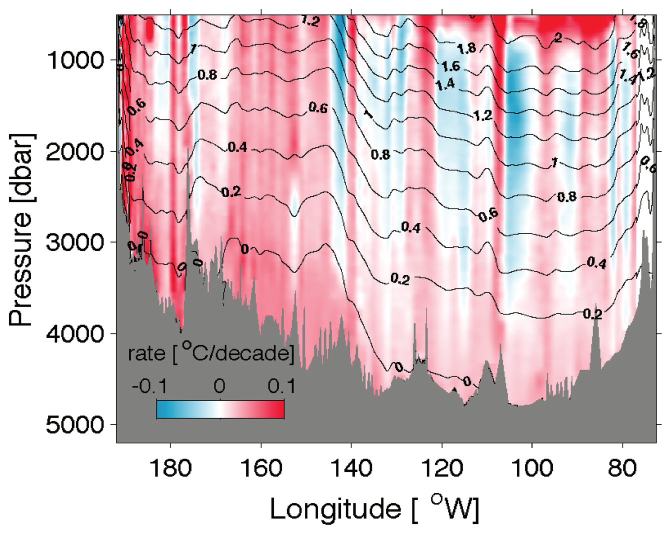
- Section occupation dates listed by their WOCE Hydrographic Program designators (right).
- Sections first occupied by WOCE with subsequent occupations supporting Climate Variability (CLIVAR) and Carbon Cycle Science Programs.
- Instrumental accuracy 0.002 °C.



References:
- Gouretski, V. V., and K. P. Koltermann, 2004: WOCE Global Hydrographic Climatology. Berichte des Bundesamtes für Seeschifffahrt und Hydrographie, 35, pp. 52 + 2 CD-ROMs.
- Orsi, A. H., T. Whitworth III, and W. D. Nowlin, Jr., 1995: On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Res. I, 42, 641-673.
- Purkey, S. G., and G. C. Johnson, 2010: Warming of Global Abyssal and Deep Southern Ocean waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. J. Climate, 23, 6336–6351. doi: 10.1175/2010JCLI3682.1.
- Purkey, S. G.,and G. C. Johnson, 2011: A slow down of Antarctic Bottom Water production and circulation between the 1980s and 2000s. J. Climate, *in prep*.
- Smith, W. H. F., and D. R. Sandwell, 1997: Global seafloor topography from satellite altimetry and ship depth sounding. Science, 277, 1956-1962.

3. Heat and SLR

- We calculate rates of change in potential temperature (θ) with time (dθ/dt) along each section from a least squares linear fit of θ vs. time. An example of dθ/dt is shown (right) along S4P (67°S). Red indicates warming and blue cooling . Mean θ values are contoured (black lines).
- We find mean dθ/dt with 95% confidence intervals along each line. Within each basin, we combine all mean dθ/dt and associated errors using length-weighted means.



- We calculate heat fluxes below an interface depth for each basin:

$$Q_i = \frac{\int_{InterfaceDepth}^{bottom} \rho \cdot C_p \cdot d\theta/dt \cdot a_i(z) \cdot dz}{a_i(4000)}$$

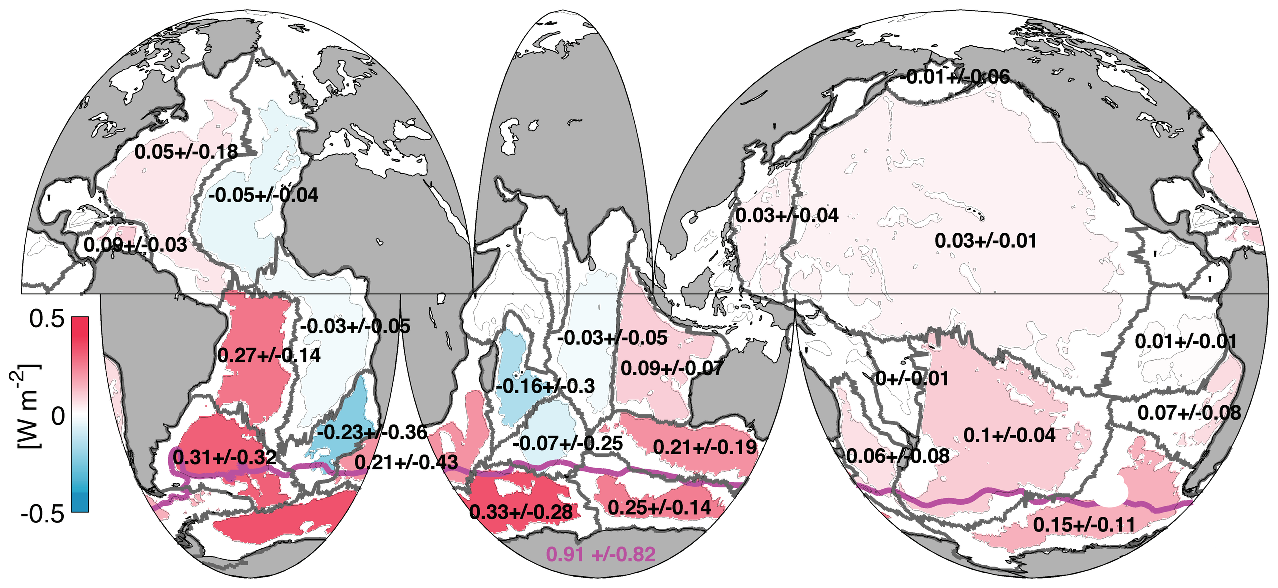
were ρ is density, Cp is the heat capacity, and a(z) is the surface area.

- We similarly calculate SLR due to thermal expansion as:

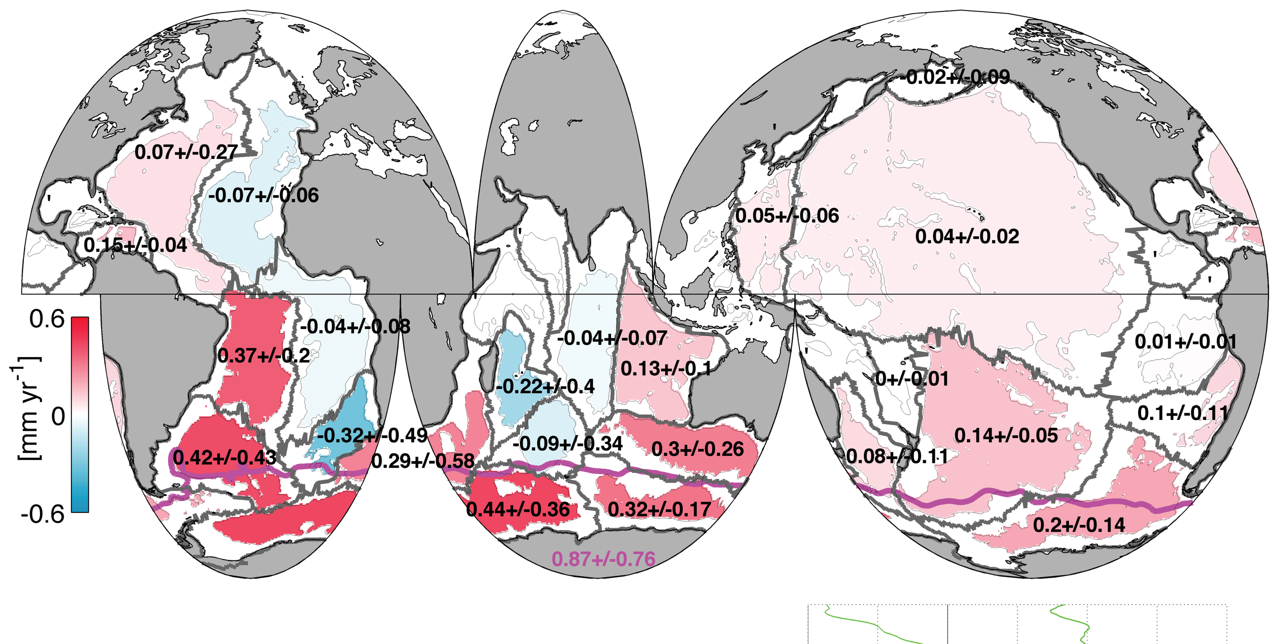
$$F_i = \frac{\int_{InterfaceDepth}^{bottom} \alpha \cdot d\theta/dt \cdot a(z) \cdot dz}{a_i(4000)}$$

were α is the thermal expansion coefficient.

- Equivalent local heat fluxes, Q , within sampled basins indicated by black numbers and color (below; see key), with 95% confidence intervals. Basin boundaries (thick gray lines) and 4000-m isobaths (thin grey lines) are shown. The local contribution to the heat flux through 1000 m south of the SAF (magenta line) implied by deep Southern Ocean warming from 1000–4000 m is also given (magenta number) with its 95% confidence interval.



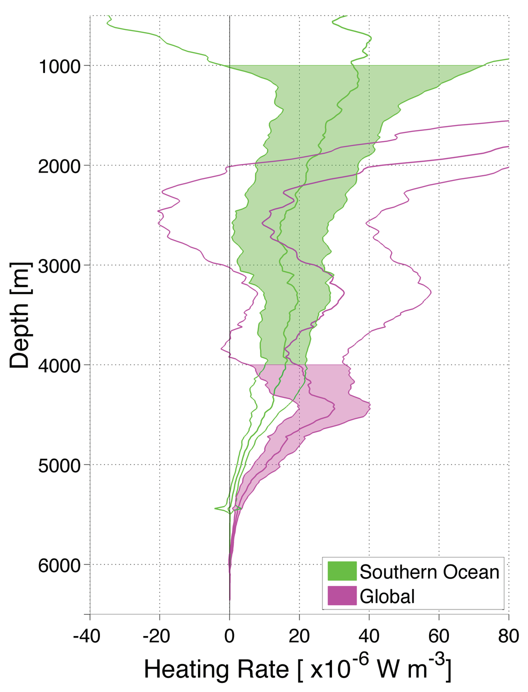
- Basin means of SLR (F) due to abyssal thermal expansion below 4000 m and deep thermal expansion in the Southern Ocean from 1000–4000 m (Below; Details follow above).



- Global abyssal heat ($Q_{abyssal}$) is estimated using:

$$Q_{abyssal} = \frac{\sum_{b=1}^{32} \rho \cdot C_p \cdot {d\theta/dt}_b(z) \cdot a_b(z) \cdot dz}{SA_{earth}} \qquad err_{95\%} = \frac{\sqrt{\sum_{b=1}^{32} (\rho \cdot C_p \cdot \sigma_{{d\theta/dt}_b} \cdot a_b)^2}}{SA_{earth}} \times 2$$

- Abyssal SLR is estimated similarly using α instead of ρ • Cp and dividing by surface area of the ocean instead of the surface area of the Earth.
- Profiles of heat gain per meter (right) with 95% confidence intervals for the global ocean (magenta) and the Southern Ocean south of the SAF (green).

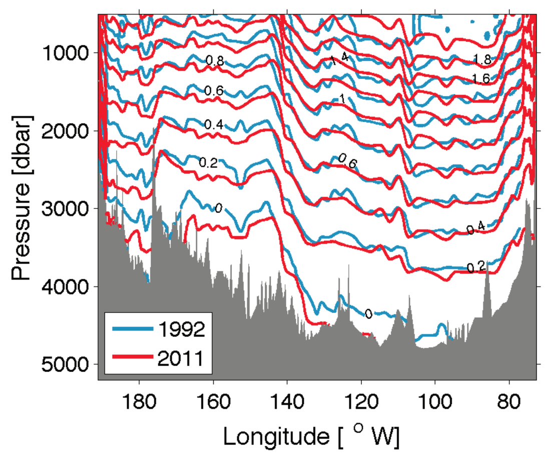


- Table: Heat fluxes over the entire surface area of the Earth required to explain the recent decadal observed temperature changes for the global ocean below the interface depth, the ocean south of the Sub Antarctic Front (SAF) between 1000 m and the interface depth, and the total of the fluxes for the previous two regions. Similarly, mean sea level rise (SLR) over the global ocean due to the thermal expansion estimated from the recent decadal temperature changes observed in the three regions described above.

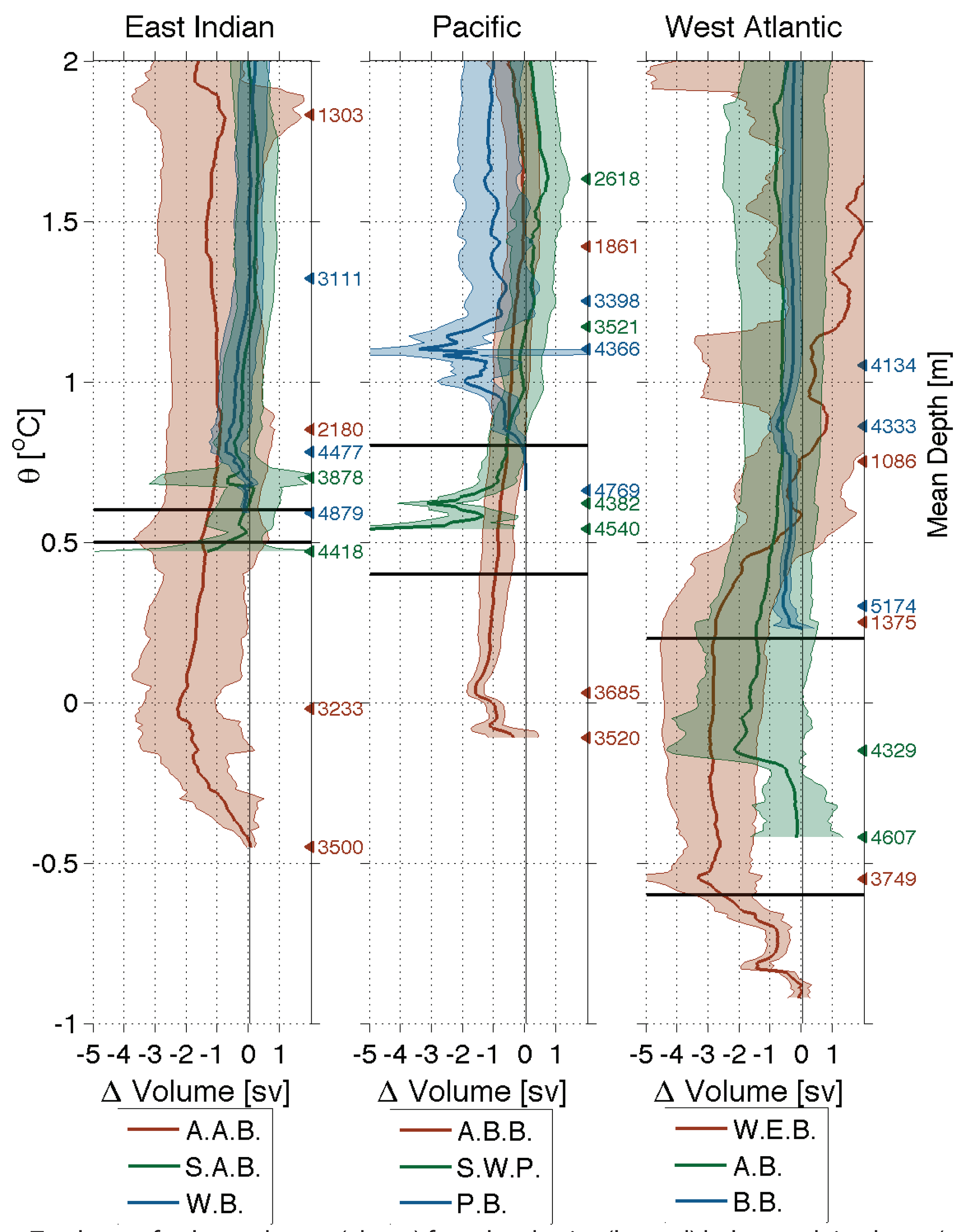
Interface depth (m)	Heat ($W\ m^{-2}$) Global: below interface depth	Heat ($W\ m^{-2}$) South of SAF: 1000-interface depth	Heat ($W\ m^{-2}$) Total	SLR ($mm\ yr^{-1}$) Global: below interface depth	SLR ($mm\ yr^{-1}$) South of SAF: 1000-interface depth	SLR ($mm\ yr^{-1}$) Total
2000	0.068 (±0.061)	0.032(±0.026)	0.099 (±0.066)	0.113 (±0.100)	0.037 (±0.030)	0.150 (±0.104)
3000	0.053 (±0.031)	0.051 (±0.047)	0.104 (±0.056)	0.097 (±0.055)	0.063 (±0.060)	0.161 (±0.081)
4000	0.027 (±0.009)	0.068 (±0.062)	0.095 (±0.062)	0.053 (±0.017)	0.093 (±0.081)	0.145 (±0.083)

4. Volume Loss

- Warming discussed in Section 3 implies a descent of isotherms and a loss in volume of the coldest water.
- Potential temperature contours (right) for the two occupations of S4P across the Amundsen-Bellinghausen Basin at 67°S with bottom topography (Smith and Sandwell 1997) shaded gray.
- We calculate a rate of change in height above the bottom with time (dh/dt) for each isotherm on a 0.01°C θ grid from least squares linear fit of h vs. time.



- We find the mean dh/dt and its uncertainty along each line within a given basin and combine all these lines using length-weighted means.
- We scale the basin mean dh/dt to a volume using climatology surface areas (Gouretski and Koltermann 2004) for each isotherm (below).



- Total rate of volume change (above) for select basins (legend) below each isotherm (solid lines) with 95% confidence intervals (shading) along three of the four pathways of the lower northeward limb of the MOC from south (red) to north (blue). The minimum θ values spreading between basins are given by the solid black lines (Gouretski and Koltermann 2004). Colored numbers along the right axis indicate the mean depth of the isotherm for the given basin. Legend abbreviations are the: Australian-Antarctic Basin (AAB), South Australian Basin (SAB), Wharton Basin (WB), Amundsen-Bellingshausen Basin (ABB), Argentine Basin (AB), and Brazil Basin (BB).
- We find a statistically significant reduction of Antarctic Bottom Water (AABW) volume in the Southern Ocean. This loss is not recovered until high in the water column where Circumpolar Deep Water (CDW) enters from the north. The AABW loss continues northward along 3 of the 4 branches of the lower MOC, suggesting a global scale contraction of AABW.

5. Conclusions

- **The abyssal ocean has warmed significantly since the 1990s owing to a loss of its coldest water.**
- **The recent decadal warming of the abyssal global ocean below 4000 m is equivalent to a global surface energy imbalance of 0.027 (±0.009) W m^{-2}, with Southern Ocean deep warming contributing an additional 0.068 (±0.062) W m^{-2} between 1000 and 4000m. The abyssal and deep warming contributes about 0.15 mm yr^{-1} to the global sea level rise.**
- **The abyssal warming is caused by a reduction of bottom water. This volume loss amounts to -8 (±2.6) Sv below 0 °C. The loss continues, albeit attenuated, northward along 3 of the 4 branches of the lower MOC, suggesting a global-scale contraction of AABW.**