On the Mechanisms of Deep-Ocean Warming in the South Pacific

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1. OVERVIEW

The observed Earth's net energy imbalance requires that all extra heat is stored in the climate system, mostly in the World Ocean, which is the dominant reservoir of heat uptake. Sea level, as a natural indicator of the full-depth ocean heat content, has been accurately measured by satellite altimetry since 1992. Measurements of ocean mass variations provided by the GRACE twin satellites since 2002 can be subtracted from altimetric sea surface height to derive steric changes (due to temperature and salinity) of sea level. The advent of Argo profiling floats has made available global observations of temperature and salinity for depths above 2000 m since 2003. In this work, we combine satellite and situ data to investigate the regional signatures and mechanisms of deep-ocean warming for the 2005-2014 time period. We observe significant deep-ocean warming in the South Pacific and propose a mechanism responsible for this warming.

2. DATA PRODUCTS USED

- Sea surface height (SSH) from AVISO satellite altimetry data;
- Products of equivalent water thickness from GRACE (Gravity Recovery and Climate Experiment) twin satellites: CSR.RL05 (Center for Space Research, U. Texas), GFZ.RL05 (GeoForschungsZentrum, Potsdam), JPL.RL05 (Jet Propulsion Laboratory, Pasadena);
- Products of gridded temperature and salinity data: Scripps Institution of Oceanography (SIO) Argo dataset, National Oceanographic Data Center (NOAA) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) datasets.
- ERA-Interim 10-m wind velocity, wind stress, and net surface heat flux.

3. STERIC SEA LEVEL CHANGE OVER 2005-2014

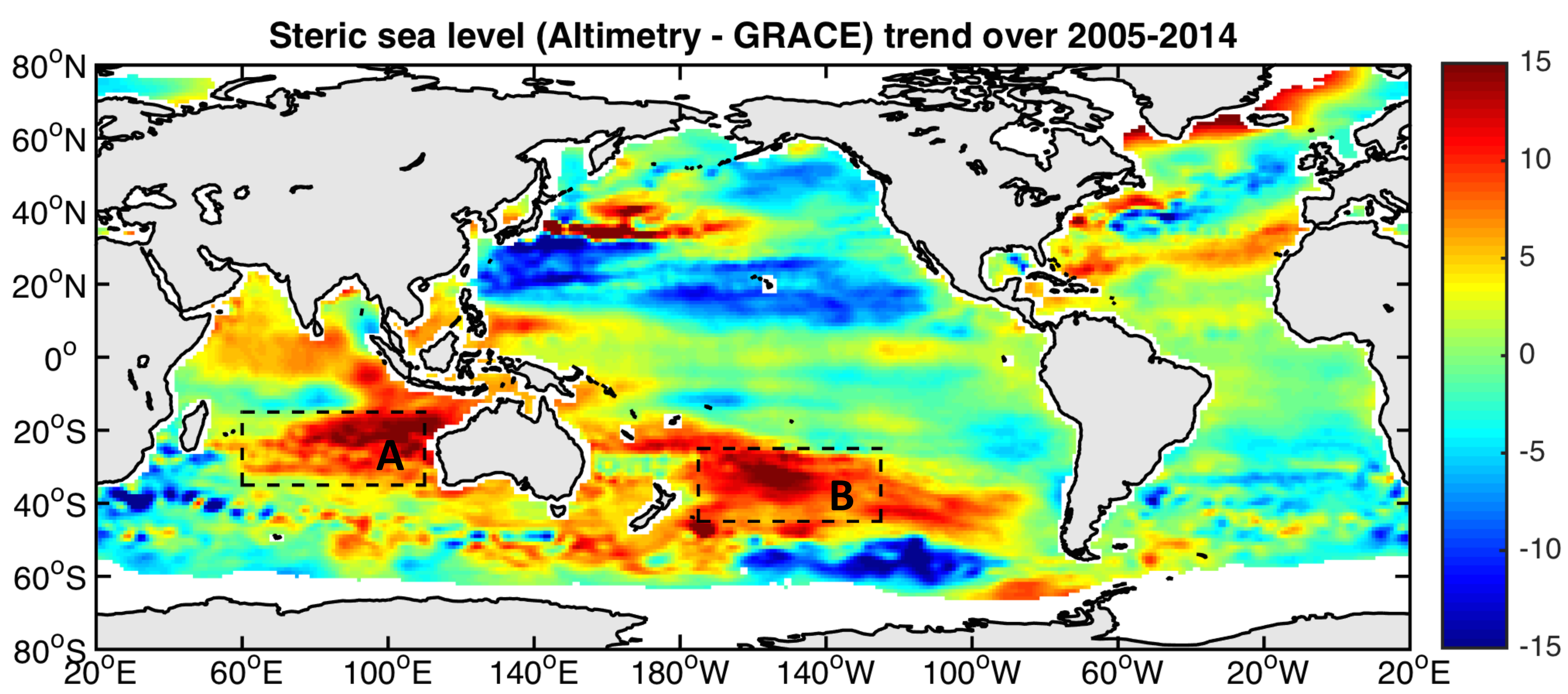

Figure 1. Linear trend of the steric sea level (mm yr^{-1}) over the 2005-2014 time interval. The steric sea level is computed as difference between satellite altimetry and GRACE (CSR.RL05) data. The average trends over the boxes A and B, computed using 3 GRACE products (CSR.RL05, GFZ.RL05, JPL.RL05) are shown in Table A.

Table A. Trends of steric SSH in boxes A and B.

Data Product	South Indian Ocean (Box A)	South Pacific Ocean (Box B)
ALT – CSR	8.3 ± 1.5	9.2 ± 1.5
ALT – GFZ	8.4 ± 1.5	7.5 ± 1.5
ALT – JPL	8.2 ± 1.5	9.6 ± 1.5

4. HEAT CONTENT CHANGE IN THE UPPER 2000 METERS

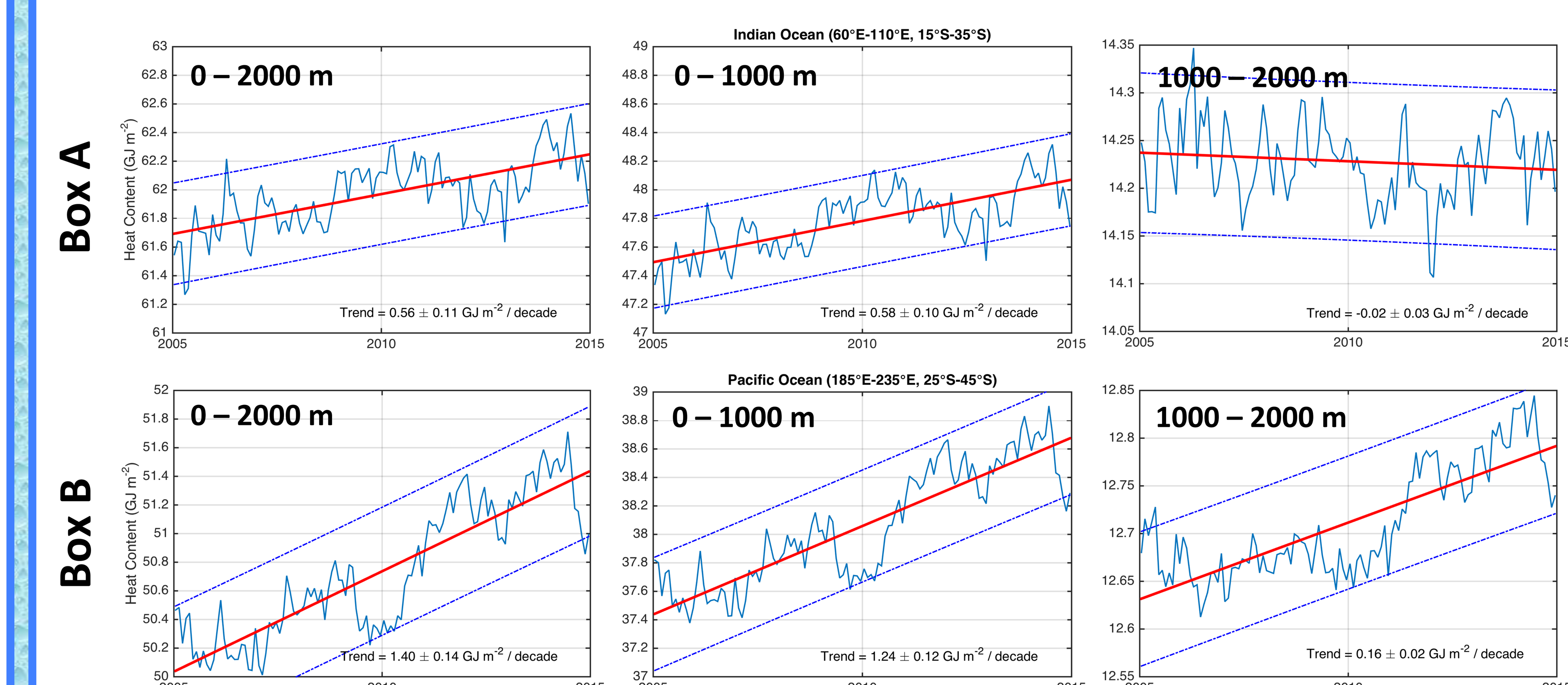

Figure 2. Heat content calculated from JAMSTEC temperature data over 0-2000 m, 0-1000 m, and 1000-2000 m depth intervals, and averaged over the box A in the South Indian Ocean (top) and over the box B in the South Pacific Ocean (bottom). ***Note that the South Indian Ocean warming is limited to the upper 1000 m, while the South Pacific exhibits a significant warming between 1000 and 2000 m depth.*** The rest of the poster is, therefore, dedicated to the South Pacific.

5. SEA LEVEL BUDGET AND INFERRED DEEP-OCEAN CONTRIBUTION

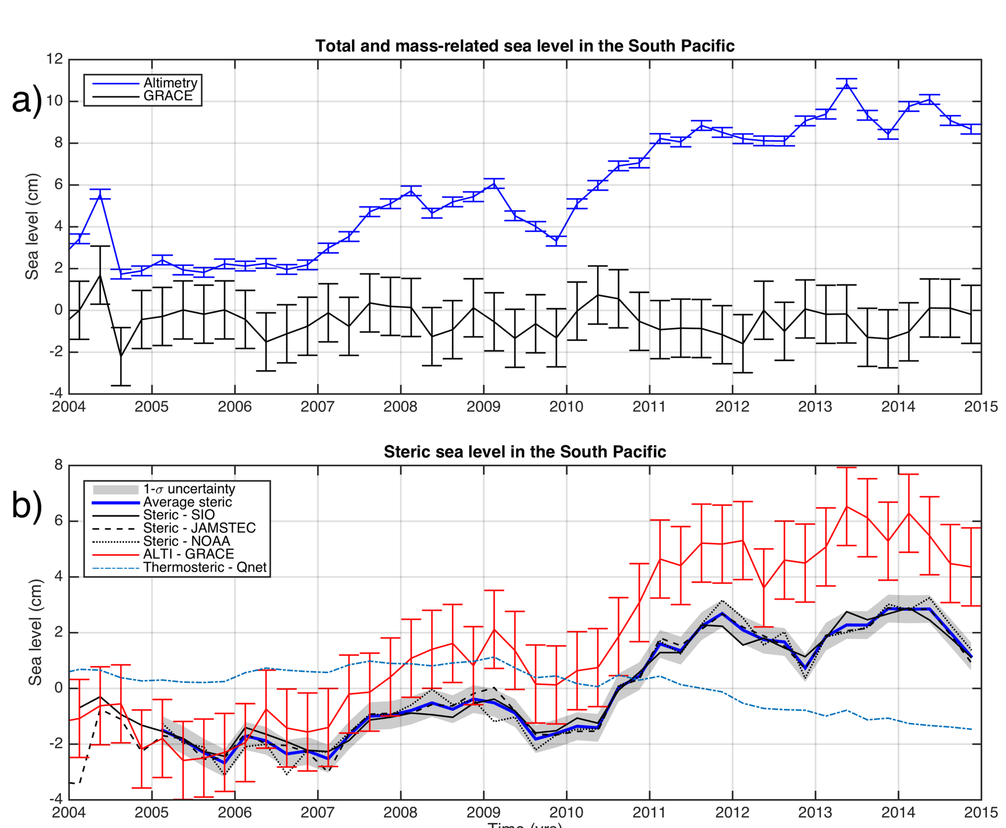

Figure 3. Sea level time series averaged over the box B (185°E-235°E, 25°S-45°S): (top) total SSH from altimetry (blue) and mass-related SSH from GRACE satellites (black); (bottom) steric SSH obtained from in situ data products for the upper 2000 m (blue) and calculated as the difference between altimetry and GRACE records for the entire water column (red). The thermosteric sea level due to the net surface heat flux is shown by the blue dotted curve. Linear trends of steric sea level calculated from in situ data products for the upper 2000 m are presented in **Table B**.

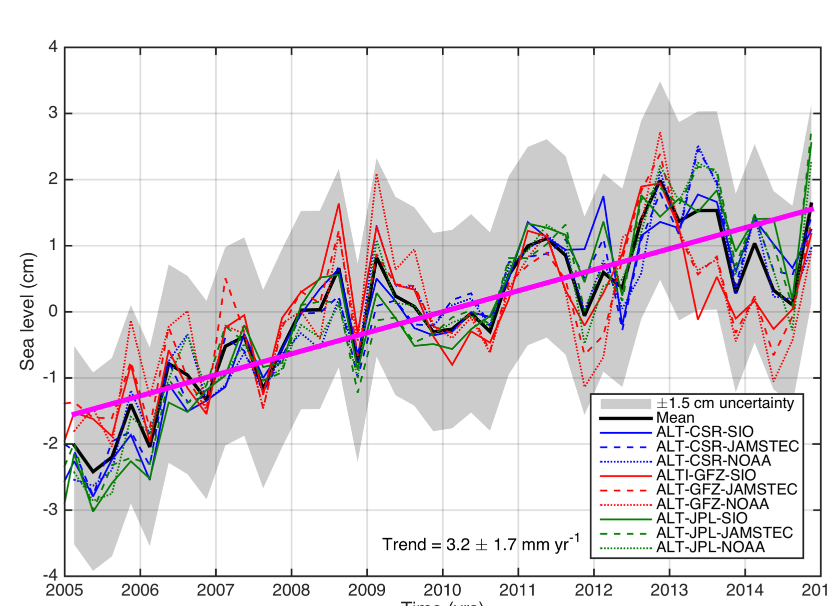

Figure 4. Difference between the satellite-derived (entire water column) and in situ-derived (for the upper 2000 m) steric sea levels, showing the contribution of the deep ocean (2000 m – bottom). The 2005-2014 trend estimates for different data products used are presented in **Table B**.

Table B. Trends of steric SSH in box B for different products.

Depth	Data Product	Linear trend (mm yr^{-1})
0 – 2000 m	*SIO*	5.4 ± 0.5
	NOAA	5.8 ± 0.5
	JAMSTEC	5.5 ± 0.5
2000 m - bottom	*ALT – CSR – SIO*	3.8 ± 1.6
	ALT – CSR – NOAA	3.4 ± 1.6
	ALT – CSR – JAMSTEC	3.6 ± 1.6
	ALT – GFZ – SIO	2.1 ± 1.6
	ALT – GFZ – NOAA	*1.7 ± 1.6*
	ALT – GFZ – JAMSTEC	2.0 ± 1.6
	ALT – JPL – SIO	4.2 ± 1.6
	ALT – JPL – NOAA	3.8 ± 1.6
	ALT – JPL - JAMSTEC	4.1 ± 1.6

6. MECHANISM OF DEEP-OCEAN WARMING

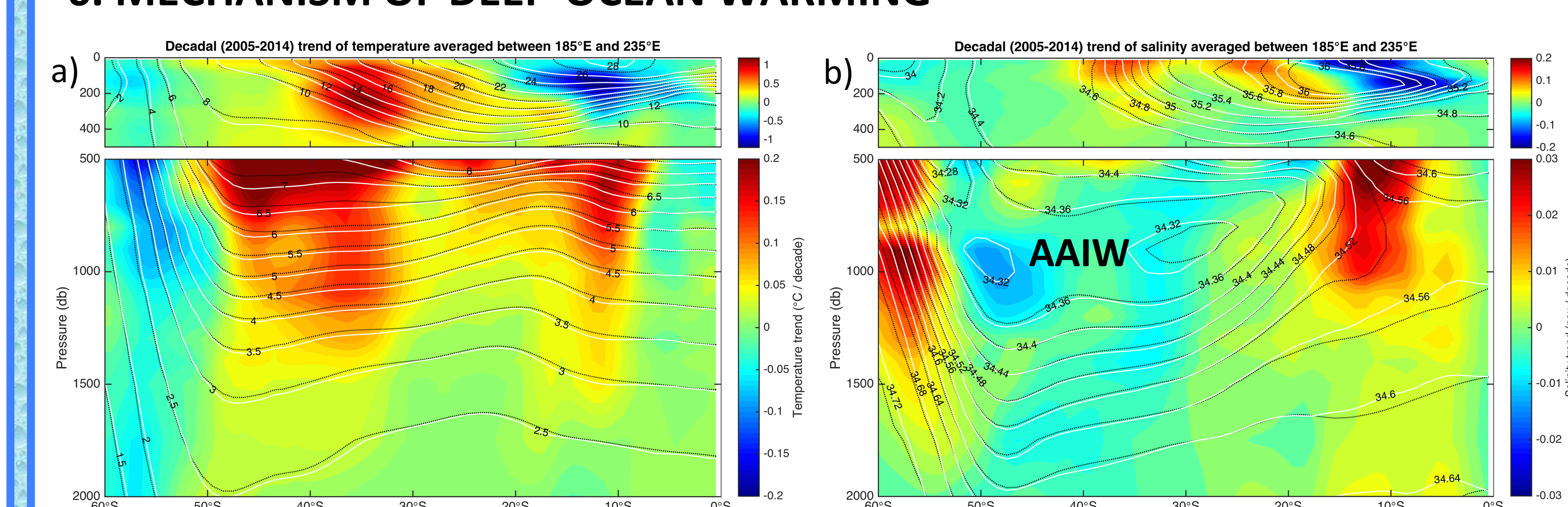

Figure 5. Decadal trends of (a) temperature and (b) salinity averaged between 185°E and 235°E. The black/white curves show the isotherms and isohalines in the first/last month of the decadal linear trend. Note that north of 50°S the isotherms are deeper at the end than at the beginning of the decade. The trends suggest a temperature increase and a salinity decrease of the Antarctic Intermediate Water (AAIW), located at about 700-1200 m depth range.

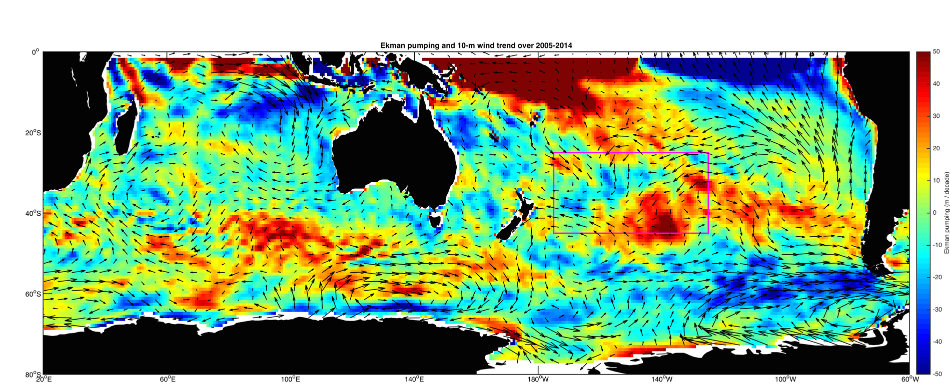

Figure 6. Decadal (2005-2014) trends of the cumulative Ekman pumping (color) and 10-m wind speed (arrows). The westerly winds over the Antarctic Circumpolar Current and trade winds were increasing over the decade. This led to a stronger convergence in the subtropical gyre and increased Ekman pumping.

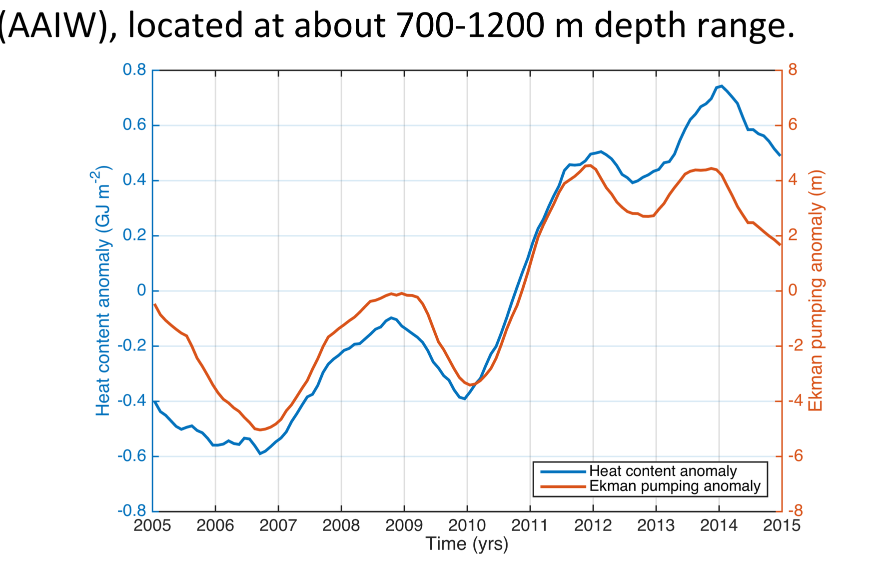

Figure 7. Heat content of the upper 2000 m calculated from JAMSTEC temperature data (blue) and the cumulative Ekman pumping averaged over 185°E-235°E, 25°S-45°S. The time series are smoothed with a yearly moving average.

7. SUMMARY

- The largest trends of the steric sea level over the 2005-2014 time interval, associated with ocean warming, are observed in the Southern Indian and Pacific Oceans (Fig. 1);
- Warming is limited to the upper 1000 m in the South Indian Ocean, while significant warming is observed between 1000 and 2000 m depth in the South Pacific Ocean (Fig. 2 and Table B);
- Indirect estimates (difference between the satellite and in situ estimates of the steric sea level change) suggest significant warming below 2000 m depth in the South Pacific Ocean; the average linear trend of the steric SSH due to this warming is 3.2±1.6 mm yr^{-1};
- We hypothesize that the observed deep-ocean warming in the South Pacific Ocean is related to Ekman convergence: strengthening of westerly winds over the Southern Ocean and trade winds in the South Pacific leads to an increased convergence in the Box B. Associated with Ekman convergence is Ekman pumping that deepens isotherms below the mixed layer.

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