Deep Ocean Warming Assessed from Altimeters, GRACE, in-situ Measurements, and a Non-Boussinesq OGCM

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Introduction: Observational surveys have shown significant oceanic bottom-water warming, but they are too spatially and temporally sporadic to quantify the deep ocean contribution to the present day sea-level rise (SLR). In this study, altimetry sea surface height (SSH), GRACE ocean mass, and *in-situ* upper-ocean (0-700m) steric height have been assessed for their seasonal variability and trend maps. It is shown that neither the global mean nor the regional trends of altimetry SLR can be explained by the upper-ocean steric height plus the GRACE ocean mass. A non-Boussinesq ocean general circulation model (OGCM), allowing the sea-level to rise as a direct response to the heat added into the ocean, is then used to diagnose the deep-ocean steric height. Constrained by sea-surface temperature data and the top-of-atmosphere (TOA) radiation measurements, the model reproduces the observed upper-ocean heat content well. Combining the modeled deep-ocean steric height with observational upper-ocean data gives the full-depth steric height. Adding a GRACE-estimated mass trend, the data-model combination explains not only the altimetry global mean SLR but also its regional trends fairly well. The deep ocean warming is mostly prevalent in the Atlantic and Indian Oceans, and along the Antarctic Circumpolar Current, suggesting a strong relation to the oceanic circulation and dynamics. Its comparison with available bottom-water measurements shows reasonably agreement, indicating that deep-ocean warming below 700 m might have contributed 1.1 mm/year to the global mean SLR or one-third of the altimeter-observed rate of 3.11±0.6 mm/year over 1993-2008.

1. Sea-Level Budget

The the altimeter-observed SLR should match the sum of the steric sea level (SSL) and the ocean mass changes:

$$SL_{total} = SL_{steric} + SL_{mass}$$

Or Mathematically:

$$\frac{\partial \eta}{\partial t} = \left(-\frac{1}{\rho_0}\int_{-700\,m}^{0} \frac{\partial \rho}{\partial t} dz - \frac{1}{\rho_0}\int_{-H}^{-700\,m} \frac{\partial \rho}{\partial t} dz \right) + \frac{1}{g\rho_0}\frac{\partial P_b}{\partial t}$$

Altimetry (Upper-Ocean + Deep-ocean) GRACE

2. Previous Studies

For the GRACE period :

- Lombard et al (2007): Altimeter (3.1 mm/yr) >> In-situ (-2.8) + GRACE (1.2)
- Willis et al (2008): Altimeter (3.2 mm/yr) >> Argo (-0.5) + GRACE (0.8)
- Leulliette & Miller (2009) : Altimeter (2.7 mm/yr) = Argo (0.8) + GRACE(0.8)
- Cazenave et al (2009): Altimeter (2.5 mm/yr) = Ago (0.3) + GRACE/Land water(2.0)
- Willis et al (2010): Altimeter (3.2 mm/yr) = Ago (1.2) + GRACE (1.3)
- Wu et al (2010): Altimeter (3.2 mm/yr) = ?? + GRACE (0.6)

For the altimetry period :

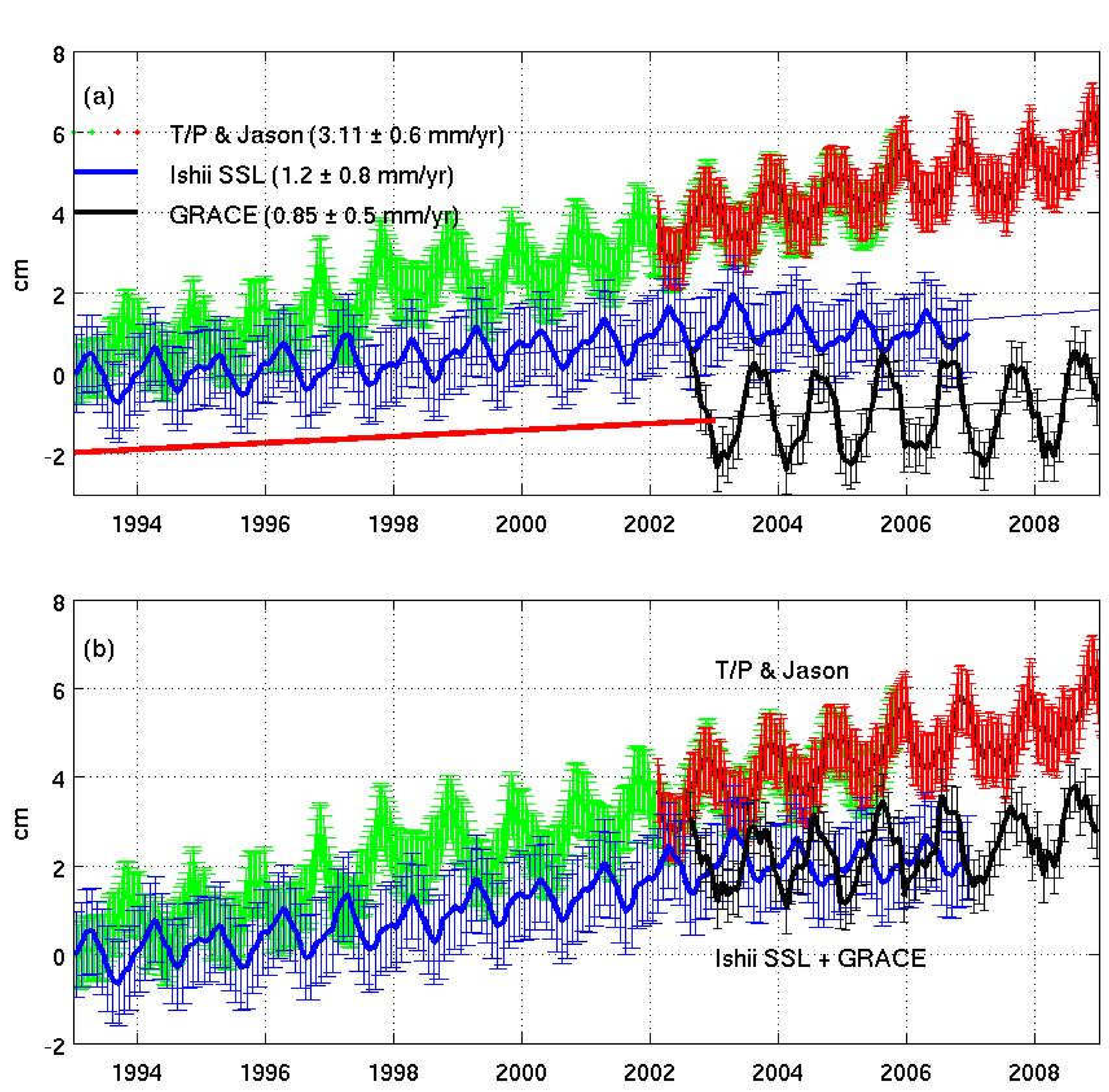
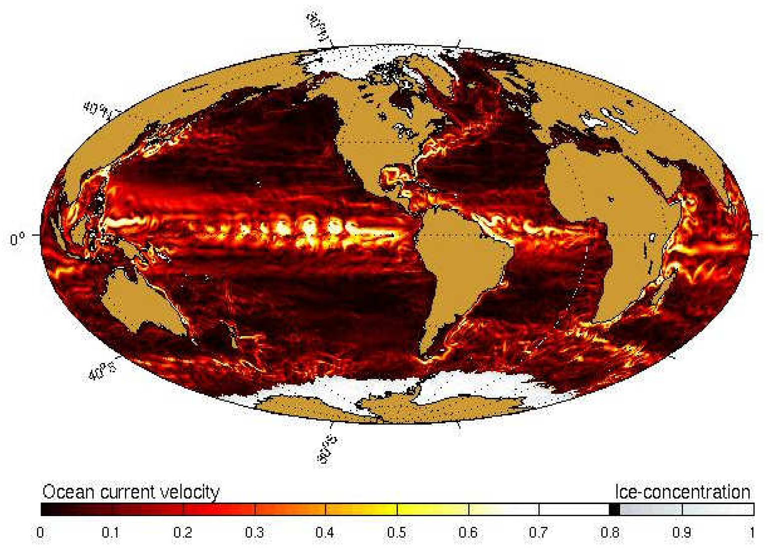


Figure 1: Time series of altimetry SSH, GRACE ocean mass, and upper-ocean (0-700m) SSL from Ishii and Kimoto [2009].

3. Deep Ocean warming from NB-OGCM



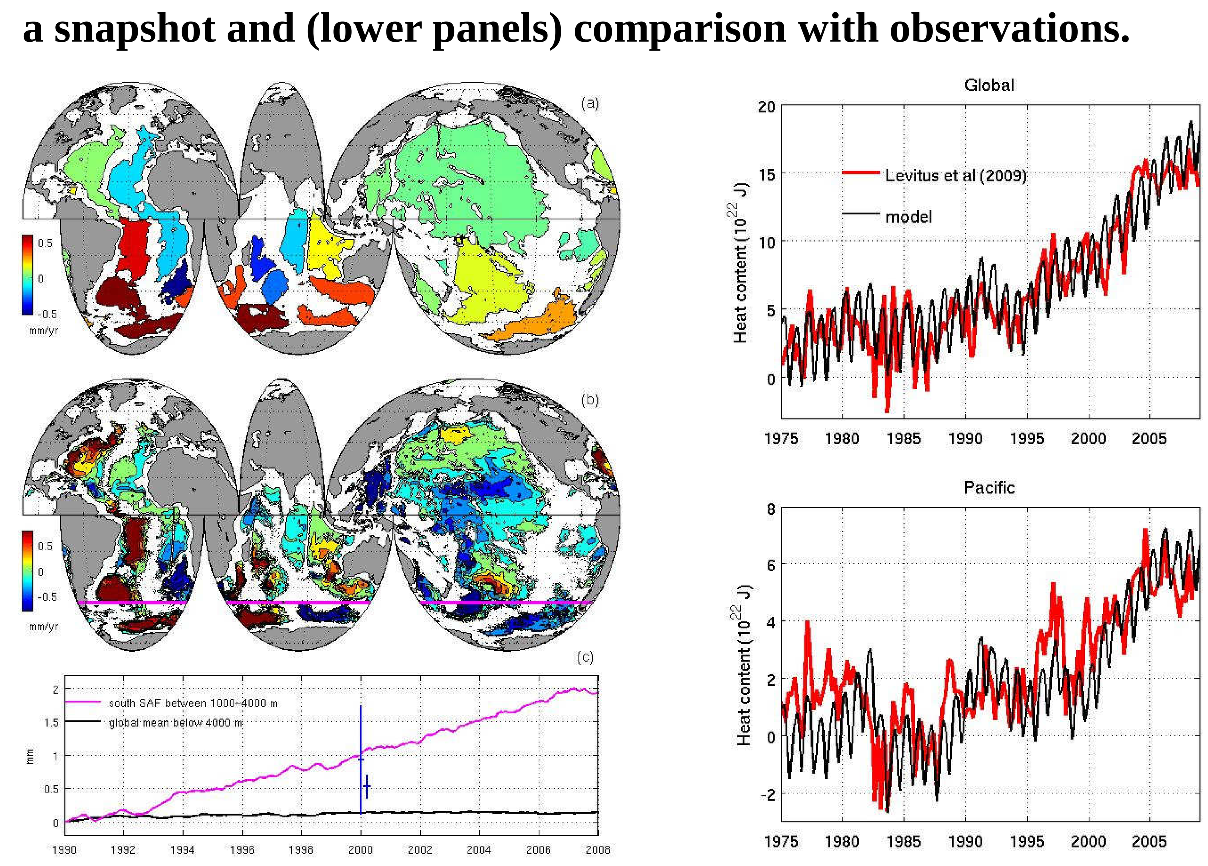


Figure 2: Coupled ice-ROMS for the global ocean: (upper panel) a snapshot and (lower panels) comparison with observations.

4. Sea-Level Budget for the Altimetry Period

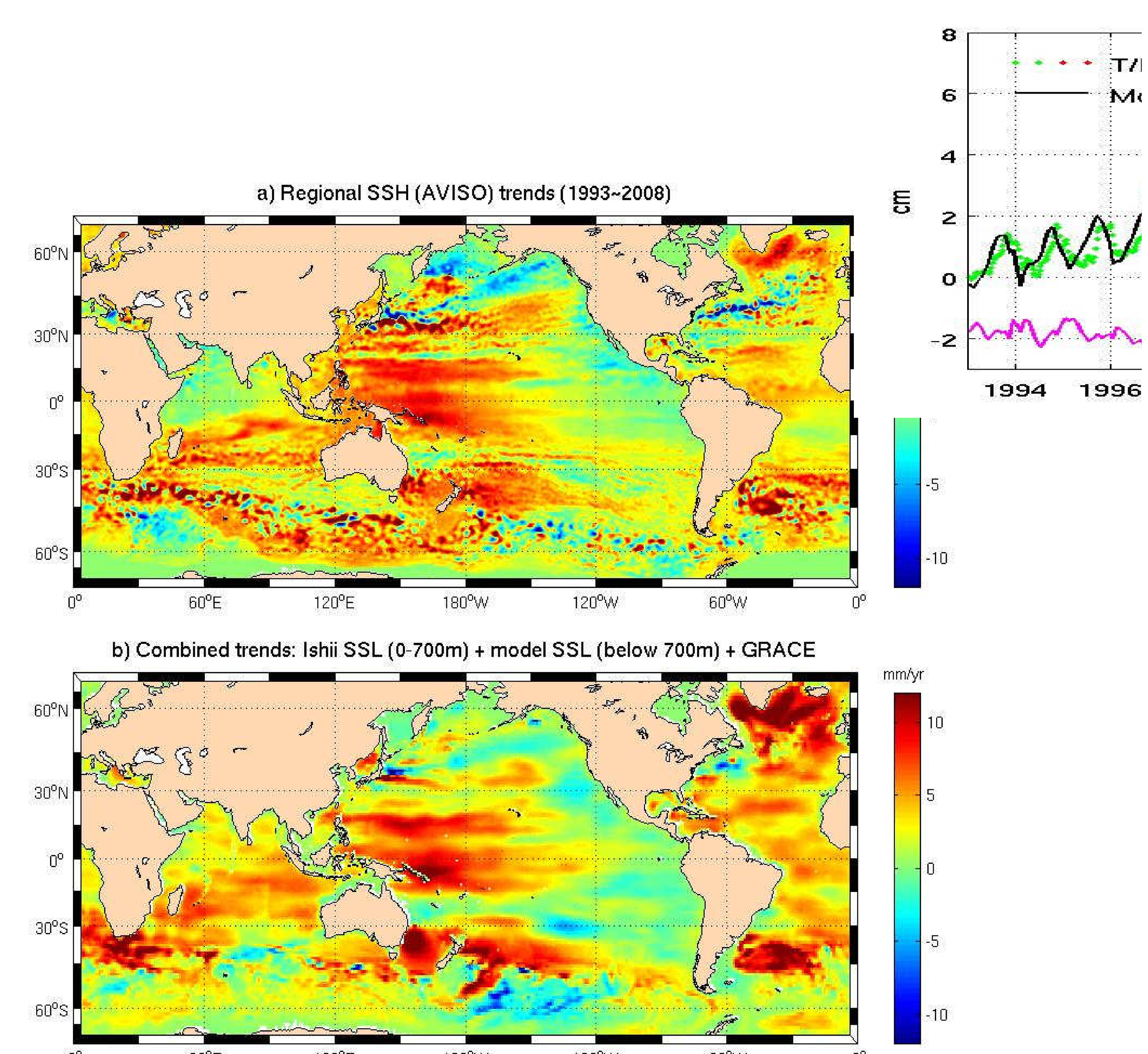


Figure 3: (upper panel) Time series of altimetry GRACE mass, and model SSL. (lower panels) Regional sea-level budget trends with deep-ocean warming included.

Reference:

Song, Y.T. and F. Colberg, 2011: Deep ocean warming assessed from altimeters, Gravity Recovery and Climate Experiment, in situ measurements, and a non-Boussinesq ocean general circulation model, *J. Geophys. Res.*, **116**, C02020, doi:10.1029/2010JC006601.

Song, Y.T., R. Gross, X. Wang, and V. Zlotnicki, 2010: A non-Boussinesq terrain-following OGCM for oceanographic and geodetic applications, *Advances in Geosciences*, **18** (Ocean Science, Eds. Gan et al.), 63-86.

Song, Y. T. and T. Y. Hou, 2006: Parametric vertical coordinate formulation for multiscale, Boussinesq, and non-Boussinesq ocean modeling, *Ocean Modelling*. Doi:10.1016/j.ocemod.2005.01.001.