Improved Ocean Warming Estimates: Implications for Climate Models and Sea-Level Rise

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1. Why **GLOBAL SEA LEVEL RISE** in the past 40 years (1961-2003) does not match what would be expected from the **SUM** of the **WATER EXCHANGE BETWEEN OCEAN AND OTHER RESERVOIRS** (ice sheets, mountain glaciers, small ice caps, land) and **THERMAL EXPANSION**?

Total = Mass (water exchange) + Volume (thermal expansion)
Ocean Heat Content / Thermal Expansion might be underestimated.

Underestimate signal (zero anomaly) in ocean areas where sampling coverage is poor (e.g. Southern Hemisphere)

(Levitus et al., GRL, 2004; Ishii et al., 2006; Gille, J. Clim., 2008, accepted).
Global ocean stores ~90% excess heat trapped in the Earth System.

Significant ocean warming (thermal expansion) contribution to sea level rise in the last 40 years.

IPCC AR4 – Chapter 5 (Bindoff et al., 2007)
Unresolved questions

2. Why don’t climate models simulate the large 10-year variability observed in the 1970s?

WCRP 20CM3 simulations with Anthropogenic Forcing used in IPCC AR4

Models without volcanic forcing

Models with volcanic forcing

Levitus et al.
Ishii et al.

Climate modelling community has questioned magnitude of decadal variability (1970-1980).

Suggested signal amplification due to uneven observational sampling (AchutaRao et al., PNAS, 2007).
XBT data comprise a significant portion of the ocean observing system.

Gouretski and Koltermann (GRL, 2007) recently identified warm biases in XBTs.

Wijffels et al. (J. Clim., 2008, accepted) show that:

**Instrument type dependent** (shallow, deep)

Characteristic of **fall-rate error**

**Time-variable** warm bias (year to year changes in XBT fall-rates)

**Spatially synchronised** (likely due to small changes in the manufacture of XBT probes)

Provide **depth-factor corrections**
Our Objective:
New Estimates of Ocean Heat Content (Thermal Expansion)

To allow for sampling and instrumental biases of the hydrographic observations:

Our quasi-global (65°S to 65°N) estimates are reconstructed for 1950-2003 and are based on a reduced space optimal analysis using quality-controlled and bias-corrected temperature profiles for the upper 700 m.

Selected temperature observations: Bottles, CTDs, XBTs from ENACT 3 (Ingleby and Huddleston, J. Mar. Syst., 2007) and local QCed version of Argo floats (Barker et al., in prep.).


New temperature climatology: LOESS mapping with a linear time dependent term on top of the annual and semi annual terms in the parametric fit (Dunn and Ridgway, DSRI, 2002; Alory et al., GRL, 2007; Wijffels et al., J. Clim., 2008, accepted).

Reduced space optimal analysis: Altimeter sea level (1993-2006) is used to estimate the global covariance structure as expressed in EOFs. Amplitude of EOFs is obtained from the relatively sparse but longer time span of ocean temperature profiles. The reconstructed global distribution of thermosteric sea level for each month is obtained as a weighted sum of these EOFs. (Kaplan et al., J. Clim., 2000; Church et al., J. Clim., 2004; Church and White, GRL, 2006).
Method

Reduced Space Optimal Analysis

\[ \text{SSH}_r(x,y,t) = \text{Ur}(x,y) \alpha(t) + \epsilon(x,y,t) \]

\[ S(\alpha) = (\text{HU}_r - \text{SSH}_o)^T R^{-1}(\text{HU}_r - \text{SSH}_o) + \alpha^T \Lambda \alpha \]

- **Altimeter sea level** (1993-2006) is used to estimate the global covariance structure as expressed in EOFs.

- Amplitude of EOFs is obtained from the relatively sparse but longer time span of ocean temperature profiles.

- The reconstructed global distribution of **thermosteric sea level** for each month is obtained as a weighted sum of these EOFs.

- Convert steric height into ocean heat content

✓ sea surface temperature (e.g. Kaplan et al., 1998)
✓ sea level pressure (e.g. Kaplan et al., 2000)
✓ sea surface height (e.g. Church et al., 2004)
Testing Reconstruction Robustness

Observational Sampling

• **White et al. (2008, in prep.)**
  have performed experiments in models to test the robustness of the reconstruction method.

• One of the tests was to subsample the model grid based on the temporal and spatial distribution of ocean temperature profiles.

They show the difference between the yearly estimates from model and reconstruction to be $\leq 5$ mm during most of the period. ($1960-2000 \rightarrow 0.13$ mm/yr)
Our New Estimates of Global Ocean Heat Content (3-year running mean)

Increased rate of warming from 1976/1977 (climate shift).

Levitus et al.
Ishii et al.
Domingues et al.
Our New Estimates of Global Ocean Heat Content

Linear trend ~50% larger than previous estimates.
~90% heat stored in the upper 300 m (~95% thermosteric sea level).
Decadal variability in models without volcanic forcing is not in good agreement.

Simulated multi-decadal trends overestimate the observed ocean warming.
Decadal variability in models that include volcanic forcing in good agreement.

Simulated multi-decadal trends tend to underestimate the observed ocean warming (30% smaller in the upper 300 m and 10% smaller in the upper 700 m).
Components of the Sea Level Budget

**Deep ocean** (Antonov et al., GRL, 2005; Kohl et al., JPO, 2007).

**Ice sheets** (linearly increases towards the 1990s estimates, as compiled in Lemke et al., IPCC, 2007)

**Glacier and small-ice caps** (Dyurgerov and Meier, 2004).

**Terrestrial storage** (Ngo-Duc et al., GRL, 2005).

(3-year running mean)

The sum of the components are in **good agreement** with updated estimates of global mean sea level.

Different **decadal variability** is an indication of the uncertainty in the estimates and unknown variability of the cryospheric contributions.

**Satellite altimeter diverges after 1999,** implying a higher rate of rise.
Conclusions

- **Better agreement** in the magnitude of observed and simulated decadal variability
- **Larger Trends** in ocean heat content and upper ocean steric rise
- **Improved closure** of the sea-level budget over multi-decadal periods
- **Progress** since the last two IPCC reports (Church et al., 2001; Bindoff et al., 2007).

- An **ongoing need** for careful quality control of observational data and for **detailed** global and regional **comparisons** of observational estimates with **climate models** to understand the **implications** for the detection, attribution and projection of **climate change and sea-level rise**.
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