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

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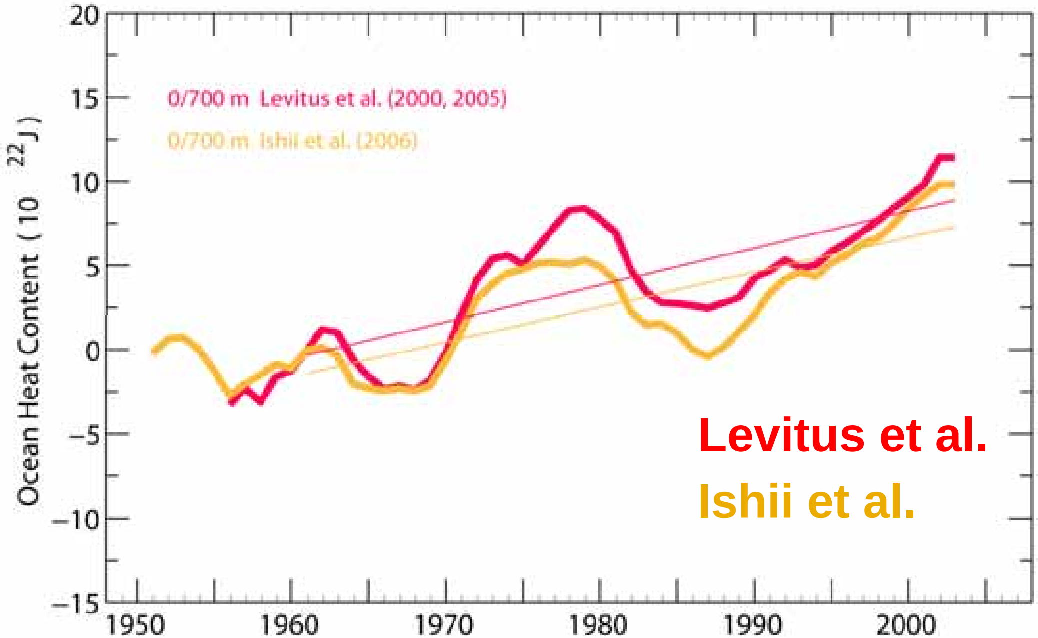
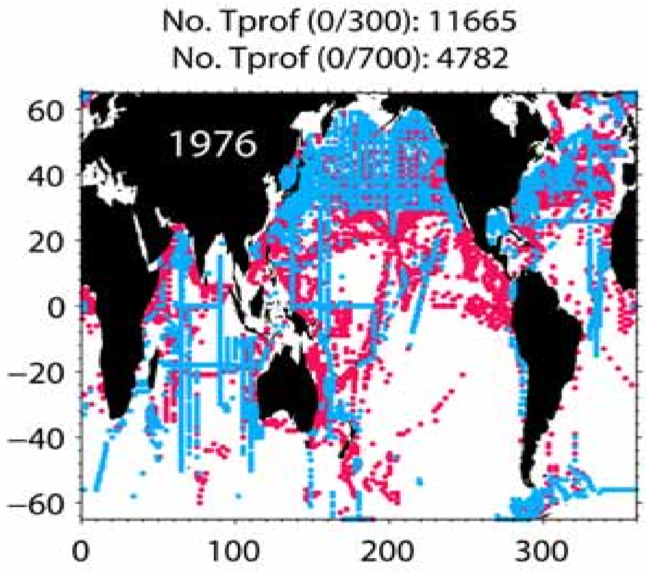
Unresolved questions

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 ??





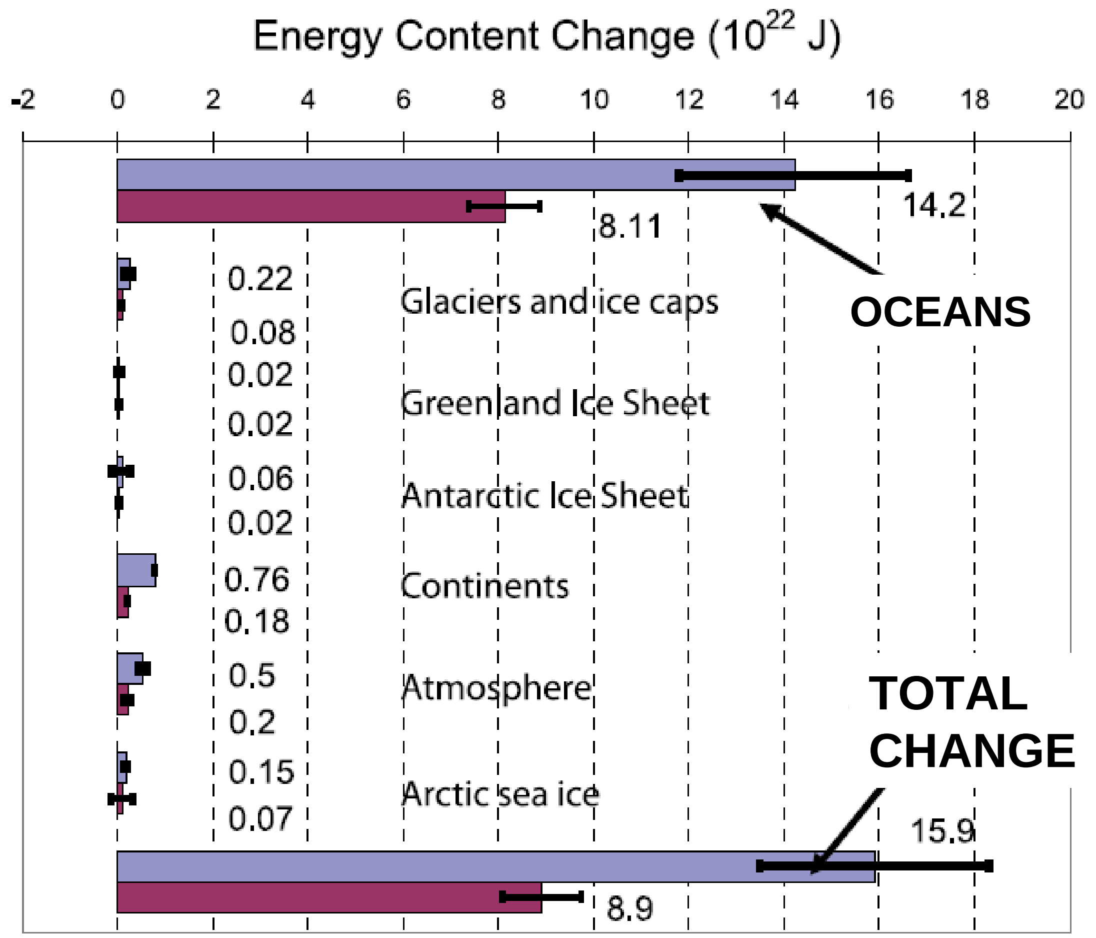
Underestimate signal (zero anomaly) in ocean areas where sampling coverage is poor (e.g. Southern Hemisphere)

(Gregory et al., GRL, 2004; Gille, J. Clim., 2008, accepted).

Have we got estimates of global ocean heat content correct?
(and Thermal Expansion)

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.



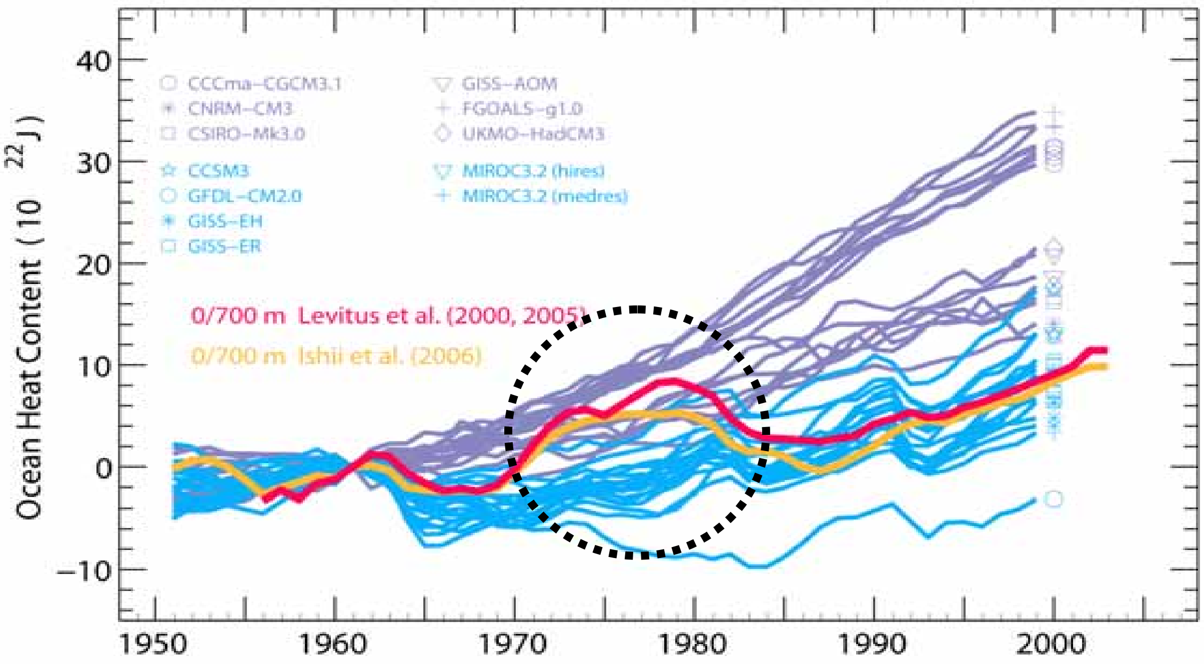
IPCC AR4 – Chapter 5 (Bindoff et al., 2007)

Unresolved questions

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

Although observational estimates show similar multi-decadal trends and decadal variability

WCRP 20CM3 simulations with Anthropogenic Forcing used in IPCC AR4



Models without volcanic forcing

Models with volcanic forcing

Levitus et al.

Ishii et al.

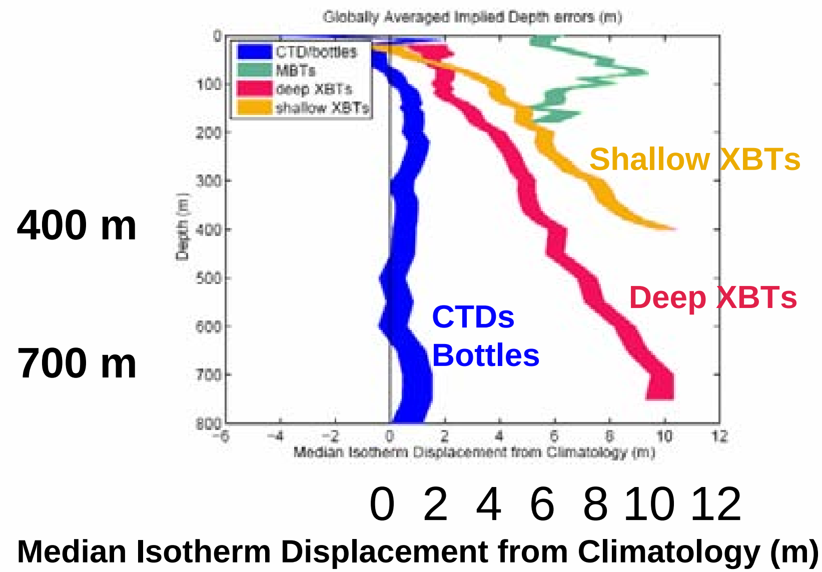
Climate modelling community has questioned magnitude of decadal variability (1970-1980).

Suggested signal amplification due to uneven observational sampling (AchutaRao et al., PNAS, 2007).

Observed Global Ocean Heat Content Now Known to Contain Instrumental Biases

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:

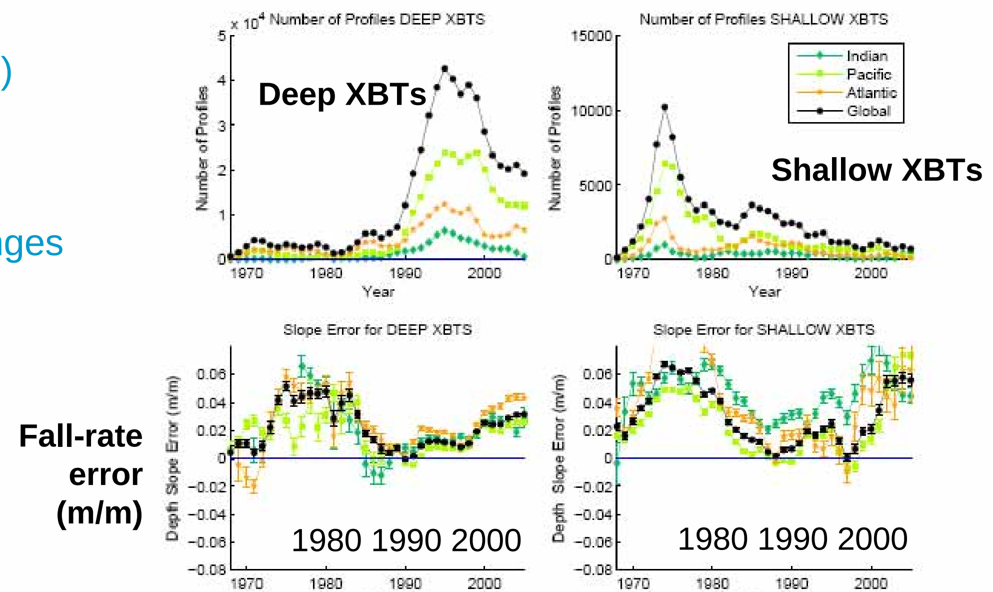
Instrument type dependent (shallow, deep)

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 (**65ºS to 65ºN**) 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.).**

Corrected for time-dependent XBT biases (Wijffels et. al., J. Clim., 2008, accepted).

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

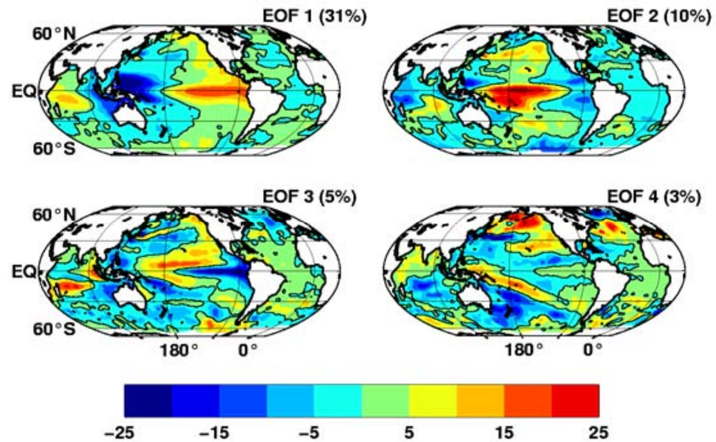
- ✓ sea surface temperature (e.g. Kaplan et al., 1998)
- ✓ sea level pressure (e.g. Kaplan et al., 2000)
- ✓ sea surface height (e.g. Church et al., 2004)

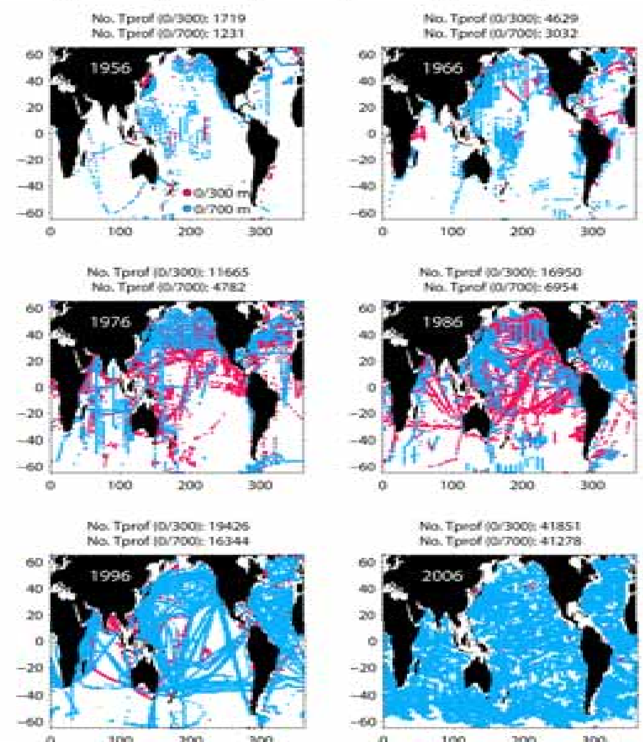
Reduced Space Optimal Analysis

$$SSHr(x,y,t) = Ur(x,y)\,\alpha(t) + \epsilon(x,y,t)$$

$$S(\alpha) = (HUr\alpha - SSHo)^T R^{-1}(HUr\alpha - SSHo) + \alpha^T \Lambda \alpha$$

- **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





Testing Reconstruction Robustness

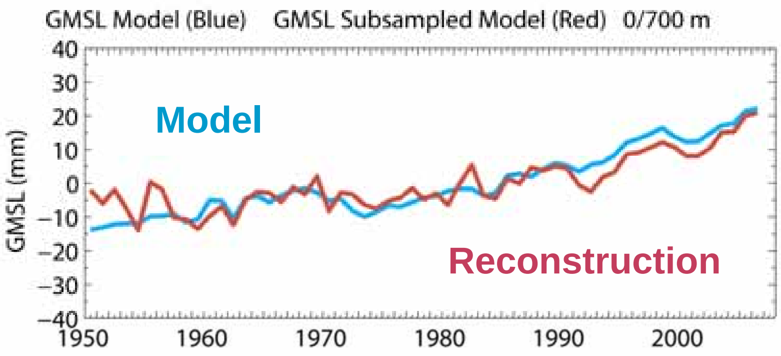
Observational Sampling

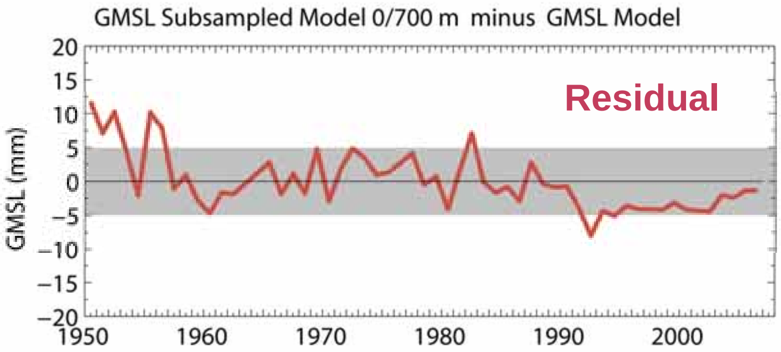
- **White et al. (2008, in prep.)**

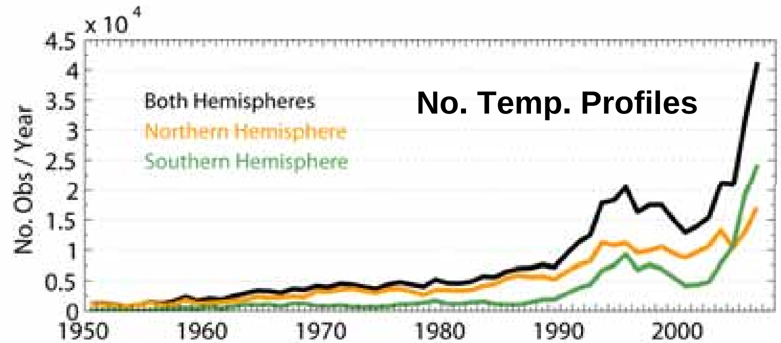
  have performed experiments in models to test the robustness of the reconstruction method.

- 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 ≤ 5 mm during most of the period. (1960-2000 → 0.13 mm/yr)

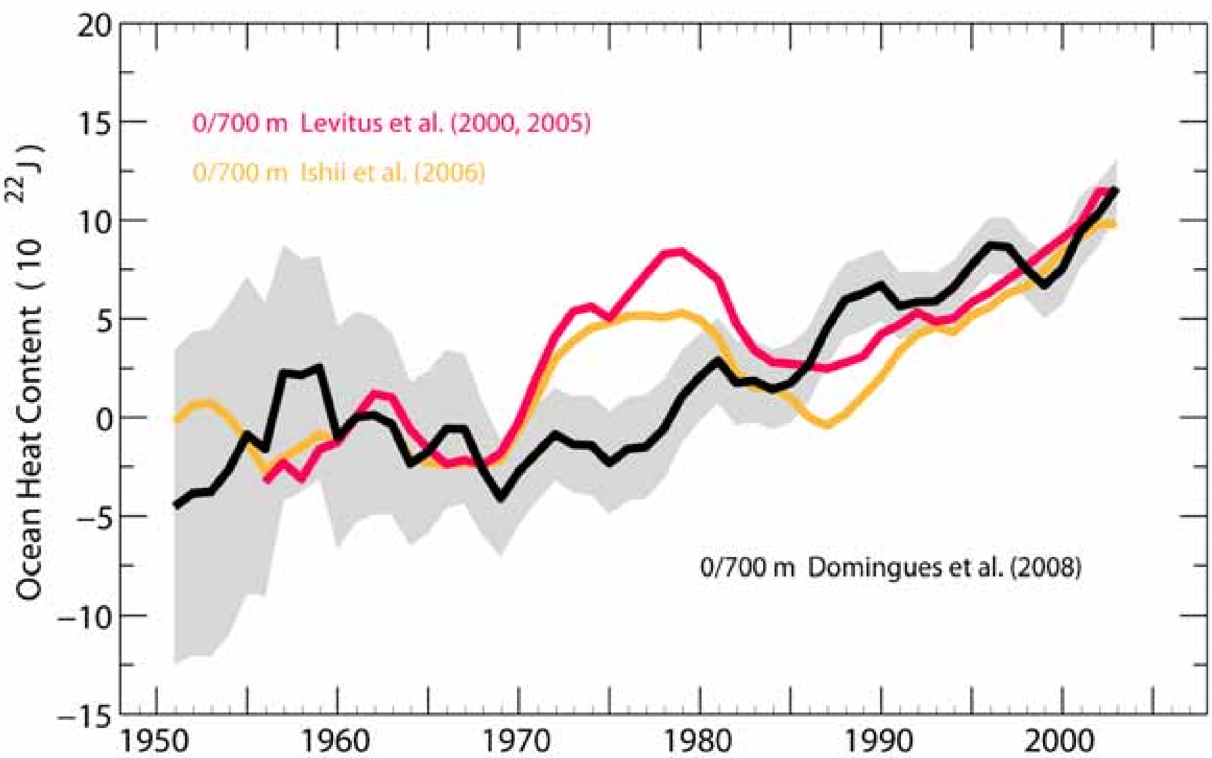






Our New Estimates of Global Ocean Heat Content

(3-year running mean)



Levitus et al.

Ishii et al.

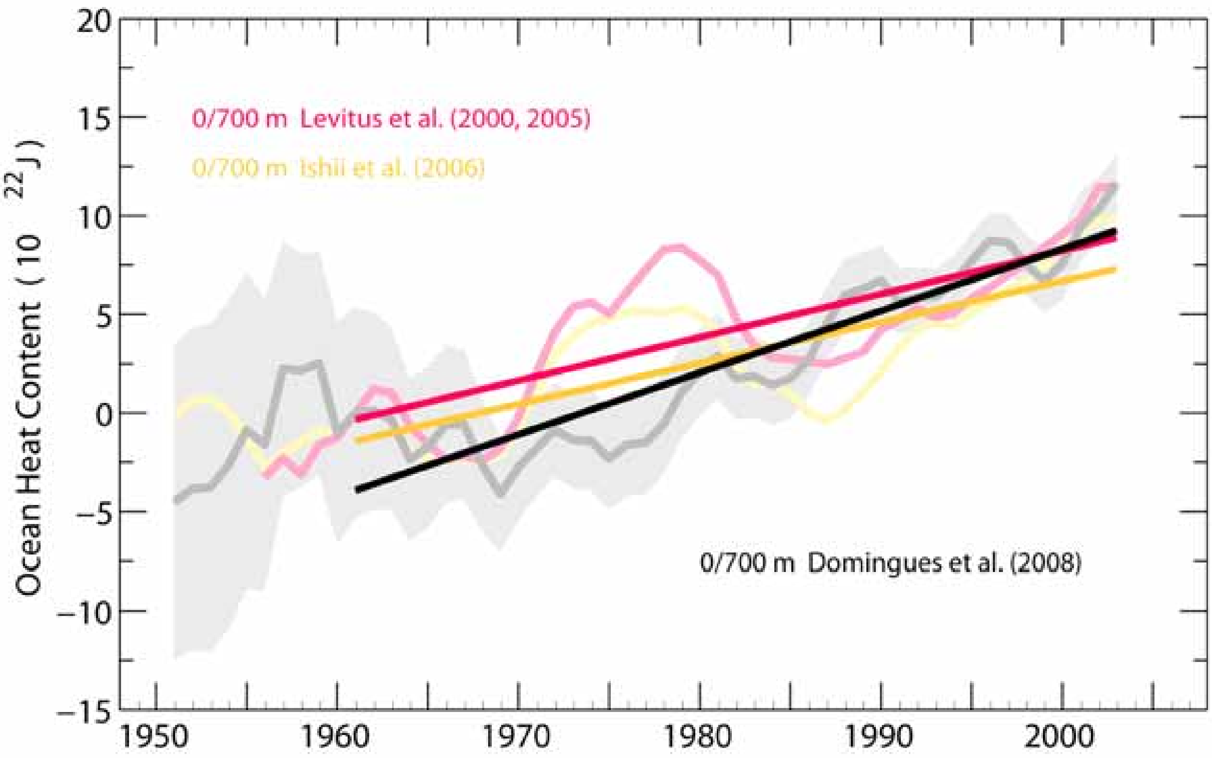
Domingues et al.

Smaller amplitude of the 1970-1980s decadal signal.

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

Smaller rate of warming for 1993-2003.

Our New Estimates of Global Ocean Heat Content Multi-Decadal Warming (1961-2003)



Levitus et al.
Ishii et al.
Domingues et al.

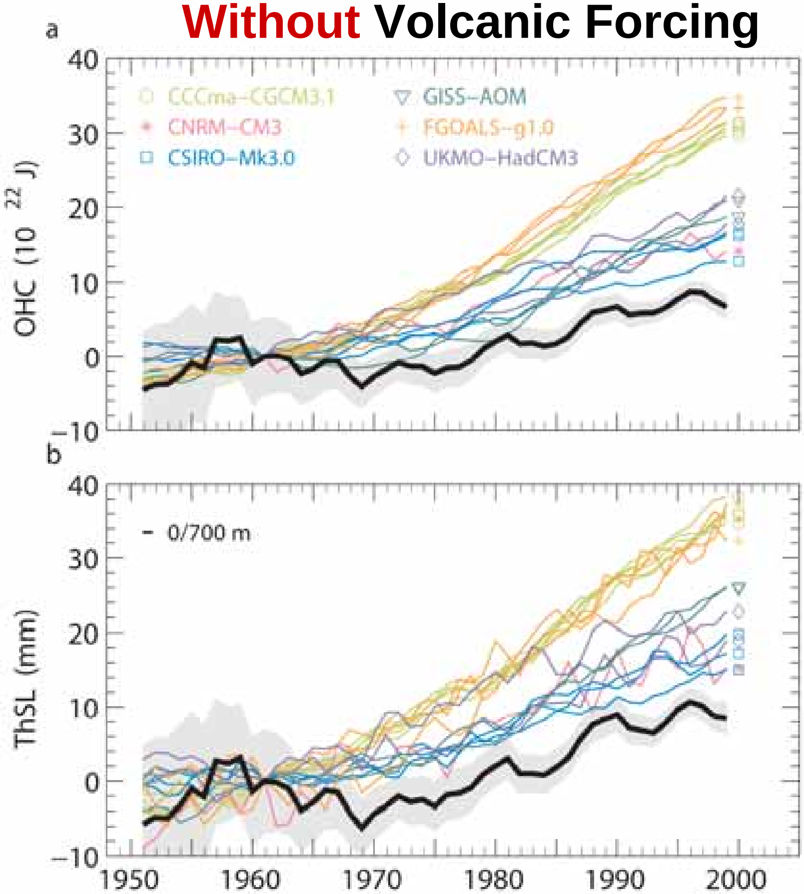
Higher rate of multi-decadal warming (1961-2003).

Linear trend ~50% larger than previous estimates.

~90% heat stored in the upper 300 m (~95% thermosteric sea level).

Comparison with IPCC AR4 Models (1961-1999) Including Anthropogenic Forcing

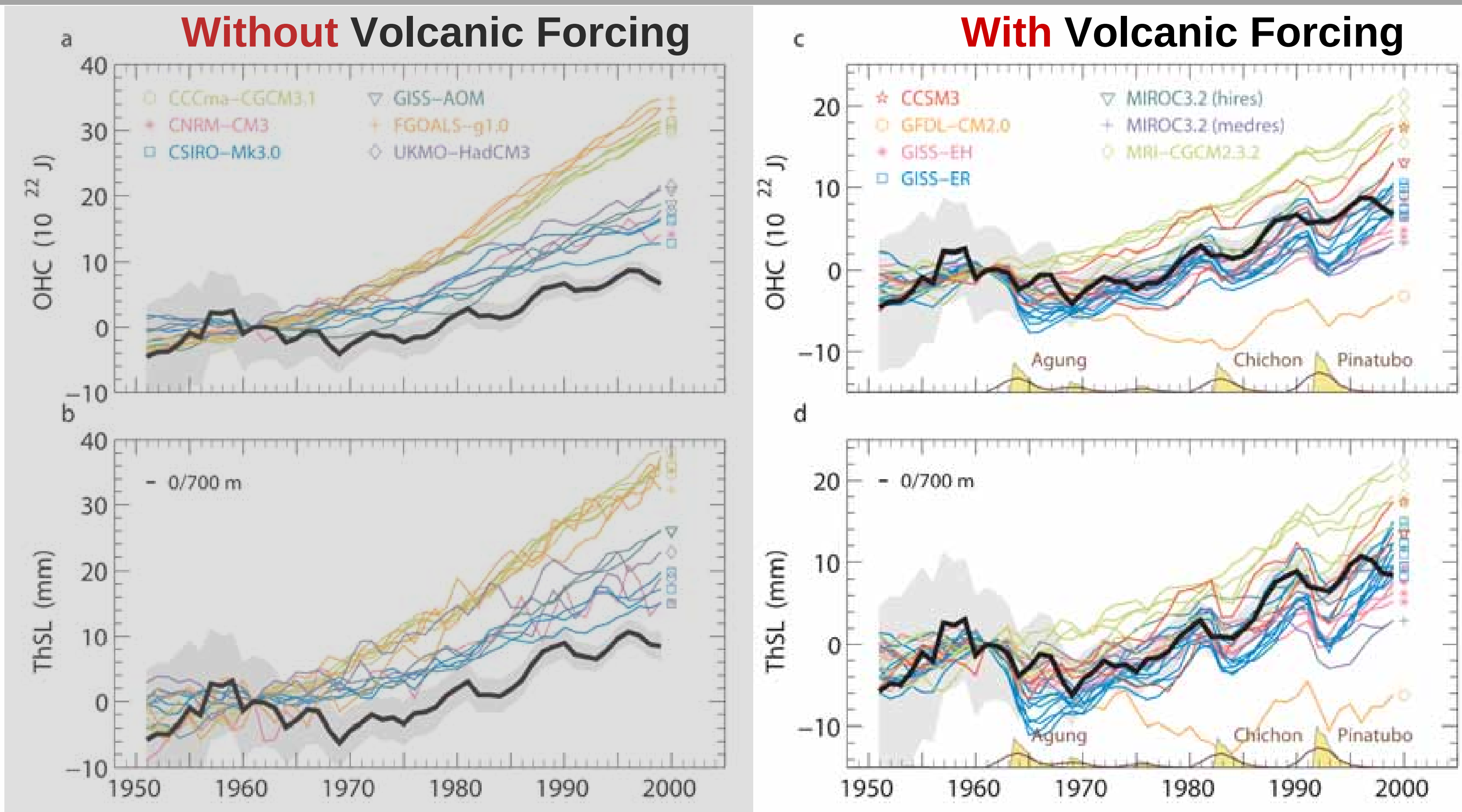
Without Volcanic Forcing



Decadal variability in models without volcanic forcing is not in good agreement.

Simulated multi-decadal trends overestimate the observed ocean warming

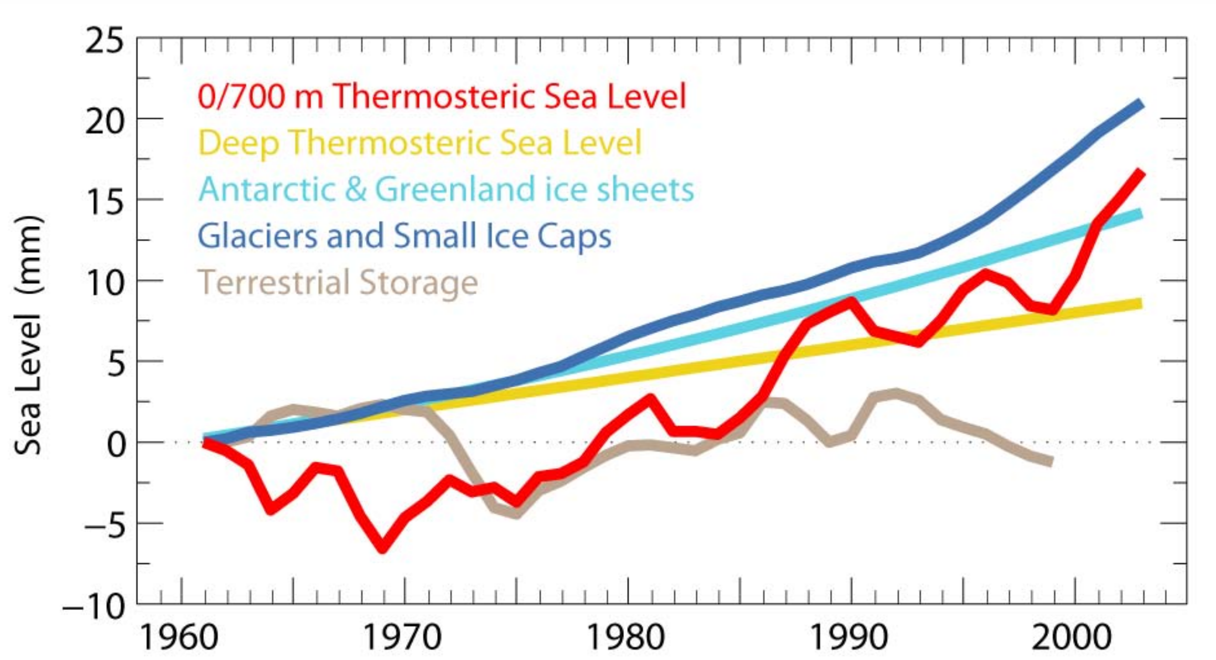
Comparison with IPCC AR4 Models (1961-1999) Including Anthropogenic Forcing



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).

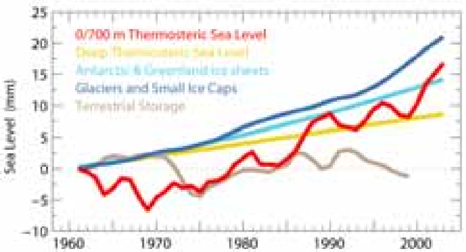
Ice sheets (linearly increases towards the 1990s estimates, as compiled in Lemke et al., IPCC, 2007)

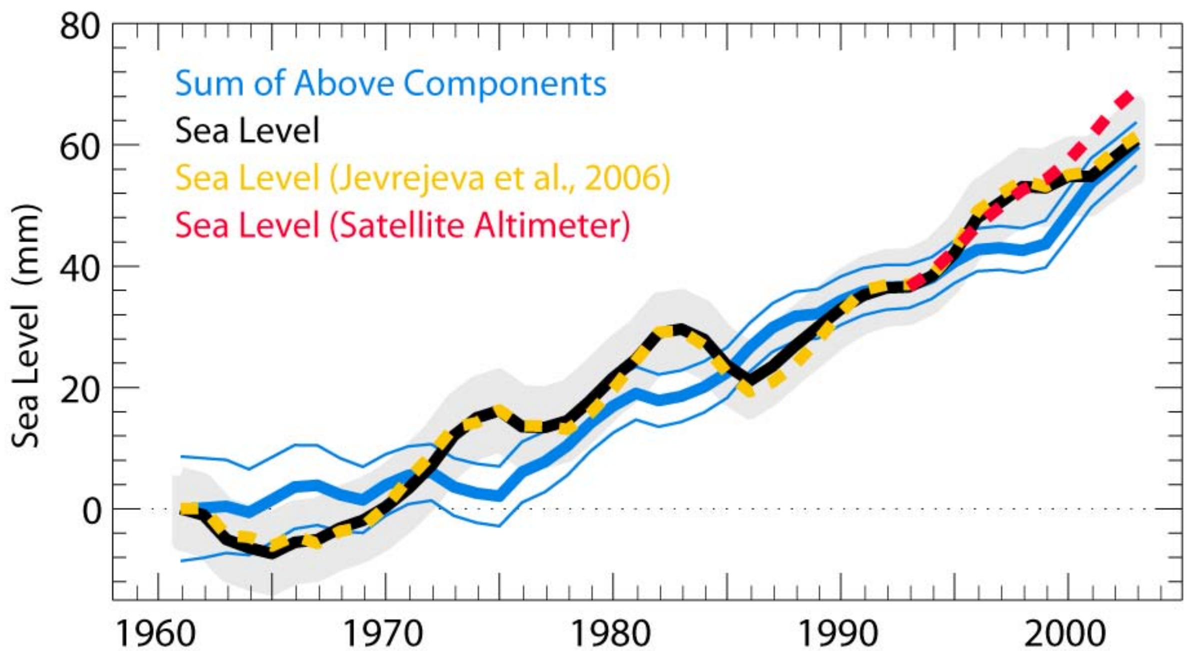
Glacier and small-ice caps (Dyurgerov and Meier, 2004).

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

The Multi-Decadal Sea Level Budget (1961-2003)

(3-year running mean)





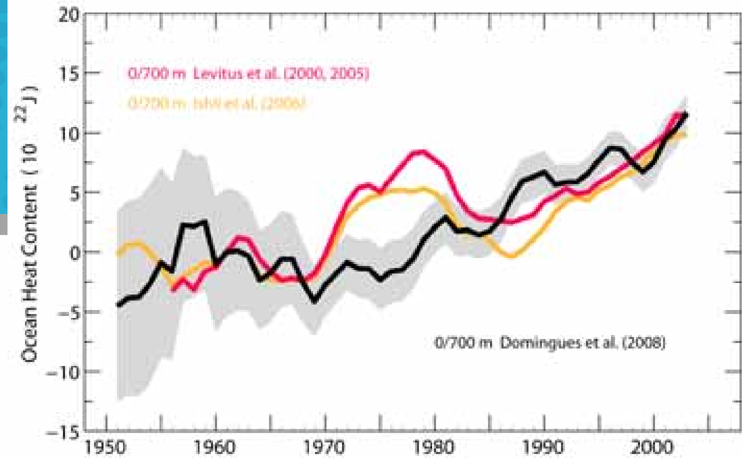
The sum of the components are in good agreement with updated estimates of global mean sea level.

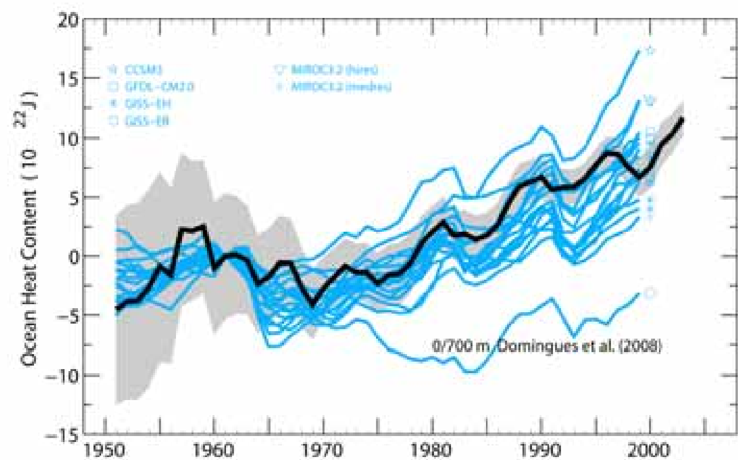
Different decadal variability is an indication of the uncertainty in the estimates and unknown variability of the cryospheric contributions.

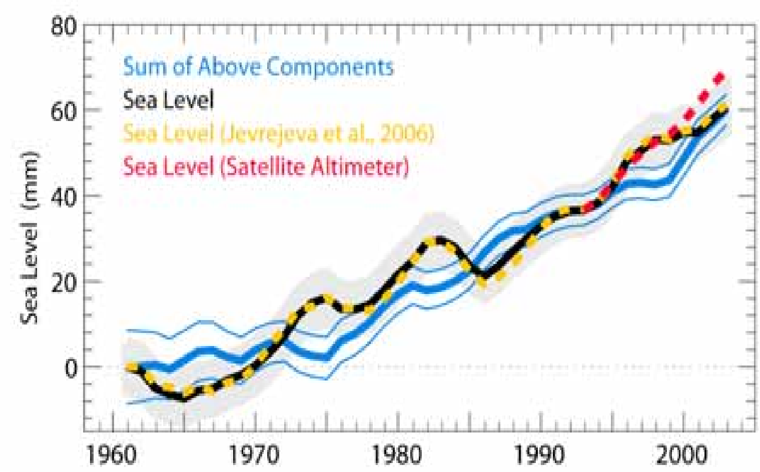
Satellite altimeter diverges after 1999, implying a higher rate of rise.

Conclusions

- **Better agreement** in the magnitude of observed and simulated decadal variability
- **Larger Trends** in ocean heat content and upper ocean steric rise
- I**mproved 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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Thank you

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