Improved estimates of upper-ocean warming and multi-decadal sea-level rise

(Dominges et al.,2008, Nature)

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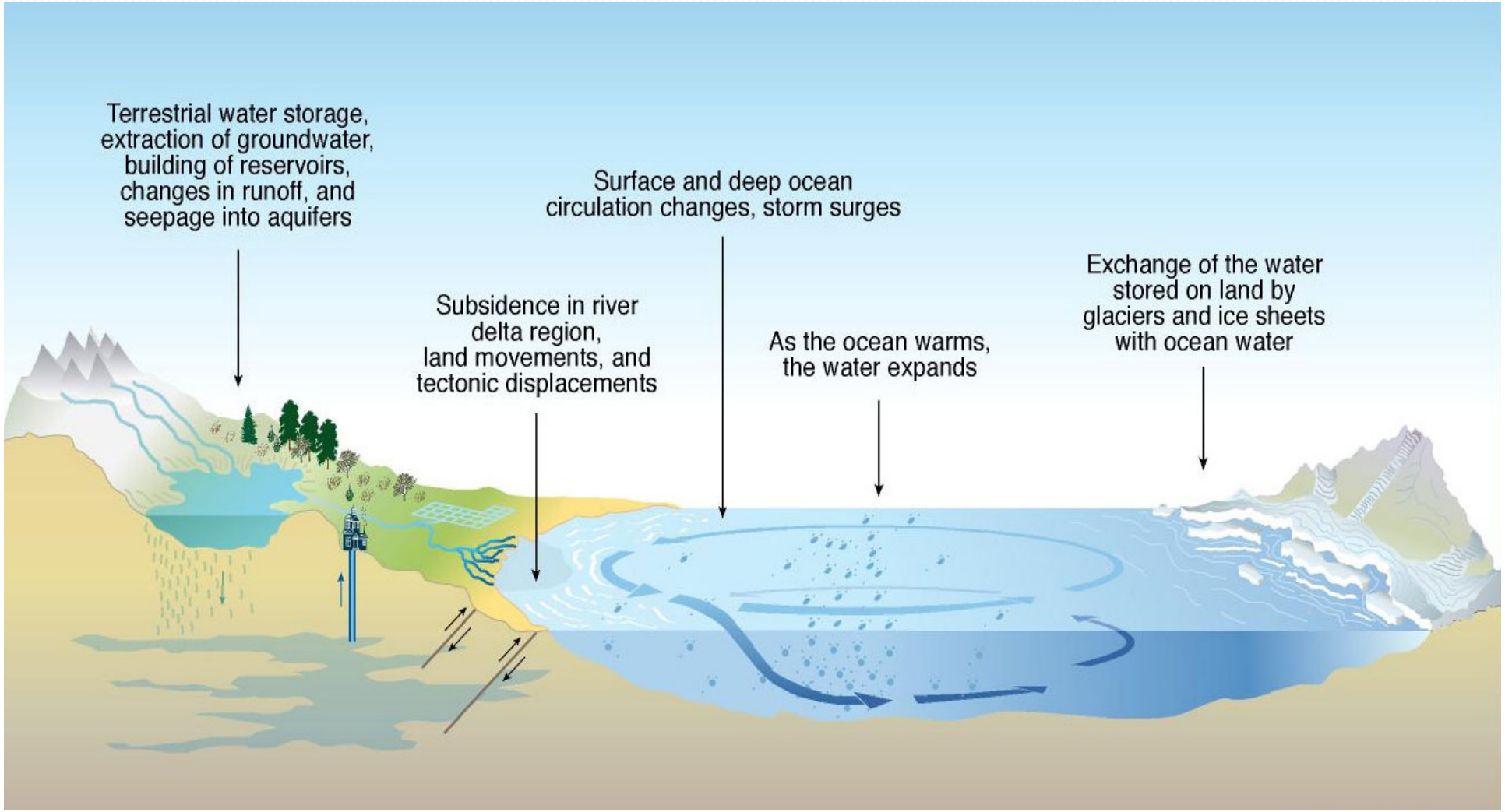
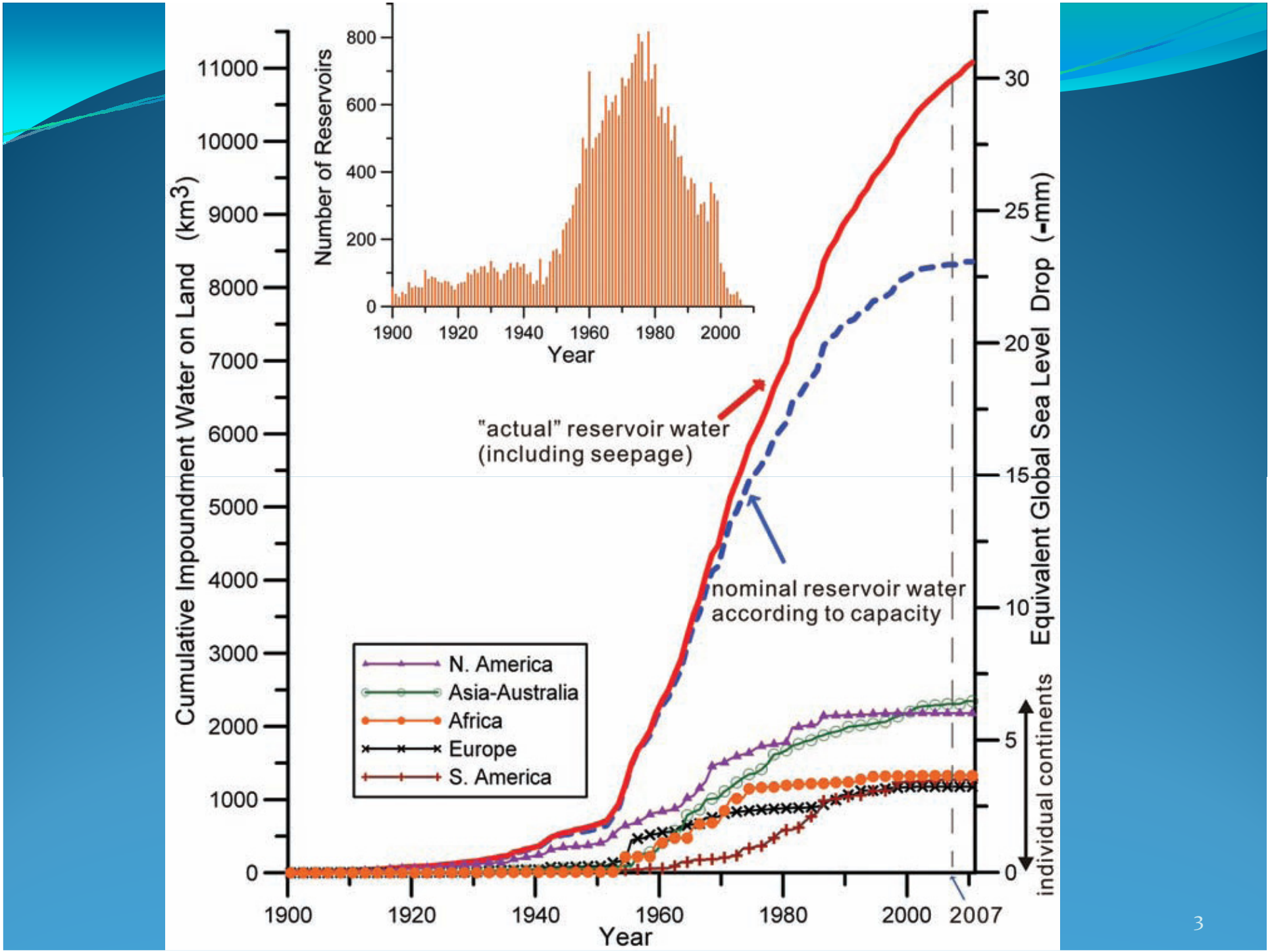
First Split Workshop in Atmospheric Physics and Oceanography

Sea level change




Number of Reservoirs
800
600
400
200
0
1900
1920
1940
1960
1980
2000
Year
Cumulative Impoundment Water on Land (km3)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Equivalent Global Sea Level Drop (-mm)
30
25
20
15
10
5
0
"actual" reservoir water
(including seepage)
nominal reservoir water
according to capacity
N. America
Asia-Australia
Africa
Europe
S. America
individual continents
1900
1920
1940
1960
1980
2000
2007
Year

- *Global Mean Sea Level Change* is the change in the average height of the oceans over the entire globe at a single point in time.
- Sea level change at a specific location in the ocean may be higher or lower than the global MSL
- Does not include ocean tides, storm surge

Changes in the climate system's energy budget

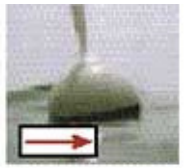
- ocean temperatures and the associated thermal expansion contribution to sea-level rise
- estimates of near-global ocean heat content and thermal expansion
- upper 300 m and 700 m of the ocean for 1950–2003
- statistical techniques

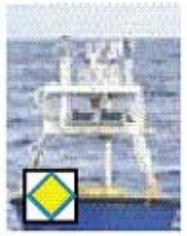
- OW & TE trends for 1961–2003:
  - 50 % larger than earlier estimates but 40 % smaller for 1993–2003
- Models with volcanic forcing → agrees approximately with the observations, but the modeled multi-decadal trends are smaller than observed.
- They add the observational estimate of upper-ocean thermal expansion contributions to sea-level rise
  - the sum of contributions is ~ 1.6 ± 0.4 mm/yr

- Temperature data:
  - Reversing thermometers (whole period),
  - Expendable bathy-thermographs (XBTs; since the late 1960s, 50 % of data)
  - Conductivity–temperature–depth (CTD) measurements from research ships (since the 1980s)
  - Argo floats (mostly from 2001)
  - Satellite altimetry

Global Ocean Observing System for Climate






Tide Gauge Network		58% complete		
3°x 3° Argo Profiling Float Array		35% complete		
5°x 5° Surface Drifting Buoy Array		45% complete		
Moored Buoy		Existing		Planned
Ocean Reference Station		Existing		Planned
High Resolution XBT* and Flux Line		Existing		Planned
Frequently Repeated XBT Line		Existing		Planned
Carbon Inventory & Deep Ocean Line		Global Survey @ 10 years		

From Space: Sea Surface Temperature, Sea Surface Height, Surface Vector Wind, Sea Ice, and Ocean Colour

*XBT: Expendable Bathythermograph (instrument used to measure temperature as a function of water depth in the ocean)

Source of graphic: Courtesy of NOAA Of. ce of GlobalPrograms.

See: http://www.oco.noaa.gov/, under "observing system" ->"system design" (20 October 2004)

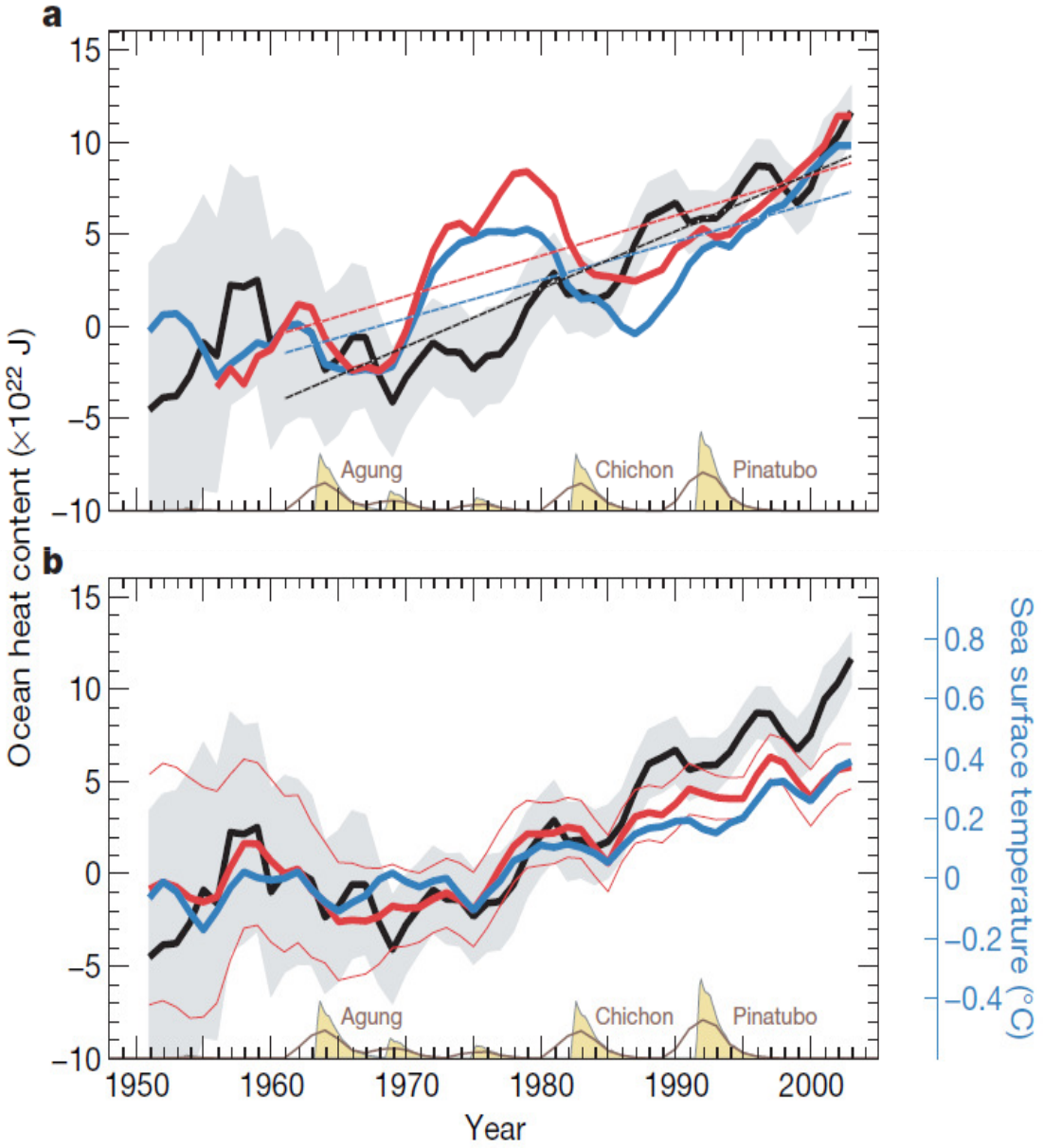


Figure 3. Estimates of ocean heat content and sea surface temperature. **a,** Comparison of our upper-ocean heat content with previous estimations. **b,** Comparison of our 700-m and 100-m results with sea surface temperature. All time series were smoothed with a three-year running average and are relative to 1961.

- Linear trend in OHC (700 m):
  - 0.36 ± 0.06 W m^{-2}
  - 91% in the upper 300 m
- Decrease in early 1980s: $6 \cdot 10^{22}$J, 10 mm → largely the instrumental bisaes (XBTs)
- Volcanic forcing: $3 \cdot 10^{22}$ J

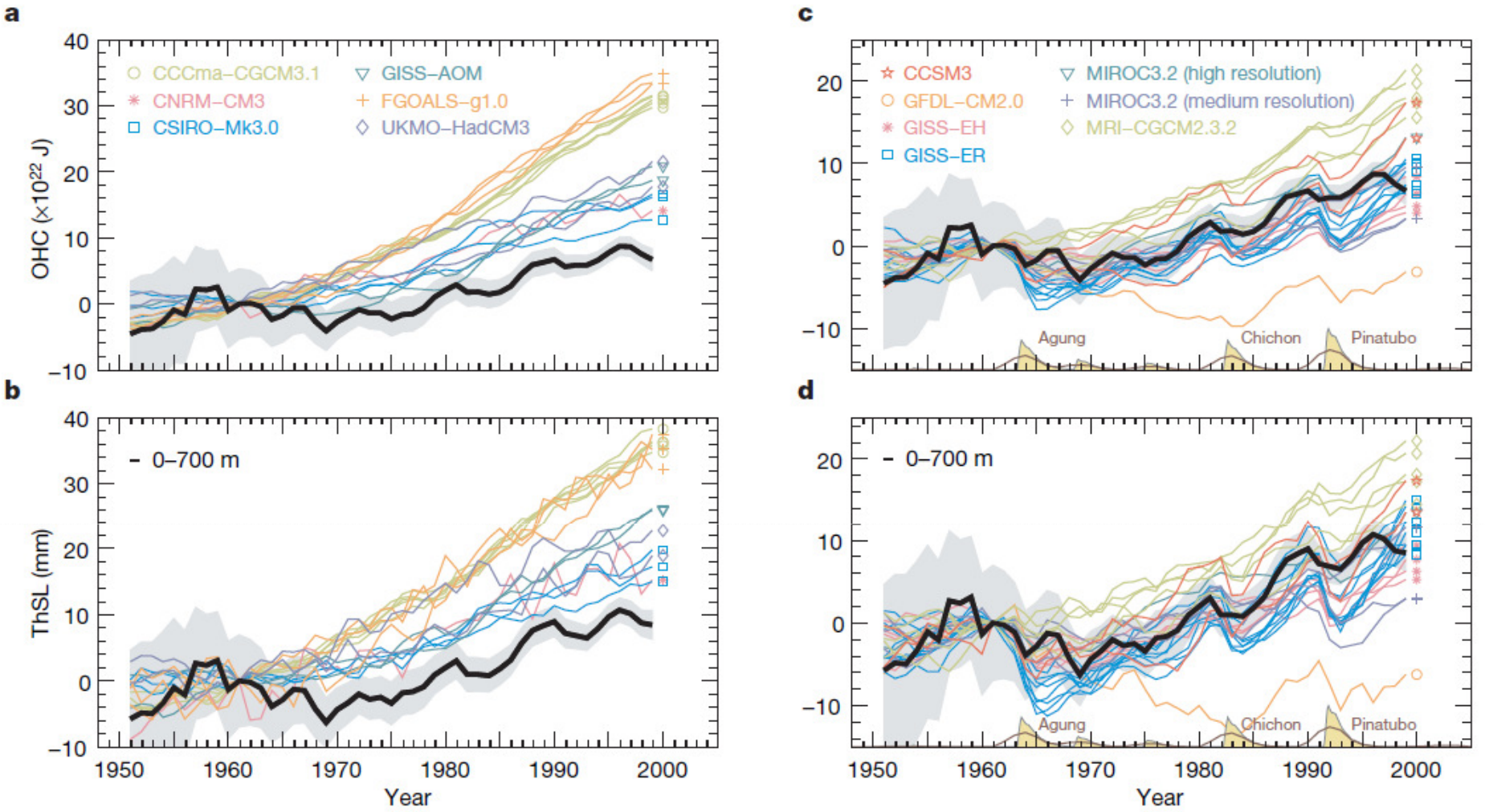


Figure 4. Comparison of observed and simulated ocean heat content(OHC) and thermosteric sea level (ThSL) estimates for the upper 700 m. **a, b,** Models with volcanic forcing, **c, d,** Models without volcanic forcing. All models include greenhouse gas and tropospheric aerosol forcings.

- ThSL:
  - rise 22 mm; trend 0.52 ± 0.08 mm yr^{-1}
  - 91% stored in the upper 300 m
- Ocean warming and ThE
  - 50 % larger for upper 700 m and 300 m
- Altimetar (1993-2003): 0.79 mm yr^{-1} (less then previous estimates)
- 1961 - 1999, the simulations with volcanic forcing are closer to observations but:
  - 28 % smaller in the upper 300 m
  - 10 % smaller in the upper 700 m
  - 73 % heat storage in upper 300 m (model) ; 93 % observations

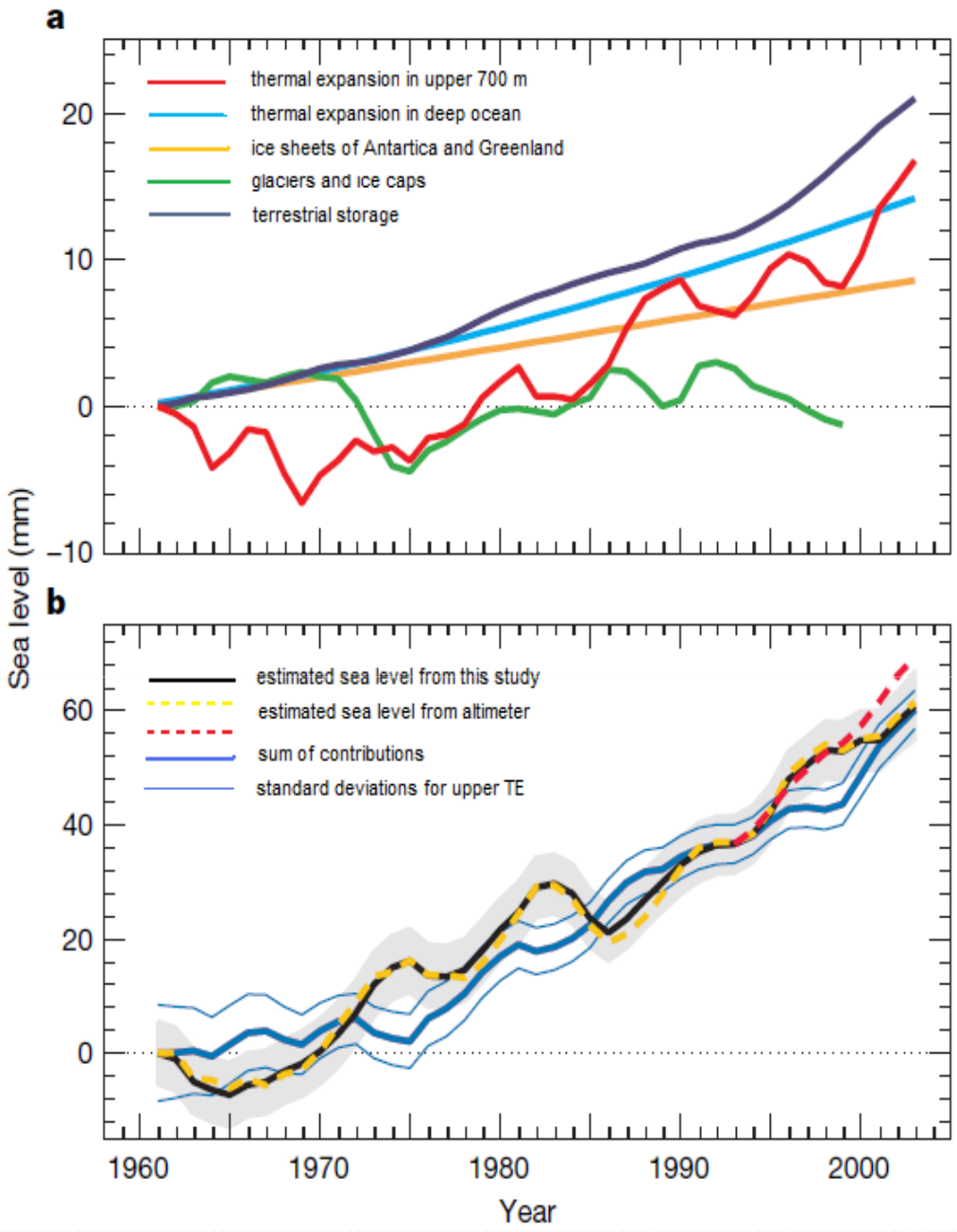


Figure 5. Total observed sea-level rise and its components.

• Observations and model: warming is in upper ocean

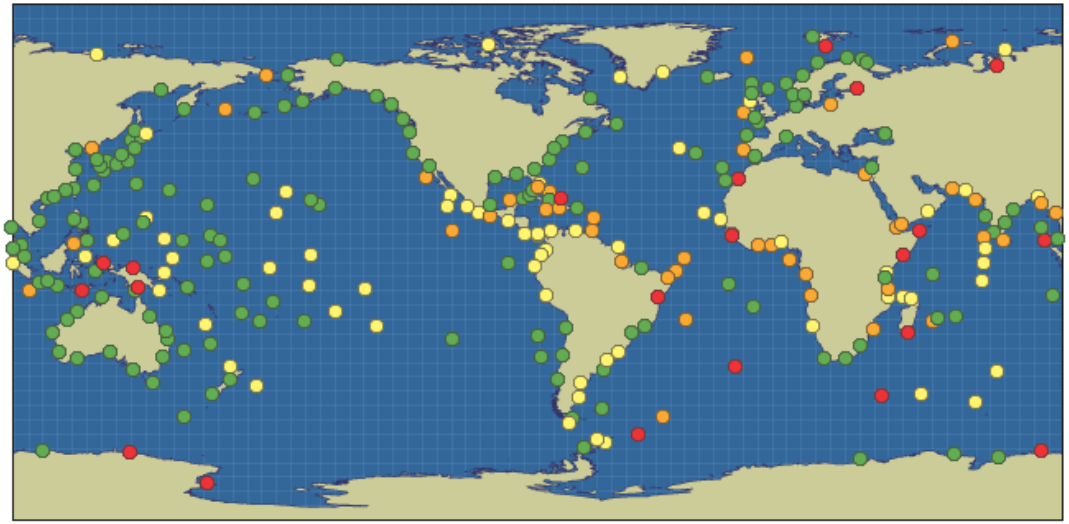
- integration to 3,000 m gives a 20 % increase on the value of 700 m (0.07 mm yr^{-1})
- deep-ocean thermal expansion 0.2±0.1 mm yr^{-1} (Fig. 5a); heat storage of about $8 \cdot 10^{22}$ J ($0.2 Wm^{-2}$)

- ice caps and glaciers to SLR:
  - 0.5 ± 0.2 mm yr^{-1} (1961-2003)
  - 0.8 ± 0.2 mm yr^{-1} (1993-2003)
    - Greenland: 0.21 ± 0.07 mm yr^{-1}
    - Antartic: 0.21 ± 0.35 mm yr^{-1}
  - Globally avarged SL trends:
    - 1.6 ± 0.2 mm yr^{-1} (1961-2003)
  - Sum of contributions to SLR
    - 1.5 ± 0.4 mm yr^{-1} (1961-2003)
    - 2.4 mm yr^{-1} (1993-2003)
      - Tide gauge: 2.3 mm yr^{-1}

- German Consortium for Estimating the Circulation and Climate of the Ocean model:
  - 1962–2001: ocean thermal expansion ~ **0.6 mm yr^{-1}** (upper 700 m); with an additional **50%** (~ 0.3 mm yr^{-1}) from the ocean below 700 m
- Hydrological models:
  - changes in terrestrial water storage but little long-term trend
  - the building of dams (about 0.55 mm yr^{-1}) and the mining of groundwater are likely to be of similar size but of opposite sign → not included

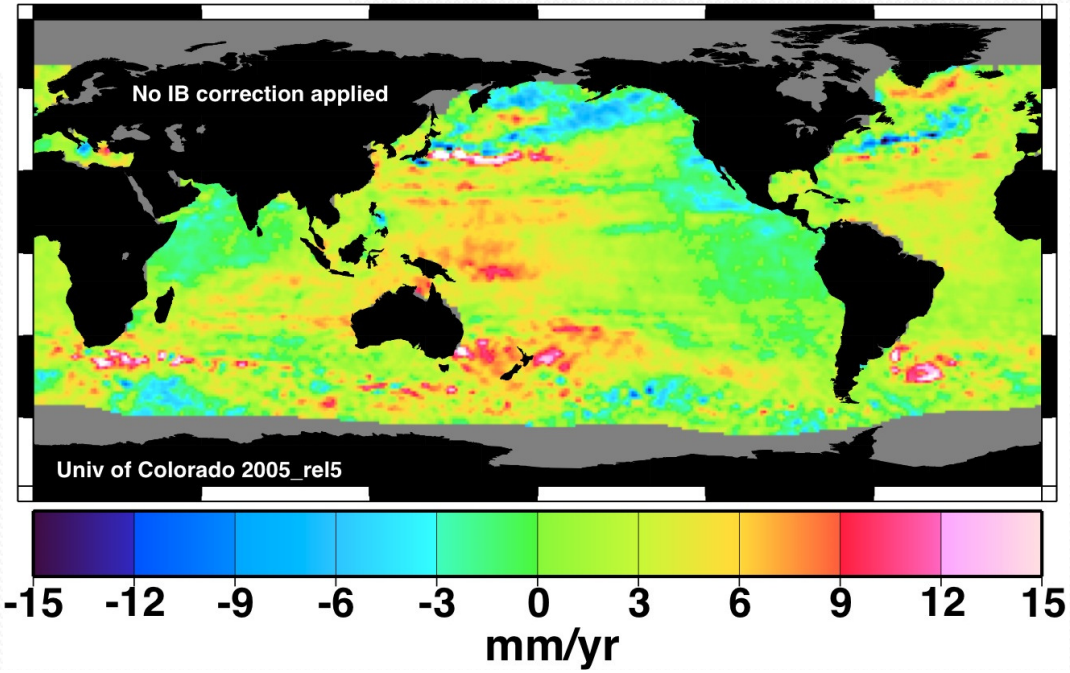
OTHER STUDIES

GLOSS status within the PSMSL data set - October 2008



- **Category 1:** "Operational" stations for which the latest data is 2004 or later.
- **Category 2:** "Probably operational" stations for which the latest data is within the period 1994-2003.
- **Category 3:** "Historical" stations for which the latest data is earlier than 1994.
- **Category 4:** "Stations for which no PSMSL data exist.

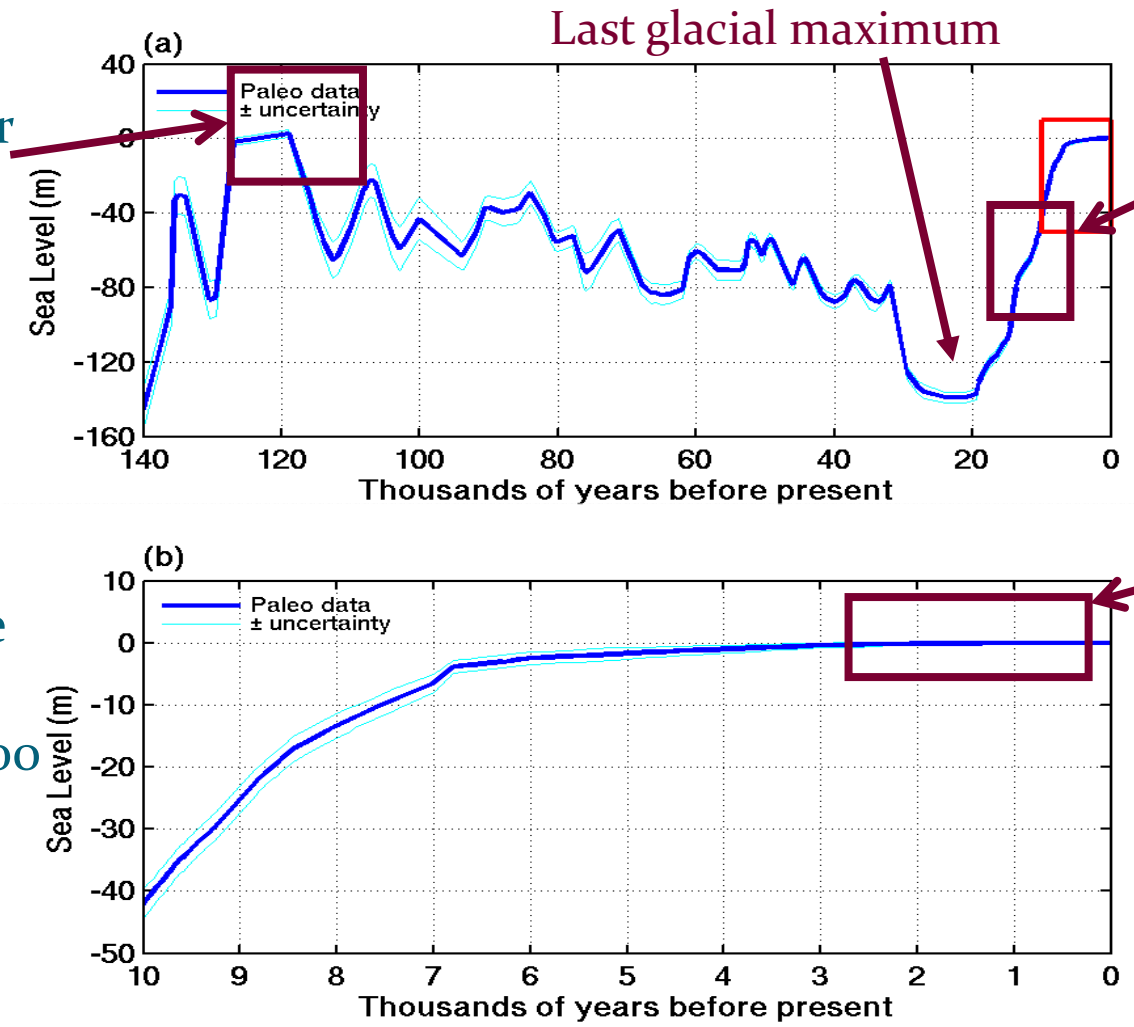
Mean sea level 1993-2005



• these trends have been determined for only a ten-year period, reflecting the impact of decadal scale climate variability on the regional distribution of sea level rise.

The paleo record tells us that Sea level has varied in the past

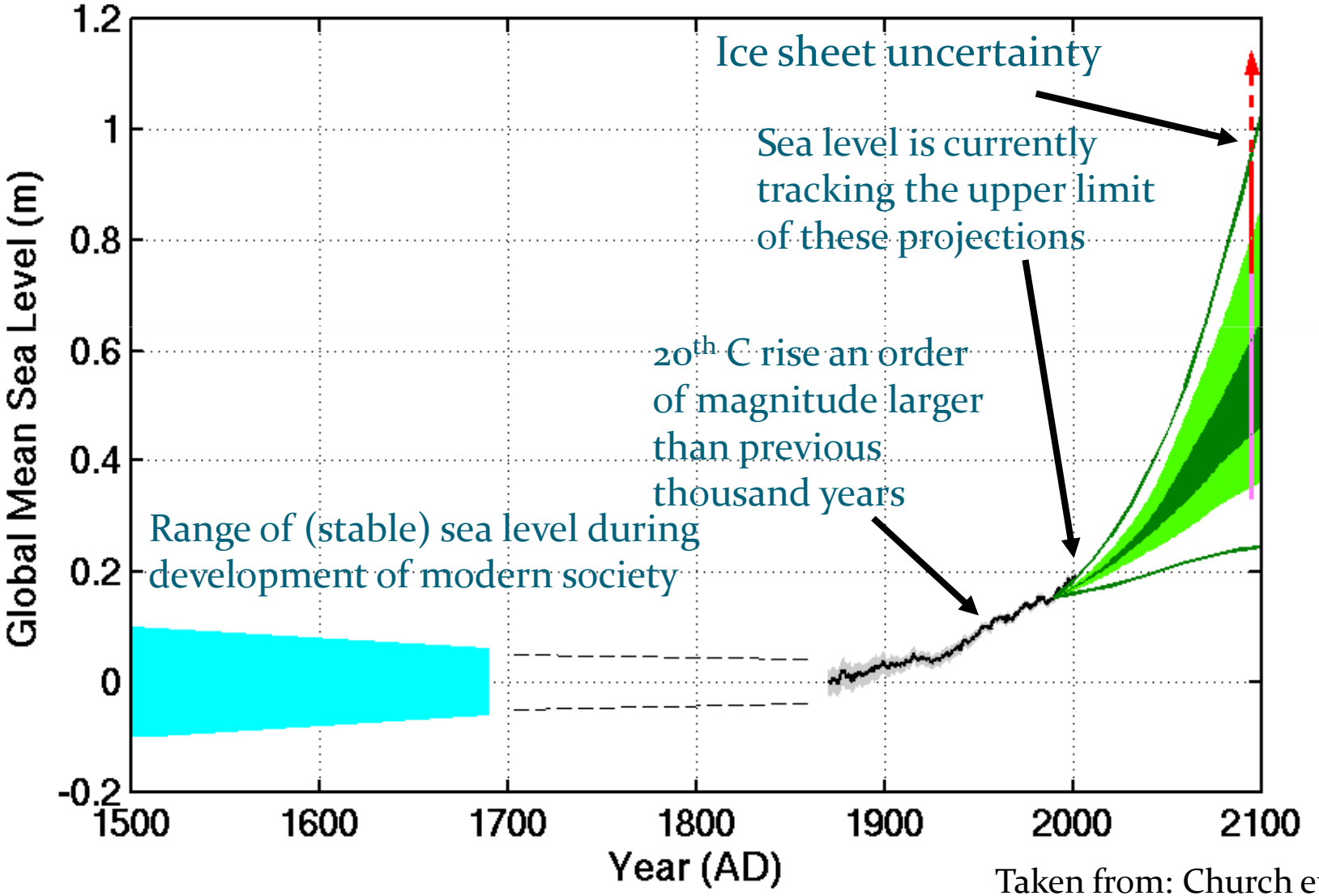
- Sea level higher than today,
- rates of rise about 1.5 m/century
- At temperature similar to what we expect by 2100



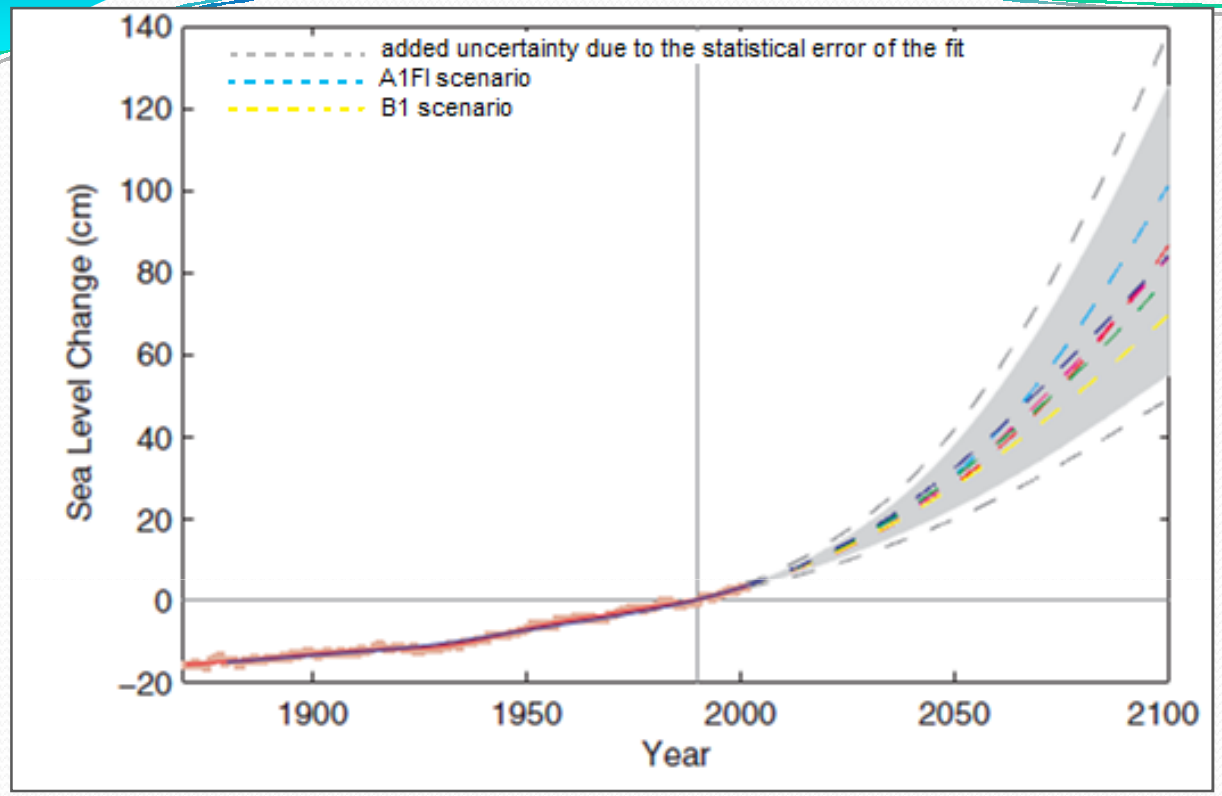
- Rates of rise up to 4 m/century
- Our coastal society developed in a time of stable sea level

Taken from: Church et al. 2008

Today's sea level unprecedented during modern civilization



Taken from: Church et al. 2008



RAHMSTORF (2007)

Figure. Past sea level and sea-level projections from 1990 to 2100 based on global mean temperature projections of the IPCC TAR.The dashed gray lines show the added uncertainty due to the statistical error of the fit.

- A semi-empirical relation is presented that connects global sea-level rise to global mean surface temperature
- proportional constant : 3.4 mm/yr per °C
- IPCC worming scenarios: SLR in 2100 of 0.5-1.4 mm/yr

GRACE & JASON-1

- Combined sea level data: GRACE & JASON 1
- GRACE: time-variable gravity data
- GRACE quantifies vertically integrated water mass changes (precision of few cm; spatial resolution ~400km)
- JASON has provided measurements of the surface height of the world's oceans to an accuracy of 3.3 cm
- Estimation of the mean steric sea level variations over the 60°S–60°N oceanic domain
- Period: August 2002 to April 2006
- After moving seasonal variations trend is: **(1.2±0.5 mm/yr)**

Updated from: A. Lombard et al., 2007: Estimation of steric sea level variations from combined GRACE and Jason-1 data

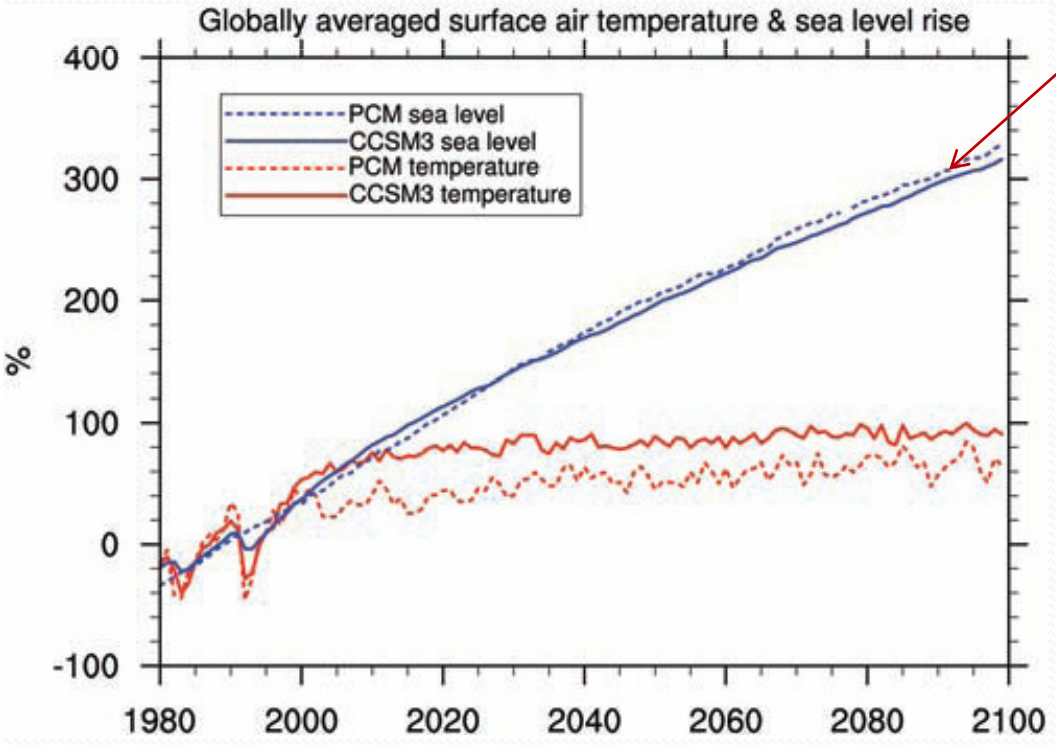
IPCC table

Table 5.2. *Recent estimates for steric sea level trends from different studies.*

Reference	Steric sea level change with errors (mm yr^{-1})	Period	Depth range (m)	Data Source
Antonov et al. (2005)	0.40 ± 0.09	1955–1998	0–3,000	Levitus et al. (2005b)
Antonov et al. (2005)	0.33 ± 0.07	1955–2003	0–700	Levitus et al. (2005b)
Ishii et al. (2006)	0.36 ± 0.06	1955–2003	0–700	Ishii et al. (2006)
Antonov et al. (2005)	1.2 ± 0.5	1993–2003	0–700	Levitus et al. (2005b)
Ishii et al. (2006)	1.2 ± 0.5	1993–2003	0–700	Ishii et al. (2006)
Willis et al. (2004)	1.6 ± 0.5	1993–2003	0–750	Willis et al. (2004)
Lombard et al. (2006)	1.8 ± 0.4	1993-2003	0-700	Guinehut et al. (2004)

How Much More Global Warming and Sea Level Rise?

- We are aleredy committed to further global worming of ~ 0.5 °C and additional 320 % sea level rise by the end of 21st century



sea level continues to rise – more than a factor 3 than for temp. change

Figure. Ensemble mean percent increase of globally averaged surface air temperature and sea level rise from the two models computed relative to values for the base period 1980–1999.

Conclusions

- Sea level rise may well exceed one meter by 2100
- Long-term rise over several centuries likely to be several meters, consistent with paleoclimate experience

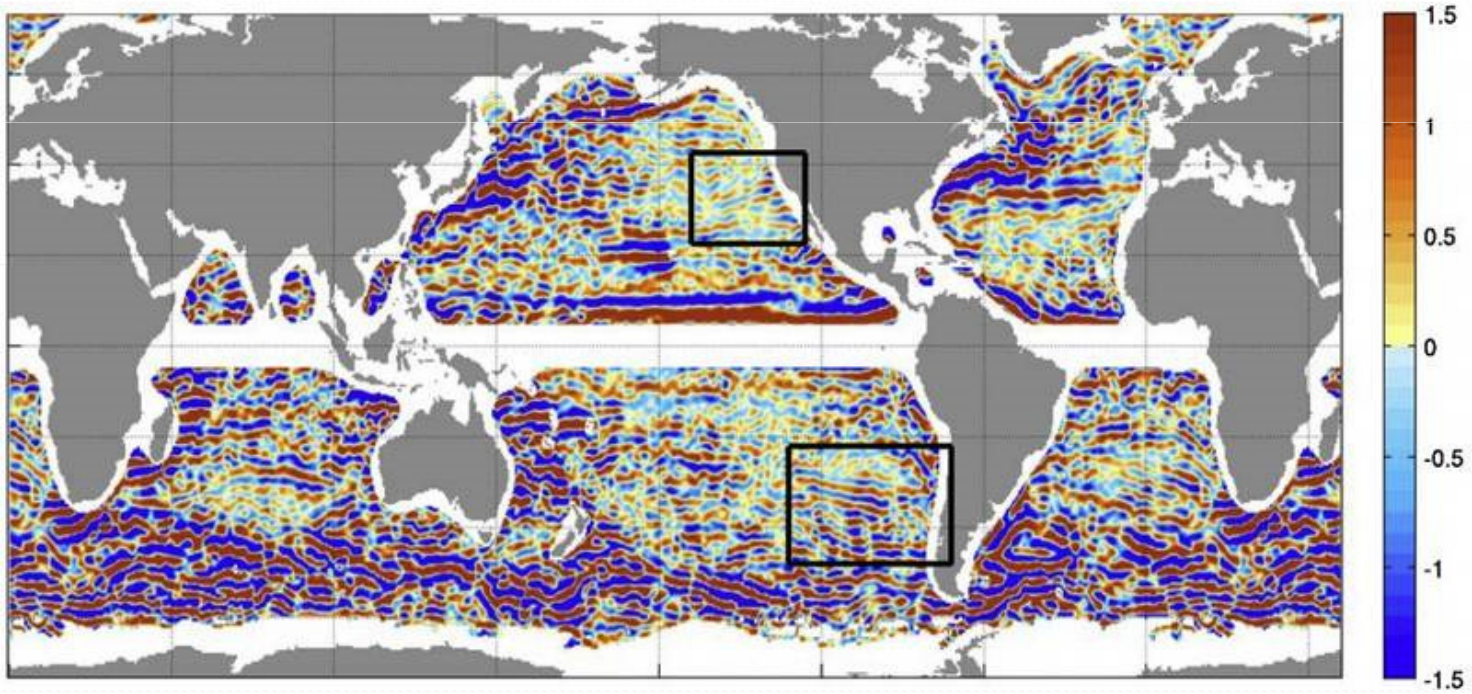


Figure: 1993–2002 mean zonal surface geostrophic velocity calculated from mean dynamic topography

Thank you for your attention!