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Causes and magnitude of sea-level rise

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Is it Dangerous?
Key Impacts in the Coastal Zone

- Sea-level variability and rise
  - Inundation

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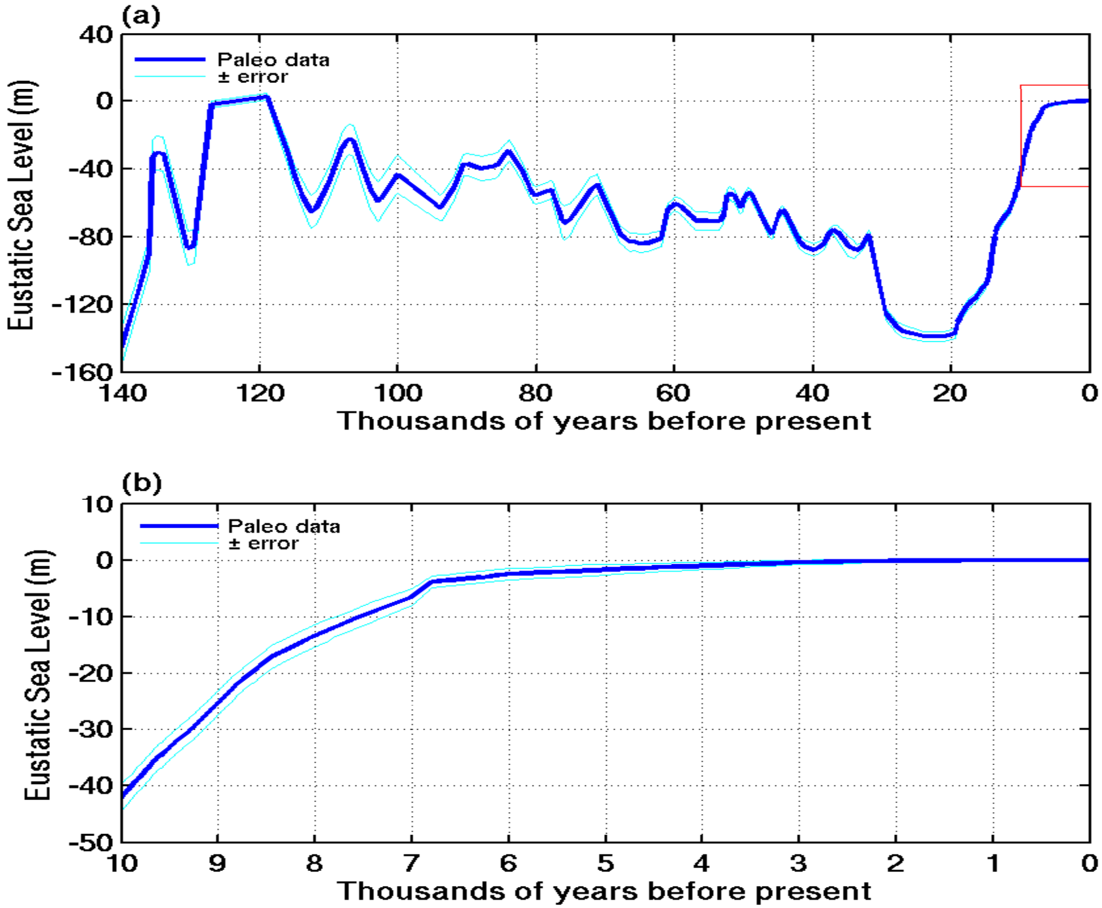
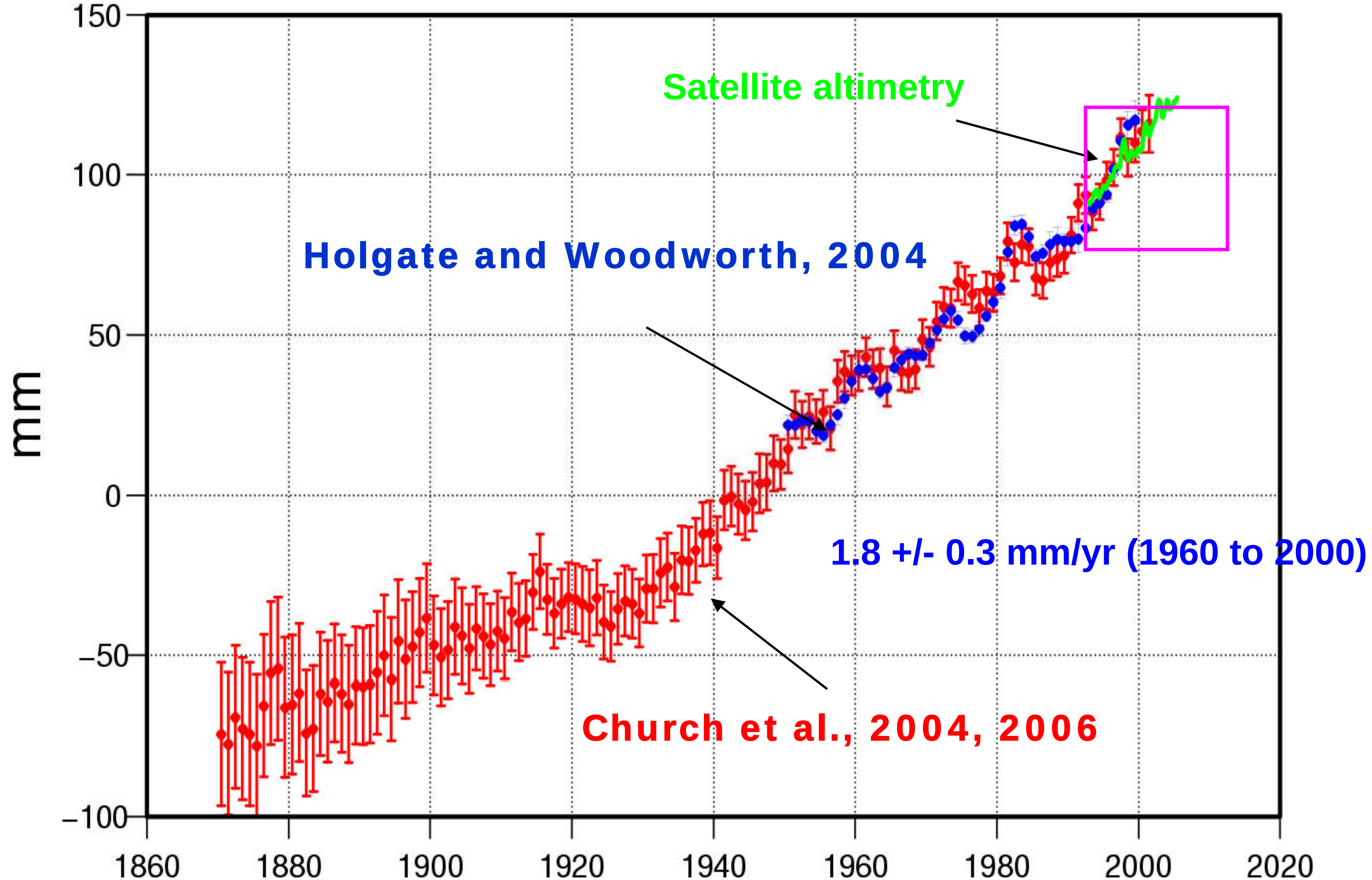
  - coastal erosion
  - Impacts on emergency and escape routes
  - Environmental refugees – a here and now issue
    - not “if” but “when and where and how will we respond?”
  - Associated issues of security, food and water security, health, poverty. What are the consequences for near and far neighbours? What are our responsibilities?

Sea level rose more than 120 m since the last glacial maximum



Church et al., 2008

Sea-level rise accelerated during the 20th century



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June 24, 2008. Drastic change in the earth system during Global Warming Symposium, University of Hokkaido

Unresolved questions

Total = Mass (water exchange) + Volume (thermal expansion)

Why GLOBAL SEA LEVEL RISE **in the past 40 years (1961-2003) did 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**?**

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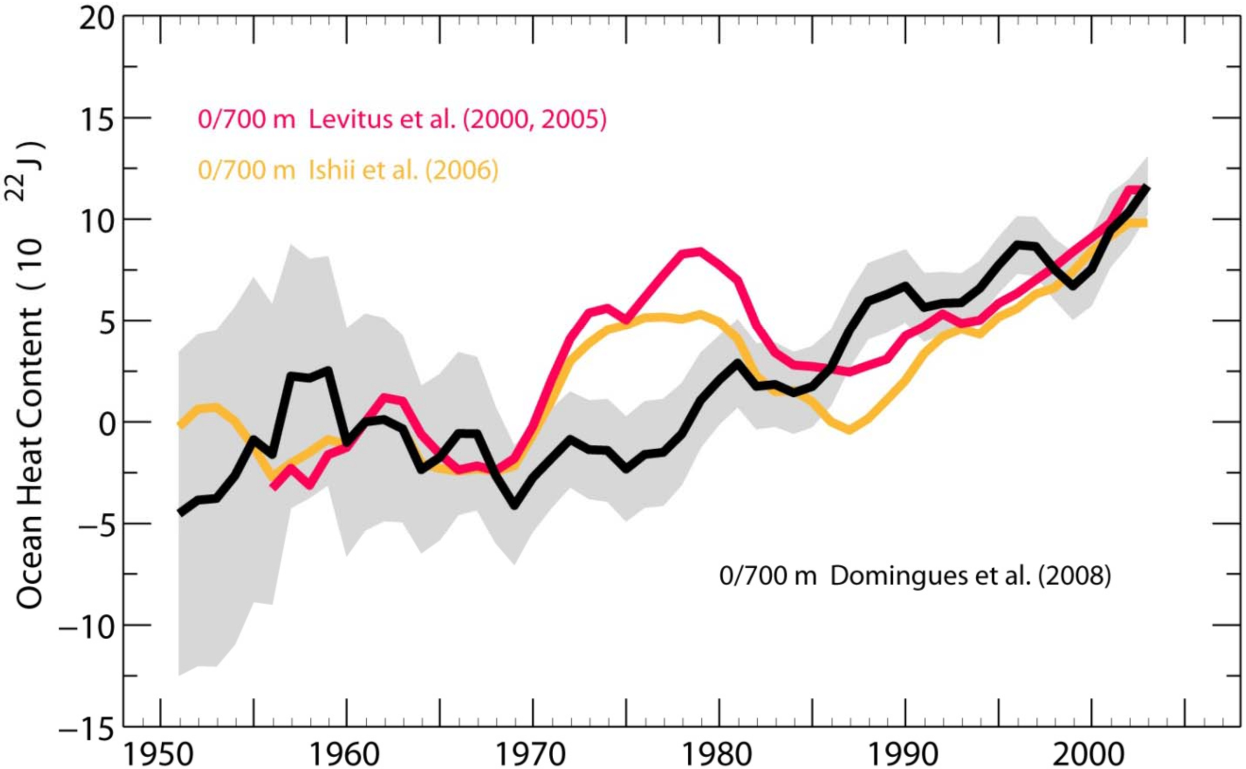
New Estimates of Global Ocean Heat Content

(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.

Comparison with WCRP CMIP Models

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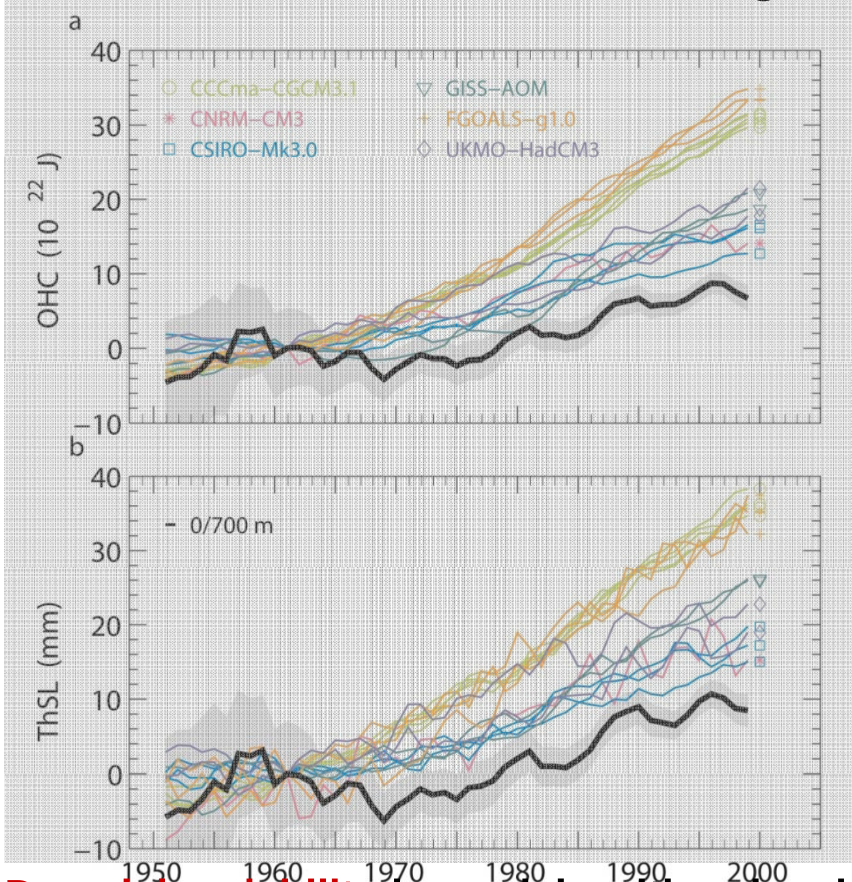
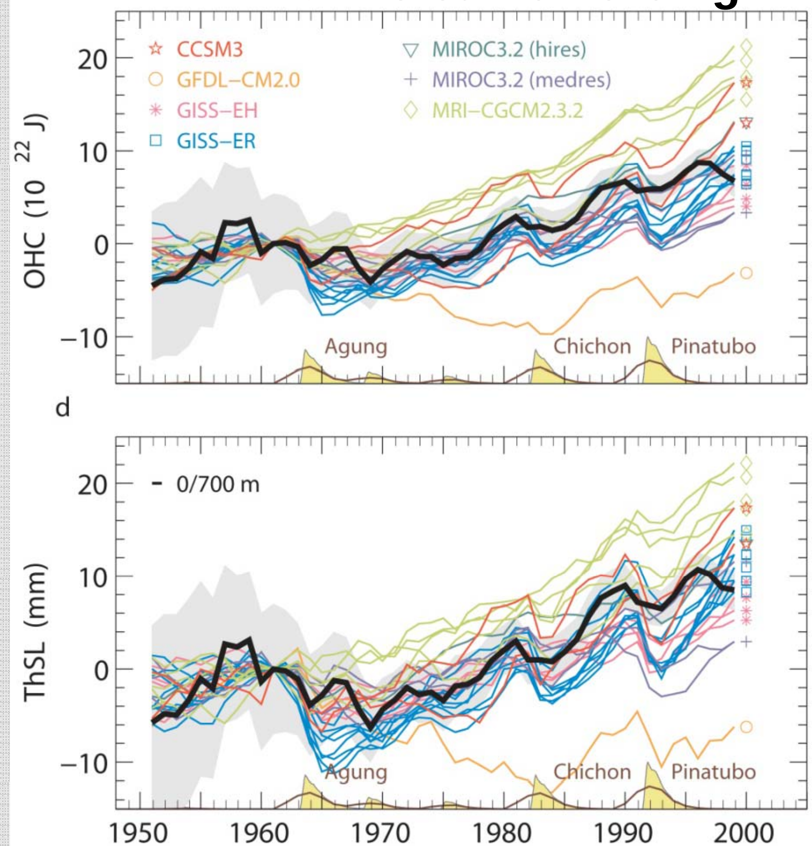
Without Volcanic Forcing

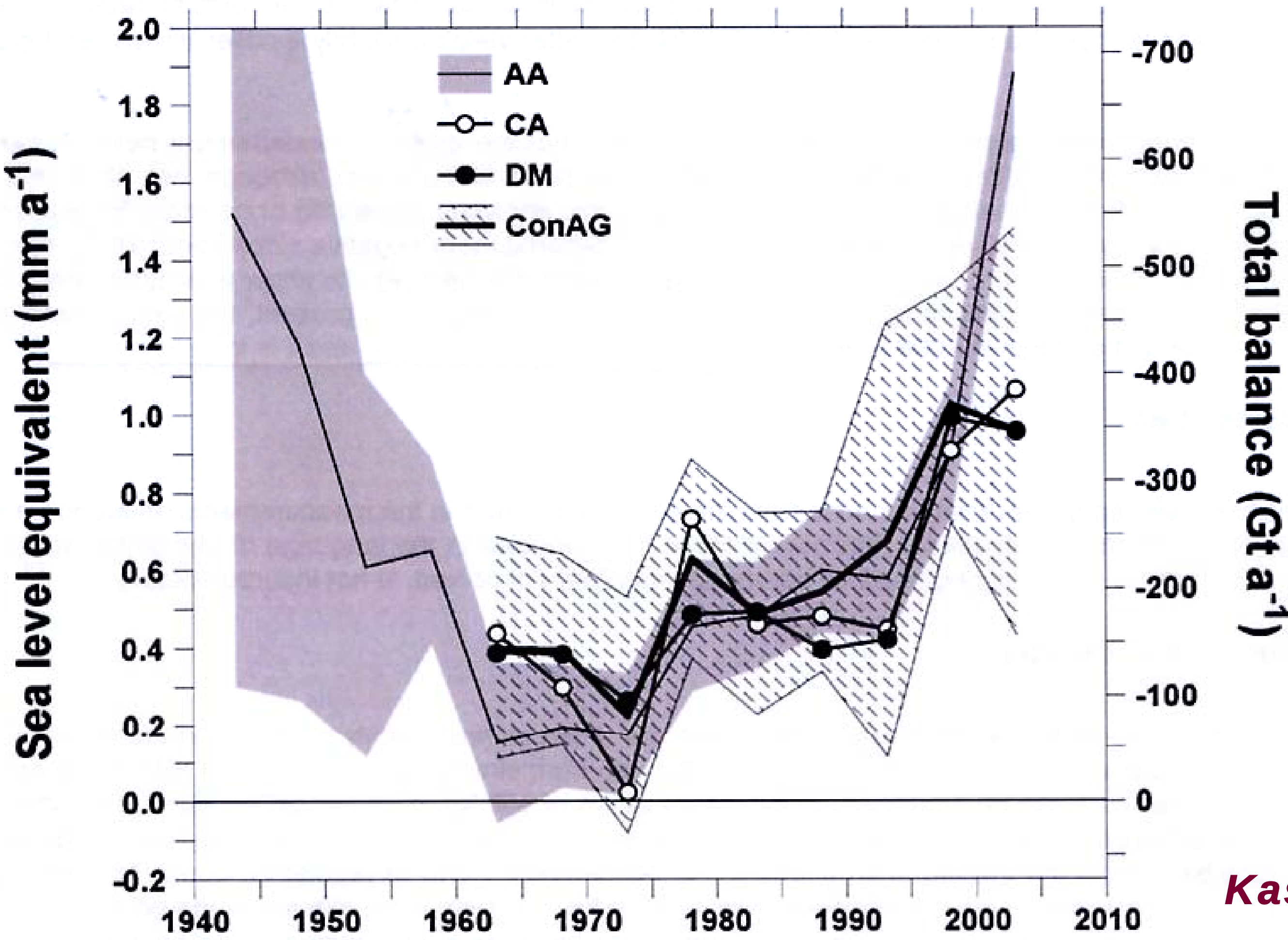


With Volcanic Forcing



Decadal variability in models with volcanic forcing in good agreement.
Simulated multi-decadal trends tend to underestimate observed warming (30% smaller in the upper 300 m and 10% smaller in the upper 700 m).

Glacier melting contributes to sea level



Kaser et al. 2005

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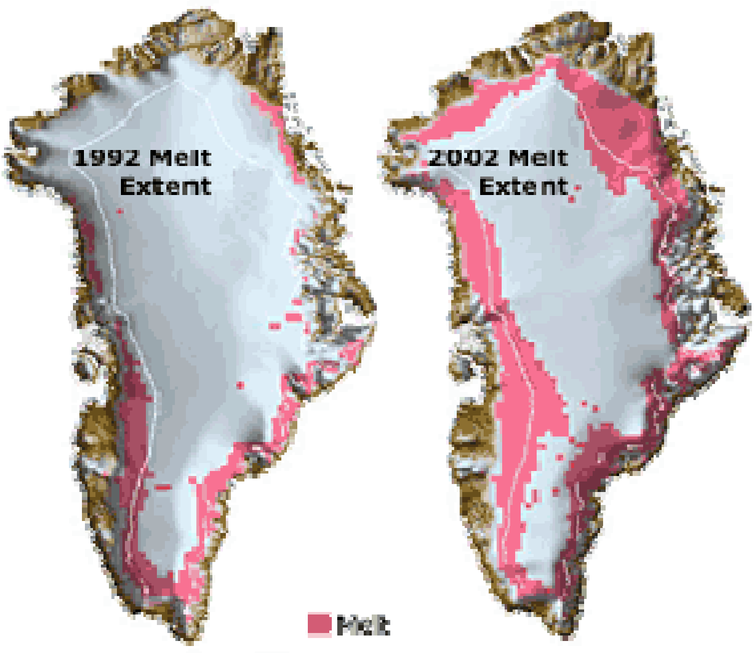
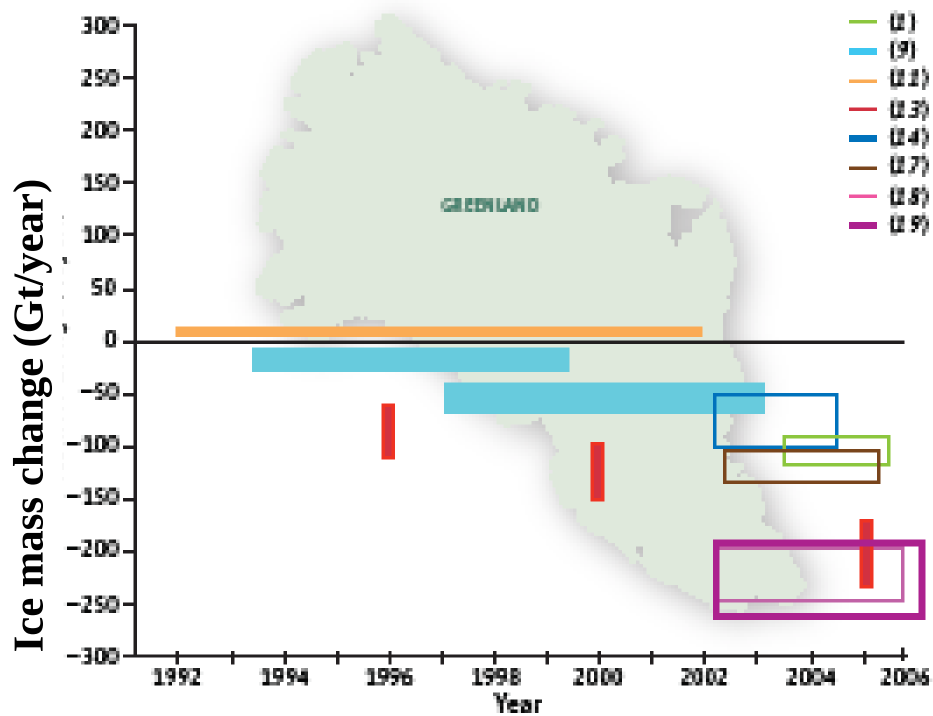
The Greenland Ice Sheet is contributing to sea-level rise



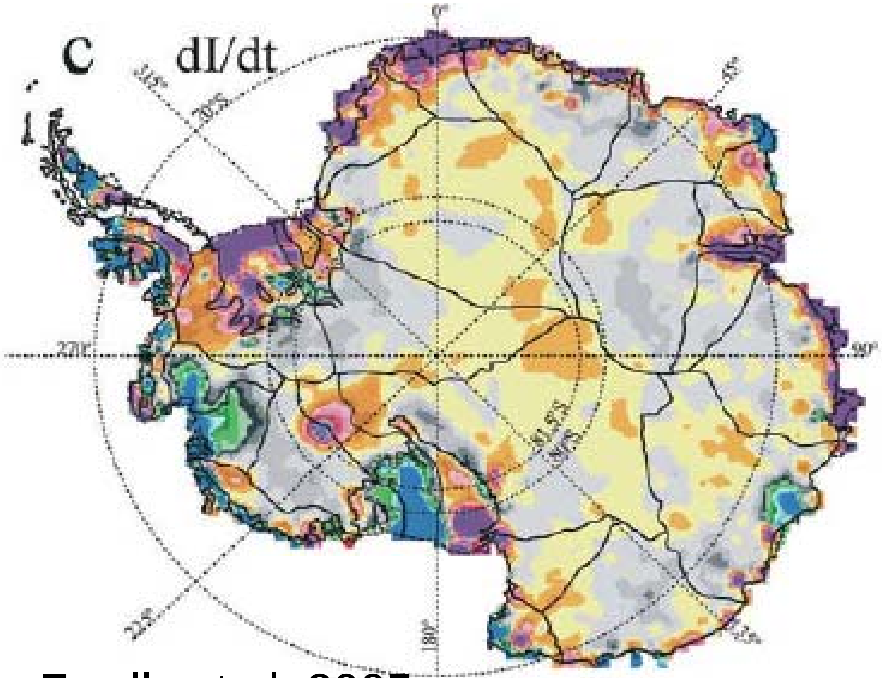


Greenland contribution to present-day sea level rise (1992-2006) : ~ 0.2 mm/year

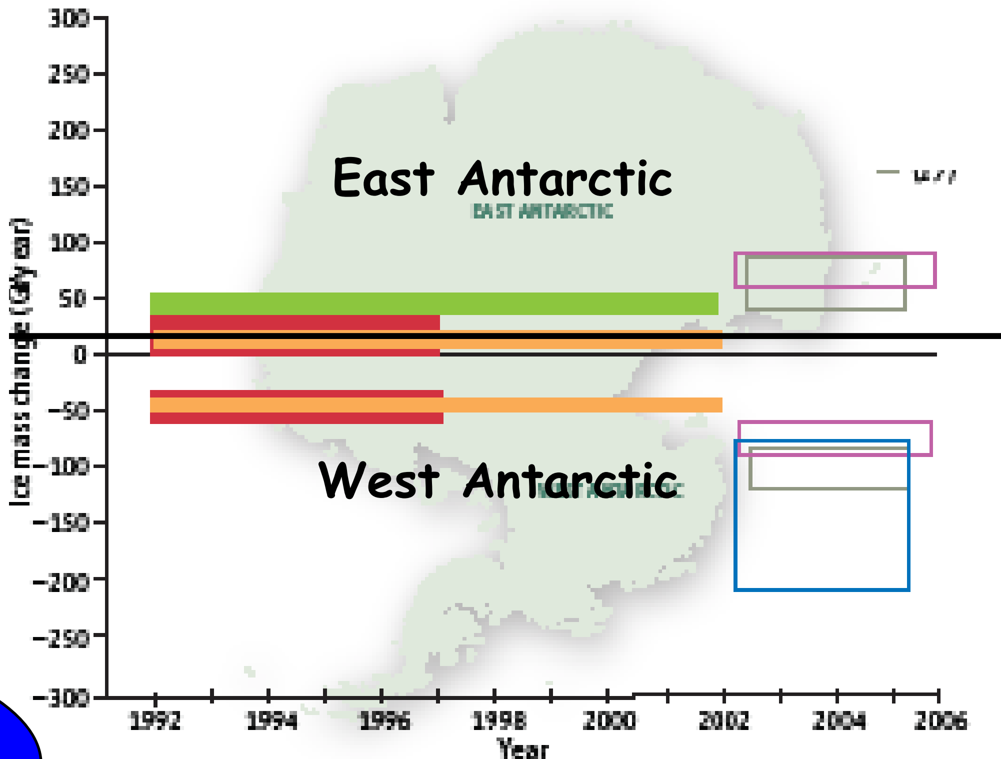
Ice mass loss measured by remote sensing techniques

Steffen et al.
Cazenave, 2006

West Antarctic Ice Sheet is contributing to sea-level rise



Zwally et al. 2005

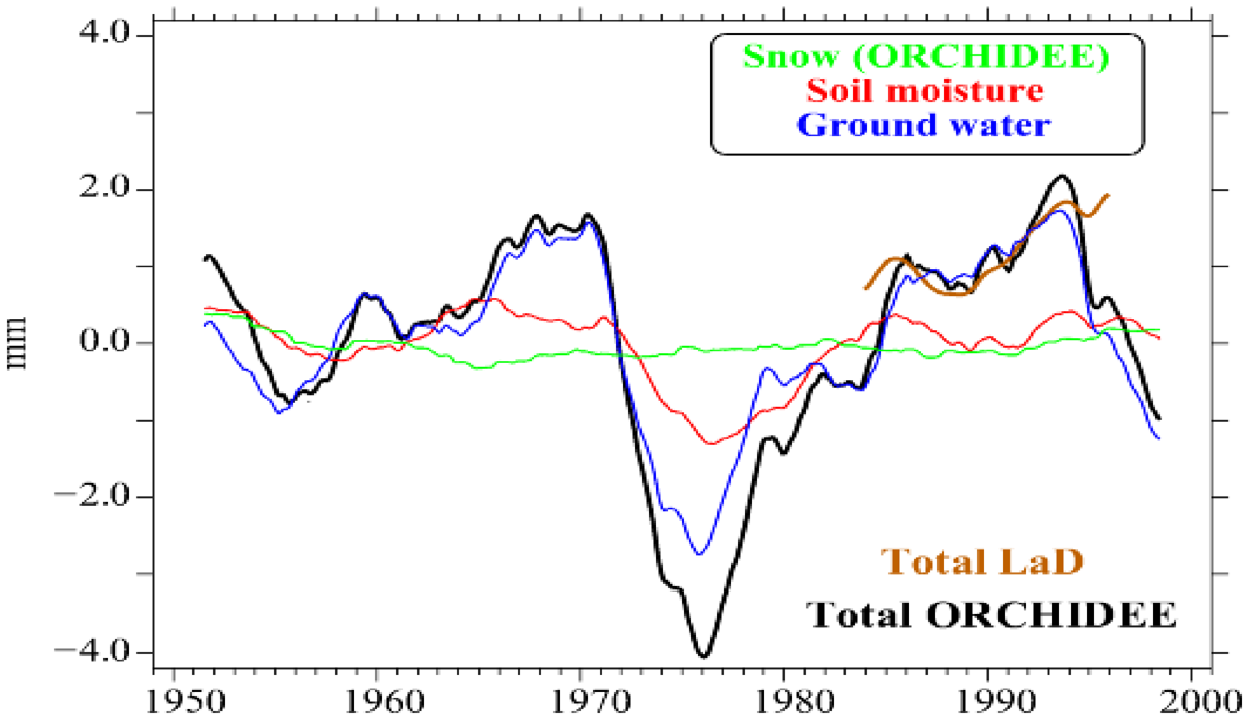


Remote sensing measurements

(Cazenave, 2006)

Contribution to present-day sea level rise (1992-2006): ~0.2 mm/an

Land water storage effects global sea level



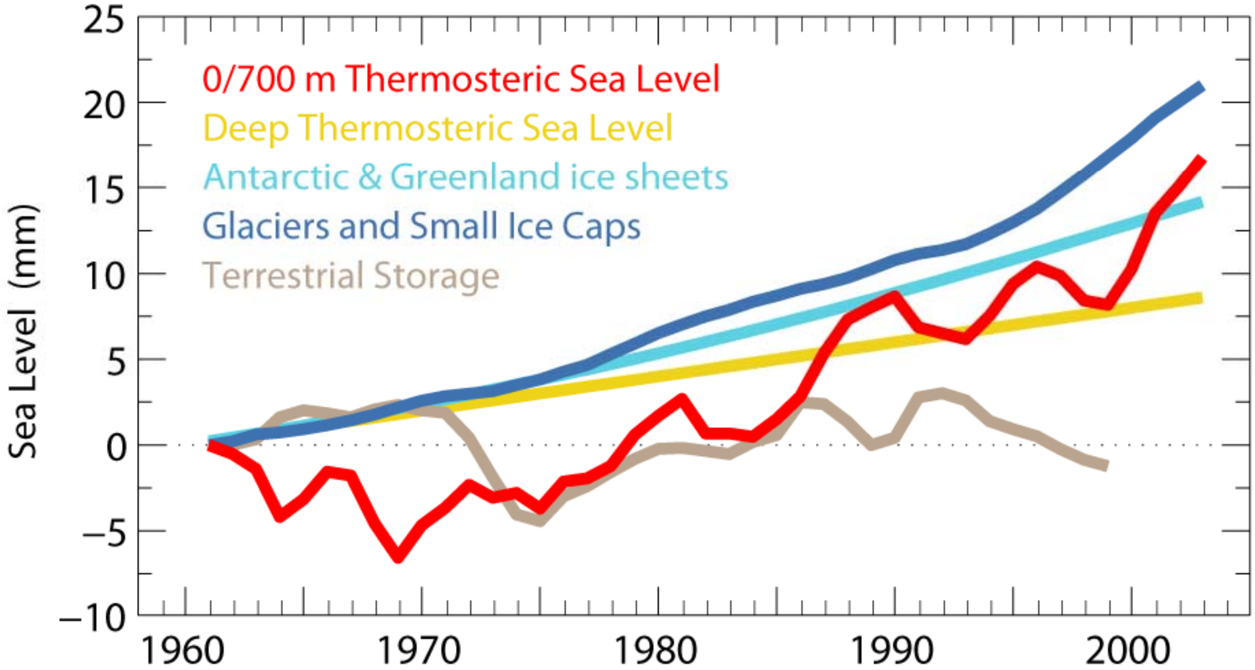
- greatest variation is associated with ground water, followed by soil moisture
- no significant trend was detected
- strong decadal variability driven by precipitation, strong decrease in the beginning of 1970s

Milly, P. C., D., A. Cazenave, and M. C. Gennero (Proc. Natl Acad. Sci, 2003)

Ngo-duc T., K. Laval, J. Polcher, A. Lombard and A. Cazenave (GRL, 2005)

- agreement between ORCHIDEE and LaD. *(Land Dynamics LSM of GFDL)*

Components of the Sea-level budget



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

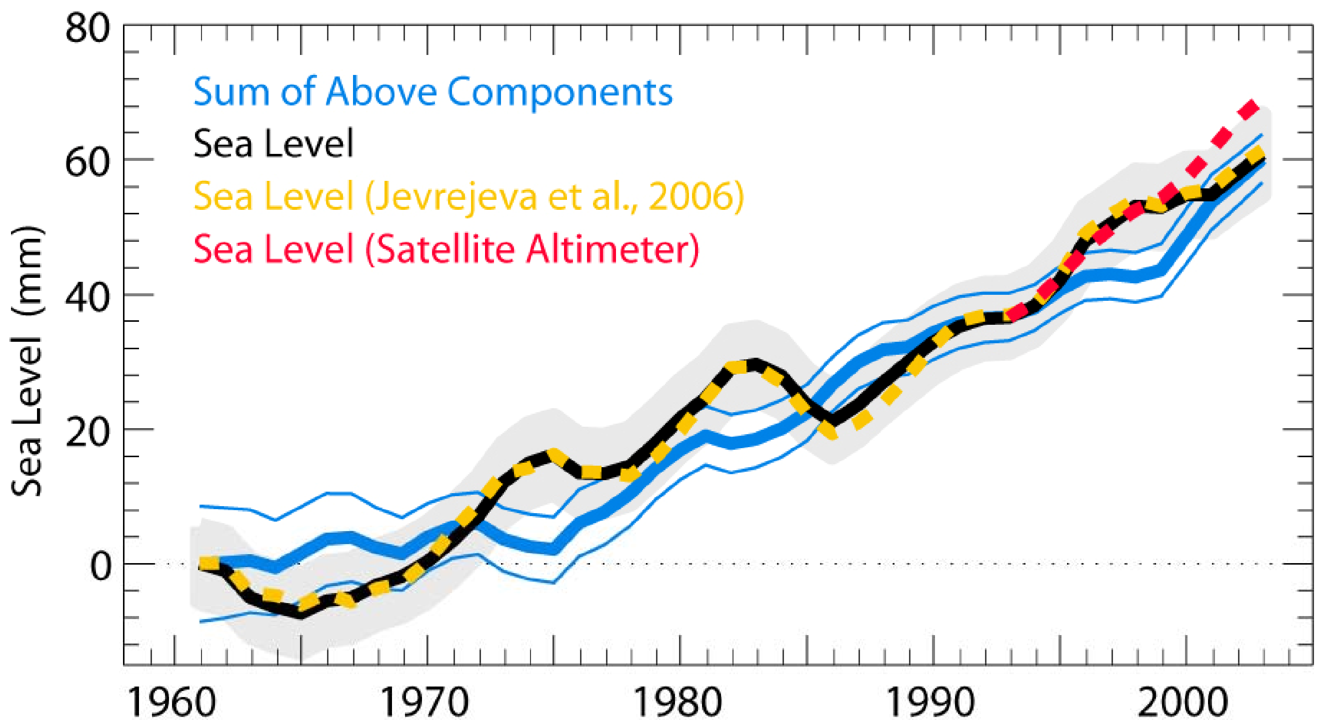
Ice sheets **(linearly increases towards the 1990s estimates, as compiled in Lemke et al., IPCC, 2007)**

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)

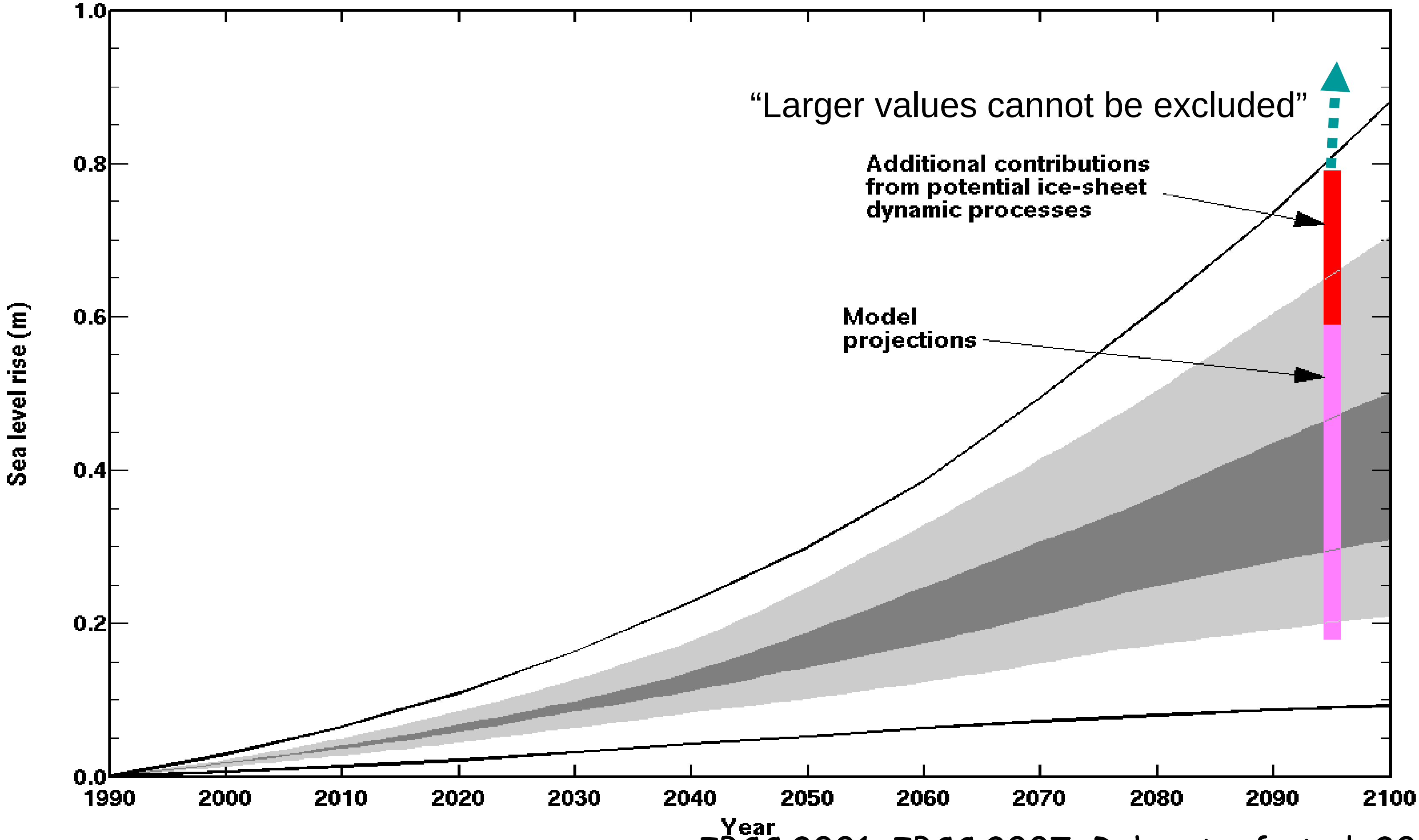


Sum of the components are in good agreement with updated estimates of sea level.

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

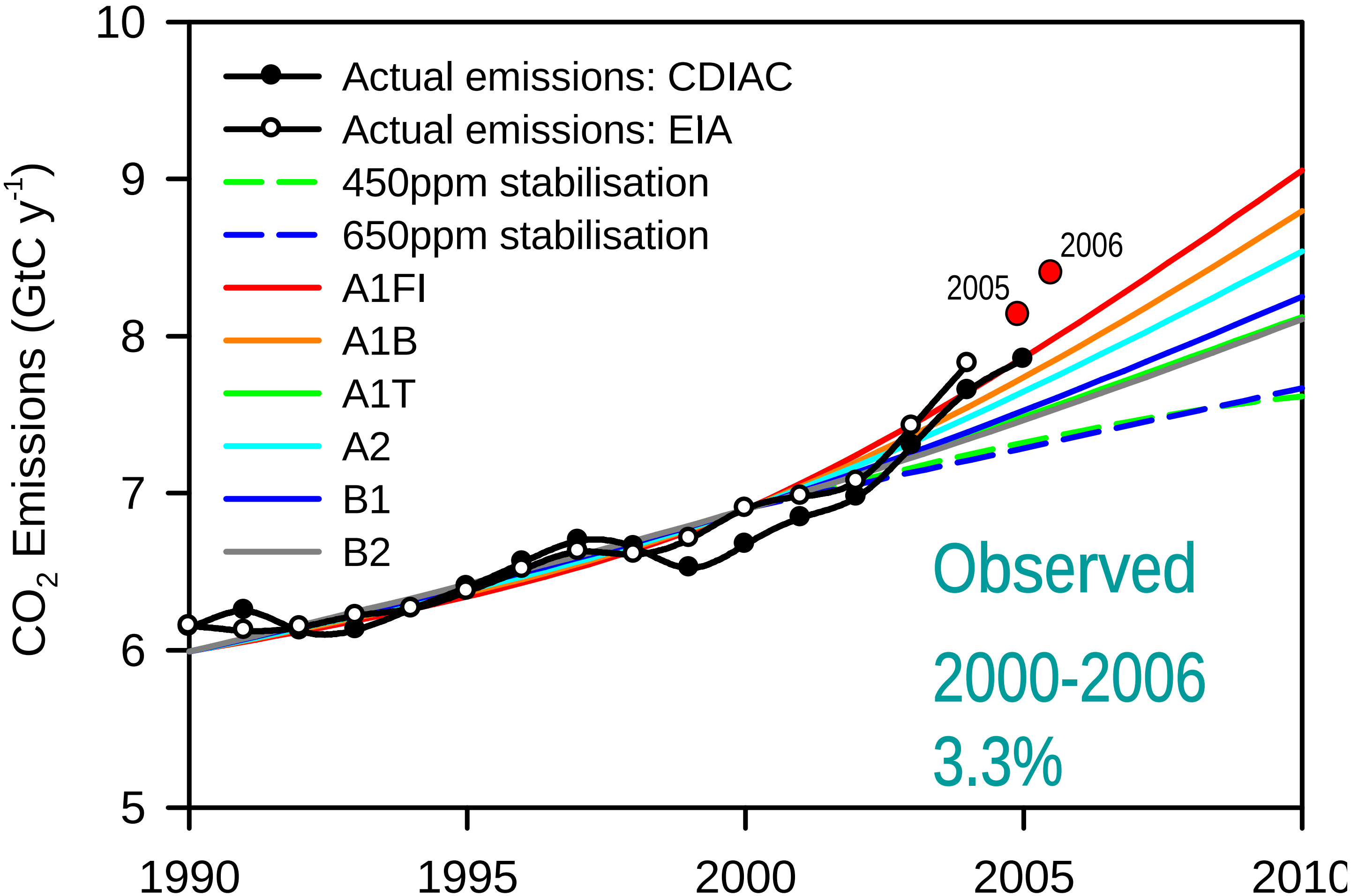
Satellite altimeter and in situ estimates diverges after 1999

IPCC TAR & AR4 both project a significant sea-level rise



IPCC 2001; IPCC 2007; Rahmstorf et al. 2007

Fossil Fuel Emissions exceeding all scenarios



Raupach et al. 2007: Canadell et al. 2007, PNAS

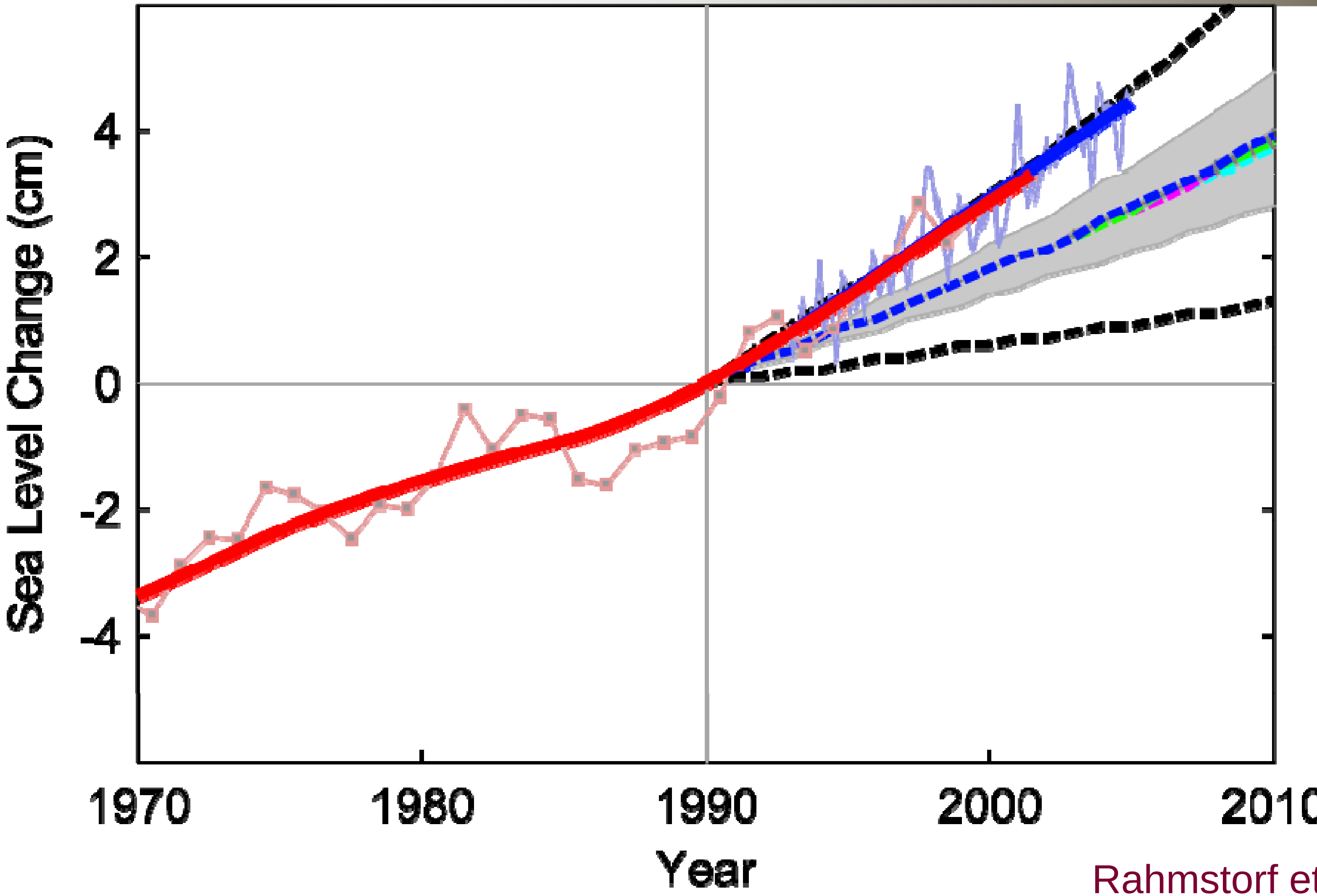
50-year constant growth rates to 2050

B1 1.1%,
A1B 1.7%,
A2 1.8%
A1FI 2.4%

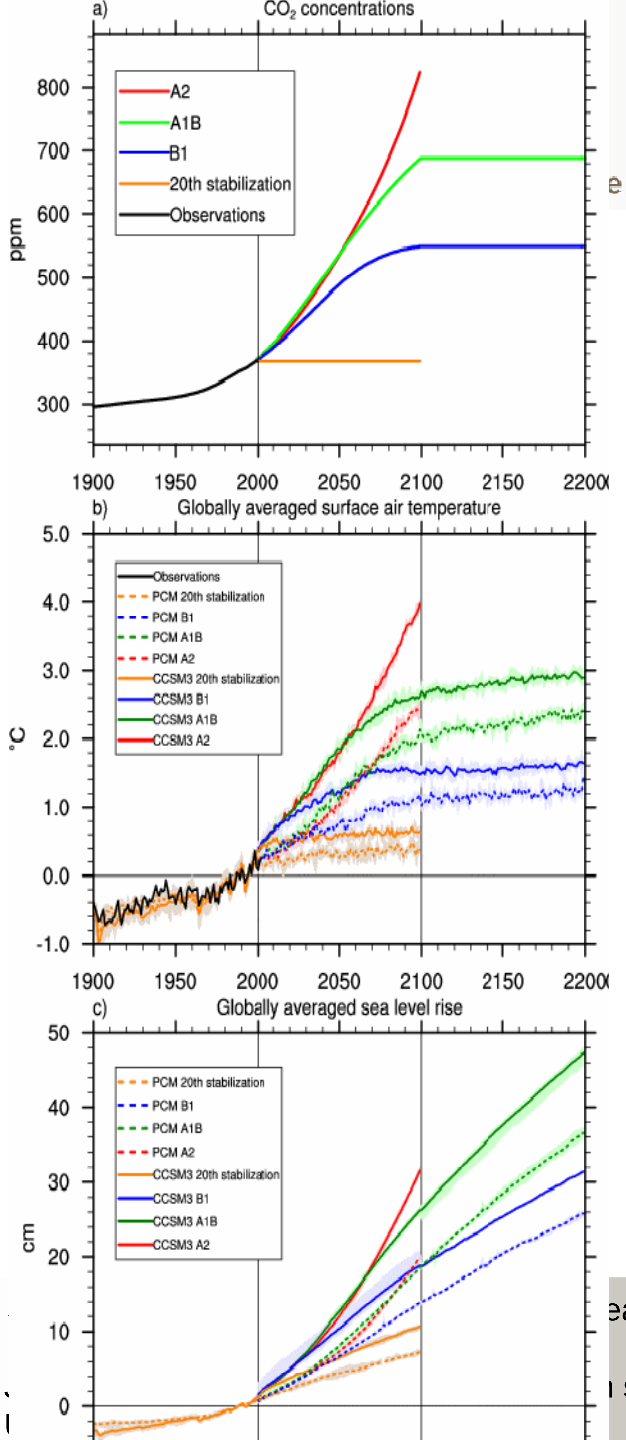
How well are the IPCC projections doing?

Rahmstorf et al. 2007

Sea level rising near the upper limit of the projections (i.e. 88 cm rise by 2100)



Rahmstorf et al. 2007



What about the longer term?

Sea-level rise continues long after stabilisation of concentrations

Stabilisation of emissions will result in larger rates of change

Meehl *et al.*, 2005

ea-level rise

http://wcrp.wmo.int

system during Global Warming Symposium,

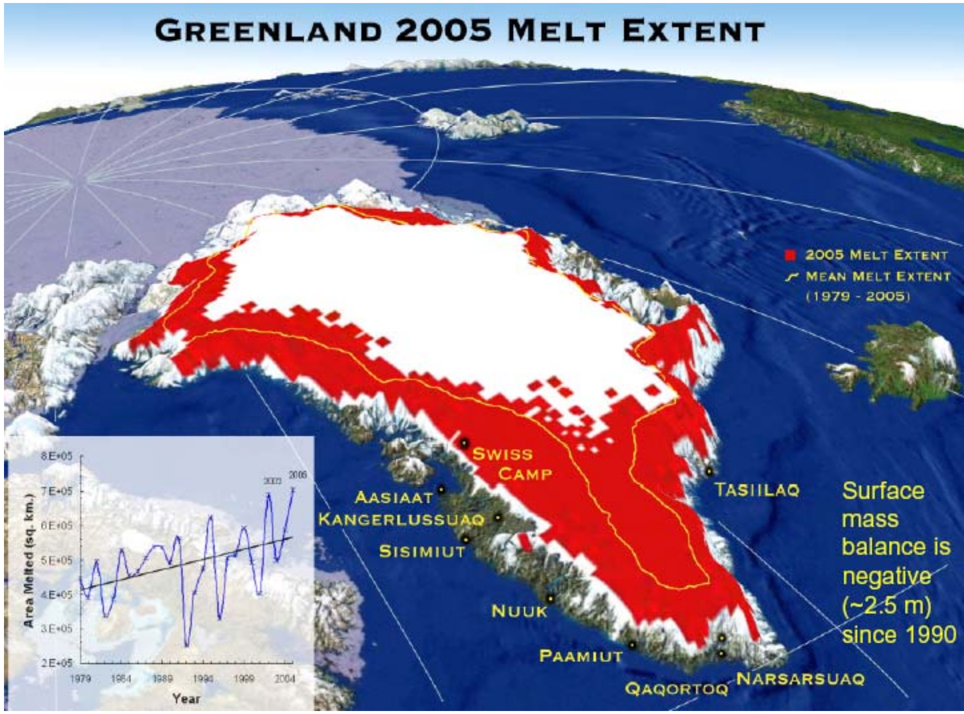
WMO IOC ICSU International Council for Science

Close to a threshold for Greenland melting!

Concern about ice-sheet stability and a substantially larger rise in sea level

- Evidence for rates of SLR on 1 m/C in last interglacial
- Surface melting

  For sustained warmings above 4.5±0.9 K in Greenland (3.1±0.8 K in global average), it is likely that the Greenland Ice Sheet would eventually be eliminated. [Gregory and Huybrechts, 2006]



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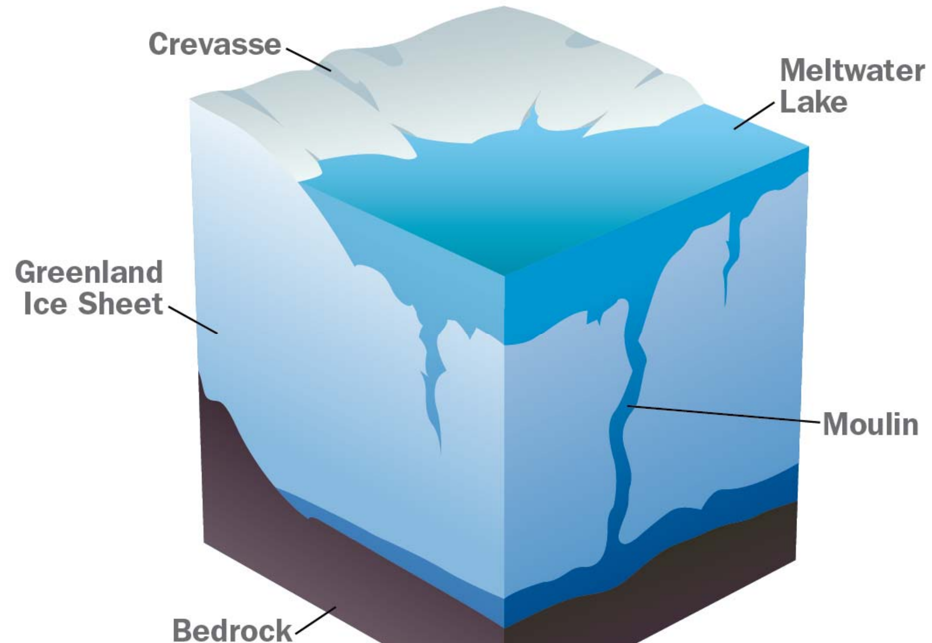
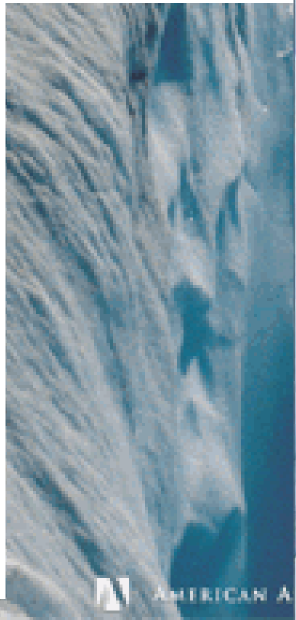
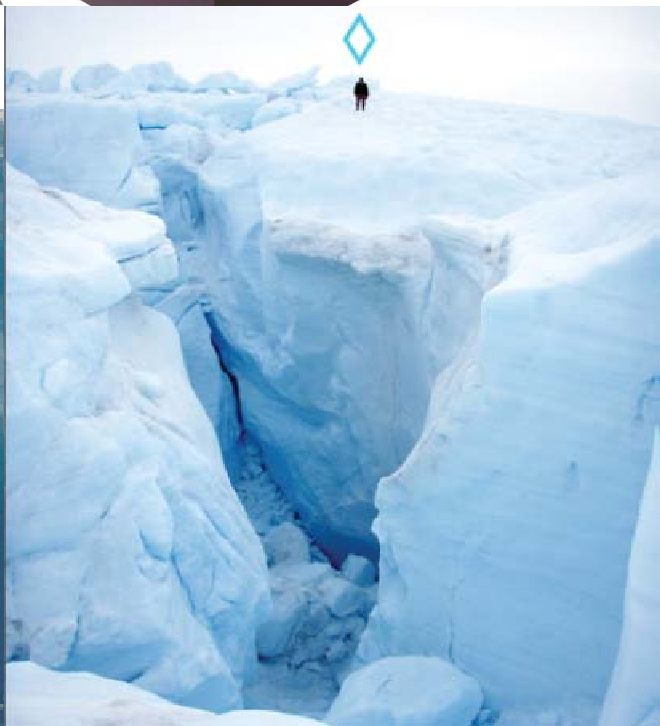
•Dynamic instability

Zwally et al. 2002, Das et al. 2008, Joughin et al. 2008







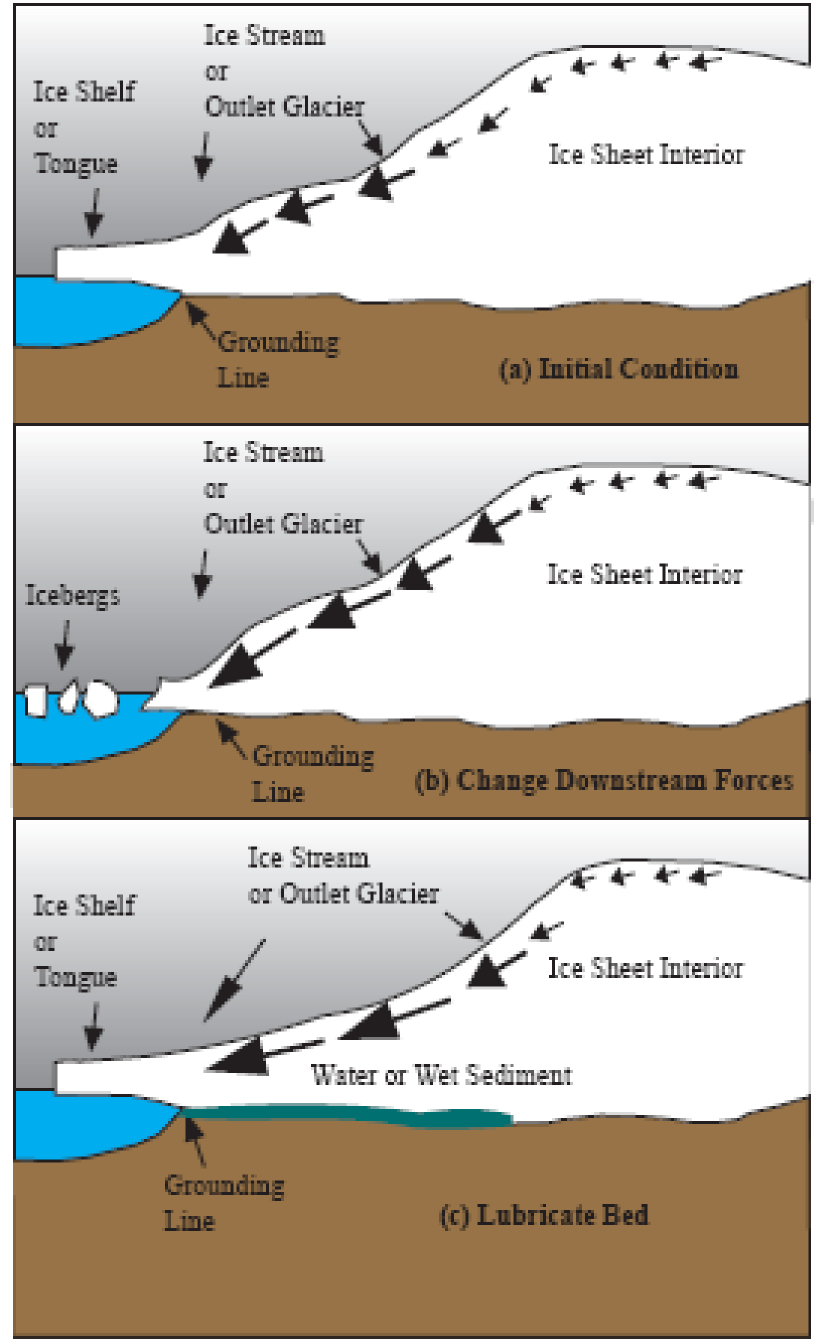
Uncertainties II Greenland and WAIS

- Loss of ice shelves

  Rapid propagation up the ice stream; Antarctic Peninsular and Greenland.

- Penetration of ocean water under the ice

  West Antarctic Ice Sheet and some outlet glaciers in Greenland.



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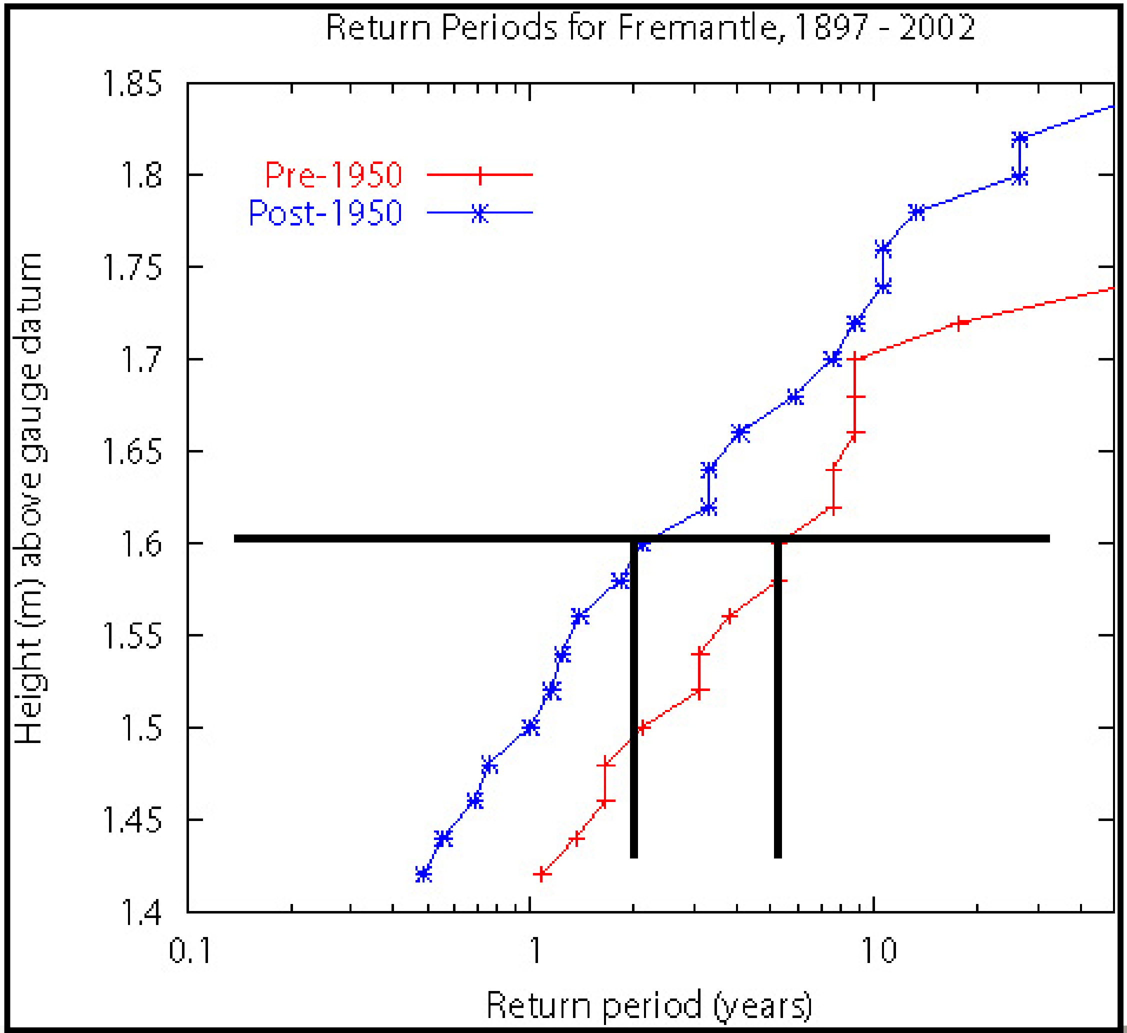
The frequency of flooding events has already increased

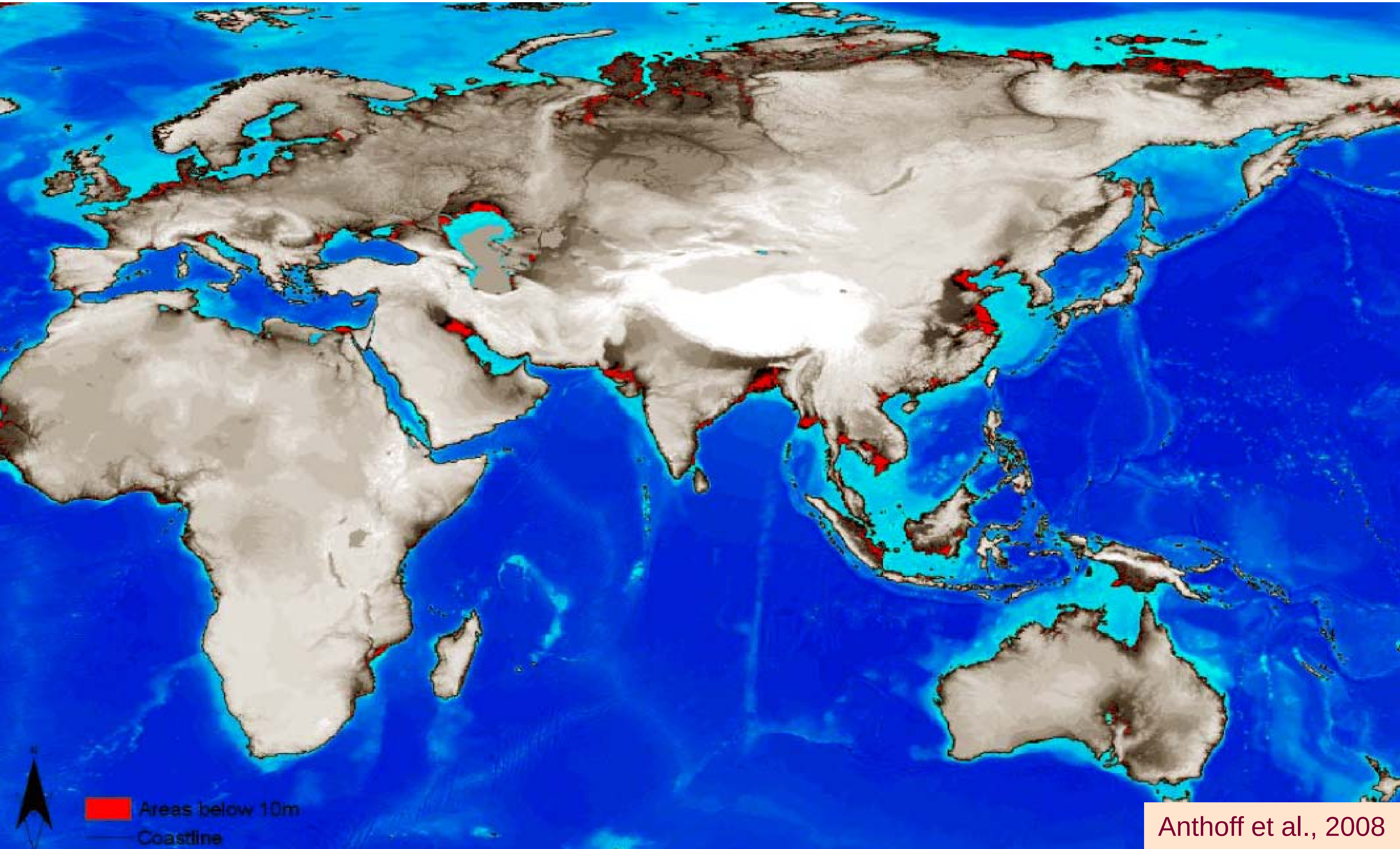


A 1 in 5 year event becomes a 1 in 2 year event.

For a 0.5 m rise, a 1 in 100 year event could happen several times/year!

Church et al., 2006

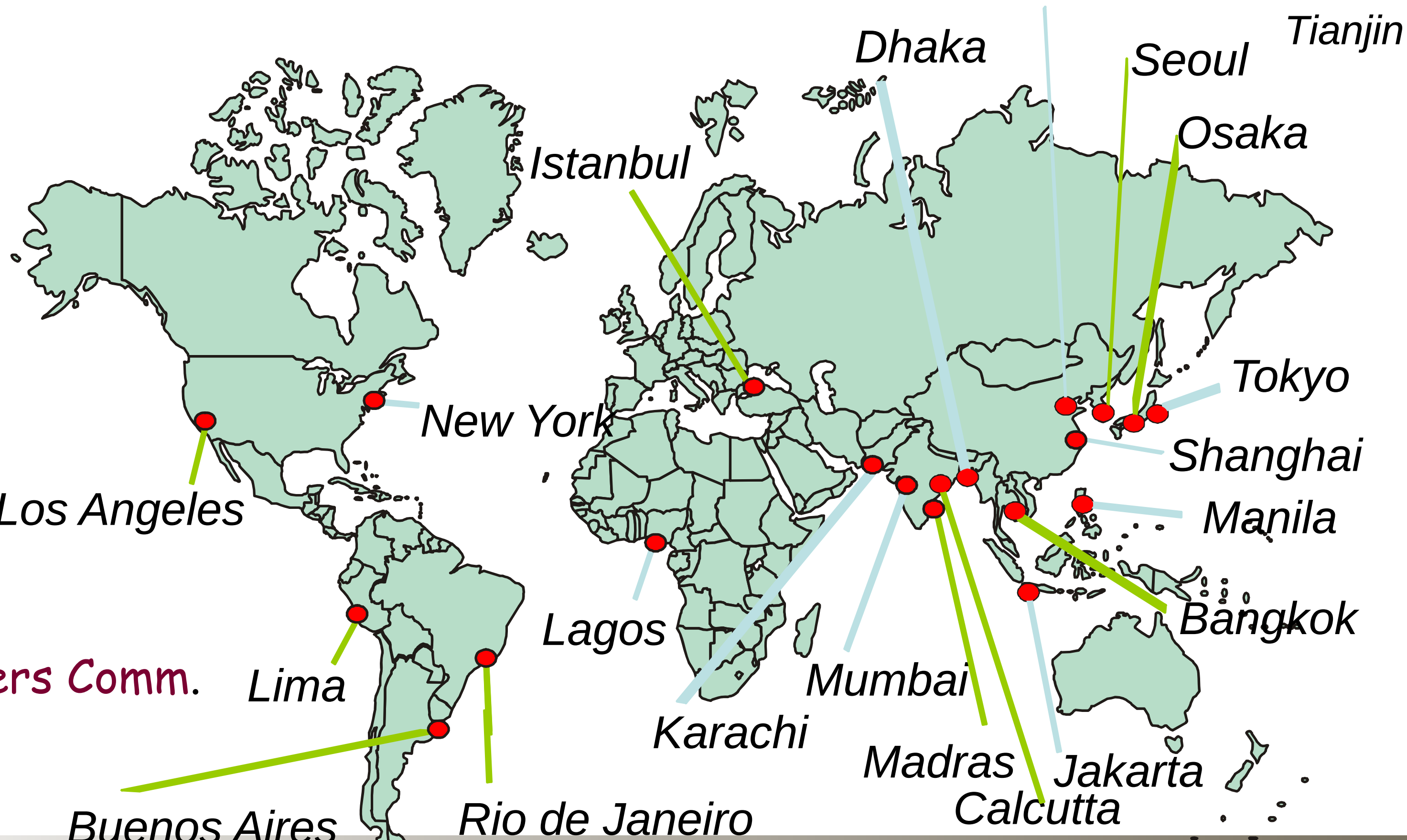
Deltaic regions less than 10 m above mean high water



Anthoff et al., 2008

Projected Coastal Megacities: 2010

By 2100, tens of millions/year will have to respond to coastal flooding;
Most vulnerable regions are South and South-East Asia; Africa; Carribean;
Indian Ocean Islands; Pacific Ocean Islands.



Bay of Bengal Major Surges

1737	300,000 killed
1864	100,000
1876	100,000
1897	175,000
1970	300,000
1971 (tide plus 6m surge)	
1991	140,000 (10 Million homeless)

And at least 23 surge events with over 10,000 killed since 1737

These considered lower limits as economic damage adds to eventual total

(Murty, Flather and Henry, 1986 Progress In Oceanography
Murty and Flather, 1994 Journal of Coastal Research)

Lowe et al. 2008

Climate projections for TE2100

- Improved storm surge projections:
  - –Ensembles
  - –Longer experiments
  - –Higher resolution
- What about the other IPCC AR4 models?

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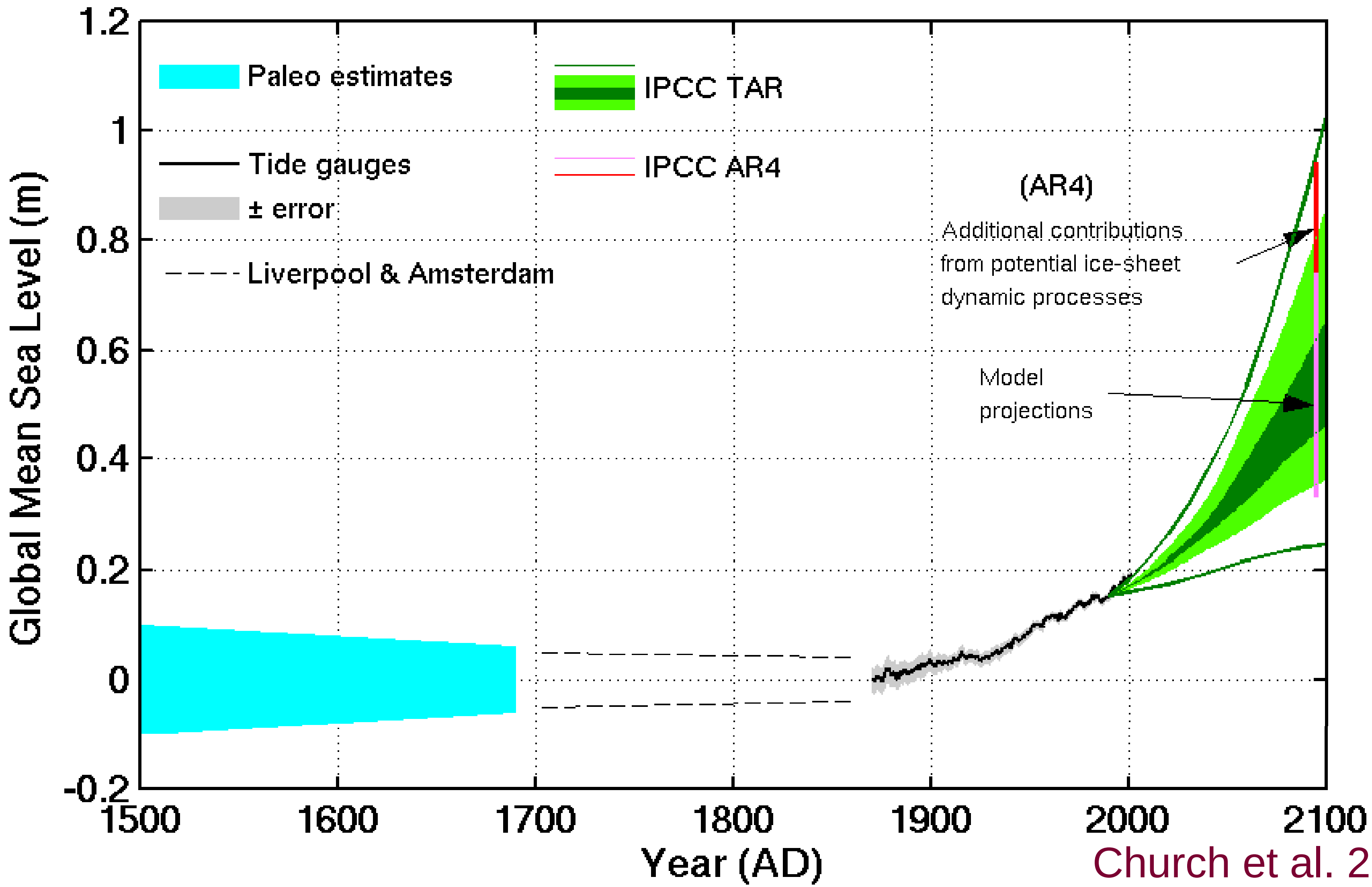
Today's sea level unprecedented during modern civilisation



Church et al. 2008

The Science Shows:

- **Ongoing sea-level rise is inevitable! It is an issue for**

  Here and now, The 21st C and The long term. Remaining gaps in ability to predict how much sea level will rise and changes in extreme events.

- **Is it dangerous? At what level? For whom?**
- **Need to adapt**

  Impacts felt through extreme events – more frequent, more severe.

  LDCs and the poor most at risk. Require local and regional planning. Planning to avoid the impacts of severe events.

  Need to narrow uncertainties

- **Need to mitigate to avoid the most extreme scenarios**

  Without significant, urgent and sustained action, we could pass a threshold during the 21st C, committing the world to metres of sea-level rise!

- **Environmental refugees a here and now issue**

  Not "if" but "when, where and how will we respond?"

- **Essential and urgent that science/government/business/community partnerships are strengthened!**

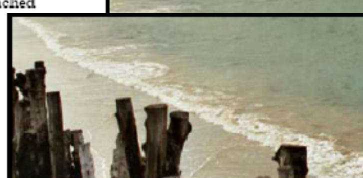
THE WORKSHOP. 163 scientists from 29 countries attended the Workshop on Understanding Sea-level Rise and Variability,[1] hosted by the Intergovernmental Oceanographic Commission of UNESCO in Paris June 6-9, 2006. The Workshop was organized by the World Climate Research Programme (WCRP)[2] to bring together all relevant scientific expertise with a view towards identifying the uncertainties associated with past and future sea-level rise and variability, as well as the research and observational activities needed for narrowing these uncertainties. The Workshop was also conducted in support of the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan;[3] as such, it helped develop international and interdisciplinary scientific consensus for those observational requirements needed to address sea-level rise and its variability.

The Issue – Since the beginning of high-accuracy satellite altimetry in the early 1990s, global mean sea-level has been observed by both tide gauges and altimeters to be rising at a rate of just above 3 mm/year, compared to a rate of less than 2 mm/year from tide gauges over the previous century. The extent to which this increase reflects natural variability versus anthropogenic climate change is unknown. About half of the sea-level rise during the first decade of the altimeter record can be attributed to thermal expansion due to a warming of the oceans; the other major contributions include the combined effects of melting glaciers and ice sheets. Changes in the storage of water on land (such as the depletion of aquifers and increases in dams and reservoirs) remain very uncertain.

The Motivation – The coastal zone has changed profoundly during the 20th century, primarily due to growing populations and increasing urbanization. In 1990, 23 percent of the world's population (or 1.2 billion people) lived both within a 100 km distance and 100 m elevation of the coast at densities about three times higher than the global average. By 2010, 20 out of 30 mega-cities will be on the coast, with many low-lying locations threatened by sea-level rise. With coastal development continuing at a rapid pace, society is becoming increasingly vulnerable to sea-level rise and variability—as Hurricane Katrina recently demonstrated in New Orleans. Rising sea levels will contribute to increased storm surges and flooding, even if hurricane intensities do not increase in response to the warming of the oceans. Rising sea levels will also contribute to the erosion of the world's sandy beaches, 70 percent of which have been retreating over the past century. Low-lying islands are also vulnerable to sea-level rise.

An improved understanding of sea-level rise and variability will help reduce the uncertainties associated with sea-level rise projections, thus contributing to more effective coastal planning and management. Adaptation measures, including enhanced building codes, restrictions on where to build, and developing infrastructures better able to cope with flooding, should help to minimize the potential losses.

Relation to the IPCC Assessments – The Third Assessment Report (TAR)[4] of the Intergovernmental Panel on Climate Change (IPCC) estimated that sea level will rise between 9 and 88 cm by the end of the 21st century. The Fourth Assessment Report (due in 2007) is currently being reviewed by governments. The Workshop complemented the TAR by starting with the set of uncertainties it identified, then focusing on the scientific and observational requirements needed to reduce those uncertainties, as well as uncertainties identified during the Workshop. The Workshop did not attempt to develop projections of future changes as the TAR did. The Workshop participants reached consensus that the increase in the rate of global mean sea-level rise towards the end of the 20th century, to just above 3 mm per year from less than 2 mm per year on average over the previous century, is a robust finding. The Extended Workshop Report[5] will address how the many uncertainties in understanding the causes of 20th century sea-level change and its recent acceleration could be reduced for input to future IPCC Assessment Reports.



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Summary Statement from the World Climate Research Programme Workshop

Understanding Sea-level Rise and Variability

Report of the WCRP Workshop

(163 participants, 29 nations)

Thank you!