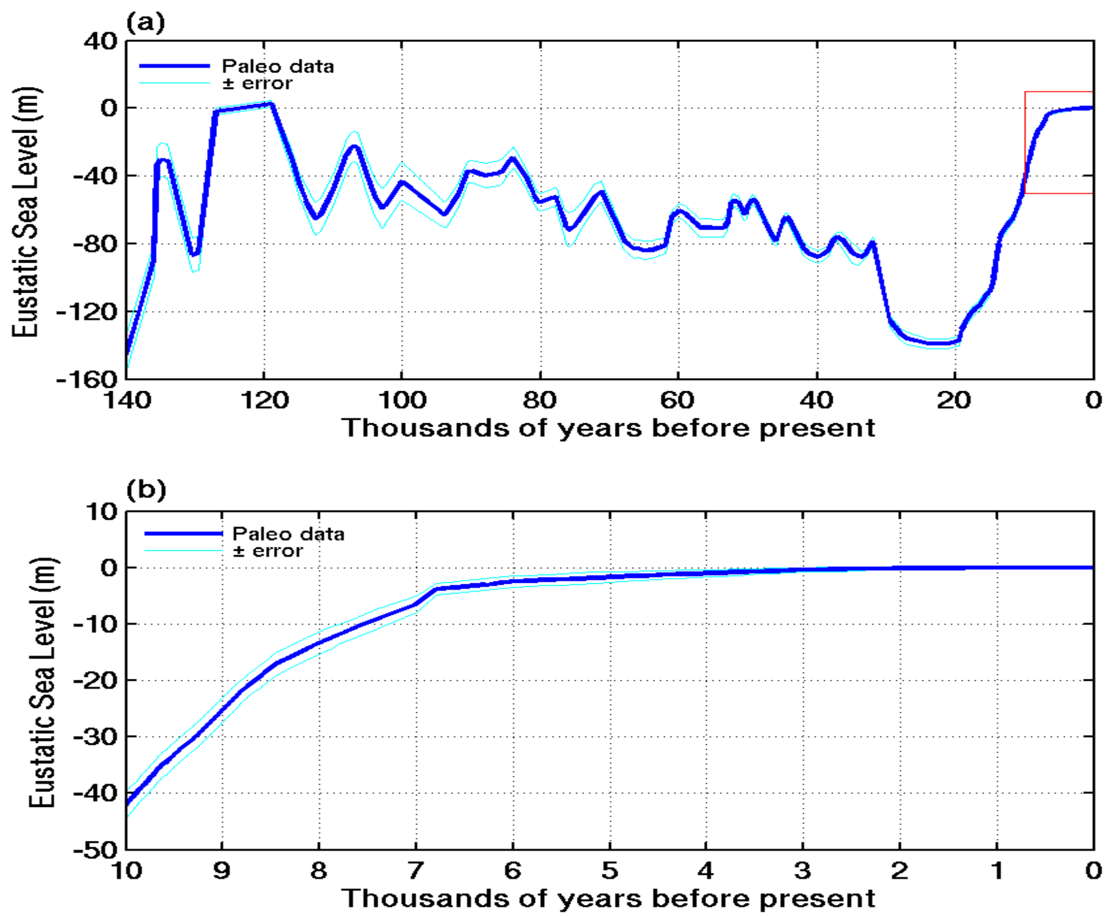
Sea Level

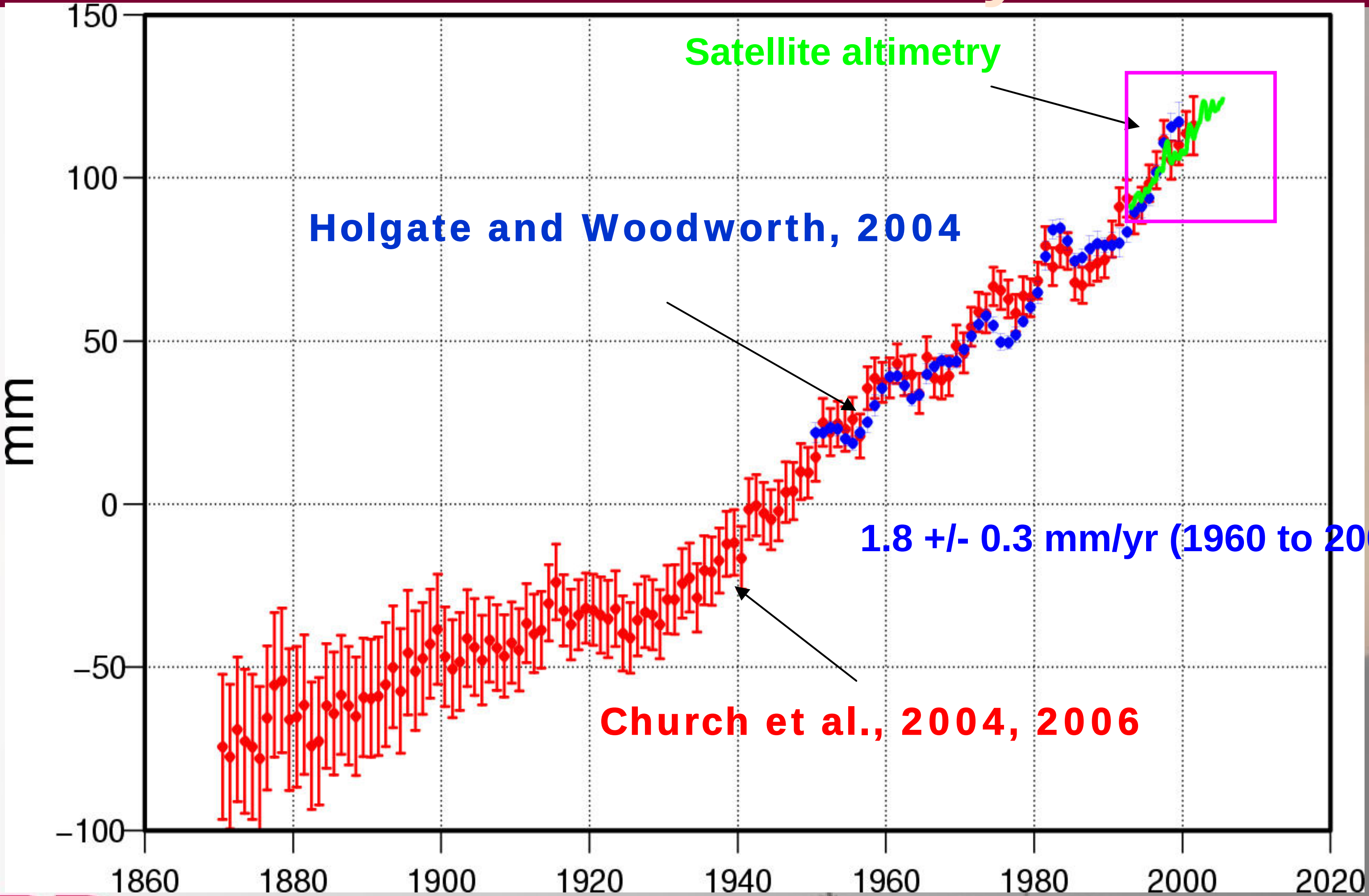
John Church
WCRP
Antarctic Climate and Ecosystems CRC
Centre for Australian Weather and Climate Research

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

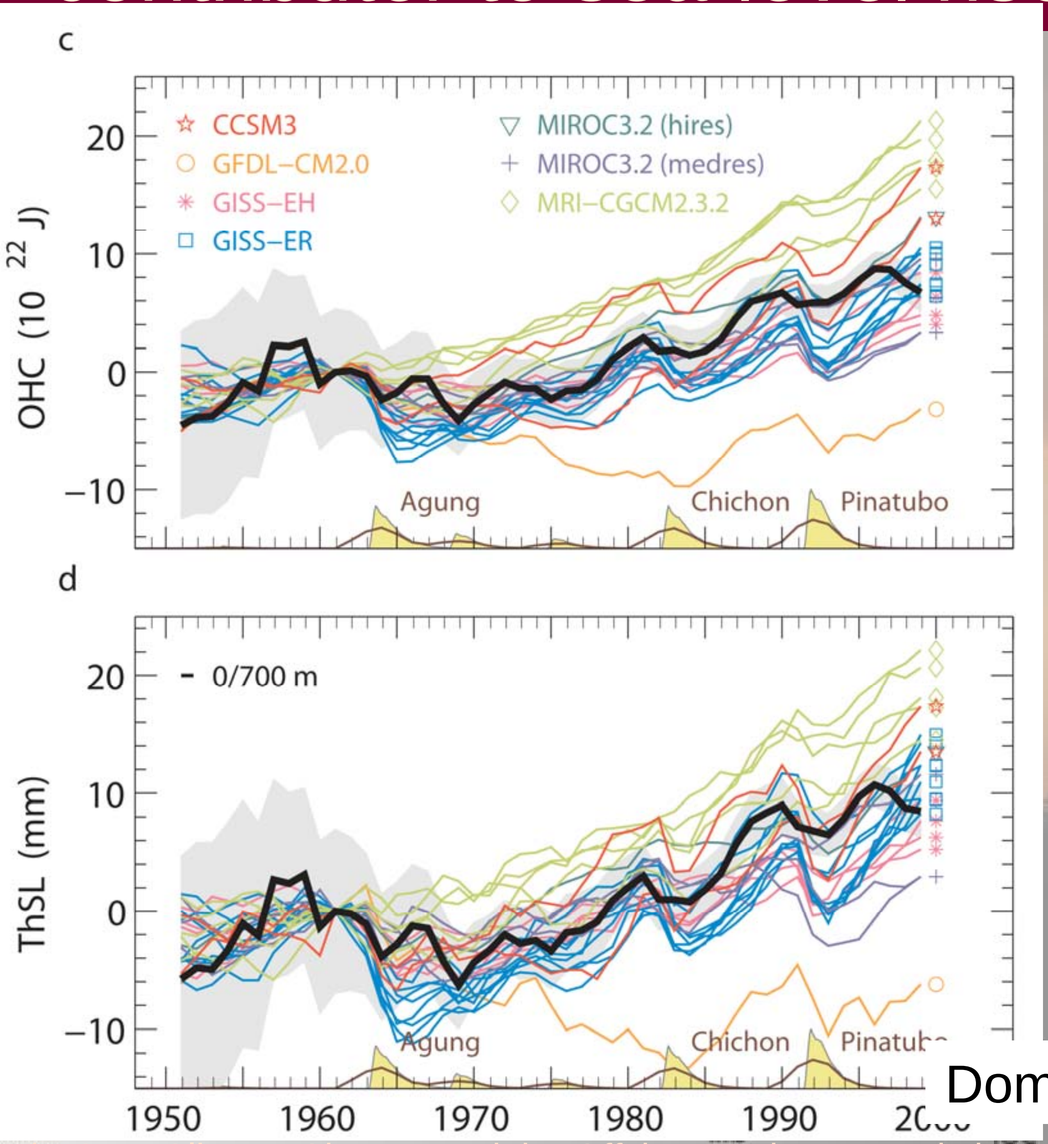


Church et al., 2008

Sea-level rise accelerated during the 20th century

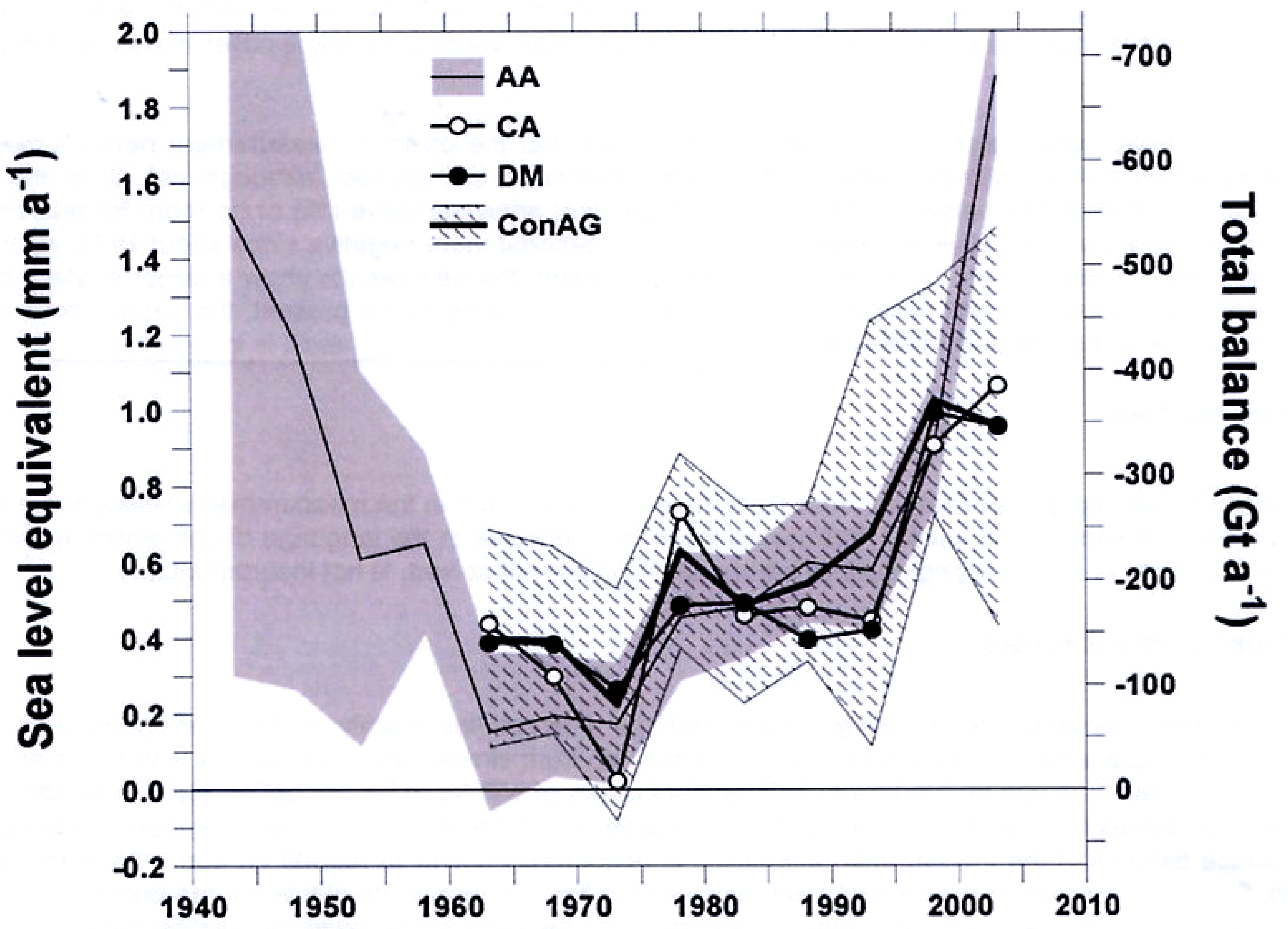


Ocean thermal expansion a major contributor to sea-level rise



Domingues et al. 2008

Glacier melting contributes to sea level



Kaser et al. 2005

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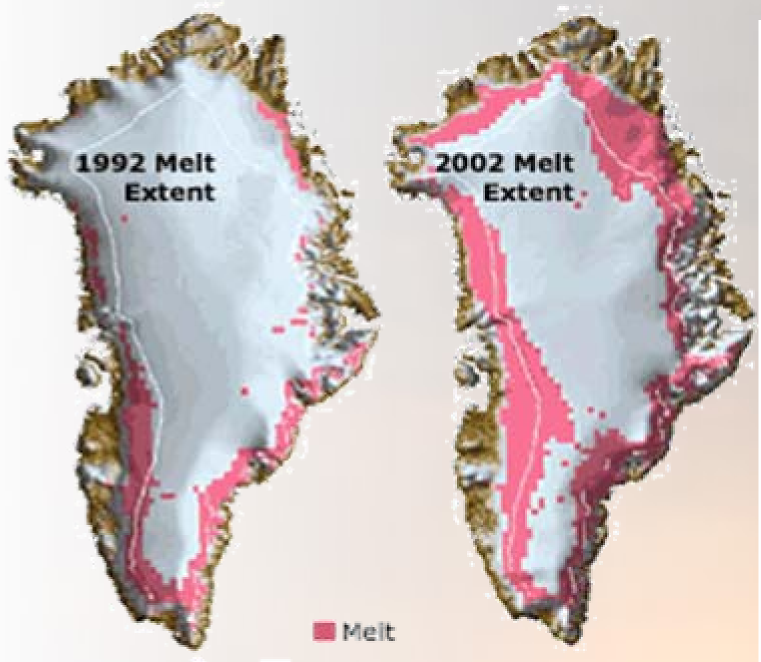
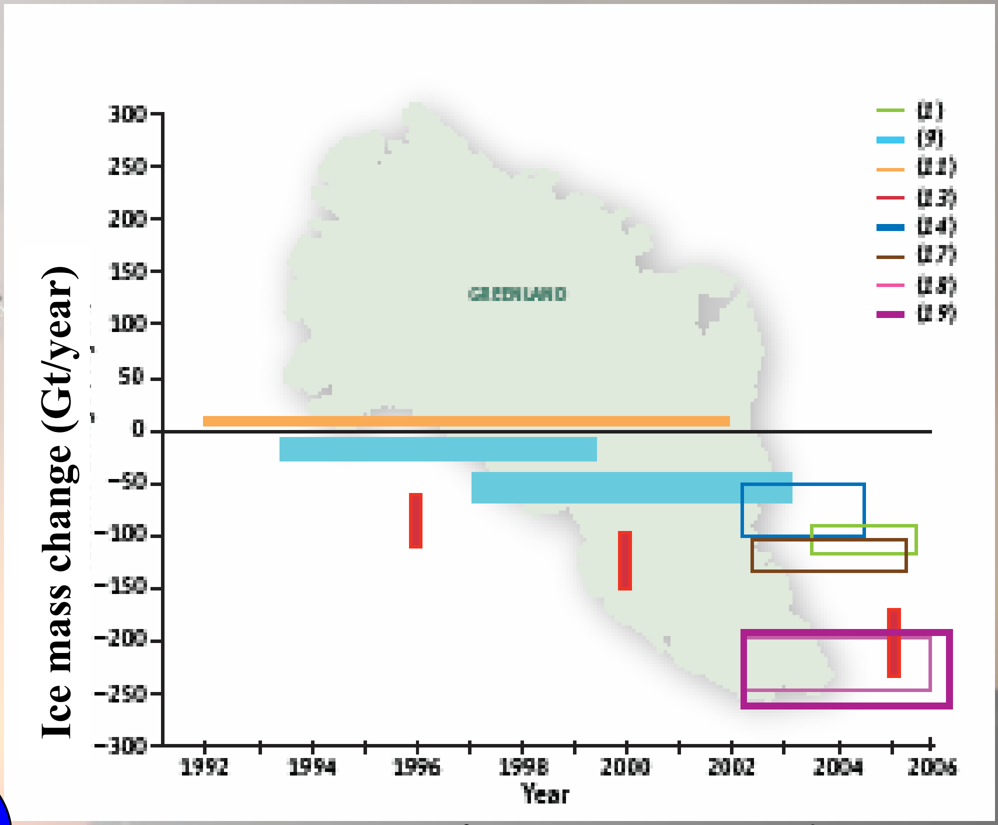
Ice mass loss of the Greenland ice sheet since 1992





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

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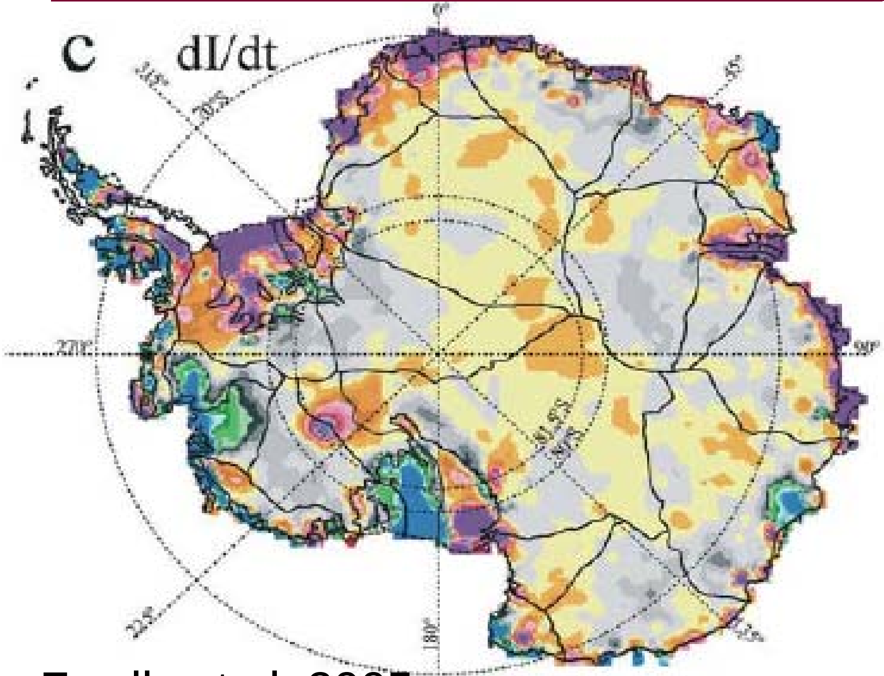
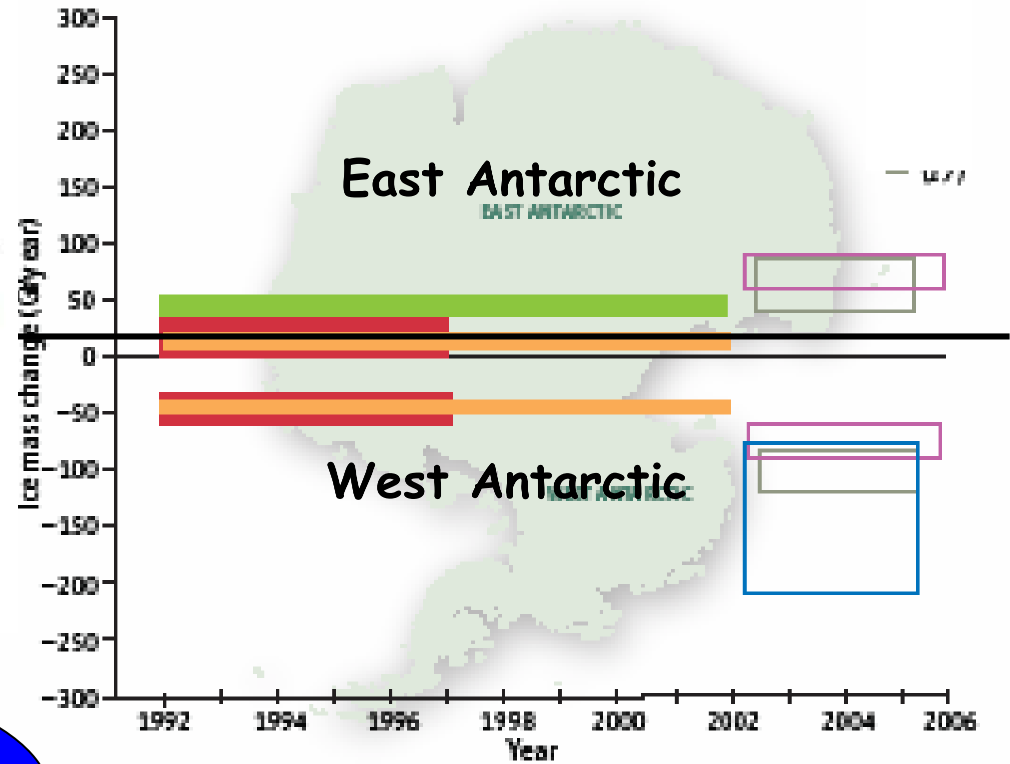
The West Antarctic Ice Sheet is loosing mass (possible long-term loss)



Zwally et al. 2005



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

Remote sensing measurements

(Cazenave, 2006)

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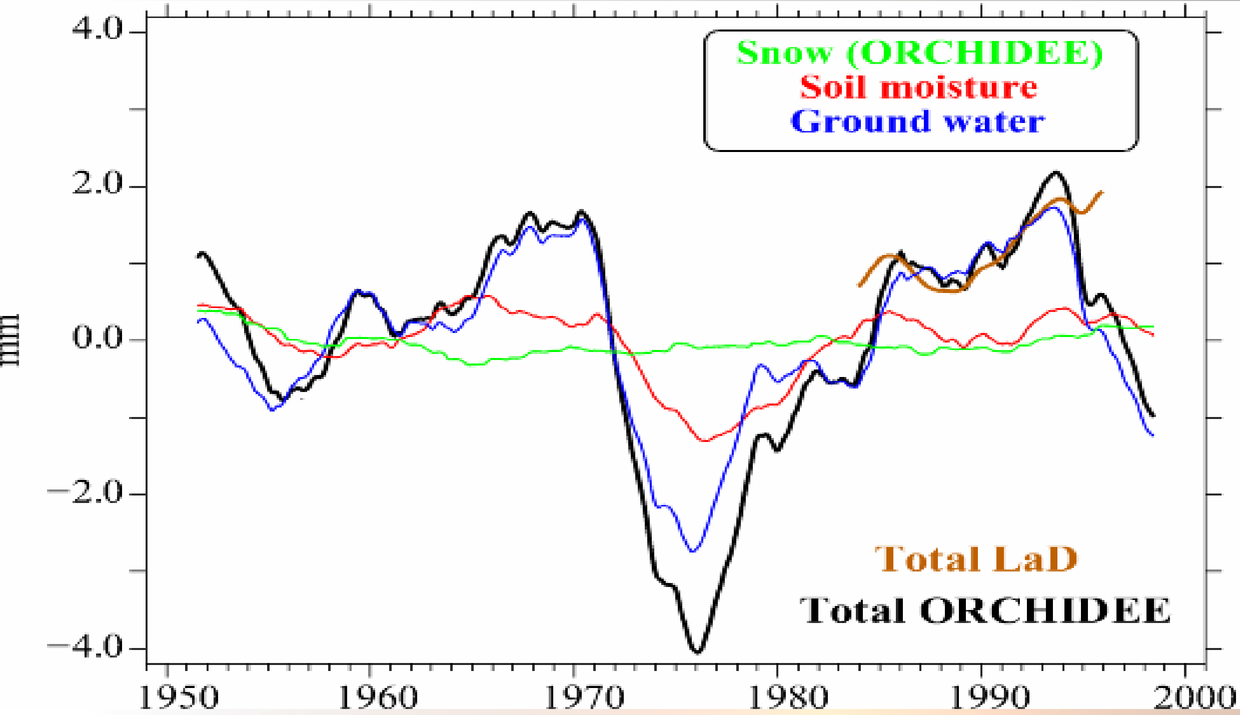
Effect of global land water storage on global mean sea level

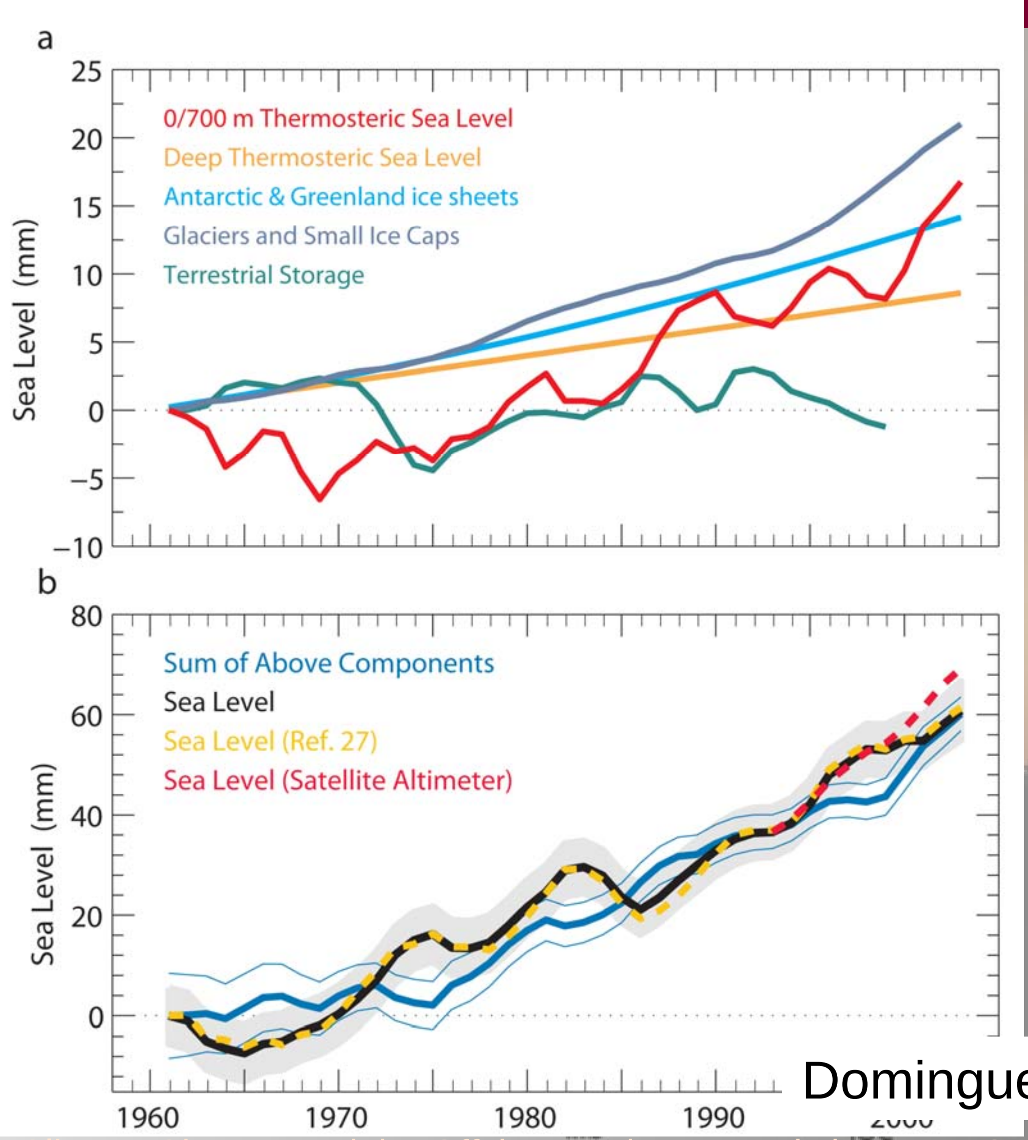


Milly, P. C., D., A. Cazenave, and M. C. Gennero (Proc. Natl Acad. Sci, 2003)

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

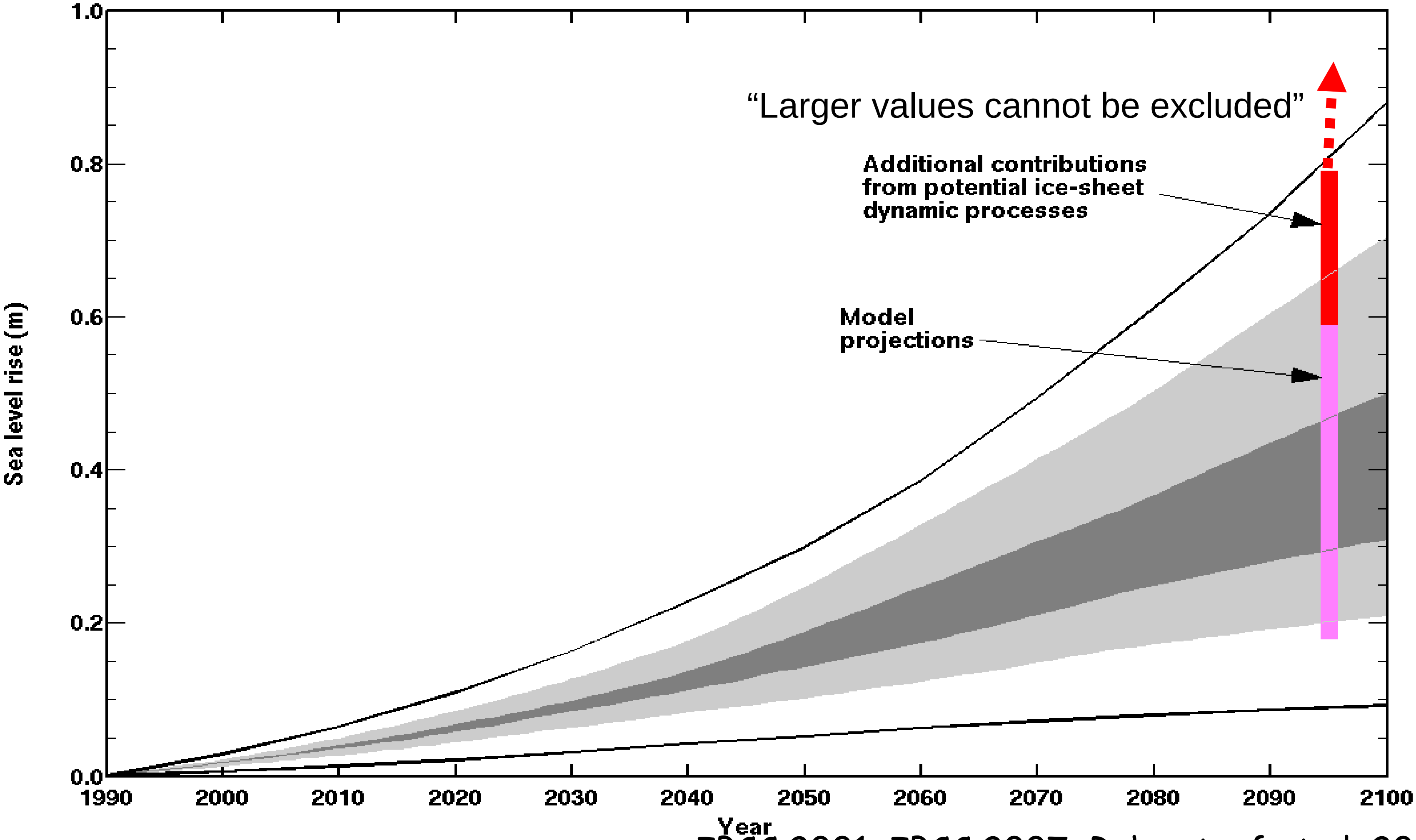
- greatest variation is associated with ground water, followed by soil moisture
- no significant trend was detected
- strong decadal variability driven by precipitation, strong decrease in the beginning of 1970s
  - agreement between ORCHIDEE and LaD. *(Land Dynamics LSM of GFDL)*

Sum of contributions is close to the observed rise (but some remaining deficiencies and omissions)



Domingues et al. 2008

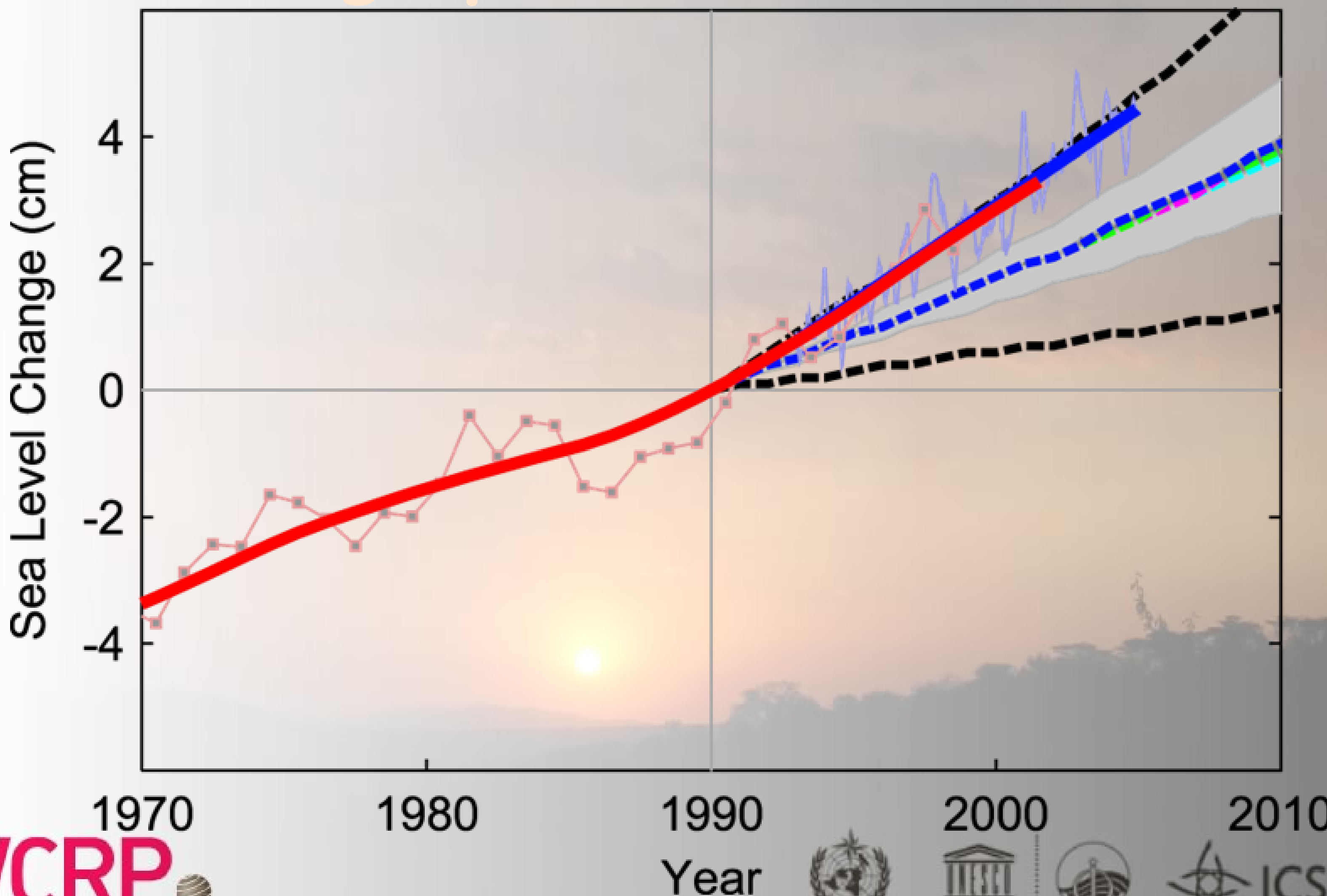
The IPCC TAR and AR4 projections of sea-level rise are similar



IPCC 2001; IPCC 2007; Rahmstorf et al. 2007

How well are the IPCC projections standing up to the test of time?

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



Rahmstorf et al. 2007

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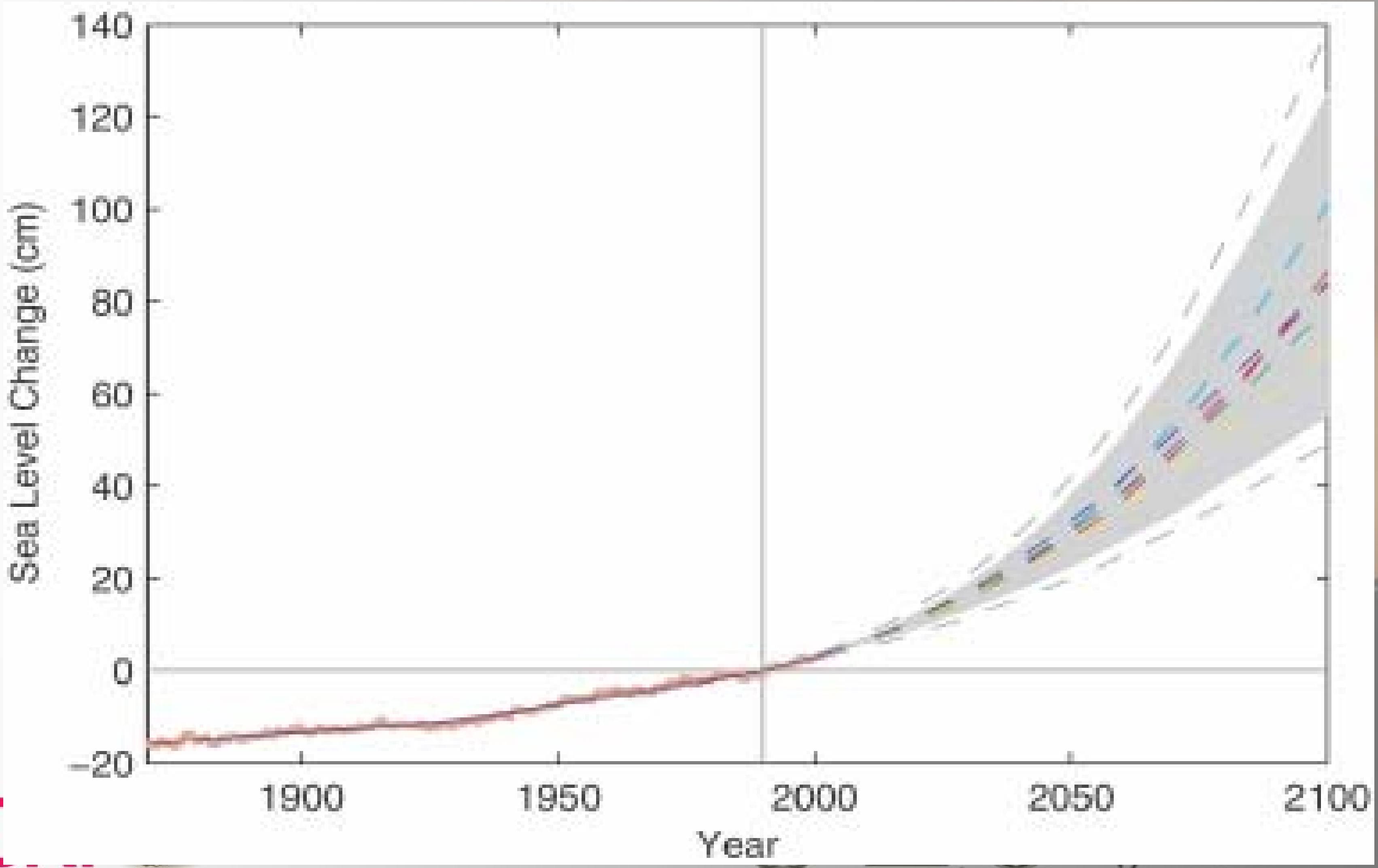
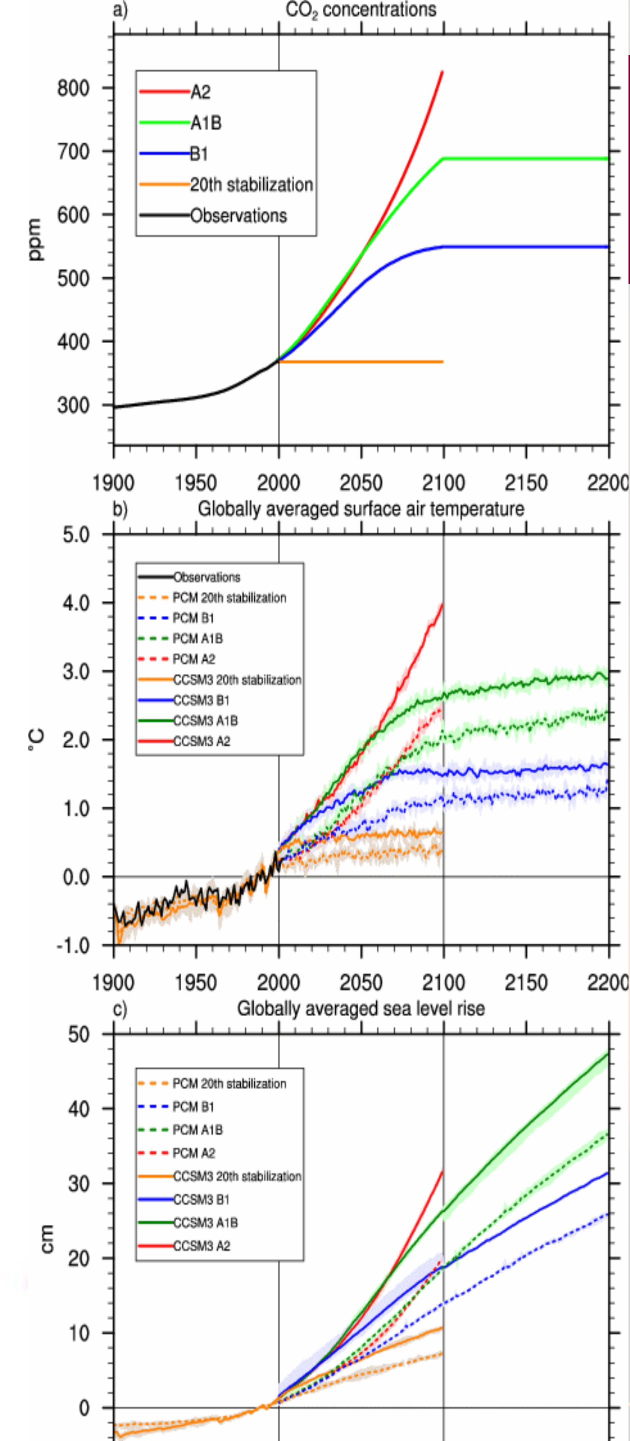
Statistical models consistent with larger 21st C rise – at/above upper end of IPCC range



Rahmstorf, 2006



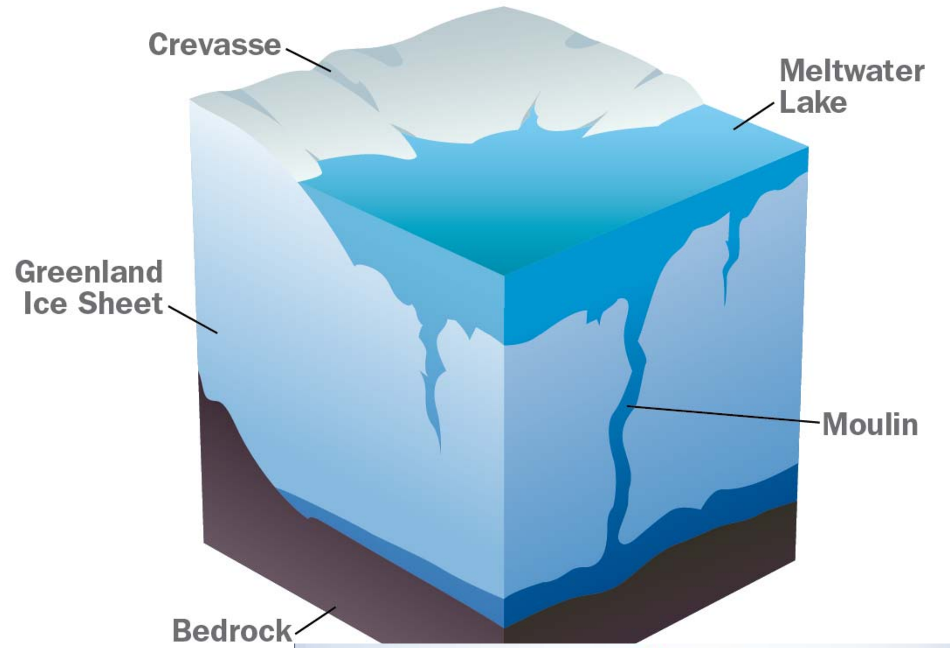
What about the longer term?

Sea-level rise continues long after stabilisation of concentrations

Stabilisation of emissions will result in larger rates of change

Meehl *et al.*, 2005

Uncertainties I
Greenland



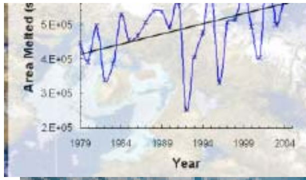
Concern about ice-sheet stability and a substantially larger rise in sea level

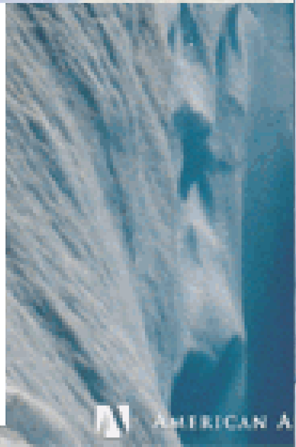
- Paleo evidence for rates of SLR of 1 m/C in Eemian
- Surface melting

  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]

- Dynamic instability

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





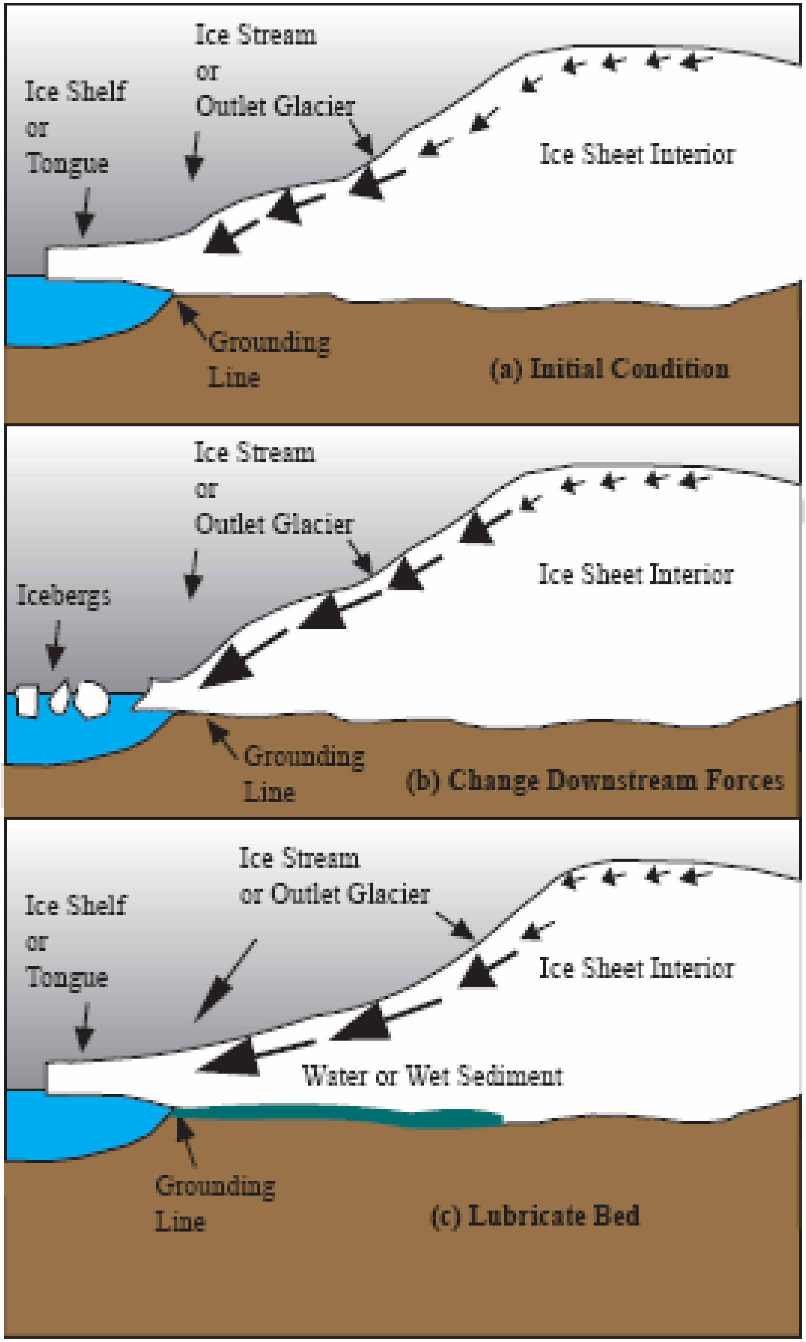
Uncertainties II
Greenland and WAIS

- 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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Sea-level rise is expected to have regional variations

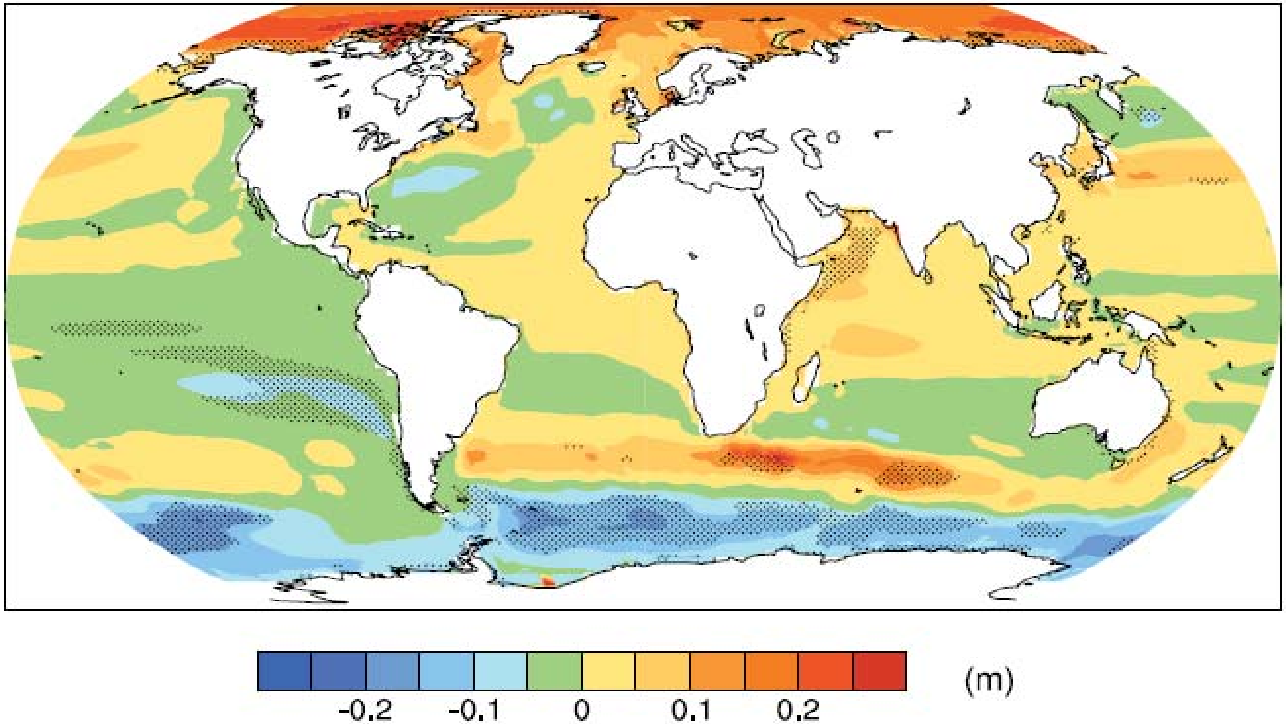
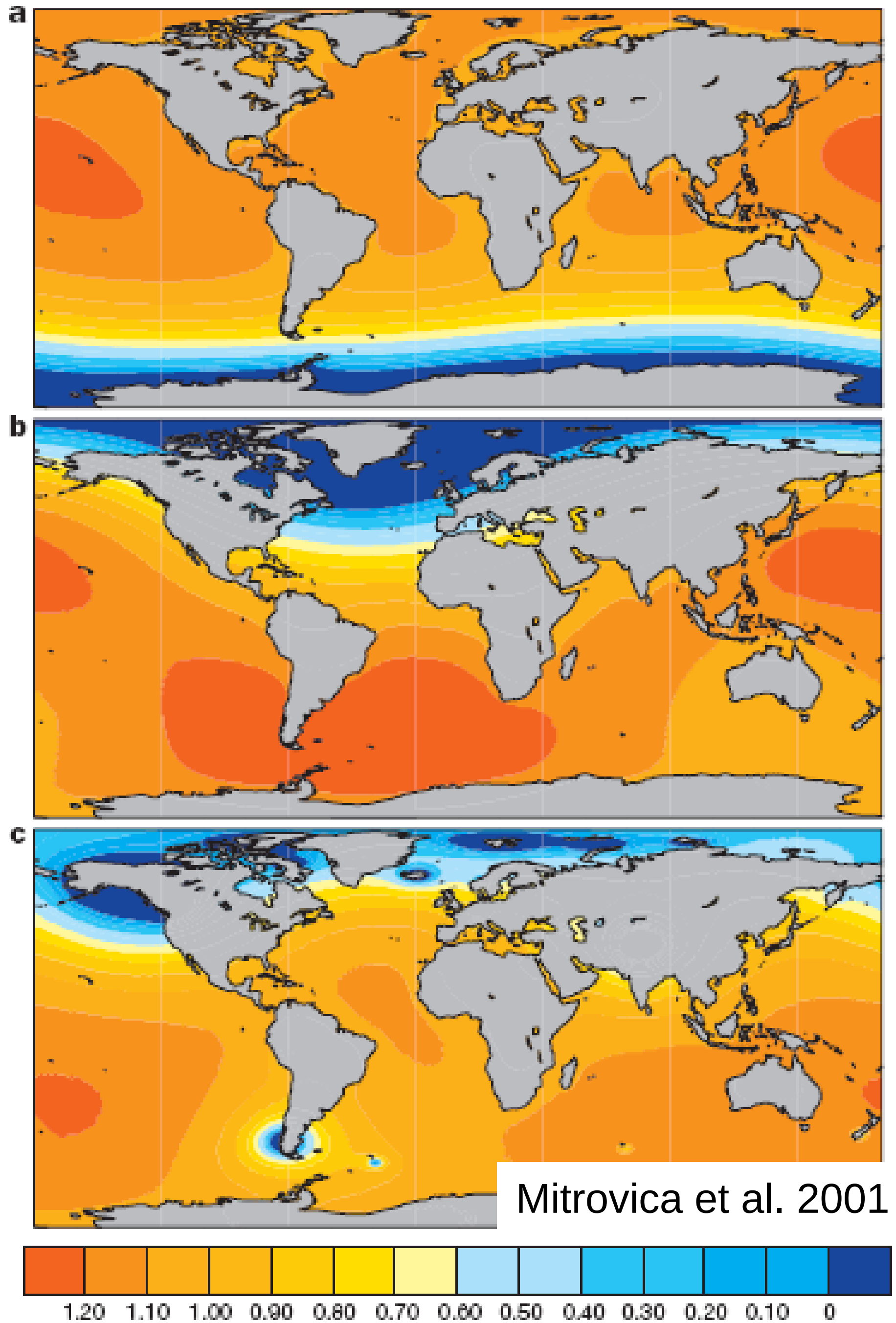


Figure 10.32. *Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0.*

Meehl et al. 2007

Response to changes is surface loading

To understand regional sea-level rise need to allow for the earth's response to changes in surface loading (and other land motions)



Mitrovica et al. 2001

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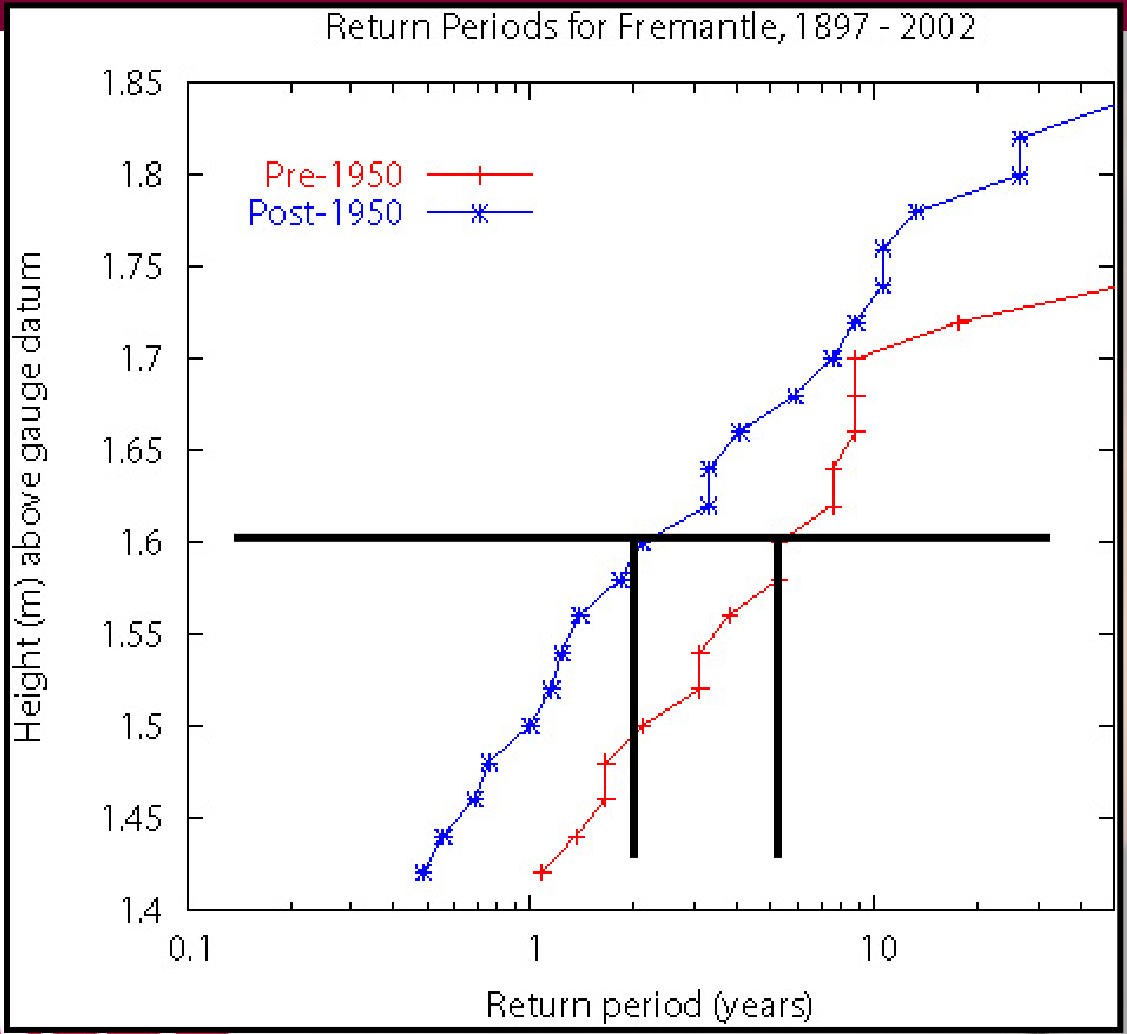
The frequency of flooding events of a given magnitude has increased



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

Church et al. 2006

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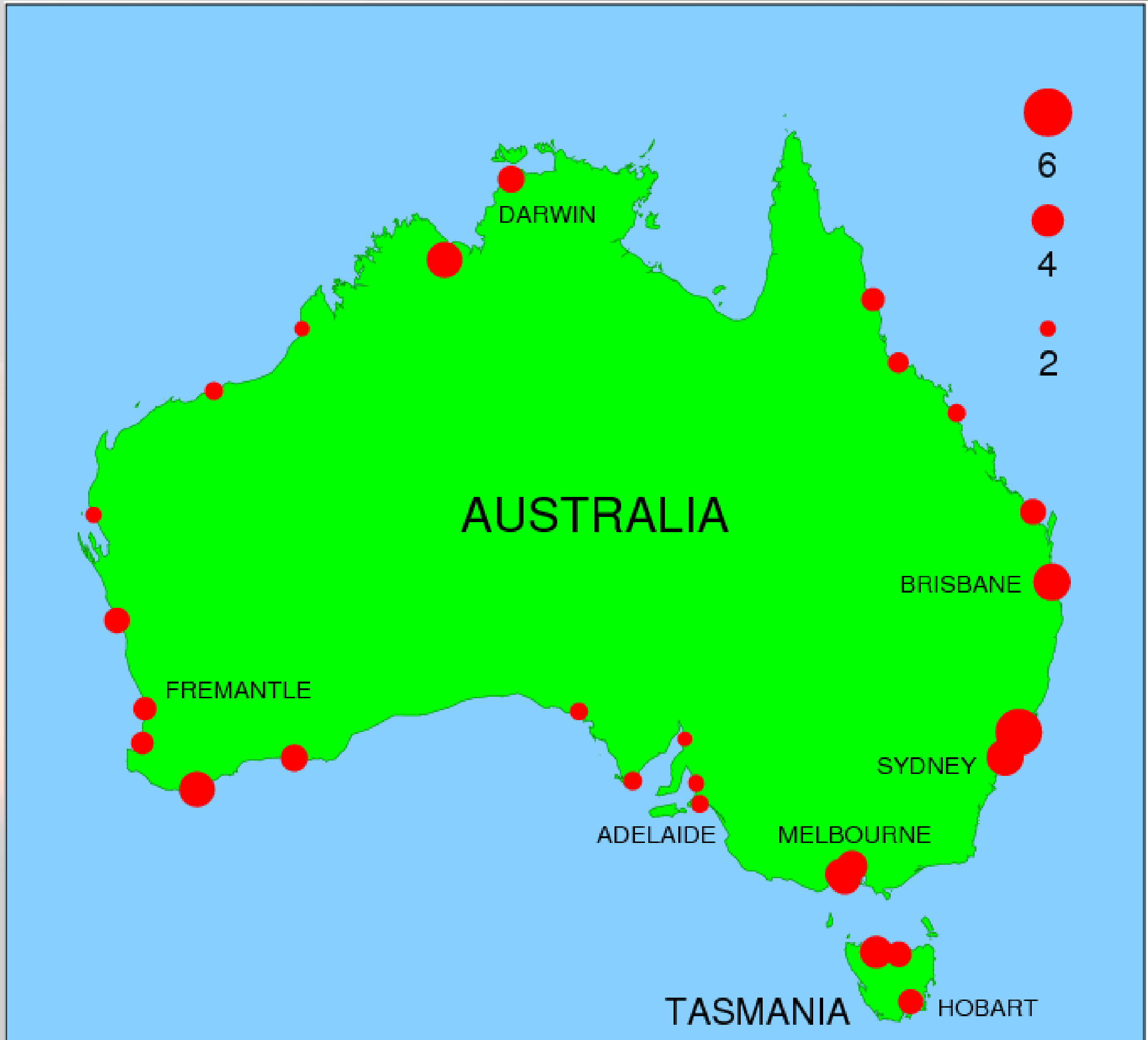
Decrease in the return period of extreme events for a 0.1 m sea-level rise

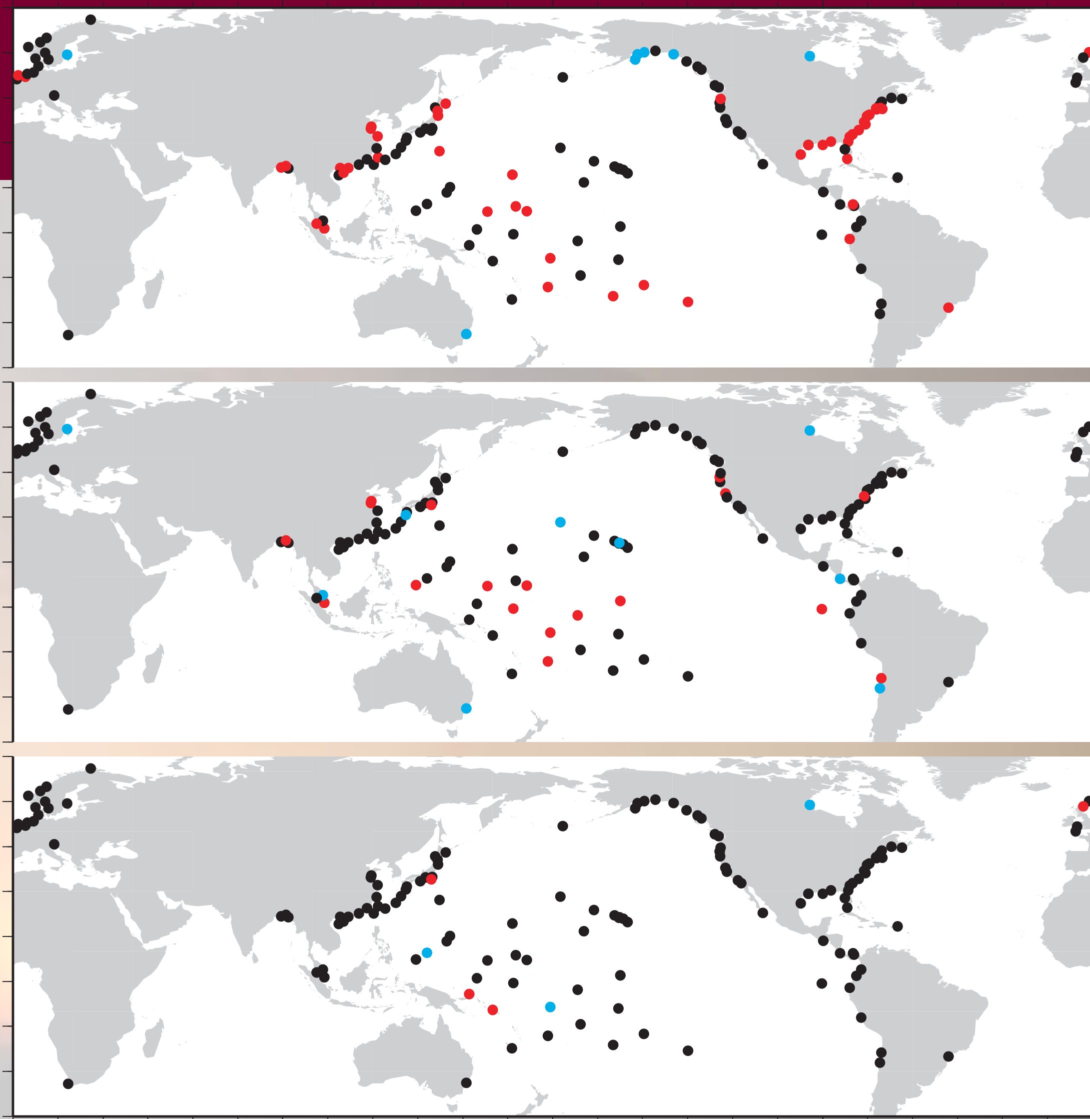
For a 0.5 m rise, a 1 in 100 year event could happen several times/year



Hunter 2007; Church et al. 2008

Locations where the period between flooding events has decreased are shown in red.

Top – relative sea level
Bottom – relative to yearly average sea level



99 Percentile Trends since 1975 (Woodworth and Blackman, 2004 J. Climate)

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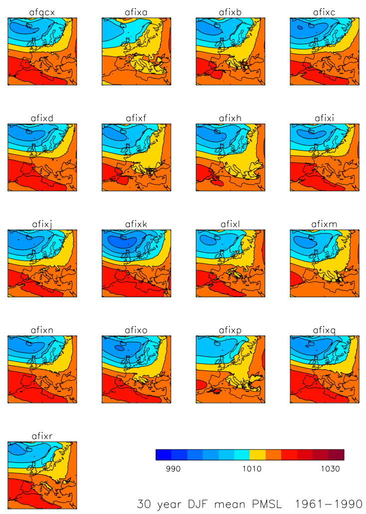
ICSU

Climate projections for TE2100

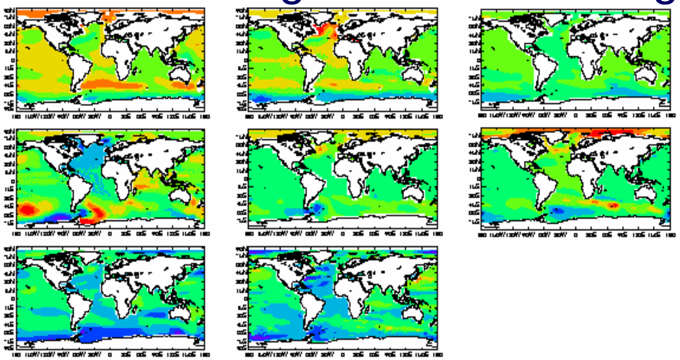
- Improved storm surge projections:
  - Ensembles
  - Longer experiments
  - Higher resolution
- What about the other IPCC AR4 models?

Ensemble projections of change in extreme sea levels

Uncertainty in large scale atmospheric forcing



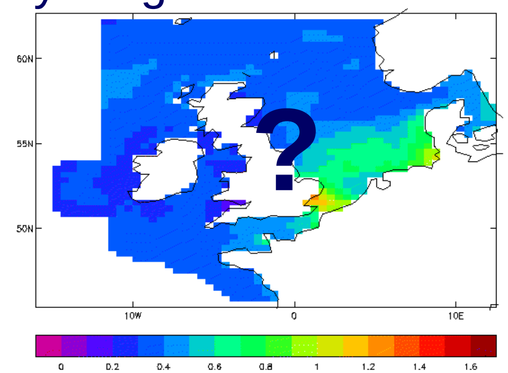
Uncertainty in large scale patterns of time average sea level change



Add in ice melt uncertainty

Downscale to get uncertainty in Regional scale atmospheric forcing

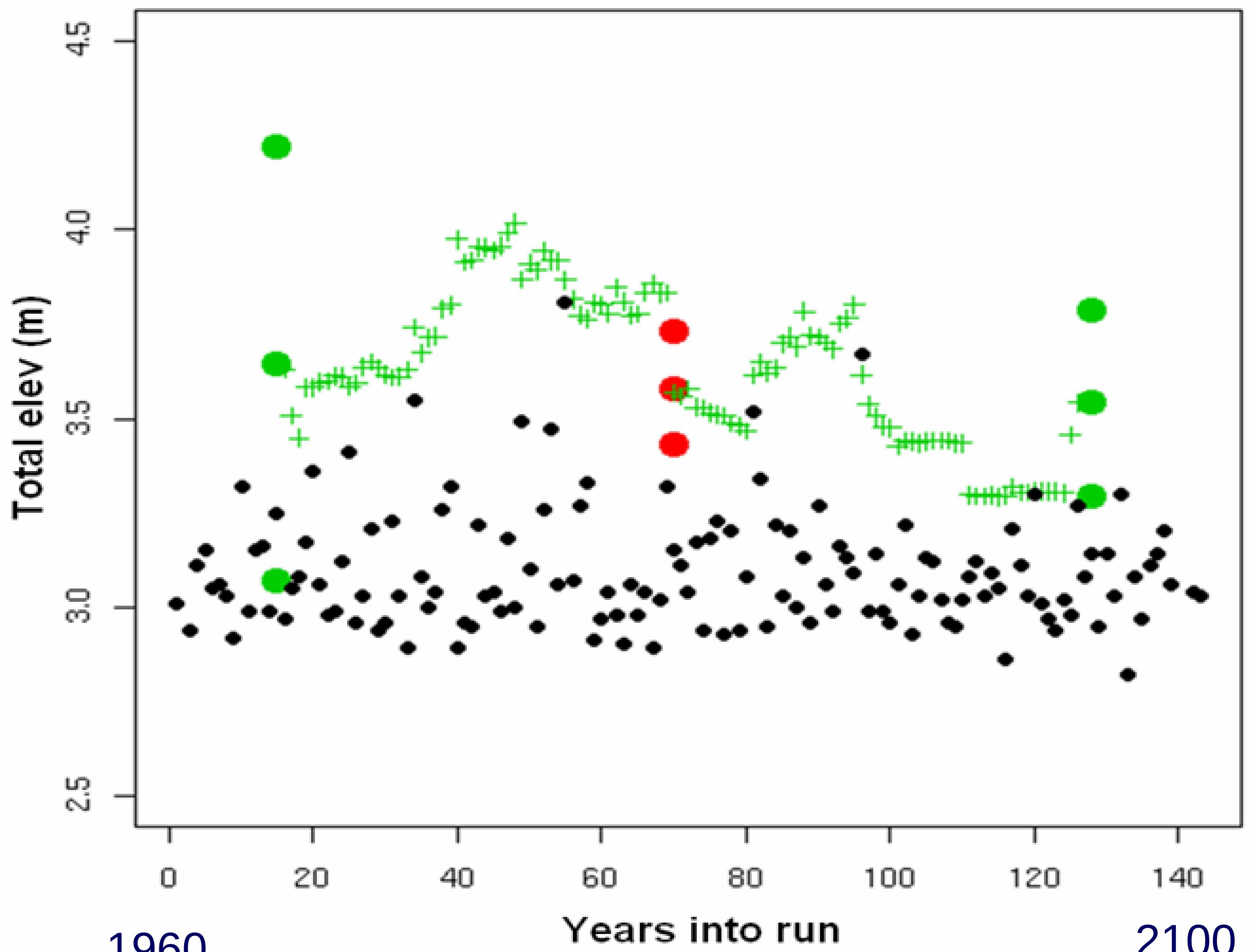
Run surge model simulations to estimate uncertainty range in local extreme water levels



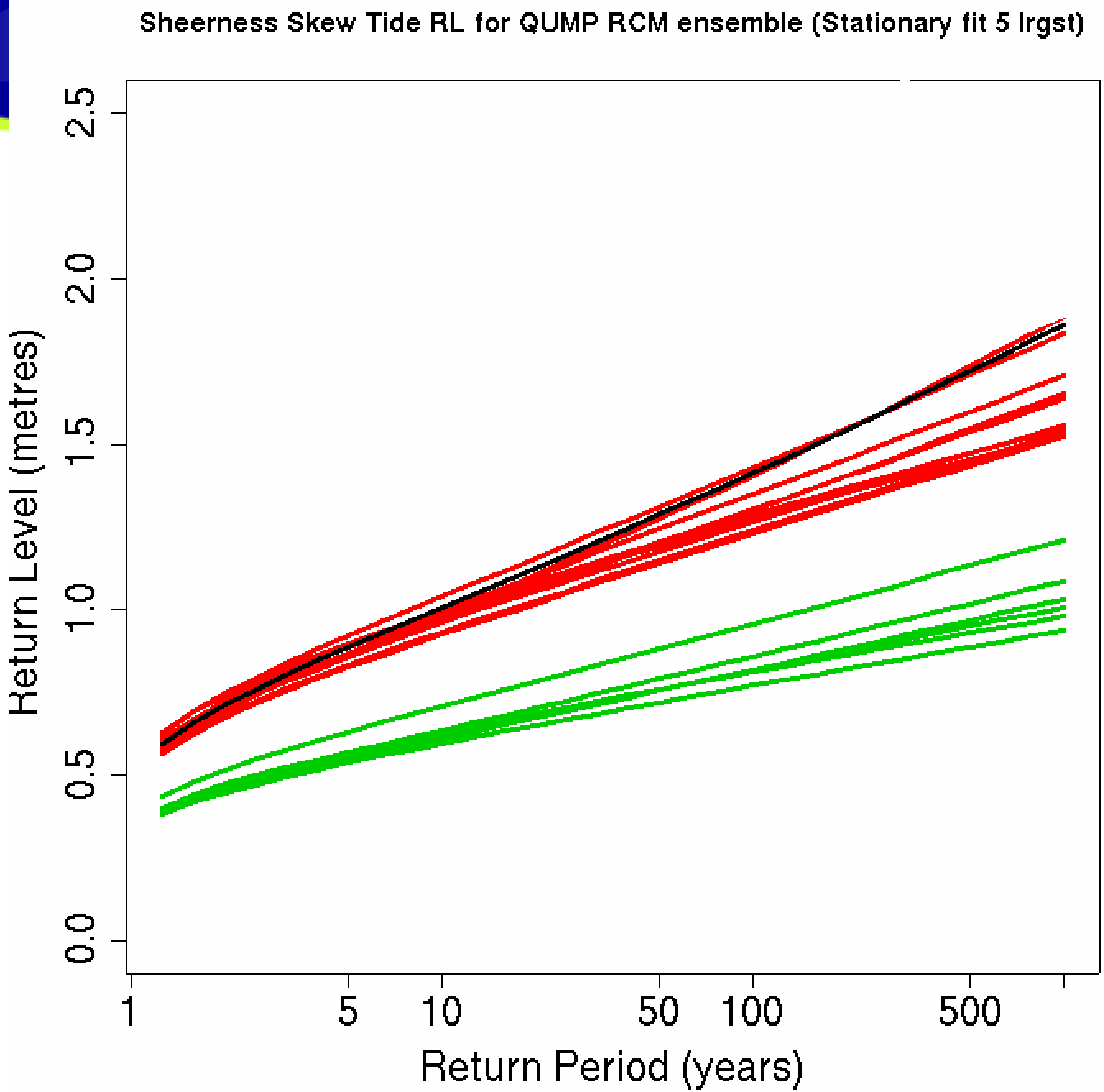
Port	50 yr Obs (m)	EA2100(unpert) 50 yr (m)	ratio	Lowe, G & F 50 yr (m)	ratio	
Wick	1.11	1.02	0.92	0.91	0.82	+
Aberdeen	1.25	1.05	0.84	0.82	0.65	+
NorthShields	1.66	1.12	0.67	0.96	0.58	+
Whitby	1.98	1.19	0.60	1.09	0.55	+
Immingham	2.14	1.60	0.75	1.52	0.71	+
Lowestoft	2.36	1.89	0.80	1.85	0.78	+
Felixstowe	2.50	2.01	0.80	2.05	0.82	
Thames	2.91	2.82	0.97	2.36	0.82	+
Dover	1.77	1.60	0.91	1.44	0.81	+
Newlyn	1.02	0.70	0.69	0.65	0.64	+
Ilfracombe	1.49	1.20	0.80	0.88	0.59	+
MilfordHaven	1.44	1.05	0.73	0.85	0.59	+
Holyhead	1.51	1.18	0.78	1.03	0.68	+
Heysham	3.16	2.32	0.73	1.60	0.50	+
Millport	1.72	1.70	0.99	1.34	0.78	+

Based on 1961-1990 data, unperturbed model

Do long time-slices provide an advantage?



1960 2100


Sheerness Skew Tide RL for QUMP RCM ensemble (Stationary fit 5 lrgst)
Return Level (metres)
0.0
0.5
1.0
1.5
2.0
2.5
1
5
10
50
100
500
Return Period (years)

Met Office

Requirements for improved projections

- Complete upper ocean observing systems
- Sustain observing systems – in situ and satellite (Altimetry, gravity, SAR); data archeology, paleo data
- Deep ocean observations?
- More rigorous testing of ocean models – reconcile existing differences
- Ice sheet and glacier contributions – in situ and satellite observations, understanding and modelling; ice sheet stability
- Extremes – high resolution data (space and time, length of series and models), waves and river flows, hurricane data sets, mid latitude storms, extend storm surge models, inundation and erosion
- Terrestrial storage, Geodetic reference frames, surface loading
- Small community with many contributions

Oil & Gas Industry and Sea Level Monitoring

Philip Woodworth, Lesley Rickards and Thorkild Aarup

- Make all met ocean (esp. sea level) data acquired by the O&G industry available. Some data are accessible via the SIMORC project (www.simorc.org) but it is not complete.
- O&G Industry could provide more access to offshore platforms for a range of operational oceanography; e.g. tide gauges and GPS for storm surge monitoring, satellite calibration or even tsunami warning.
- O&G Industry could host permanent GLOSS-standard coastal tide gauges at sites that it owns. Priority locations include W. Africa (e.g. Nigeria, Cote d'Ivoire), Caribbean, S America, N Africa and Middle East.
- O&G Industry could support training of operators of GLOSS stations in developing countries, and support installations/maintenance to complete global networks.
- Support workshops – extremes, sea level
- Encourage OGP Metocean Committee to send representatives to meetings of the GLOSS Programme.

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.

WCRP World Climate Research Programme | WMO | IOC | ICSU International Council for Science

Summary Statement from the World Climate Research Programme Workshop

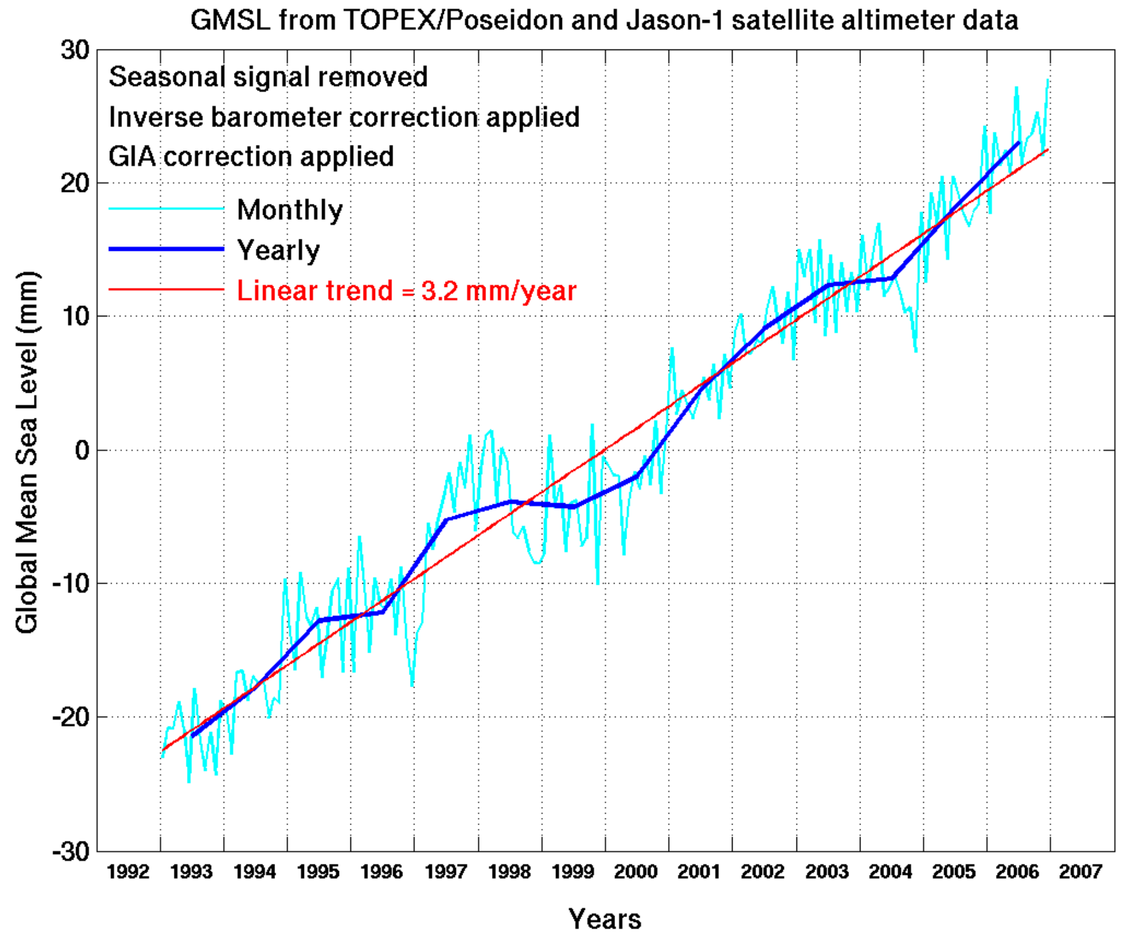
Understanding Sea-level Rise and Variability

Report of the WCRP Workshop

(163 participants, 29 nations)

Thank you!

Sea levels currently rising at over 3 mm/yr



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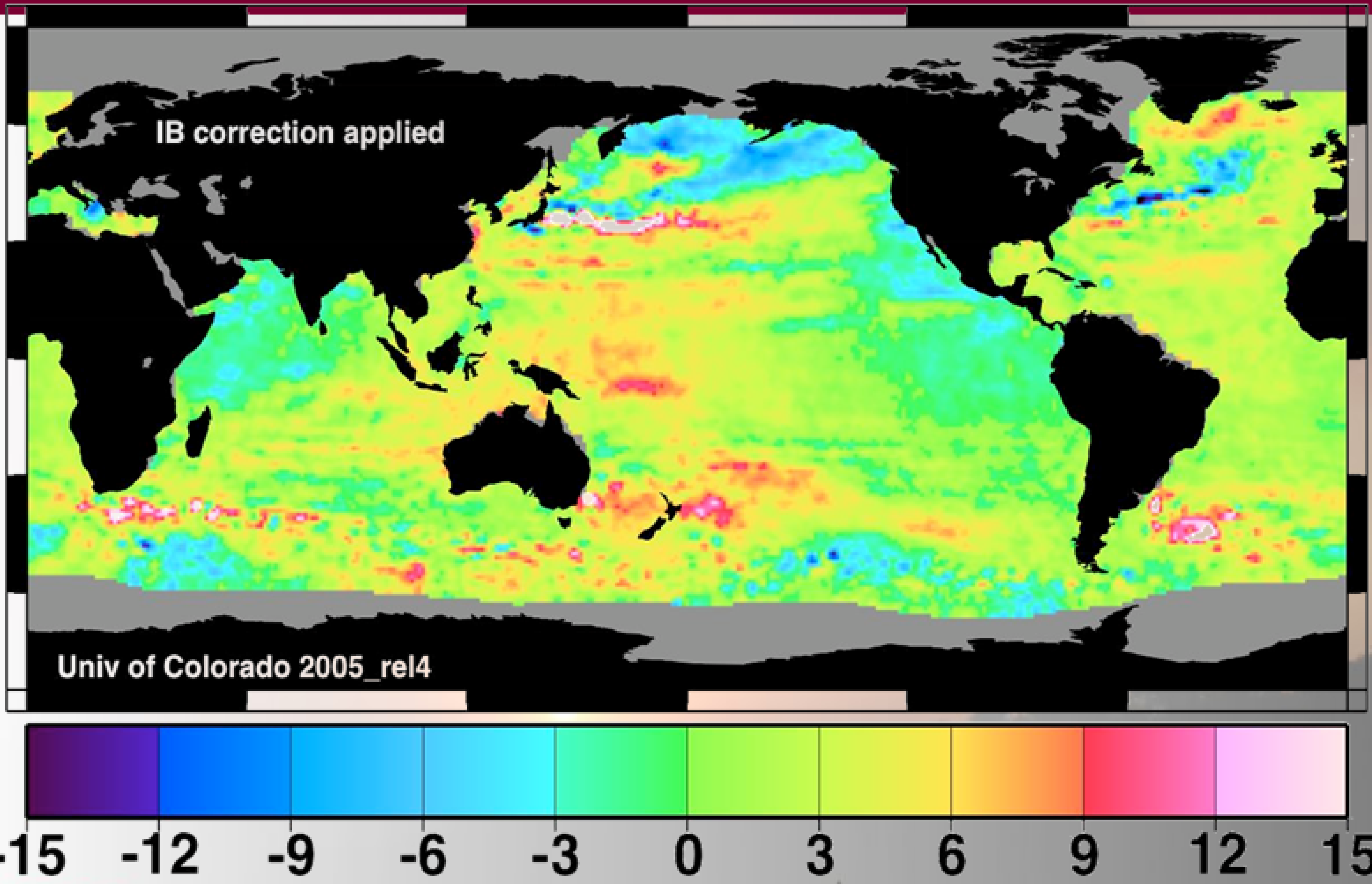
WMO IOC ICSU

Regional patterns of Sea-level Rise
Global Sea Level Trends: 1993-2005



Nerem, 2005

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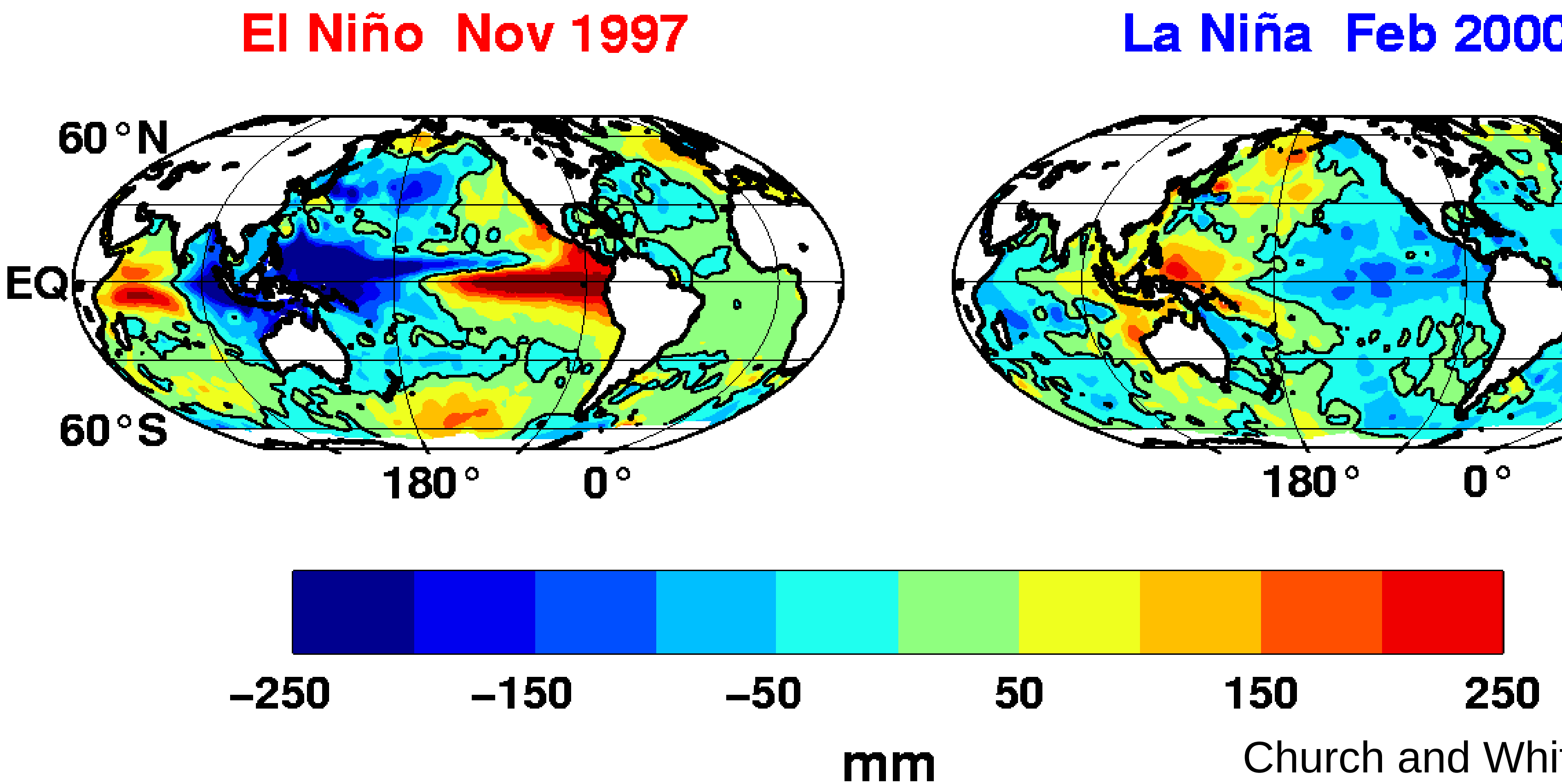
Estimate sea-level by representing the variability using patterns determined from altimeter data



Church and White, 2006

Approach I

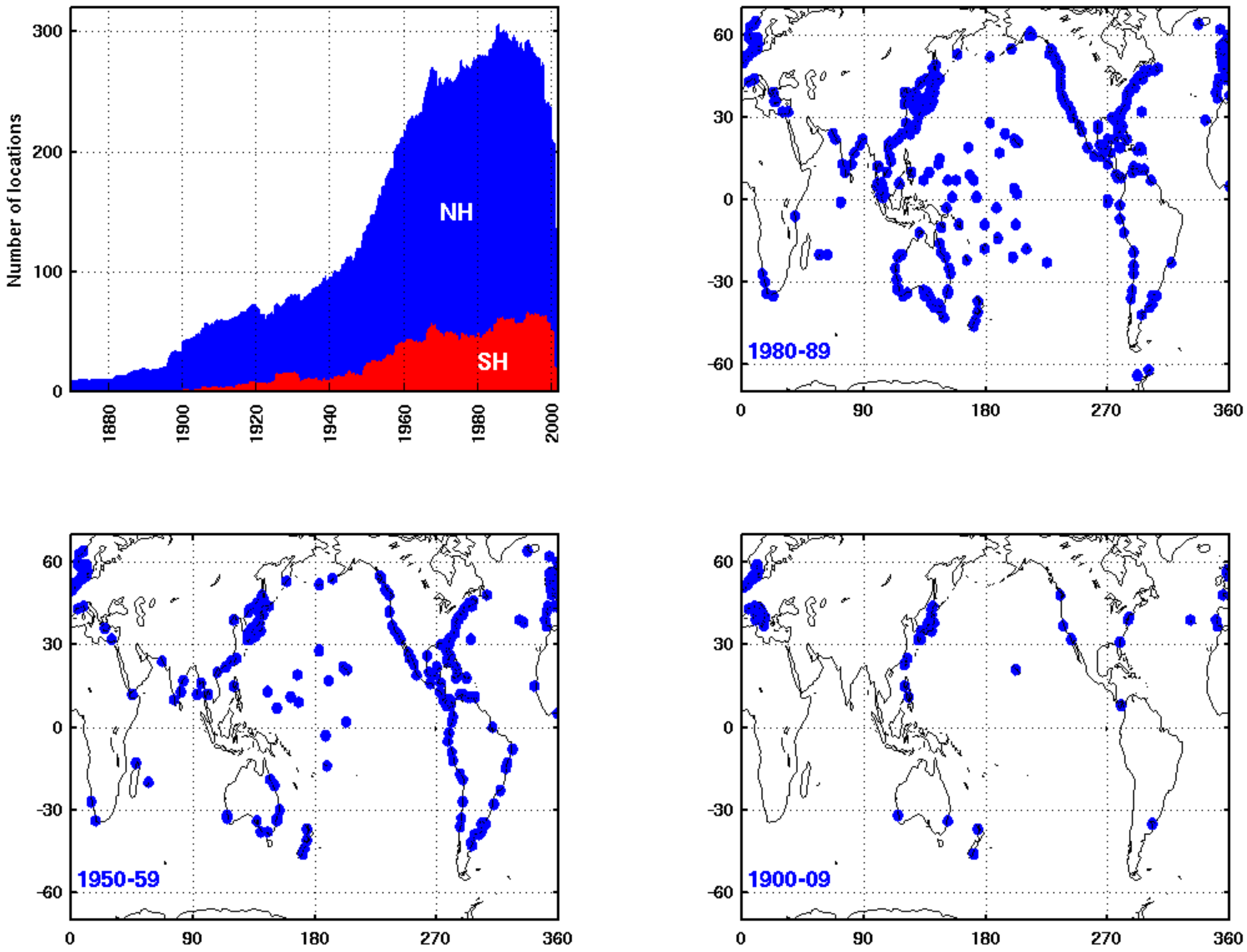
- Use satellite altimeter data to identify patterns of spatial variability
- Expand historical tide gauge data as a sum of these patterns; ie

$$\mathbf{SSH}^r(x,y,t) = \mathbf{U}^r(x,y)\boldsymbol{\alpha}(t)$$

- Determine amplitudes of patterns by minimising difference between observed and reconstructed sea level
- Take account of error estimates and available information on spatial correlations; ie minimise

$$\mathbf{S}(\boldsymbol{\alpha}) = (\mathbf{HU}^r\boldsymbol{\alpha} - \mathbf{SSH}^o)^T \boldsymbol{R}^{-1} (\mathbf{HU}^r\boldsymbol{\alpha} - \mathbf{SSH}^o) + \boldsymbol{\alpha}^T\boldsymbol{\Lambda}\boldsymbol{\alpha}$$

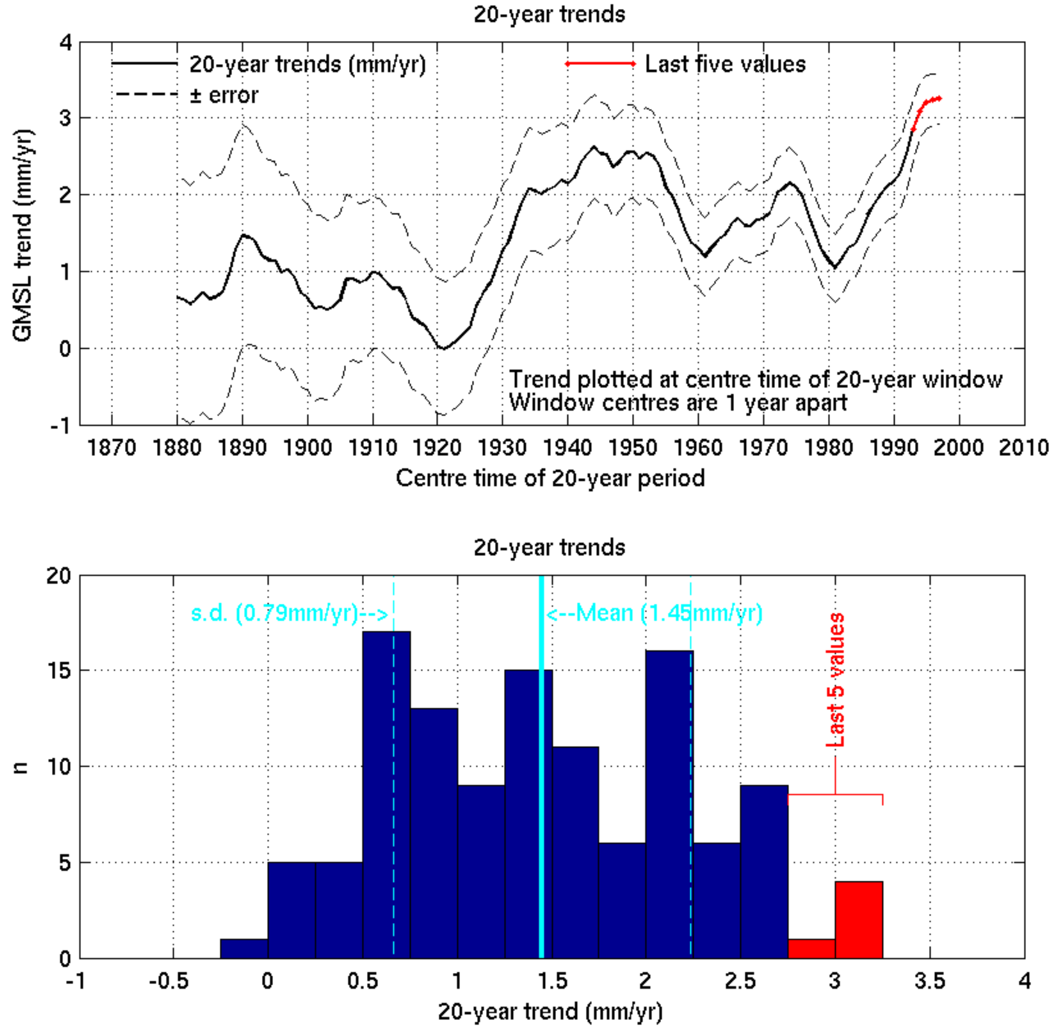
The distribution of available sea-level data changes with time



Church and White, 2006

Acceleration of Sea-level Rise

The rate of rise for the last 20 years is 25% greater than any 20 year period over the preceding 110 years



Church and White 2006

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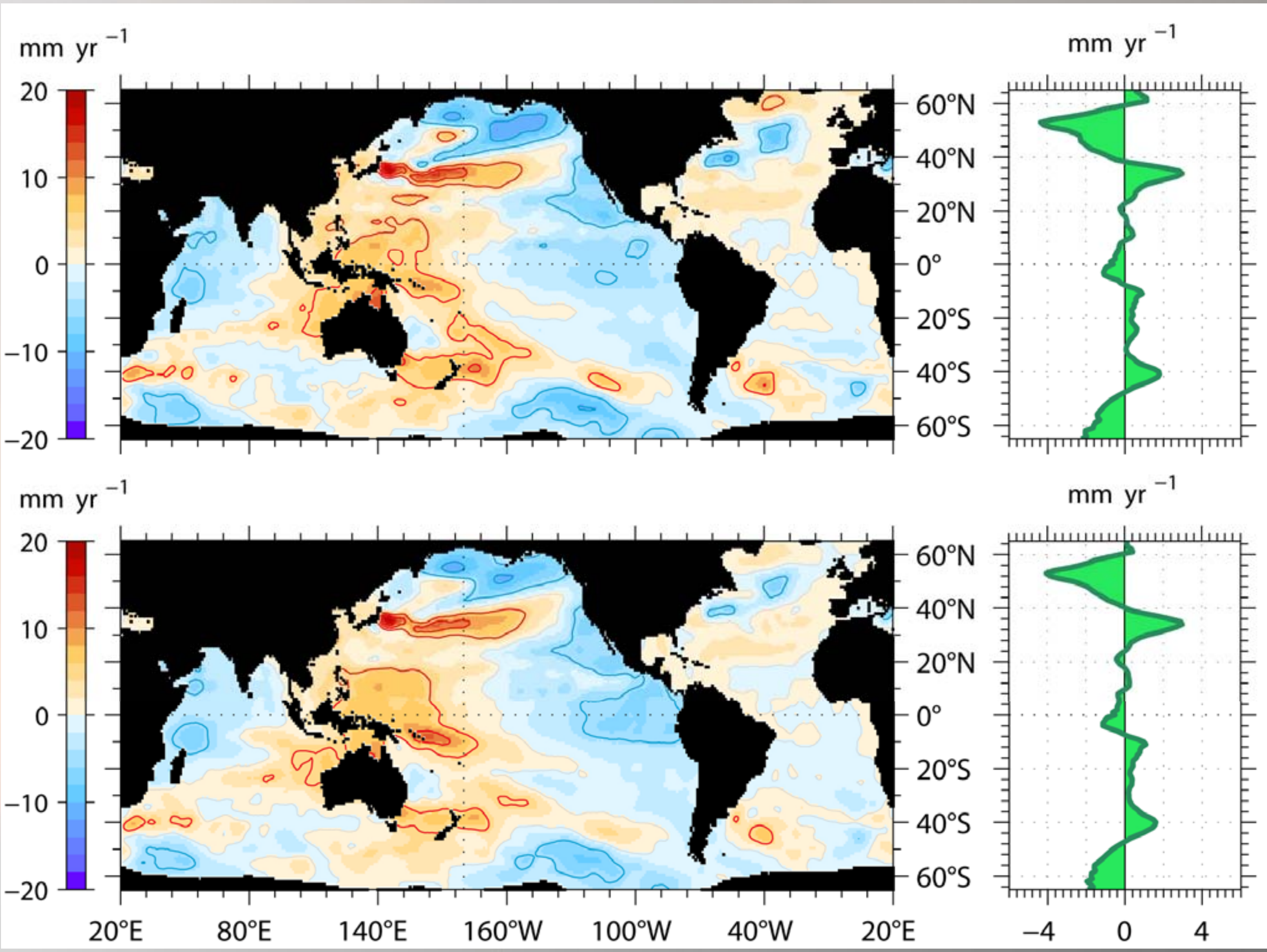
Ocean temperatures control the regional patterns of sea-level

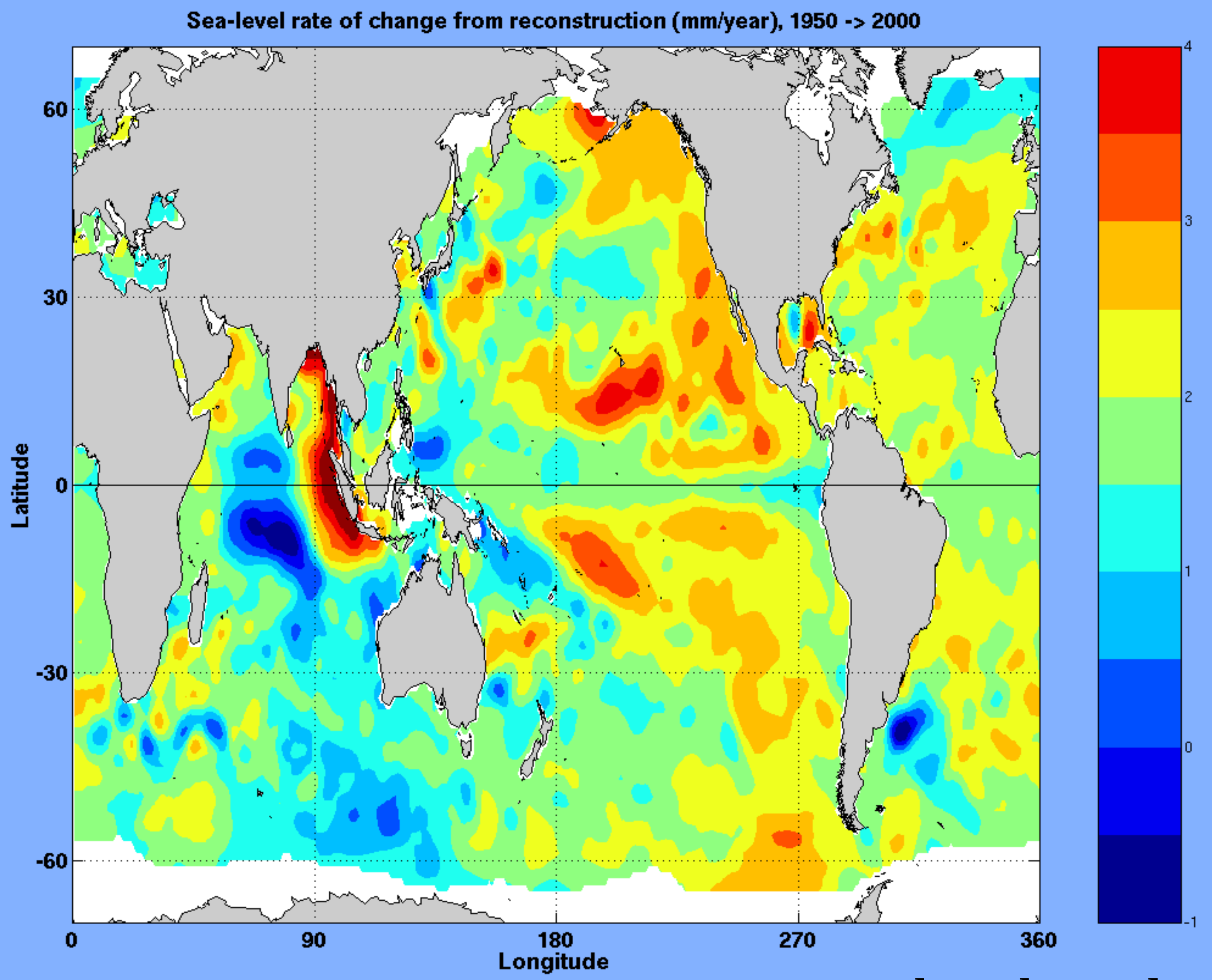
Satellite sea-level trends 1993-2003

Steric sea-level trends 1993-2003



Domingues et al. in prep

Significant spatial variations in trends of sea level rise from 1950 to 2000



Church et al., 2004

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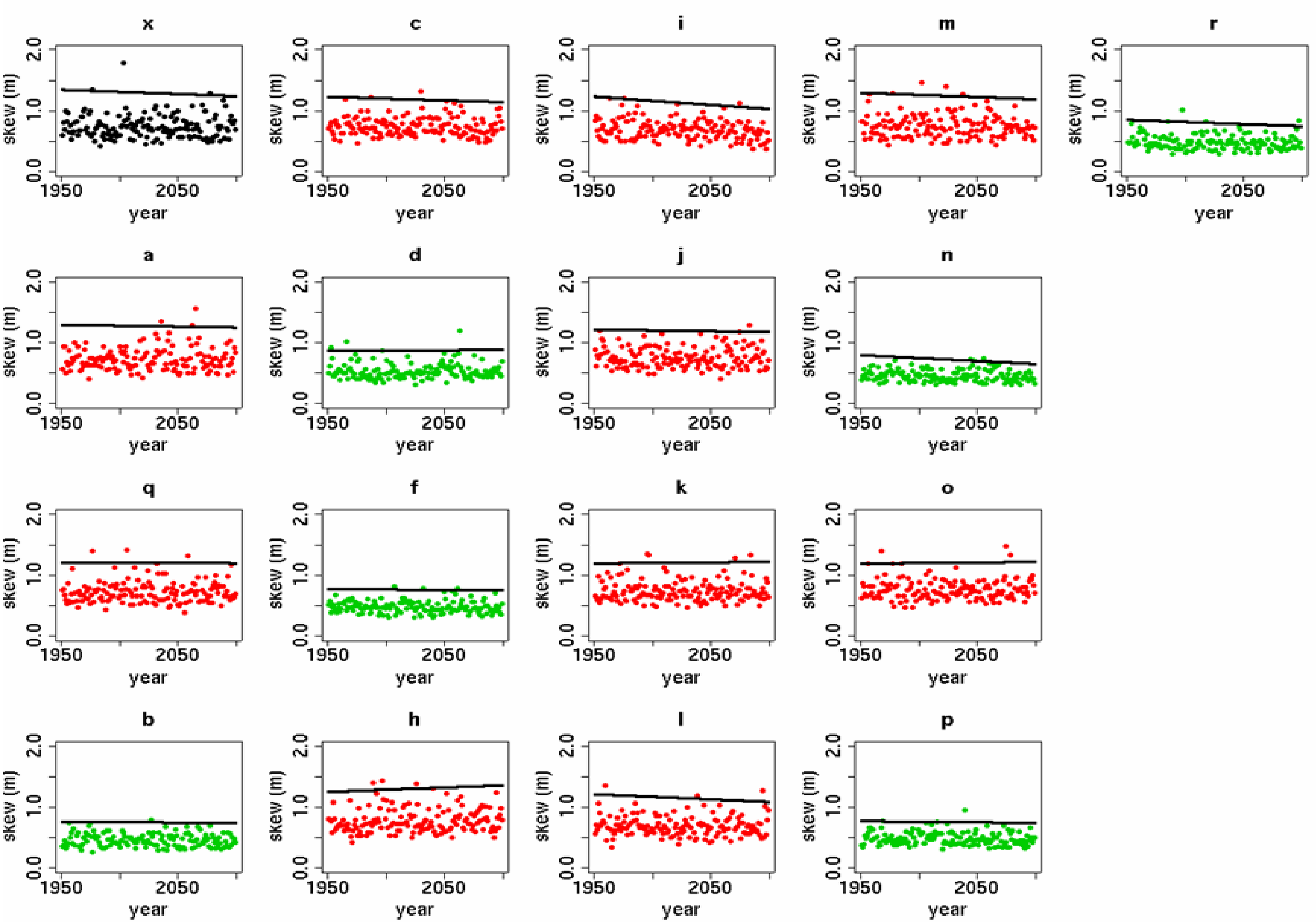
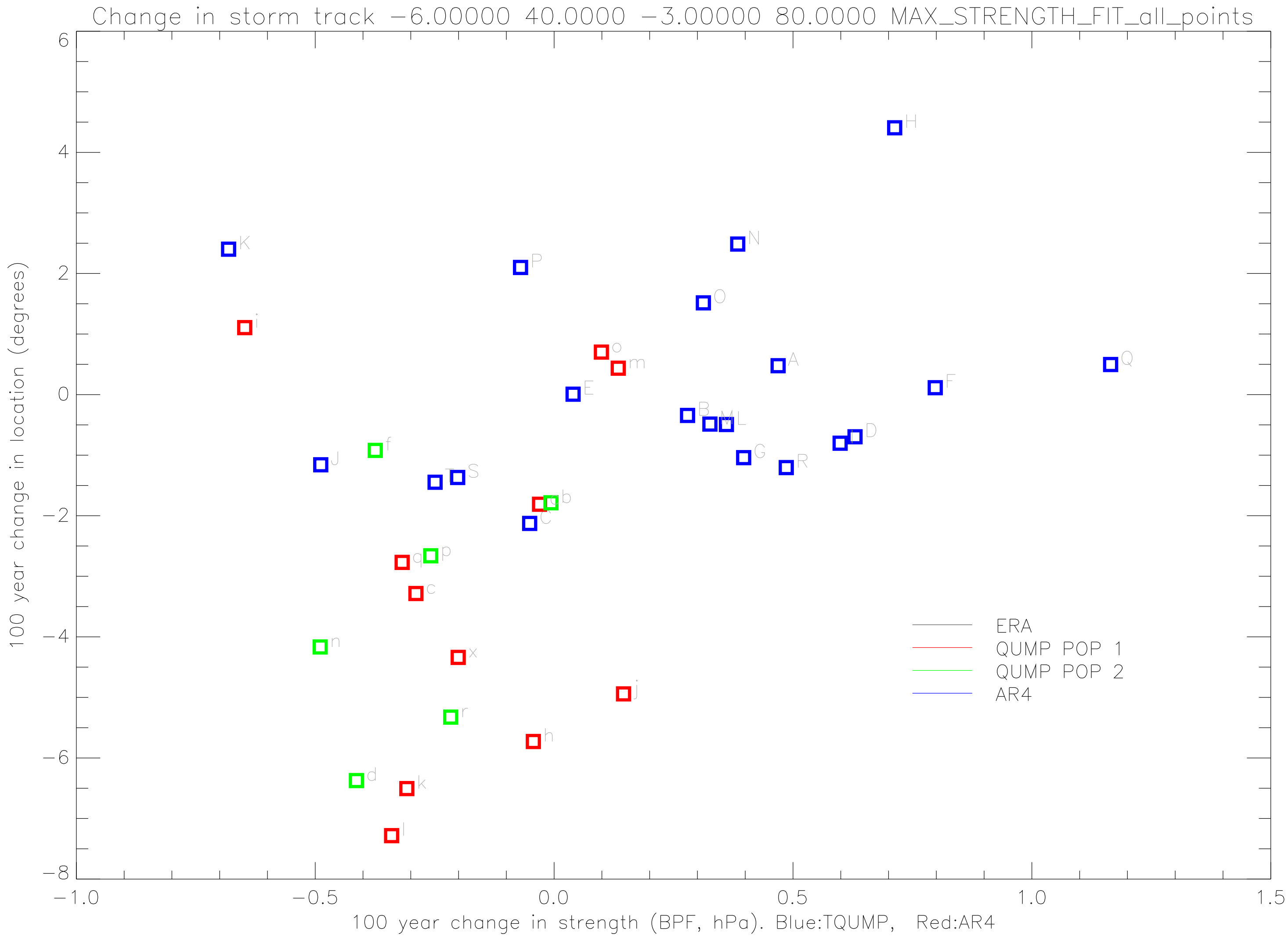
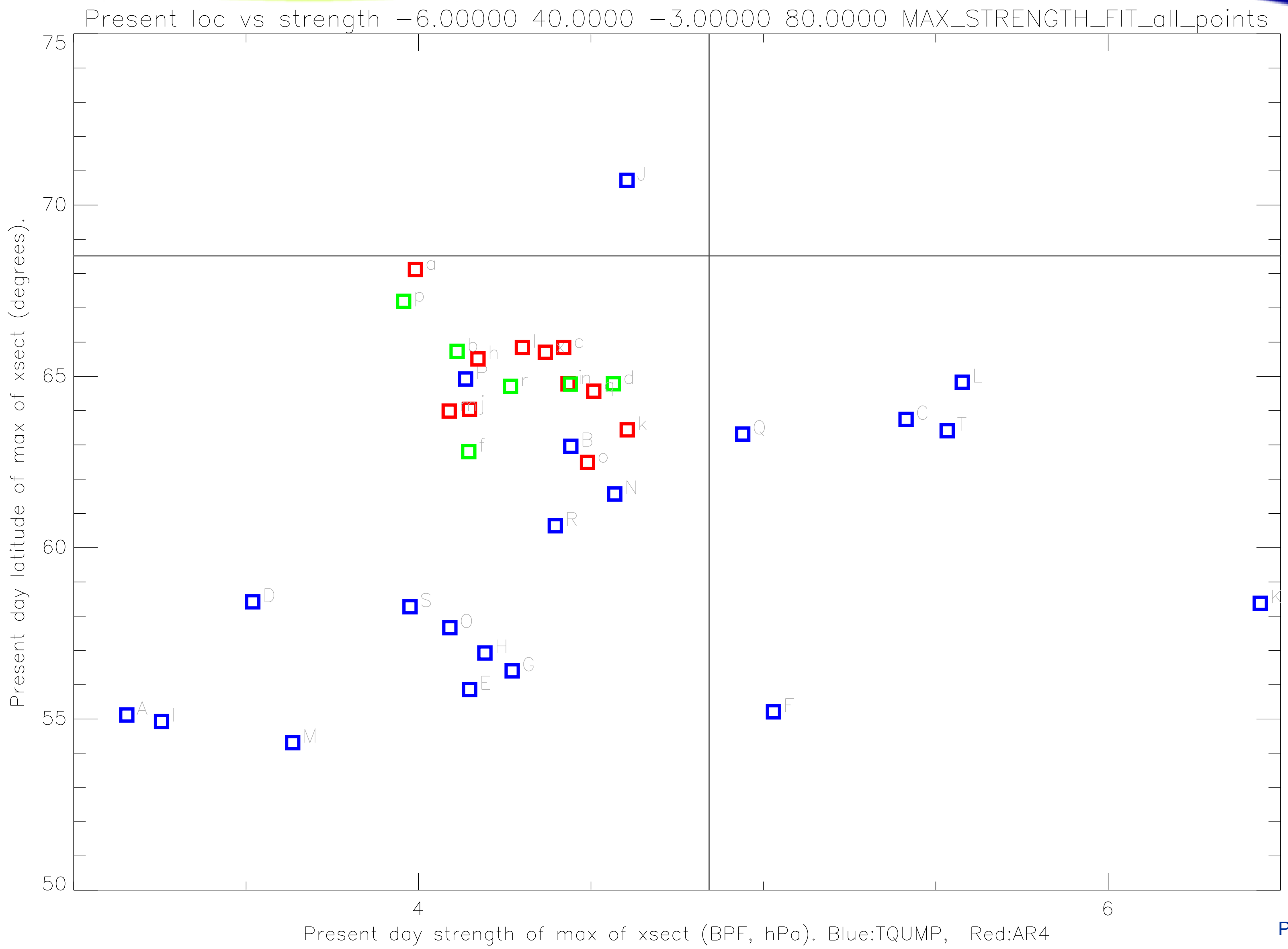
World Climate Research

What about the trends?



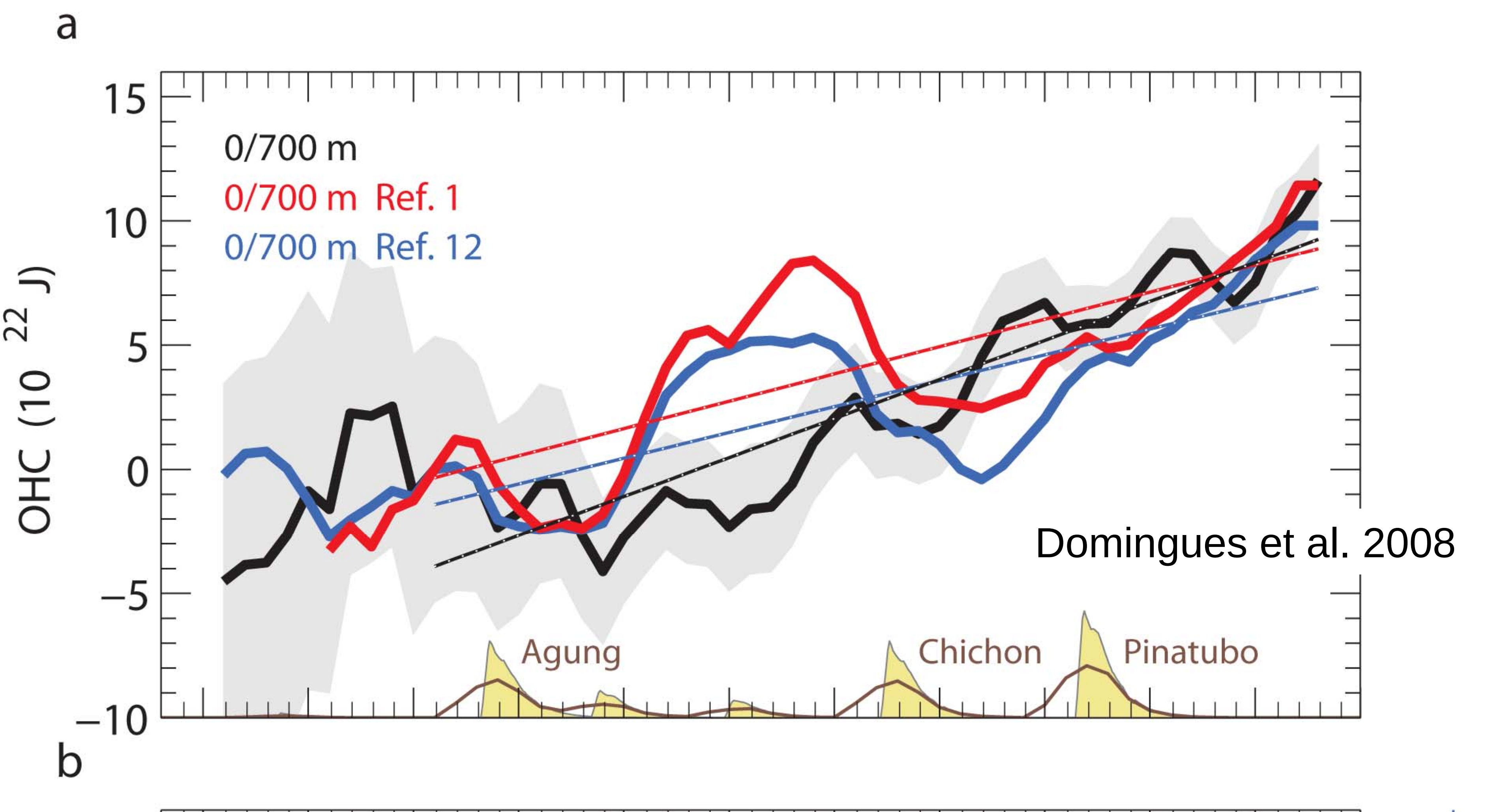
~hadto/extremes/R/trend_signif_rLargest_Thames_ppt_slide_all_runids_with_trendy_50yr_RL.R


Change in storm track −6.00000 40.0000 −3.00000 80.0000 MAX_STRENGTH_FIT_all_points
100 year change in location (degrees)
100 year change in strength (BPF, hPa). Blue:TQUMP, Red:AR4
ERA
QUMP POP 1
QUMP POP 2
AR4
6
4
2
0
−2
−4
−6
−8
−1.0
−0.5
0.0
0.5
1.0
1.5



Present loc vs strength -6.00000 40.0000 -3.00000 80.0000 MAX_STRENGTH_FIT_all_points
Present day latitude of max of xsect (degrees).
Present day strength of max of xsect (BPF, hPa). Blue:TQUMP, Red:AR4
75
70
65
60
55
50
4
6

New estimates of ocean heat content and ocean thermal expansion



Domingues 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!**