Projection of global and regional sea level change for the 21st century

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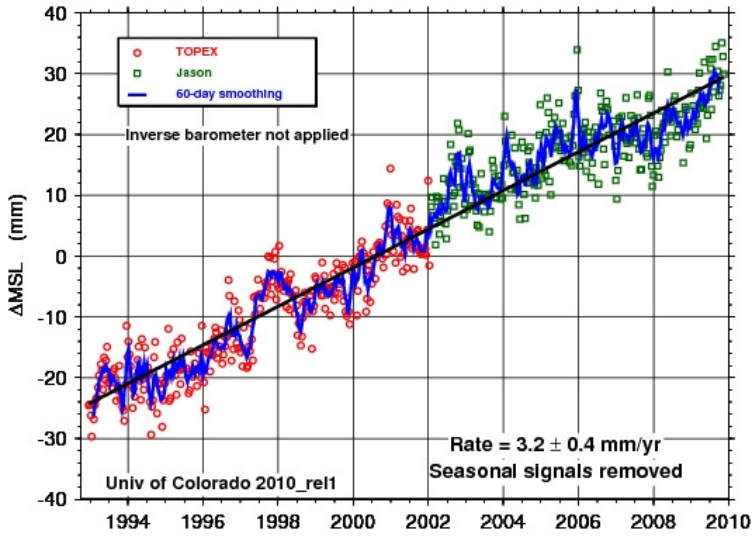
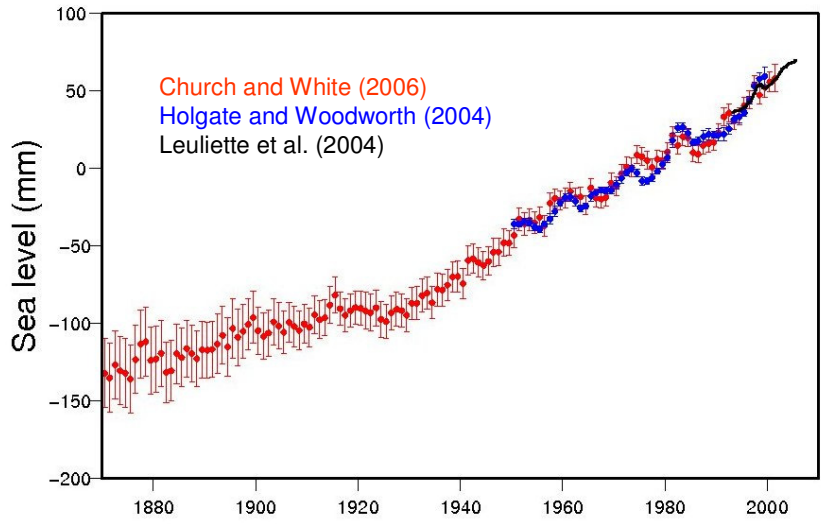
Global mean sea level rise observed by satellite altimeter



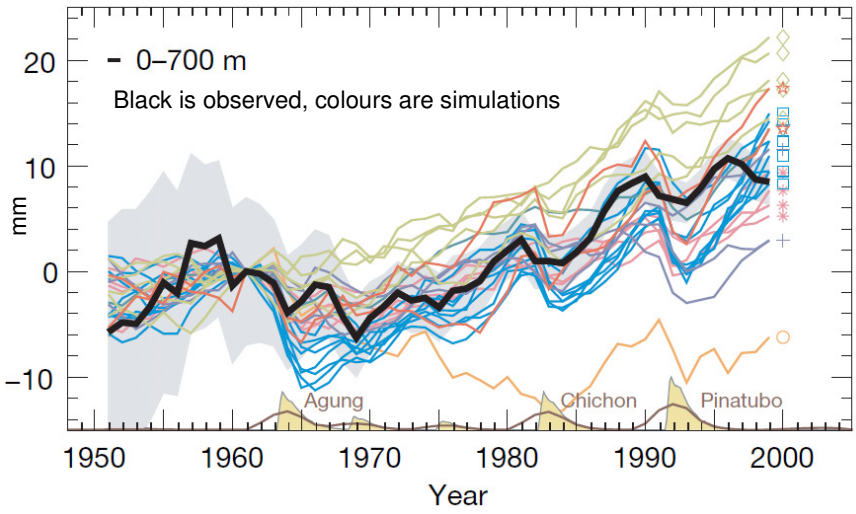
1993-2003 3.1 ± 0.7 mm yr^{-1}

Observed global mean sea level rise



1961-2003 1.8 ± 0.5 mm yr^{-1} 1993-2003 3.1 ± 0.7 mm yr^{-1}

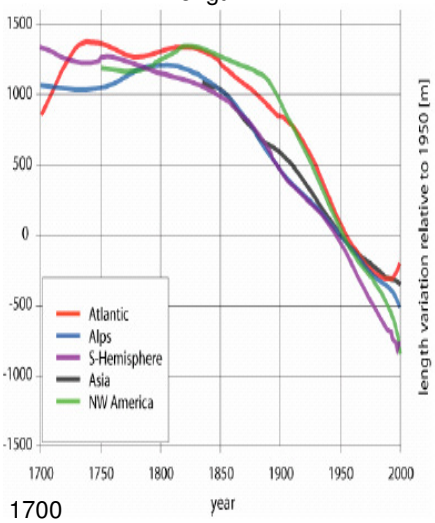
Observed and simulated thermal expansion



Domingues et al. (2008)

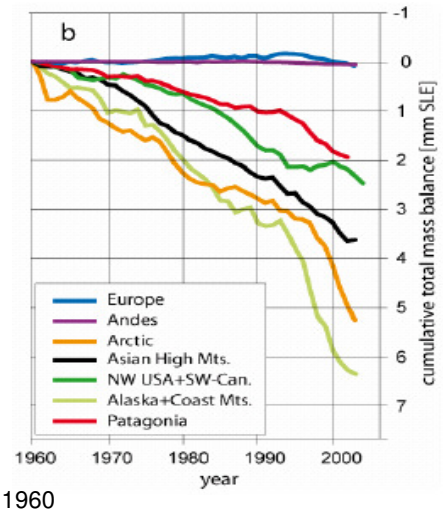
Observed changes in glaciers and ice caps (not ice sheets)

Length



1700

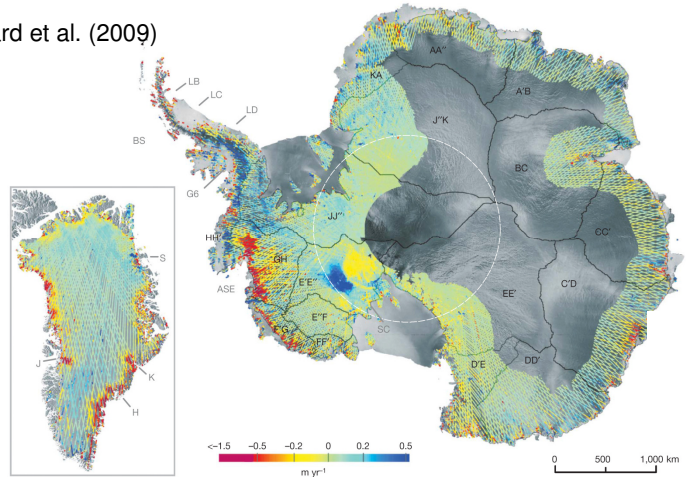
Mass



1960

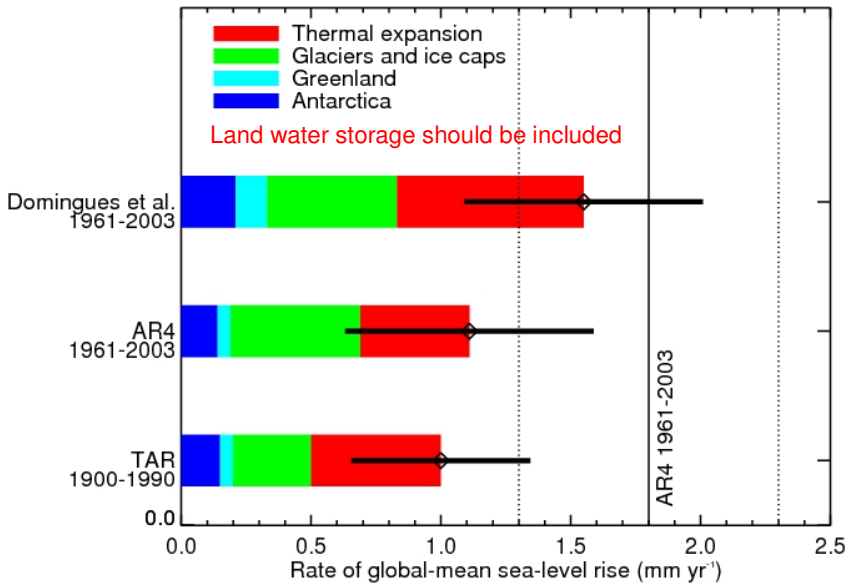
Observed recent ice-sheet thickness change

Pritchard et al. (2009)

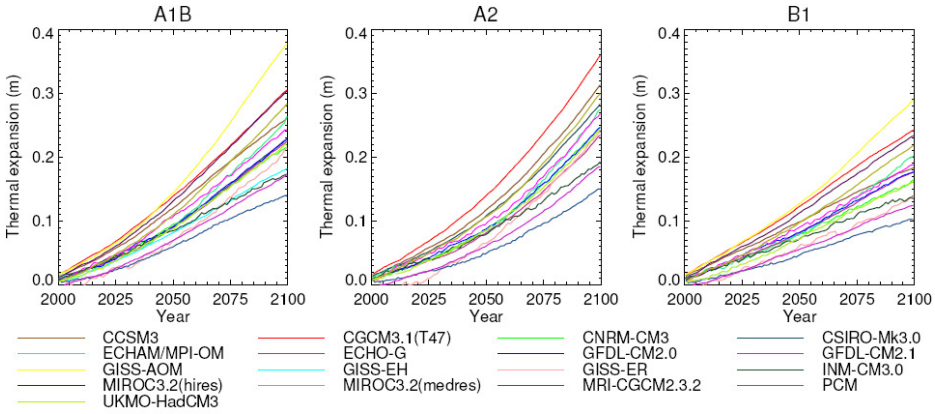


Flow speed has increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior of the ice sheets, often following thinning, reduction or loss of ice shelves or loss of floating glacier tongues.

Budget of global-mean sea-level rise



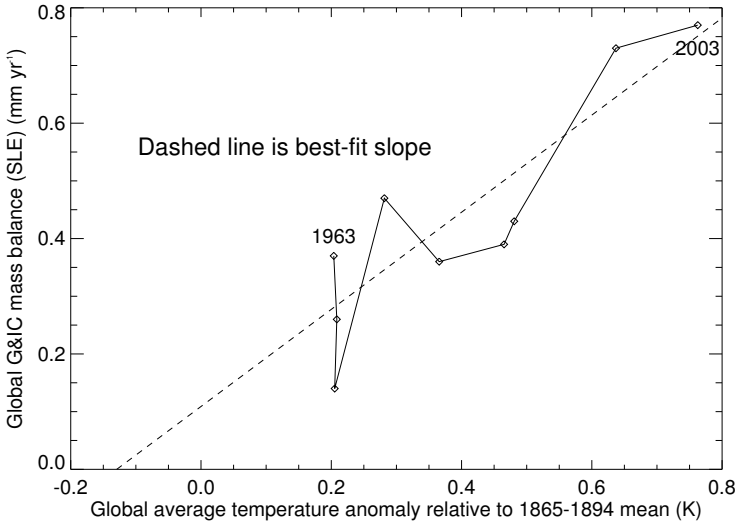
IPCC AR4 (CMIP3) projections of thermal expansion



AOGCMs have large ranges of transient climate response, ocean heat uptake efficiency and expansion efficiency of heat.

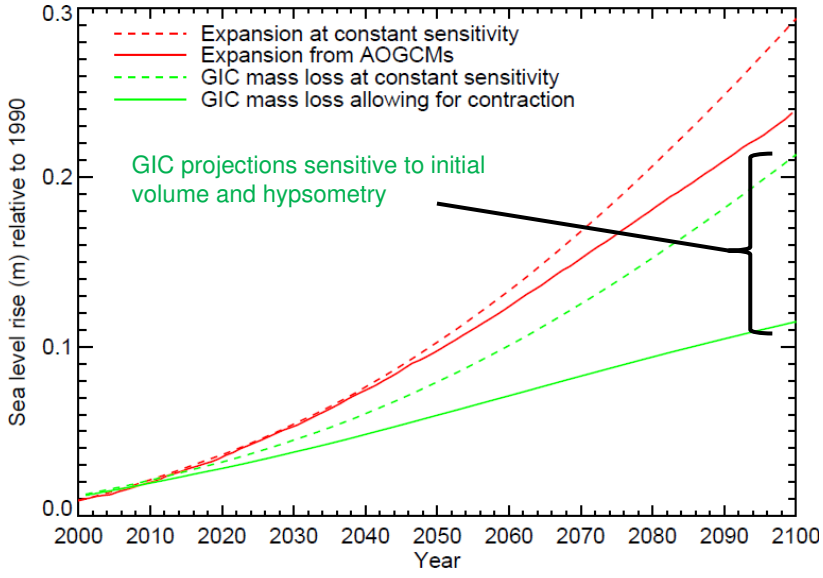
Can we constrain these observationally?

Glaciers and ice caps



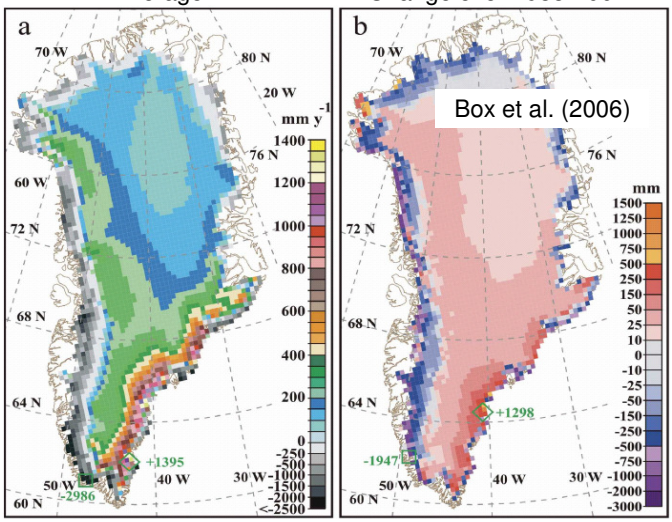
Marginal regions of Greenland and Antarctica should be included.

Constant sensitivity overestimates GIC and expansion



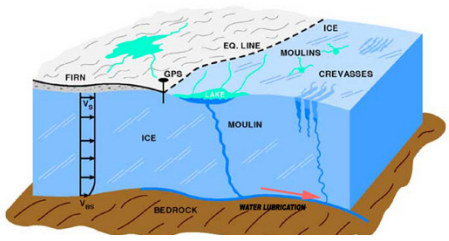
Regional atmosphere models for ice sheet SMB

Average | Change over 1988-2004



Can recent changes be simulated well? How does regional climate change relate to global climate change?

Greenland dynamic change is mainly not caused by surface meltwater lubricating the bed



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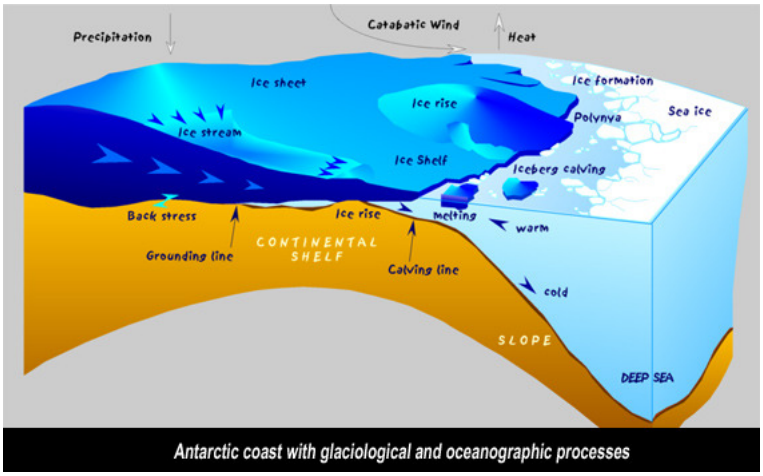
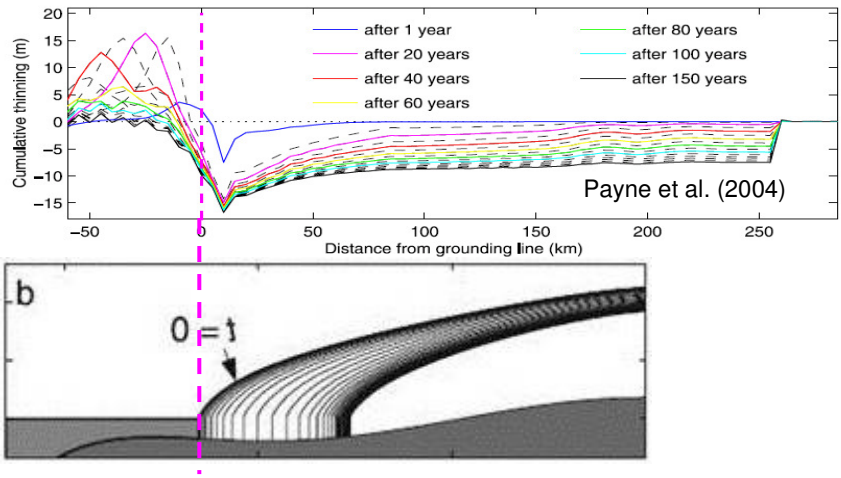
The effect is geographically restricted and rather small on average.

Ice-sheet processes



To make projections, we need high-resolution models of ocean circulation and melting/freezing adjacent to and under the ice, coupled to regional and global ocean and atmospheric circulation, responding to external climate forcing.

Ice stream accelerates and thins and grounding line retreats



To make projections of this, we need ice dynamic models with high resolution at the grounding line and in ice streams, including relevant stresses.

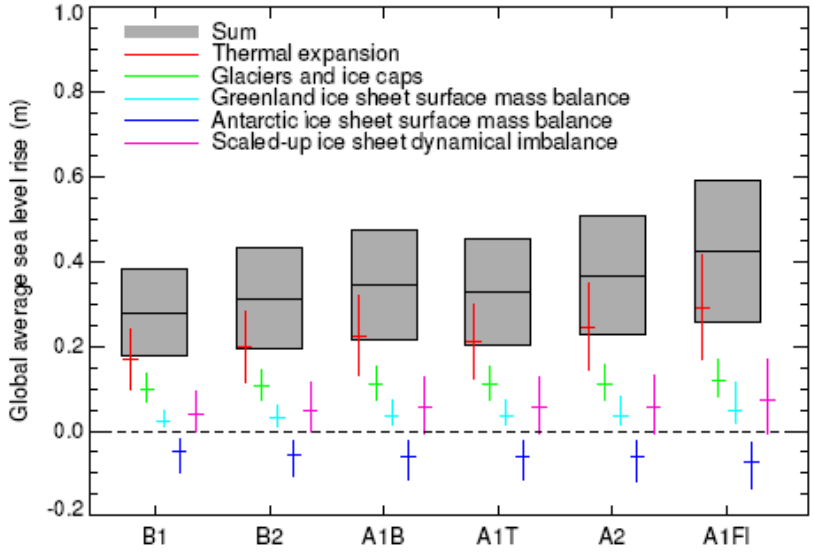
IPCC AR4 SPM comments on projecting ice-sheet dynamics

Models used to date do not include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. Ice flow from Greenland and Antarctica could increase or decrease in the future.

Understanding of these effects is too limited to assess their likelihood or to provide a best estimate or an upper bound for sea level rise.

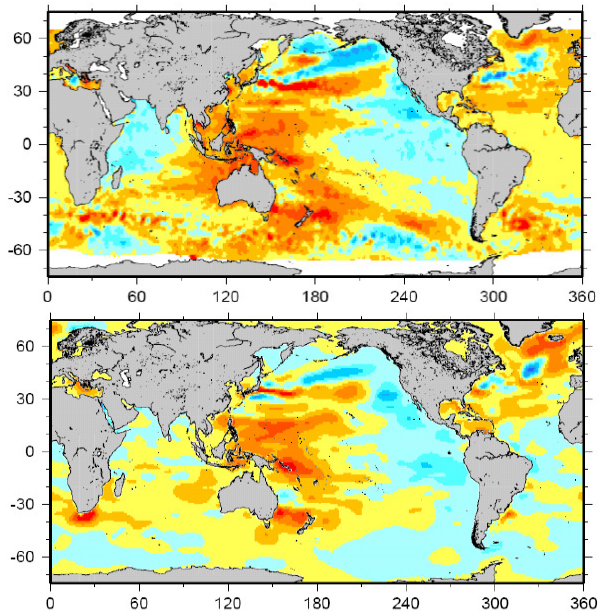
Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude.

AR4 projections of 21st century global-mean sea level rise

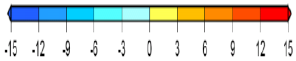


Time dependence is needed. Uncertainty ranges should be better characterised.

Geographical variation of trends 1993-2003



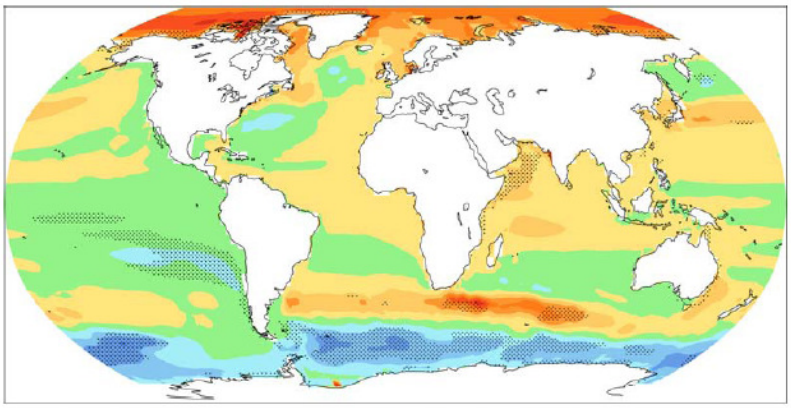
Sea level change from TOPEX/Poseidon data (Cazenave and Nerem, 2004)



mm yr^{-1}

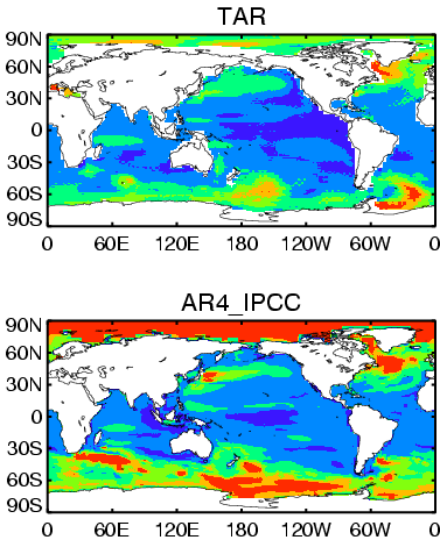
Thermosteric sea level change down to 700 m (Ishii et al., 2006)

Projected sea level change is not globally uniform



Sea level change **due to ocean density and circulation change** during 21st century (2080-2099 relative to 1980-1999) under A1B, average of 16 AOGCMs, shown relative to global mean. Spatial variation is about 25% of global mean.

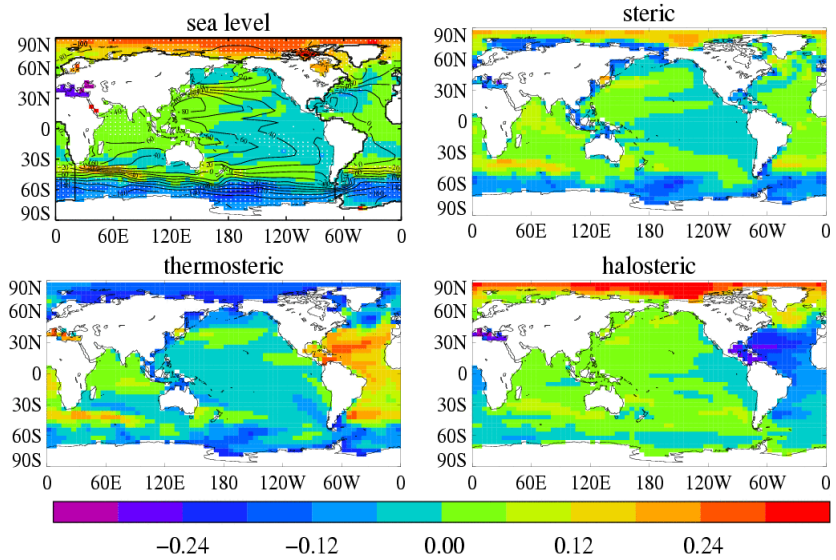
Large uncertainty in projections of regional sea level change



Spread in projections has not been reduced since the TAR.

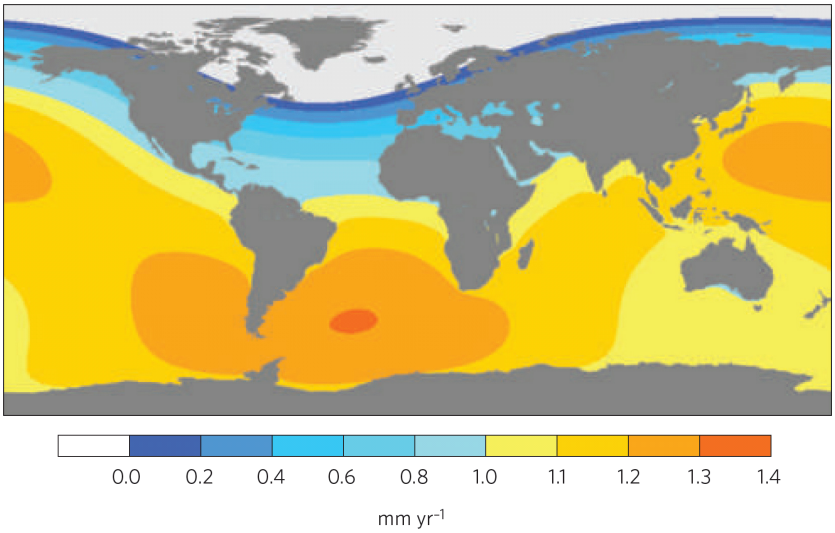
Pardaens et al. (in press)

Geographical pattern is predominantly steric



Pardaens et al. (in press)

Geoid and solid Earth response should be included



Sea-level change due to Greenland mass loss of 1 mm yr^{-1}, Milne et al. (2009)

Summary

Thermal expansion, glaciers and ice caps and ice sheets have all contributed substantially to sea level in recent decades.

Observed sea level rise cannot be accounted for with full confidence. Decadal variability and observational uncertainty are substantial.

Sea level rise in the 21st century will very likely be larger than in the 20th. For scenario A1B, the IPCC AR4 projection is 0.21-0.48 m.

Future rapid changes in ice sheets cannot yet be projected.

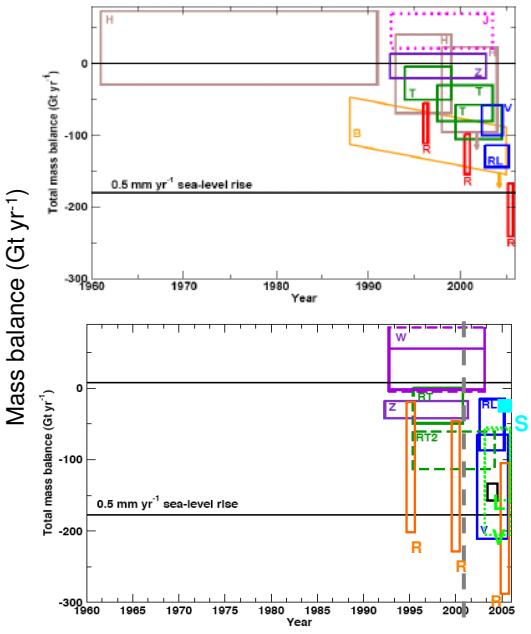
We need to constrain and reduce the large systematic uncertainty in projections of climate change, ocean heat uptake and ocean interior transport processes.

Spatial variation is substantial compared with the global average. Geoid and solid Earth response should also be included regional SL projections.

Sea level rise due to thermal expansion and ice sheet changes would continue for many centuries after stabilisation of climate. The Greenland ice sheet would be eliminated for a global average warming exceeding 1.9-4.6°C. Partial loss could become irreversible within 100s years.

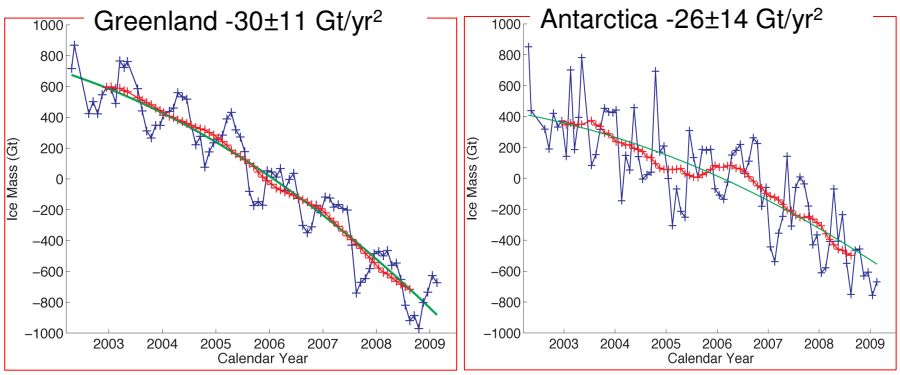
Provide time-dependent projections with well-defined uncertainties. Planners should keep options open.

Sea-level contribution from ice sheets



Mass losses from the ice sheets of Greenland (0.21±0.07 mm yr^{-1}) and Antarctica (0.21±0.35 mm yr^{-1}) have *very likely* contributed to sea level rise over 1993 to 2003 (3.1±0.7 mm yr^{-1}).

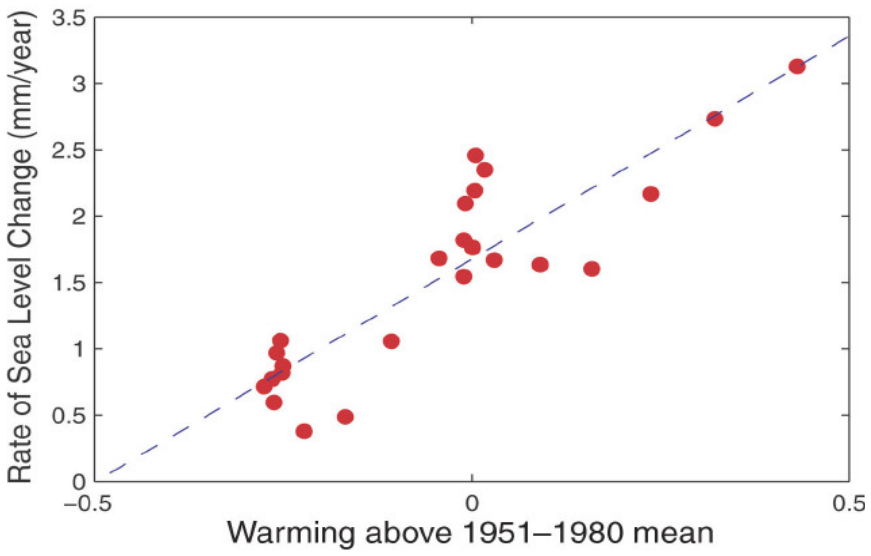
Both ice sheets are losing mass at an increasing rate



Velicogna, from GRACE

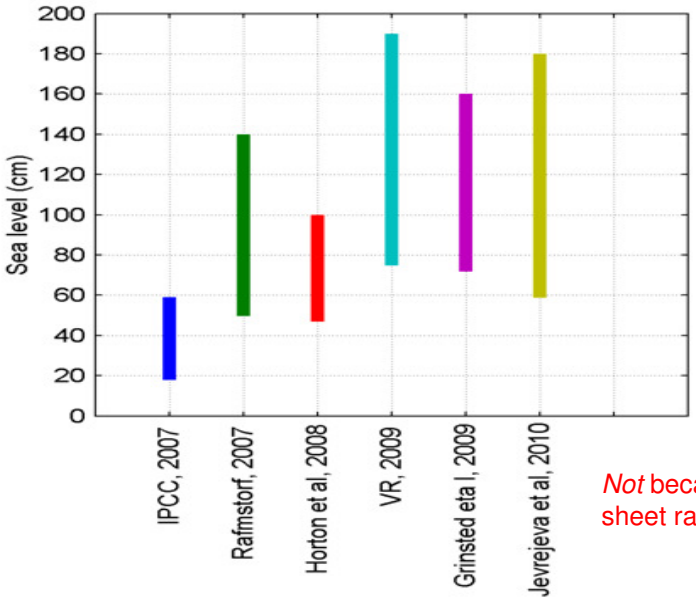
A quadratic function of time describes the observations well, but to make projections we need physically based models.

A semi-empirical approach to predicting sea-level rise



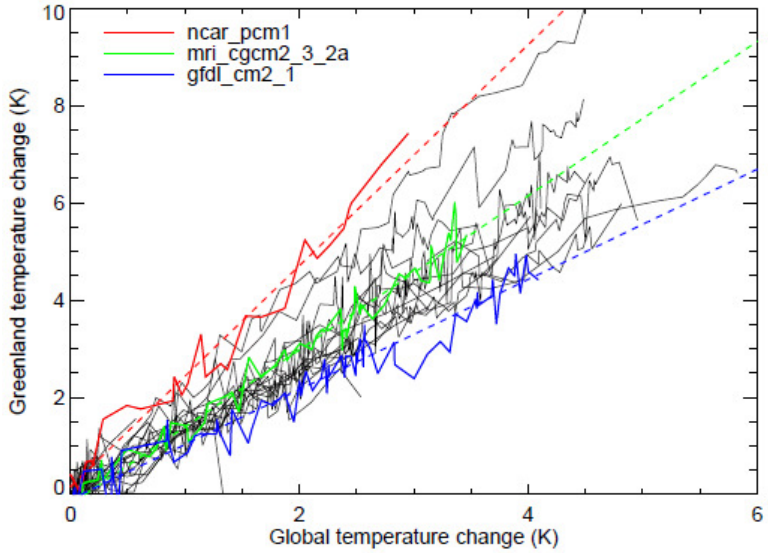
Rahmstorf (2006)

Why are semi-empirical > process-based projections?



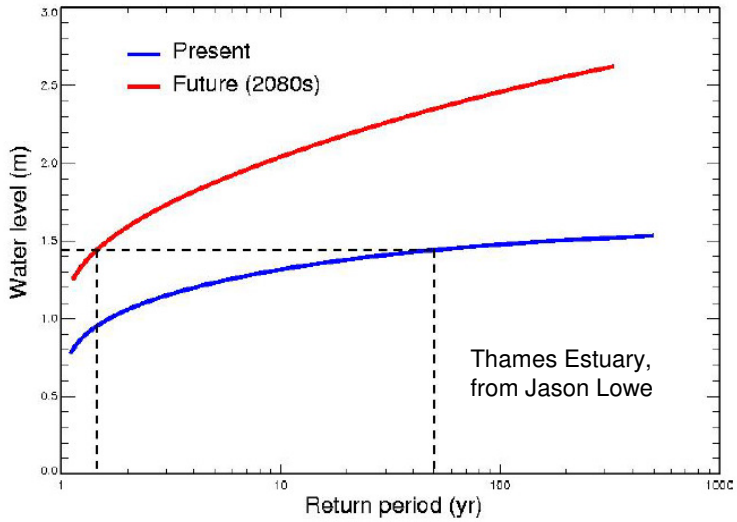
Not because of ice-sheet rapid dynamics

Uncertainty in ice sheet regional climate change



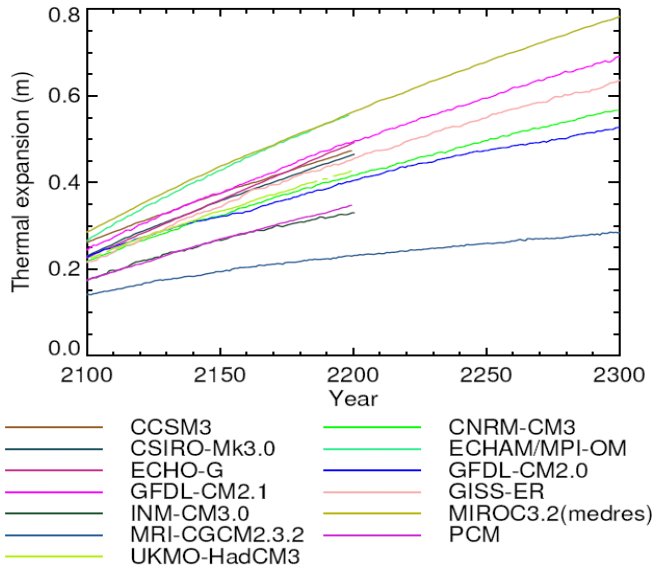
Antarctica and Greenland are small regions that have global impact!

The impact of sea-level change comes from extreme events



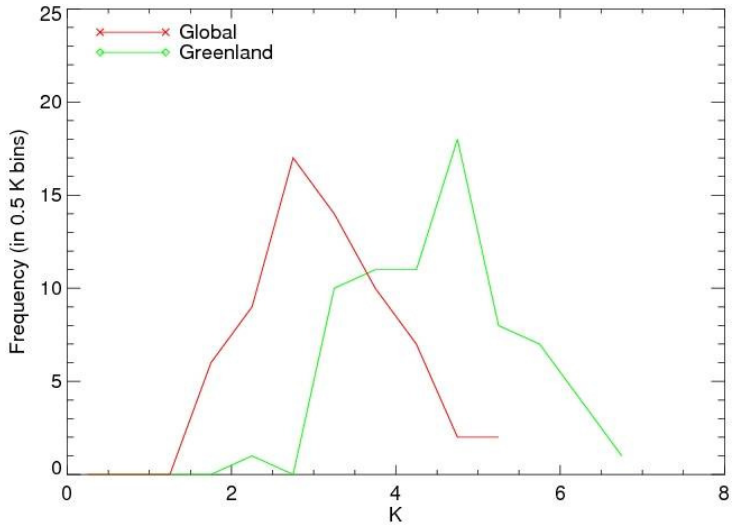
First approximation is to add a constant SL change to the existing return period curve. Better is to use regional climate and storm surge model.

Thermal expansion for stabilisation at A1B 2100 concentrations



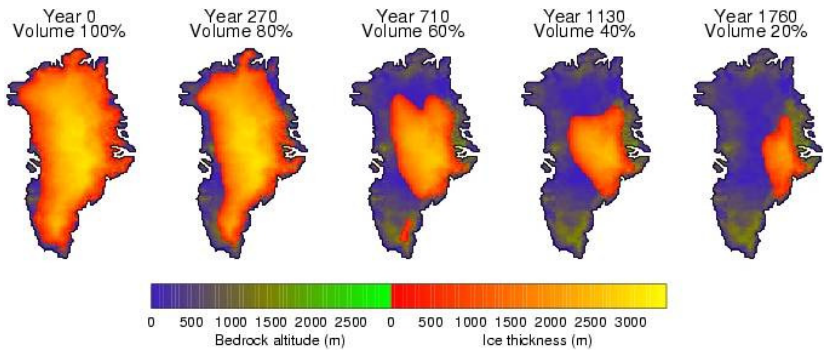
EMICs suggest final steady state of 0.2-0.6 m K^{-1}

Threshold for negative SMB of the Greenland ice sheet



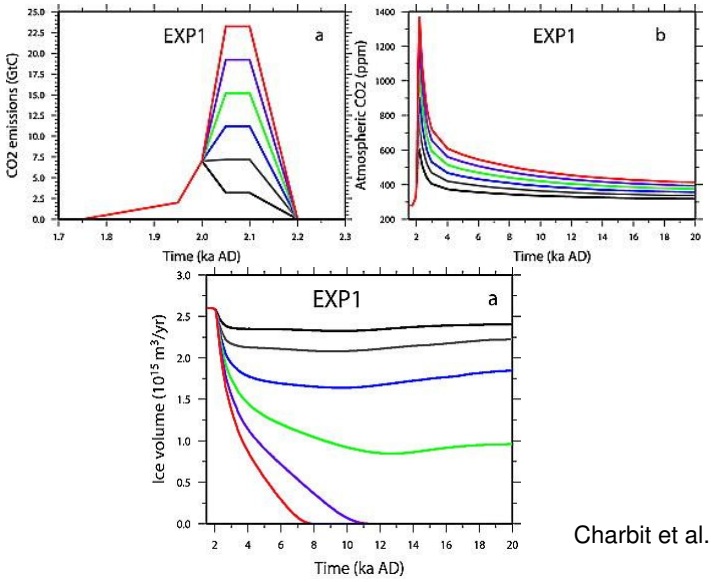
Gregory and Huybrechts (2006)

Greenland ice sheet evolution under 4×CO_2



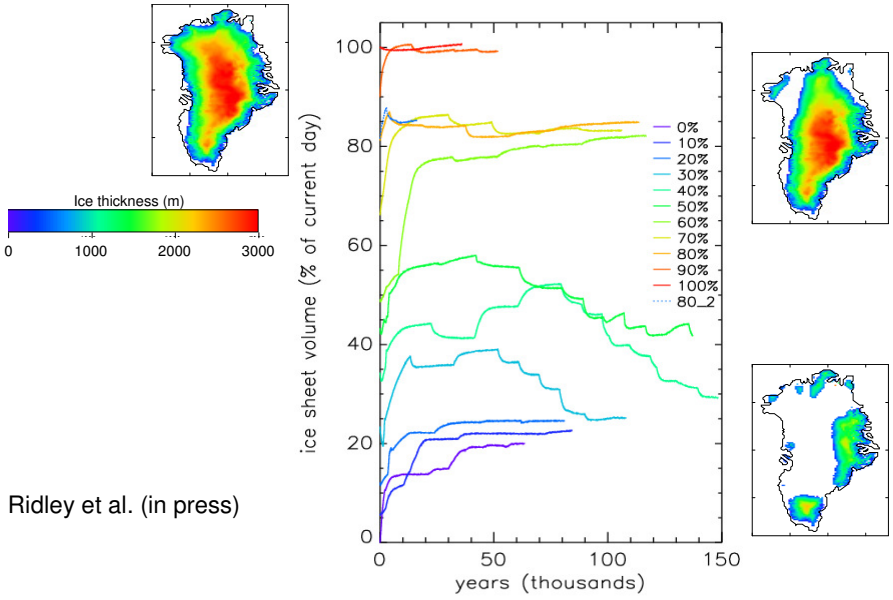
Simulated using the HadCM3 AOGCM coupled to the ice sheet model of Huybrechts and De Wolde (Ridley et al., 2005)

Irreversible loss of the Greenland ice sheet



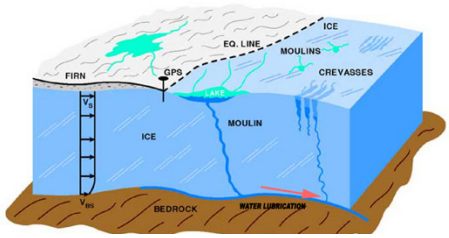
Charbit et al. (2008)

Irreversibility of deglaciation



Ridley et al. (in press)

Greenland dynamic change is mainly not caused by surface meltwater lubricating the bed



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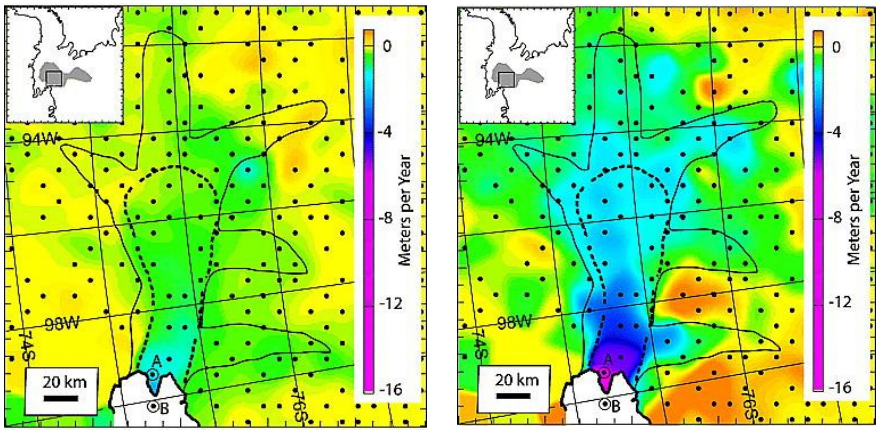
- Weak seasonal reaction to meltwater (Rignot and Kanagaratnam, 2006; Joughin et al., 2008).
- Annual velocity negatively correlated with melt (van der Wal et al., 2008).

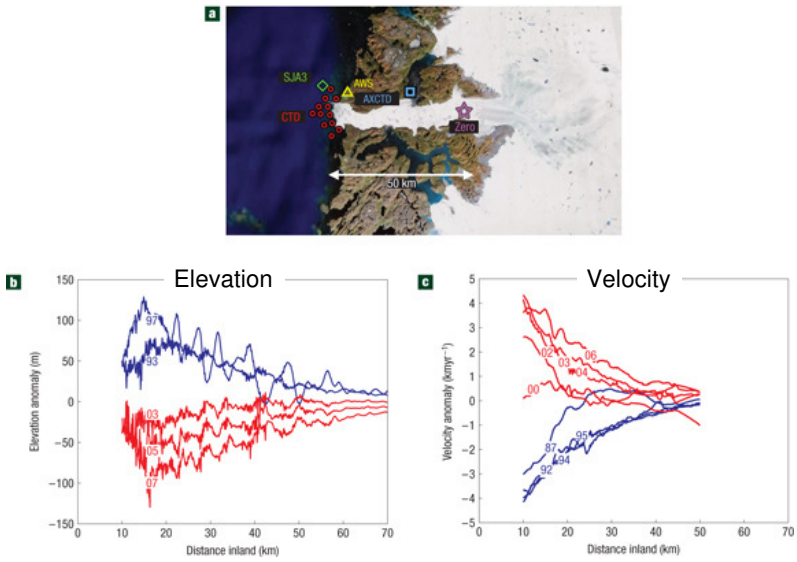
Thinning of Pine Island Glacier, West Antarctica

1995 2006



Wingham et al. (2009)

Jakobshavn Isbrae, West Greenland



Holland et al. (2008)