Ice Sheet – Climate Interaction Learned from Modeling the Past for the Future

WCRP OSC
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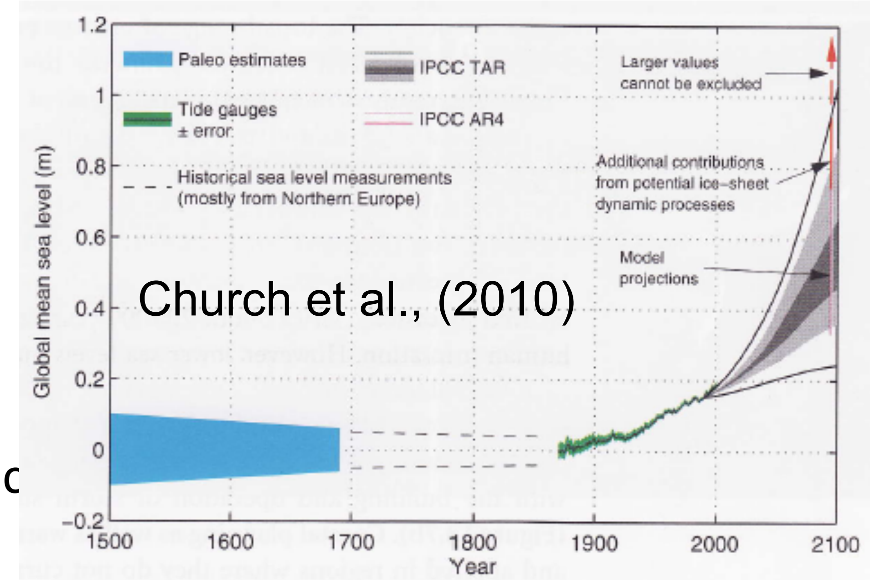
Outline of this talk

- Introduction
- Part1: Sources of uncertainty in the future ice sheet surface mass balance projections
- Part2: Note on the interpretation of observed recent changes
- Part3: A challenge of modelling the last interglacial ice sheet and sea level
- Conclusions

Observed and future sea level change

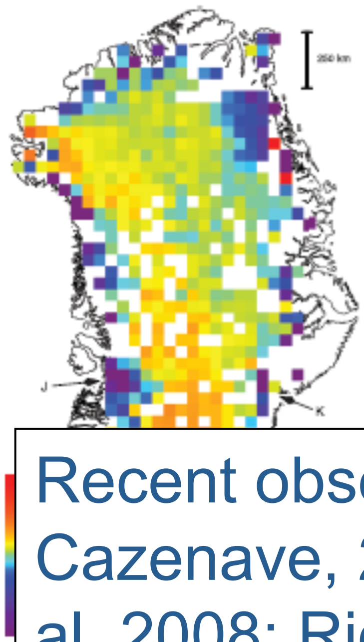


- IPCC-AR4 (2007)
  - 20th century : +17 cm
  - Late 20th century (1993-2003)
    - ~50% by steric component
    - ~25% by glaciers and ice caps
    - ~14% by Greenland and Antarctic
  - 21st century
    - Without rapid ice discharge : +18 (B1 lower)～+59 (A1FI upper) cm
    - If observed ice flow acceleration were scaled up with global surface temperature: add +10～+20 cm to the upper bound, but no estimate in SPM
- Cazenave et al. (2009), Rignot (2011)
  - More relative contribution from the polar ice sheets recently

Large uncertainty exists

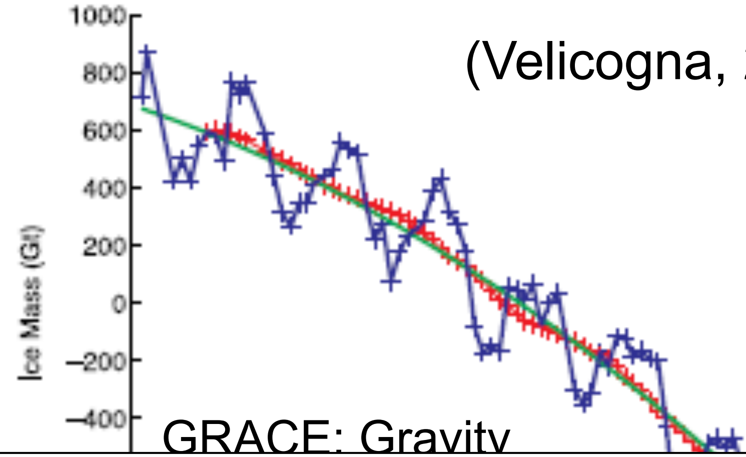
→ need to examine individual (e.g., ice sheet) contributions through physical understanding

Observed Greenland ice sheet mass balance



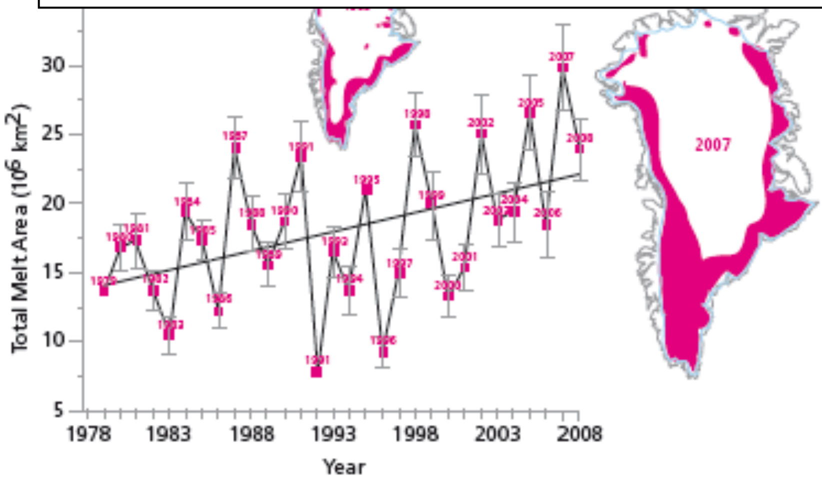
Rates of elevation change (cm/yr) from ATM+ICESat

(Velicogna, 2009)

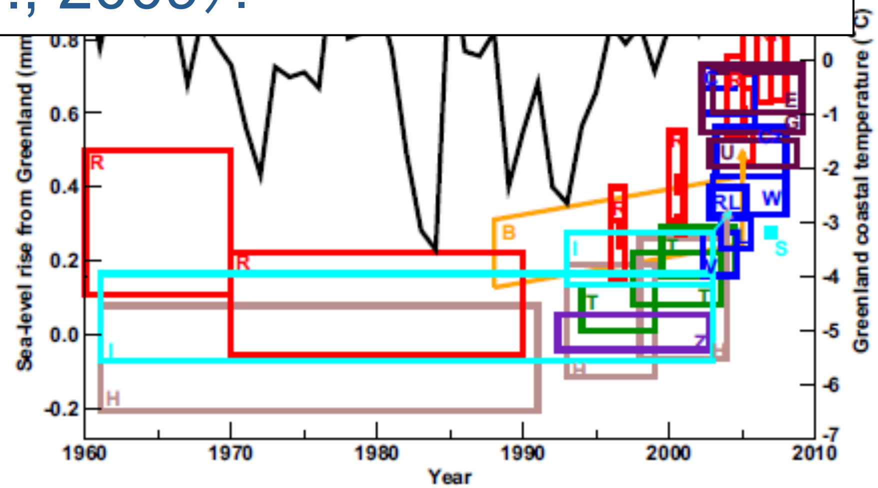


GRACE: Gravity

Recent observations indicate rapid mass loss（e.g., Cazenave, 2006; Shepherd and Windgham, 2007; Hanna et al. 2008; Rignot et al., 2008; Wouters et al., 2008; Velicogna, 2009; Pritchard et al., 2009）.

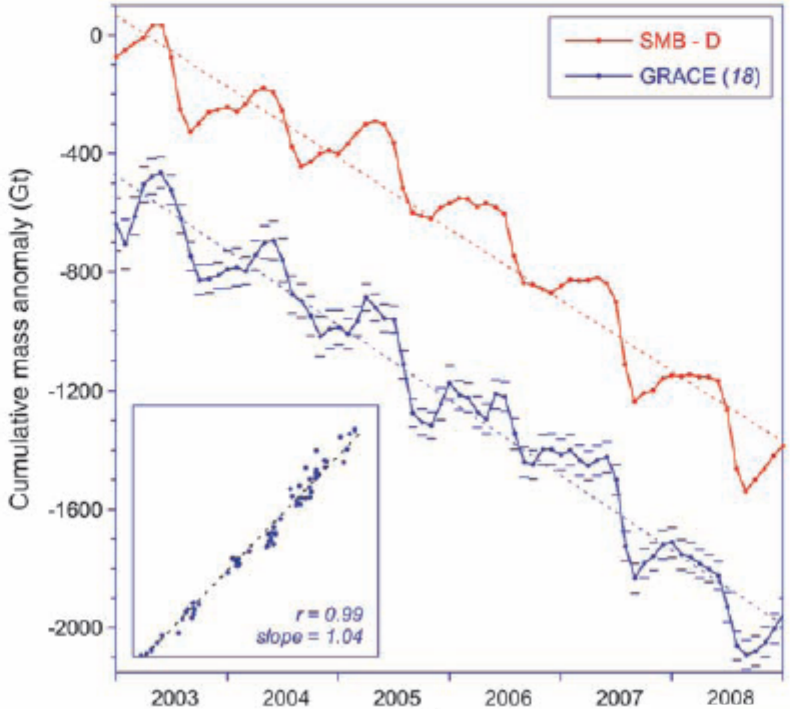


(Jensen and Steffen, 2009)



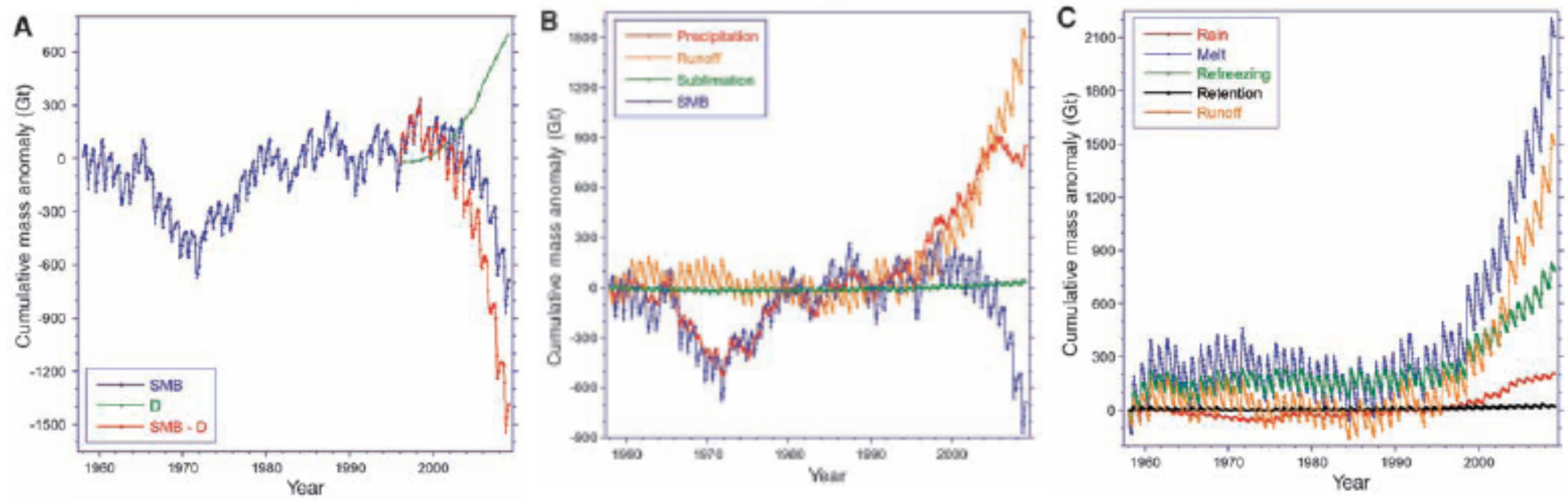
(Alley et al., 2010)

Mass balance estimate based on observations and RCM



Both ice discharge and melting are important.

(Broeke et al., 2009)



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Previous studies：Greenland ice-sheet SMB future projections

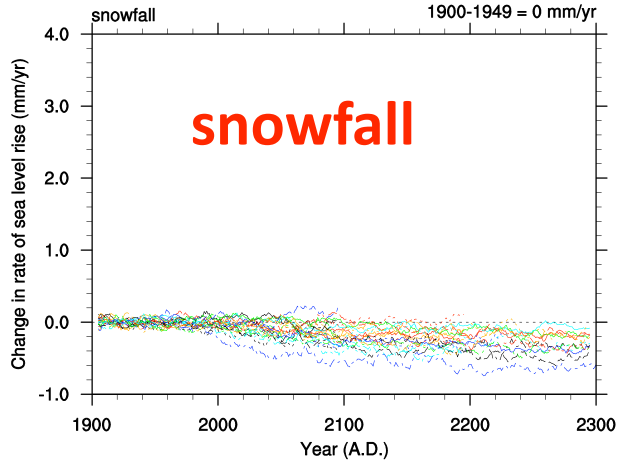
- Run high-res. (∼1.1°) AGCM with lower boundary conditions taken from low-res. AOGCM
  - Ohmura and Wild (1996), Wild and Ohmura (2000)
- Interpolate climate change simulated by GCM onto fine resolution (~2 km) and add to observations; use empirical formula
  - Wild et al. (2003), Suzuki et al. (2005)
- Run snowpack model on 20 km res. using EMIC output
  - Bugnion and Stone (2002)
- Scale climate change patterns simulated by high-res. GCM by low-res. GCM/ EMIC simulations; use empirical formula（20 km res.）.
  - IPCC-TAR (2001), Huybrechts et al. (2004), Gregory and Huybrechts (2006), IPCC-AR4 (2007)
- Apply a regression equation derived from RCM for specific regions
  - Fettweis et al. (2008)

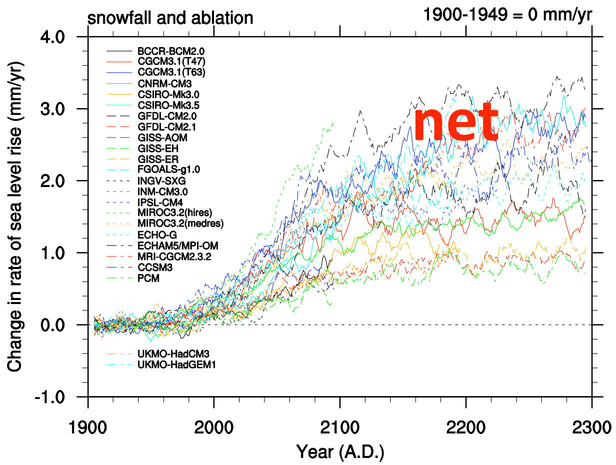
There are many studies, but few investigated mechanisms behind the difference among climate models.

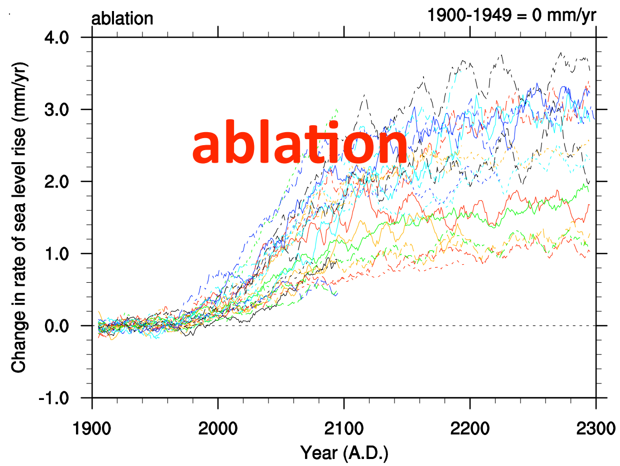
Our approach (follow Suzuki et al., 2005)

- Purpose : to analyze reasons for intermodel difference
- Important: melting occurs narrow and steep margin
- Input data: CMIP3
- Ablation
  - Interpolate GCM simulated temperature change onto fine resolution: 0.05°x 0.02°(~2.8km@60N x ~2.2km)
  - Compute summer temperature by adding the anomaly to observations on the fine resolution (take steep margin into account; remove model bias as a by-product)
  - use empirical formula (function of summer surface air temperature proposed by Ohmura, 1996)
- Accumulation
  - Interpolate GCM simulated snowfall onto the fine resolution

Rate of sea level rise due to Greenland SMB (A1B)

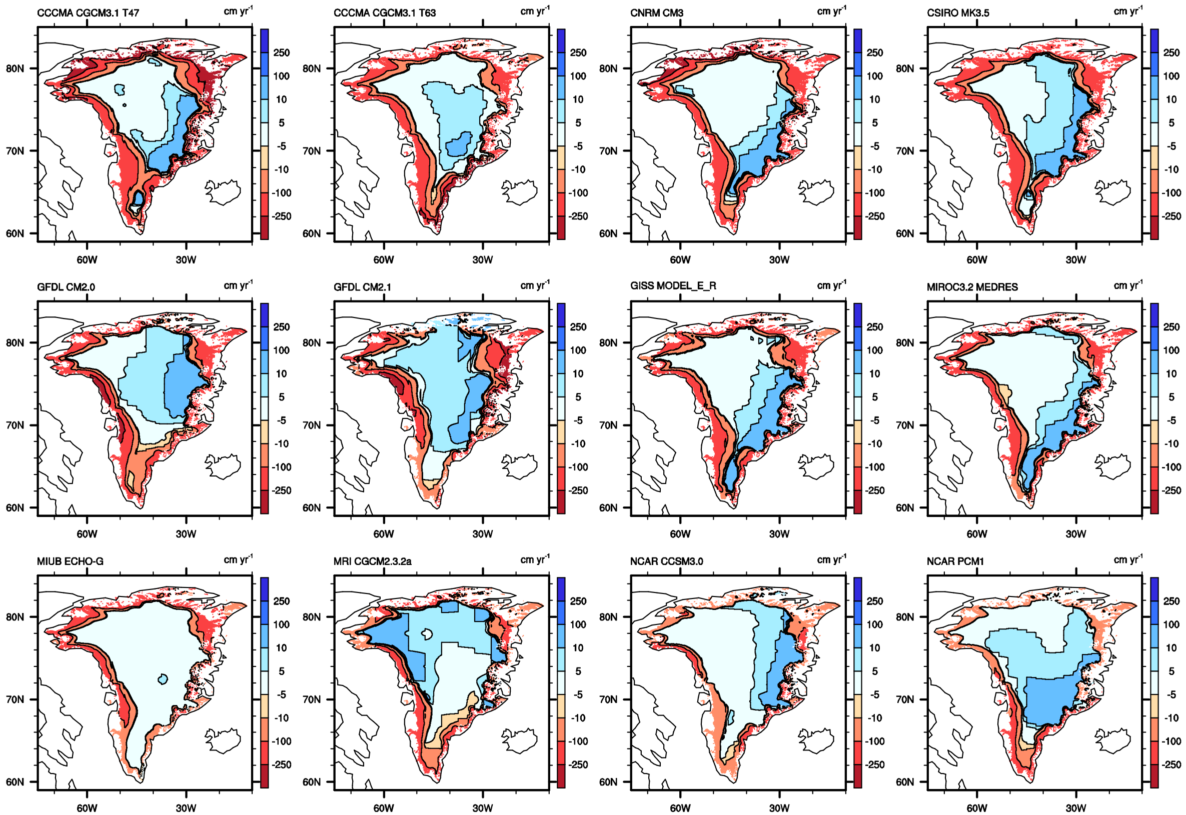




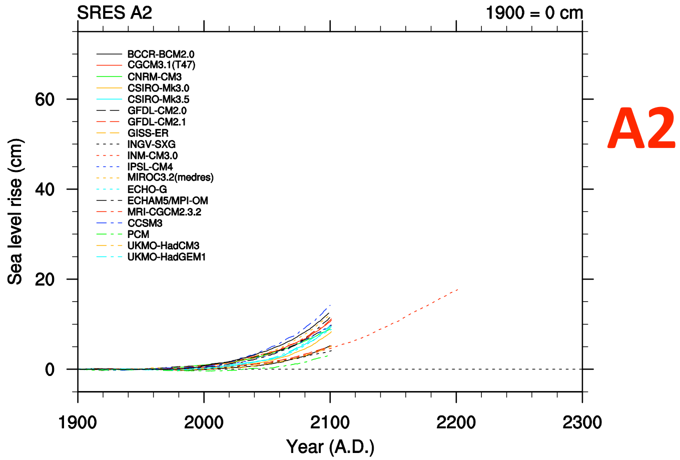


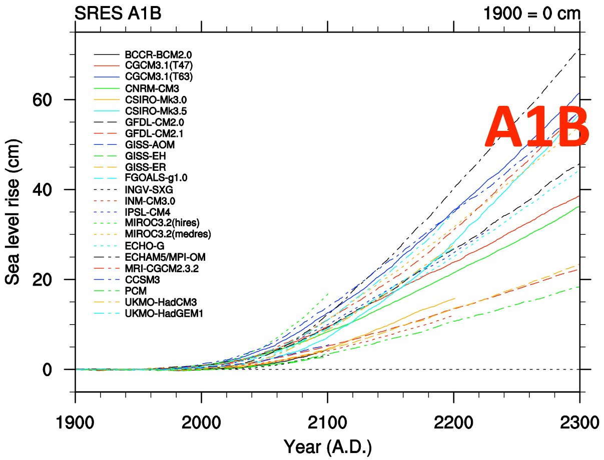
Ablation change dominates over snowfall change.

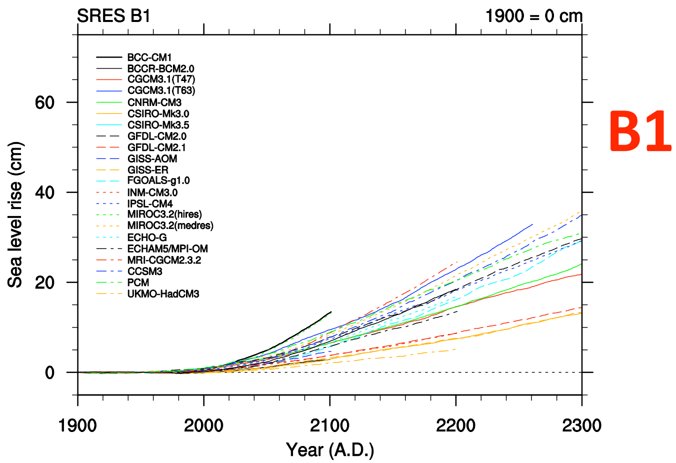
A1B Scenario Net Accumulation Change 2300-2000



Sea level change due to Greenland SMB (A1B, A2, & B1)

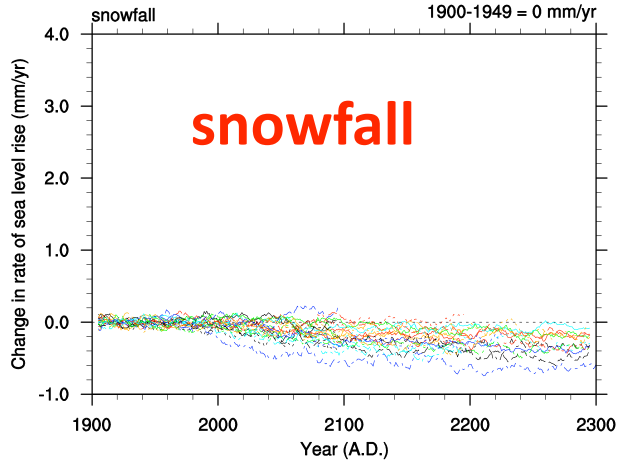


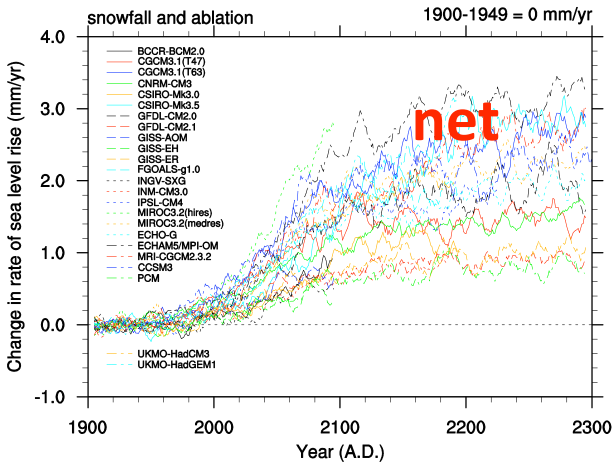


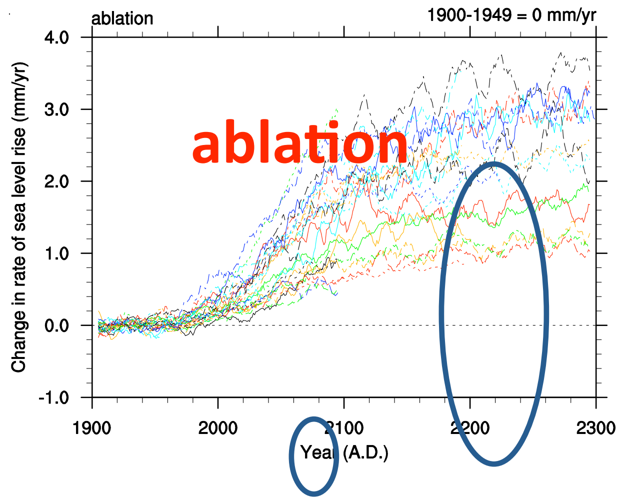


Small scenario dependency by 2100, but becomes large by 2300

Rate of sea level rise due to Greenland SMB (A1B)



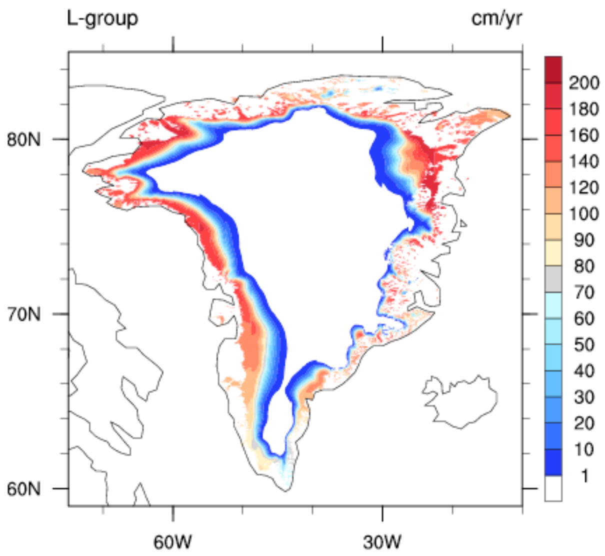


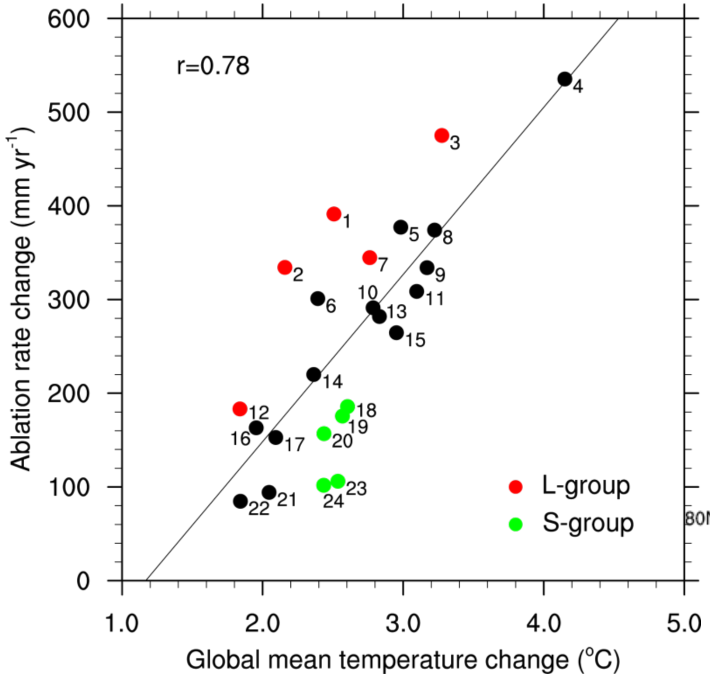


Investigate intermodel difference.

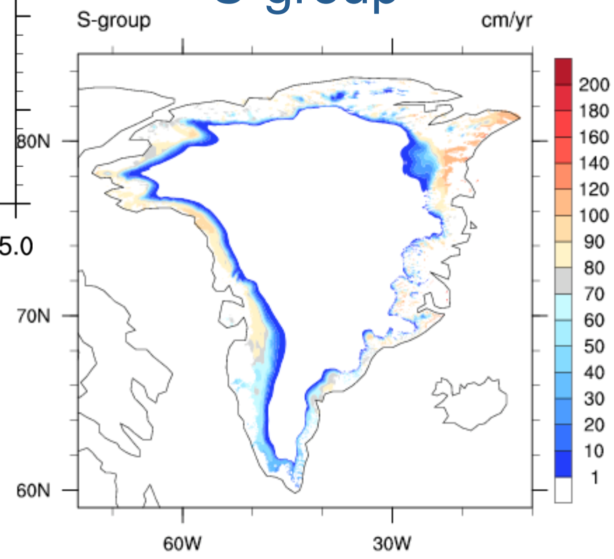
The relationship between 21st century global mean warming and GrIS ablation rate change

L-group





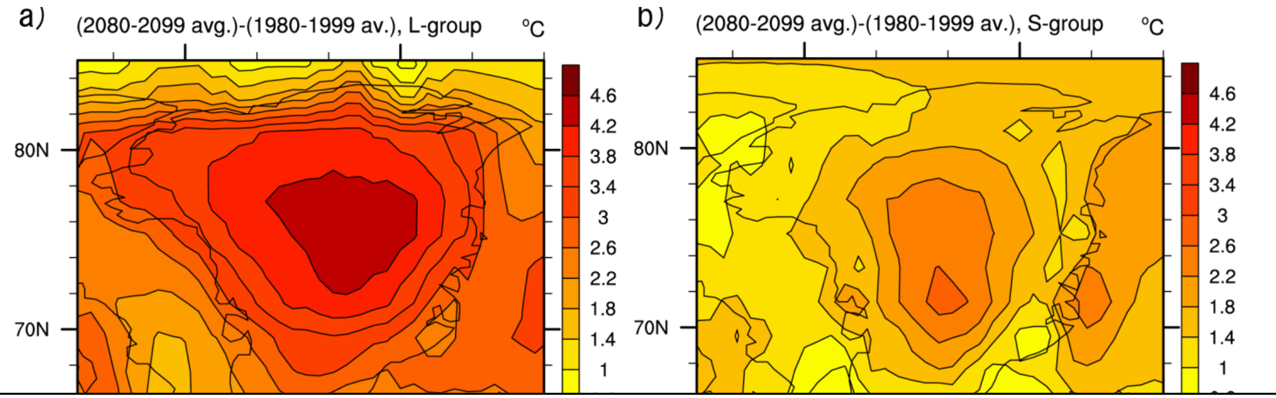
S-group



- About **61%** of the intermodel spread is explained by global mean temp. change.
- We investigate other processes.
- Composite analysis based on ablation rate increase normalized by global temp. change during the 21st century; **L** group = 5 largest, **S** group = 5 smallest

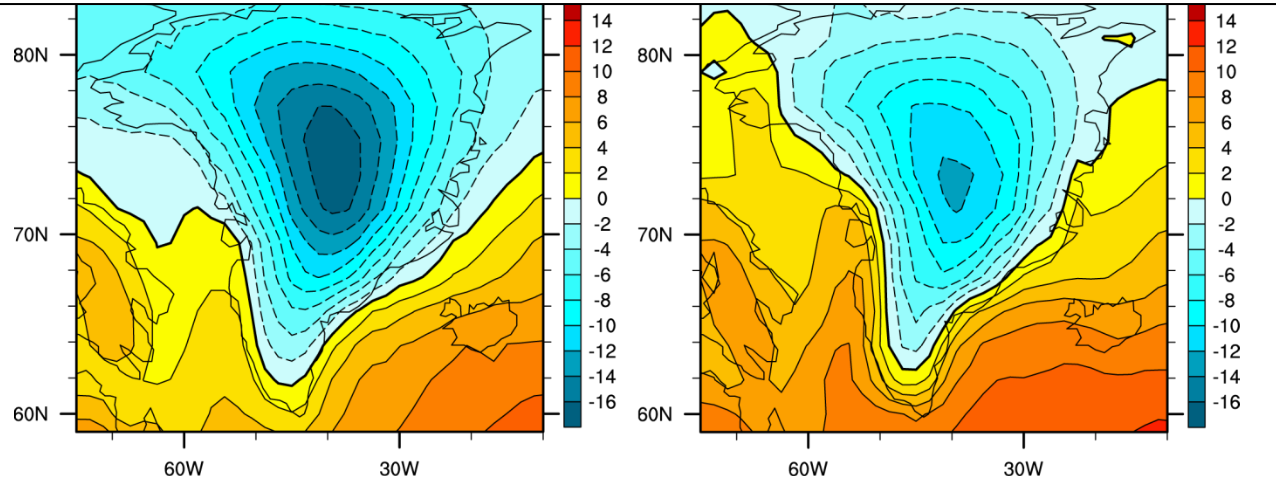
The effect of temperature bias over Greenland

Large ablation increase (L) **Small ablation increase (S)**



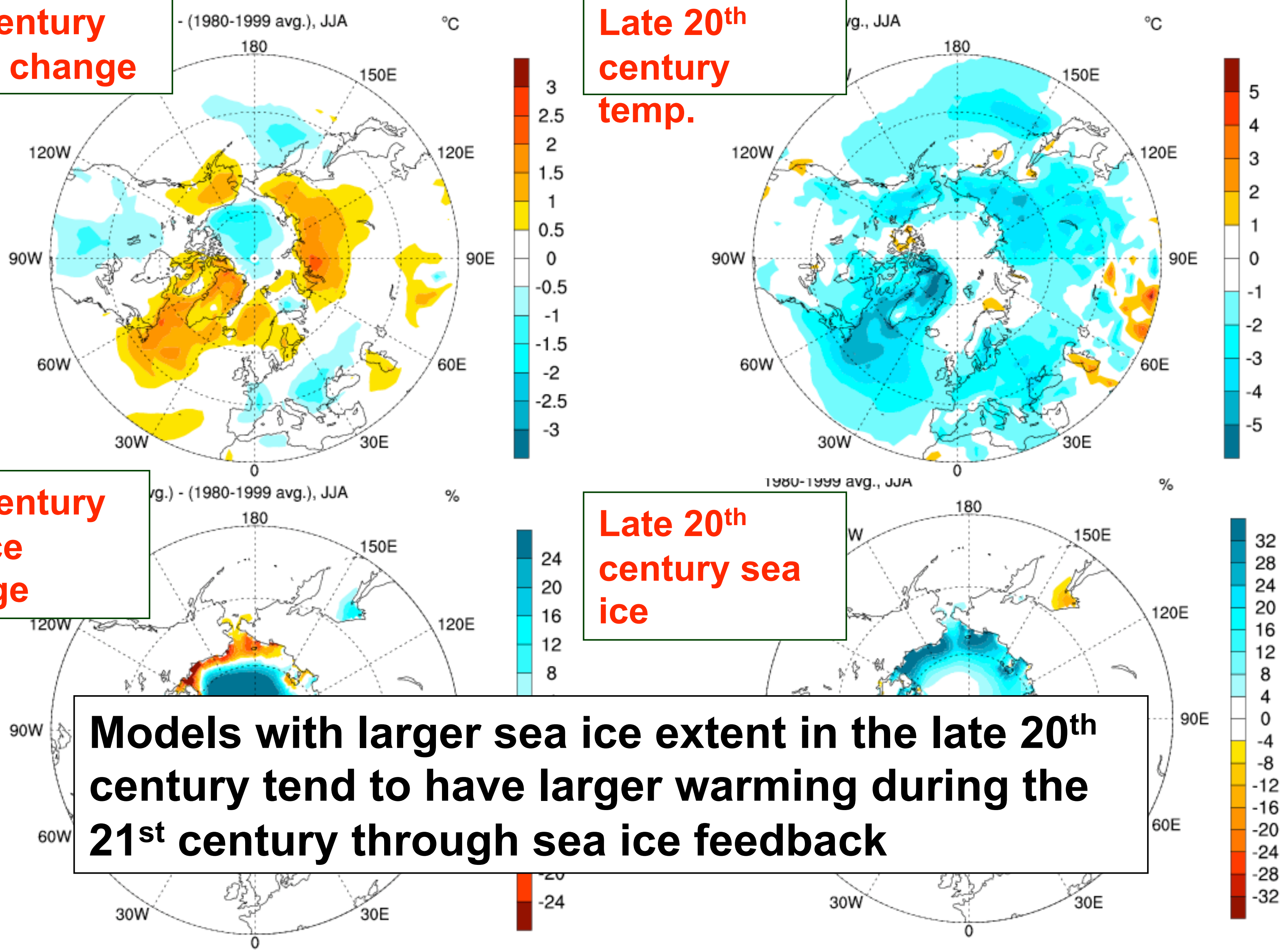
21st century summer

Max. surface temperature in melting region is limited to the melting point→initially colder models require more warming to occur until reaching 0℃



late 20th century summer

Large ablation models (L) – Small ablation models (S)



21st century temp. change

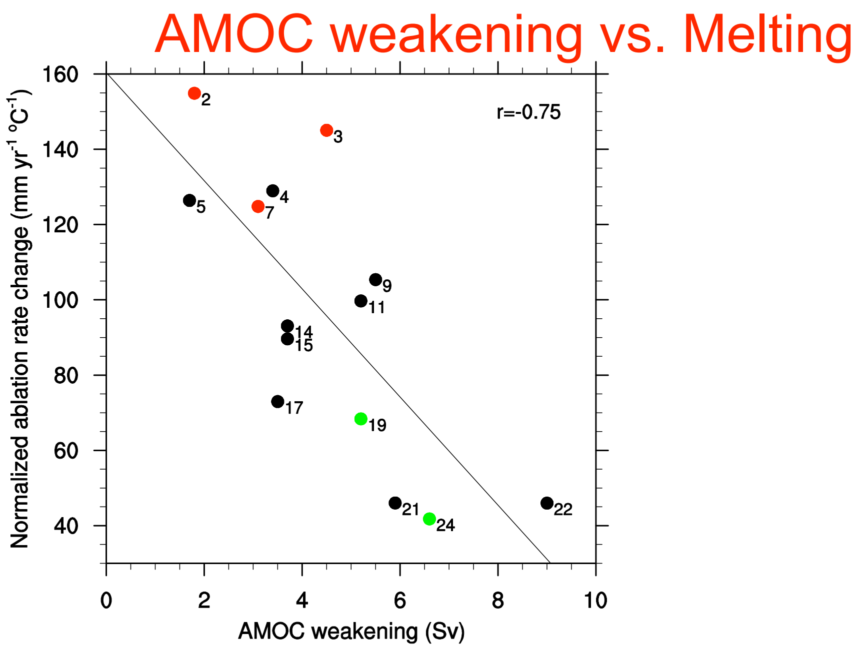
Late 20th century temp.

21st century sea ice change

Late 20th century sea ice

Models with larger sea ice extent in the late 20th century tend to have larger warming during the 21st century through sea ice feedback

Relation to Atlantic meridional overturning circulation (AMOC)



- Models with larger weakening of AMOC exhibit smaller increase of normalized ablation（r=-0.75）.

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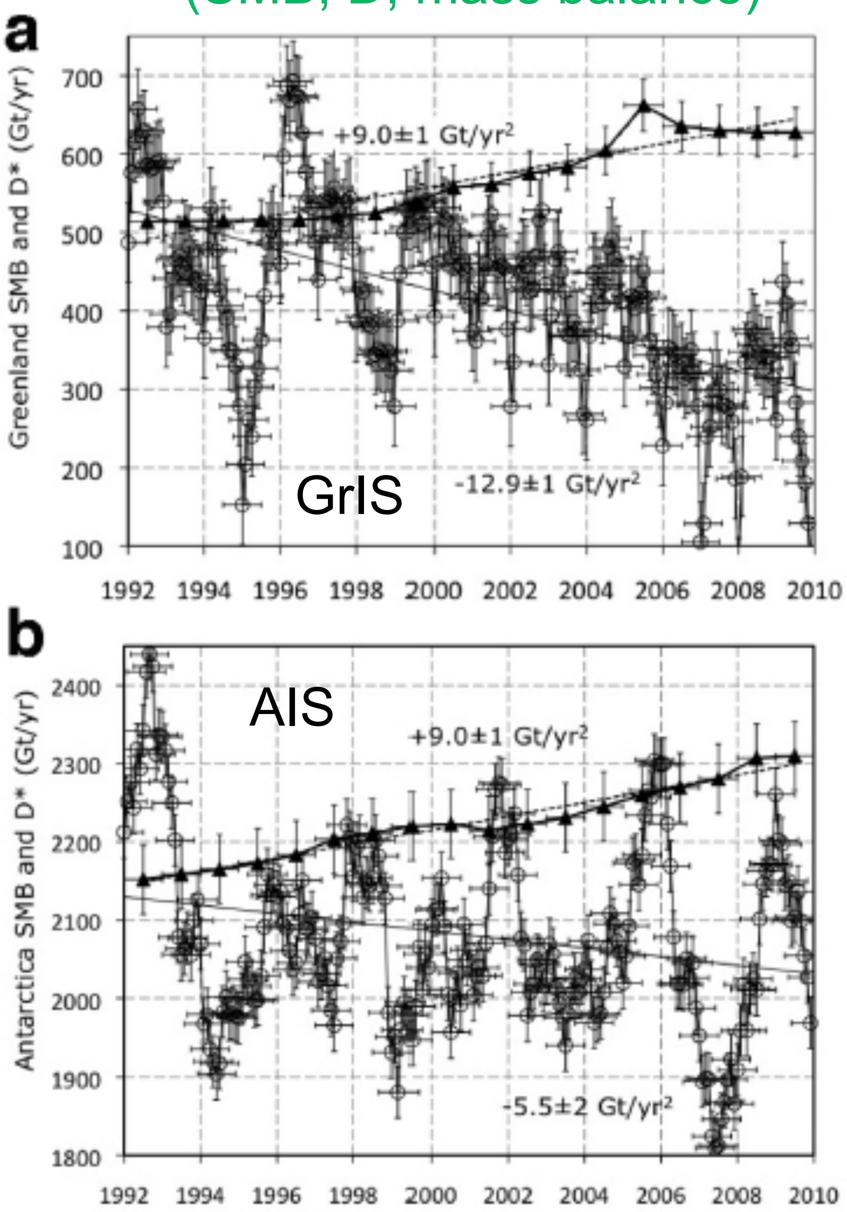
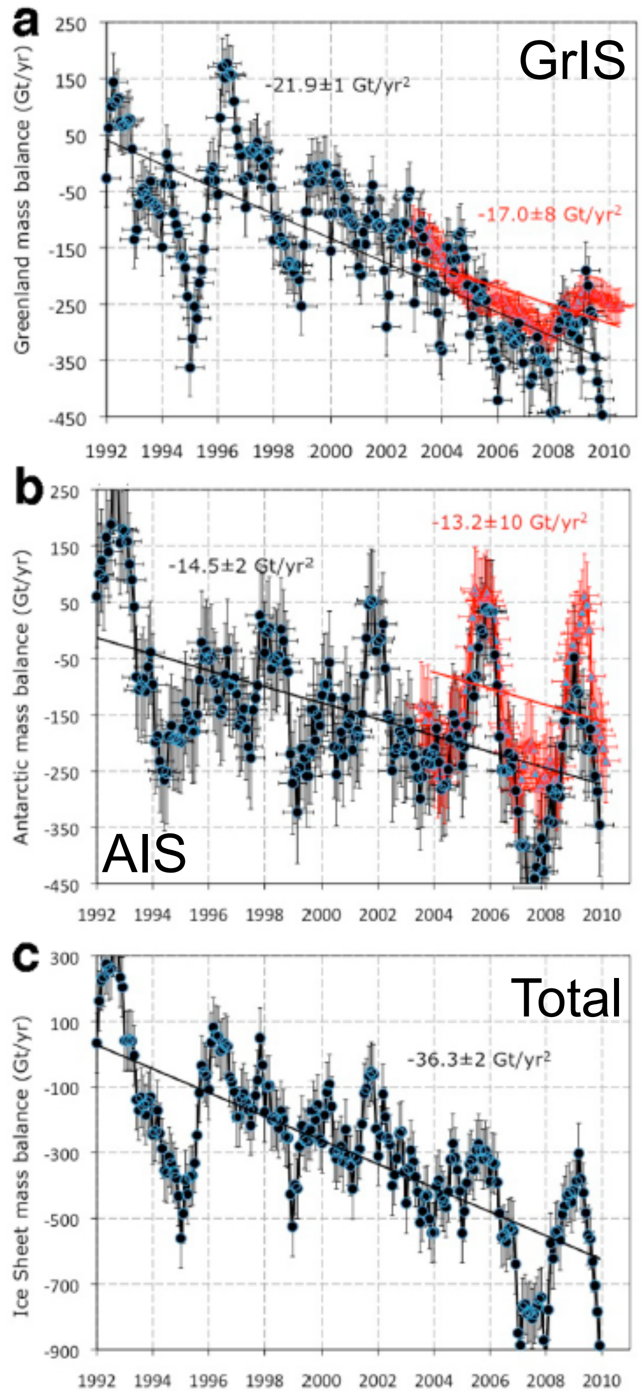
Recent observations and RCM (SMB, D, mass balance)

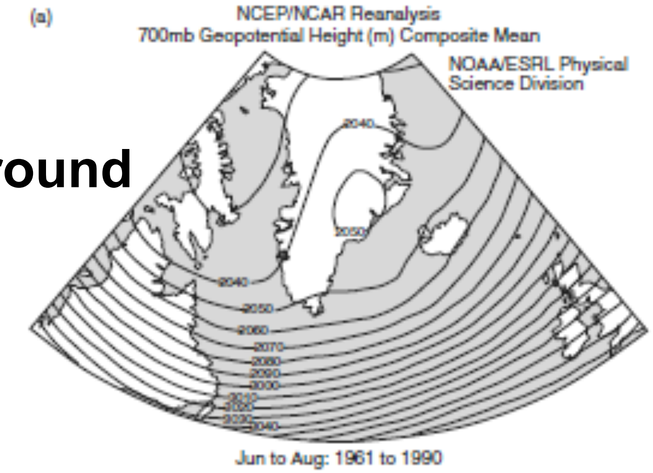


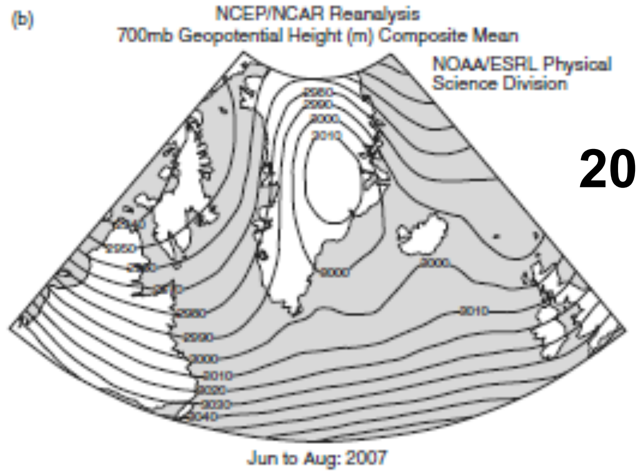


(Rignot et al. 2011)

Internal variability or climate change?
(1) 2007 record melting

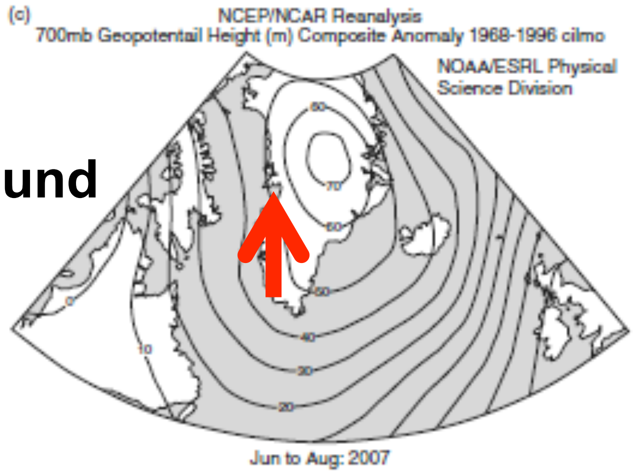
background



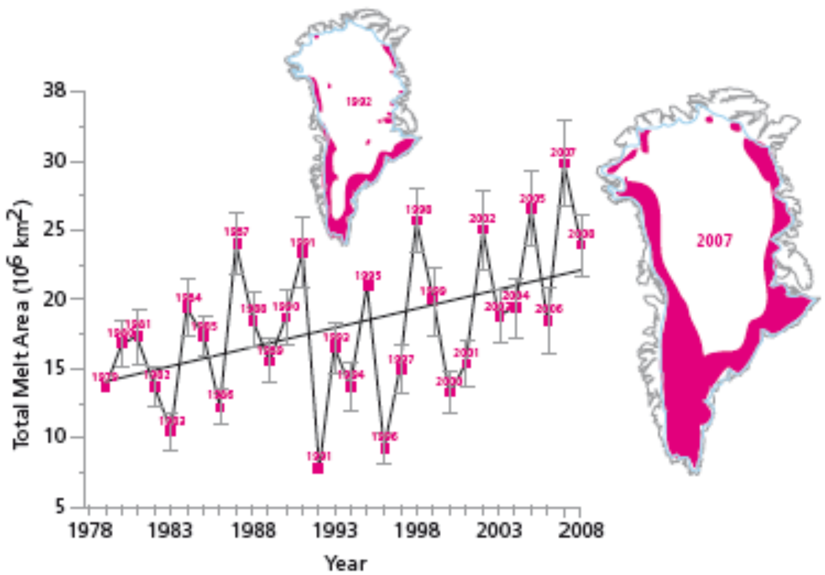


2007

2007 - background



(Hanna et al., 2009: large scale changes in the sub-polar jet stream)



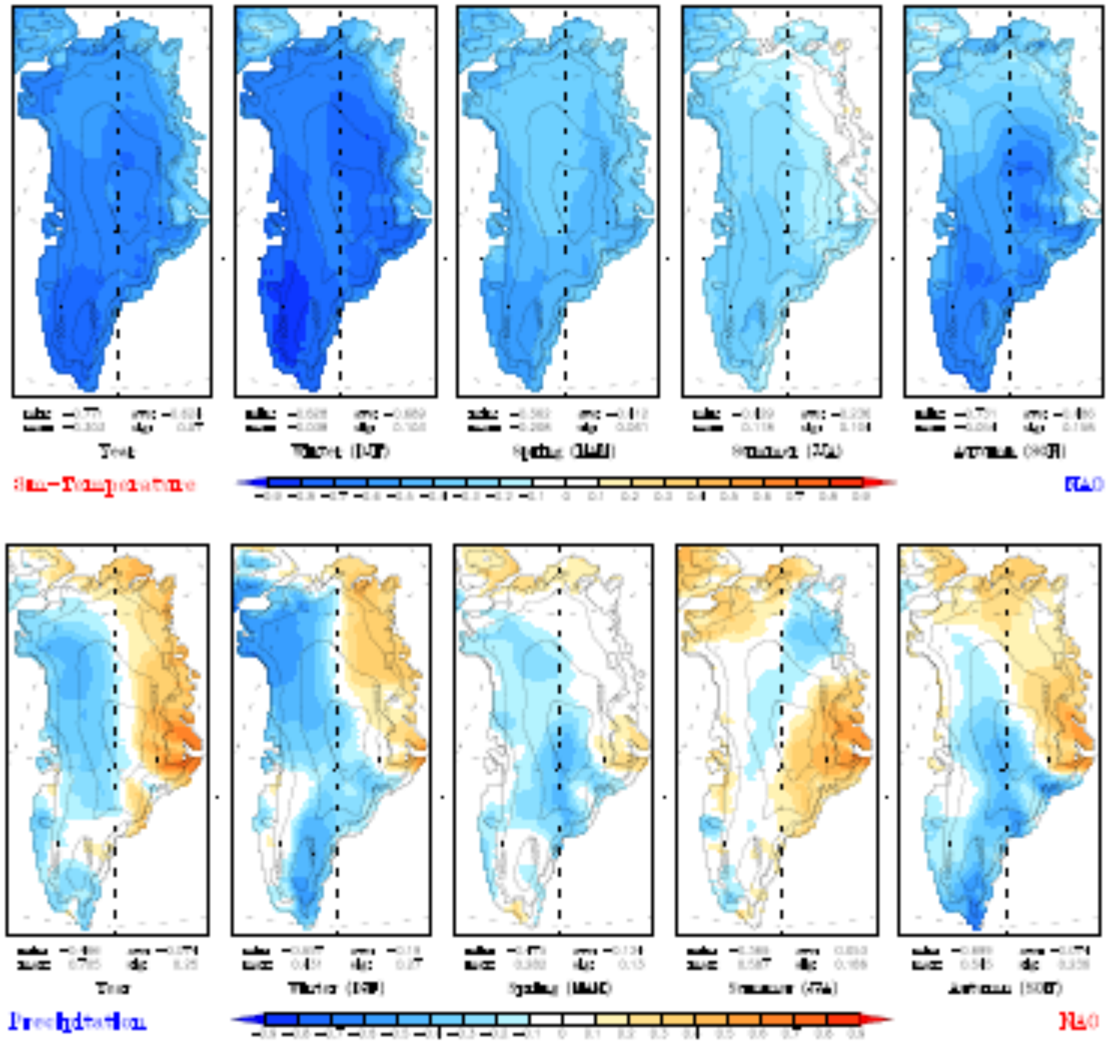
(Jensen and Steffen, 2009)

Internal variability or climate change?
(2) Relation to NAO

Year DJF MAM JJA SON

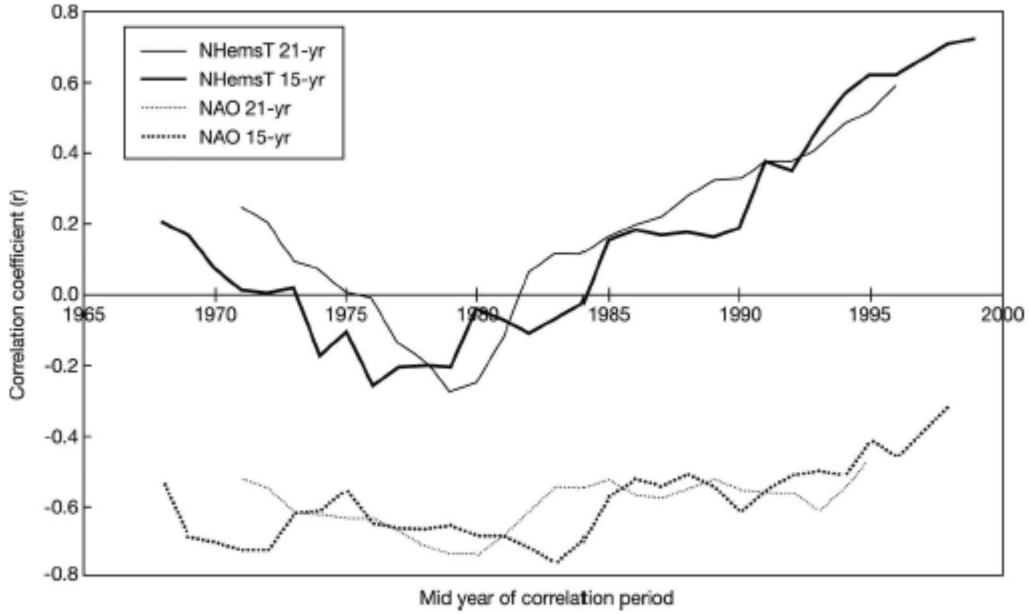
NAO and Temperature

NAO and Precipitation

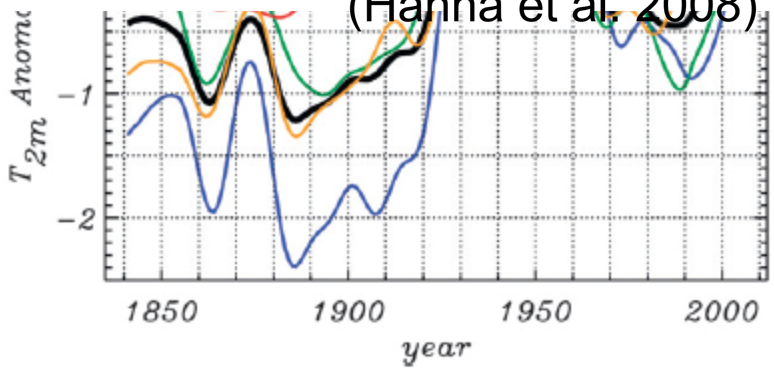


(Fettweis, 2007)

Internal variability or climate change? (3) Recent warming



(Hanna et al. 2008)

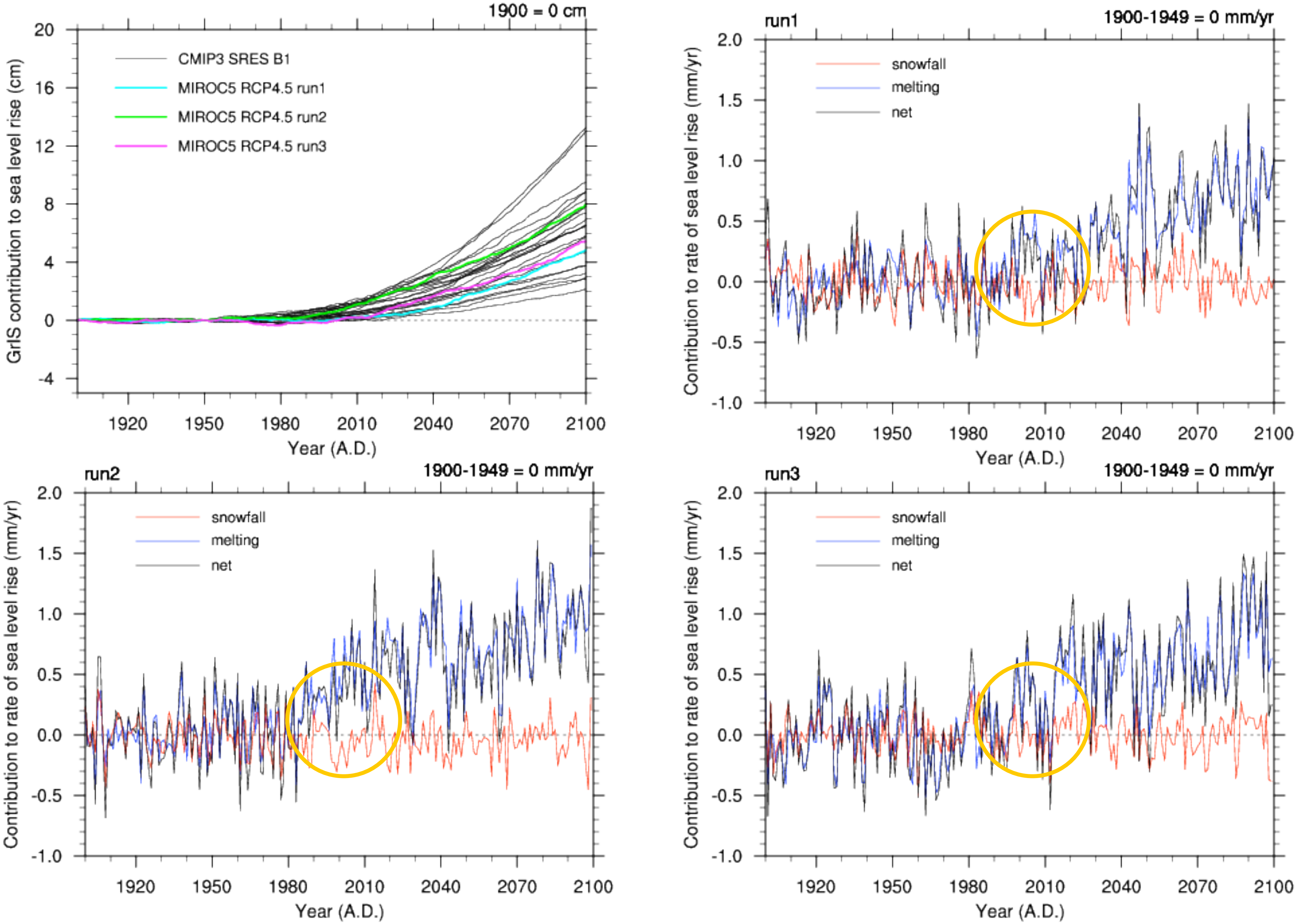


(Box et al., 2009)

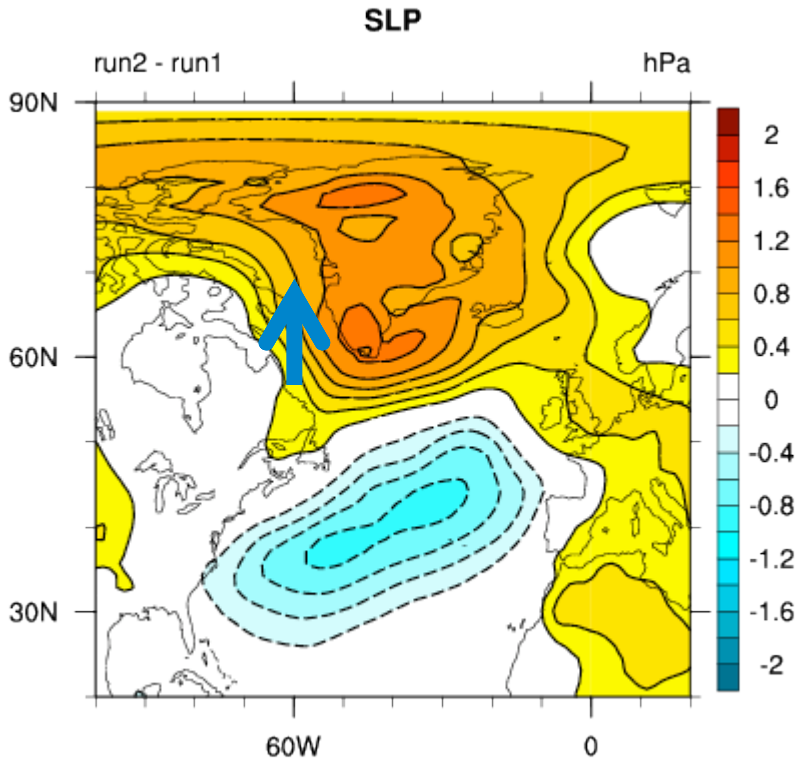
Link to N. Hem. warming

- NAO is a good proxy for the Greenlan
  for winter snowfall nor summer temp
  (Fettweis, 2007).
- The correlation of NAO with temperat
  index has a positive trend for the last 40 years (Fettweis, 2007).
- Summer temperature-NAO relationship breaks down after the early 1990s (Hanna et al., 2008).

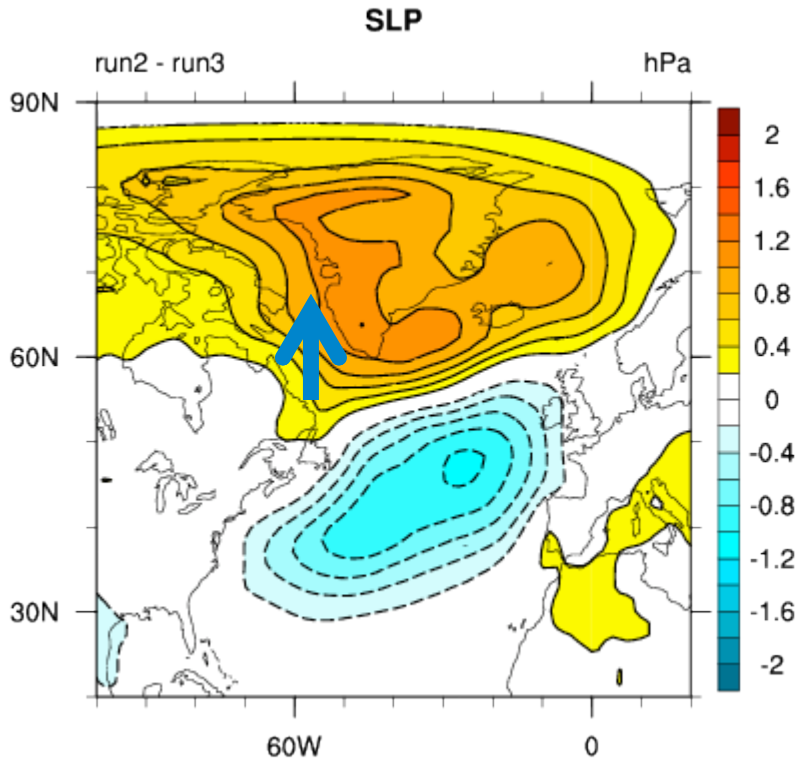
An example of ensemble spread (same model, same bias correction, different initial conditions) – MIROC5 -



Dipole SLP anomaly (1991-2020 avg.) may have caused the difference among ensemble members in MIROC5 RCP4.5



RUN2 – RUN1



RUN2 – RUN3

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Previous studies: Reconstructed sea-level and GrIS simulations during the LIG period

Studies	LIG sea level from today
Lambeck et al. (2002)	**2 – 4 m**
Overpeck et al. (2006)	**> 4 – 6 m**
Kopp et al. (2009)	**> 6.6 m (95%)**
Alley et al. (2010)	**5 – 8 m**

Studies	GrIS contribution	Forcing and constraint
Cuffey and Marshall (2000)	**4.0 – 5.5 m**	O isotope
Tarasov and Peltier (2003)	**2.7 – 4.5 m**	O isotope + obs. constraints
Lhomme et al. (2005)	**3.5 – 4.5 m**	O isotope + obs. Constraints
Otto-Bliesner et al. (2006)	**2.2 – 3.4 m**	AOGCM

There are large uncertainties in both estimates.
The direct analogue for the future is not possible (Crowley 1990; van de Berg et al. 2011).
→ Useful if we understand mechanisms of the changes.

Ice Sheet Model for Integrated Earth System Studies (ICIES)

(Abe-Ouchi et al, 2007)

Perturbed monthly mean Temp. and Precipitation: sensitivity obtained by GCM in advance.

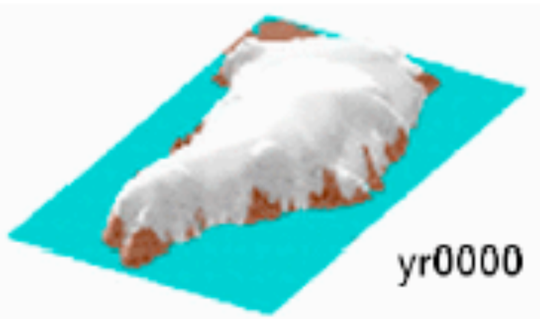
Orbital Forcing (Berger 1978)

T = T(Observed)
+dT (Orbital Forcing direct effect)
+ dT (CO_2 direct effect) ← Vostok/EPICA Ice core CO2
+ dT (ice sheet-atmosphere feedback)
P = P (Observed) *f(dT)

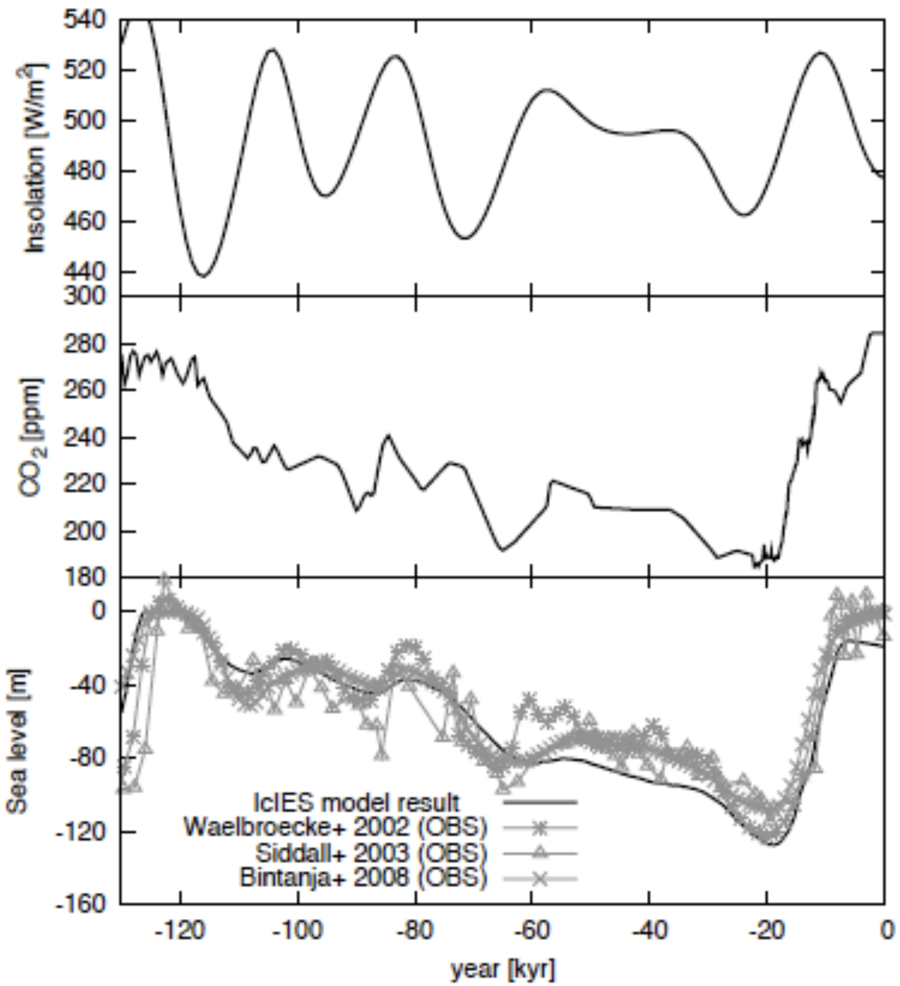
(Abe-Ouchi et al, 2007, CP)

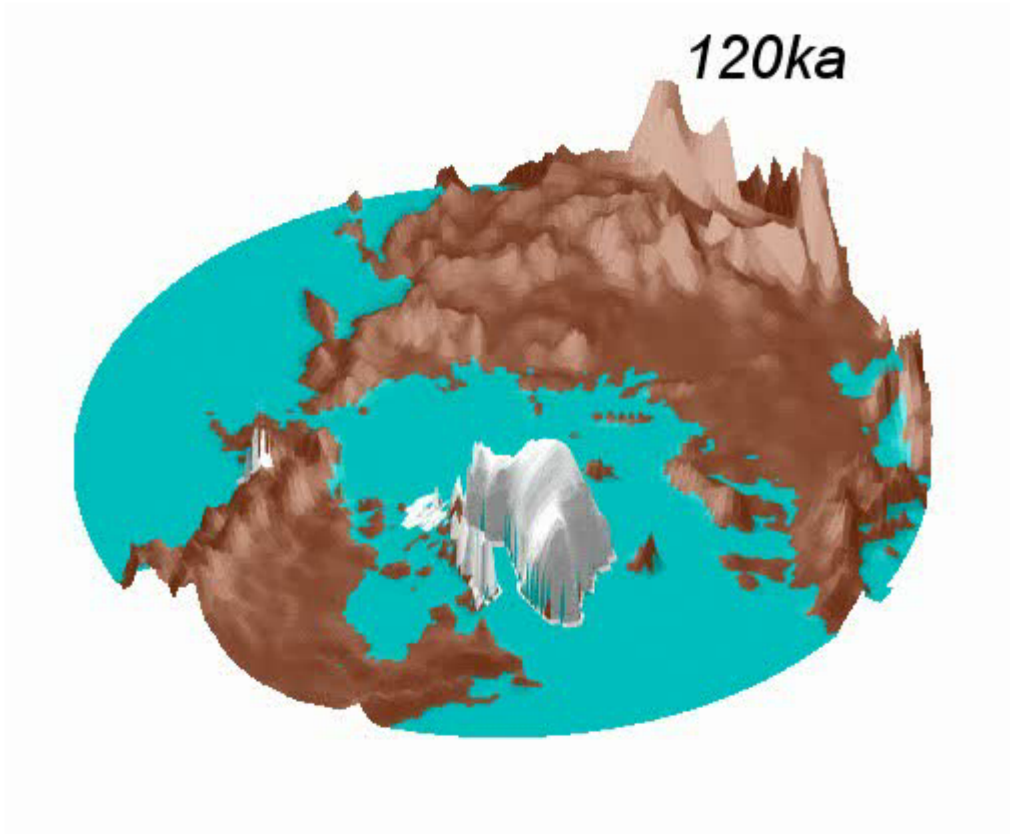
Ice Sheet Altitude and Area ← **3D thermo-mechanical ice sheet model** (Saito and Abe-Ouchi, 2004)

- Shallow ice approximation
- Thermodynamics-dynamics coupling
- Sliding depends on basal temperat.
- Delayed Bedrock isostacy included
- Horizonal resolution 1 deg lon./lat.
- Vertical 20 layers
- Degree Day mass balance model



Simulation of the last glacial cycle



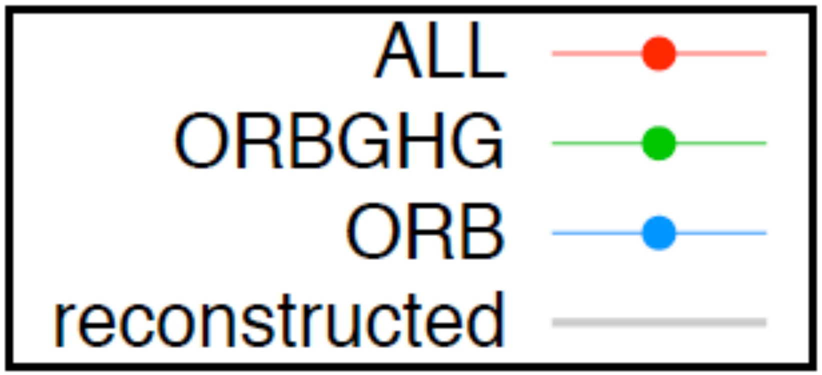


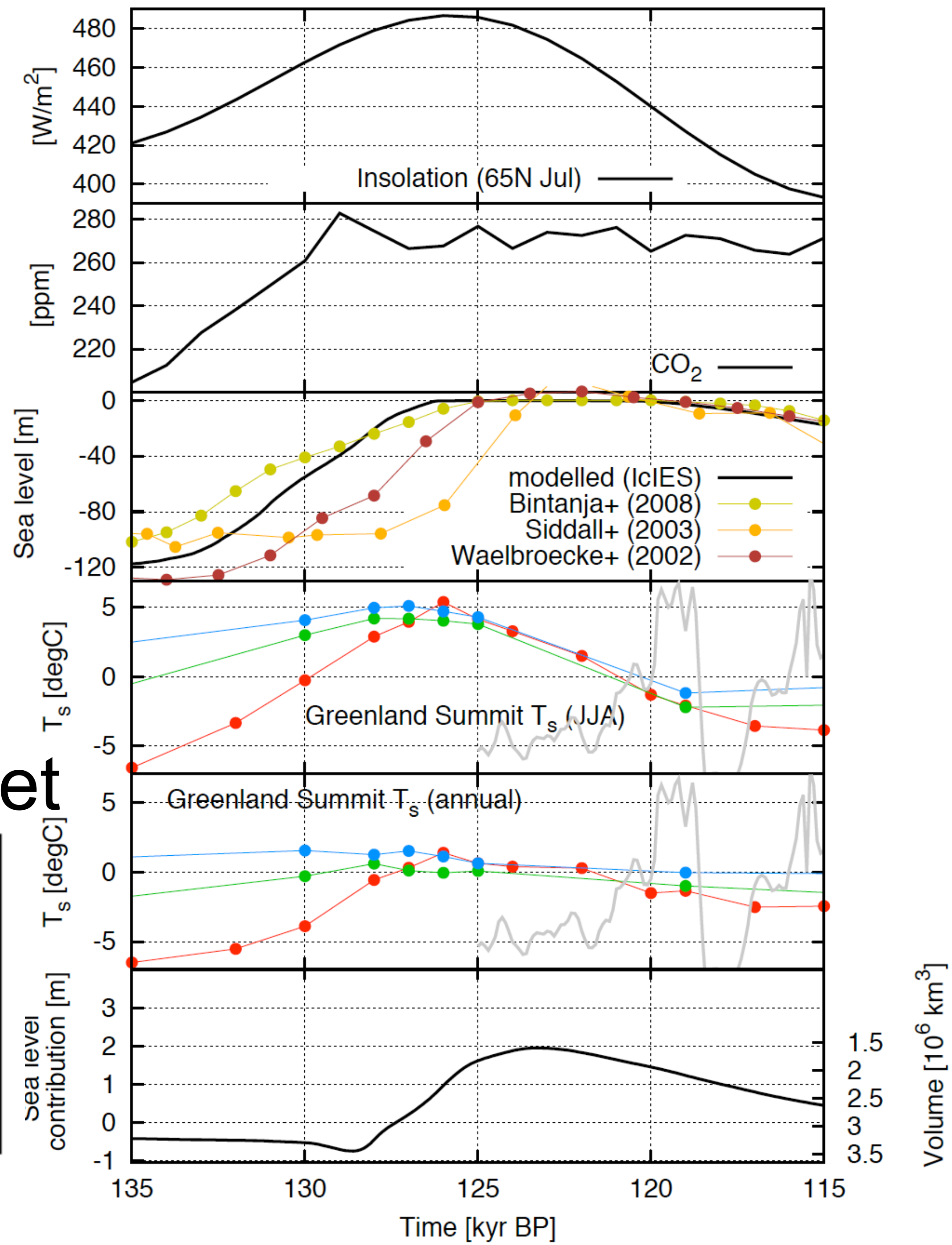
(Abe-Ouchi et al. 2007)

Basic features (e.g., 100-kyr cycle) of glacial cycles can be simulated with insolation and atmospheric CO2 changes.

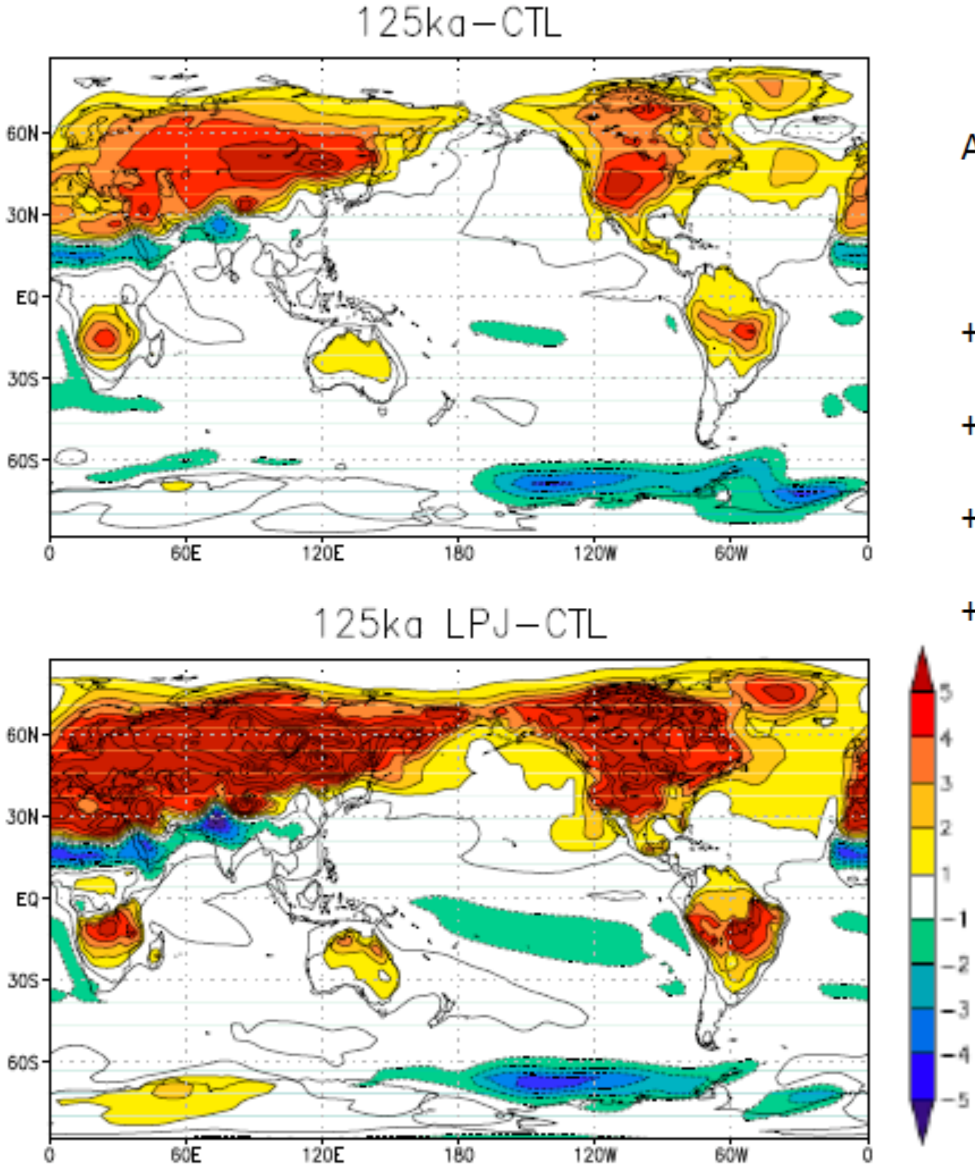
Time slice Ice age cycle run with MIROC GCM and IcIES

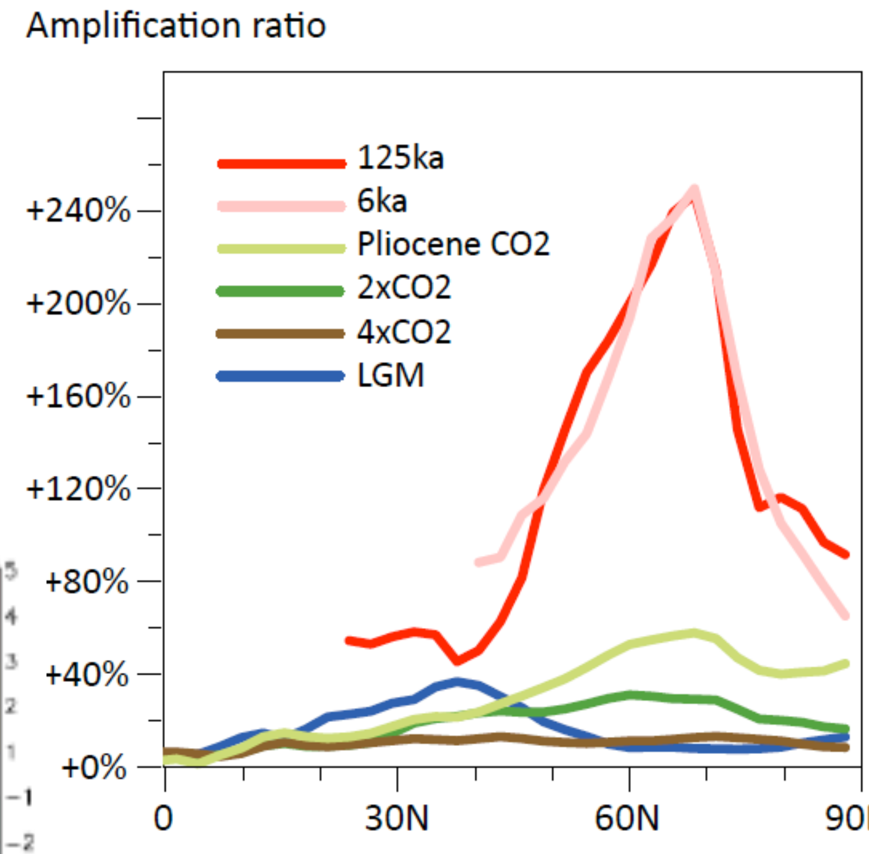
Forced by Insolation, GHG and NH Ice sheet





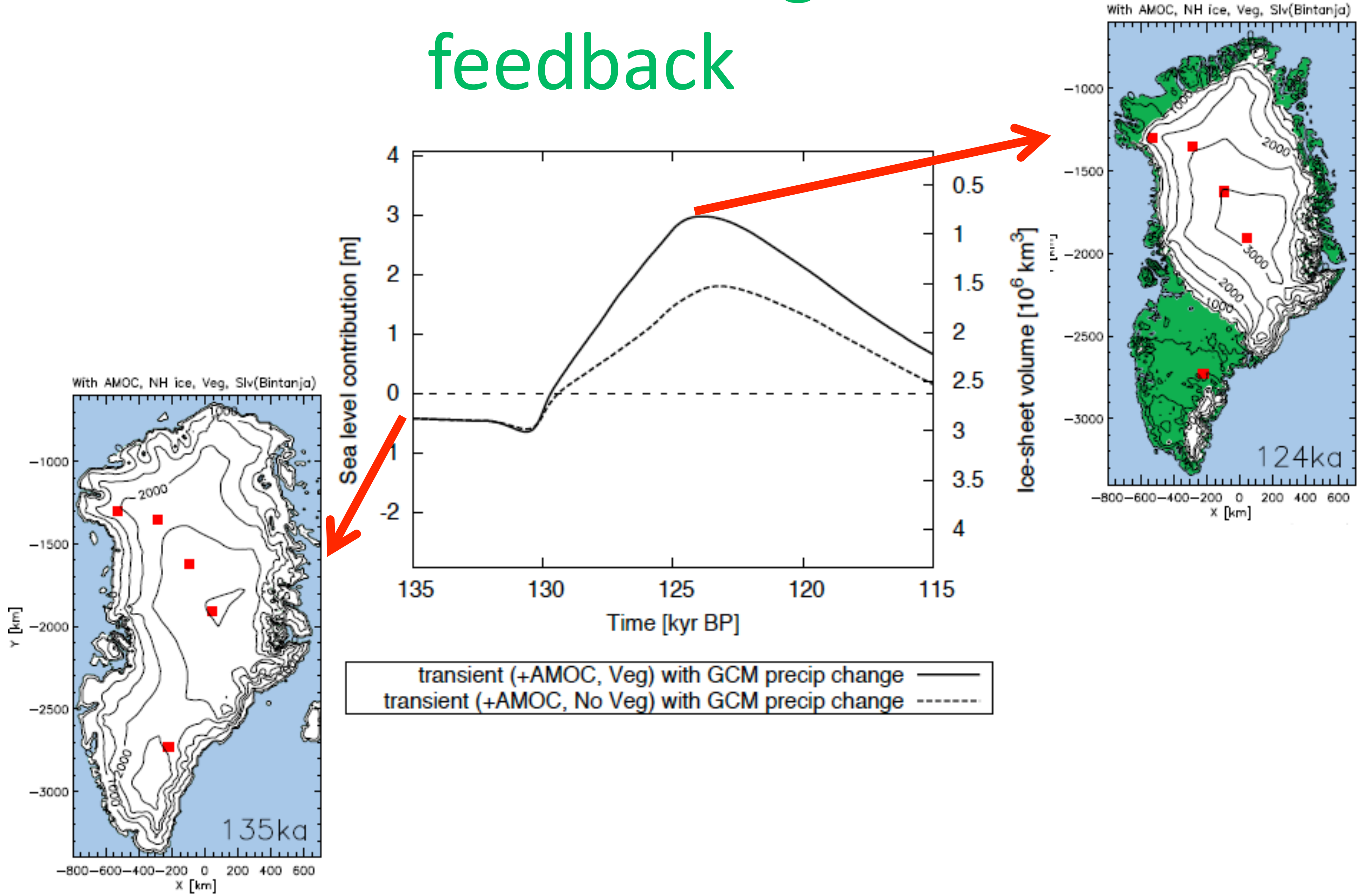
The effect of vegetation feedback





Amplification of annual averaged warming[cooling] by vegetation change: temperature change due to vegetation change is divided by temperature change induced by all boundary conditions except for vegetation.

With and without vegetation feedback



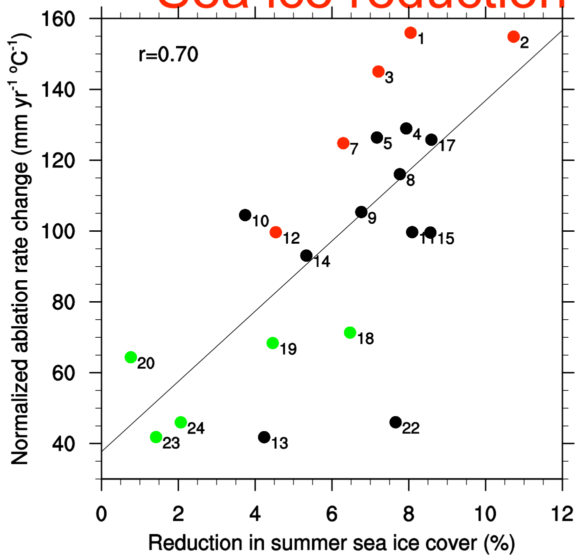
Concluding remarks

- A majority of spread in multi-model projections of GrIS SMB is accounted for by global mean temperature change (i.e., climate sensitivity and ocean heat uptake). There are, however, other processes that are important (i.e., sea ice, ocean circulation). It is important to correctly simulate the present-day conditions.
- There is a possibility of narrowing the uncertainty by assessing performance in the present-day simulations. To do so based on short observation records, we need to distinguish externally-forced and unforced-internal components in them.
- There is no perfect past analogue for the future change in ice sheet and sea level changes, but the bridge can be build and insight may be gained through quantitative understanding of the underlying mechanisms of the past changes.

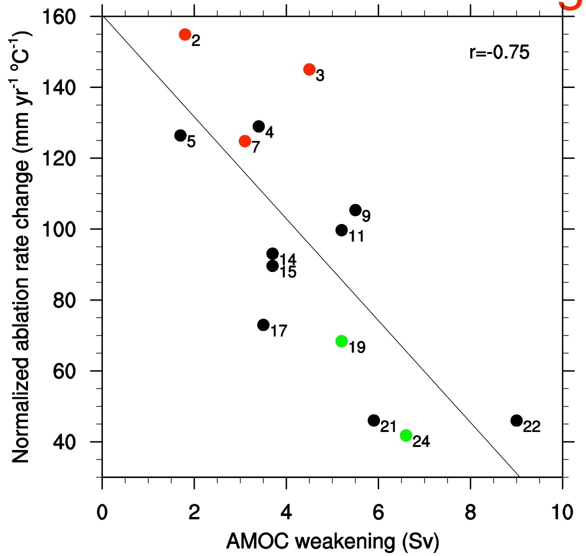
END

Relation to Sea Ice and Atlantic MOC

Sea ice reduction vs. Melting



AMOC weakening vs. Melting



- Models with larger reduction of sea ice exhibit larger increase of normalized ablation（r=0.7）.
- Models with larger weakening of AMOC exhibit smaller increase of normalized ablation （r=-0.75）.

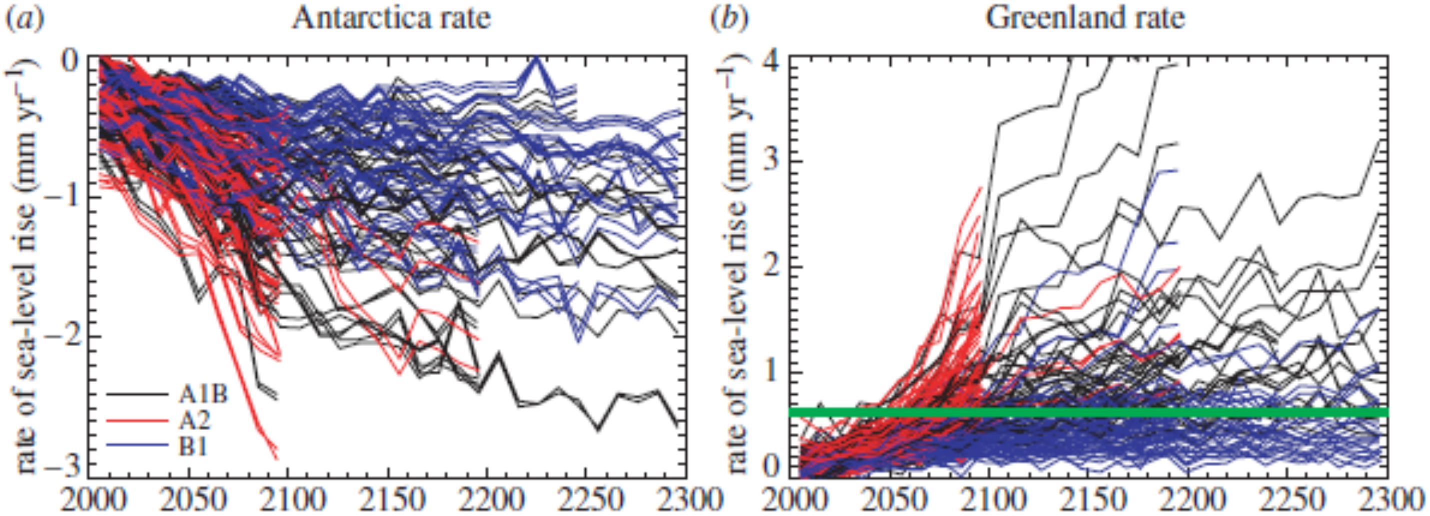
Sources of uncertainty in estimating future contribution of ice sheet to sea level change

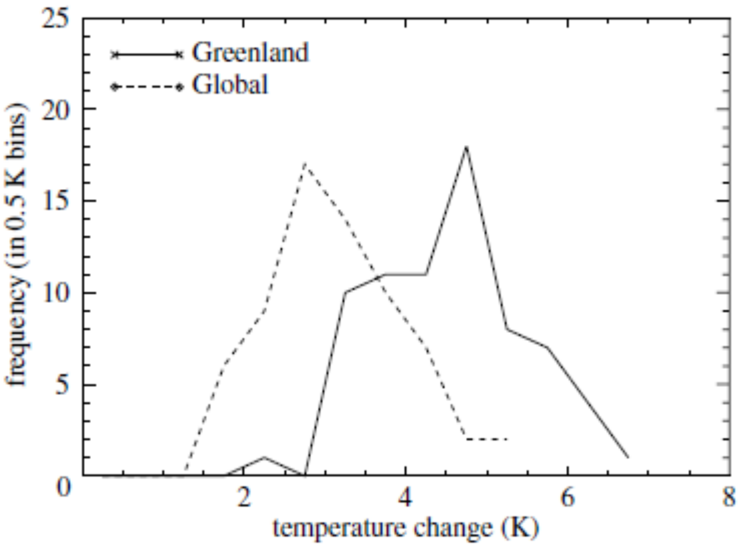
- Huybrechts et al. (2004) lists following 4 points:
  1. Long-term background evolution
  2. Surface mass balance (SMB) changes
  3. Ice-dynamic response to these mass balance changes
  4. Poorly represented rapid dynamical changes in ice flow
     - Inland transmission of stress after ice-front thinning or break-up
     - Enhanced basal lubrication after surface melting

Here, we focus on the Greenland ice sheet (GrIS) surface mass balance changes.

Previous research：Gregory and Huybrechts (2006)

- 3つの高解像度AGCMと1つのAOGCM(MIROC)の気温，降水量の空間変化パターンを，各CMIPモデル，各氷床平均の気温，降水量でスケーリング．
- 解像度20kmの表面質量収支モデルにて，質量収支を計算．



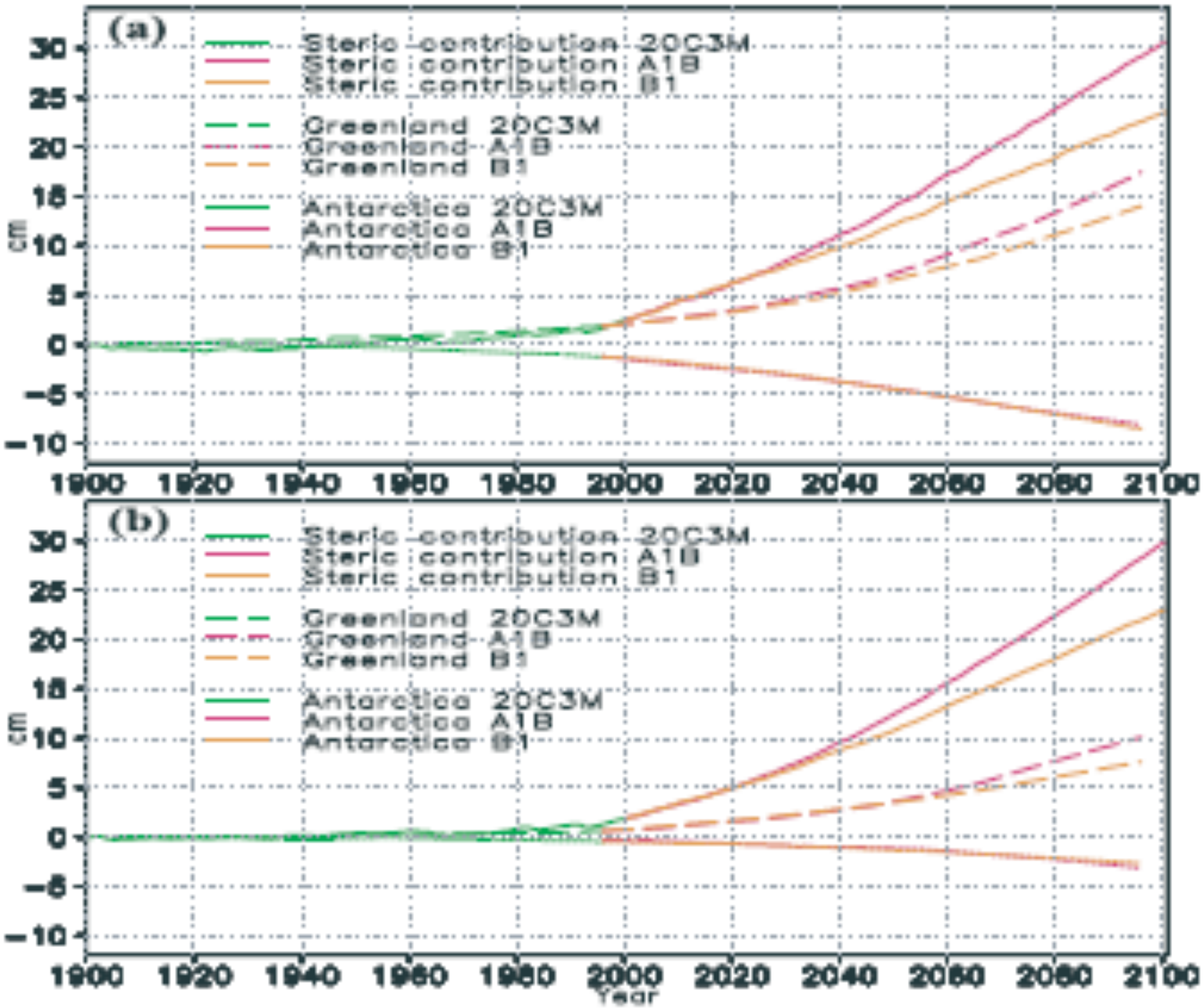


グリーンランドの平均気温が4.5+/-0.9 K，全球平均で3.1+/-0.8 K以上に上昇すると表面質量収支が負になる．
→たとえ力学プロセスによる海への流失がなくても氷床は縮小し，やがて消滅する．

Previous research : Suzuki et al. (2005)

MIROC3.2
High res.

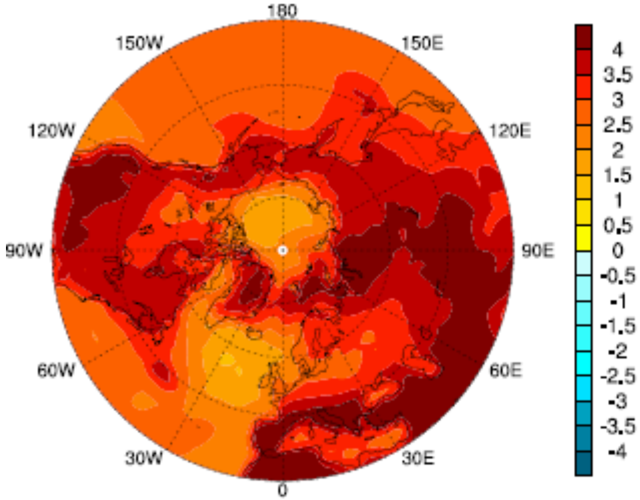
MIROC3.2
Low res.



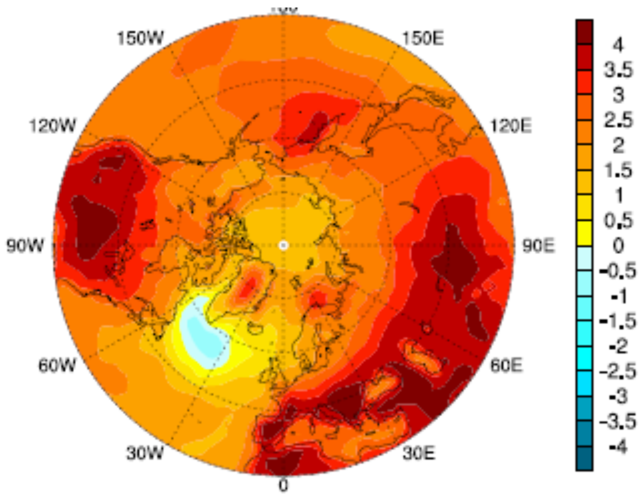
Summer temperature change during the 21st century

Ablation composite

Large ablation model (L)

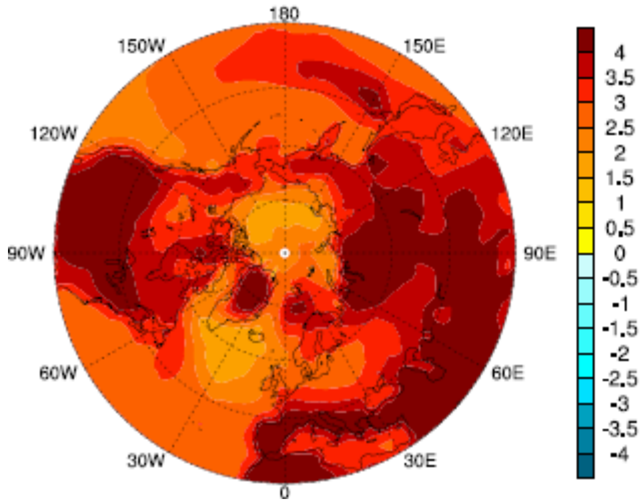


Small ablation model (S)

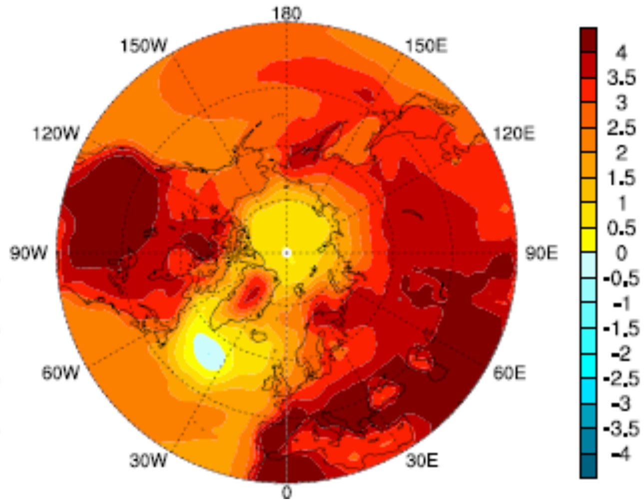


AMOC composite

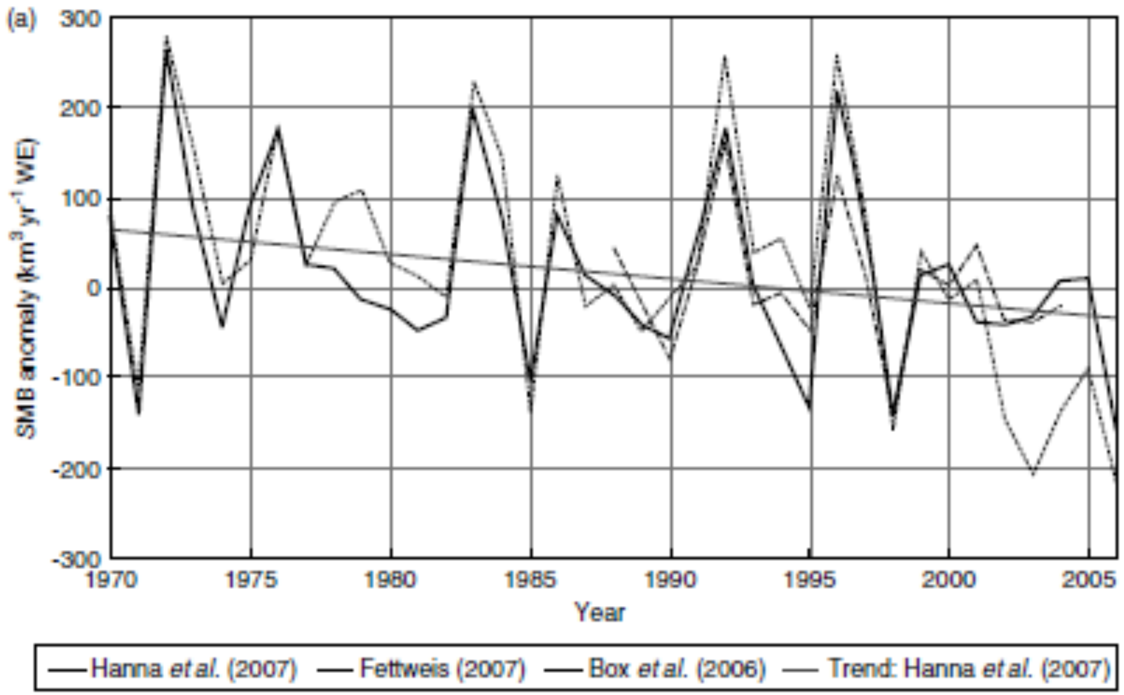
Small AMOC weakening



Large AMOC weakening

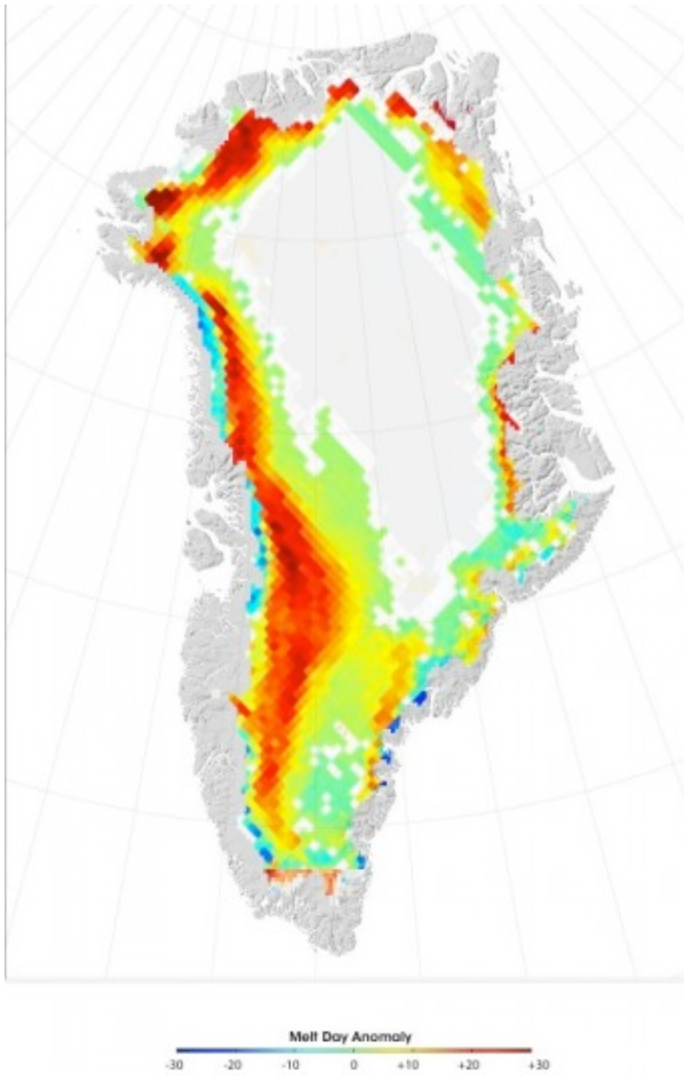


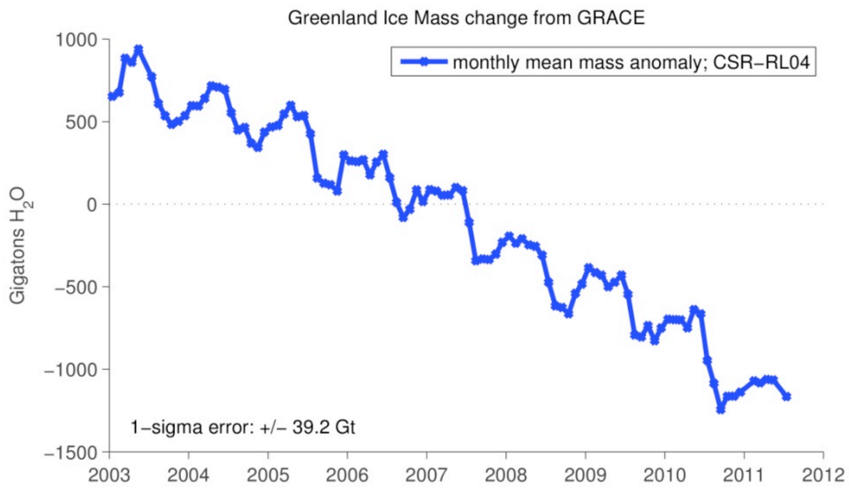
SMB estimate from different calibrated regional models

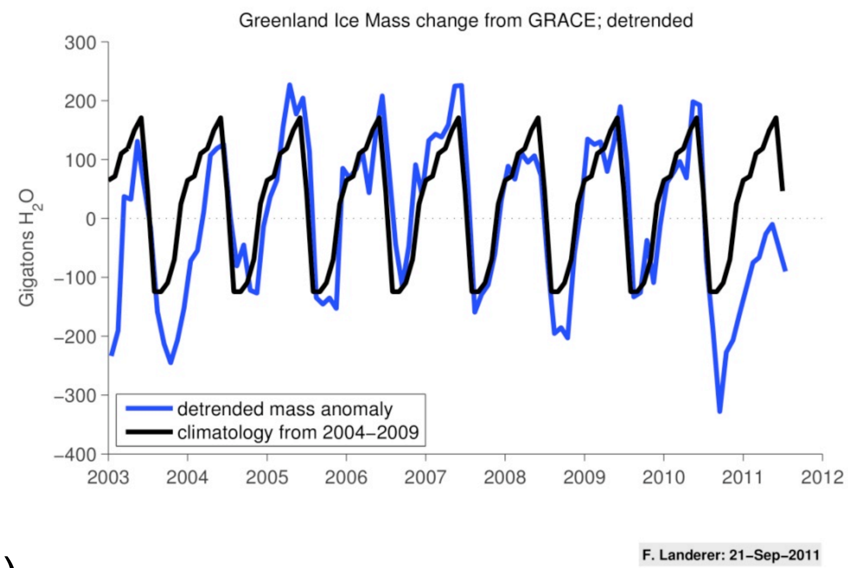


(Hanna et al., 2009)

2010 record melting (Not for presentation)







(from http://www.realclimate.org)