CESM over Greenland: ice sheet versus ice-free regions (the SMB)

Miren Vizcaino
Dep. Geoscience and Remote Sensing,
Delft University of Technology

"Icebergs from Jakobshavn Isbrae", courtesy of Mark Drinkwater, ESA

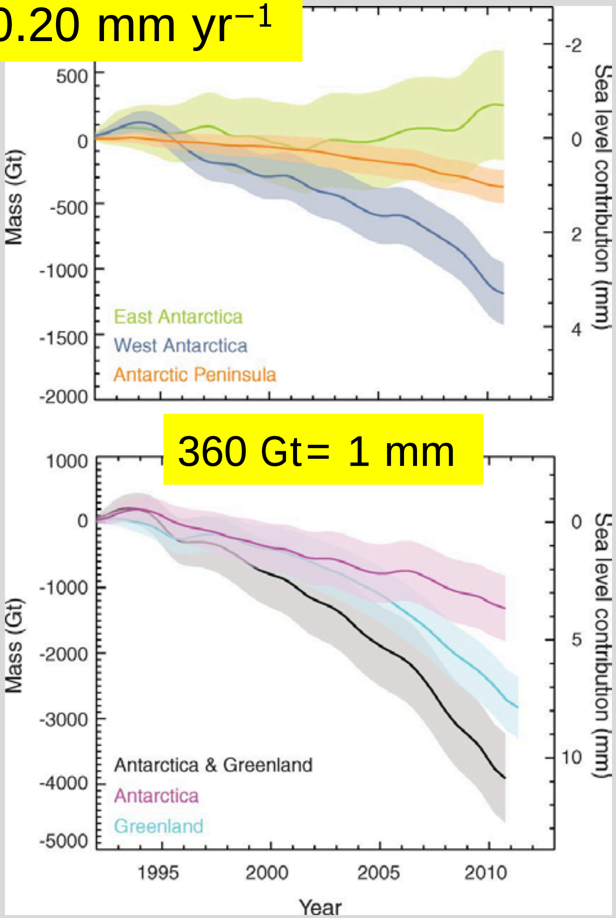
Outline: **uniqueness** of CESM, **challenges ahead** & **new opportunities**

1. SMB over Greenland **ice sheet**
2. **Ice-free** regions
3. **Elevation classes: why?**
   - **The 1.5-way coupling: CESM can account "off-line" for SMB variations due to small ice sheet elevation change**

Motivation: Greenland and Antarctic ice sheets are losing mass

- **In response to** both **atmospheric** and **ocean** forcing
  - Several surface melt extremes over GrIS in the last two decades
  - Ocean melt reduces buttressing of AIS & GIS grounded ice

Mean since 1992
0.59 ± 0.20 mm yr^{-1}



360 Gt= 1 mm

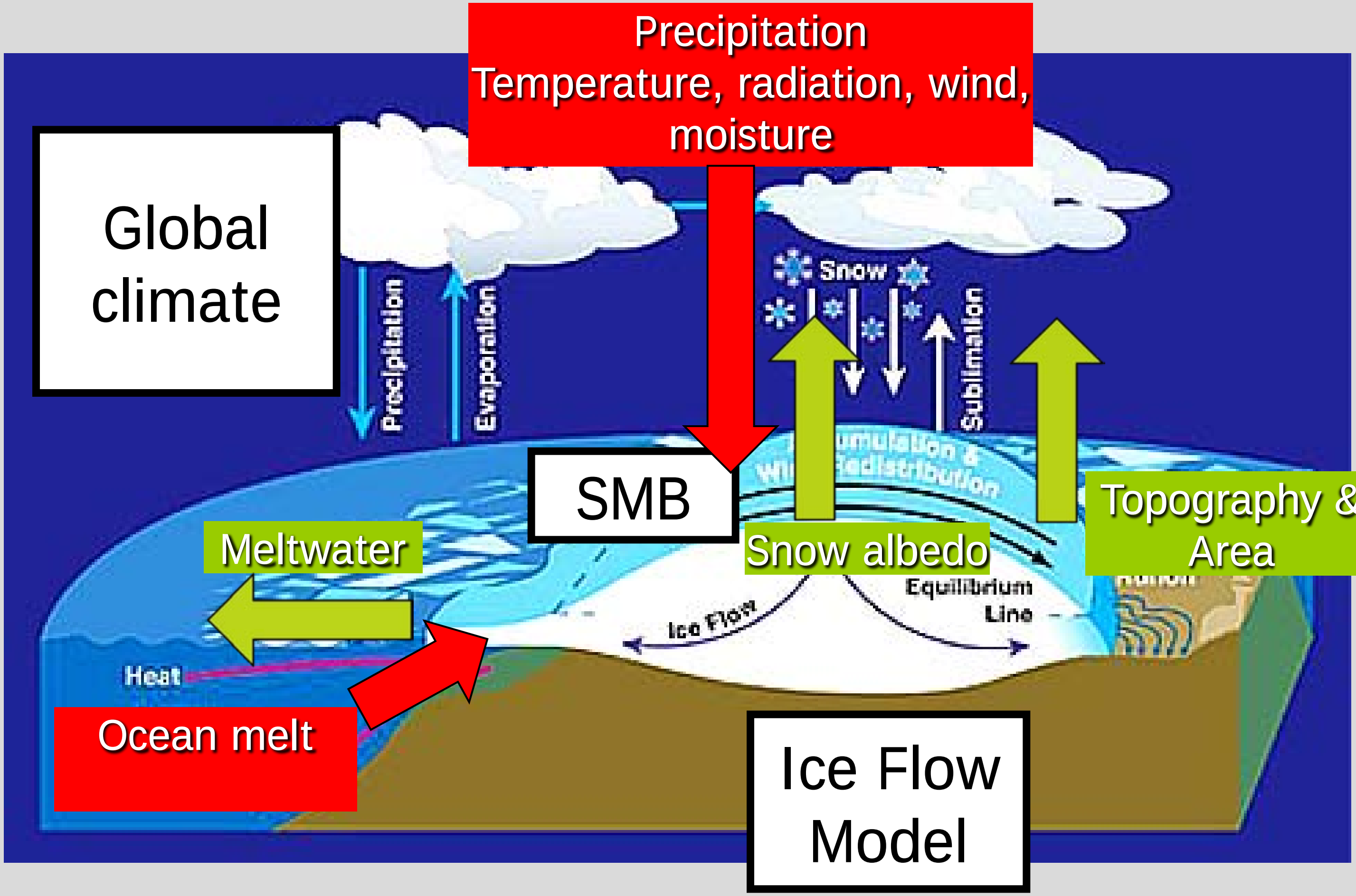
HOW MUCH?

WHY?

A Shepherd et al. Science 2012;338:1183-1189

Modeling climate ⇄ ice interaction

Total mass budget= Surface Mass Balance – ice discharge to ocean



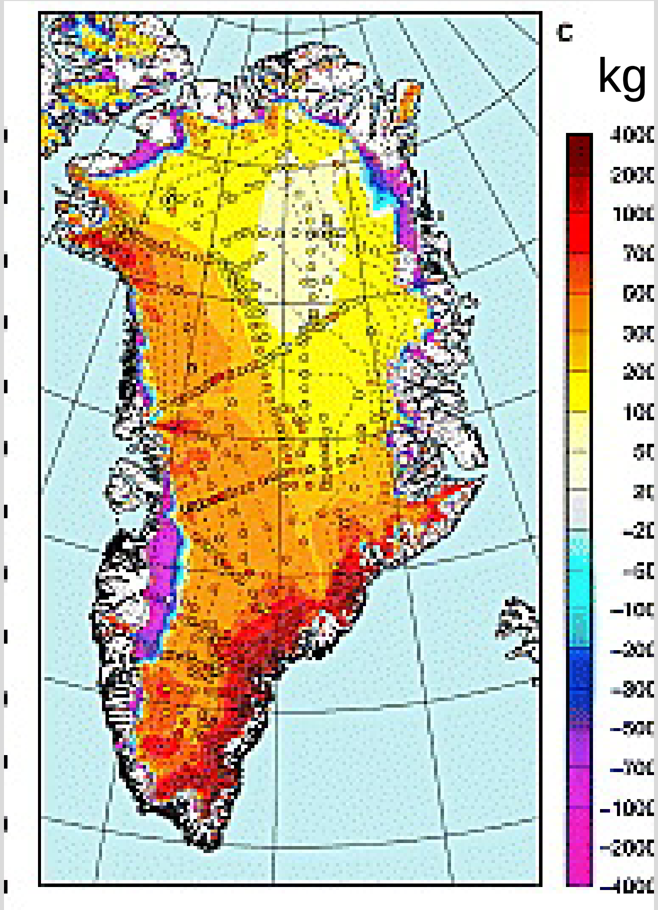
SMB = PREC-RUNOFF-SUBLIMATION
RUNOFF=MELT+RAIN-Refreezing

The challenge of modeling SMB with a global climate model

- High Surface Mass a Balance gradients at ice sheet margins (steep topography)

Until very recently:

- Climate models considered unsuitable: coarse resolution (~tens of km needed), climate biases
- Regional climate models preferred.
  But:
  - Lateral forcing from GCMs needed
  - No direct global climate-ice coupling (e.g. no meltwater-ocean feedbacks)
  - Un-suited for multi-century studies (e.g. no elevation feedback)



Surface mass balance (precip-su-melt) as modeled by RACMO2

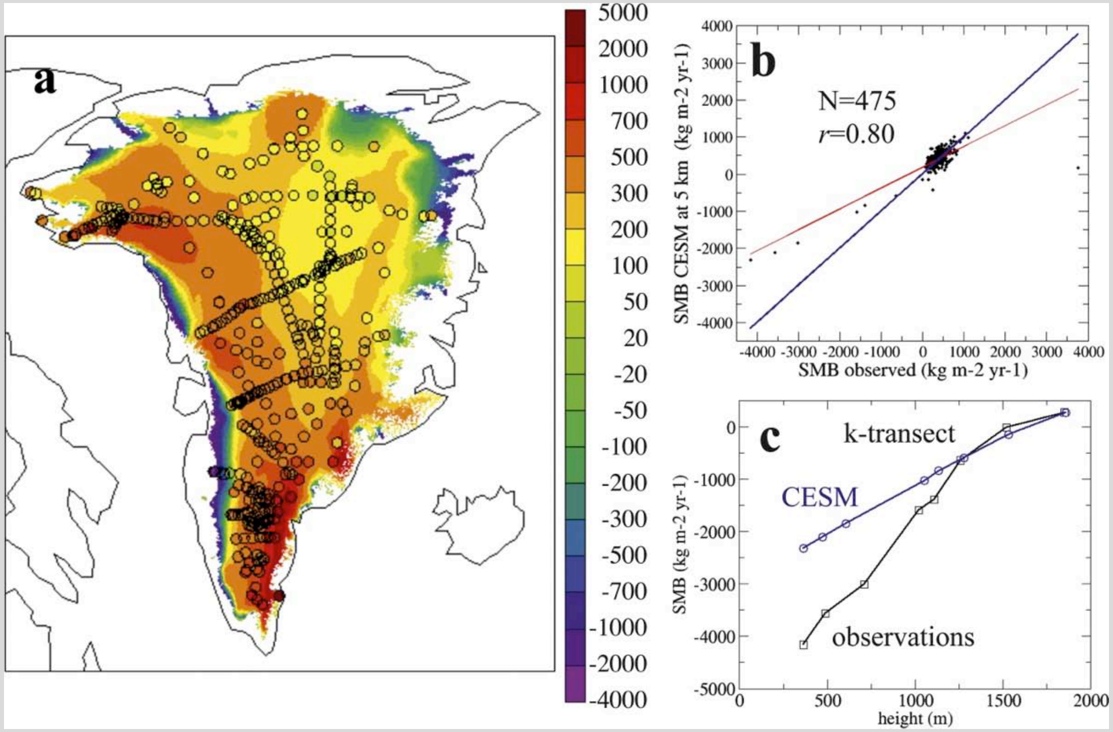
The first realistic simulation of SMB with a global climate model (yes, CESM!)

- Results for 1850-2100 GrIS SMB published in SC J. Climate

CESM compares well (r=0.80) with in-situ observations from N=475 stations

- Accumulation rates overestimated in N interior
- Good match in the southern part, except in the wet SE
- 67 ° N, west margin ("k-transect")
  - Modeled equilibrium line altitude (~1500 m) is close to observations
  - Small differences over 1000 m
  - Gradient is underestimated:
    - Local terrain not resolved (narrow fjord framed by tundra)
    - Local anomaly in bare ice albedo ("dark zone")

1960-2005 SMB from CESM downscaled at 5 km & from N=475 stations (kg m^{-2} yr^{-1})

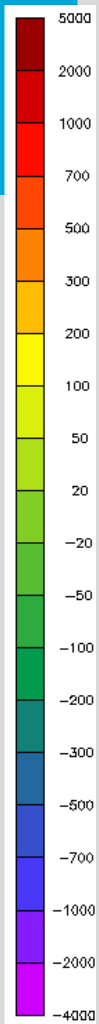


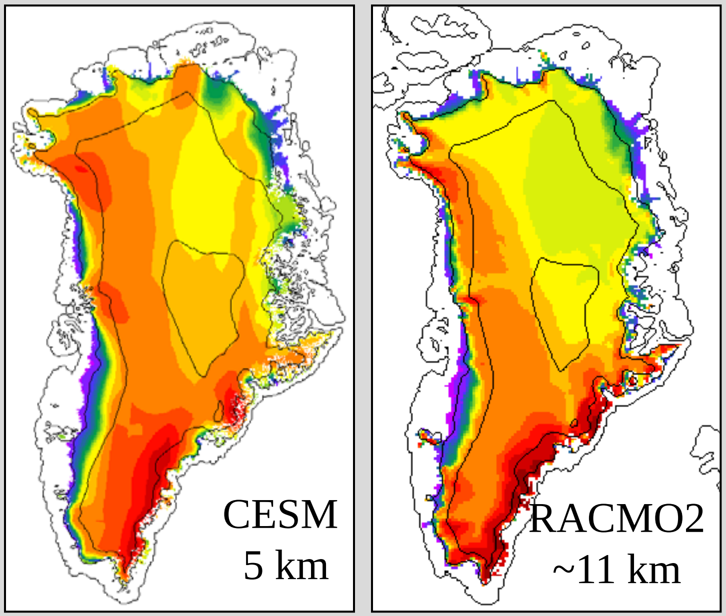
Vizcaino, M., W. Lipscomb, W. Sacks, J. van Angelen, B. Wouters, and M. van den Broeke (2013), **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part I: Model Evaluation and 1850-2005 Results**, Journal of Climate (SC)

CESM compares well with RCMs

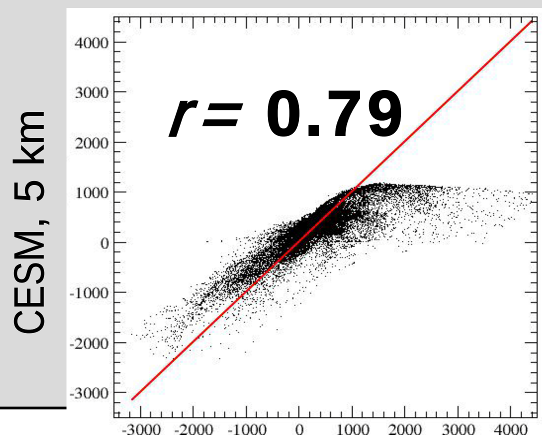
SMB>0

1960-2005 SMB (kg m^{-2} yr^{-1})





SMB<0



SMB = PREC-RU-SU
RU=MELT+RAIN-REF

(standard deviation in parenthesis)

Gt yr^{-1}	CESM	RACMO2	Other RCMs (MAR/PMM5/ERA40-d)
Net SMB	**359 (120)**	**376 (117)**	**288/356/287**
PREC	**866 (88)**	**723 (74)**	600/696/610
MELT	**568 (112)**	**504 (111)**	
Refreezing	242 (25)	245 (38)	
RUN-OFF	**457(95)**	**306 (86)**	
SU	54	40	5/108/38

- Bands of precip. maxima are well reproduced
- Higher precip. in the interior & lower in SE
- Major ablation zones well captured
- Narrow SE ablation areas in both models
- Refreezing: 35% of available liquid water

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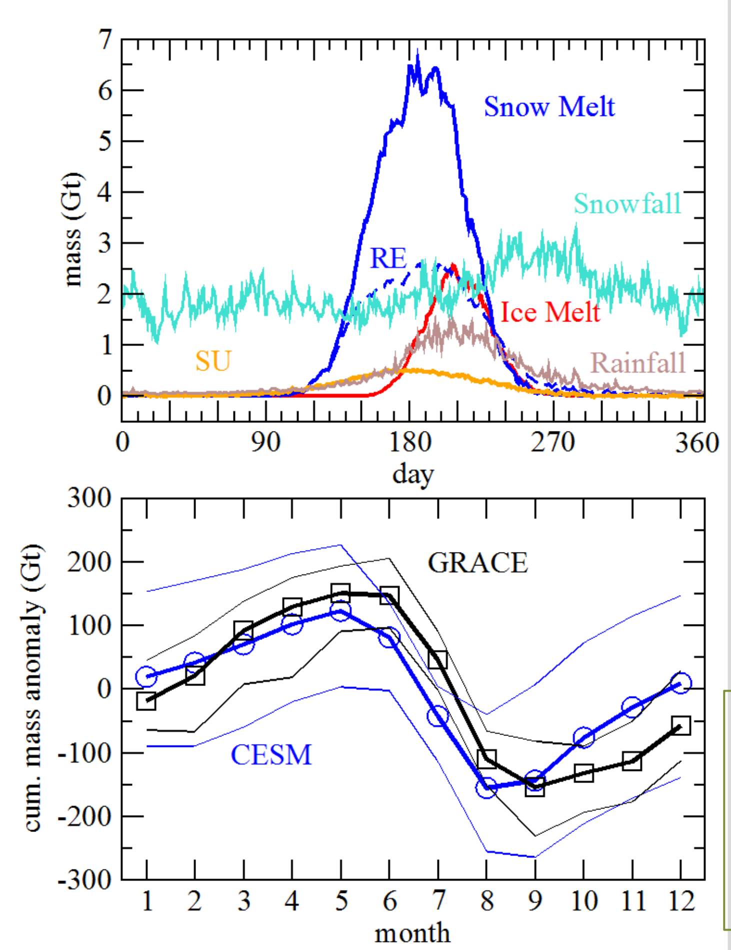
Intra-annual mass evolution compares well with gravimetry data (GRACE)



CESM seasonal cycle of snowmelt, bare ice melt, refreezing, snowfall, rain, and sublimation (Gt).

Mean (thick lines) and range (thin lines) of de-trended monthly cumulative mass anomalies (Gt) for CESM (1996-2004, blue) and GRACE (2003-2011, black).

- **Similar maximum, minimum & amplitude**, regardless of influence of climate variability & "different" periods (GRACE data starts later, in 2003 vs. 1996 of CESM)

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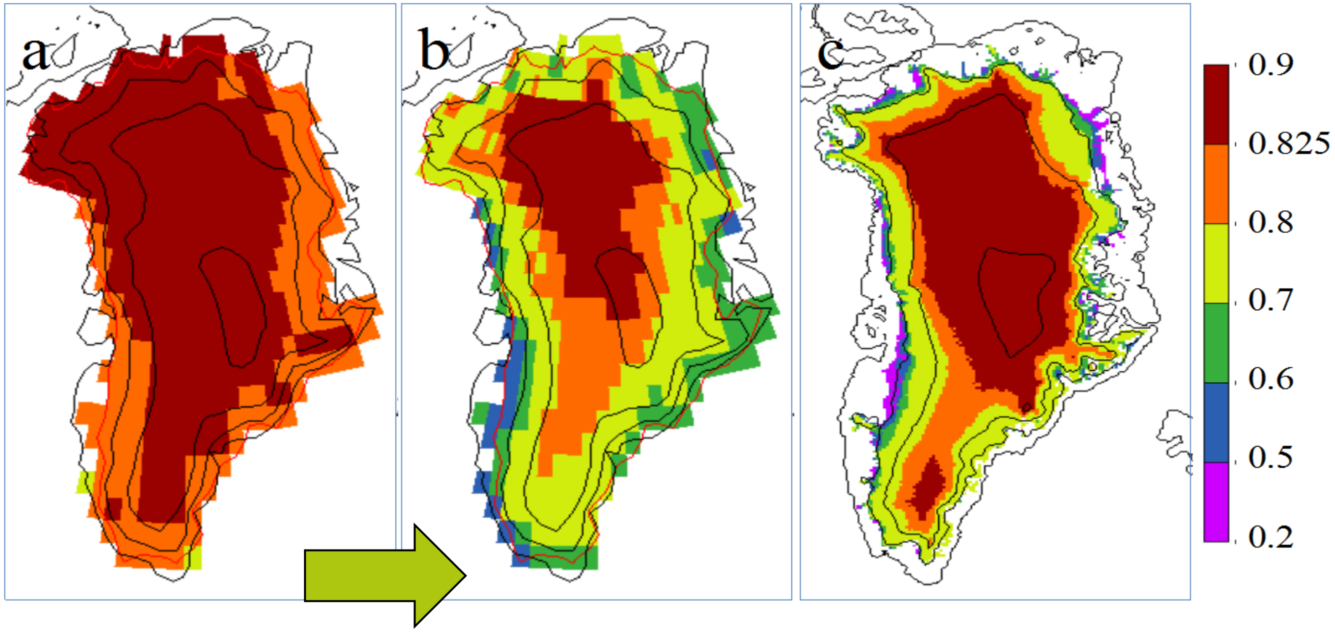
CESM recipe for a good SMB

1. Realistic **atmospheric forcing** (radiation, wind, humidity)
2. Explicit simulation of **snow processes**: albedo, compaction, refreezing.
   - SMB in CESM is calculated in land component (giving “immediate” ice-atmospheric coupling)
   - Albedo depends on snow grain size, solar zenit angle, spectral band, snow impurities (SNICAR model)
3. Sub-grid representation of **elevation dependency of SMB**
   ① Atmospheric forcing (temperature, humidity) is downscaled to ice sheet grid
   ② SMB is re-calculated **at several fixed elevations**
   ③ SMB maps are interpolated to ice sheet grid (horizontally & vertically)

Explicit albedo simulation

Before melt season (April)

At melt season peak (July)



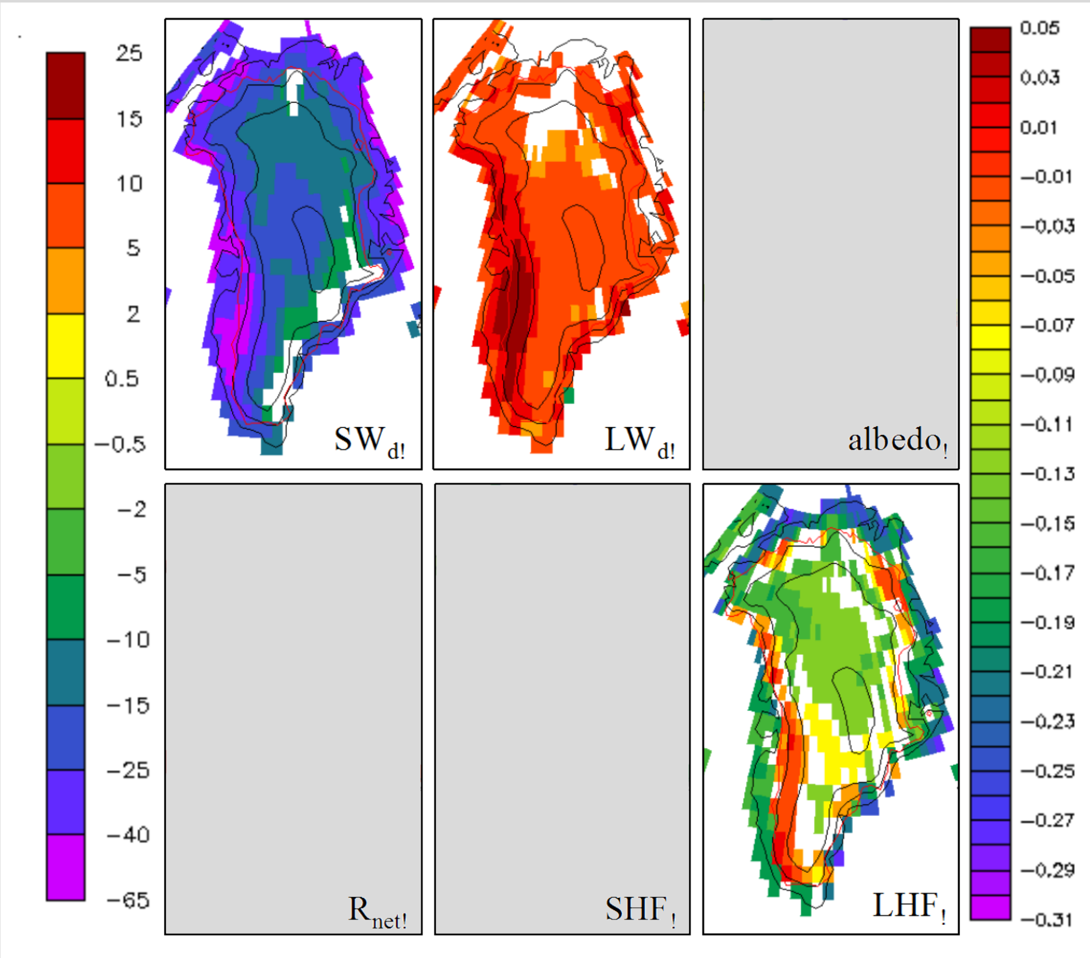
1960-2005 mean albedos

CESM (global model)

RACMO2 (regional model)

Vizcaino, M., W. Lipscomb, W. Sacks, J. van Angelen, B. Wouters, and M. van den Broeke (2013), **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part I: Model Evaluation and 1850-2005 Results**, Journal of Climate (SC)

Change in surface fluxes (RCP8.5)

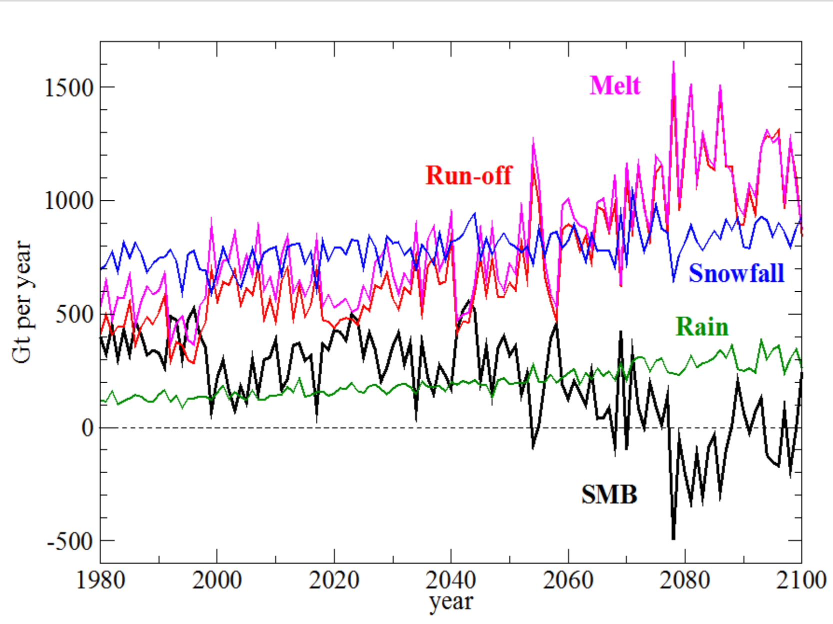


- More incoming LW
- **Less incoming SW** due to increased cloudiness
- Albedo decreases
- **Net radiation increases**
- Turbulent flux increases

Miren Vizcaíno, William H. Lipscomb, William J. Sacks, Michiel van den Broeke. (2014) **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part II: Twenty-First-Century Changes.** *Journal of Climate* (SC)

Projections: SMB components (Gt yr^{-1})

SMB = PREC-RUNOFF-SUBLIMATION
RUNOFF=MELT+RAIN-Refreezing



(standard deviation in parenthesis)
% indicates increase 2080-99 wrt 1980-99

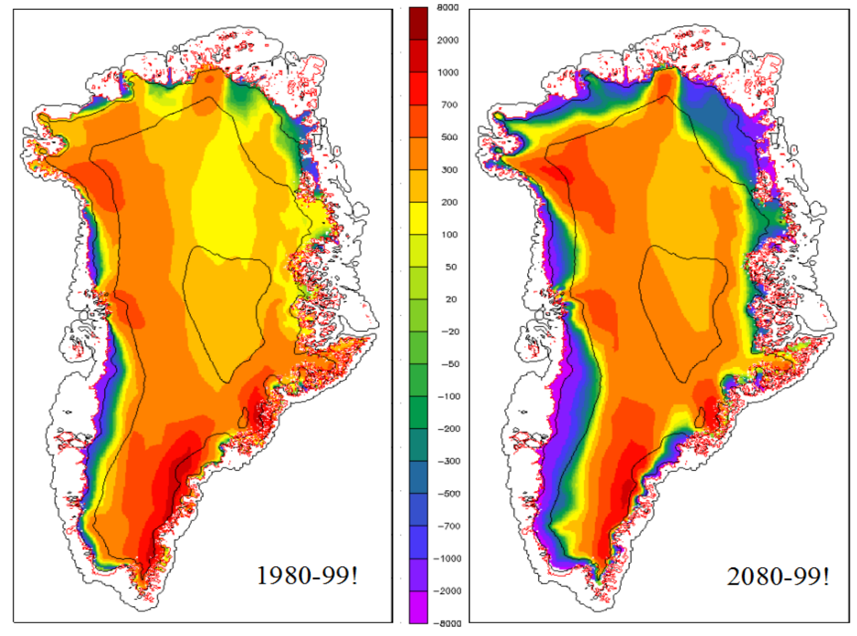
	1980-99	2080-99
SMB	**372 (100)**	**-78 (143)**
PRECIPITATION	**855 (70)**	**1158 (74) +35%**
Snowfall	728 (59)	857 (47) +18%
SURFACE MELT	**552 (119)**	**1186 (155) +215%**
Refreezing	240 (25)	318 (25) +33%
RUN-OFF	438 (98)	1168 (168) +266%
SUBLIMATION	54 (3)	60 (4) +11%

- SMB becomes negative
- Snowfall increases by 18%
- Melt doubles
- **Refreezing capacity decreases**
- **5.5 cm SLE by 2100**

Miren Vizcaíno, William H. Lipscomb, William J. Sacks, Michiel van den Broeke. (2014) **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part II: Twenty-First-Century Changes.** *Journal of Climate* (SC)

New equilibrium line ~500 m higher

SMB>0 *kg m^{-2} yr^{-1}*

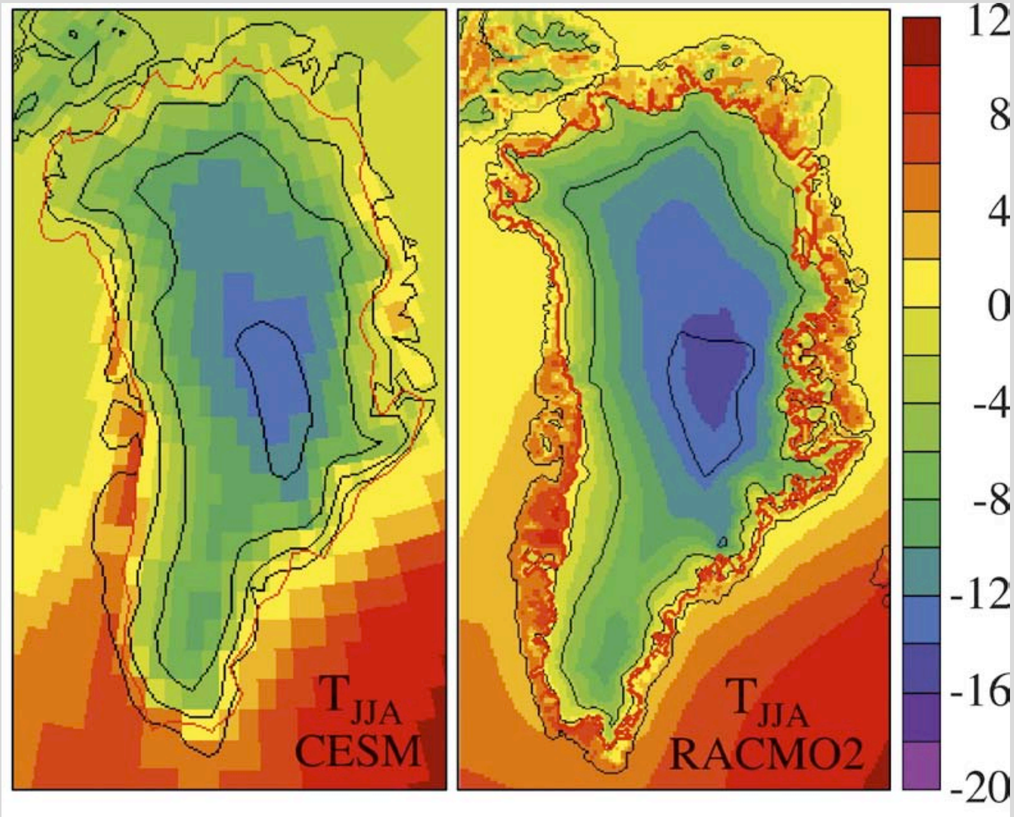


SMB<0

- Ablation area increases from 9% to 28% of ice sheet (SMB variability increases, Fyke et al, GRL, 2014)
- Max. increase of eq. line in NE (~1000 m higher)
- SMB increases over 2000 m
- Map is **similar to projections from regional models (RACMO, MAR)**

Miren Vizcaíno, William H. Lipscomb, William J. Sacks, Michiel van den Broeke. (2014) **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part II: Twenty-First-Century Changes.** *Journal of Climate* (SC)

Cold bias in N-Greenland (CAM4)



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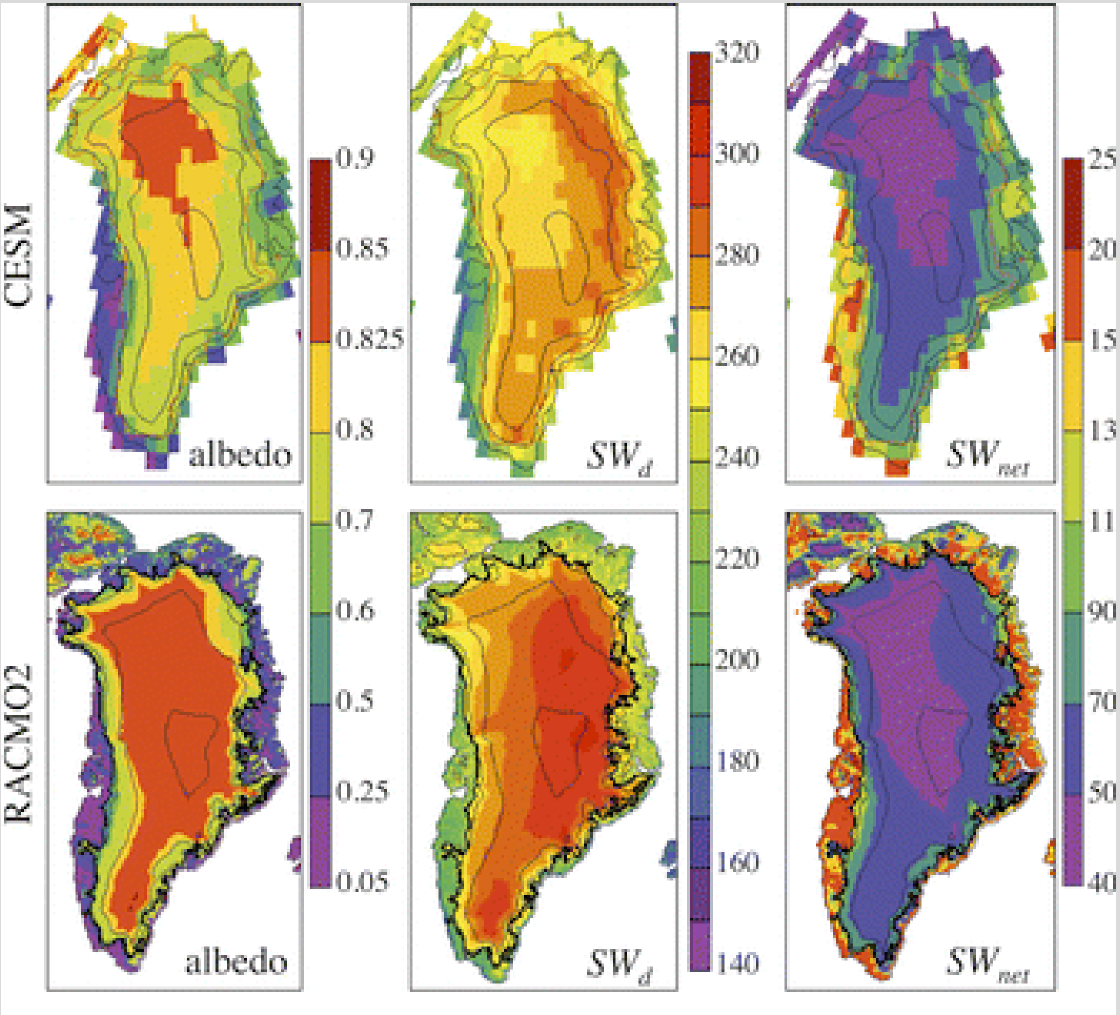
Cold bias: solar radiation (JJA)



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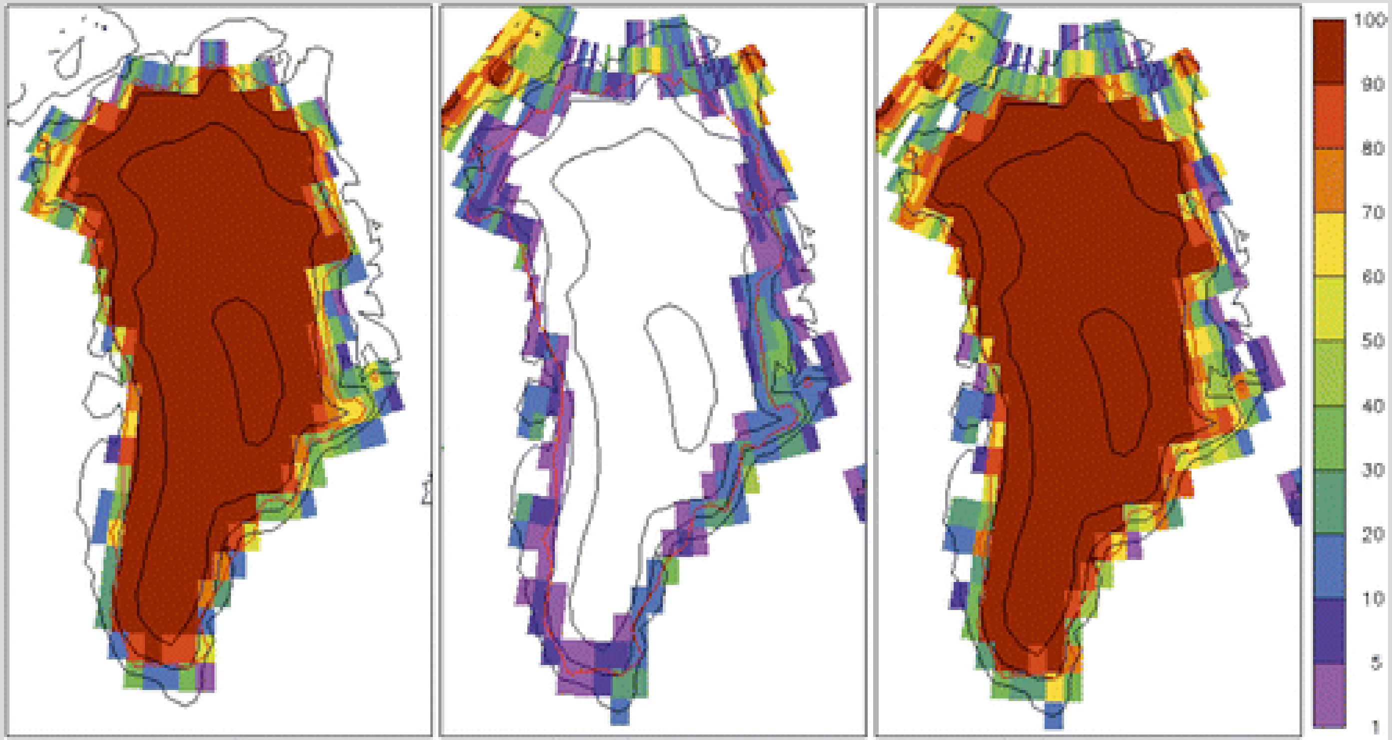
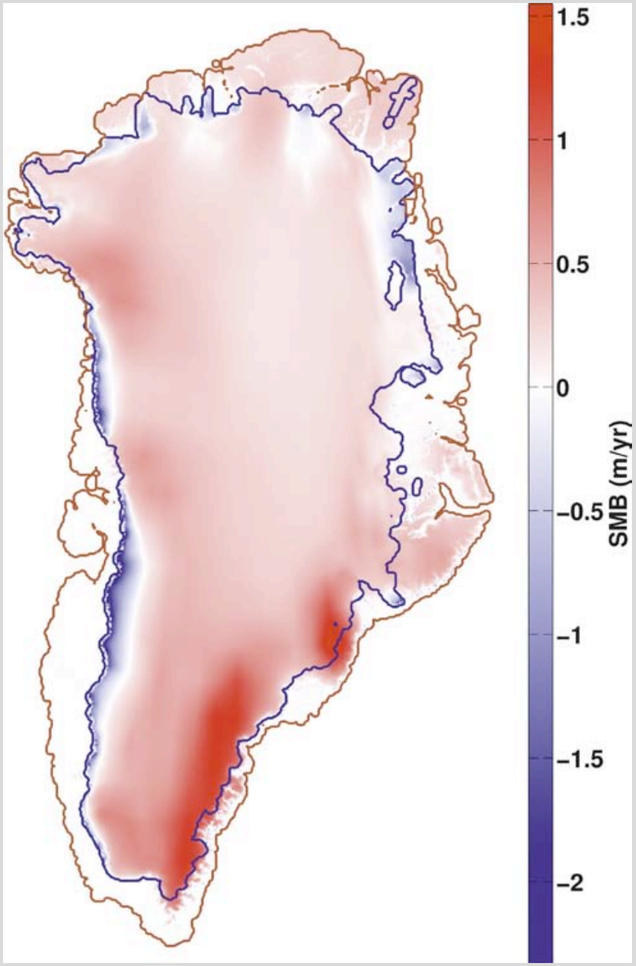
N Greenland is an area with high glacier-coverage



Ice sheet Glacier and ice caps Total

Vizcaino, M., W. Lipscomb, W. Sacks, J. van Angelen, B. Wouters, and M. van den Broeke (2013), **Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part I: Model Evaluation and 1850-2005 Results**, Journal of Climate (SC)

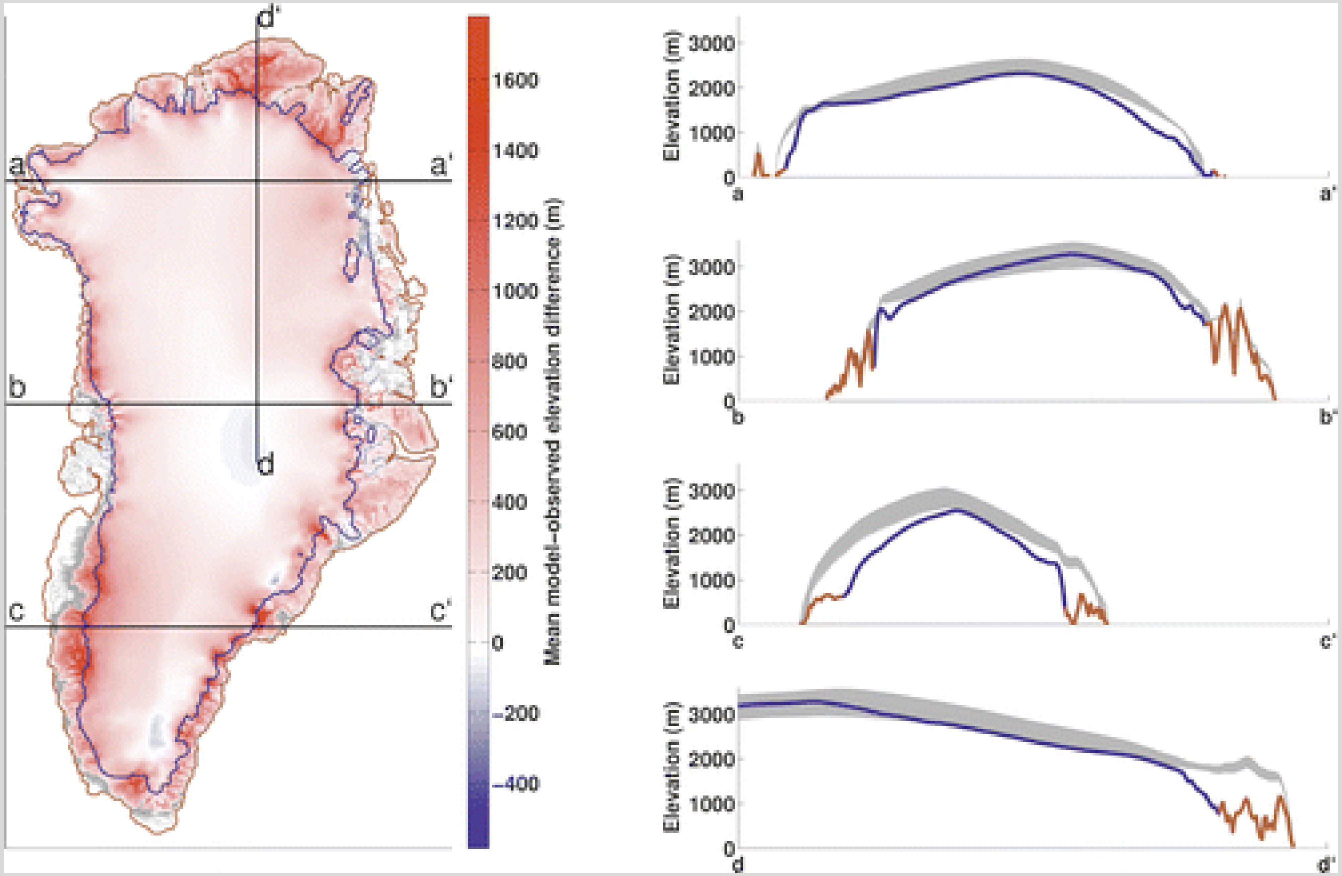
Cold bias: implications



SMB as "seen" by CISM
(figure from Lipscomb et al. 2013)

Lipscomb, W., J. Fyke, M. Vizcaino, W. Sacks, J. Wolfe, M. Vertenstein, A. Craig, E. Kluzek, and D. Lawrence (2013), **Implementation and Initial Evaluation of the Glimmer Community Ice Sheet Model in the Community Earth System Model**, Journal of Climate (SC)

Ice sheet spreads over N Greenland



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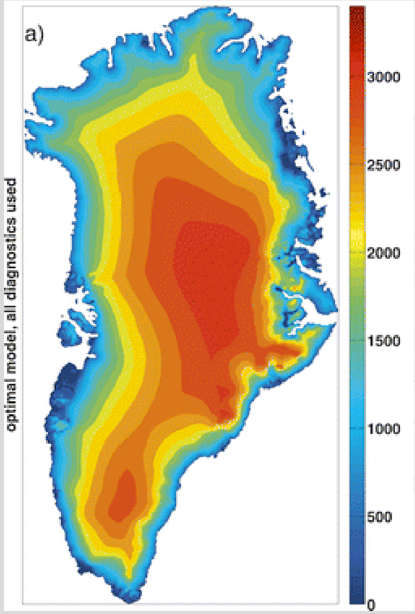
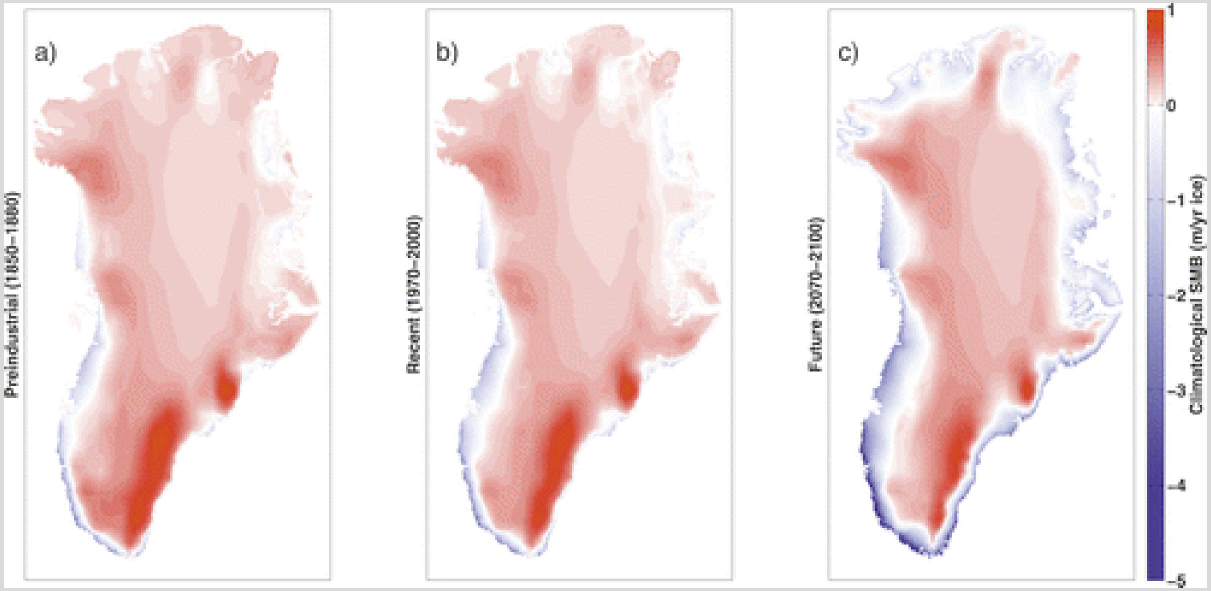
Cold bias: implications

- (a) modeled surface elevation (m)



Climatological SMB of the simulated GIS for the (a) preindustrial (1850–80), (b) modern (1970–2000), and (c) future (2070–2100) periods



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Other challenges and fixes

- **Rainfall** overestimation at low temperatures in CAM4 (fixed in CAM5)
- **Snowpack model**: e.g. refreezing

A fix? Distinguishing between glaciated and vegetated areas

Glacier fraction
• Snow albedo depends on temperature, melt, aerosol deposition, solar angle, spectral band
• If all winter accumulation snow is seasonally melted, bare ice with ~0.5 albedo exposed
"Cold summers over this cell"

Vegetated fraction (usually "tundra")
• Vegetation and snow contribute to albedo (canopy can stick over the snow layer)
• If all winter accumulation snow is seasonally melted, vegetation or bare ground with low albedo (~0.2) exposed
"Warm summers over this cell"

Distinguishing is critical for "cell" glacial **inception** or **deglaciation** (hysteresis)

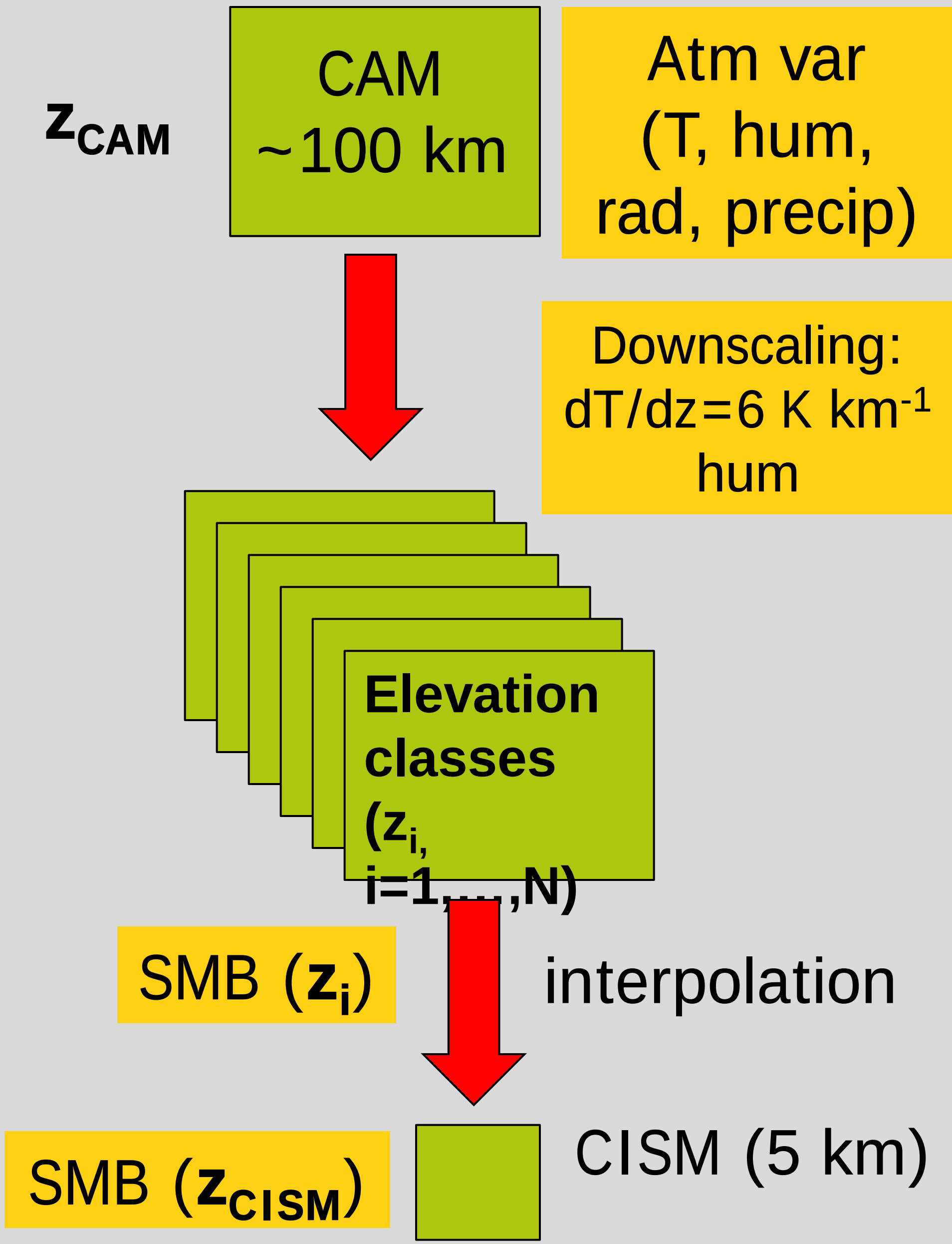
→ Being considered in (ongoing) **2-way CISM-CESM**

Elevation classes

- Only **T** & **humidity** are currently downscaled

(& possibility of sub-grid rain/snow fraction)

- SMB is recalculated at 10 or more fixed elevations
- It works pretty well



State-of-the-art in "off-line" SMB forcing of ice sheet models

- SMB is a boundary condition for ice sheet models
- State of the art in off-line forcing (**1-way** coupling)

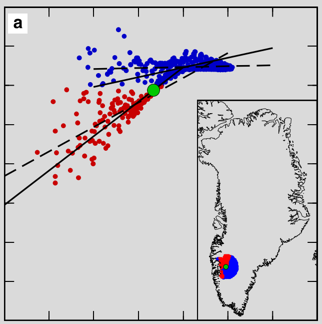
Two **current approaches**:

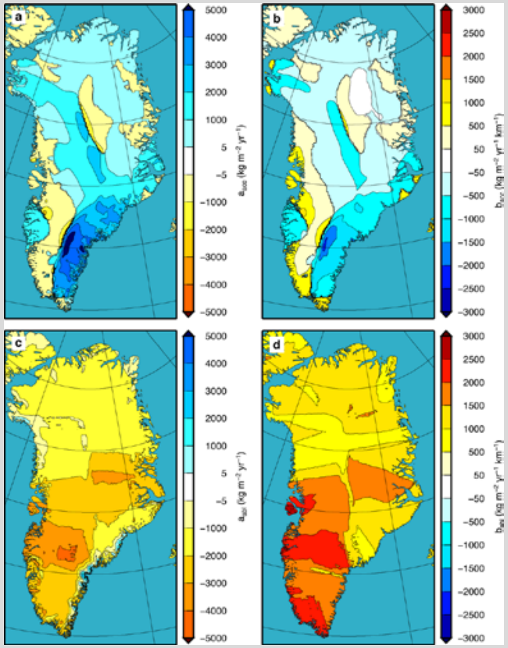
- Highly parameterized SMB(T) calculation (e.g. PDDs): weak coupling between climate & ice sheet, validity in different climate and/or locations?
- SMB from regional climate model calculated at **fixed** $z_{observed}$: (SMB error as z departs from $z_{observed}$; NOT VALID BEYOND 2100)

Most often combined with **ANOMALY COUPLING** (Δatm-forcing or ΔSMB is used)

Some alternatives to force ice sheet models with SMB($z(t)$)?

Helsen, M. M., van de Wal, R. S. W., van den Broeke, M. R., van de Berg, W. J., and Oerlemans, J.: **Coupling of climate models and ice sheet models by surface mass balance gradients: application to the Greenland Ice Sheet**, The Cryosphere, 2012





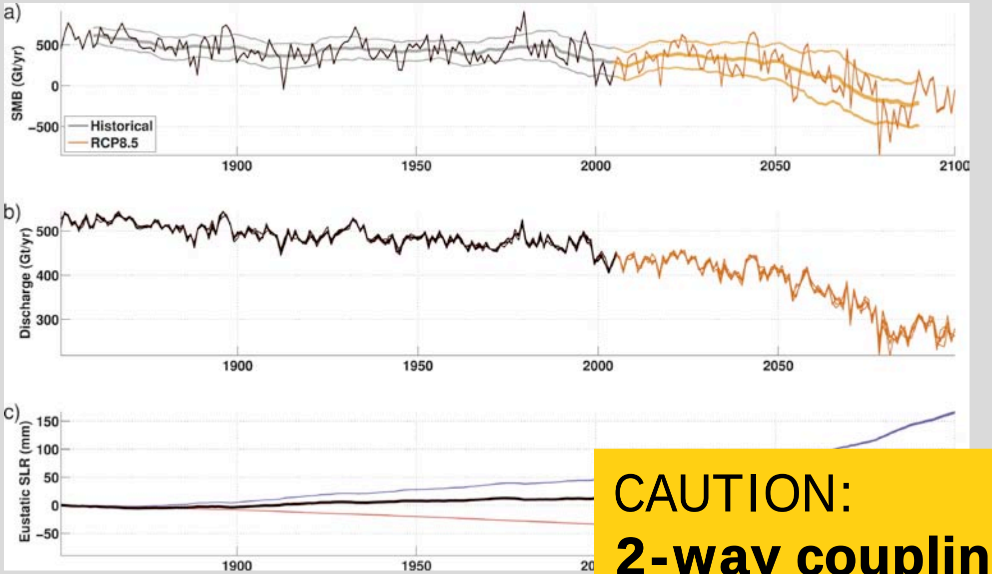
Some alternatives to force ice sheet models with SMB(z(t))?

CESM?

- Realistic simulation of present-day climate & SMB
- Direct connection of SMB-climate: no intermediaries, physics-based SMB processes
- **SMB(z(t))**
- Already applied to
  - New initialization technique (Fyke et al, 2013, GMDD)
  - 1850-2100 (with forcing from Vizcaino et al., 2013,2014)

1.5-coupling CESM-CISM: 1850-2100 results

- CISM is forced with SMB(z_i), accounting for "first-order" effect of z_{CISM} on SMB_{CISM} (valid for **small dz/dt**)



CAUTION:
2-way coupling needed for large dz/dt and/or major area change (changes in atm. circulation and large scale land cover), e.g. beyond 2100

Lipscomb, W., J. Fyke, M. Vizcaino, W. Sacks, J. Wolfe, M. Vertenstein, A. Craig, E. Kluzek, and D. Lawrence (2013), **Implementation and Initial Evaluation of the Glimmer Community Ice Sheet Model in the Community Earth System Model**, Journal of Climate, 2013

Transient spin-up of coupled CISM-CESM

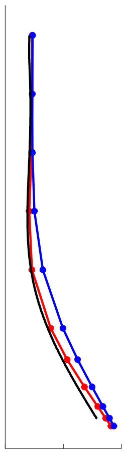
New technique:

- CESM simulates 3 x SMB(x,y,z) for LGM, mid-Holocene & pre-industrial climates
- At other t, composites with weighting from $T_{ice\text{-}core}(t)$

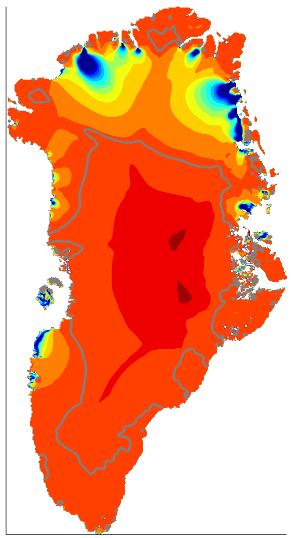
Fyke, J. G., Sacks, W. J., and Lipscomb, W. H.**: A technique for generating consistent ice sheet initial conditions for coupled ice-sheet/climate models**, Geosci. Model Dev. Discuss., 2013

Result:

- Equilibrated pre-industrial ice sheet
- Memory of past climate:
  - Colder ice temperatures
  - Thinner margins due to mid-Holocene thinning and retreat



quilibrium spin-up, black: observations.



een transient and equilibrium spin-up simulations (blue: transient simulation is lower). Dashed line is the zero-contour.

Fyke, J. G., Sacks, W. J., and Lipscomb, W. H.**: A technique for generating consistent ice sheet initial conditions for coupled ice-sheet/climate models**, Geosci. Model Dev. Discuss., 2013