# First realistic simulation of GIS SMB with a global climate model:

## *CESM evaluation, projections & challenges*

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# Introduction: GCMs and GIS SMB

- GIS SMB modeling requires resolution of ~10s km
  - To resolve steep gradients at the margins
- To date, global climate models not suitable due to model biases & insufficient resolution
- Regional Climate Models (RCMs) are state of the art
  - Caveat: depend on GCMs for lateral forcing
- The Community Earth System Model (CESM) includes atm, ocean, land, sea ice and a **new land ice** components (*Lipscomb et al., submitted to J.Clim.)*
- Results are comparable to RCMs!! Success due to
  - **Good climate simulation**
  - **Sophisticated calculation of snow processes (e.g. albedo)**
  - **Adequate downscaling**

# SMB calculation

Done in land module (CLM)

- Resolution: ~1°
- With an Energy Balance Scheme
- At **10** fixed elevations (0, 200,400, 700, 1000, 1300, 1600, 2000, 2500, 3000, 10000 m)
- Then, interpolation to ISM resolution (5 km)

**SMB (ice + snow) = PREC-RUNOFF-SU**
**RUNOFF=MELT+RAIN-REF**

- Two systems: SNOW (5 layers) + ICE
  - Max. SNOW thickness $H_{snow}$ is prescribed (1 m WLE)
  - SNOW if $H_{snow} = H_{max}$: ICE GAIN ($SMB_{ice}>0$)
  - Ablation when $H_{snow}$ =0 m : ICE LOSS ($SMB_{ice}<0$)
  - Rain when $H_{snow}$ =1 m: runs off
- T & humidity change between elevation classes (prec & rad fixed)
- Physical modeling of snow processes (alb & rad from SNICAR)
  - Albedo = f(grain size, aerosols, solar angle, …)
  - Percolation, retention & refreezing of meltwater
- Ice albedo is prescribed

# Simulations

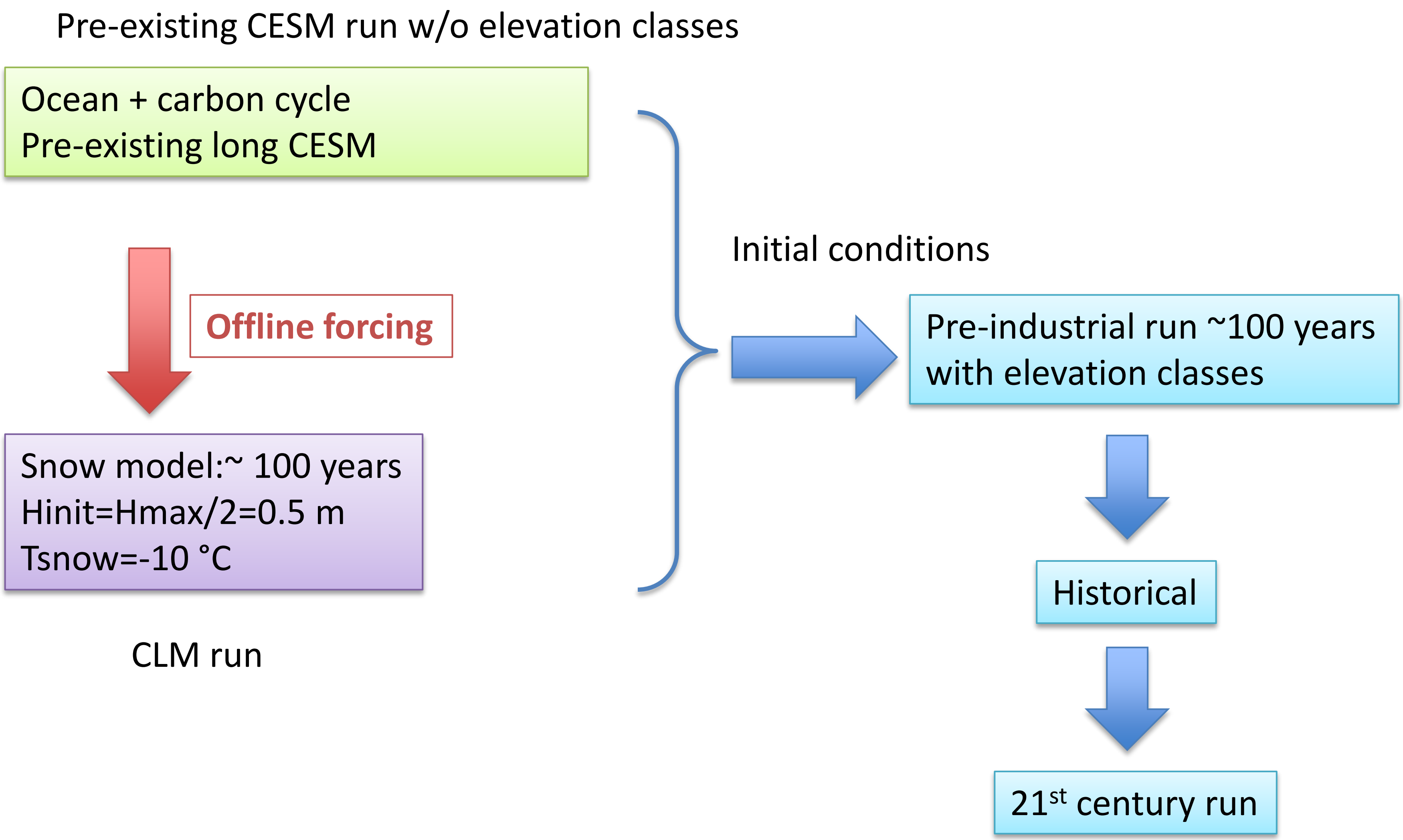
BG_CN configuration: atm, ocean, sea ice, land, CN cycle

| SIMULATION | Length | Forcing |
|---|---|---|
| **Pre-industrial** | Years 0-100 | |
| **Historical** | 1850-2005 | Insolation, Aerosols, volcanoes |
| **21$^{st}$-century** | 2005-2100 | RCP8.5 |

Results submitted to special issue of J. Clim on CESM

- Model description: Lipscomb et al.
- Model evaluation: Vizcaino et al.
- Projections 21$^{st}$ century: Vizcaino et al.

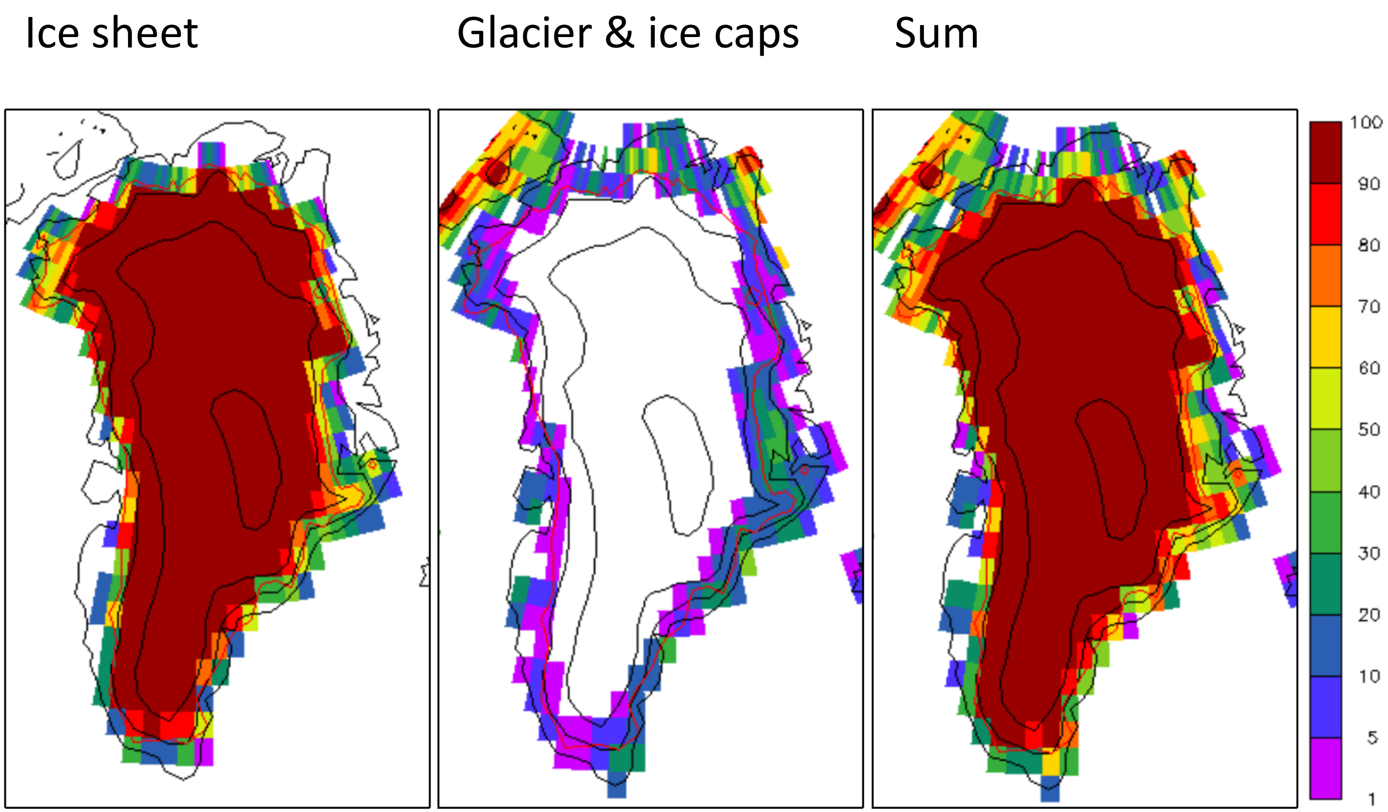
# Spin-up


Pre-existing CESM run w/o elevation classes
Ocean + carbon cycle
Pre-existing long CESM
Offline forcing
Snow model:~ 100 years
Hinit=Hmax/2=0.5 m
Tsnow=-10 °C
CLM run
Initial conditions
Pre-industrial run ~100 years
with elevation classes
Historical
21st century run

# Outline

- Evaluation: 1860-2005 compared with RACMO2
  - Near-surface temperature
  - Energy fluxes
  - SMB terms
- 21st century projections

# Ice sheet and glacier masks (%)




Built from *Bamber et al. 2001*

# 1960-2005 Greenland climate

Surface fluxes

M= $SW_d$ –$SW_u$ +$LW_d$-$LW_u$+SHF+LHF+G

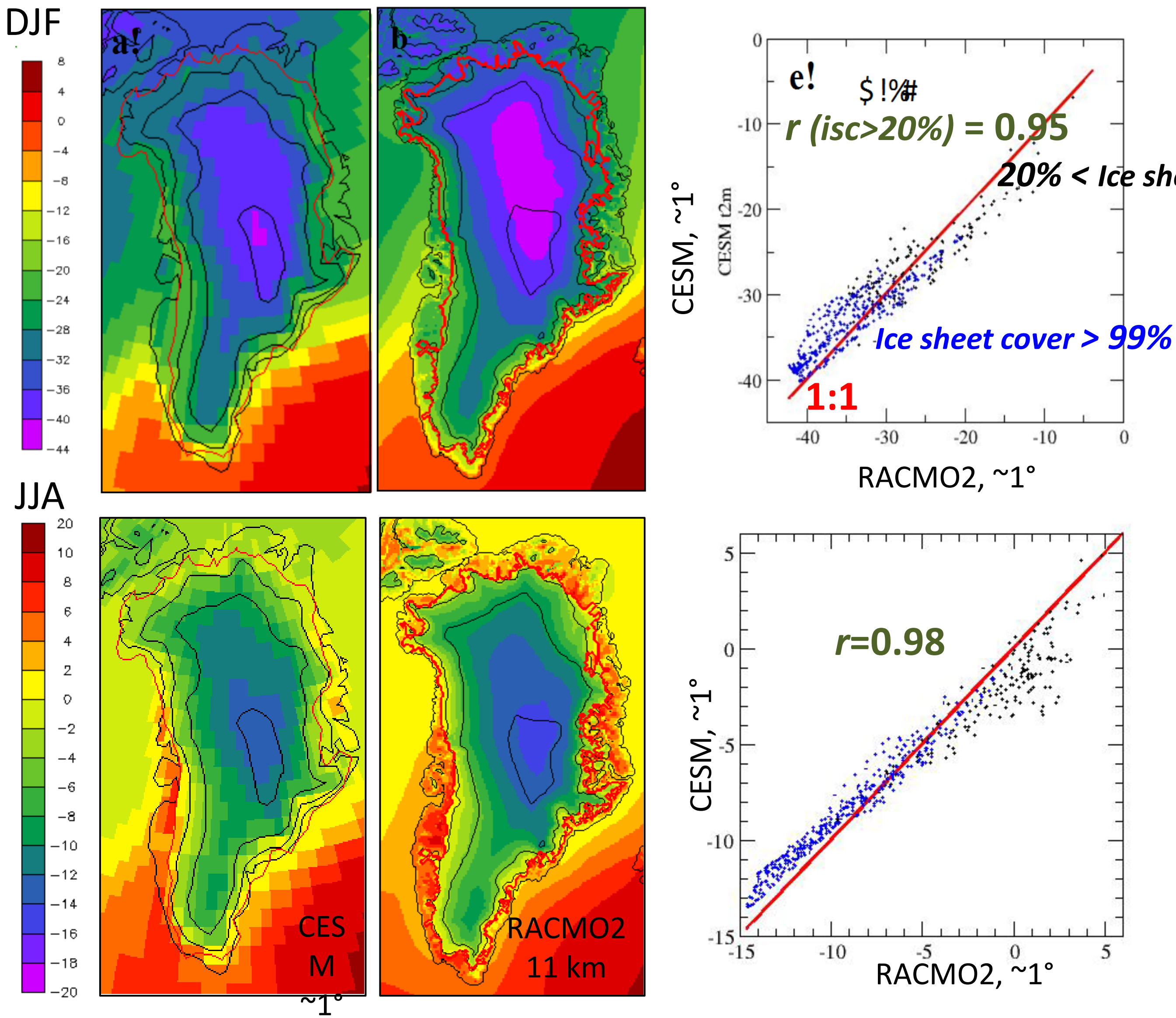
$$SW_u = \alpha SW_d$$

$$LW_u = \varepsilon \sigma T_s^4$$

CAM input, constant with z

Ts (z), T2m (z) follow fixed lapse rate

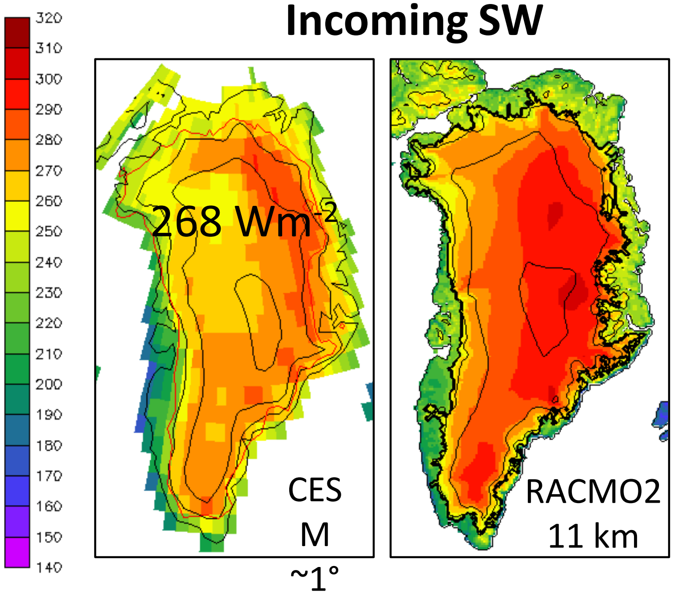
# 1960-2005 Near-surface temperature (°C)

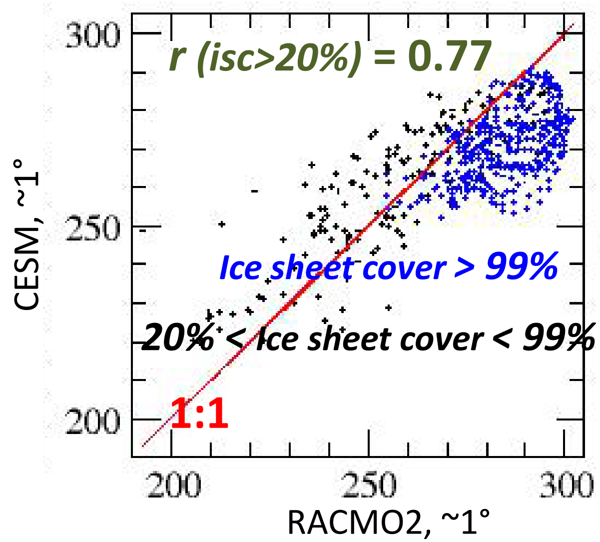



| | Bias (CESM-RACMO2 means) |
|---|---|
| DJF | +0.4 |
| JJA | +0.2 |

# 1960-2005 JJA Surface climate: Incoming Radiation ($Wm^{-2}$)

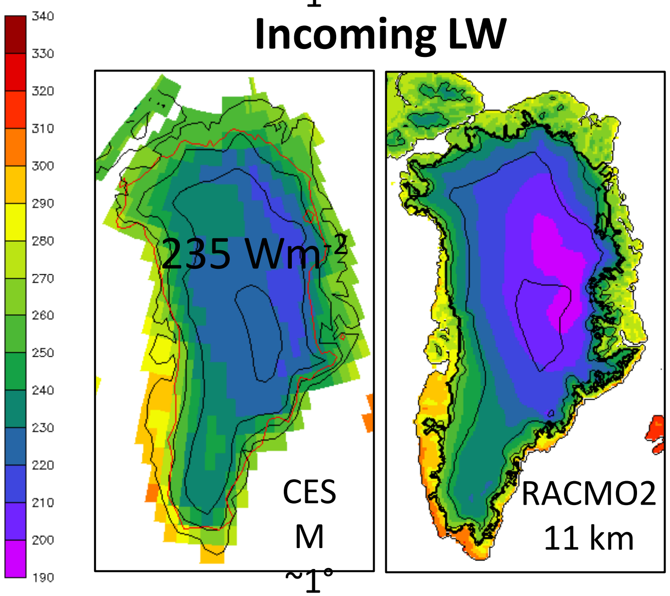
## Incoming SW

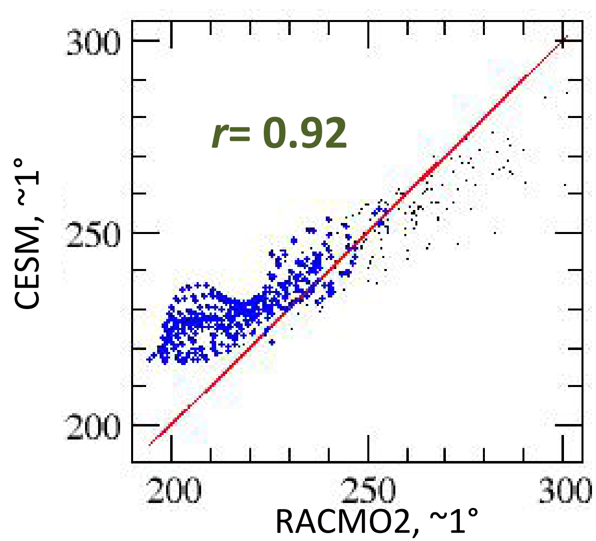



| Flux term | Bias |
|---|---|
| Incoming SW | -11 |
| Incoming LW | +7 |

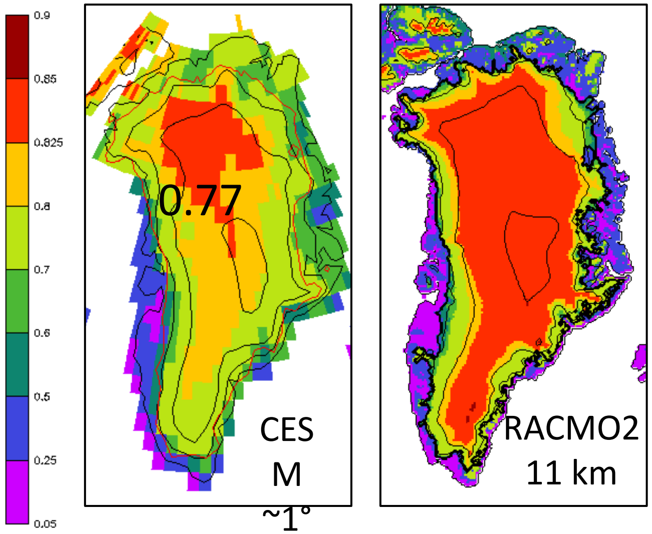
## Incoming LW

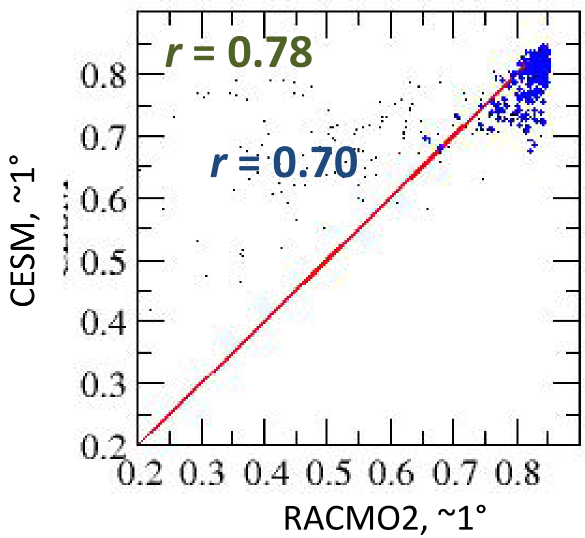


# 1960-2005 JJA Surface climate: SW ($Wm^{-2}$)

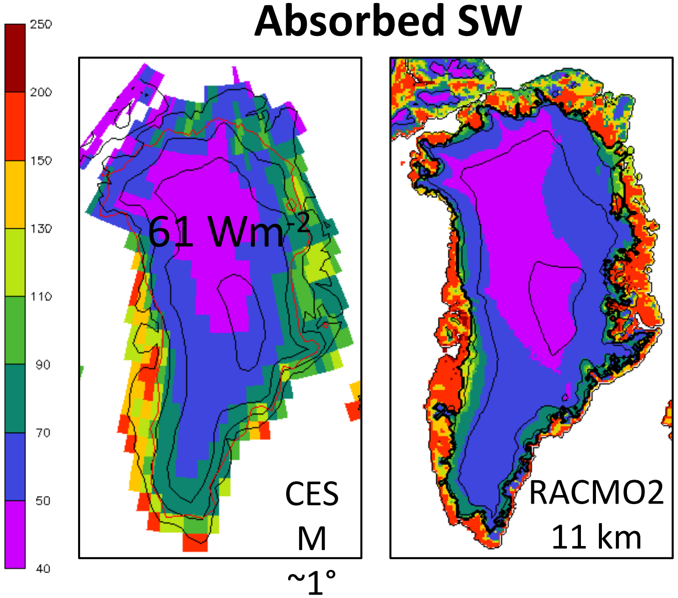
**Albedo**




| Flux term | Bias |
|---|---|
| Incoming SW | -11 |
| Net SW | -3 |

**Absorbed SW**




i!

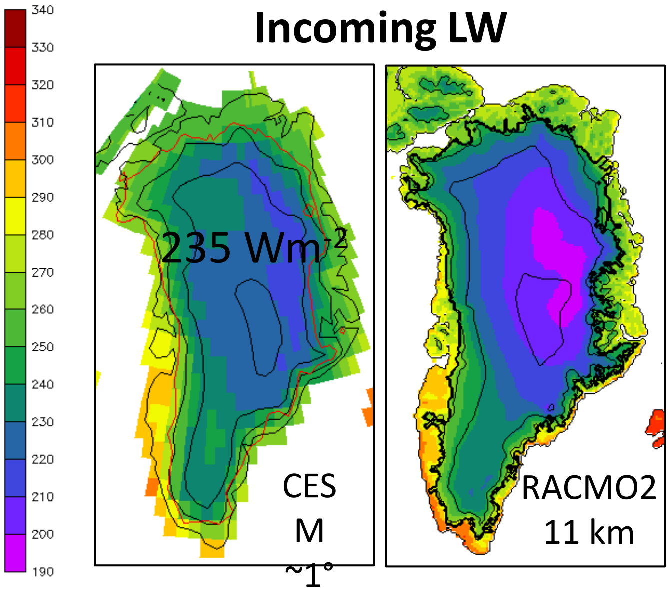
*r* = 0.76

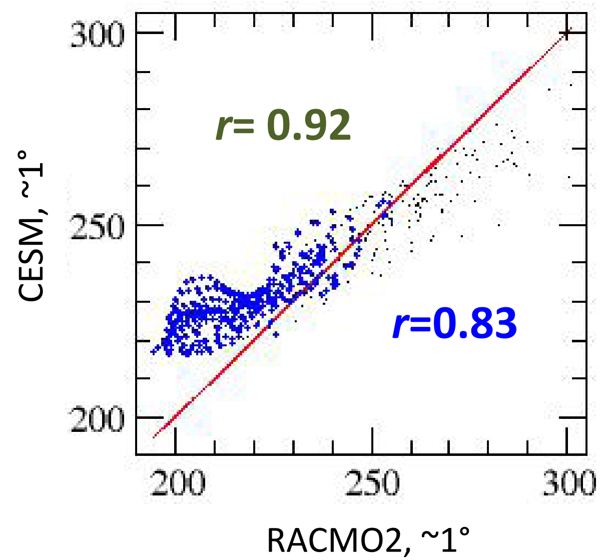
CESM, ~1°

**1:1**

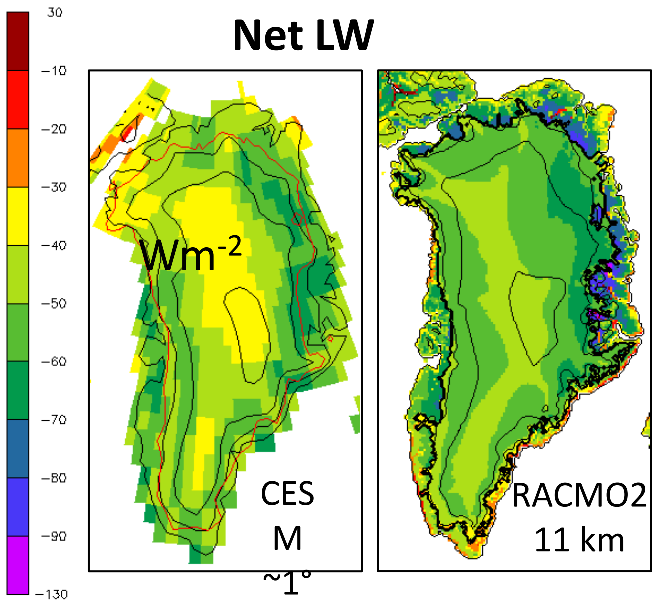
RACMO2, ~1°

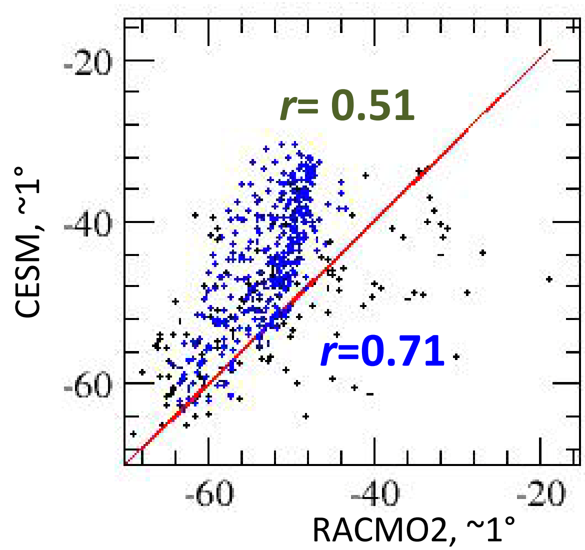
# 1960-2005 JJA Surface climate: LW ($Wm^{-2}$)



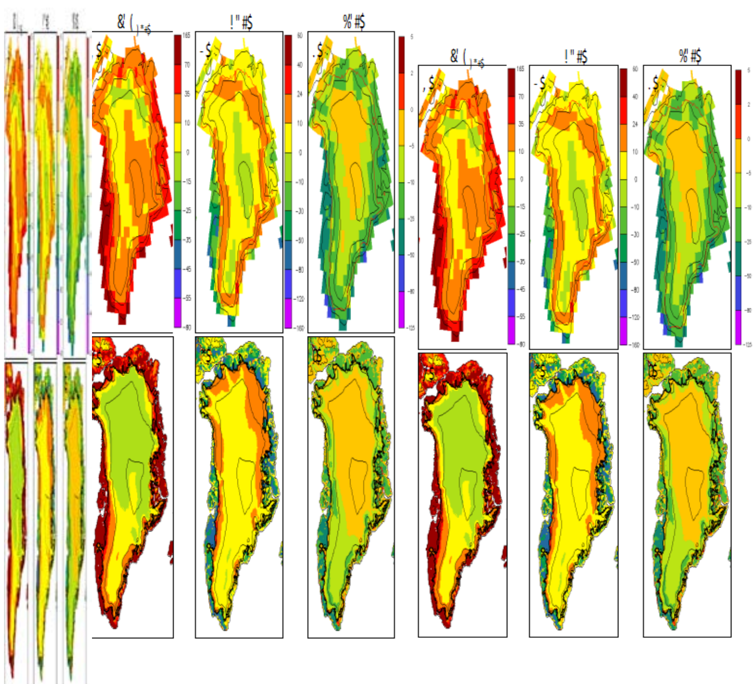



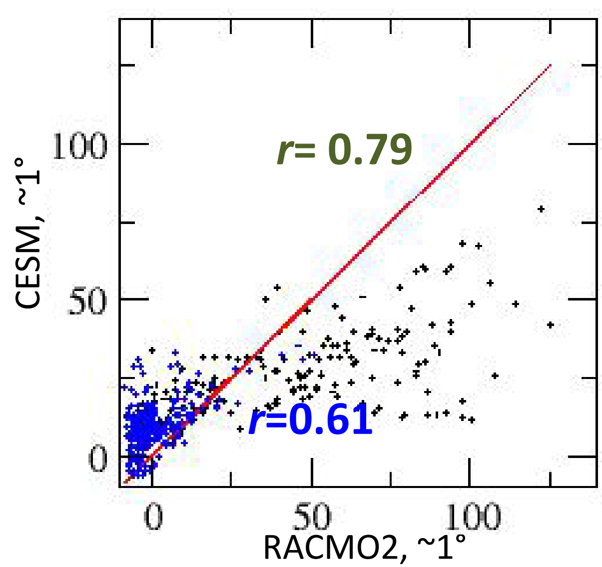

| Flux term | Bias |
|---|---|
| Incoming LW | +7 |
| Net LW | +6 |



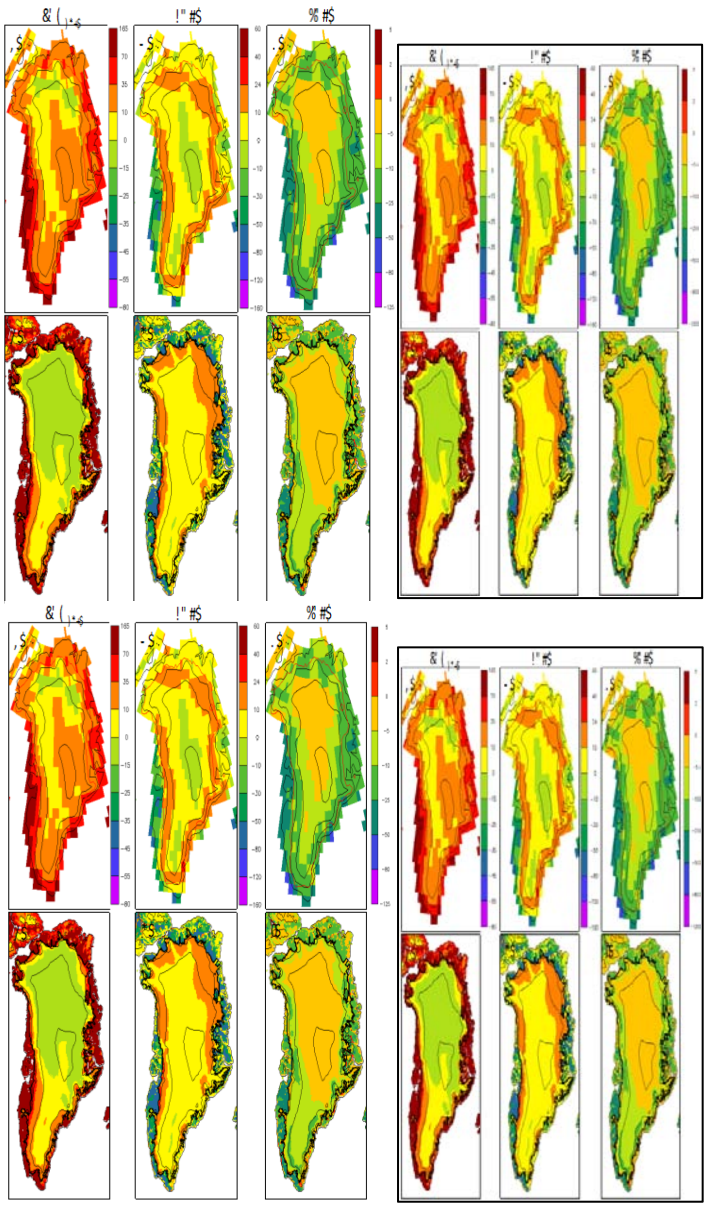
# 1960-2005 JJA Surface climate: Total radiation ($Wm^{-2}$)

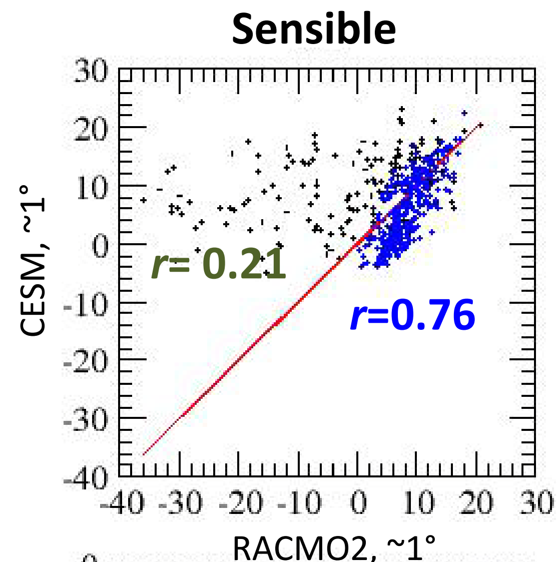


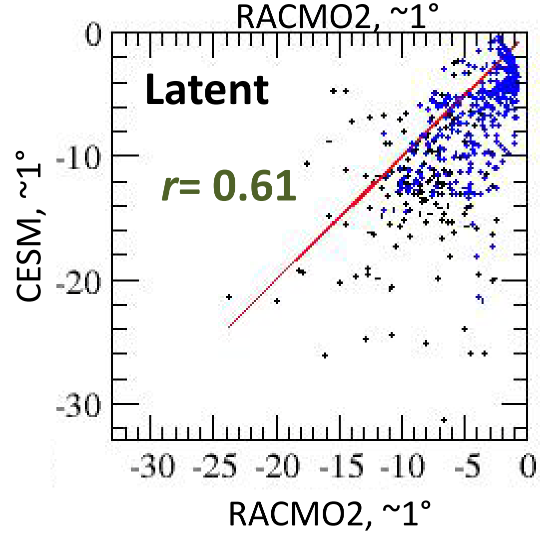



| Flux term | Bias |
|---|---|
| Incoming SW | -11 |
| Net SW | -3 |
| Incoming LW | +7 |
| Net LW | +6 |
| **Net radiation** | **+4** |

# 1960-2005 JJA Surface climate: Turbulent fluxes ($Wm^{-2}$)

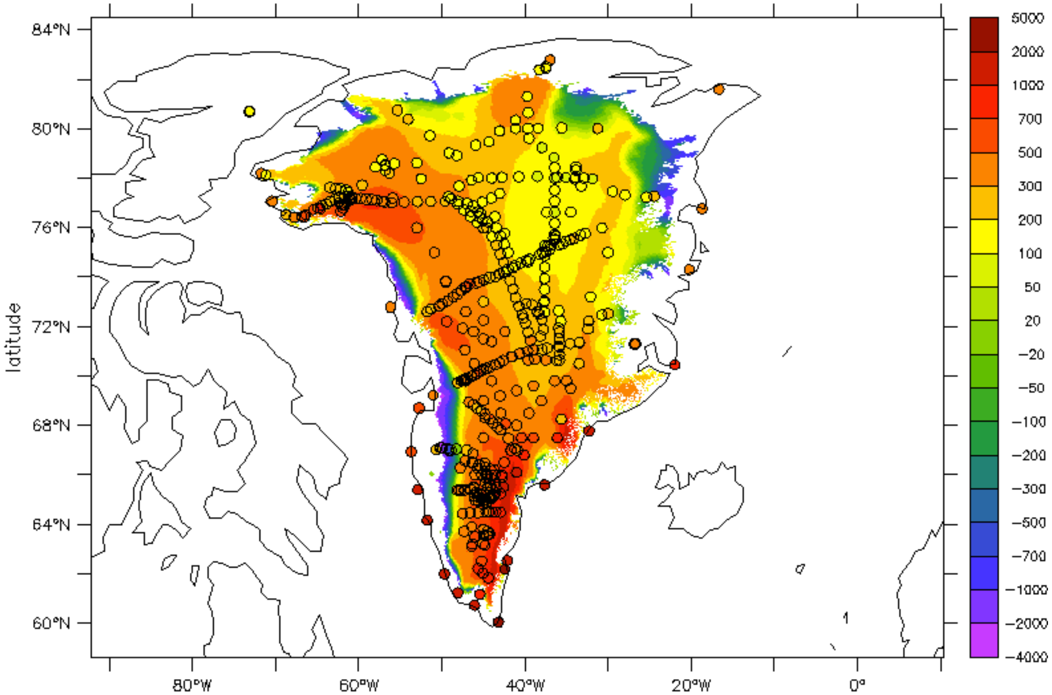


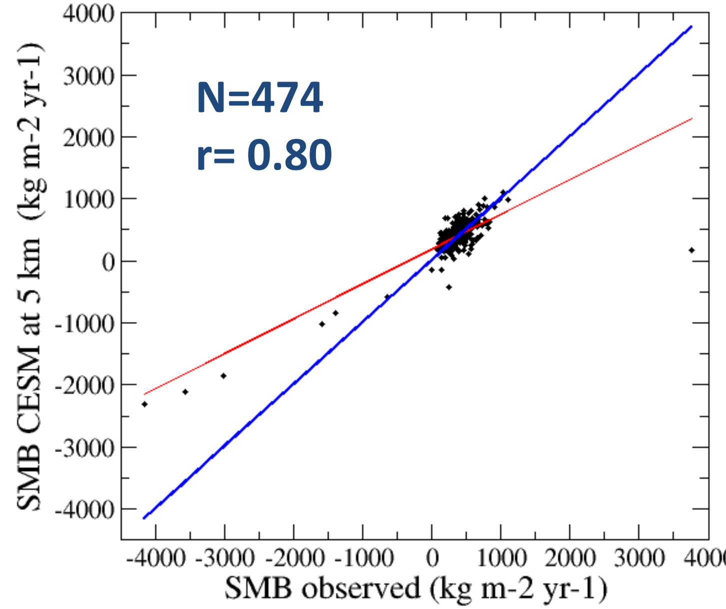



| | Bias |
|---|---|
| Net radiation | +4 |
| **Sensible** | **+0.2** |
| **Latent** | **-3** |
| **Temperature** | **+0.2** |

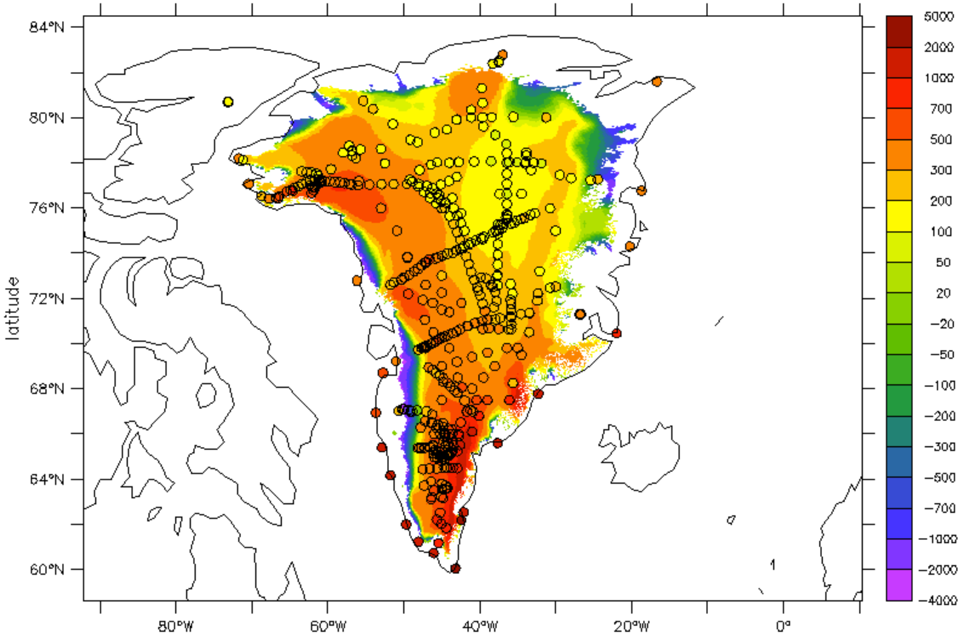
# 1960-2005 SMB: comparison with in-situ data



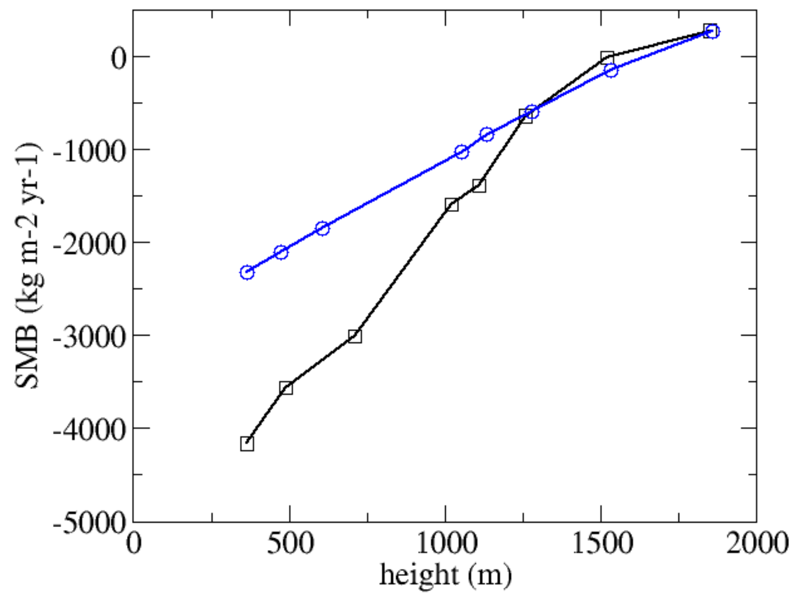




Cogley et al. 2004
Van de Wal et al. 2005
Jason Box, 2005 at 62.2◦N & 42.4◦W, 714 m asl

# 1960-2005 SMB: comparison with in-situ data



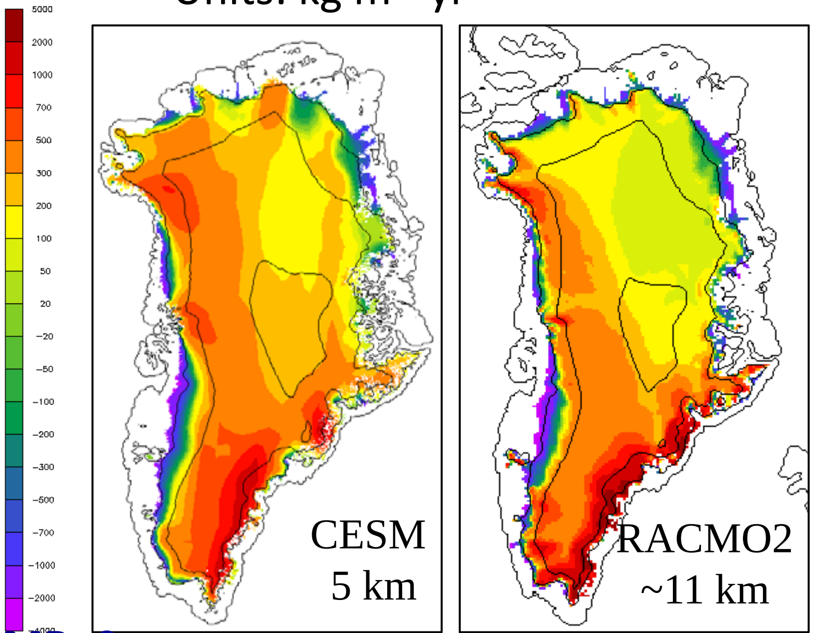

## K-transect (W margin, 67 N)



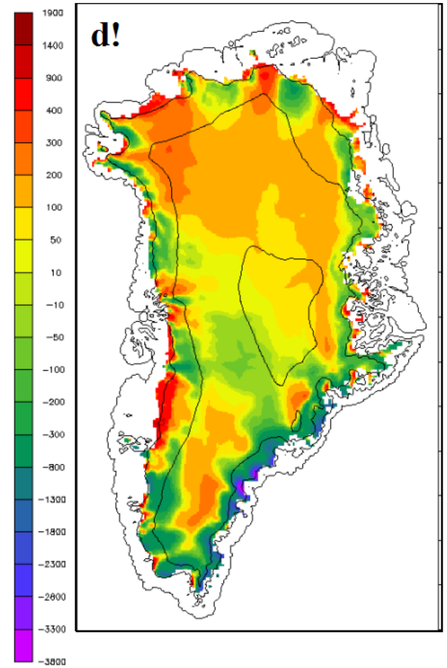
# 1960-2005 SMB: comparison with RCMs

SMB>0

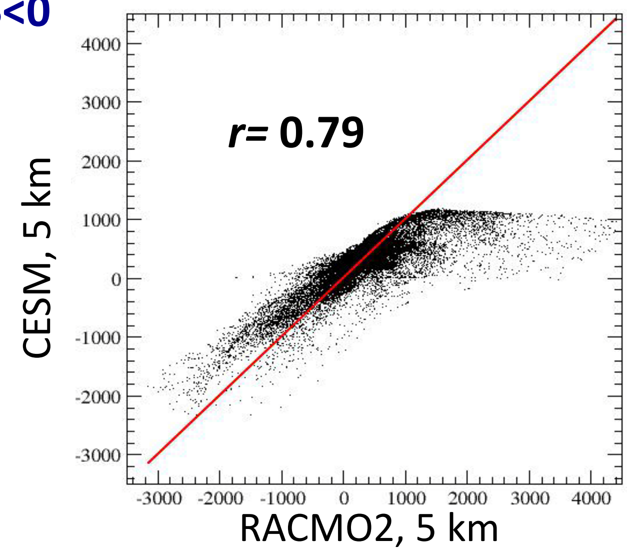
Units: kg m$^{-2}$ yr$^{-1}$




SMB<0




CESM minus RACMO2 5 km




- Bands of precip. maxima are well reproduced
- Higher precip. in the interior & lower in SE
- Major ablation areas well captured
  - 10% total ablation area (12% in RACMO)
- No ablation zone in SE in both models

# 1960-2005 SMB: comparison with RCMs

SMB (ice + snow) = PREC-RU-SU
RU=MELT+RAIN-REF=ALW-REF

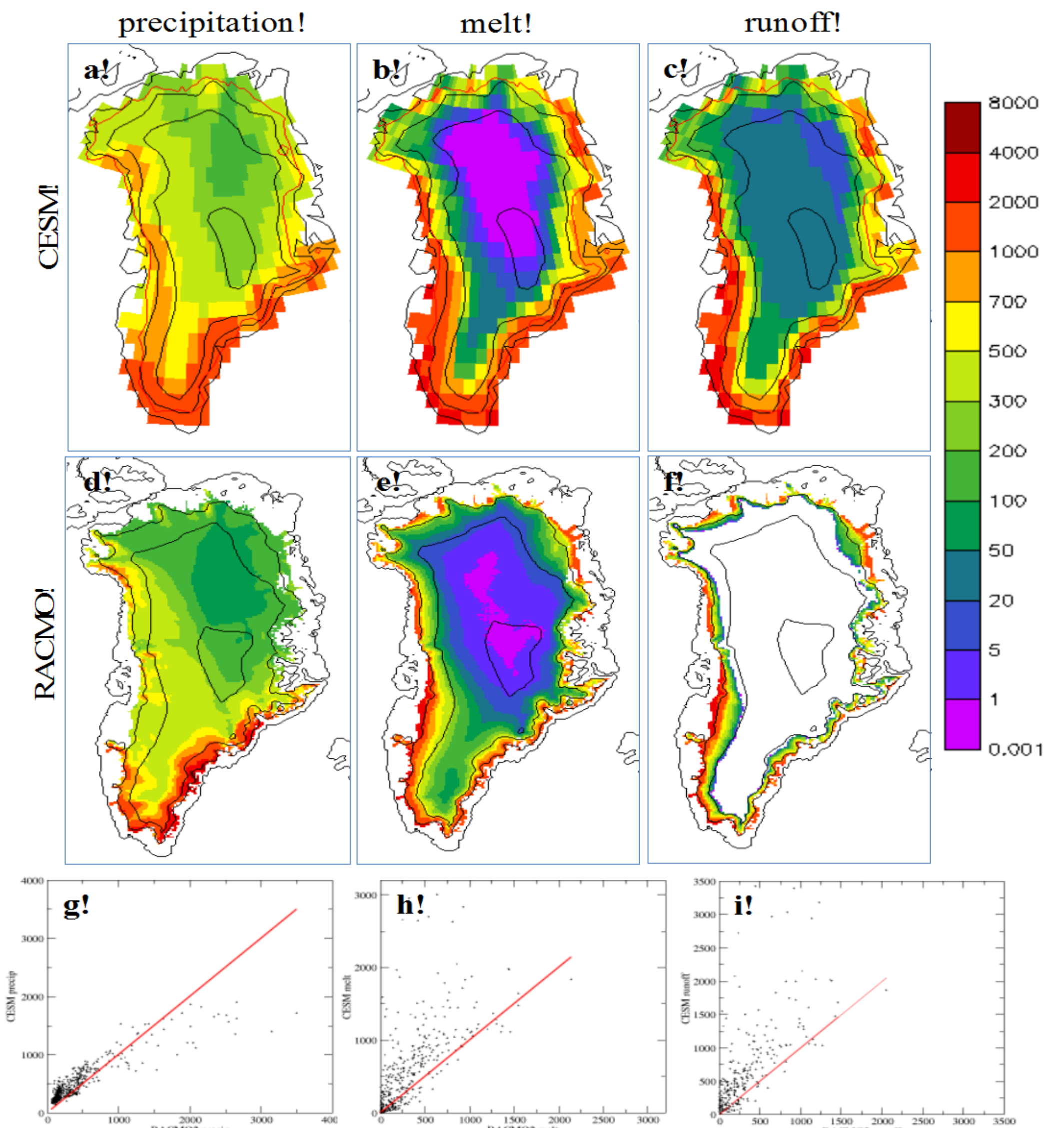
Units: Gt $yr^{-1}$

| | CESM | RACMO 2 | Other RCMs (MAR/PMM5/ERA40-d) |
|---|---|---|---|
| **Net SMB** | **359 (120)** | **376 (117)** | **288/356/287** |
| **PREC** | **866 (88)** | **723 (74)** | 600/696/610 |
| Snowfall | 735 | 676 | |
| Rainfall | 131 | 47 | 22/18/28 |
| Rain/PREC | 0.15 | 0.05 | 0.04/0.03/0.05 |
| **MELT** | **568** | **504** | |
| Refreezing | 242 (35% ALW) | 245 | |
| **RUN-OFF** | **457** | **306** | |
| SU | 54 | 40 | 5/108/38 |

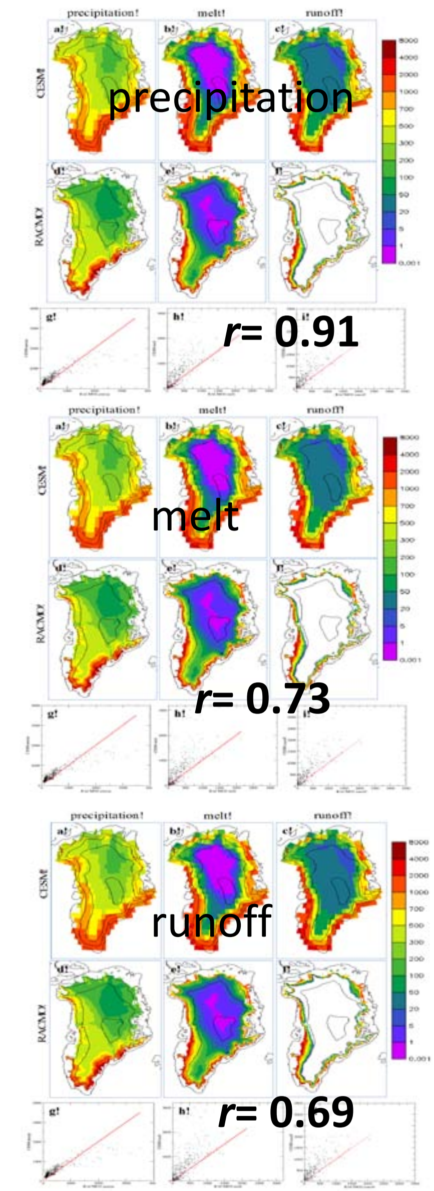
# Maps of SMB components

C
E
S
M

R
A
C
M
O




CESM, ~1°

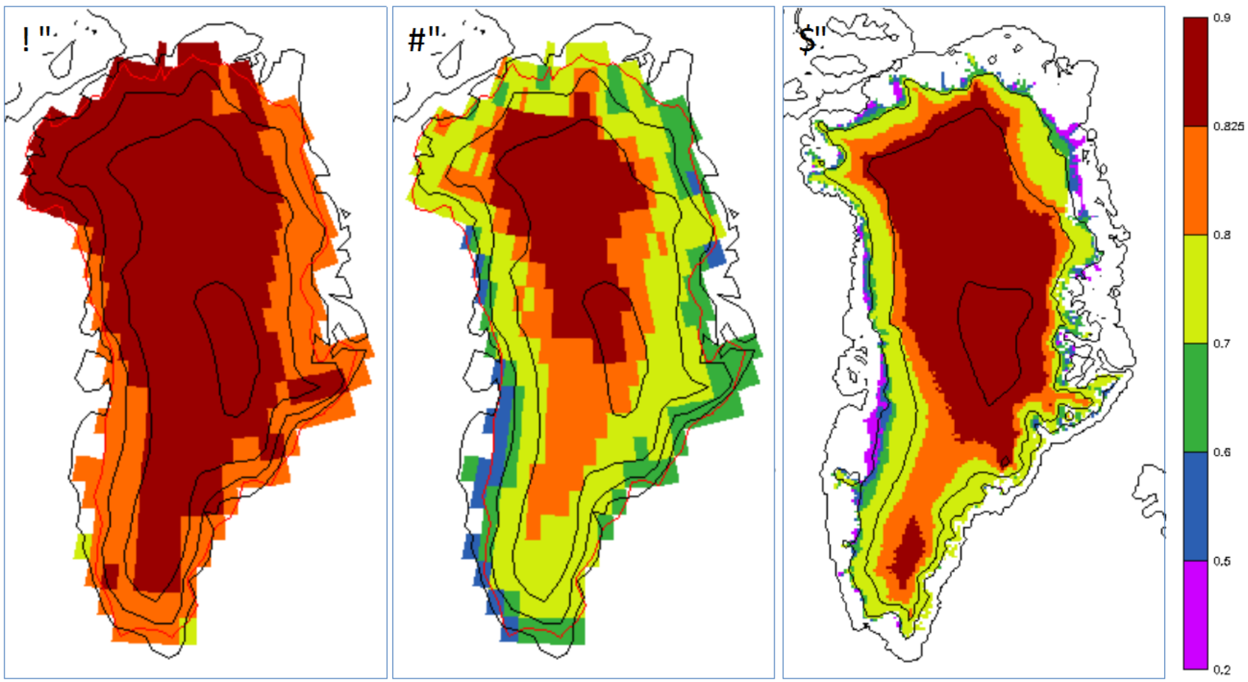



RACMO2, ~1°

# Albedo

- Surface radiation is most important energy contributor to melt
- Albedo change is driven by temperature, snowfall, rainfall, melt, exposure of bare ice
- **Dry snow: ~0.8; Wet snow:~0.7; Bare ice: 0.60 (vis)/0.40 (near IR)**

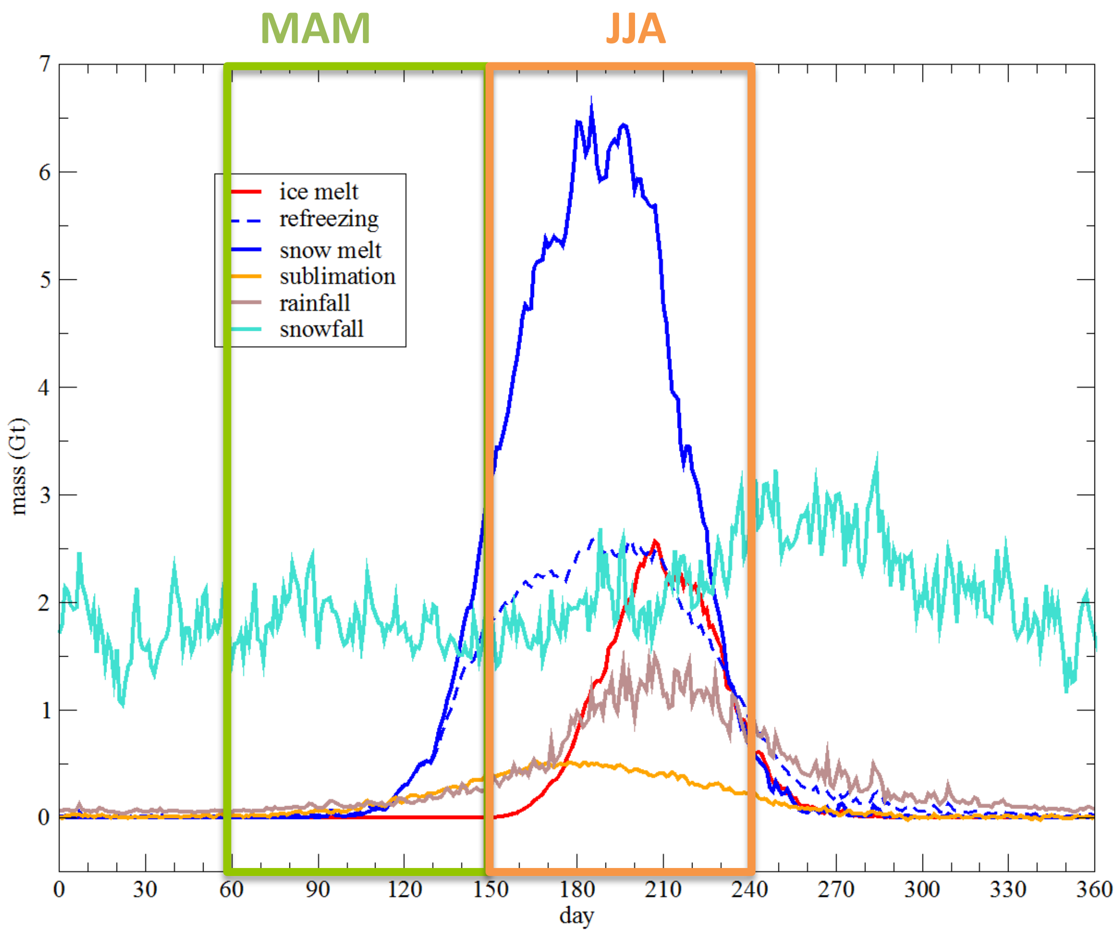
April | July | July, RACMO




0.84 | 0.76 | 0.74

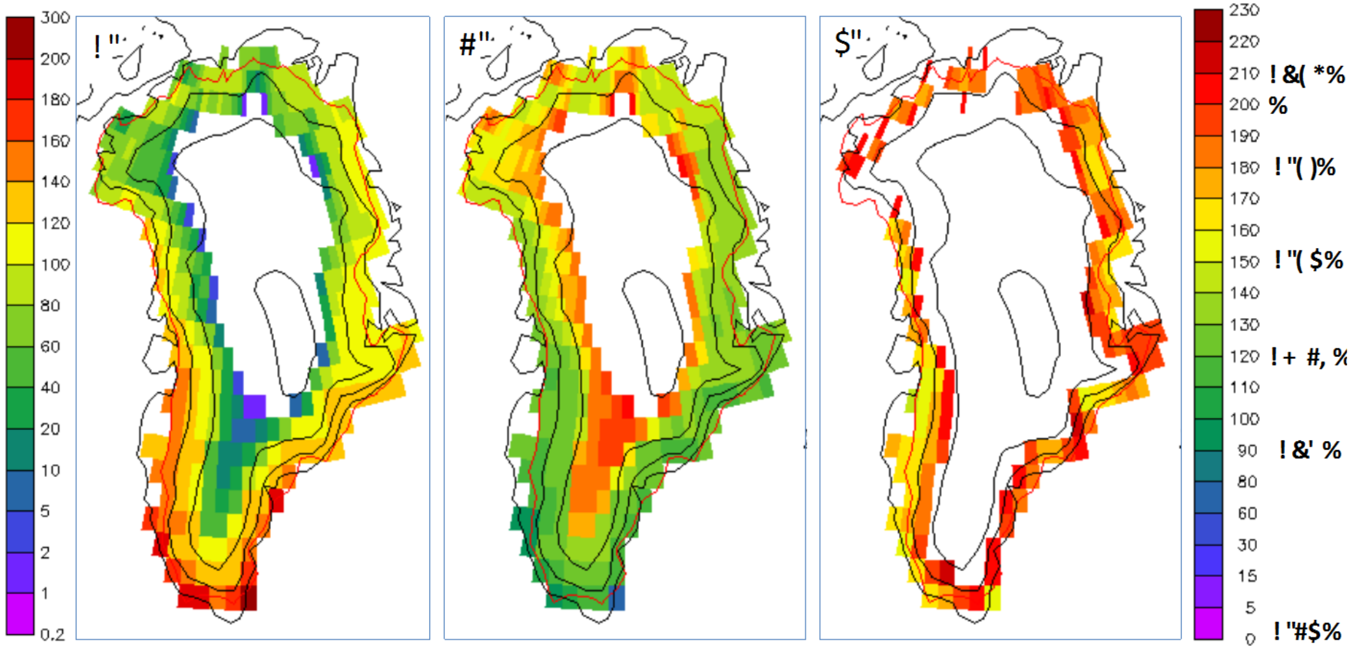
- CESM albedo wrt RACMO2 is +0.02 for April and July

# Seasonality of SMB components



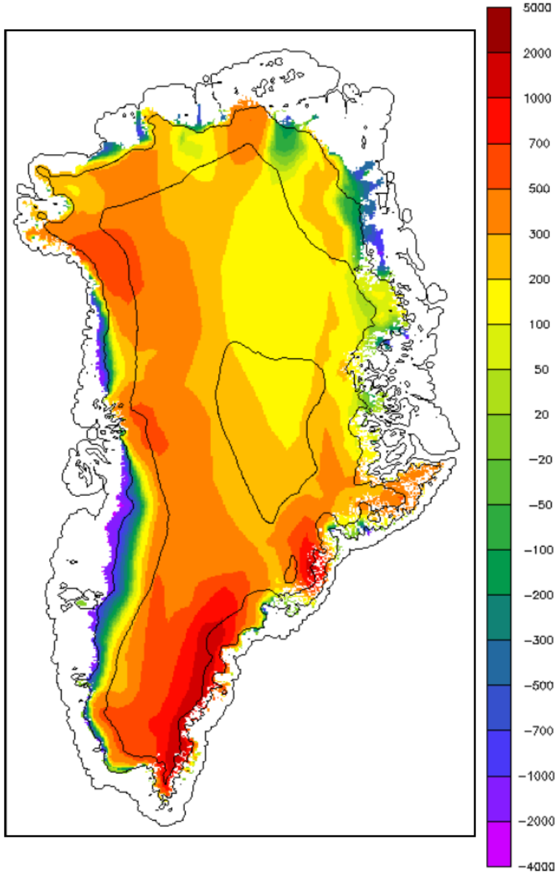
# Duration of melt

N melt days	1st day of melt	1st day ice melt



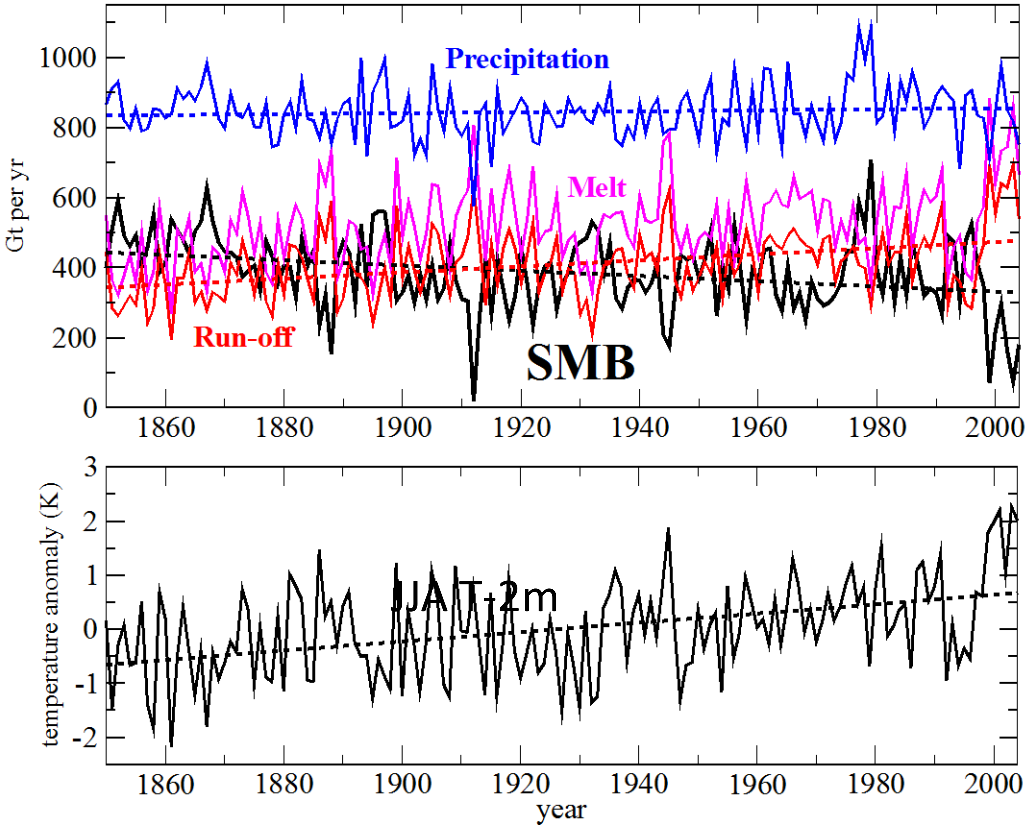

Threshold for melt: 1 kg $m^{-2}$ $yr^{-1}$

# Pre-industrial SMB




| | Pre-industrial | 1960-2005 |
|---|---|---|
| SMB (std, Gt $yr^{-1}$) | 386 (107) | 359 (120) |
| Ablation area (%) | 8 | 10 |

# 1850-2005 evolution




$+0.14$ Gt yr$^{-2}$

**$+0.87$ Gt yr$^{-2}$**

**$-0.75$ Gt yr$^{-2}$**

**$+0.0086$ K yr$^{-2}$**

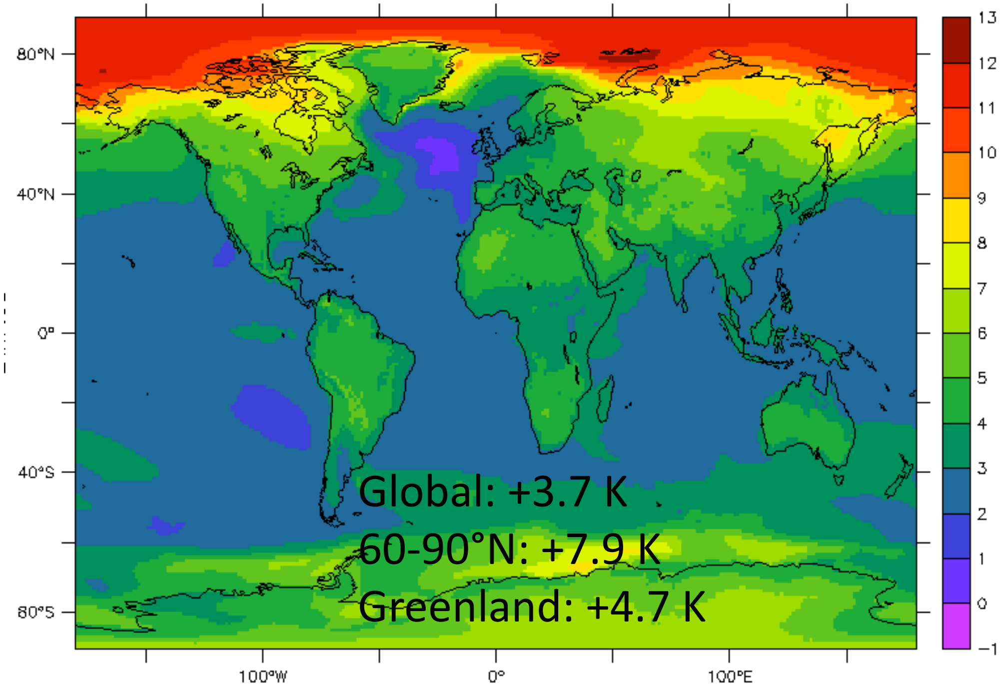
- RU, SMB & T trends are significant
- SMB ranges between 17 and 710 Gt yr$^{-1}$
- Second & third lowest SMB values after 1990
- SMB increases between 1991 & 1992 in response to Pinatubo eruption

| SIMULATION | Length | Forcing |
|---|---|---|
| **Pre-industrial** | Years 0-100 | |
| **Historical** | 1850-2005 | Insolation, Aerosols, volcanoes |
| **21$^{st}$-century** | **2005-2100** | **RCP8.5** |

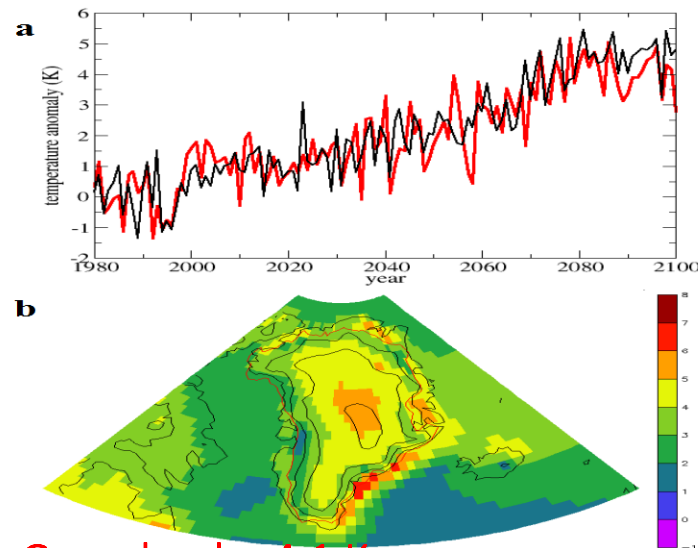
# PROJECTIONS 21$^{ST}$ CENTURY

# Temperature change under RCP8.5

Annual, 2080-99 minus 1980-99 (K)



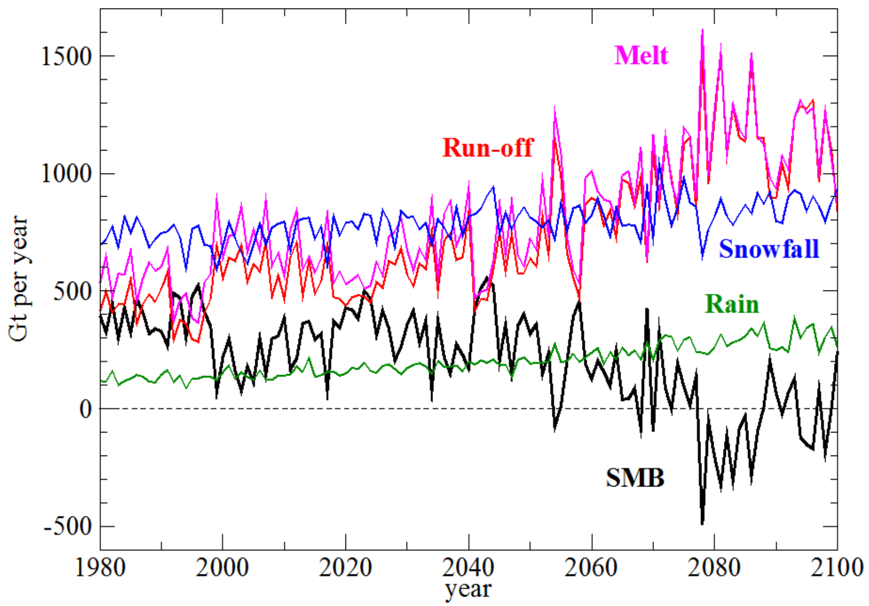

Summer, 2080-99 minus 1980-99 (K)




Greenland: +4.1 K

- MOC reduction reduces warming SE of Greenland
- JJA increase is highest
  - In ice-free regions to N & E, in part due to stronger sea ice losses (>40%) along the coast
  - In the interior of the ice sheet, which remains below melting point

# Change in integrated SMB terms (Gt yr$^{-1}$)

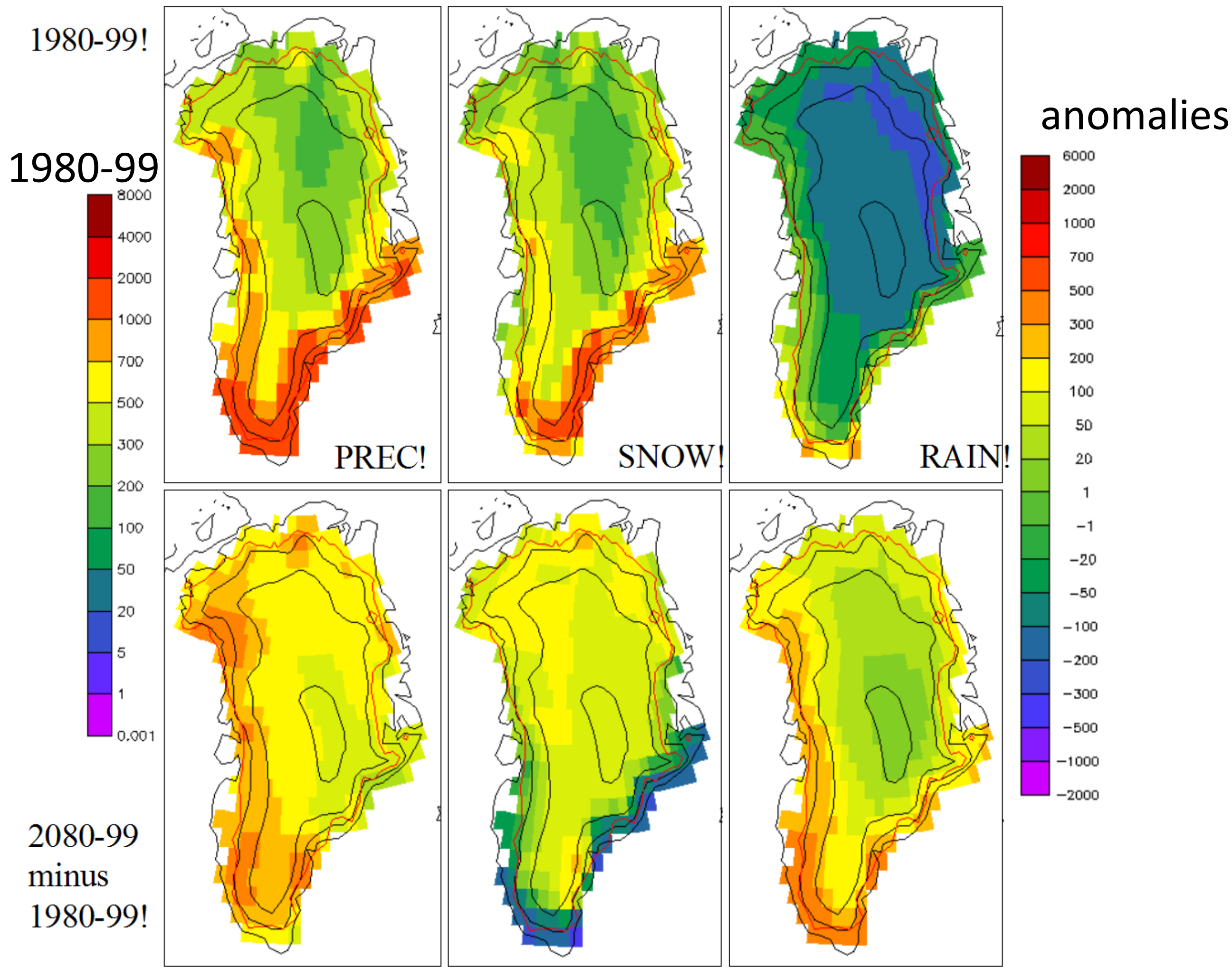



SMB (ice + snow) = PREC-RU-SU
RU=MELT+RAIN-REF=ALW-REF

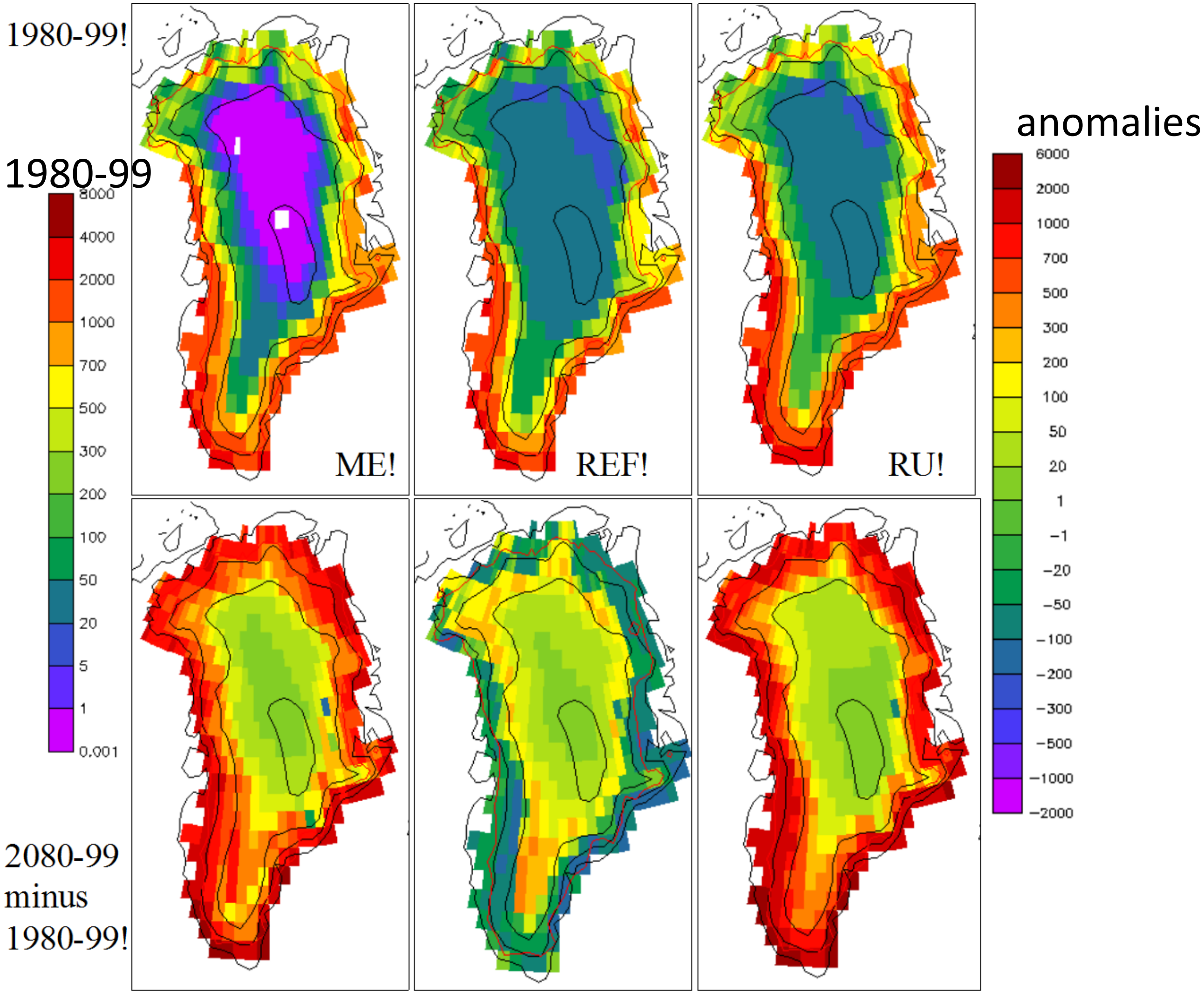
| | 1980-99 | 2080-99 |
|---|---|---|
| **Net SMB$_{ice}$** | **372** | **-78** |
| **PRECIPITATION** | **855** | **1158 (+35%)** |
| Snowfall | 728 | 857 (+18%) |
| **SURFACE MELT** | **552** | **1186 (+215%)** |
| Refreezing | 240 | 318 (+33%) |
| RUN-OFF | 438 | 1168 (+266%) |
| SUBLIMATION | 54 | 60 (+11%) |

- SMB becomes negative
- Snowfall increases by 18%
- Melt doubles
- Refreezing increases only slightly

# Changes in precipitation (kg $m^{-2}$ $yr^{-1}$)

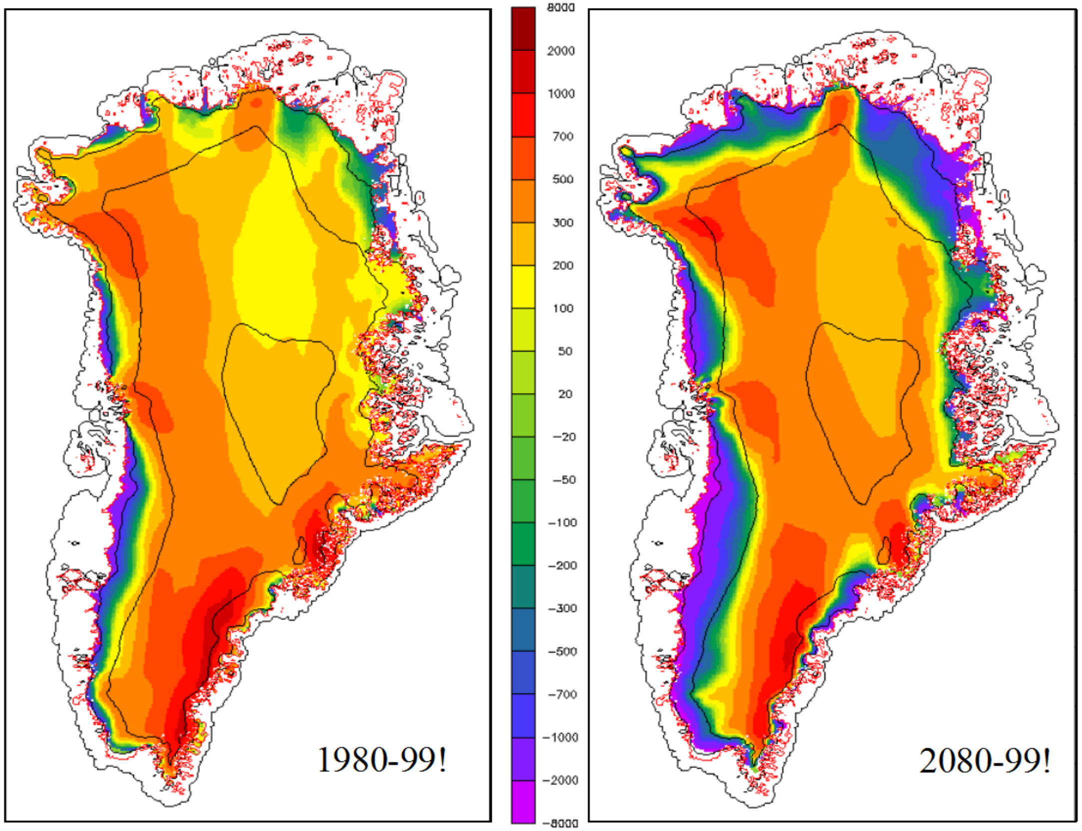


# Changes in melt & runoff (kg $m^{-2}$ $yr^{-1}$)



# New equilibrium line ~500 m higher

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

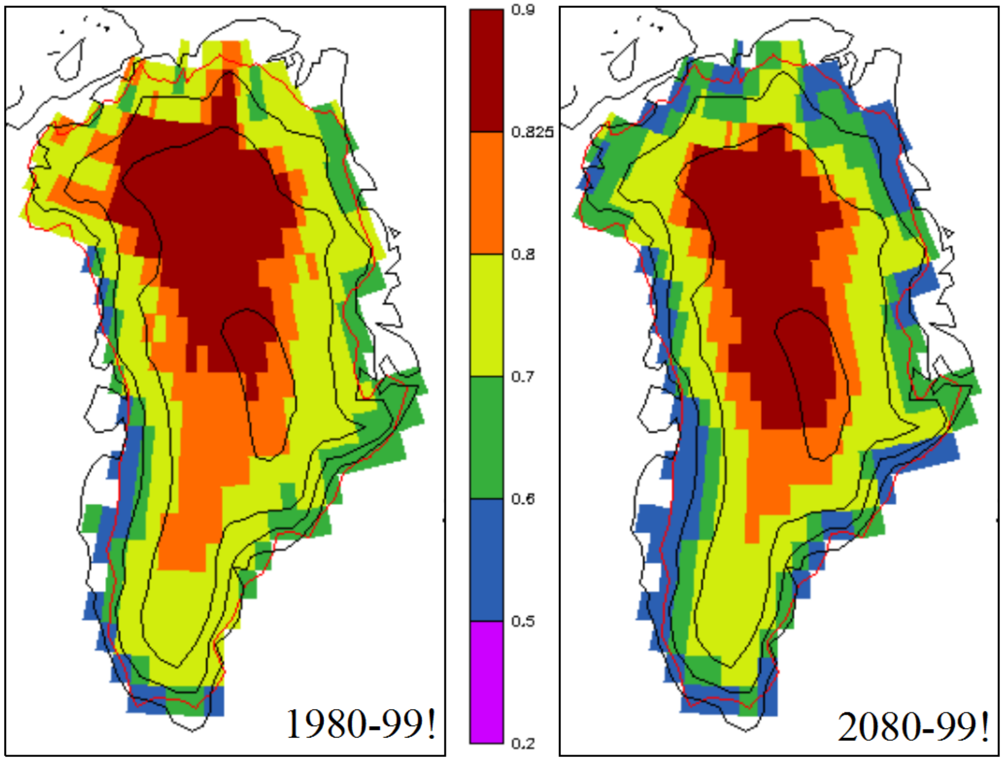



**SMB<0**

- Ablation area increases from 9% to 28% of ice sheet
- Max. increase of eq. line in NE (~1000 m higher)
- SMB increases over 2000 m

# Albedo change, July

- Surface radiation is most important energy contributor to melt
- Albedo change is driven by temperature, snowfall, rainfall, melt, exposure of bare ice
- Dry snow: ~0.8; Wet snow:~0.7; Bare ice: 0.60 (vis)/0.40 (near IR)

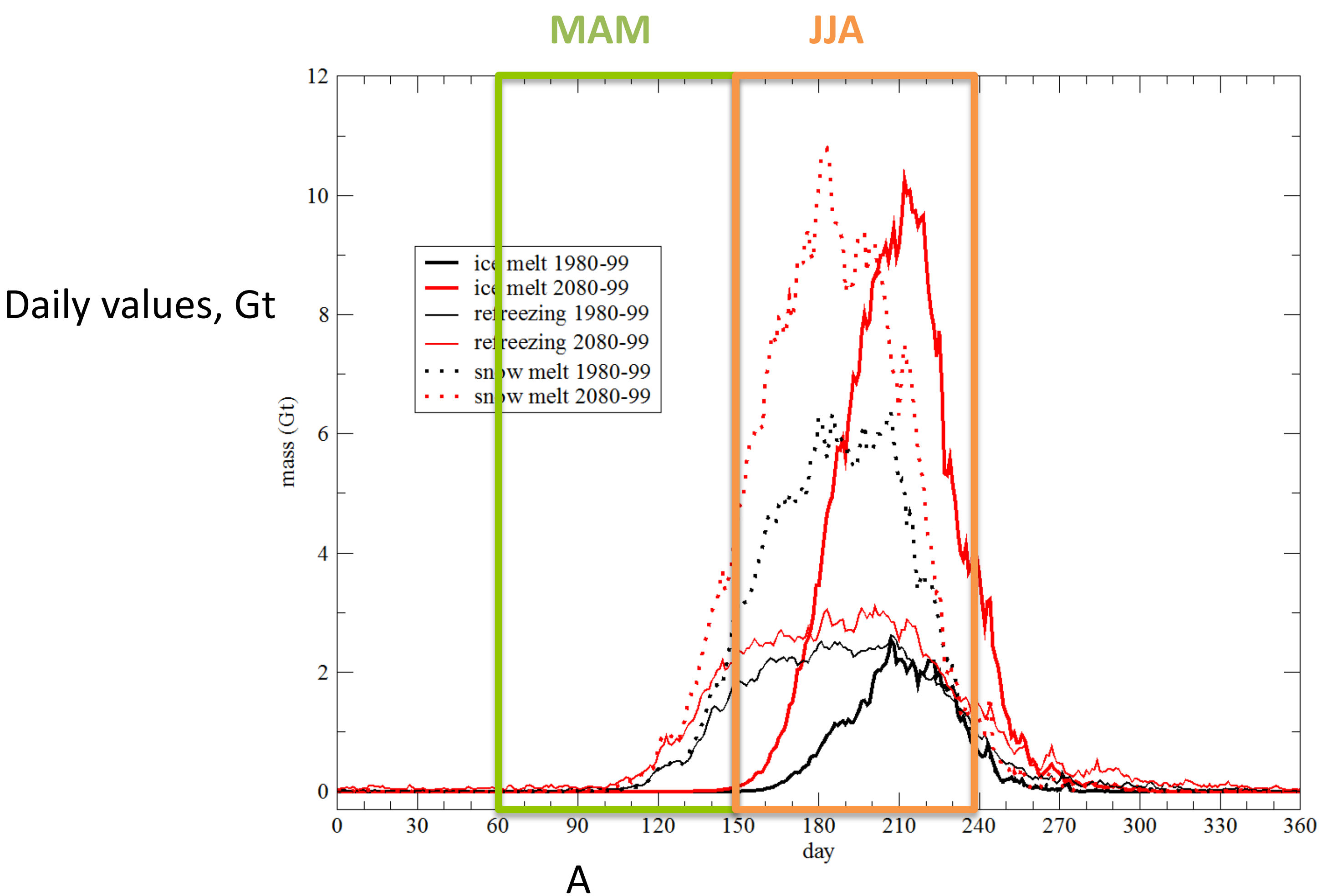



mean albedo: 0.78 mean albedo: 0.75

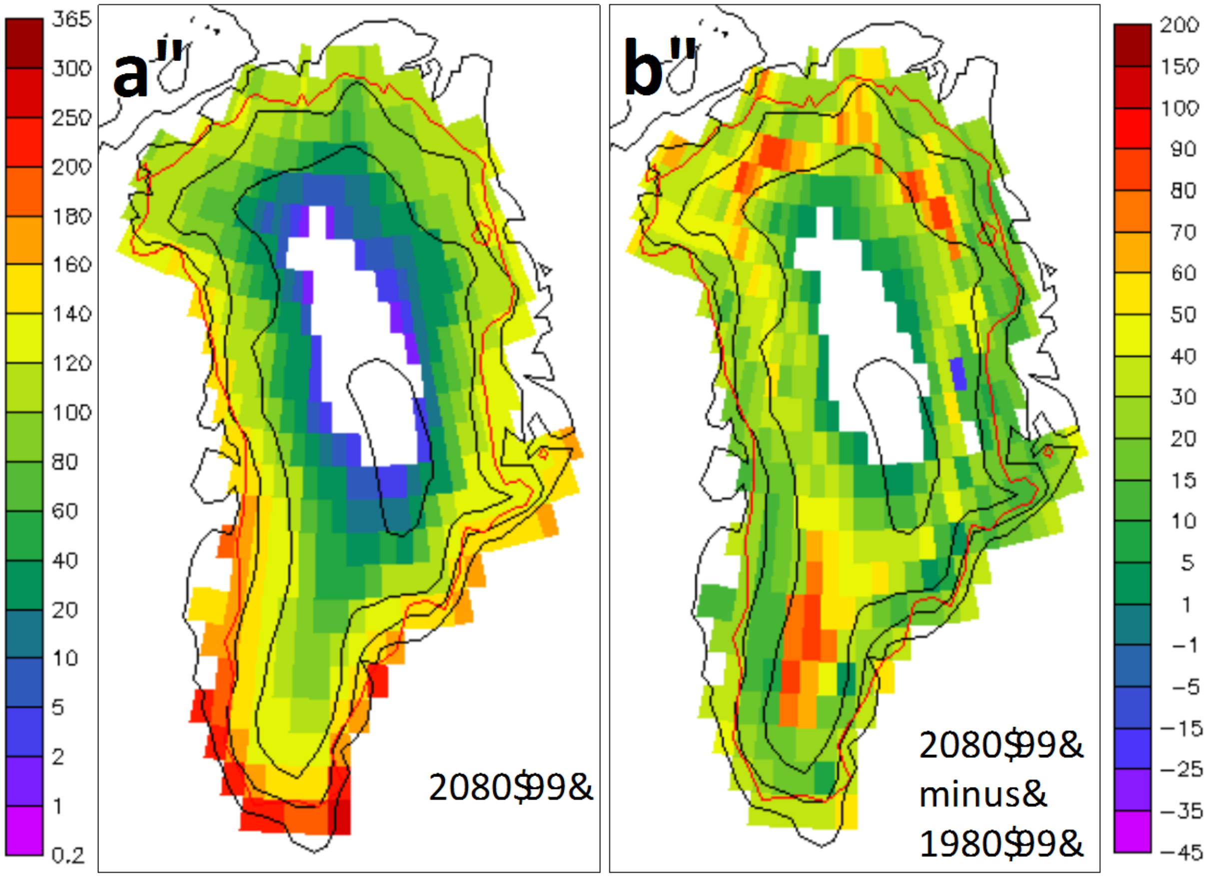
By 2080-99:

- Albedo increases slightly in the interior
- Highest increase below 1500 m, due to exposure of bare ice
- **12% incr. in absorbed solar radiation**

# Changes in seasonality

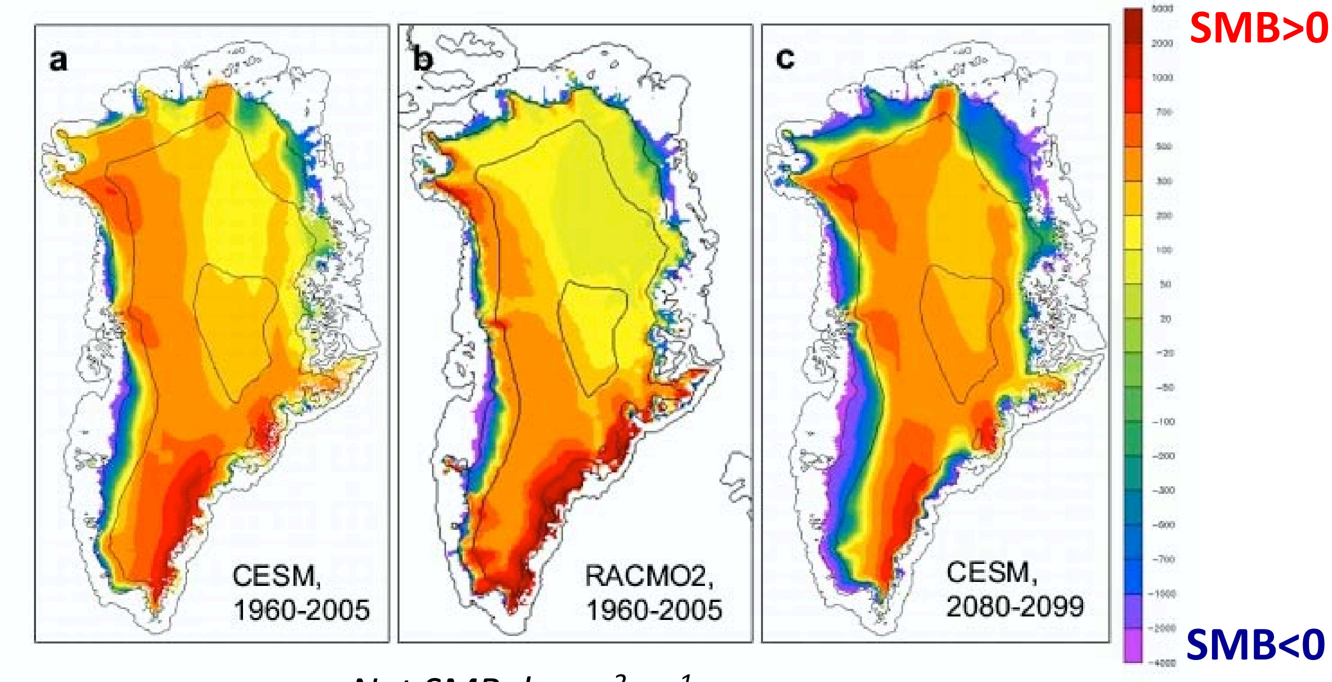


# Number of melt days



# Summary

- **First GCM that simulates realistically GIS SMB**
- SMB becomes negative by 2080-99 under RCP8.5
  - 5.5 cm SLE
  - Snowfall increases by 18%
  - Surface melt doubles
- Model limitations: rainfall bias, fixed thickness of snowpack




*Net SMB, kg $m^{-2}$ $yr^{-1}$*

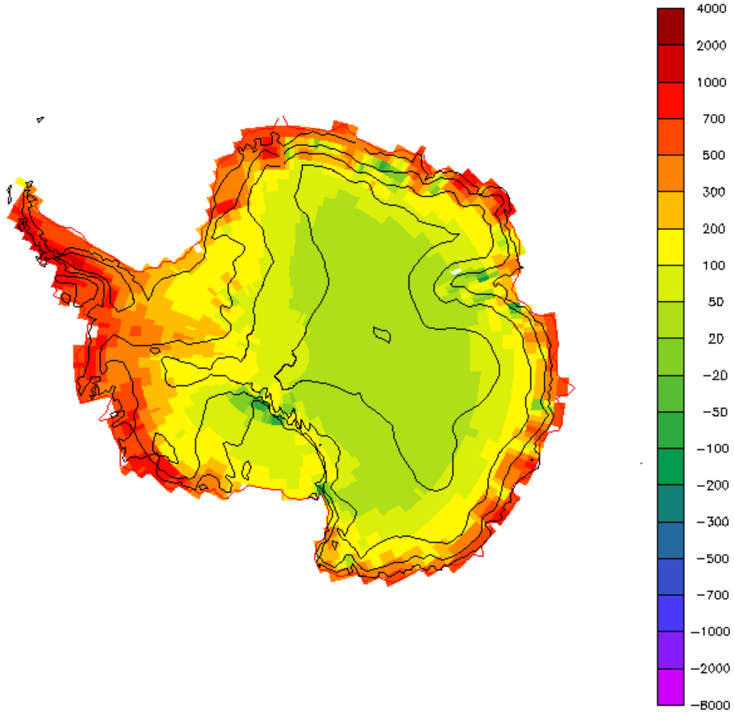
# Future work

- Antarctic climate & SMB
  - Present-day
  - Sensitivity to greenhouse forcing (RCP8.5)
- Simulation outside the Greenland ice sheet
- SMB(z): evaluation of the downscaling method
- Ice sheet SMB for LGM & mid-Holocene climates

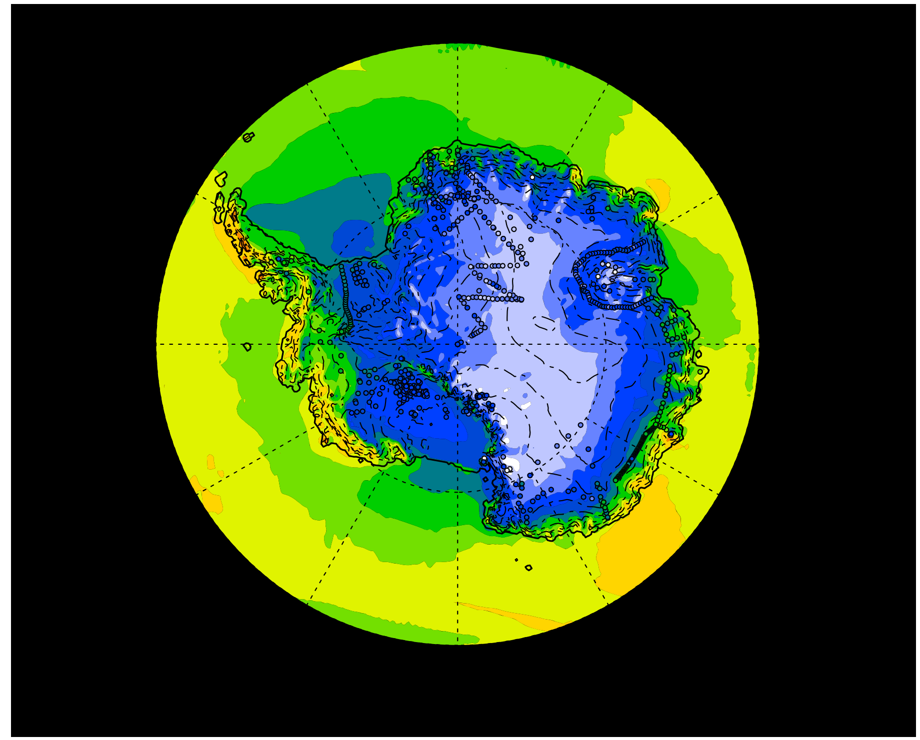
(with Jeremy Fyke)

# 1980-99 SMB & 1979-2010 RACMO2

CESM

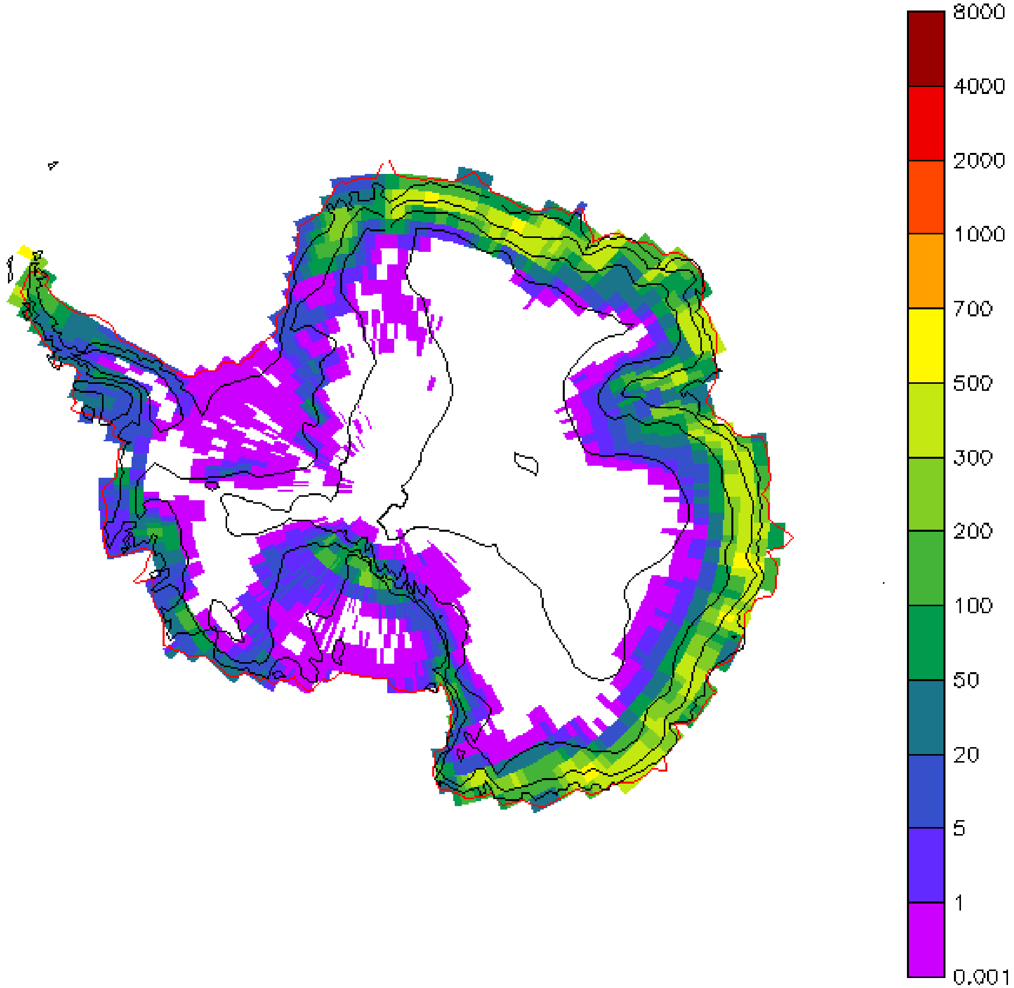



RACMO2



*Lenaerts et al, GRL, 2012*

# 1980-99 Surface Melt




Why do we see so high rates between 1000-2000 m?

# RACMO2, 1979-2010

Kuipers Munneke et al. 2012