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)

\[
\text{SMB (ice + snow)} = \text{PREC-RUNOFF-SU} \\
\text{RUNOFF=MELT+RAIN-REF}
\]

- Two systems: SNOW (5 layers) + ICE
  - Max. SNOW thickness \( H_{\text{snow}} \) is prescribed (1 m WLE)
  - SNOW if \( H_{\text{snow}} = H_{\text{max}} \): ICE GAIN (\( \text{SMB}_{\text{ice}} > 0 \))
  - Ablation when \( H_{\text{snow}} = 0 \) m: ICE LOSS (\( \text{SMB}_{\text{ice}} < 0 \))
  - Rain when \( H_{\text{snow}} = 1 \) 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

<table>
<thead>
<tr>
<th>SIMULATION</th>
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Results submitted to special issue of J. Clim on CESM
• Model description: Lipscomb et al.
• Model evaluation: Vizcaino et al.
• Projections 21st 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
T_{snow}=-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 (%)

<table>
<thead>
<tr>
<th>Ice sheet</th>
<th>Glacier &amp; ice caps</th>
<th>Sum</th>
</tr>
</thead>
</table>

Built from *Bamber et al. 2001*
1960-2005 Greenland climate

Surface fluxes
\[ M = SW_d - SW_u + LW_d - LW_u + SHF + LHF + G \]

CAM input, constant with z

\[ SW_u = \alpha SW_d \]
\[ LW_u = \varepsilon \sigma T_s^4 \]

Ts (z), T2m (z) follow fixed lapse rate
1960-2005 Near-surface temperature (°C)

DJF

JJA

Ice sheet cover > 99%

Bias (CESM-RACMO2 means)

DJF  +0.4

JJA  +0.2

r = 0.98
1960-2005 JJA Surface climate:
Incoming Radiation (Wm$^{-2}$)

Incoming SW

- 268 Wm$^{-2}$
- CESM
- RACMO2
- $\sim 1°$

Incoming LW

- 235 Wm$^{-2}$
- CESM
- RACMO2
- $\sim 1°$

Correlation coefficients:
- $r (isc>20\%) = 0.77$
- $r = 0.92$

Flux term | Bias
---|---
Incoming SW | -11
Incoming LW | +7
1960-2005 JJA Surface climate: SW (Wm$^{-2}$)

Albedo

Absorbed SW

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

$r = 0.78$

$r = 0.70$

$r = 0.76$

1:1
1960-2005 JJA Surface climate: LW (Wm\(^{-2}\))

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

**Incoming LW**
- Value: 235 Wm\(^{-2}\)
- CESM, ~1°
- RACMO2, 11 km

**Net LW**
- CESM, ~1°
- RACMO2, 11 km
- Value: 235 Wm\(^{-2}\)

**Correlation Coefficients**
- \(r = 0.92\)
- \(r = 0.83\)
- \(r = 0.51\)
- \(r = 0.71\)
1960-2005 JJA Surface climate: Total radiation (Wm^{-2})

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<th>Bias</th>
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<tr>
<td>Incoming SW</td>
<td>-11</td>
</tr>
<tr>
<td>Net SW</td>
<td>-3</td>
</tr>
<tr>
<td>Incoming LW</td>
<td>+7</td>
</tr>
<tr>
<td>Net LW</td>
<td>+6</td>
</tr>
<tr>
<td>Net radiation</td>
<td>+4</td>
</tr>
</tbody>
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1960-2005 JJA Surface climate: Turbulent fluxes (Wm$^{-2}$)

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<th>Bias</th>
</tr>
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<tbody>
<tr>
<td>Net radiation</td>
<td>+4</td>
</tr>
<tr>
<td>Sensible</td>
<td>+0.2</td>
</tr>
<tr>
<td>Latent</td>
<td>-3</td>
</tr>
<tr>
<td>Temperature</td>
<td>+0.2</td>
</tr>
</tbody>
</table>
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

Units: kg m\(^{-2}\) yr\(^{-1}\)

- 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

<table>
<thead>
<tr>
<th></th>
<th>CESM</th>
<th>RACMO 2</th>
<th>Other RCMs (MAR/PMM5/ERA40-d)</th>
</tr>
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<tr>
<td>Net SMB</td>
<td>359 (120)</td>
<td>376 (117)</td>
<td>288/356/287</td>
</tr>
<tr>
<td>PREC</td>
<td>866 (88)</td>
<td>723 (74)</td>
<td>600/696/610</td>
</tr>
<tr>
<td>Snowfall</td>
<td>735</td>
<td>676</td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>131</td>
<td>47</td>
<td>22/18/28</td>
</tr>
<tr>
<td>Rain/PREC</td>
<td>0.15</td>
<td>0.05</td>
<td>0.04/0.03/0.05</td>
</tr>
<tr>
<td>MELT</td>
<td>568</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>Refreezing</td>
<td>242 (35% ALW)</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>RUN-OFF</td>
<td>457</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>SU</td>
<td>54</td>
<td>40</td>
<td>5/108/38</td>
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Units: Gt yr⁻¹
Maps of SMB components

C
E
S
M

precipitation!
melt!
runoff!

RACMO

CESM, ~1°

RACMO2, ~1°

r = 0.91
r = 0.73
r = 0.69
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: 0.84
July: 0.76
July, RACMO: 0.74

- CESM albedo wrt RACMO2 is +0.02 for April and July
Seasonality of SMB components
Duration of melt

Threshold for melt: 1 kg m\(^{-2}\) yr\(^{-1}\)
Pre-industrial SMB

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<td>SMB (std, Gt yr⁻¹)</td>
<td>386 (107)</td>
<td>359 (120)</td>
</tr>
<tr>
<td>Ablation area (%)</td>
<td>8</td>
<td>10</td>
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1850-2005 evolution

- 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

\[+0.14 \text{ Gt yr}^{-2}\]
\[+0.87 \text{ Gt yr}^{-2}\]
\[-0.75 \text{ Gt yr}^{-2}\]
\[+0.0086 \text{ K yr}^{-2}\]
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PROJECTIONS 21st CENTURY
Temperature change under RCP8.5

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

- Global: +3.7 K
- 60-90°N: +7.9 K
- Greenland: +4.7 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 becomes negative
- Snowfall increases by 18%
- Melt doubles
- Refreezing increases only slightly

| SMB (ice + snow) = PREC-RU-SU RU=MELT+RAIN-REF=ALW-REF |
|---------------------------------|-----------------|-----------------|
| 1980-99                  | 2080-99                  |
| Net SMB\(_{\text{ice}}\)   | 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%)                 |
Changes in precipitation (kg m\(^{-2}\) yr\(^{-1}\))
Changes in melt & runoff (kg m$^{-2}$ yr$^{-1}$)
New equilibrium line ~500 m higher

- 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)

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**

![Albedo change maps](image-url)

Mean albedo:
- 1980-99: 0.78
- 2080-99: 0.75
Changes in seasonality

Daily values, Gt
Number of melt days

2080$99$ minus 1980$99$
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, $kg \, m^{-2} \, yr^{-1}$](image)
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