Cloud Radiative Forcing in Central Greenland

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Polar Climate Working Group Meeting
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• Location
• Instrumentation
• Results
• CESM Validation
• Future Directions
Greenland Ice Sheet

The GIS is over 3.2 km deep at Summit Station.

Observed increase in GIS melt rate and extent (Mernild et al. 2011, J. Glac.) has global and regional impacts.

For surface temperatures close to 273K a small change in the surface energy budget can have substantial implications for the surface mass balance.
ICECAPS
Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation at Summit, Greenland

• **Atmospheric State** - temperature and moisture profiles throughout the troposphere
• **Cloud Macrophysics** - cloud occurrence and vertical boundaries
• **Cloud Microphysics** - cloud phase, water content, optical depth, and particle size
• **Precipitation** - precipitation type and rate
• **Cloud Radiative Forcing** - impact of clouds on the surface radiation budget

Elevation 3255 m
72°35’ N
38°25’ W

*Shupe et. al. BAMS 2013*
Mobile Science Facility

Photos (right):
M. Shupe,
M. Okrazewski

- Precip Sensor:
  Snowfall rate

- Microwave Radiometers:
  PWV, LWP, T

- Sodar:
  Boundary layer depth

- Cloud Radar:
  Cloud macrophysics, phase, microphysics, dynamics

- Ceilometer:
  Cloud base

- Depolarization Lidars:
  Cloud base, phase, microphysics, orientation

- Spectral Infrared Interferometer:
  Cloud phase, microphysics, LW radiation
Broadband Radiometers

\[ \text{Net} = \text{LW}_\downarrow - \text{LW}_\uparrow + \text{SW}_\downarrow - \text{SW}_\uparrow \]

ETH measurements –
courtesy of Dr. Konrad Steffen
– Swiss Federal Institute, Zürich
2004 - present
Annual Cycle of Surface Flux

3-hour averages, Jan 2011-Oct 2013

Miller et. al. J. Climate [submitted]
CRF Defined

- Cloud radiative forcing (CRF) is an estimation of a cloud’s impact on the radiative flux at the surface.

\[
\text{CRF} = \text{Flux}_{\text{all-sky, measured}} - \text{Flux}_{\text{clear-sky, modeled}}
\]

Rapid Radiative Transfer Model (RRTM)
Annual Cycle of CRF

- SW CRF [Wm$^{-2}$]
  - Downwelling
  - Upwelling
- LW CRF [Wm$^{-2}$]
- CRF [Wm$^{-2}$]

Month of Year: J F M A M J J A S O N D
Surface albedo important for CRF

- Central Greenland is a unique Arctic location

(Shupe and Intrieri 2004, J. of Climate)  M. Shupe
(Dong et. al. 2010, JGR)
- High year round cloud fraction – 86%
- LW CRF magnitude corresponds to the presence of liquid-bearing clouds
- Changes in cloud frequency of occurrence or microphysical properties would change CRF magnitude.
Community Earth System Model

CESM validation

– Radiative Fluxes (daily averages)
– Precipitable water vapor (monthly averages)
– Liquid water path (monthly averages)
– Cloud radiative forcing (daily averages)
– Near-surface air temperatures (daily values)
Annual Cycle of Surface Flux

- **Components and Fluxes**
  - **a) SW ETH**
  - **b) LW ETH**
  - **c) Total ETH**

- **CESM**

- **Flux Units:** \[ \text{Wm}^{-2} \]

- **Month of Year:**
  - J: January
  - F: February
  - M: March
  - A: April
  - M: May
  - J: June
  - J: July
  - A: August
  - S: September
  - O: October
  - N: November
  - D: December
Summit Monthly averaged PWV

CESM, 3 Runs

ICECAPS
Summit, Monthly averaged LWP

CESM, 3 runs
ICECAPS
Annual Cycle of CRF

 CESM CRF

 a) SW CRF

 b) LW CRF

 c) Total CRF

 Observations

 CESM

<table>
<thead>
<tr>
<th>Annual CRF</th>
<th>Summer CRF</th>
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<tbody>
<tr>
<td>30 Wm⁻²</td>
<td>34 Wm⁻²</td>
</tr>
<tr>
<td>12 Wm⁻²</td>
<td>8 Wm⁻²</td>
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Modeled values are bimodal.

Observed extremes not captured by CESM.
In order to accurately represent surface temperatures, need to capture the presence and phase of clouds above the GIS.

Summer maximum temperatures are critical to represent because they have the greatest impact on melt extent.

At Summit, clouds can force surface temperatures to the melting point of snow (i.e. Bennartz et. al. Nature 2013).

If 26 Wm\(^{-2}\) (summer CRF residual) was added to the surface energy budget then, -13C \(\rightarrow\) -7C.

Of course it is more complicated – turbulent flux response and heat conduction into the snowpack.
Future CESM fields to investigate

- LW↓, LW↑, SW↓, SW↑
- Albedo
- IWP
- Cloud Fraction
- Latent Heat Flux
- Sensible Heat Flux
- Skin temperature
- Surface Pressure
- Temperature and humidity profiles
  - Stability of the boundary layer
  - Inversion Strength
Thank you

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- Thanks to Dr. Konrad Steffen for providing the ETH broadband radiometer measurements.
- National Oceanic and Atmospheric Administration’s Global Monitoring Division
- European Centre for Medium-Range Weather Forecasts
- Professor Kay for providing the CESM data.
CESM average daily summer temperatures are:
- too cold (CAM5)
- too warm (CAM4)

R. Bennartz
Rapid radiative transfer model (RRTM)

Inputs:

- Merged temperature profiles
  - ECMWF, twice daily radiosondes, MWR derived boundary layer profiles
- Merged moisture profiles
  - ECMWF, twice daily radiosondes, scaled by MWR derived PWV
- Snow emissivity = 0.985
- Clear-sky snow albedo →
- CO$_2$ mixing ratio
- Standard subarctic winter
  - N$_2$O, CO, CH$_4$ and O$_2$
- Ozonesonde profile
- Surface temperature
  - derived from LW measurements

![Clear Sky Albedo](chart)

\[ y = 0.74715 + 0.00145x \]
The physical depth of an ice-cloud influences the optical depth

Linear relationship between cloud thickness and LW CRF

The physical depth of an ice-cloud influences the optical depth

Linear relationship between cloud thickness and LW CRF
SW CRF is sensitive to changes in sun angle and LWP.
Maximum Total CRF for optically thin clouds with low LWP