Diagnosing Recent Changes in Cryosphere Radiative Forcing

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Motivation

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- We now have 30 years of continuous remote sensing observations with which to diagnose cryosphere radiative forcing.
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- Model cloud processes and climate influence are often diagnosed with *cloud radiative forcing*.
- A similar diagnostic for model cryosphere processes would enable isolation of the influence of snow/ice processes on surface albedo and TOA energy balance.
- We now have 30 years of continuous remote sensing observations with which to diagnose cryosphere radiative forcing.
- Recent reductions in seasonal snow cover (spring) and sea-ice (autumn) are evident. What is the radiative impact of these changes?
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- We derive CrRF over a region $R$ from:

\[
\text{CrRF}(t, R) = \frac{1}{A} \int_R S_x(t, r) \left[ \frac{\partial \alpha}{\partial S_x}(t, r) \frac{\partial F}{\partial \alpha}(t, r) \right] dA(r) \quad [\text{W m}^{-2}]
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- We partition CrRF into contributions from:
  - seasonal snow cover
  - sea-ice
Methods and Data

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- NOAA/Rutgers binary snow cover product, derived from AVHRR data (Robinson and Frei, 2000), continuous from 1972
- 1979–2008 sea-ice concentration derived from microwave remote sensing (Cavalieri et al., 2008, NSIDC)
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Snow-covered albedo: 2000-2008 monthly-resolved MODIS surface albedo, filtered with NOAA/Rutgers binary snow cover. Data are filled with annual-mean snow-covered albedo, APP-x surface albedo (*Wang and Key*, 2005), and land-class-mean albedo.

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- Characterize uncertainty with albedo variability by land-class
- Sea-ice albedo partitioned into first-year and multi-year ice albedo, determined from Perovich et al. (2002)
- Radiative kernels derived from CAM and GFDL models (Shell et al., 2008; Soden et al., 2008) and remote sensing cloud products (ISCCP, APP-x)
Snow-covered / snow-free albedo contrast

Large spatial variability
- Reduced snow impact over mature forests
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- Largest variability in albedo contrast over open shrublands, grasslands, and sparsely vegetated terrain
- NOAA/Rutgers “snow-covered” surfaces can be up to 50% snow-free
Mean CrRF

- Annual-mean Northern Hemisphere CrRF of land snow: 
  $-2.0 \pm 0.6 \text{ W m}^{-2}$
Seasonal cycle of CrRF

Peak land-snow CrRF season: March–May
**Seasonal cycle of CrRF**

- **Peak land-snow CrRF season:** March–May
- **In May,** the Northern Hemisphere reflects an additional $\sim 9$ W m$^{-2}$ to space because of the cryosphere
1979–2008 evolution of CrRF

- 30-year trends are determined from anomalies in CrRF
1979–2008 evolution of CrRF

30-year trends are determined from anomalies in CrRF

2007–2008 land-based snow had the smallest radiative impact on record, although sea-ice changes were even more anomalous (relatively)
1979–2008 change in CrRF

- Mean CrRF change in CrRF: +0.22 ± 0.08 W m\(^{-2}\)
1979–2008 change in CrRF

- 30-year change in land snow CrRF: $+0.22 \pm 0.08 \text{ W m}^{-2}$
- Large spring increase, small autumn effect from *increased* snow
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- 30-year change in land snow CrRF: $+0.22 \pm 0.08 \text{ W m}^{-2}$
- Large spring increase, small autumn effect from *increased* snow
- Mountain snow changes should be interpreted with caution
Seasonal cycle of change in CrRF

- 'X' indicates statistically-significant change ($p = 0.05$)
- Land-snow CrRF changes are significant during March–August
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- Land-snow CrRF changes are significant during March–August
- Peak change during June:

![Graph showing seasonal cycle of change in CrRF]
Seasonal cycle of change in CrRF

- 'X' indicates statistically-significant change ($p = 0.05$)
- Land-snow CrRF changes are significant during March–August
- Peak change during June: influenced by Himalaya, Tien Shan snow cover loss (again, caution)
**Change in CrRF produced with different methods**

Table: Change in Northern Hemisphere CrRF (W m\(^{-2}\)) during 1979–2008. Numbers in parenthesis indicate the percent of change due to land-based snow.

<table>
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<th>Kernel ((\partial F/\partial \alpha))</th>
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<th>Central</th>
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<tr>
<td>CAM</td>
<td>+0.26 (42)</td>
<td>+0.38 (50)</td>
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CrRF changes are greater with actual, annually-varying cloud conditions (ISCCP and APP-x) than with model-derived kernels. Clouds mask about half of the radiative impact of snow and ice.
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- Next step: Compare observations with CrRF (and $\Delta \text{CrRF}$) produced by CLM, and identify physical/biophysical snow processes that can be improved.

- Model CrRF is influenced by:
  - Surface downwelling insolation (cloudiness) (Qian et al., 2006)
  - Snow cover fraction (Niu and Yang, 2007)
  - Snow burial fraction (Wang and Zeng, 2009)
  - Snow metamorphosis (Flanner and Zender, 2006)
  - Impurity-induced snow darkening