Diagnosing Recent Changes in Cryosphere Radiative Forcing

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- 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:

$$\mathrm{CrRF}(t,R) = \frac{1}{A}\int_R S_x(t,r)\,\underbrace{\frac{\partial \alpha}{\partial S_x}(t,r)}_{\text{albedo}}\,\underbrace{\frac{\partial F}{\partial \alpha}(t,r)}_{\text{kernel}}\,dA(r) \qquad [\mathrm{W\,m^{-2}}] \tag{1}$$

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- We partition CrRF into contributions from:
  - seasonal snow cover
  - sea-ice

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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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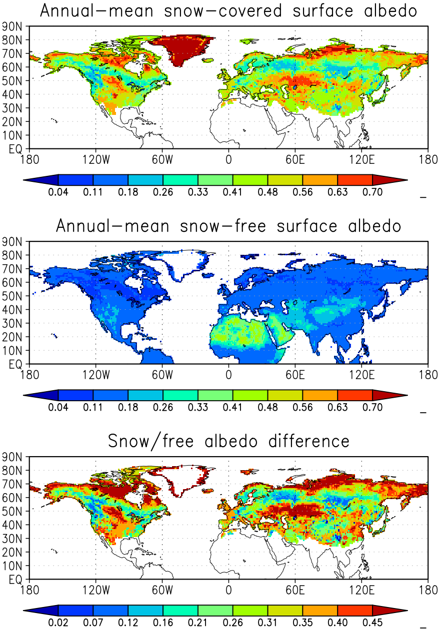
- *Radiative kernels* derived from CAM and GFDL models (*Shell et al.*, 2008; *Soden et al.*, 2008) and remote sensing cloud products (ISCCP, APP-x)

Snow-covered / snow-free albedo contrast



Large spatial variability

- Reduced snow impact over mature forests

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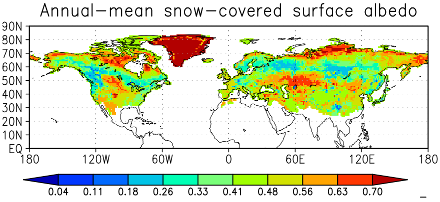

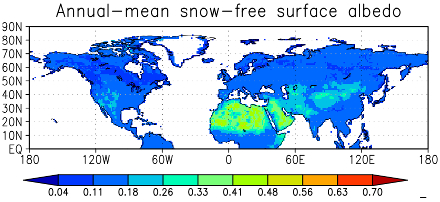

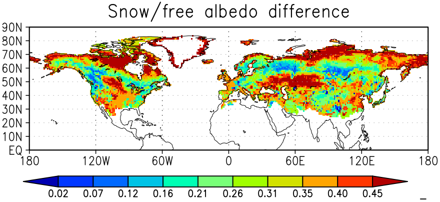

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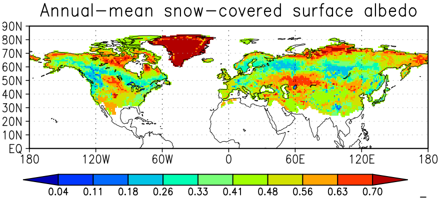
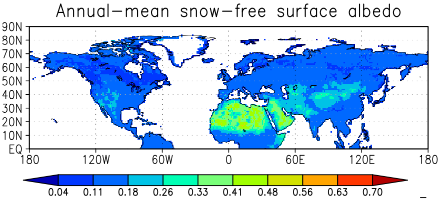
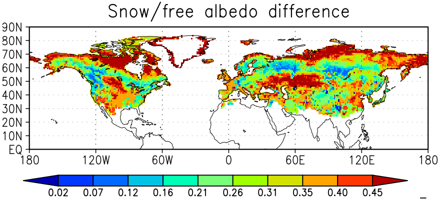


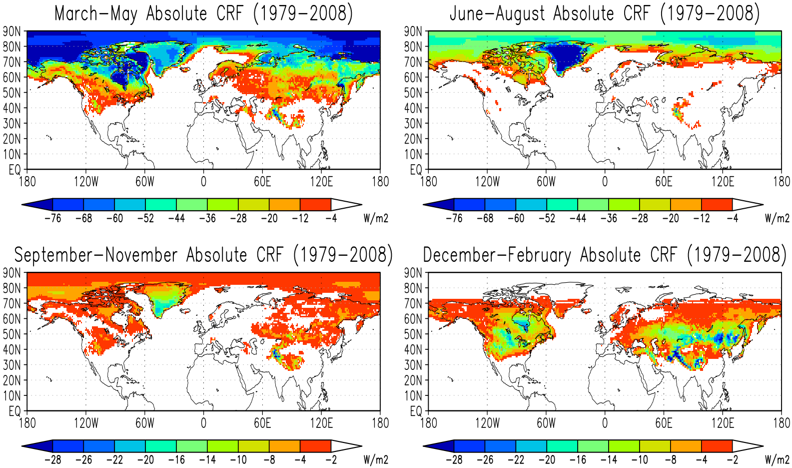




Large spatial variability

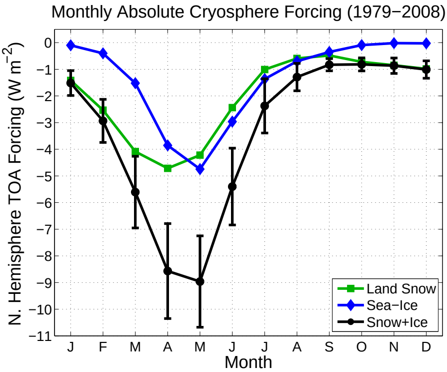
- Reduced snow impact over mature forests
- Largest *variability* in albedo contrast over open shrublands, grasslands, and sparsely vegetated terrain
- NOAA/Rutgers "snow-covered" surfaces can be up to 50% snow-free

Mean CrRF



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

Seasonal cycle of CrRF



- Peak land-snow CrRF season: March–May

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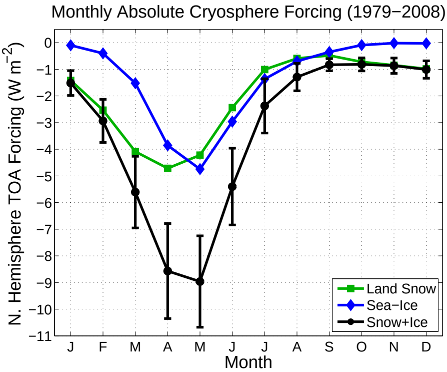
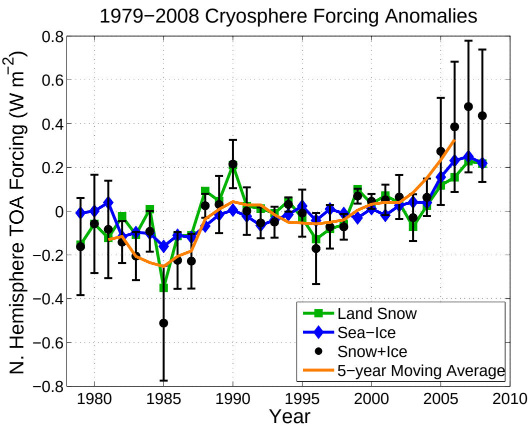


- Peak land-snow CrRF season: March–May
- In May, the Northern Hemisphere reflects an additional $\sim 9\,\mathrm{W\,m^{-2}}$ to space because of the cryosphere

1979–2008 evolution of CrRF



- 30-year trends are determined from anomalies in CrRF

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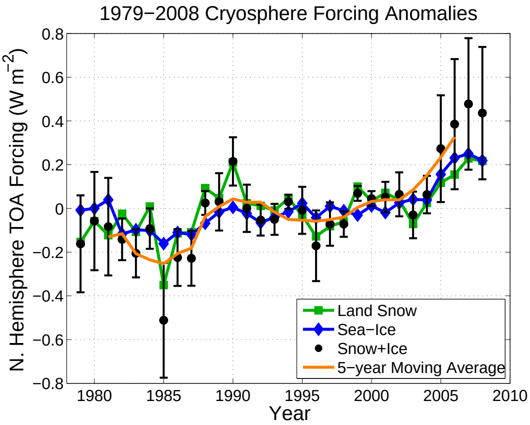
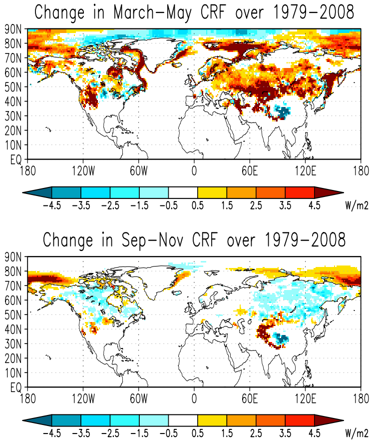


- 30-year trends are determined from anomalies in CrRF
- 2007–2008 land-based snow had the smallest radiative impact on record, although sea-ice changes were even more anomalous (relatively)

1979–2008 change in CrRF



- 30-year change in land snow CrRF: $+0.22 \pm 0.08\,\mathrm{W\,m^{-2}}$

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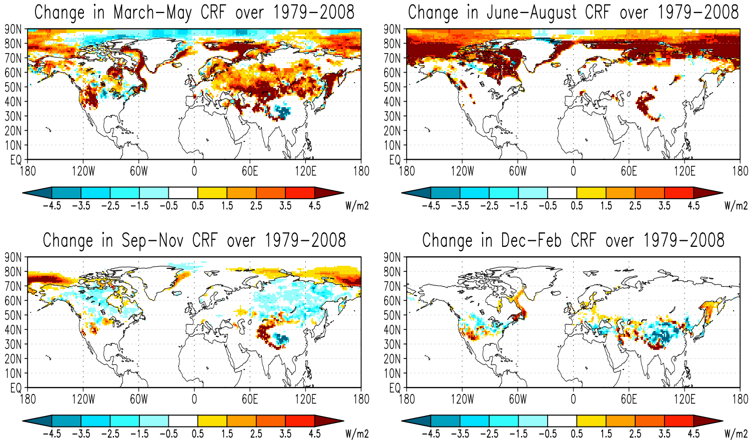

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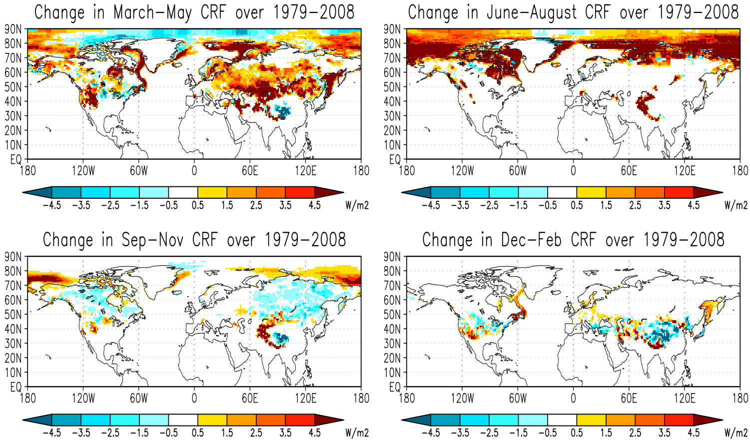
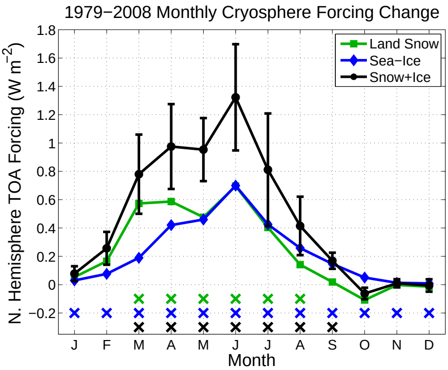


- 30-year change in land snow CrRF: $+0.22 \pm 0.08\,\mathrm{W\,m^{-2}}$
- Large spring increase, small autumn effect from *increased* snow
- Mountain snow changes should be interpreted with caution

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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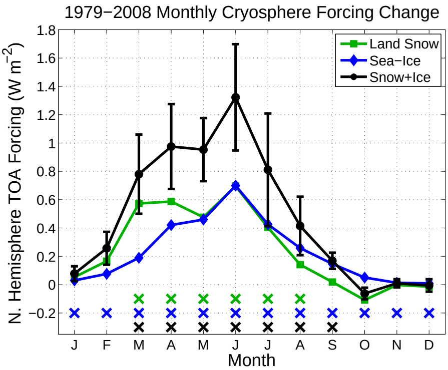

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- Peak change during June:

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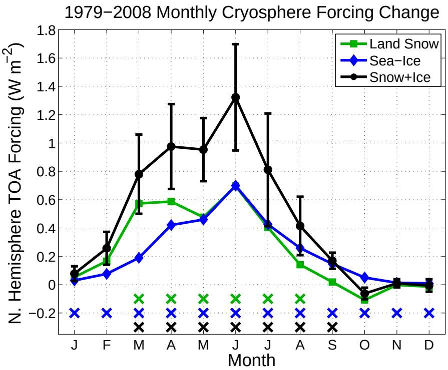

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- Land-snow CrRF changes are significant during March–August
- Peak change during June: influenced by Himalaya, Tien Shan snow cover loss (again, caution)

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.

	$\Delta\alpha$ estimate		
Kernel ($\partial F/\partial\alpha$)	Low	Central	High
CAM	+0.26 (42)	+0.38 (50)	+0.48 (53)
GFDL	+0.29 (41)	+0.40 (49)	+0.49 (52)
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- Clouds mask about half of the radiative impact of snow and ice

Conclusions and future directions

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- 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 metamorphism (*Flanner and Zender*, 2006)
  - Impurity-induced snow darkening