Cryosphere radiative forcing and albedo feedback

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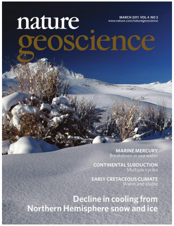

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- Questions:
  1. What is the influence of the cryosphere on Earth's solar energy budget?
  2. What has been the radiative impact and associated albedo feedback of recent changes in seasonal snow cover and sea-ice?
- We have 30 years of remote sensing observations from which to diagnose these quantities and the cryospheric contribution to Earth's climate sensitivity

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

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- Contributions separated from:
  - Land snow and ice
  - Sea-ice

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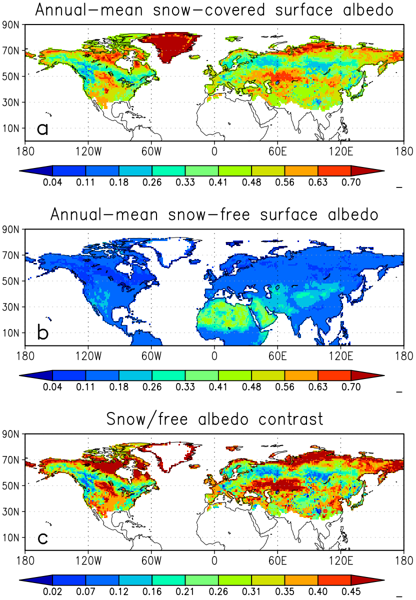
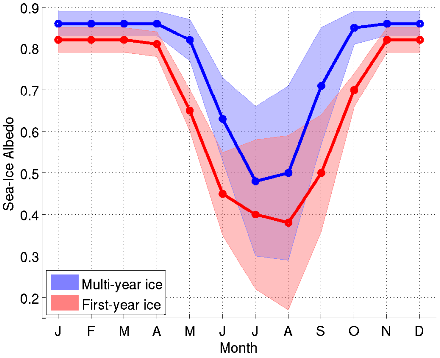
- WCRP CMIP3 model archive

Snow-covered / snow-free albedo contrast ($\Delta\alpha_{snow}$)



- Reduced snow albedo impact over mature forests
- Large $\Delta\alpha_{snow}$ over grasslands and tundra
- NOAA/Rutgers "snow-covered" surfaces can be up to 50% snow-free

Sea-ice albedo



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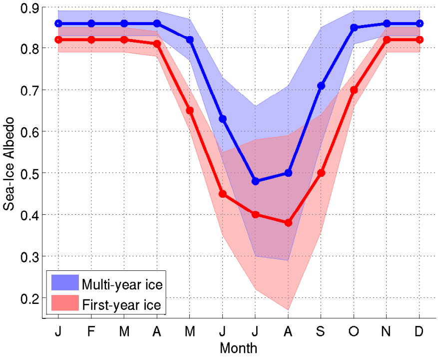

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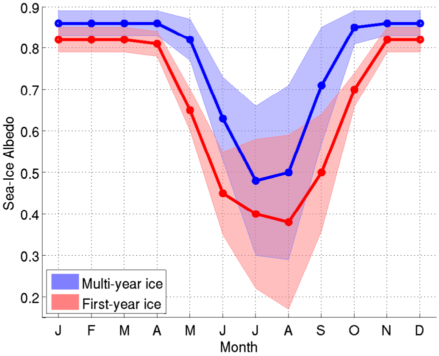
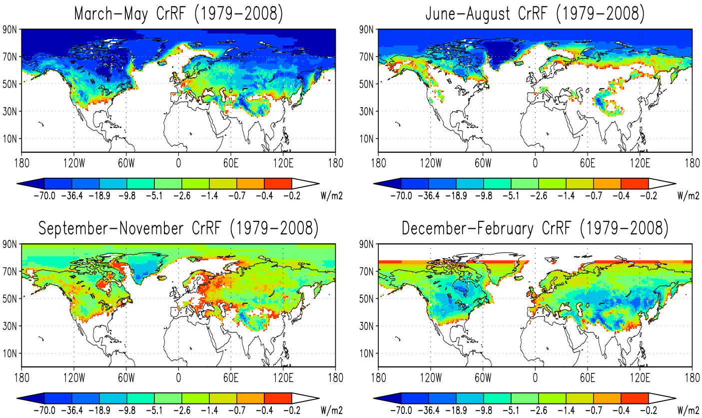


- Ranges indicate variability applied in min/max $\Delta\alpha_{\text{ice}}$ scenarios
- Substantial darkening during summer melt
- First-year ice tends to be darker because of greater morphological susceptibility to ponding and tendency to be thinner

1979–2008 mean cryosphere forcing (log-scale)



- Annual-mean N. Hemisphere CrRF over land: $-2.0 \pm 0.8\,\mathrm{W\,m^{-2}}$
- Over sea-ice: $-1.3 \pm 0.4\,\mathrm{W\,m^{-2}}$

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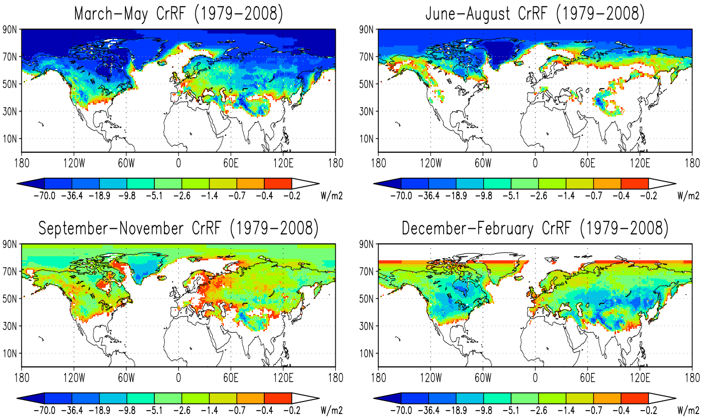

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- Sea-ice estimate from *Hudson* (2011): $-1.36\,\mathrm{W\,m^{-2}}$

Cryosphere forcing produced with different methods

Table: N. Hemisphere CrRF [$\mathrm{W\,m^{-2}}$] averaged over 1979–2008

Kernel ($\partial F/\partial\alpha$)	Albedo contrast ($\Delta\alpha$)		
	Low	Central	High
CAM3	–2.3	–3.1	–3.9
AM2	–2.7	–3.6	–4.4
ISCCP	–2.2	–3.1	–4.0
APP-x	–2.6	–3.6	–4.6
CAM3 clear-sky	–4.5	–6.1	–7.7
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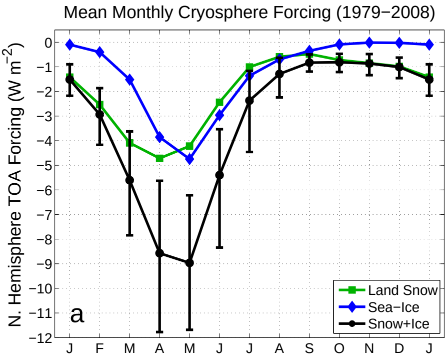
- Clouds mask slightly less than half of the cryosphere radiative impact. Consistent with *Qu and Hall* (2005, 2007).

Seasonal cycle of cryosphere forcing



- Peak season for CrRF land: March–May

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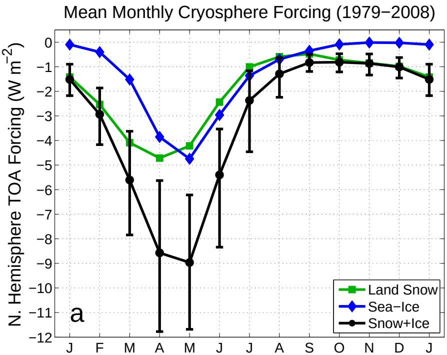

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- In May, the Northern Hemisphere reflects an additional $\sim 9\,\mathrm{W\,m^{-2}}$ to space because of the cryosphere

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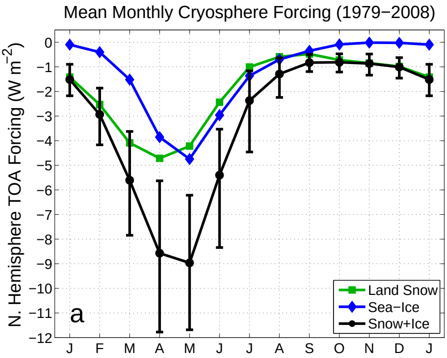
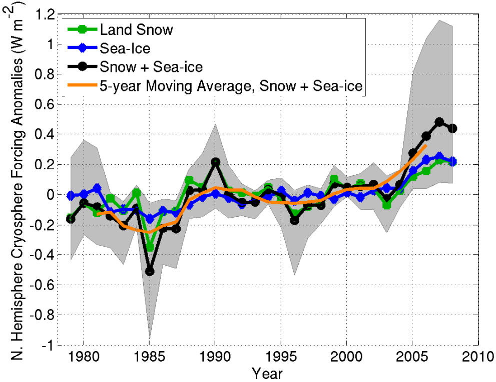


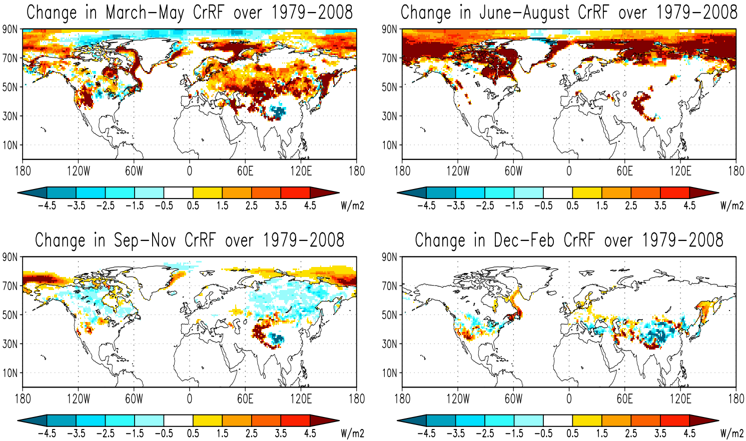
- Peak season for CrRF land: March–May
- In May, the Northern Hemisphere reflects an additional $\sim 9\,\mathrm{W\,m^{-2}}$ to space because of the cryosphere
- Larger sea-ice effect in May than June because:
  1. Larger areal coverage
  2. Ice is more reflective (snow cover)

1979–2008 evolution of cryosphere forcing



- 30-year trends determined from anomalies in CrRF

1979–2008 change in cryosphere forcing



- 30-year change in land CrRF: $+0.22\ (0.11 - 0.41)\ \mathrm{W\,m^{-2}}$
- 30-year change in sea-ice CrRF: $+0.22\ (0.15 - 0.32)\ \mathrm{W\,m^{-2}}$

1979–2008 change in CrRF: Seasonal cycle

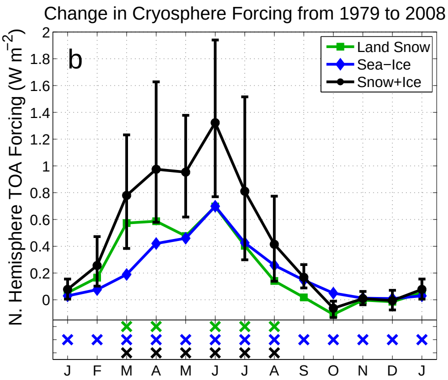


Figure: 'X' indicates month of statistically-significant change ($p = 0.01$)

- Sea-ice peak change occurs in **summer**

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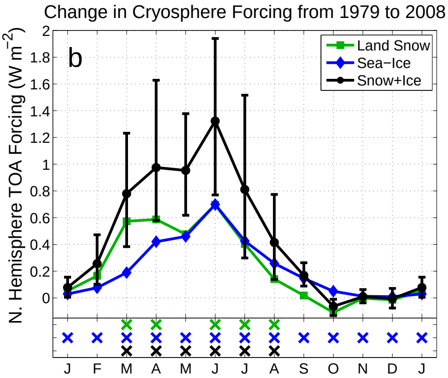

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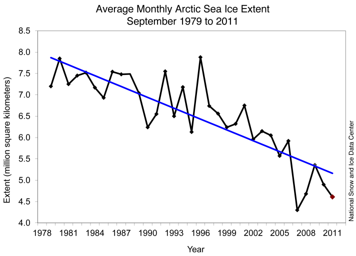
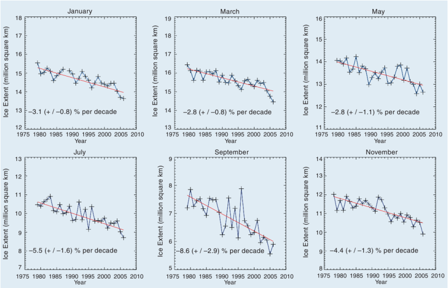
- June peak in land snow change is sensitive to mountain snow cover estimates (Himalaya, Tien Shan)

Changes in sea-ice extent



(a) September ice extent (NSIDC)



(b) Serreze et al (2007)

- Largest changes in extent have occured in September, but associated radiative perturbation is only modest

Change in CrRF produced with different methods

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Kernel ($\partial F/\partial\alpha$)	Albedo Contrast ($\Delta\alpha$)		
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CAM3	0.26	0.38	0.48
AM2	0.29	0.40	0.49
ISCCP	0.40	0.57	0.72
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- CrRF *changes* are greater with annually-varying cloud conditions (ISCCP and APP-x) than with single-year model kernels
- Coupled cryosphere–cloud evolution needs to be studied on different scales (e.g., *Kay and Gettelman*, 2009)

Climate feedback components

- Climate sensitivity (λ) can be quantified in terms of parallel feedback mechanisms (i) as:

$$\lambda = -\left(\sum_{i=1}^{N} \frac{\partial F_i}{\partial T_s}\right)^{-1} \qquad [\mathrm{K\,(W\,m^{-2})^{-1}}] \tag{2}$$

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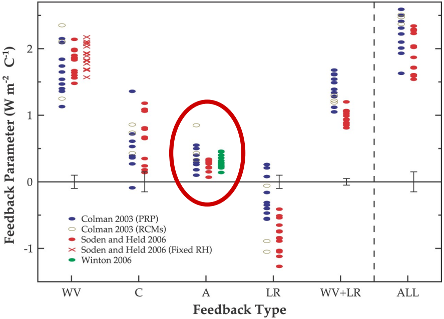

- IPCC AR4 figure 8.14
- WCRP CMIP3 global albedo feedback: $\sim 0.3\,\mathrm{W\,m^{-2}\,K^{-1}}$ (*Winton*, 2006; *Soden et al.*, 2008; *Shell et al.*, 2008)

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- Global cryosphere feedback is less because SH sea-ice extent has increased (e.g., *Cavalieri and Parkinson*, 2008)

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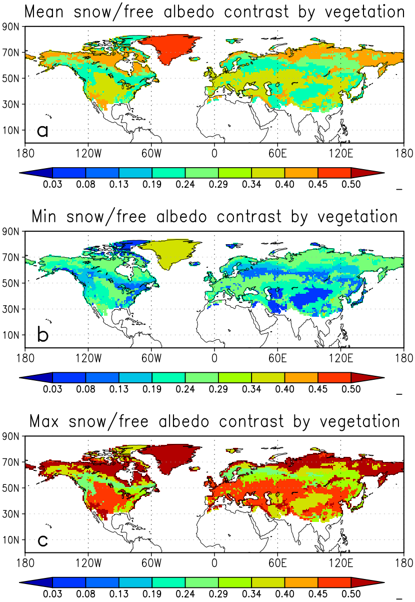
- Thanks to WCRP for supporting CMIP archive

Albedo contrast variability



- Minimum, central, and maximum $\Delta\alpha_{snow}$ products derived from variance in albedo contrast by land classification.
- This variability is caused by:
  1. Unresolved snow cover variability within the binary snow product
  2. Variability in the influence of vegetation (within each land class) on albedo contrast

MODIS albedo and variability by land class

	Snow-covered albedo		Snow-free albedo	
UMD Land Class	μ	σ	μ	σ
Evergreen Needleleaf forest	0.31	0.07	0.10	0.02
Evergreen Broadleaf forest	–	–	0.14	0.01
Deciduous Needleleaf forest	0.36	0.06	0.12	0.01
Deciduous Broadleaf forest	0.35	0.08	0.14	0.02
Mixed forest	0.34	0.09	0.12	0.02
Closed shrublands	0.59	0.06	0.15	0.02
Open shrublands	0.60	0.12	0.19	0.05
Woody savannas	0.42	0.08	0.14	0.02
Savannas	0.49	0.09	0.16	0.02
Grasslands	0.55	0.13	0.19	0.04
Croplands	0.55	0.10	0.16	0.03
Urban and built-up	–	–	0.12	0.02
Barren or sparsely vegetated	0.48	0.14	0.26[c]	0.07
Greenland	0.76	0.07	–	–

Factors influencing model land cryosphere forcing

- 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