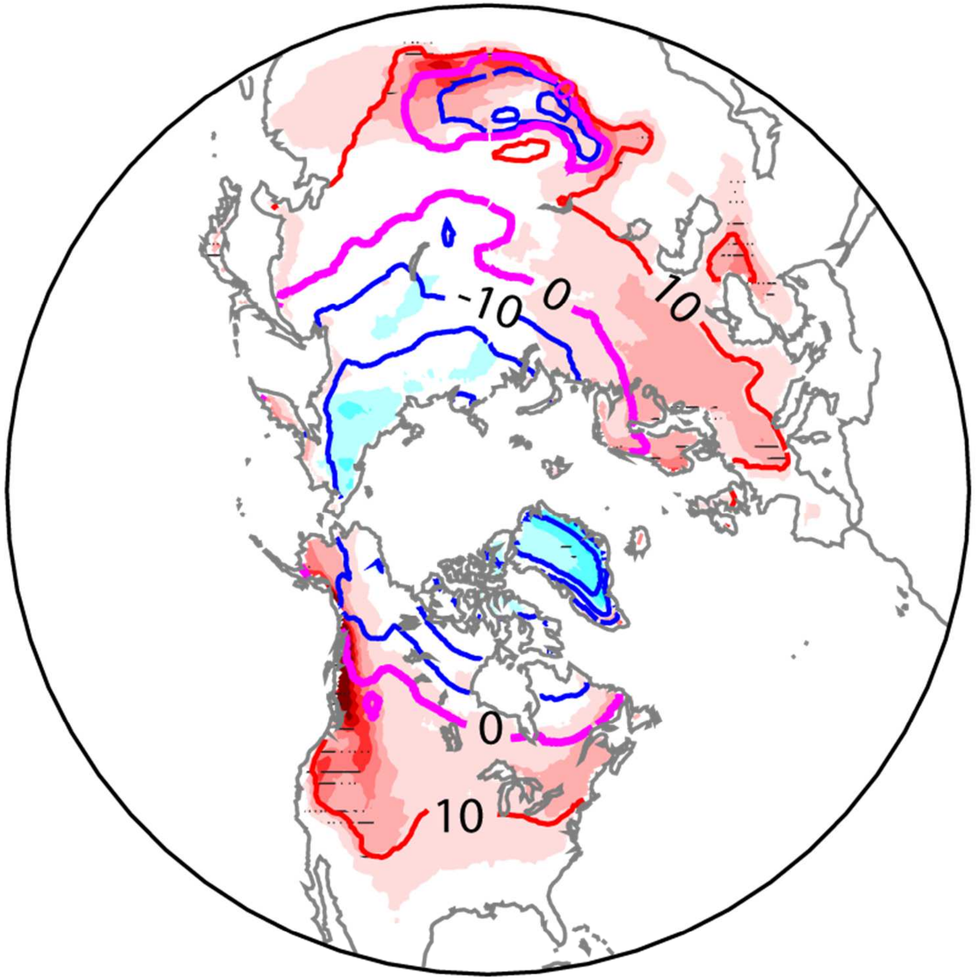
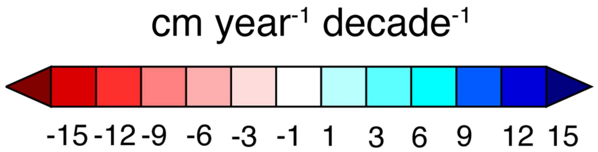
Response of snowfall extremes to climate change: theory and simulations

Paul O'Gorman, MIT

Workshop on Water in the Climate System, 2014

Simulations of climate warming: declines in annual-mean snowfall in many regions





CMIP5 multimodel mean trends in snowfall depth (2006-2100 based on rcp4.5)

Contours of 2m temperature shown in degrees Celsius for 1986-2005

Krasting et al, J. Climate, 2013

What about snowfall extremes?
(heavy daily snowfall events)

- Important because of disruption of transportation (roads, air, rail), business, schools

- May not respond to climate change like mean snowfall
  e.g., heavy snowfall events in both anomalously cold and warm years (Kunkel et al, 2013; Changnon et al 2006)

Regional studies of observed snowfall extremes: Decadal variability but inconsistent long-term trends

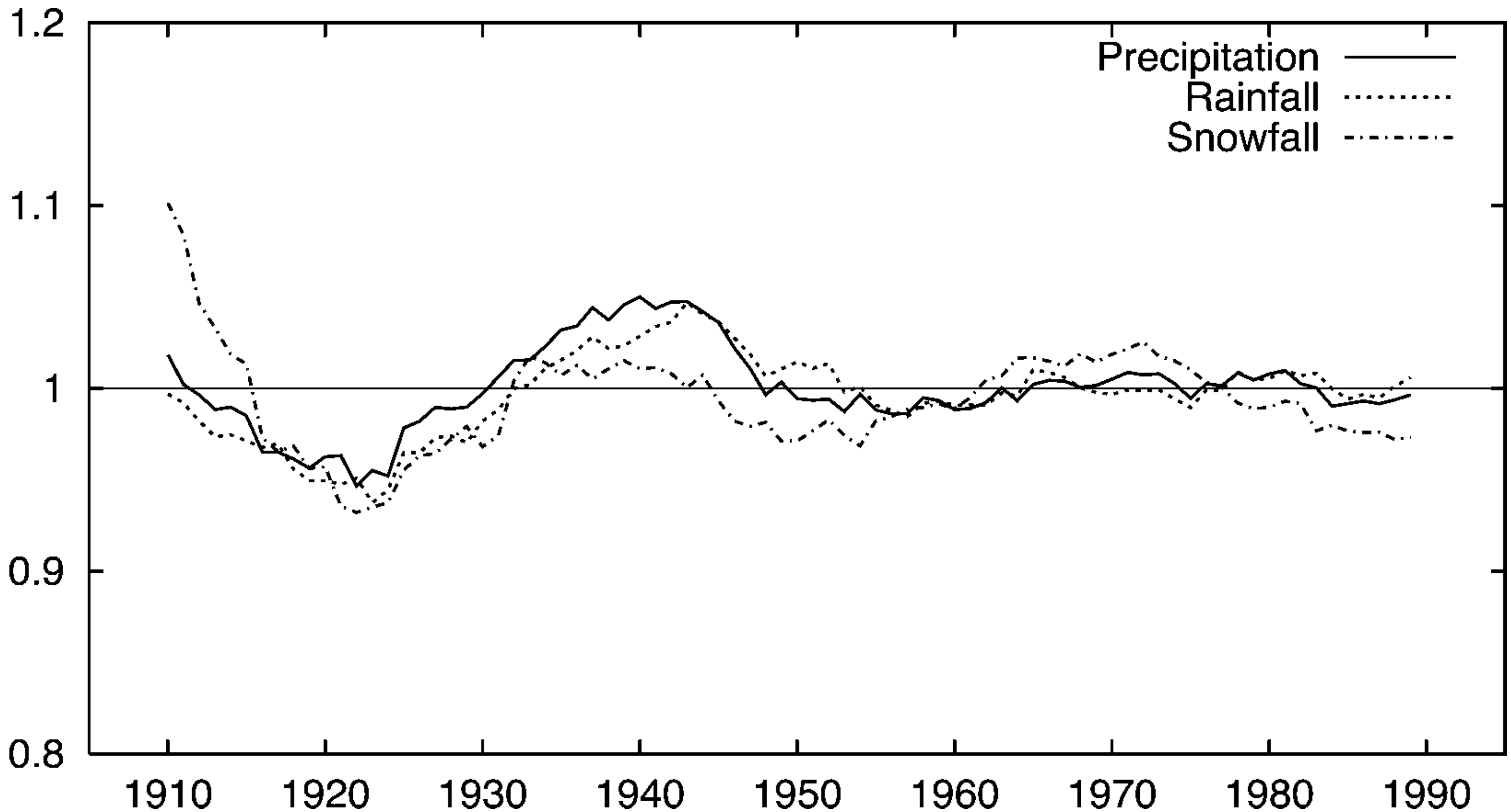


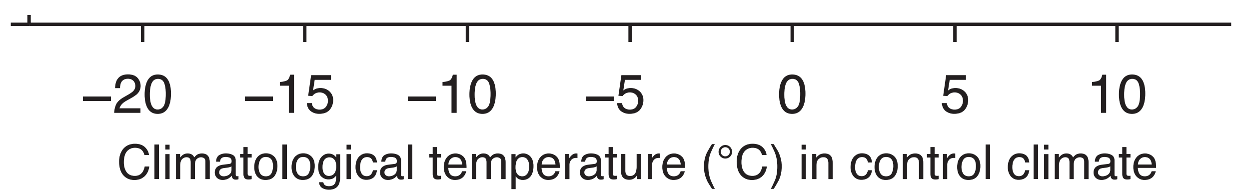
FIG. 6. Nationally averaged 20-yr return values (relative to the values for 1971–90) of annual maximum daily precipitation, rainfall, and snowfall. The 20-yr return values are first estimated using 20-yr running windows for every station, and then normalized by the values estimated for the period 1971–90. Values are plotted in the center of the 20-yr window.

Zhang et al, J. Climate, 2001 (Canadian observations)

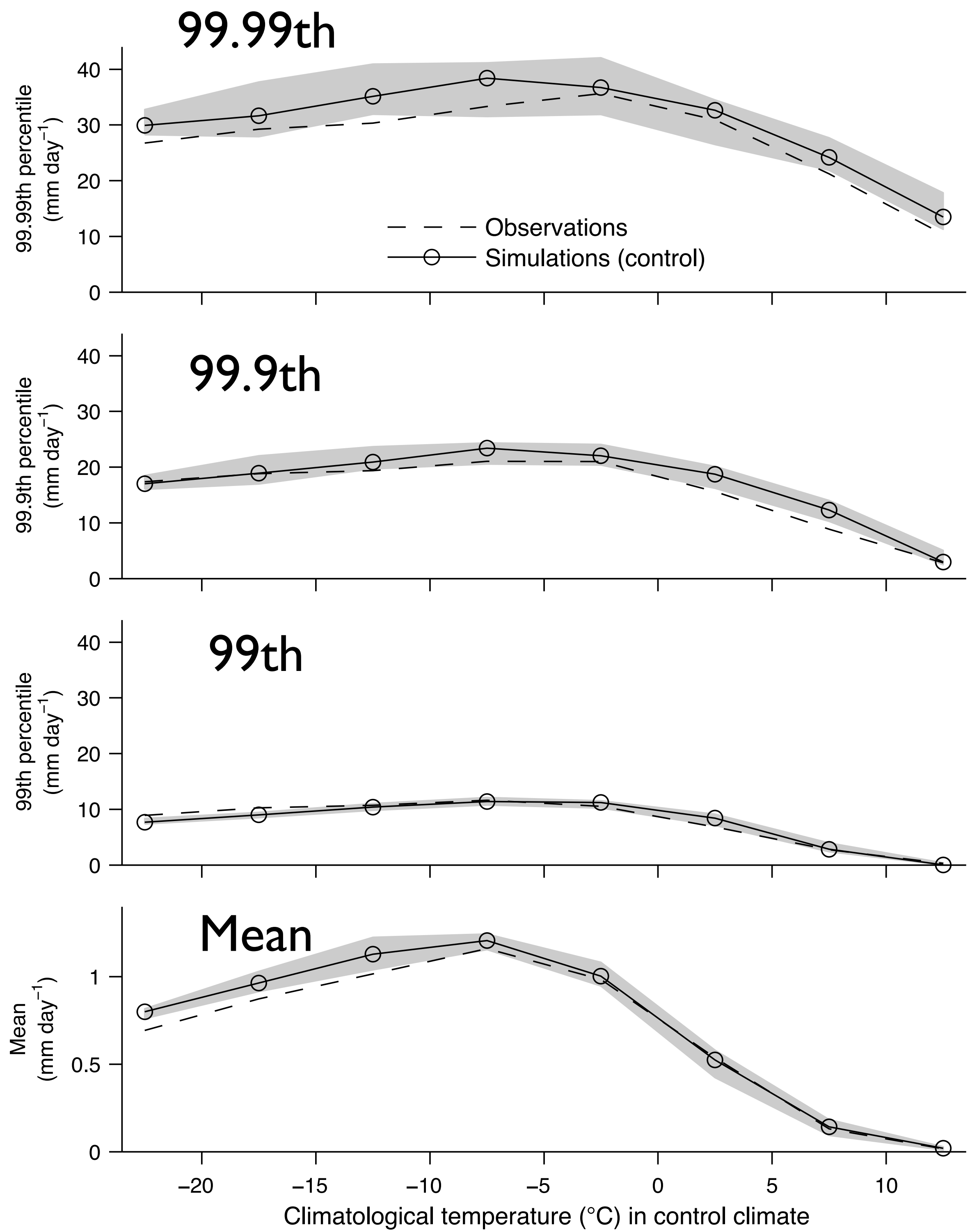
Effect of climate change on daily snowfall extremes in global simulations

- High percentiles of daily snowfall in liquid water equivalent
- CMIP5 (use 20 models) under RCP8.5
- Compare warm climate (2081-2100) to control climate (1981-2000)

Analyze according to climatological temperature in control climate



Grid boxes and days binned by climatological monthly surface air temperature in control climate

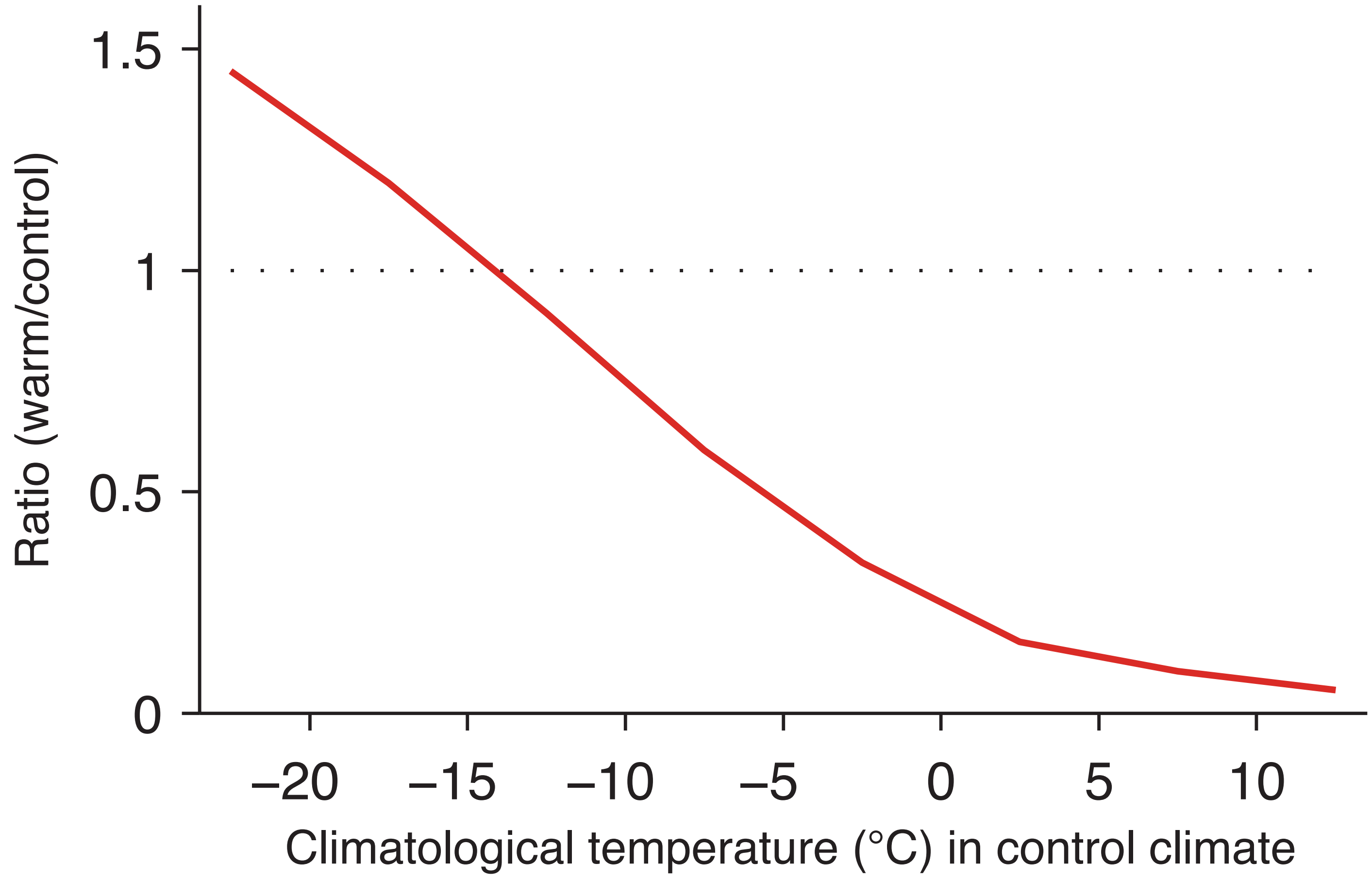


Simulated snowfall extremes compare well with estimates from observations

Northern hemisphere land only

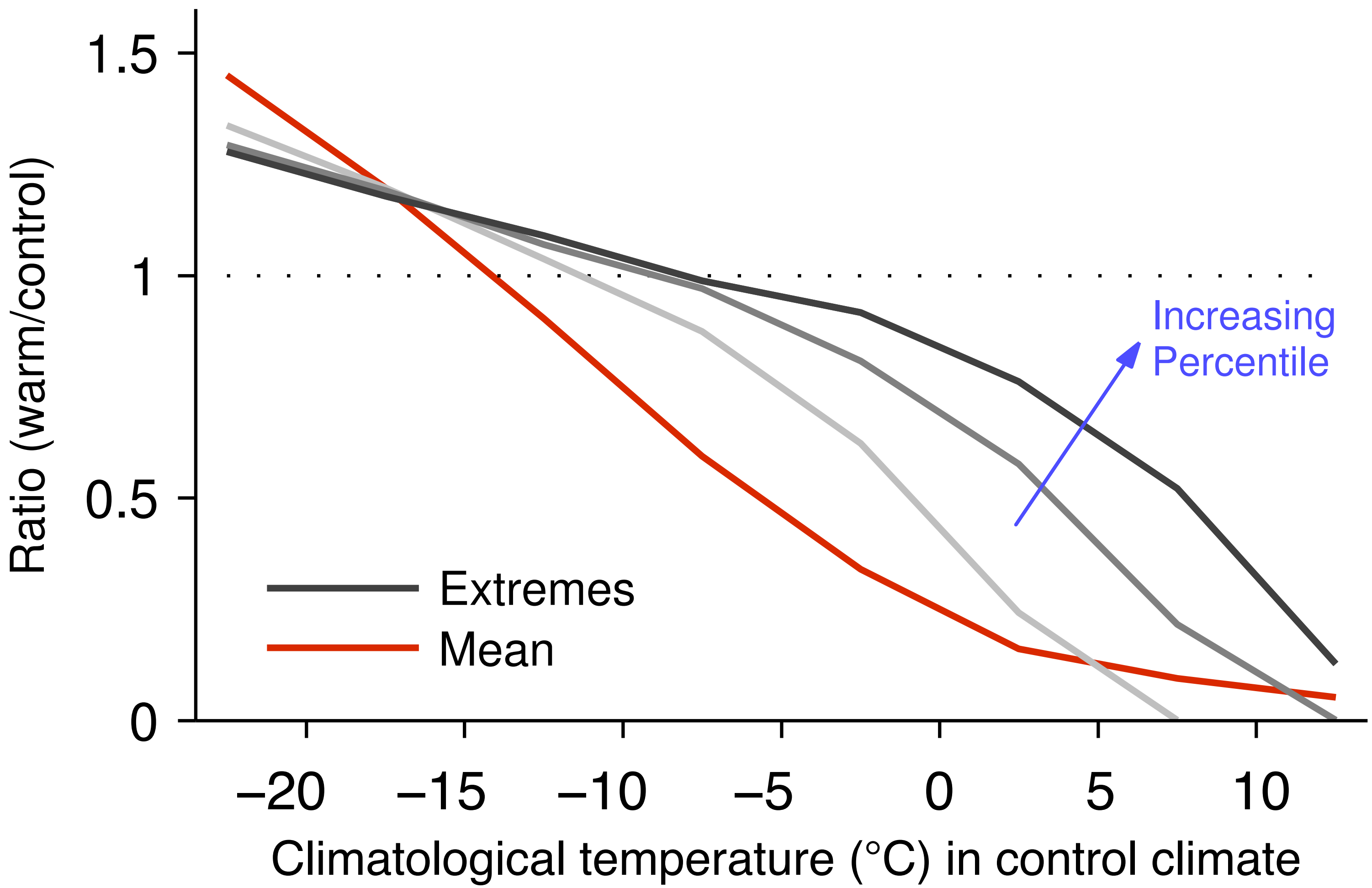
Observational estimates based on daily precipitation rates (GPCP 1DD), snowfall fraction (Feiccabrino et al 2013), and daily surface temperatures (NCEP2)

Response of mean snowfall to climate warming: ratio of warm over control-climate values



(Northern Hemisphere land below 500m)

Weaker response of daily snowfall extremes as compared to mean snowfall



99th, 99.9th and 99.99th percentiles of daily snowfall

Features of the response of snowfall extremes that would like to understand:

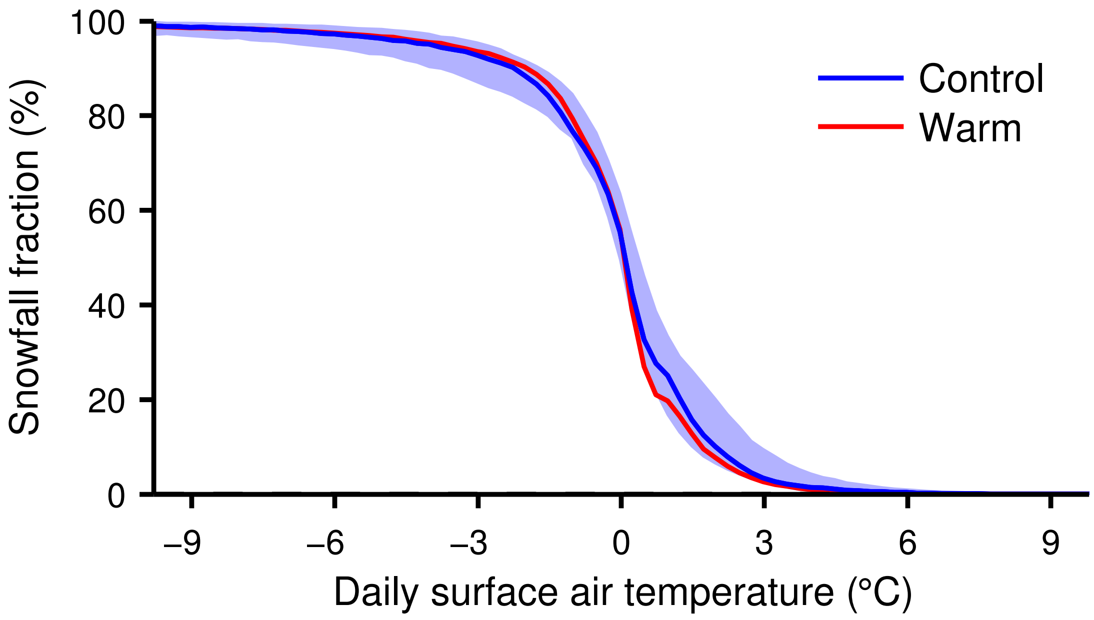
- Climatological temperature at which snowfall extremes response goes from positive to negative
- Weaker fractional changes at higher percentiles

Simple theory (based on known physics/ observations) for the response of snowfall extremes to changes in climate

Theory assumptions 1:
Relate daily snowfall rate (s) to precipitation rate (p) and surface air temperature (T)

$$s = f(T)p$$

Snowfall fraction: $f(T)$



Theory assumptions 2:
Relate precipitation rate (p) to temperature (T)

$$p = e^{\beta T}\hat{p}$$

$$\beta = 0.06^{\circ}\mathrm{C}^{-1}$$

- Normalized precipitation variable $\hat{p}$ behaves like upward velocity; follows gamma distribution on wet days
- Temperature is normally distributed and independent of $\hat{p}$

Integral expression for qth percentile of snowfall (s_q)

$$1 - \frac{q}{100} = \int_{-\infty}^{\infty} dT \int_{hs_q}^{\infty} d\hat{p}\, \frac{w\gamma^k}{\Gamma(k)}\, \hat{p}^{k-1}\, e^{-\gamma\hat{p}}\, \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(T-\overline{T})^2}{2\sigma^2}}$$

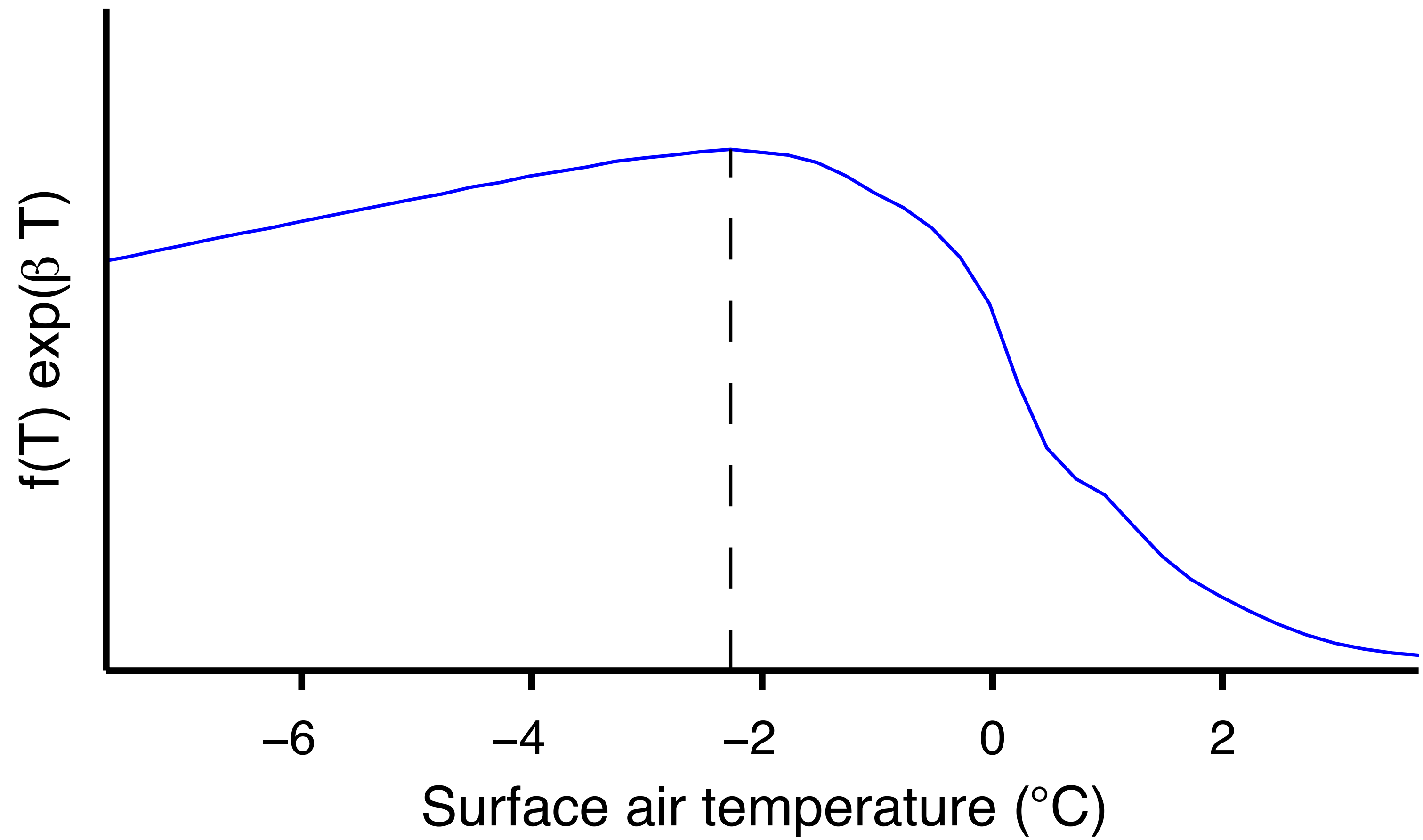
where the fraction of wet days is w and $h(T) = e^{-\beta T} f(T)^{-1}$

→ Evaluate using asymptotic methods for large s_q

Asymptotics gives expression for snowfall extremes that involves optimal temperature T_m

$$\left(\gamma s_q h_m\right)^{\frac{3}{2}-k} e^{\gamma s_q h_m} = \frac{w}{\sigma\left(1-\frac{q}{100}\right)\Gamma(k)}\sqrt{\frac{h_m}{h''_m}}e^{-\frac{(\overline{T}-T_m)^2}{2\sigma^2}}$$

Temperature dependence of snowfall reaches a maximum at T_m (roughly -2°C)



Competition between increasing precipitation and decreasing snowfall fraction with increasing temperature

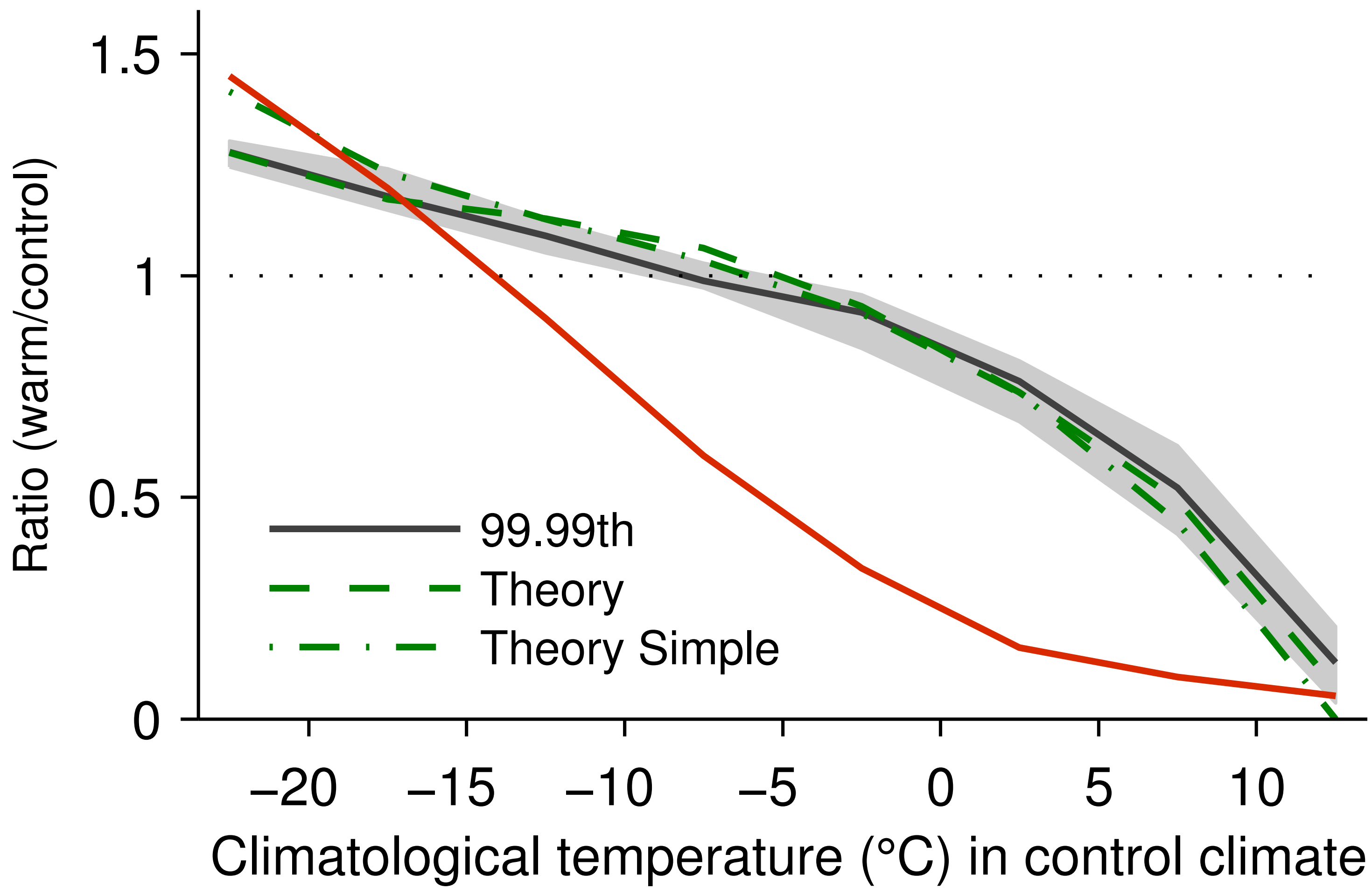
Simple result if only mean temperature changes

$$\delta s_q = -\frac{\delta\overline{T}}{\sigma^2\gamma h_m}\left(\overline{T} + \frac{\delta\overline{T}}{2} - T_m\right)$$

δs_q	Change in q[th] percentile of snowfall with climate change
$\delta\overline{T}$	Change in mean temperature
σ^2	Variance of daily temperature
T_m	Optimal temperature
γh_m	Inverse precipitation scale

Theory matches simulations

(and dynamic changes don't matter very much)



Shading shows interquartile range of model ratios

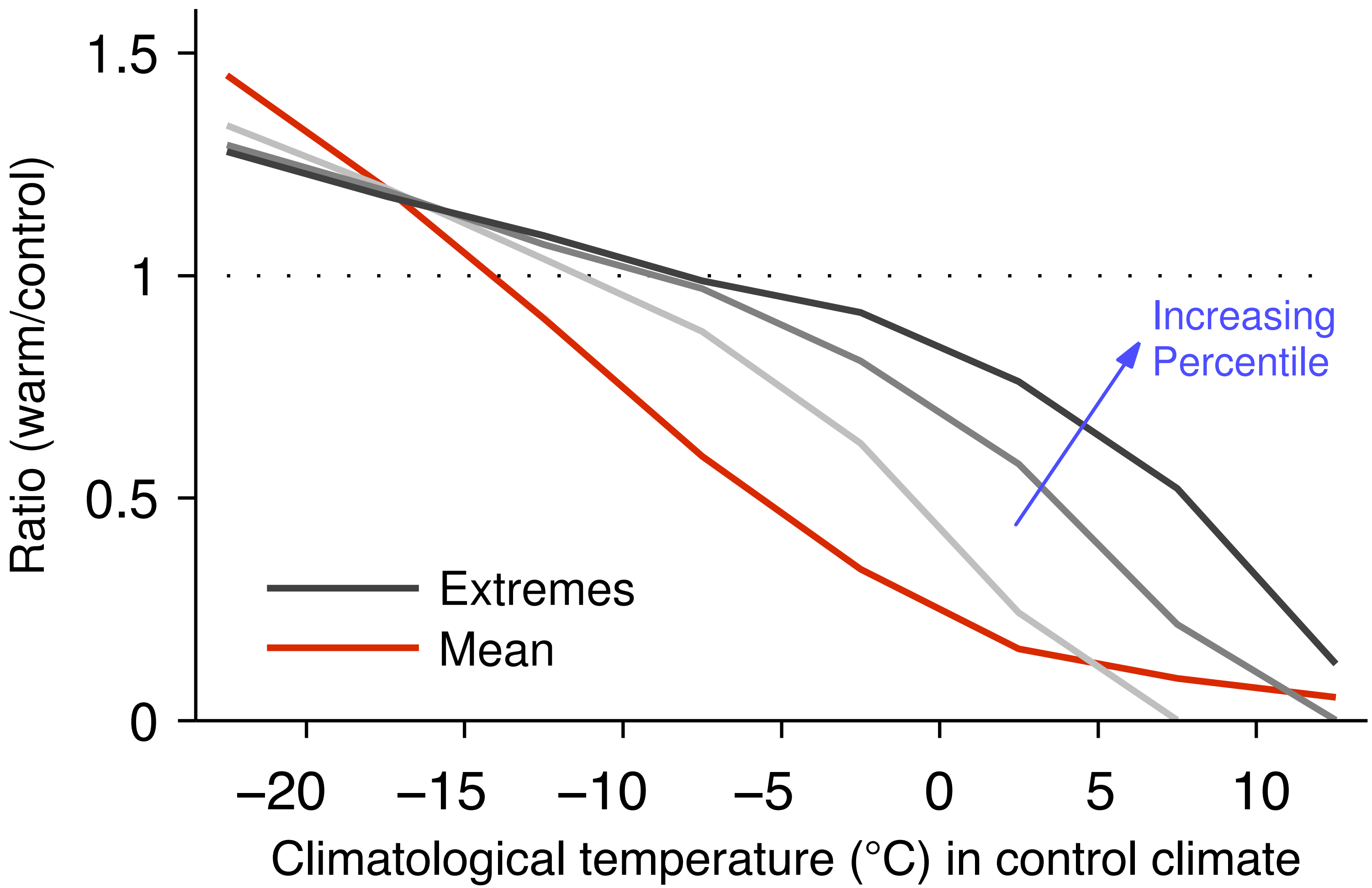
Changes in snowfall extremes don't depend on percentile q!

$$\delta s_q = -\frac{\delta \overline{T}}{\sigma^2 \gamma h_m} \left(\overline{T} + \frac{\delta \overline{T}}{2} - T_m \right)$$

Example: same change for 99th percentile as 99.99th percentile

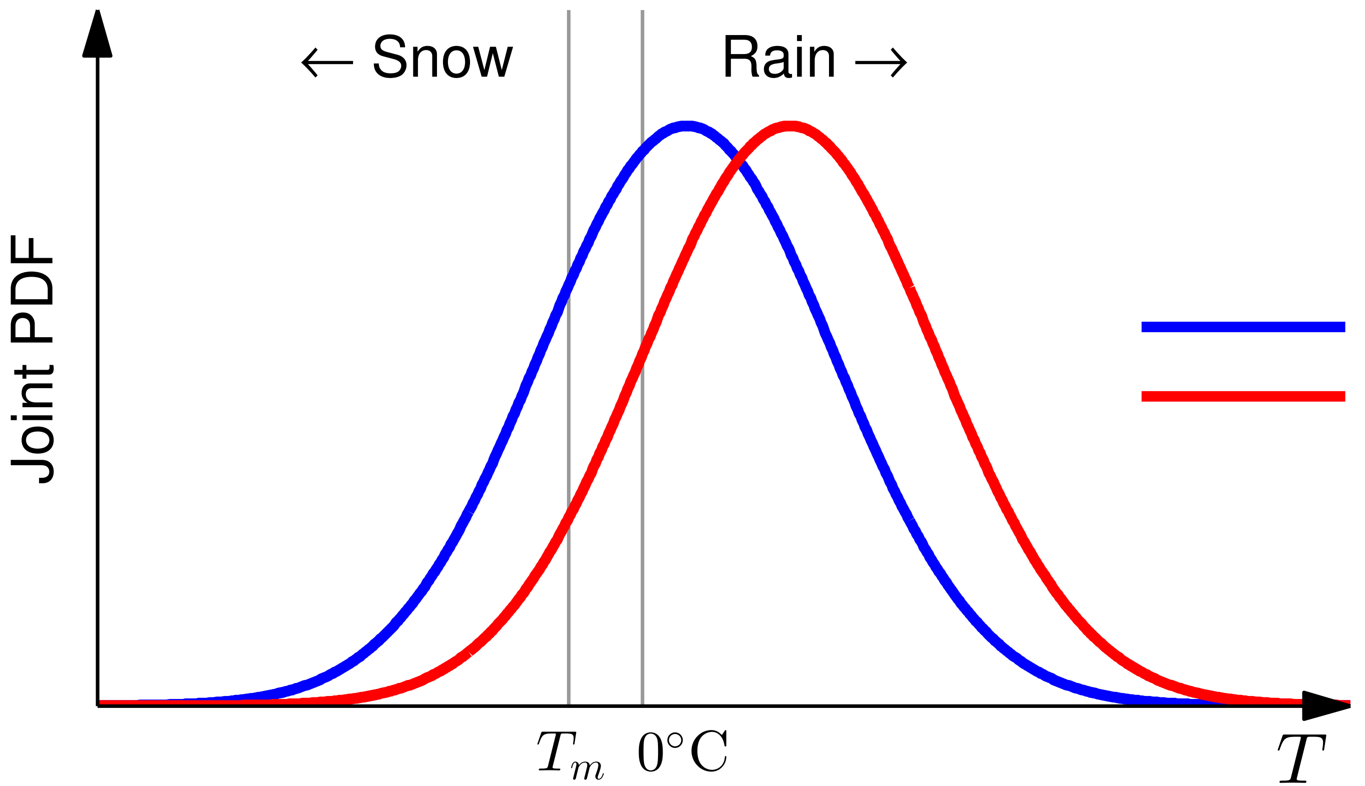
$$\Rightarrow \ \delta s_q / s_q \rightarrow 0 \text{ as } s_q \rightarrow \infty$$

Fractional changes in snowfall extremes tend to zero for high percentiles



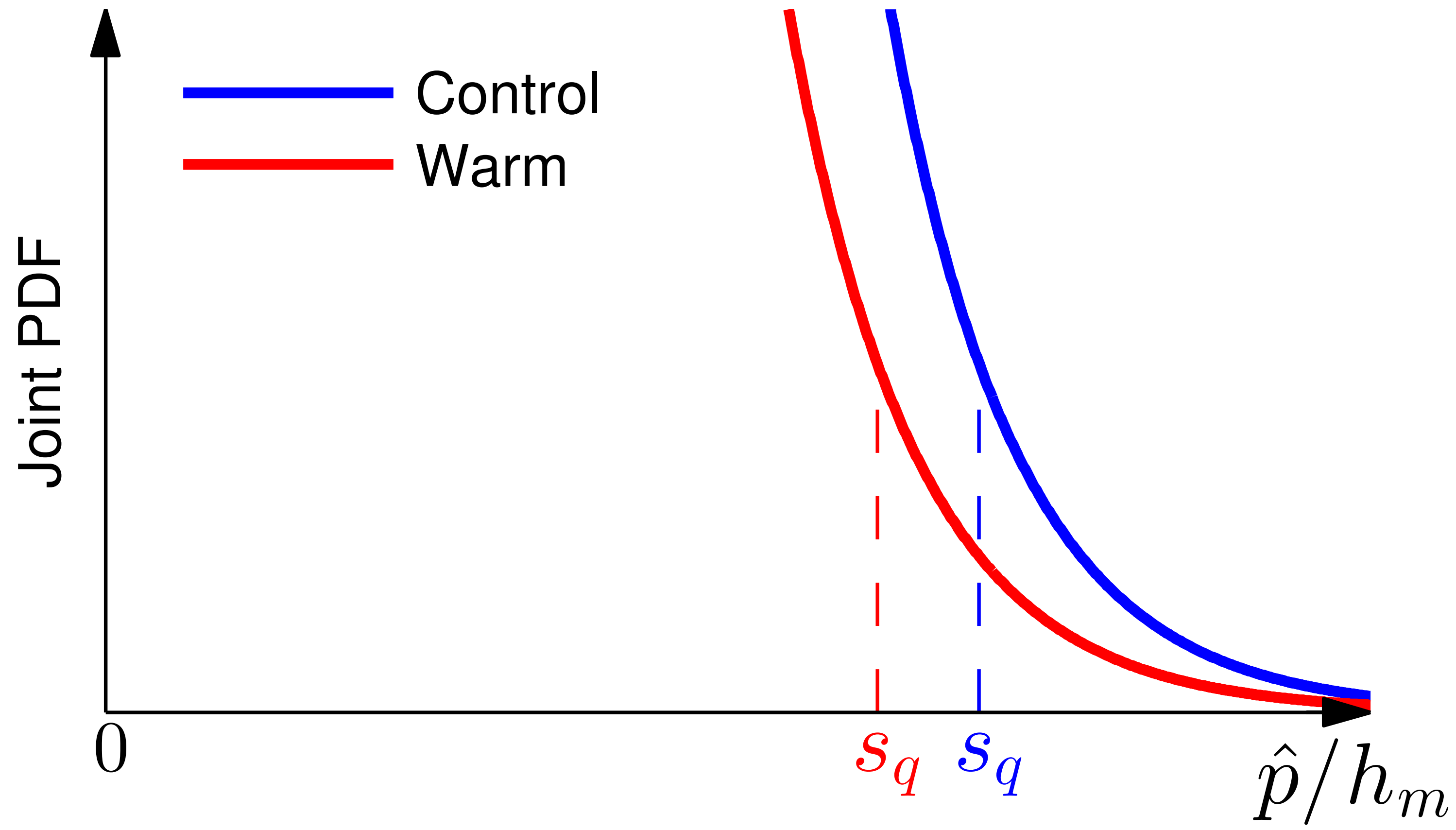
99th to 99.99th percentiles of daily snowfall

Intuition: Probability of optimal temperature (T_m) for snowfall extremes does change as climate warms

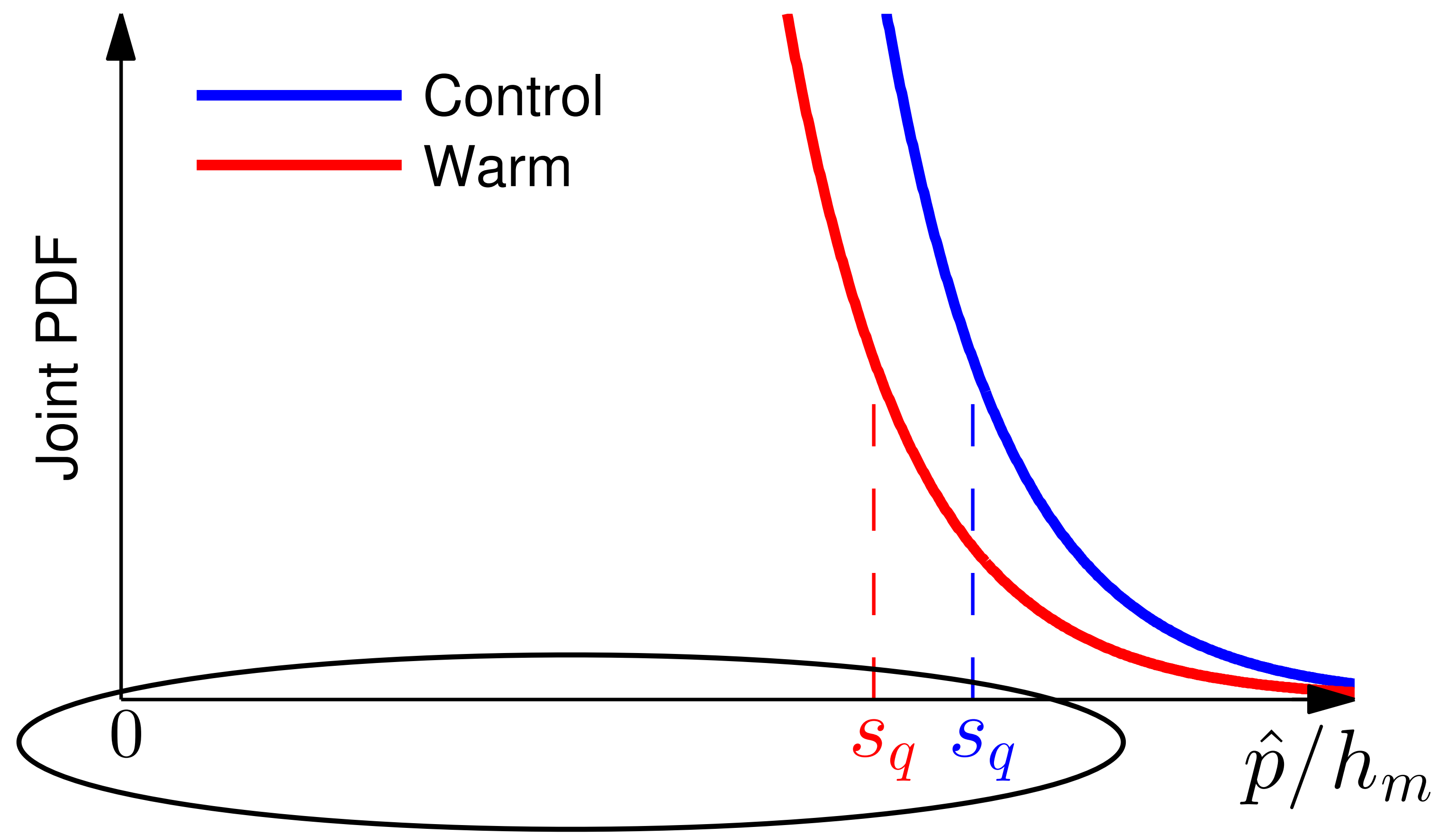


Also mean snowfall decrease substantially

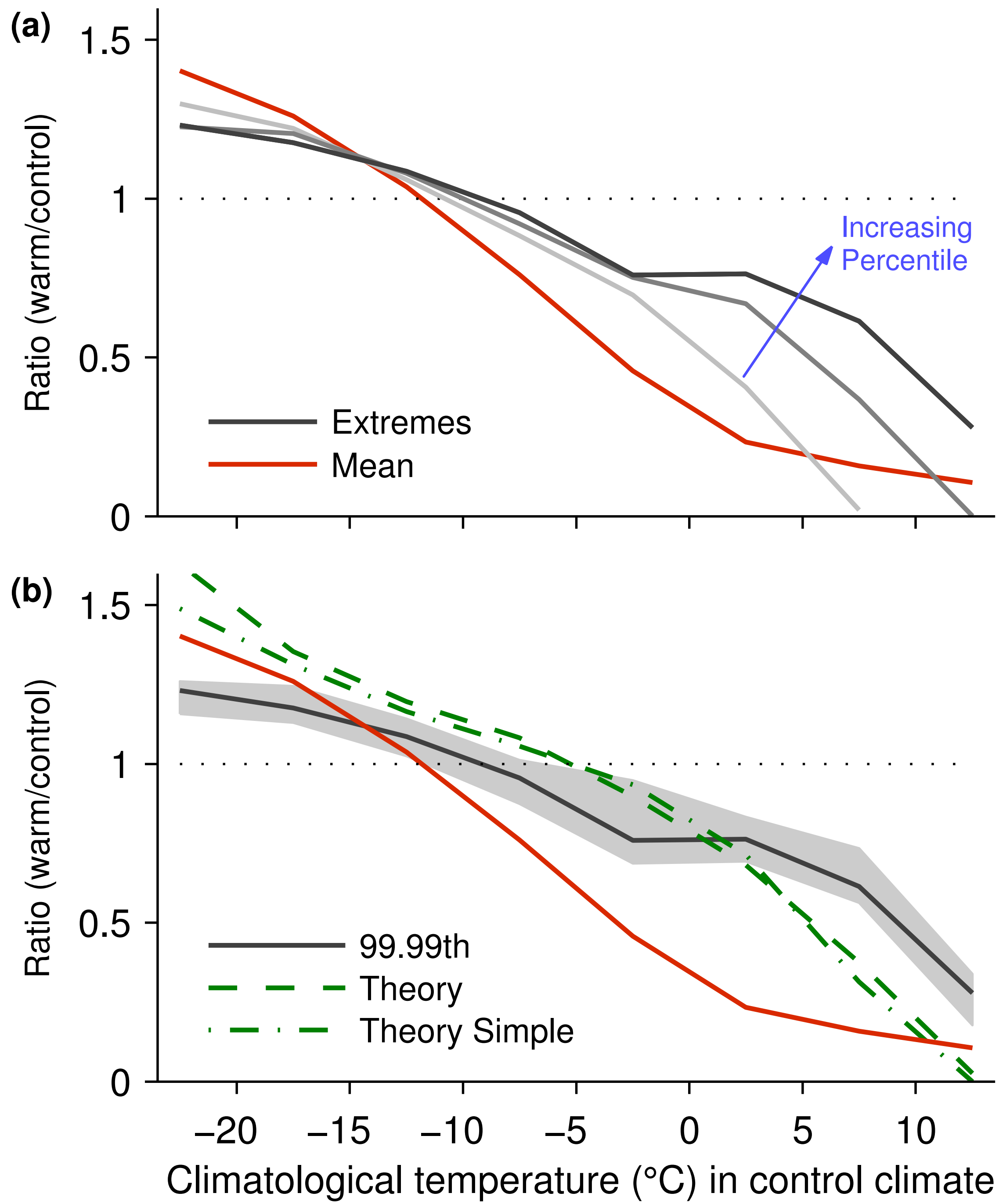
Results in changes in snowfall percentiles



Results in changes in snowfall percentiles



...but fractional change in s_q is fairly small and is similar for all high percentiles



Similar results above 500m elevation (but models have issues there)

cf. Kapnick & Delworth, 2013

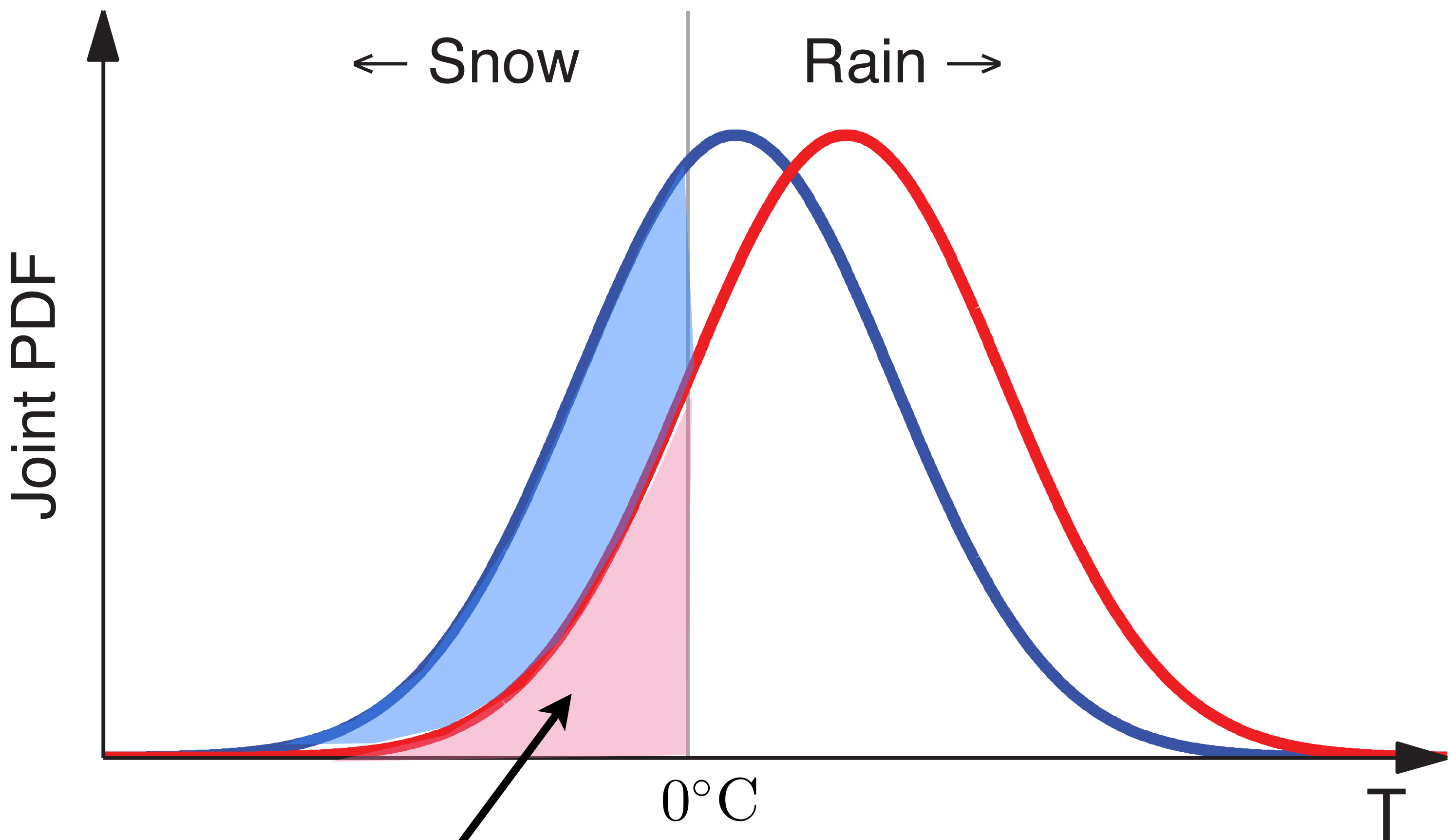
Conclusions

- *Simulations*: Smaller fractional changes in snowfall extremes than in mean snowfall in many cases
- *Simple asymptotic theory:* captures main features of response

$$\delta s_q = -\frac{\delta \overline{T}}{\sigma^2 \gamma h_m}\left(\overline{T} + \frac{\delta \overline{T}}{2} - T_m\right)$$

- *Implications:* detection and perception of climate change, changes in snowfall extremes still likely to have impacts

By contrast:
Probability of snowfall and mean snowfall decrease substantially



Big decrease in area under curve to left of rain-snow transition temperature

Rapidly changing snow cover in Northern Hemisphere

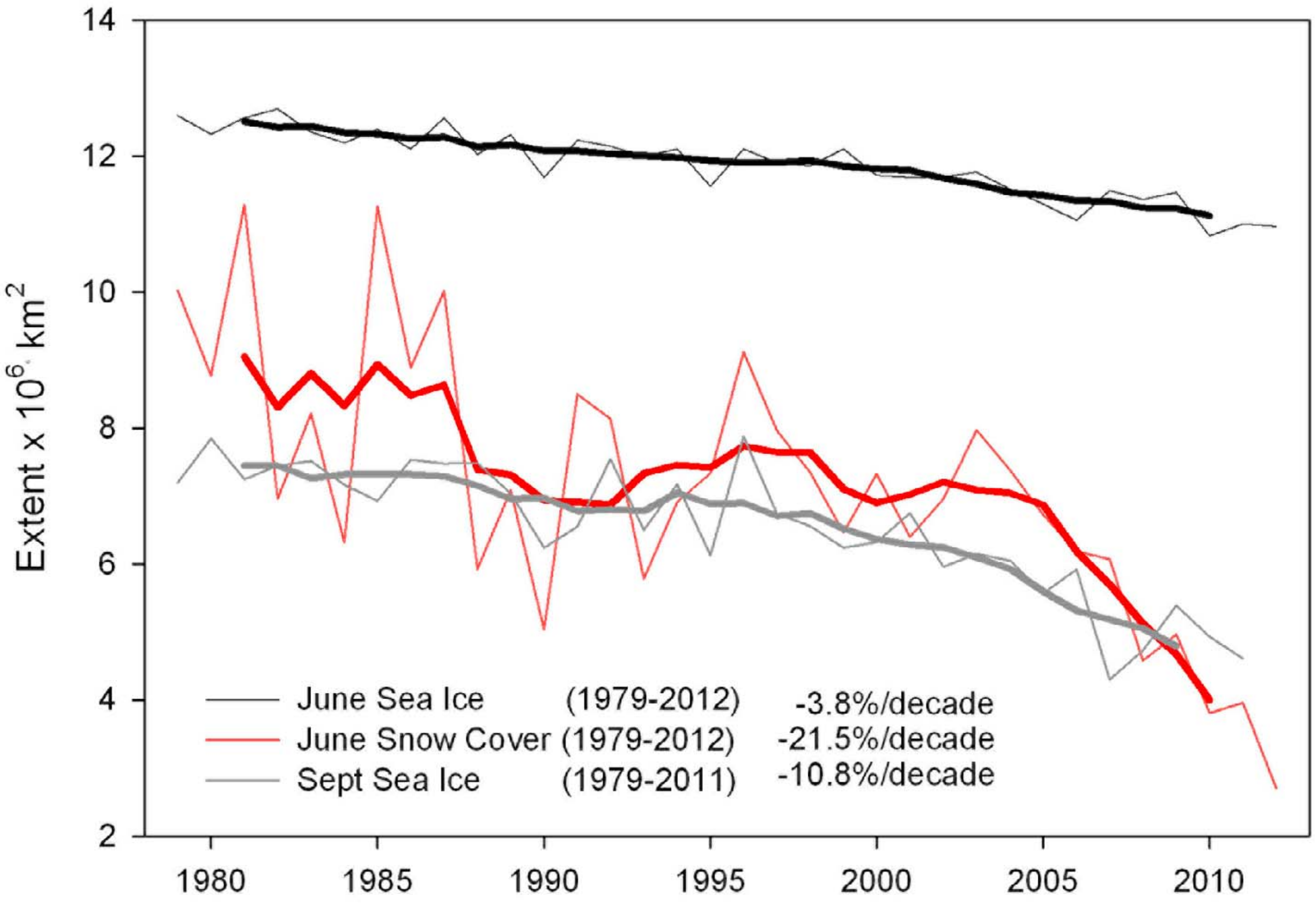
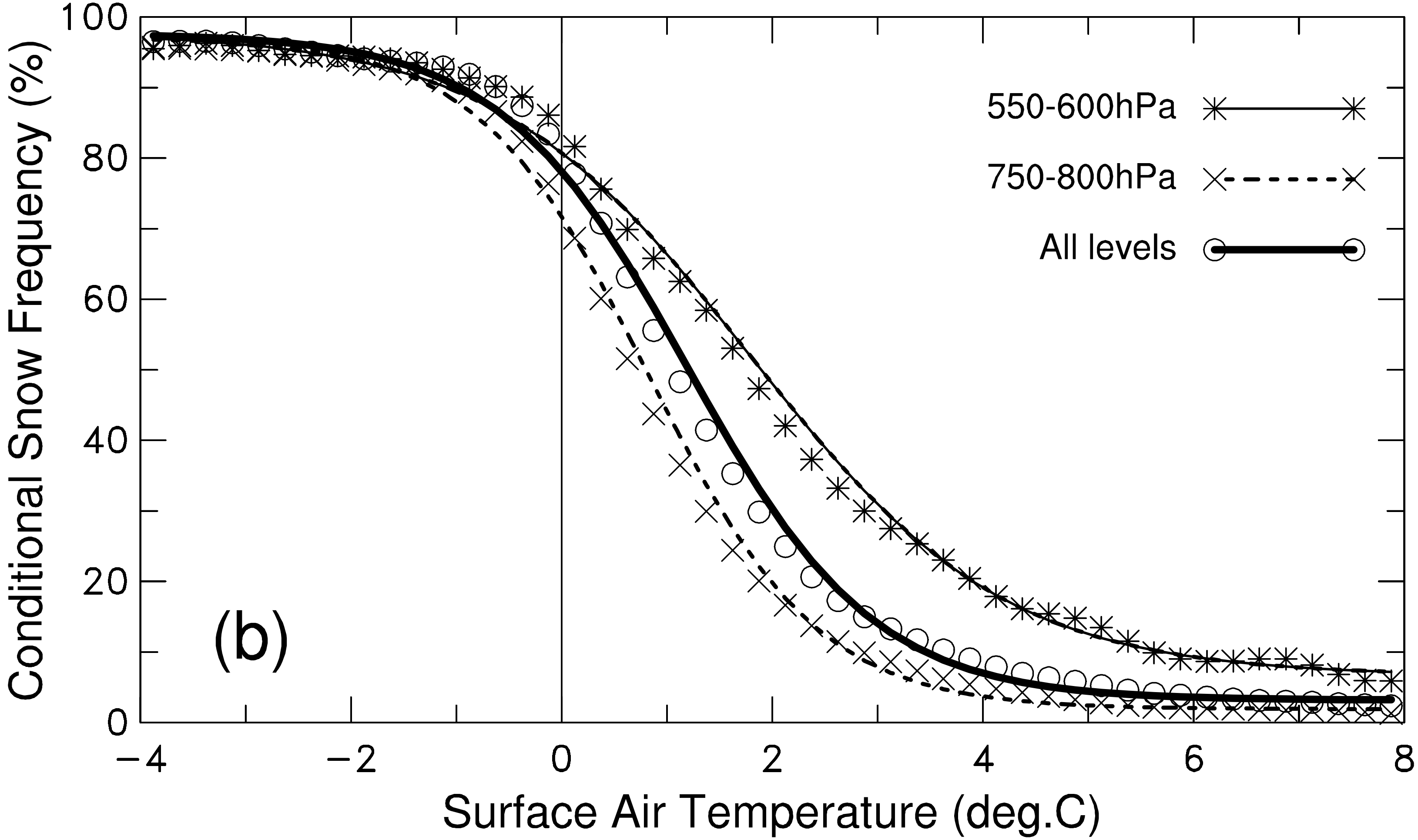


Figure 2. Time series of Northern Hemisphere June snow cover (NOAA snow chart CDR) and sea ice extent (NASA TEAM) for 1979–2012 (1979–2011 for sea ice). Thick line denotes 5-yr running mean.

Derksen and Brown, GRL, 2012

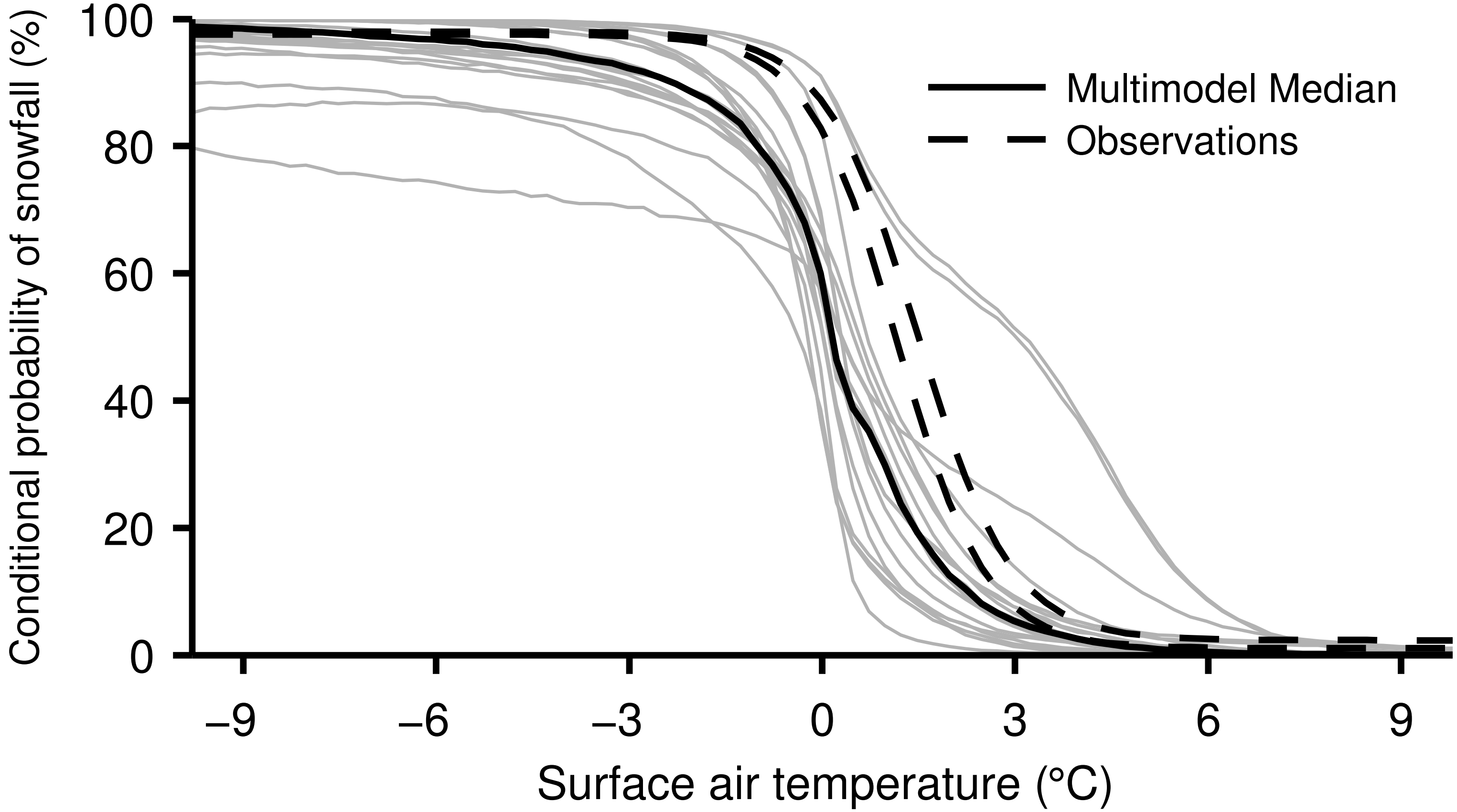
Probability of snowfall given that precipitation occurs



3-hourly synoptic weather reports over land aggregated globally

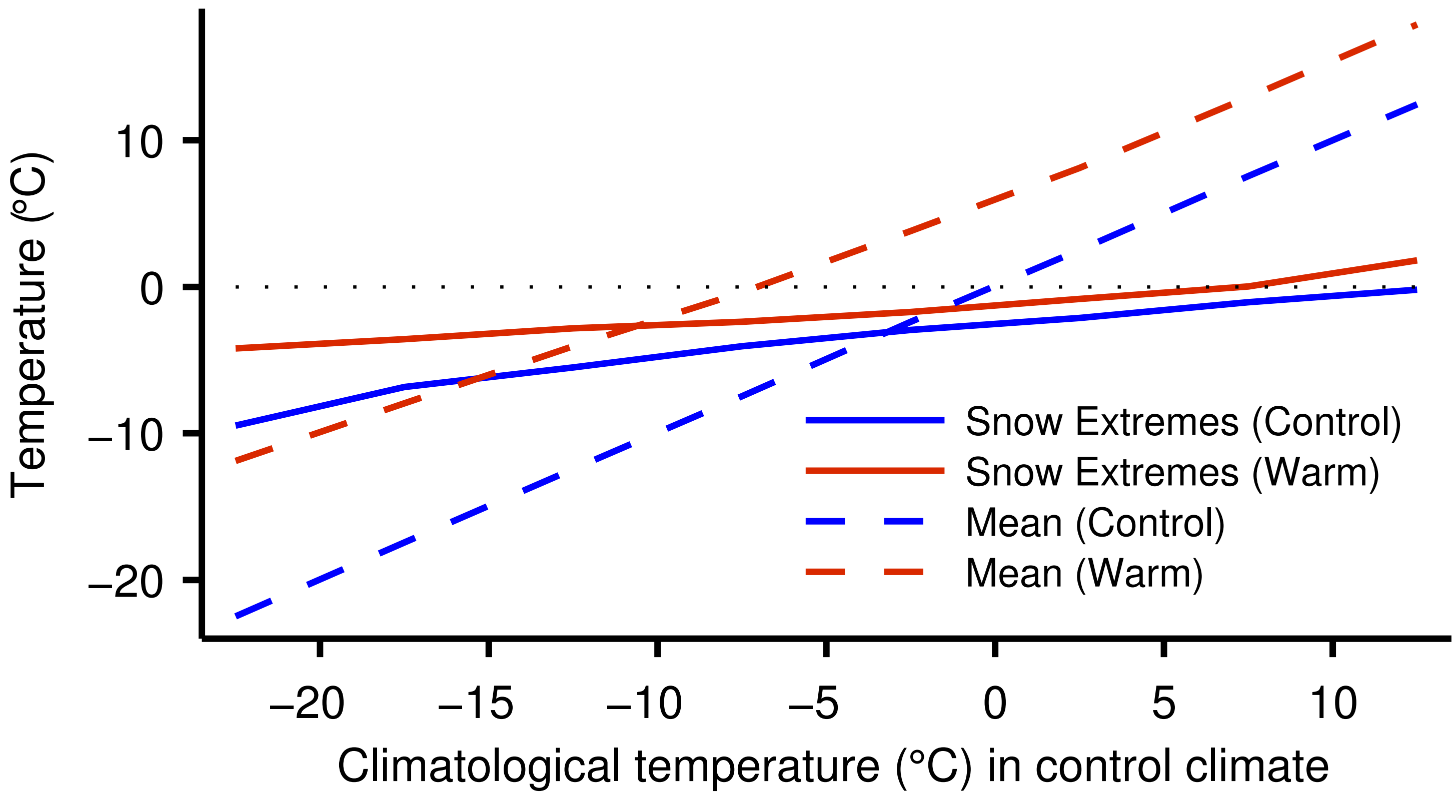
Dai, GRL, 2008

Rain-snow transition in climate models (CMIP5) versus observations



- 3-hourly observed (Dai 2008): 2 curves depending on whether mixed counted as snow
- Daily accumulations in multimodel median (black) and individual models (gray); snowfall taken to occur if precipitation is 50% solid

Intuition: snowfall extremes occur when temperatures close to freezing
(otherwise too cold to snow heavily)



Note snowfall extremes remain at roughly same temperature (with same humidities) as climate changes - unlike rainfall extremes

Quiz: World record daily snowfall

Where?

How much (inches of depth)?

World record (probably): 75.8 inches in 24 hours

RECORD SNOWFALL OF APRIL 14–15, 1921, AT SILVER LAKE, COLORADO

J. L. H. PAULHUS

U. S. Weather Bureau, Washington, D. C.

[Manuscript received January 27, 1953]

ABSTRACT

A snowfall of 87 inches in 27½ hours on April 14–15, 1921, was reported at Silver Lake, Colo. This snowfall, if correctly measured, exceeds others generally accepted as being record values for the United States. Consequently it is important to determine the reliability of the observation. There is no evidence to indicate that the measurement was any less reliable than that of other heavy snowfalls, and it appears that a snowfall of this magnitude is meteorologically possible. The Silver Lake snowfall is therefore acceptable as the highest known recorded value for the United States.

Changes in precipitation extremes: some aspects are well understood!

- Theory

- Climate models

- Observed trends

Theory: factors controlling intensity of precipitation extremes

Saturation specific humidity

Precipitation rate

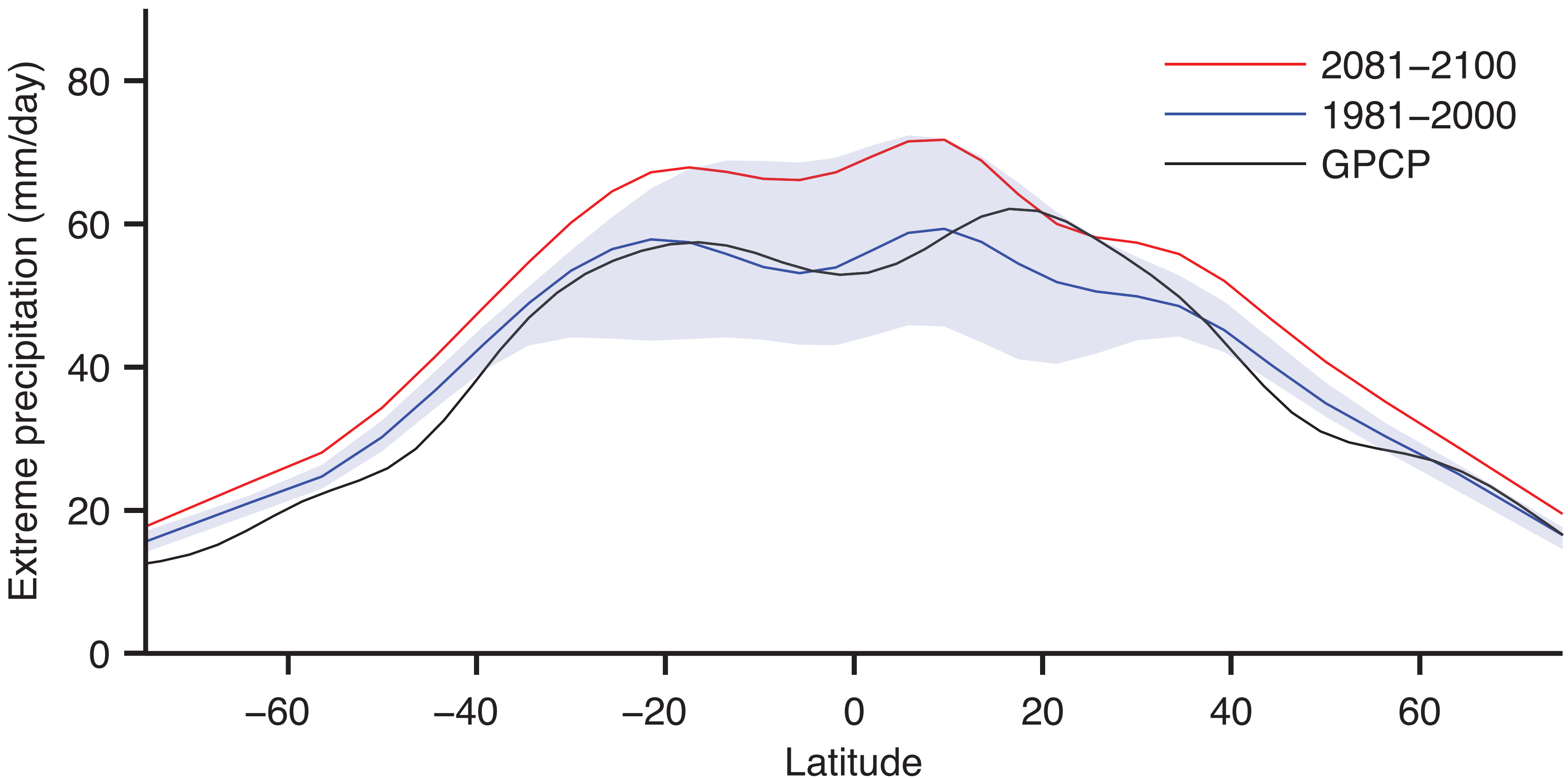
$$P_e \sim -\left\{ \omega_e \left. \frac{dq_s}{dp} \right|_{\theta^*, T_e} \right\}$$

Vertical velocity

Moist adiabatic derivative

O'Gorman and Schneider, PNAS, 2009
O'Gorman and Schneider, J. Climate, 2009

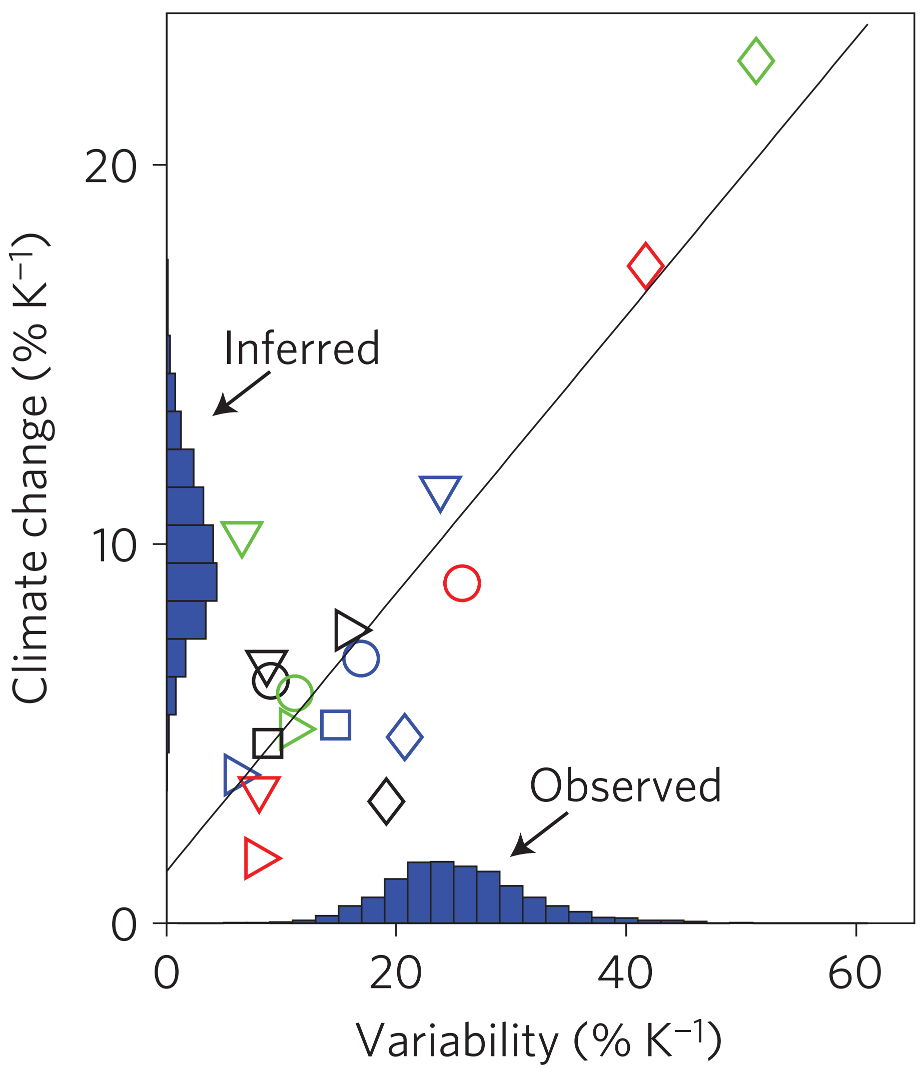
Growth of precipitation extremes with warming in simulations with climate models



CMIP3 multi-model mean 99.9th percentile of daily precipitation (20c3m to A1B) and current observations (GPCP)

O'Gorman and Schneider, PNAS, 2009

Problem: Response of tropical precipitation extremes varies widely between models



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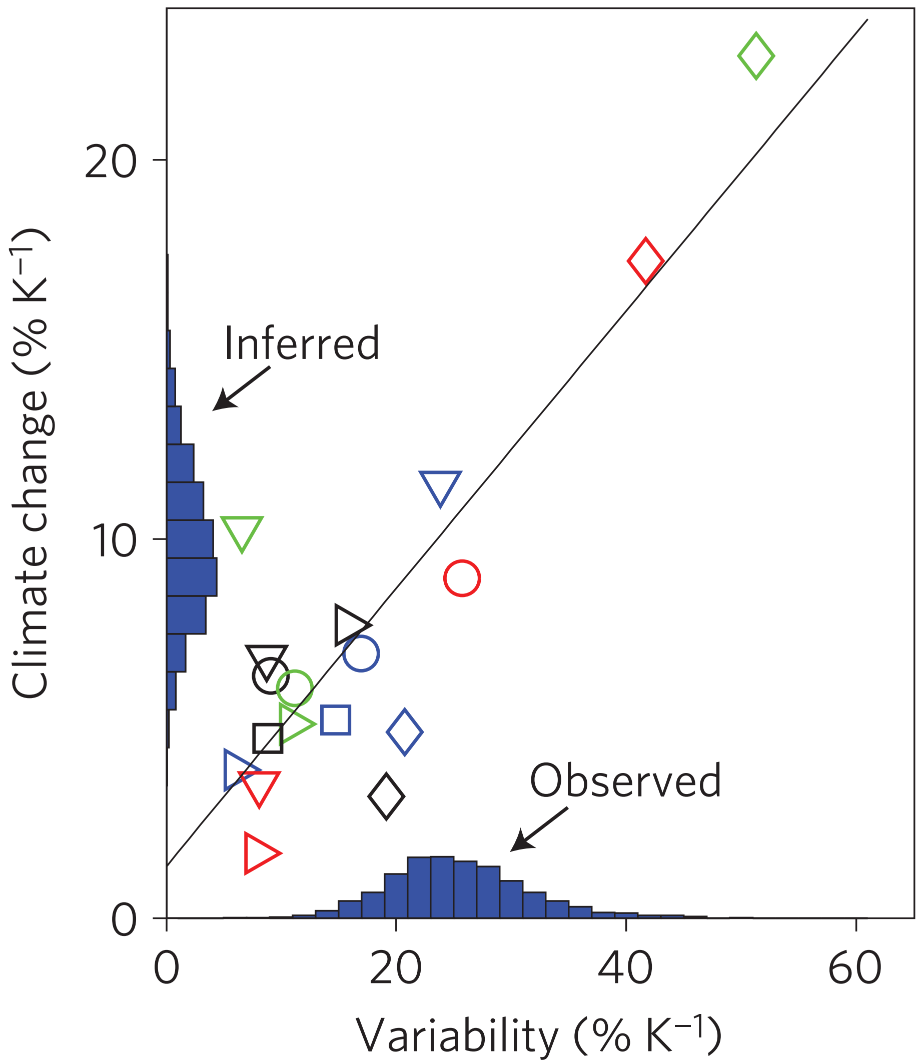
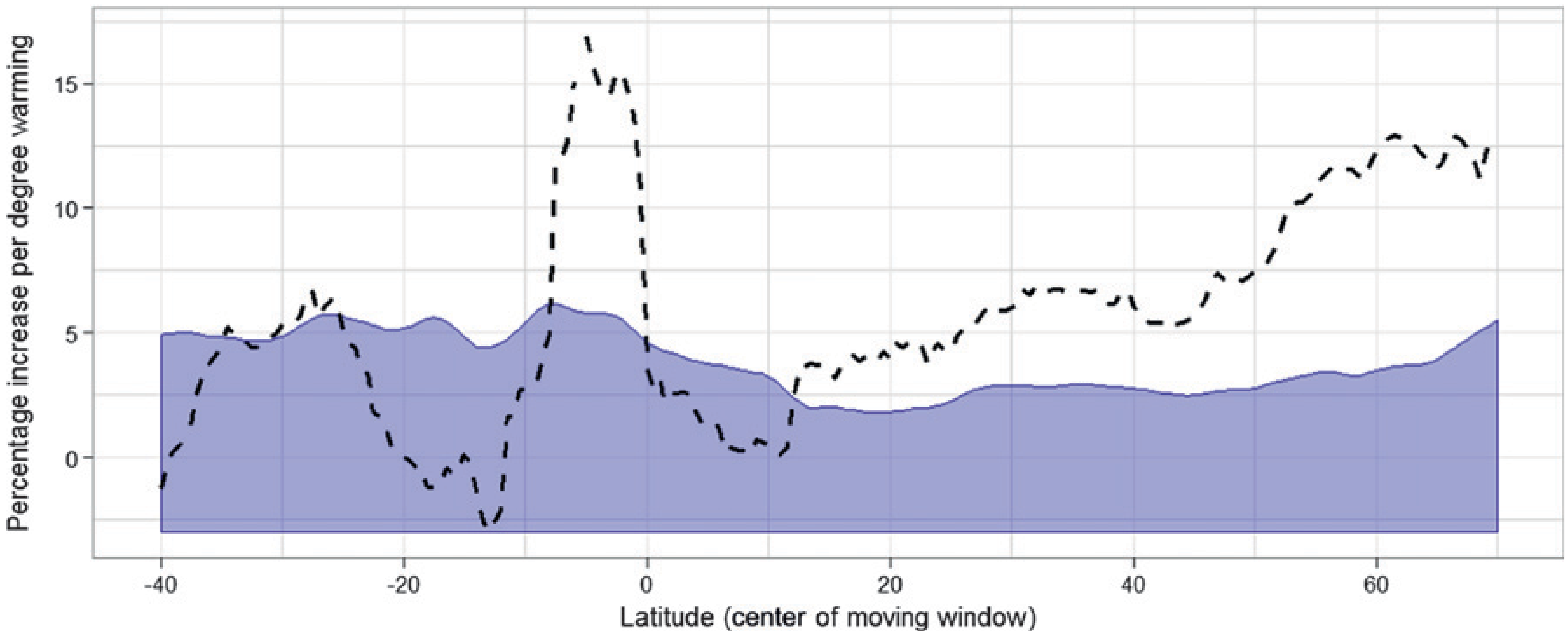


Use observed variability to constrain: 10±4%/K

(O'Gorman, Nature Geo. 2012)

(see also Muller, O'Gorman, Back 2011)

Observed trends in annual-maximum precipitation over land



Sensitivity (%) of annual maximum precipitation per kelvin warming of global near-surface temperature (1900-2009; records > 30 years), with light blue shading indicating the upper 97.5% confidence bound

Westra et al, J. Climate, 2013

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(otherwise too cold to snow heavily)