Hydroclimatology: an integrated view

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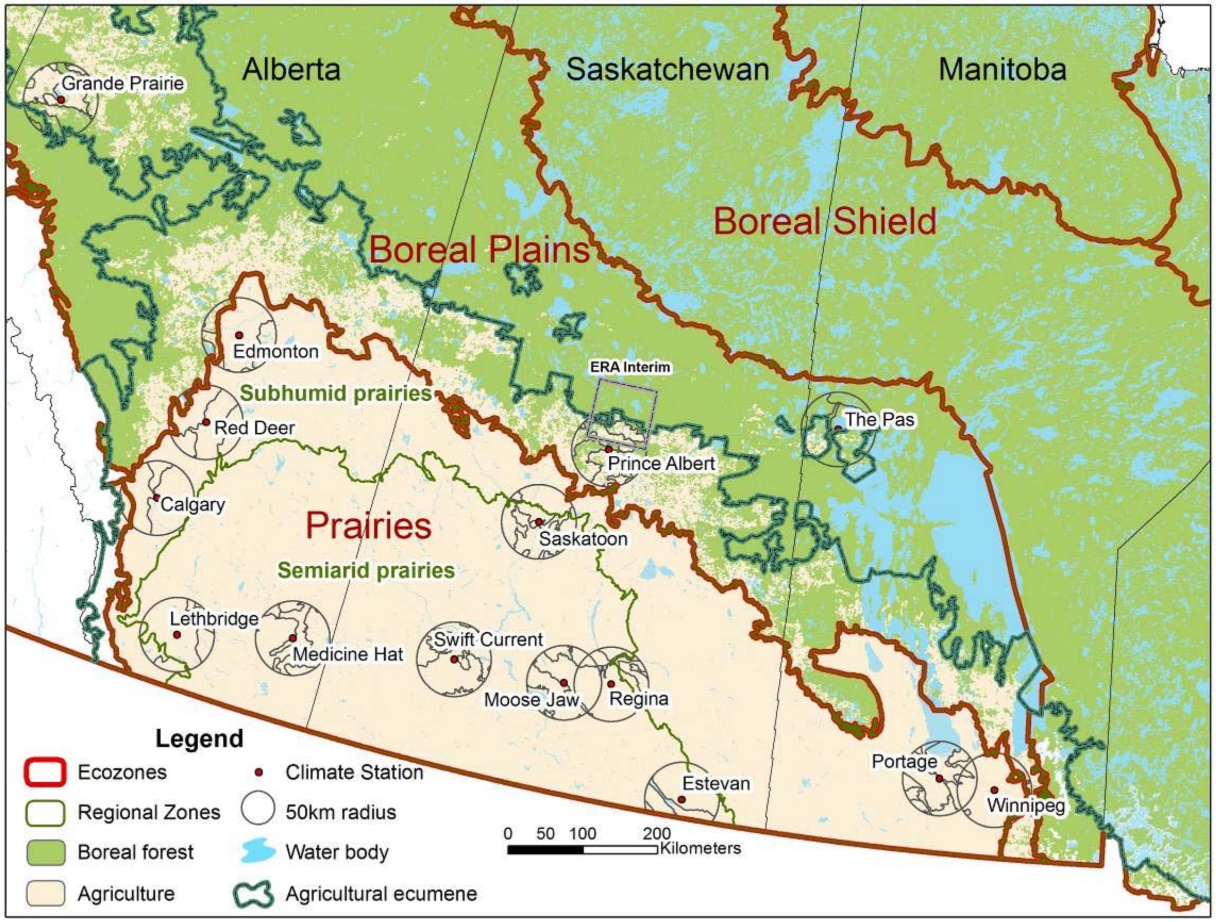
This talk

- ***Background:*** ***Remarkable 55-yr hourly Prairie data set with opaque/reflective cloud observations***
- **Northern latitude climate**
  - **Large seasonal cycle**
    - **Snow is a fast climate switch**
    - **Two separate "climates" - above and below the freezing point of water**
  - **Summer hydrometeorology**
    - **T and RH have joint dependence on radiation and precipitation on monthly timescales**
  - **Observational evaluation of reanalysis**

15 Prairie stations: 1953-2011



- *Hourly* p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})
- *Daily* precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

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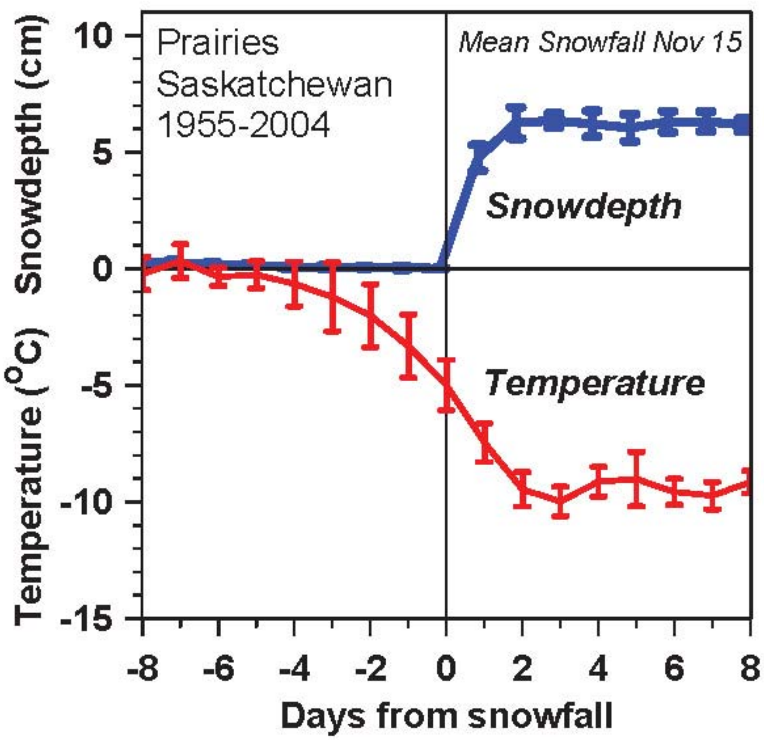
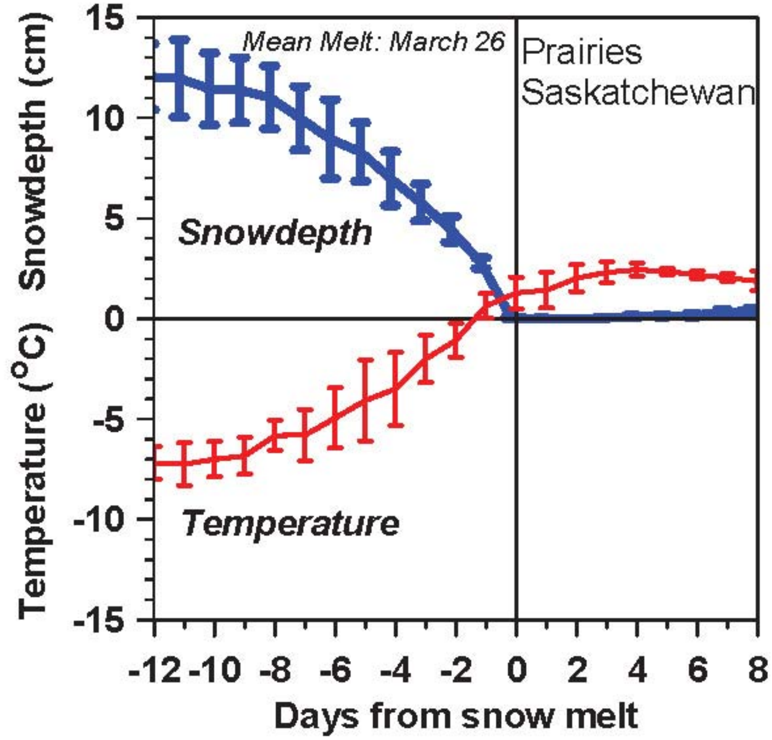
- Betts, A. K., R. Desjardins and D. Worth (2016). The Impact of Clouds, Land use and Snow Cover on Climate in the Canadian Prairies. Adv. Sci. Res., 1, 1–6, doi:10.5194/asr-1-1-2016
- Betts, A.K., A.B. Tawfik and R.L. Desjardins (2017): Revisiting Hydrometeorology using cloud and climate observations. *J. Hydrometeor., 18*, 939-955.
- Betts, A. K. and A. C.M. Beljaars (2017): Analysis of near-surface biases in ERA-Interim over the Canadian Prairies. Submitted to JAMES.

Snowfall and Snowmelt
ΔT Canadian Prairies

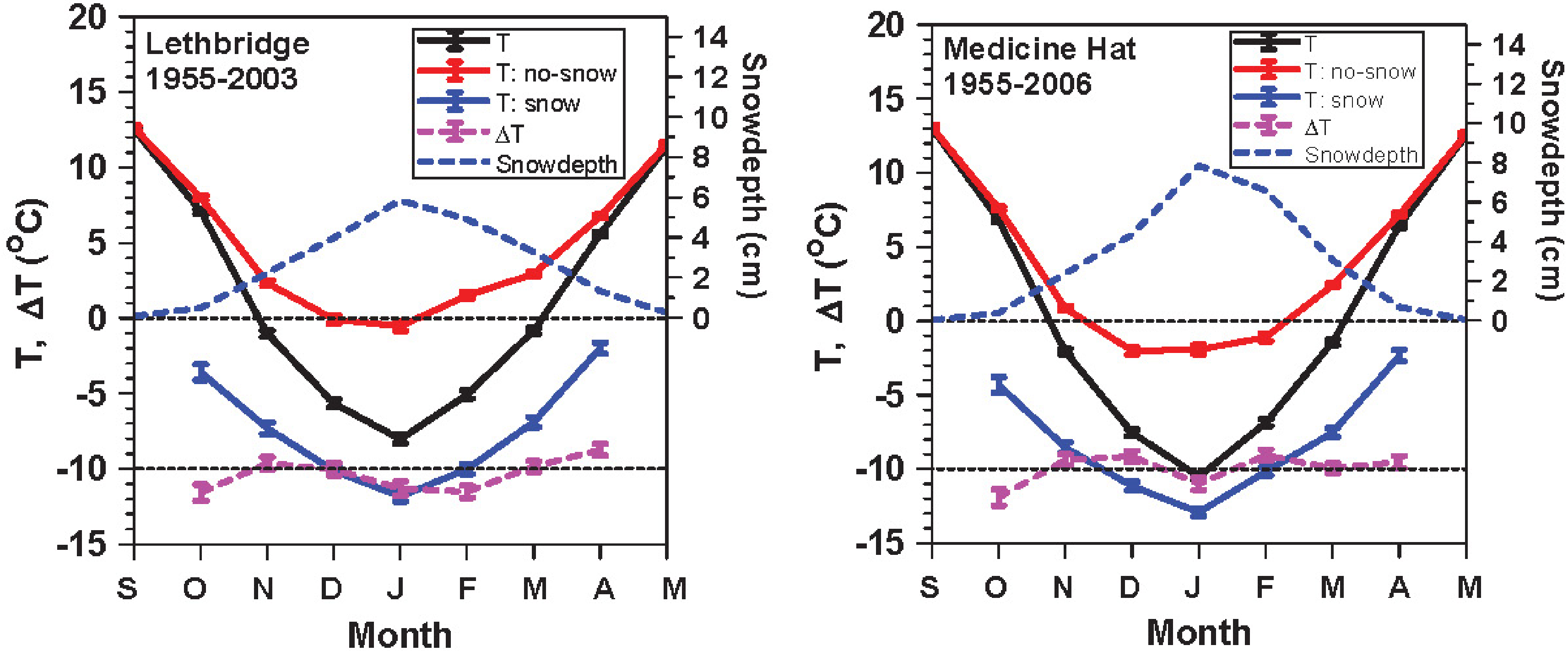




- **Temperature falls/rises 10K with first snowfall/snowmelt**
  - ***Local climate switch between warm and cold seasons***

Betts et al. 2014

Impact of Snow on Climate



Separate mean climatology into days with no-snow and snowdepth >0

ΔT = T:no-snow –T:snow = -10.2(±1.1)°C

Betts et al. (2016)

Interannual variability of T coupled to Snow Cover

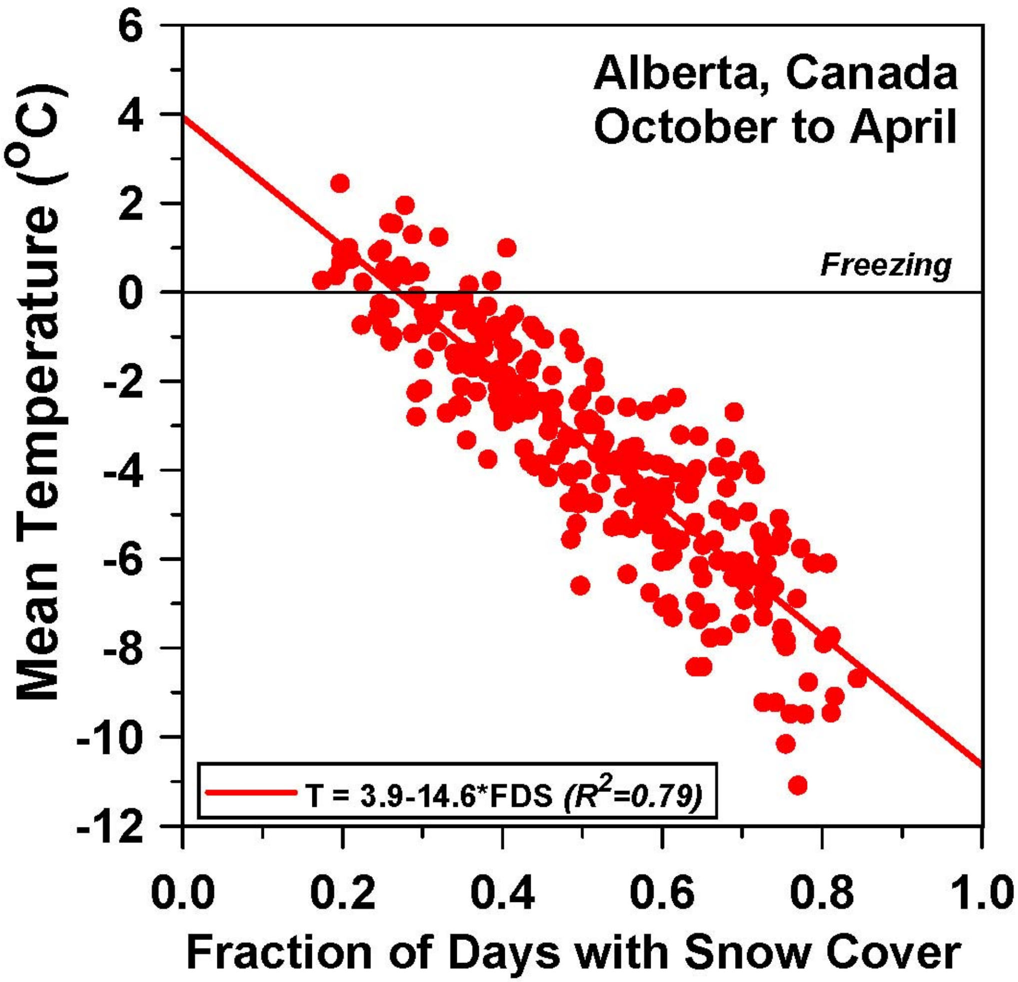
- **Alberta: 79% of variance**
- **Slope T_m - 14.7 (± 0.6) K**

10% fewer snow days

= 1.5K warmer

on Prairies

More snow cover - Colder temperatures



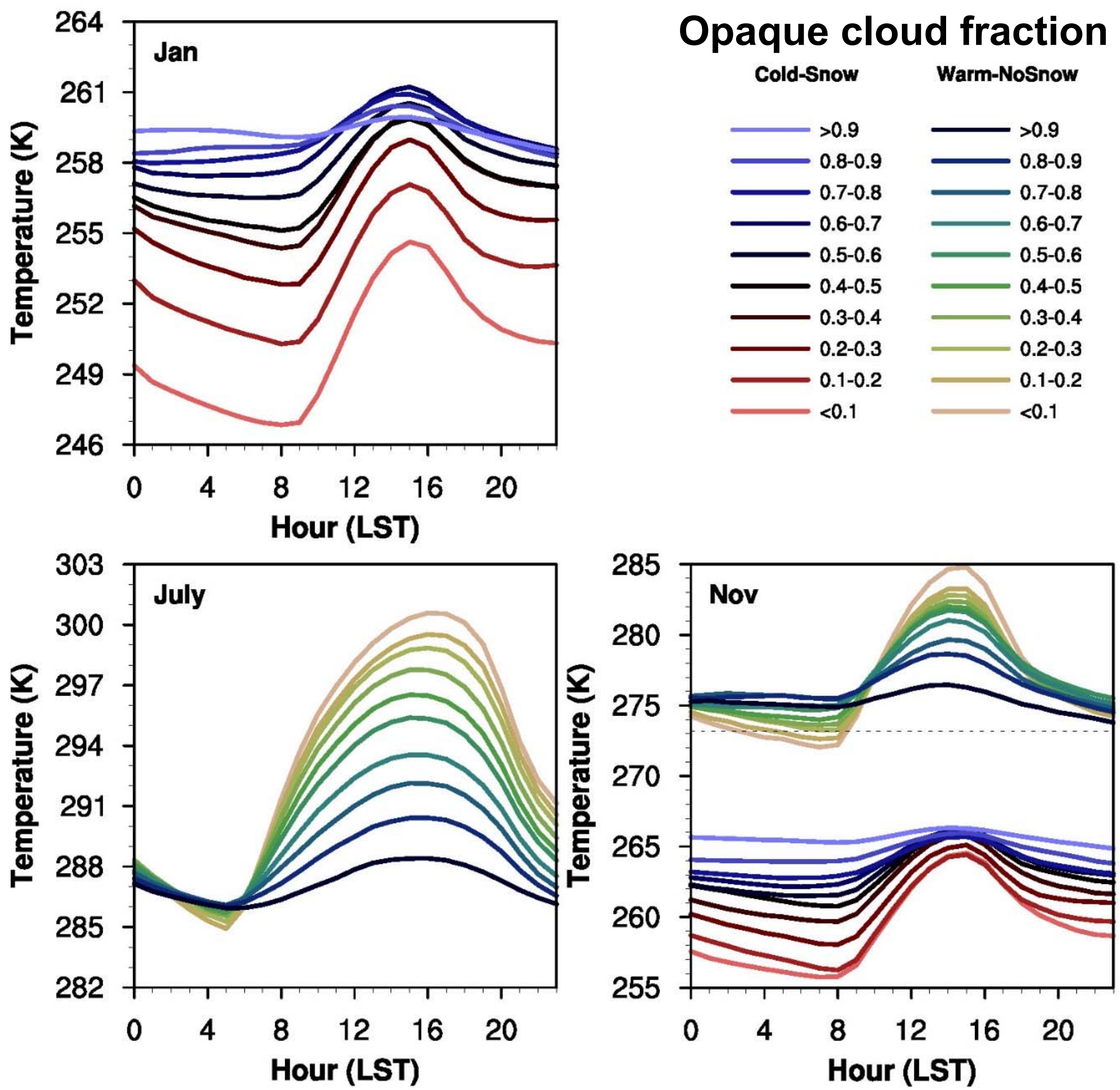
Diurnal cycle: Clouds & Snow

Canadian Prairies
660 station-years of data

Winter climatology
- **Colder when clear**
- **LWCF dominant with snow**

Summer climatology
- **Warmer when clear**
- **SWCF dominant: no snow**

Transition months:
- **Show both climatologies**
- **With 11K separation**
- **Fast transitions with snow**
- **Snow is “Climate switch”**



Warm and Cold Seasons

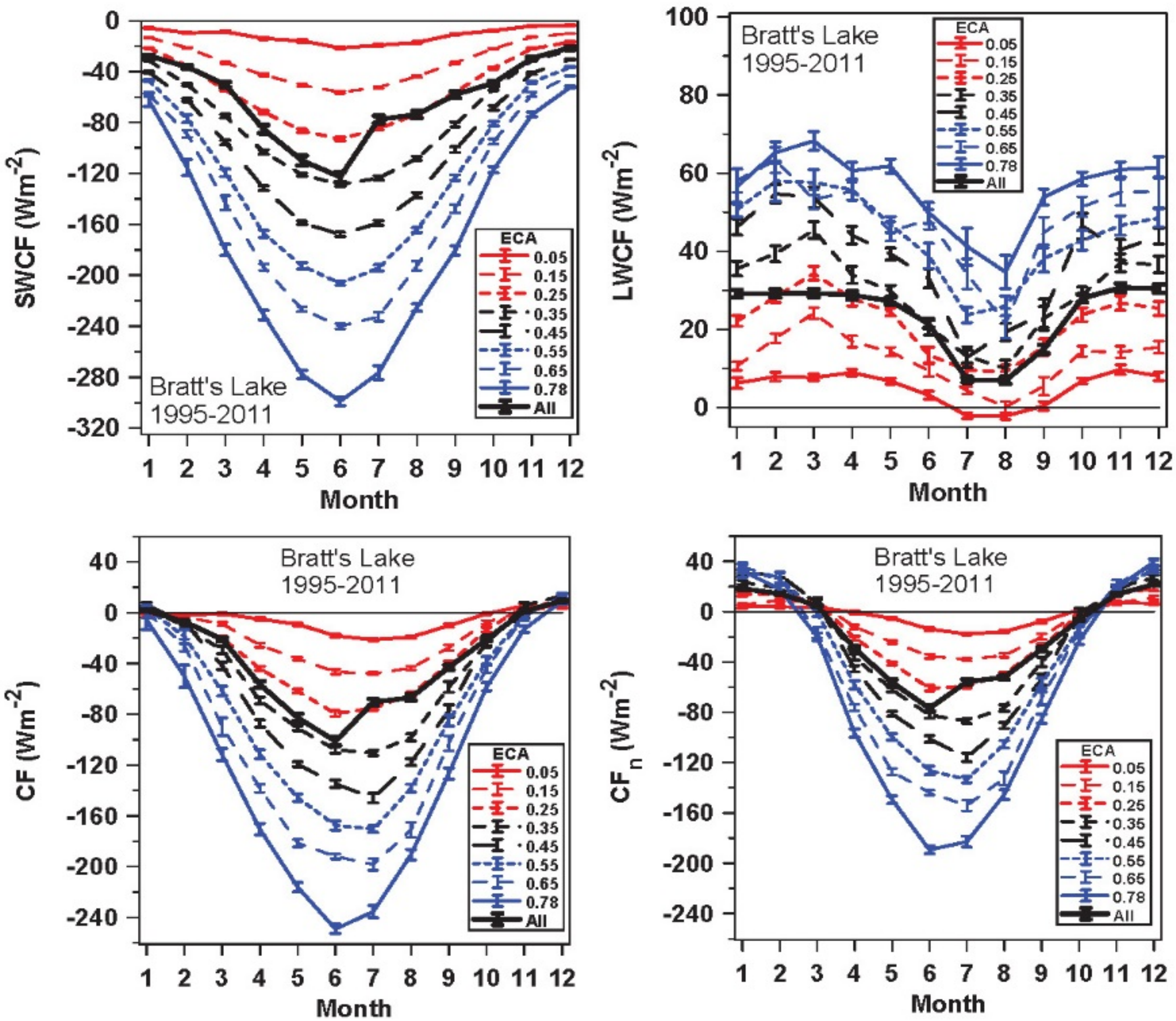
- Unstable BL: SWCF -
- Clouds at LCL
  - reflect sunlight

- Stable BL: LWCF +
- Cloud reduce LW loss
- Snow - reflects sunlight

SW and LW 'Cloud Forcing'
BSRN at Bratt's Lake, SK

- "Cloud Forcing"
  - *Change from clear-sky flux*
- Clouds reflect SW
  - *SWCF*
  - *Cool*
- *Clouds trap LW*
  - *LWCF*
  - *Warms*
- *Sum is CF*
- *Surface albedo reduces SW_n*
  - *Net is CF_n*
  - *Add reflective snow, and CF_n goes +ve*
- ***Regime change***

(Betts et al. 2015)



Impact of Snow

- **Distinct warm and cold season states**
- **Snow cover is the "climate switch"**
- **Prairies: $\Delta T = -10^{o}C$ (winter albedo = 0.7)**
- **Vermont: $\Delta T = -6^{o}C$ (winter albedo 0.3 to 0.4)**

- **Snow transforms BL cloud coupling**
  - **No-snow 'Warm when clear' - convective BL**
  - **Snow 'Cold when clear' - stable BL**

- **Don't average snow/no-snow climates**

Warm Season Climate
(April – October with no snow)

- ***"Climate" historically: T and Precip.***
- ***In the fully coupled system***
  - ***Diurnal cycle of T and RH coupled***
  - ***to Radiation/cloud and Precipitation***
- ***Monthly timescale: strongest link is to cloud but precipitation memory long***

Betts et al. 2014b, 2017

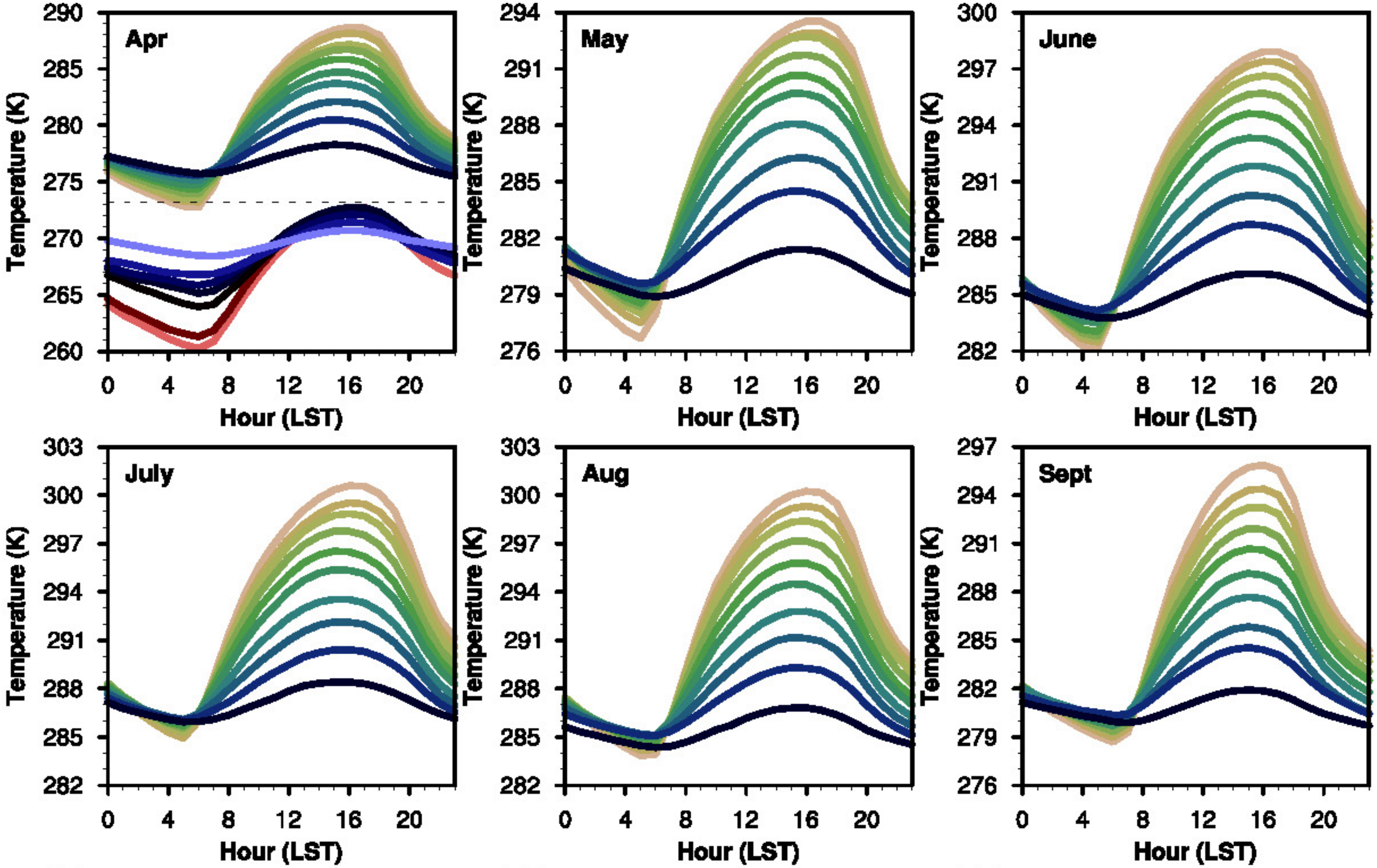
Diurnal Cycle Climate

Diurnal cycle: T, RH, θ_E, P_{LCL}

- **DTR = T_x – T_n**
- **DRH = RH_x – RH_n**
- **$D\theta_E$, DP_{LCL} similarly**

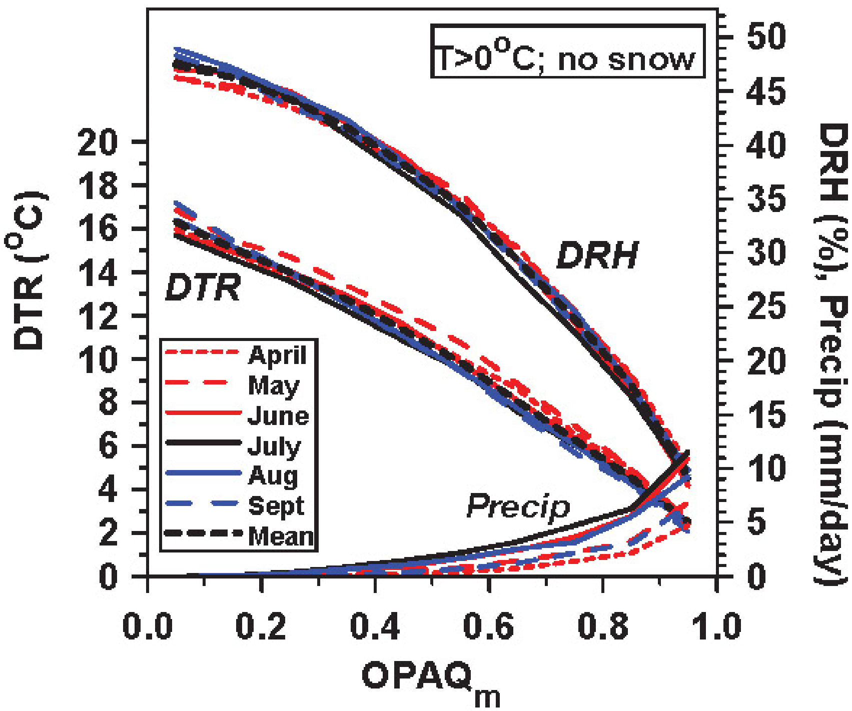
- ***Imbalance of diurnal cycle "climate"***

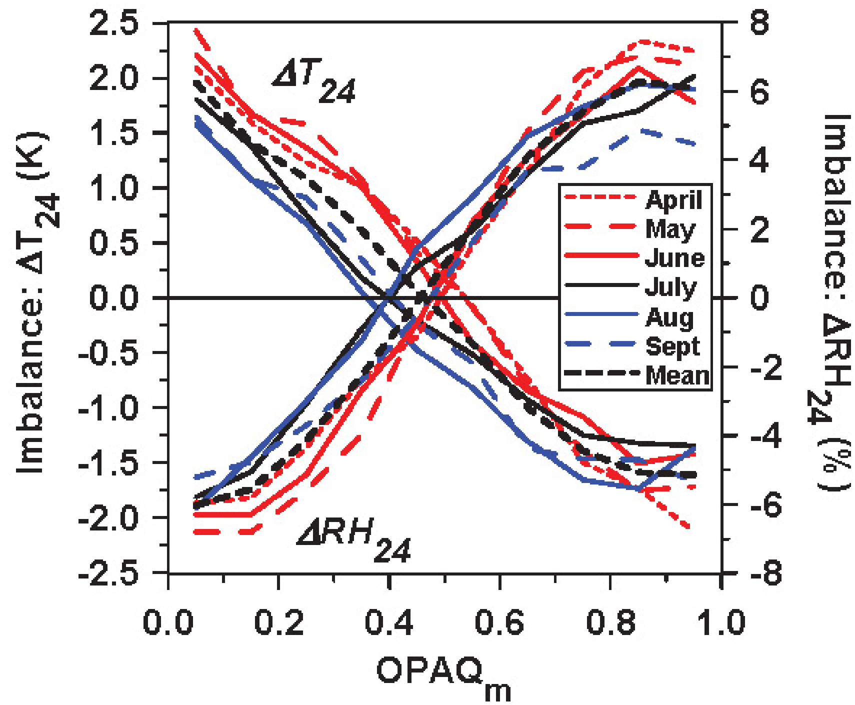
Monthly Diurnal Climatology:
Dependence on opaque cloud



Q: How much warmer is it at the end of a clear day?

Diurnal Ranges & Imbalances

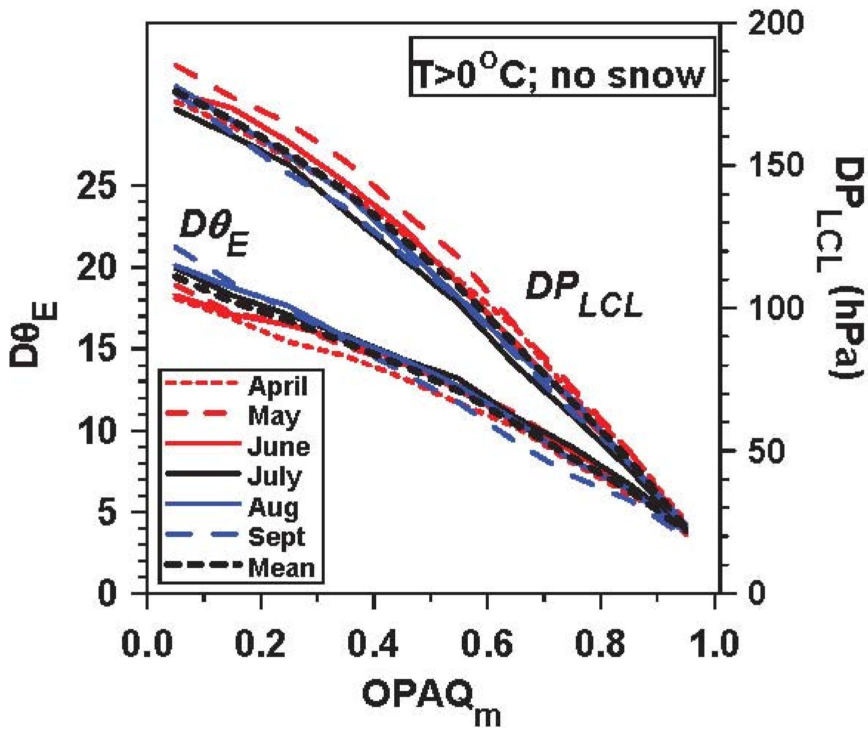


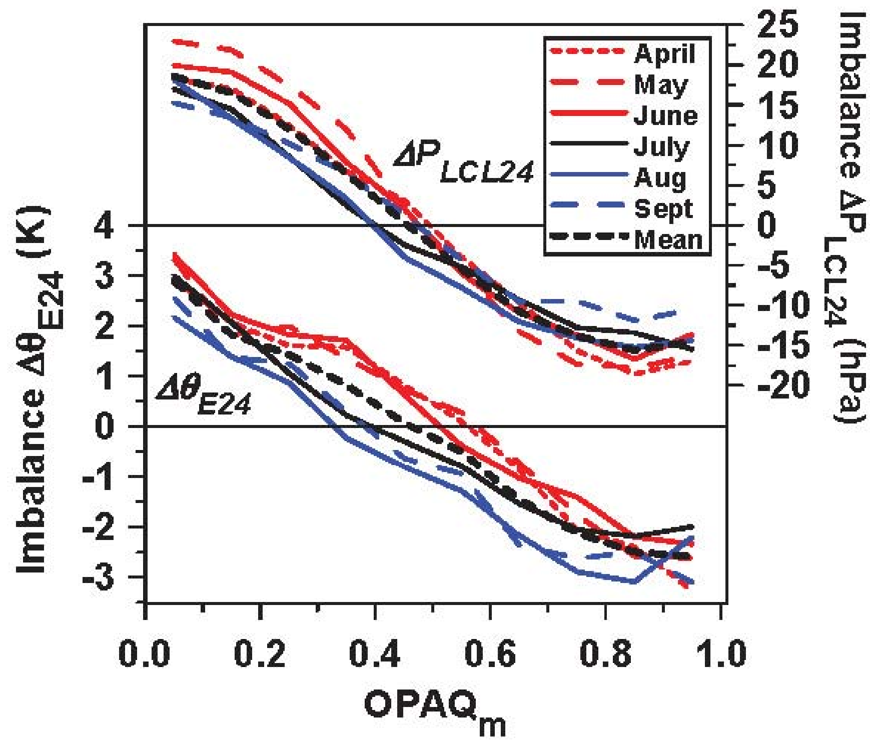


- **April to Sept: *<u>same coupled structure</u>***
- **Q: Clear-sky: warmer (+2°C), drier (-6%)**

(Betts and Tawfik 2016)

Diurnal Ranges & Imbalances





- April to Sept: <u>same coupled structure</u>
- Clear-sky: θ_E (+3K), LCL higher (+18hPa)

(Betts and Tawfik 2016)

Multiple Regression on Cloud and Lagged Precip. Anomalies

- **Monthly anomalies (normalized by STD of means)**
  - **opaque cloud (CLD)** ***(surrogate for radiation)***
  - **precip. (PR0, PR1, PR2): current, previous 2 to 5 months**

δ<u>DTR</u> = **A*δCLD + B*δPR0 + C*δPR1 + D*δPR2 ...**

(Month) (Month) (Month-1) (Month-2)

Soil moisture memory

<u>April: </u>memory of precipitation back to November

<u>June, July, Aug:</u> moisture has memory back to March

April: Multiple Regression on Cloud and Lagged Precipitation

1953-2010: 12 stations (620 months)

Variable $R^2 =$	δDTR 0.67	δT_x 0.47	δRH_n 0.65	δP_{LCLx} 0.66	
Cloud-Apr	-0.52±0.02	-0.78±0.04	0.76±0.03	-0.93±0.04	Dominant
PR-Apr	-0.06±0.02	(0.01±0.04)	0.20±0.03	-0.19±0.04	
PR-Mar	-0.12±0.02	-0.22±0.04	0.23±0.03	-0.27±0.03	
PR-Feb	-0.07±0.02	-0.12±0.04	0.16±0.03	-0.19±0.03	
PR-Jan	-0.09±0.02	-0.19±0.04	0.17±0.03	-0.21±0.03	
PR-Dec	-0.06±0.02	(-0.06±0.04)	0.16±0.03	-0.19±0.03	
PR-Nov	-0.08±0.02	-0.13±0.04	0.07±0.03	-0.11±0.03	

April remembers precip. back to freeze-up

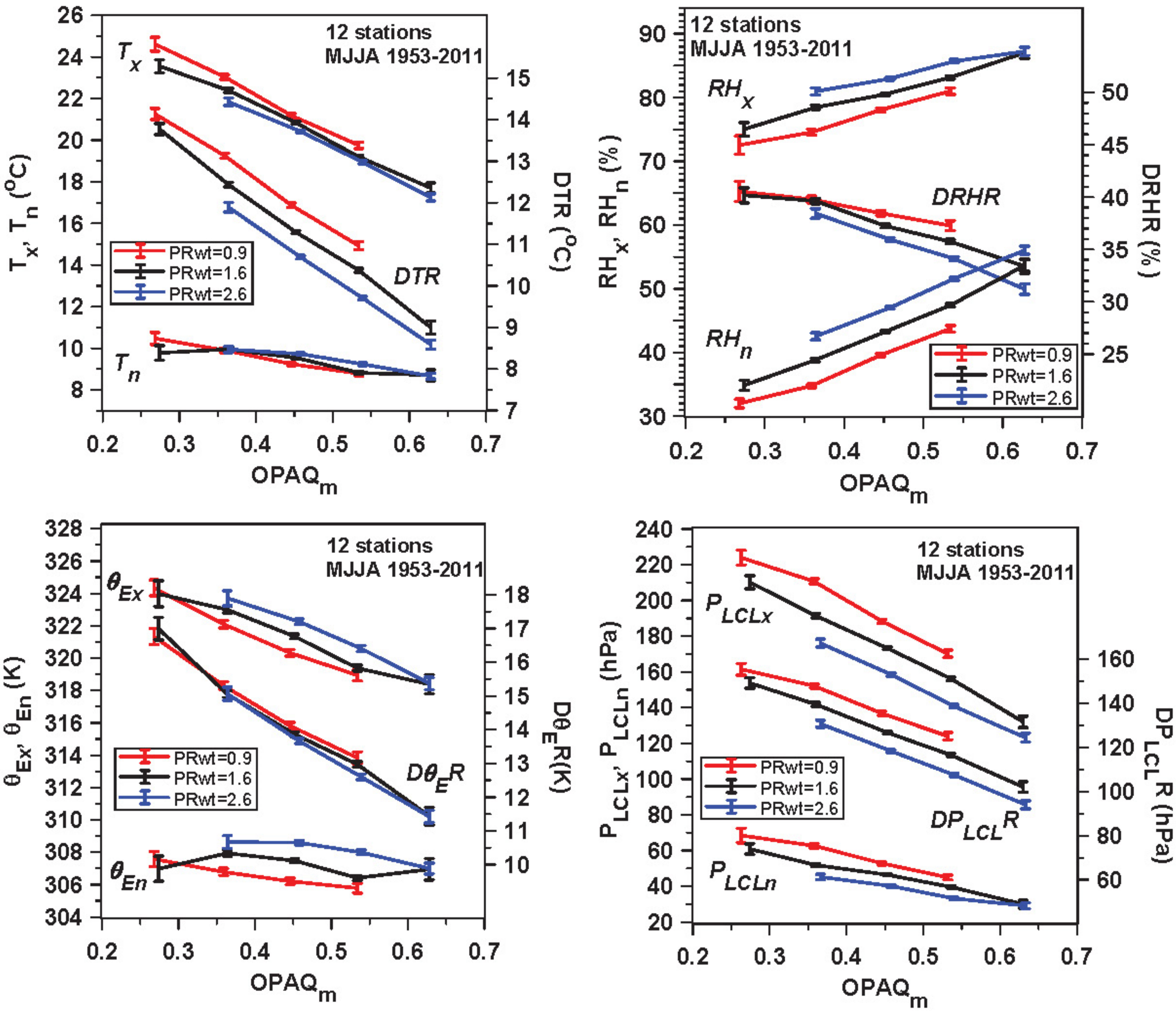
Summer Precip Memory back to March

JULY 1953-2010: 12 stations (614 months)

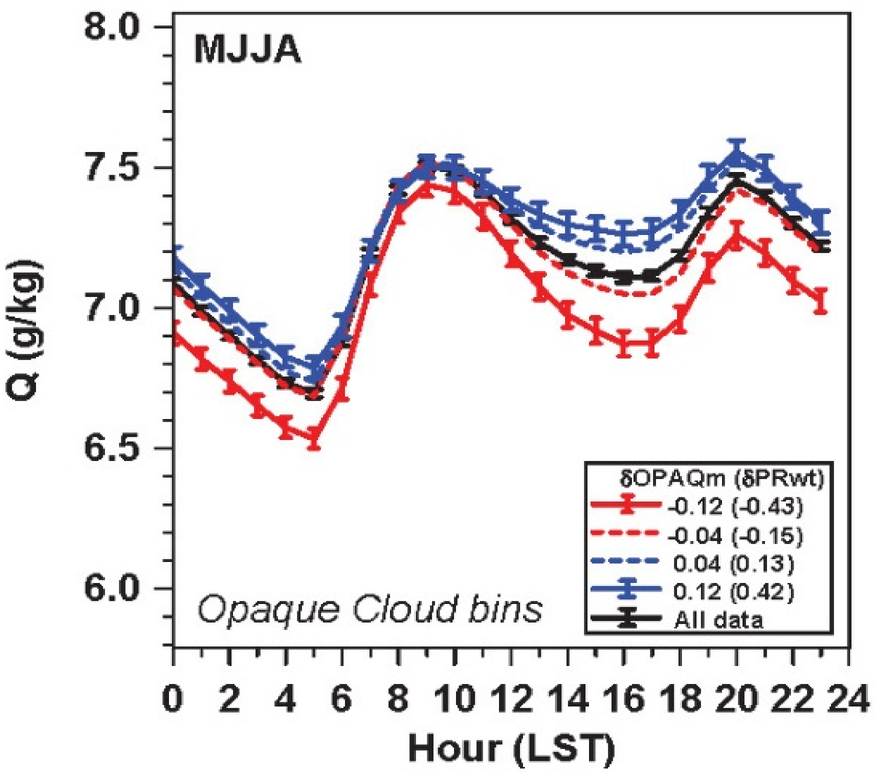
JULY R^2	δDTR 0.68	δRH_n 0.61	δP_{LCLx} 0.62	δQ_{Tx} 0.26
Cloud-July	**-0.56±0.03**	**0.50±0.03**	**-0.63±0.04**	(0.03±0.04)
PR-July	**-0.31±0.02**	**0.37±0.03**	**-0.45±0.04**	**0.34±0.04**
PR-June	**-0.22±0.02**	**0.34±0.03**	**-0.44±0.04**	**0.38±0.04**
PR-May	**-0.12±0.02**	**0.11±0.03**	**-0.16±0.04**	**0.16±0.04**
PR-Apr	-0.04±0.02	0.06±0.03	-0.06±0.03	**0.12±0.04**
PR-Mar		0.06±0.03	-0.07±0.03	**0.10±0.04**

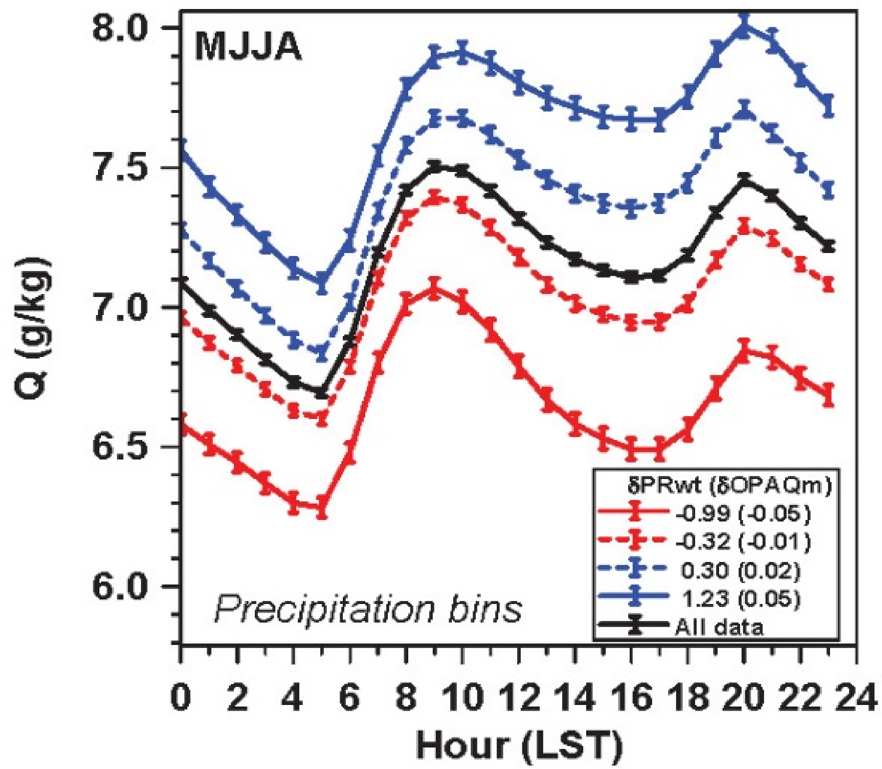
June, July, Aug have precip memory back to March

MJJA on cloud and Precipitation



Diurnal cycle: Mixing Ratio Q





Dependence on cloud small; on precipitation large

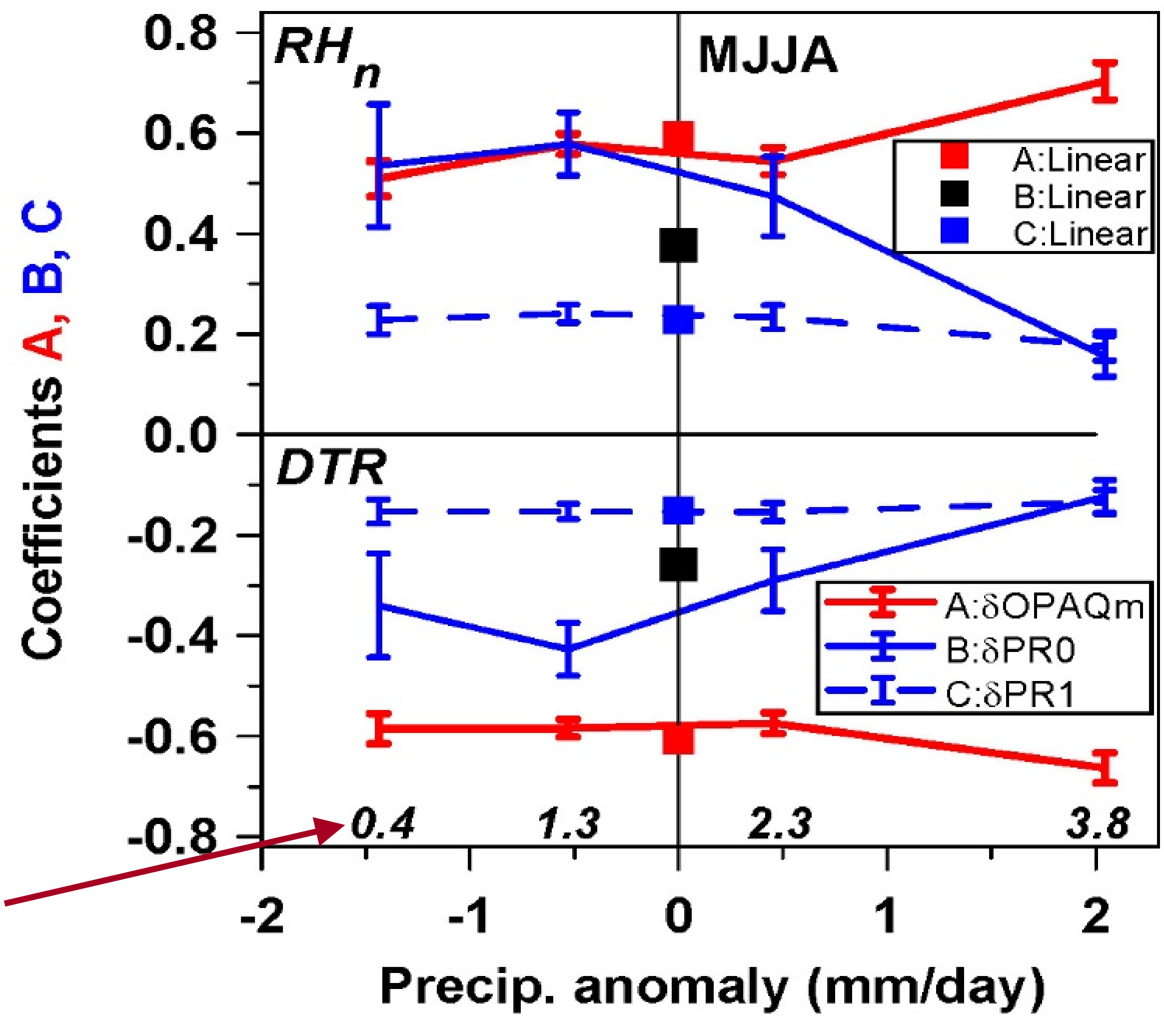
Non-linear coupling to precipitation:

Stratify by precipitation anomaly δPR0 for current month

A: Opaque cloud
B: δPR0: this month
C: δPR1: last month

The solid squares are the A, B, C linear regression coefficients

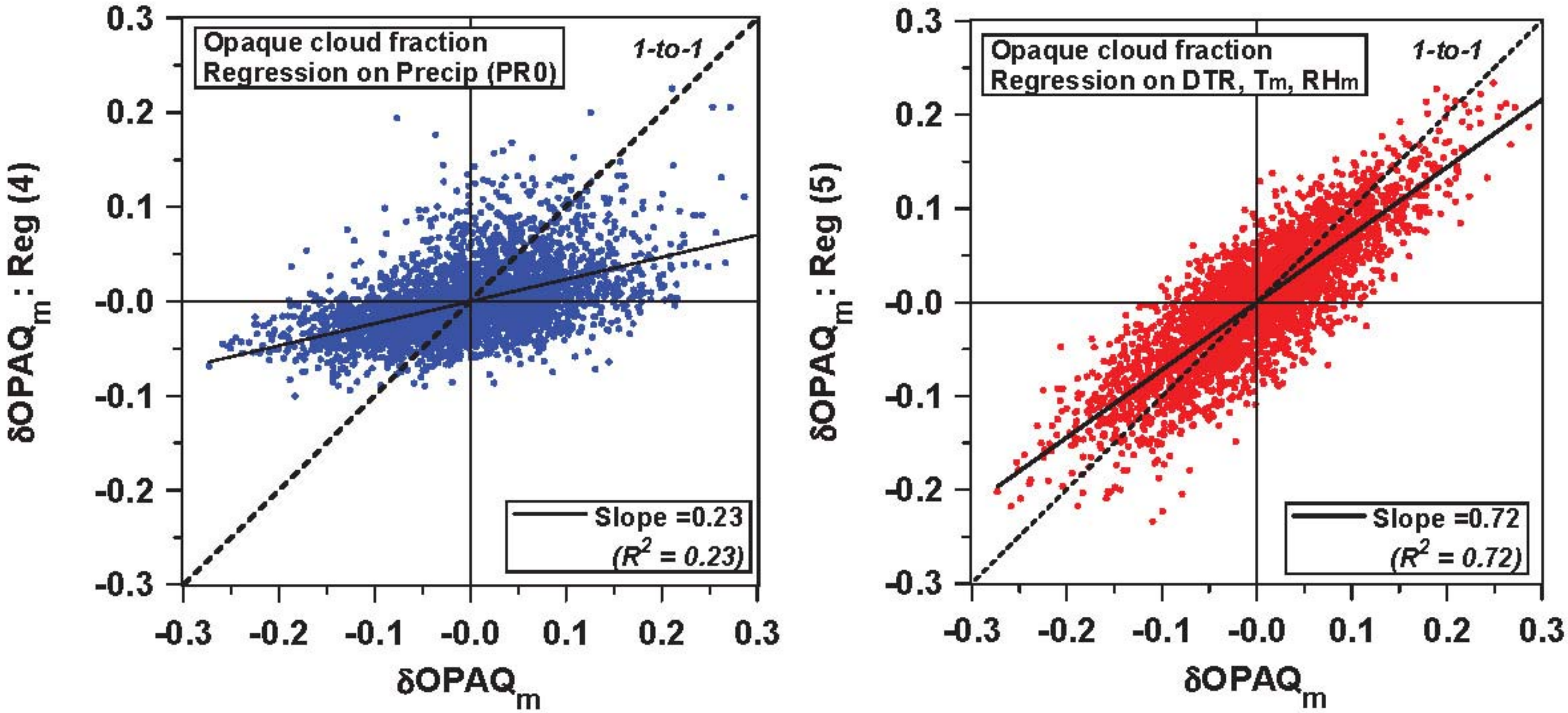
Coupling less in wetter months



Mean monthly precipitation

Cloud on Climate variables

MJJAS



Precipitation **DTR, T_m, RH_m**

Regression equations

$$\delta OPAQ_m = 0.48*\delta PR0 \quad (R^2 = 0.26)$$

$$\delta OPAQ_m = -0.64*\delta DTR - 0.23*\delta T_m + 0.11*\delta RH_m \quad (R^2 = 0.72)$$

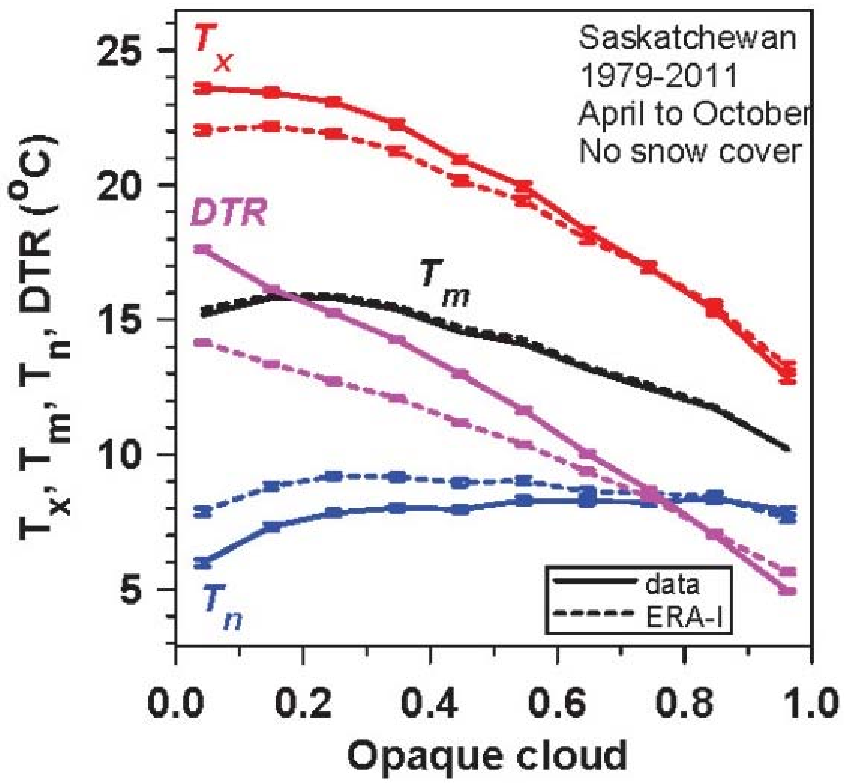
Tight inverse coupling: cloud and DTR

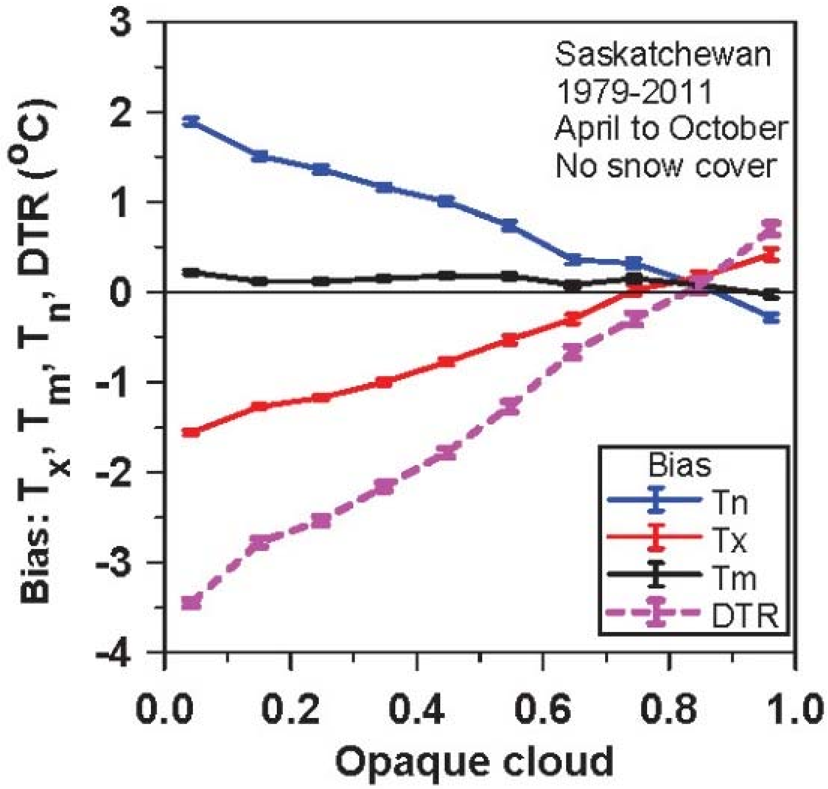
Warmer climate ⇄ less cloud?
Moister climate ⇄ more cloud?

Conclusions-1

- Remarkable dataset with opaque cloud
- Cloud radiative forcing variability dominates diurnal and monthly timescales
- Warm season precipitation memory back to March (early snowmelt)
  - Stronger for moisture variables than DTR
- Coupling of monthly climate to precipitation anomalies is non-linear
- *Clouds and climate are tightly coupled on monthly timescale*

ERA-Interim Biases

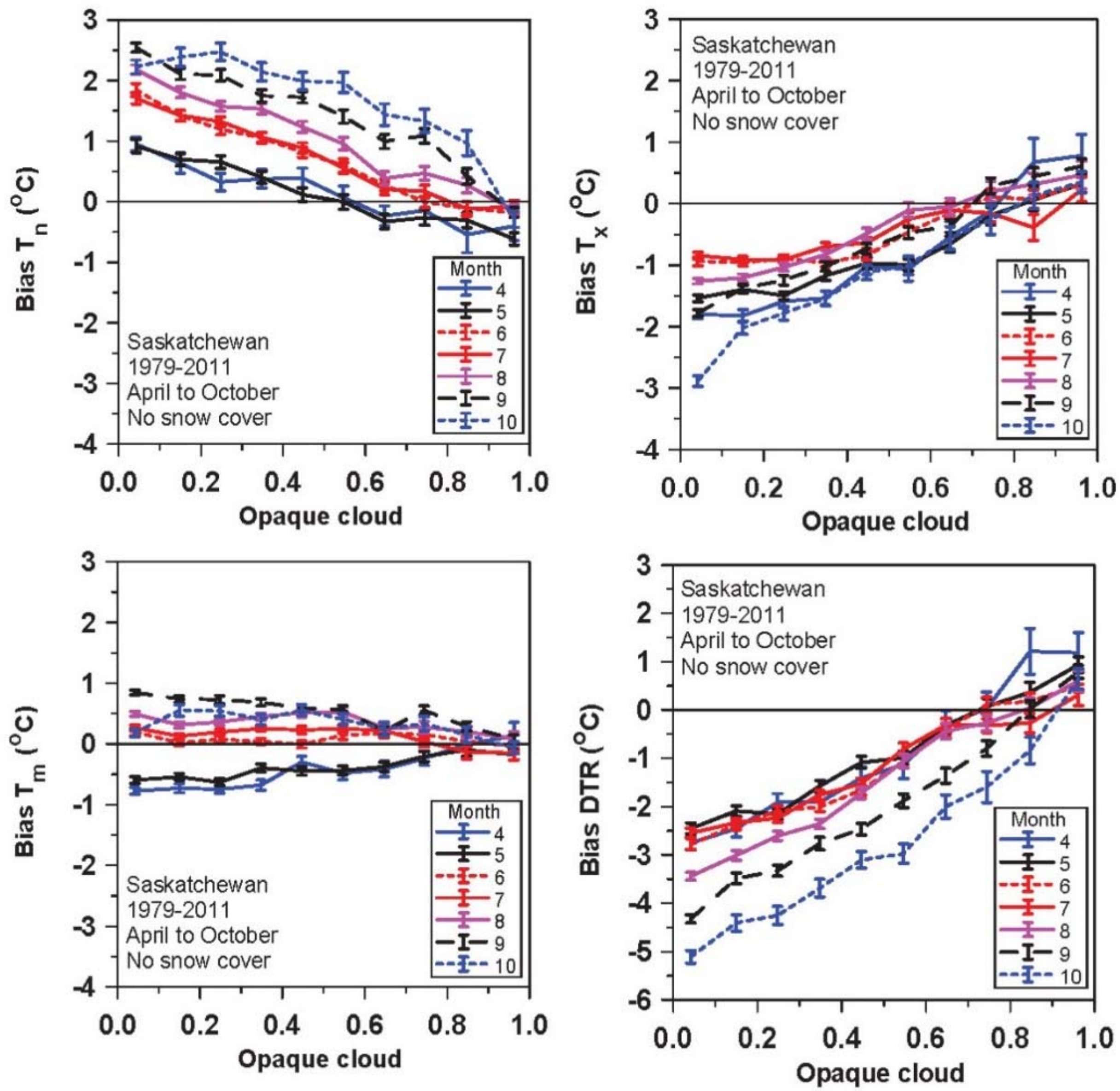




- **Warm season (no snow cover)**
  - ***T_x cold, T_n warm; DTR too small***

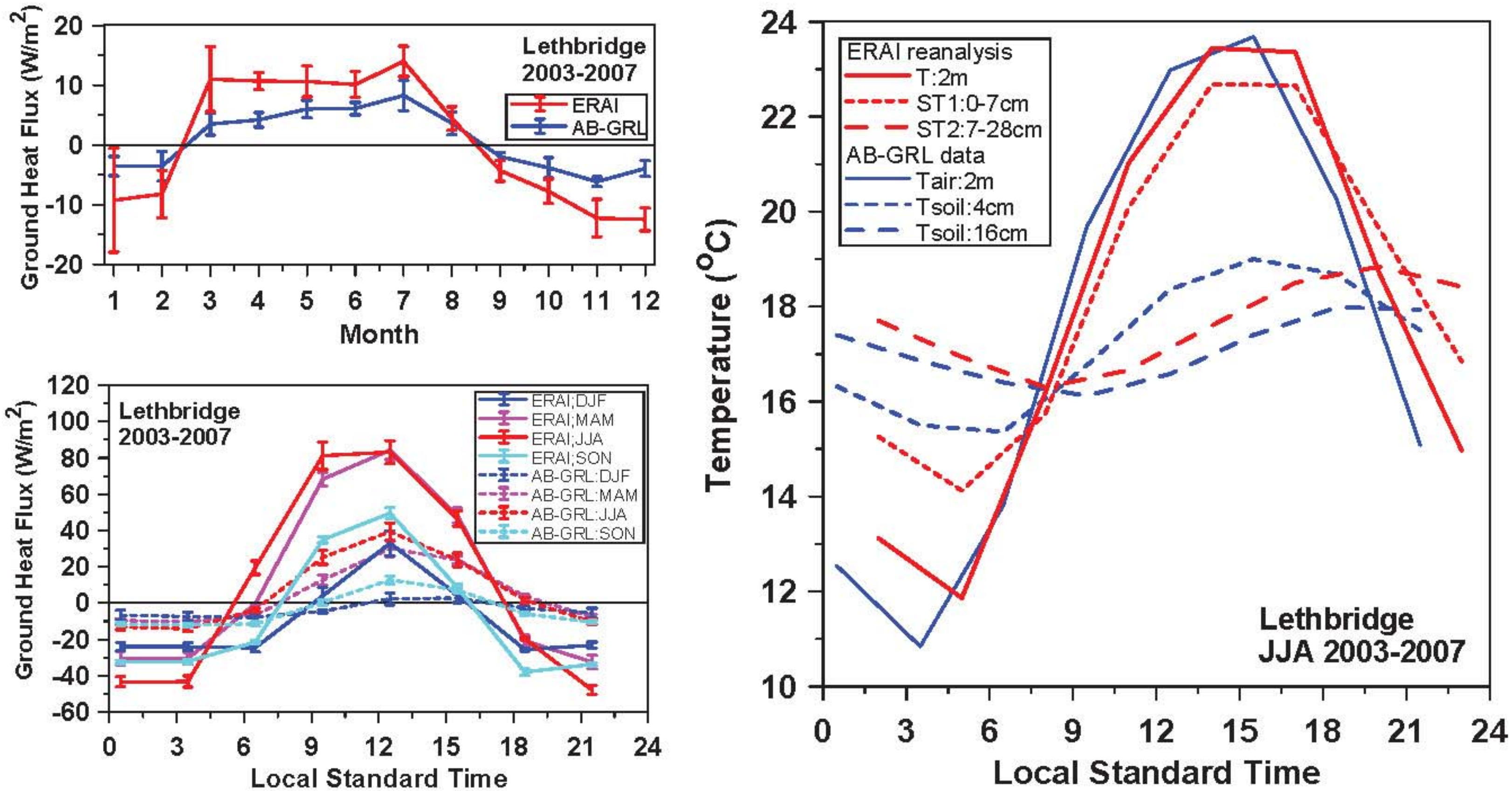
Monthly biases

- Seasonal trends large
- bias:T_n increases April to Oct
- bias:T_x min in JJ
- bias:T_m changes sign: spring to fall
- bias:DTR reaches -5°C in Oct



WHY?

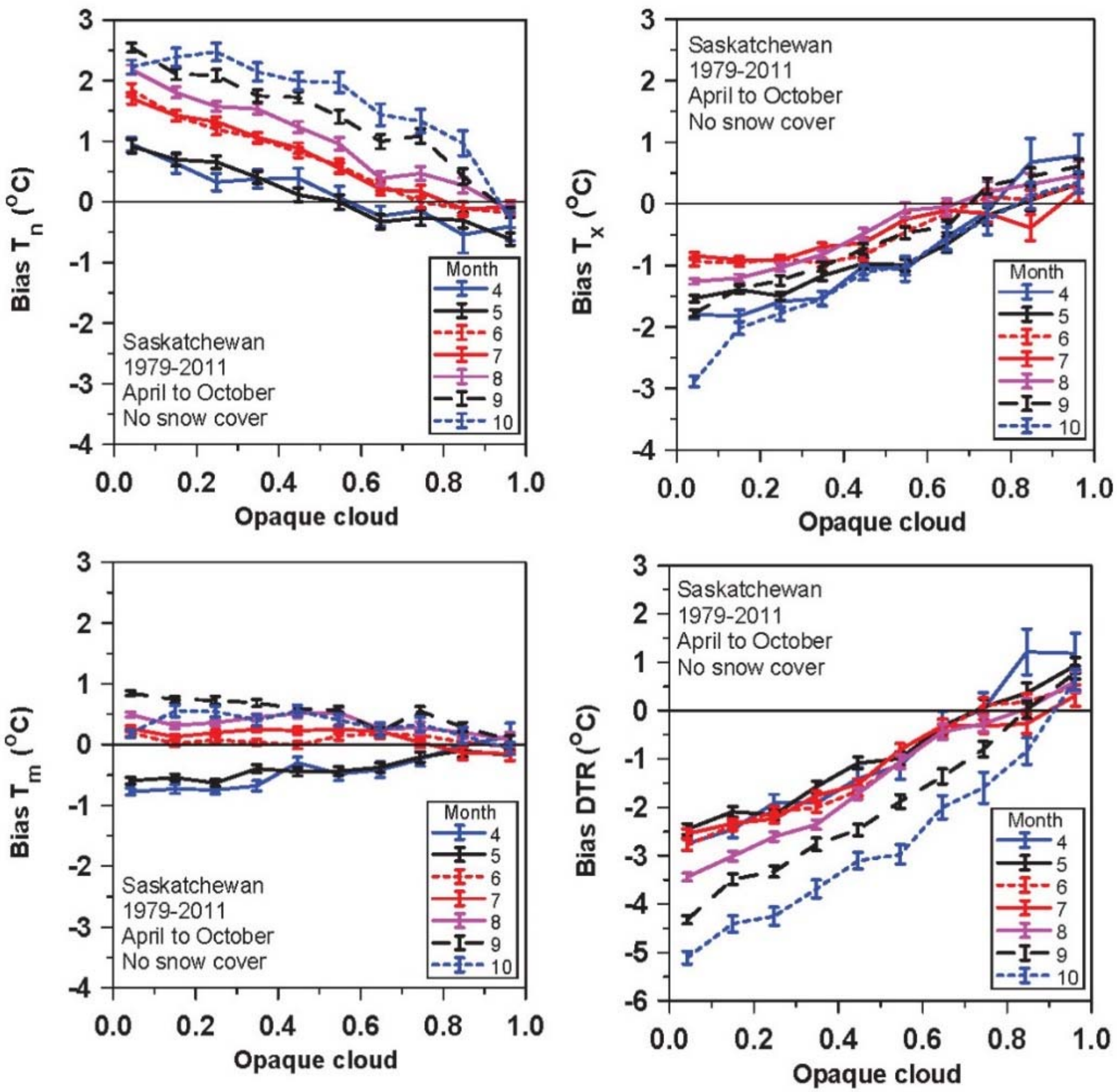
Ground coupling too strong



- **Diurnal and seasonal ground flux in ERA-I too large**
- **Ground temperatures too warm in summer**

Biases

- T_n warm: ground flux too large at night : ground cold in April, warm in Oct
- T_x cold: ground flux too large in day: G/R_{net} smallest in June, July
- T_m changes sign: ground too cold in spring, too warm in fall



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- **Don't average snow/no-snow climates!**

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Warm Season Climate

- *"Climate" historically: T and Precip.*
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ERA-Interim biases

- ***Surprisingly large***
- ***Surprising seasonal shifts***
- ***Qualitatively linked to bias in ground fluxes***
- ***Importance?***
  - ***Agricultural models use seasonal forecasts and reanalysis: need to remove model biases!***
  - ***Model biases need to be fixed!***

- ***DATA, DATA, DATA matters***