Land-surface-snow-cloud Climate Coupling

Alan K. Betts

akbetts@aol.com

http://alanbetts.com

Co-authors:

Ray Desjardins, Devon Worth

Agriculture and Agri-Food Canada

Ahmed Tawfik

NCAR

Atmospheric Sciences,Texas A&M

College Station, TX

April 4, 2016

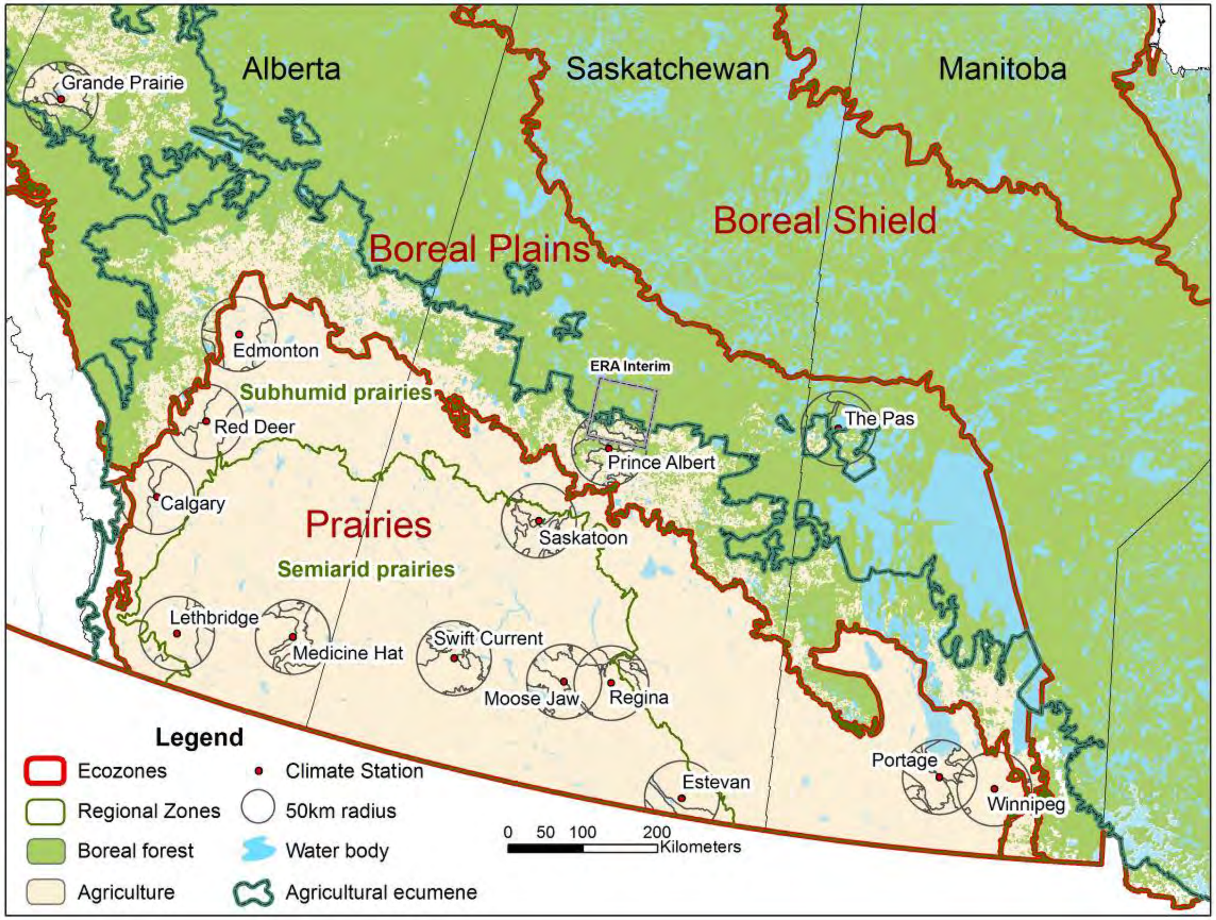
Climate Processes

- *Solar seasonal cycle*
- *Temp., RH, Cloud, Precip. coupled*
- Reflection of SW
  - Clouds: Water drops, ice crystals
    - Cools surface
  - Snow and ice on surface
    - Cools surface
- Water vapor/clouds trap LW
    - Re-radiation down warms surface

This talk

- **Northern latitude climate**
  - **Large seasonal cycle**
    - **Cold winters with snow**
    - **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 models**
    - ***Remarkable 55-yr hourly data set with opaque/reflective cloud observations***

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)

http://alanbetts.com

- Betts, A.K., R. Desjardins and D. Worth (2013a), Cloud radiative forcing of the diurnal cycle climate of the Canadian Prairies. *J. Geophys. Res. Atmos., 118,* 1–19, doi:10.1002/jgrd.50593
- Betts, A. K., R. Desjardins, D. Worth, and D. Cerkowniak (2013), Impact of land use change on the diurnal cycle climate of the Canadian Prairies, J. Geophys. Res. Atmos., 118, 11,996–12,011, doi:10.1002/2013JD020717.
- Betts, A.K., R. Desjardins, D. Worth, S. Wang and J. Li (2014), Coupling of winter climate transitions to snow and clouds over the Prairies. *J. Geophys. Res. Atmos*., 119, doi:10.1002/2013JD021168
- Betts, A.K., R. Desjardins, D. Worth and B. Beckage (2014), Climate coupling between temperature, humidity, precipitation and cloud cover over the Canadian Prairies. J. Geophys. Res. Atmos. 119, 13305-13326, doi:10.1002/2014JD022511
- Betts, A.K., R. Desjardins, A.C.M. Beljaars and A. Tawfik (2015). Observational study of land-surface-cloud-atmosphere coupling on daily timescales. Front. Earth Sci. 3:13. http://dx.doi.org/10.3389/feart.2015.00013
- Betts, AK and A.B. Tawfik (2016) Annual Climatology of the Diurnal Cycle on the Canadian Prairies. Front. Earth Sci. 4:1. doi: 10.3389/feart.2016.00001
- 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

Diurnal Climate Dataset

- **Reduce hourly data to**
  - **daily means: T_m , RH_m, $OPAQ_m$ etc**
  - **data at $T_{max/min}$: T_x and T_n**
- ***Diurnal cycle approx. climate***
  - **DTR = $T_x - T_n$**
  - **$\Delta RH = RH_{tn} - RH_{tx}$**
- ***Full diurnal Cycle:***
  - ***'True' diurnal ranges (Critical for winter)***
  - ***Energy imbalance of diurnal cycle***

Surface Radiation Budget

- $R_n = SW_n + LW_n$
- Define Effective Cloud Albedo

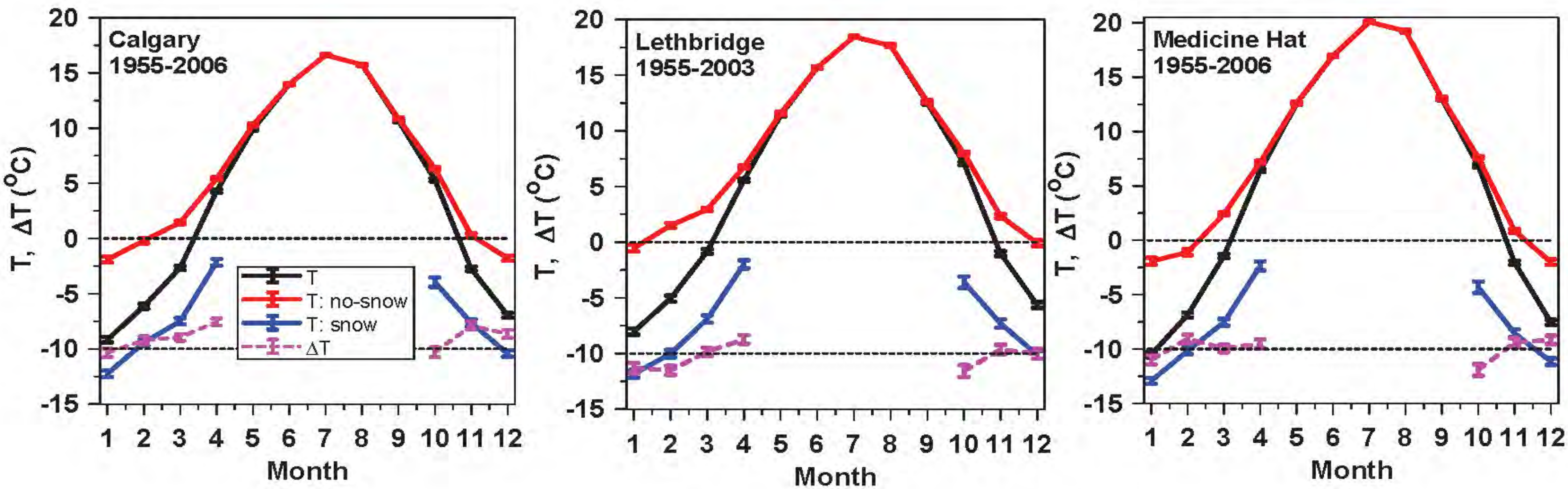
$$ECA = - SWCF / SW_{dn}(clear)$$

$$SW_n = (1 - \alpha_s)(1 - ECA)\ SW_{dn}(clear)$$

Reflected by surface, clouds

MODIS ***Calibrate Opaque Cloud data with Baseline Surface Radiation Network (BSRN)***

Snow-No-snow Impact on Climate

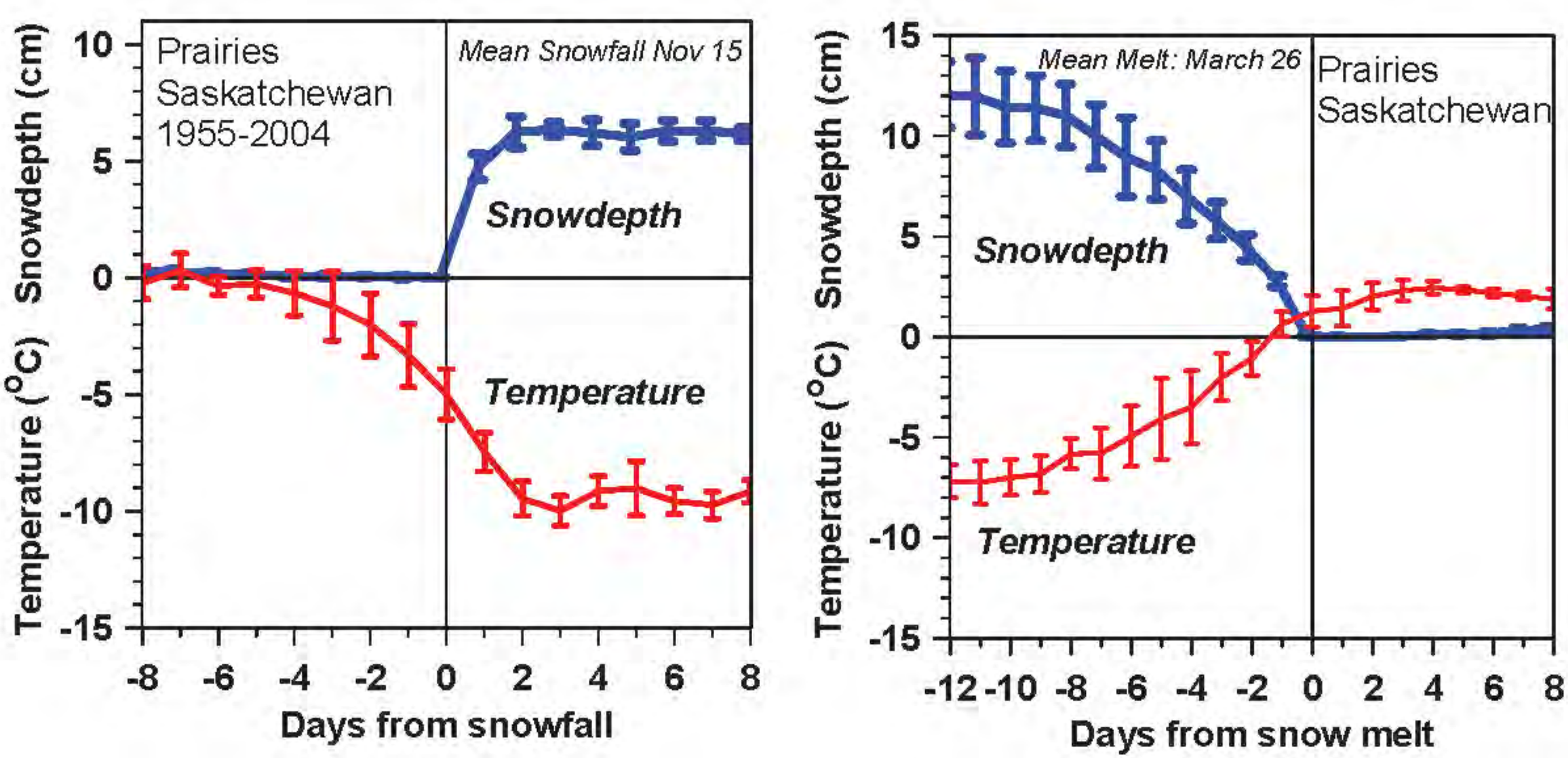


Separate mean climatology into days with no-snow and Snowdepth >0

ΔT = T:no-snow –T:snow = -9.8(±0.8)°C

Betts et al. (2016)

Snowfall and Snowmelt
Winter and Spring transitions



- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; shift to cold stable BL***
  - ***Local climate switch between warm and cold seasons***
  - ***Winter comes fast with snow***

Betts et al. 2014

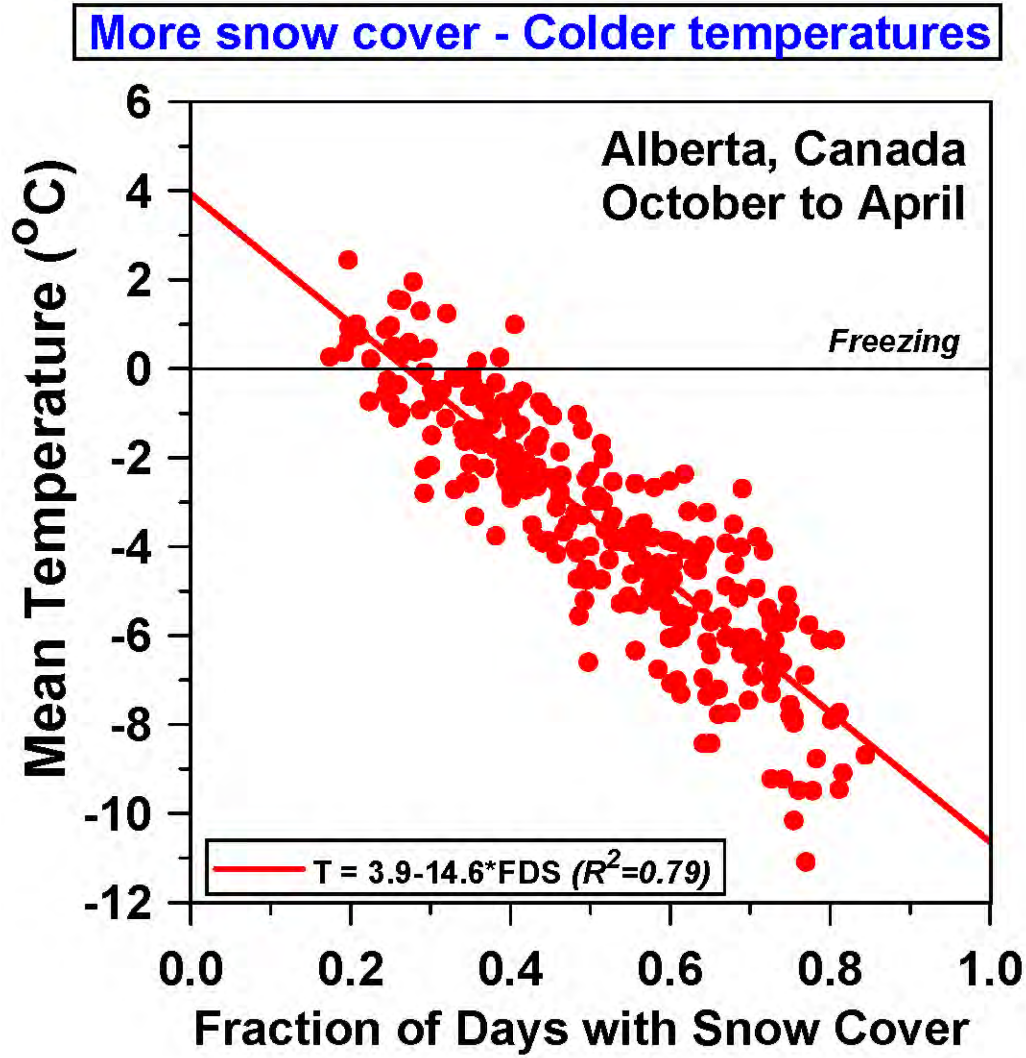
Interannual variability of T coupled to Snow Cover

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

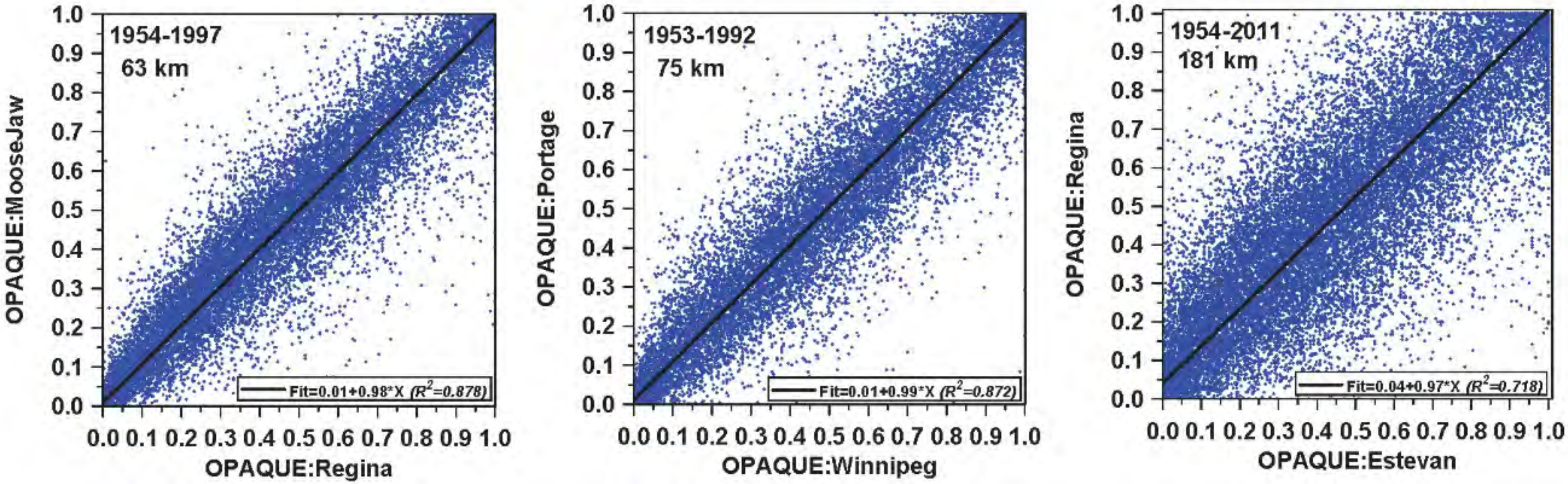
10% fewer snow days

= 1.5K warmer

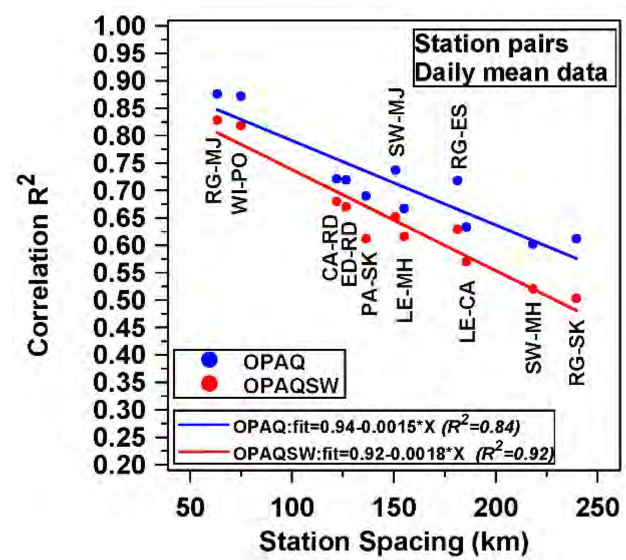
on Prairies



Opaque Cloud (Observers)

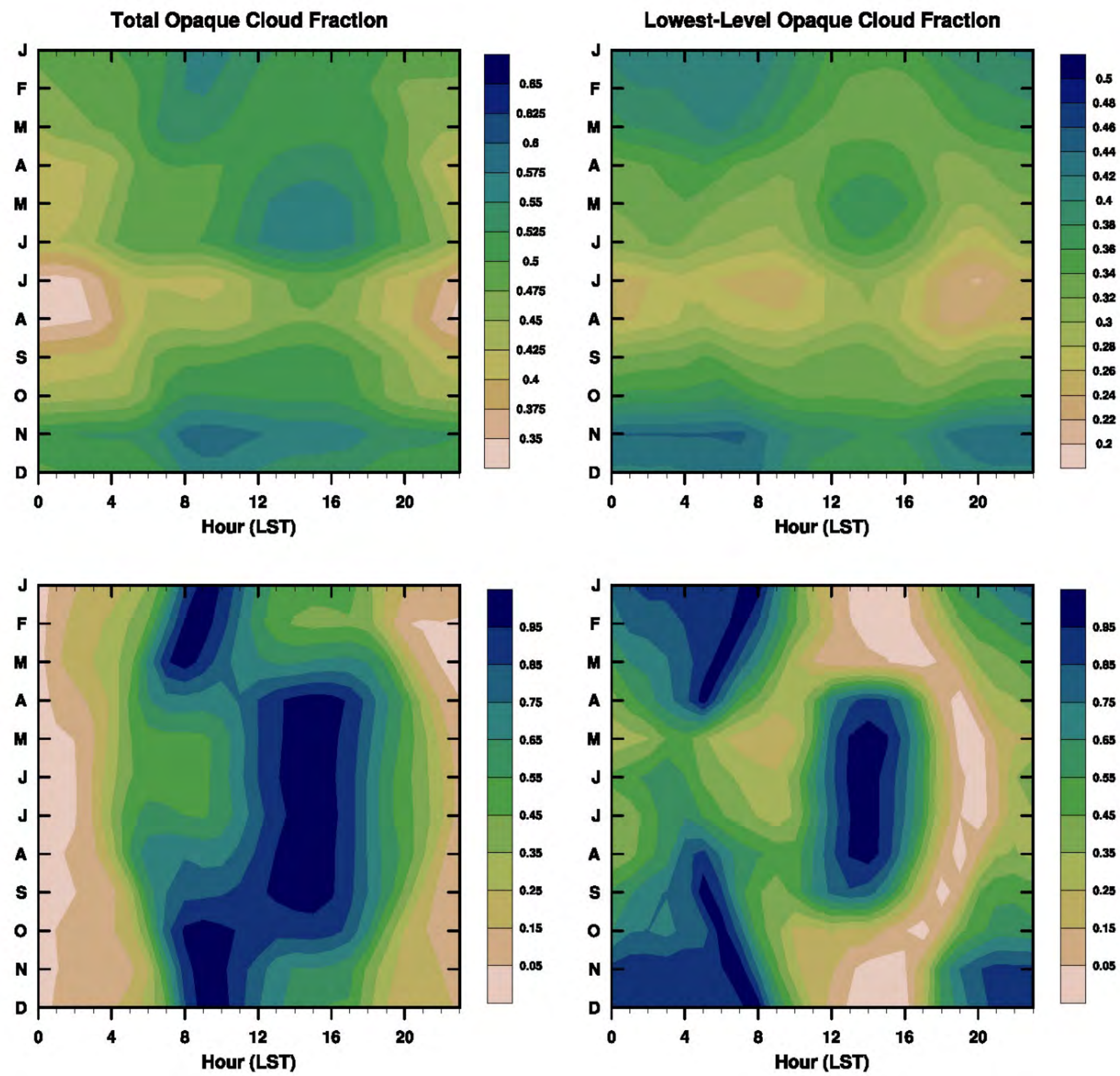


- **Daily means unbiased**
- **Correlation falls with distance**
- **Good data!**



Annual/Diurnal Opaque Cloud

- **Total opaque cloud fraction and lowest-level opaque cloud**
- **Normalized diurnal cycles (where 1 is the diurnal maximum and 0 is the minimum.**
- **Regime shift between cold and warm seasons: Why? Cloud forcing changes sign**



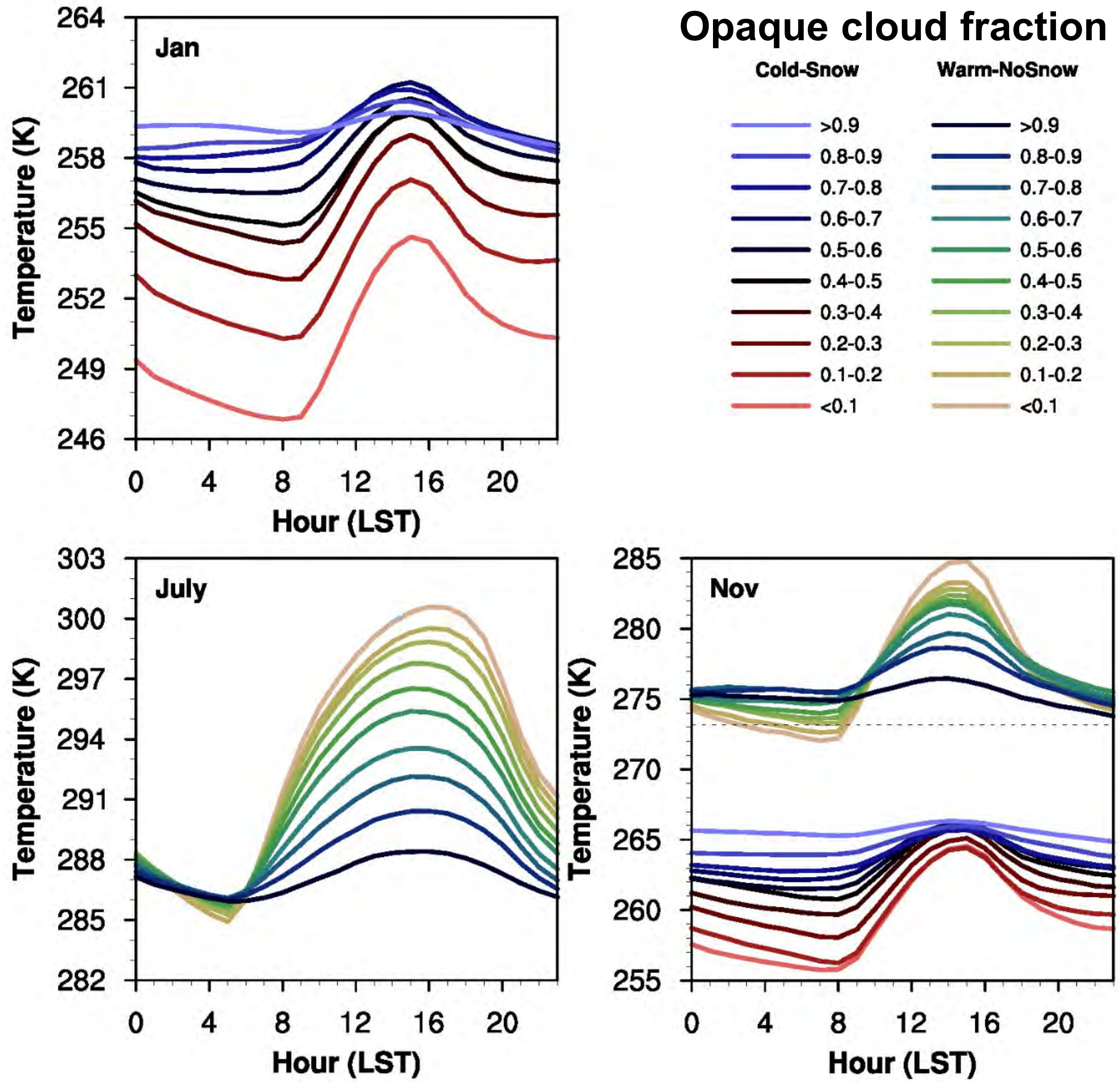
Diurnal cycle: Clouds & Snow

Canadian Prairies
660 station-years of data

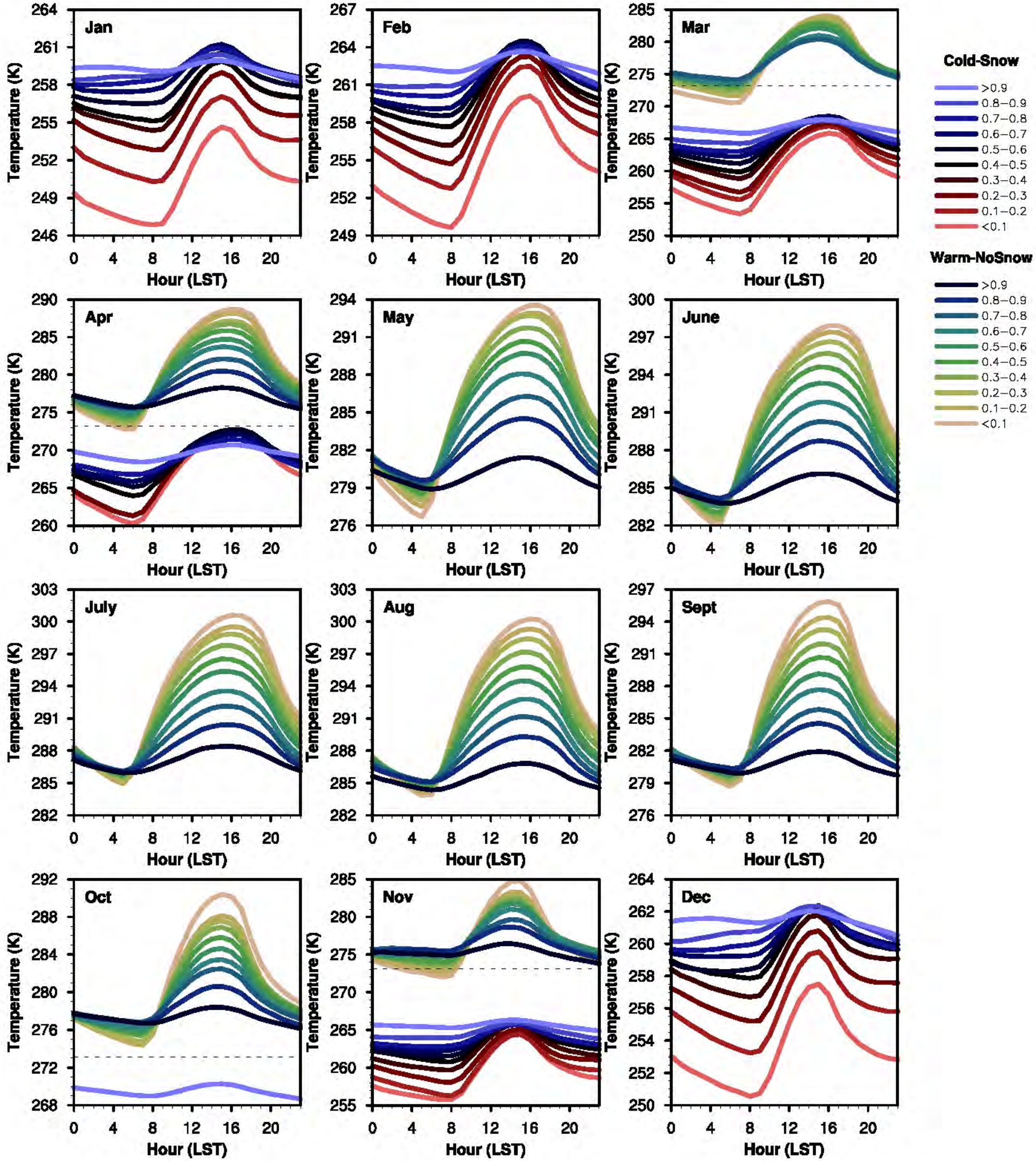
Winter climatology
- Colder when clear
- LWCF dominant with snow

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"



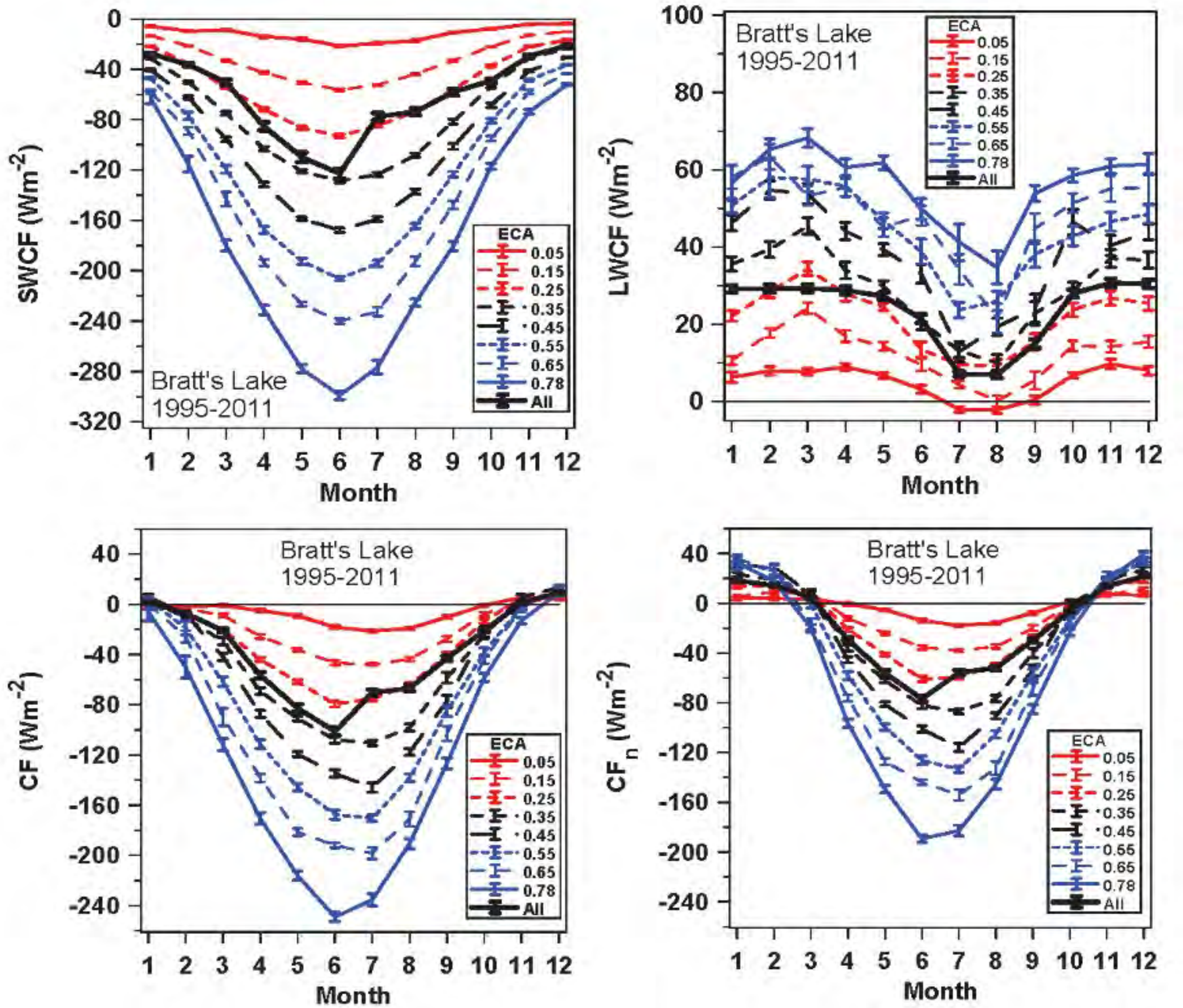
Monthly diurnal climatology (by snow and cloud)



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***

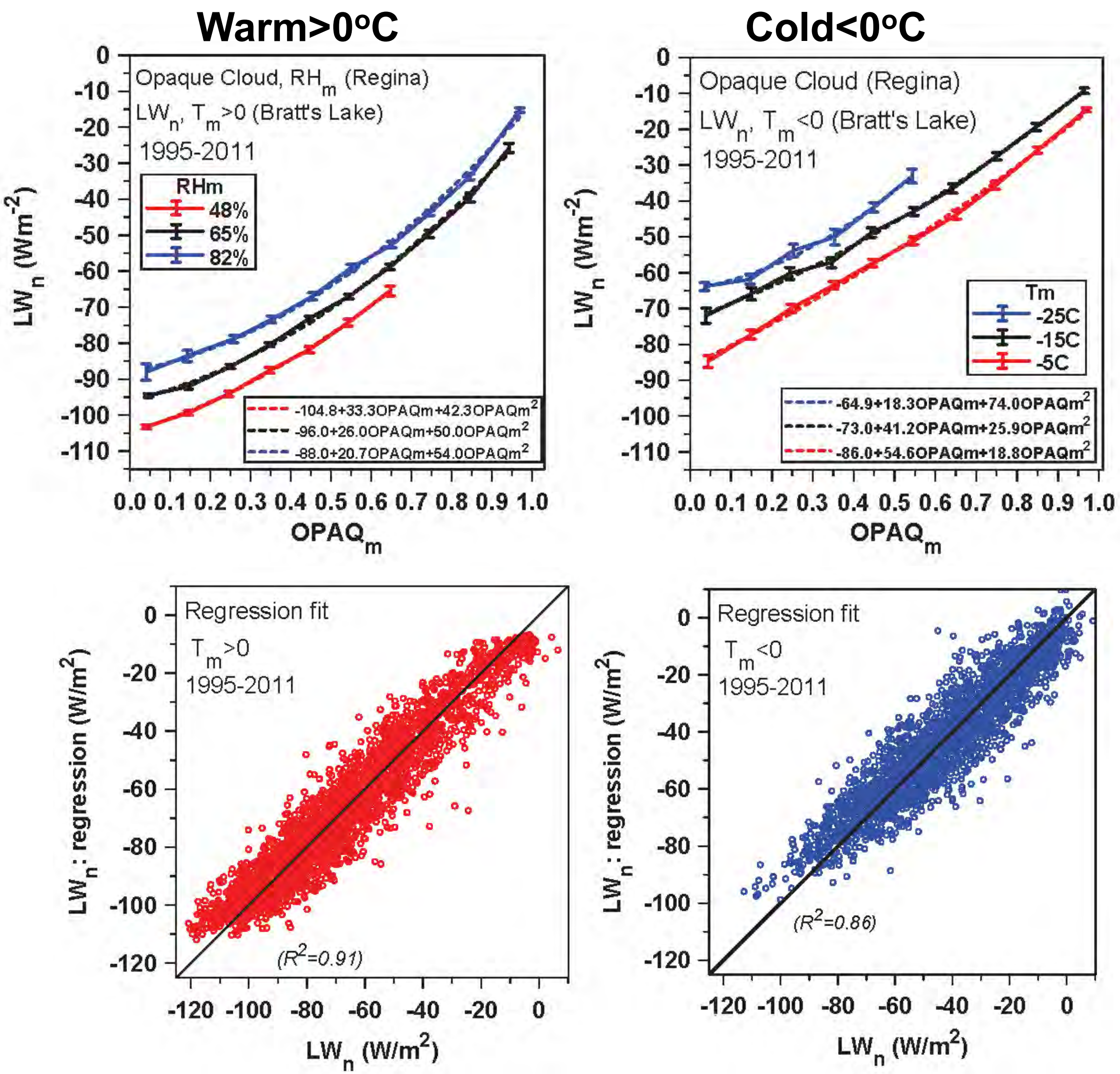


(Betts et al. 2015)

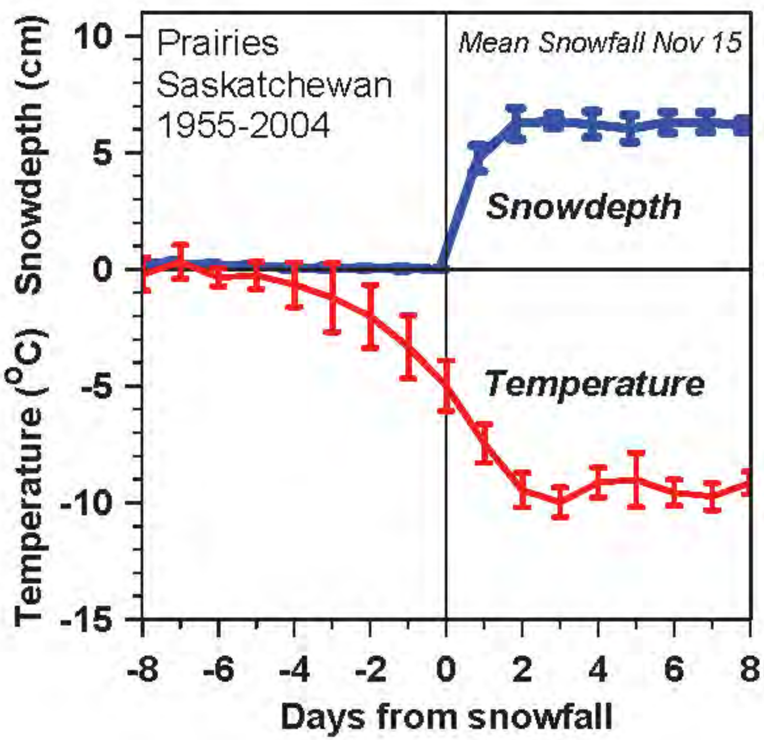
Use BSRN data to "calibrate" daily opaque/reflective Cloud at Regina

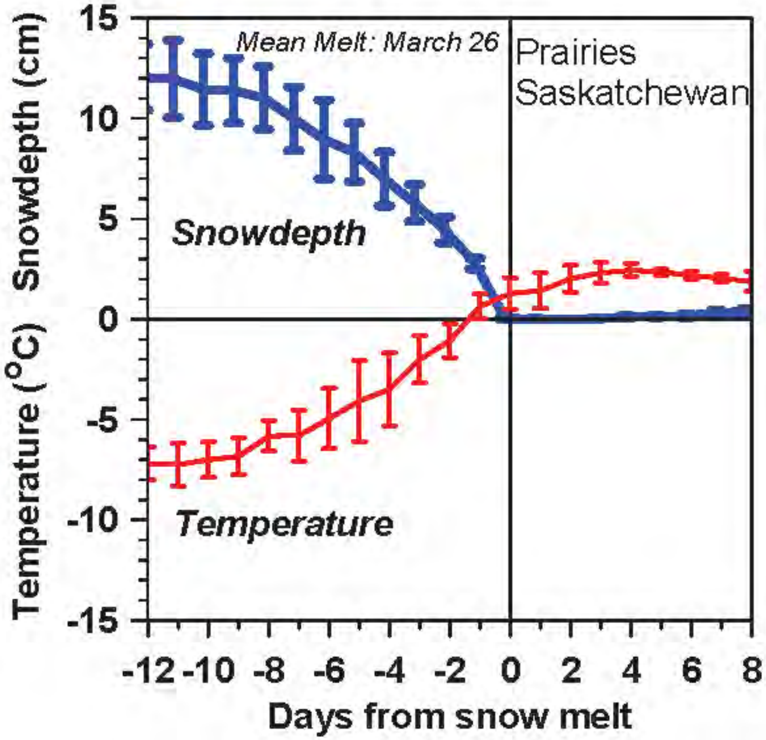
- **Daily mean opaque cloud $OPAQ_m$**
- ***LW cools but clouds reduce cooling***
- **Net LW: LW_n**
  - *T>0: RH dependence*
  - *T<0: T, TCWV also*
- ***Regression gives LW_n to ± 8W/m^2 for T_m>0 (R^2=0.91)***

(Betts et al. 2015)



Snowfall and Snowmelt
ΔT Canadian Prairies





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

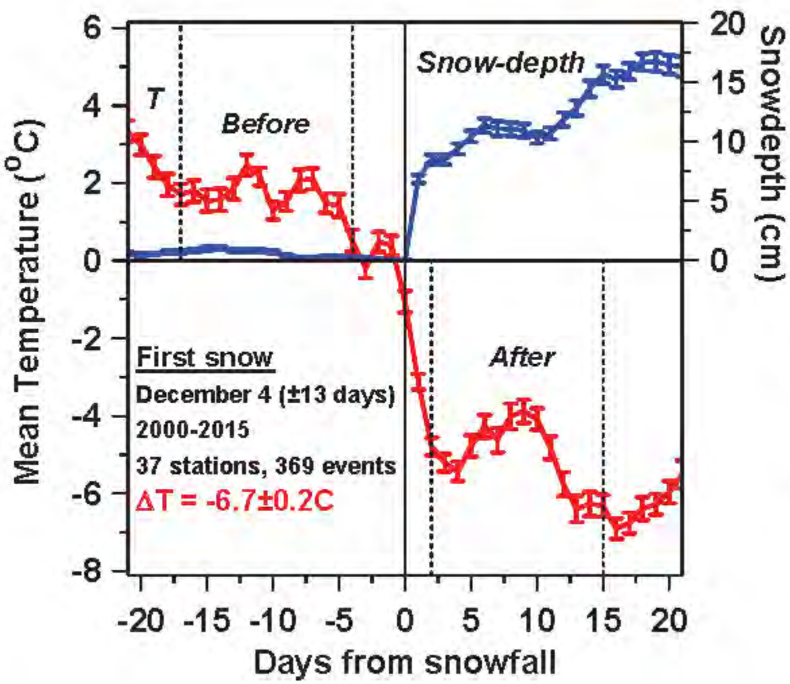
Betts et al. 2014

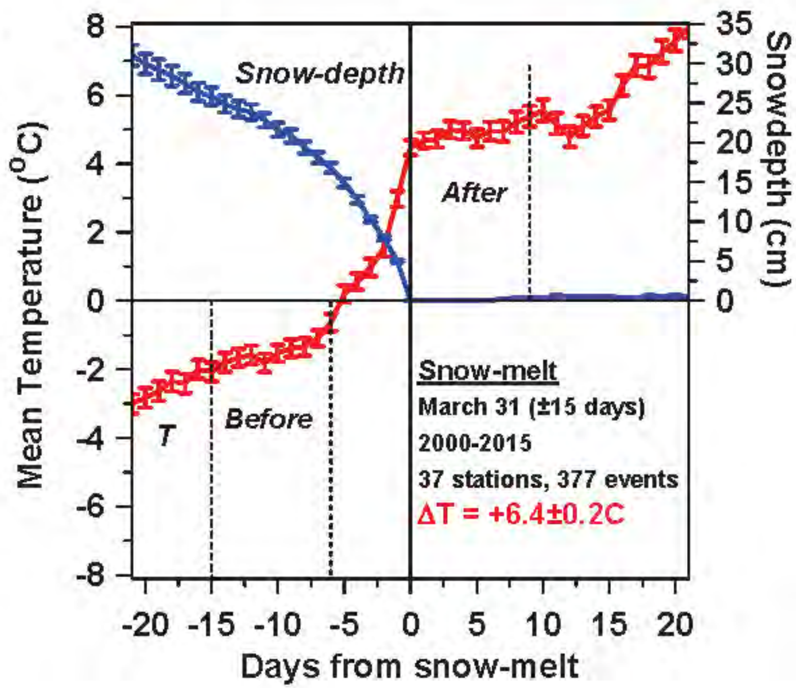
Warm and Cold Seasons

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

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

Snowfall and Snowmelt
ΔT Vermont





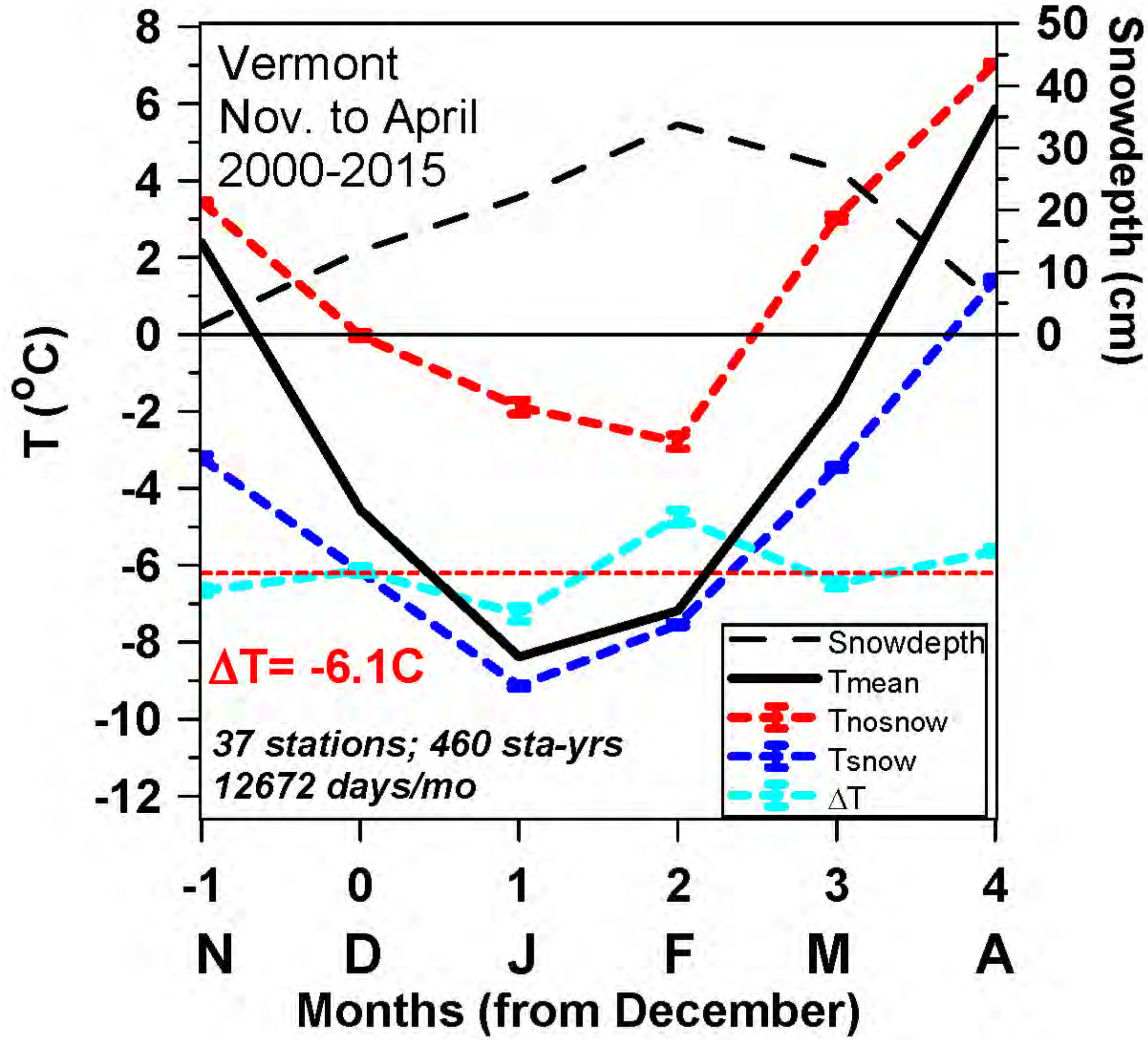
- **Temperature falls/rises 6.5 °C with first snowfall/snowmelt**
- **Albedo with snow less than Prairies**

Climatological Impact of Snow: Vermont

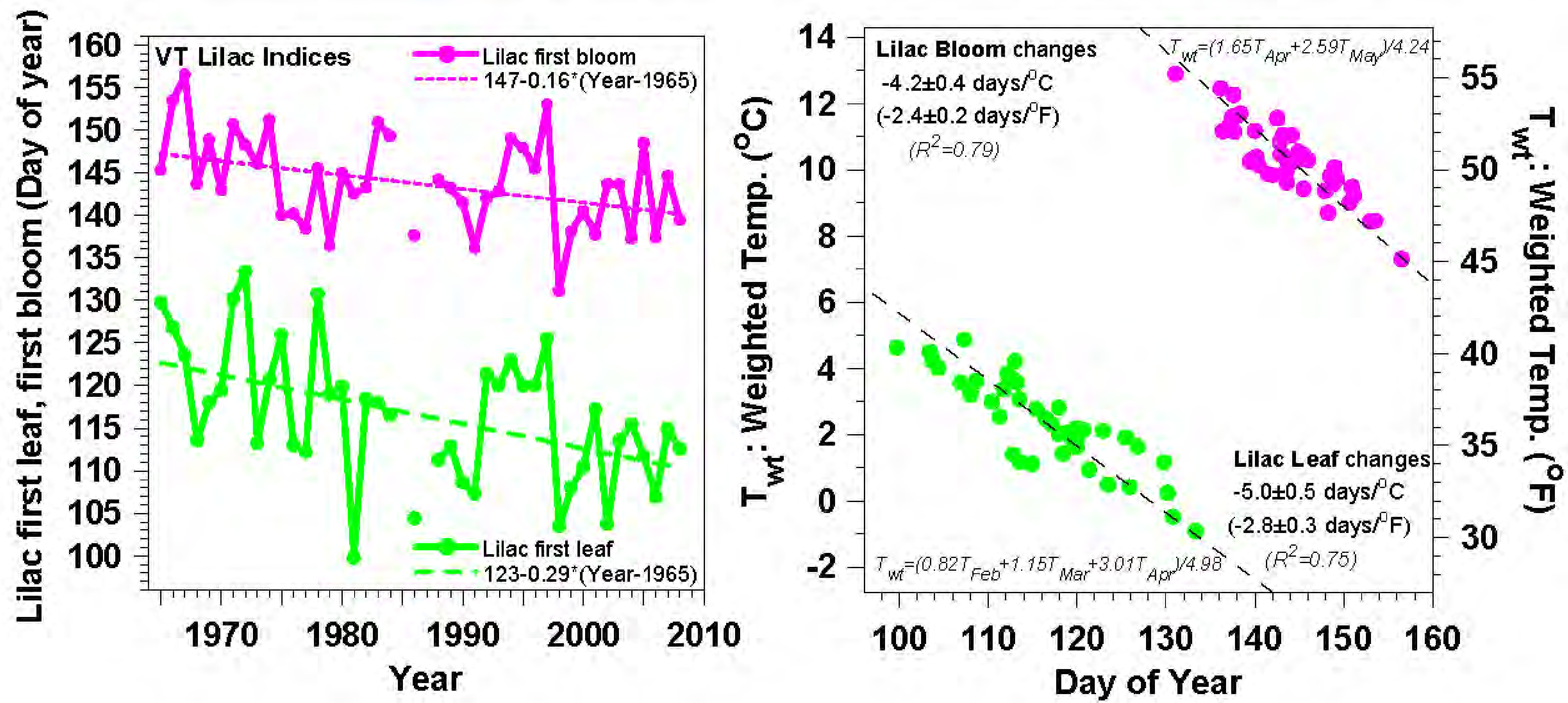
Separate mean climatology into days with no-snow and with snow

Difference ΔT= -6.1(±0.7)°C

Snow-free winters: warmer than snowy winters: +6°C



Coupling to Phenology -Lilacs



- **Leaf-out earlier by 3 days/decade (tracks ice-out)**
- **Leaf-out changes 5 days/°C**
- **<u>Snow-free winters: +6°C * 5days = 30 days earlier</u>**

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)**
  - **VT Spring phenology change = 30 days**

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

Warm Season Climate: T>0°C
(April – October with no snow)

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Cannot do climate with just T & Precip !***
- ***Daily timescale is radiation driven***
  - ***Night LW_n; day SW_n (and EF)***
- ***Monthly timescale: Fully coupled***
- ***(Long timescales: separation)***

Betts et al. 2014b; Betts and Tawfik 2016)

Warm Season Diurnal Climatology

- **Averaging daily values (Conventional)**

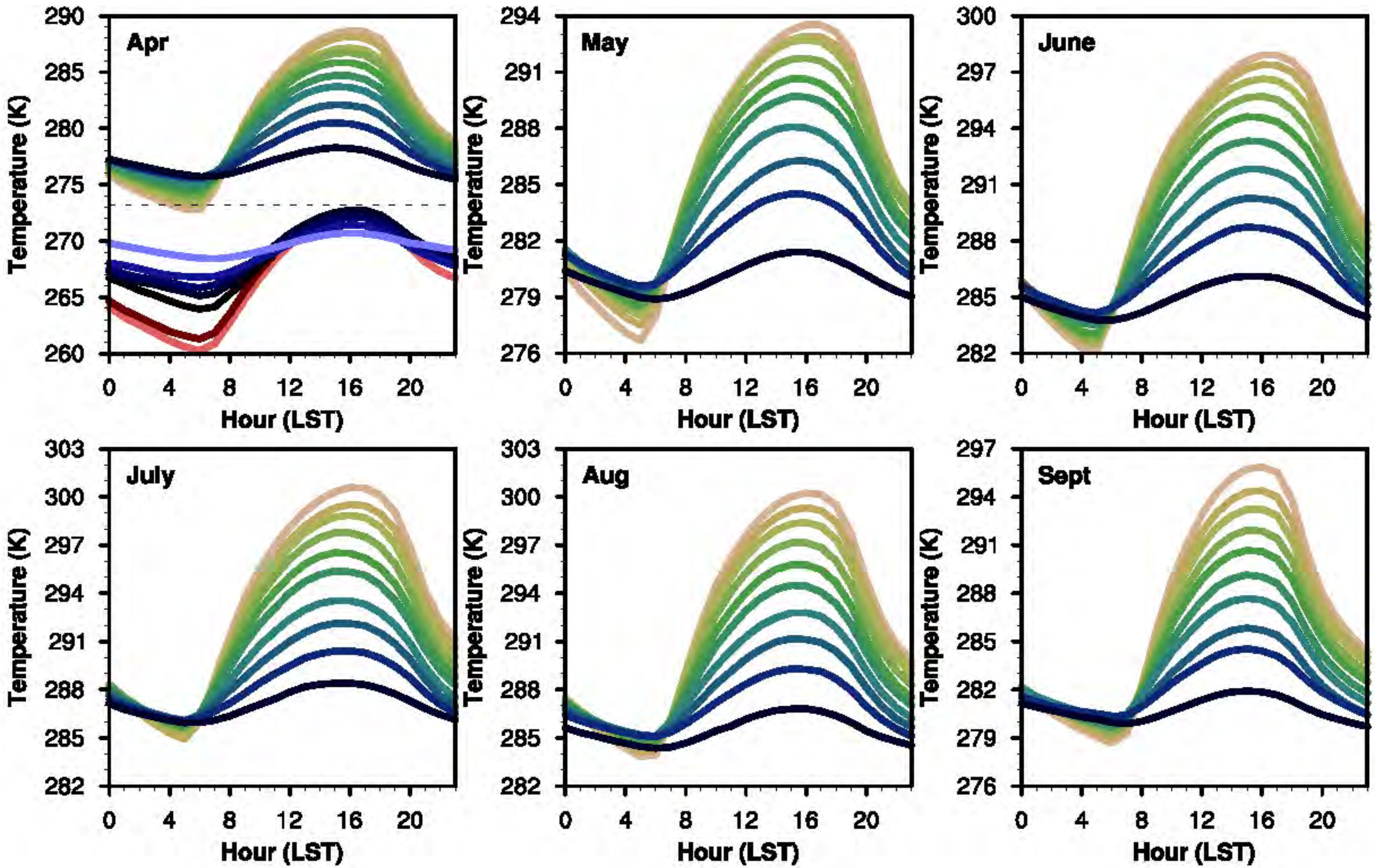
  $$DTR_D = T_{xD} - T_{nD}$$
  $$DRH_D = RH_{xD} - RH_{nD} \text{ (rarely)}$$

- **Extract mean diurnal ranges from composites *('True' radiatively-coupled diurnal ranges: damps advection)***

  $$DTR_T = T_{xT} - T_{nT}$$
  $$DRH_T = RH_{xT} - RH_{nT}$$

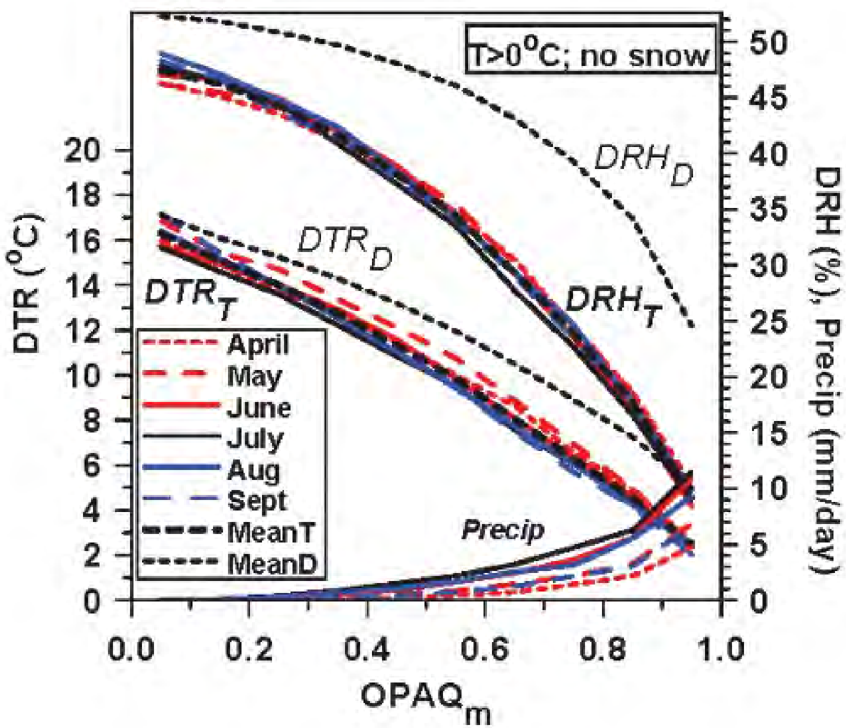
- **Q1: How are they related? $DTR_T < DTR_D$**

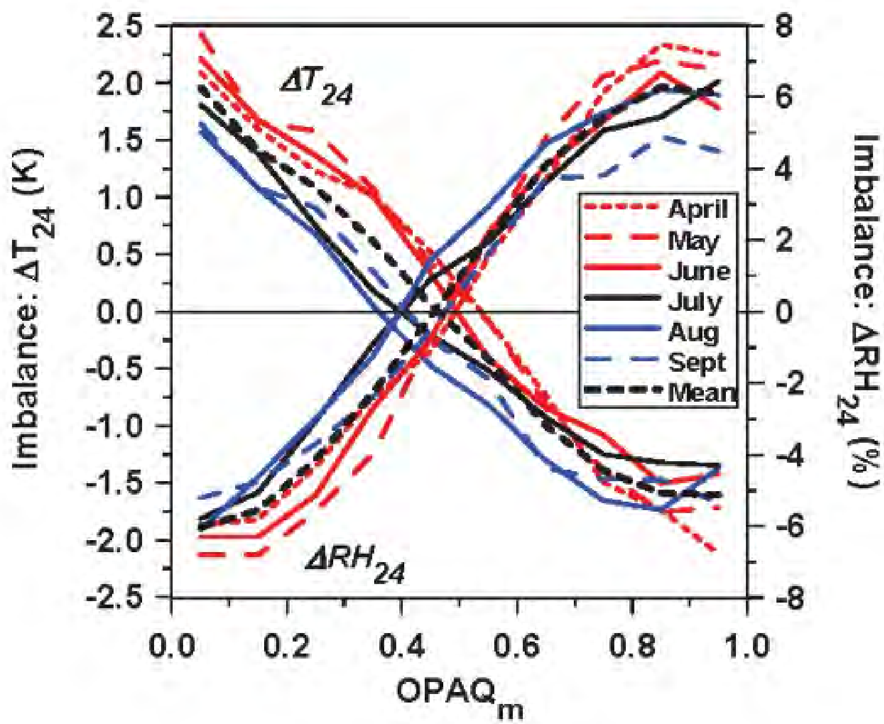
Monthly Diurnal Climatology



Q2: How much warmer is it at the end of a clear day?

Diurnal Ranges & Imbalances





- April to Sept: <u>same coupled structure</u>
- Q1: DTR_T, DRH_T < DTR_D, DRH_D <u>always</u>
- Q2: Clear-sky: warmer (+2°C), drier (-6%)

Warm Season Climate: T>0°C
(April – October with no snow)

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Cannot do climate with just T & Precip !***
- ***Monthly timescale: Fully coupled***
  - ***Use regression to couple anomalies***

Betts et al. 2014b

Monthly timescale: Regression

$$\delta DTR = K + A^* \delta Precip(Mo-2) + B * \delta Precip(Mo-1) + C * \delta Precip + D * \delta OpaqueCloud$$

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

δDTR anomalies

Month	K	A *(Mo-2)*	B*(Mo-1)*	C *(Mo)*	D *(Mo)*	R^2 All	R^2 Precip	R^2 Cloud
May	0±0.8		-0.37±0.05	-0.37±0.04	-1.10±0.05	**0.73**	0.41	0.66
Jun	0±0.7		-0.30±0.03	-0.32±0.02	-0.97±0.04	**0.69**	0.42	0.52
July	0±0.7	-0.20±0.03	-0.25±0.02	-0.33±0.03	-1.10±0.05	**0.67**	0.42	0.48
Aug	0±0.7	-0.07±0.02	-0.21±0.03	-0.40±0.03	-1.24±0.04	**0.79**	0.46	0.71
Sept	0±0.8		-0.22±0.03	-0.49±0.04	-1.27±0.04	**0.82**	0.43	0.75
Oct	0±0.8		-0.27±0.03	-0.70±0.07	-1.33±0.04	**0.77**	0.37	0.70

Betts et al. 2014b

Monthly timescale: Regression

δRH_{tx} = K + A* δPrecip(Mo-2) + B * δPrecip(Mo-1) + C * δPrecip + D * δOpaqueCloud
(Month-2) (Month-1) (Month) (Month)

Afternoon δRH_{tx} anomalies

Month	K	A *(Mo-2)*	B*(Mo-1)*	C *(Mo)*	D *(Mo)*	R^2 All	R^2 Precip	R^2 Cloud
May	0±3.6	1.30±0.38	1.47±0.22	2.07±0.17	4.75±0.20	0.72	0.46	0.62
Jun	0±3.6	0.69±0.23	1.26±0.15	1.96±0.12	4.36±0.22	0.68	0.47	0.48
July	0±4.1	0.84±0.18	1.71±0.12	1.81±0.17	4.40±0.30	0.59	0.43	0.33
Aug	0±3.6	0.66±0.11	1.23±0.13	2.42±0.16	4.08±0.20	0.73	0.53	0.56
Sept	0±3.5		1.40±0.13	2.10±0.18	4.35±0.16	0.75	0.45	0.63
Oct	0±4.3		1.28±0.19	5.02±0.39	4.58±0.23	0.67	0.44	0.53

Betts et al. 2014b

Monthly Regression Fits

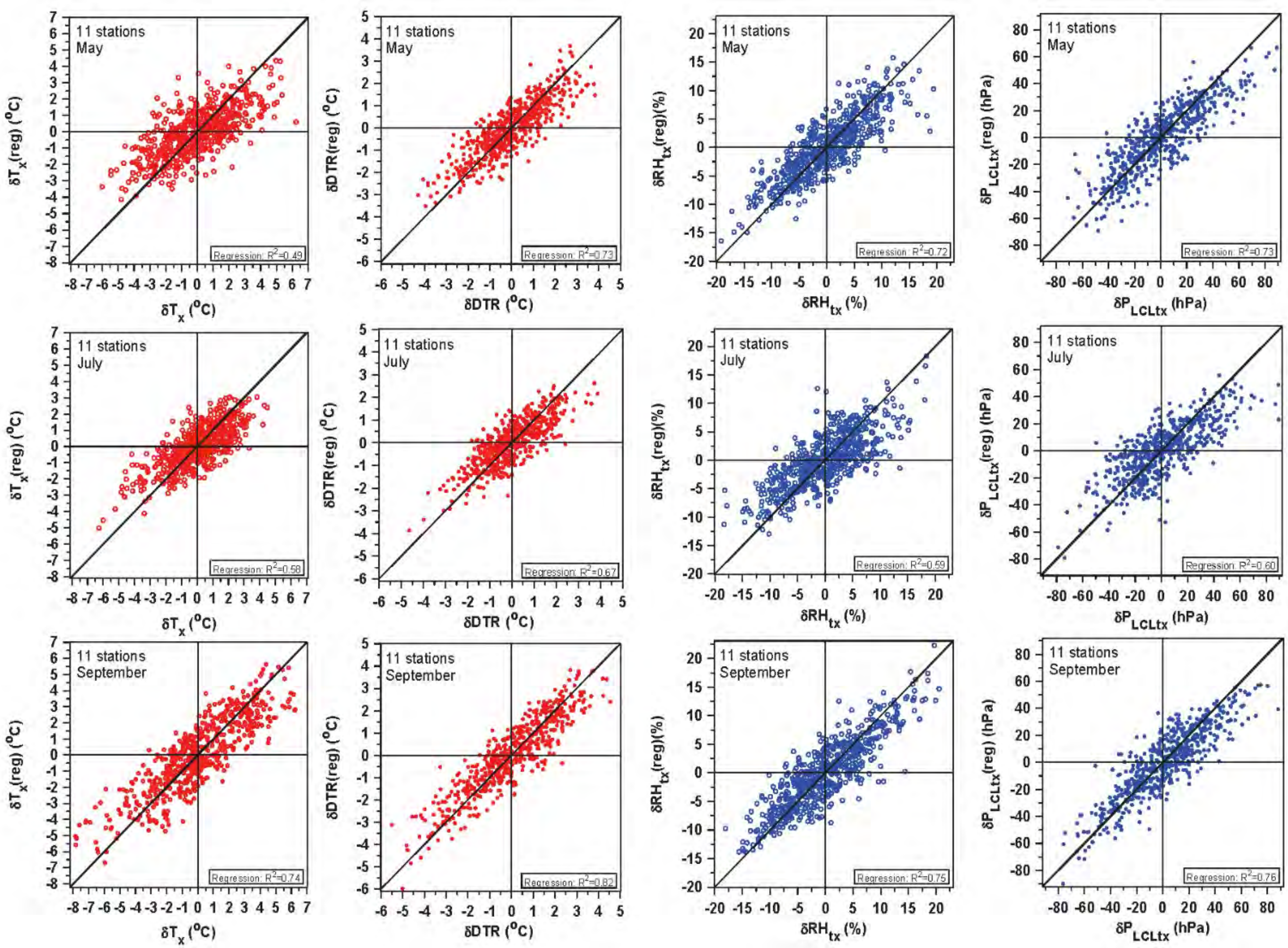
δT_x | δDTR | δRH_{tx} | δP_{LCLtx}

regression

May

July

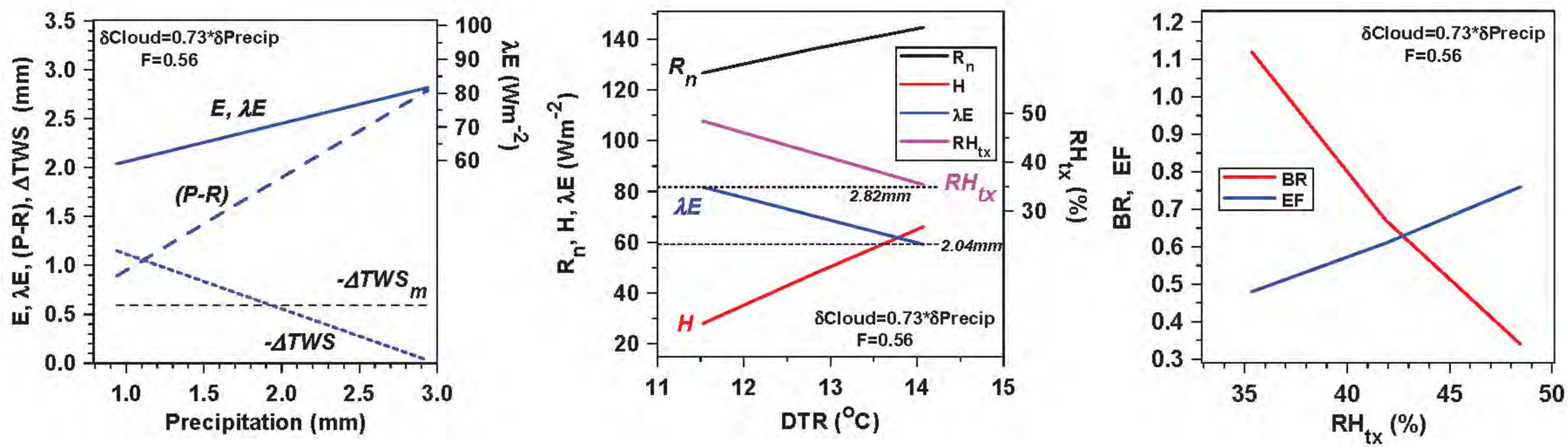
Sept



MJJA Growing Season (Merge, Normalize by SD)
$\delta Y_\sigma = K_\sigma + B_\sigma * \delta Precip(AMJJA)_\sigma + C_\sigma * \delta OpaqueCloud_\sigma$

Variable: δY_σ	K_σ	B_σ (Precip)	C_σ (Cloud)	R^2_σ	$\sigma(\delta Y)$
$\delta T_{x\sigma}$	0±0.7	**-0.33±0.03**	**-0.52±0.03**	**0.52**	**1.11 °C**
$\delta T_{m\sigma}$	0±0.8	-0.21±0.05	-0.50±0.07	0.38	**0.88 °C**
δDTR_σ	0±0.6	**-0.55±0.03**	**-0.39±0.03**	**0.62**	**0.83 °C**
$\delta RH_{tx\sigma}$	0±0.6	**0.56±0.03**	**0.35±0.03**	**0.60**	**4.35 %**
$\delta RH_{m\sigma}$	0±0.7	0.51±0.03	0.33±0.03	0.50	**4.61 %**
$\delta P_{LCLtx\sigma}$	0±0.6	**-0.56±0.03**	**-0.37±0.03**	**0.61**	**18.6 hPa**
$\delta Q_{tx\sigma}$	0±0.9	0.50±0.04	0.03±0.04	0.26	**0.58 g/kg**
$\delta\theta_{Etx\sigma}$	**0±1.0**	**0.22±0.04**	**-0.31±0.04**	**0.09**	**1.95 K**

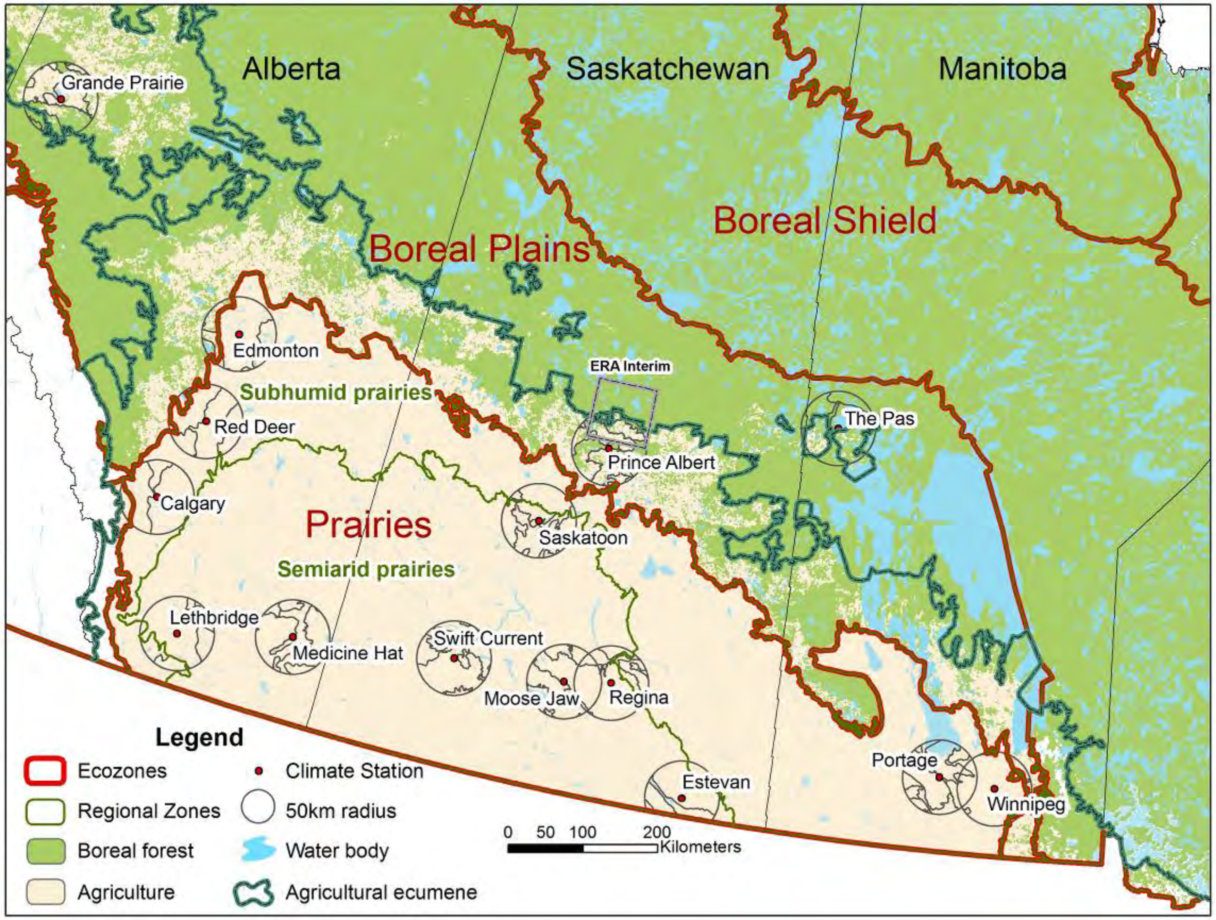
Growing Season Coupling between Energy and Water Budgets and Surface Climate



Betts et al. 2014b

- **Total water storage (GRACE) coupled to precipitation variability (F=0.56)**
- **Climate cloud coupling: δCloud = 0.73 δPrecip**
- **R_n coupled to cloud variability**
- **Diurnal climate coupled to cloud and precipitation variability (regression)**

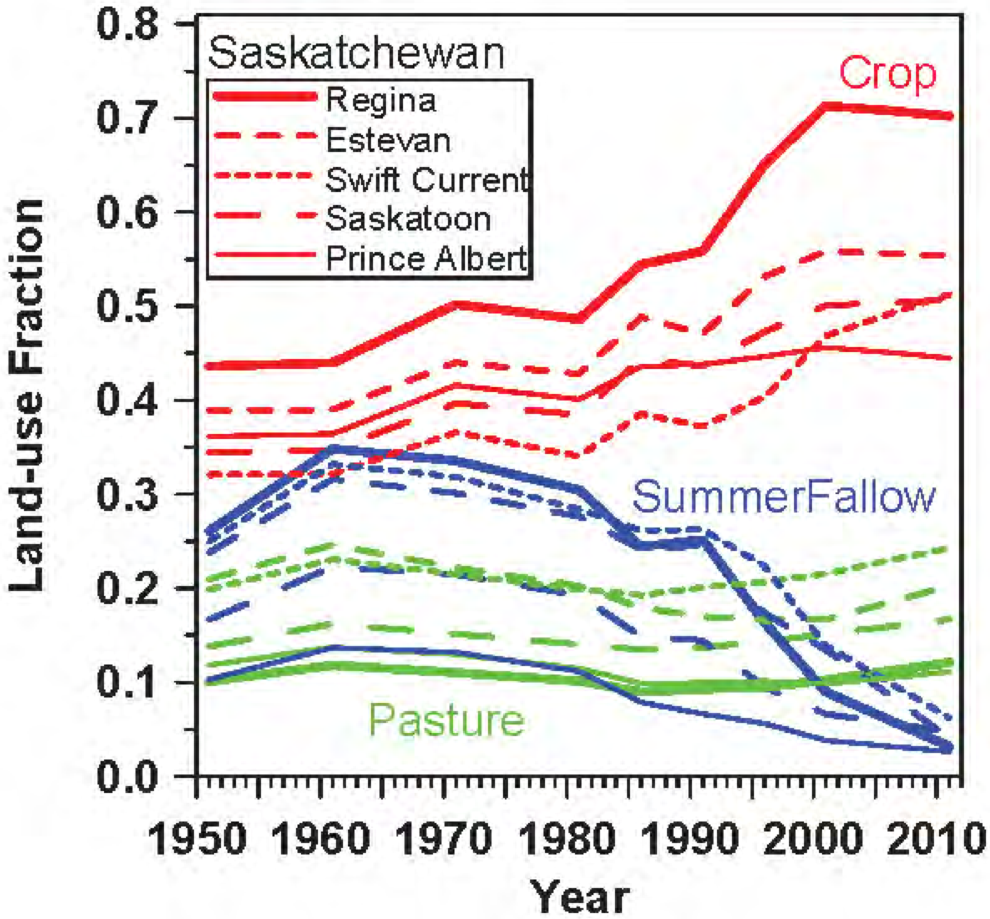
15 Prairie stations: 1953-2011



- ***How has changes in cropping changed the growing season climate?***

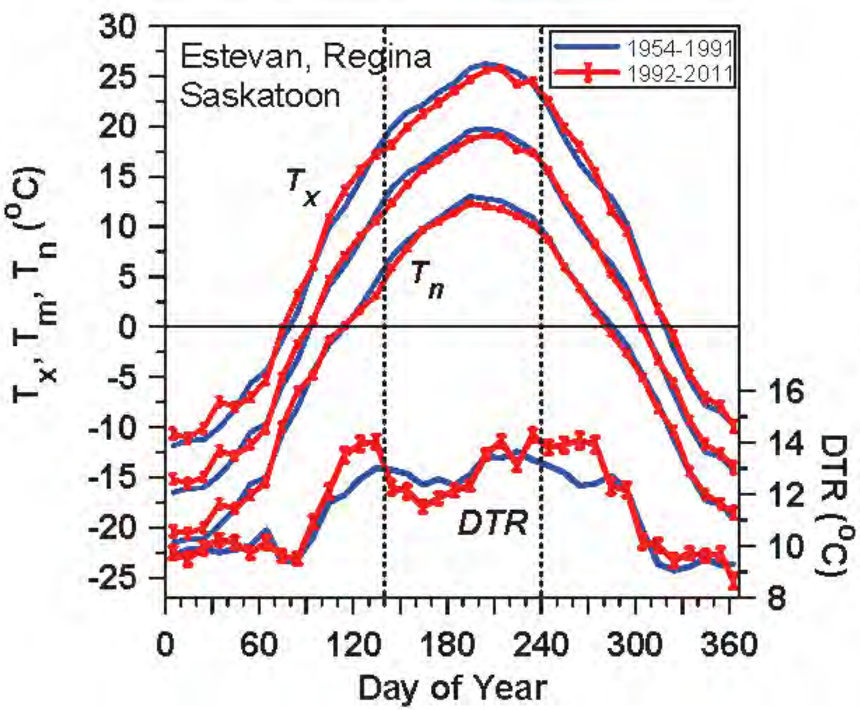
Change in Cropping (SK)

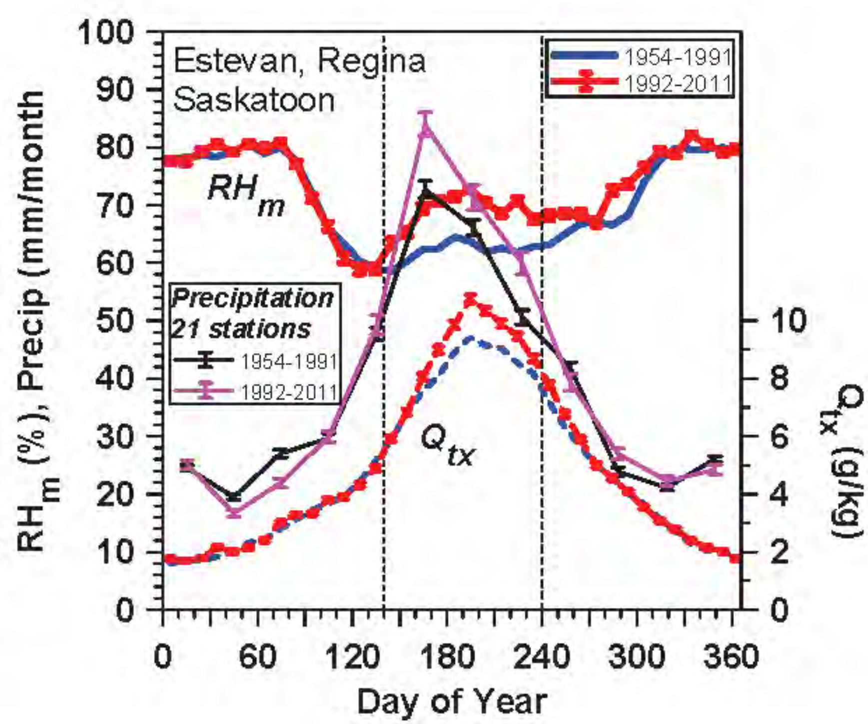
- **Ecodistrict mean for 50-km around station**
- **5 Mha drop (25%) in 'SummerFallow'**
  - **no crops: save water**
- ***Split at 1991 – Ask***
- ***Has summer climate changed?***



Betts et al. 2013b

Three Station Mean in SK





- **Growing season (Day of Year: 140-240)**
- **(T_x, T_m) cooler (-0.93±0.09, -0.82±0.07 ^oC)**
- **(RH_m, Q_{tx}) (+6.9±0.2%, +0.70±0.04 g/kg)**
- **Precipitation: +25.9±4.6 mm for JJA (+10%)**

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)**
  - **VT Spring phenology change = 30 days**

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

Papers at http://alanbetts.com

Warm Season Climate: T>0°C

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Can't 'understand climate' with T & Precip.***
- ***Monthly/seasonal timescale: coupled***
  - ***But T_x, T_m depend more on cloud/radiation***
  - ***RH_x, RH_m, DTR depend more on precip.***

Papers at *http://alanbetts.com*

Betts et al. 2014b