Understanding land-atmosphere coupling

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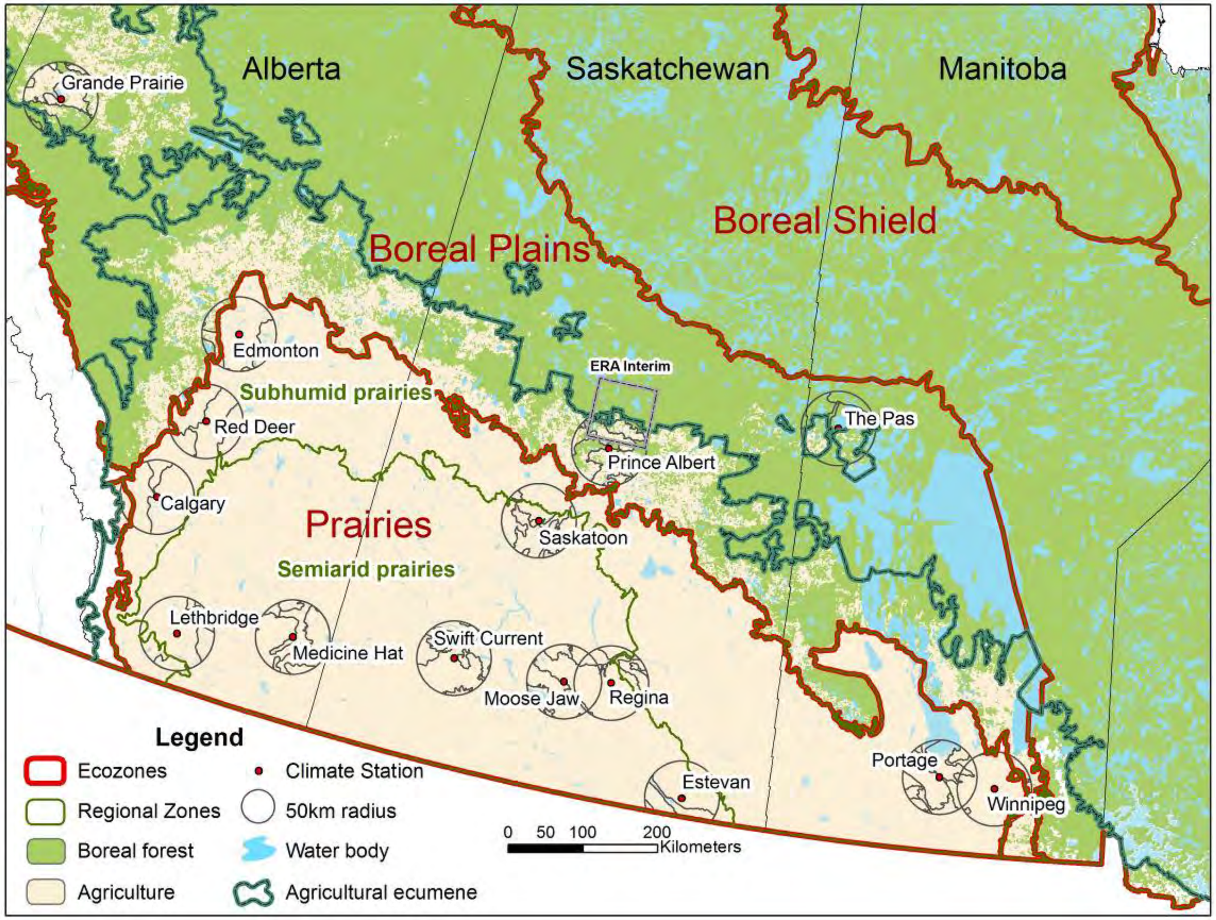
Water in the Climate System

- Vapor, liquid and ice
  - Ocean and land
- Latent heat of phase changes
  - LH release drives clouds and storms
  - Precip, soil moisture, stomatal control $EF=\lambda E/(R_n-G)$
- Vapor IR absorption (WV greenhouse)
  - Clouds 'black' in IR
- SW reflectivity of clouds and snow
  - Effective cloud albedo, surface albedo with snow

14 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)**

Prairie Station Locations

Station Name	Station ID	Province	Latitude	Longitude	Elevation (m)
Red Deer*	3025480	Alberta	52.18	-113.62	905
Calgary*	3031093	Alberta	51.11	-114.02	1084
Lethbridge†	3033880	Alberta	49.63	-112.80	929
Medicine Hat	3034480	Alberta	50.02	-110.72	717
Grande Prairie*	3072920	Alberta	55.18	-118.89	669
Regina*	4016560	Saskatchewan	50.43	-104.67	578
Moose Jaw	4015320	Saskatchewan	50.33	-105.55	577
Estevan*	4012400	Saskatchewan	49.22	-102.97	581
Swift Current†	4028040	Saskatchewan	50.3	-107.68	817
Prince Albert*	4056240	Saskatchewan	53.22	-105.67	428
Saskatoon*	4057120	Saskatchewan	52.17	-106.72	504
Portage-Southport	5012320	Manitoba	49.9	-98.27	270
Winnipeg*†	5023222	Manitoba	49.82	-97.23	239
The Pas*†	5052880	Manitoba	53.97	-101.1	270

Outline

Part 1: Review of published papers

- **Clouds and Diurnal Cycle over seasons**
  - ***Betts et al (2013a)***
- **Annual crops and seasonal diurnal cycle**
  - ***Betts et al (2013b)***
- **Winter snow transitions and climate**
  - ***Betts et al (2014a)***

Part 2: Work in progress

- **Climate coupling between temperature, humidity, precipitation and cloud cover**
- **Land-atmosphere coupling in the warm season on daily timescales**
  - **Coupling to SW and LW; wind, RH**

References

- Betts, A. K. (2009), Land-surface-atmosphere coupling in observations and models. *J. Adv. Model Earth Syst., Vol. 1, Art. #4,* 18 pp., doi: 10.3894/JAMES.2009.1.4

- 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 (2013b), 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

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Methods: Analyze Coupled System

- *Seasonal diurnal climate by station/region*
- **220,000 days of excellent data (600 years)**

- **Composite by daily mean opaque cloud**
  - **Calibrate SWCF, LWCF against radiation data**

- **Change of seasonal climate with cropping**
  - **'Summerfallow' to annual crops on 5MHa in 30 yrs**

- **Composite across snow transitions**
  - **First snow in fall; spring melt of snowpack**
  - **Winter climate and % days snow cover**

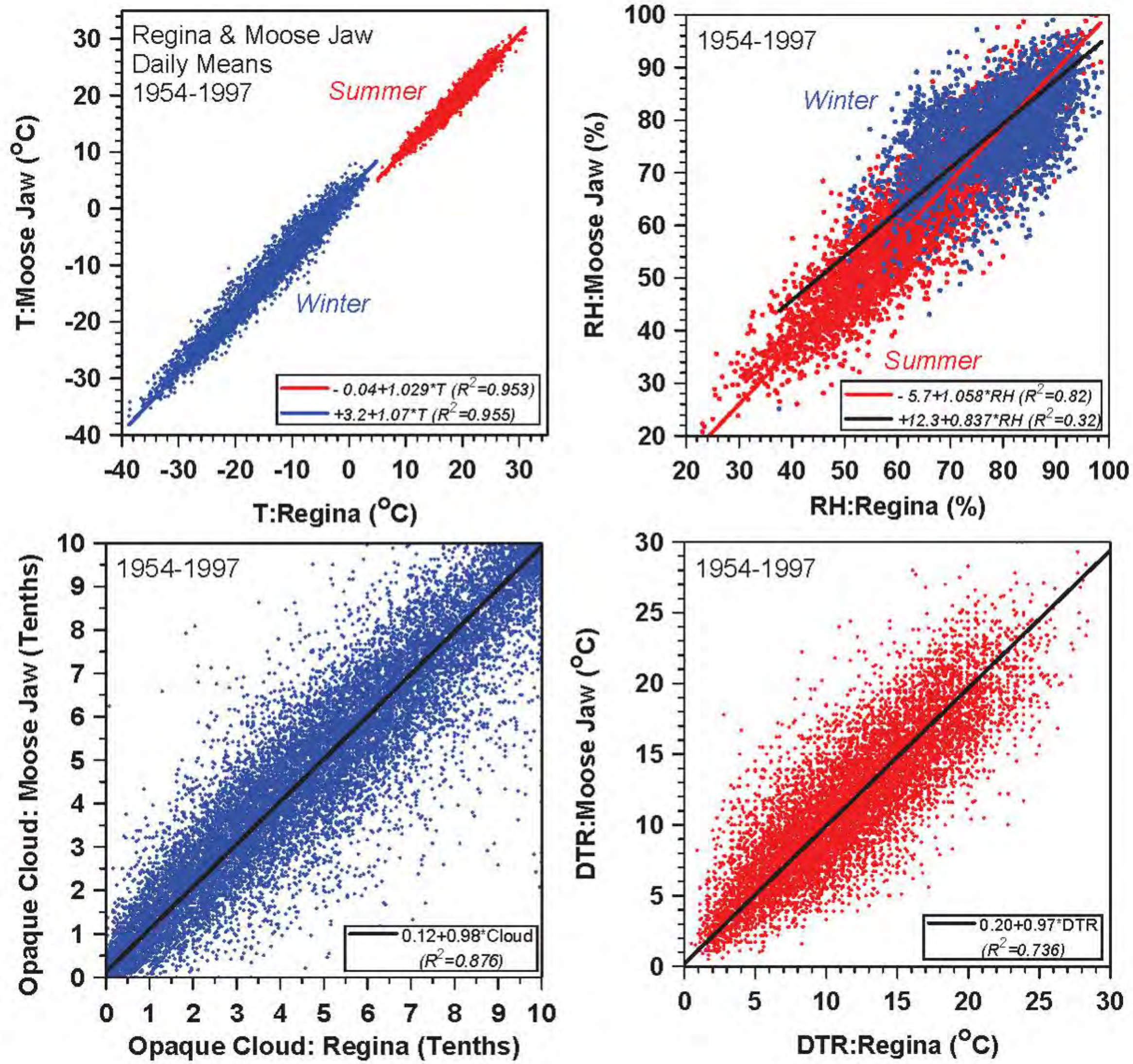
- ***Link T, RH to precipitation and cloud cover on monthly and seasonal timescales***

Clouds and Diurnal Climate

- **Reduce hourly data to**
  - **daily means: T_{mean} , RH_{mean} etc**
  - **data at T_{max} and T_{min}**
- ***Diurnal cycle climate***
  - **DTR = T_{max}-T_{min}** ***(T_x-T_n)***
  - **ΔRH = RH_{tn} –RH_{tx}**
- ***Almost no missing hourly data (until recent government cutbacks!)***

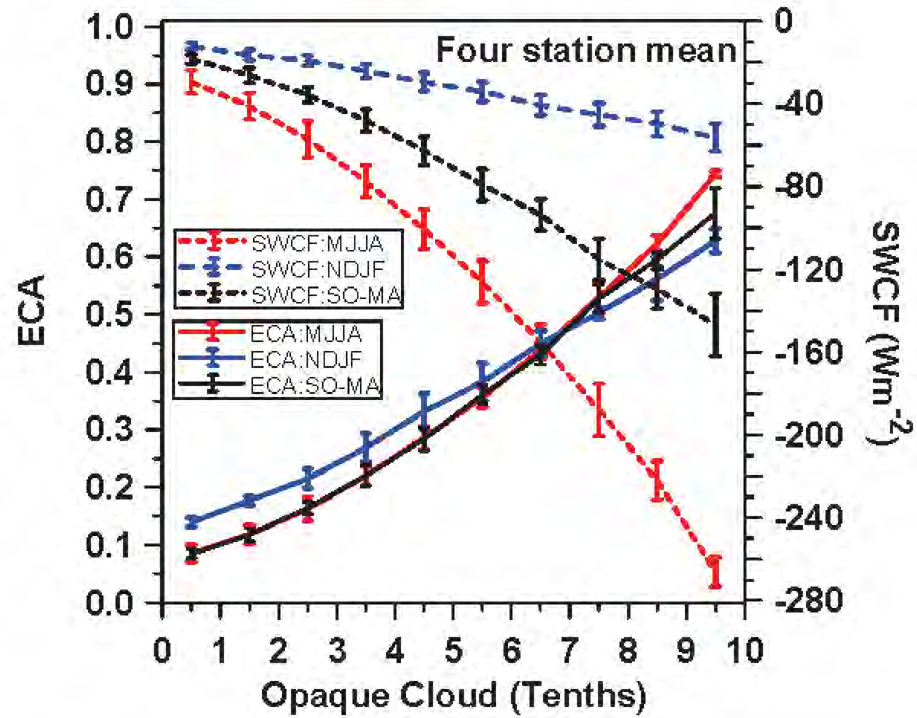
Compare Neighbors: 64 km

- **Daily means**
- **T: R^2>0.95**
- **DTR: 1 to 1**
- **RH poorly correlated in winter**
- **Opaque Cloud 1 to 1**



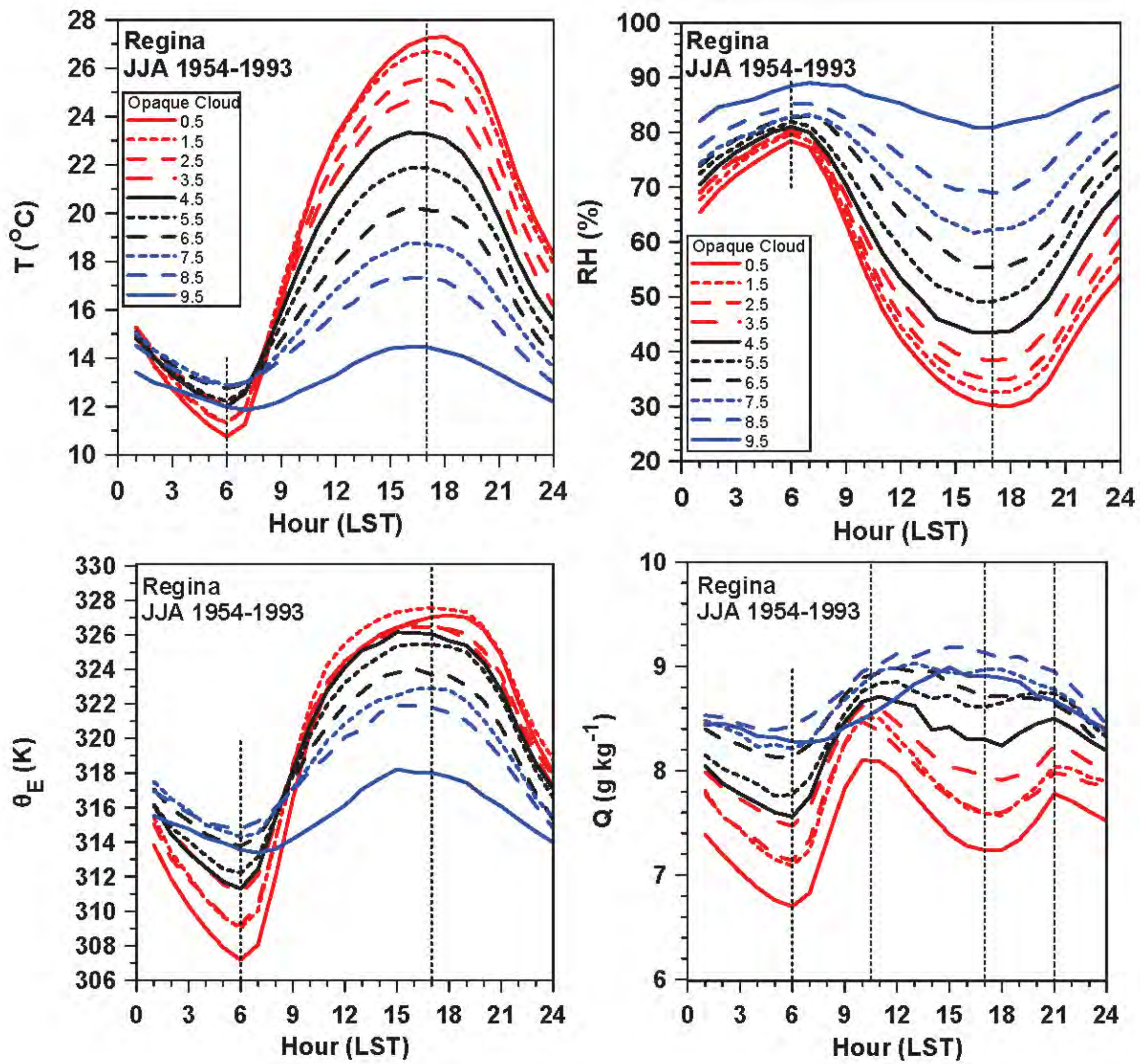
Calibration of Opaque Cloud to Effective Cloud Albedo (ECA)

- **SW_{dn} data**
  - *Lethbridge, Swift Current, The Pas, Winnipeg*
  - 82 station-years
- **Tight relationship**
  - OpaqueCloud to ECA
  - NDJF a little flatter



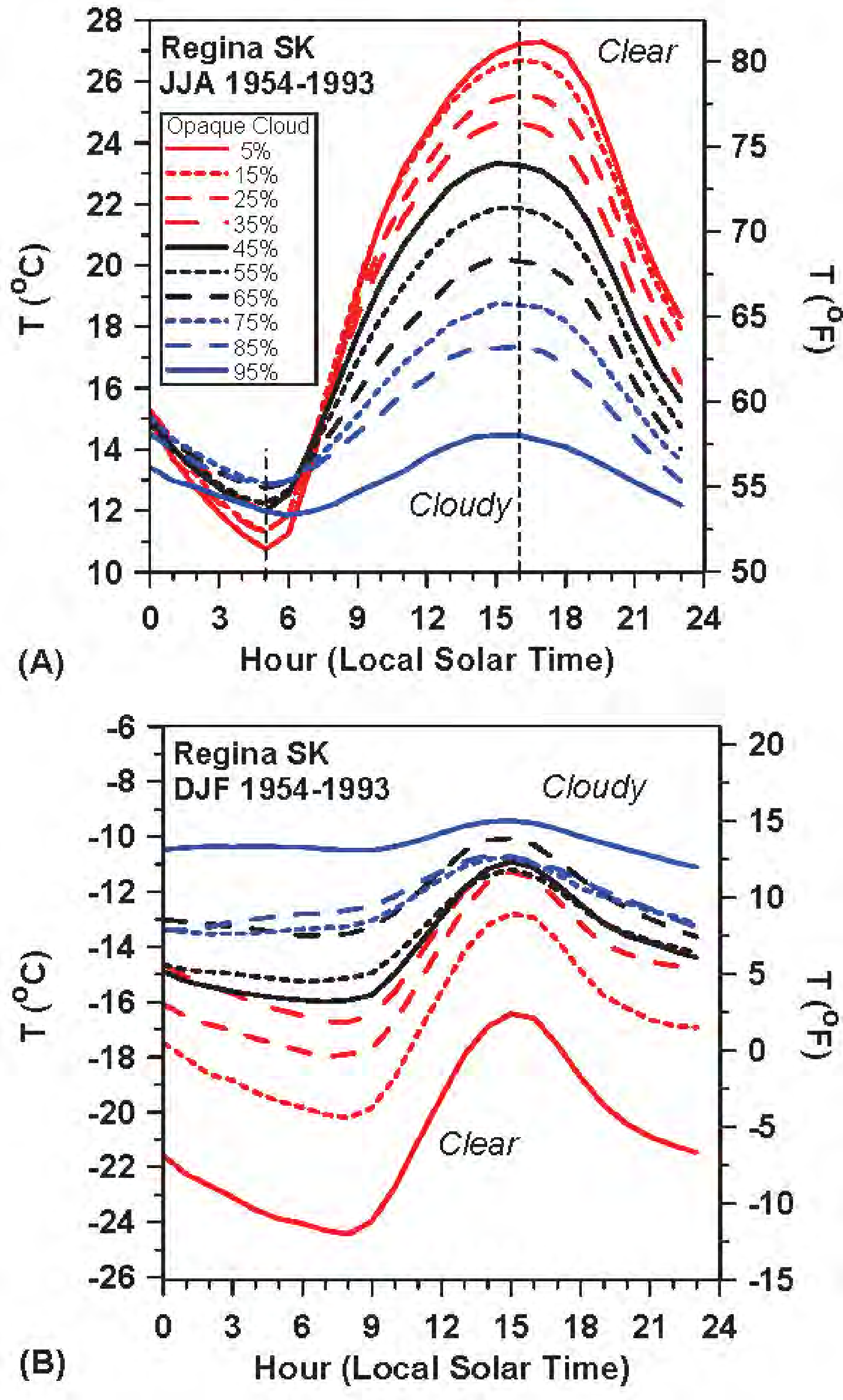
Clouds to Summer Diurnal Cycle

- ***40-yr climate***
- **T and RH are inverse**
- **Q has double maximum for BL transitions**
- **θ_E flatter**
- ***Overcast (rain) only outlier***



Cloud Impacts

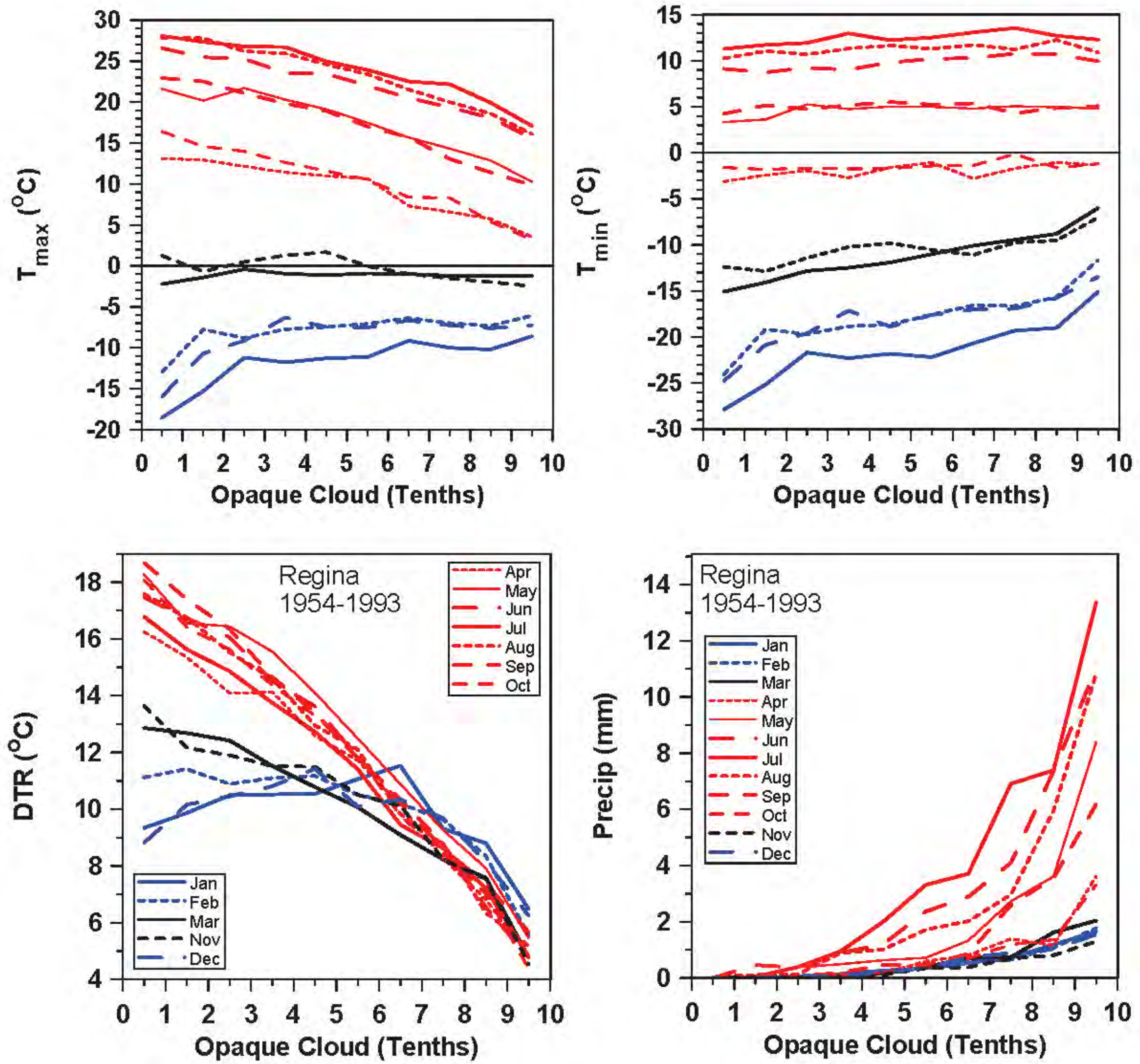
- **Summer:** Clouds reflect sunlight
  - no cloud, hot days; only slightly cooler at night
- **Winter:** Clouds are greenhouse
  - snow reflects low sun
  - clear & dry sky, cold days, very cold nights
- ***Fast transition with snow in 5 days***



Betts et al. 2013

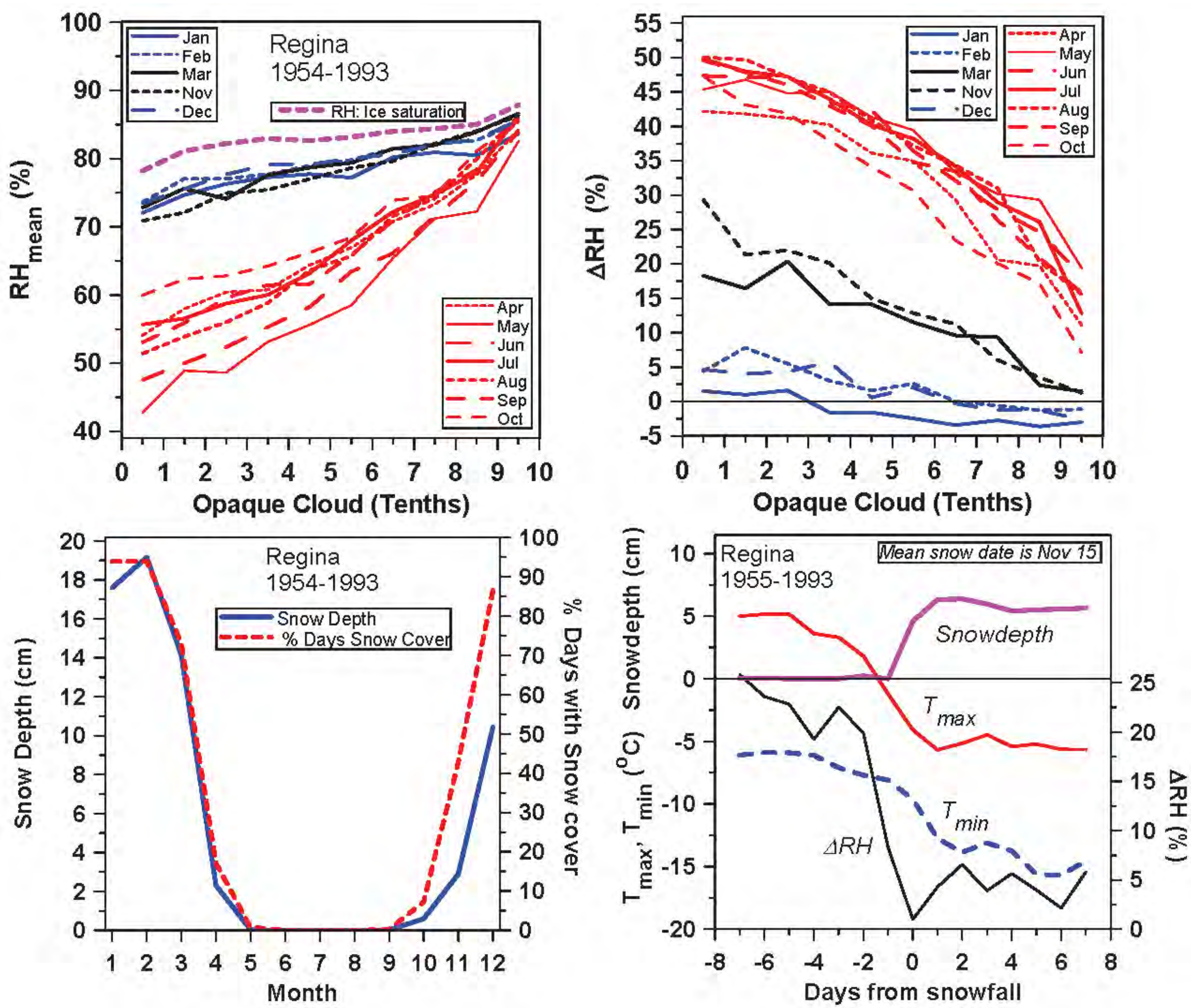
Annual Cycle: T_{max}, T_{min}, DTR, Precip

- **Warm state: April – Oct**
- **Cold state: Dec – Feb**
- **Transitions: Nov, Mar**
  $T_{max} \approx 0^oC$
- ***Actually occur in <5 days***

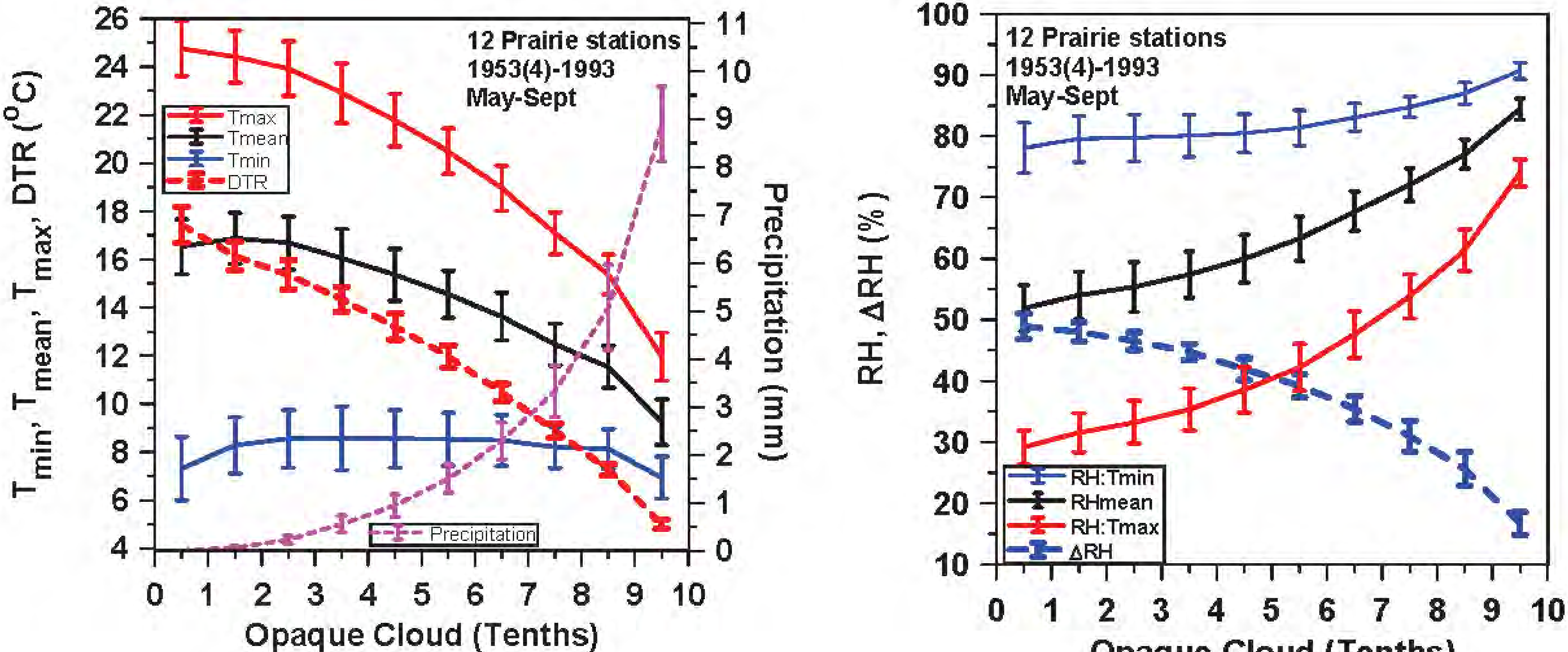


Annual Cycle: RH and ΔRH

- **Warm state: April – Oct**
- **Cold state: Dec – Feb**
- **Transitions: Nov, Mar**
  $T_{max} \approx 0^oC$
- **Transition**
  - *in <5 days with snow*



Prairie Warm Season Climate



- **12 stations:** ***Uniform climatology***
- **<u>Tiny variability</u> in DTR and ΔRH**

Surface Radiation Budget

- $R_{net} = \quad SW_{net} \quad + \quad LW_{net}$

  $= (SW_{dn} - SW_{up}) + (LW_{dn} - LW_{up})$

Define Effective Cloud Albedo (reflection)

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

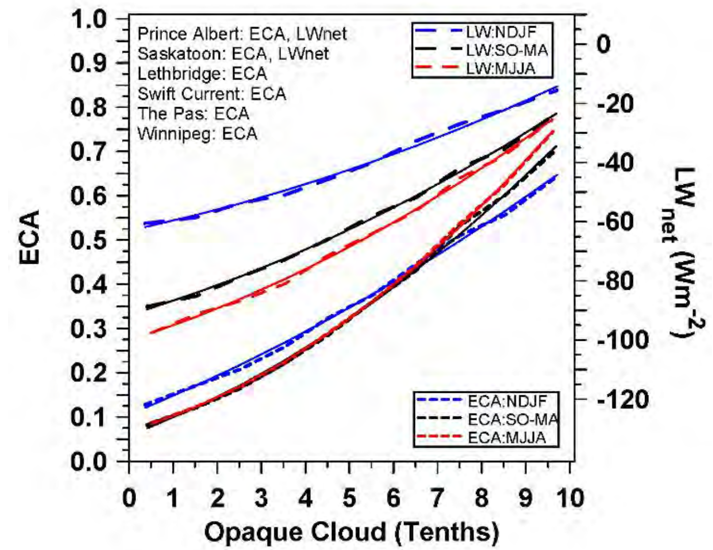
  Clear sky

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

  Reflected by surface,   clouds

  MODIS   Calibrate Opaque Cloud data

Fit ECA and LW_{net} to Opaque Cloud



NDJF: ECA = 0.1056 + 0.0404 Cloud + 0.00158 Cloud^2

SO-MA: ECA = 0.0588 + 0.0365 Cloud + 0.00318 Cloud^2

MJJA: ECA = 0.0681 + 0.0293 Cloud + 0.00428 Cloud^2

Gives SW_{net} from SW_{dn}(clear) and albedo α_s

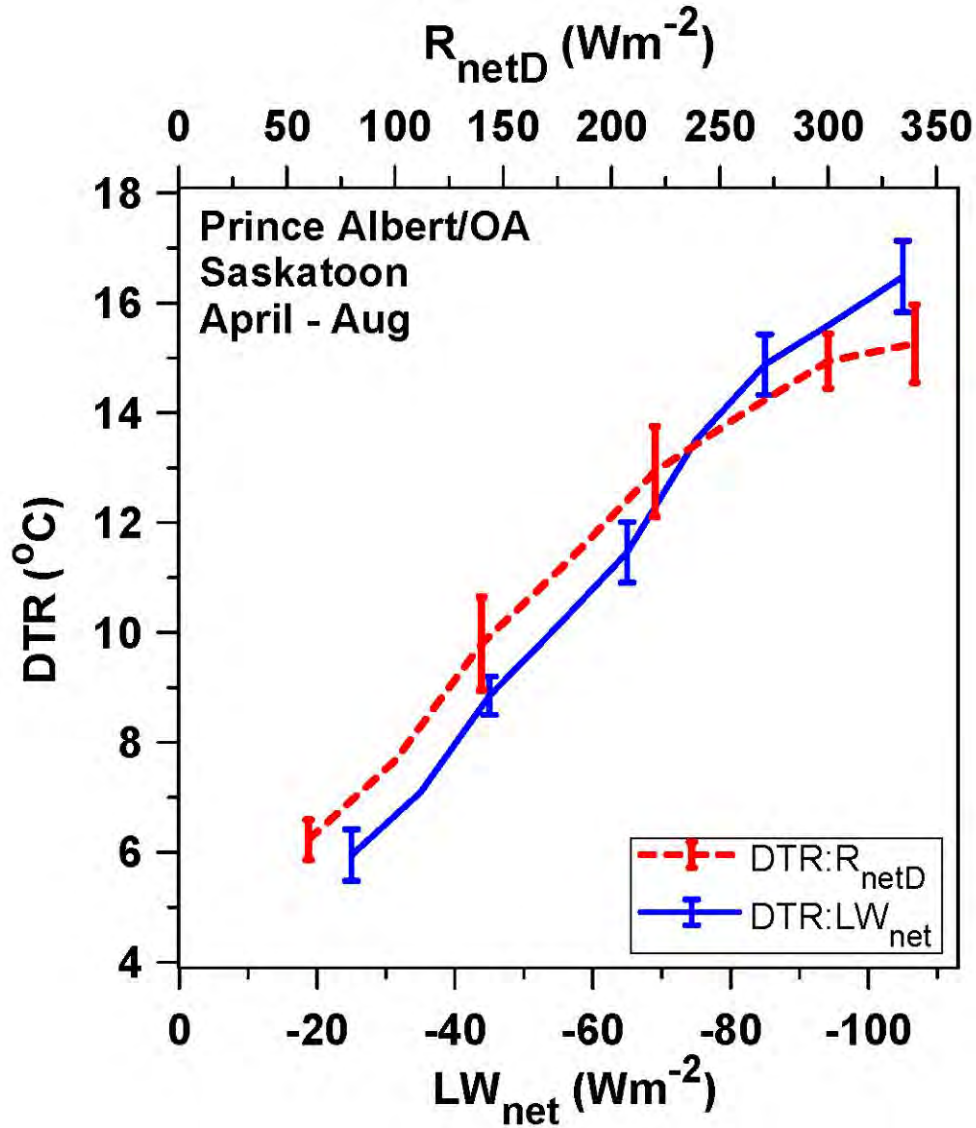
NDJF: LW_{net} = -63.0 + 3.14 Cloud + 0.193 Cloud^2

SO-MA: LW_{net} = -91.5 + 4.43 Cloud + 0.267 Cloud^2

MJJA: LW_{net} = -100.1 + 4.73 Cloud + 0.317 Cloud^2

Diurnal Temperature Range

- *Warms in daytime and cools at night*
- **Daytime Driver: R_{netD}**
- **Nighttime driver: LW_{net}**



(Betts JGR 2006)

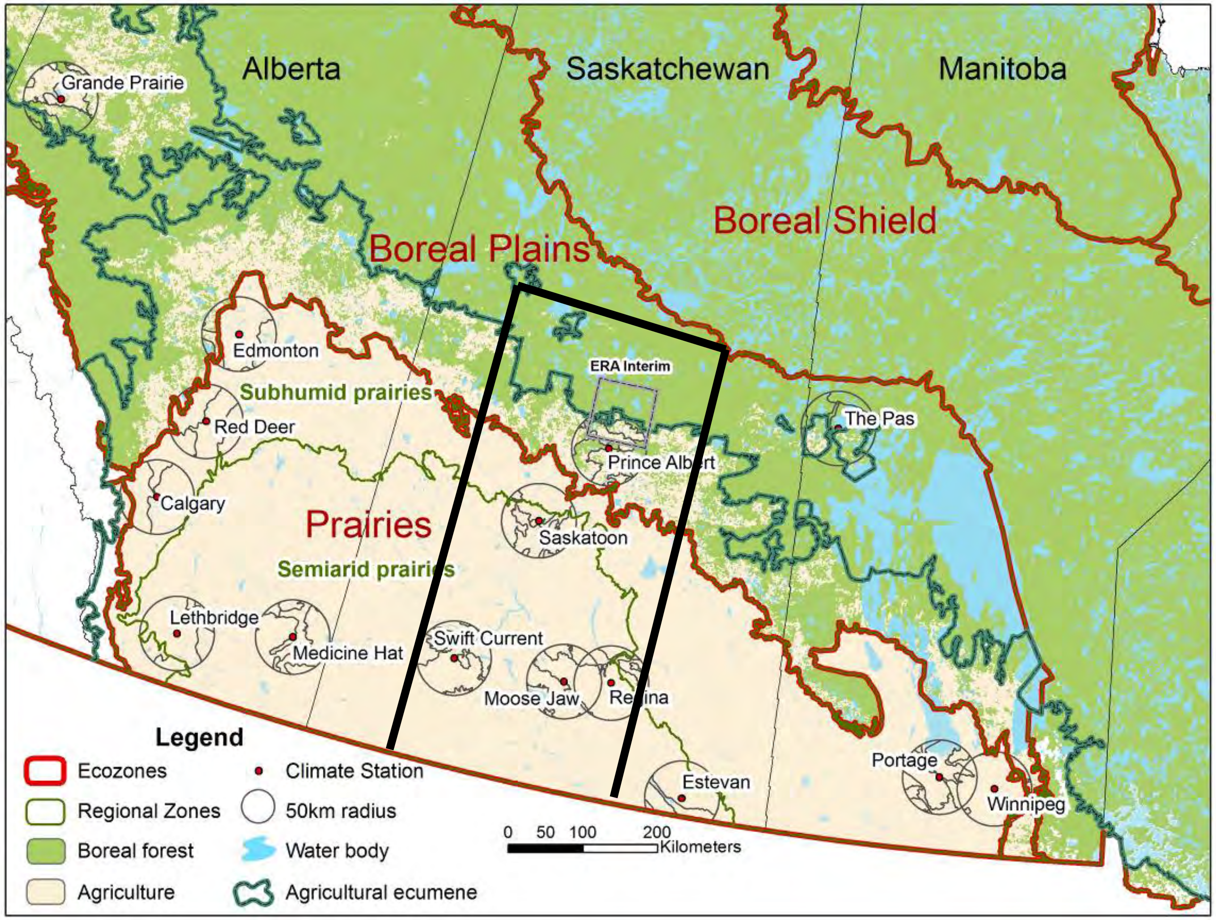
Impact of Snow on Climate

"Winter transitions"

- Composite about snow date
  - First lying snow in fall
  - Final snow-pack melt in spring
- Gives mean climate transition with snow
  - 13 stations with 40-50 years of data
- *Snow cover and winter climate*

- Snow cover cools surface 10-14K
  - Snow cover is a fast "*climate switch*"
  - Shift to 'LW cloud forcing' from 'SW cloud forcing'
    - Shift to 'Cold when clear' from 'Warm when clear'

14 Prairie stations: 1953-2011

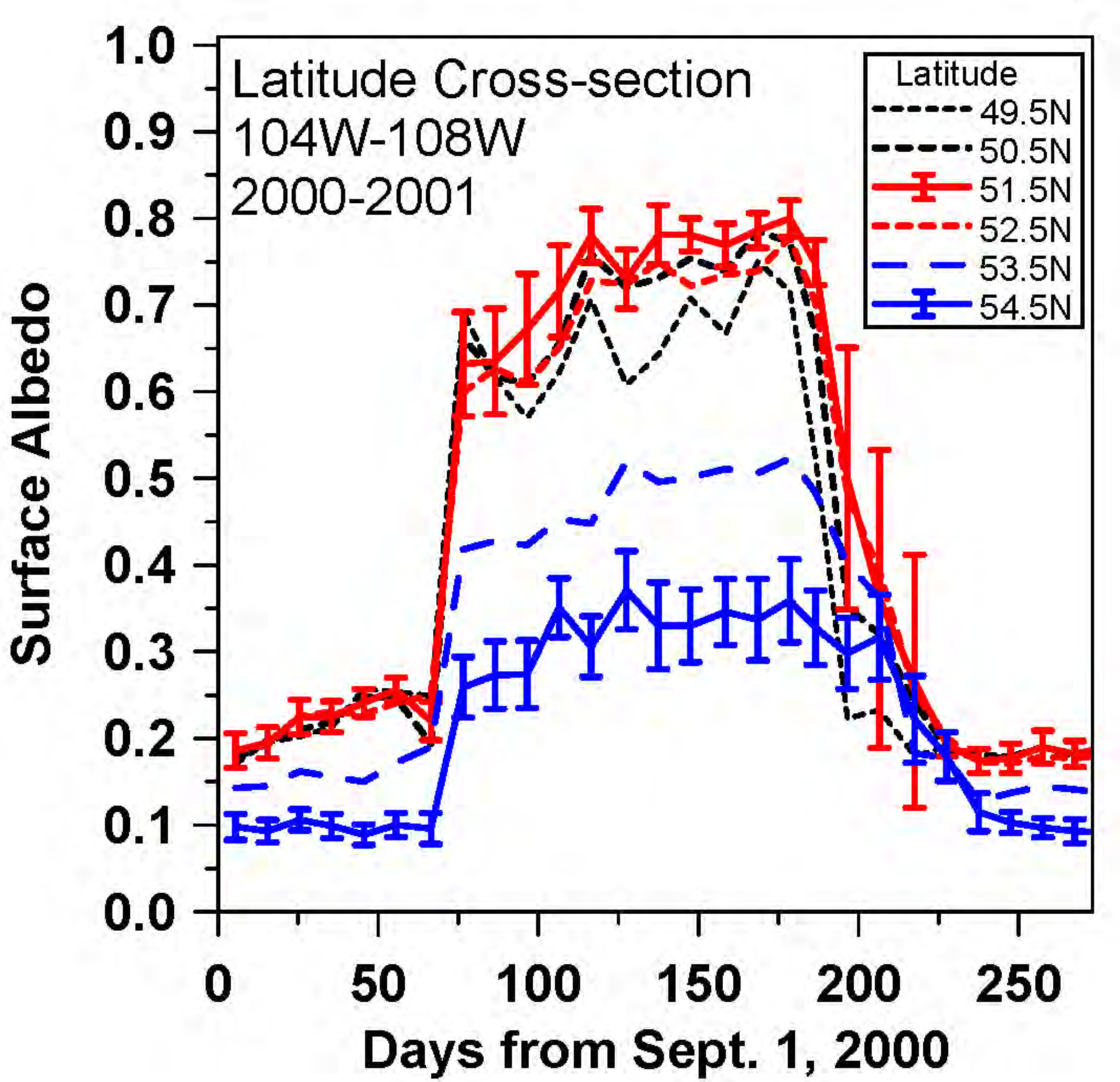


- Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})
- Daily precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

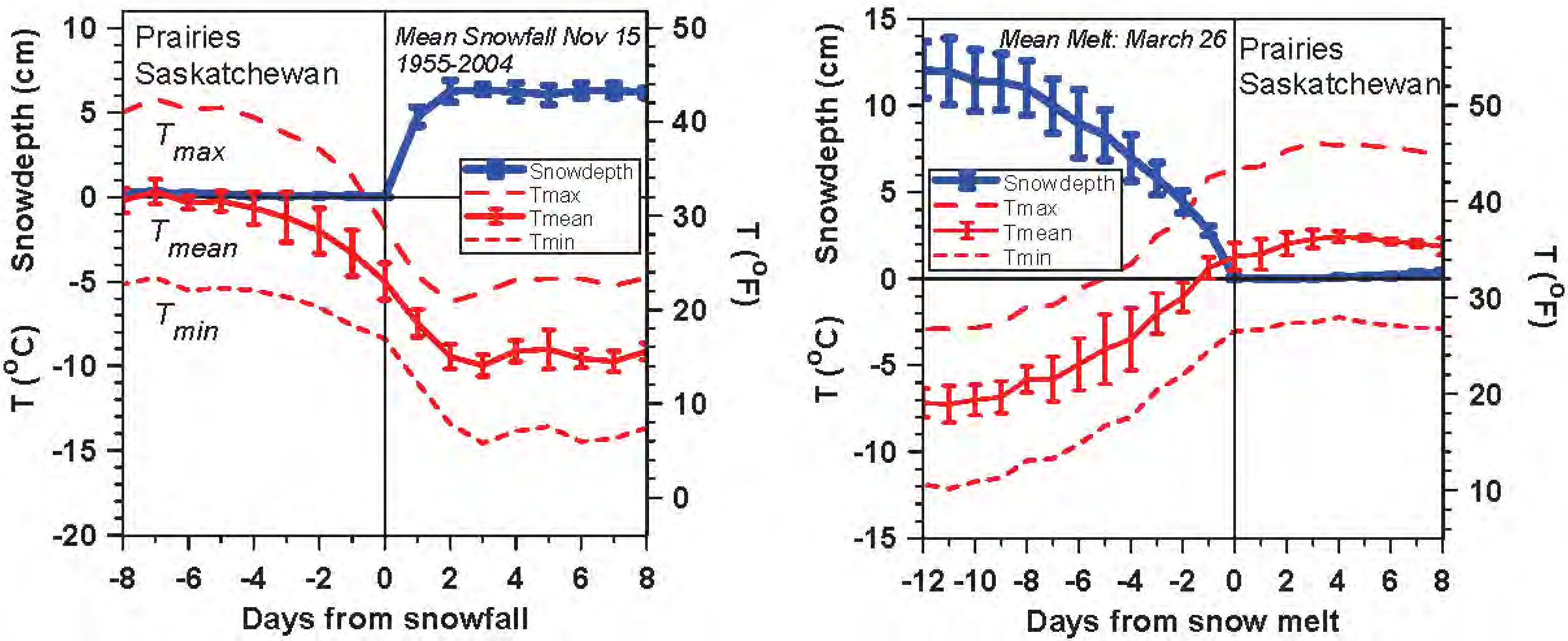
N-S Albedo through Winter

- **Prairies (SK)**
  α_s: 0.2 to 0.73
- **Boreal forest**
  α_s: 0.1 to 0.35

- ***MODIS: 10day, 250m, avg. to 50x50km to latitude bands***
  - ***CCRS product***



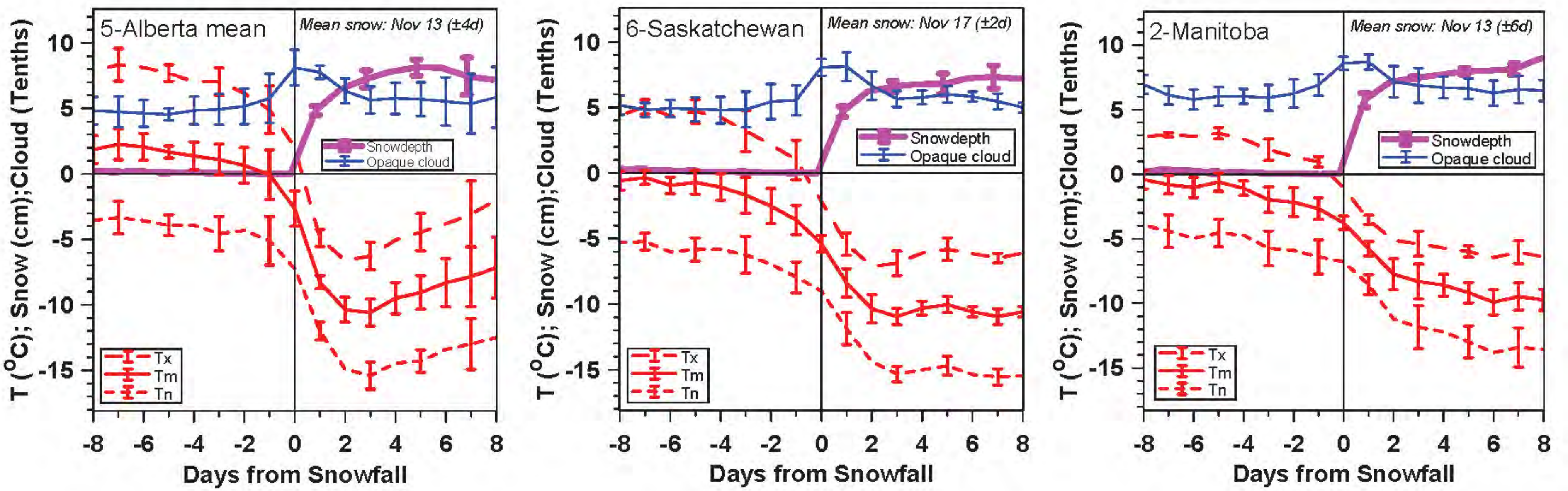
Snowfall and Snowmelt
Winter and Spring transitions



- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms 'local climate'***
  - ***Same feedbacks that are speeding Arctic ice melt in summer***
  - ***Local climate switch between warm and cold seasons***

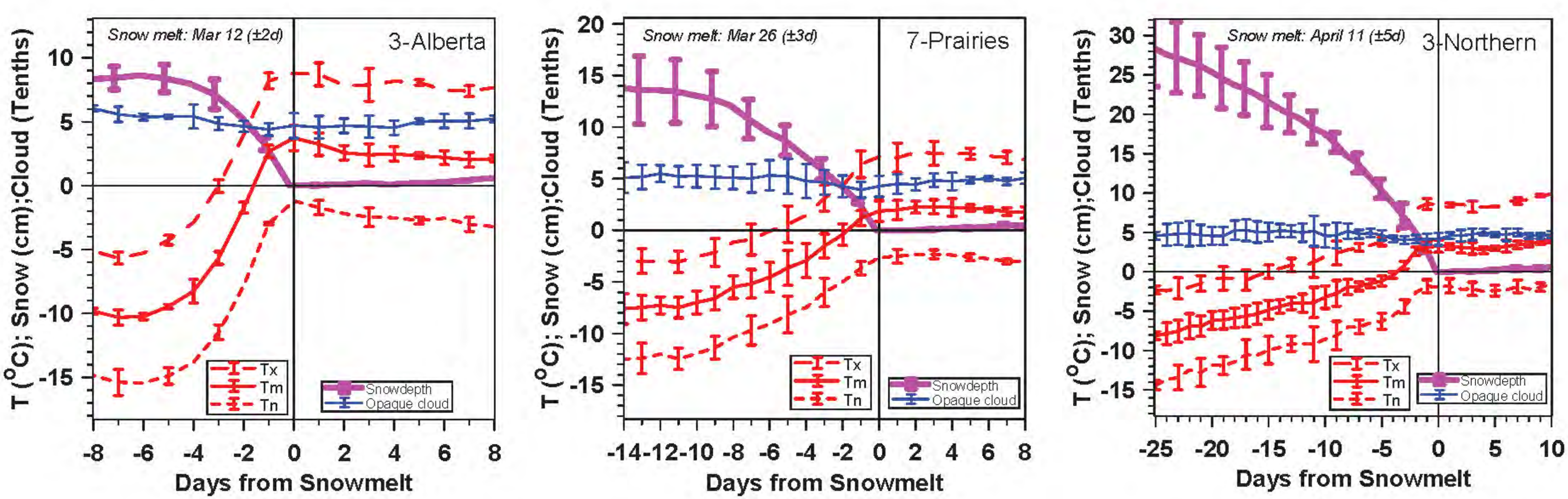
Betts et al. 2014

Fall Snow Transition Climatology



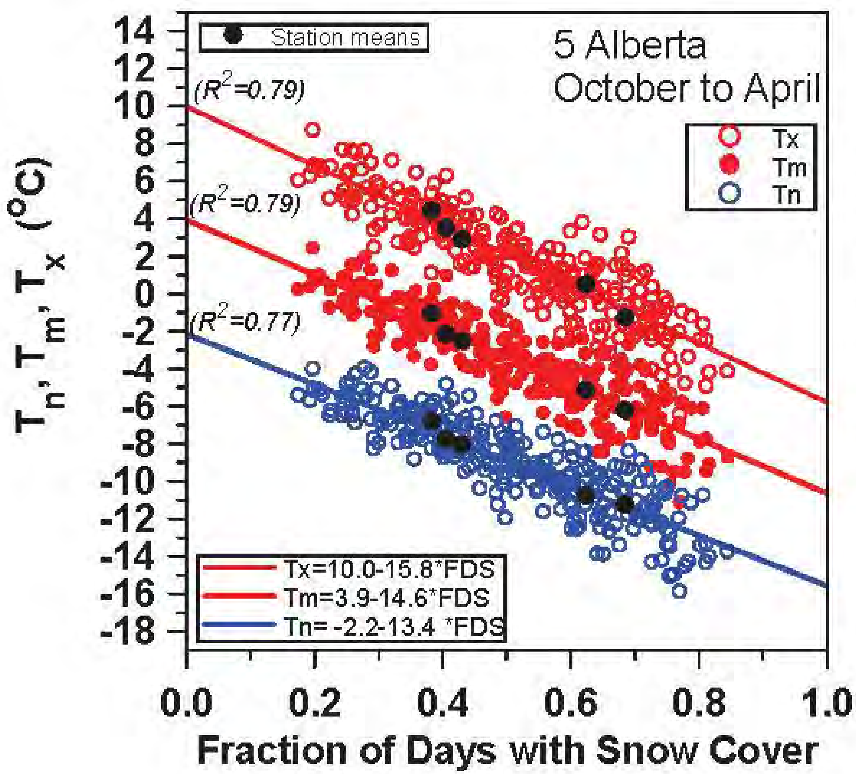
- T_x, T_m, T_n fall about 10K
- **Cloud peaks with snow; increases ≈10%**
- **Snow date: Nov 15 ± 3 days**

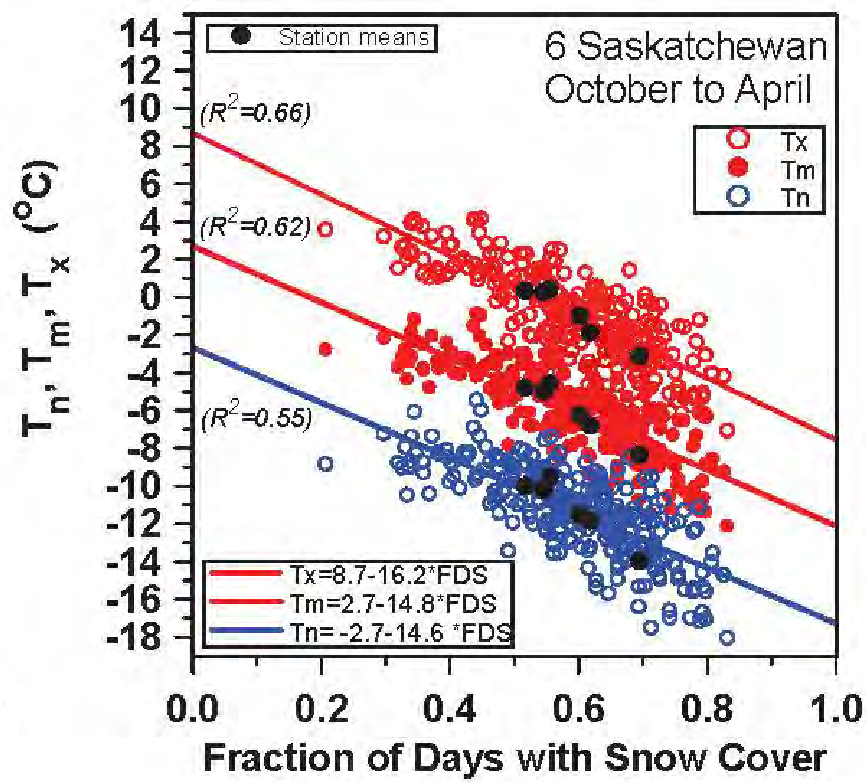
Snow-melt Transition Climatology



- **SW Alberta: T increase about 11K**
- **Saskatchewan: T increase about 10K**
- **3 northern stations: increase 10K, slower**
- **Melt date: March 12–April 11**

Snow Cover: Winter Climatology





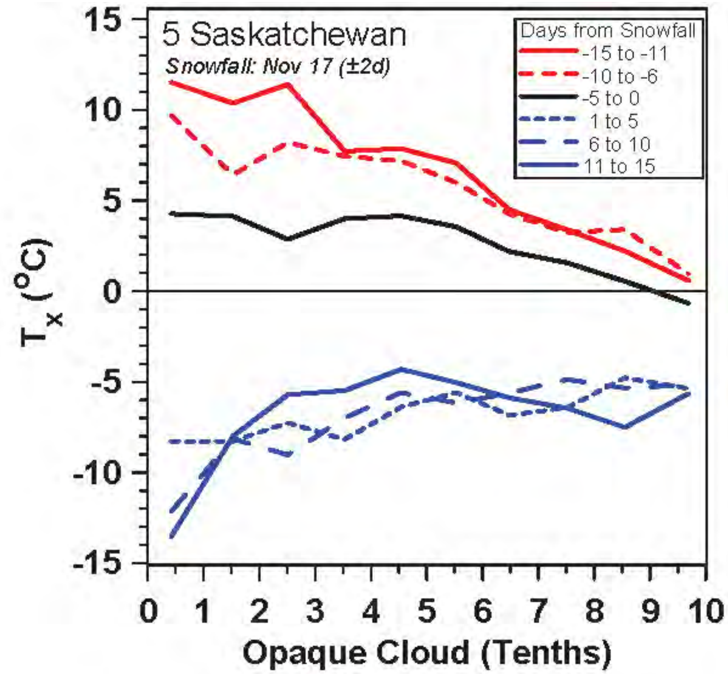
- **Alberta: 79% of variance**
- **Slopes**
  - **T_x -16.0(± 0.6) K**
  - **T_m -14.7 (± 0.6) K**
  - **T_n -14.0 (± 0.7) K**

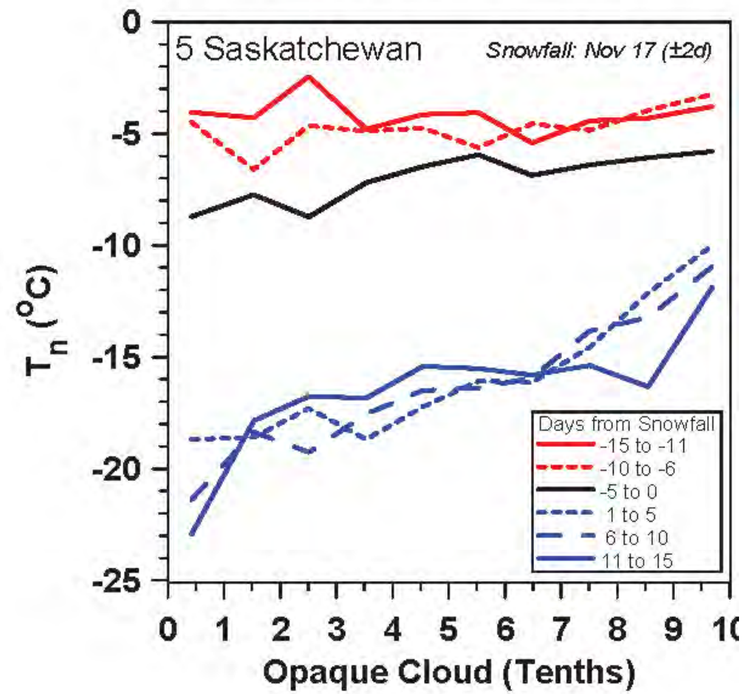
10% fewer snow days

= 1.5K warmer

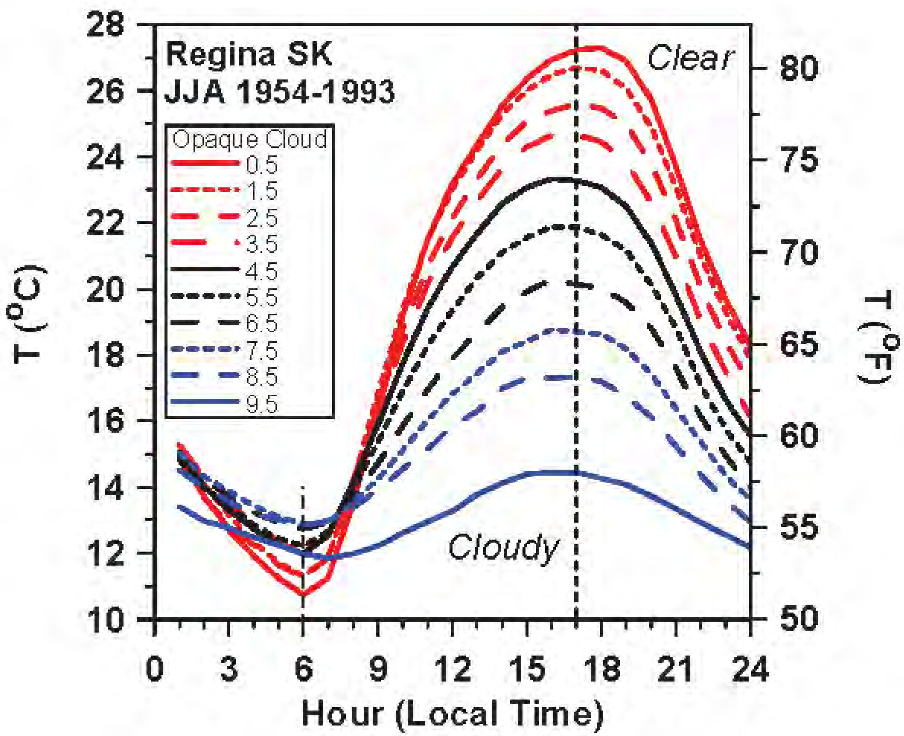
Coupling to Cloud Cover Across Snowfall

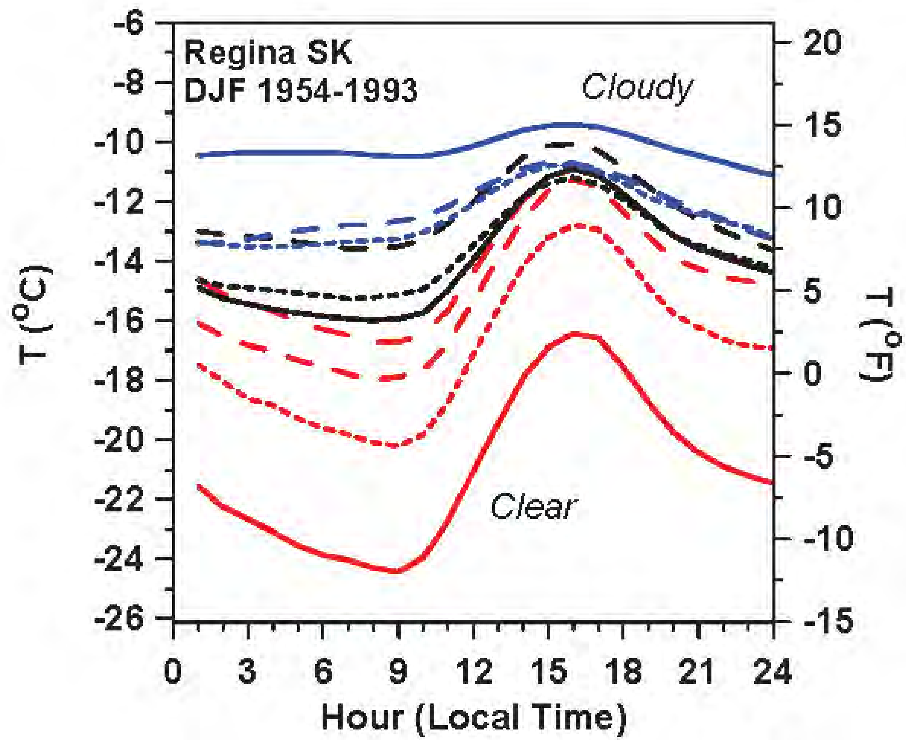
- **Mid-November**
- **5-day means (6000 days)**
  - ***red: no snow***
  - ***blue: snow***
- **With snow**
  - **T_x, T_n plunge**
- **Cloud coupling shifts in 5 days**
  - **from 'Warm when clear' to 'Cold when clear**
  - **"SWCF to LWCF"**





Clouds: Summer & Winter Climate
Opposite Impact



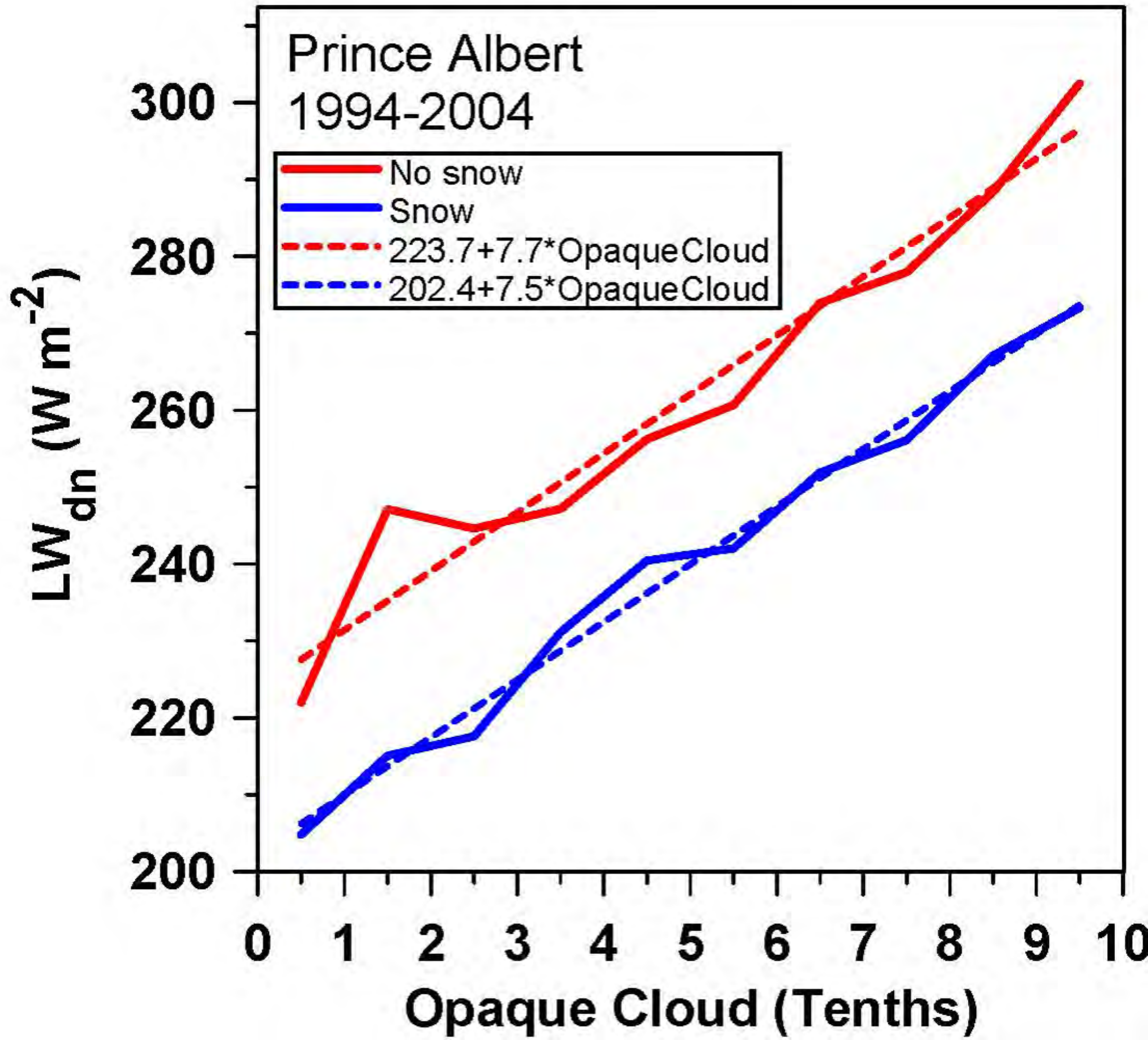


- **Summer:** **Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
  - **Convective boundary layer in daytime**
- **Winter:** **Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**
  - **Stable boundary layer**

Betts et al. 2013a

Role of LW_{dn} in Surface Radiation

- **Snow reduces vapor flux**
- **Atmosphere cooler and drier**
  - **Less water vapor greenhouse**
  - **-22 W/m^2**
- ***Offset by 10% cloud increase with snow***



Surface Radiation Balance

- **Across snow transition**
  - **Surface albedo α_s increases: 0.2 to 0.73**
  - **LW_{dn} decreases**
  - **Opaque cloud increases**

- **SW_{net} falls 34 W/m^2**
- **LW_{dn} falls 15 W/m^2**
- **<u>Total 49 W/m^2</u>**

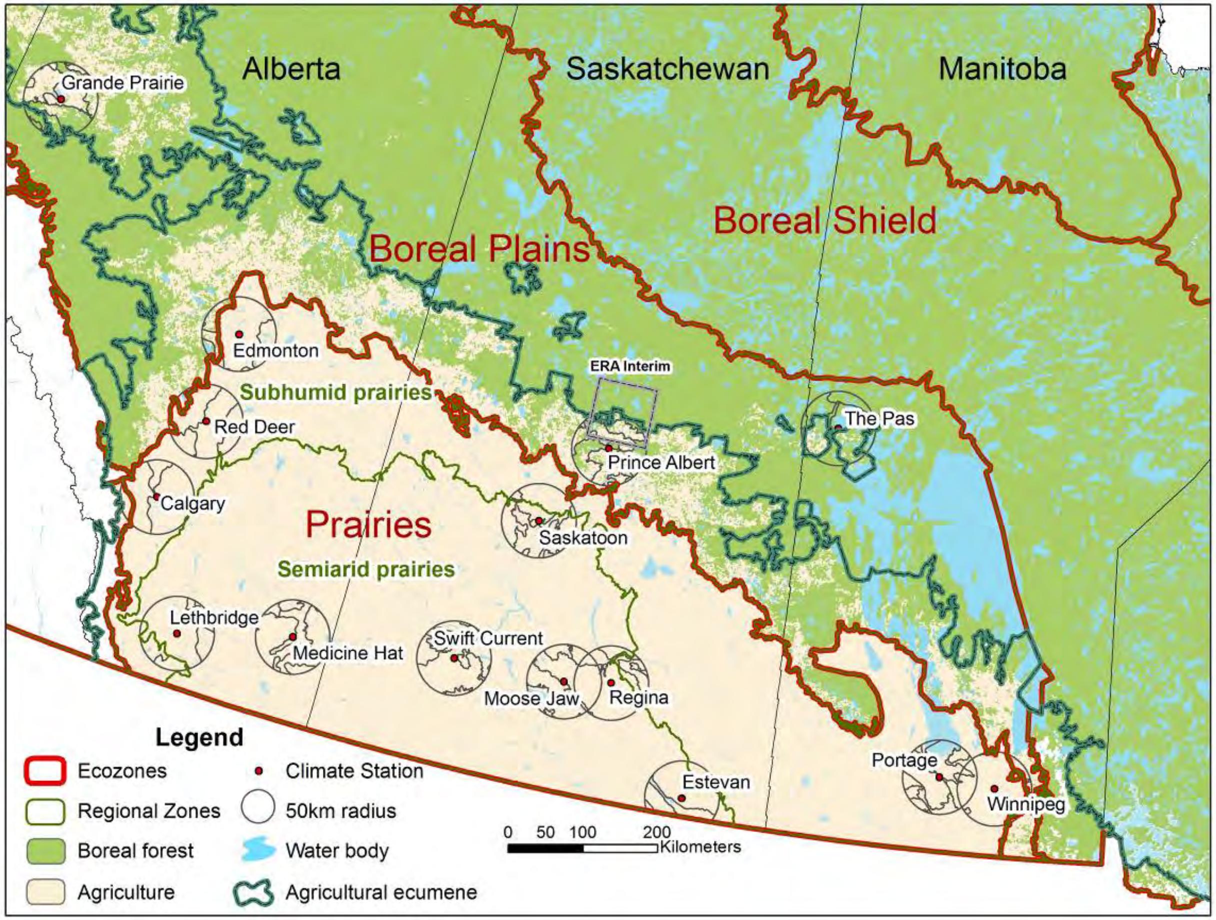
- **Surface skin T falls: $\Delta T = -11K$ to balance**

  (Stefan-Boltzman law: $\Delta LW = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)

Annual crops and seasonal diurnal cycle

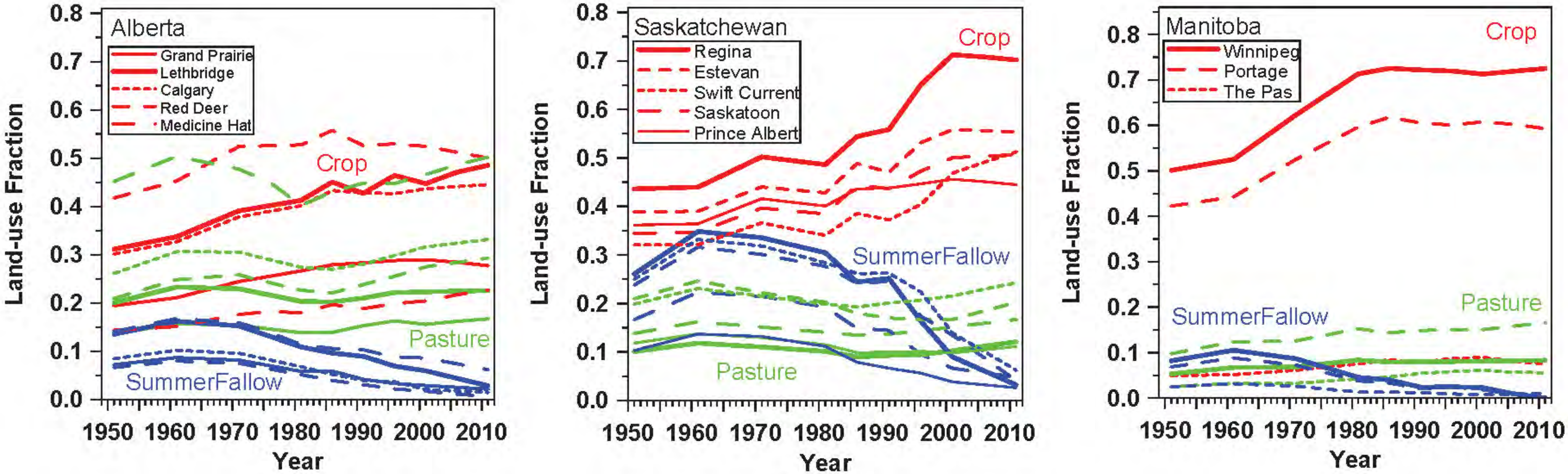
- **Ecodistrict crop data since 1955**
  - Ecodistricts mapped to soils
  - Typical scale: 2000 km^2 (500-7000)
- **Ecozones**
  - boreal plains ecozone
  - semiarid/subumid prairie regional zones
- **Shift from 'Summerfallow' (no crops) to annual cropping on 5 MHa (11 M acres)**
  - *Large increase in transpiration: Jun-Jul*

13 Prairie stations: 1953-2011



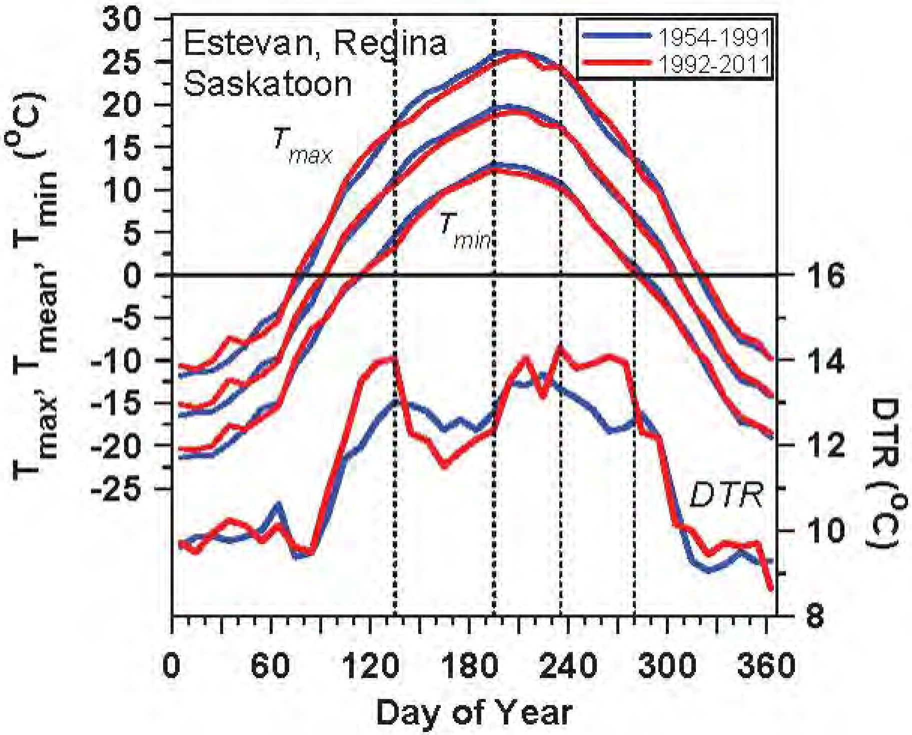
- **Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})**
- **Daily precipitation and snowdepth**
- **Ecodistrict crop data since 1955**
- **Albedo data (MODIS/CCRS: 250m, after 2000)**

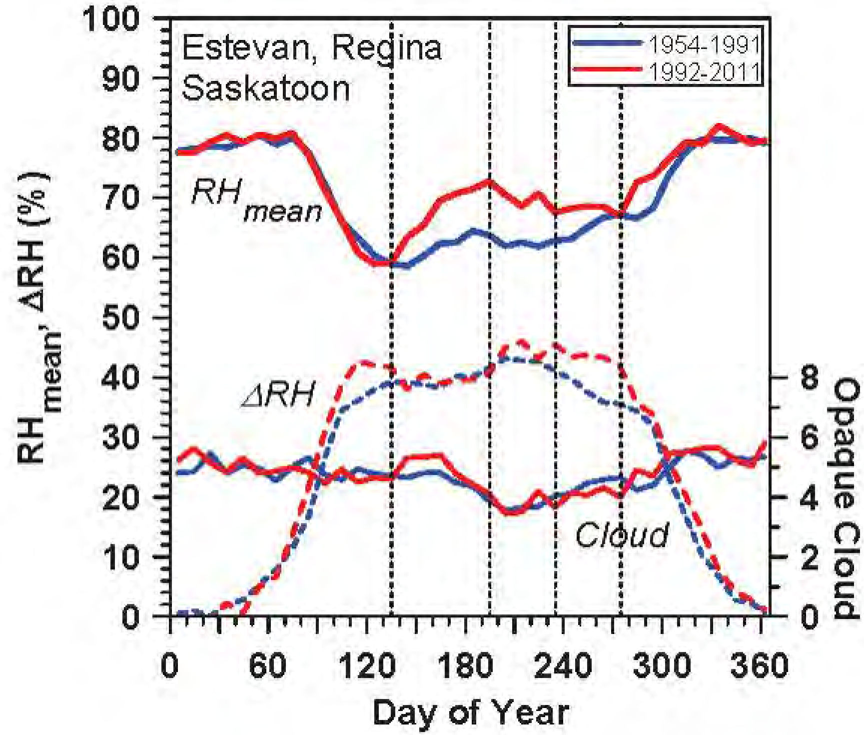
Change in Cropping



- **Ecodistrict mean for 50-km around station**
- **Saskatchewan: 25% drop ‘SummerFallow’**
- ***Split at 1991- has summer climate changed?***

Three Station Mean in SK



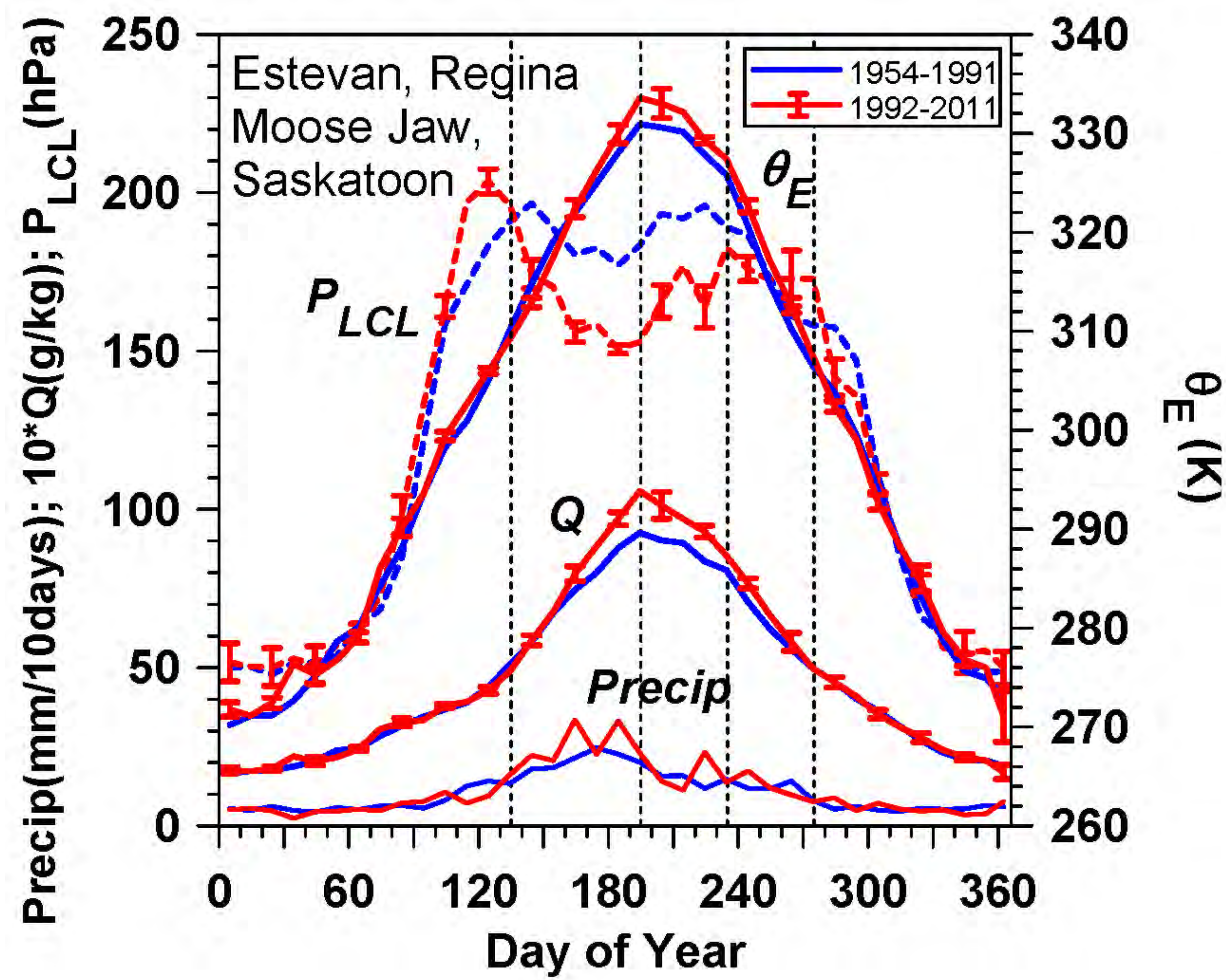


- **Growing season**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal structure changes**

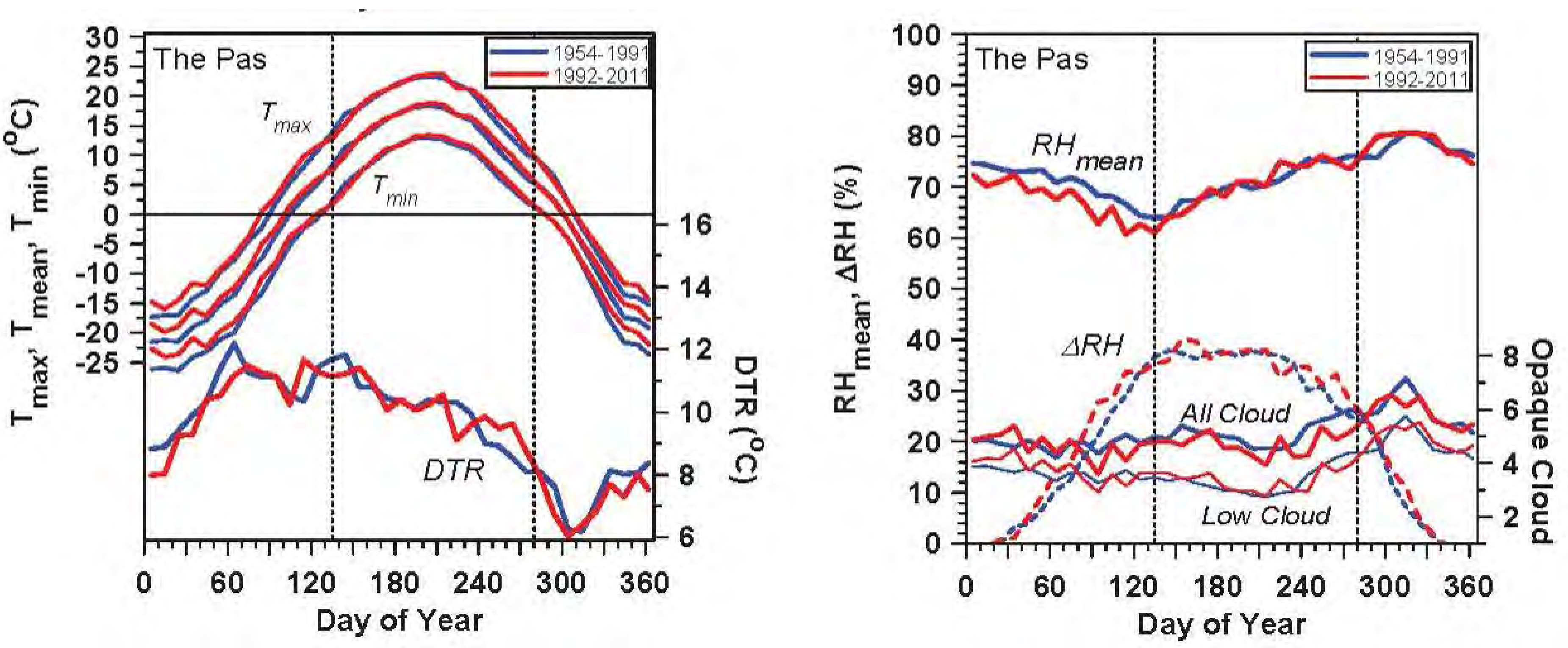
Impact on Convective Instability

Growing season

- **Lower LCL**
- **Higher θ_E**
- **More Precip**



Contrast Boreal Forest



- **No RH, DTR signal**

Summary (Part 1)

- ***High quality dataset with Opaque cloud***
- **Understand cloud coupling to climate**
- **Transpiration from crops changes climate**
  - **Cools and moistens summer climate**
  - **Lowers cloud-base and increases θ_E**
- **Distinct warm and cold season states**
  - **Sharp transitions with snow cover: $\alpha_s = 0.7$**
  - **Snow cover is a "climate switch"**
    - **From 'Warm when clear', convective boundary layer**
    - **To 'Cold when clear', with stable boundary layer**

Papers at http://alanbetts.com

Transformative Concepts

- Snow as climate switch

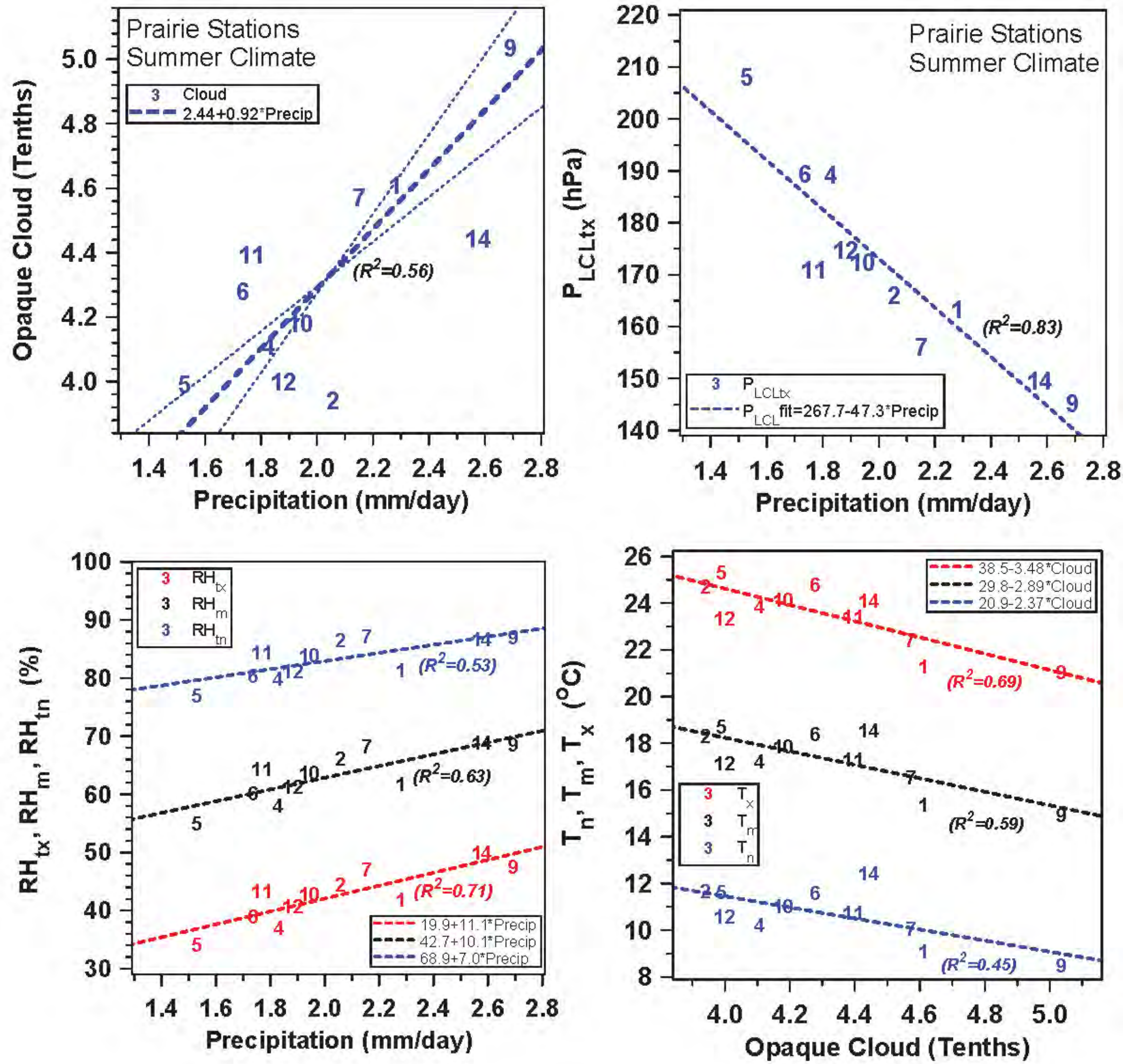
- <u>Opaque/reflective cloud</u>
  - SWCF, LWCF $\longrightarrow$ R_n
- Diurnal climate analysis of T, RH
  - Dominated by cloud/R_n
  - *BUT*: *Radiation only analysis*
  - Because no soil moisture, or EF

Monthly, Seasonal, 50-yr Climate

- **Observables**
- **Opaque/reflective cloud** → R_n
- **Precipitation coupled to Evaporation**
- **50-yr timescale see separation**
  - **RH to precipitation and soil moisture**
  - **T to opaque cloud and R_n**
- ***Monthly, seasonal timescale blended***

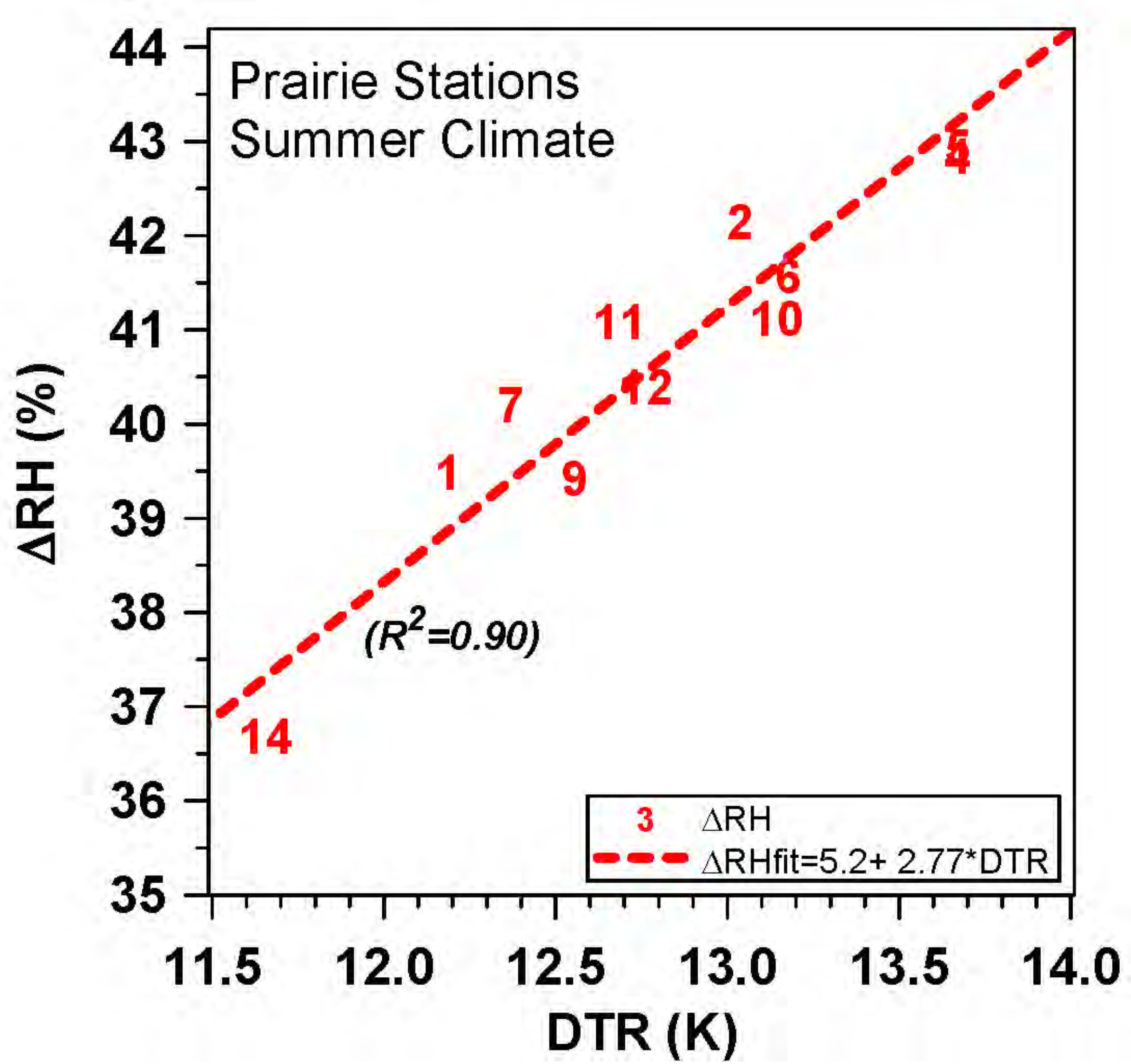
11 stations: 53-yr JJA climate

- **Precip to *(R^2)***
  - Cloud (0.56)
  - P_{LCLtx} (0.83)
  - RH_{tx} (0.71)
- **Cloud to**
  - T_x (0.69)
- **Separation**
- ***Month: blend***
- ***Daily: cloud***



Diurnal cycle tightly coupled

- **ΔRH to DTR**
- **2.77 %/K**
  (R^2 = 0.90)



Monthly timescale: Regression

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

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

δDTR anomalies

	K	A	B	C	D	R^2 All	R^2 Precip	R^2 Cloud
May	**0±0.83**		**-0.35±0.05**	**-0.37±0.04**	**-1.10±0.05**	**0.69**	**0.39**	**0.62**
Jun	**0±0.70**		**-0.30±0.03**	**-0.32±0.02**	**-0.97±0.04**	**0.69**	**0.42**	**0.52**
July	**0±0.73**	**-0.20±0.03**	**-0.25±0.02**	**-0.32±0.03**	**-1.10±0.05**	**0.67**	**0.42**	**0.48**
Aug	**0±0.74**	**-0.07±0.02**	**-0.21±0.03**	**-0.40±0.03**	**-1.24±0.04**	**0.79**	**0.46**	**0.71**
Sept	**0±0.77**		**-0.22±0.03**	**-0.49±0.04**	**-1.27±0.04**	**0.82**	**0.43**	**0.75**
Oct	**0±0.78**		**-0.27±0.03**	**-0.70±0.07**	**-1.33±0.04**	**0.78**	**0.37**	**0.70**

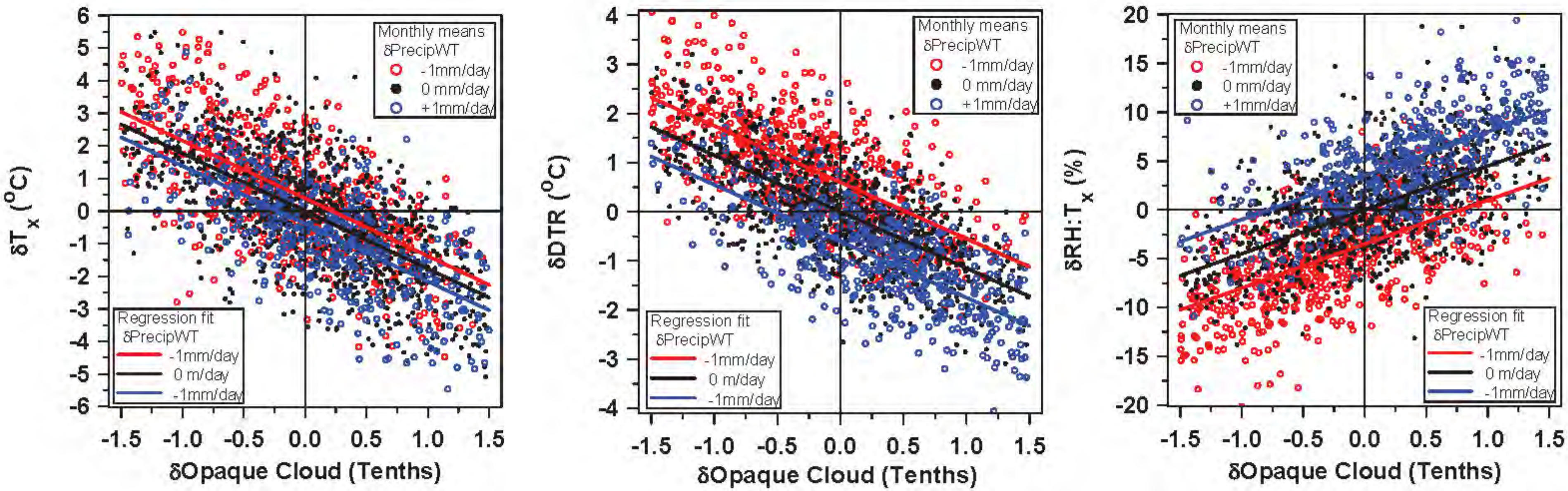
Monthly timescale: Regression

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

δRH_{tx} anomalies

Month	K	A *(Mo-2)*	B*(Mo-1)*	C*(Mo)*	D	R^2 All	R^2 Precip	R^2 Cloud
May	0.0±3.6	1.13±0.38	1.41±0.23	2.01±0.17	4.67±0.20	0.70	0.43	0.61
Jun	0.0±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	0.0±4.1	0.84±0.18	1.72±0.12	1.80±0.17	4.42±0.30	0.59	0.43	0.33
Aug	0.0±3.6	<u>0.66±0.11</u>	<u>1.23±0.13</u>	<u>2.42±0.16</u>	<u>4.08±0.20</u>	<u>0.73</u>	<u>0.53</u>	<u>0.56</u>
Sept	0.0±3.5		1.40±0.13	2.10±0.18	4.35±0.16	0.75	0.45	0.63
Oct	0±4.3		1.30±0.19	5.06±0.38	4.61±0.22	0.67	0.44	0.53

Monthly anomalies (MJJA: 2346 months)



- Less cloudy and less rain (this month and last)
  - δT_x warmer (cloud mostly) ($R^2 = 0.55$)
  - δDTR larger (both) ($R^2 = 0.72$)
  - δRH drier (both) ($R^2 = 0.68$)

How good is the regression fit?

- **September**

  T_x ±1.4°C

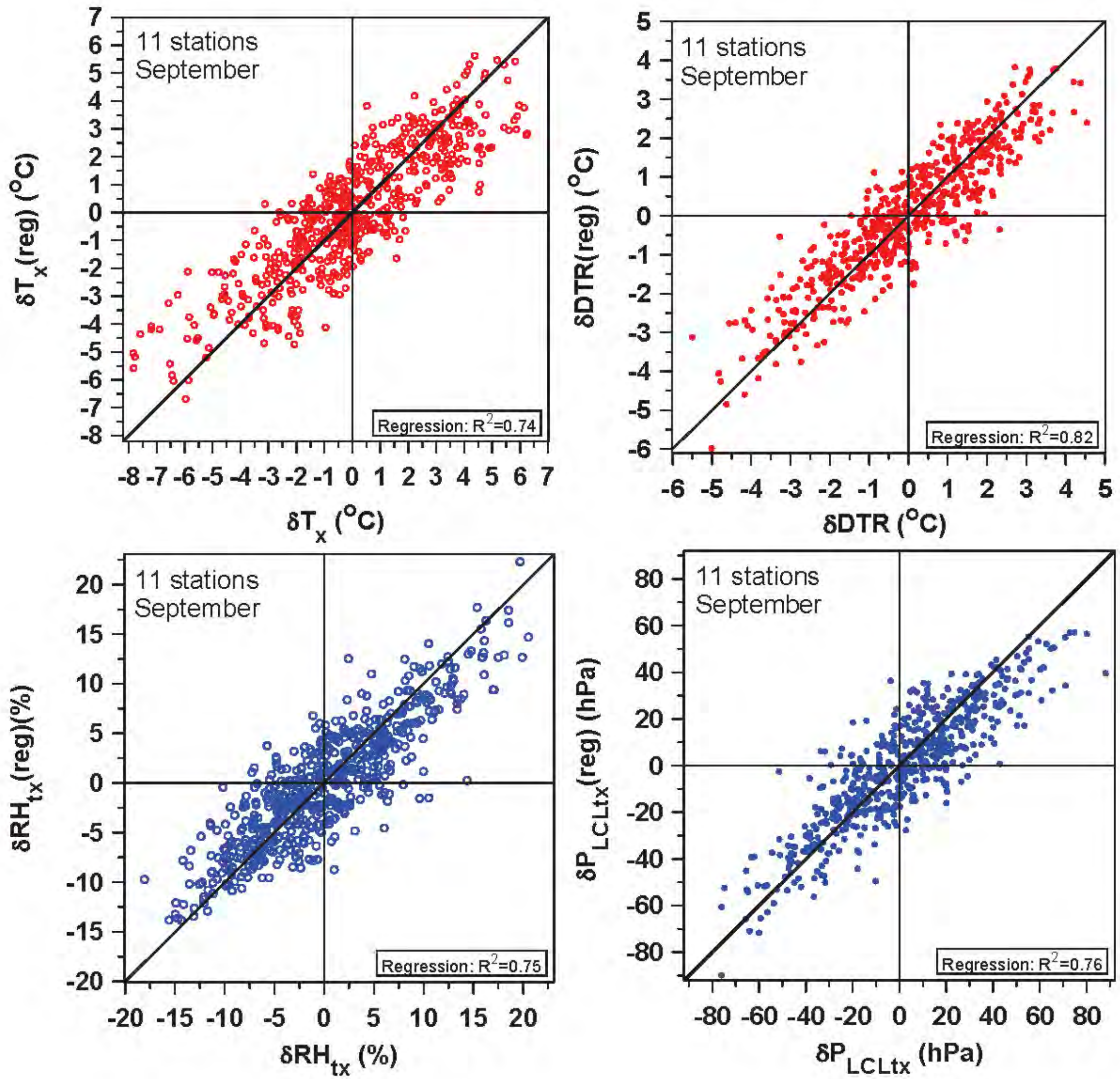
  DTR ±0.8°C

  RH_{tx} ±3.5%

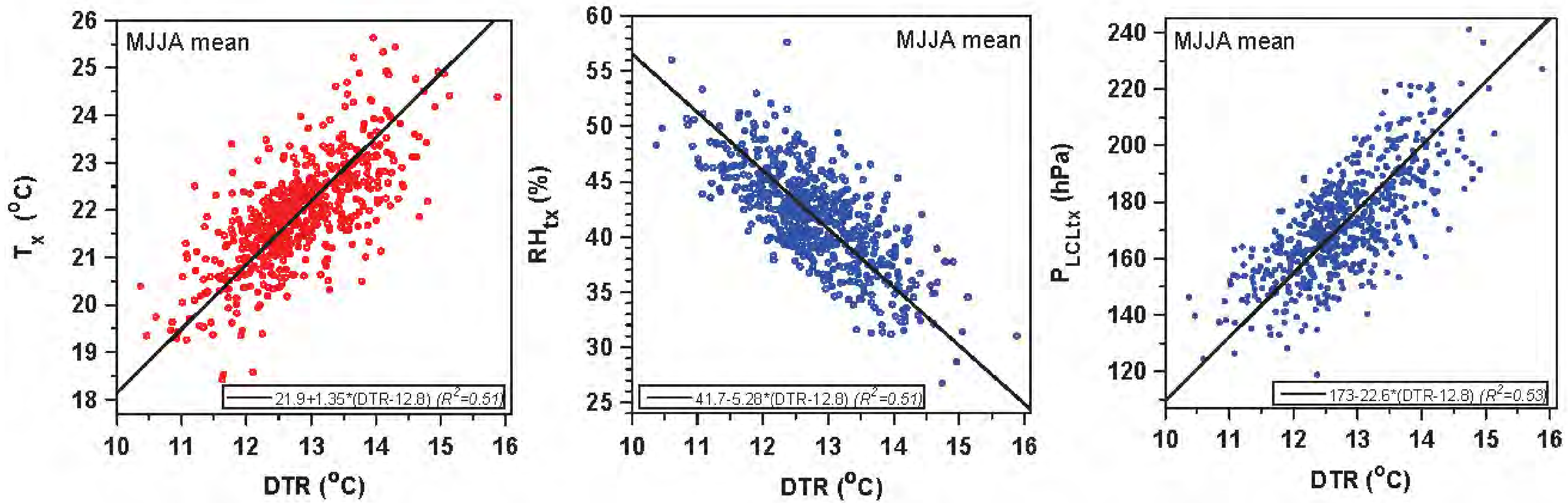
  P_{LCLtx} ±13hPa

- **Some extremes underestimated**

(586 station-yrs)



Diurnal coupling: MJJA mean



- **Internal coupling well-defined**
  - **Slopes ≈ 60% of 50-yr climate**

MJJA Surface Water Balance

$$E = P - R - \Delta TWS$$

where ΔTWS is change in Total Water Storage

$$P = P_m + \delta Precip(AMJJA)$$

where mean P_m = 1.92 mm/day

R/P = 0.5 ***(assumed: rivers managed)***

$$\Delta TWS = \Delta TWS_m + F^*\delta Precip(AMJJA)$$

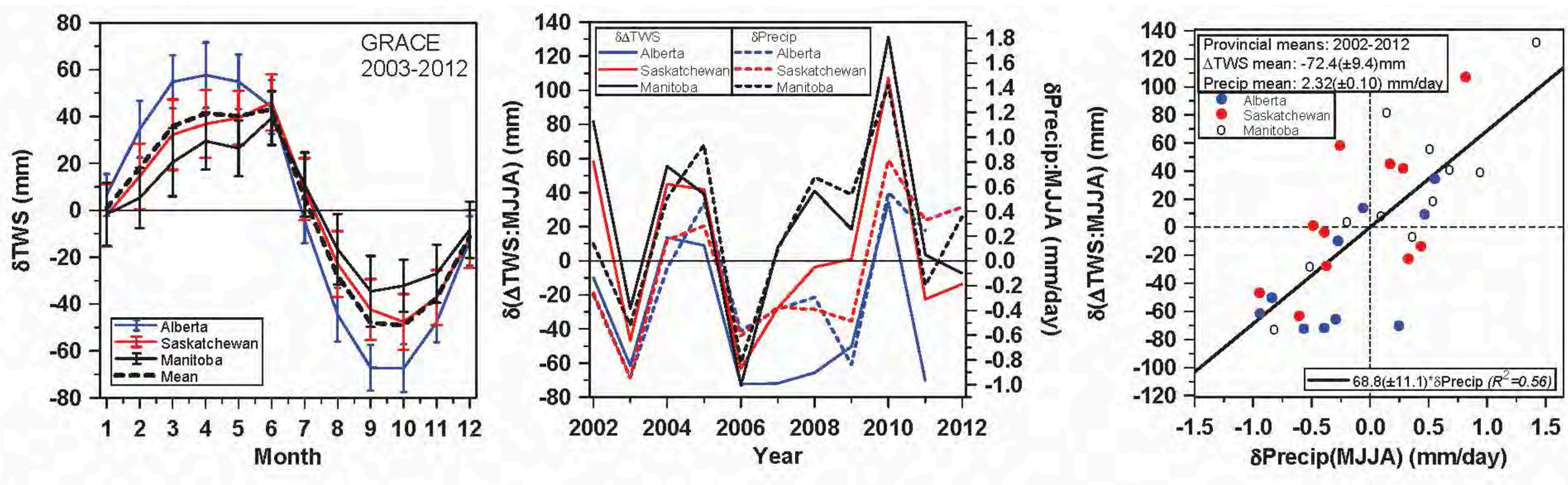
We estimate from GRACE data (2002-12)

ΔTWS_m= - 0.59(±0.08)mm/day (72mm/122 days)

F = +0.56(±0.09) (for AB, SK and MB)

(F is 56% damping of precipitation anomalies)

GRACE seasonal dry-down

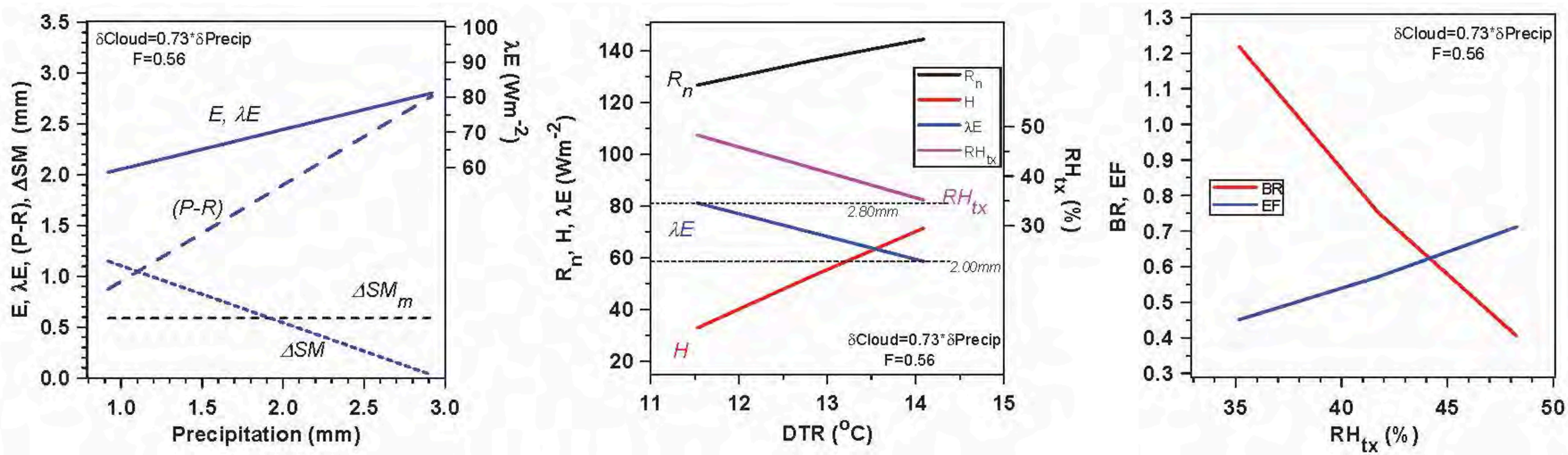


ΔTWS_m= - 0.59(±0.08)mm/day (72mm/122 days)

F = +0.56(±0.09) (for AB, SK and MB)

(F is 56% damping of precipitation anomalies)

Energy and Water “Budget”



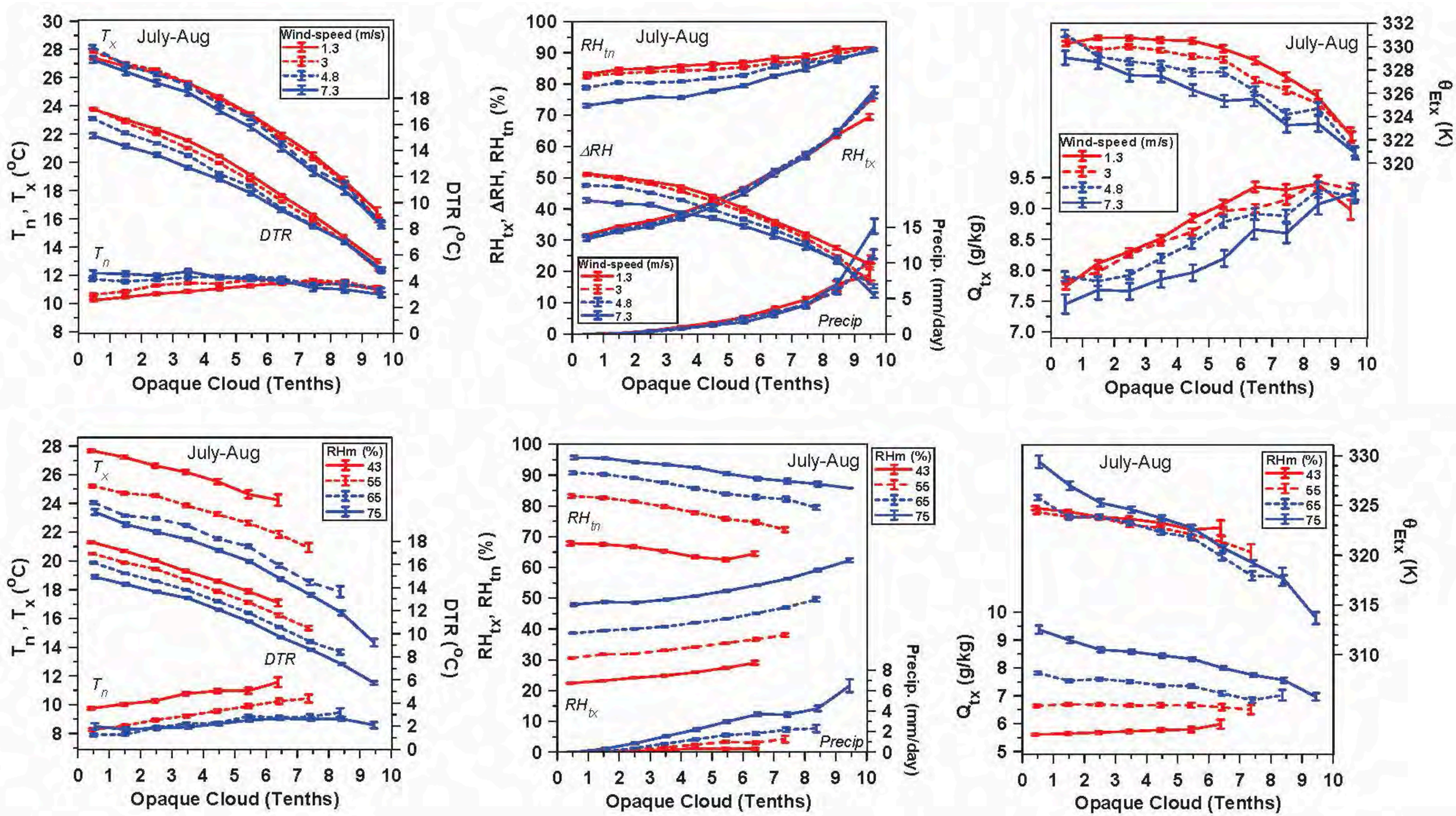
- ***Cloud and precip. anomalies***
  - ***Give anomalies of DTR, RH$_{tx}$ (and T$_x$..)***
  - ***Cloud gives R$_n$ anomalies***
- ***Closures***
  - ***Climate coupling: cloud to precip. (0.73)***
  - ***GRACE estimate F = 0.56 gives E anomalies***
- ***Gives BR, EF anomalies***

Summary (Part 2)

- ***High quality dataset with <u>Opaque cloud</u>***
  - ***Estimate SWCF, LWCF and R_n***
- **Map coupling of T, RH climate anomalies**
  - **To cloud on daily time-scale**
  - **To cloud and precip. on monthly/seasonal**
- **Dependence splits for 50-yr climate**
  - **T depends on cloud/radiation**
  - **RH and DTR depend on precip.**

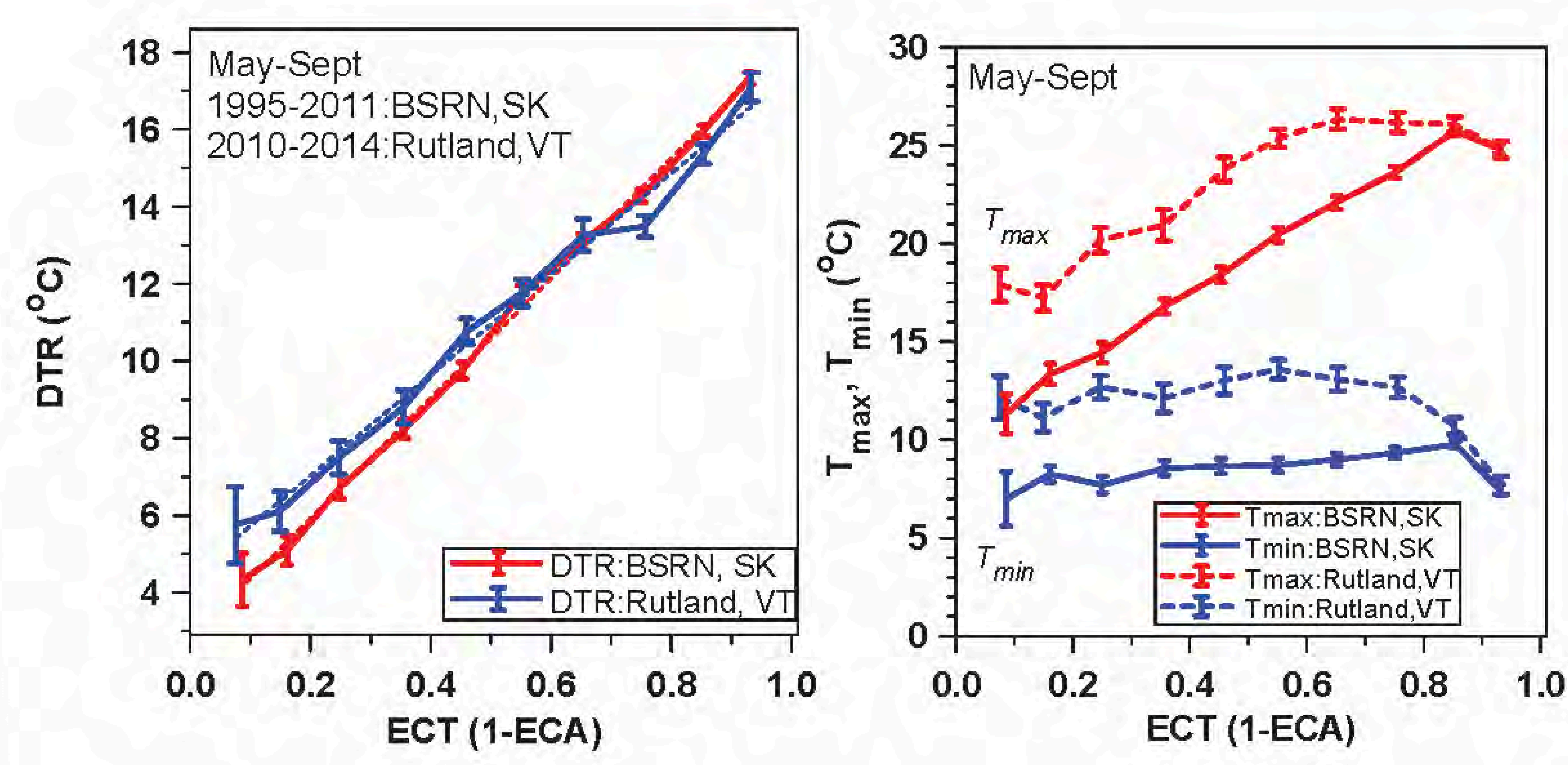
- ***Estimate evaporation using GRACE data for coupling changes in TWS to precip. anomalies***

Partition Further



- **11 stations: 37600 days in July, August**
  - **Precip–RH regression gives Evap. anomalies?**

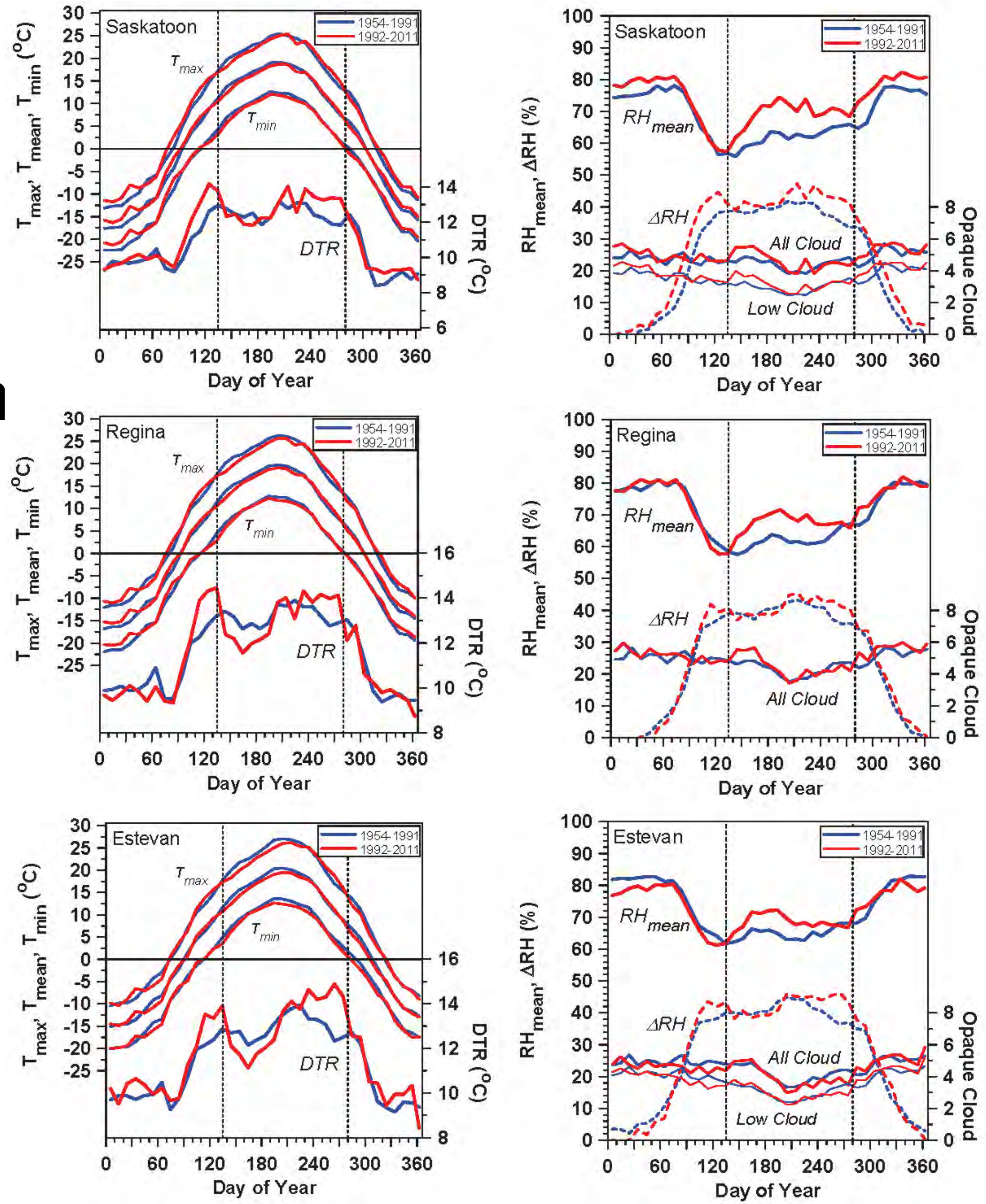
DTR linear on ECT (1-ECA)



- **Prairie: Bratt's Lake (BSRN data)**
- **Solar array: Rutland VT** (Licor: LI-200SA)

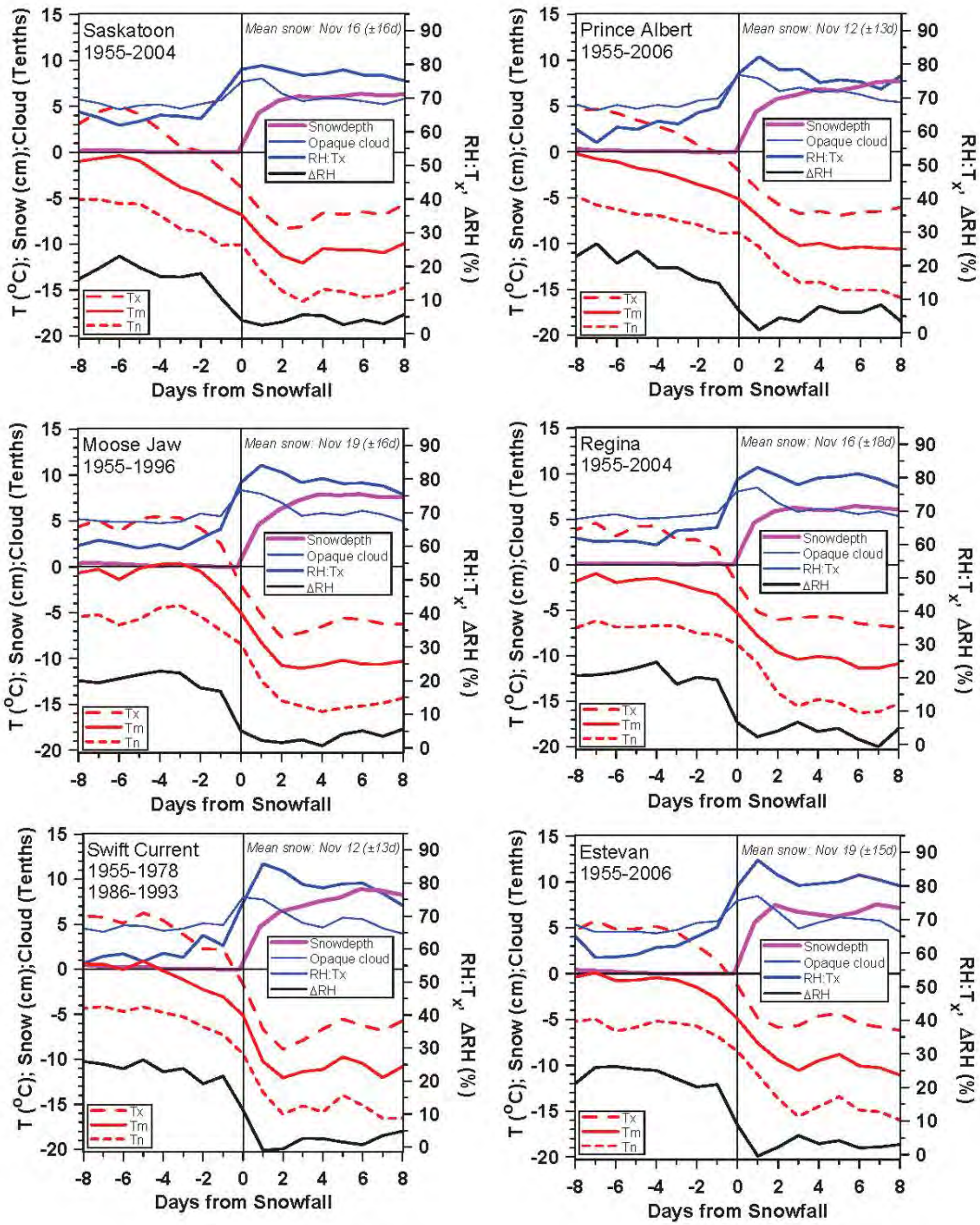
Diurnal Climate Change

- **Annual cycle in Saskatchewan**
- **DTR change**
- **RH_{mean} up**
- **Cloud peak**



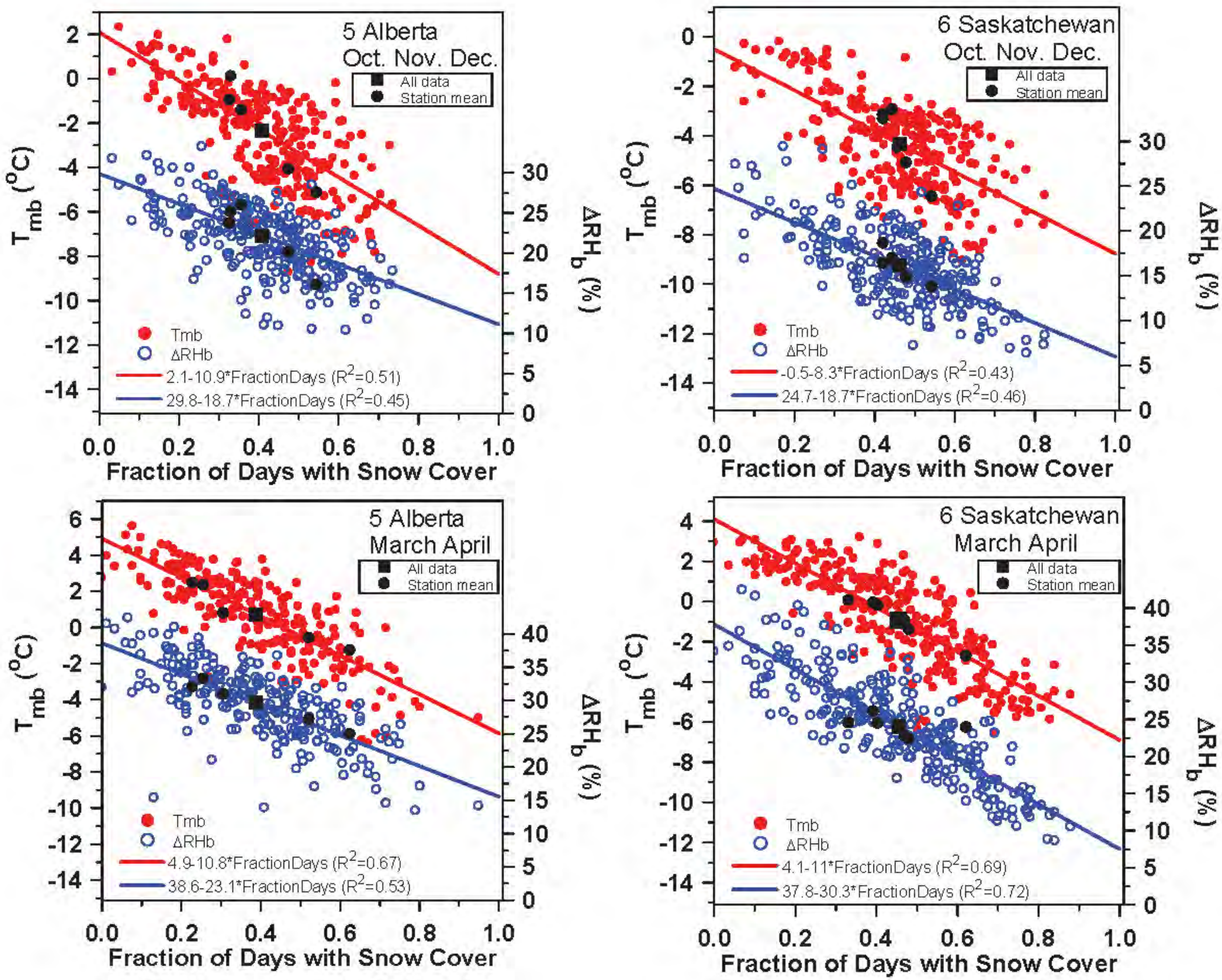
6 Stations in Saskatchewan

- T_x, T_m, T_n fall about 10K
- ΔRH falls to <10%, afternoon RH rises
- Cloud increases 10% (peaking with snow)
- Snow date: Nov 15 ± 15 days



Snow Cover: Fall and Spring Climatology

- **Fraction of days with snow cover drives much of interannual T variability**
- **More in spring than fall**
- **T- Slopes: -11, -8, -11, -11**



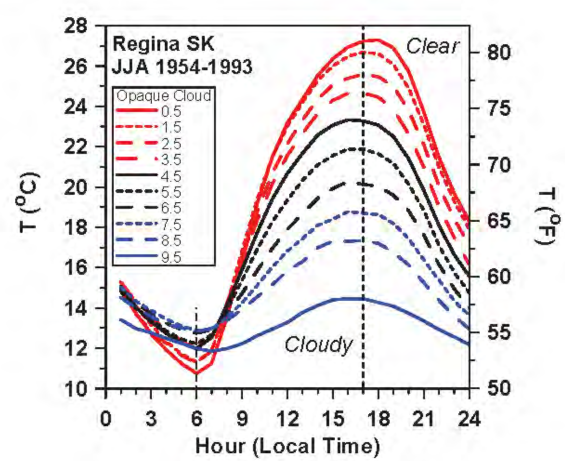
Daily Mean Climate vs Long-term Diurnal Mean

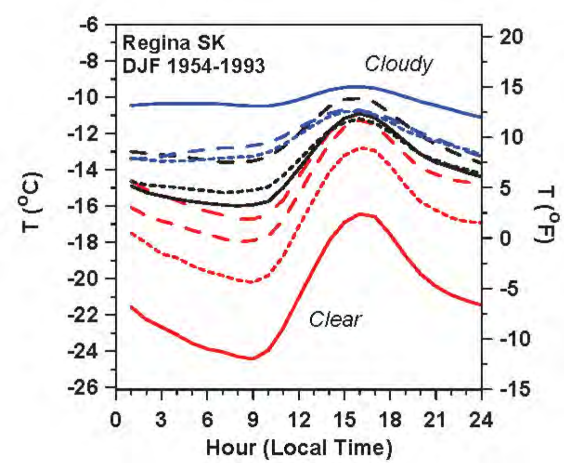
- *Definitions*
  - $DTR = T_x - T_n$
  - $\Delta RH = RH{:}T_x – RH{:}T_n$

Monthly mean diurnal cycle

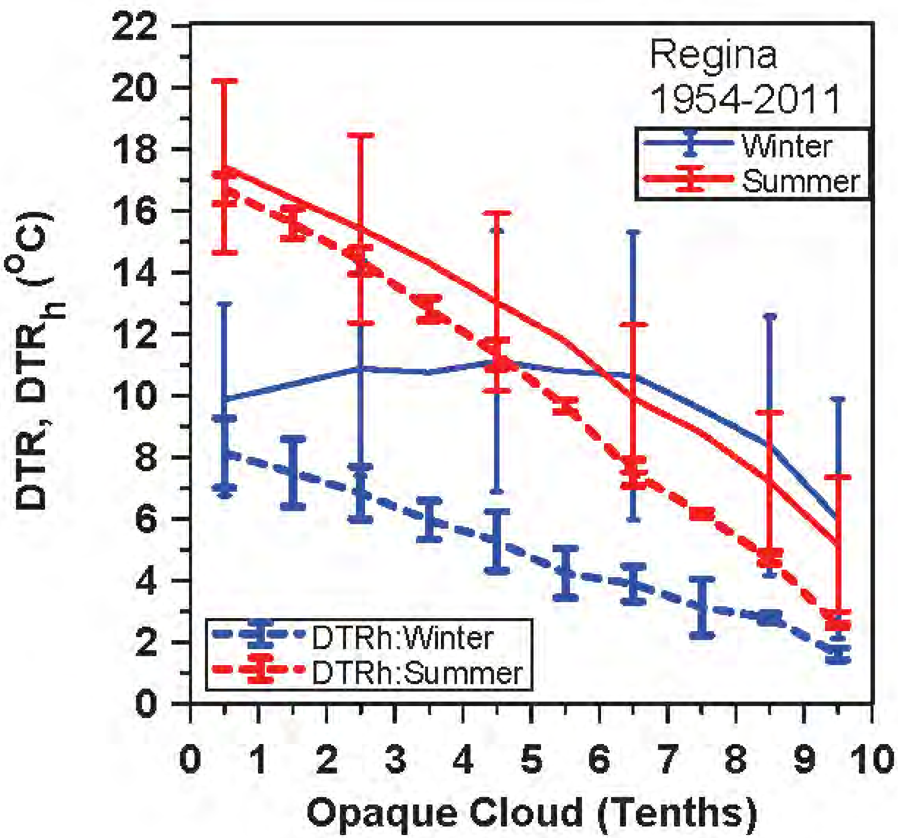
  - $DTR_h = T_{xh} – T_{nh}$
  - $\Delta RHh = RH_{xh} – RH_{nh}$

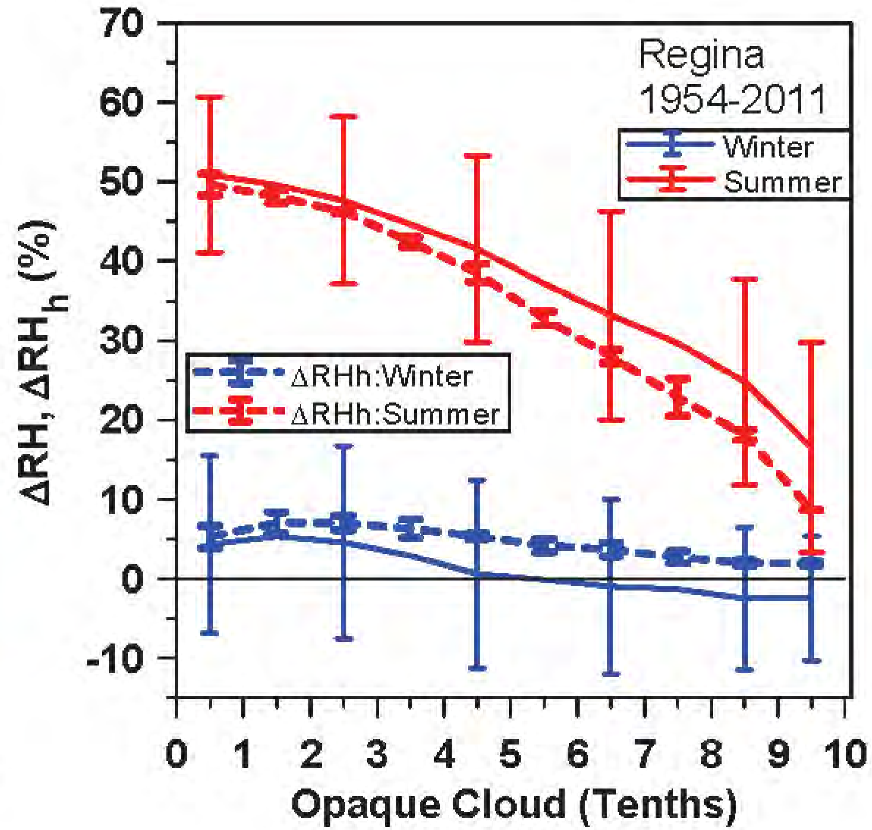
Radiatively forced signal small in winter compared to daily advection





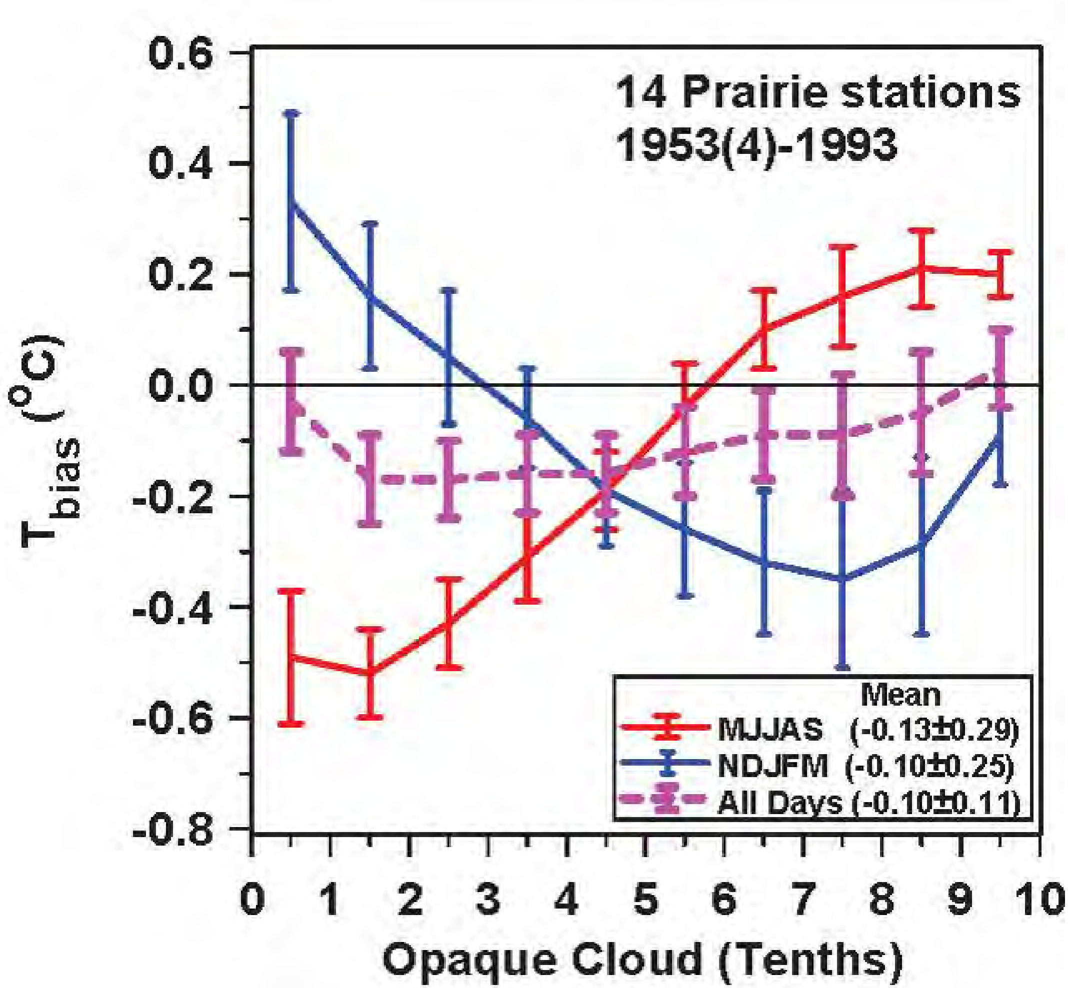
Daily Mean Climate vs Monthly Diurnal Mean Climate





- **Daily variability in winter large**
- **Monthly variability small: DTR$_h$ quasi-linear**

$T_{bias} = (T_{max} + T_{min})/2 - T_{mean}$



- **Opposite in warm and cold season**