Coupling Climate to Clouds, Land-use, Precipitation and Snow

Alan K. Betts

akbetts@aol.com

http://alanbetts.com

Co-authors:

Ray Desjardins, Devon Worth, Darrel Cerkowniak

Agriculture and Agri-Food Canada

Shusen Wang and Junhua Li

Natural Resources Canada

University of Texas, Austin

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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

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

- ***Betts et al. 2014b: Warm season coupling of temperature and humidity to precipitation and cloud cover***

Papers at http://alanbetts.com

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.**

Methods: Analyze Coupled System

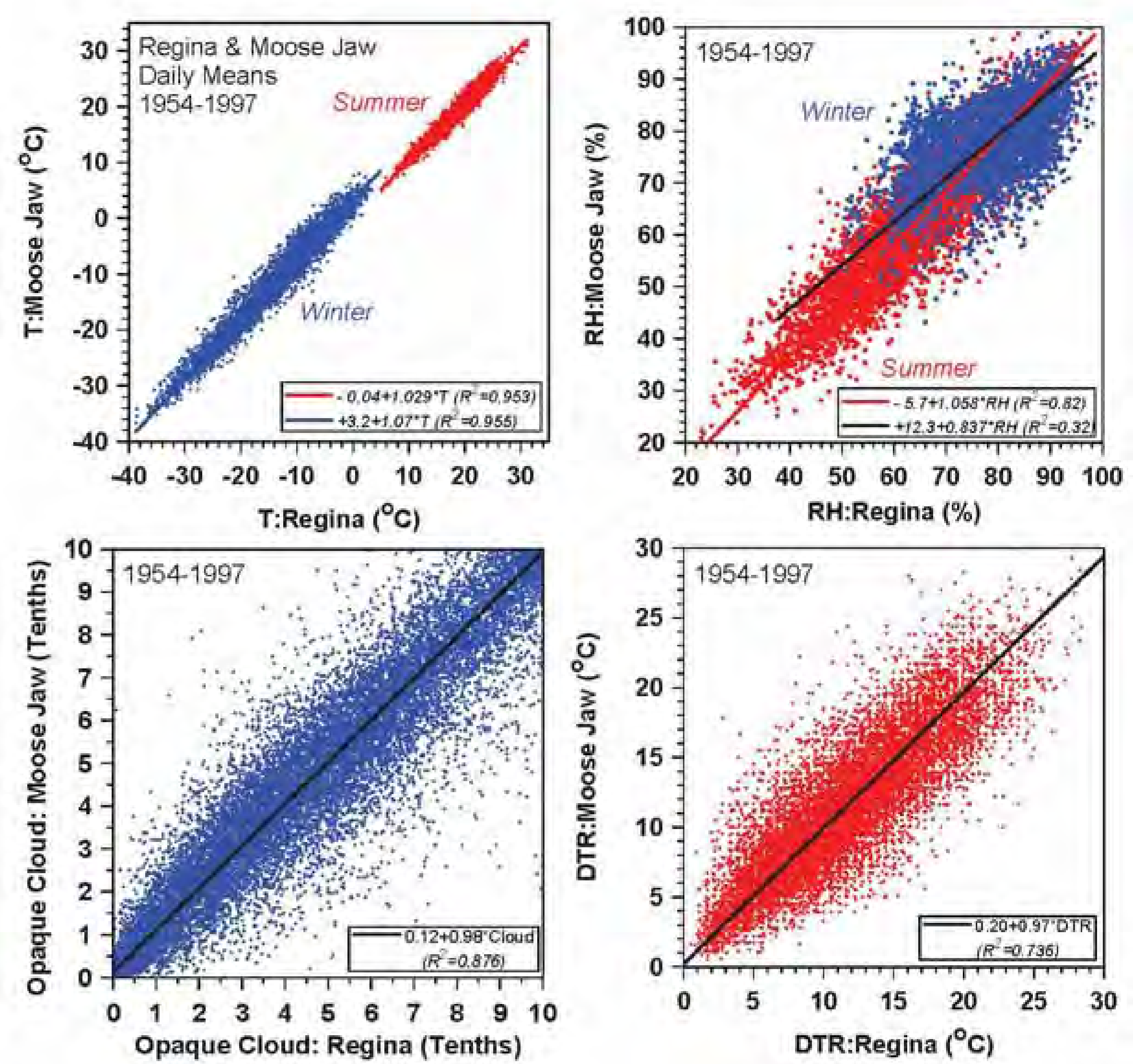
- ***Seasonal diurnal climate by station/region***
- **220,000 days of excellent data (600 years)**
- **Composite by daily mean opaque cloud**
  - **Calibrate SWCF, LWCF against radiation data**
- **Change of seasonal climate with cropping**
  - **'Summerfallow' to annual crops on 5MHa in 30 yrs**
- **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)***
  - **$\Delta RH = RH_{tn} - RH_{tx}$**
- ***Almost no missing hourly data (until recent government cutbacks!)***

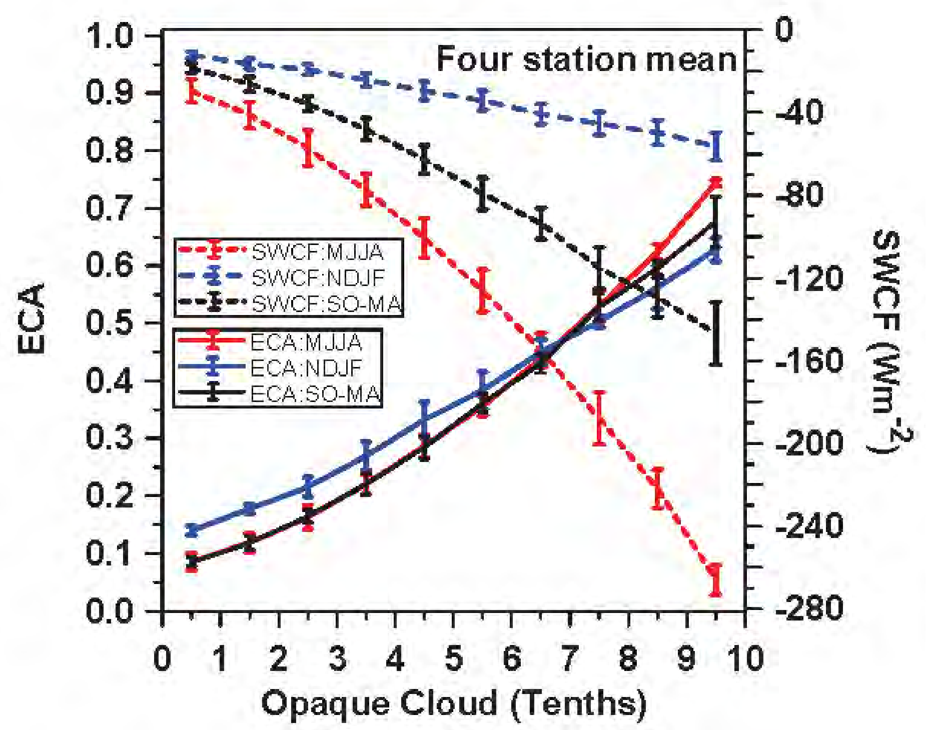
Compare Neighbors: 64 km

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



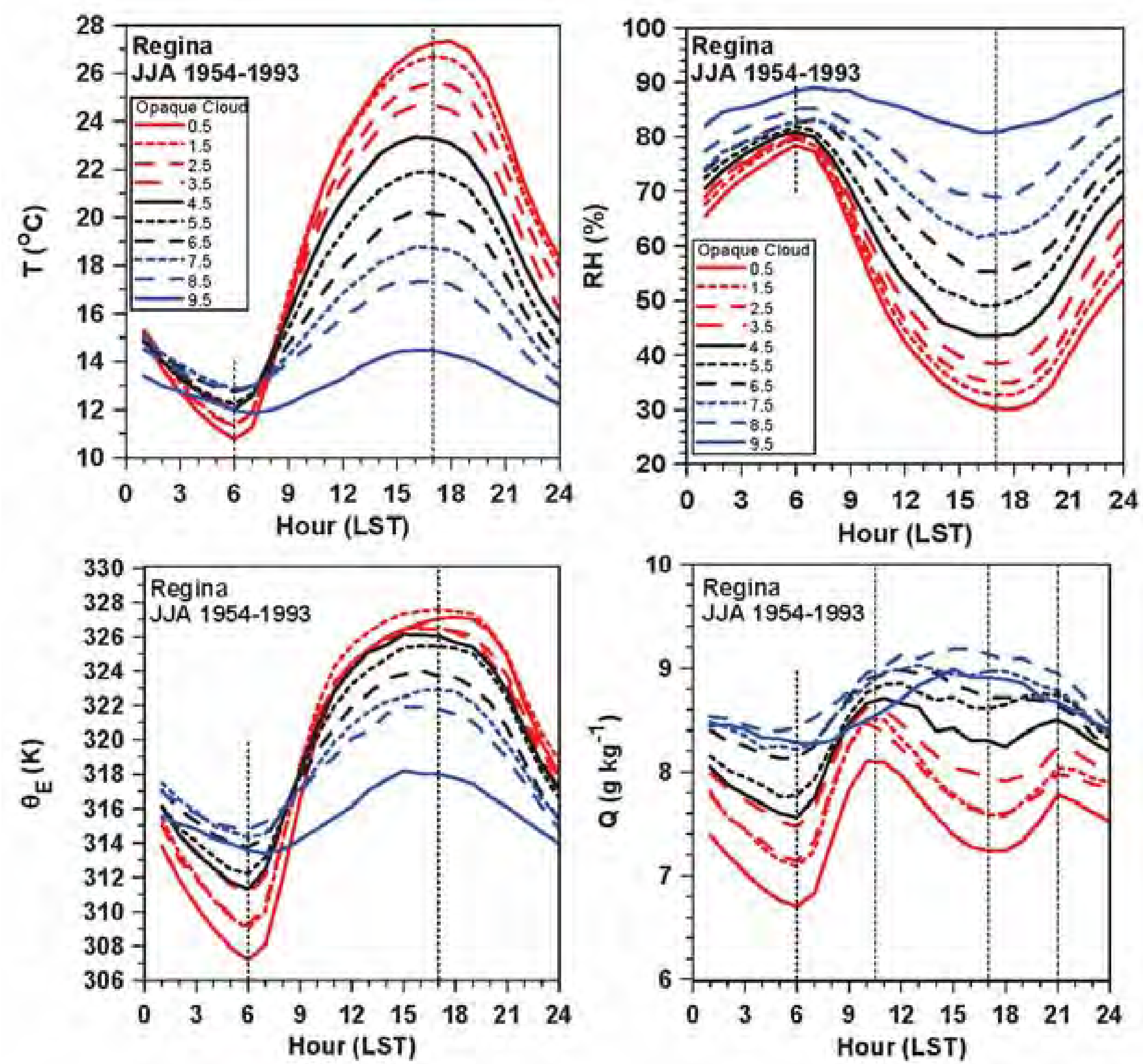
Calibration of Opaque Cloud to Effective Cloud Albedo (ECA)

- **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

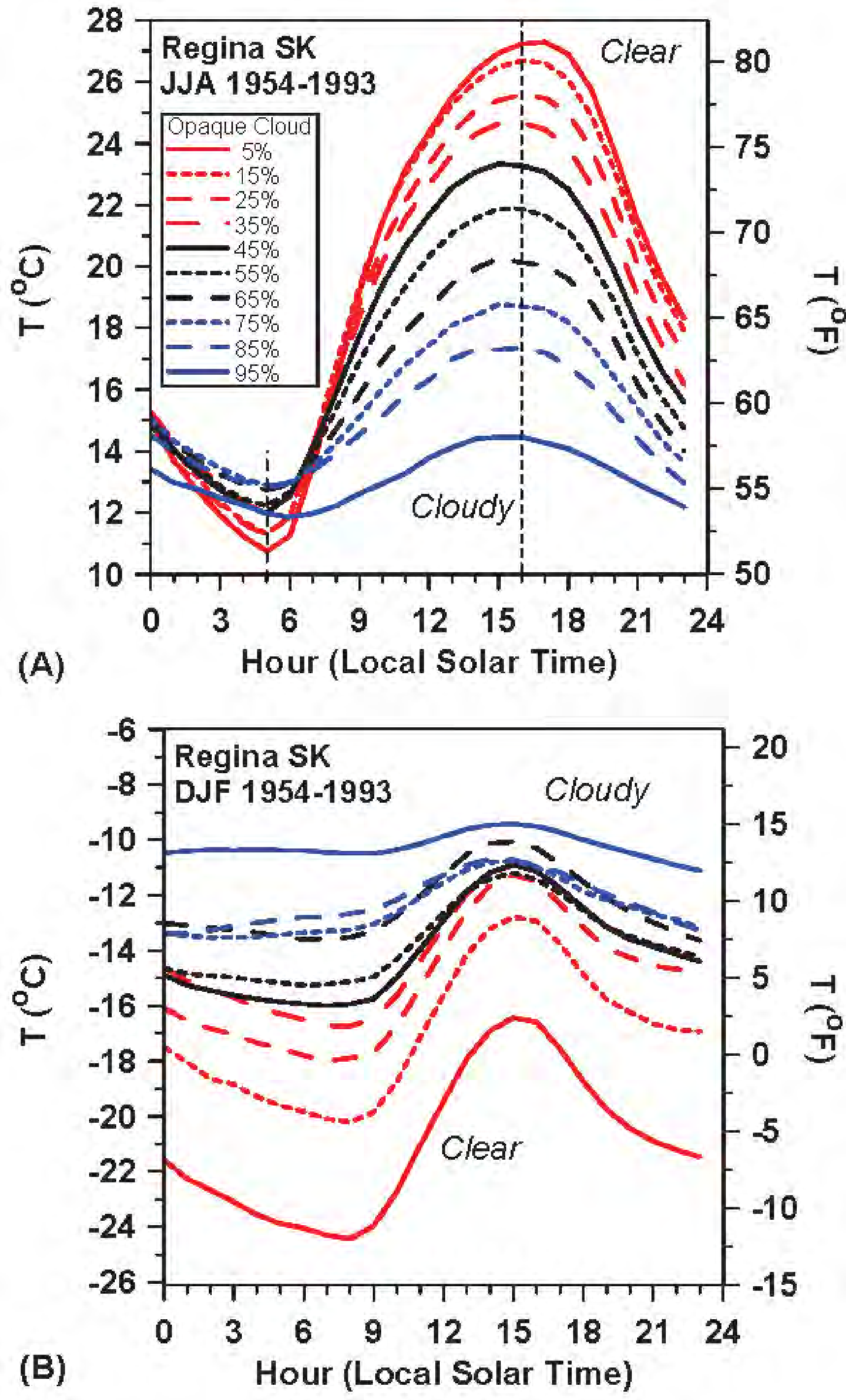
- ***40-yr climate***
- **T and RH are inverse**
- **Q has double maximum for BL transitions**
- **θ_E flatter**
- ***Overcast (rain) only outlier***



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***

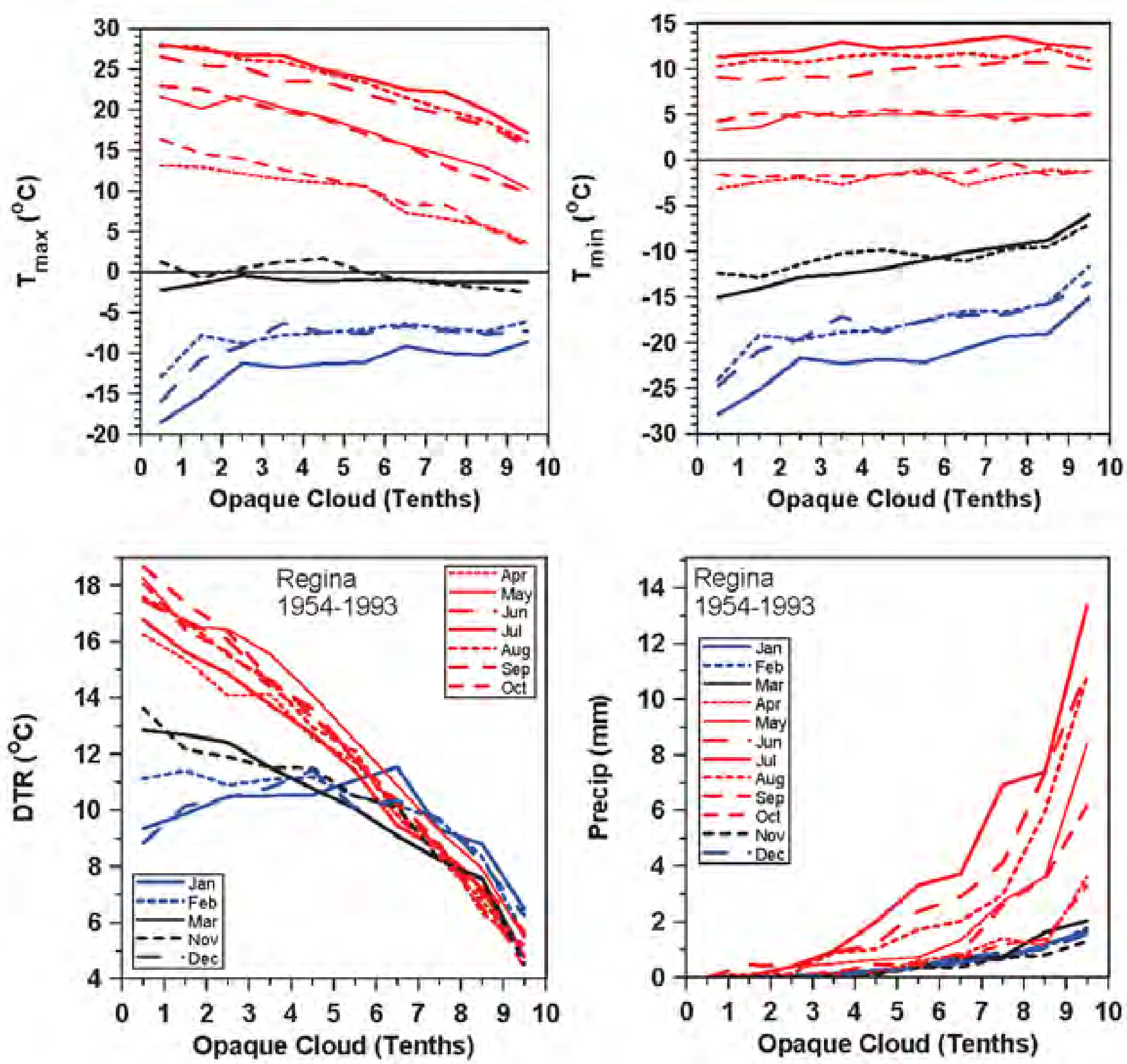
Betts et al. 2013



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

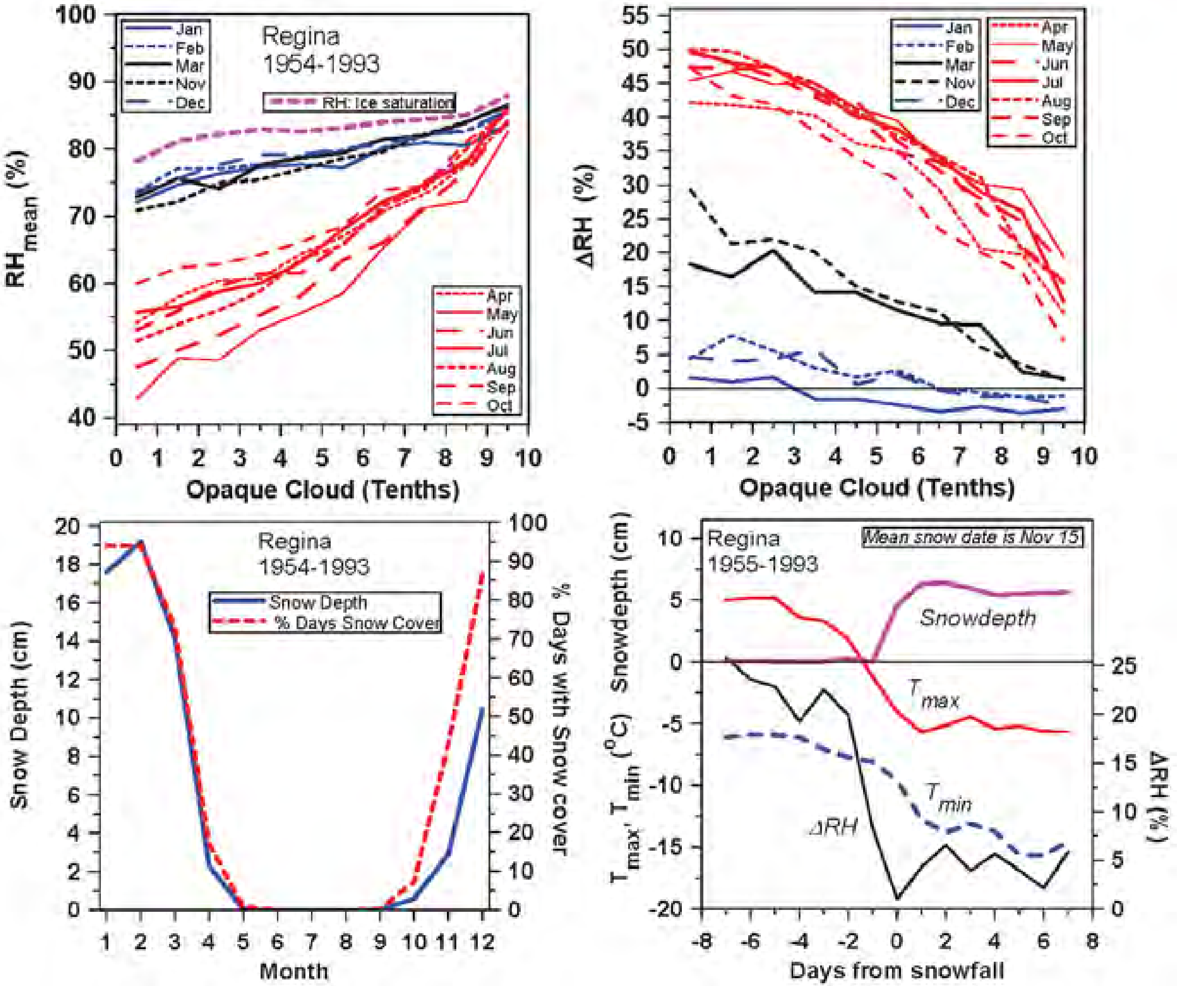
- **Warm state: April – Oct**
- **Cold state: Dec – Feb**
- **Transitions: Nov, Mar**
  $T_{max} \approx 0^oC$

- ***Actually occur in <5 days***

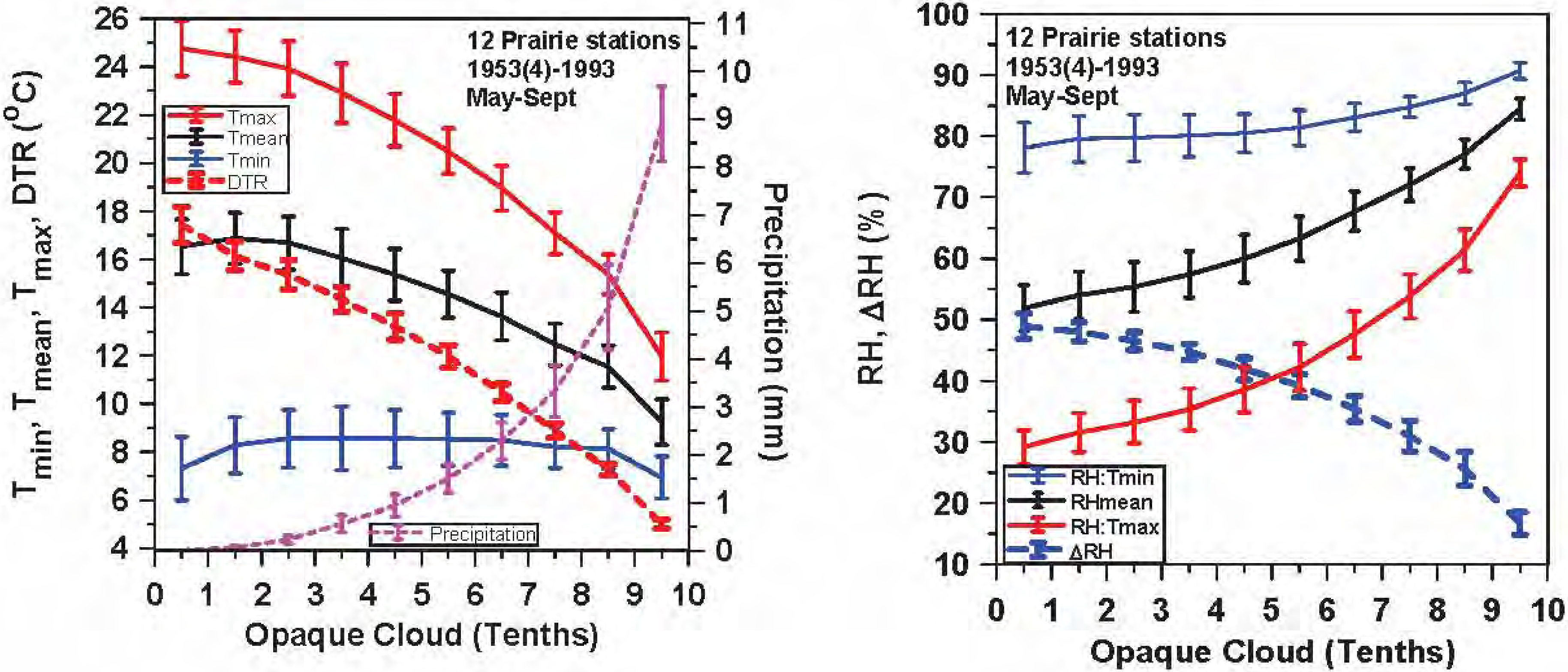


Annual Cycle: RH and ΔRH

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



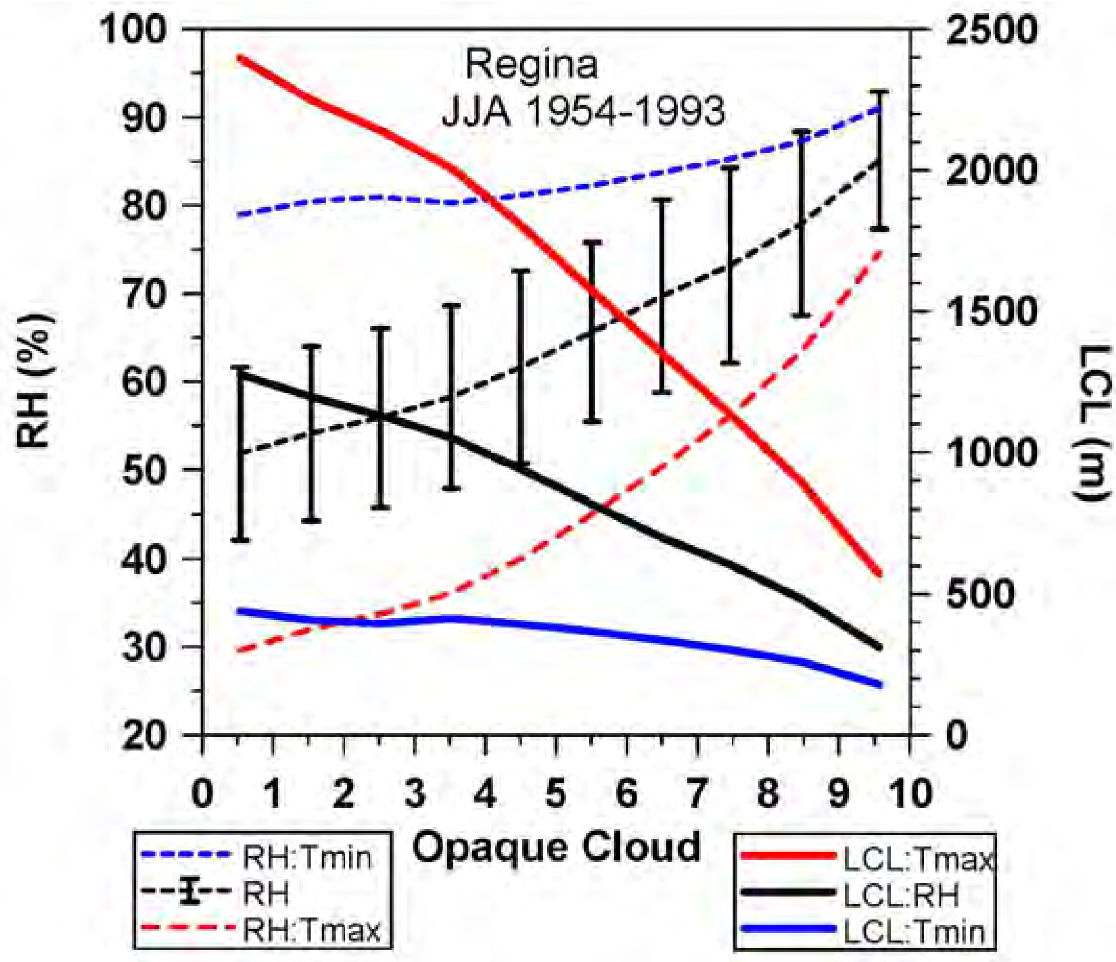
Prairie Warm Season Climate



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

RH is linked to LCL

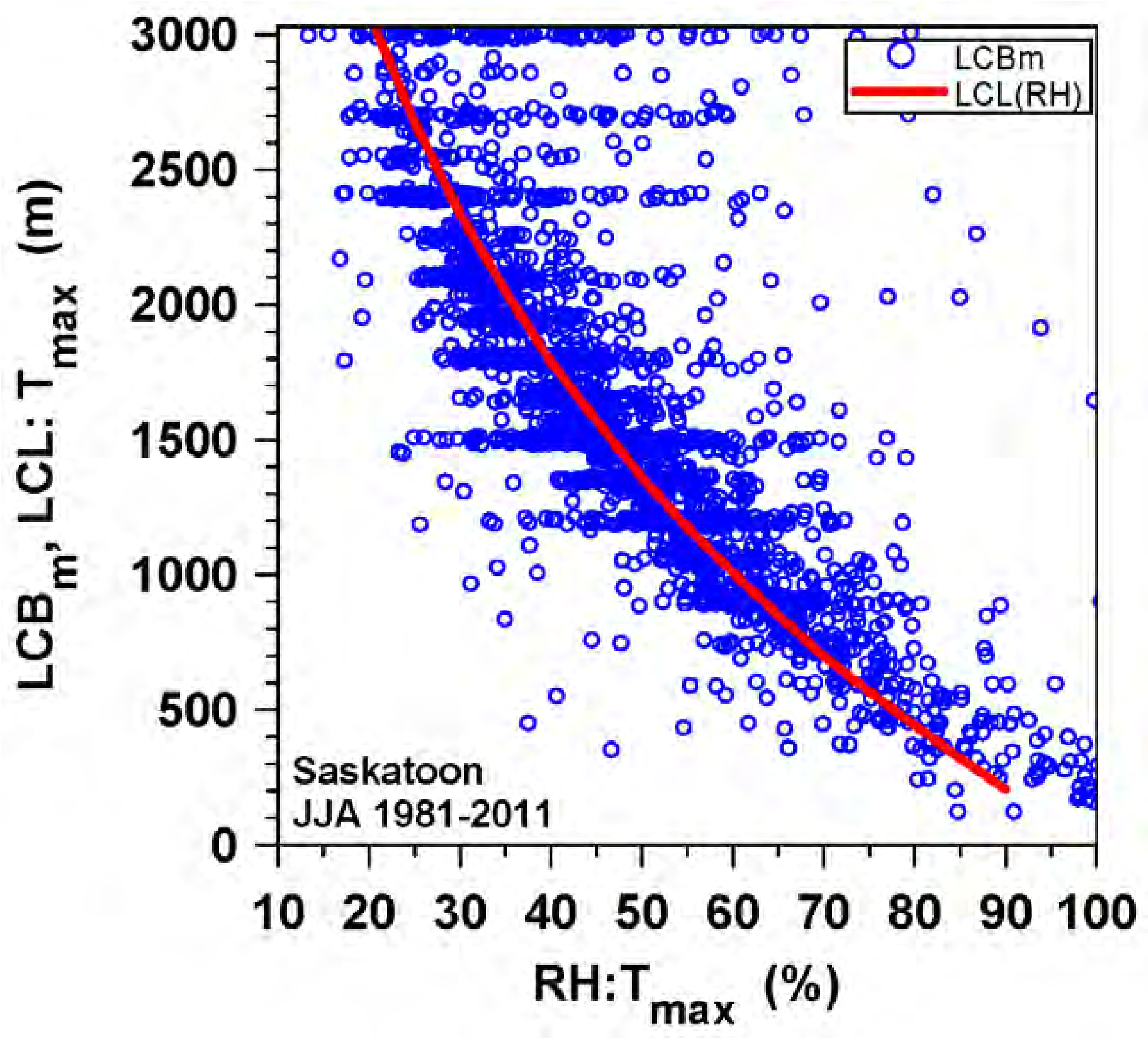
- RH increases with cloud
- Cloud-base LCL decreases
- Afternoon LCL 550 - 2350m



Afternoon LCL is Cloud-base

- At T_{max}
- **Lowest cloud-base** *(ceilometer)*
- **LCL (surface)**

- ***Coupled CBL***



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)

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

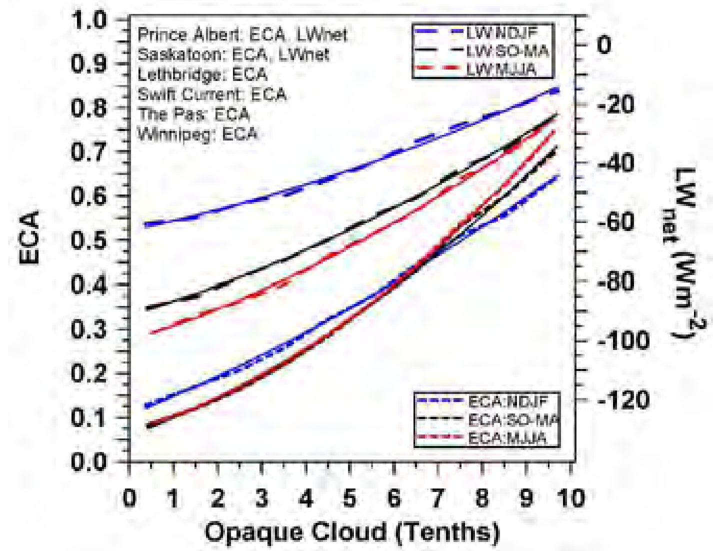
  Clear sky

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

  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

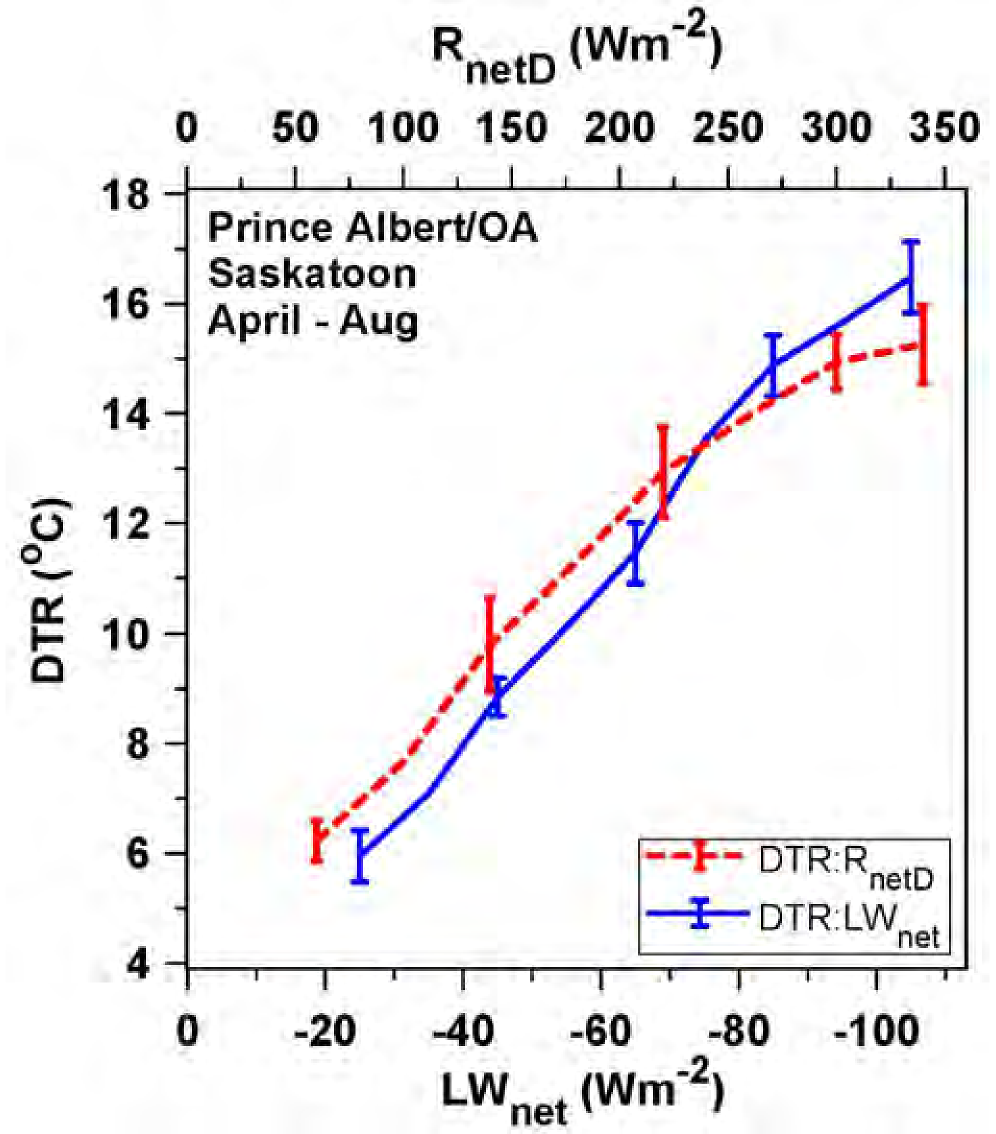
NDJF: LW_{net} = -63.0 + 3.14 Cloud + 0.193 Cloud^2

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)

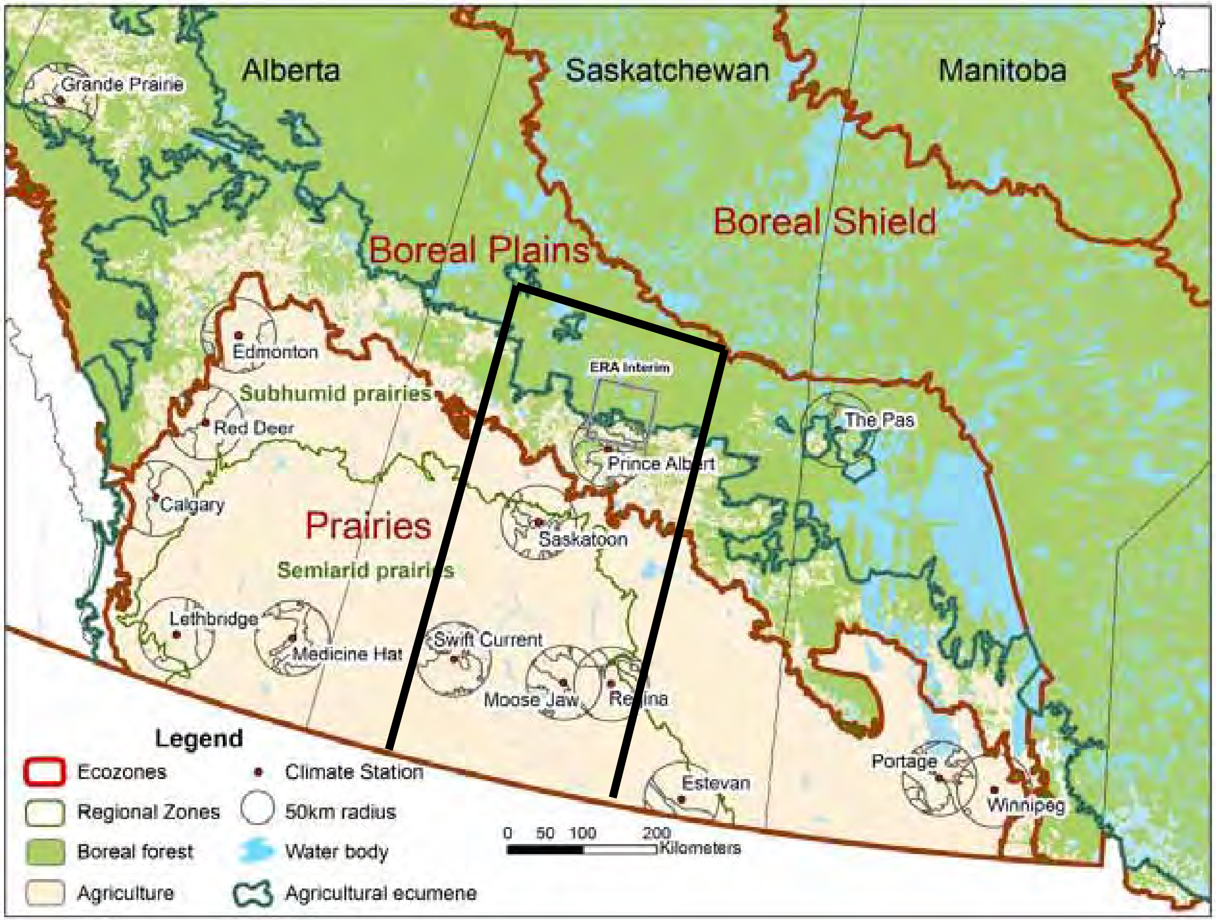
Impact of Snow on Climate

"*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

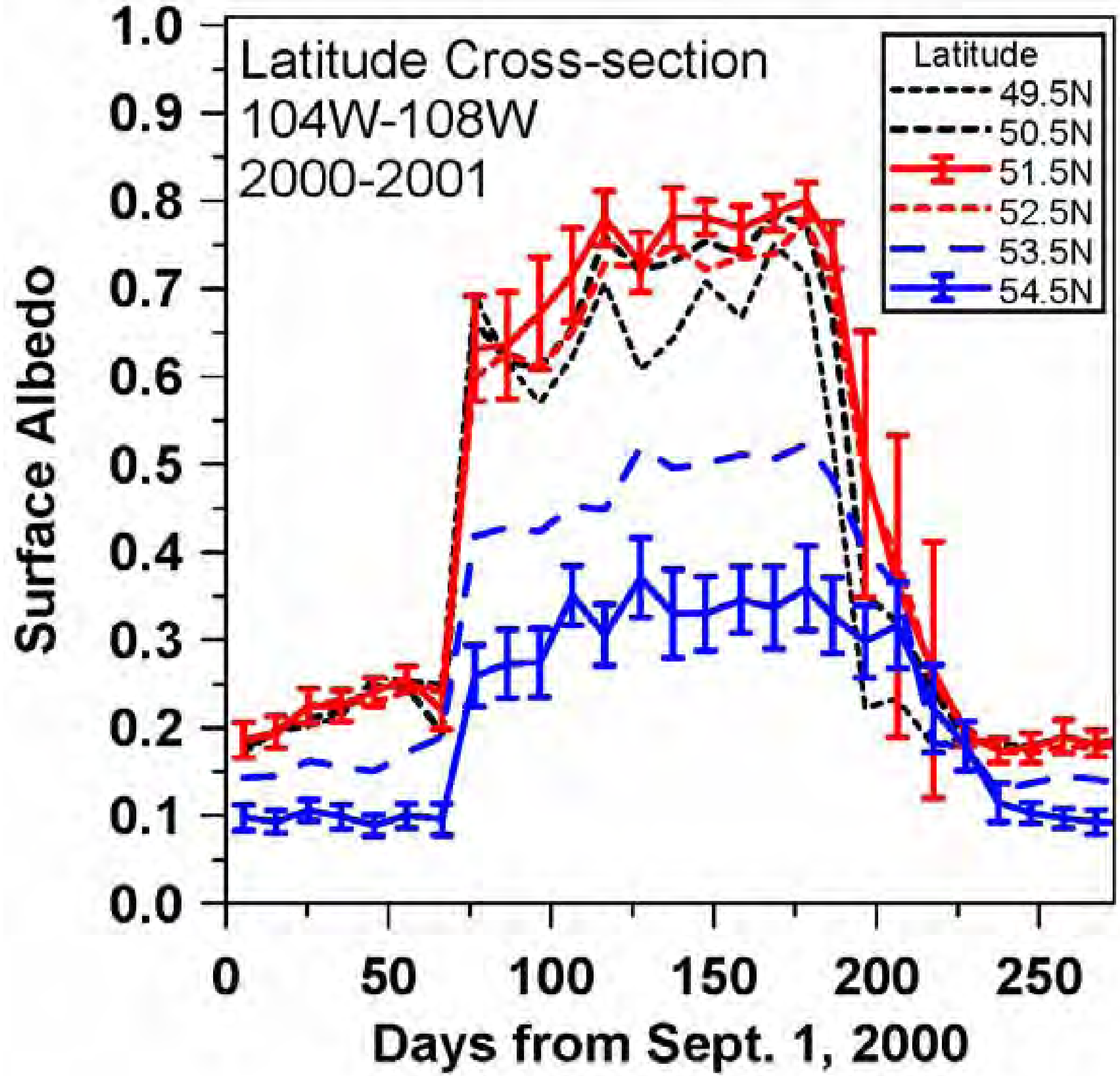


- Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})
- Daily precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

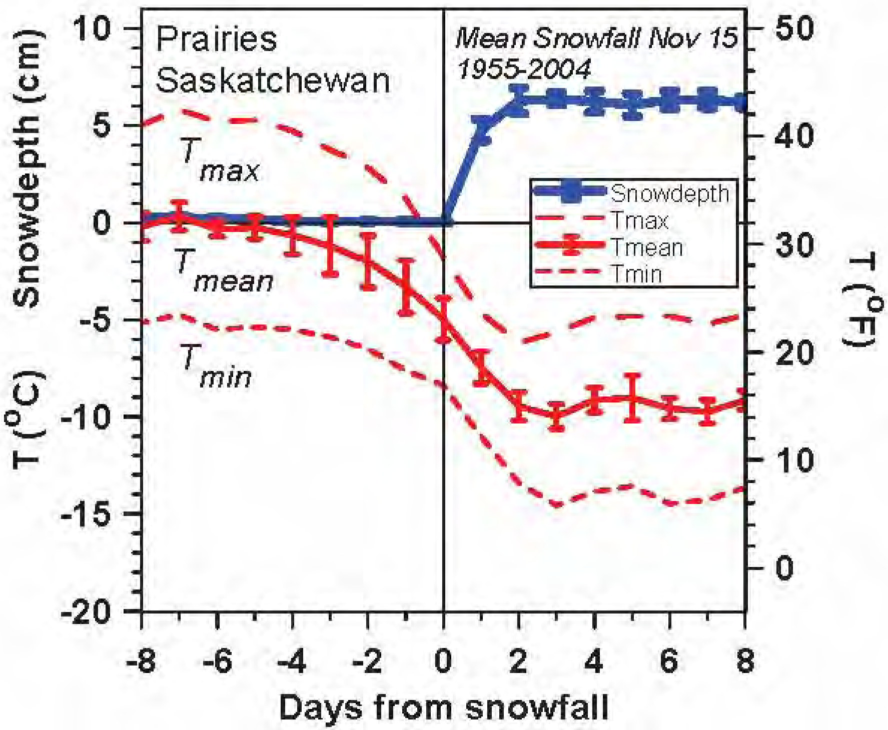
N-S Albedo through Winter

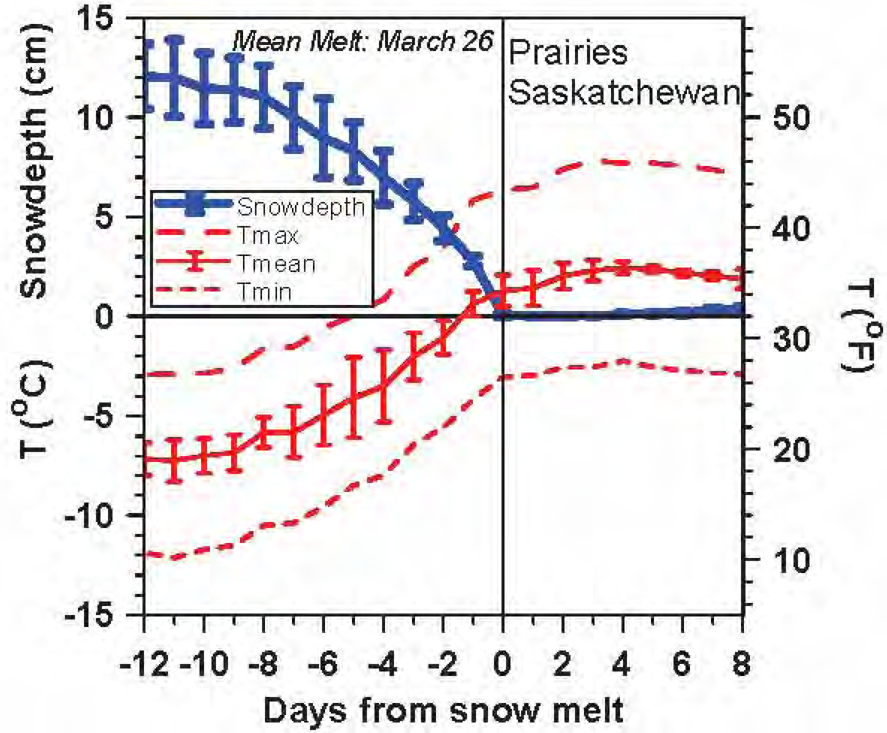
- **Prairies (SK)** α_s: **0.2 to 0.73**
- **Boreal forest** α_s: **0.1 to 0.35**

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



Snowfall and Snowmelt
Winter and Spring transitions

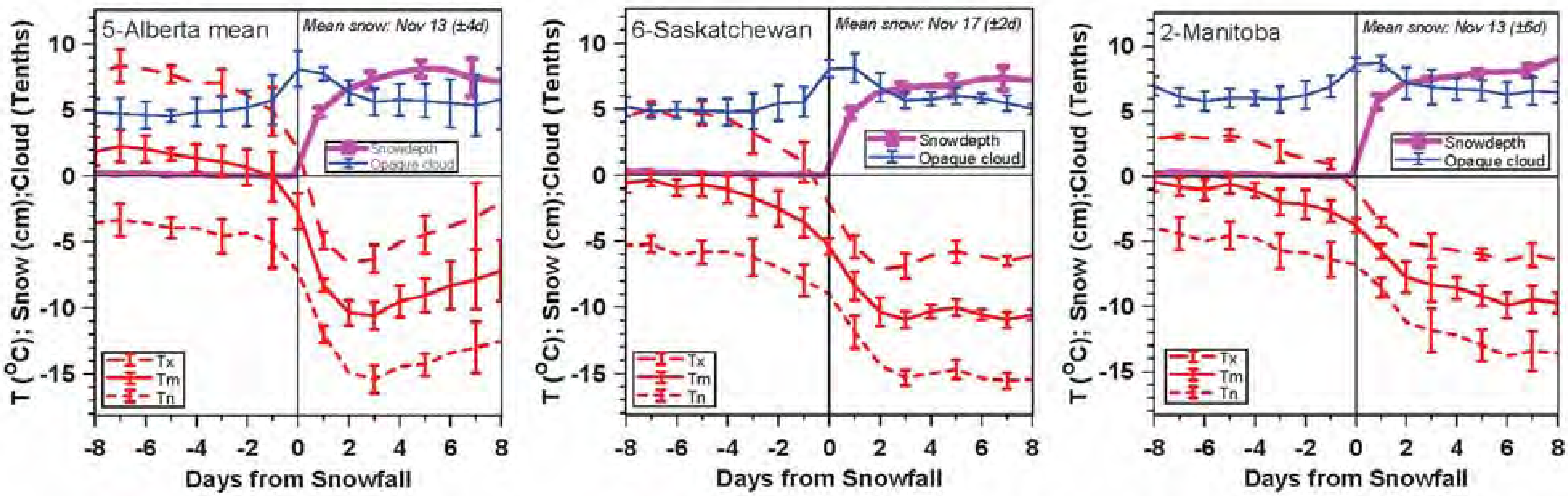




- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms 'local climate'***
  - ***Same feedbacks that are speeding Arctic ice melt in summer***
  - ***Local climate switch between warm and cold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

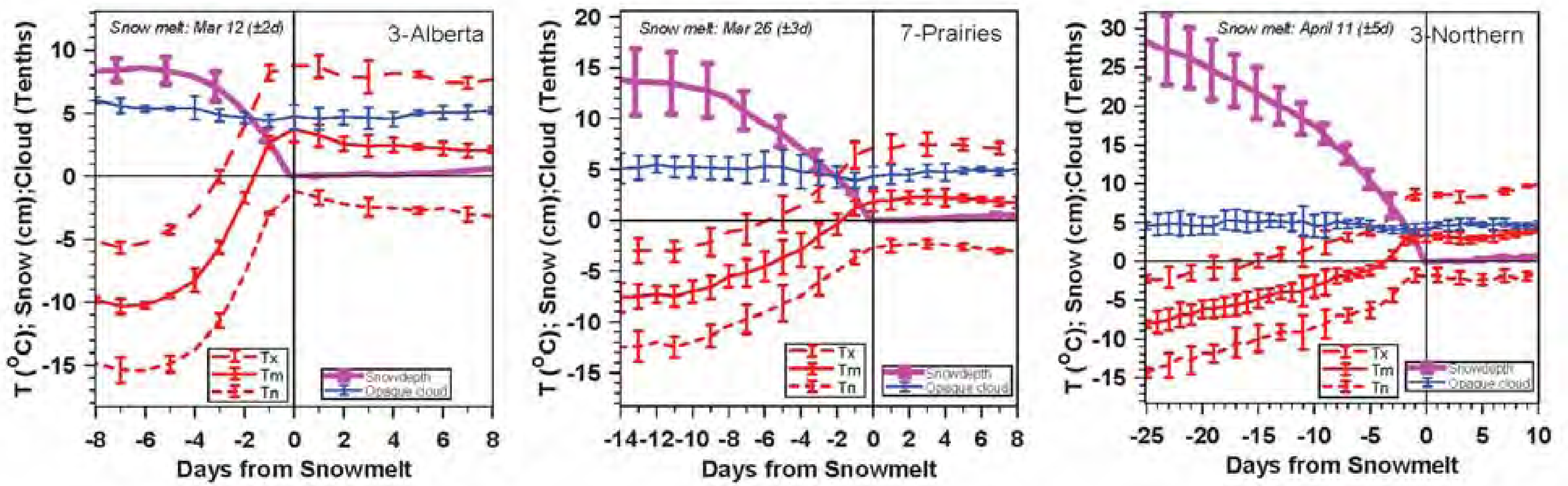
Betts et al. 2014

Fall Snow Transition Climatology



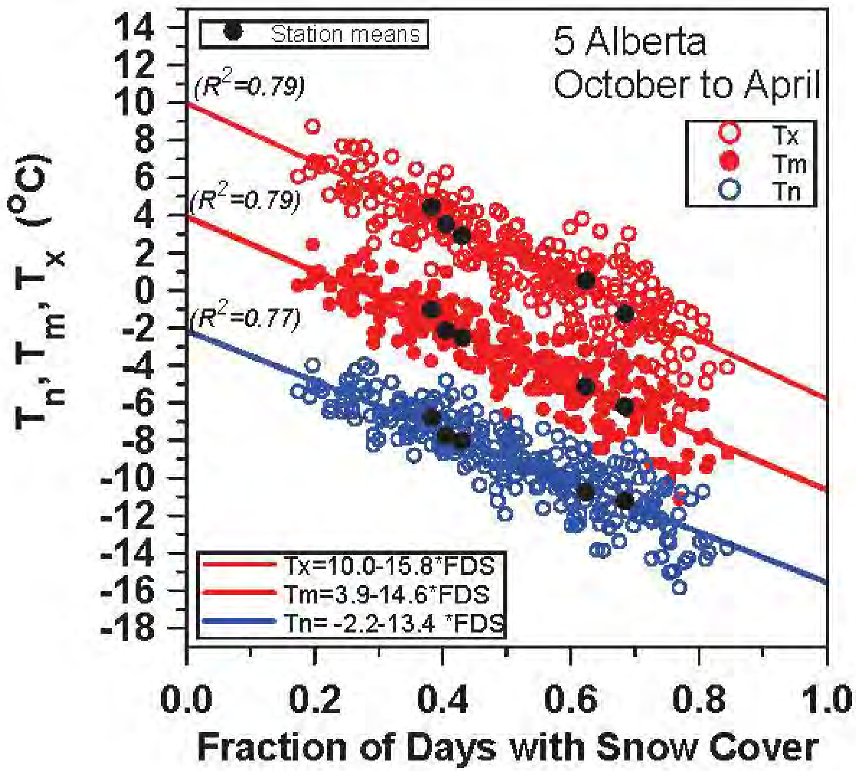
- T_x, T_m, T_n fall about 10K
- Cloud peaks with snow; increases ≈10%
- Snow date: Nov 15 ± 3 days

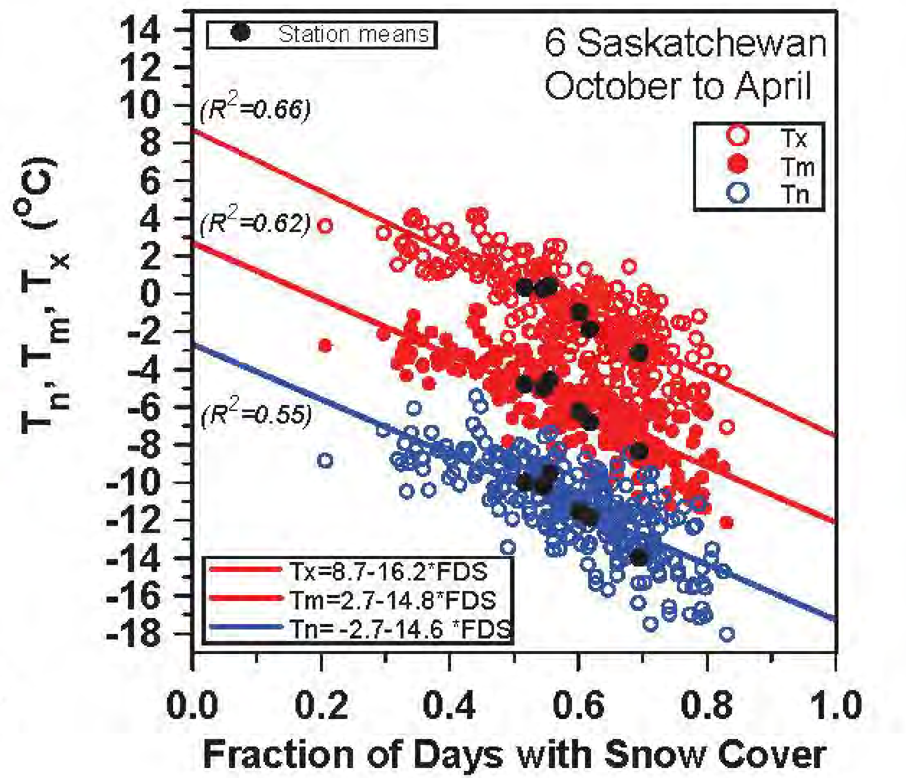
Snow-melt Transition Climatology



- **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





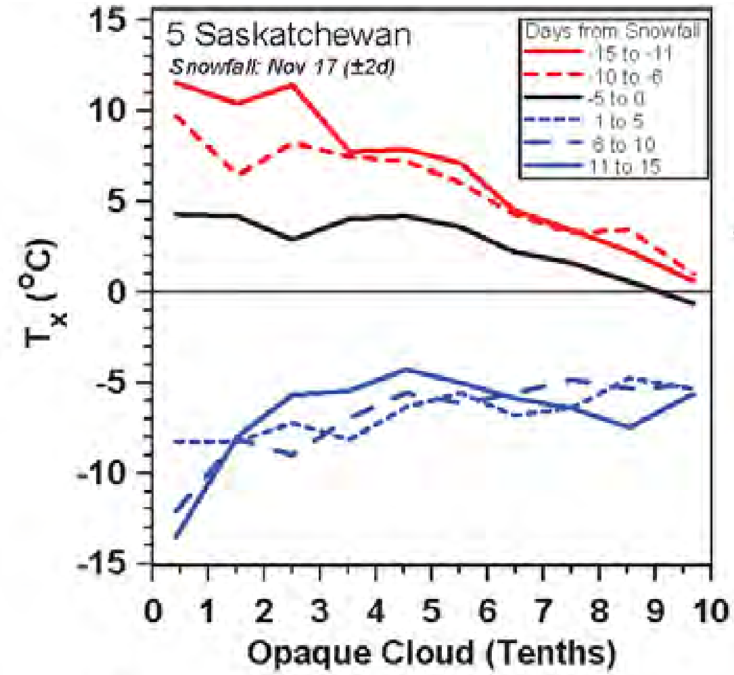
- **Alberta: 79% of variance**
- **Slopes**
  - **T_x -16.0(± 0.6) K**
  - **T_m -14.7 (± 0.6) K**
  - **T_n -14.0 (± 0.7) K**

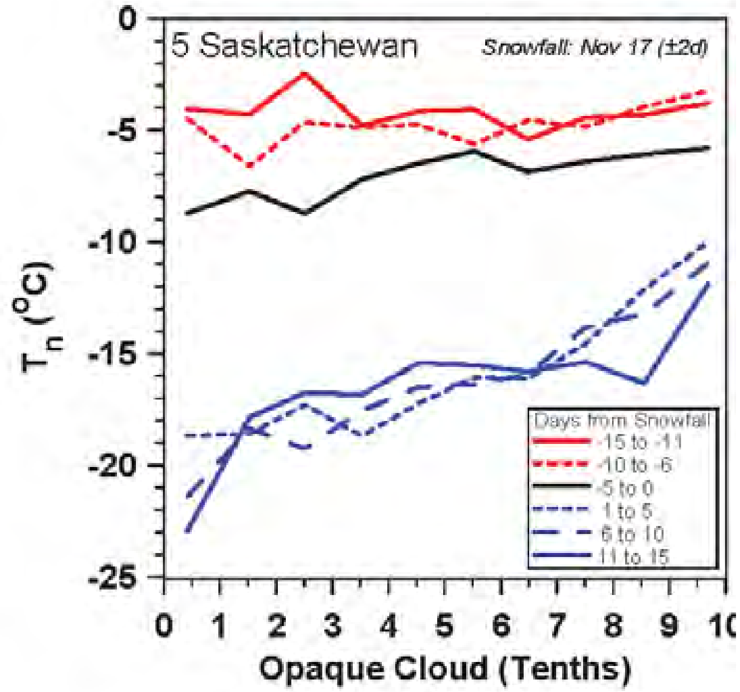
10% fewer snow days

= 1.5K warmer

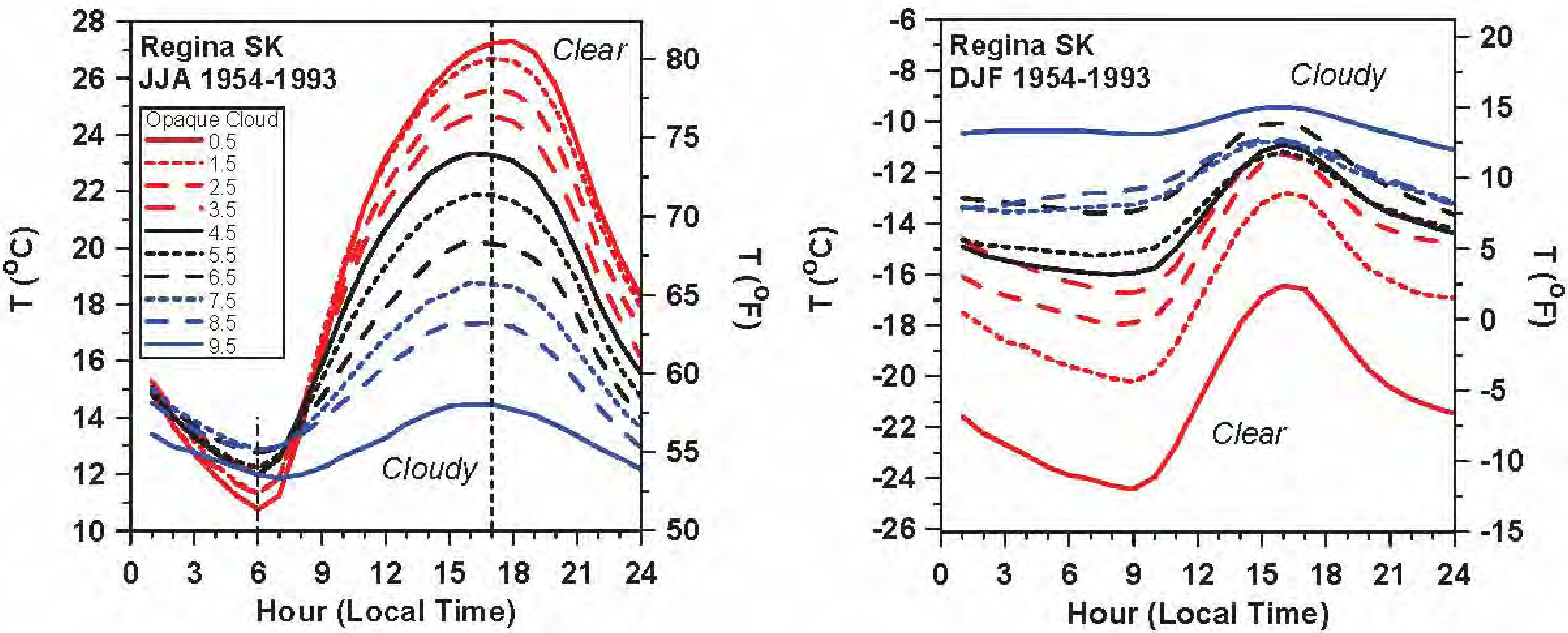
Coupling to Cloud Cover Across Snowfall

- **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

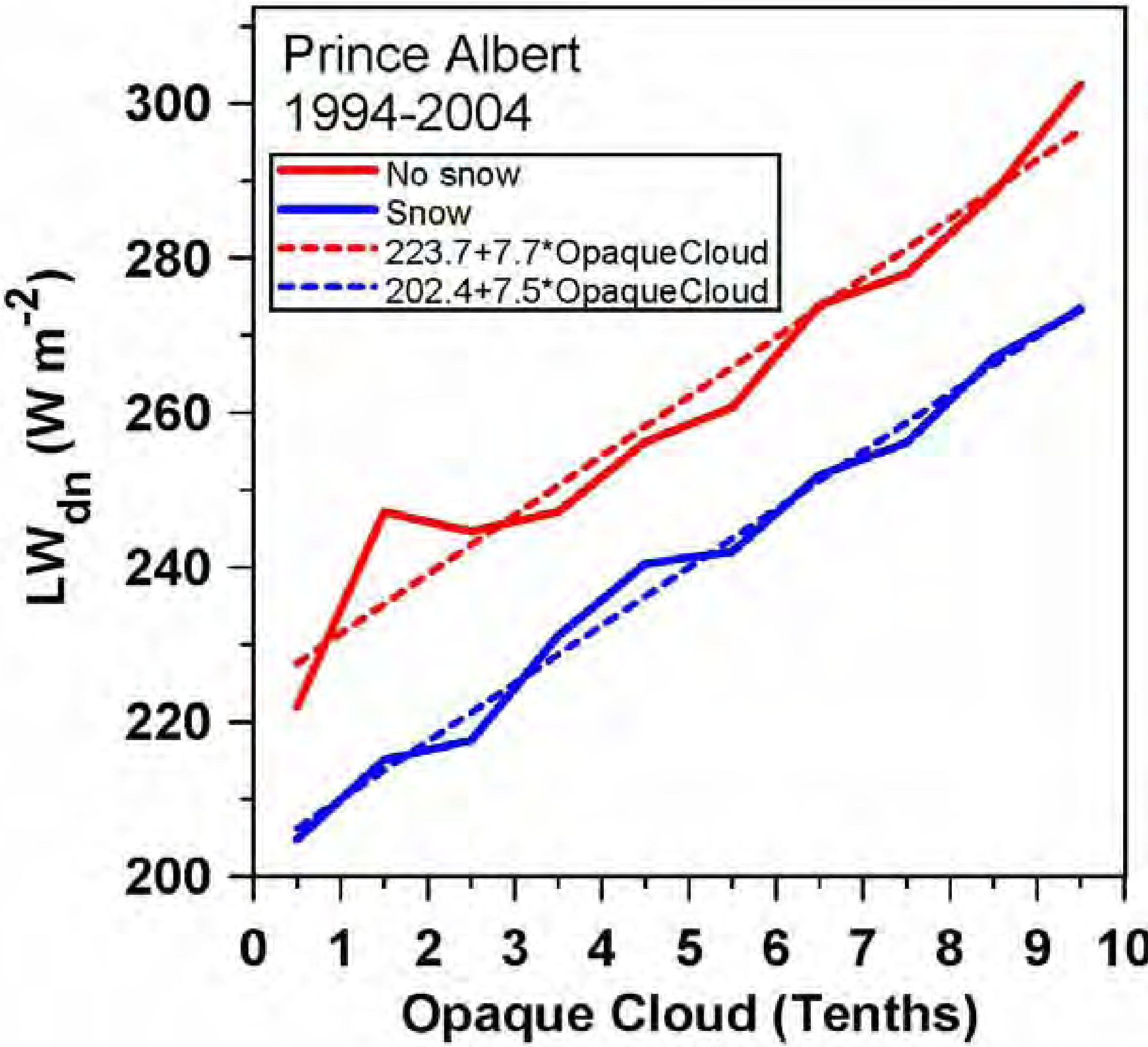


- **Summer: Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
  - **Convective boundary layer in daytime**
- **Winter: Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**
  - **Stable boundary layer**

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**
- **Total 49 W/m^2**

- **Surface skin T falls: $\Delta T = -11K$ to balance**
  (Stefan-Boltzman law: $\Delta LW = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)

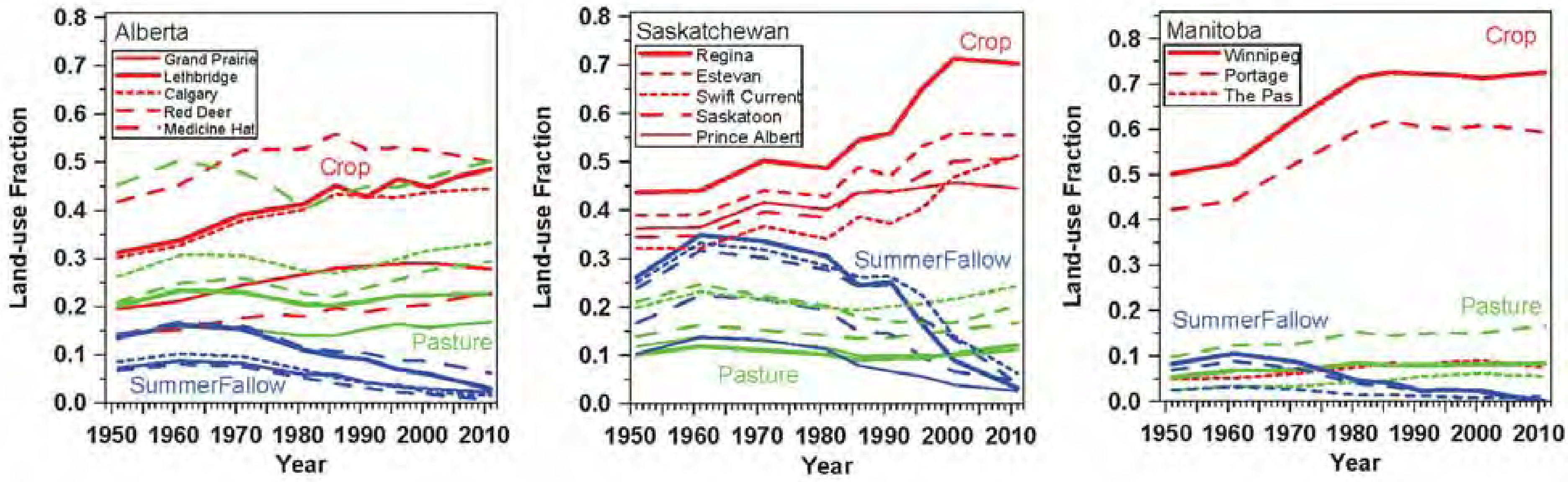
Annual crops and seasonal diurnal cycle

- **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

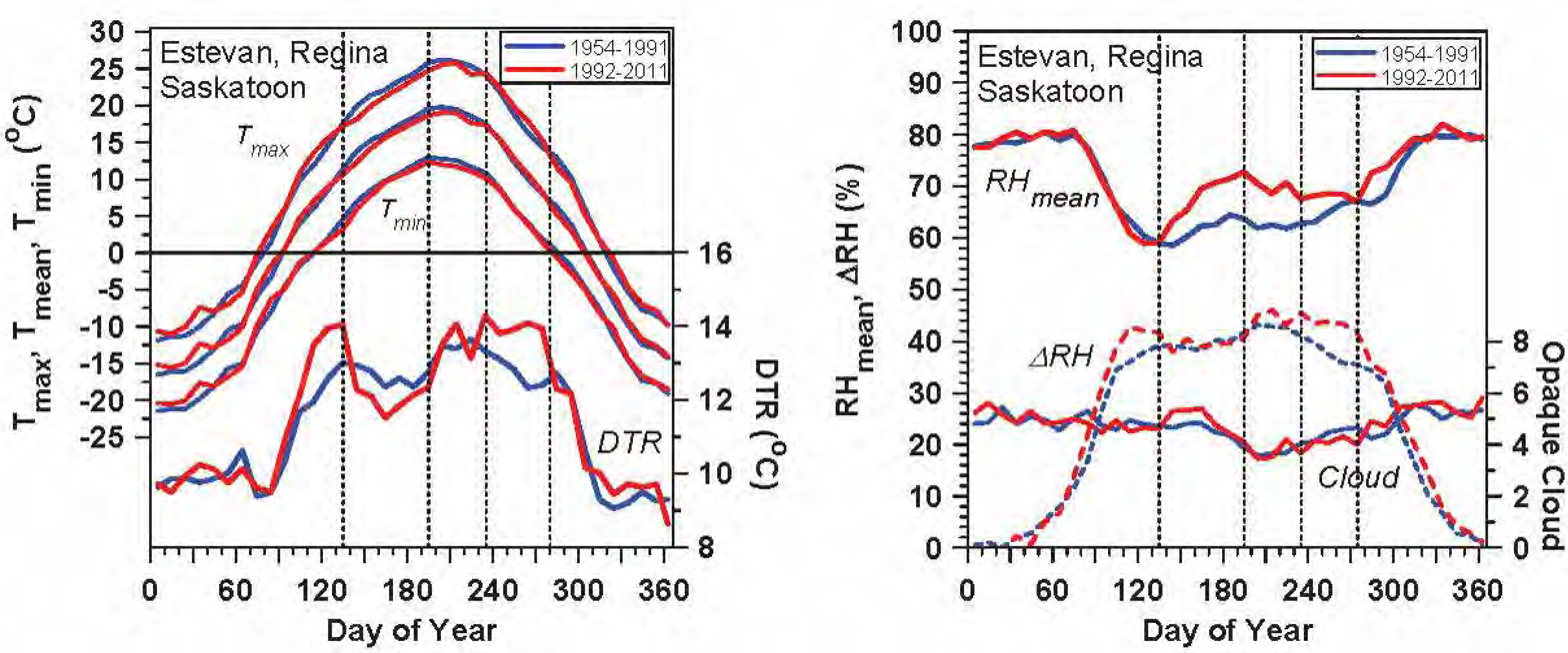
- **Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})**
- **Daily precipitation and snowdepth**
- **Ecodistrict crop data since 1955**
- **Albedo data (MODIS/CCRS: 250m, after 2000)**

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

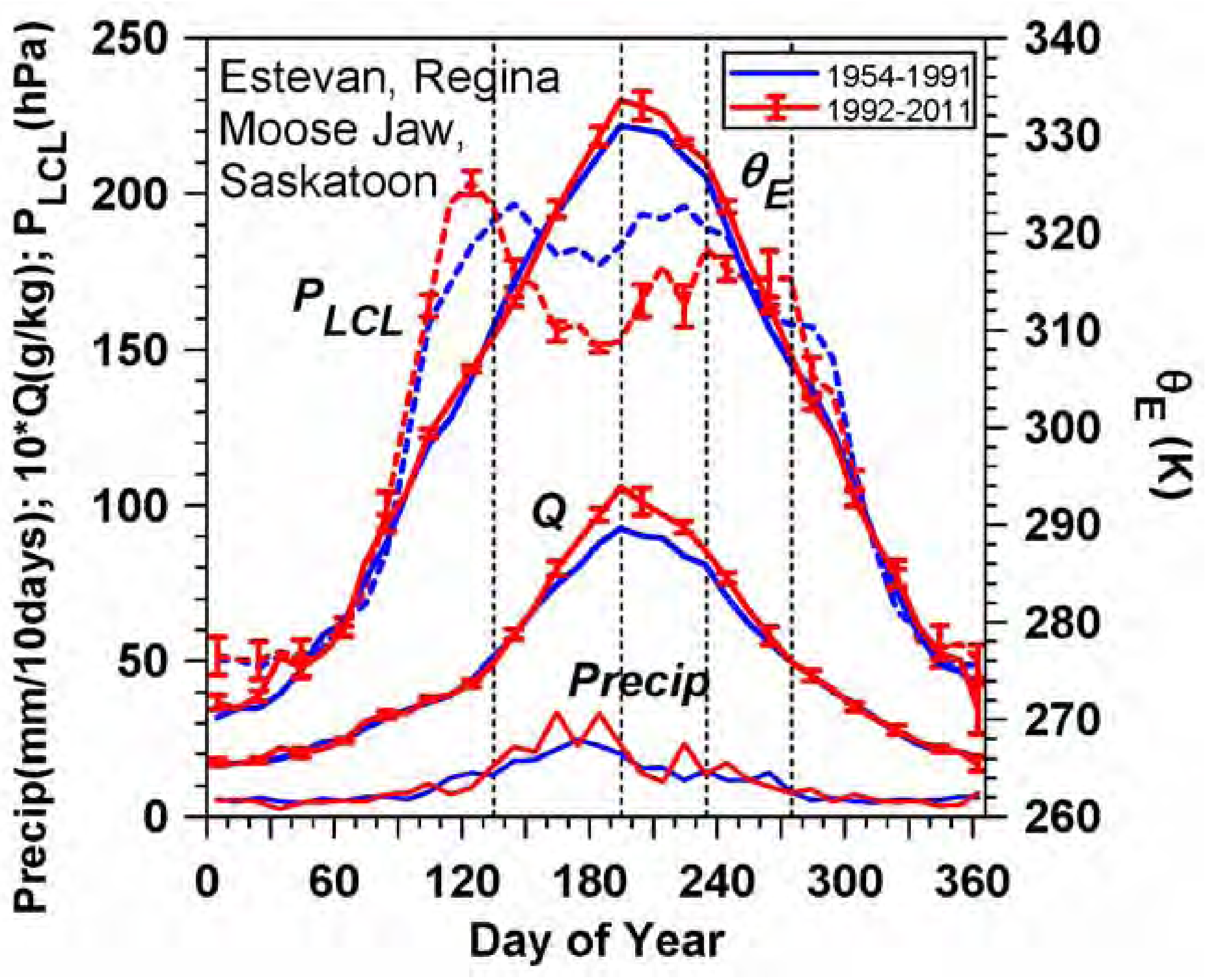


- **Growing season**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal structure changes**

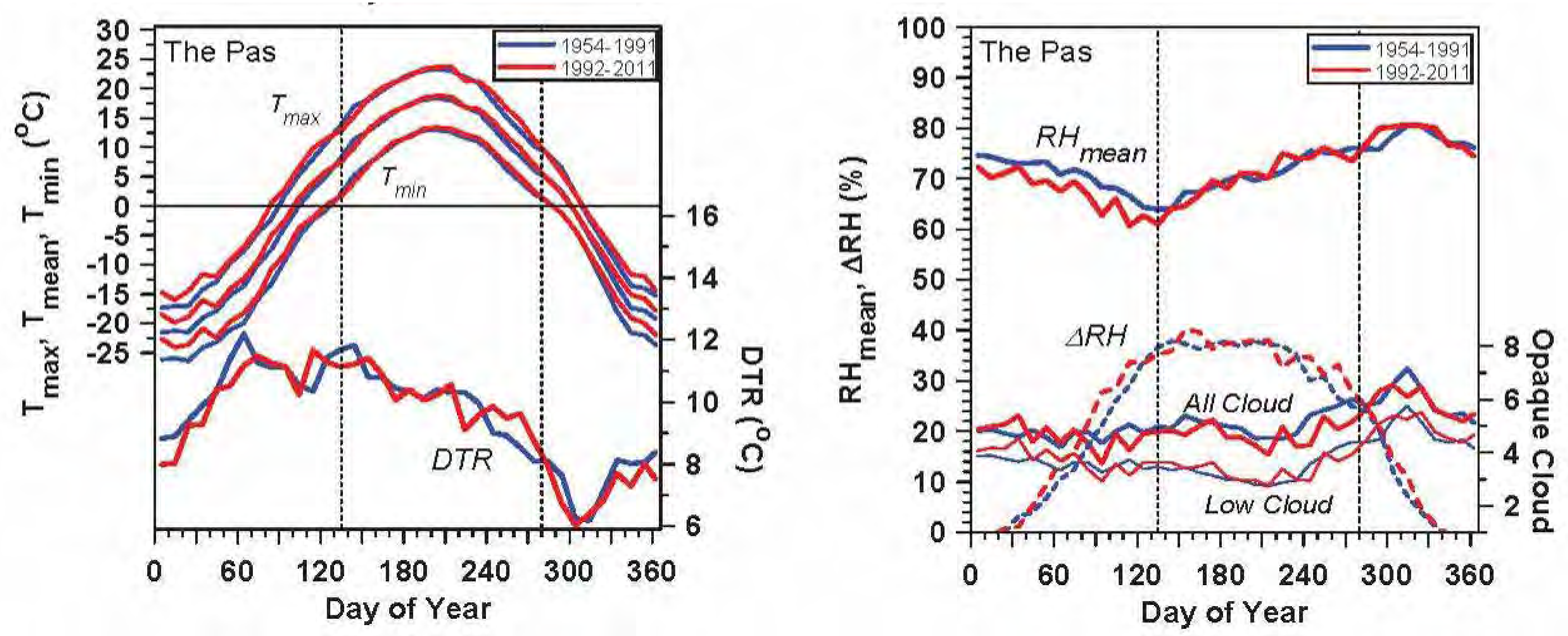
Impact on Convective Instability

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

- Opaque/reflective cloud
  - SWCF, LWCF → R_n
- Diurnal climate analysis of T, RH
  - Dominated by cloud/R_n
  - *BUT*: *Radiation only analysis*
  - Because no soil moisture → EF

Monthly, Seasonal, 50-yr Climate

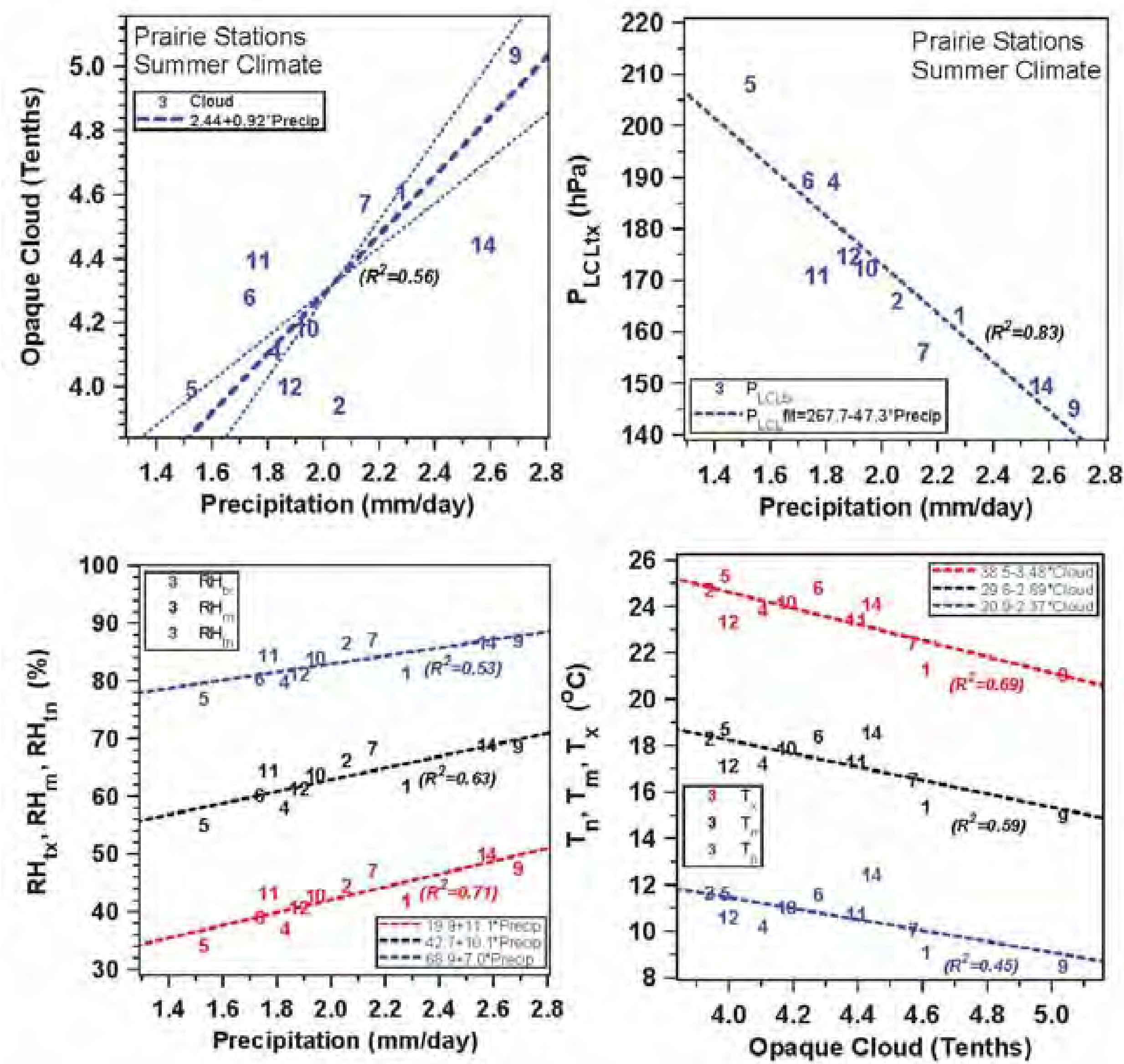
- Opaque/reflective cloud → R_n
- Precipitation linked to
  - Evaporation, soil moisture, EF
- Separate land-surface coupling?
  - YES, 50-yr climate coupling is
  - RH to precipitation and soil moisture
  - T to opaque cloud and R_n
- *Monthly timescale blended*

11 stations: 53-yr JJA climate

- **Precip to *(R^2)***
  - Cloud (0.56)
  - P_{LCLtx} (0.83)
  - RH_{tx} (0.71)

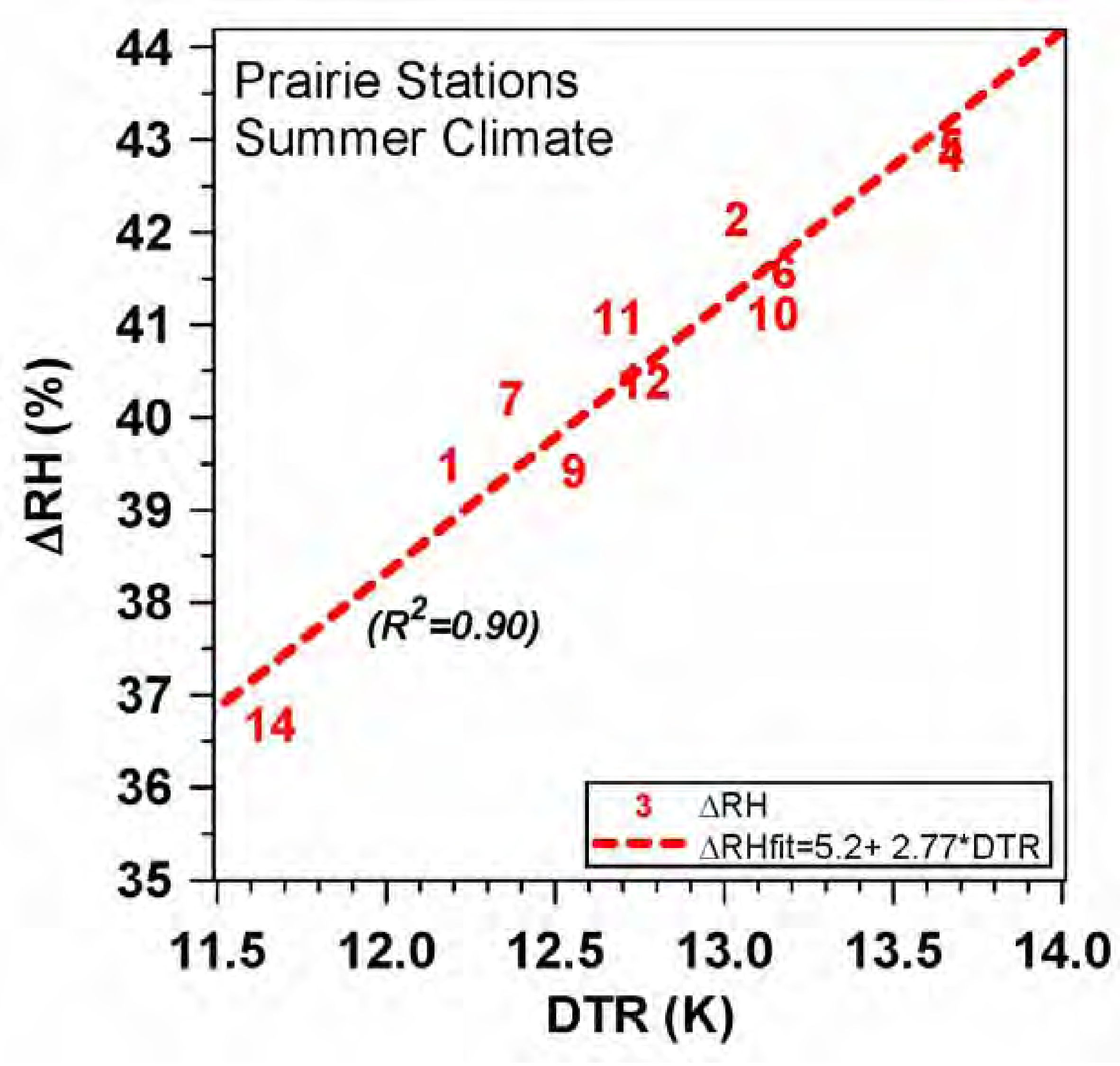
- **Cloud to**
  - T_x (0.69)

- **Separation**
- ***Month: blend***
- ***Daily: cloud***



Diurnal cycle tightly coupled

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



Monthly timescale: Regression

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

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

δDTR

	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**

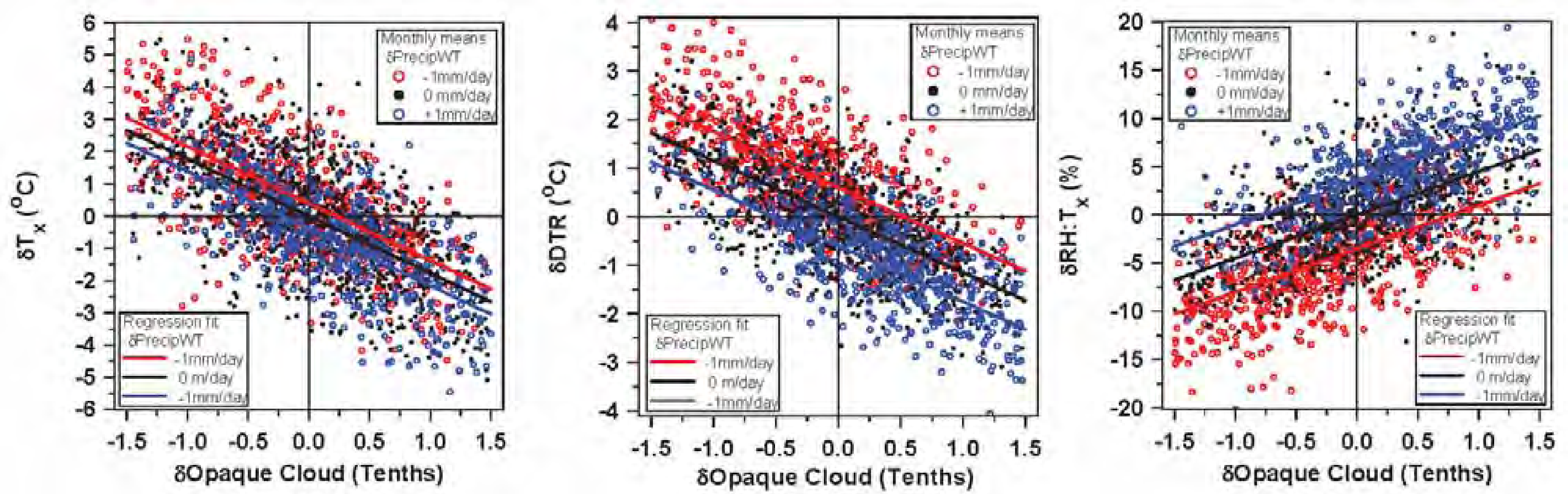
Monthly timescale: Regression

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

δRH_{tx}

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**	**0.66±0.11**	**1.23±0.13**	**2.42±0.16**	**4.08±0.20**	**0.73**	**0.53**	**0.56**
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)



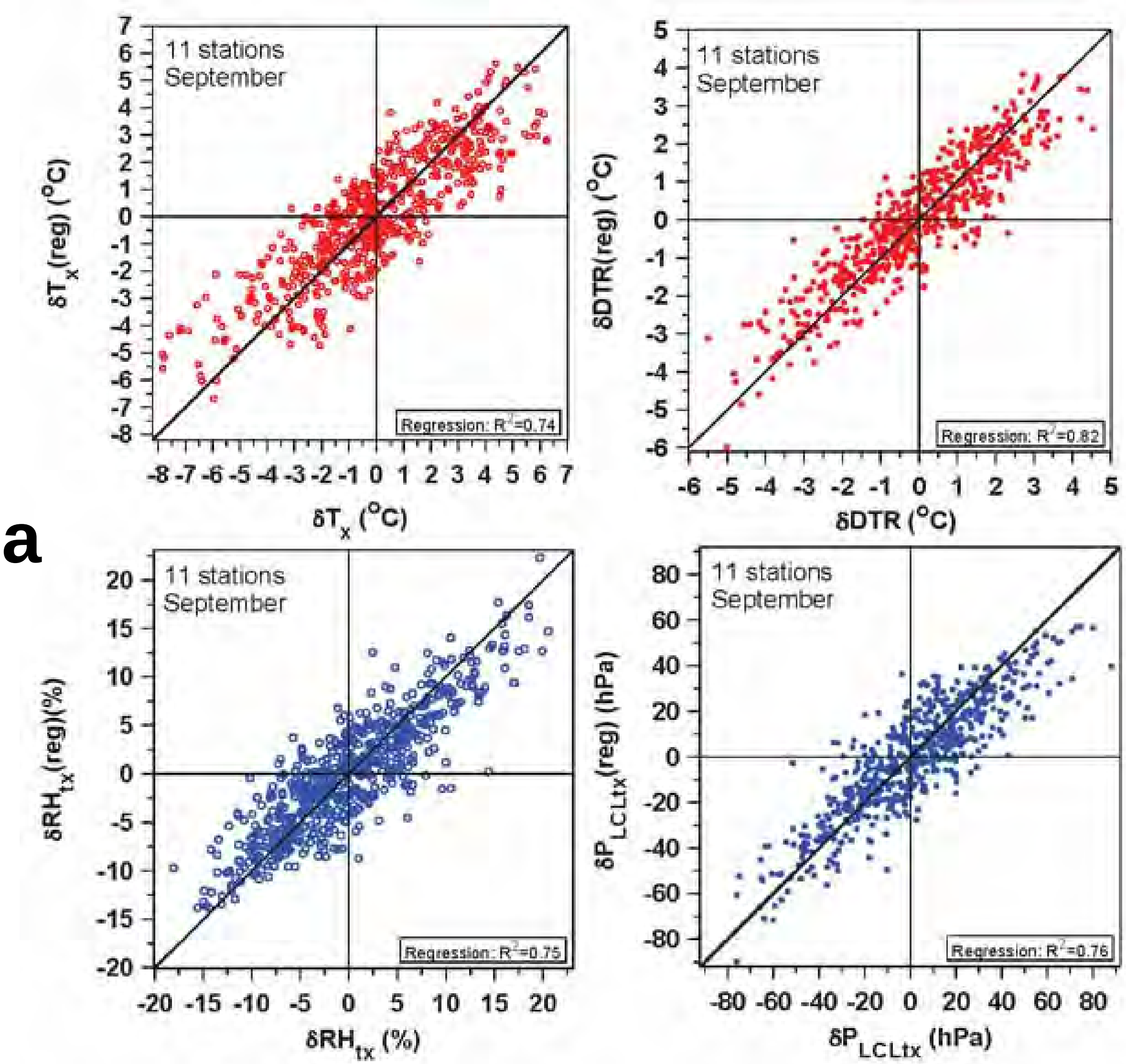
- Less cloudy and less rain (this month and last)
  - δT_x warmer (cloud mostly) ($R^2 = 0.55$)
  - δDTR larger (both) ($R^2 = 0.72$)
  - δRH drier (both) ($R^2 = 0.68$)

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**

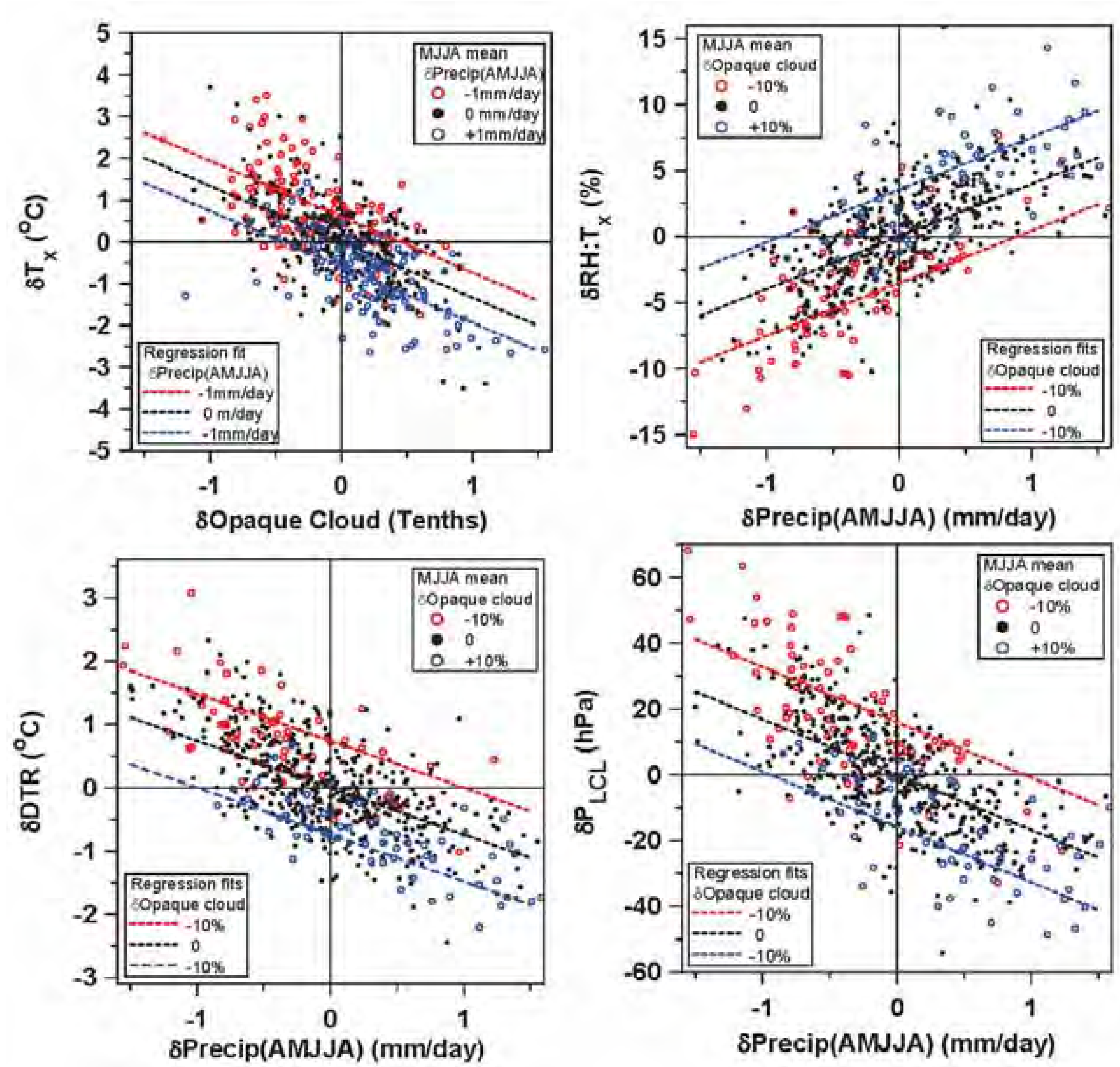
(586 station-yrs)



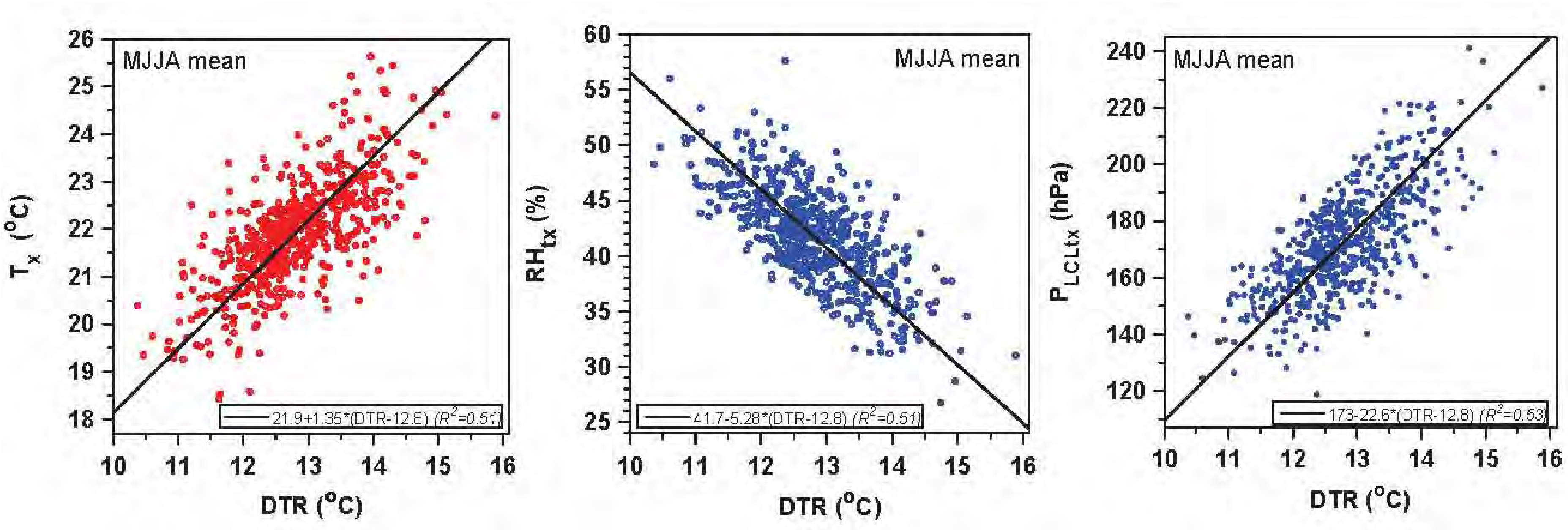
MJJA Mean: Regression Fit

Growing Season Means

δPrecip(AMJJA) =0.25*δPrecip(April) +δPrecip(MJJA)



Diurnal coupling: MJJA mean



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

MJJA Surface Water Balance

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

(R/P ≈ 0.05: (P-R) = 0.95P)

RH_x depends on δPrecip(AMJJA)

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

$$\Delta SM = \Delta SM_m + F^*\delta Precip(AMJJA)$$

where P_m = 1.92 mm/day

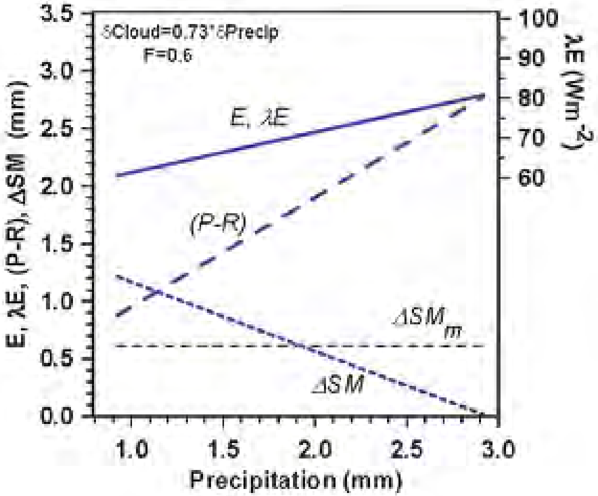
ΔSM_m= - 0.61 mm/day (75mm/122 days)

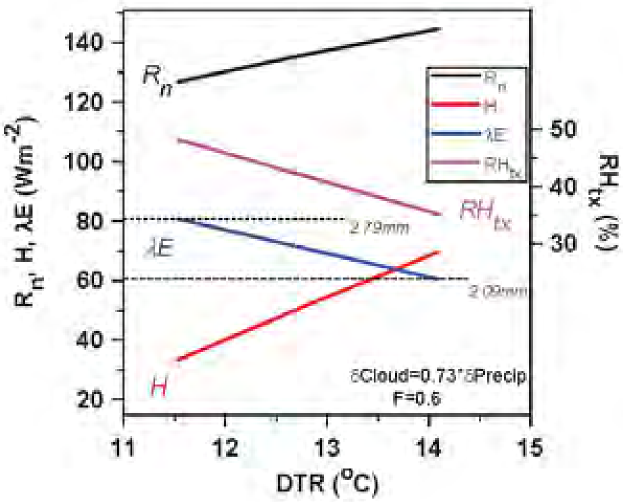
(Just an estimate)

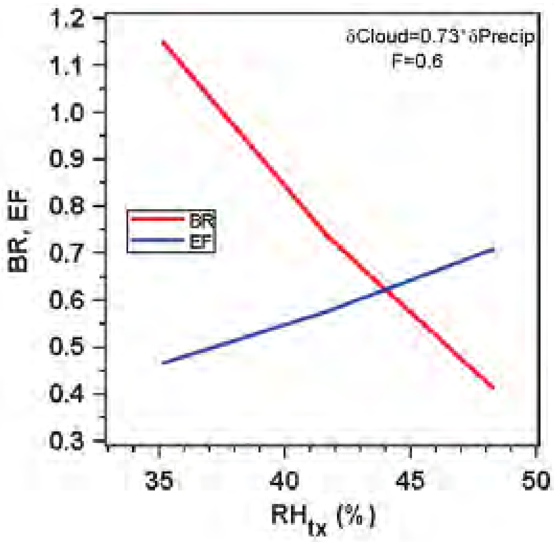
But F is unknown

- ***change of ΔSM with precipitation anomalies***
- ***damps impact of precipitation anomalies***

Energy and Water "Budget"







- ***Start with cloud and precip. anomalies***
  - ***Gives anomalies of T, RH***
  - ***Gives R_n anomalies***
- ***Close with assumptions***
  - ***Climate coupling of cloud to precip. (0.73)***
  - ***F = 0.6: soil water extraction heavily damped by precip. anomalies***

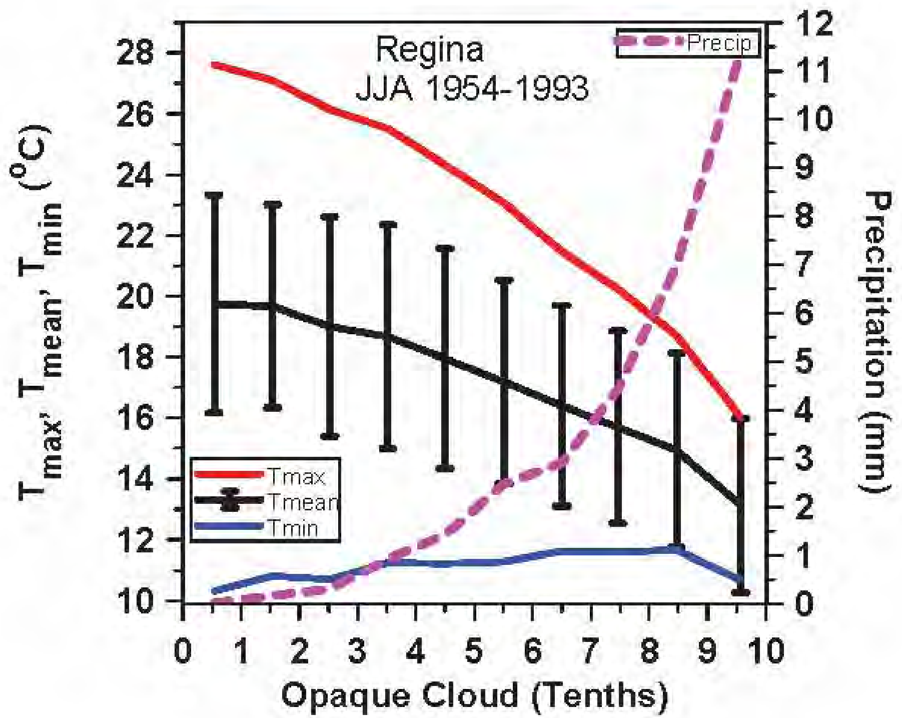
Summary (Part 2)

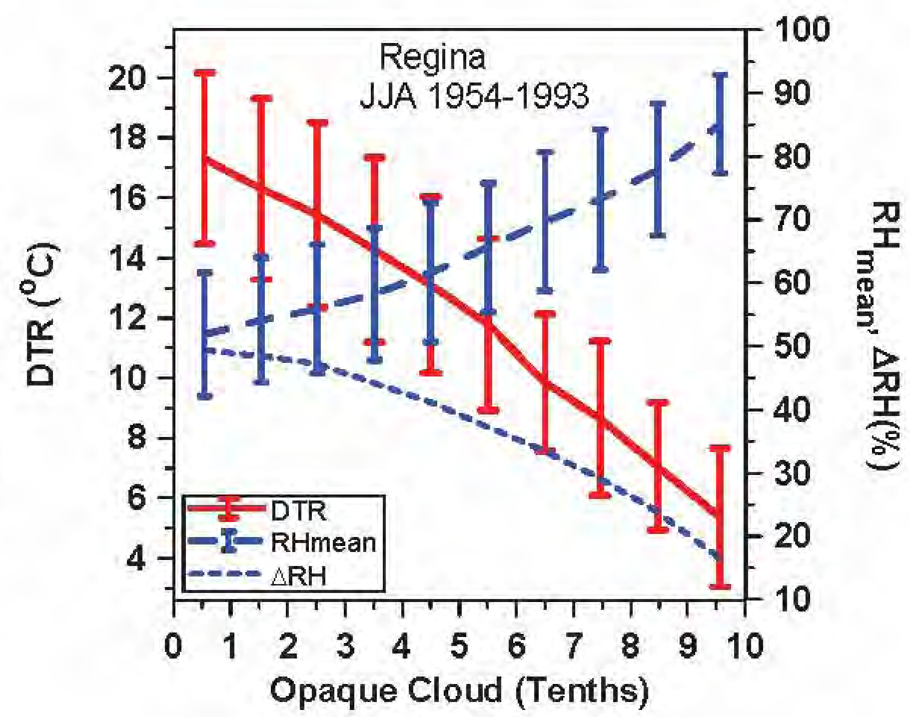
- ***High quality dataset with <u>Opaque cloud</u>***
  - ***Estimate SWCF, LWCF and R_n***
- **Map coupling of T, RH climate anomalies**
  - **To cloud on daily time-scale**
  - **To cloud and precip. on monthly/seasonal**
- **Dependence splits for 50-yr climate**
  - **T depends on cloud/radiation**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

- ***Estimate evaporation anomalies***
  - ***Feedback to daily timescale***

Papers at http://alanbetts.com

Summer Diurnal Cycle Climate

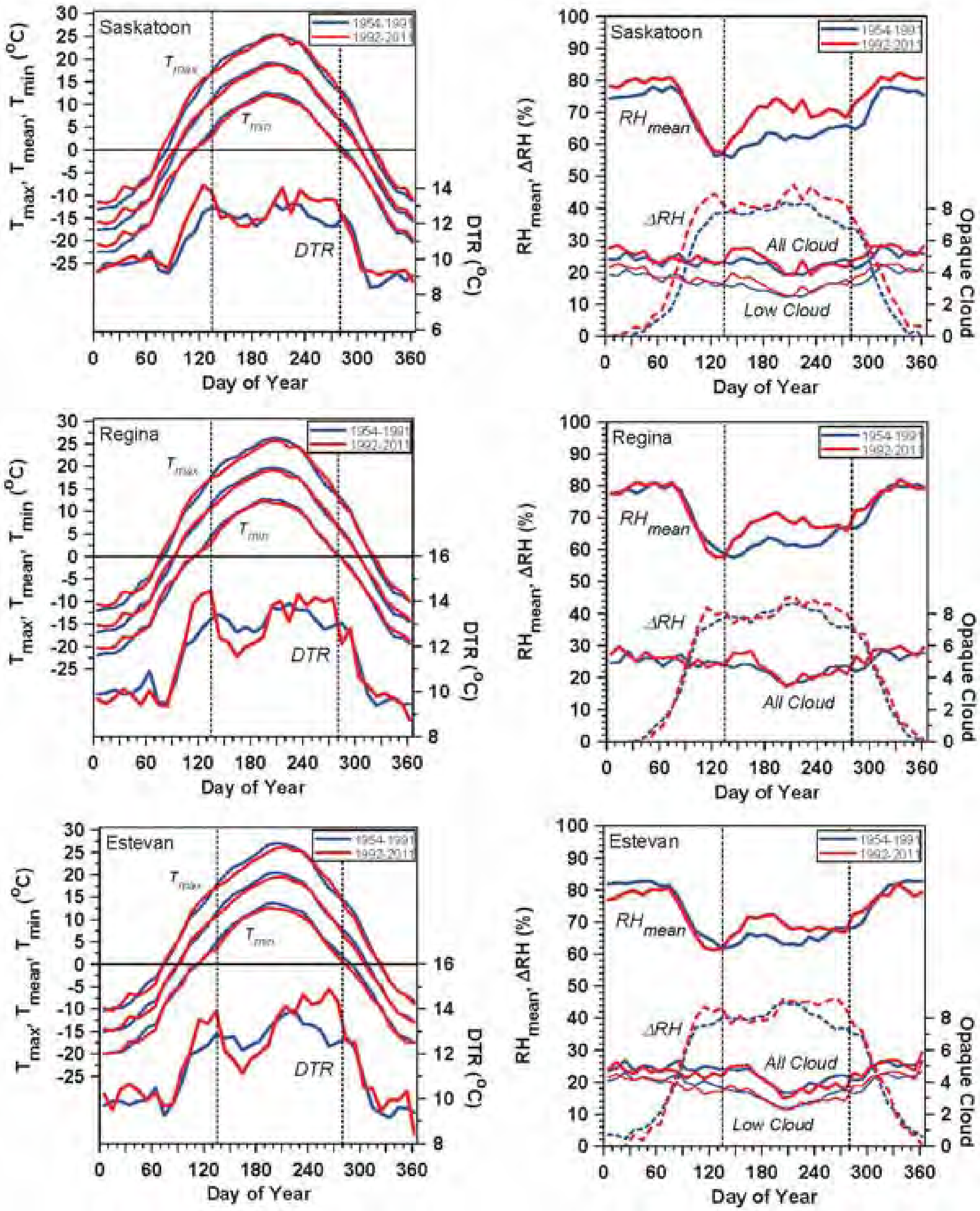




- ***Climate emerges from daily variability***
- **Cloud increases, precipitation increases**
- **T_{max}, DTR increase, T_{min} flat**
- **RH_{mean} increases, ΔRH decreases**

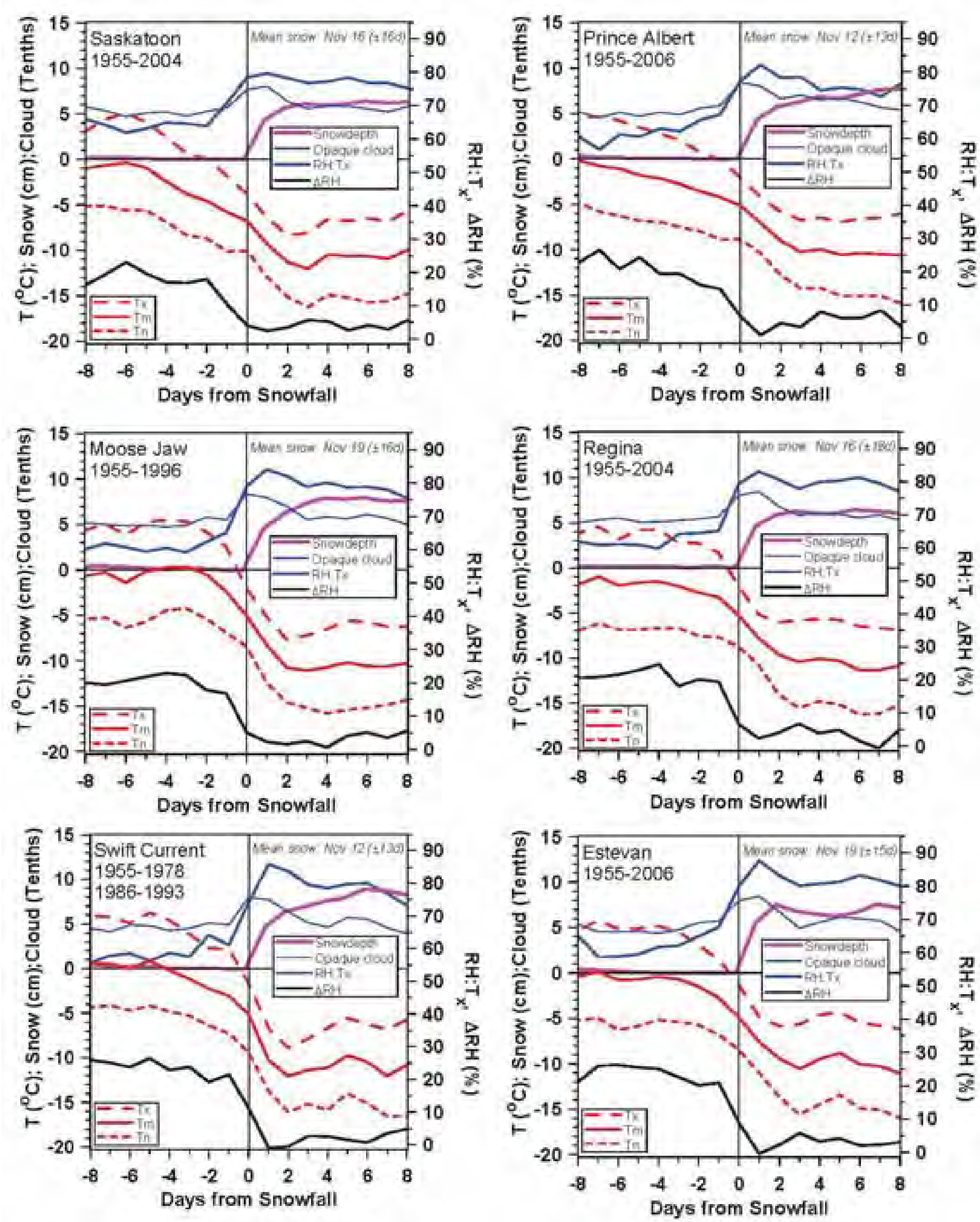
Diurnal Climate Change

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



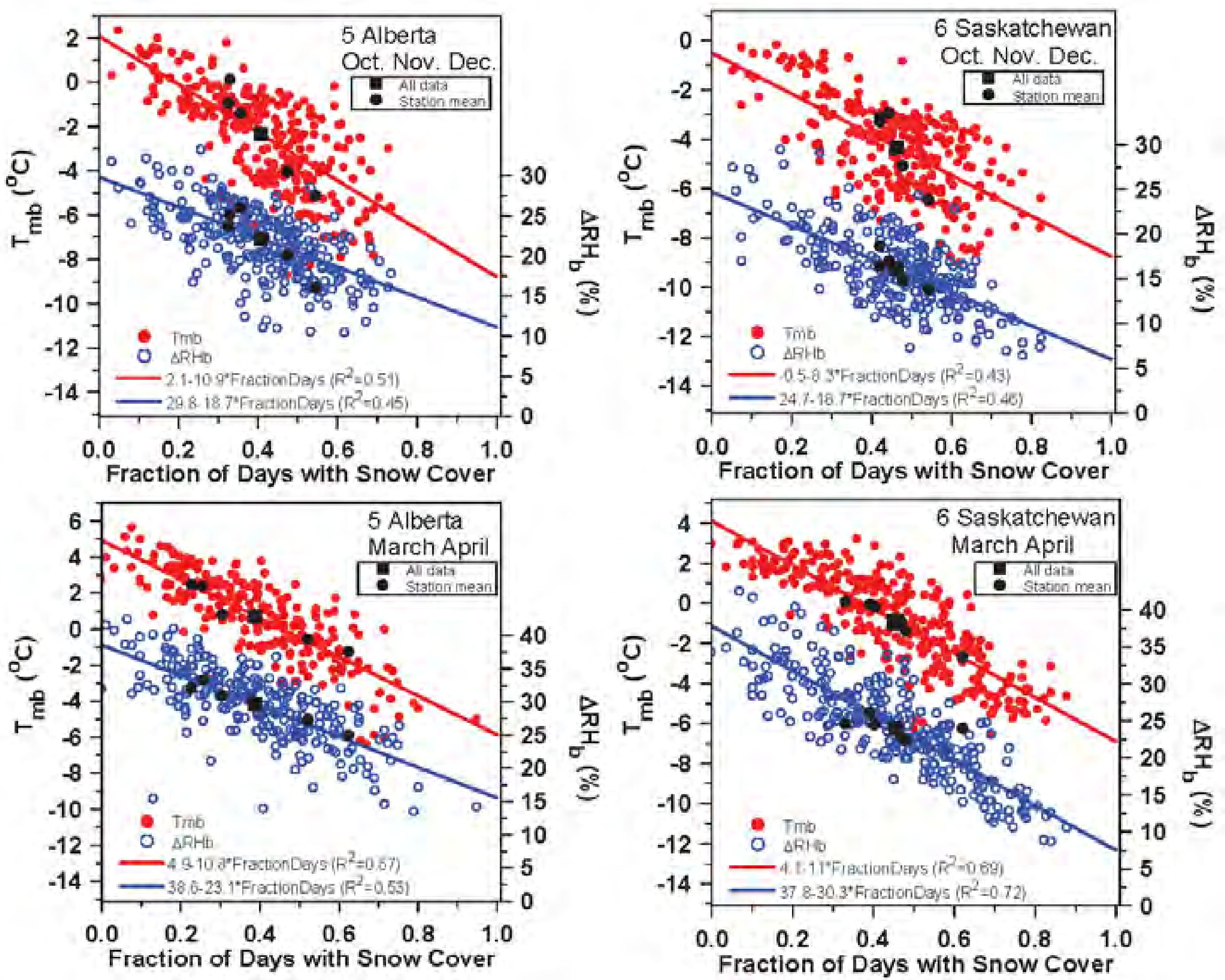
6 Stations in Saskatchewan

- 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**



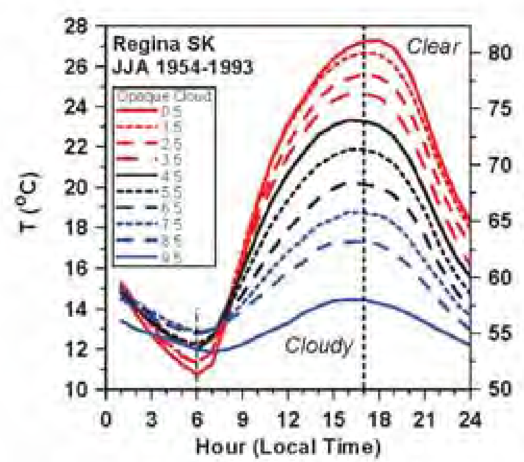
Daily Mean Climate vs Long-term Diurnal Mean

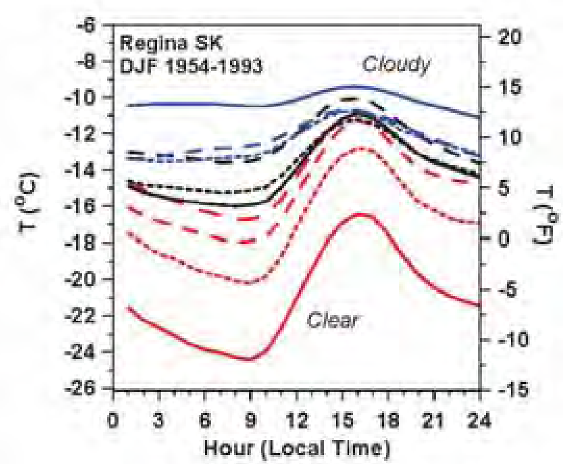
- *Definitions*
  - **DTR = T_x - T_n**
  - **ΔRH = RH:T_x – RH:T_n**

Monthly mean diurnal cycle

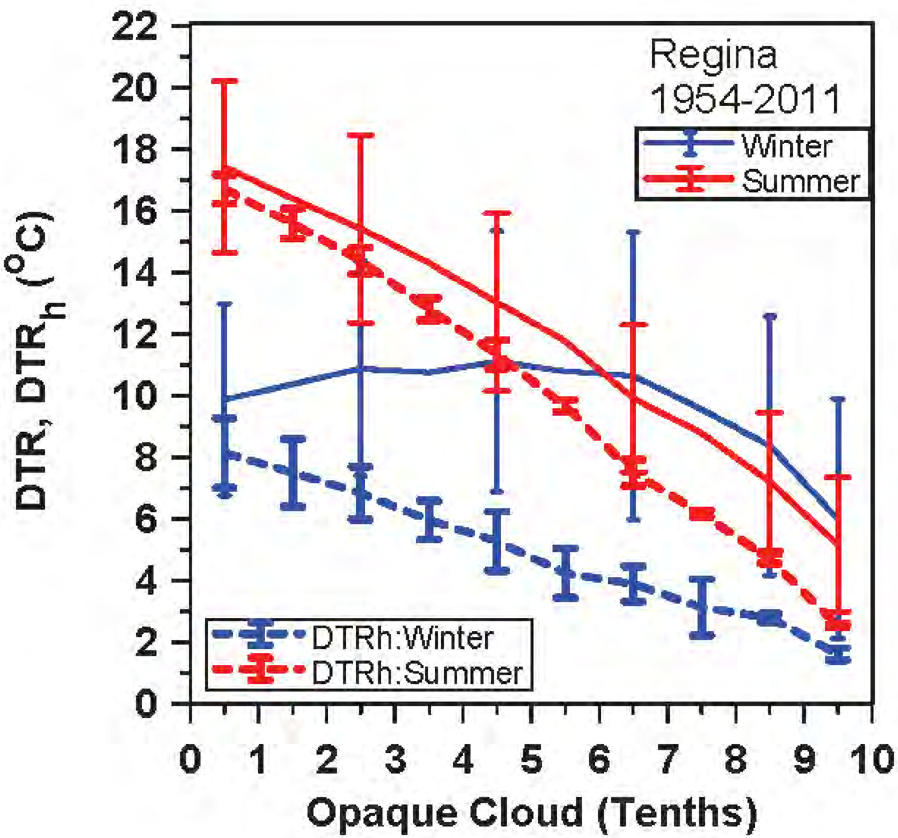
  - **DTR_h = T_{xh} – T_{nh}**
  - **ΔRHh = RH_{xh} – RH_{nh}**

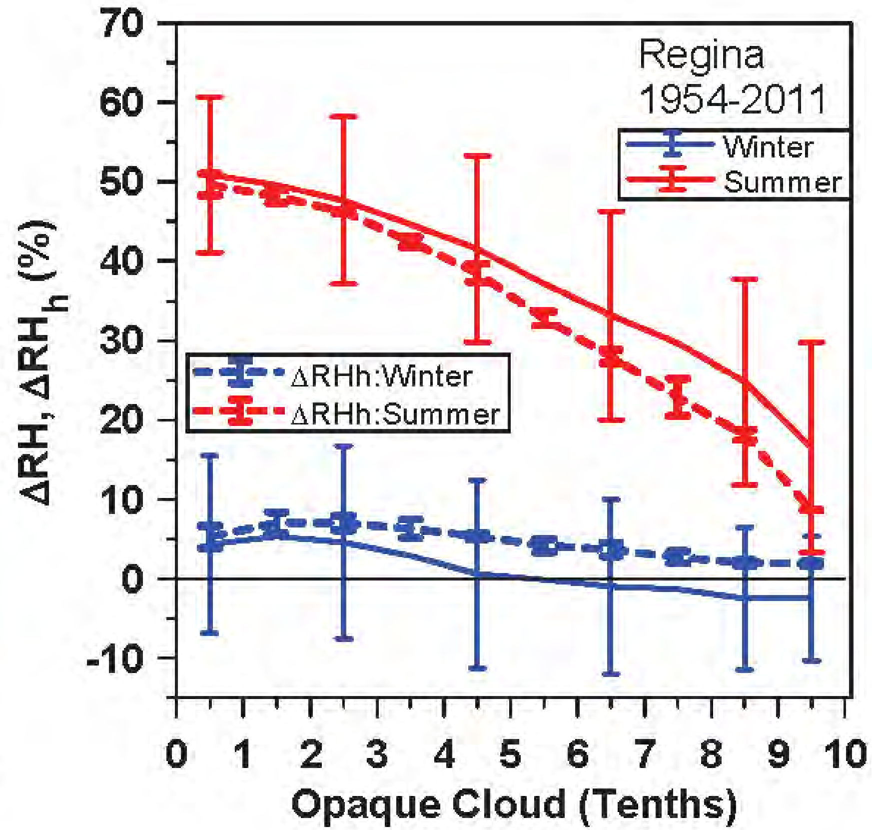
Radiatively forced signal small in winter compared to daily advection





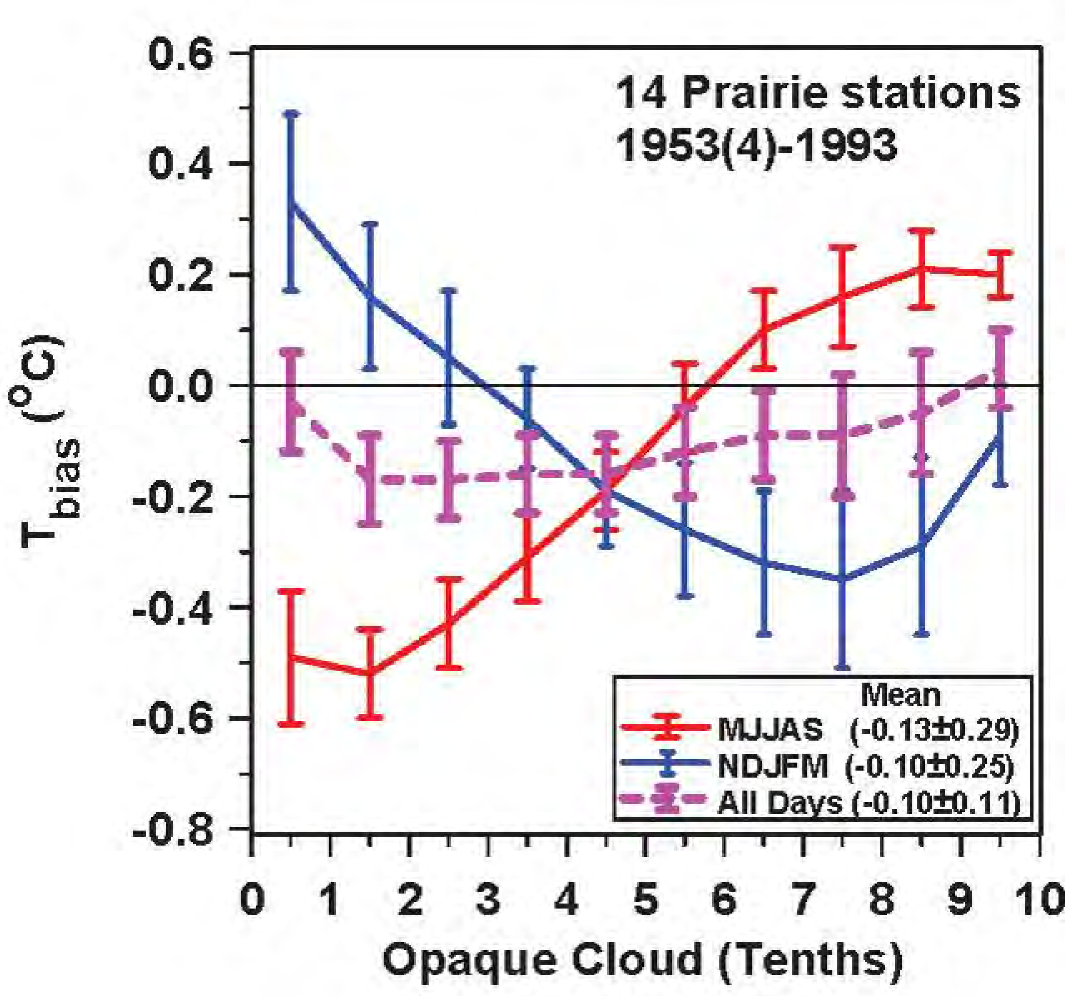
Daily Mean Climate vs Monthly Diurnal Mean Climate





- **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**