

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

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“Water in the Climate System”

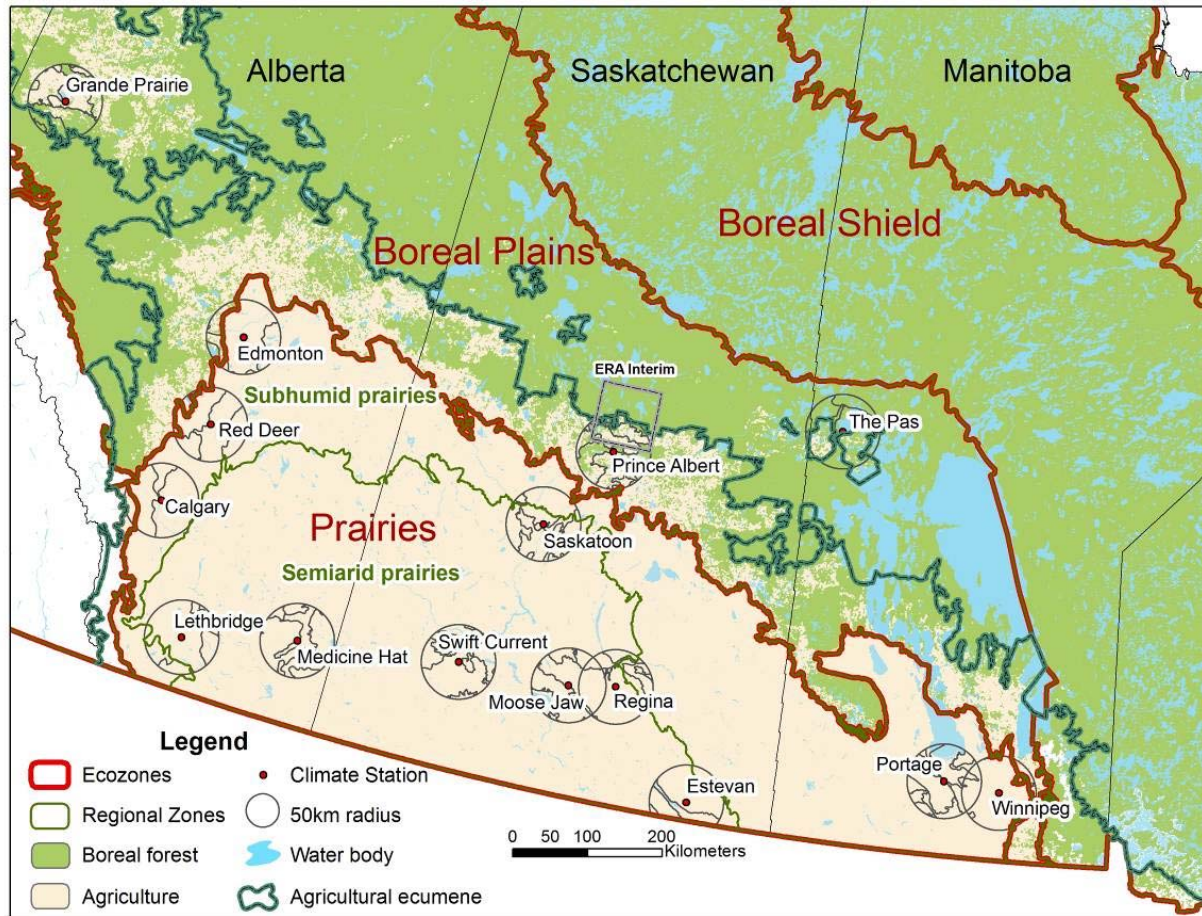
MIT Endicott House

Feb 12, 2014

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

- **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)*
- [*Betts et al. 2014b: Coupling of temperature and humidity to precipitation and cloud cover in the growing season*]

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. Cerkowski (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

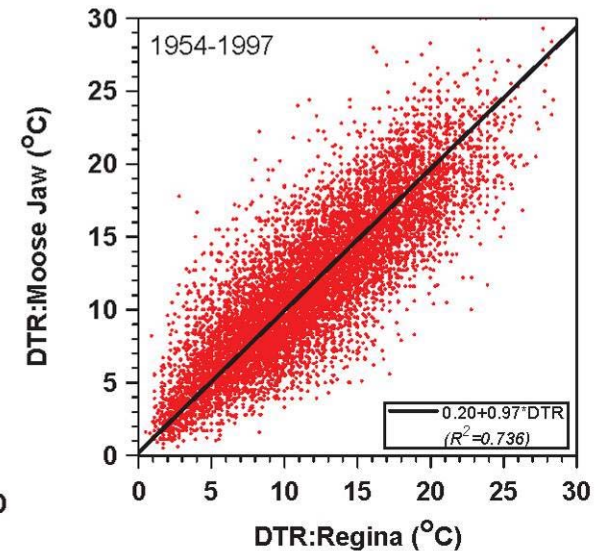
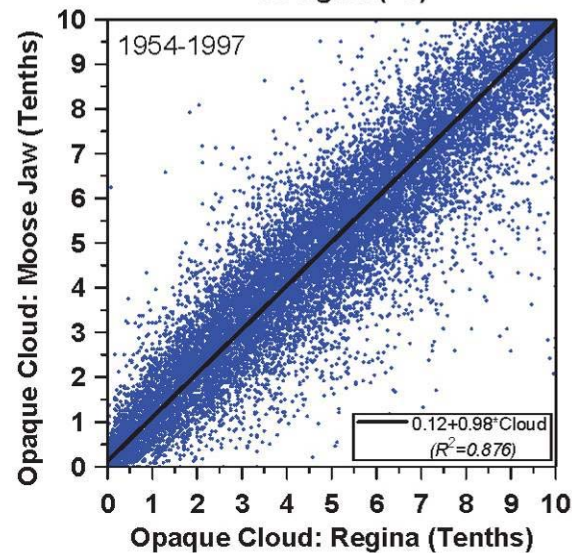
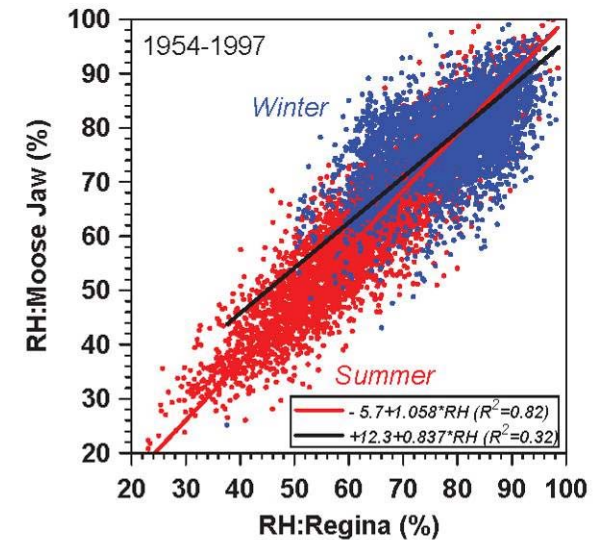
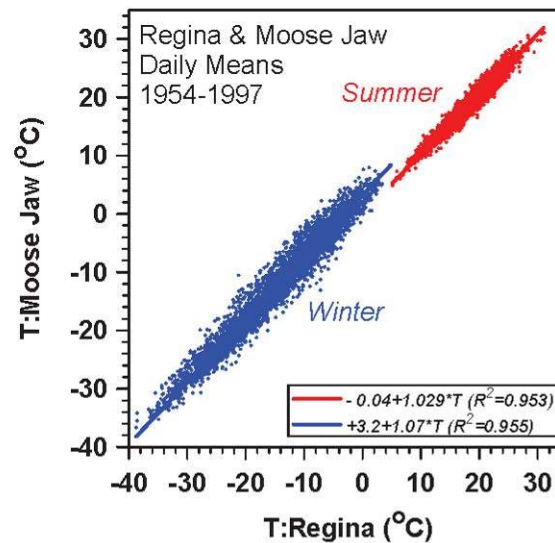
- *Seasonal diurnal climate by station/region*
- **220,000 days of excellent data (600 years)**
- Composite by **daily mean opaque cloud**
 - Calibrate SWCF, LWCF against radiation data
- Change of seasonal climate with **cropping**
 - ‘Summerfallow’ to annual crops on 5MHa in 30 yrs
- Composite across **snow transitions**
 - First snow in fall; spring melt of snowpack
 - Winter climate and % days snow cover

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*
 - $\text{DTR} = T_{\text{max}} - T_{\text{min}} \quad (T_x - T_n)$
 - $\Delta\text{RH} = \text{RH}:T_x - \text{RH}:T_n$
- *Almost no missing hourly data (until recent government cutbacks!)*

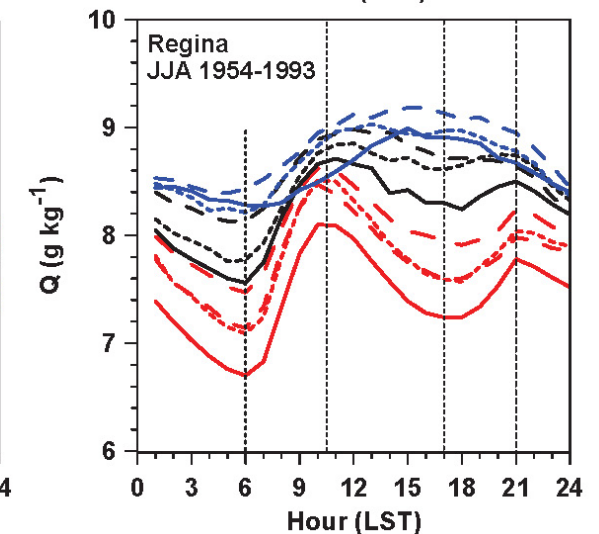
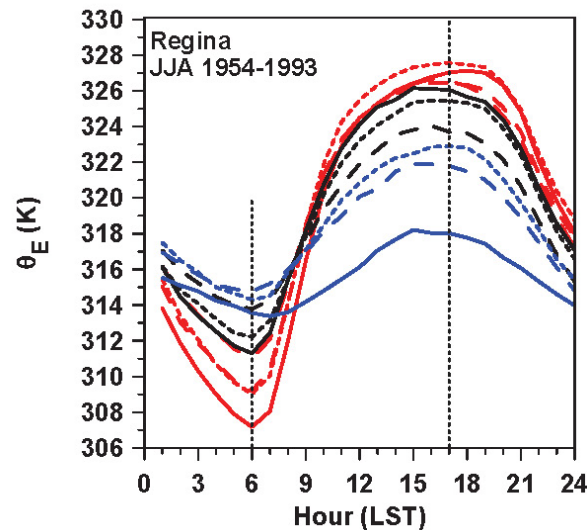
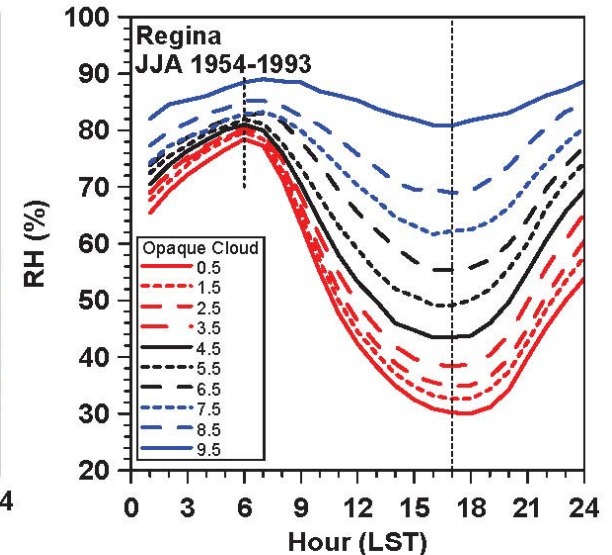
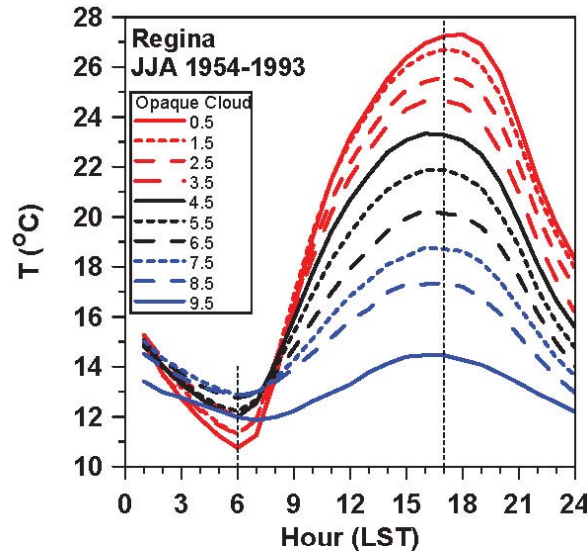
Compare Neighbors: 64 km

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



Clouds to Summer Diurnal Cycle

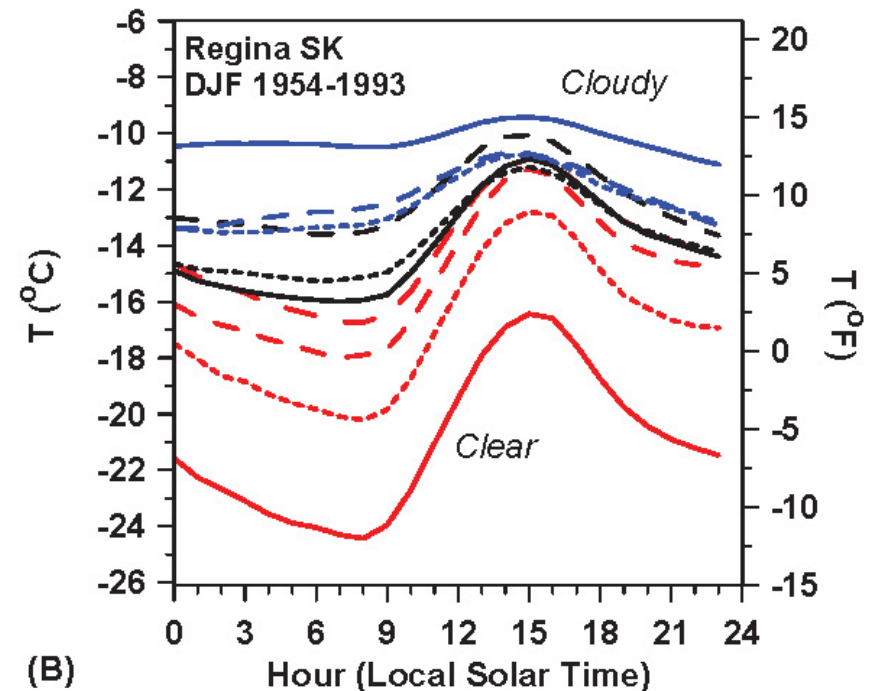
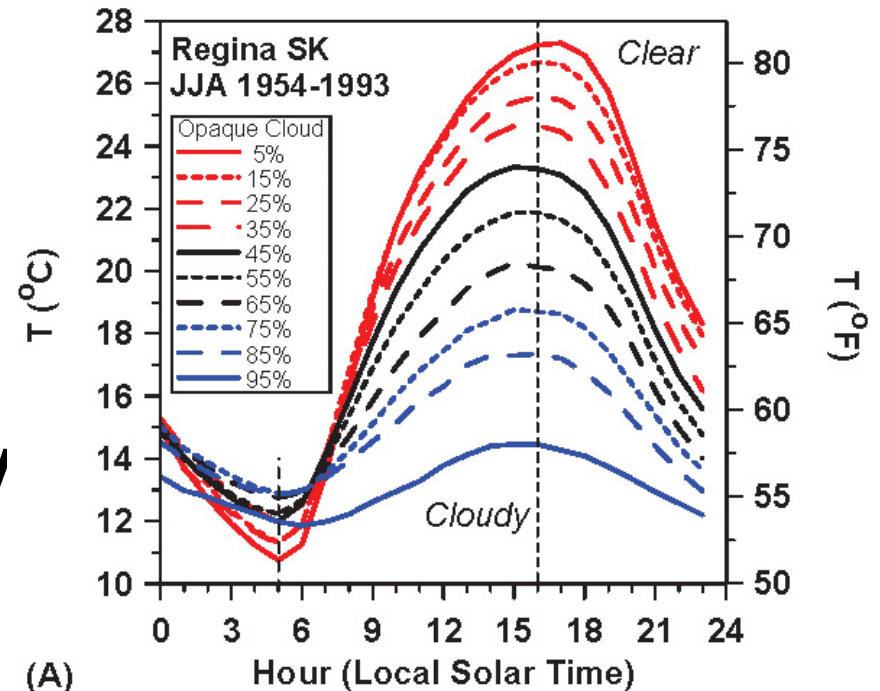
- *40-yr climate*
- T and RH are inverse
- Q has double maximum for BL transitions
- θ_E flatter
- *Overcast (rain) only outlier*



Cloud Impacts

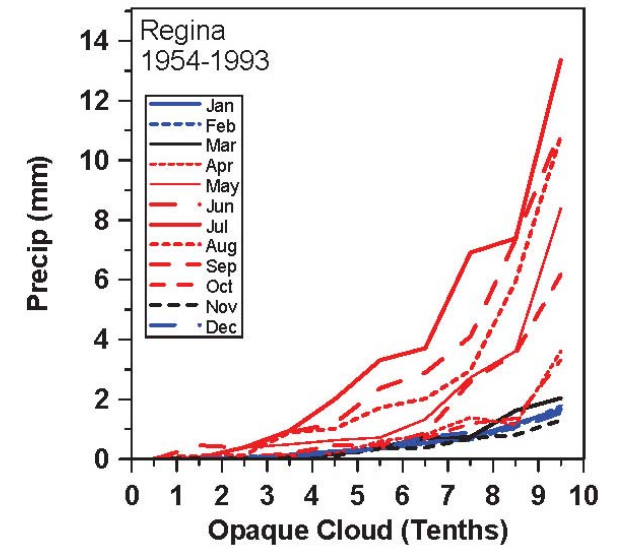
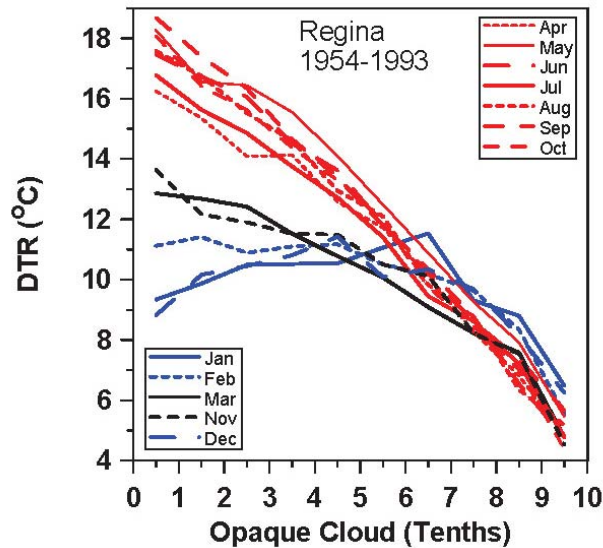
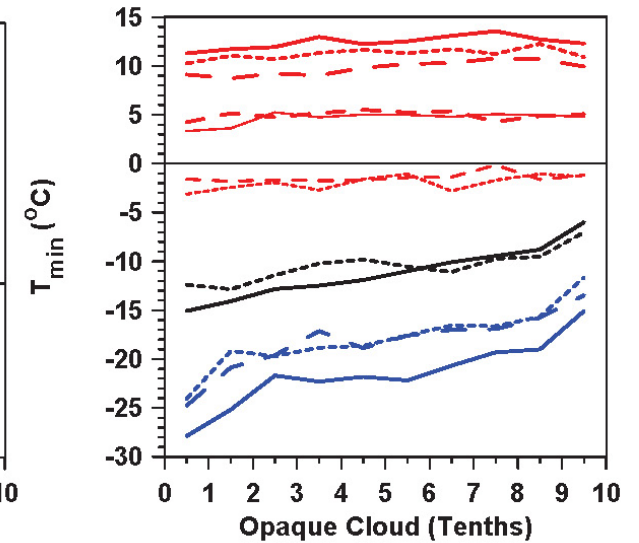
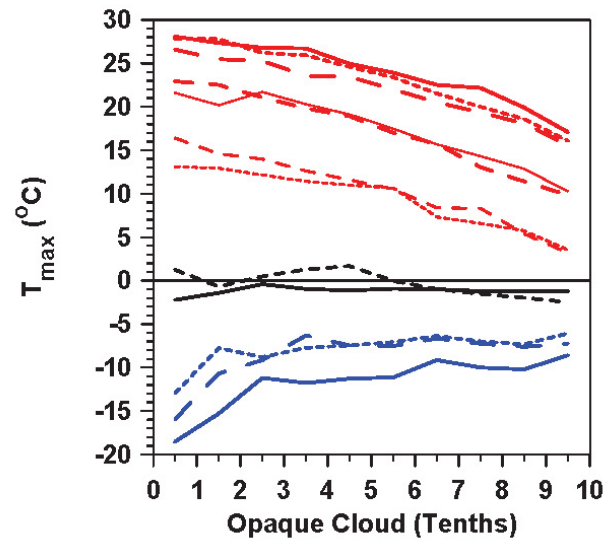
- **Summer:** Clouds reflect sunlight
 - no cloud, hot days; only slightly cooler at night
- **Winter:** Clouds are greenhouse
 - snow reflects low sun
 - clear & dry sky, cold days, very cold nights
- *Fast transition with snow in 5 days*

Betts et al. 2013



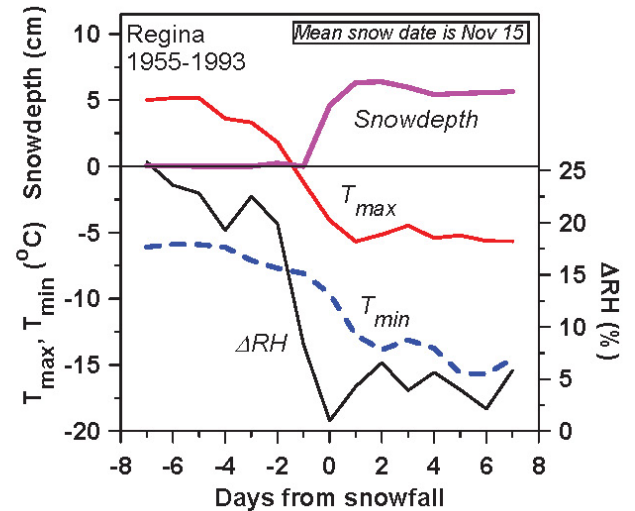
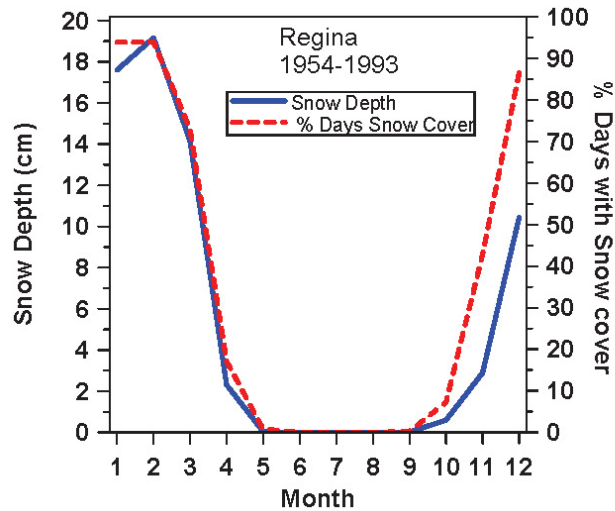
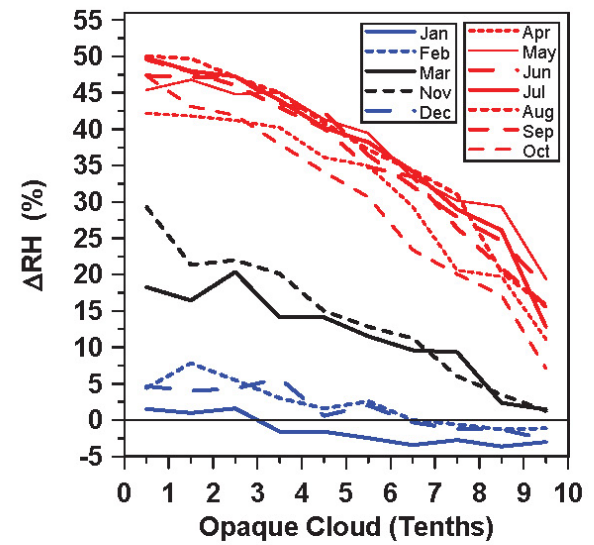
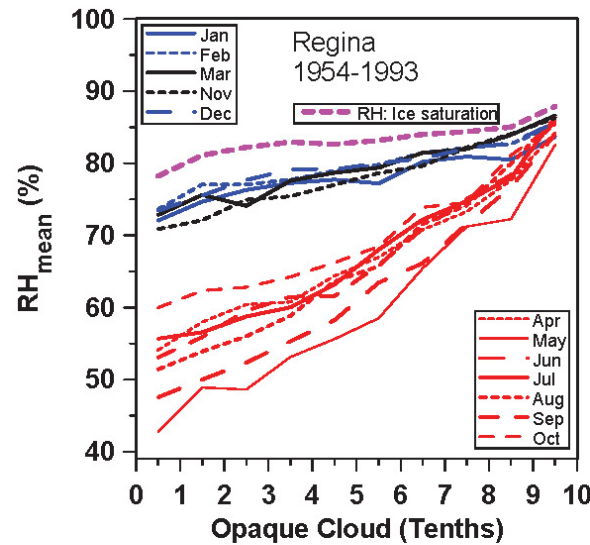
Annual Cycle: T_{\max} , T_{\min} , DTR, Precip

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

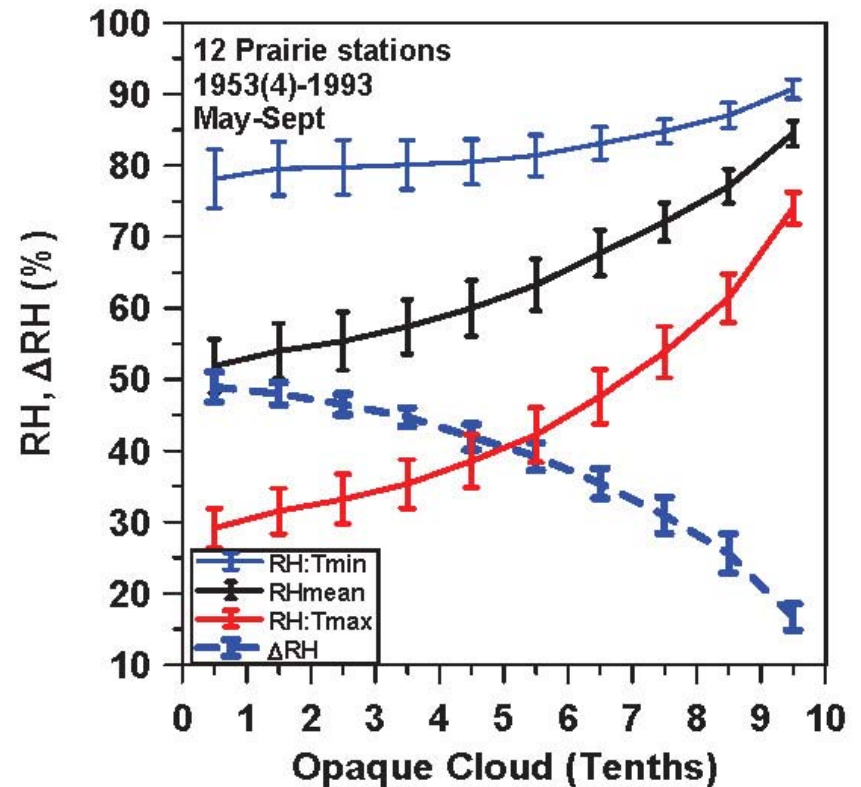
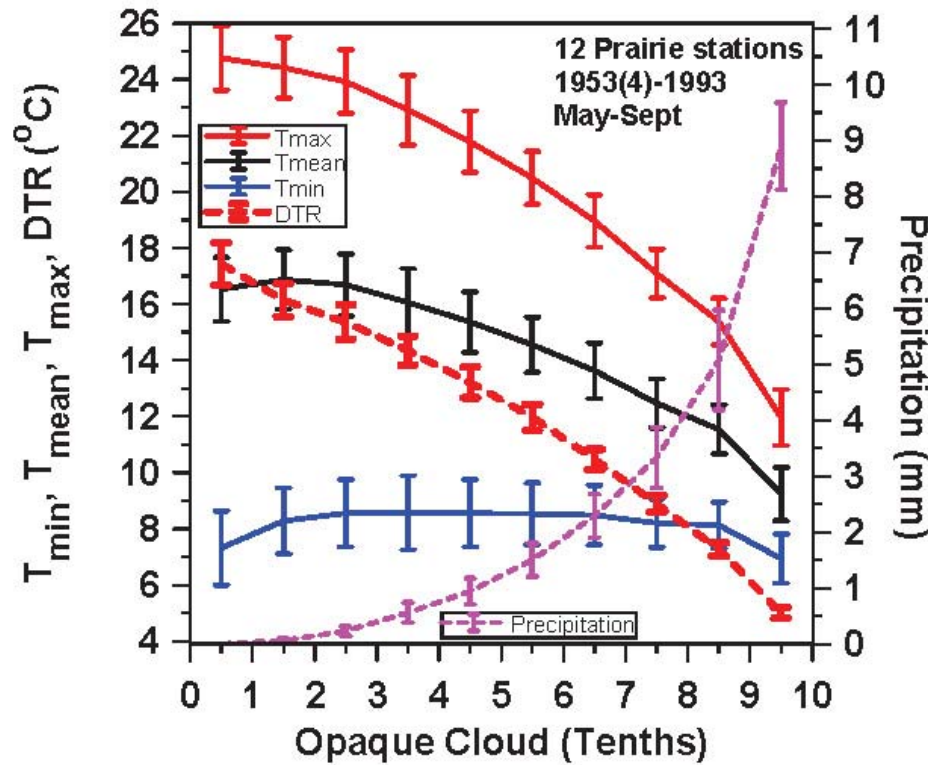


Annual Cycle: RH and ΔRH

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



Prairie Warm Season Climate



- 12 stations: *Uniform climatology*
- Tiny variability in DTR and ΔRH

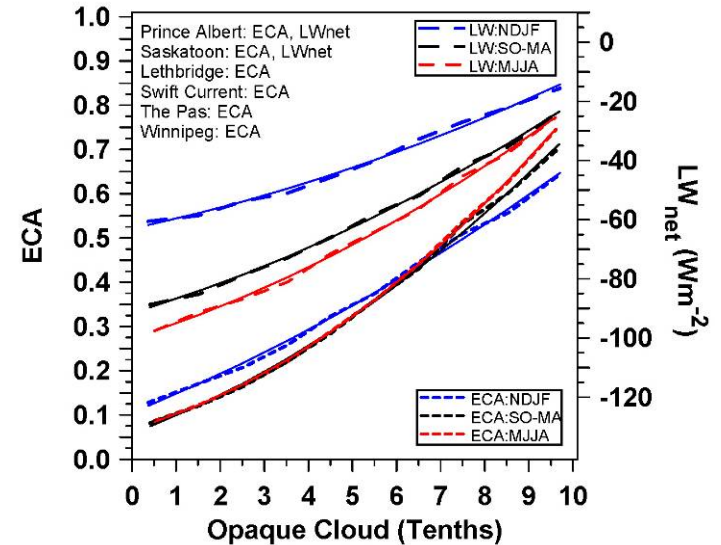
Surface Radiation Budget

- $R_{\text{net}} = SW_{\text{net}} + LW_{\text{net}}$
 $= (SW_{\text{dn}} - SW_{\text{up}}) + (LW_{\text{dn}} - LW_{\text{up}})$

Define Effective Cloud Albedo (reflection)

- $ECA = (SW_{\text{dn}}(\text{clear}) - SW_{\text{dn}}) / SW_{\text{dn}}(\text{clear})$
Clear sky
- $SW_{\text{net}} = (1 - \alpha_s)(1 - ECA) SW_{\text{dn}}(\text{clear})$
Reflected by surface, clouds
MODIS *Calibrate Opaque Cloud data*

Fit ECA and LW_{net} to Opaque Cloud



NDJF: $ECA = 0.1056 + 0.0404 \text{ Cloud} + 0.00158 \text{ Cloud}^2$

SO-MA: $ECA = 0.0588 + 0.0365 \text{ Cloud} + 0.00318 \text{ Cloud}^2$

MJJA: $ECA = 0.0681 + 0.0293 \text{ Cloud} + 0.00428 \text{ Cloud}^2$

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

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

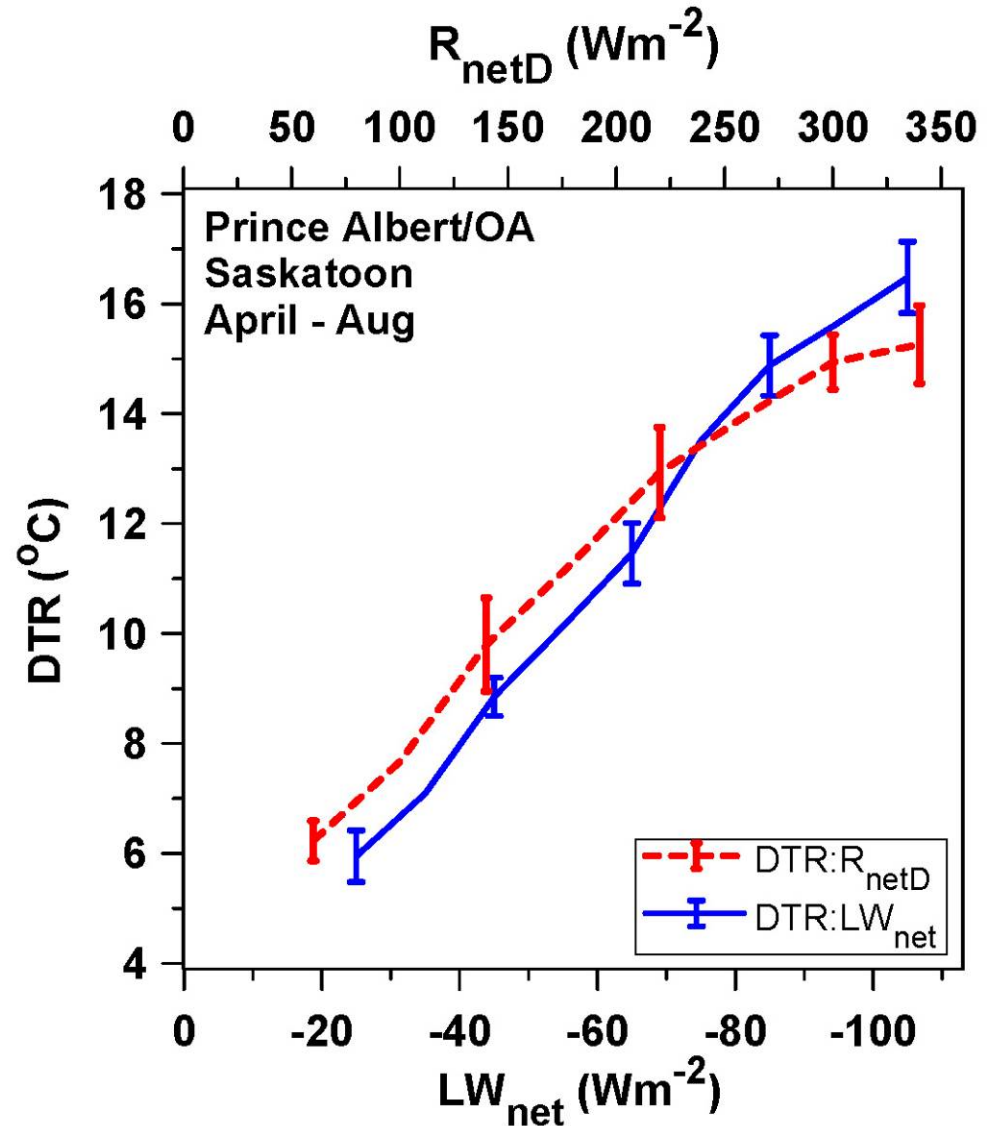
SO-MA: $LW_{net} = -91.5 + 4.43 \text{ Cloud} + 0.267 \text{ Cloud}^2$

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

Diurnal Temperature Range

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

(Betts JGR 2006)

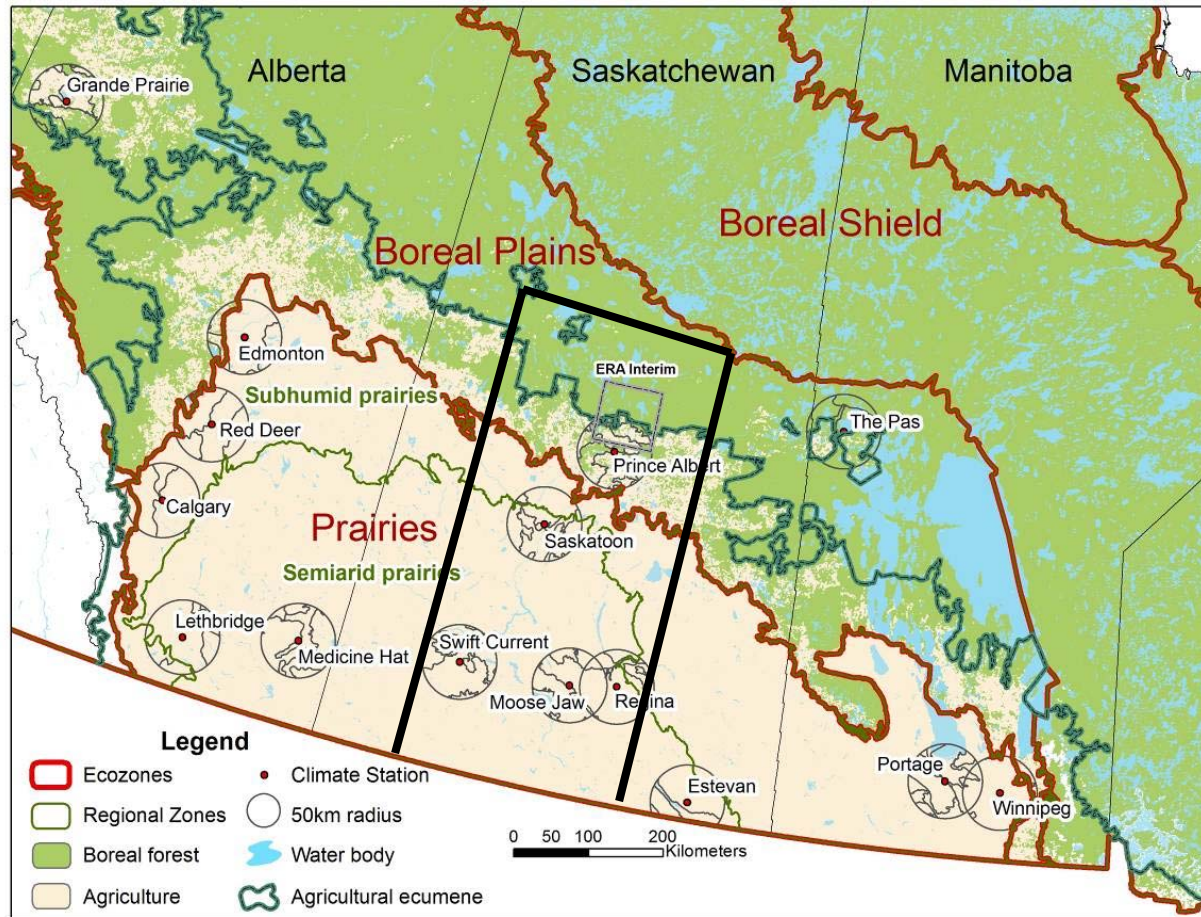


Impact of Snow on Climate

“*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’

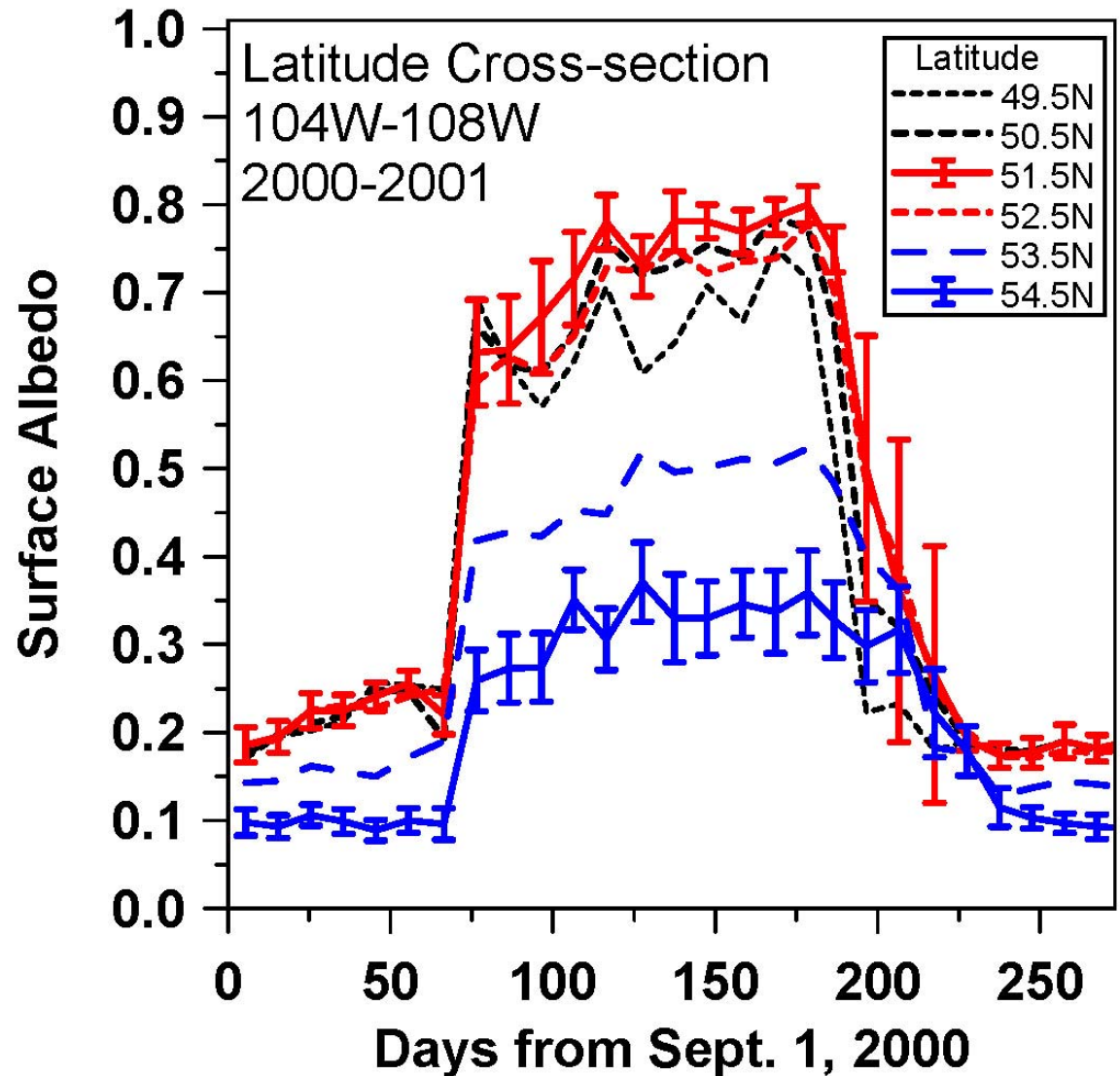
14 Prairie stations: 1953-2011



- 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)

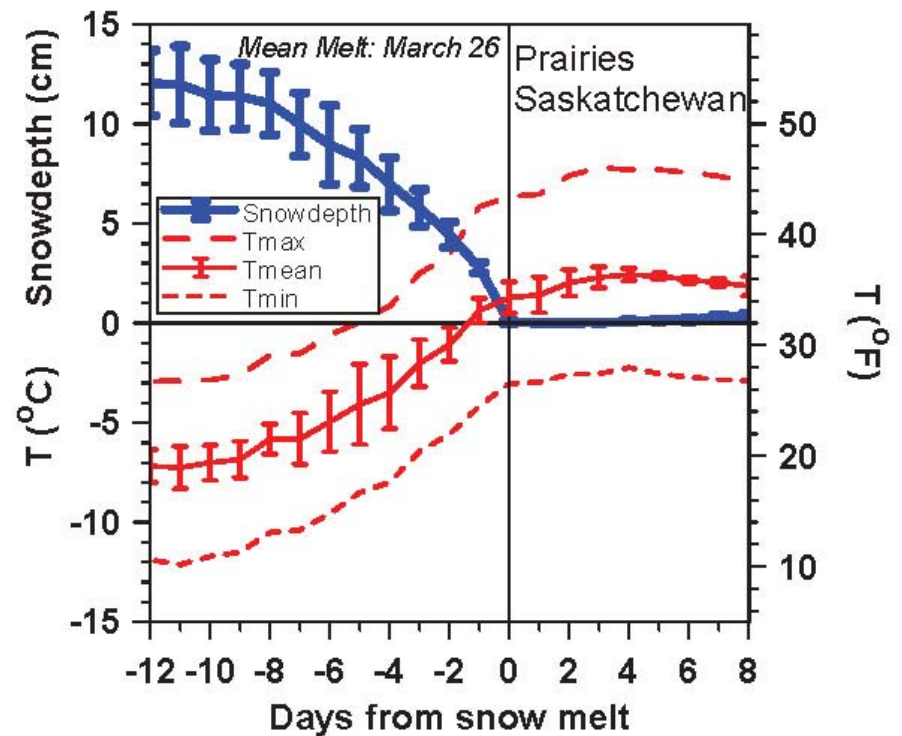
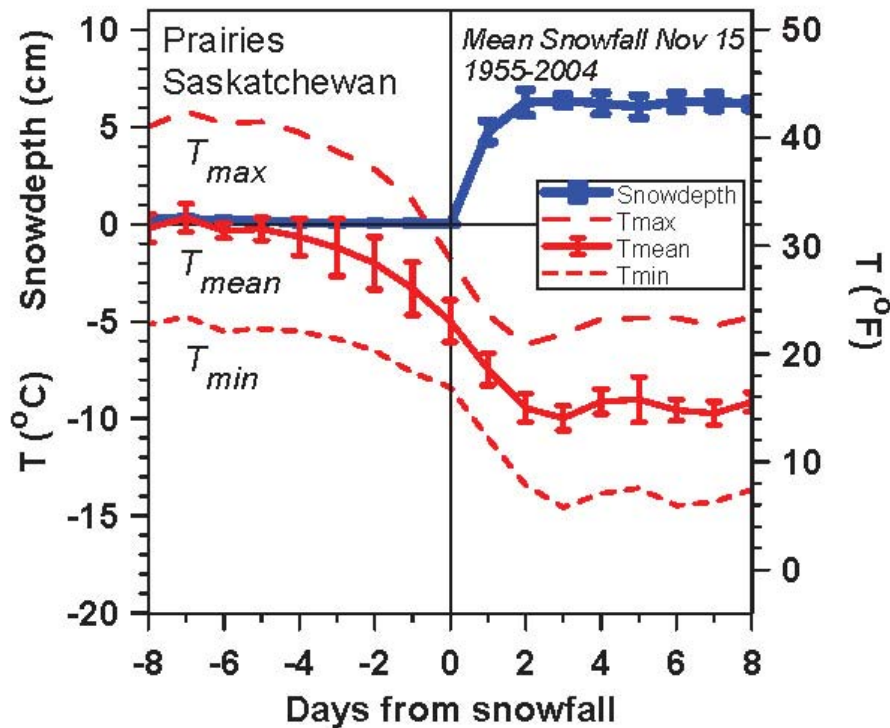
N-S Albedo through Winter

- **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



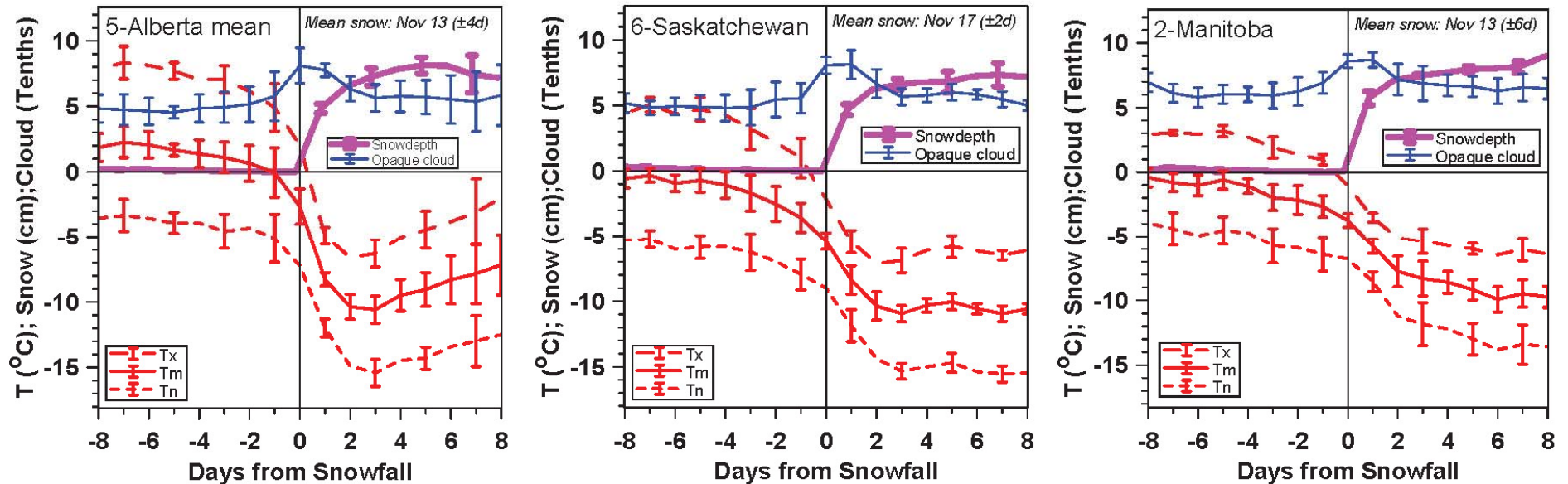
Snowfall and Snowmelt

Winter and Spring transitions



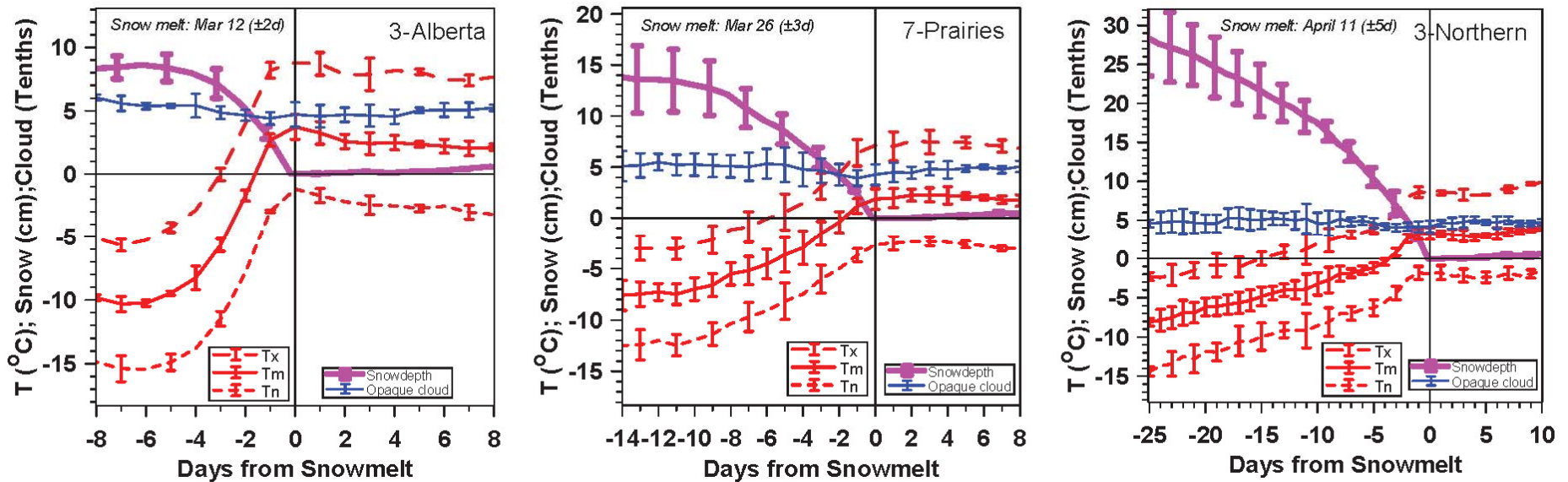
- Temperature falls/rises about 10K with first snowfall/snowmelt
- **Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms ‘local climate’**
 - Same feedbacks that are speeding Arctic ice melt in summer
 - Local climate switch between warm and cold seasons

Fall Snow Transition Climatology



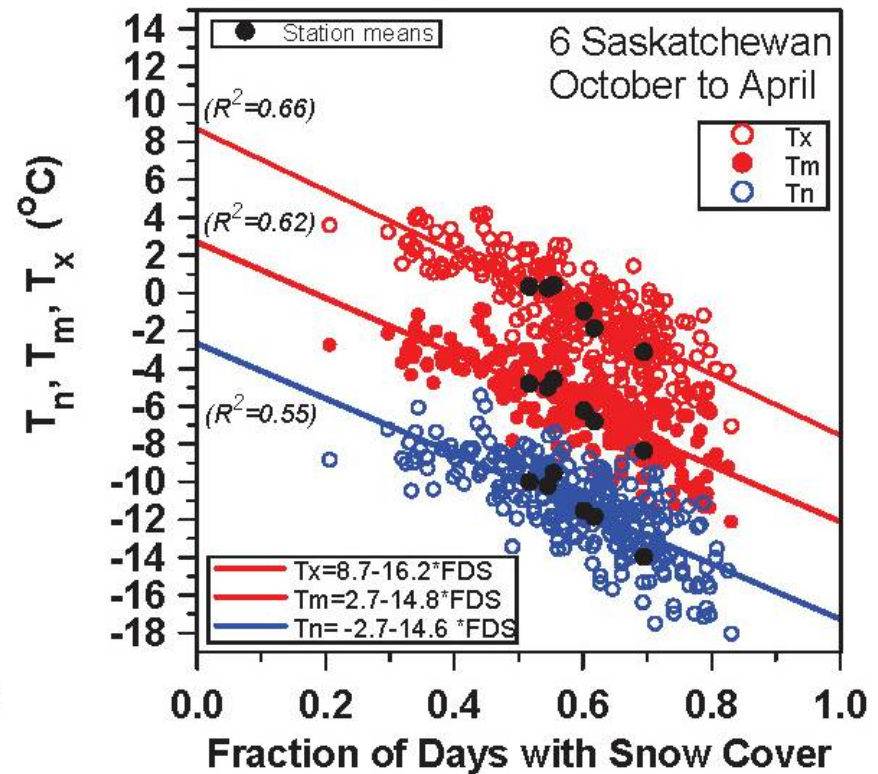
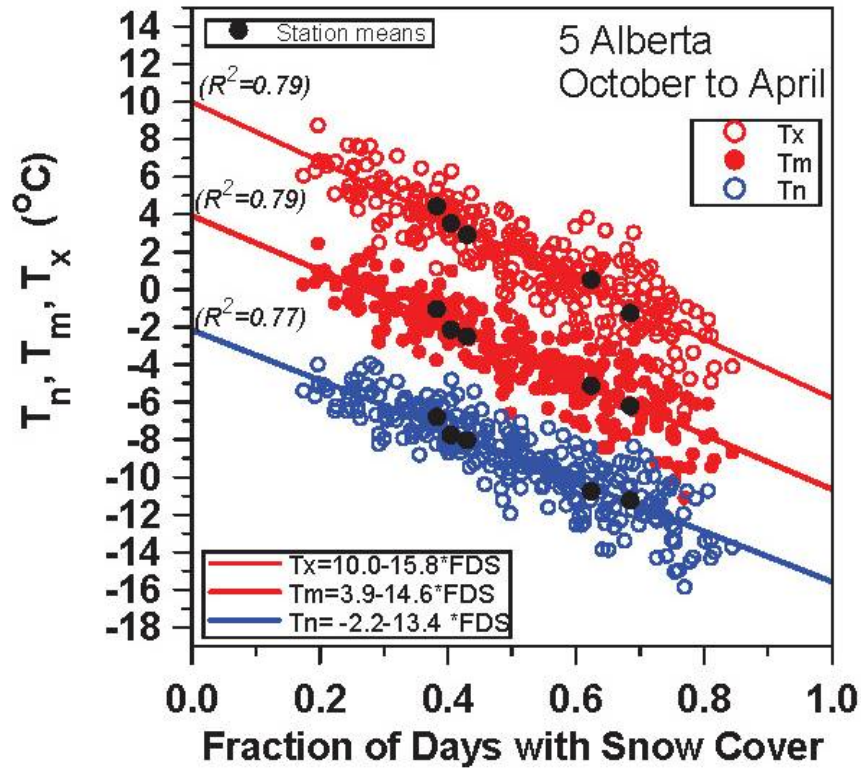
- T_x , T_m , T_n fall about 10K
- Cloud peaks with snow; increases $\approx 10\%$
- Snow date: Nov 15 \pm 3 days

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

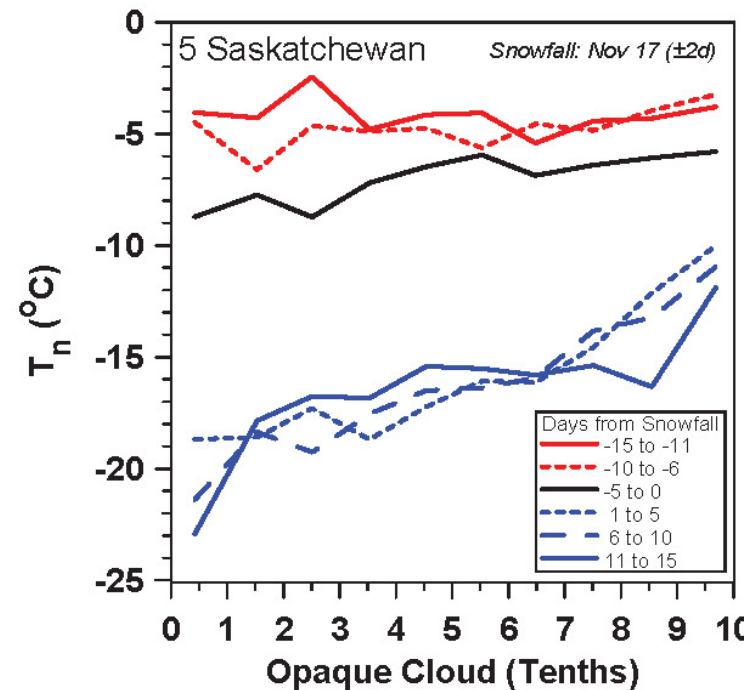
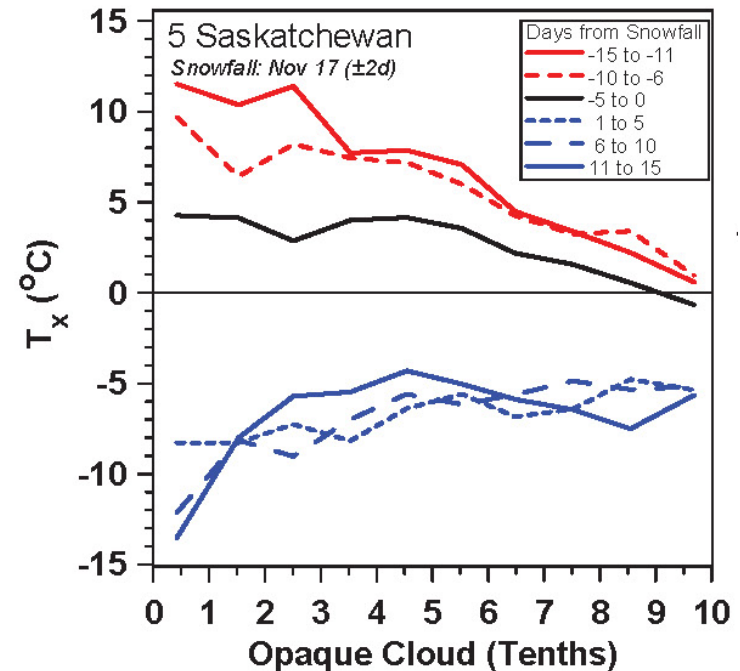


- Alberta: 79% of variance
- Slopes
 - T_x -16.0 (± 0.6) K
 - T_m -14.7 (± 0.6) K
 - T_n -14.0 (± 0.7) K

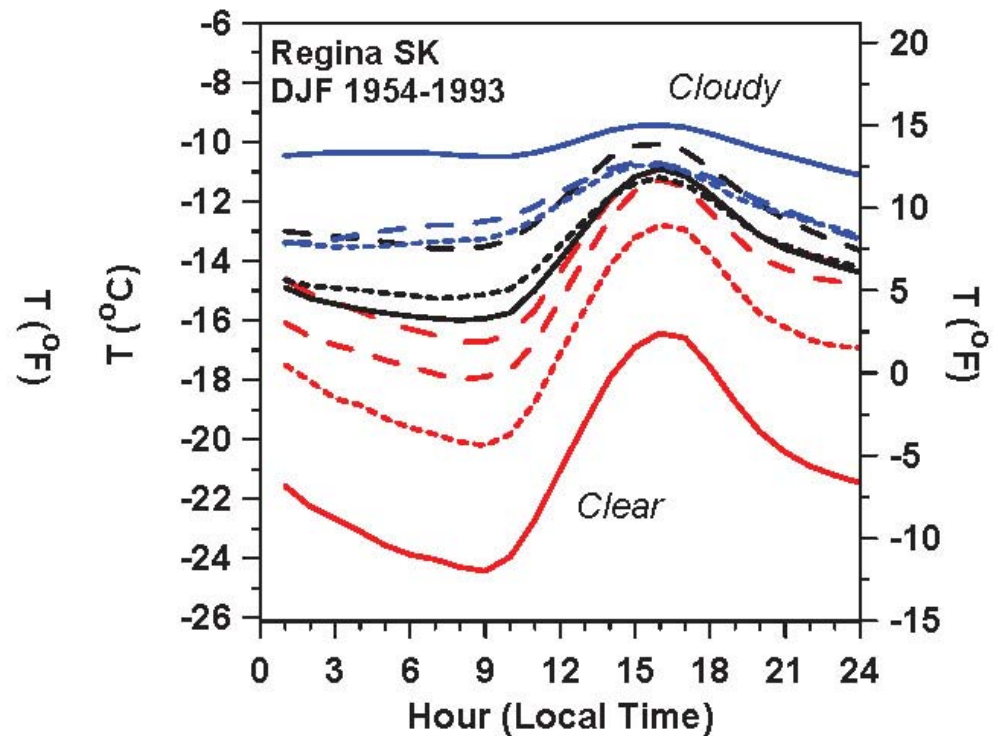
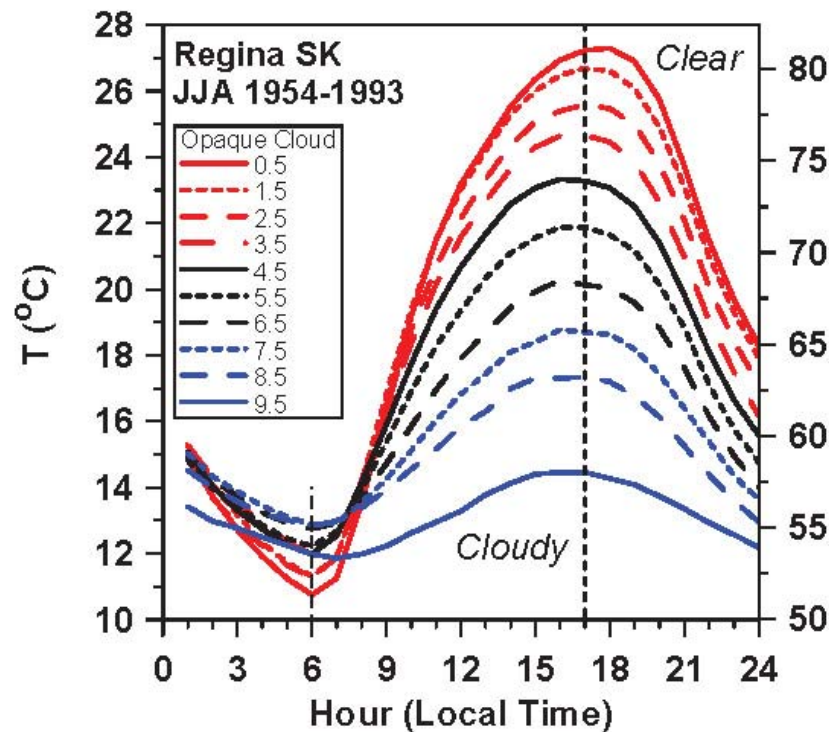
10% fewer snow days
= 1.5K warmer

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”



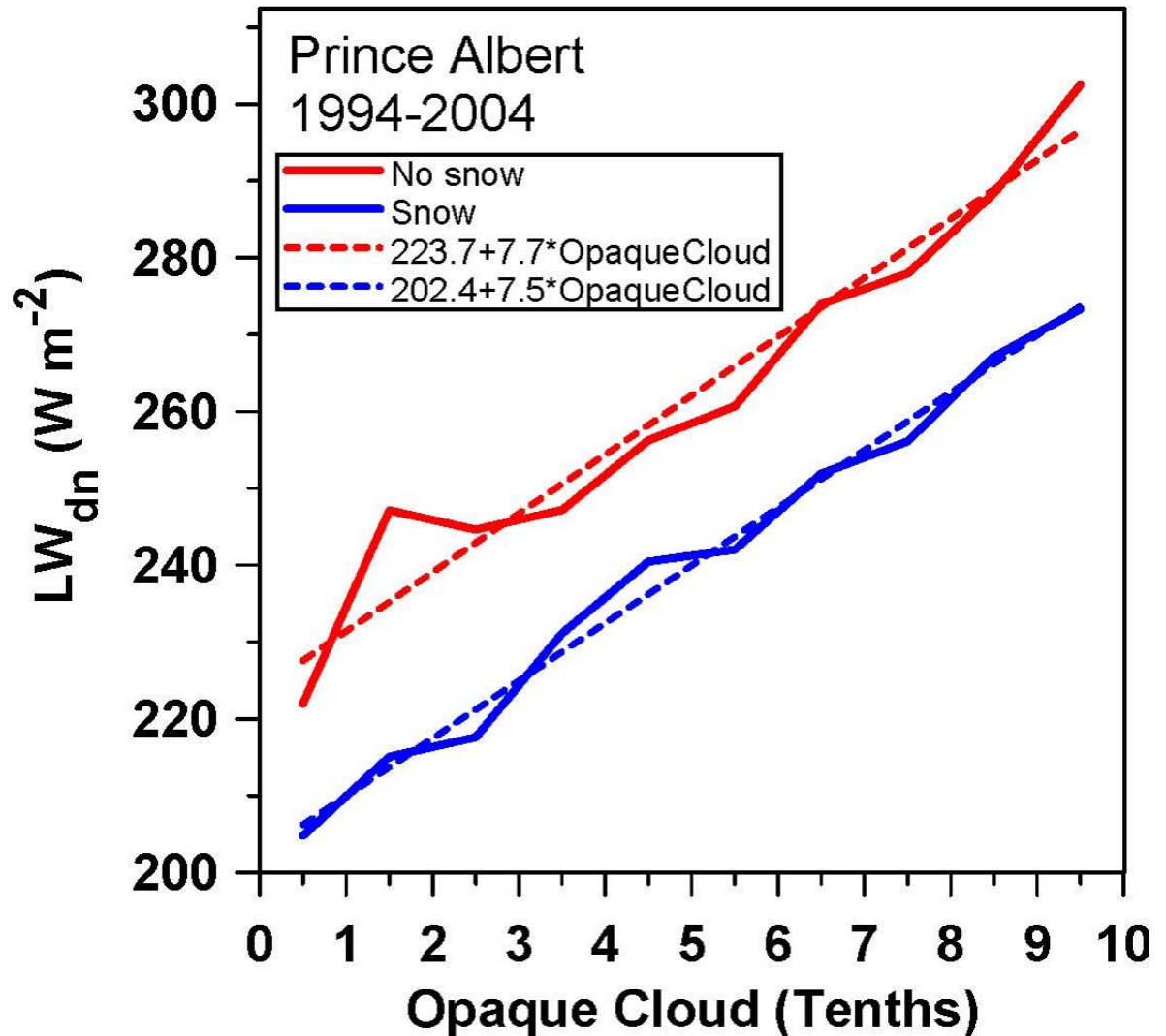
Clouds: Summer & Winter Climate *Opposite Impact*



- **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**

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***



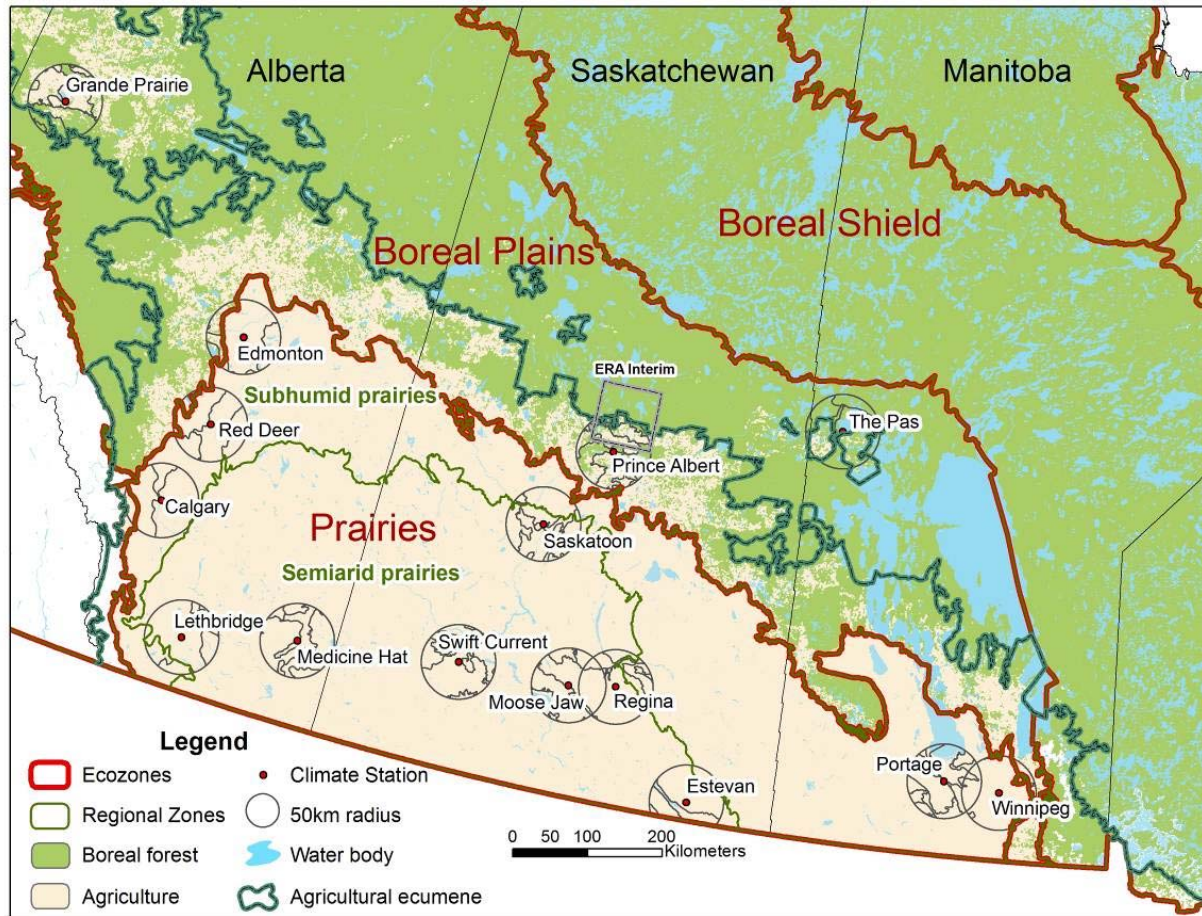
Surface Radiation Balance

- **Across snow transition**
 - Surface albedo α_s increases: **0.2 to 0.73**
 - LW_{dn} decreases
 - Opaque cloud increases
- **SW_{net} falls 34 W/m²**
- **LW_{dn} falls 15 W/m²**
- **Total 49 W/m²**
- **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

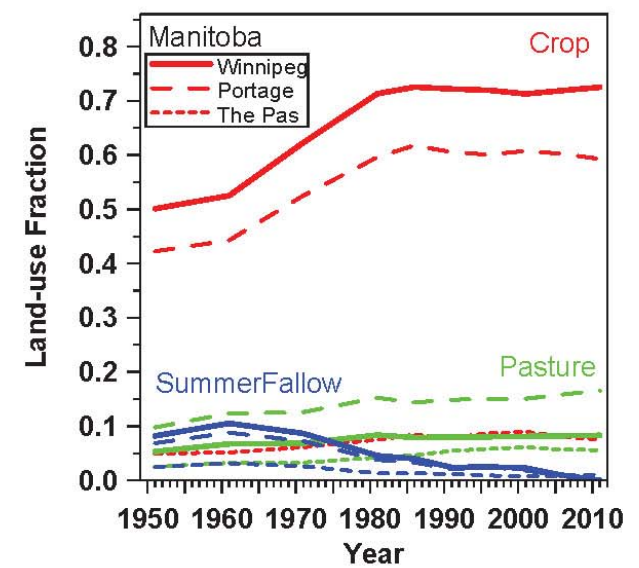
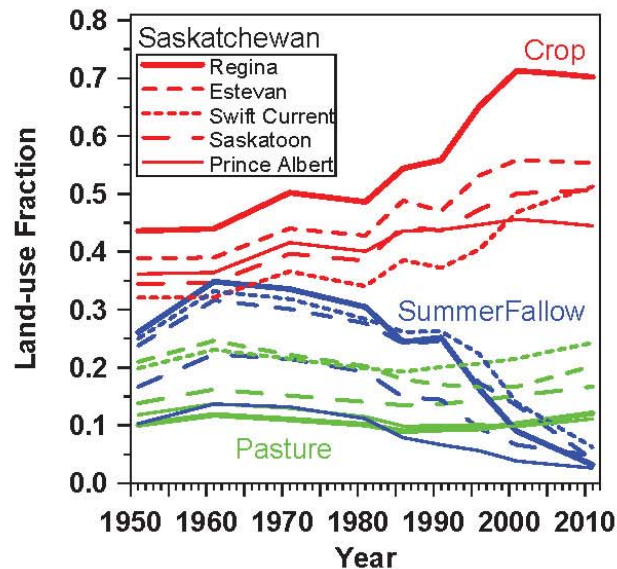
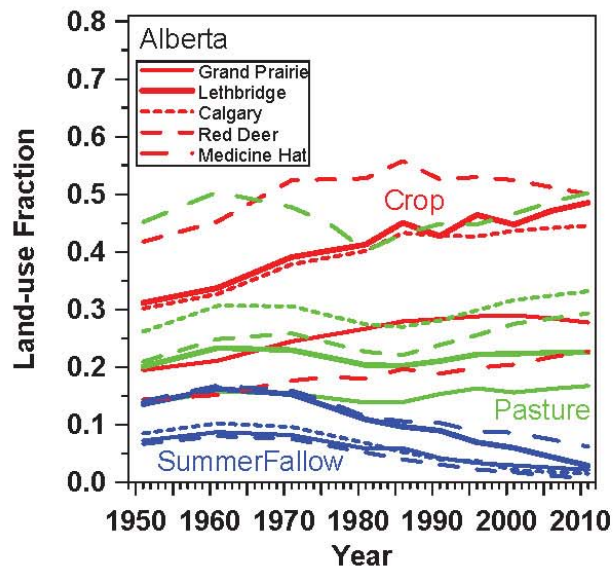
- **Ecodistrict crop data since 1955**
 - Ecodistricts mapped to soils
 - Typical scale: 2000 km² (500-7000)
- **Ecozones**
 - boreal plains ecozone
 - semiarid/subumid prairie regional zones
- **Shift from 'Summerfallow' (no crops) to annual cropping on 5 MHa (11 M acres)**
 - *Large increase in transpiration: Jun-Jul*

13 Prairie stations: 1953-2011



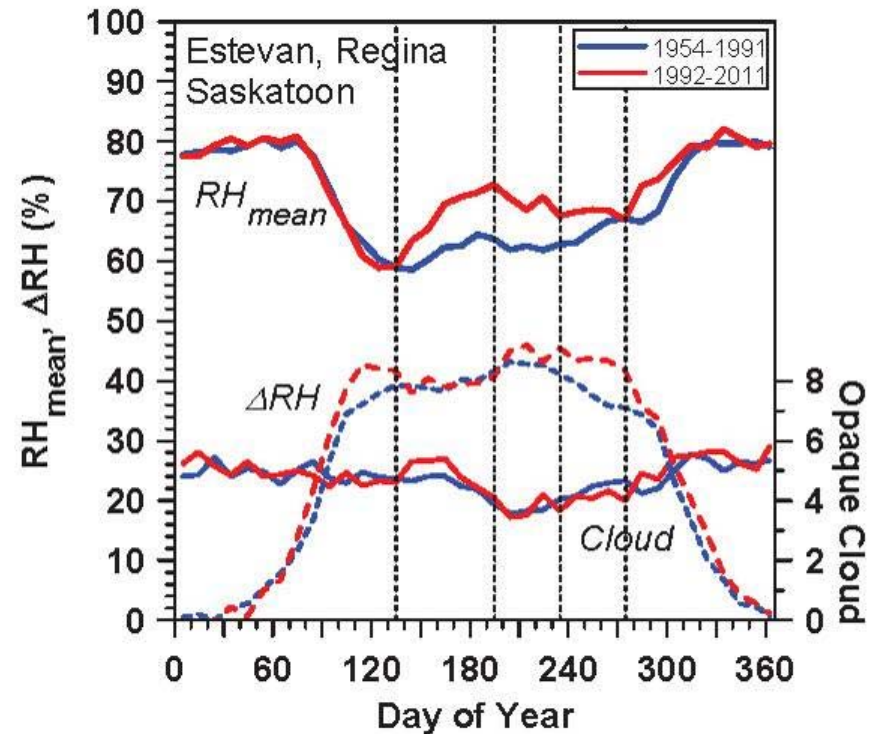
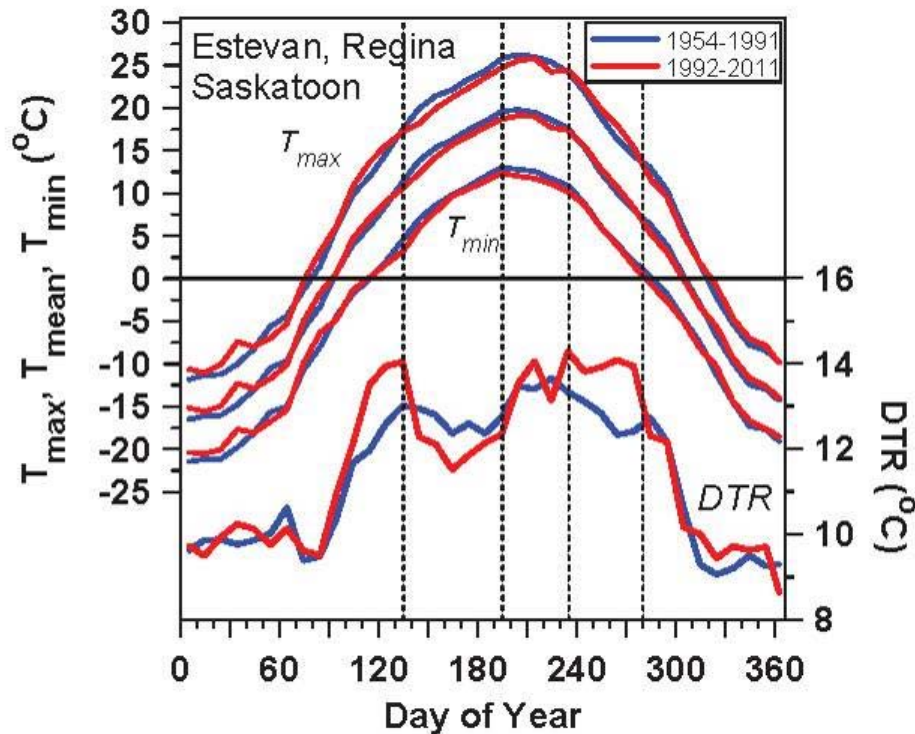
- Hourly p, T, RH, WS, WD, **Opaque Cloud** by level, (SW_{dn} , LW_{dn})
- Daily precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

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**

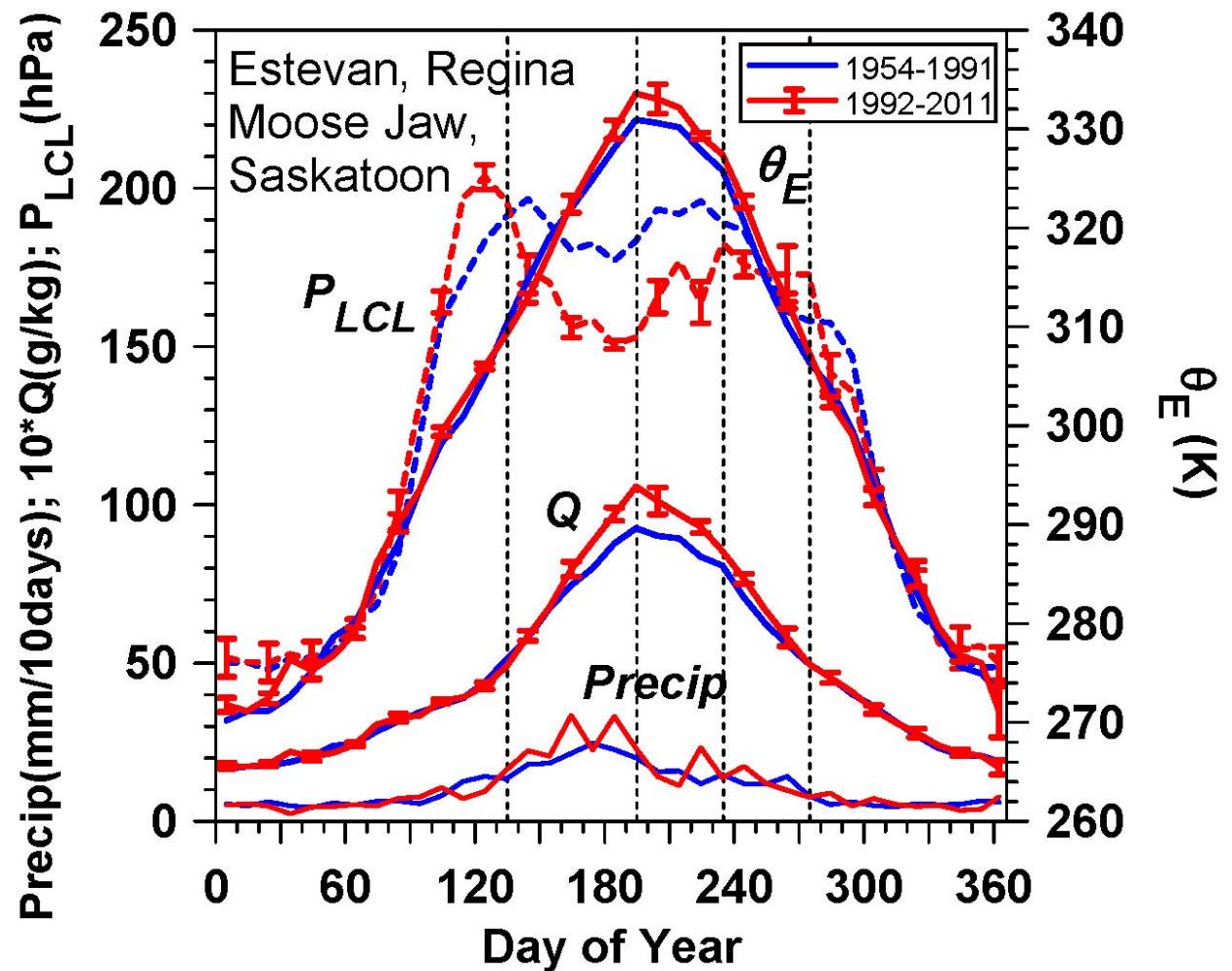
- T_{max} cooler; RH moister

- DTR and ΔRH seasonal structure changes

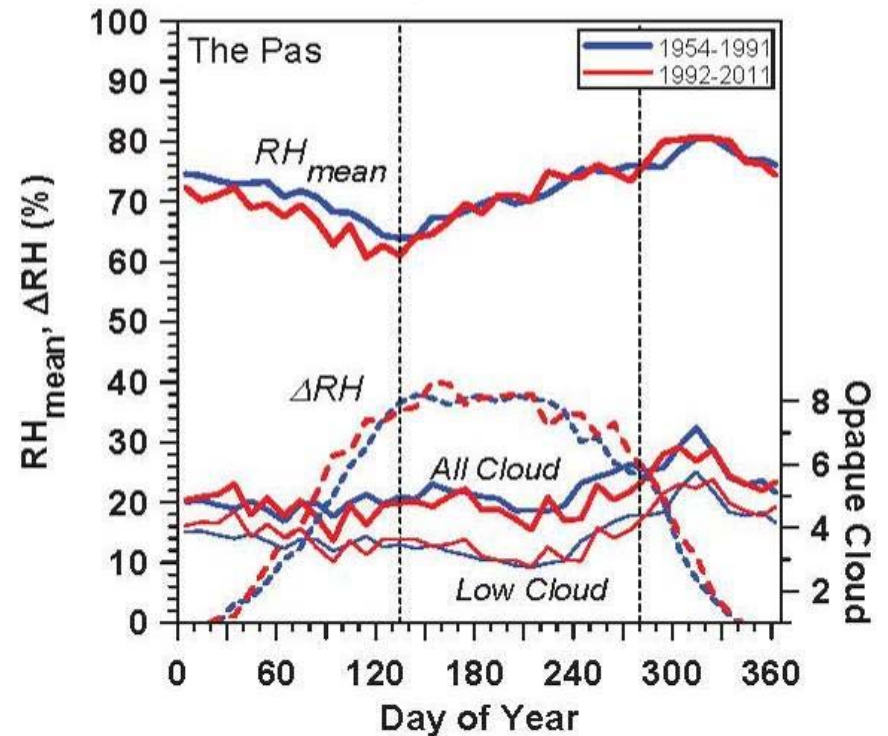
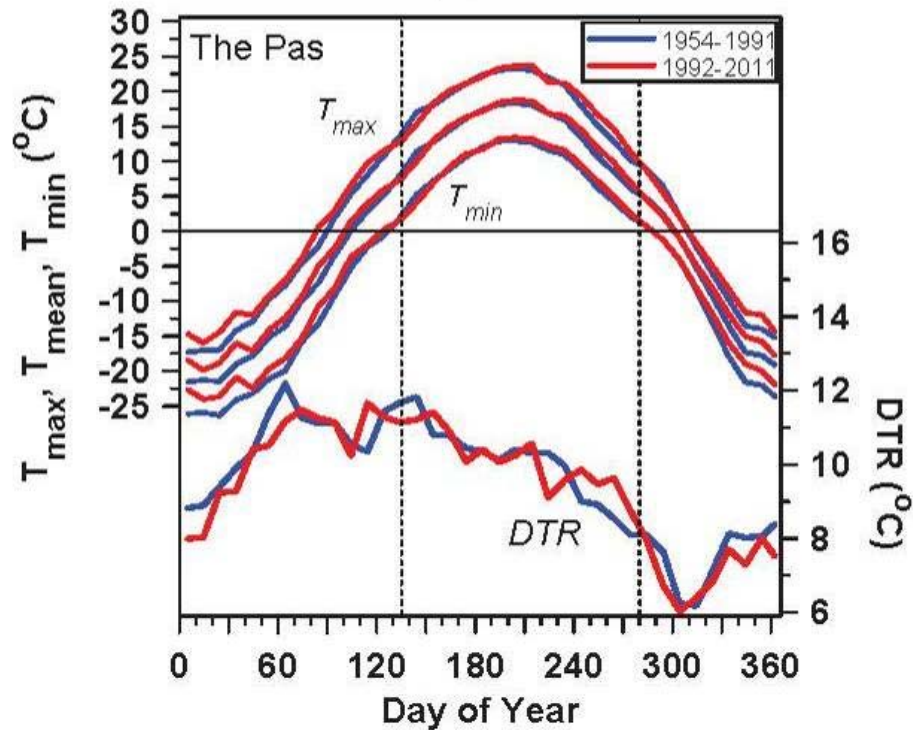
Impact on Convective Instability

Growing season

- Lower LCL
- Higher θ_E
- More Precip



Contrast Boreal Forest



- No RH, DTR signal

Summary

- *High quality dataset with Opaque cloud*
- **Understand cloud coupling to climate**
- **Transpiration from crops changes climate**
 - Cools and moistens summer
 - 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

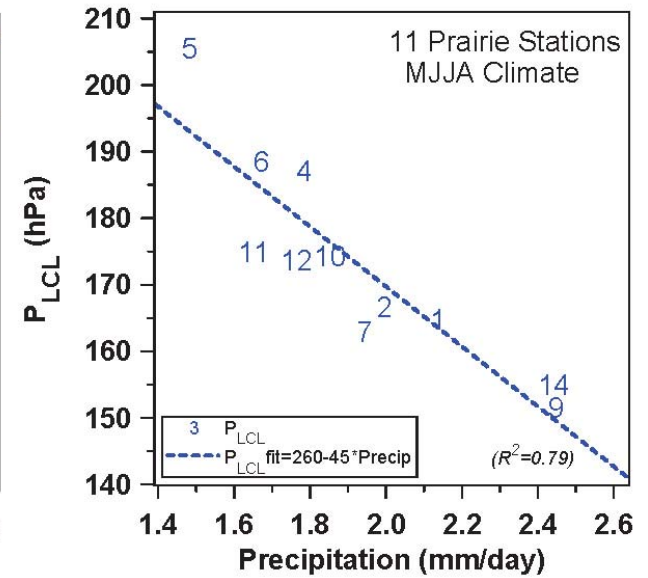
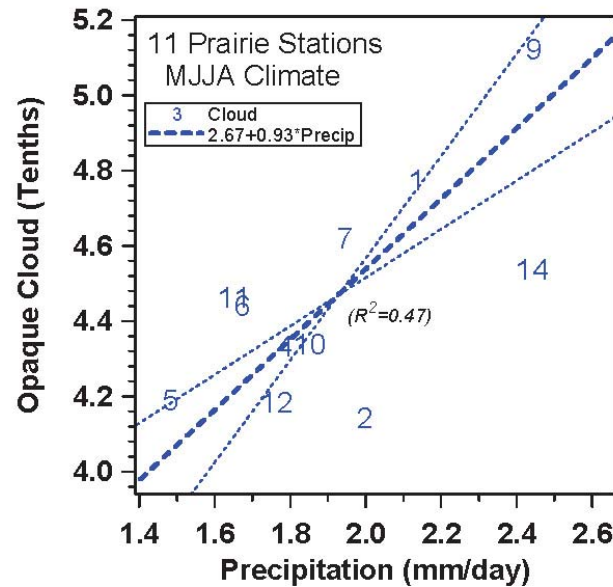
Papers at <http://alanbetts.com>

Transformative Concepts

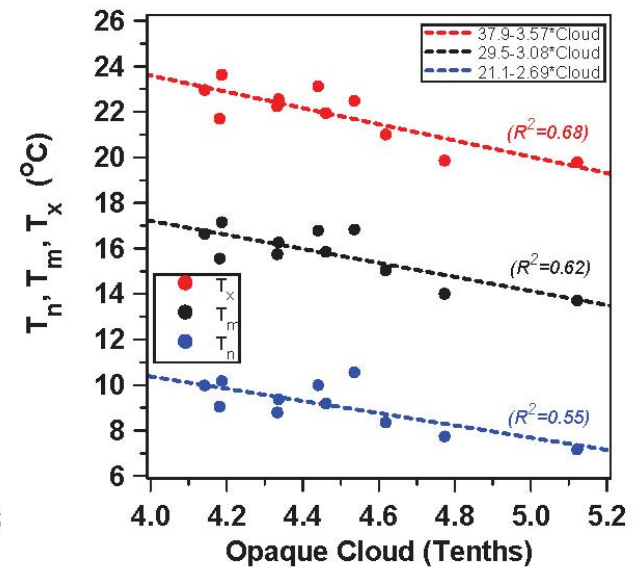
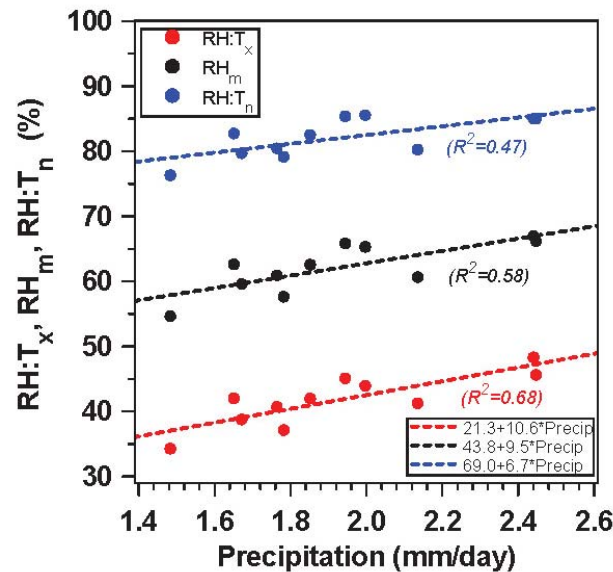
- Snow as climate switch
- Opaque/reflective cloud → R_n
- Separation of land-surface coupling
 - RH to precipitation and soil moisture
 - T to opaque cloud and R_n

11 stations: 55-yr MJJA climate

- **Precip to**
 - Cloud (0.47)
 - LCL (0.79)
 - RH:T_x (0.68)

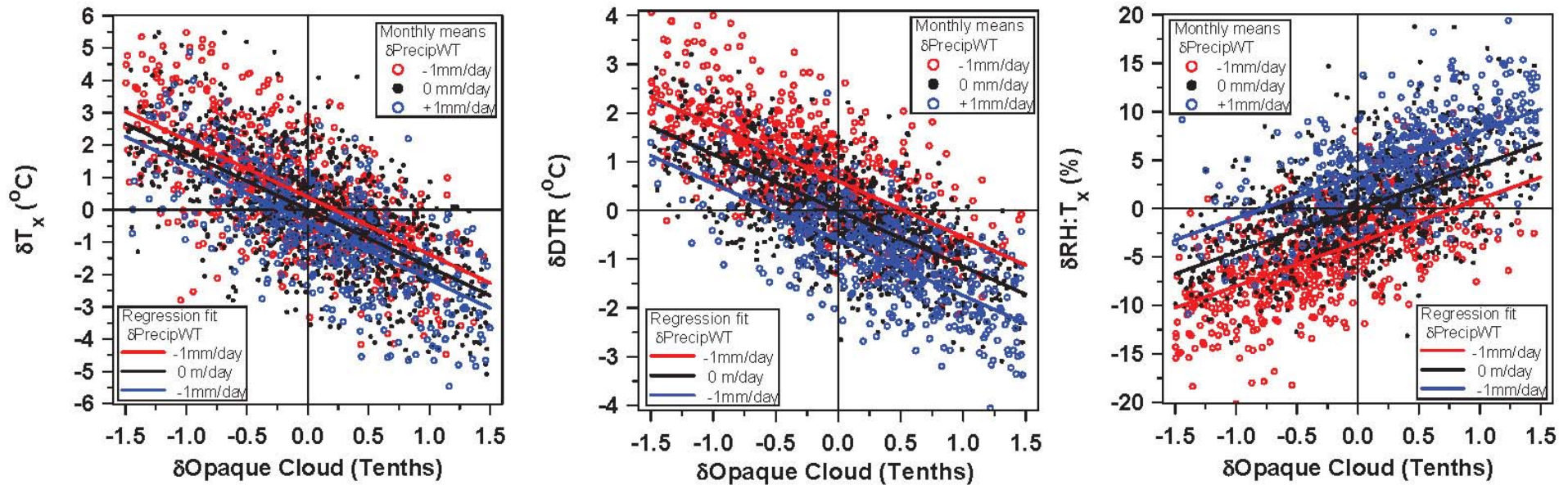


- **Cloud to**
 - T_x (0.68)



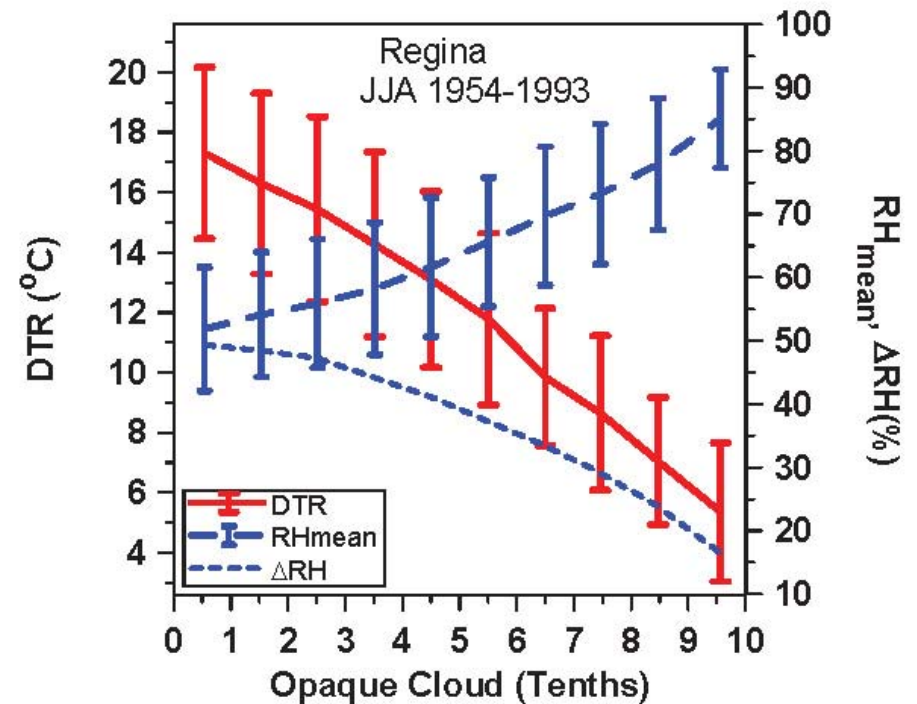
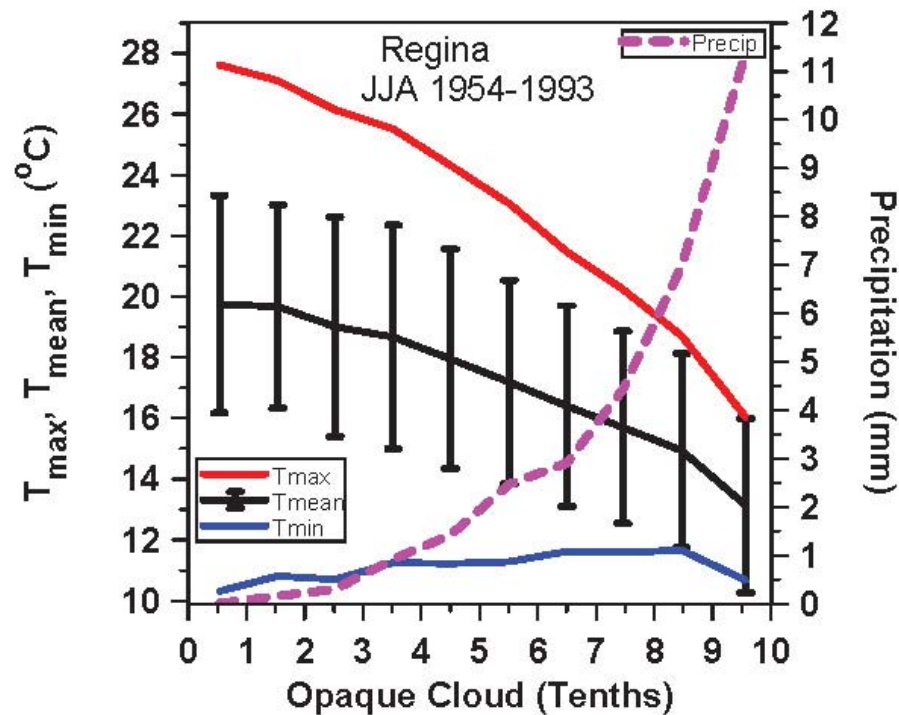
- **Month: blend**
- **Daily: cloud**

Monthly anomalies (MJJA: 2346 months)



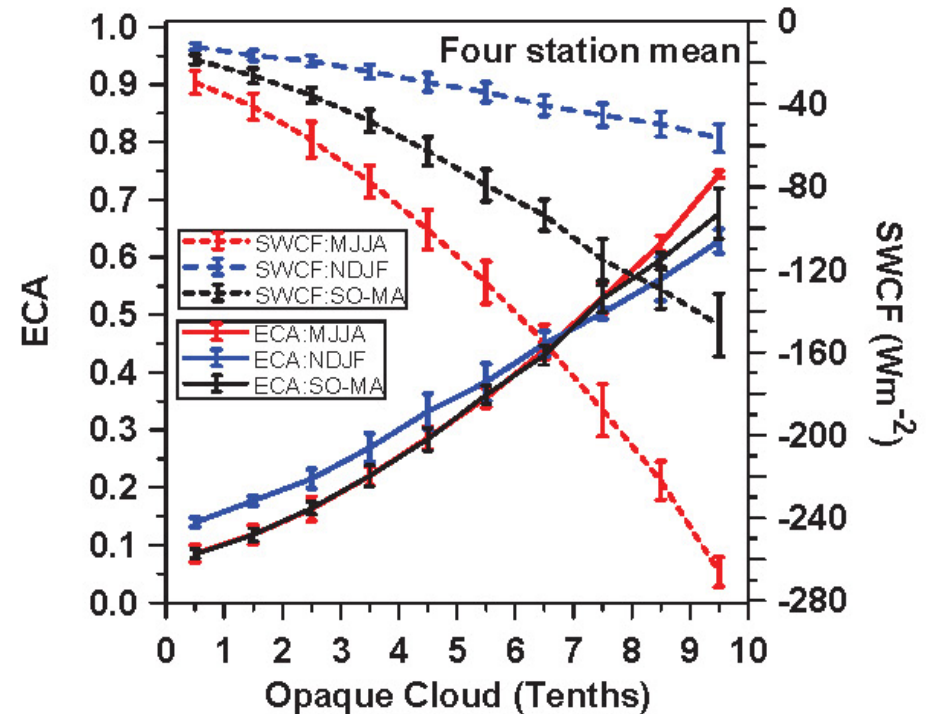
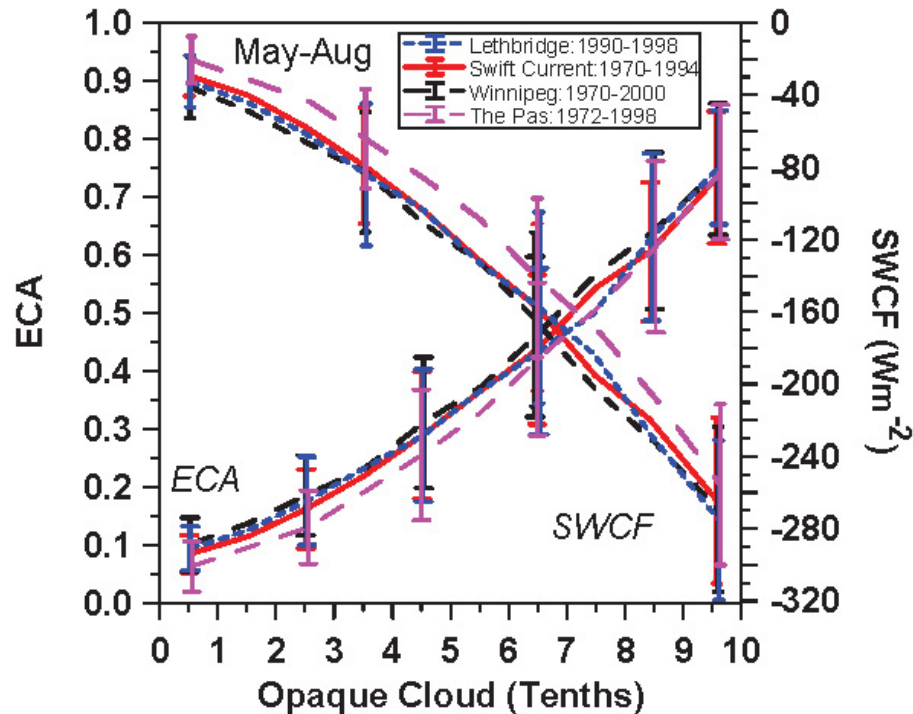
- **Less cloudy and less rain (this month and last)**
 - δT_x warmer (cloud mostly) ($R^2 = 0.55$)
 - δDTR larger (both) ($R^2 = 0.72$)
 - δRH drier (both) ($R^2 = 0.66$)

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**

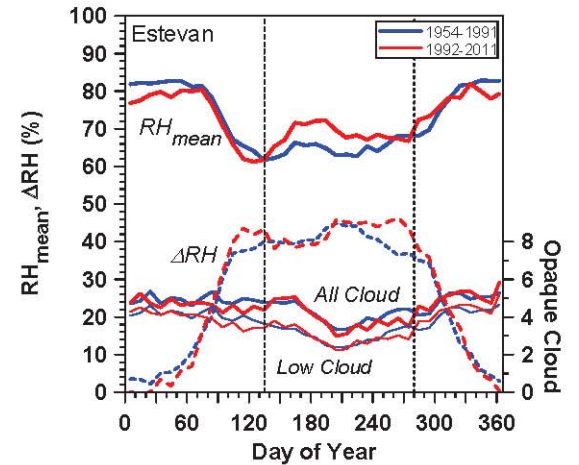
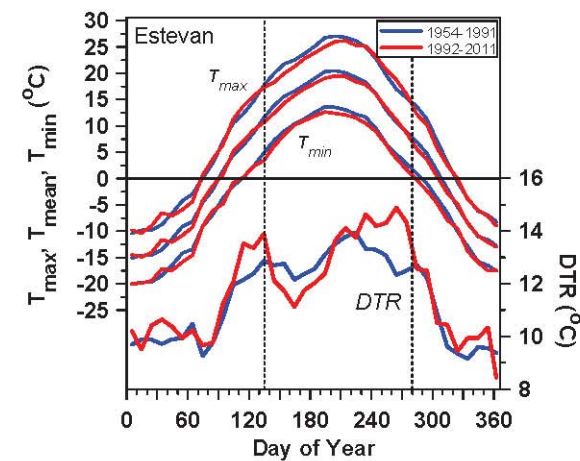
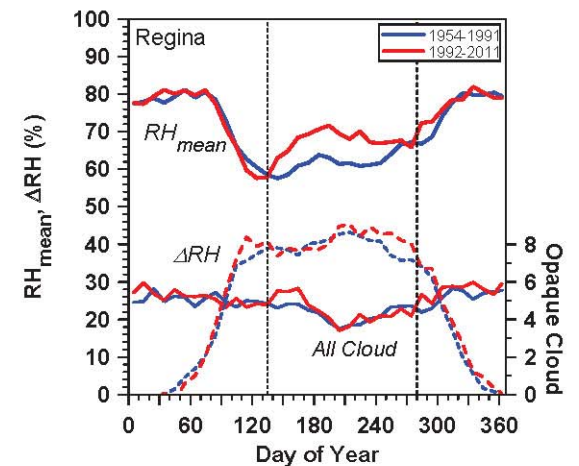
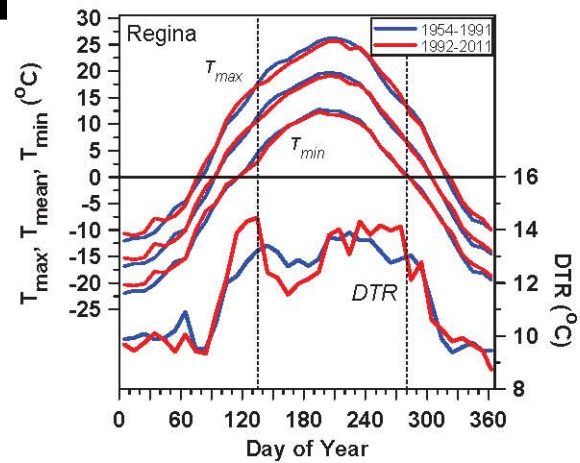
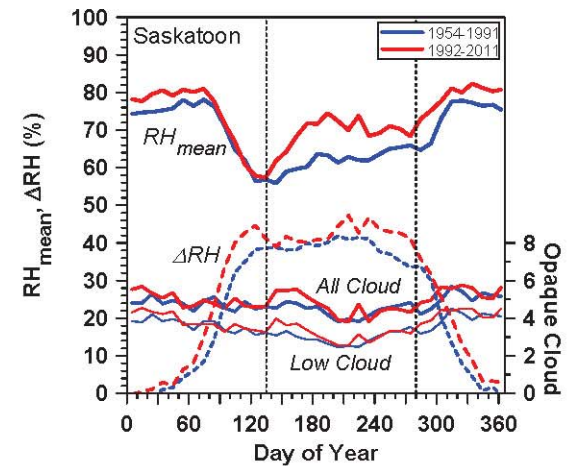
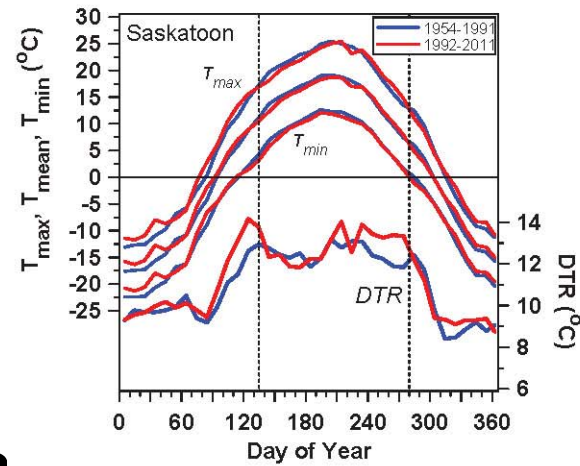
Calibration of Opaque Cloud to ECA-Effective Cloud Albedo



- **Tight relationship: ECA to Opaque Cloud**
- **NDJF a little flatter**

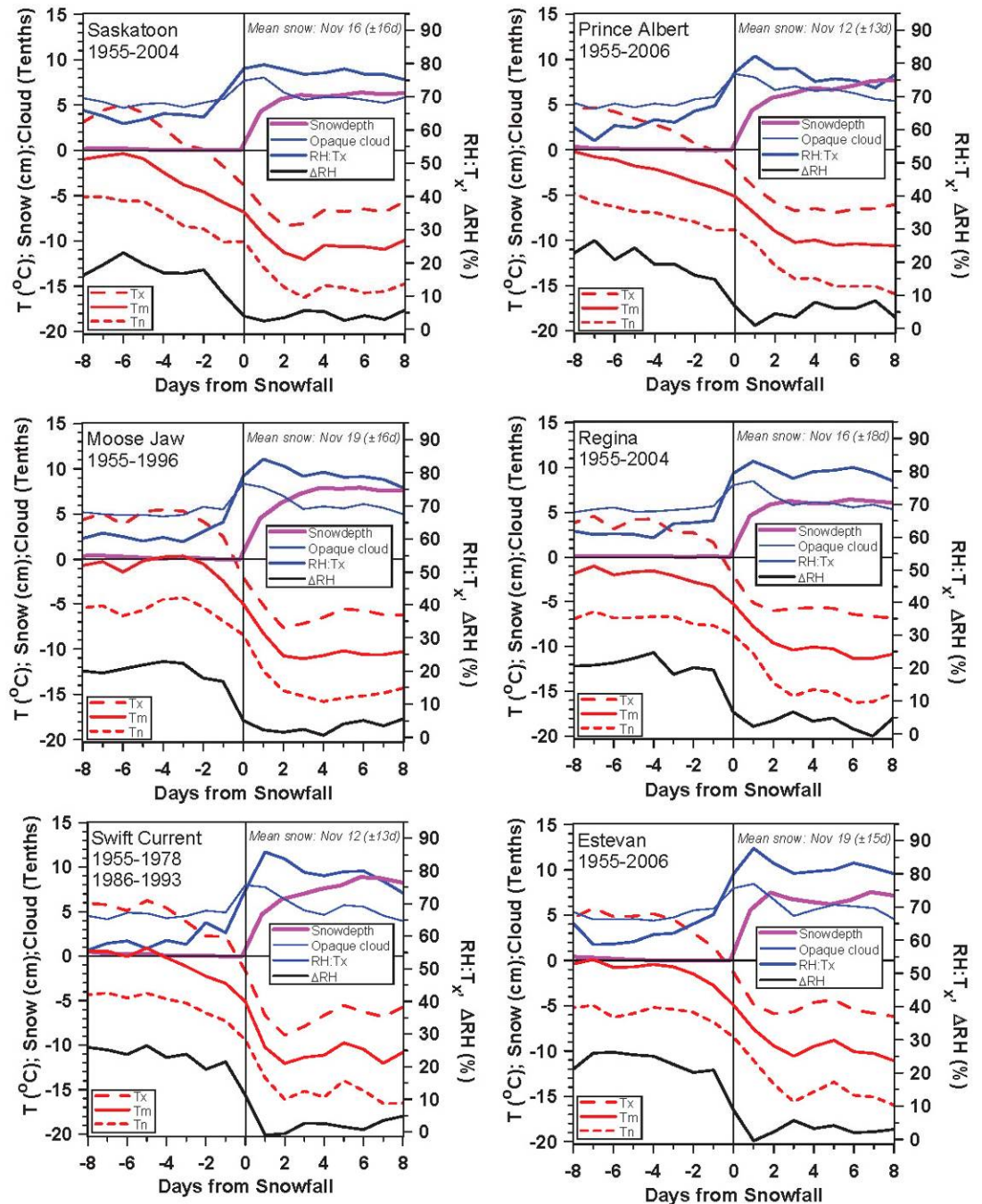
Diurnal Climate Change

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



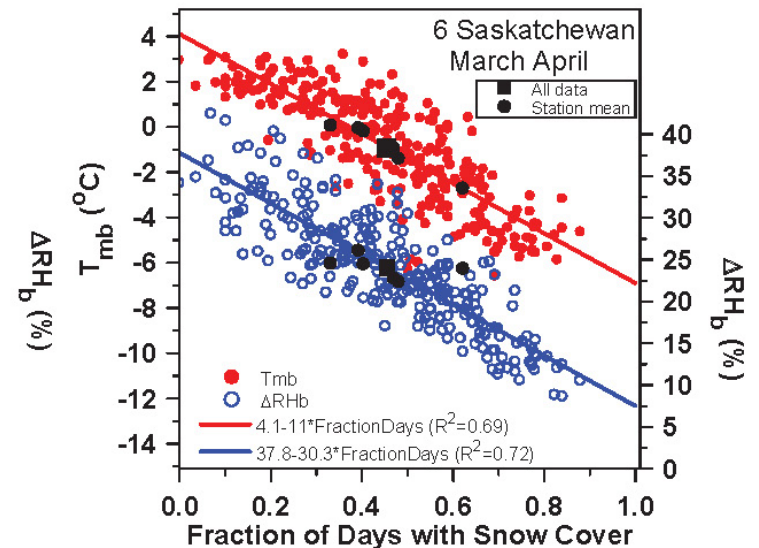
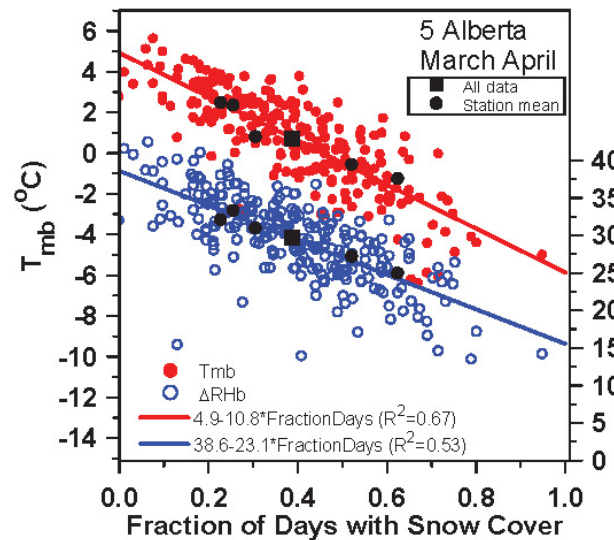
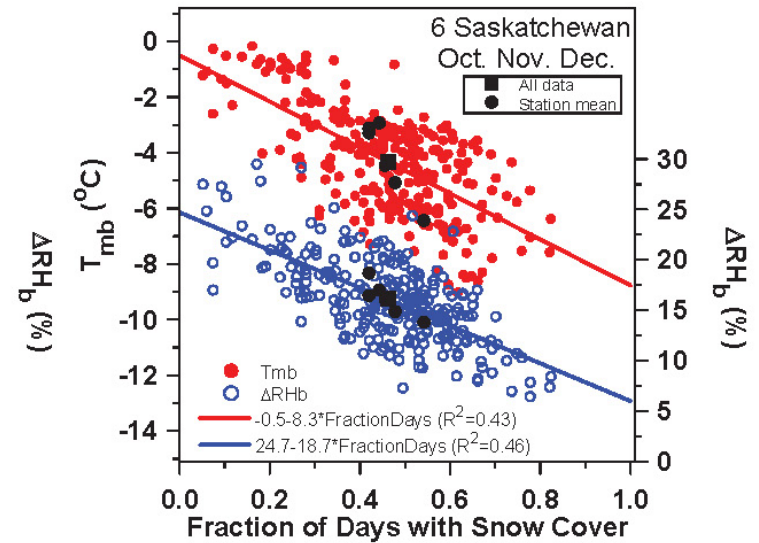
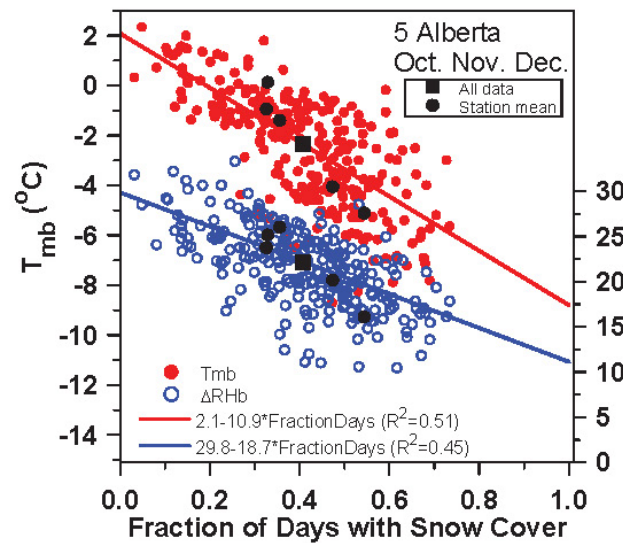
6 Stations in Saskatchewan

- 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

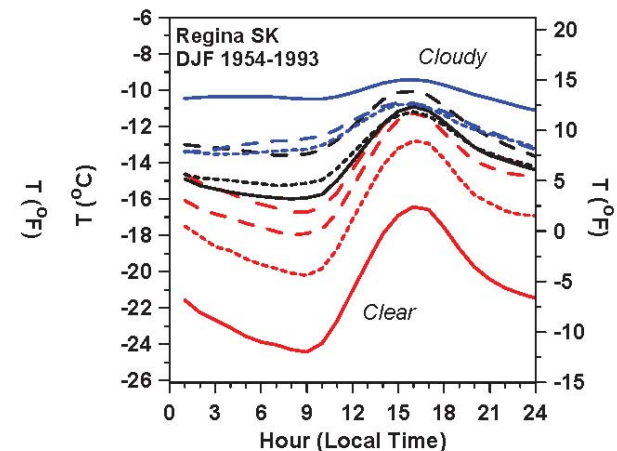
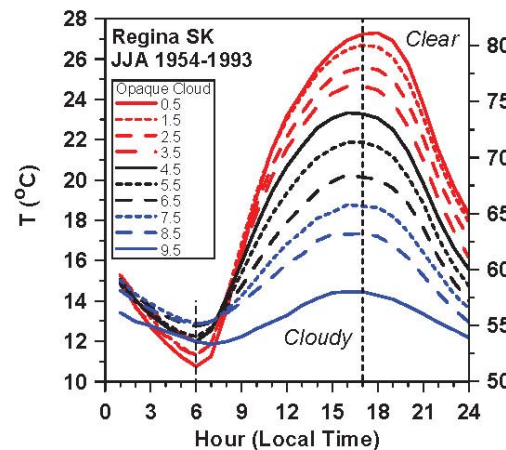
- *Definitions*

- $DTR = T_x - T_n$
- $\Delta RH = RH:T_x - RH:T_n$

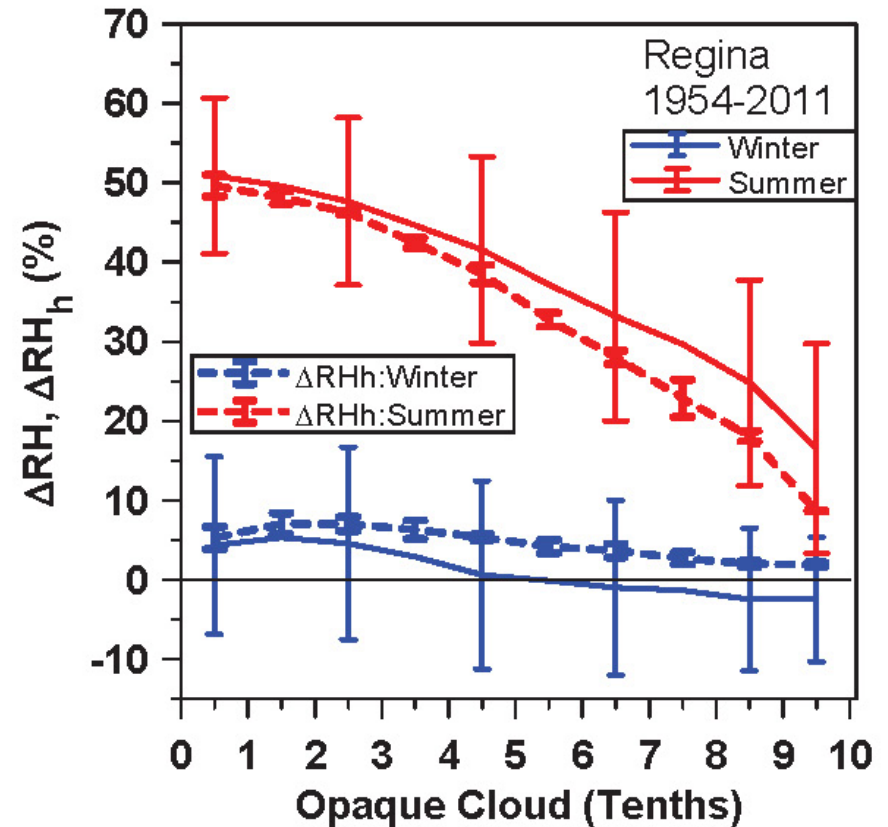
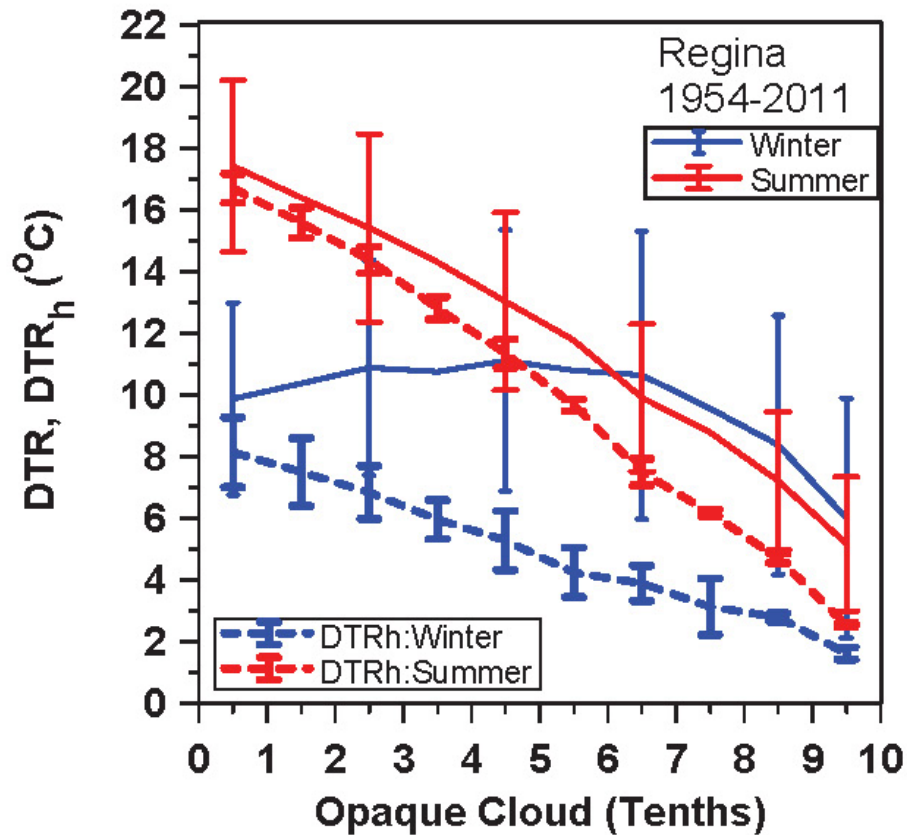
Monthly mean diurnal cycle

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

Radiatively forced signal small in winter compared to daily advection

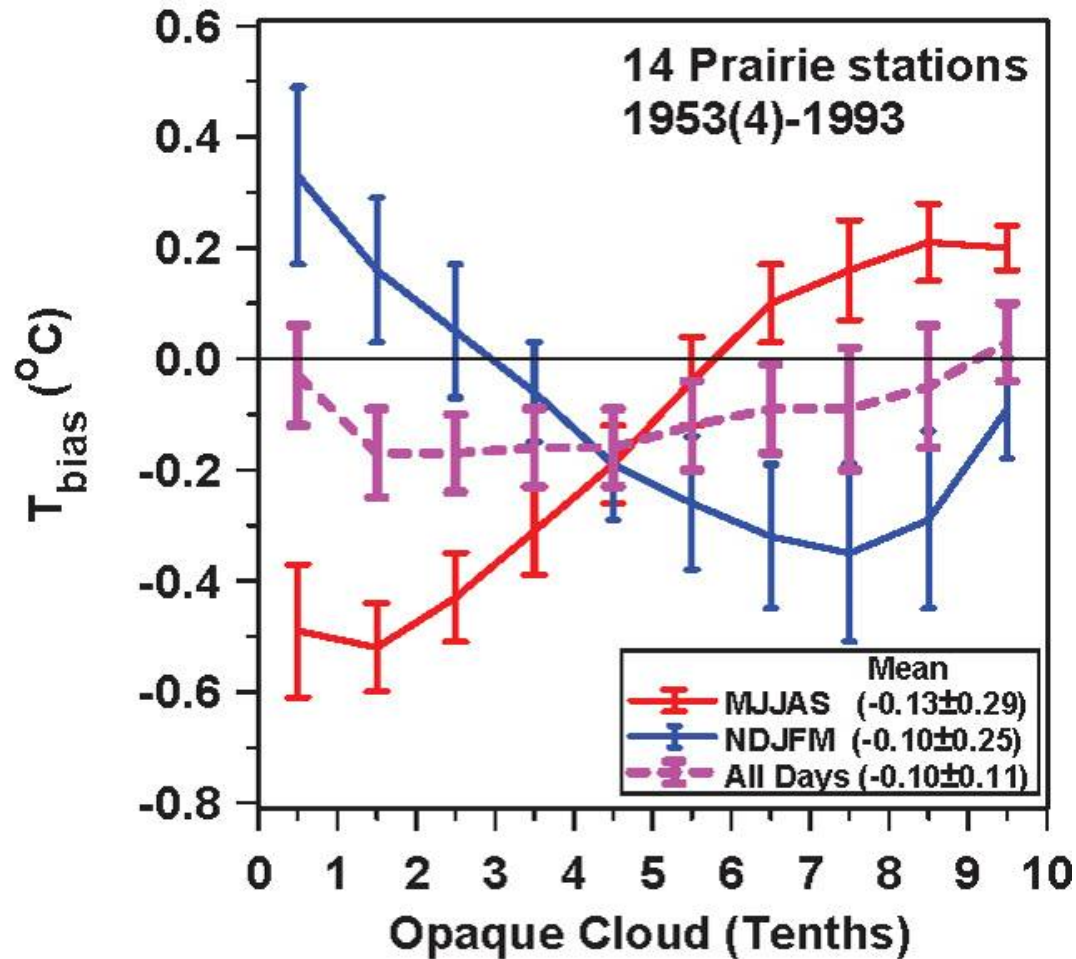


Daily Mean Climate vs Monthly Diurnal Mean Climate



- Daily variability in winter large
- Monthly variability small: DTR_h quasi-linear

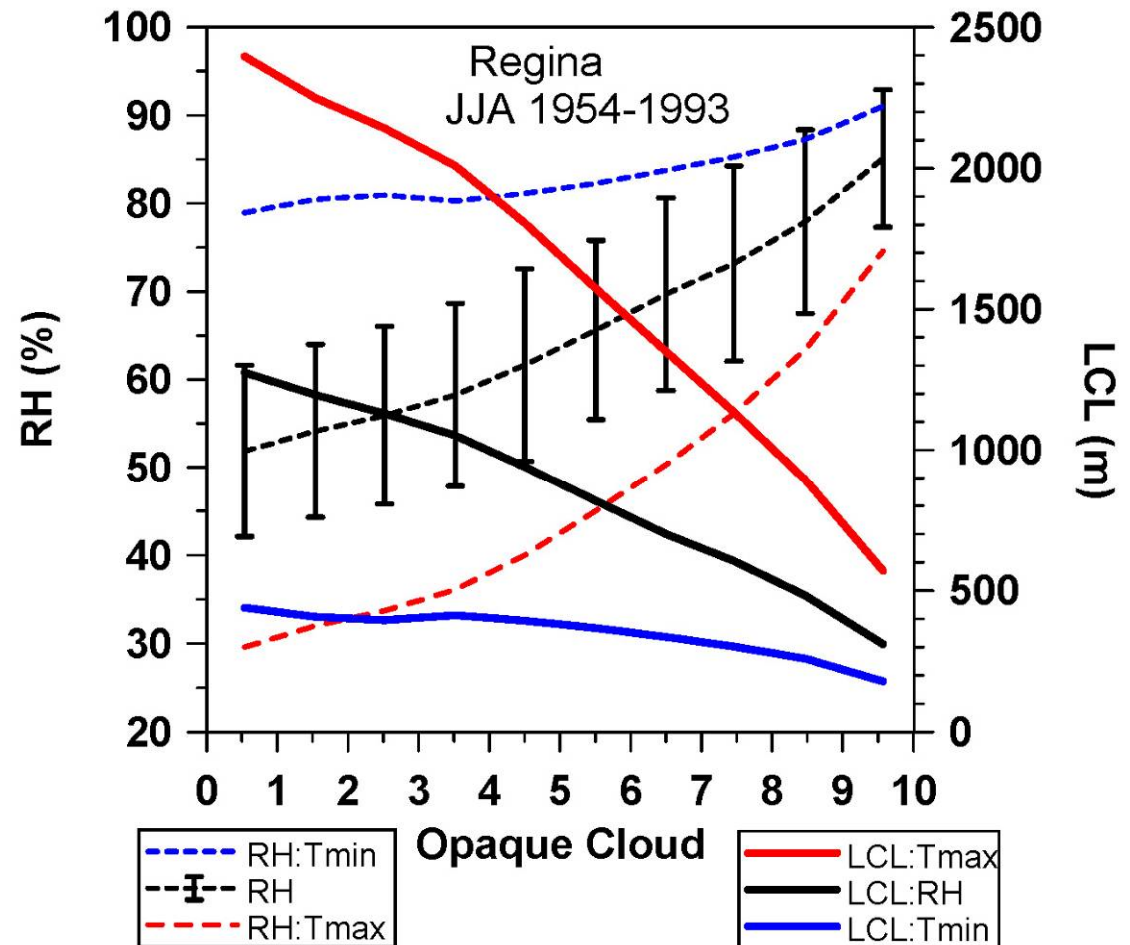
$$T_{\text{bias}} = (T_{\text{max}} + T_{\text{min}})/2 - T_{\text{mean}}$$



- Opposite in warm and cold season

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***

