Coupling of Diurnal Climate to Clouds, Land-use and Snow

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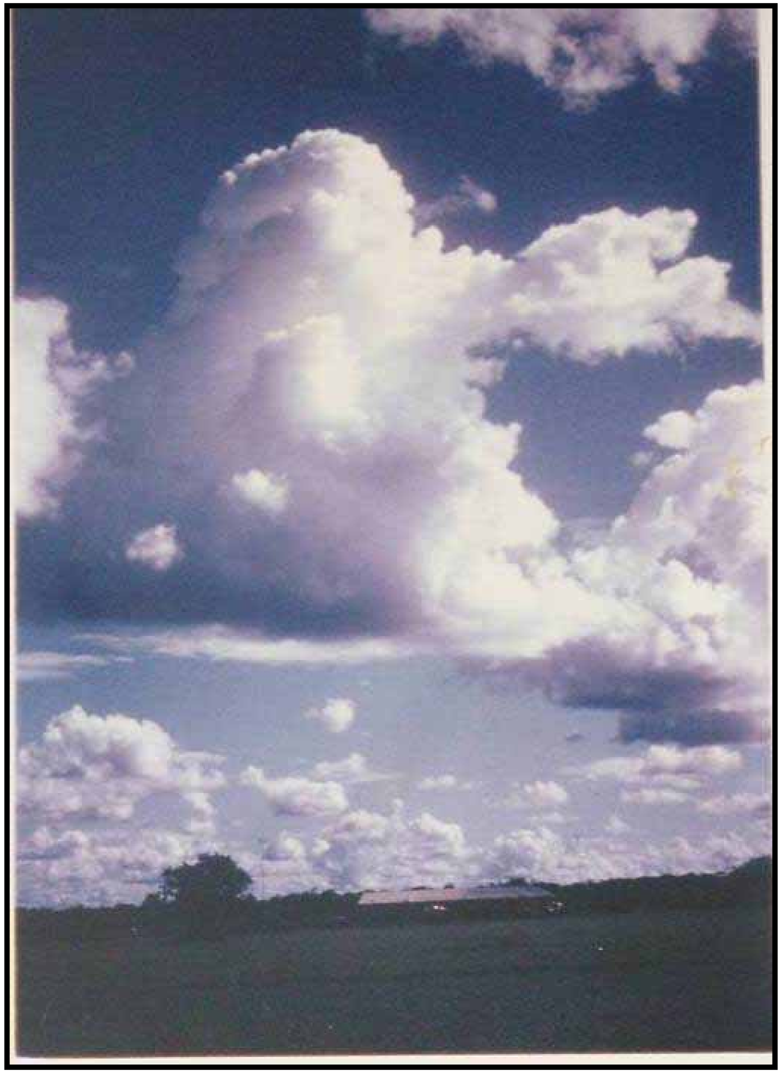
1969: Barbados to Venezuela



BOMEX to VIMHEX
PhD student, London,
"Cumulus Convection"

Vermont Winter 2006

- **Snow reflects sunlight, except where trees shadow**
- **Cold; little evaporation, clear sky; earth cools to space**
- ***2012 warm winter, snow melts*** ⟶ ***positive feedback***
- ***2014 cold winter, snow cover*** ⟶ ***stays cold***

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: 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 (2014)*

Available at http://alanbetts.com/research

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 % snow cover

Clouds and Diurnal Climate

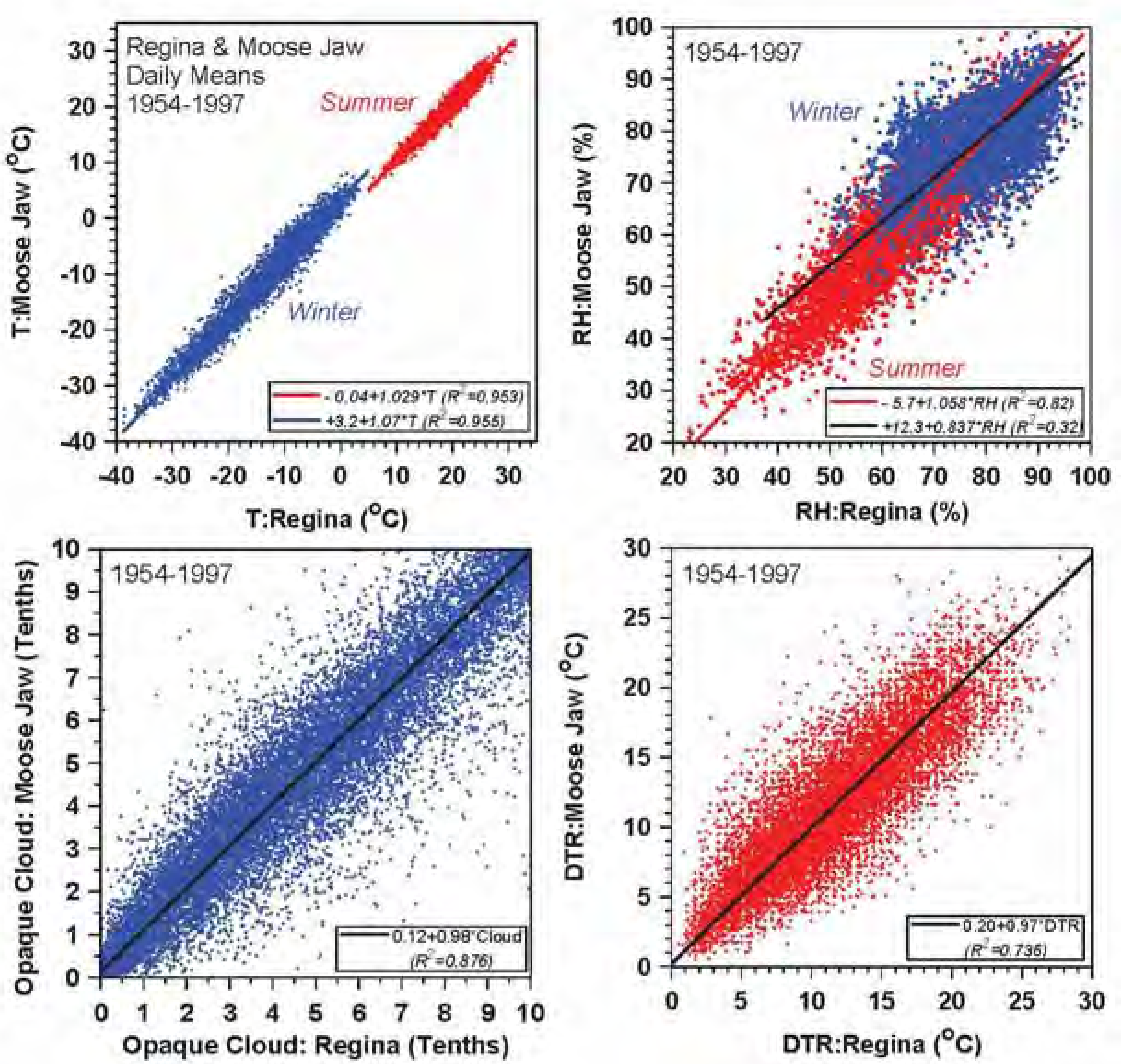
- **Reduce hourly data to**
  - **daily means: T_{mean} , RH_{mean} etc**
  - **data at T_{max} and T_{min}**

- ***Diurnal cycle climate***
  - **DTR = T_{max}-T_{min}** ***(T_x-T_n)***
  - **ΔRH = RH:T_x – RH:T_n**

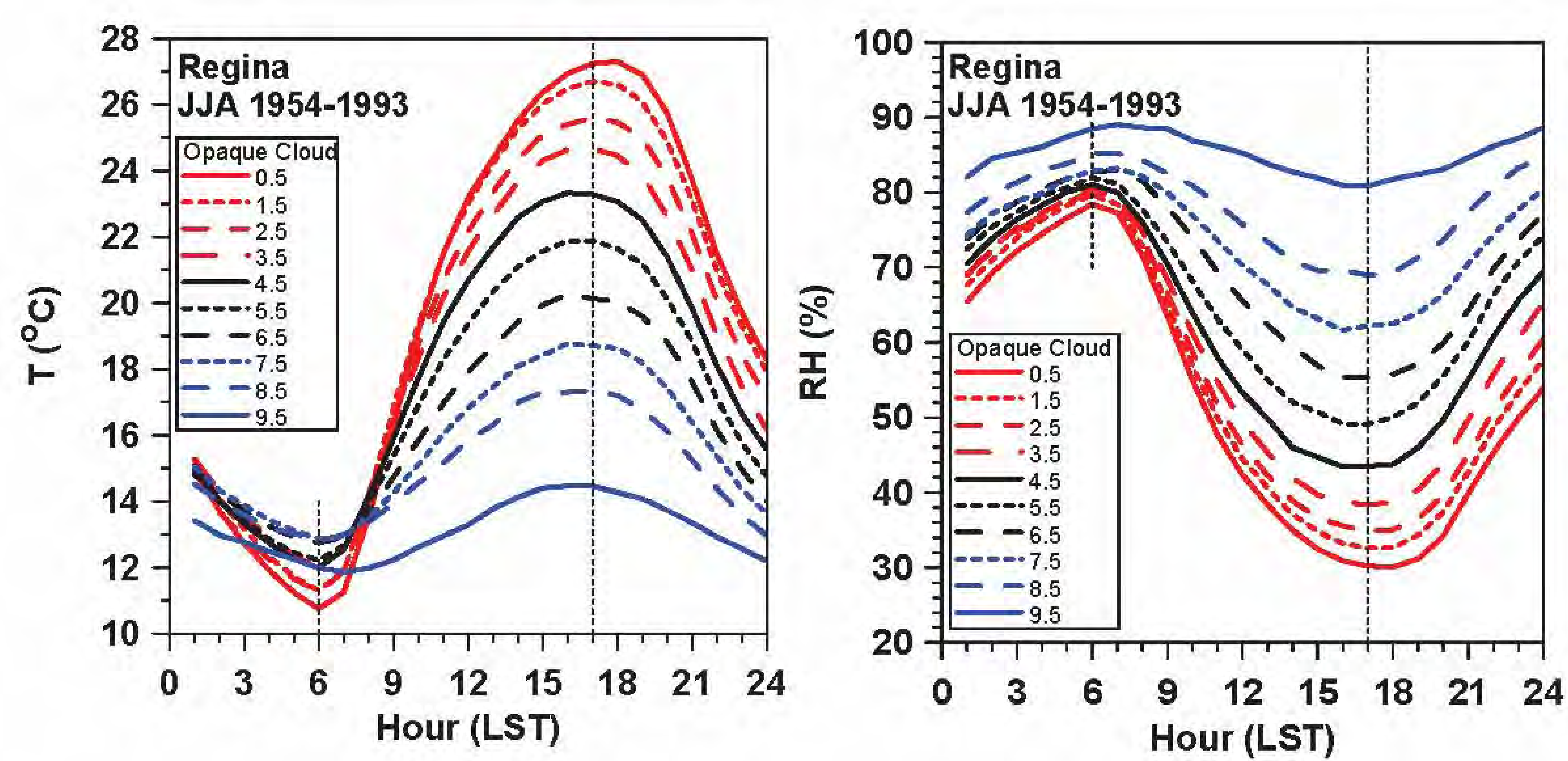
- **Almost no missing data**

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** →



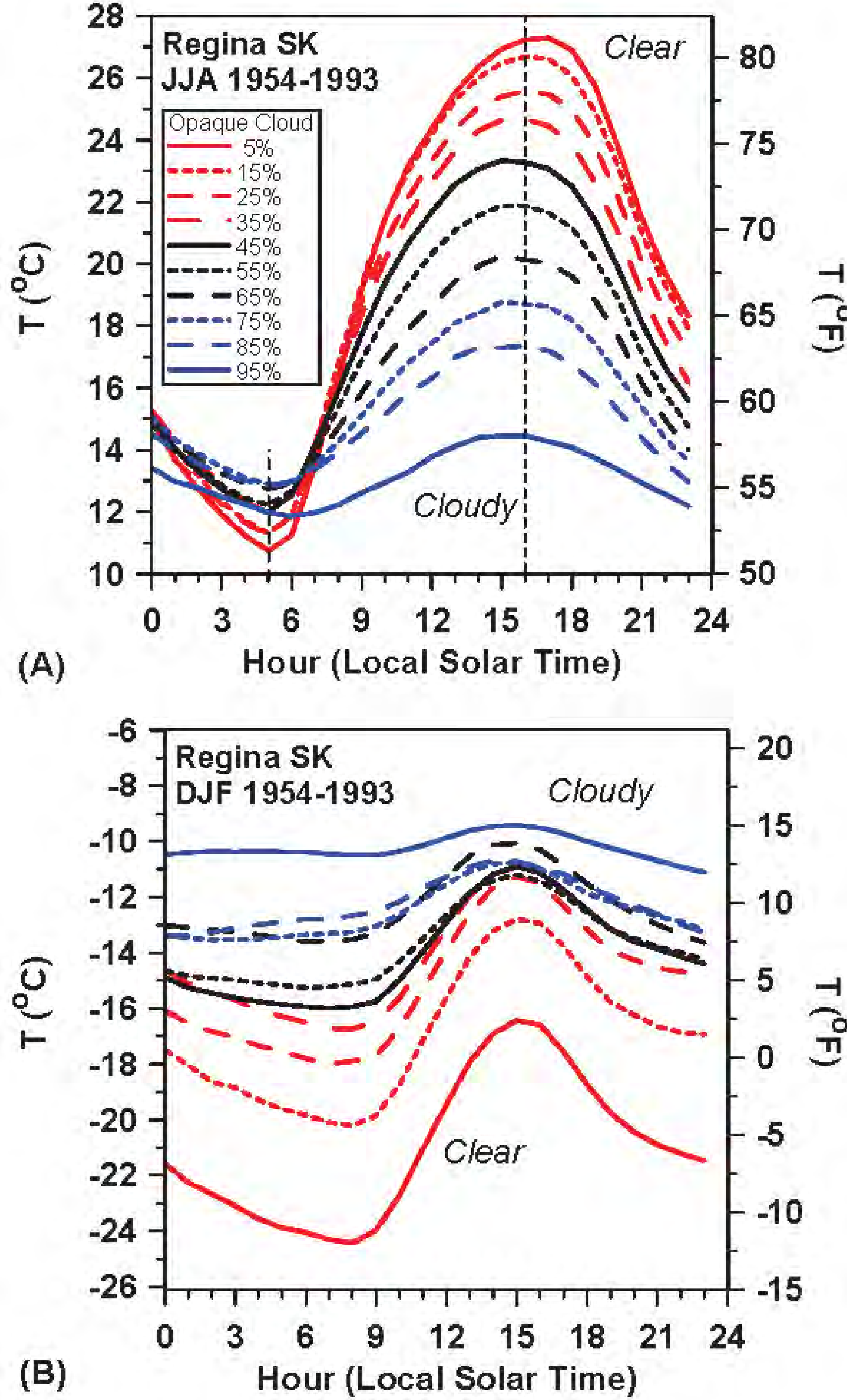
Clouds to Summer Diurnal Cycle



- ***40-yr climate (local standard time)***
- **T and RH are inverse**
- ***Overcast with rain only 'outlier'***

Cloud Impacts

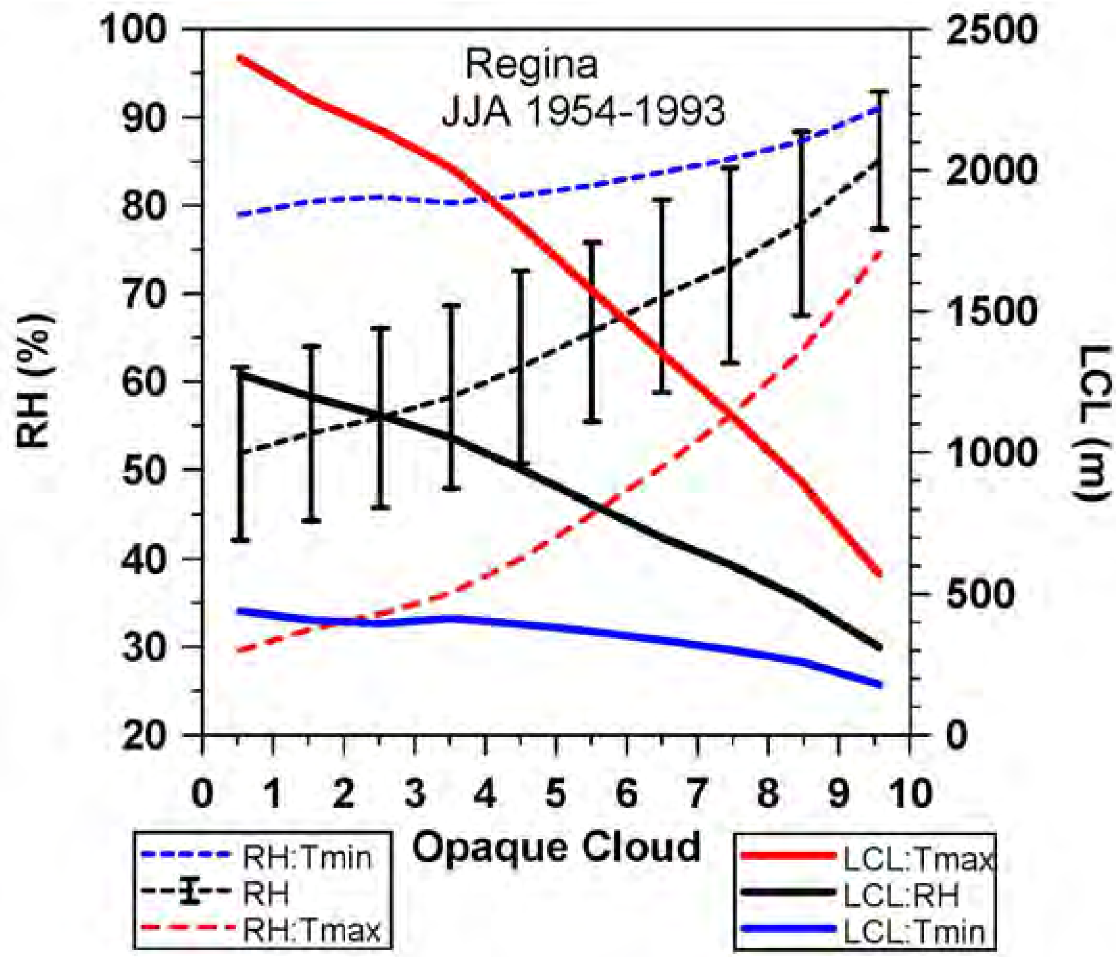
- **Summer:** Clouds reflect sunlight
  - no cloud, hot days; only slightly cooler at night
- **Winter:** Clouds are greenhouse
  - snow reflects low sun
  - clear & dry sky, cold days, very cold nights
- **Fast transition with snow in 5 days**



Betts et al. 2013

RH is linked to LCL

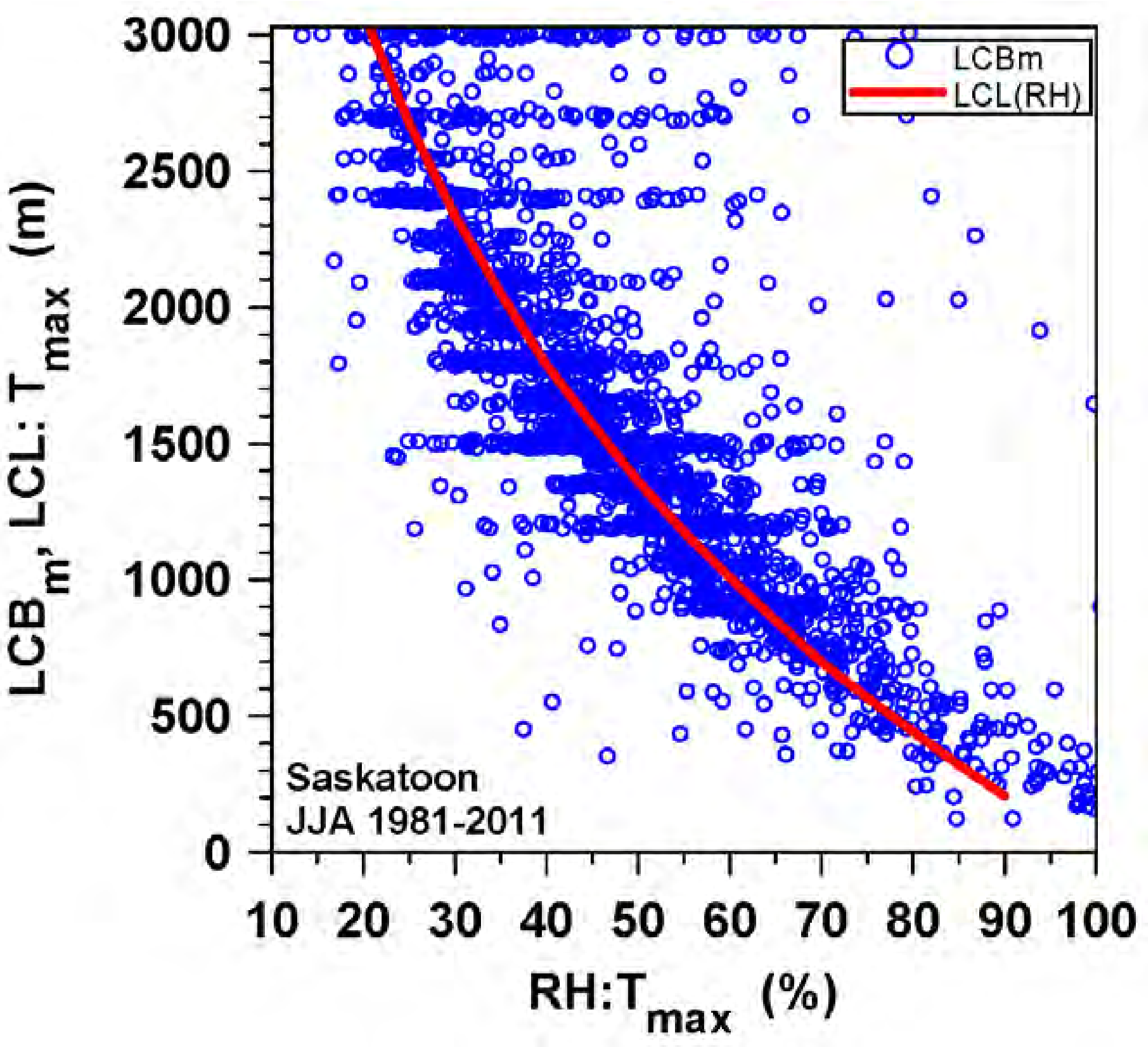
- RH increases with cloud
- Cloud-base LCL decreases
- Afternoon LCL 550 - 2350m



Afternoon LCL is Cloud-base

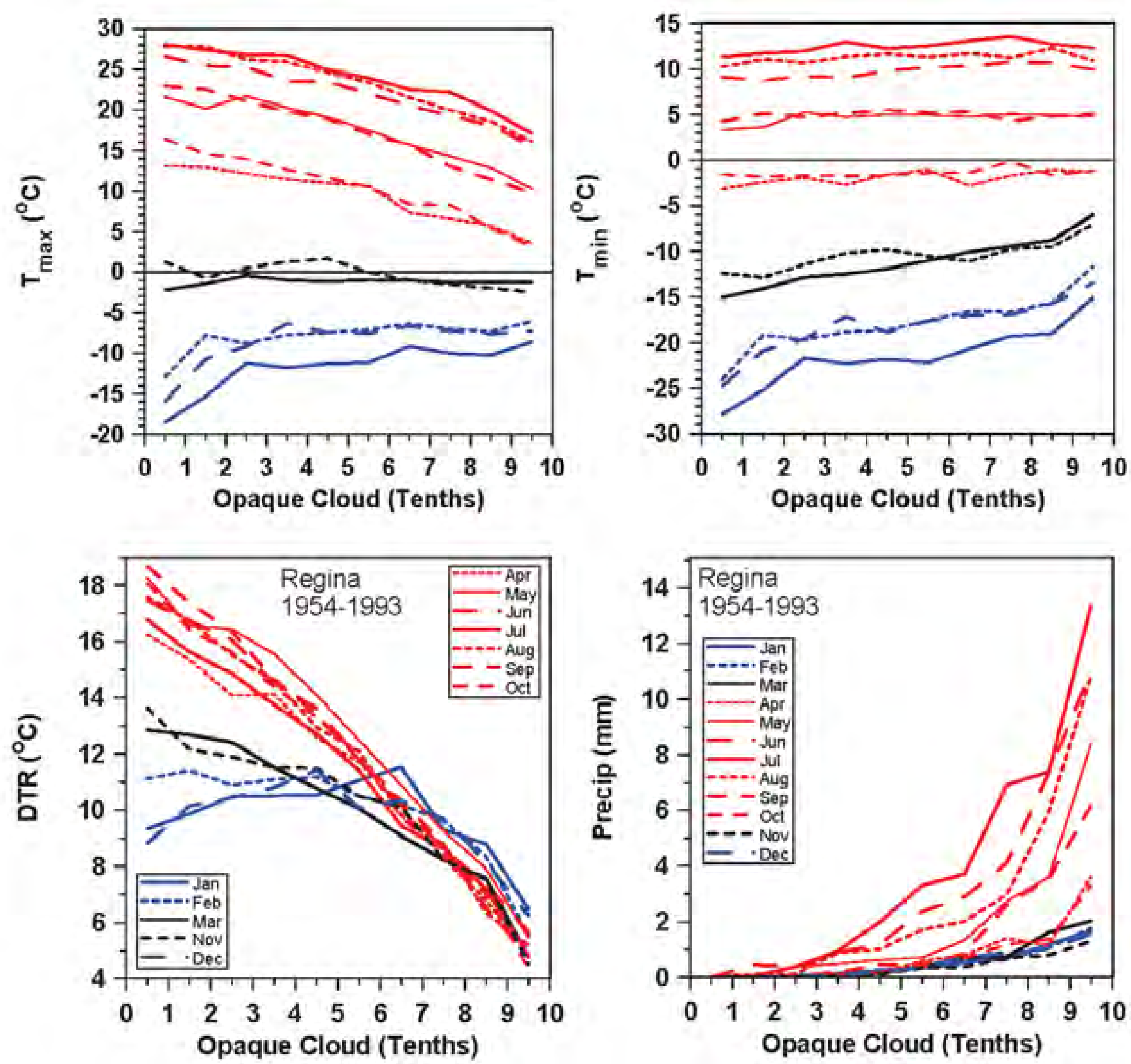
- At T_{max}
- Lowest cloud-base *(ceilometer)*
- LCL (surface)

- ***Coupled CBL***



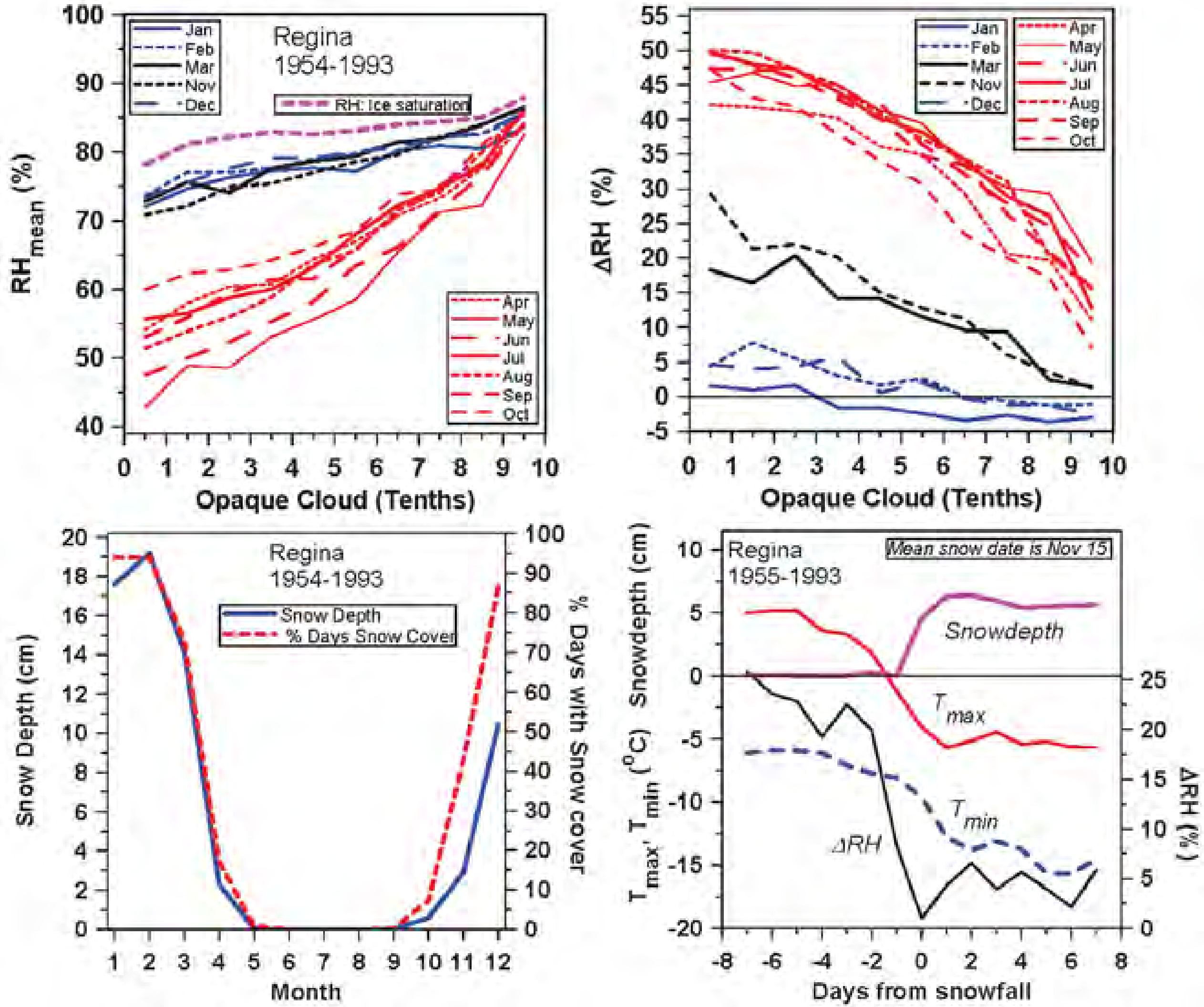
Annual Cycle: T_{max},T_{min}, DTR, Precip

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

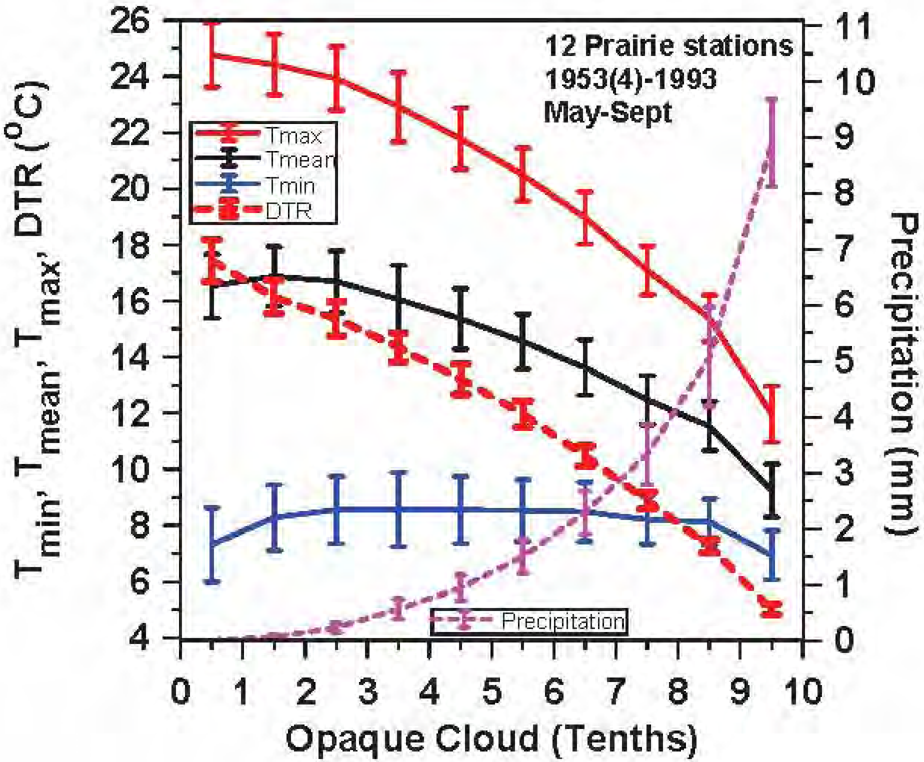


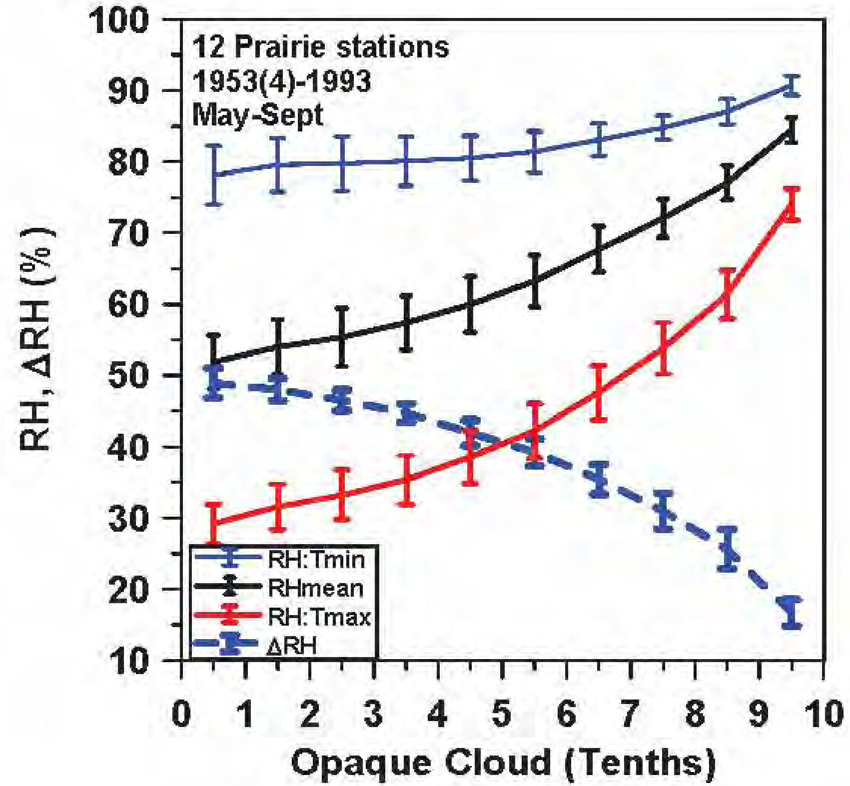
Annual Cycle: RH and ΔRH

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



Prairie Warm Season Climate





- **12 stations: small variability**
- **Variability in DTR and ΔRH *tiny***
- ***Structure same as Regina***

Surface Radiation Budget

- **Net radiation = net shortwave + net longwave**
- R_{net} = SW_{net} + LW_{net}

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

Define Effective Cloud Albedo (reflection)

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

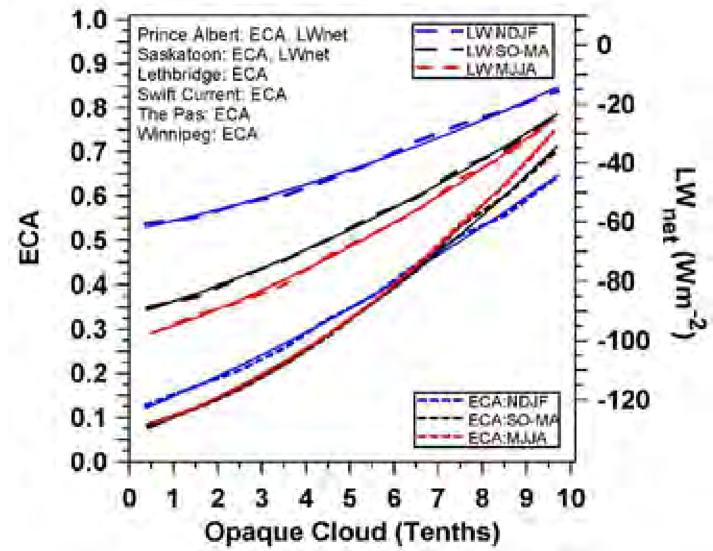
  Clear sky

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

  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

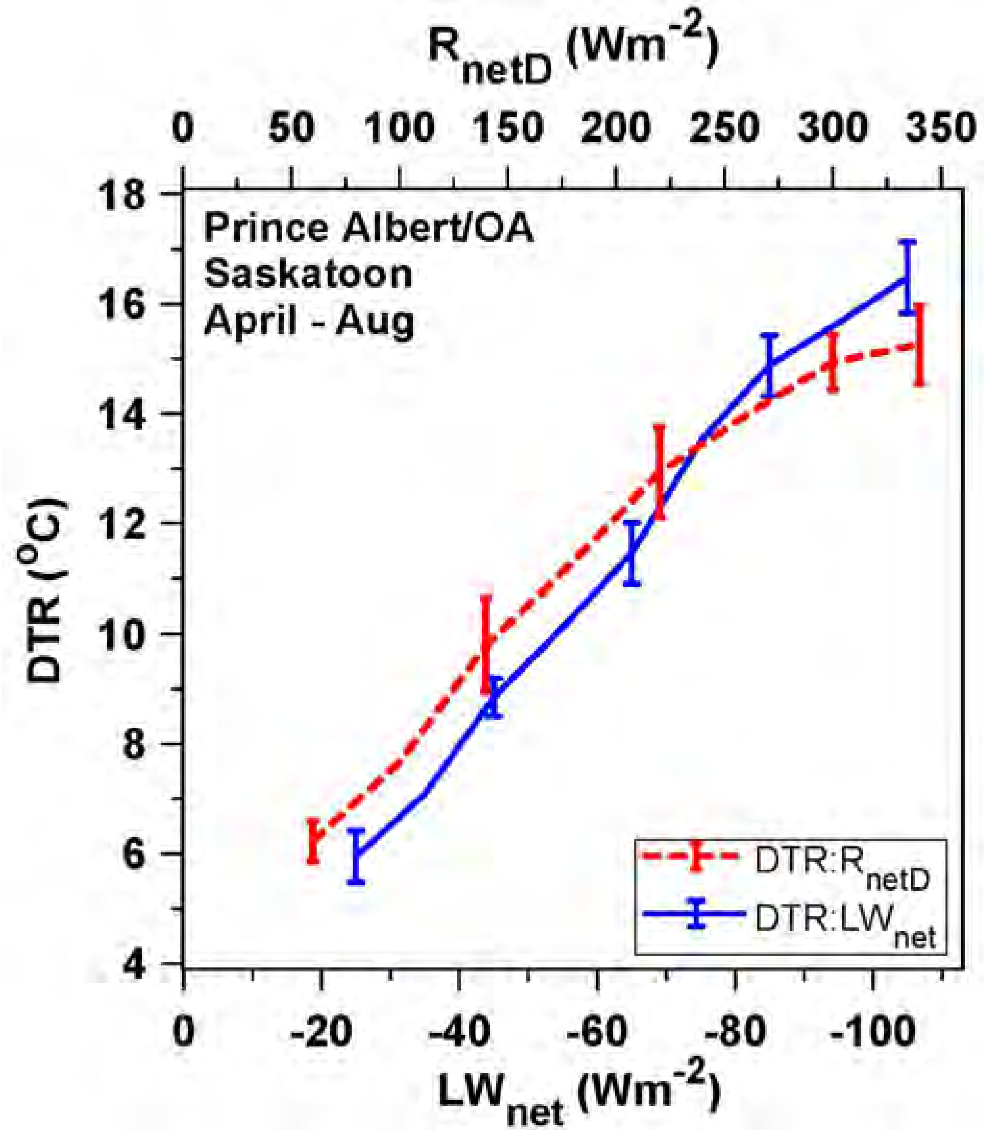
NDJF: LW_{net} = -63.0 + 3.14 Cloud + 0.193 Cloud^2

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_{netDay}**
- **Nighttime driver: LW_{net}**



(Betts JGR 2006)

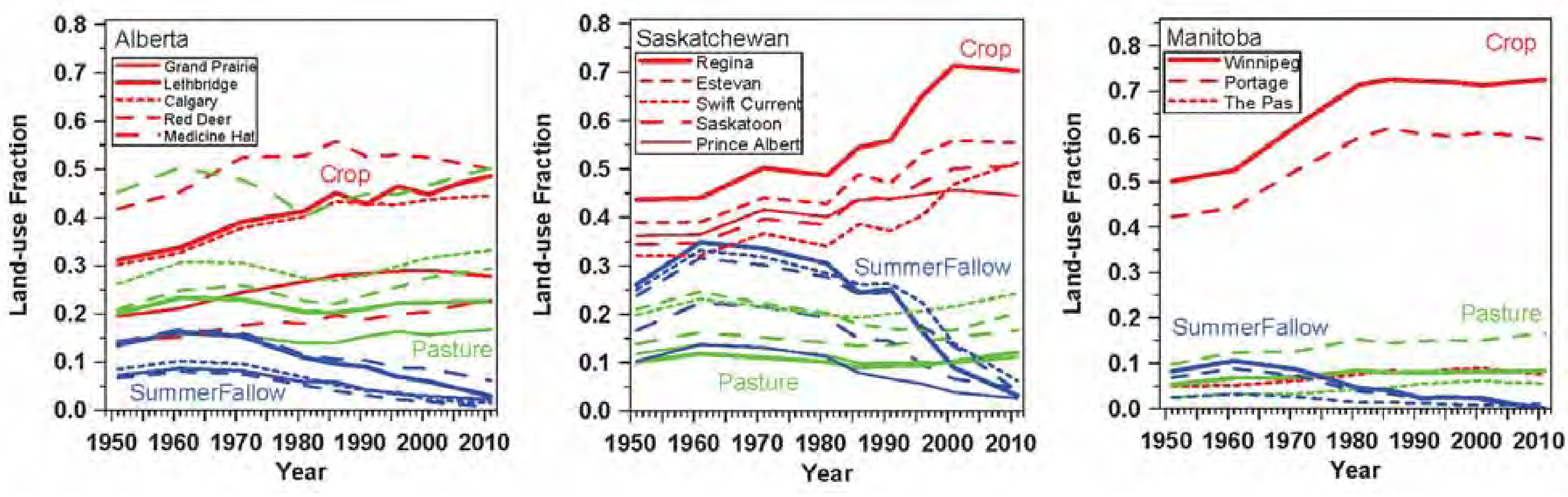
Annual crops and seasonal diurnal cycle

- **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***

14 Prairie stations: 1953-2011

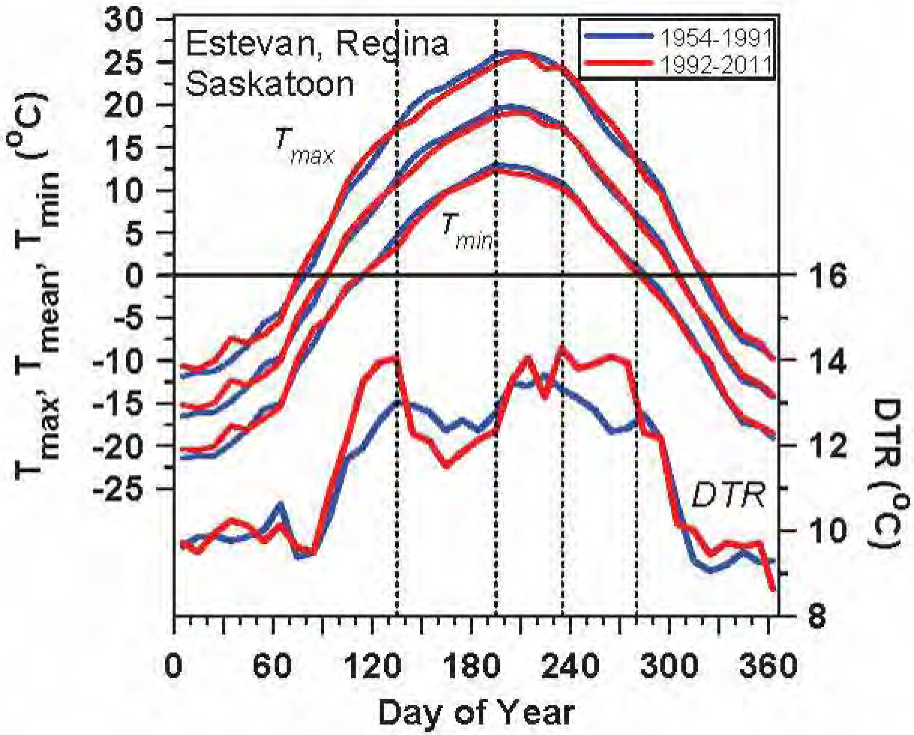
- **Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})**
- **Daily precipitation and snowdepth**
- **Ecodistrict crop data since 1955**
- **Albedo data (MODIS: 250m, after 2000)**

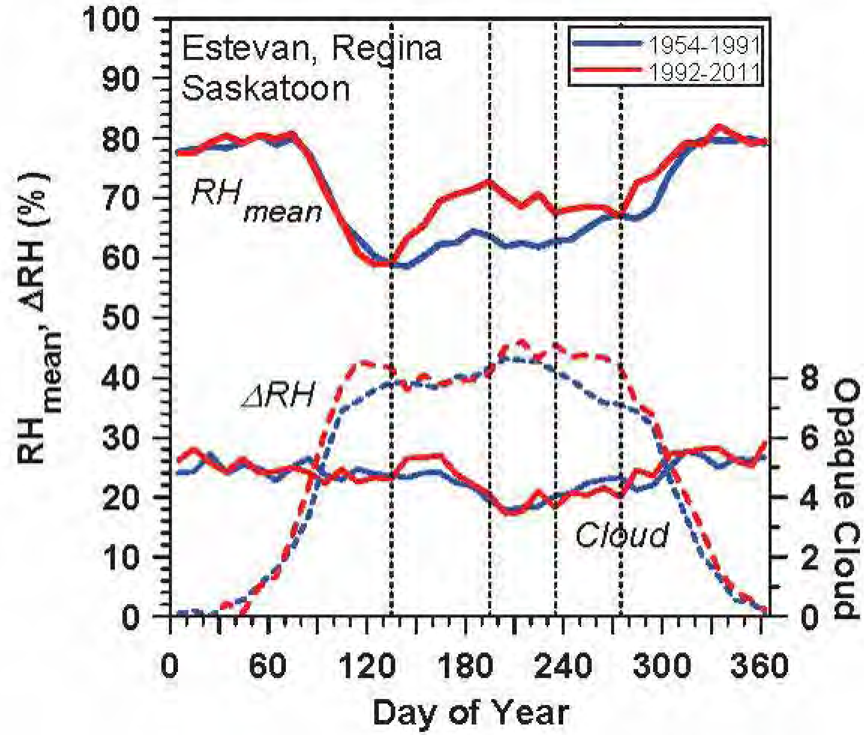
Change in Cropping



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

Three Station Mean in SK



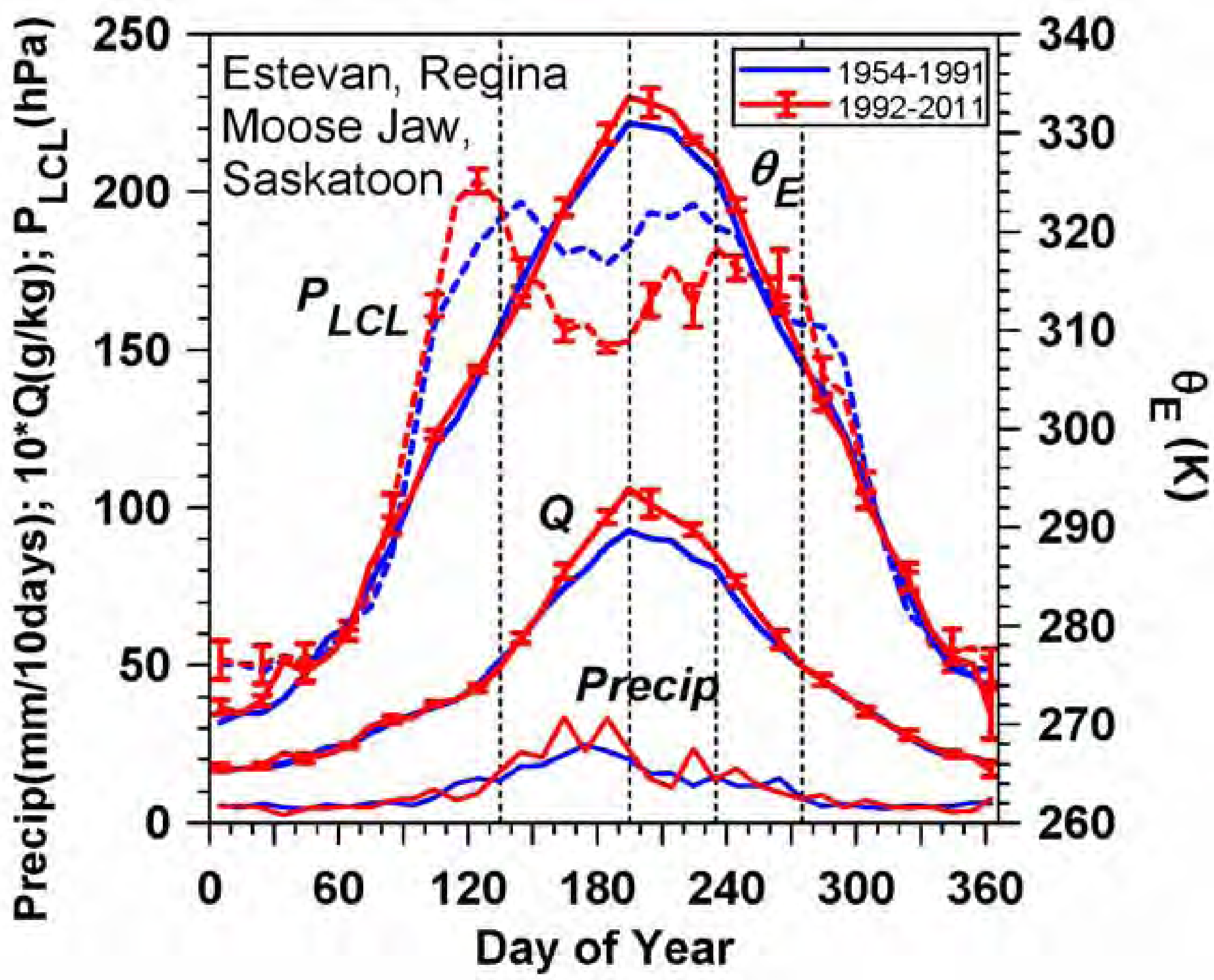


- **Growing season**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal structure changes**

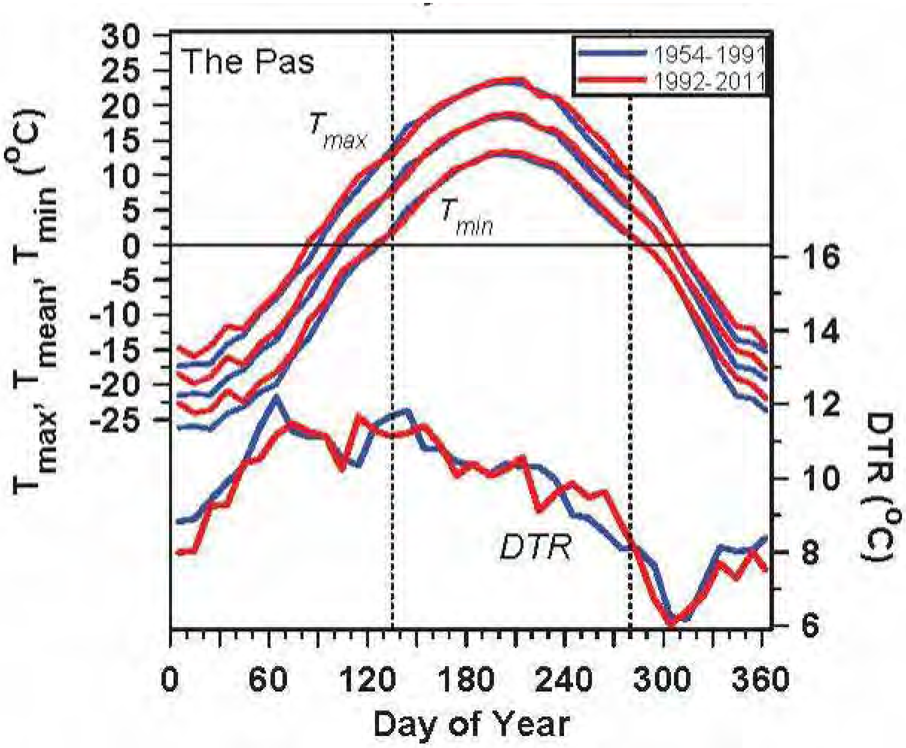
Impact on Convective Instability

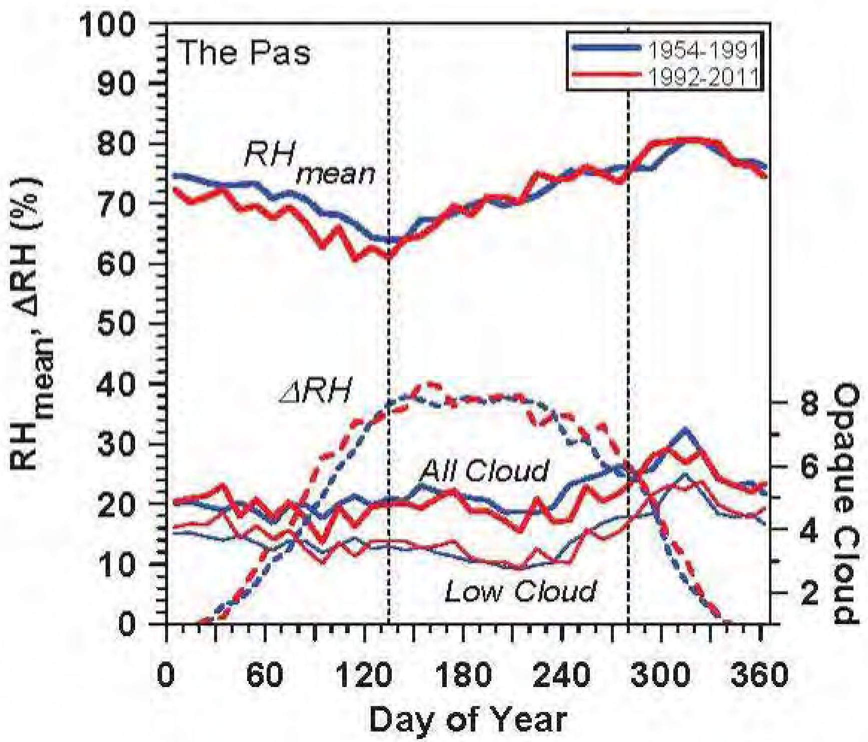
Growing season

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



Contrast Boreal Forest





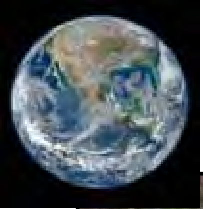
- **No RH, DTR signal**

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'

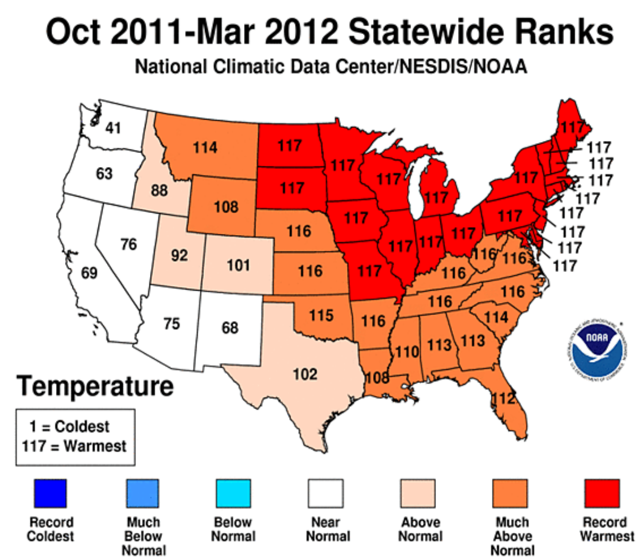


January 2, 2012

March 11, 2012

October 2011– March 2012

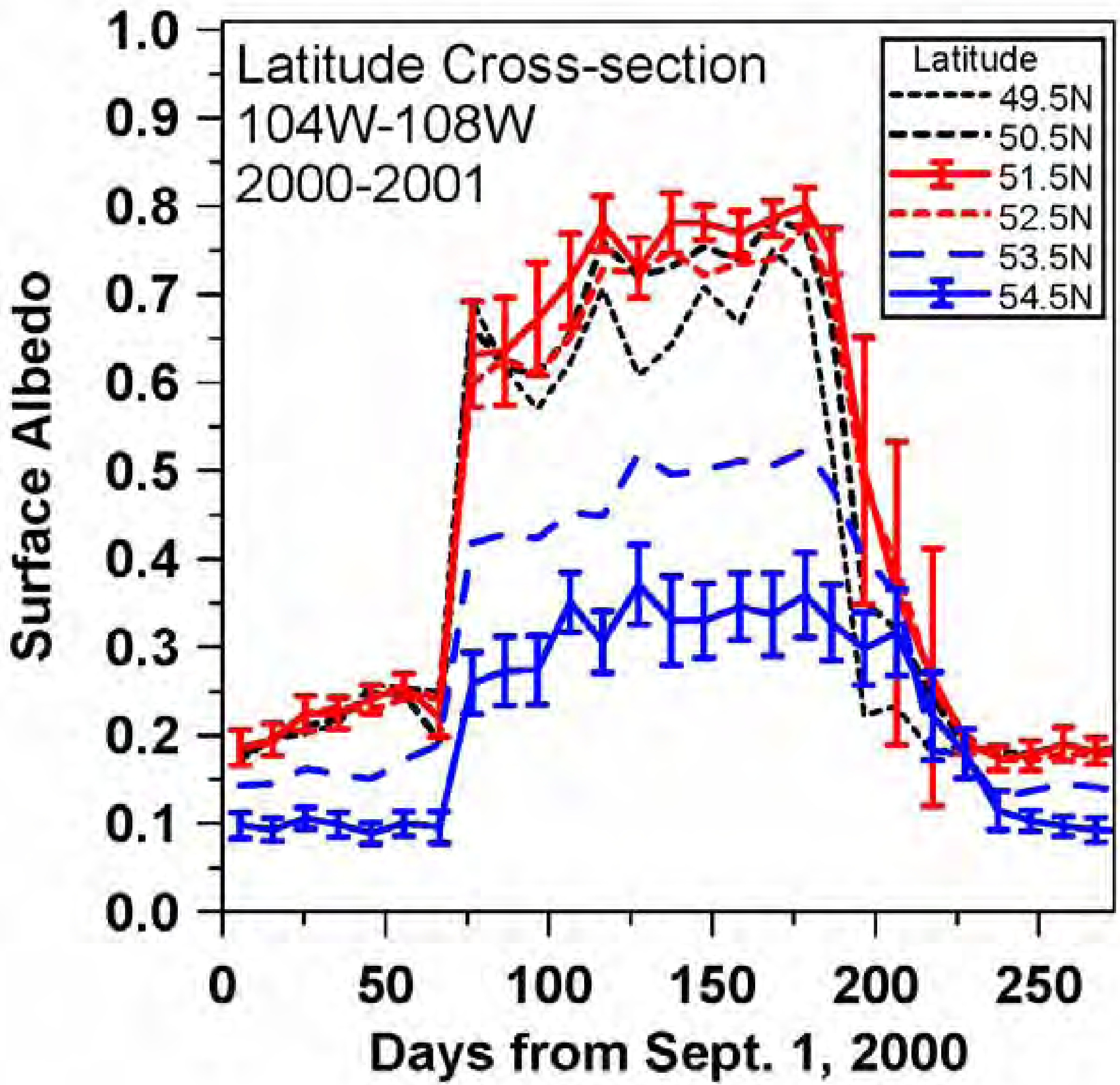
- **Warmest 6 months on record**
- **My garden frozen only 67 days**
- **No permanent snow cover west of Green Mntns**
- **Contrast snowy winter 2013-14**



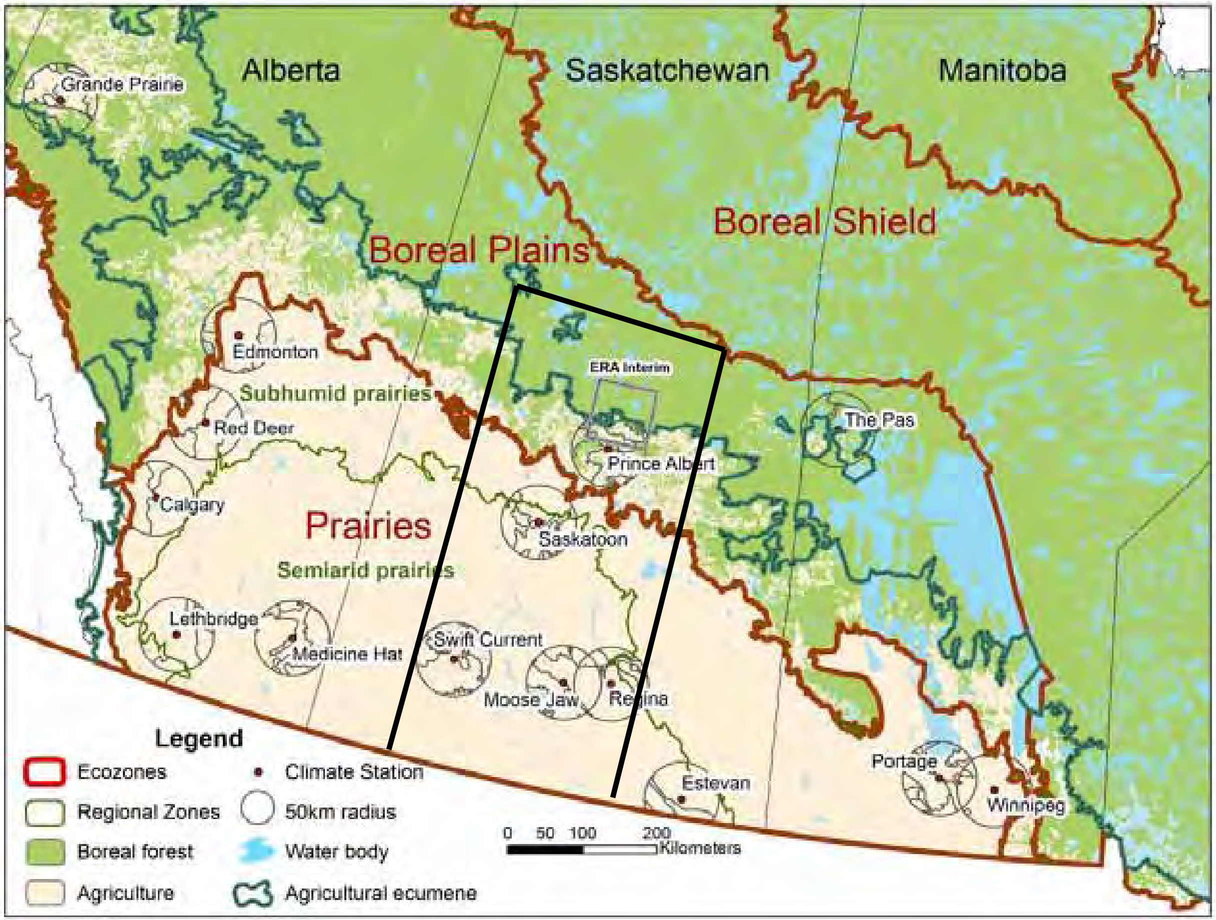
N-S Albedo through Winter

- **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***

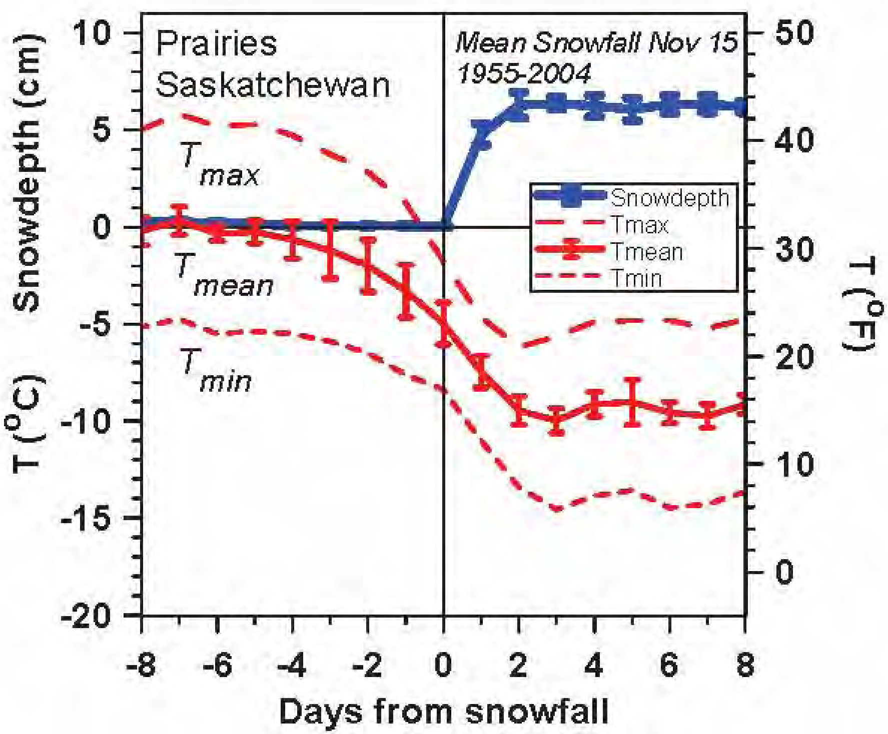


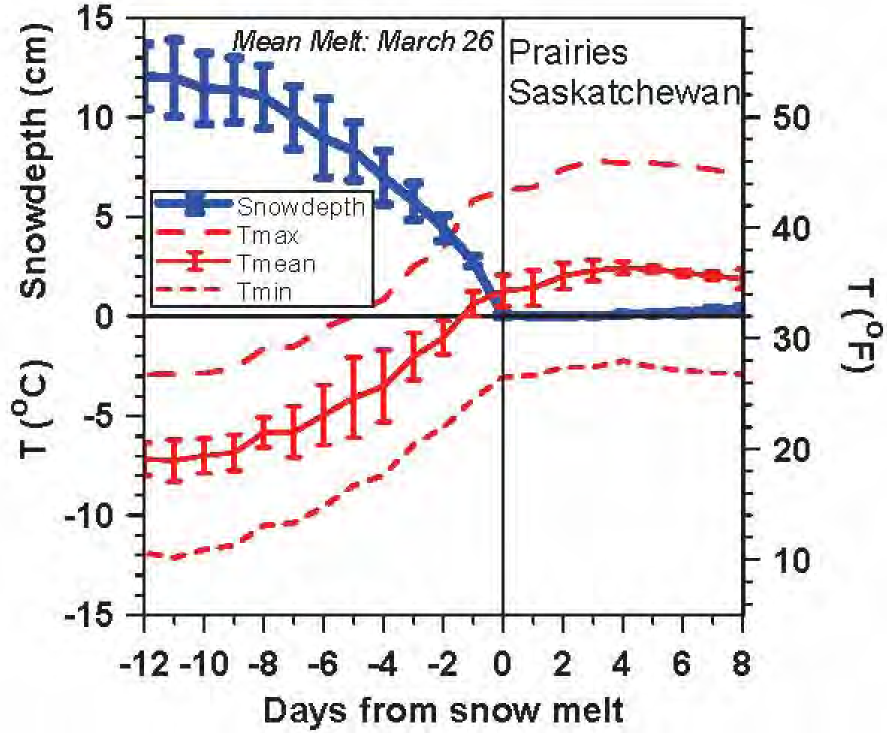
14 Prairie stations: 1953-2011



- **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: 250m, after 2000)**

Snowfall and Snowmelt
Winter and Spring transitions

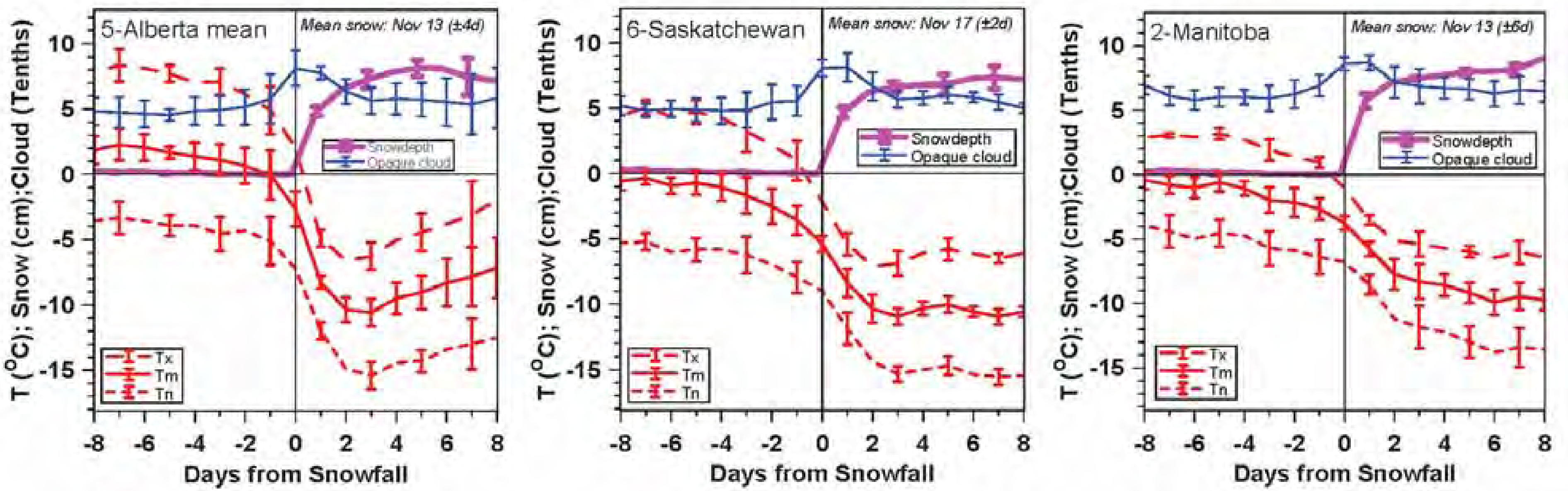




- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms 'local climate'***
  - ***Same feedbacks that are speeding Arctic ice melt in summer***
  - ***Local climate switch between warm and cold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

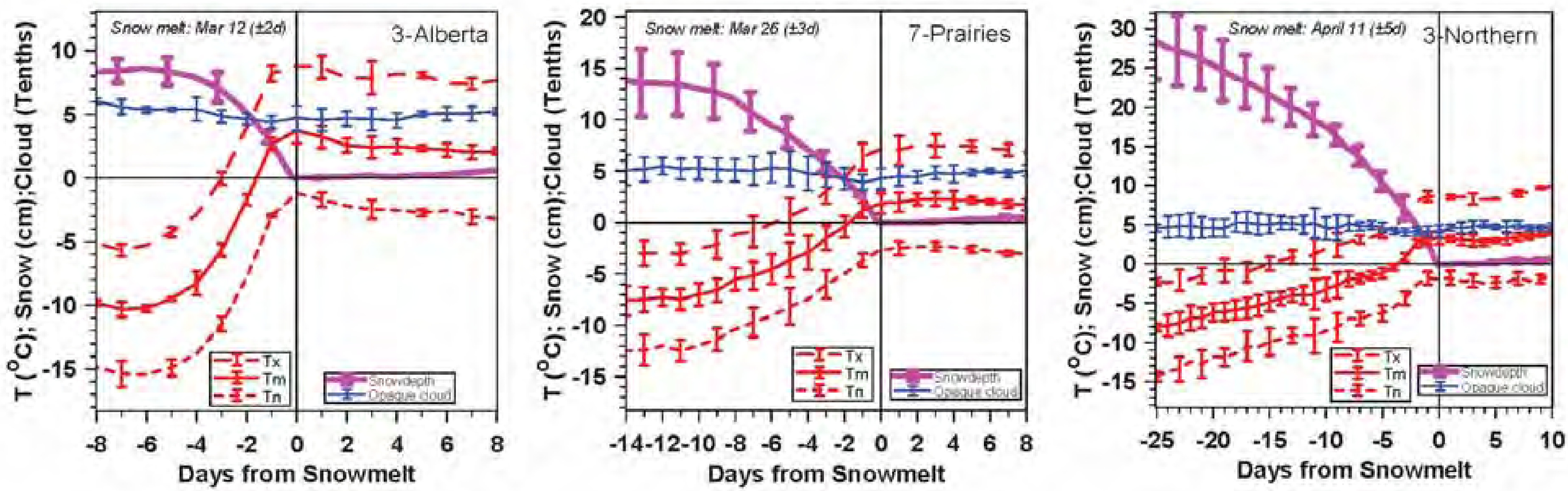
Betts et al. 2014

Fall Snow Transition Climatology



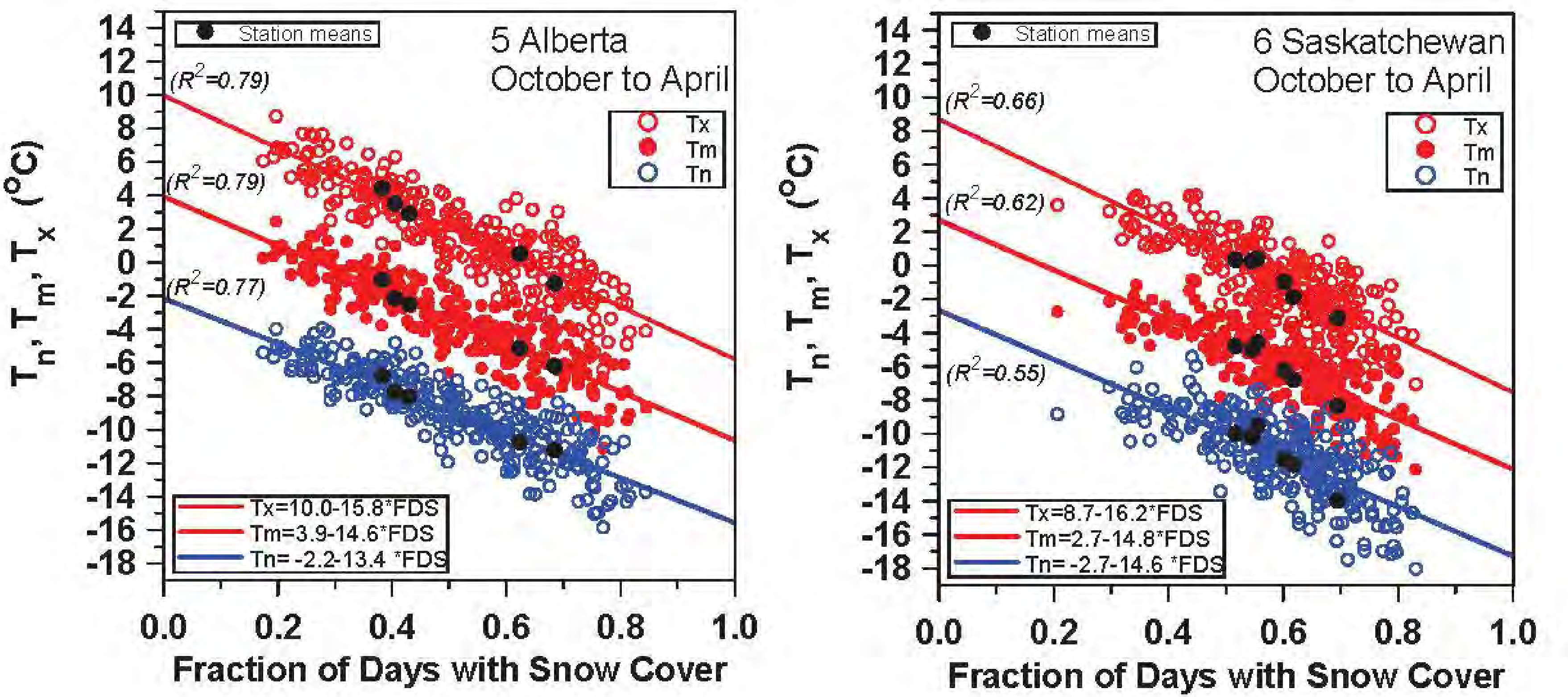
- T_x, T_m, T_n fall about 10K
- **Cloud peaks with snow; increases ≈10%**
- Snow date: Nov 15 ± 3 days

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



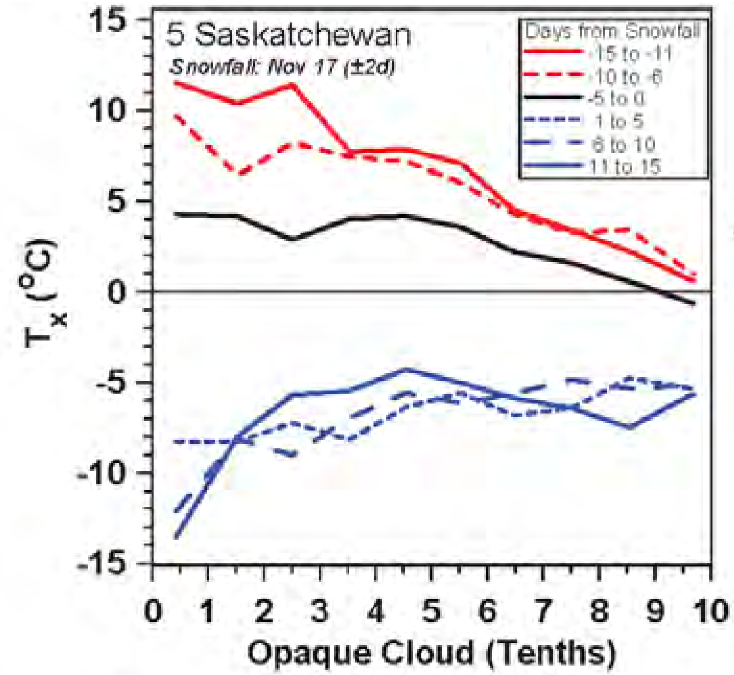
- **Alberta: 79% of variance**
- **Slopes**
  - **T_x -16.0K**
  - **T_m -14.7K**
  - **T_n -14.0K**

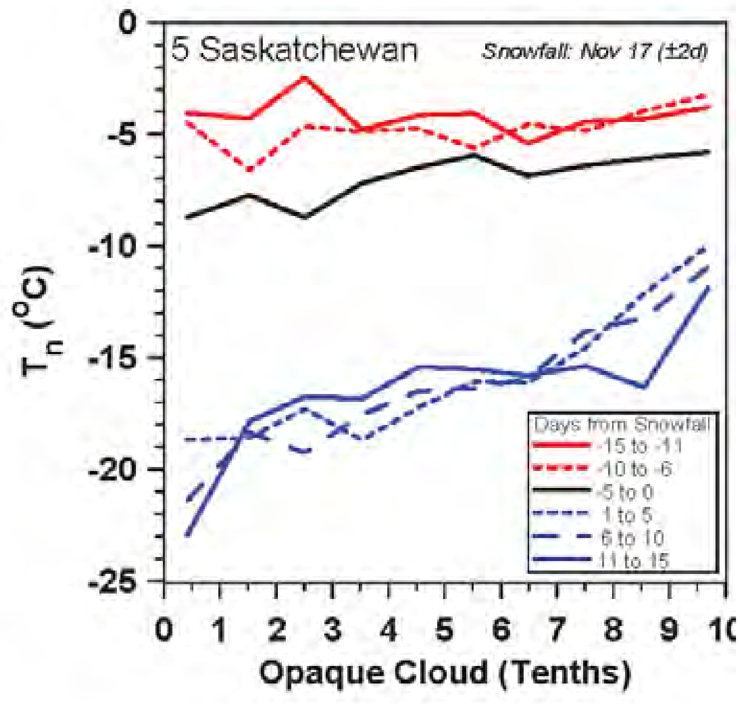
10% fewer snow days

= 1.5K warmer

Coupling to Cloud Cover Across Snowfall

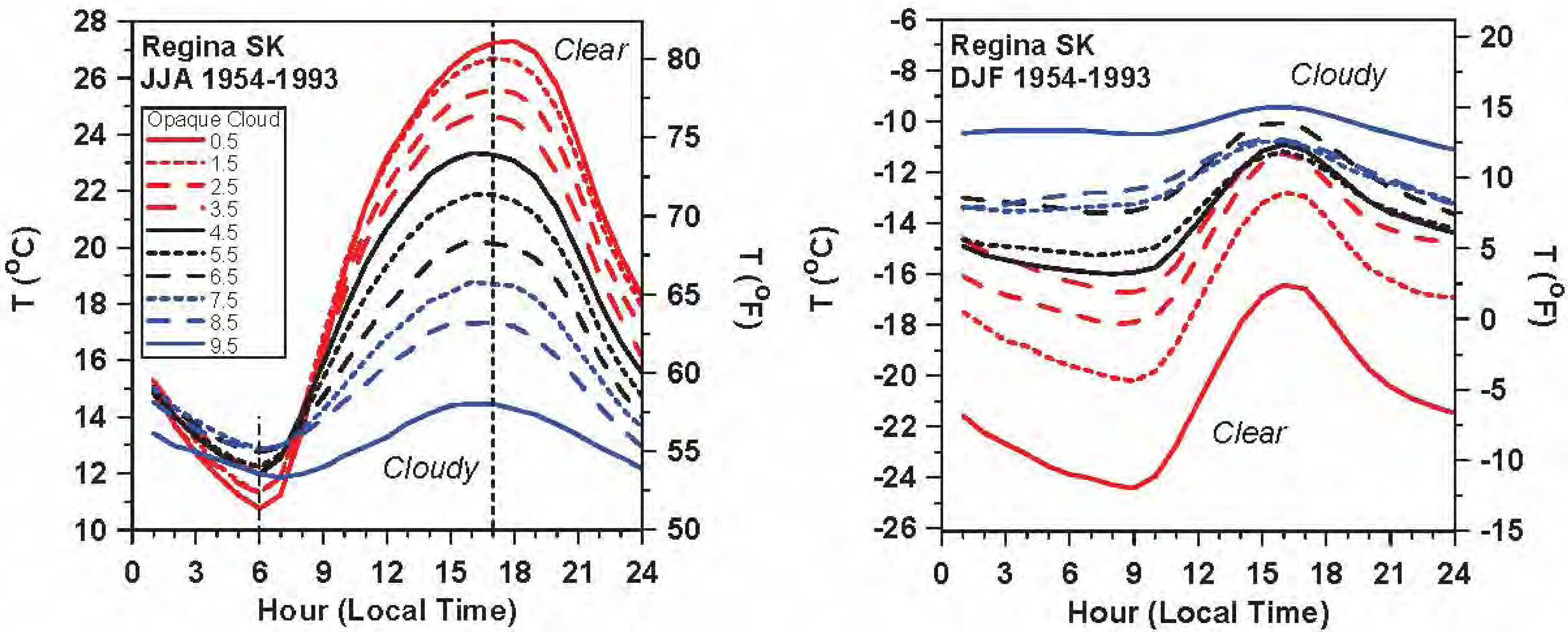
- **Mid-November**
- **5-day means**
  - *red: no snow*
  - *blue: snow*
- **With snow**
  - **T_x, T_n plunge**
- **Cloud coupling shifts in 5 days**
  - **from 'Warm when clear' to 'Cold when clear**
  - **"SWCF to LWCF"**





Clouds: Summer & Winter Climate

Opposite Impact



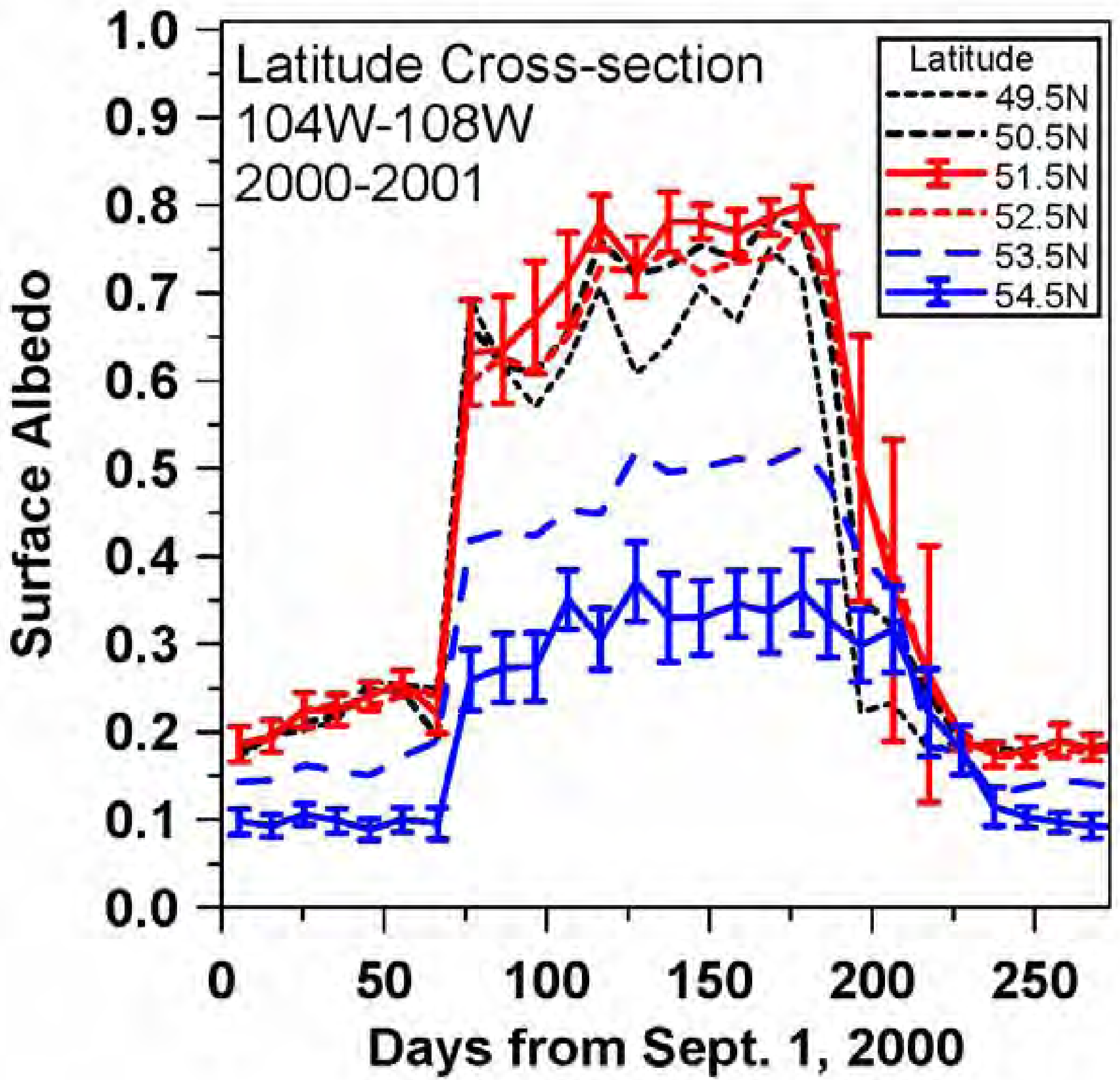
- **Summer: Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
  - **Convective boundary layer in daytime**
- **Winter: Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**
  - **Stable boundary layer**

Betts et al. 2013a

N-S Albedo through Winter

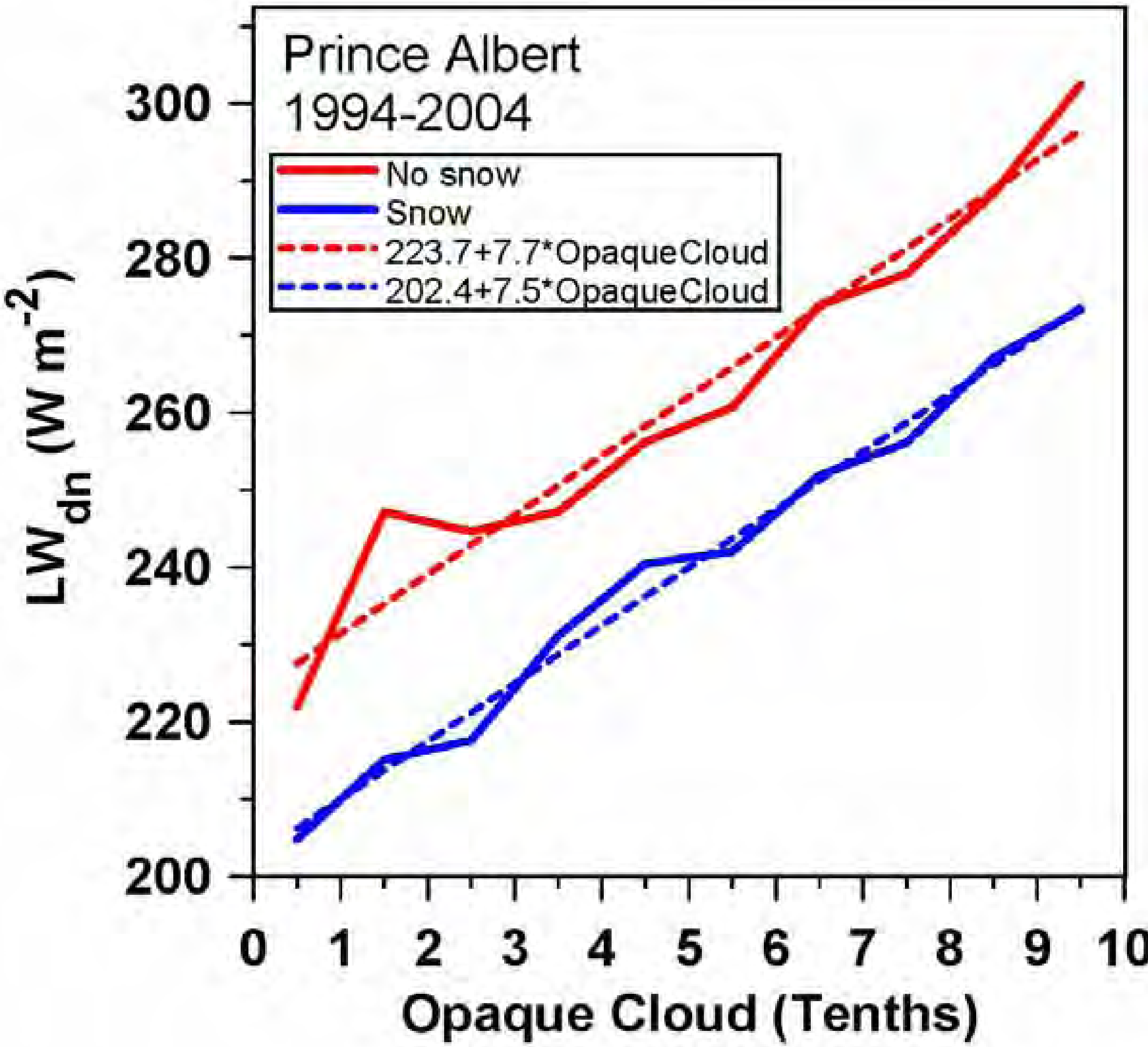
- **Prairies**
  α_s: **0.2 to 0.73**
- **Boreal forest**
  α_s: **0.1 to 0.35**

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



Role of LW_{dn} in Surface Radiation

- **Snow reduces vapor flux**
- **Atmosphere cooler and drier**
  - **Less watervapor 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: $\Delta LW = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)

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**
  - **Feedback increases precipitation**
- **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

Outline Revisited

- **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 (2014)***

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

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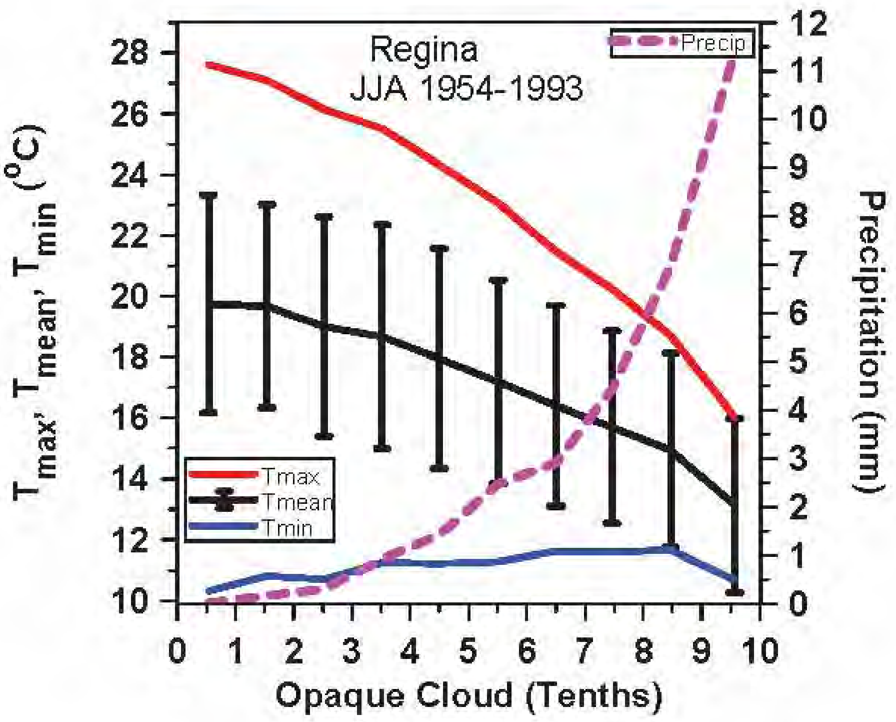
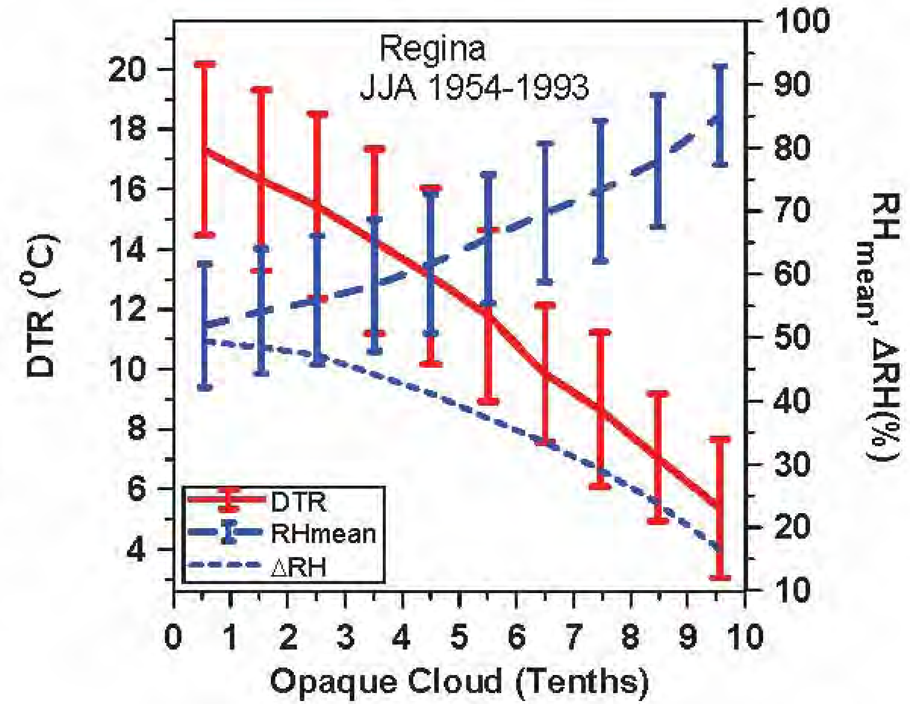
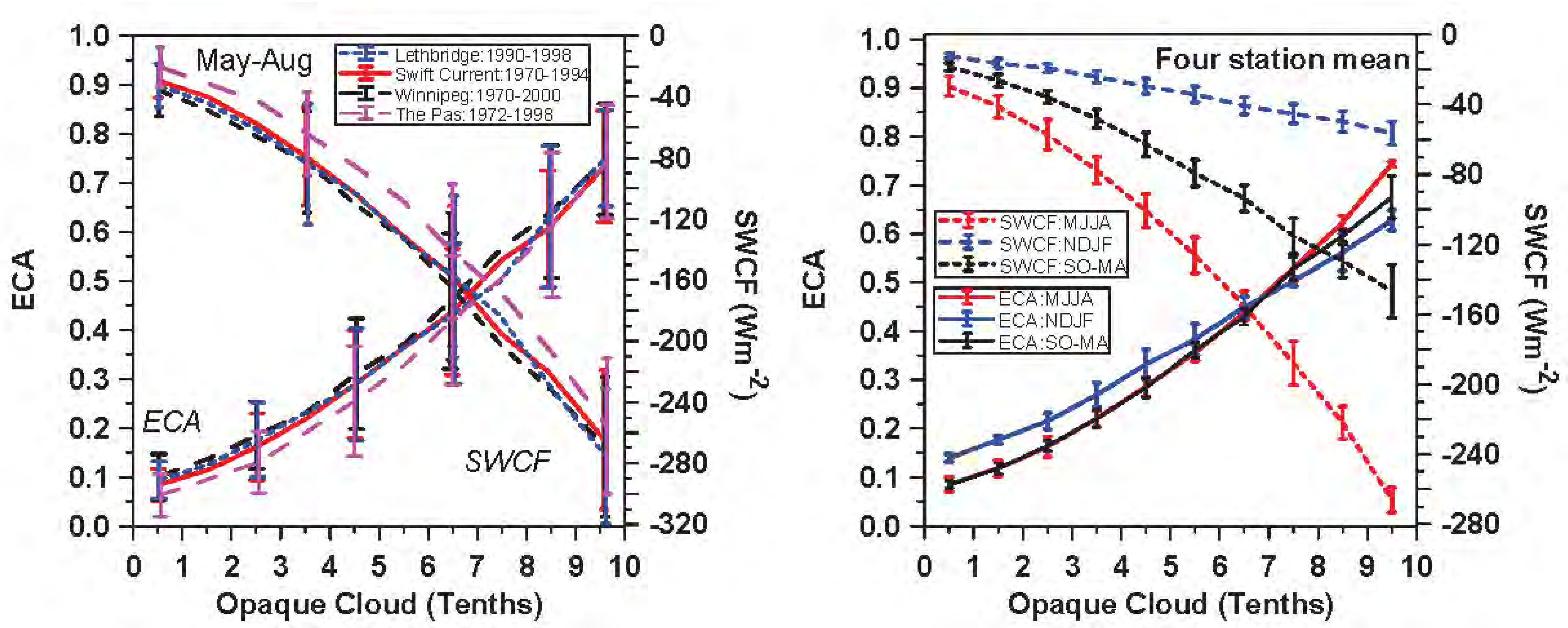
Summer Diurnal Cycle Climate





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

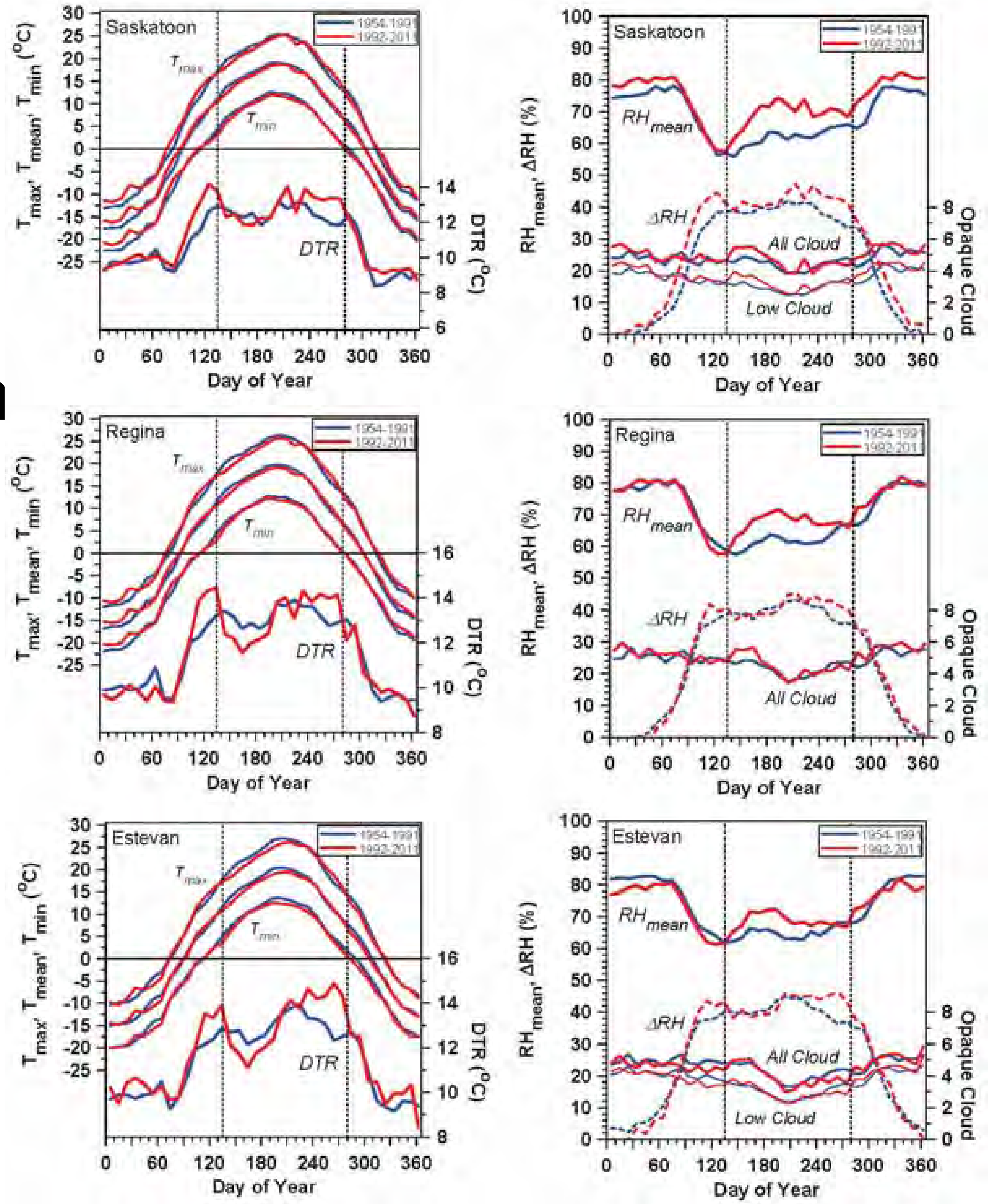
Calibration of Opaque Cloud to ECA-Effective Cloud Albedo



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

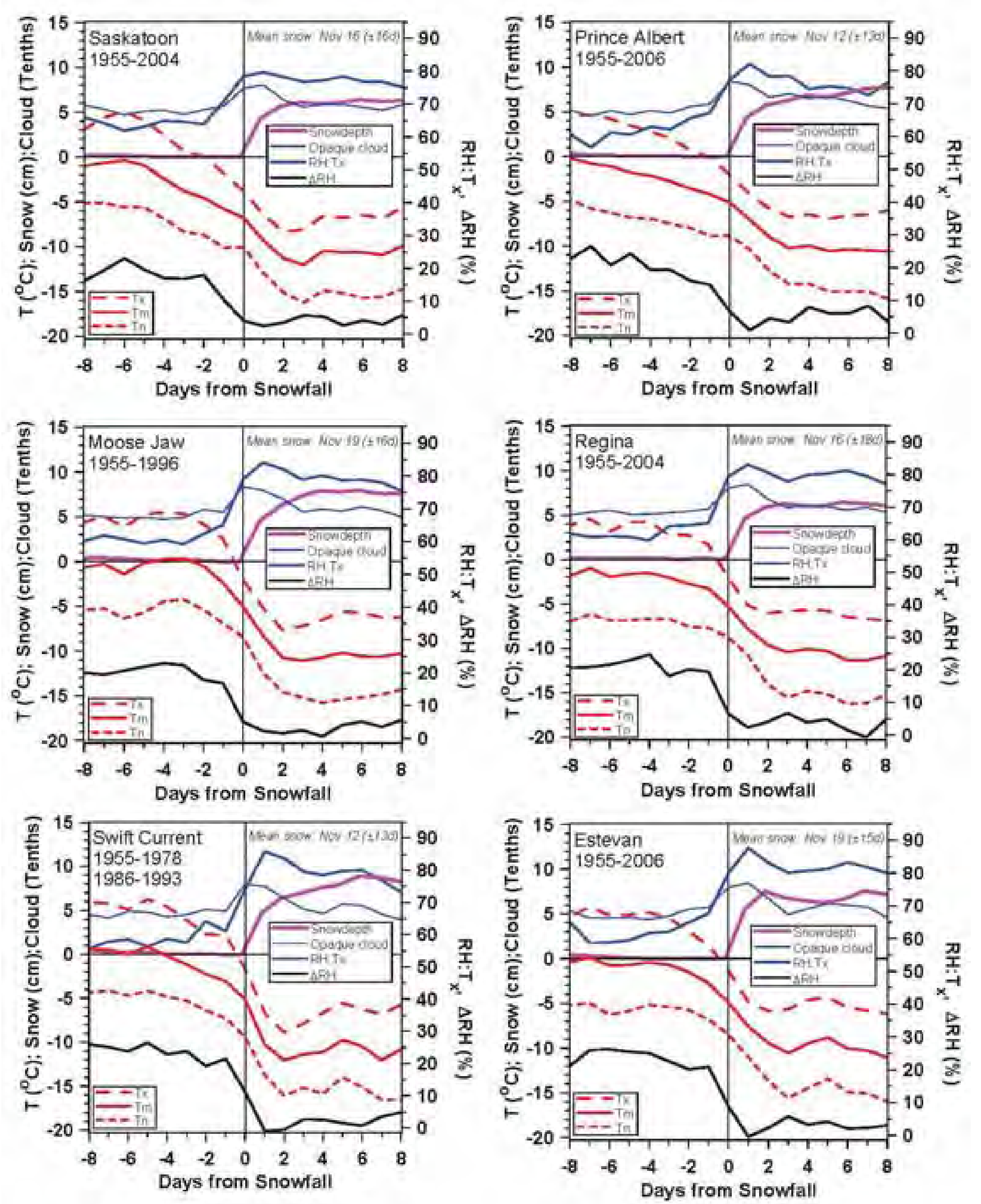
Diurnal Climate Change

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



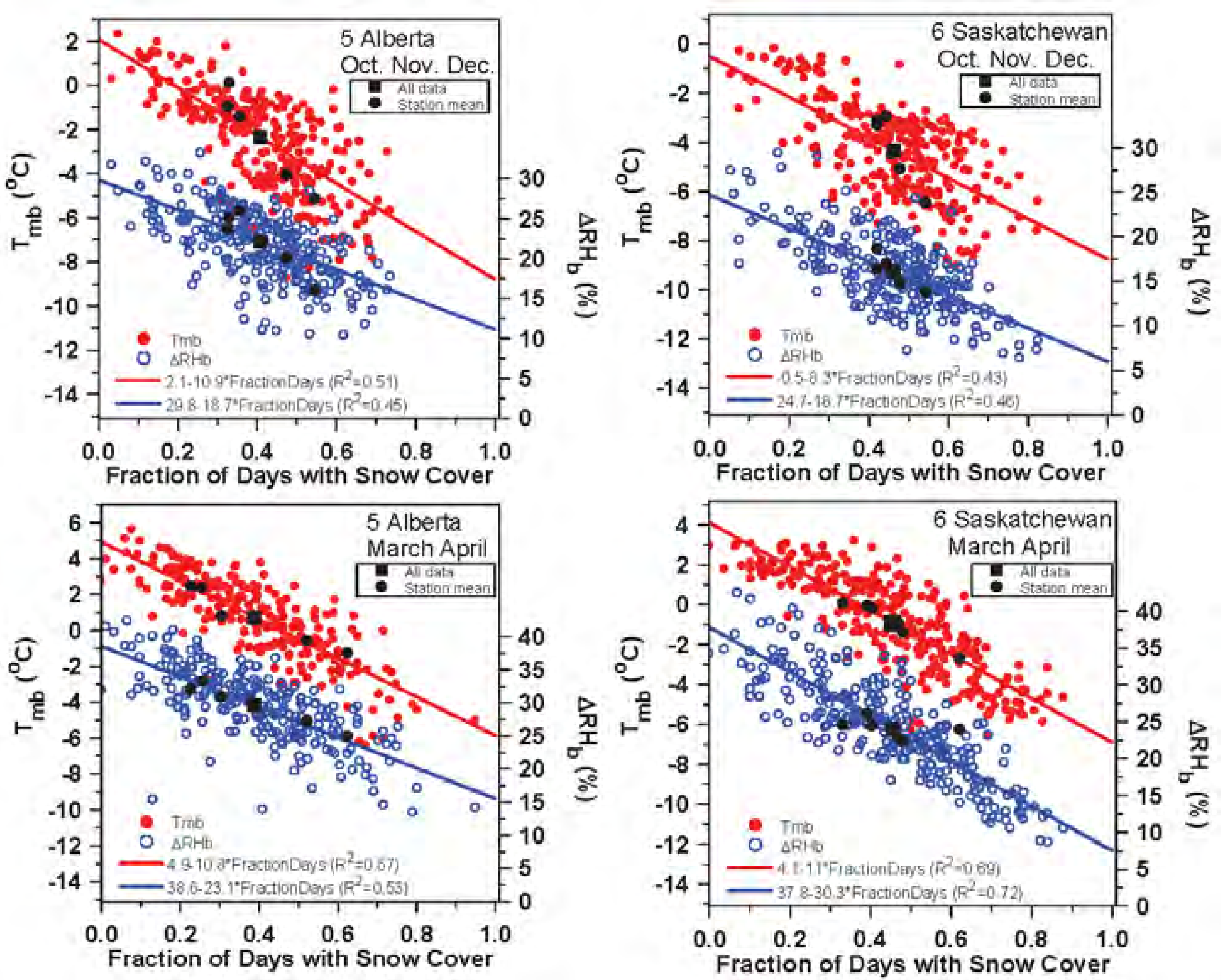
6 Stations in Saskatchewan

- 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**



Communicating Climate Science

Background *(alanbetts.com)*

- **Betts, A. K. (2011)**, Communicating Climate Science. EOS Trans. AGU, 92 (24), p. 203
- **Betts, A.K. and E. Gibson (2012)**, Environmental journalism revisited. Ch. 41, pp. 382-390
- **Betts, A.K. (2011)**: Vermont Climate Change Indicators. Weather, Climate and Society, 3, 106-115
- **Climate, Energy and Community: Vermont 2013**
  - ***alanbetts.com/writings***

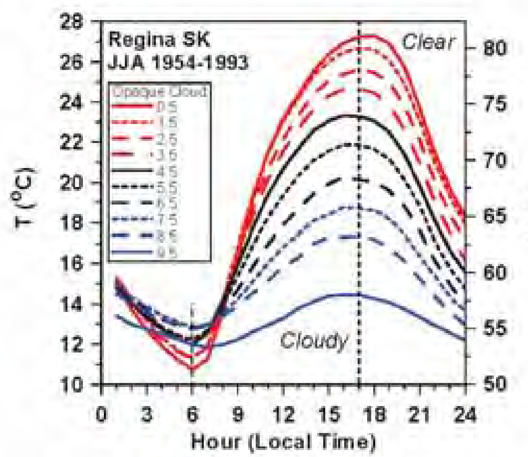
Daily Mean Climate vs Long-term Diurnal Mean

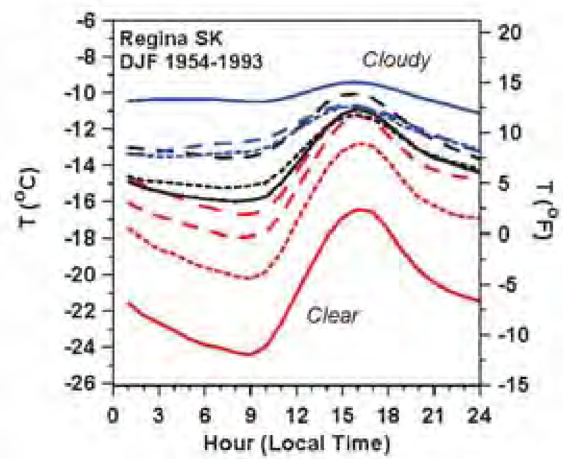
- *Definitions*
  - **DTR = T_x - T_n**
  - **ΔRH = RH:T_x – RH:T_n**

Monthly mean diurnal cycle

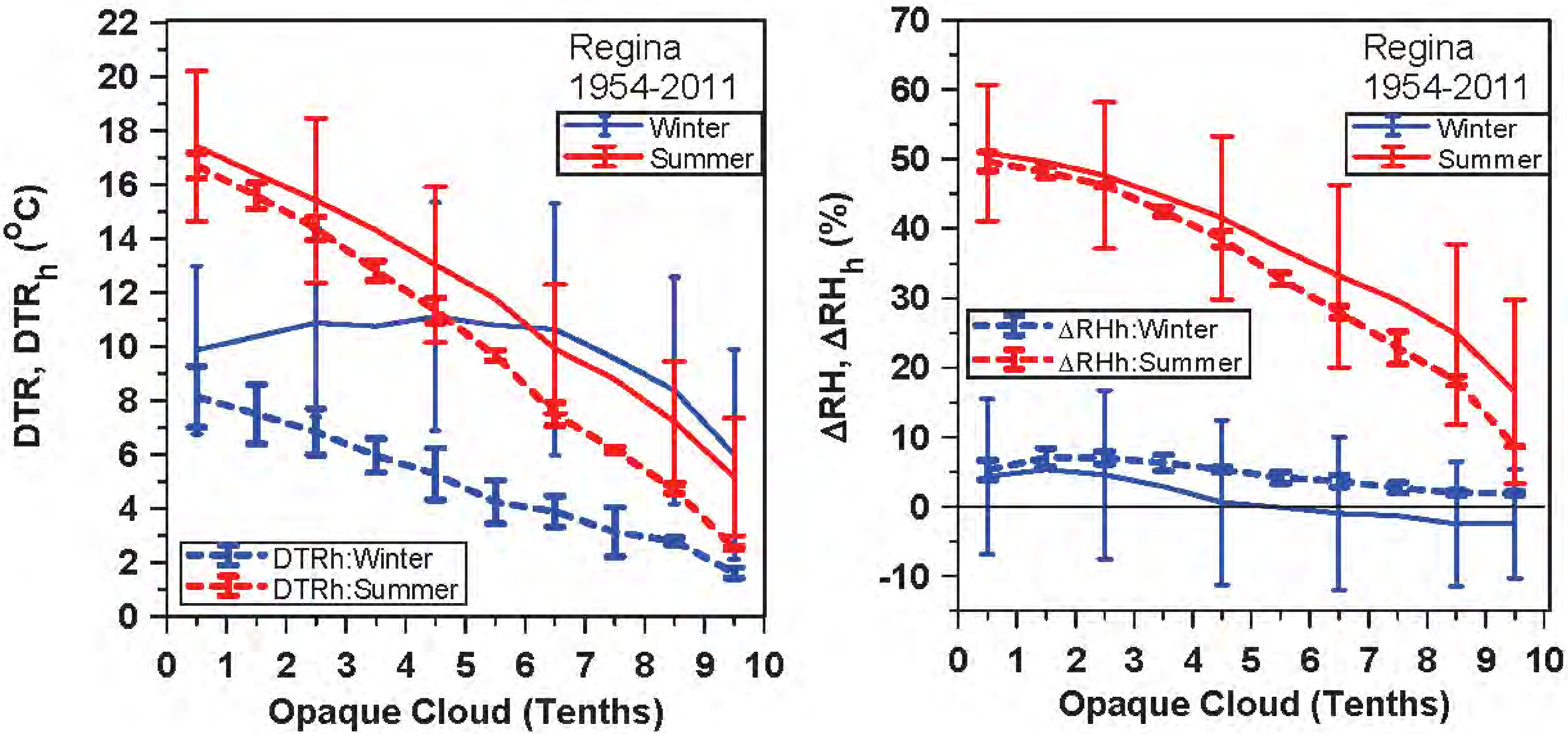
  - **DTR_h = T_{xh} – T_{nh}**
  - **ΔRHh = RH_{xh} – RH_{nh}**

Radiatively forced signal small in winter compared to daily advection



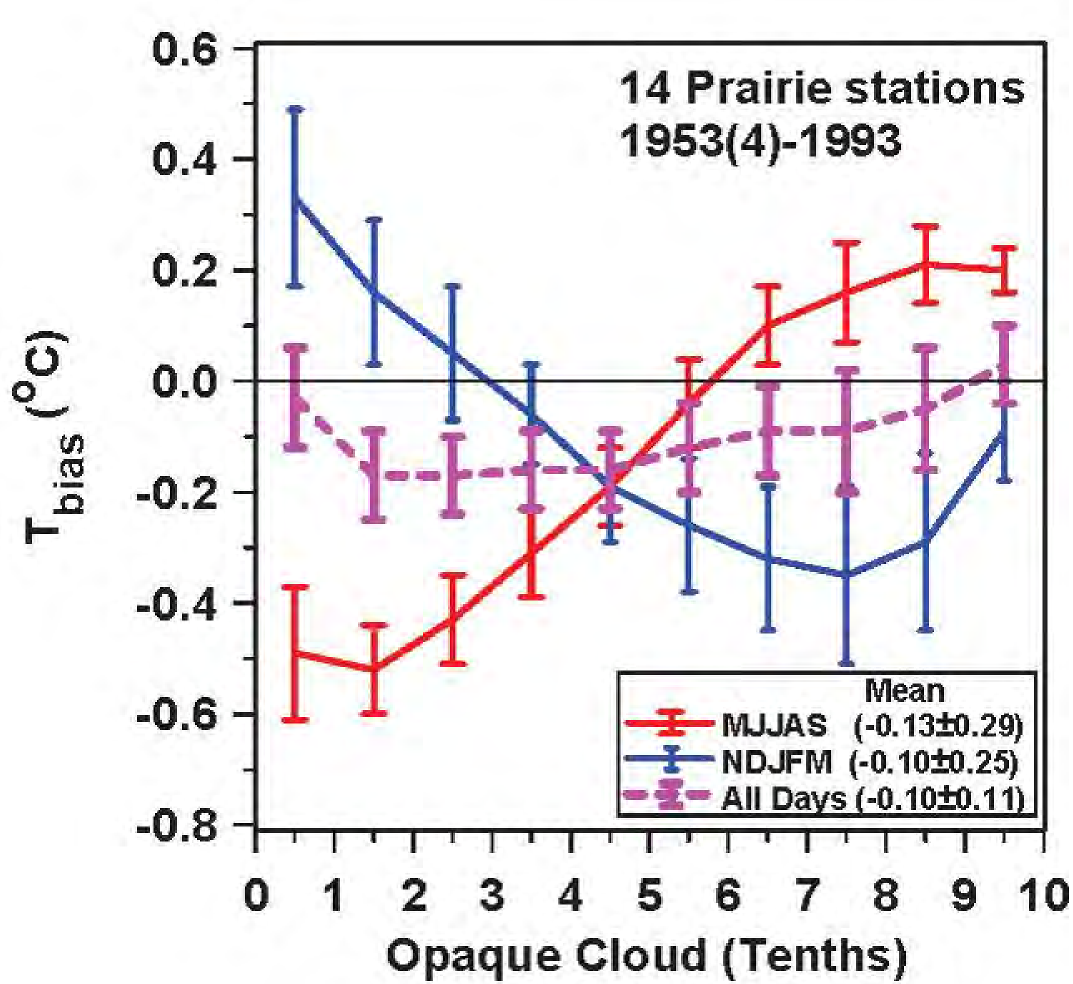


Daily Mean Climate vs Monthly Diurnal Mean Climate



- 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**