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

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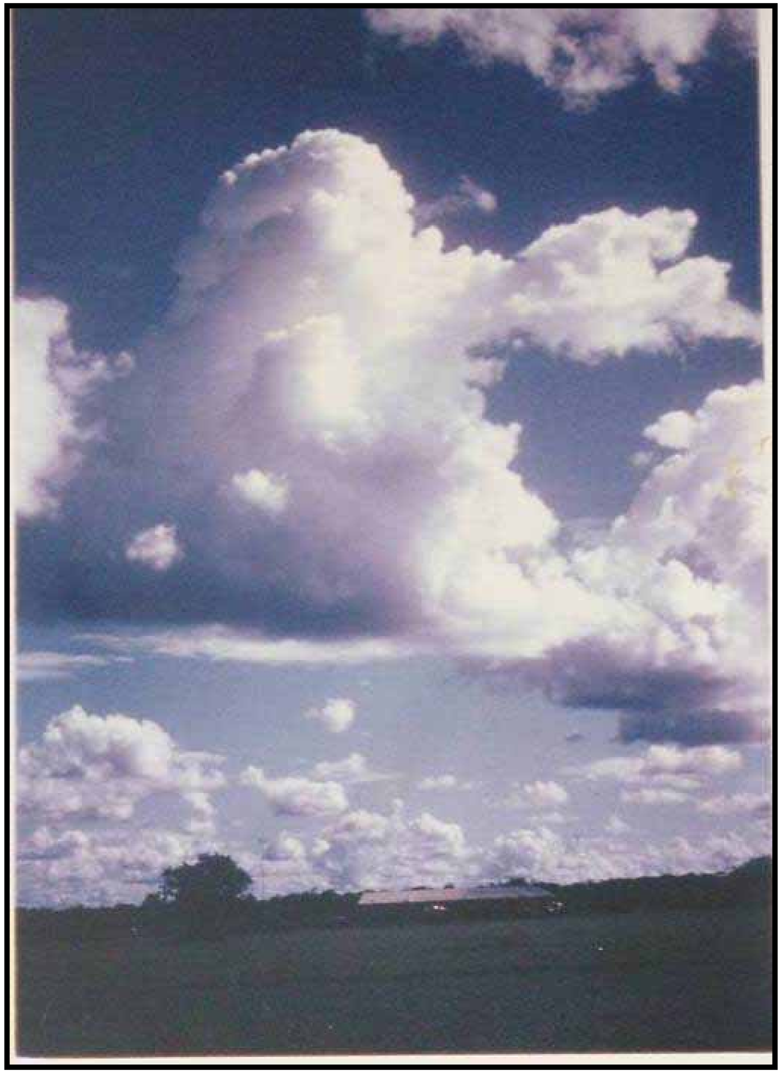
1969: Barbados to Venezuela



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***
- ***"Understanding Climate Change" "Advise Vermont"***

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)**

O (Madison)

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)***

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*., doi:10.1002/jgrd.50904 (in press)**
- **Betts, A.K., R. Desjardins, D. Worth, Shusen Wang and Junhua Li (2014), Coupling of winter climate transitions to snow and clouds over the Prairies** (JGR 2013JD021168 submitted)

Methods: Analyze Coupled System

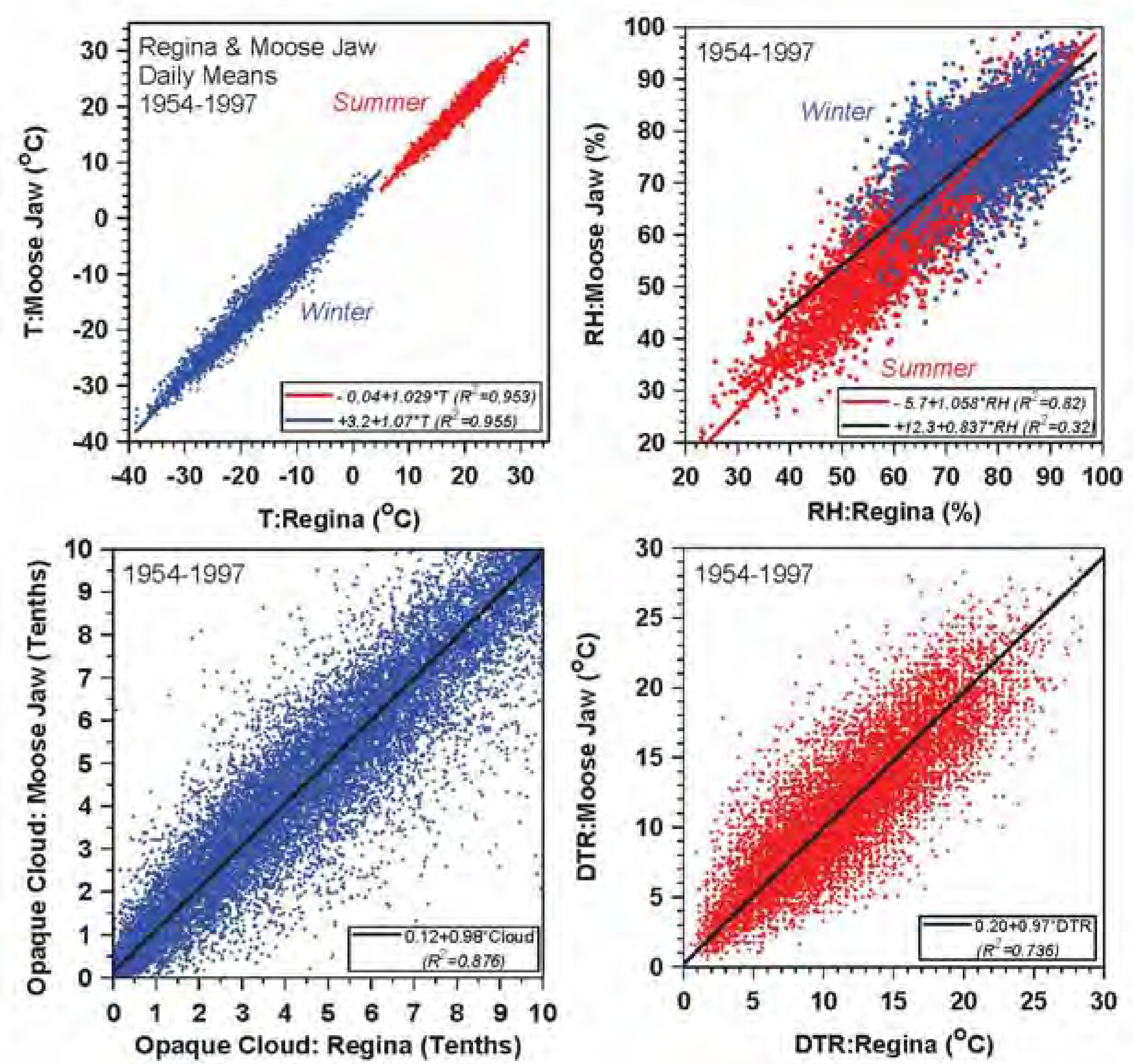
- *Seasonal diurnal climate by station/region*
- 220,000 days of excellent data (600+ years)
- Composite by daily mean opaque cloud
  - Calibrate SWCF, LWCF against radiation data
    - Sub-stratify by RH
- Change of seasonal climate with cropping
  - Summerfallow to annual crops on 5MHa in 30 yrs
  - Comparison with ERA-Interim grid-box
  - Drydown after precipitation events
- 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 mean, $T_{mean)}$ + data at T_{max} and T_{min}**
- ***Definitions: Diurnal cycle climate***
  - **DTR = T_{max}-T_{min} *(T_x-T_n)***
  - **ΔRH = RH:T_x – RH:T_n**
- **Almost no missing data *(until government cutbacks*!), reject a day if <23h data**

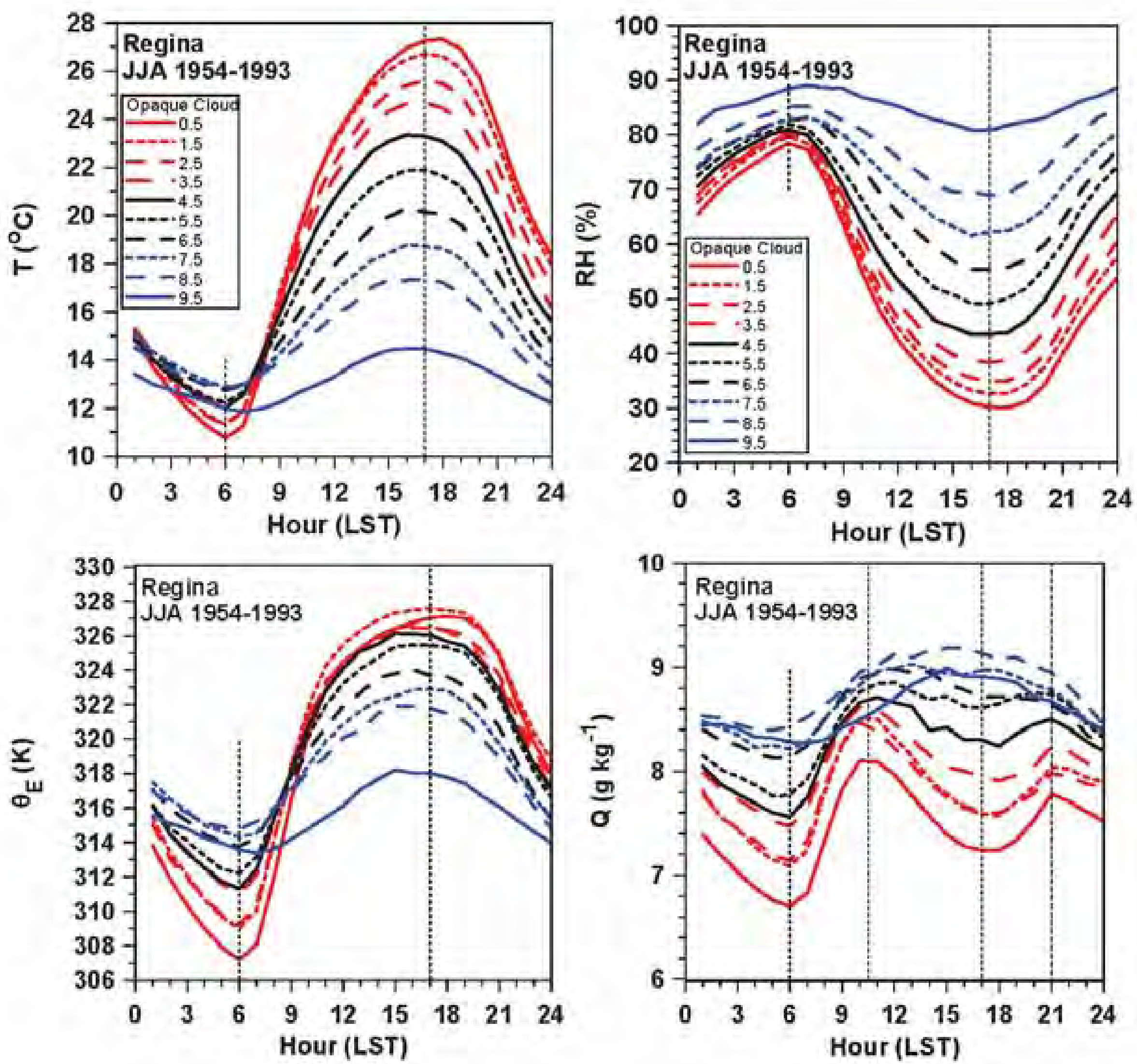
Compare Neighbors: 64 km

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



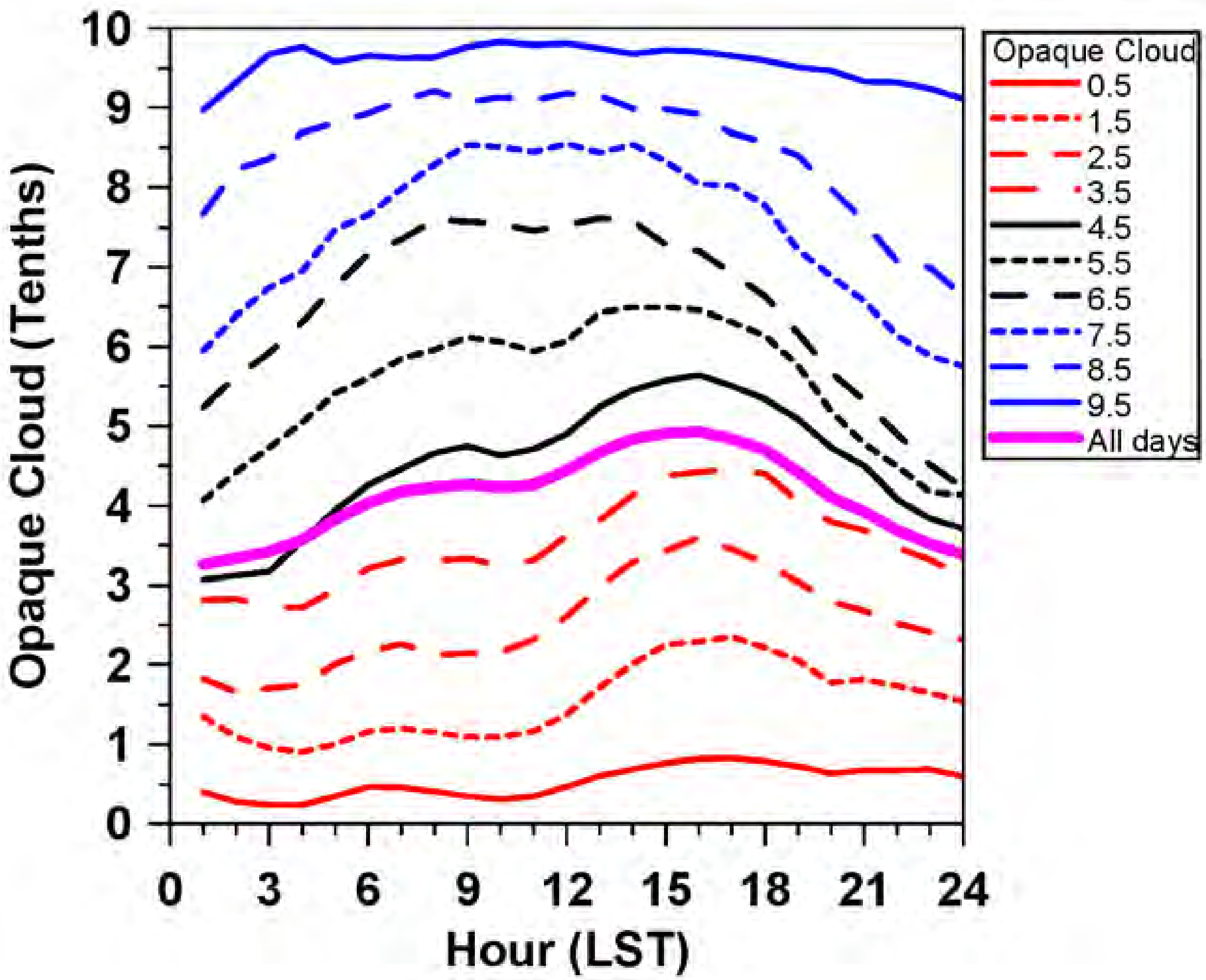
Clouds to Summer Diurnal Cycle

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

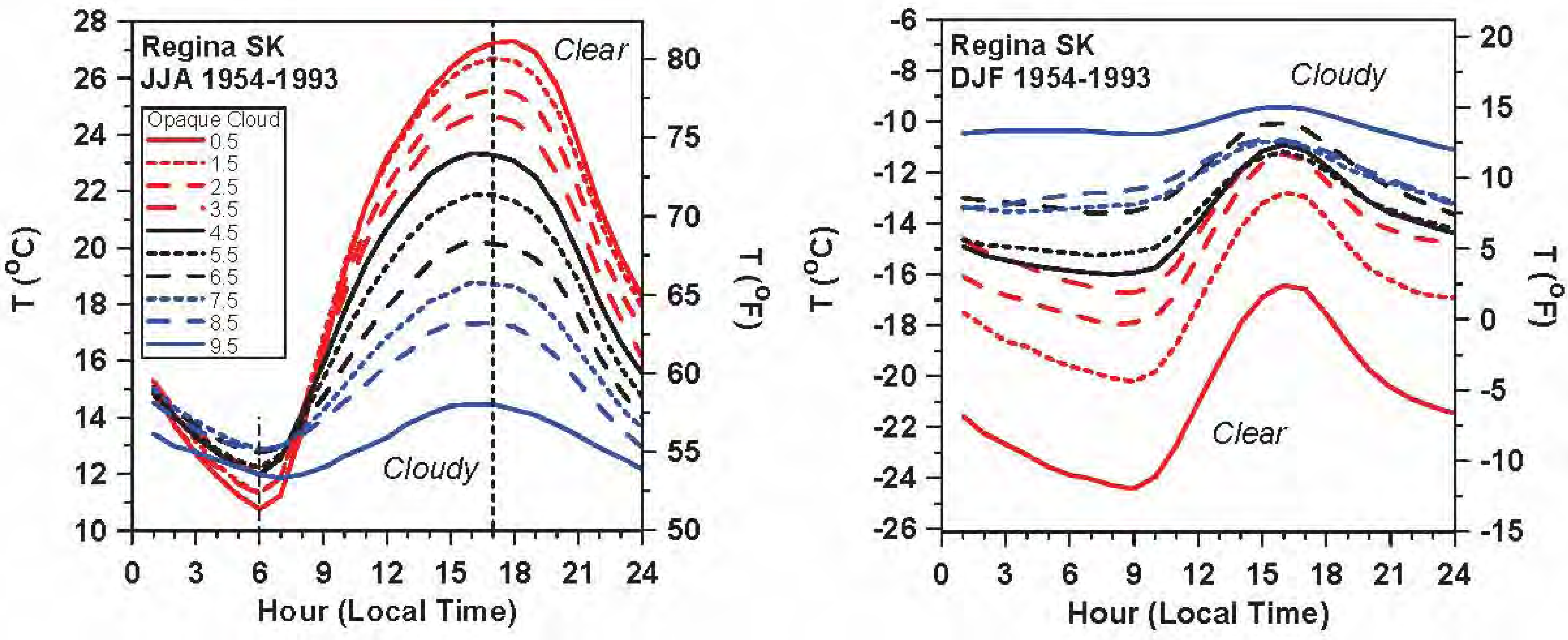


Diurnal Cycle of Cloud Cover

- **Noon peak for >6/10s**
- **Afternoon broken Cu for <6/10**



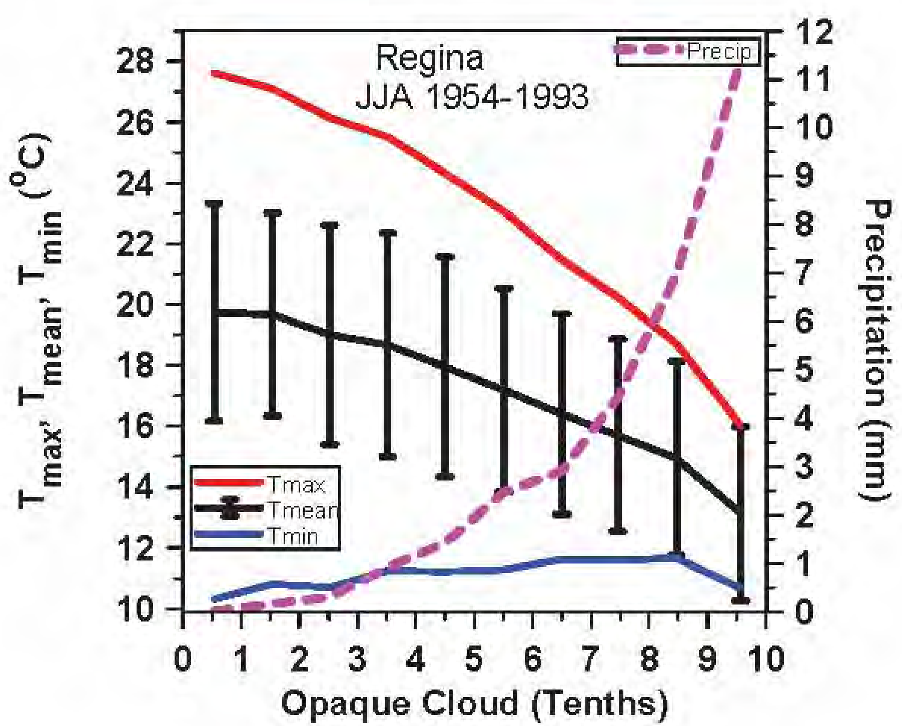
Clouds: Summer & Winter Climate
Opposite Impact

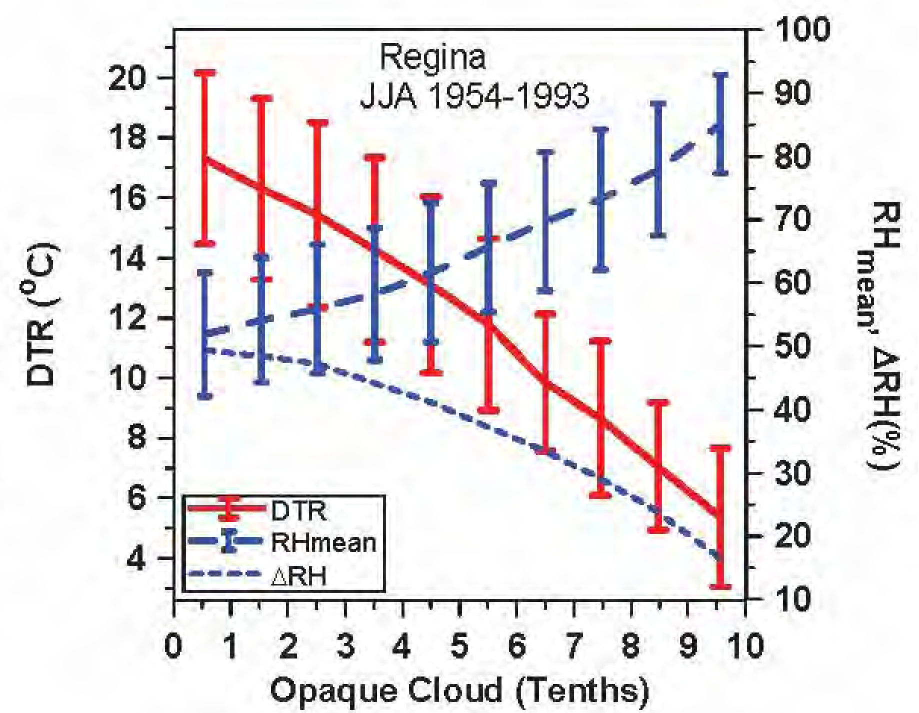


- **Summer:** **Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; barely cooler at night - *SWCF***
- **Winter:** **Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights - *LWCF***

Betts et al. 2013

Summer Diurnal Cycle Climate

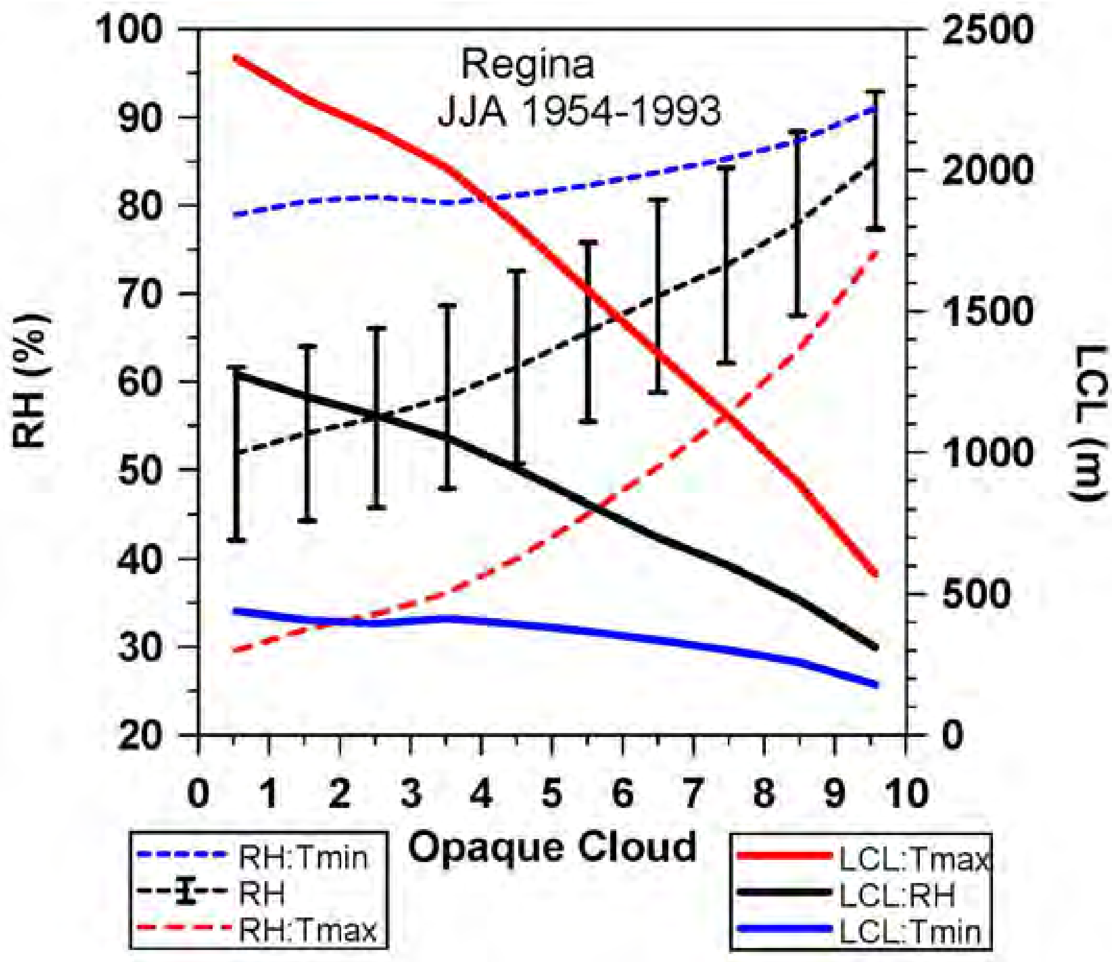




- ***Climate emerges from daily variability***
- **Cloud increases, precipitation increases**
- **T_{max}, DTR increase, T_{min} flat**
- **RH_{mean} increases, ΔRH decreases**

RH is linked to LCL

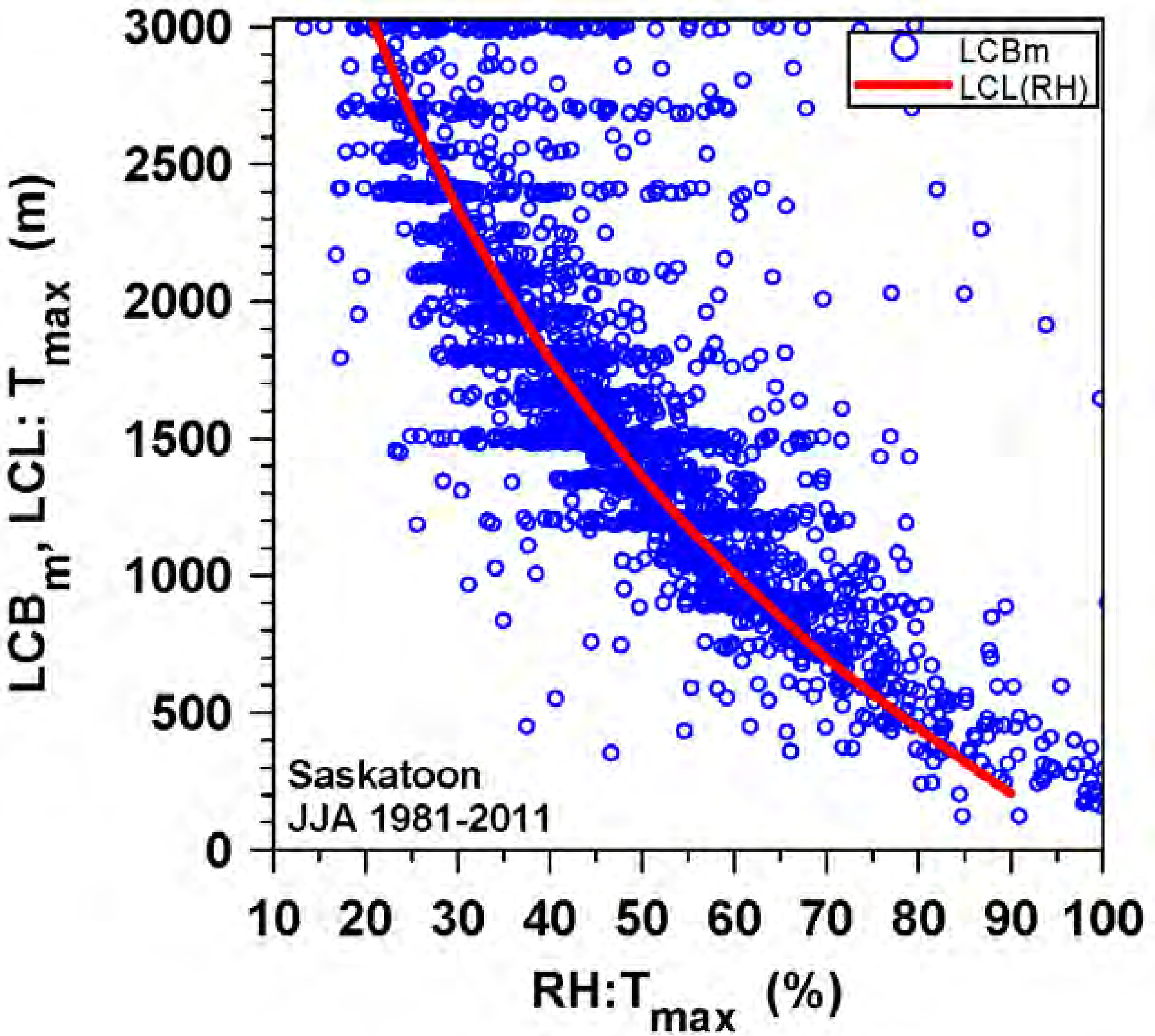
- RH increases with cloud
- Cloud-base LCL decreases
- Afternoon LCL 550 - 2350m



Afternoon LCL is Cloud-base

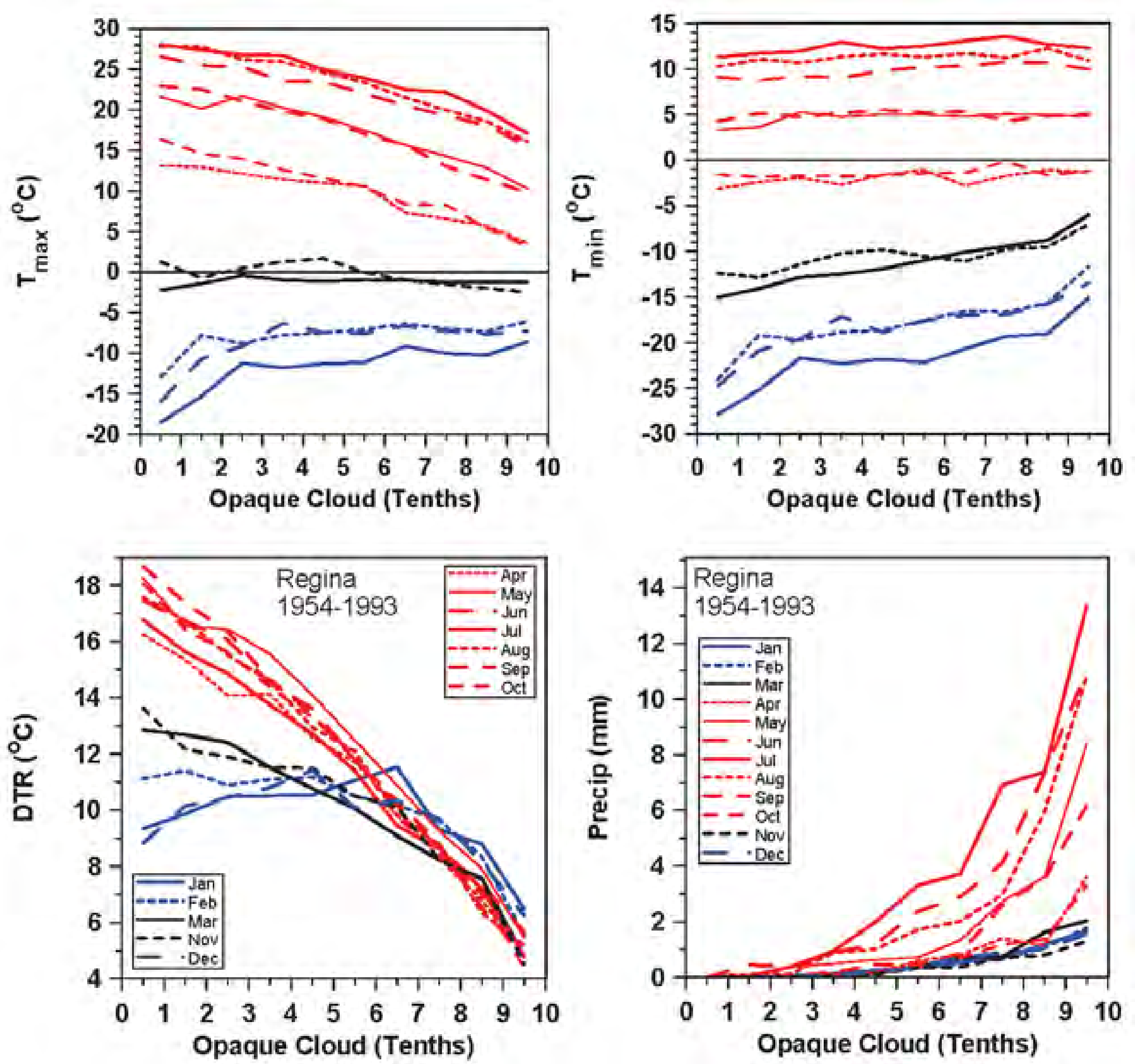
- At T_{max}
- Lowest cloud-base *(ceilometer)*
- LCL (surface)

- ***Coupled CBL***



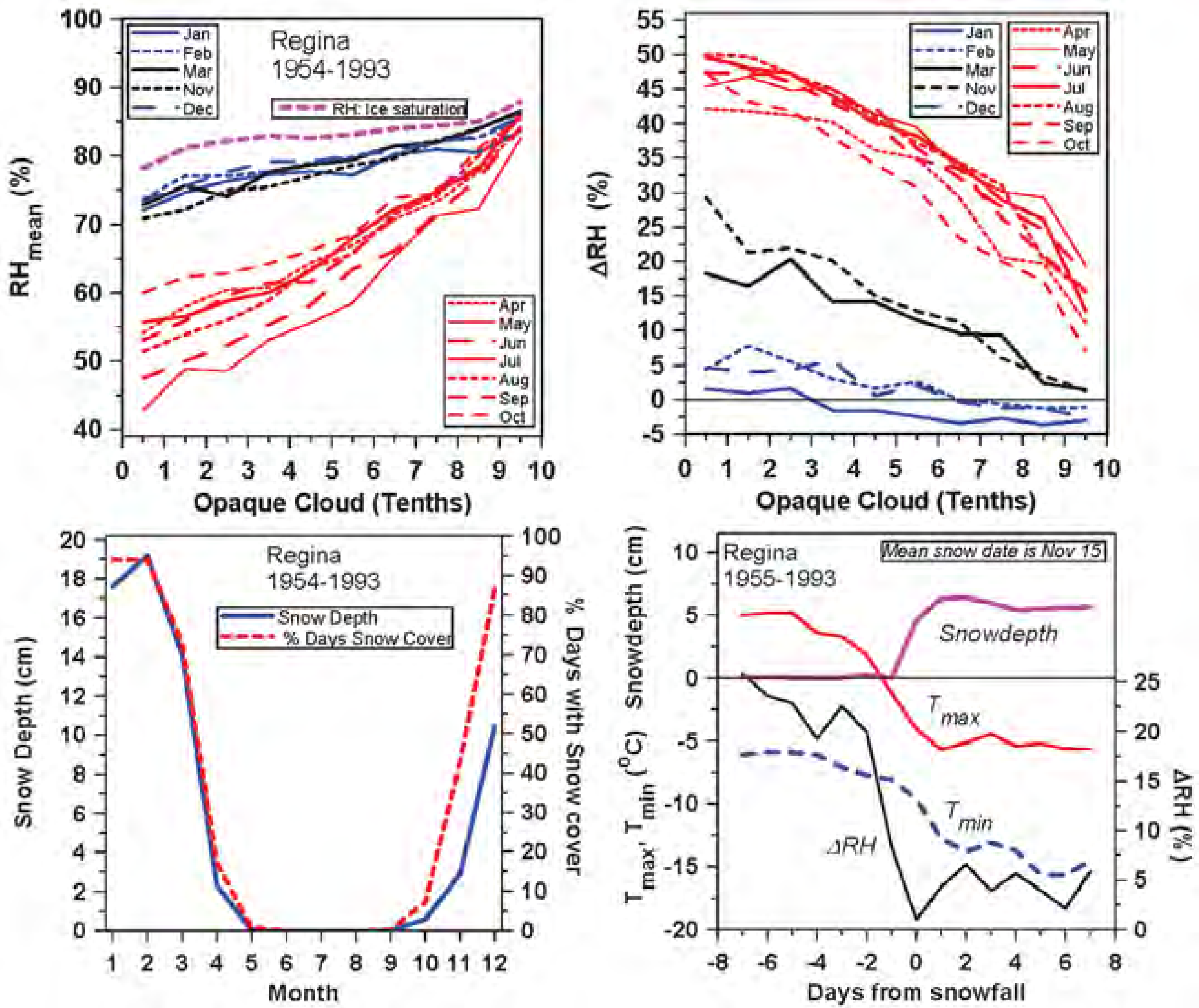
Annual Cycle: T_{max},T_{min}, DTR, Precip

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

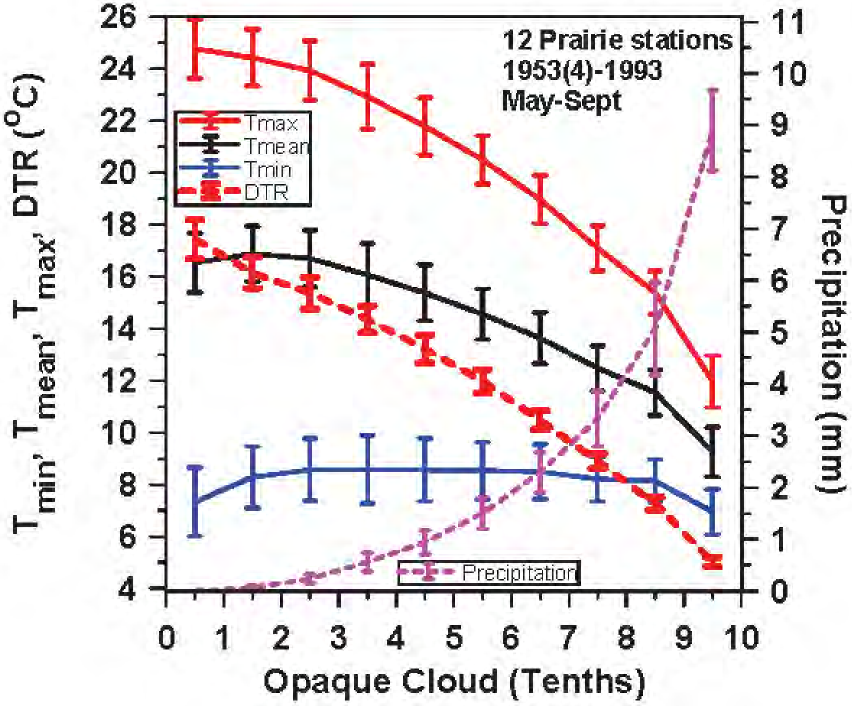


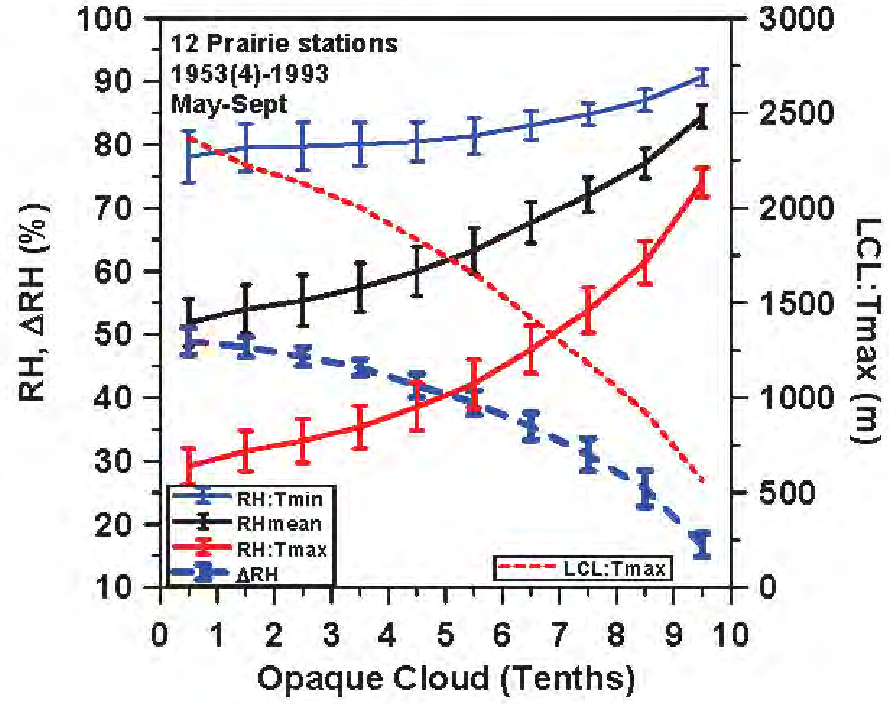
Annual Cycle: RH and ΔRH

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

Surface Radiation Budget

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

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

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

  Fit clear days or calculate

Define Effective Cloud Albedo

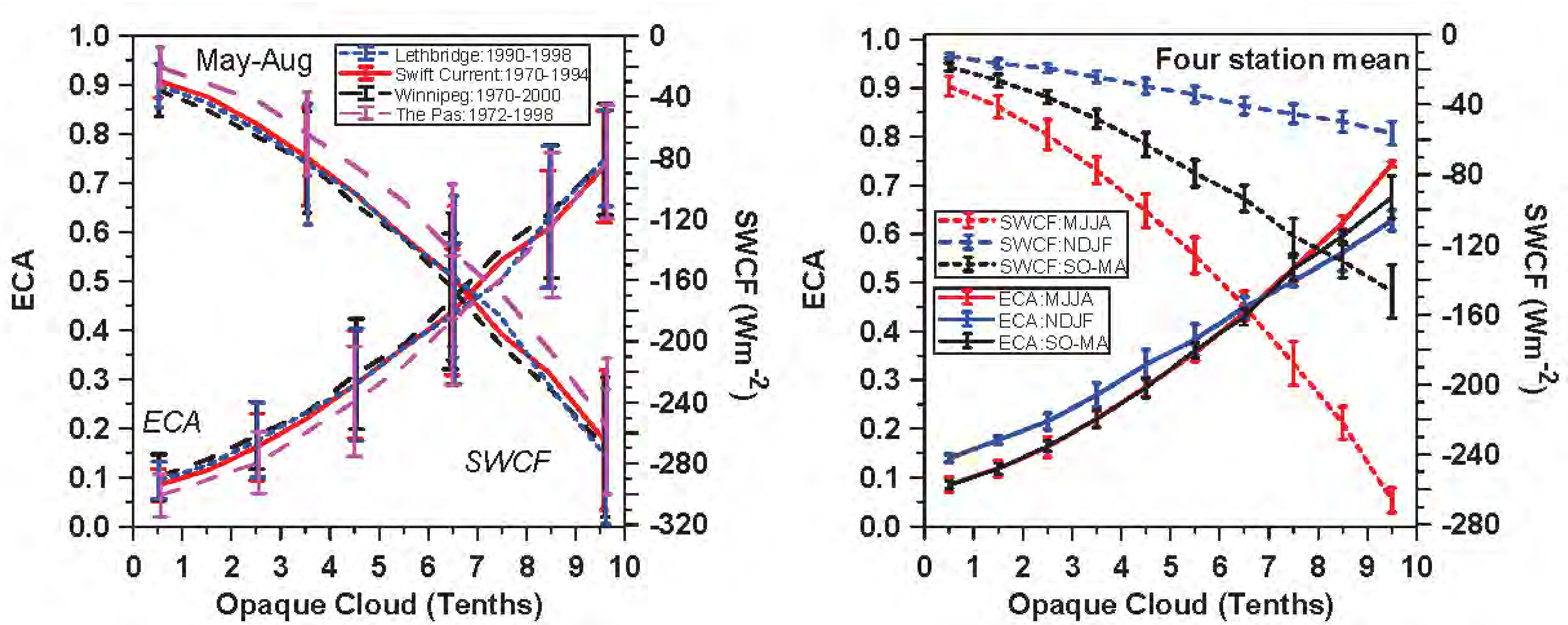
- $ECA = - SWCF/ SW_{dn}(clear)$

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

  Reflected by surface, clouds

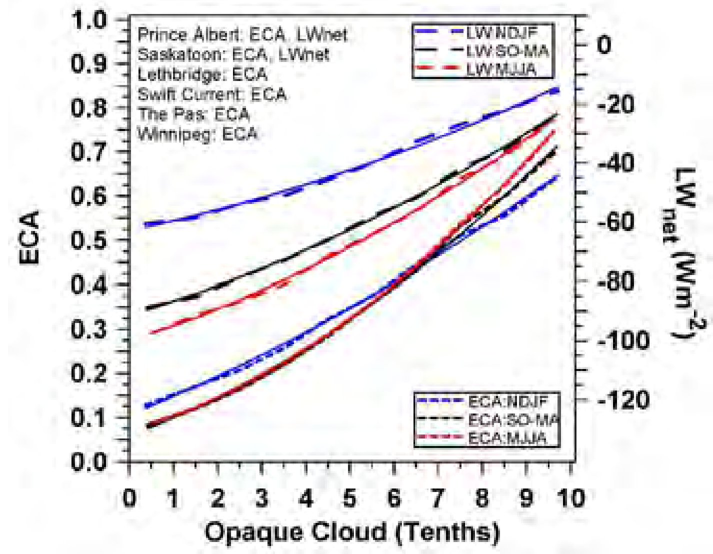
  MODIS Calibrate Opaque Cloud data

Calibration of Opaque Cloud to ECA-Effective Cloud Albedo



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

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

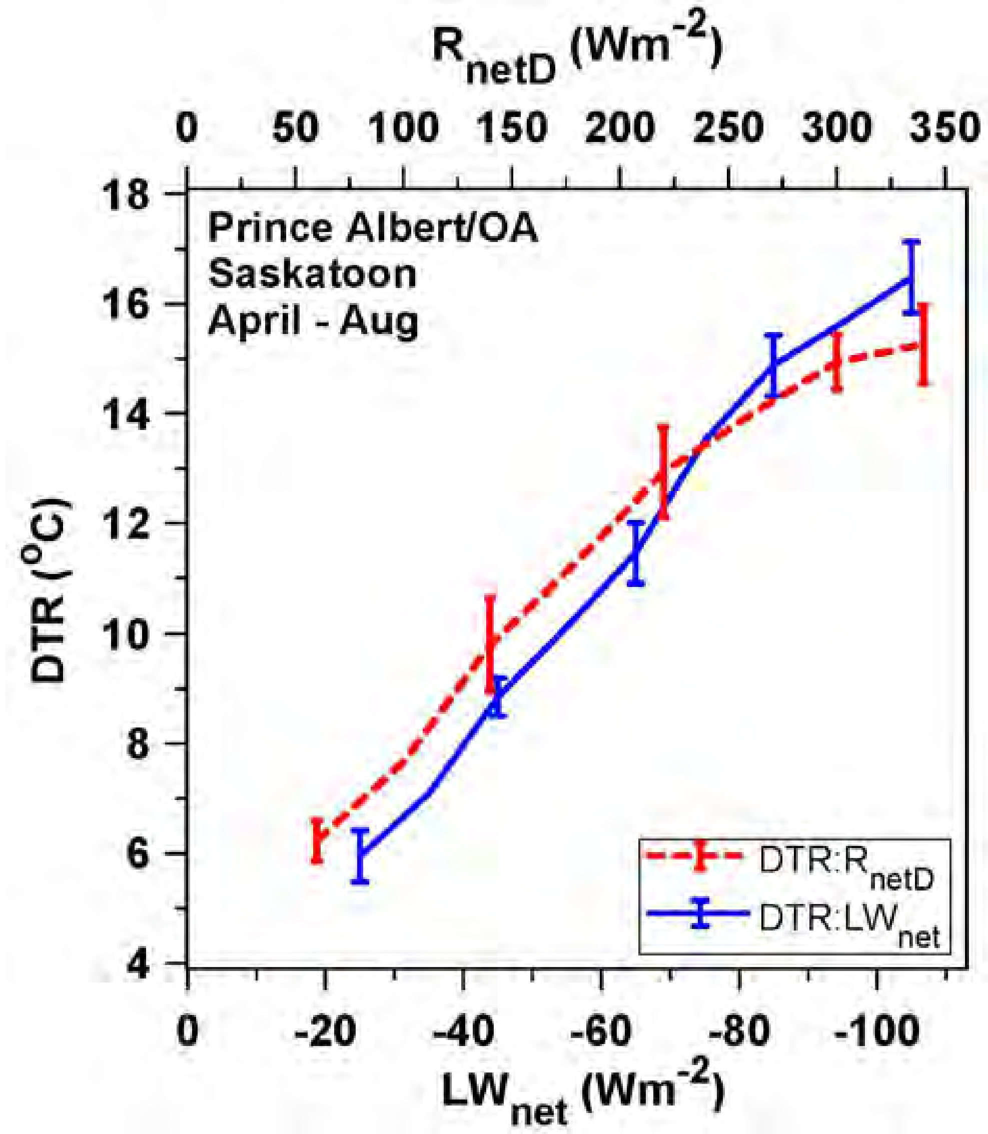
NDJF: LW_{net} = -63.0 + 3.14 Cloud + 0.193 $Cloud^2$

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

- **Daytime Driver: R_{netD}**
- **Nighttime driver: LW_{net}**
- ***Fully coupled diurnal system in warm season***



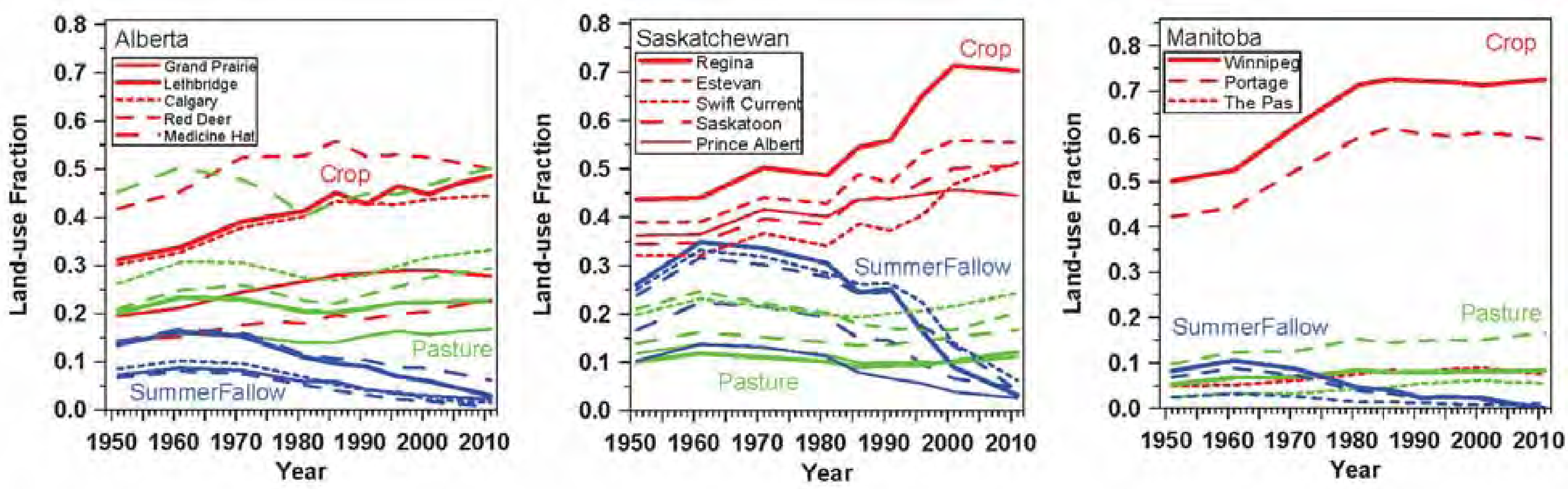
Annual crops and seasonal diurnal cycle

- **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)**

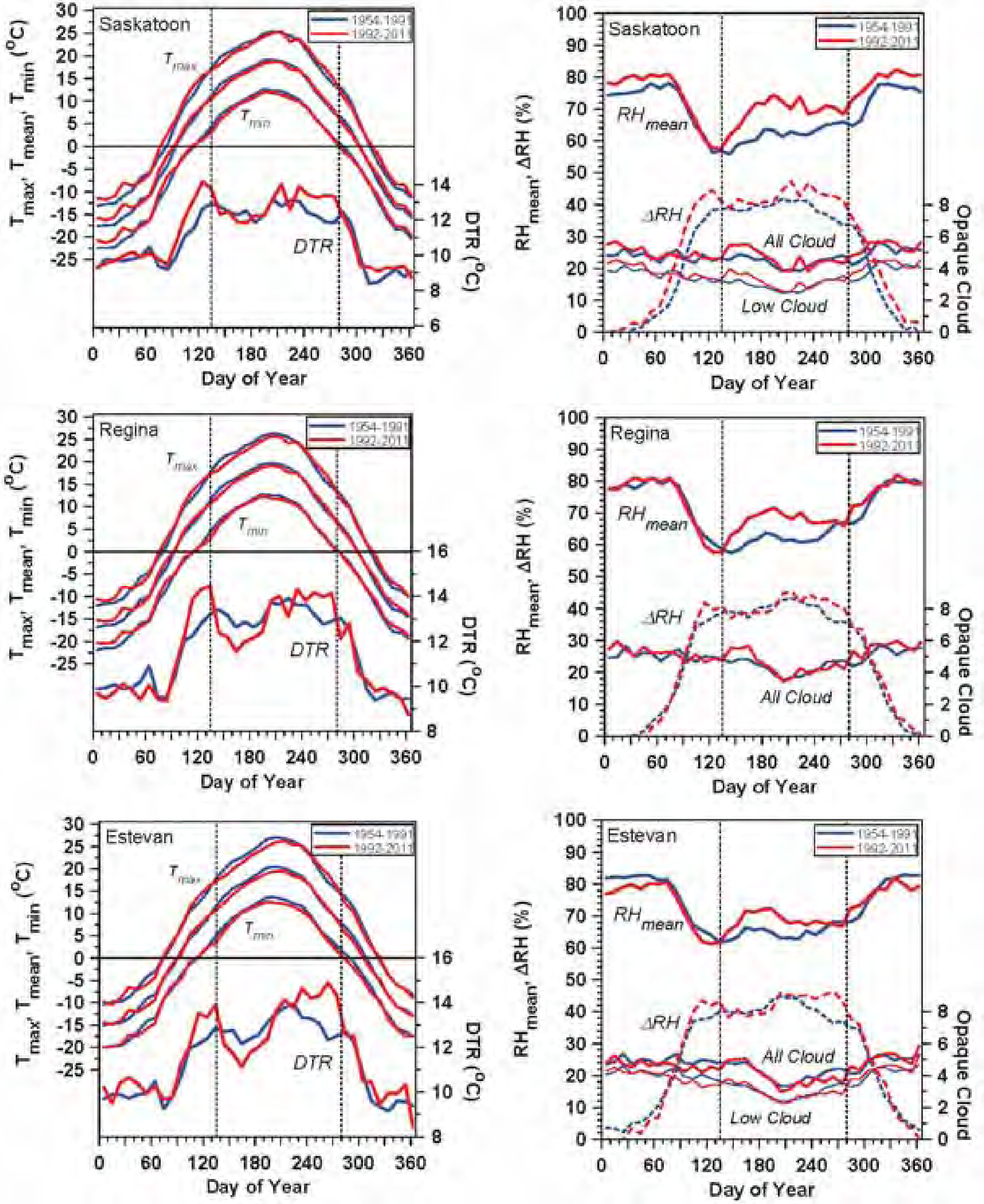
Change in Cropping



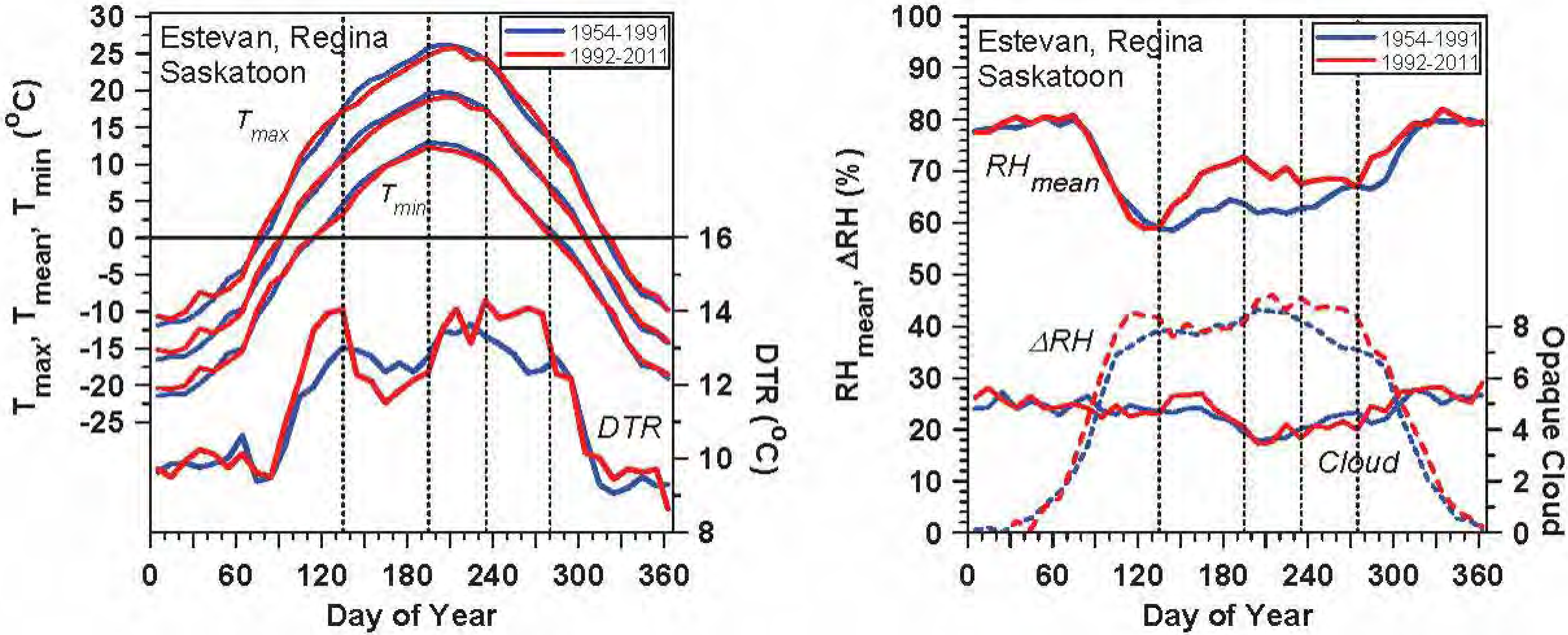
- **Ecodistrict mean for 50-km around station**
- **Saskatchewan: 25% drop SummerFallow**
- ***Split at 1991- has summer climate changed?***

Diurnal Climate Change

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



Three Station Mean in SK

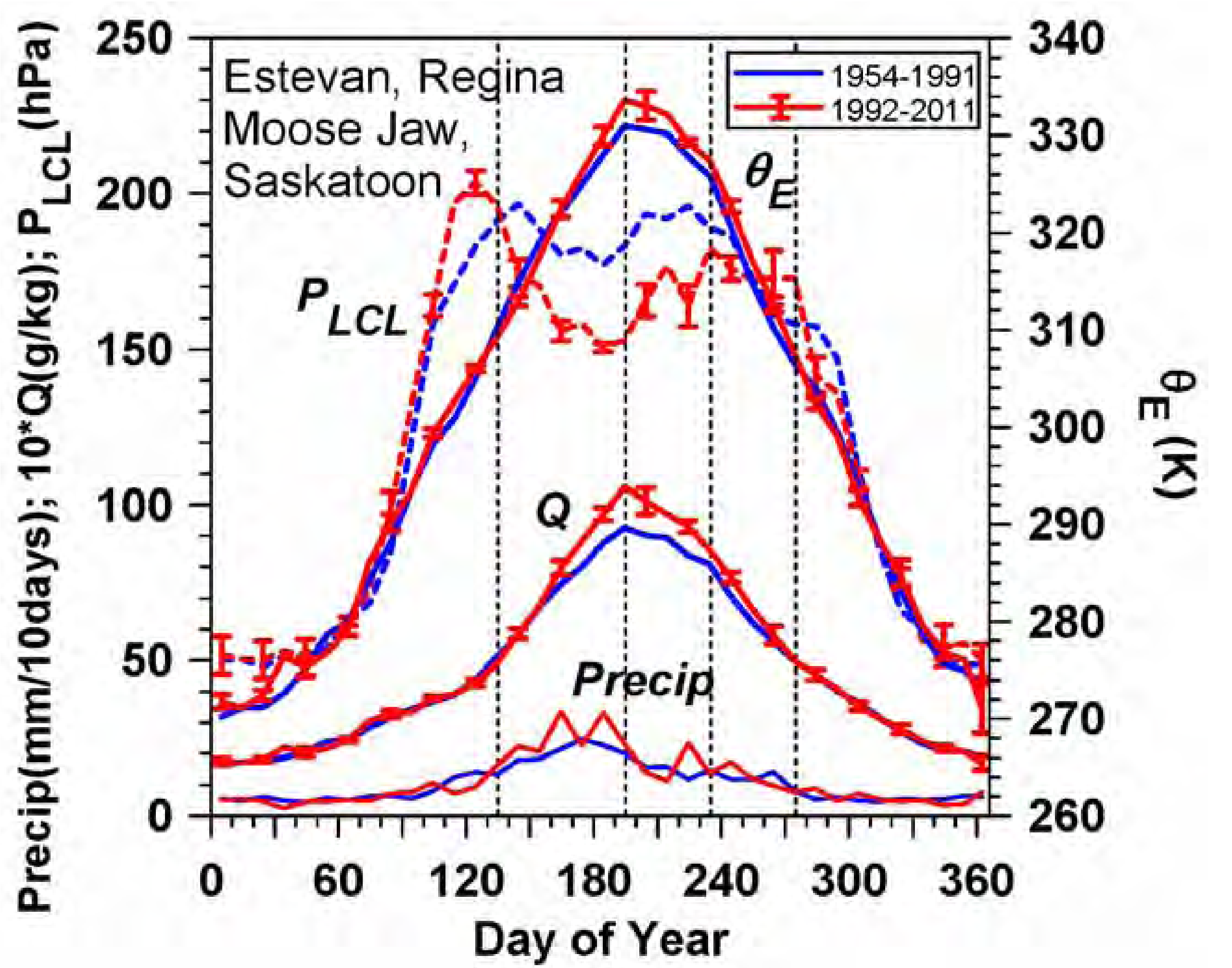


- **Growing season**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal structure changes**

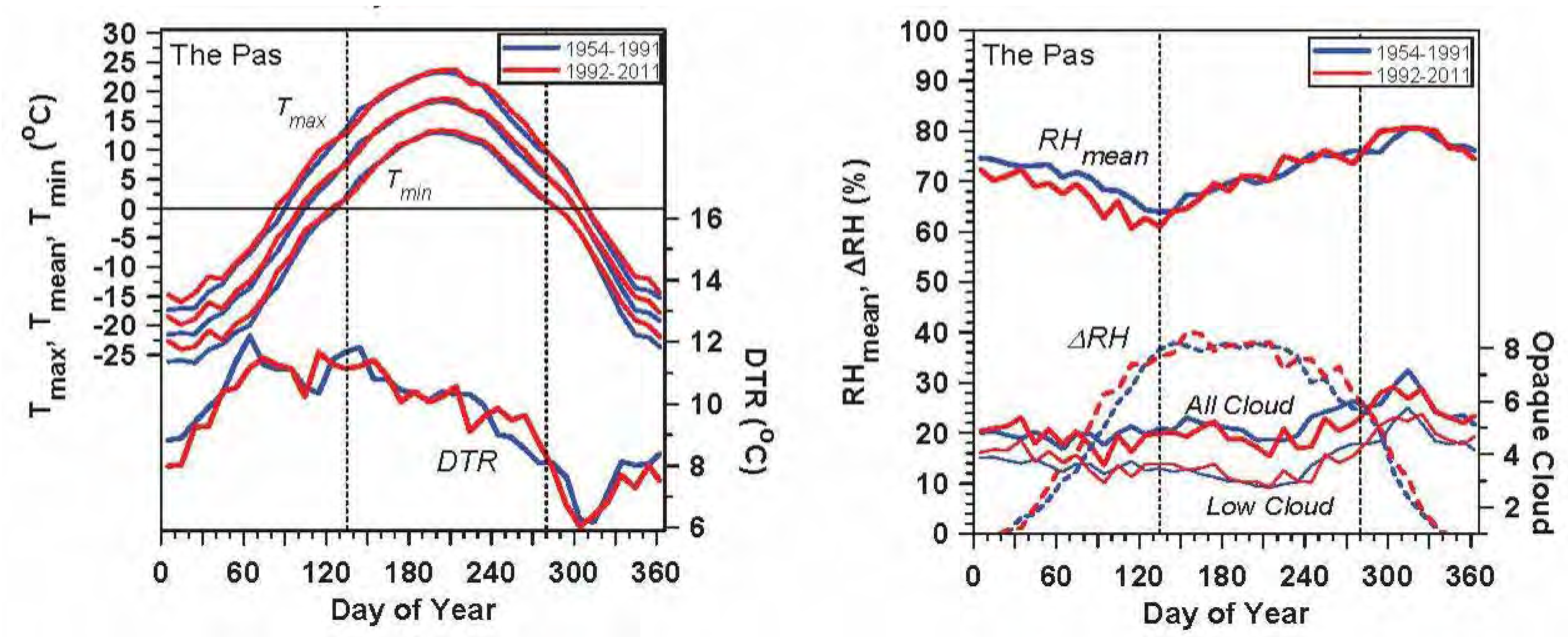
Impact on Convective Instability

Growing season

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



Contrast Boreal Forest

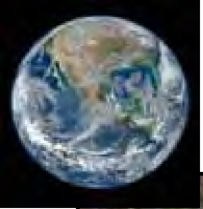


- **No RH, DTR signal**

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
  - Shift to LWCF control from SWCF
  - Snow cover is a fast *“climate switch”*

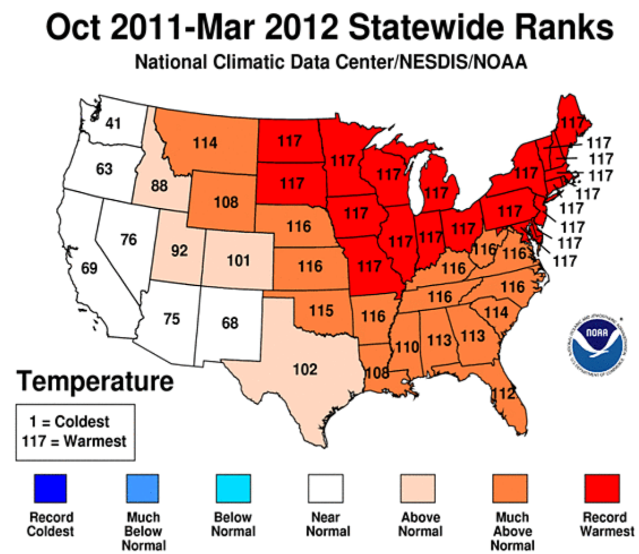


January 2, 2012

March 11, 2012

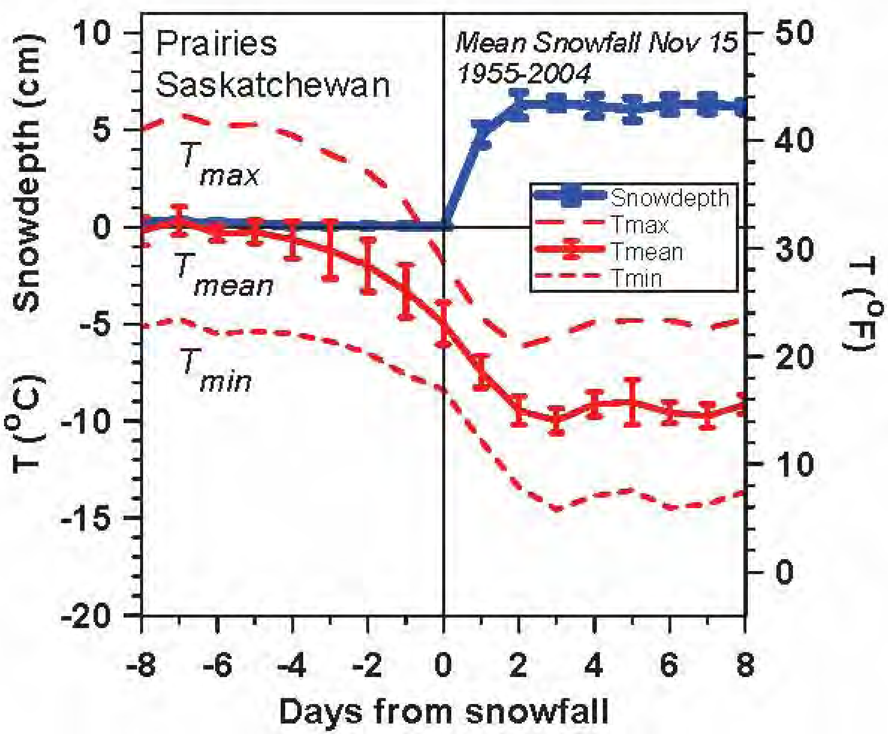
October 2011– March 2012

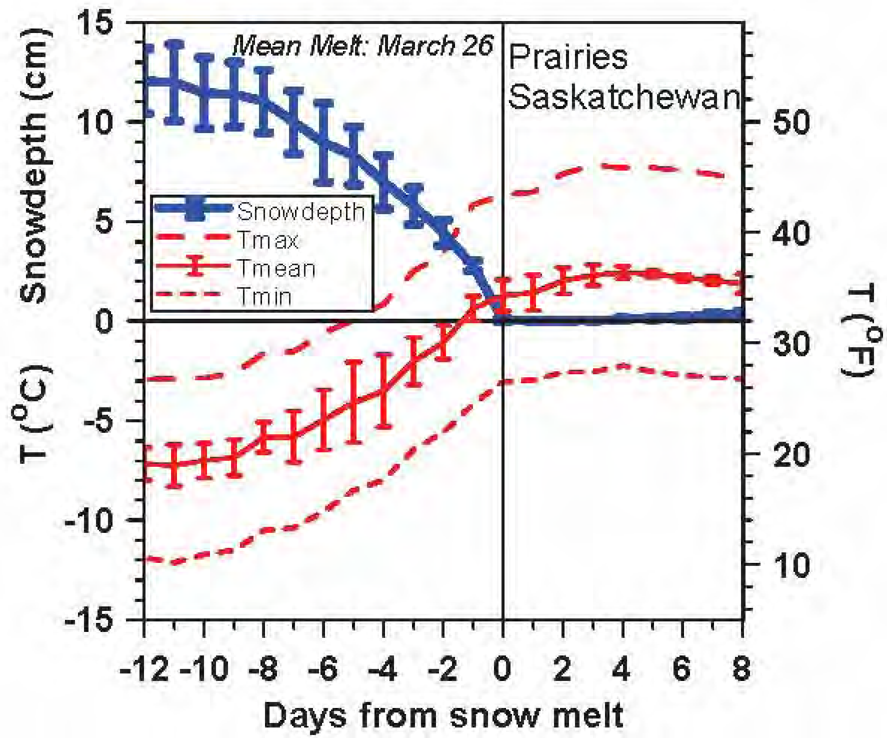
- **Warmest 6 months on record**
- **My garden frozen only 67 days**
- **No permanent snow cover west of Green Mntns**
- **Contrast snowy winter 2010-11**



Snowfall and Snowmelt

Winter and Spring transitions



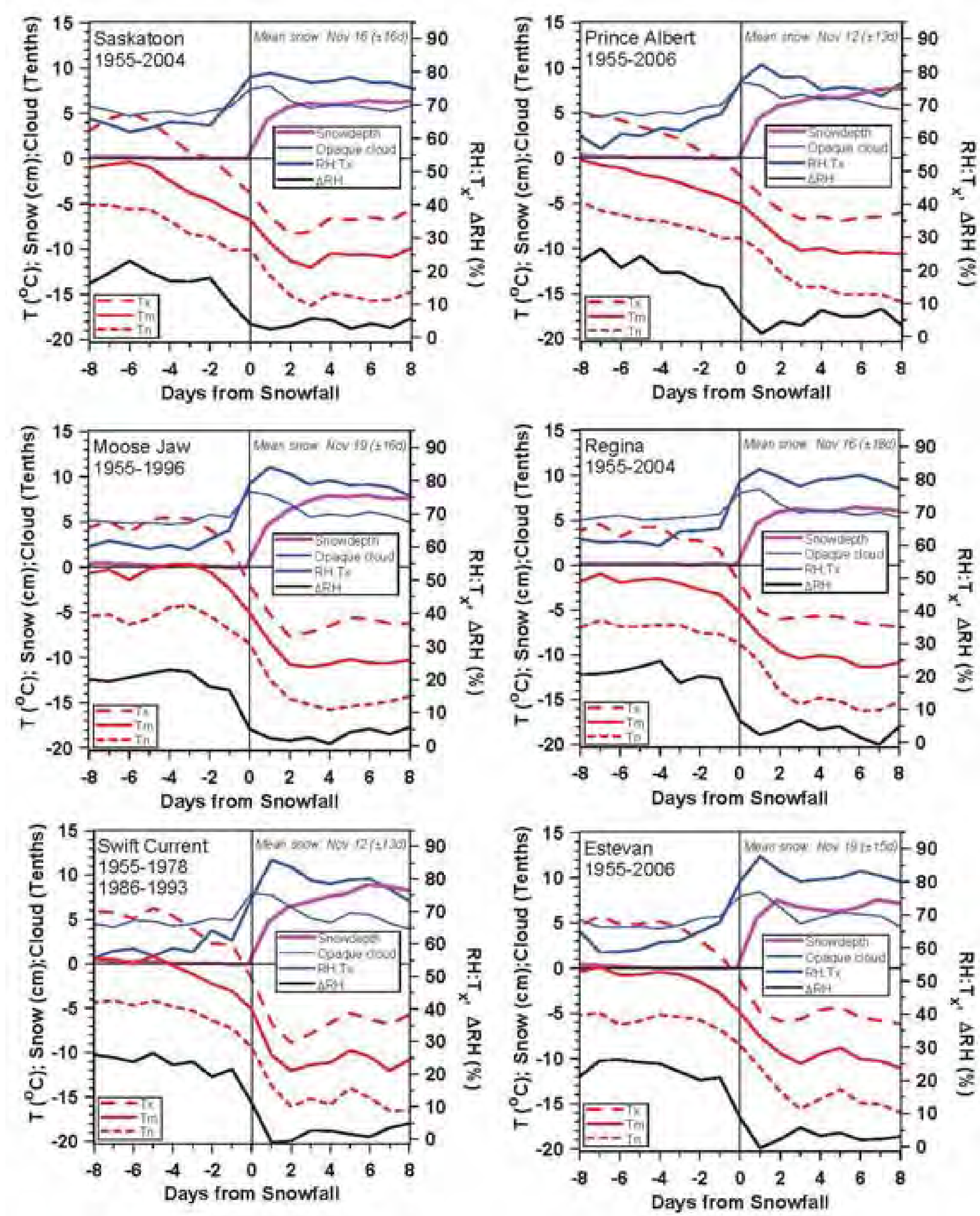


- **Temperature falls 9K with first snowfall**
- **Rise with snowmelt is similar**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms 'local climate'***
  - ***Same feedbacks that are speeding Arctic ice melt in summer***

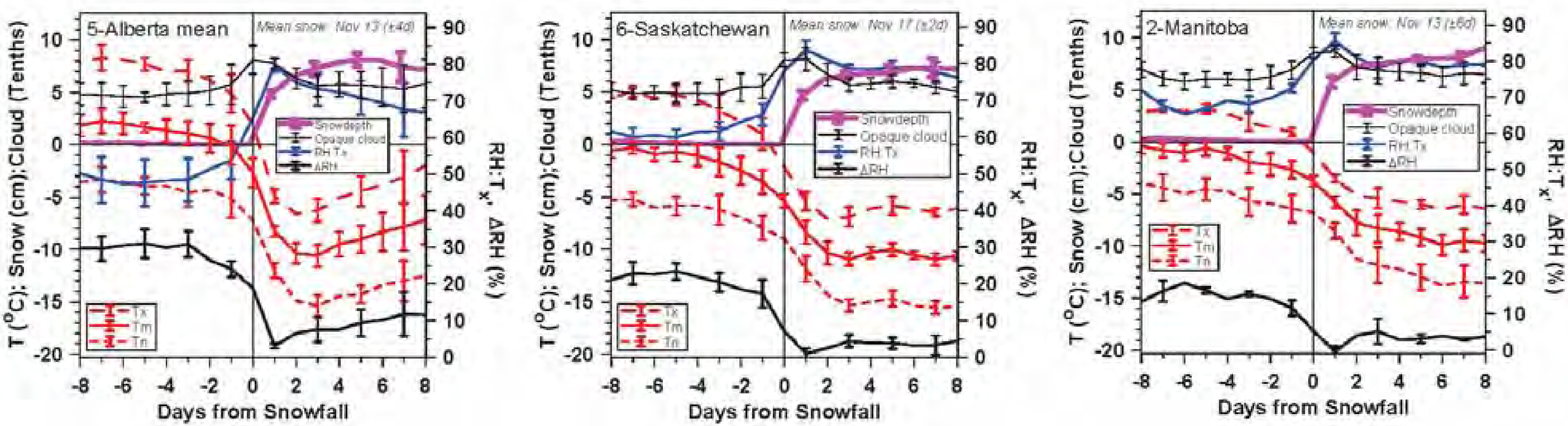
Betts et al. 2014

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

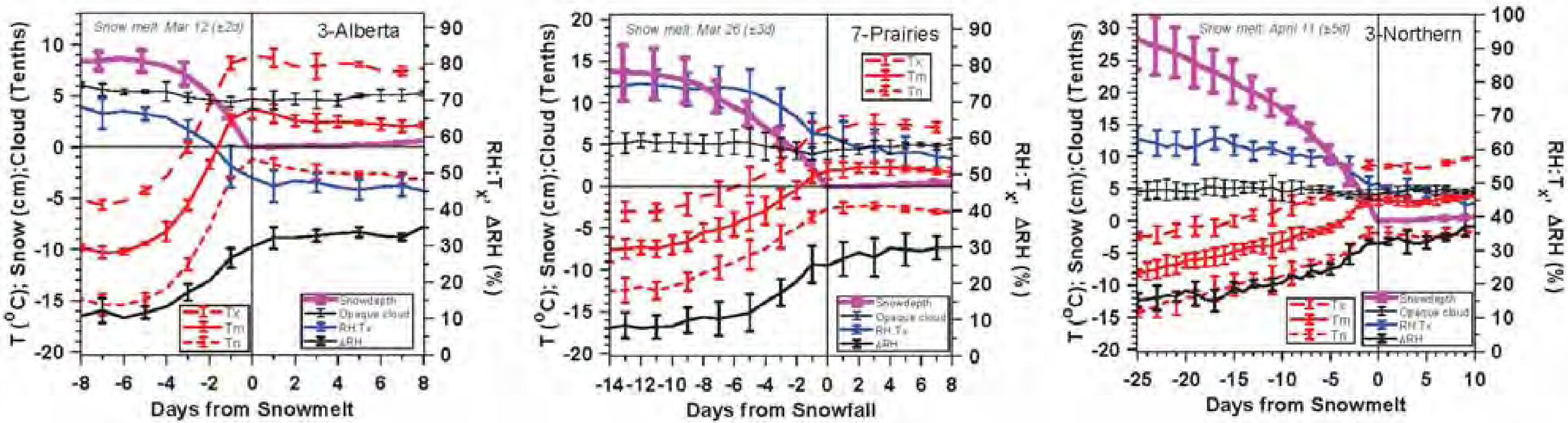


Fall Snow Transition Climatology



- 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 ± 3 days

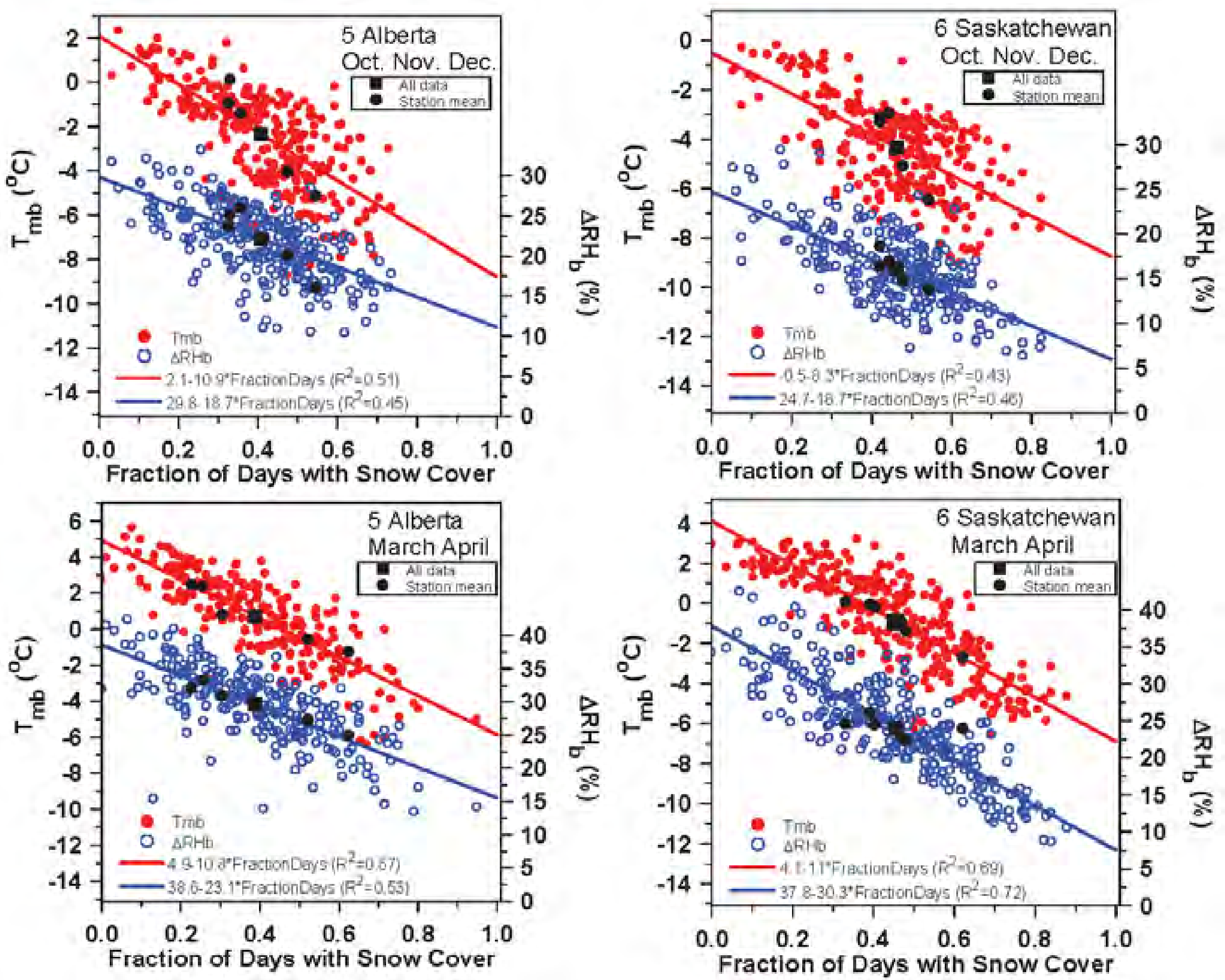
Snow-melt Transition Climatology



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

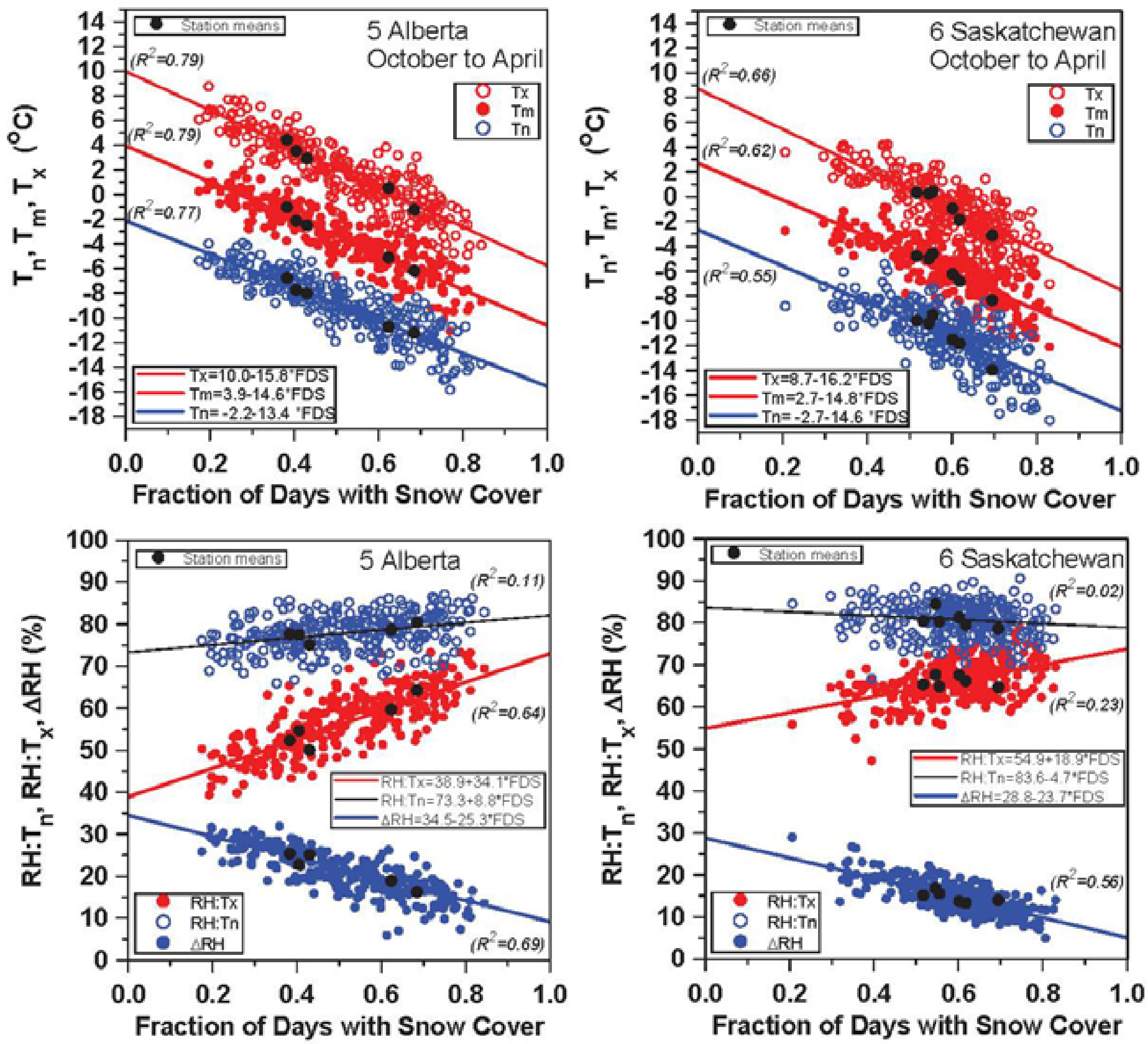
Snow Cover: Fall and Spring Climatology

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



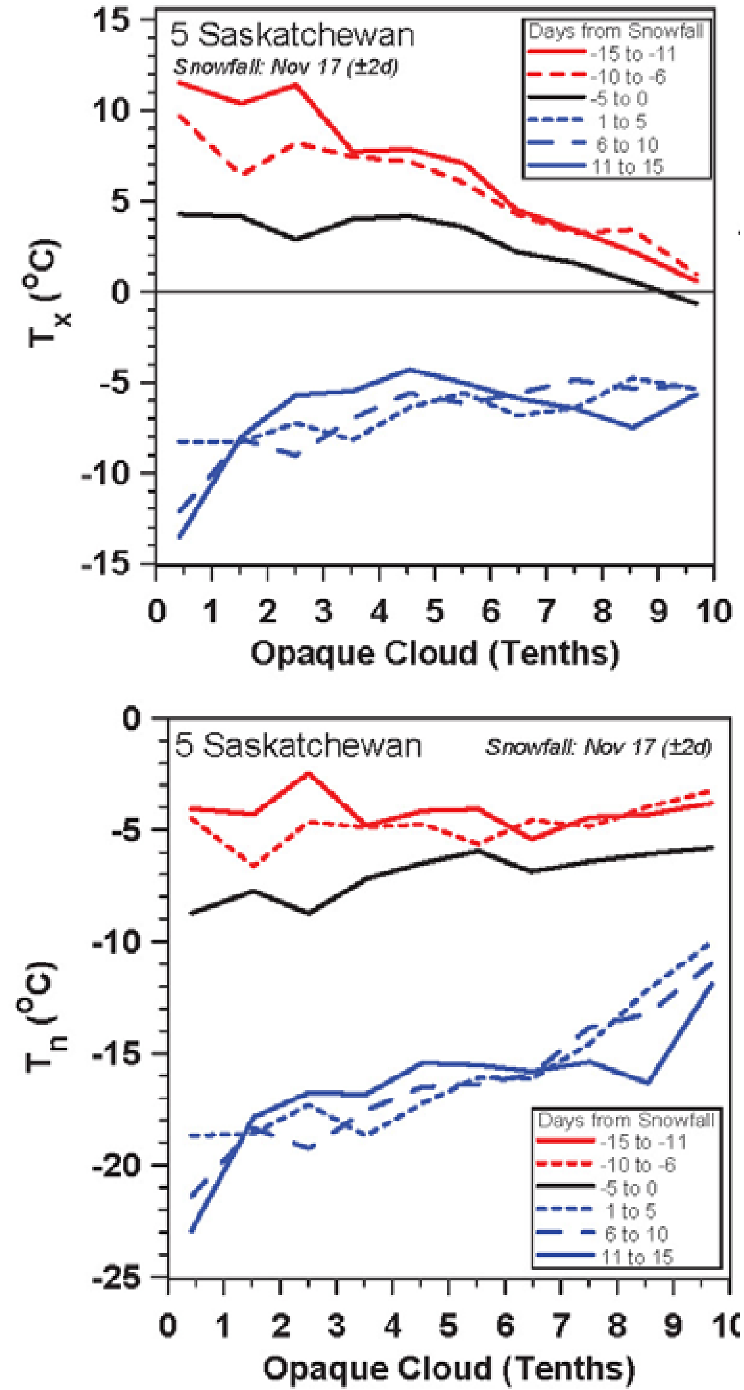
Snow Cover: Cold Season Climate

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

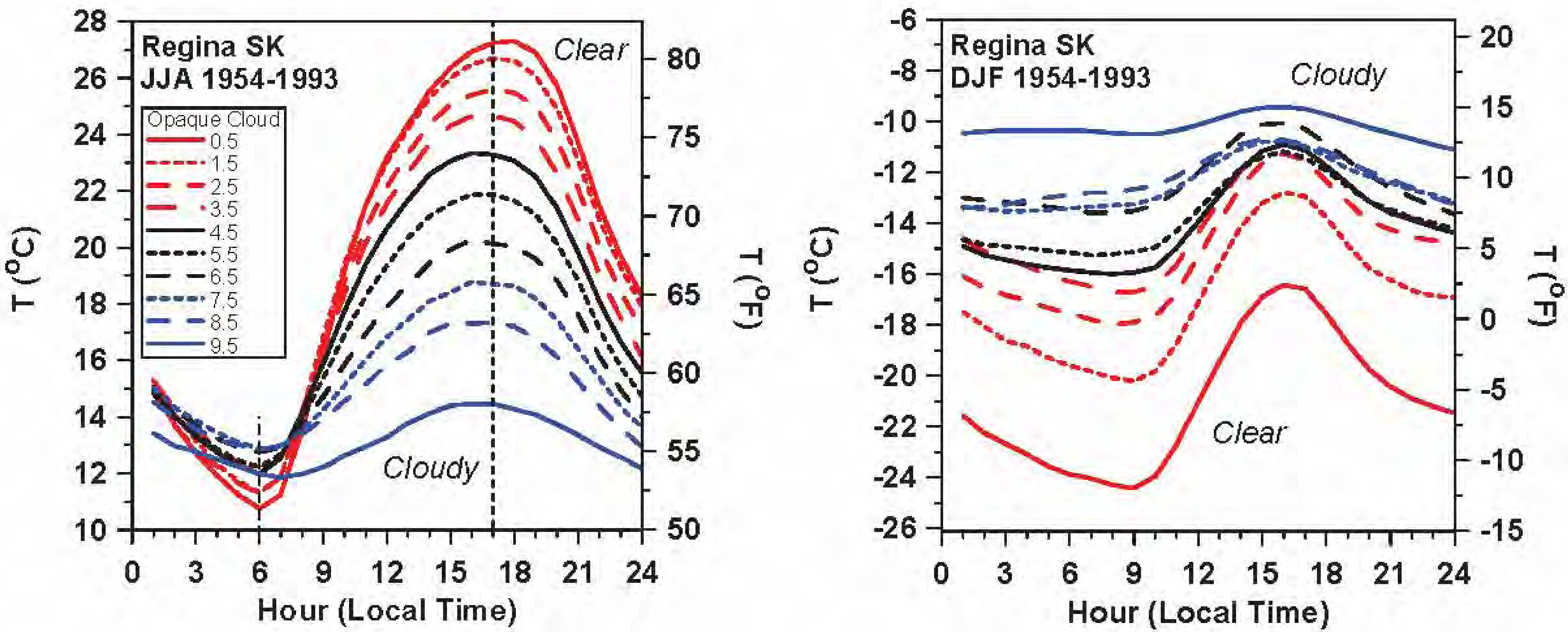


Coupling to Cloud Cover Across Snowfall

- **Mid-November**
- **5-day means**
  - *red: no snow*
  - *blue: snow*
- **With snow T_x, T_n plunge**
- **Cloud coupling shifts: SWCF to LWCF**



Clouds: Summer & Winter Climate
Opposite Impact



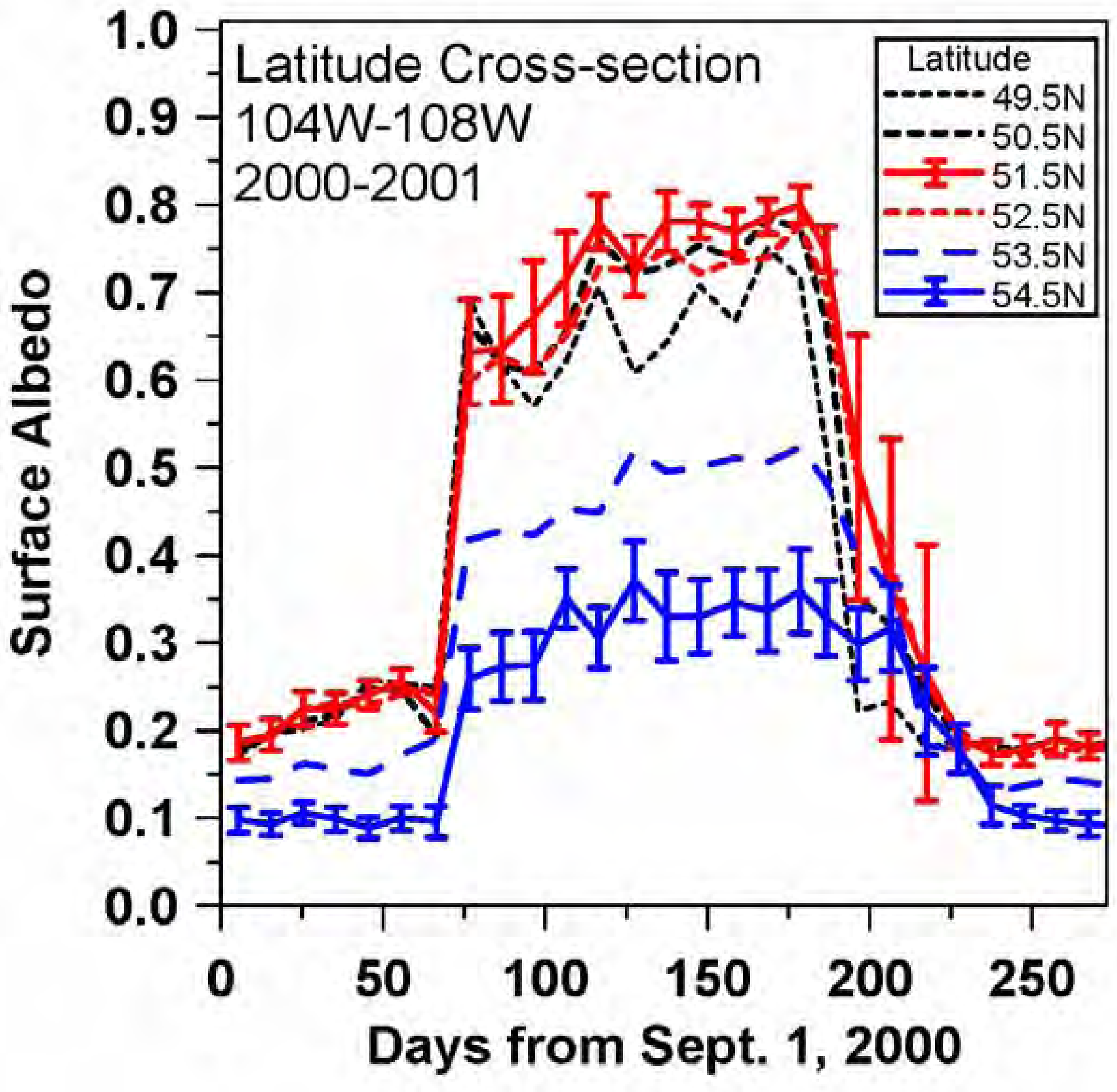
- **Summer:** **Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
- **Winter:** **Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**

Betts et al. 2013

N-S Albedo through Winter

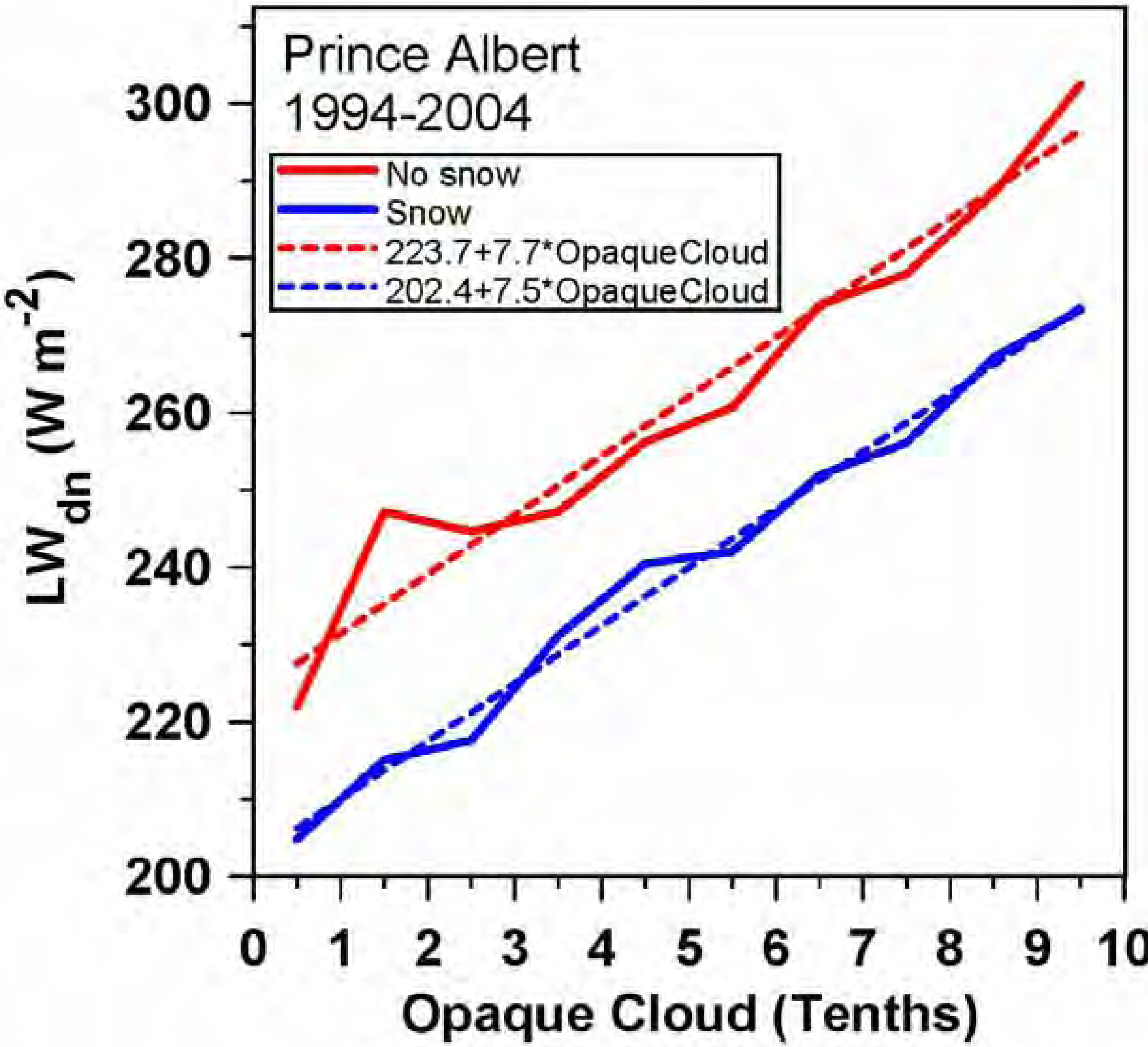
- **Prairies**
  α_s: **0.2 to 0.73**
- **Boreal forest**
  α_s: **0.1 to 0.35**

- ***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**
  - **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: -11K to balance**

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: $\alpha_s = 0.7$**
  - **From SWCF dominated, with coupled CBL**
  - **To LWCF dominated, with stable BL**
  - **Snow cover is a "climate switch"**

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)***

Papers at http://alanbetts.com

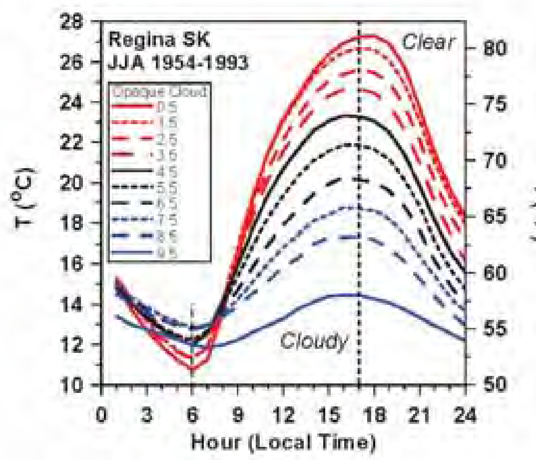
Daily Mean Climate vs Long-term Diurnal Mean

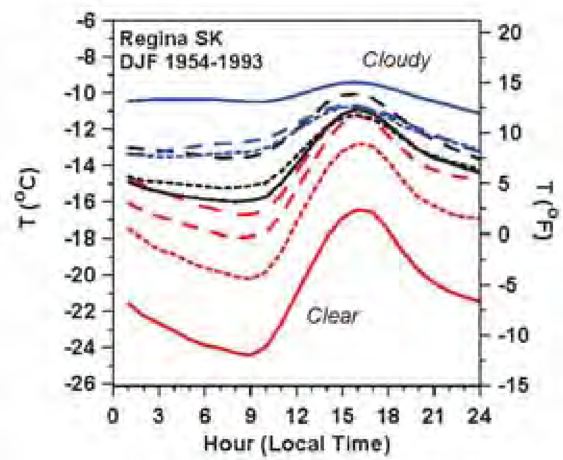
- *Definitions*
  - **DTR = T_x - T_n**
  - **ΔRH = RH:T_x – RH:T_n**

Monthly mean diurnal cycle

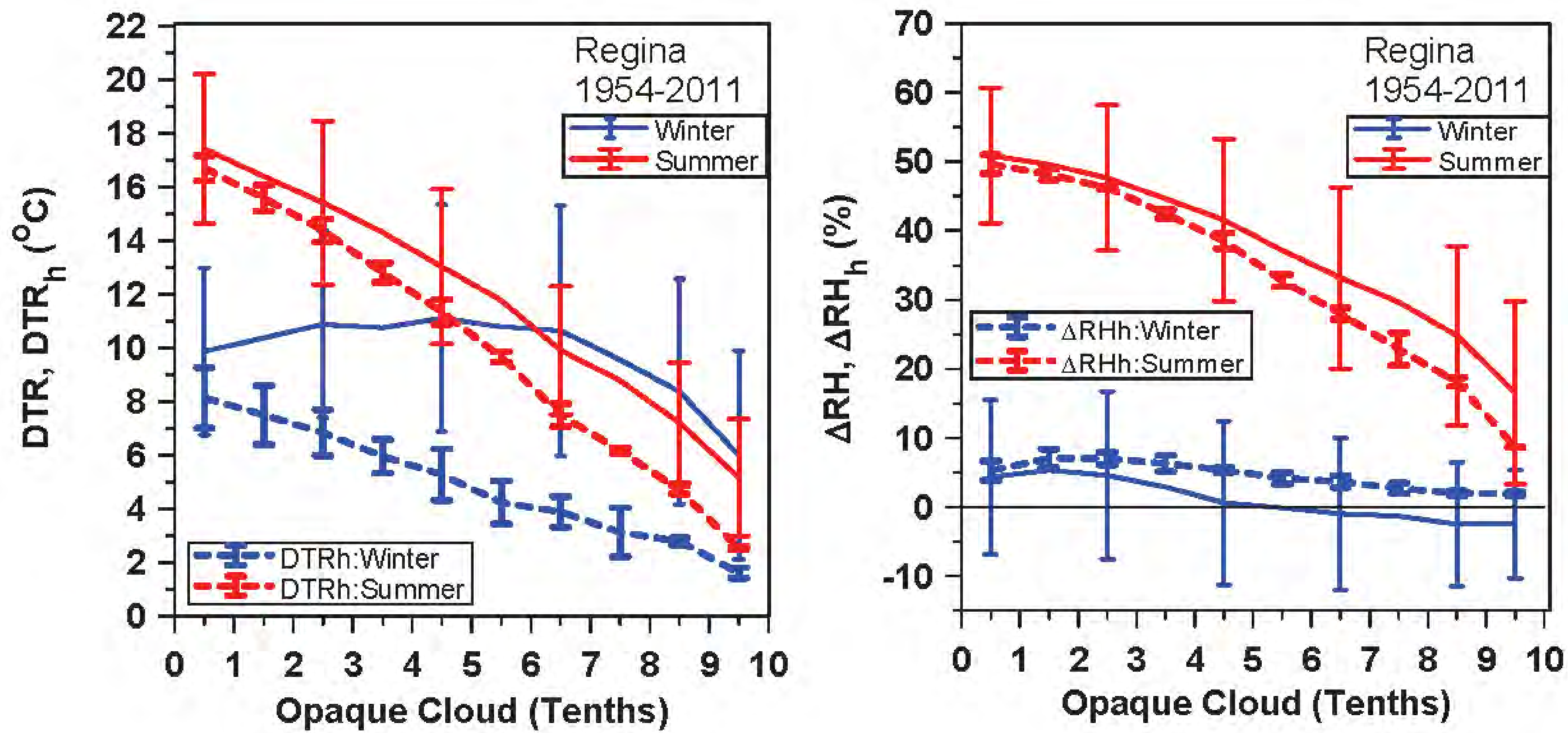
  - **DTR_h = T_{xh} – T_{nh}**
  - **ΔRHh = RH_{xh} – RH_{nh}**

Radiatively forced signal small in winter compared to daily advection



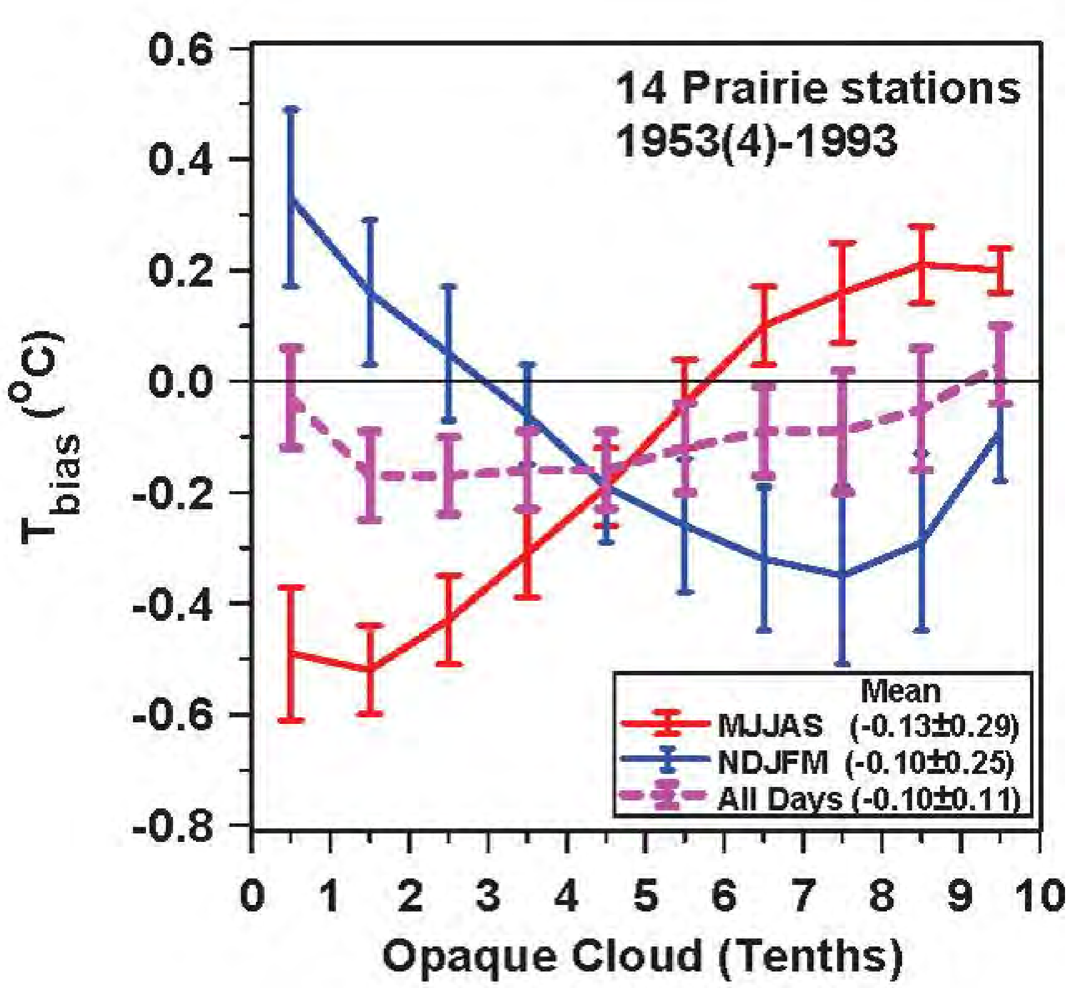


Daily Mean Climate vs Monthly Diurnal Mean Climate



- **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**