Land-cloud-climate Coupling on the Canadian Prairies

Dr. Alan K. Betts
(Atmospheric Research, Pittsford, VT 05763)
Ray Desjardin, D. Cerkowniak
(Agriculture-Canada)
and Ahmed Tawfik (NCAR)

akbetts@aol.com
http://alanbetts.com

CGU/AGU Montreal

RACC
Research on Adaptation to Climate Change

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Outline

- Northern latitude climate
  – Large seasonal cycle
    - Cold winters with snow
  – Freezing point of water critical

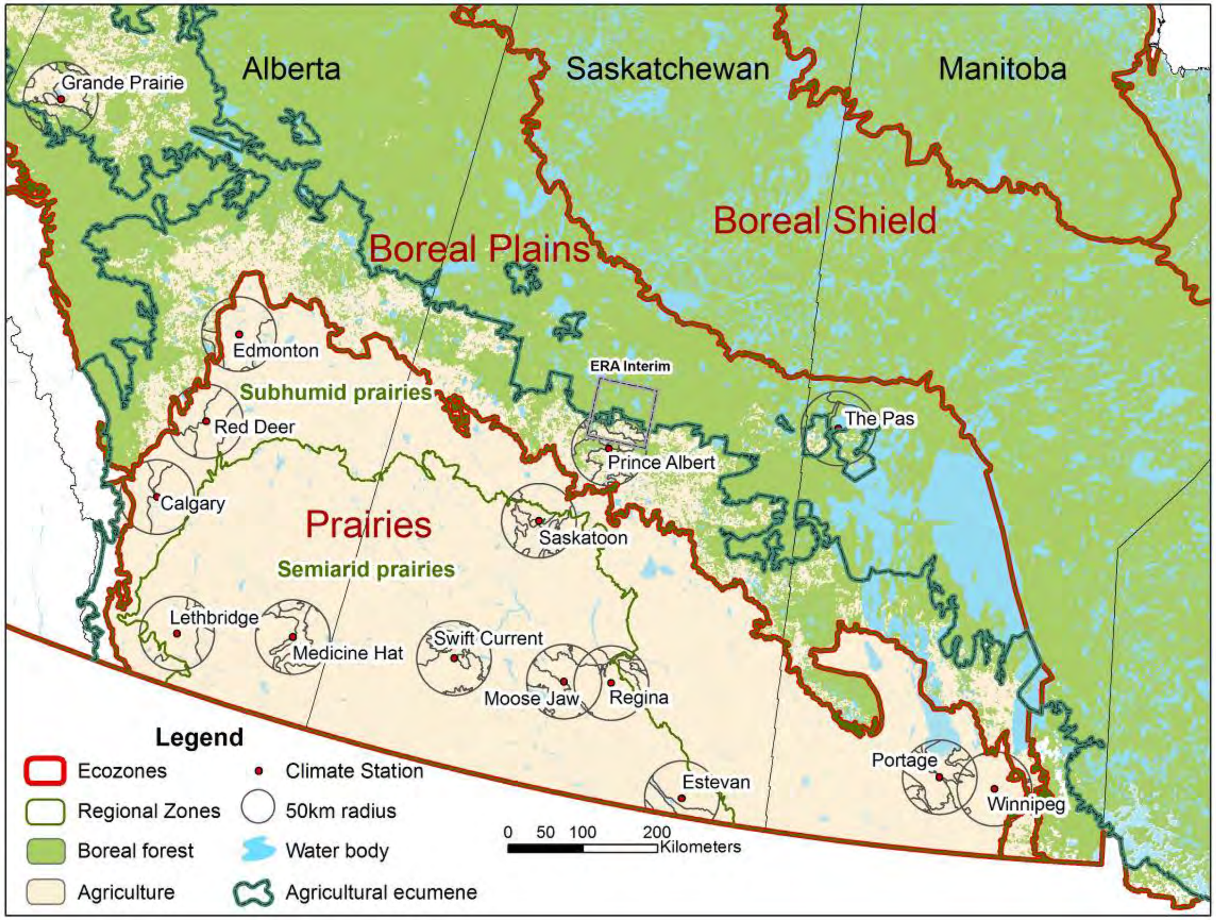
  – Summer hydrometeorology
    - T and RH depend on radiation and precip.

  – Observational evaluation of models

Climate Processes

- ***Solar seasonal cycle***
- ***Precipitation***
- **Reflection of SW**
  - **Clouds: Water drops, ice crystals**
    - **Cools surface**
  - **Snow and ice on surface**
    - **Cools surface**
- **Water vapor/clouds trap LW**
    - **Re-radiation down warms surface**

15 Prairie stations: 1953-2011



- *Hourly* p, T, RH, WS, WD, opaque/reflective cloud
- *Daily* precipitation and snowdepth

References

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- Betts, A.K., R. Desjardins, A.C.M. Beljaars and A. Tawfik (2015), Observational study of land-surface-cloud-atmosphere coupling on daily timescales. *Front. Earth Sci. 3:13*. http://dx.doi.org/10.3389/feart.2015.00013

- ***http://alanbetts.com/research***

Diurnal Climate

- **Reduce hourly data to**
  - **daily means: T_m , RH_m, $OPAQ_m$ etc**
  - **data at max/min: T_x and T_n**
- ***Diurnal cycle climate***
  - **DTR = T_x-T_n**
  - **ΔRH = RH_{tn} – RH_{tx}**

- ***Almost no missing hourly data***

  (until recent cutbacks)

Surface Radiation Budget

- $R_n = SW_n + LW_n$
- Define Effective Cloud Albedo

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

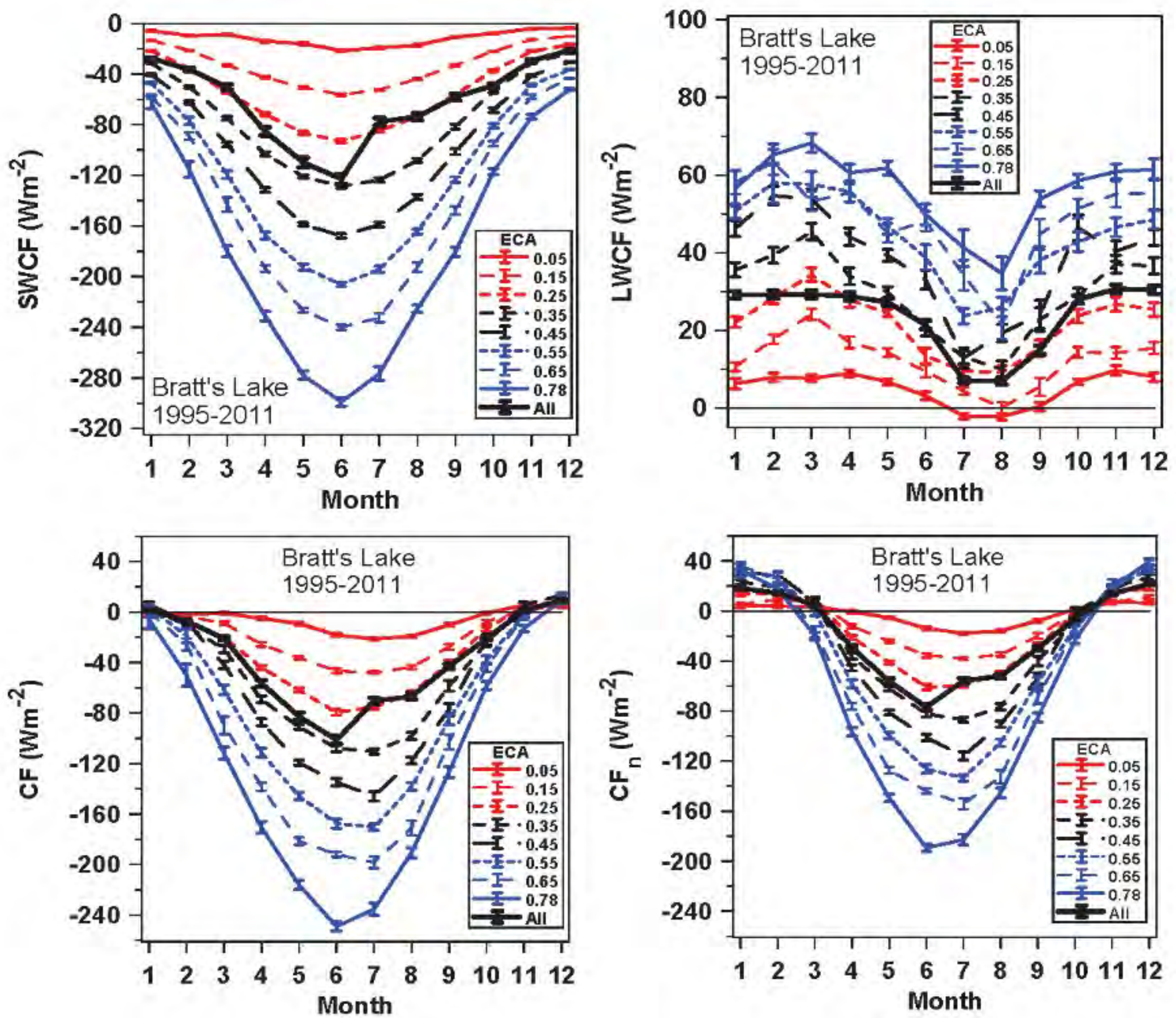
$$SW_n = (1 - \alpha_s)(1 - ECA)\, SW_{dn}(clear)$$

Reflected by surface, clouds

MODIS *Calibrate Opaque Cloud data with Baseline Surface Radiation Network (BSRN)*

SW and LW Cloud Forcing
BSRN at Bratt's Lake, SK

- **"Cloud Forcing"**
  - ***Change from clear-sky (ERA-I)***
- **Clouds reflect SW**
  - ***SWCF***
  - ***Cool***
- ***Clouds trap LW***
  - ***LWCF***
  - ***Warms***
- ***Sum is CF***
- ***Surface albedo reduces SW***
  - ***Net is CF_n***
  - ***Add reflective snow, and CF_n goes +ve***



(Betts et al. 2015)

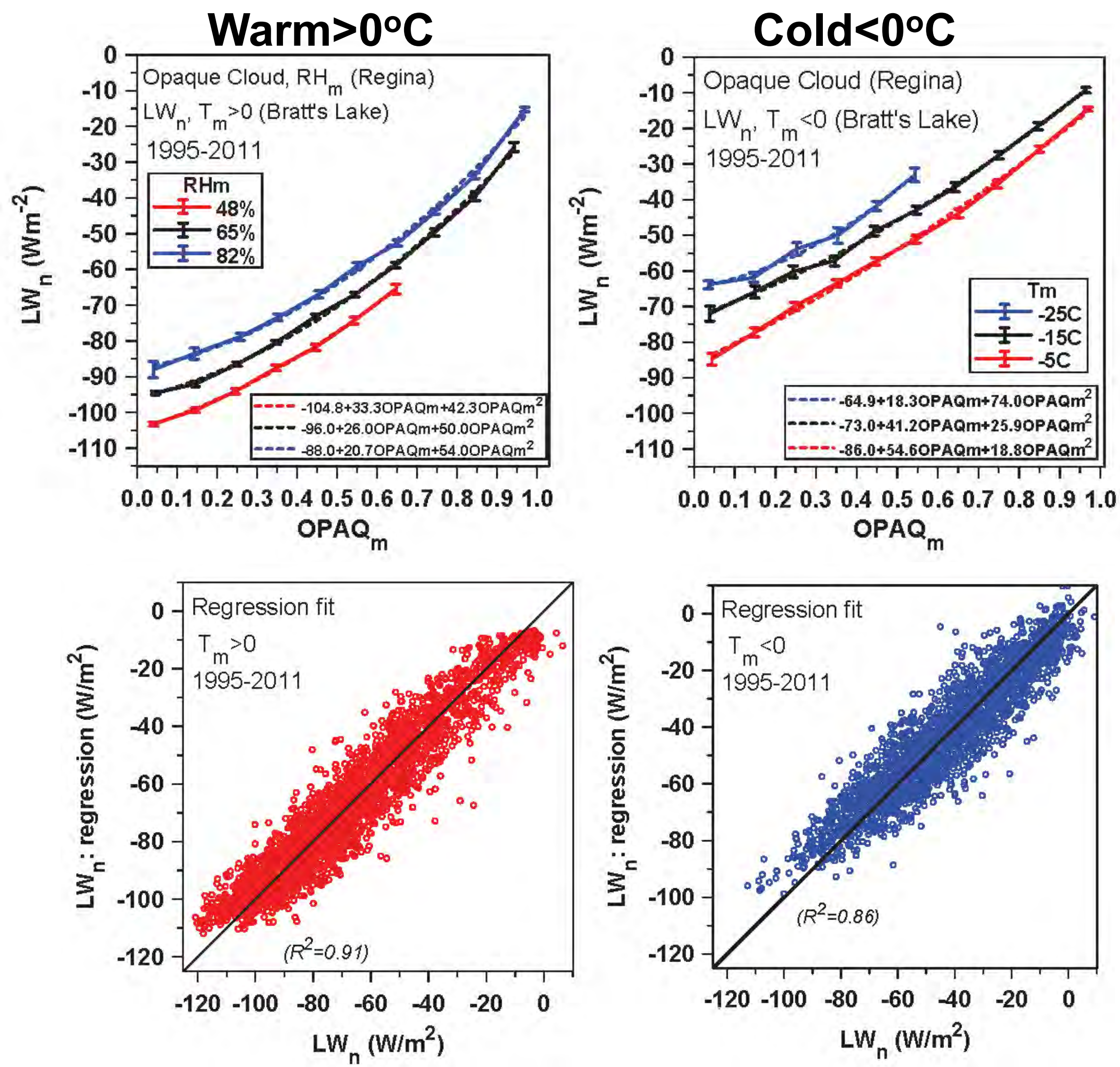
Use BSRN data to "calibrate" opaque/reflective Cloud

- **Daily mean opaque cloud $OPAQ_m$**

- ***LW cools but clouds reduce cooling***

- **Net LW: LW_n**
  - *T>0: depends on RH as well*
  - *T<0: depends on T and TCWV*

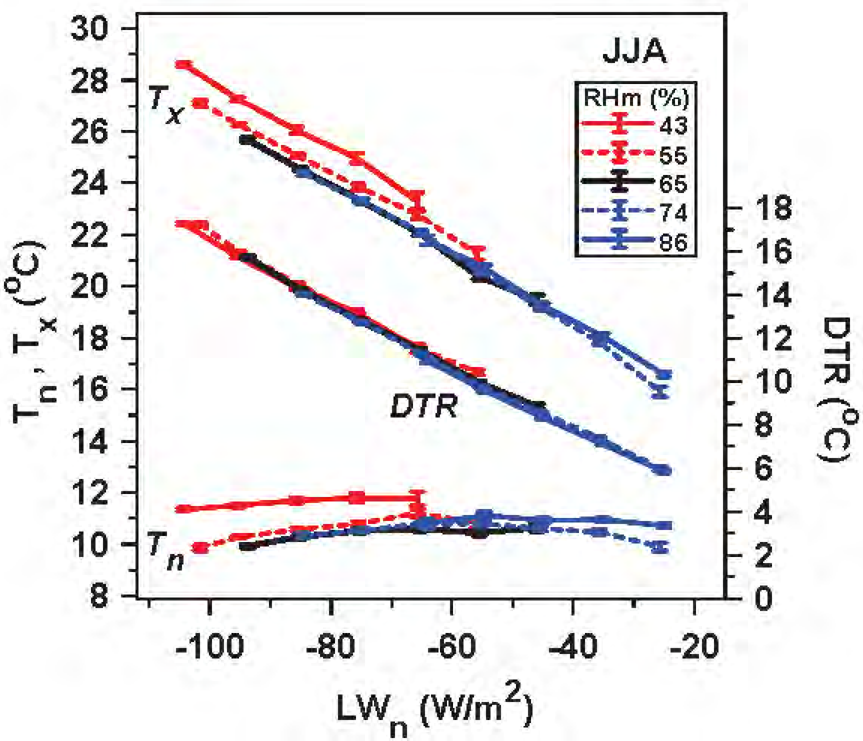
- ***Regression gives LW_n to ± $8W/m^2$ if T_m>0 (R^2=0.91)***

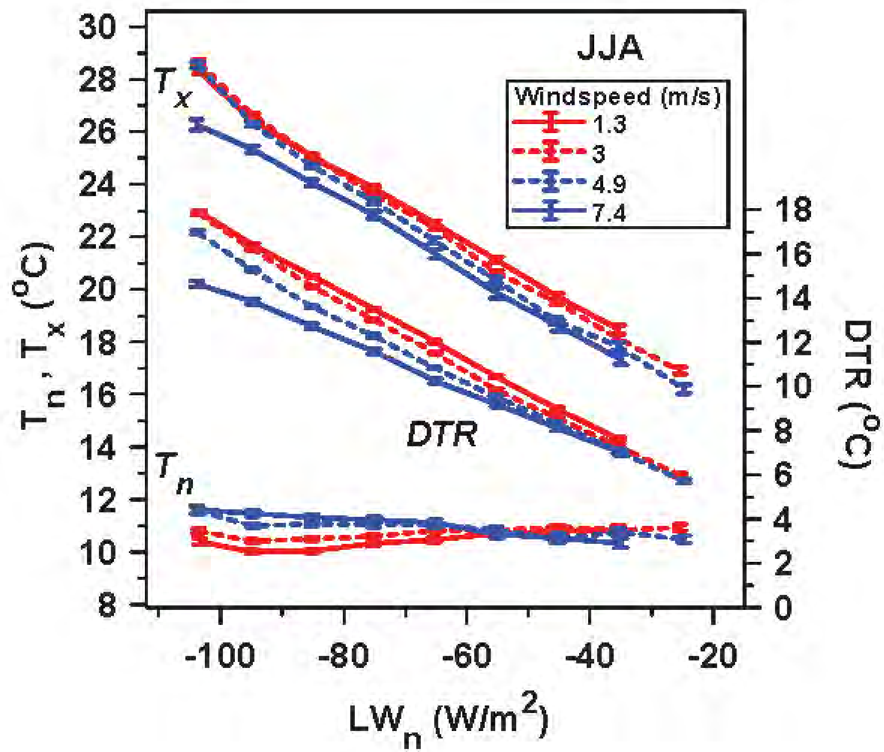


(Betts et al. 2015)

DTR to LW_n: RH and Wind

Summer JJA: 54000 days





- ***DTR depends <u>linearly</u> on LW_n [Betts, 2004, 2006]***
  - *cooling from afternoon T_x to sunrise T_n*
- ***Increasing wind reduces DTR***
  - *T_x falls and T_n increases*

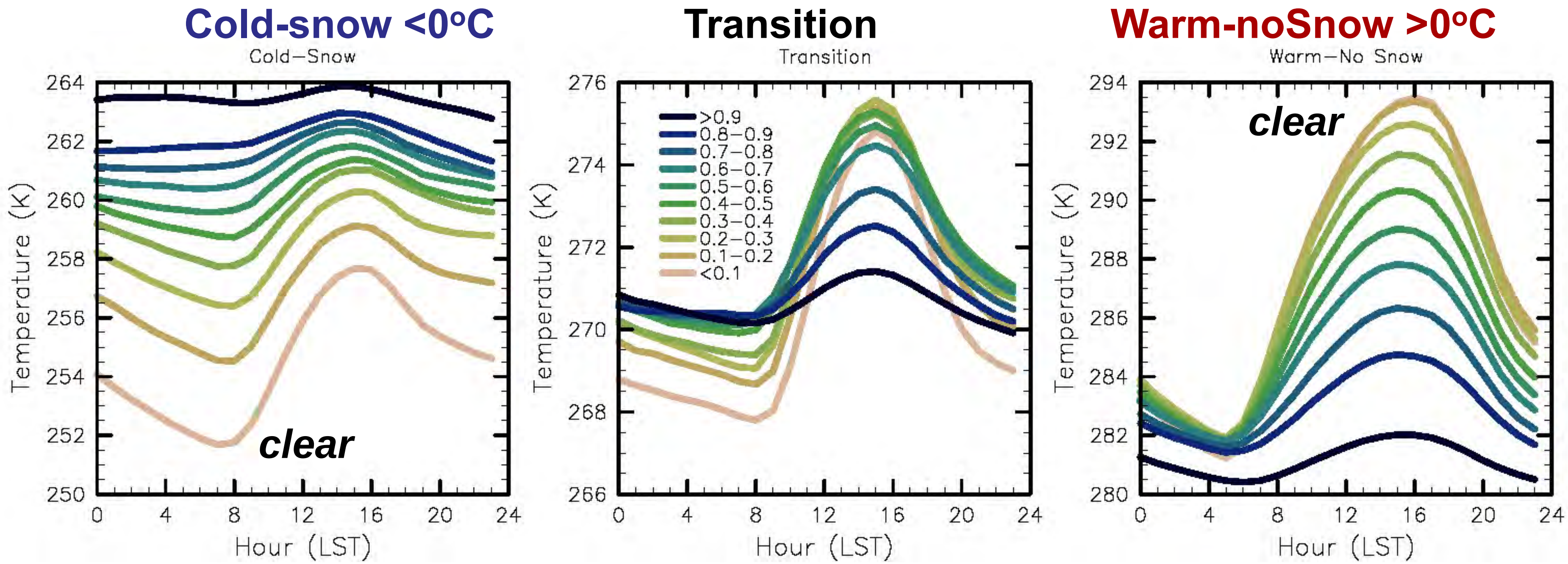
Betts et al. 2015

Warm and Cold Seasons

- Unstable BL: SWCF
- Clouds at LCL
  - reflecting sunlight

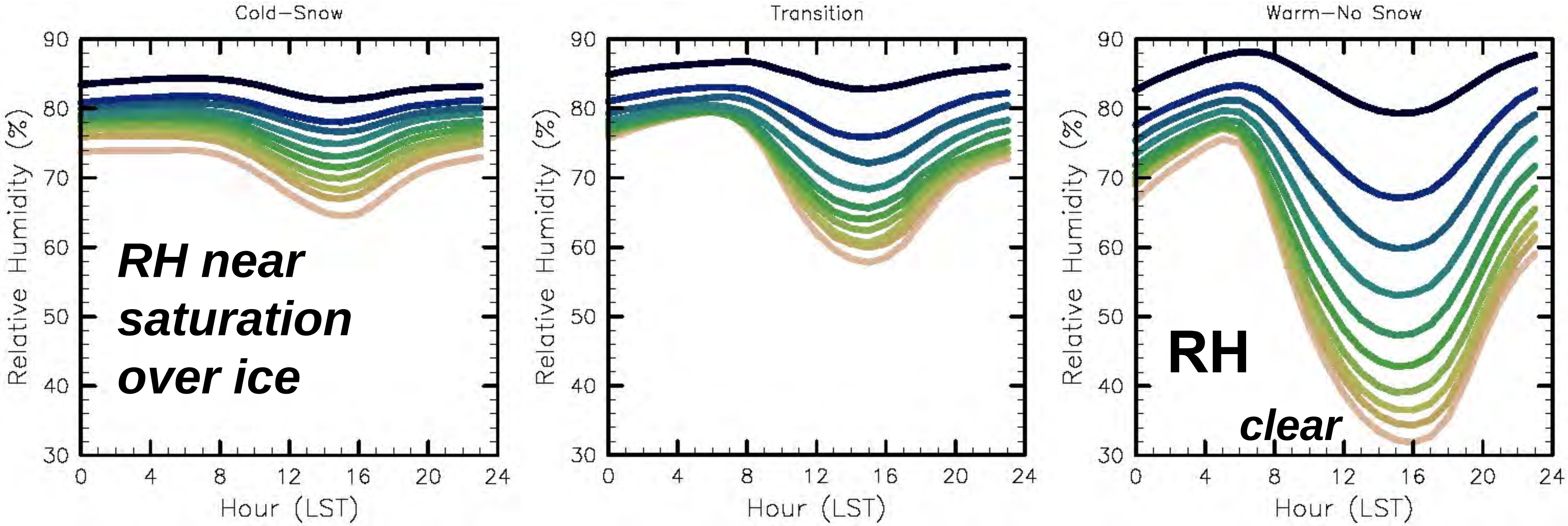
- Stable BL: LWCF
- Snow
  - reflecting sunlight

Clouds: Warm & Cold Climates

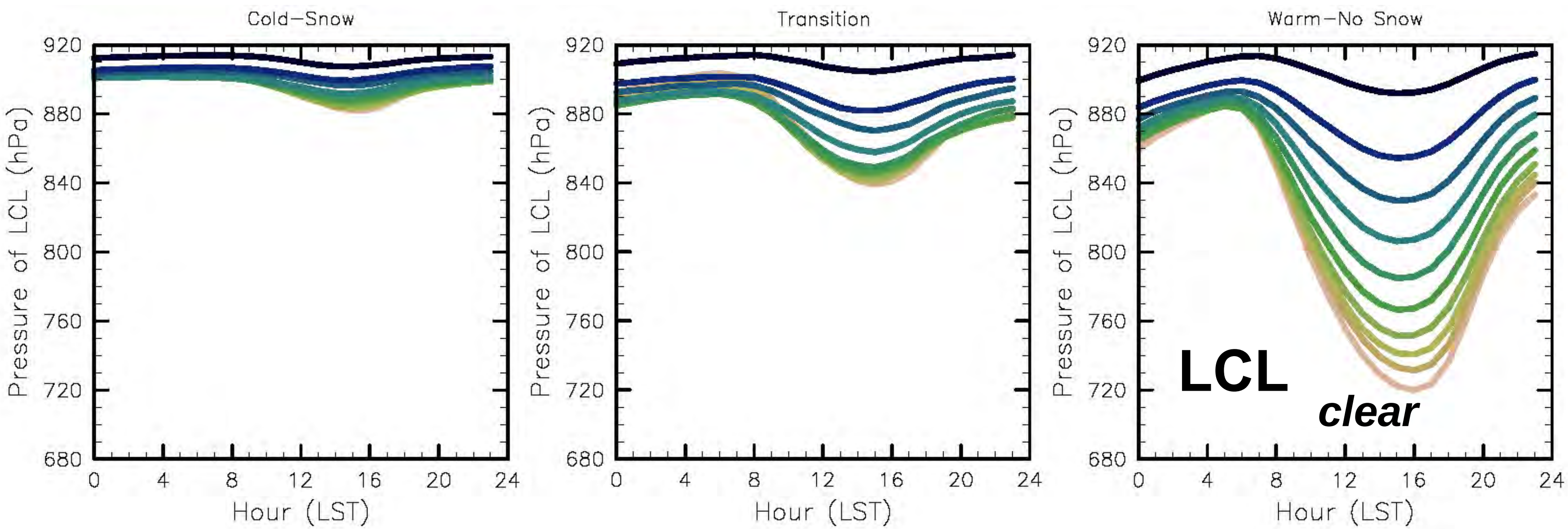


- ***250,000 days (Prairies: 650 station-years: 1953-2011)***
- **Freezing point of water changes everything**
- **Cold <0^{o}C: Snow: Surface cools radiatively, clouds 'blanket'**
  - ***stable boundary layer***
- **Transition: >0^{o}C: Snow; <0^{o}C: No Snow: near freezing**
- **Warm >0^{o}C: No Snow: Surface solar heating, clouds reflect**
  - ***Daytime unstable boundary layer***

Freezing point of water changes everything



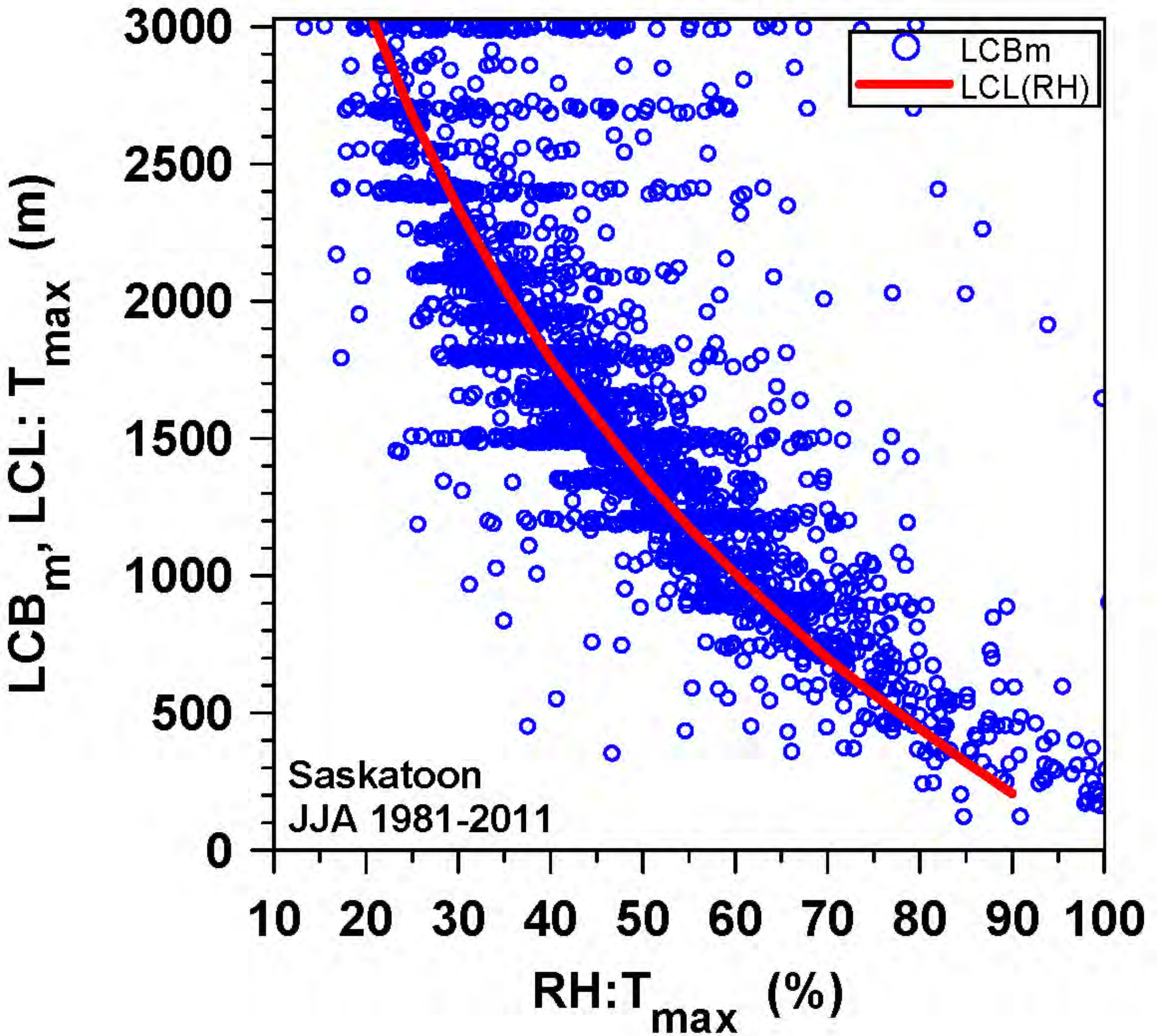
- Cold <0°C: Snow   Transition   Warm >0°C: No Snow:



Afternoon LCL is Cloud-base

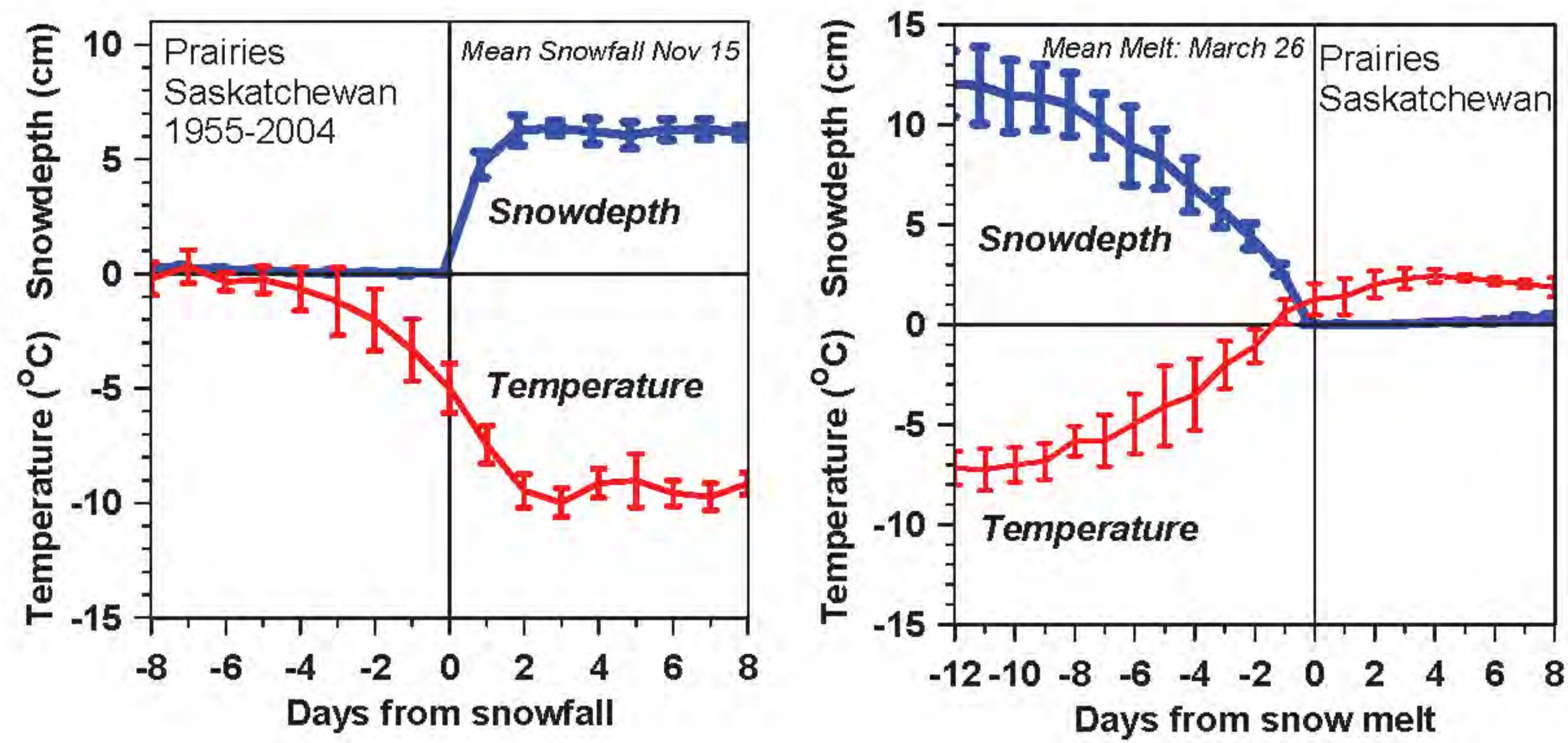
- **At T_x**
- **Lowest cloud-base *(ceilometer)***
- **LCL (surface)**

- ***Coupled convective boundary layer (CBL)***



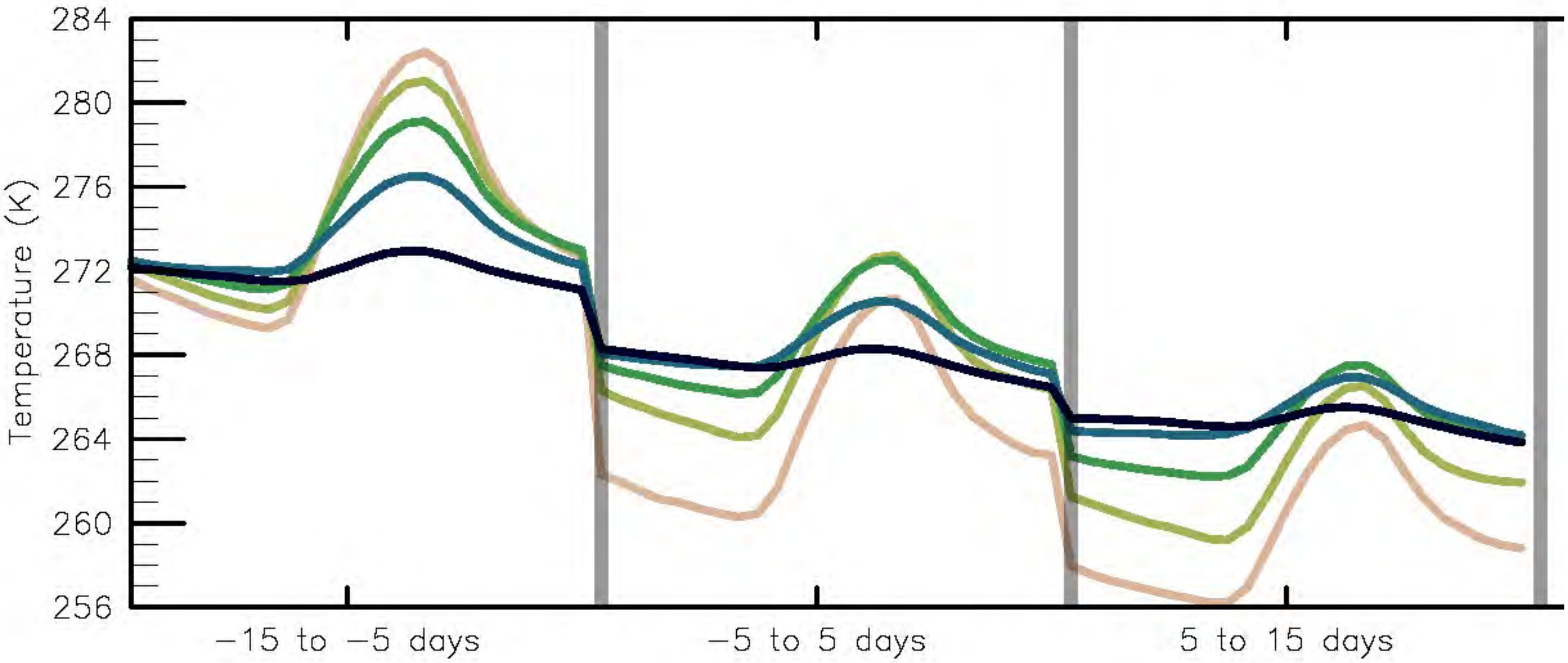
Winter Ice and Snow

Snowfall and Snowmelt



- **Temperature falls 10°C with first snowfall**
- **And rises again with snowmelt**
- ***Fast transitions in 'local climate': a 'climate switch'***
  - ***Snow reflects sunlight***
  - ***Reduces evaporation and water vapor greenhouse***

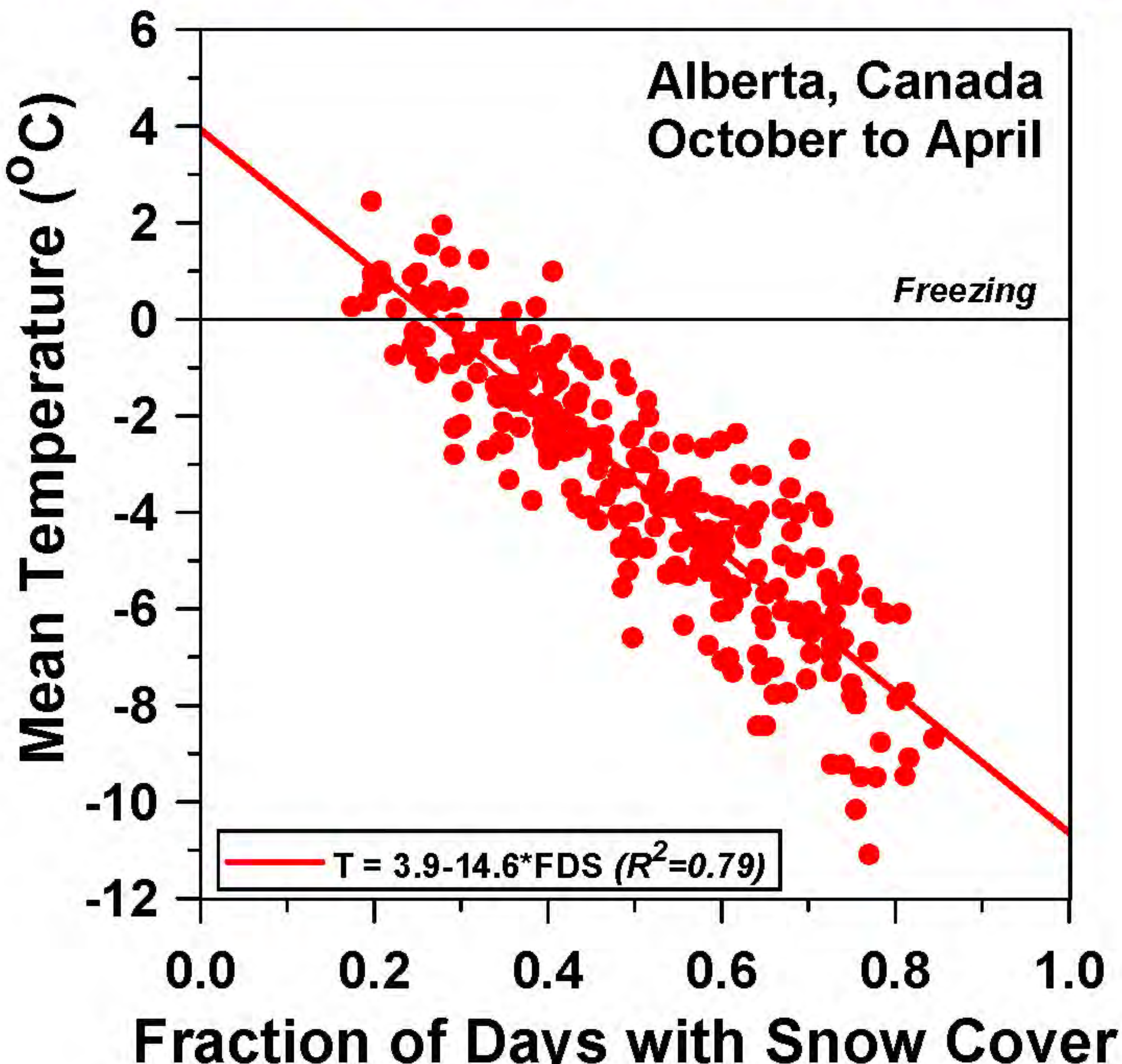
Mid-Nov. Snow Transition
(Cloud partition)



- Ahead of snow Transition After Snow
- Warm >0°C: No Snow Transition Cold <0°C: Snow

- Time sequence shows the three regimes

More snow cover - Colder temperatures



Betts et al. 2014a

Warm Season Climate: T>0°C
(No snow: May – October)

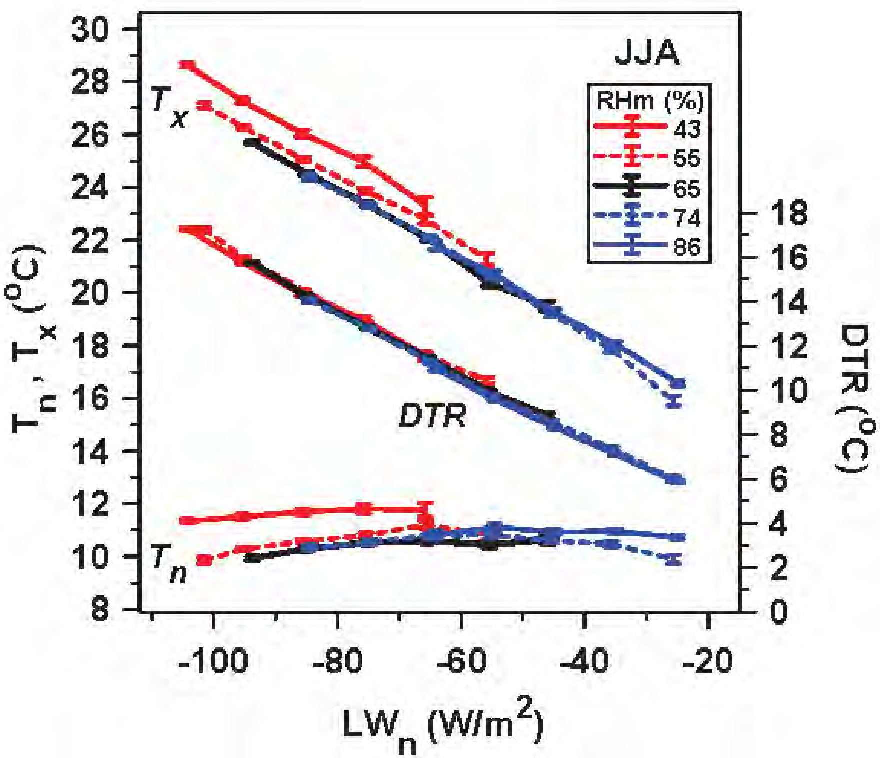
- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***

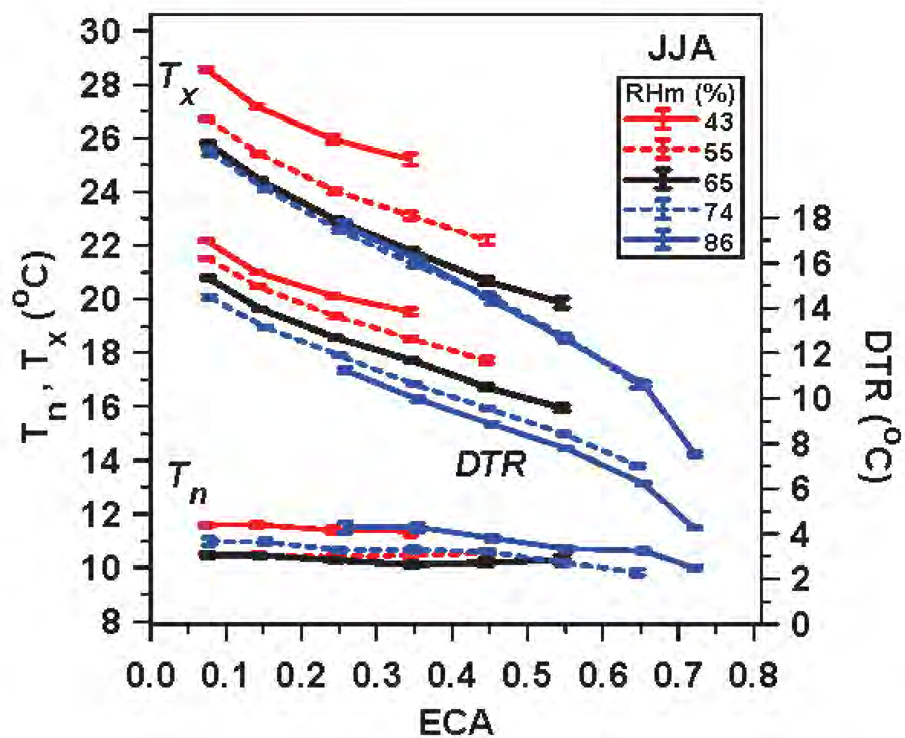
- ***Daily timescale is radiation driven***
  - ***Night LW_n; day ECA (and EF)***
- ***Monthly timescale: Fully coupled***

Betts et al. 2014b

DTR to LW_n and ECA

Summer, JJA: 54000 days





- ***DTR depends <u>linearly</u> on LW_n*** ***(daily $R^2 = 0.61$)***
  - ***cooling from afternoon T_x to sunrise T_n***
- ***DTR depends on ECA and RH_m***
  - ***RH_m is 'climate response' to energy partition by soil moisture***

Betts et al. 2015

Monthly timescale: Regression

δDTR = K + A* δPrecip(Mo-2) + B * δPrecip(Mo-1) + C * δPrecip + D * δOpaqueCloud
(Month-2) (Month-1) (Month) (Month)

δDTR anomalies

Month	K	A *(Mo-2)*	B*(Mo-1)*	C *(Mo)*	D *(Mo)*	R^2 All	R^2 Precip	R^2 Cloud
May	**0±0.8**		**-0.37±0.05**	**-0.37±0.04**	**-1.10±0.05**	**0.73**	**0.41**	**0.66**
Jun	**0±0.7**		**-0.30±0.03**	**-0.32±0.02**	**-0.97±0.04**	**0.69**	**0.42**	**0.52**
July	**0±0.7**	**-0.20±0.03**	**-0.25±0.02**	**-0.33±0.03**	**-1.10±0.05**	**0.67**	**0.42**	**0.48**
Aug	**0±0.7**	**-0.07±0.02**	**-0.21±0.03**	**-0.40±0.03**	**-1.24±0.04**	**0.79**	**0.46**	**0.71**
Sept	**0±0.8**		**-0.22±0.03**	**-0.49±0.04**	**-1.27±0.04**	**0.82**	**0.43**	**0.75**
Oct	**0±0.8**		**-0.27±0.03**	**-0.70±0.07**	**-1.33±0.04**	**0.77**	**0.37**	**0.70**

Betts et al. 2014b

Monthly timescale: Regression

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

Afternoon δRH_{tx} anomalies

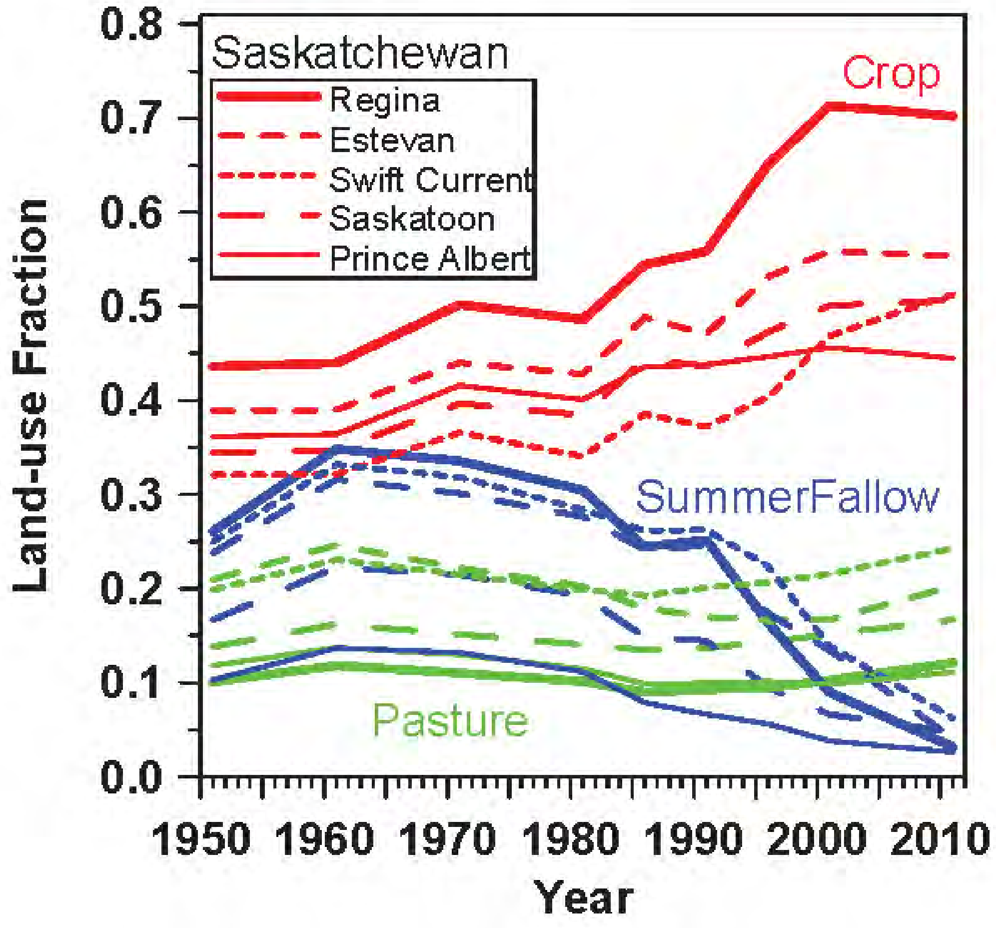
Month	K	A *(Mo-2)*	B*(Mo-1)*	C *(Mo)*	D *(Mo)*	R^2 All	R^2 Precip	R^2 Cloud
May	0±3.6	1.30±0.38	1.47±0.22	2.07±0.17	4.75±0.20	0.72	0.46	0.62
Jun	0±3.6	0.69±0.23	1.26±0.15	1.96±0.12	4.36±0.22	0.68	0.47	0.48
July	0±4.1	0.84±0.18	1.71±0.12	1.81±0.17	4.40±0.30	0.59	0.43	0.33
Aug	0±3.6	0.66±0.11	1.23±0.13	2.42±0.16	4.08±0.20	0.73	0.53	0.56
Sept	0±3.5		1.40±0.13	2.10±0.18	4.35±0.16	0.75	0.45	0.63
Oct	0±4.3		1.28±0.19	5.02±0.39	4.58±0.23	0.67	0.44	0.53

Betts et al. 2014b

Change in Cropping (SK)

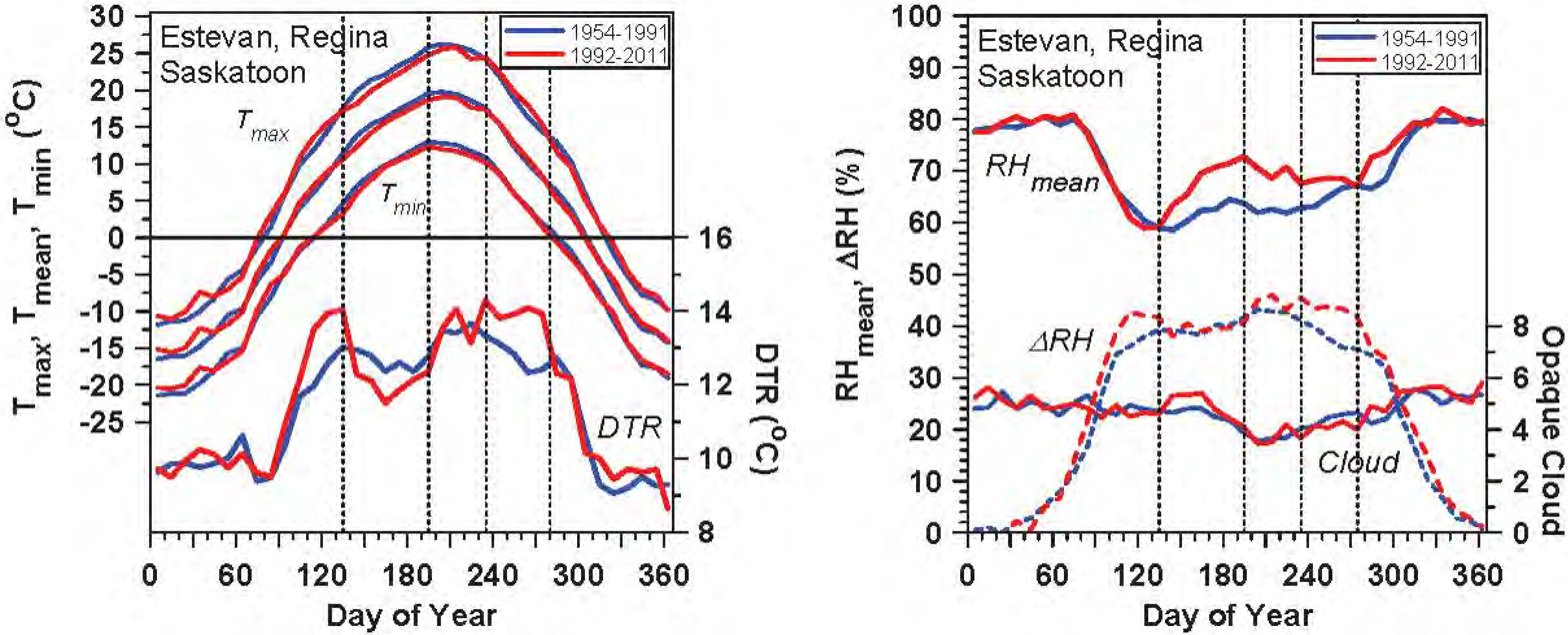
- **Ecodistrict mean for 50-km around station**
- **Saskatchewan:**
  - **25% drop in 'SummerFallow'**

- ***Split at 1991 - has summer climate changed?***



Betts et al. 2013b

Three Station Mean in SK

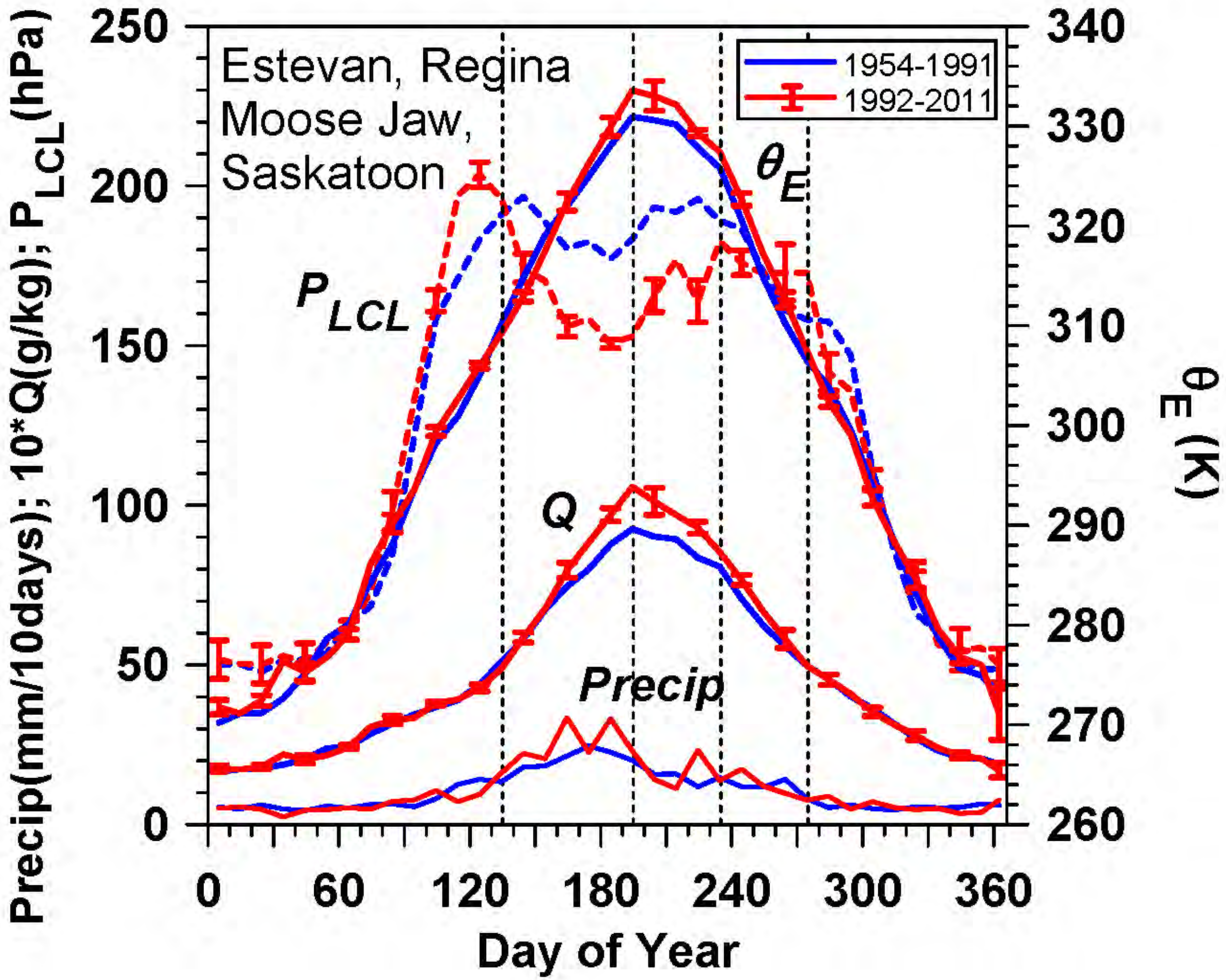


- Growing season (winter warmer)
  - T_{max} cooler; RH moister
  - DTR and ΔRH <u>seasonal transitions</u>

Impact on Convective Instability

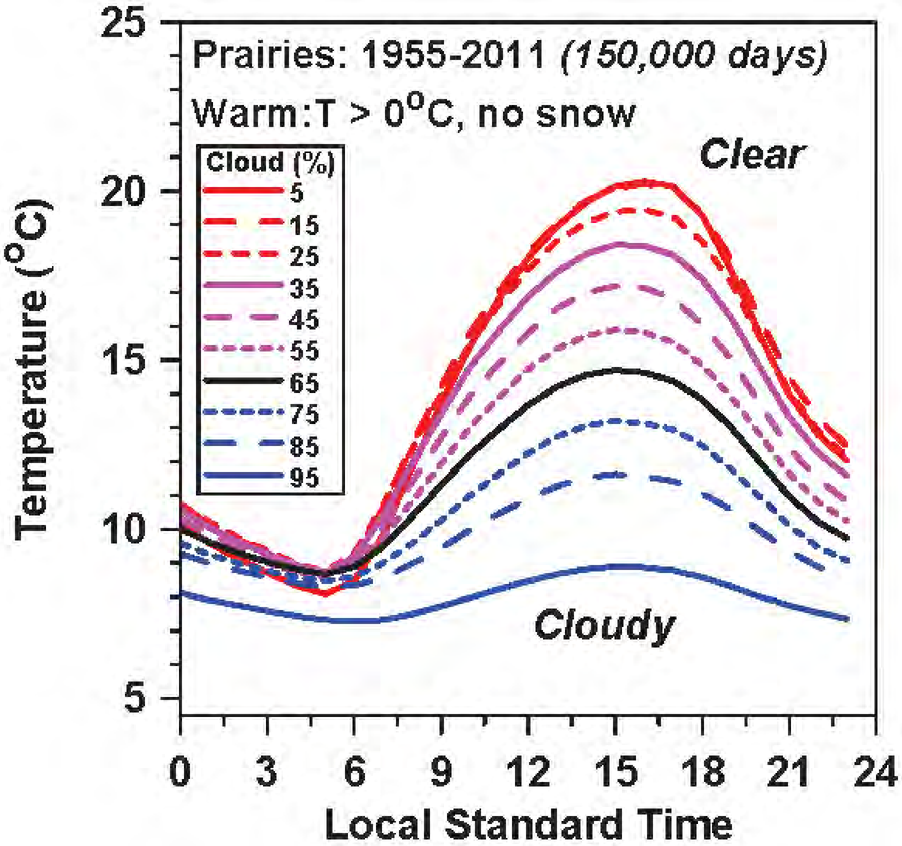
Growing season

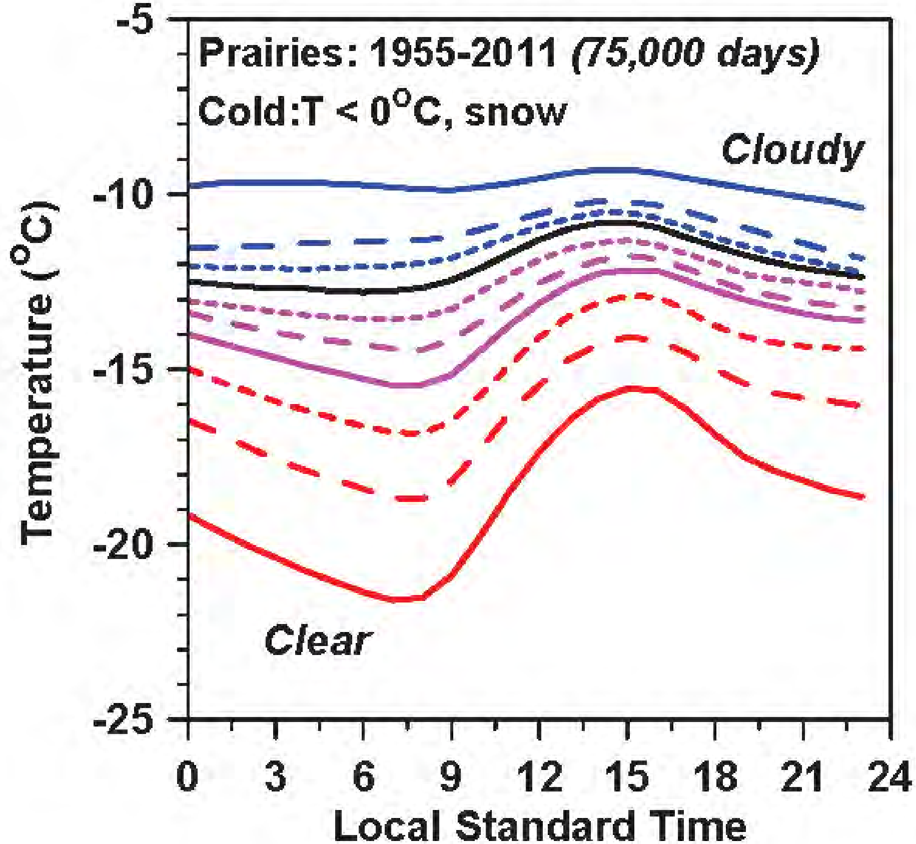
- **Lower LCL**
- **Higher θ_E**
- **More Precip**



Betts et al. 2013b

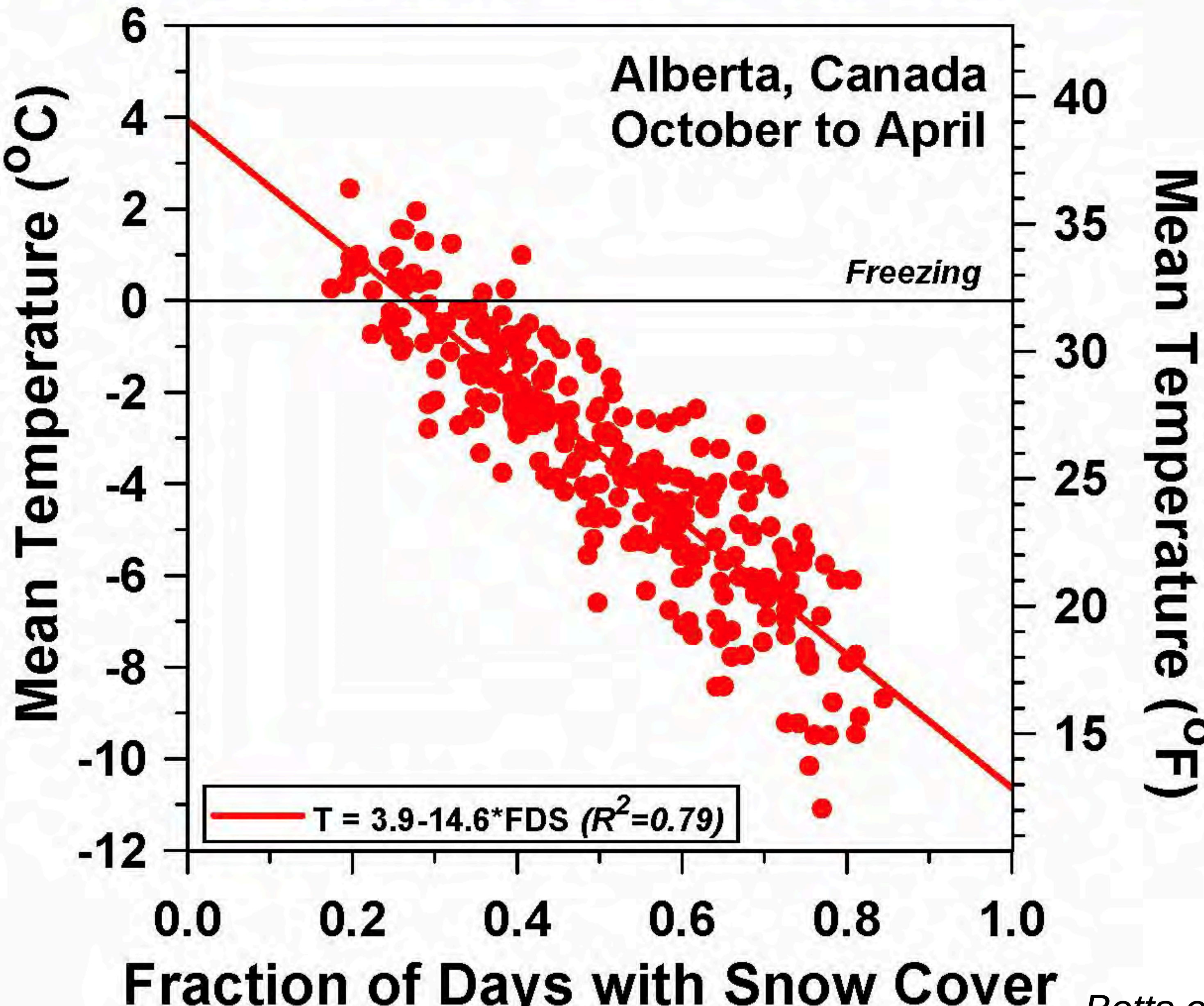
Warm & Cold Climates: T><0^{o}C





- **Warm >0^{o}C:** Clouds reflect sunlight
- **Cold <0^{o}C:** Clouds are greenhouse & snow reflects sun
- **T falls 10^{o}C with snow - *Fast climate transition***

More snow cover - Colder temperatures



Betts et al. 2014a

Summary

- **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**

- **Increased transpiration changed climate**
  - **Cools and moistens summer climate**
  - **Lowers cloud-base and increases θ_E**
  - **(While winter climate has warmed)**

Papers at http://alanbetts.com

Conclusions

- Hydrometeorology requires
  - Precipitation and cloud/radiation
    - Cloud dominates on daily timescale
    - Both affect monthly to seasonal anomalies
  - Temperature and RH
    - Giving LCL and θ_E: feedback to Precip
- Canadian Prairie data
  - Describe fully coupled Land-Atmos system
  - Invaluable for model evaluation
- http://alanbetts.com/ *(5 papers)*

MJJA Growing Season

$\delta Y_\sigma = K_\sigma + B_\sigma * \delta Precip(AMJJA)_\sigma + C_\sigma * \delta OpaqueCloud_\sigma$

Variable: δY_σ	**K_σ**	**B_σ**	**C_σ**	**R^2_σ**	**$\sigma(\delta Y)$**
$\delta T_{x\sigma}$	0±0.7	**-0.33±0.03**	**-0.52±0.03**	**0.52**	**1.11**
$\delta T_{m\sigma}$	0±0.8	-0.21±0.05	-0.50±0.07	0.38	**0.88**
δDTR_σ	0±0.6	**-0.55±0.03**	**-0.39±0.03**	**0.62**	**0.83**
$\delta RH_{tx\sigma}$	0±0.6	**0.56±0.03**	**0.35±0.03**	**0.60**	**4.35**
$\delta RH_{m\sigma}$	0±0.7	0.51±0.03	0.33±0.03	0.50	**4.61**
$\delta P_{LCLtx\sigma}$	0±0.6	**-0.56±0.03**	**-0.37±0.03**	0.61	**18.6**
$\delta Q_{tx\sigma}$	0±0.9	0.50±0.04	0.03±0.04	0.26	**0.58**
$\delta \theta_{Etx\sigma}$	**0±1.0**	**0.22±0.04**	**-0.31±0.04**	**0.09**	**1.95**

Diurnal range of Q