Land-cloud-climate coupling on the Canadian Prairies

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Land-Atmosphere Interactions
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RACC
Research on Adaptation to Climate Change

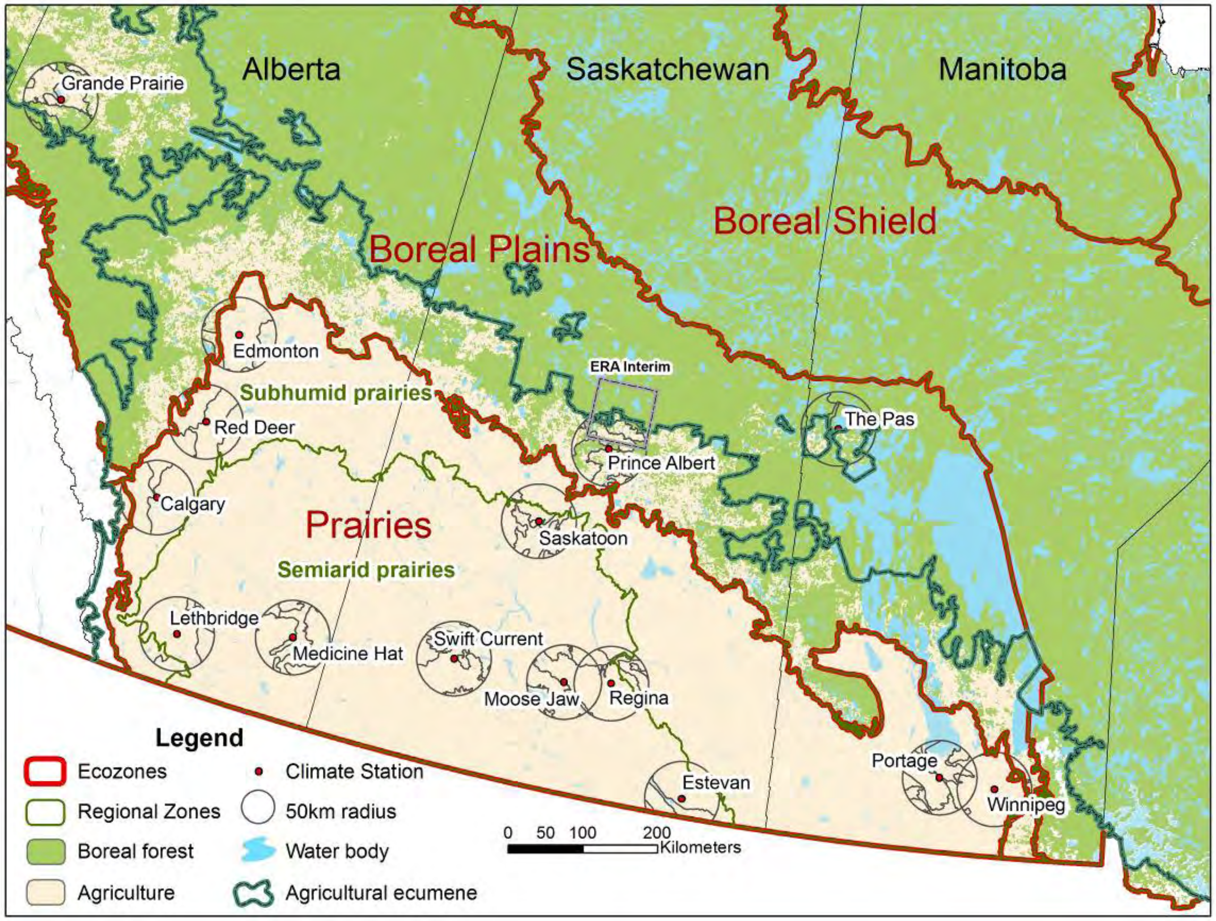
Key Issues

- **Northern latitude climate**
  - **Large seasonal cycle**
    - **Cold winters with snow**
    - **Snow is a fast climate switch**
    - **Two “climates” - above and below the freezing point of water**
  - **Summer hydrometeorology**
    - **T and RH have joint dependence on radiation and precipitation on monthly timescales**
  - **Observational evaluation of models**
    - ***Remarkable 55-yr hourly data set with opaque/reflective cloud observations***

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

- **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 (2014a), Coupling of winter climate transitions to snow and clouds over the Prairies. *J. Geophys. Res. Atmos*., 119, doi:10.1002/2013JD021168.**
- **Betts, A.K., R. Desjardins, D. Worth and B. Beckage (2014b), Climate coupling between temperature, humidity, precipitation and cloud cover over the Canadian Prairies. *J. Geophys. Res. Atmos*. 119, 13305-13326, doi:10.1002/2014JD022511**
- **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 Dataset

- **Reduce hourly data to**
  - **daily means: T_m , RH_m, $OPAQ_m$ etc**
  - **data at $T_{max/min}$: T_x and T_n**
- ***Diurnal cycle climate***
  - **DTR = $T_x - T_n$**
  - **$\Delta RH = RH_{tn} - RH_{tx}$**
- ***Almost no missing hourly data***

  (until recent cutbacks)

Surface Radiation Budget

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

($ECA \equiv \alpha_{cloud}$)

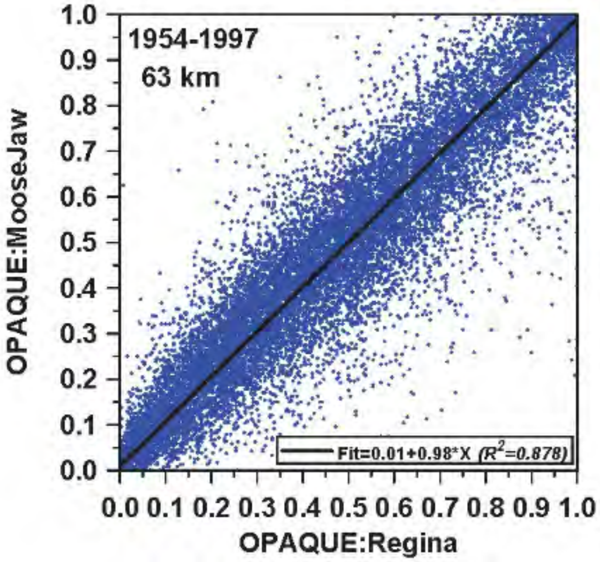
$$ECA = - SWCF / SW_{dn}(clear)$$

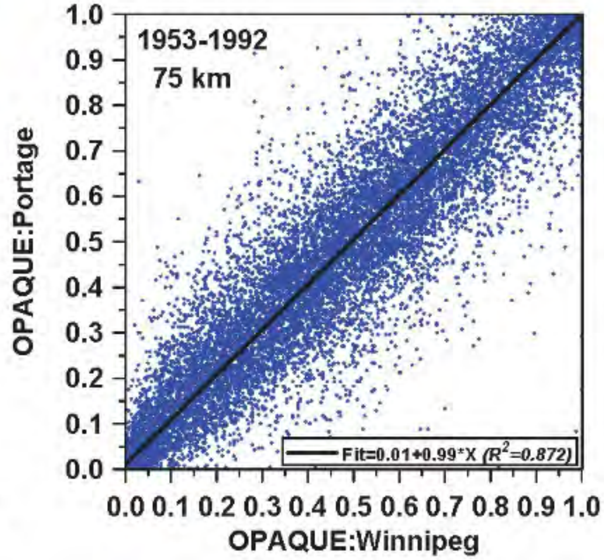
$$SW_n = (1 - \alpha_s)(1 - ECA)\ SW_{dn}(clear)$$

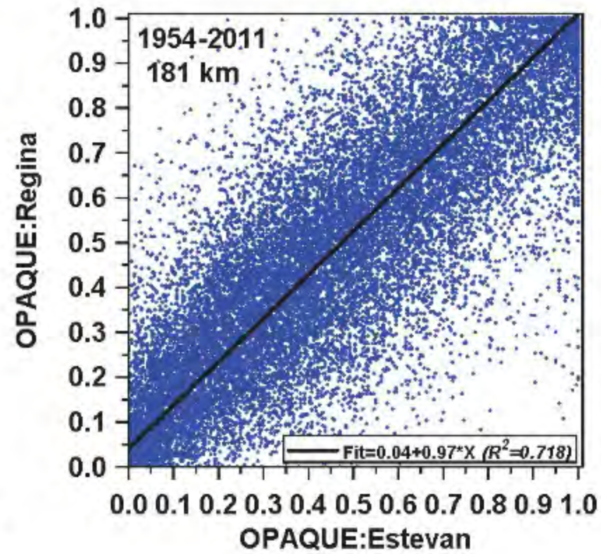
Reflected by surface, clouds

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

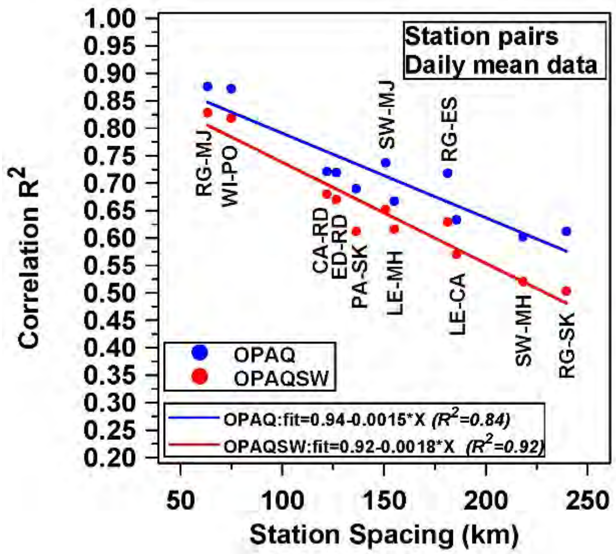
Opaque Cloud Quality



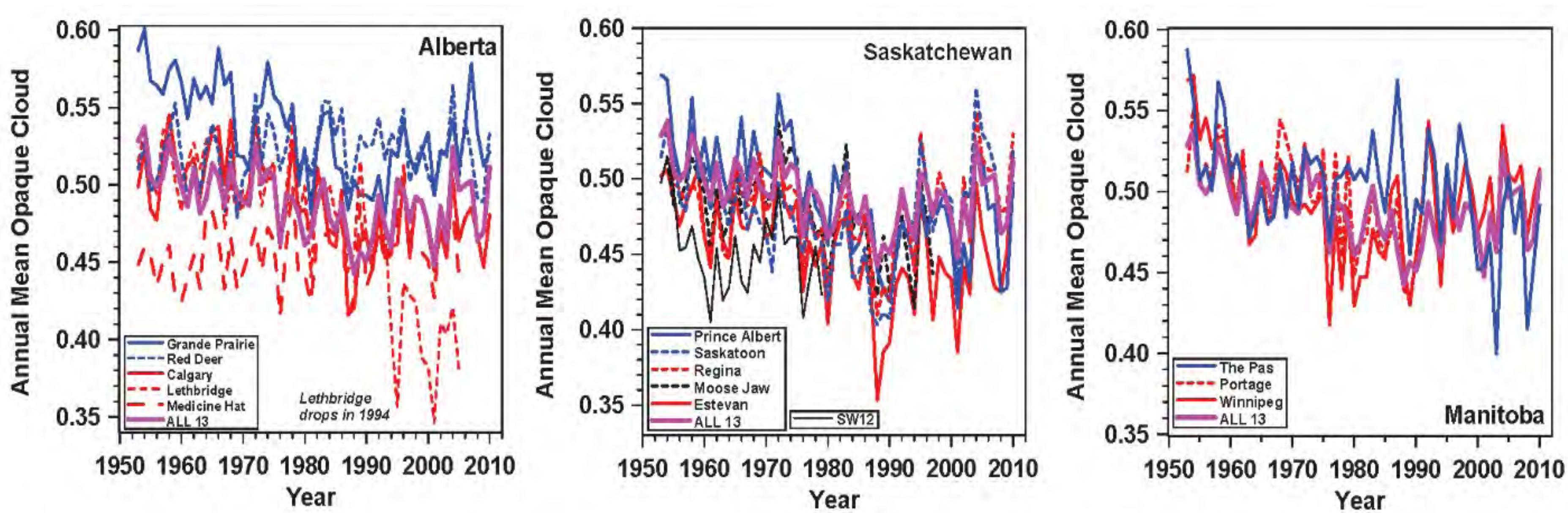




- **Daily means unbiased**
- **Correlation falls with distance**
- **Good data!**



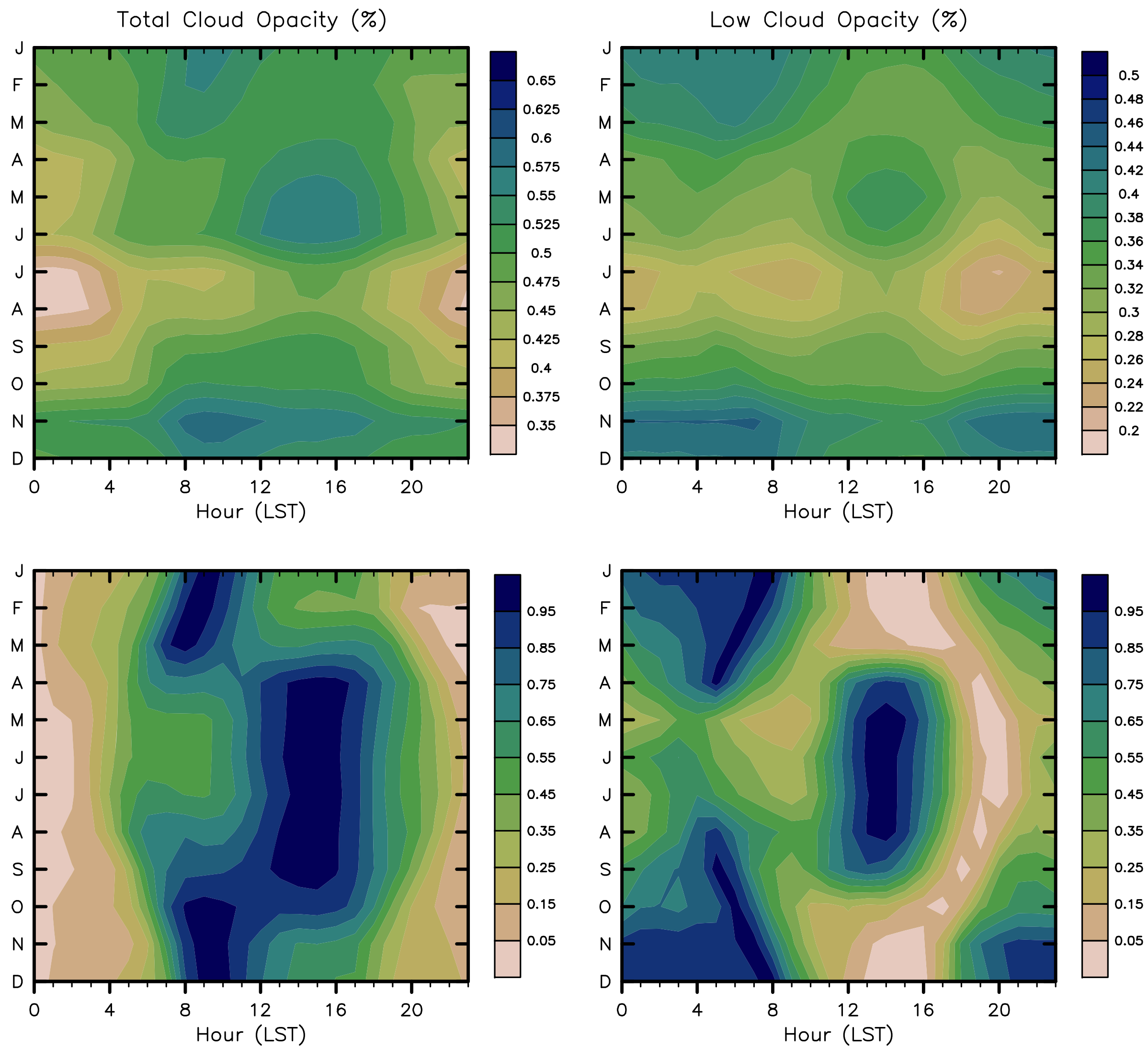
Long-term variability



- **Annual means**
  - **Interesting long-term variability**
  - ***Only Lethbridge has obvious bias after 1994***

Annual/D

- **Total opaque cloud fraction and lowest-level opaque cloud**

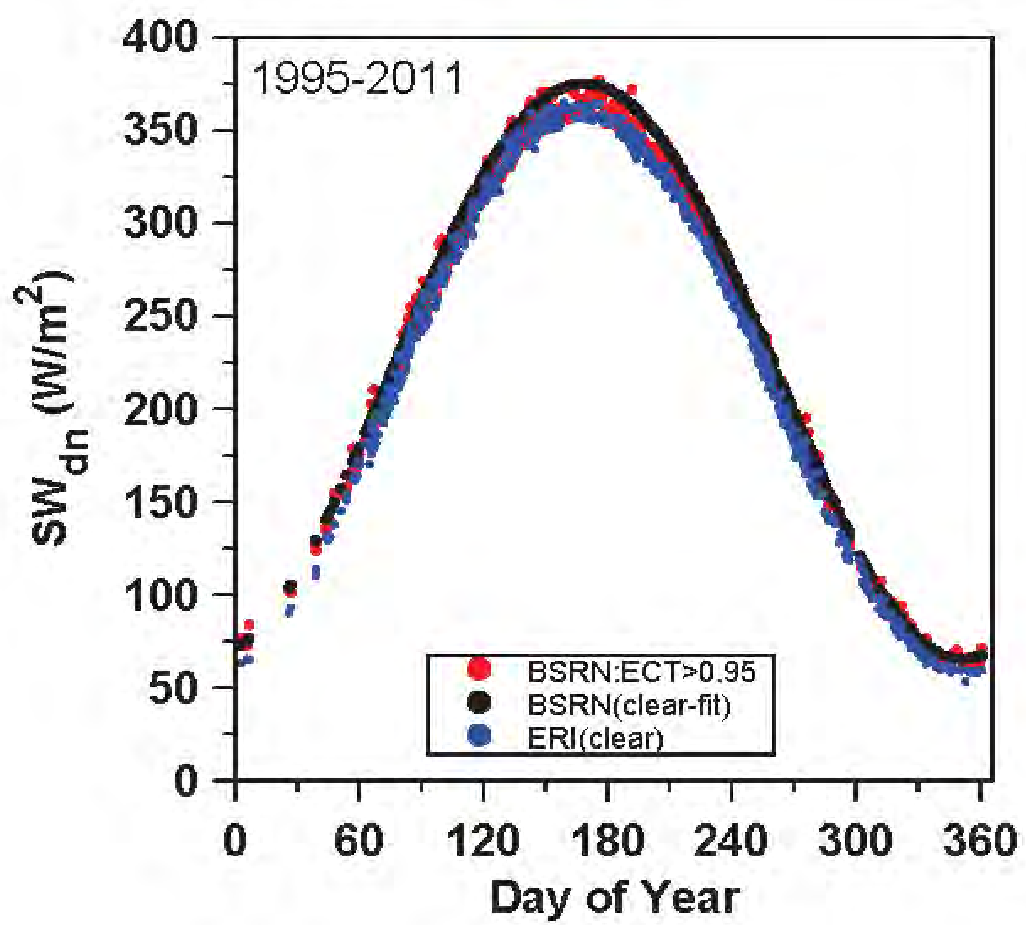


- **Normalized diurnal cycles (where 1 is the diurnal maximum and 0 is the minimum.**

- **Regime shift between cold and warm seasons: Why?**

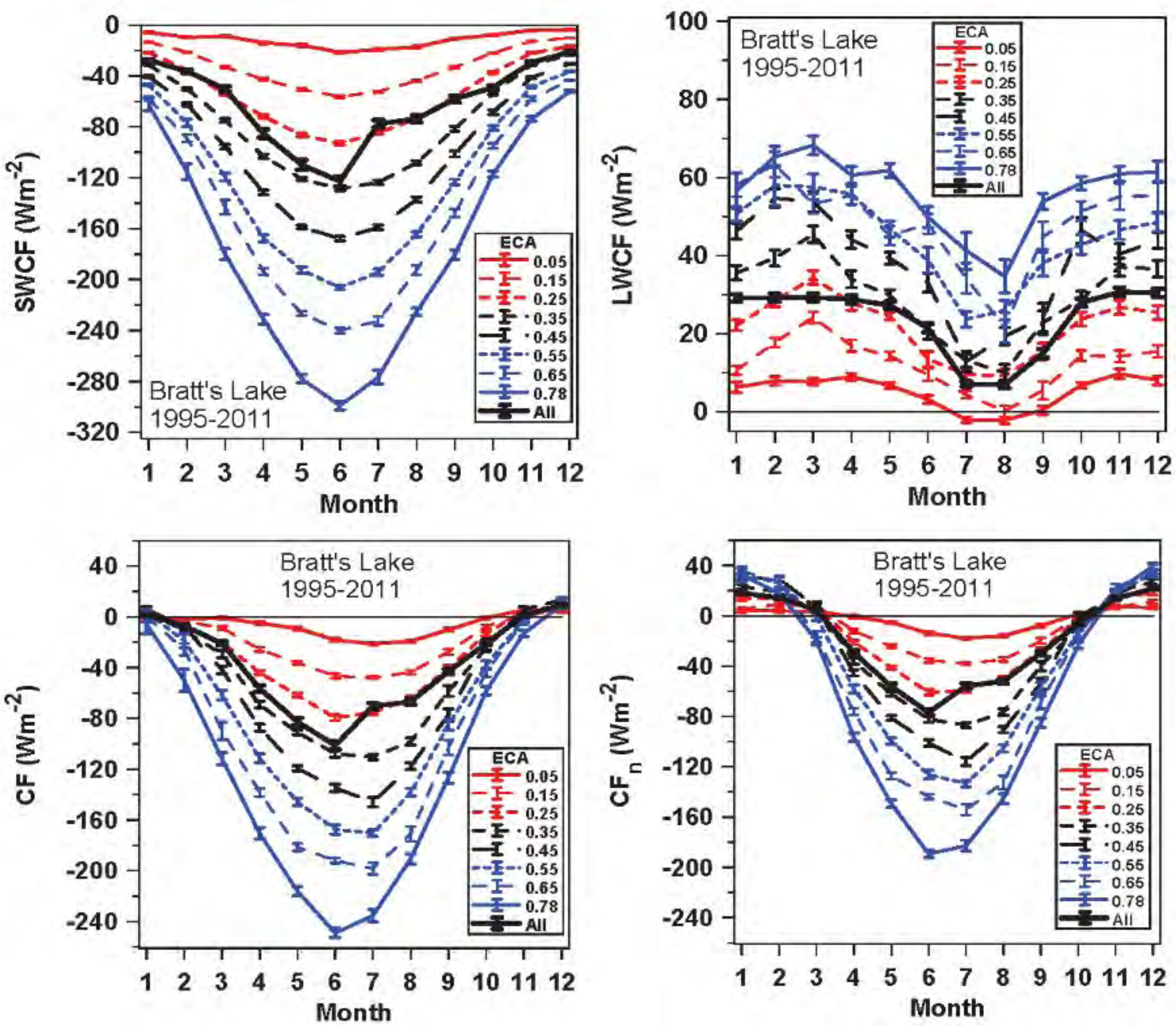
Cloud Forcing Needs Clear-sky Fluxes:

- **Compare ERA-Interim (ERI) and 'clear' BSRN days**
  - **SW_{dn}(clear): ERI biased low**
  - **Fit BSRN**
  - **LW_{dn}(clear): ERI unbiased**



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

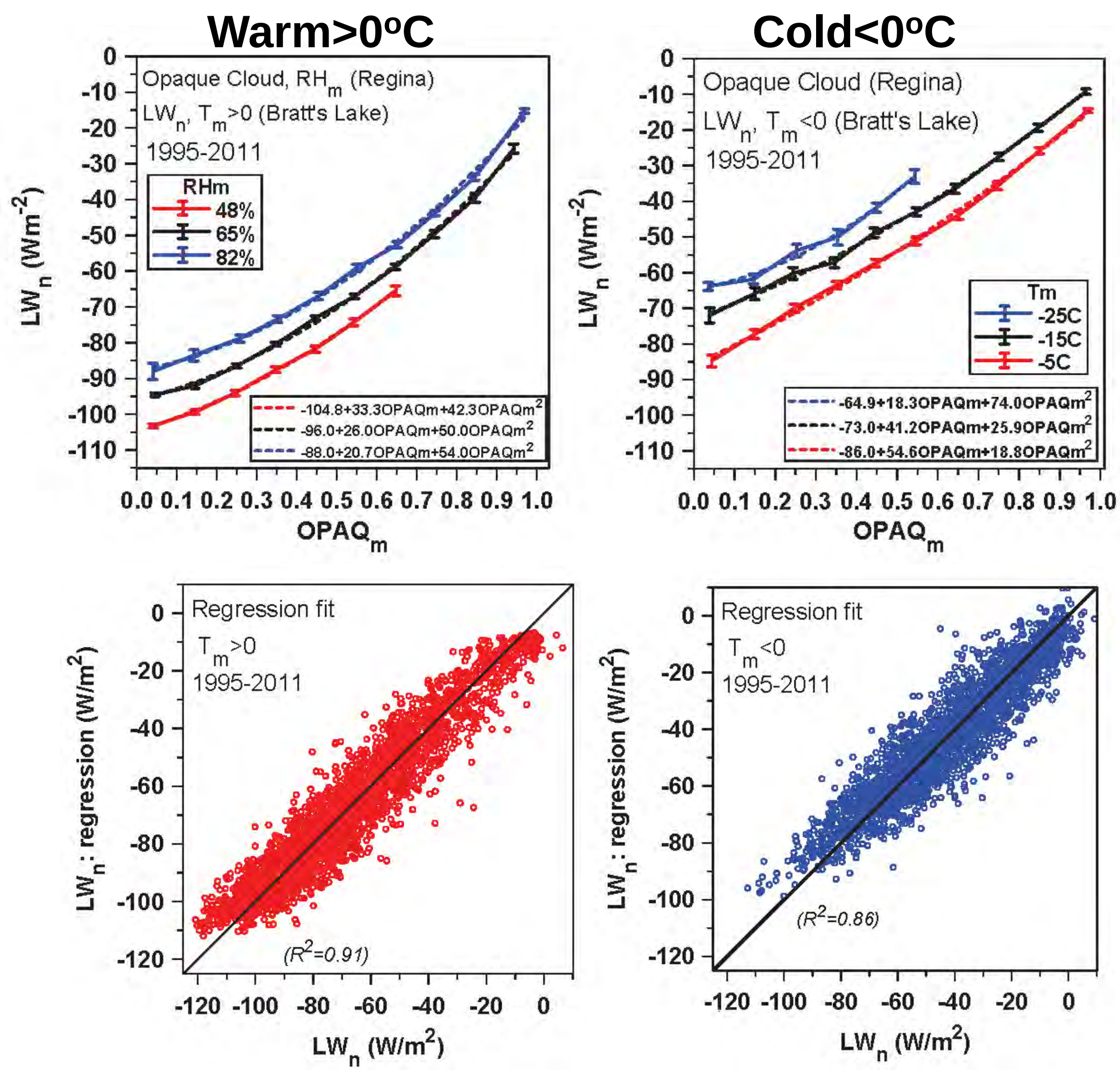
- **"Cloud Forcing"**
  - ***Change from clear-sky***
- **Clouds reflect SW**
  - ***SWCF***
  - ***Cool***
- ***Clouds trap LW***
  - ***LWCF***
  - ***Warms***
- ***Sum is CF***
- ***Surface albedo reduces SW_n***
  - ***Net is CF_n***
  - ***Add reflective snow, and CF_n goes +ve***
- ***Regime change***



(Betts et al. 2015)

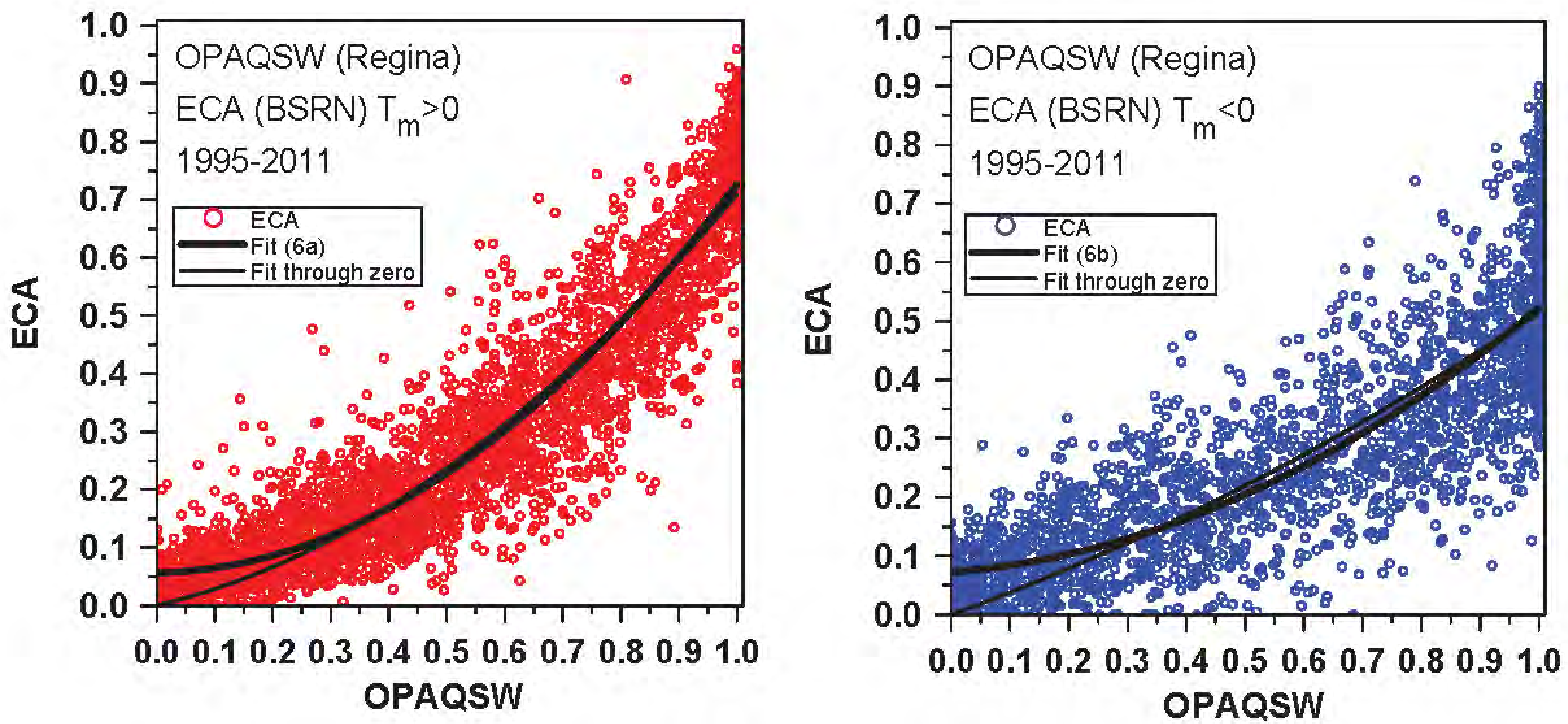
Use BSRN data to "calibrate" daily opaque/reflective Cloud at Regina

- **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/m² if T_m>0 (R^2=0.91)***



(Betts et al. 2015)

SW calibration



- *Contrast simple quadratic fit with fit through zero*
- *Uncertainty at low opaque cloud end*
  - *Thin cirrus not opaque*

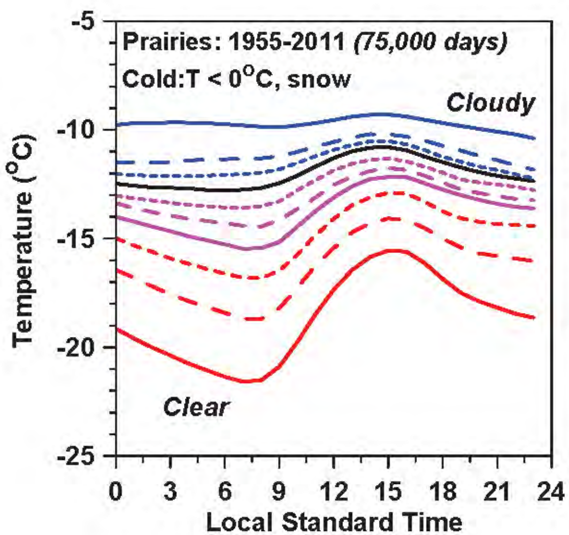
Warm and Cold Seasons

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

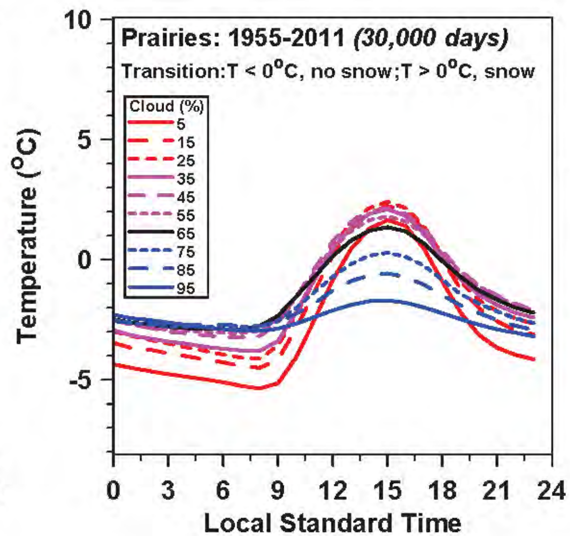
- **Stable BL: LWCF**
- **Snow**
  - **reflecting sunlight**

Clouds: Cold & Warm Climates

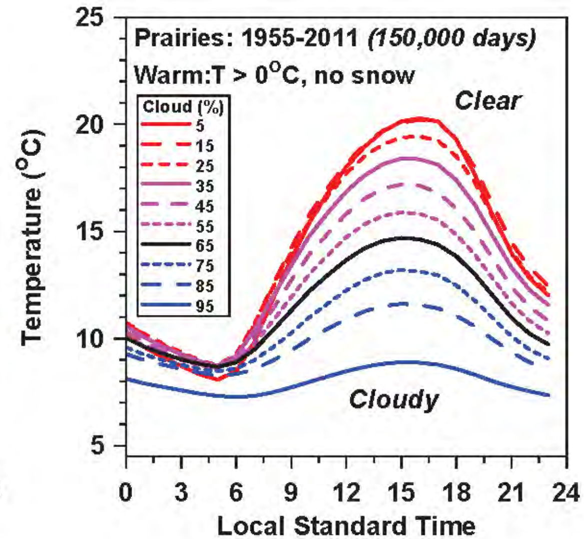
Cold-snow <0ºC



Transition



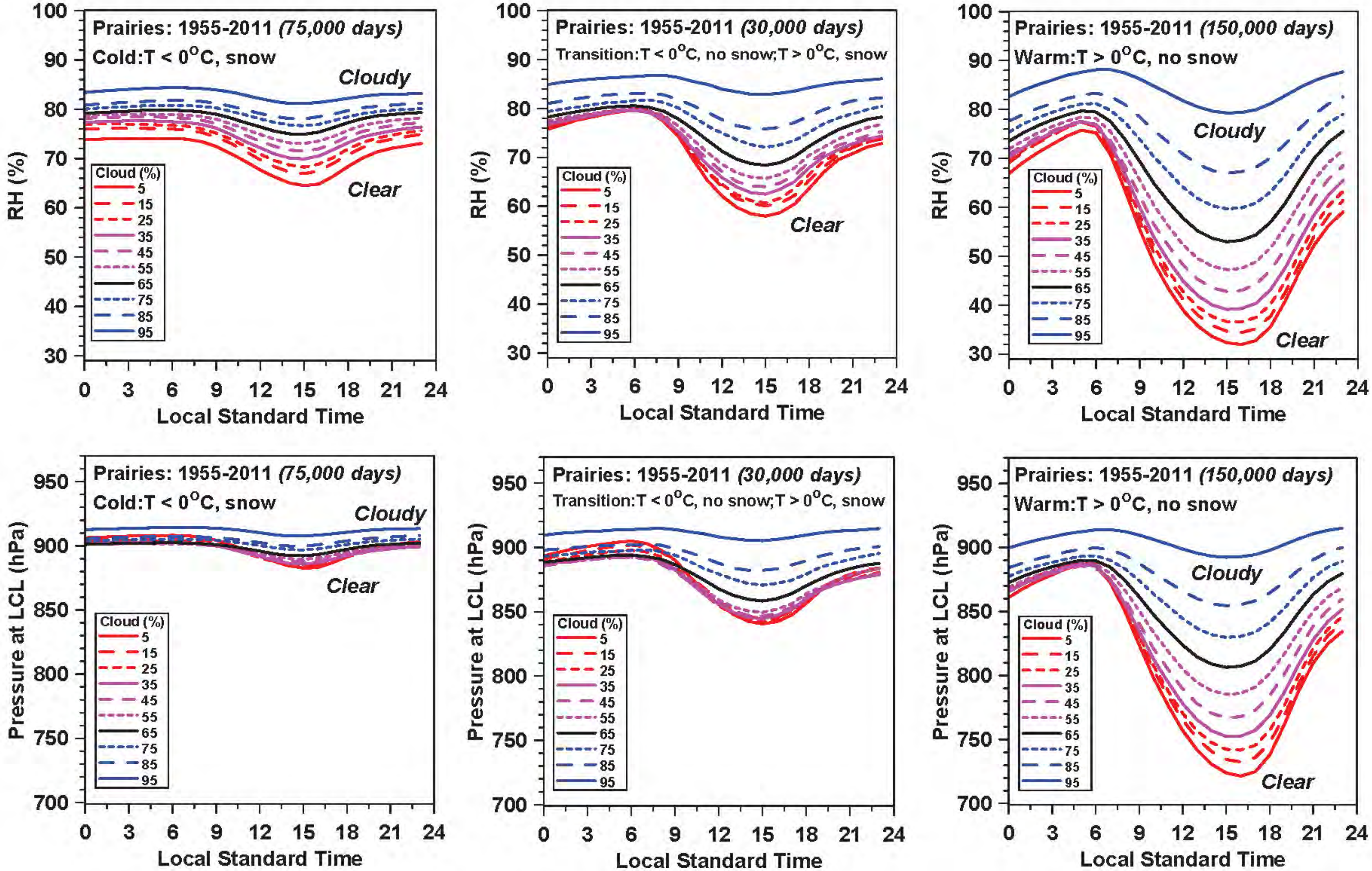
Warm-noSnow >0ºC



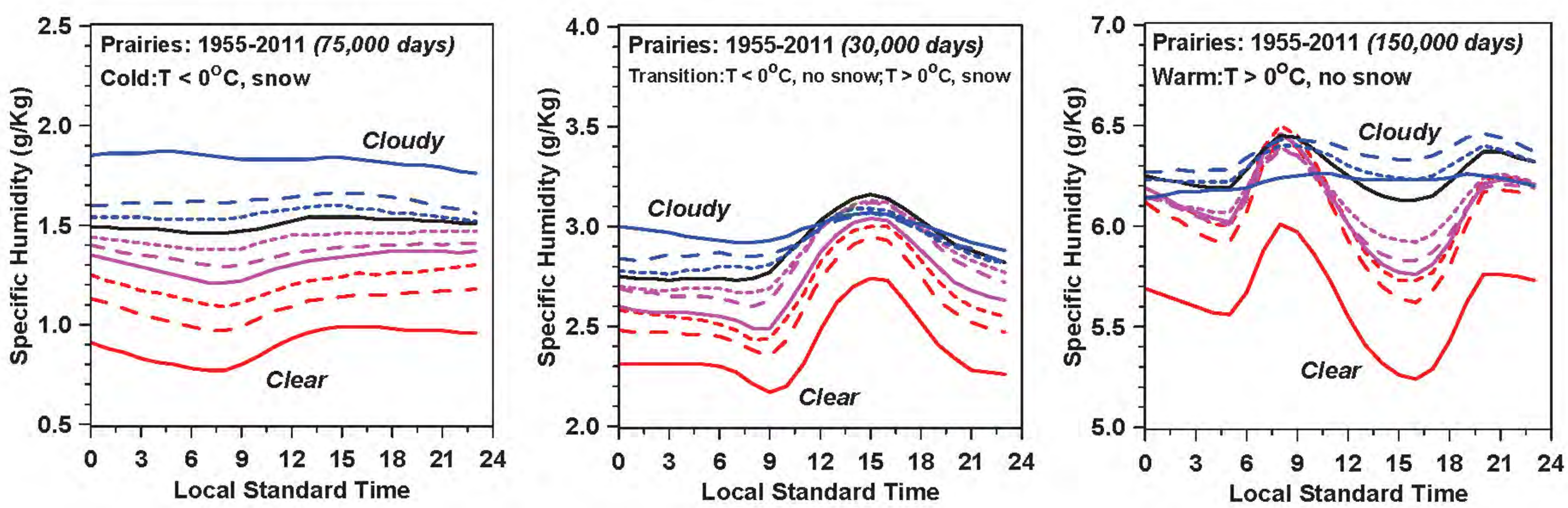
- ***250,000 days (Prairies: 650 station-years: 1953-2011)***
- **Freezing point of water changes everything**
- **Cold <0ºC: Snow: Surface cools radiatively, clouds 'blanket'**
  - ***stable boundary layer***
- **Transition near freezing: >0ºC: Snow; <0ºC: No Snow**
- **Warm >0ºC: No Snow: Surface solar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

RH and Pressure of LCL

- **Cold <0ºC: Snow** **Transition** **Warm >0ºC: No Snow**



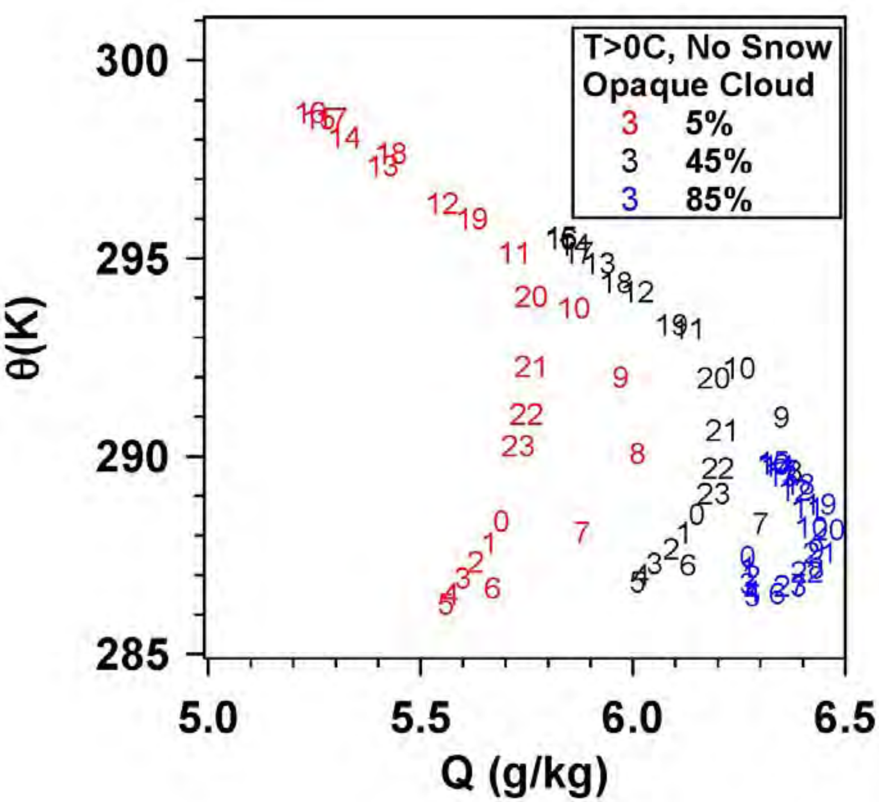
Specific Humidity



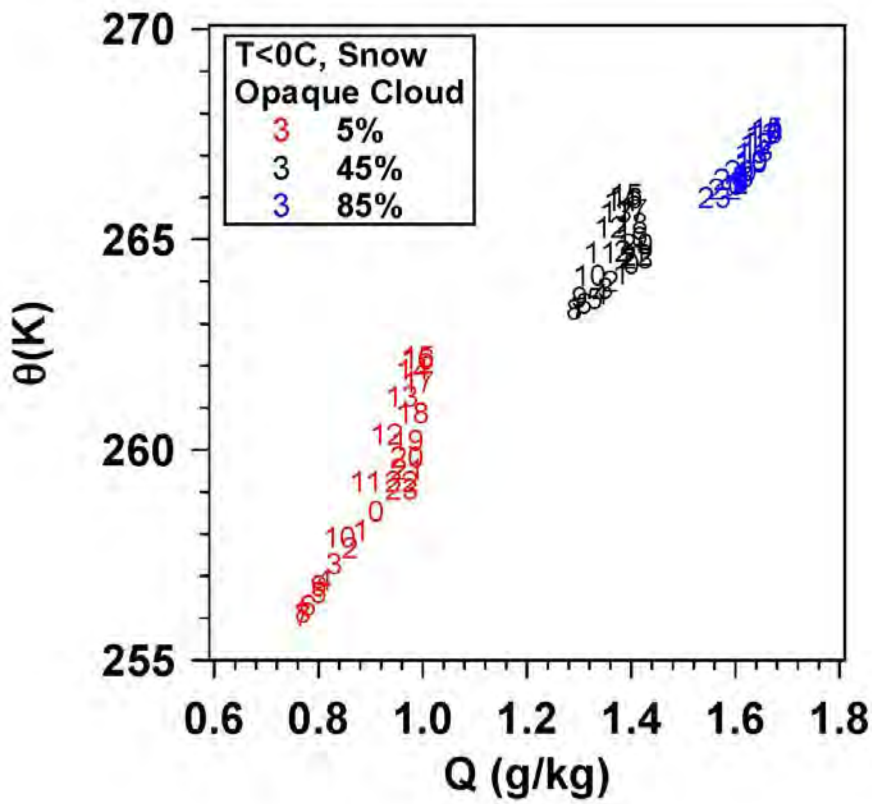
- **Three Q regimes**

- **Cold <0°C: Snow: *stable BL, no diurnal cycle***
- **Transition near freezing: diurnal cycle**
- **Warm >0°C: *unstable BL***
  - **Morning and late afternoon BL coupling/uncoupling**
  - **Clear is 'drier', while cloudy is cooler/drier/flat**

Above/Below Freezing Conserved Variables



SWCF

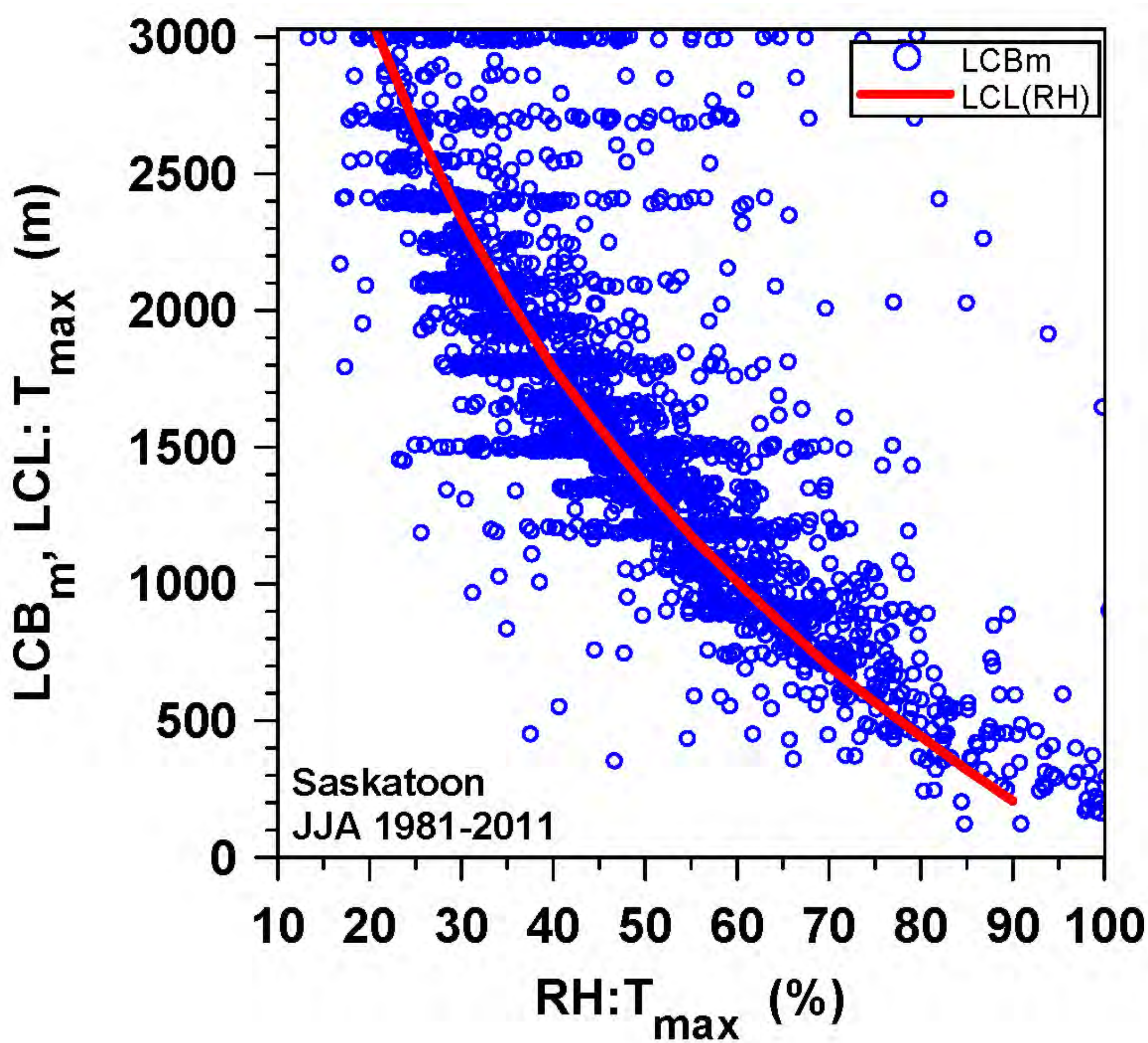


LWCF

Afternoon LCL is Cloud-base

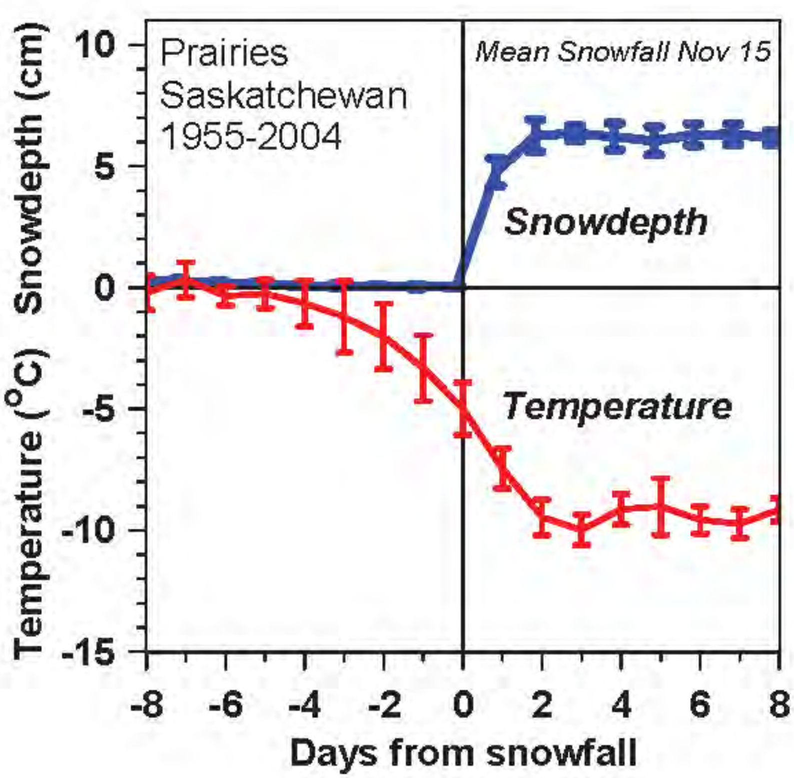
- At T_{max}
- Lowest cloud-base *(ceilometer)*
- LCL (surface)

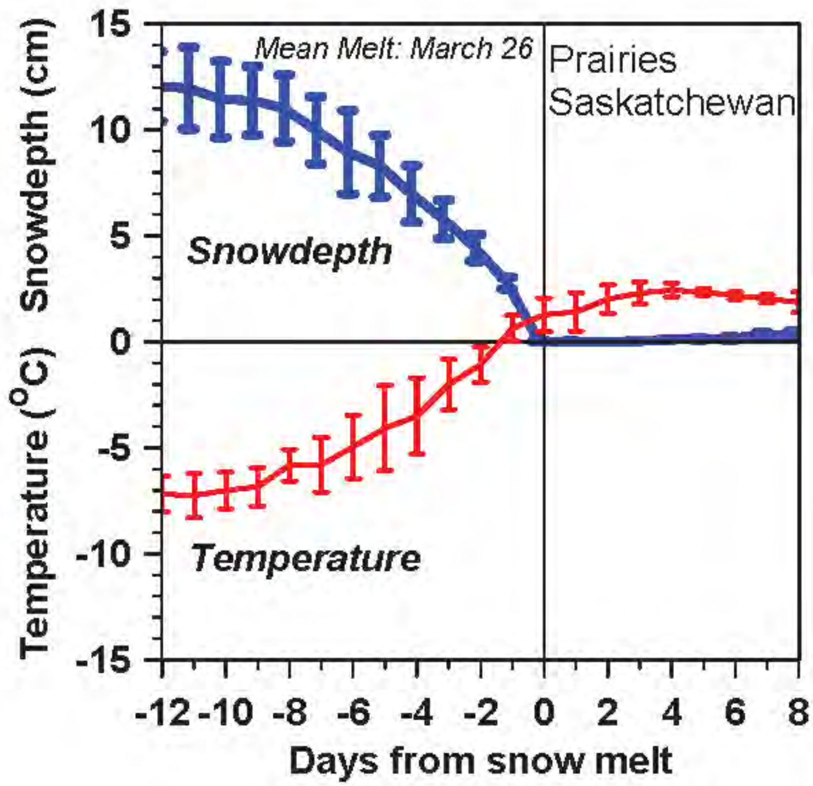
- ***Coupled convective boundary layer (CBL)***



Winter Ice and Snow

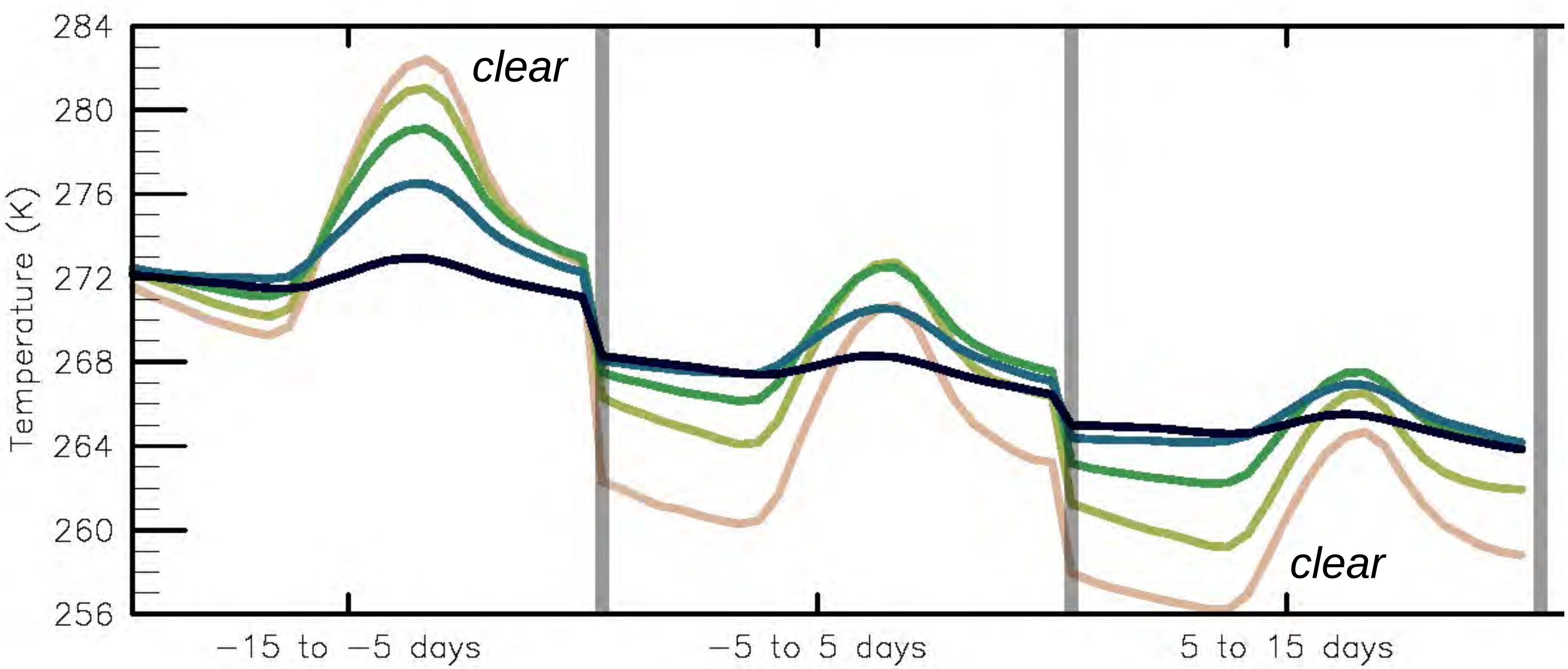
Snowfall and Snowmelt





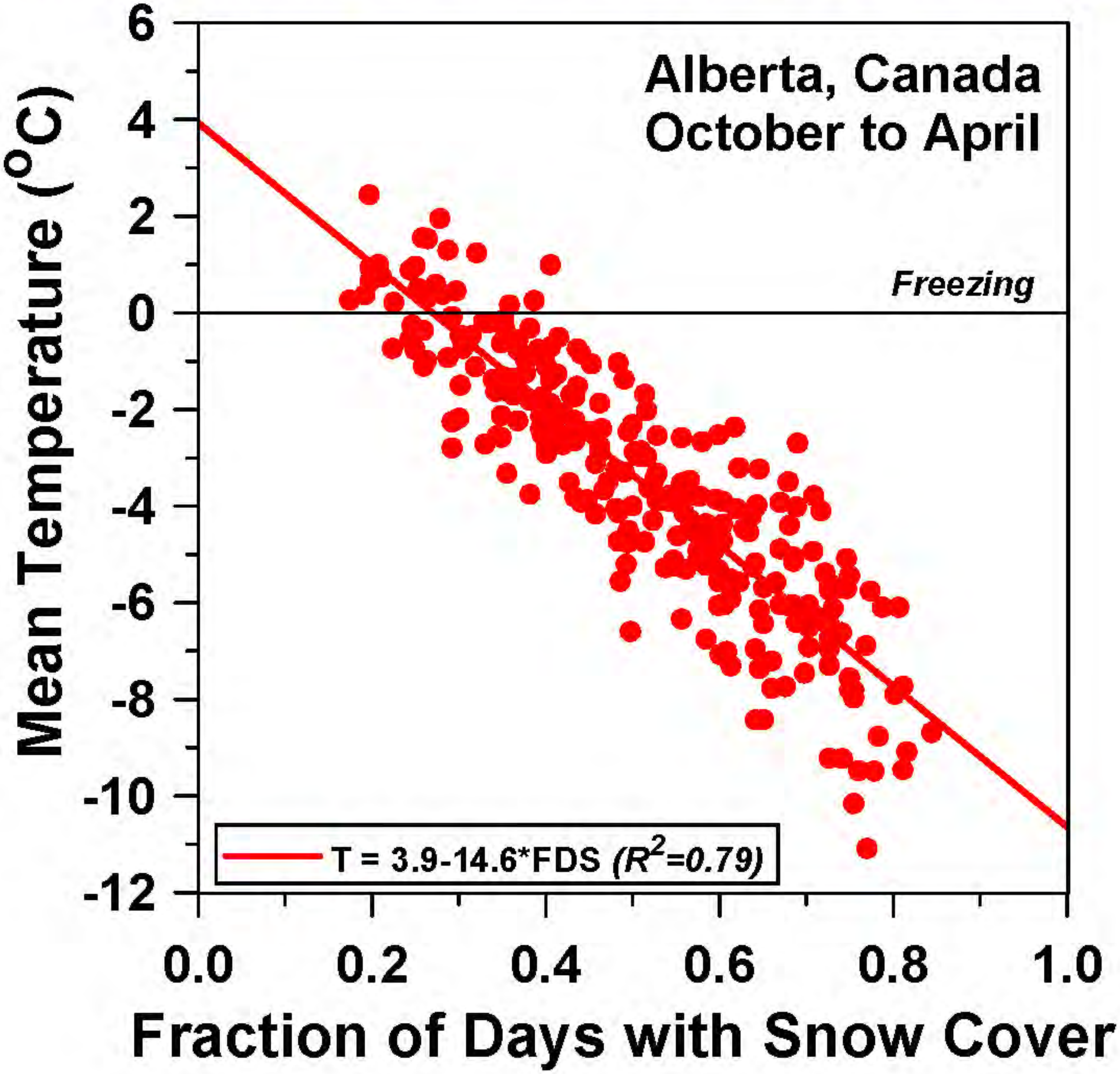
- **Temperature falls 10°C with first snowfall**
- **And rises again with snowmelt**
- ***Fast transitions in 'local climate': a 'climate switch'***
  - ***Snow reflects sunlight***
  - ***Reduces evaporation and water vapor greenhouse***

Mid-Nov. Snow Transition
(Cloud partition)



- Ahead of snow Transition After Snow
- Warm >0ºC: No Snow Transition Cold <0ºC: Snow
- Time sequence shows the three regimes

More snow cover - Colder temperatures



Betts et al. 2014a

Warm Season Climate: T>0^{o}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/R_n (and EF)***
- ***Monthly timescale: Fully coupled***
- ***(Long timescales: separation)***

Betts et al. 2014b

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

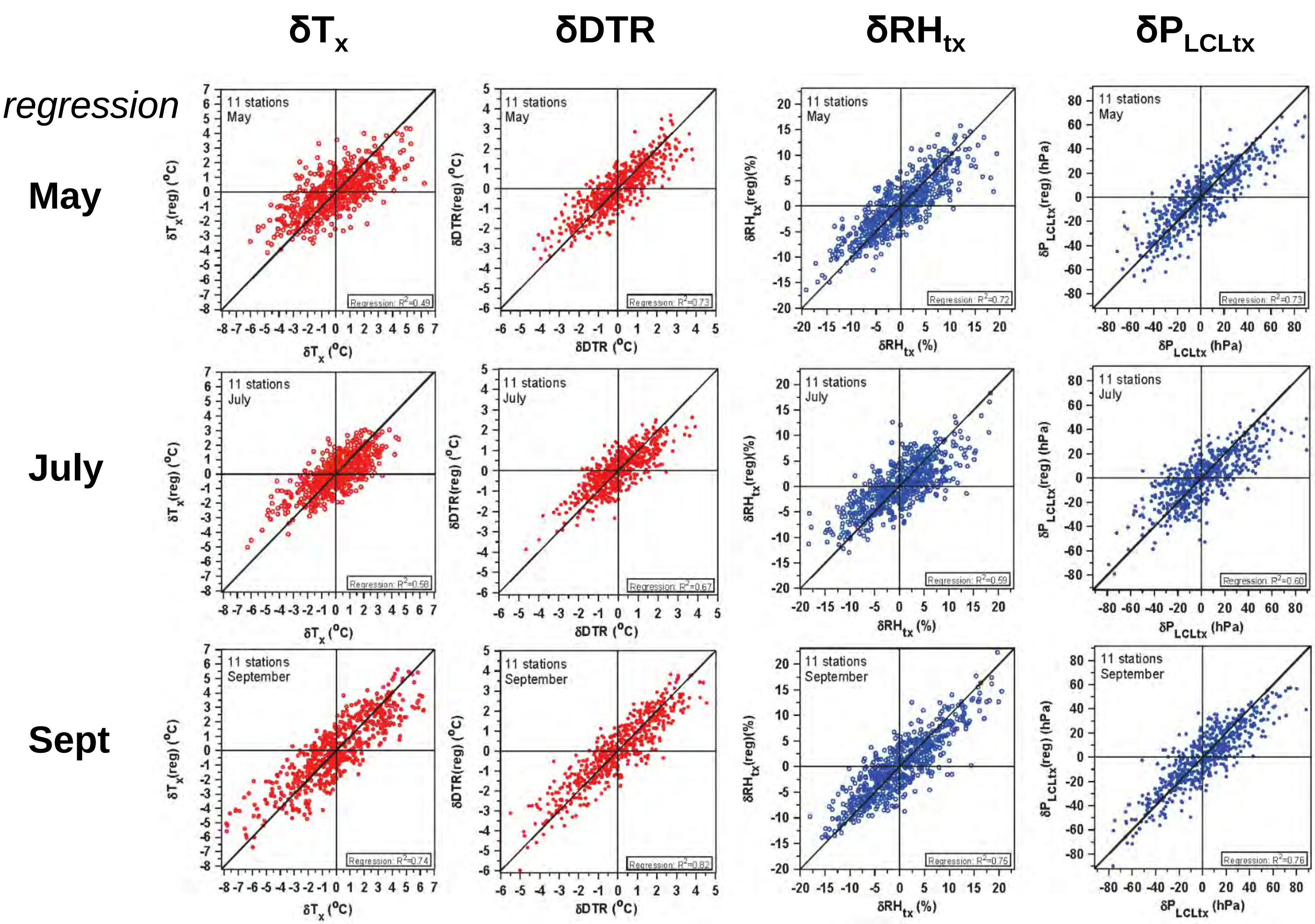
δRH_{tx} = K + A* δPrecip(Mo-2) + B * δPrecip(Mo-1) + C * δPrecip + D * δOpaqueCloud
(Month-2) (Month-1) (Month) (Month)

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

Monthly Regression Fits

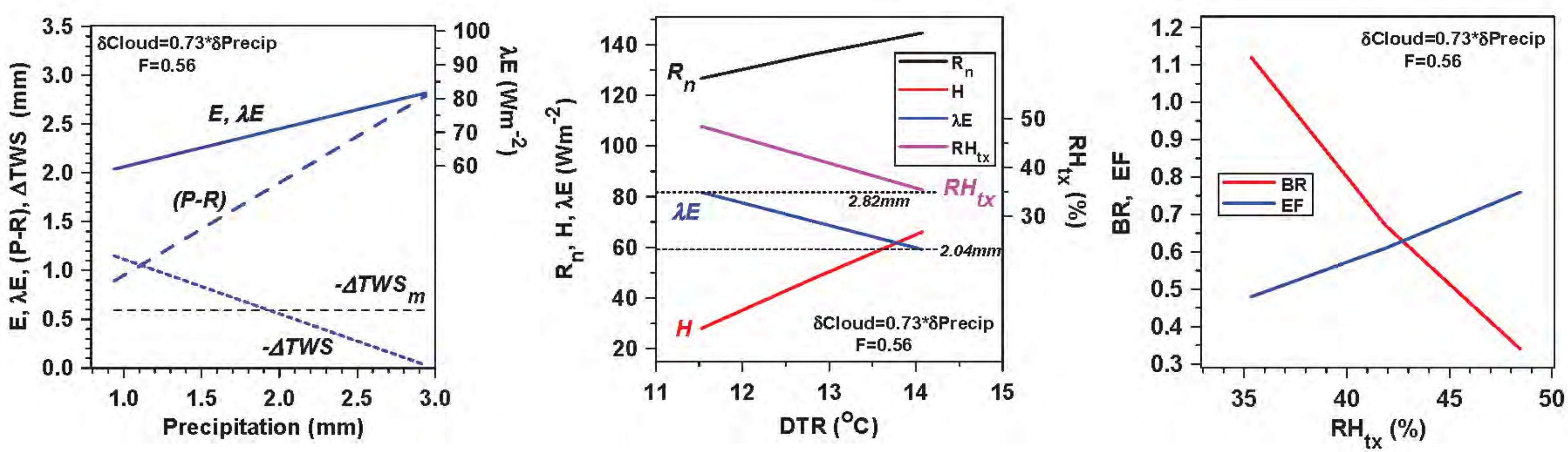


MJJA Growing Season

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

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**

Growing Season Coupling between Energy and Water Budgets and Surface Climate



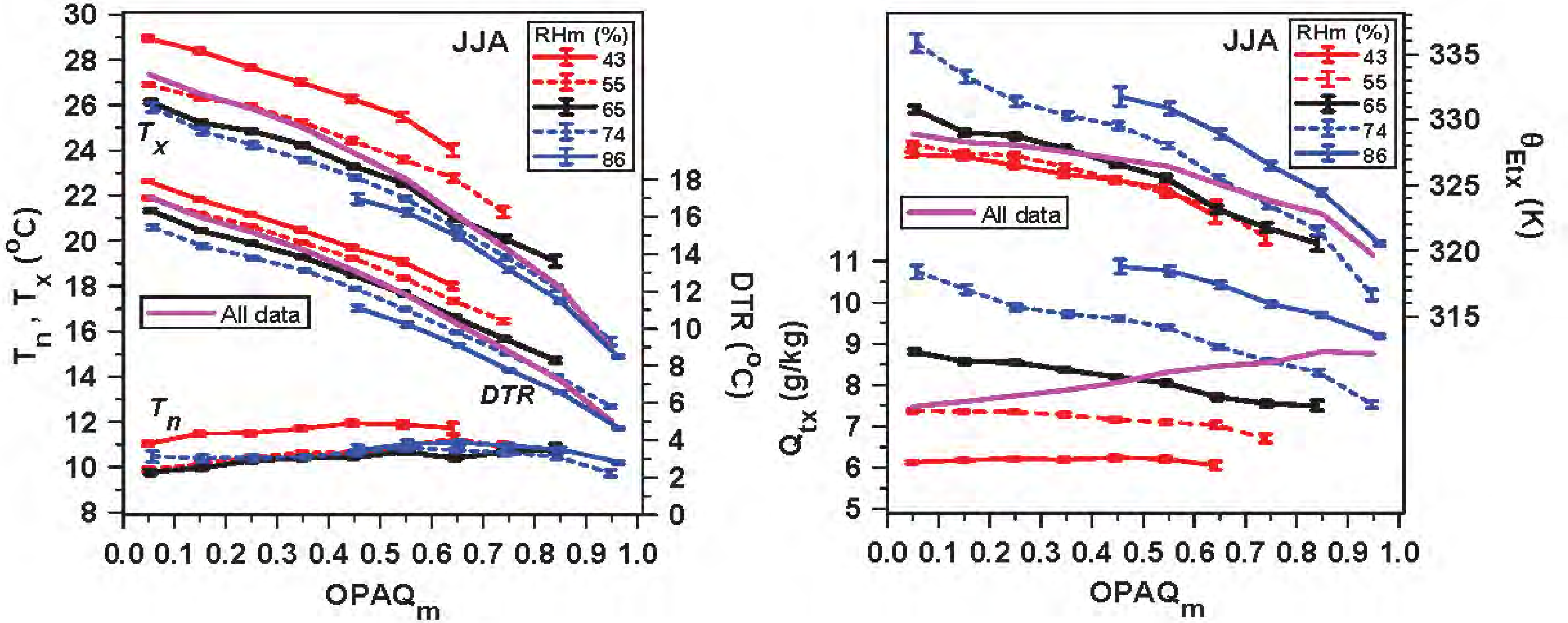
- Total water storage (GRACE) coupled to precipitation variability (F=0.56)
- R_n coupled to cloud variability
- Climate cloud coupling: δCloud = 0.73 δPrecip
- Diurnal climate coupled to cloud and precipitation variability (regression)

Daily Timescale in Summer

- 11 Prairie stations: 1953-2011 (Betts et al. 2015)
- 54000 days: (standard error of mean small)
- Partition by cloud, sub-partition by
  - RH_m
  - Wind
  - (Day-night cloud asymmetry)
  - Precipitation anomalies

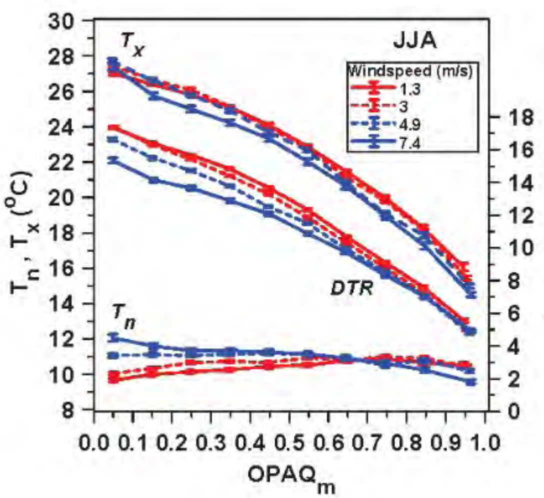
Daily Summer Climate Partitioned by Cloud and RH

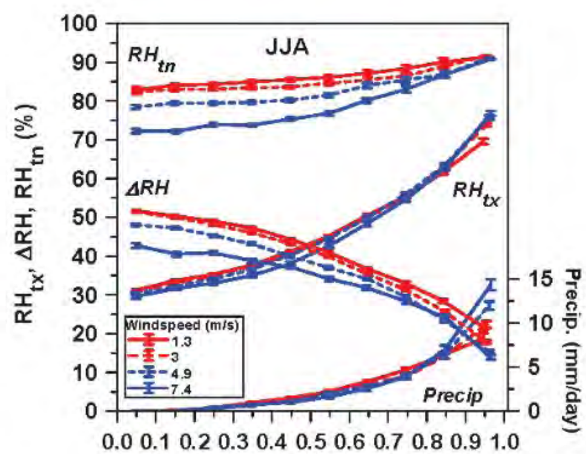
Summer, JJA: 54000 days

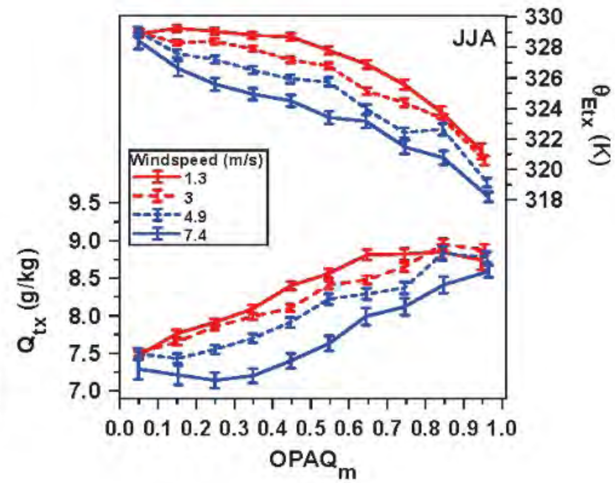


- **DTR increases with decreasing cloud and RH**
  - ***Increasing R_n (and falling soilwater)***
- **Upward shift to higher θ_{Etx} with increasing RH_m**
  - **Despite falling T_x because of Q_x increase**

Daily Summer Climate Partitioned by Cloud and Wind





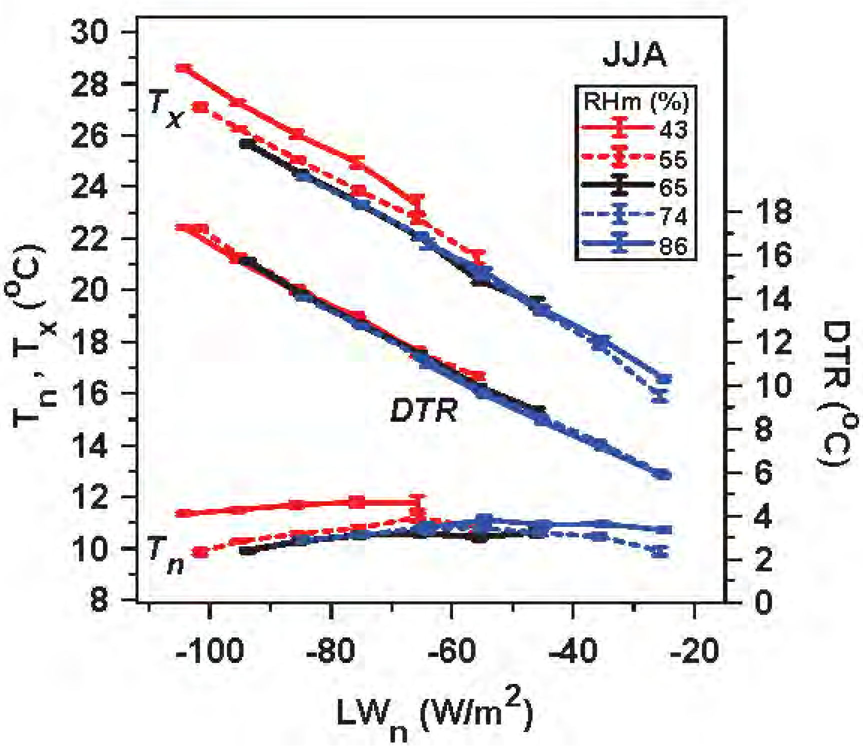


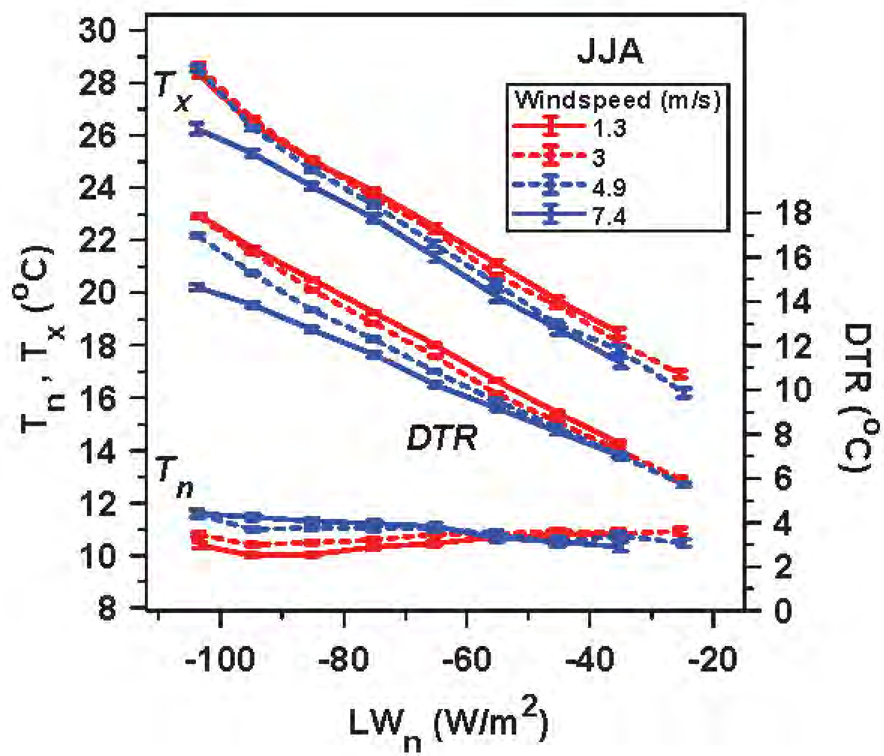
- **DTR increases with decreasing wind**
  - ***Falling T_n under clear skies at low windspeed***
  - ***Increasing sunrise RH_{tn} at low windspeed***

- **Higher θ_{Etx} with decreasing wind**
  - **Stronger superadiabatic layer?**

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***

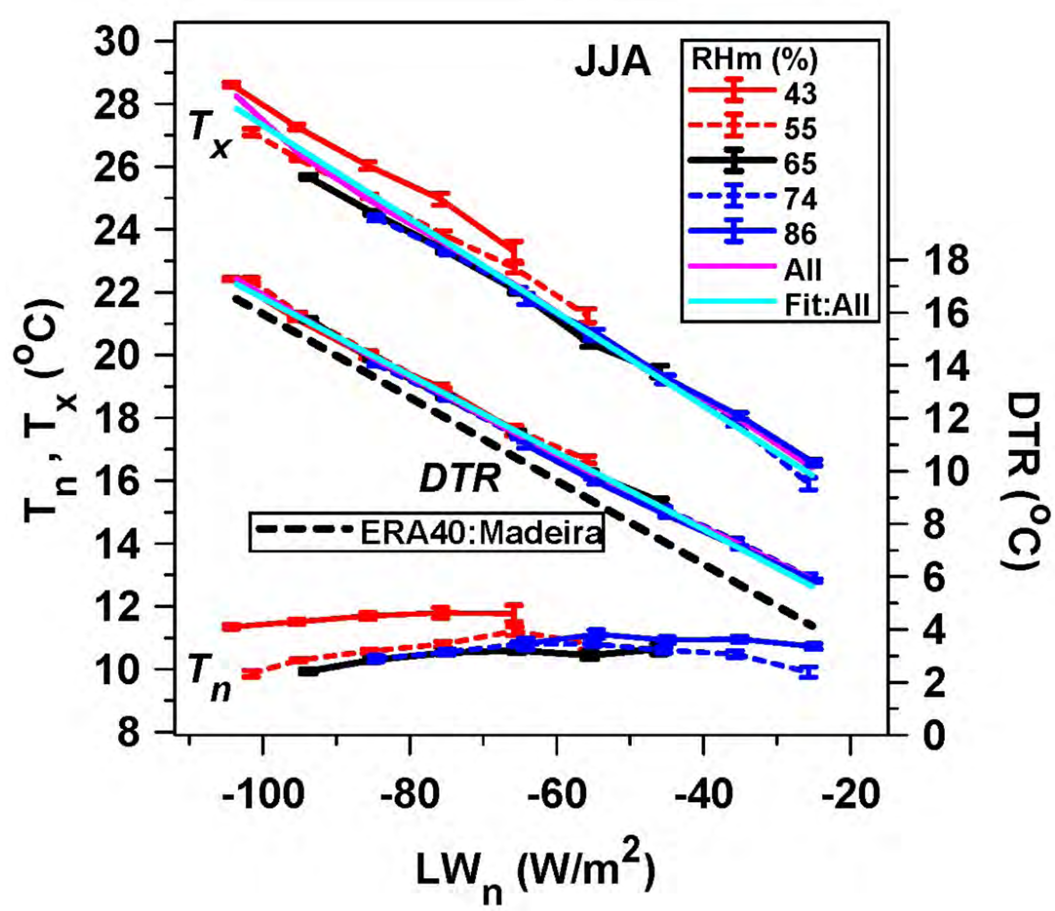
Betts et al. 2015

Compare ERA40
Madeira River (Amazon)

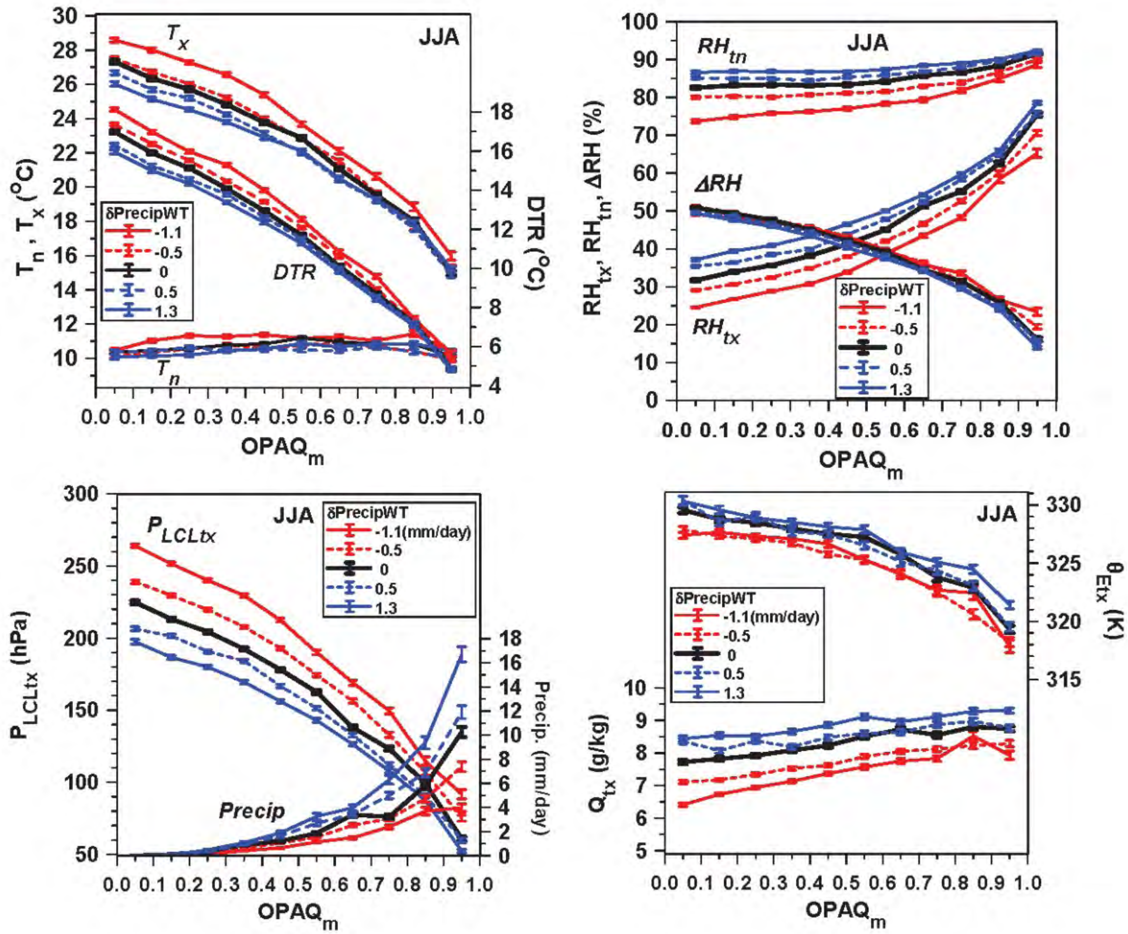
Canadian Prairie station data

versus ERA40 Madeira River basin mean

Not bad



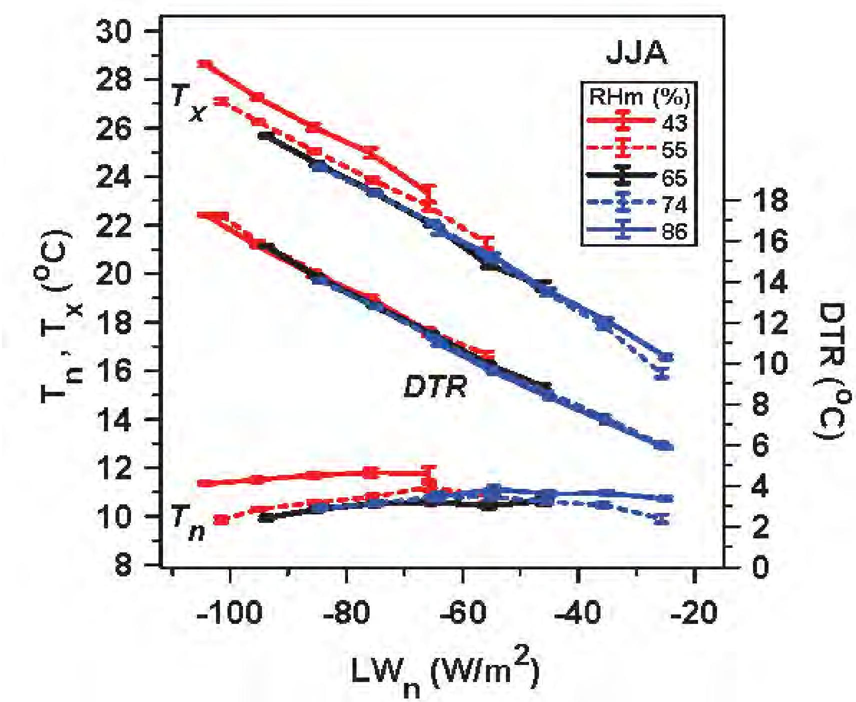
Partition by Cloud & Precip. Anomalies

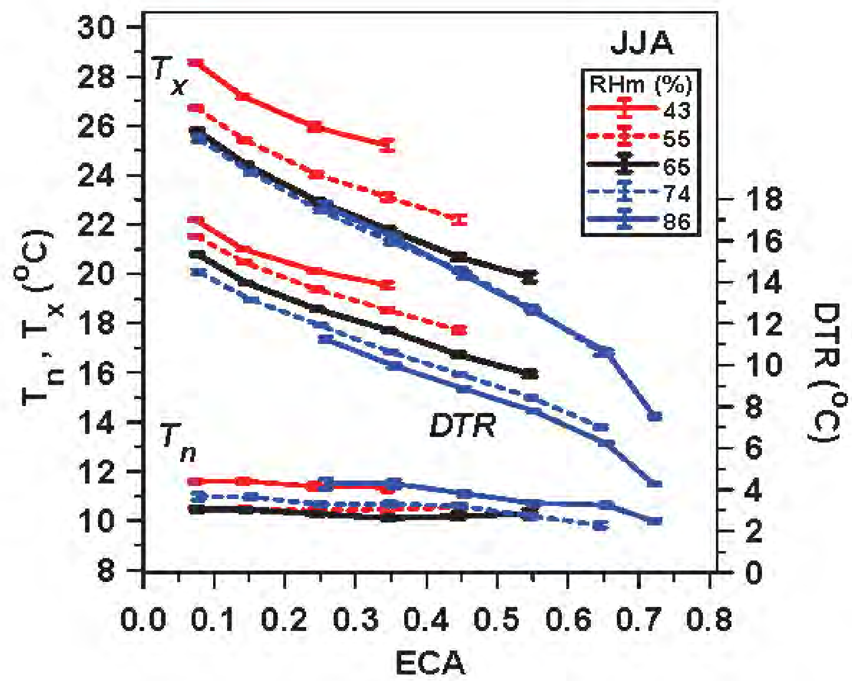


- **Weighted precipitation anomalies as surrogate for soil moisture**
- **Cooler, moister, lower P_{LCLtx}, higher θ_{Etx} with increasing δPrecipWT**

DTR to LW_n and Precip

Summer, JJA: 54000 days

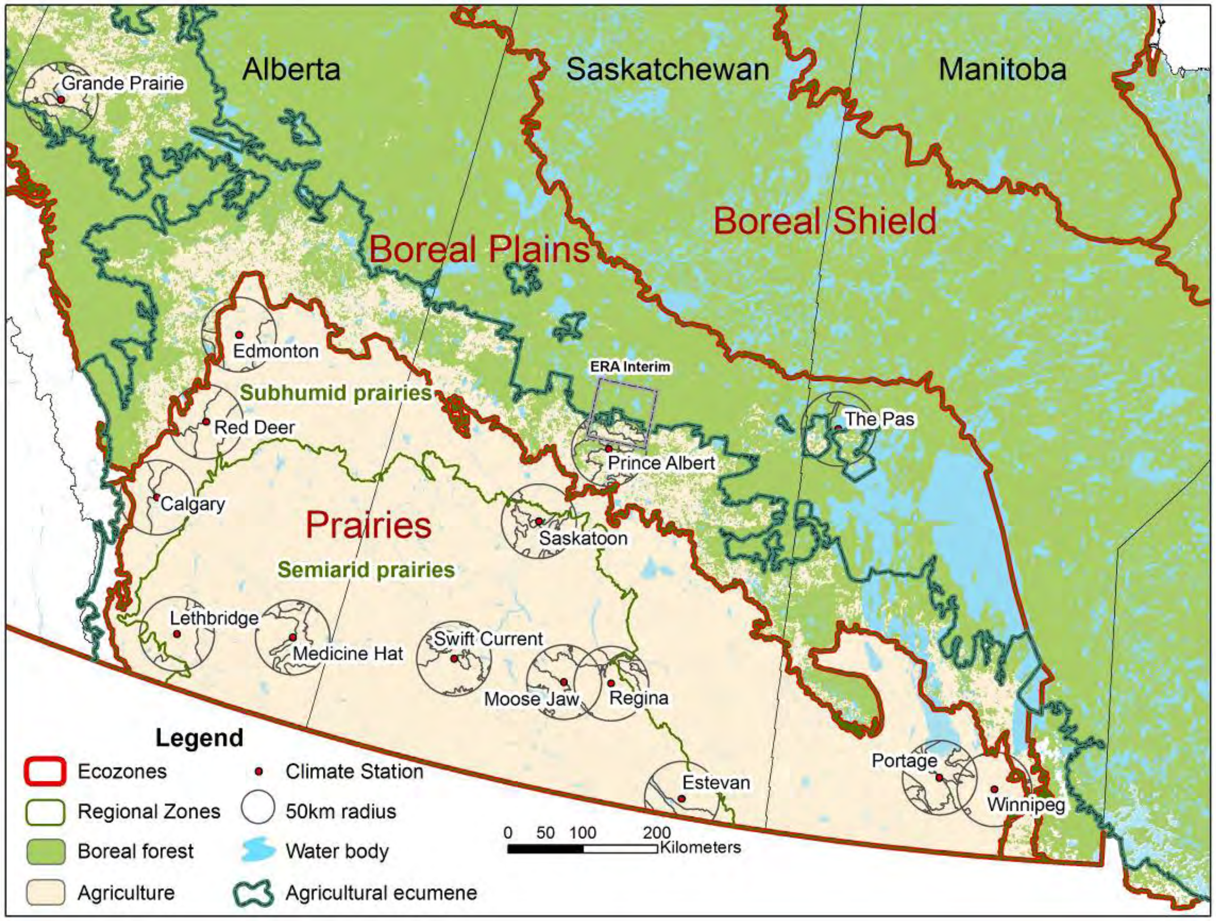




- ***DTR depends <u>linearly</u> on LW_n*** ***(daily R^2 = 0.61)***
  - ***cooling from afternoon T_x to sunrise T_n***
- ***DTR depends on ECA and RH_m***
  - ***RH_m is 'climate response' to energy partition by soil moisture***

(Betts et al. 2015)

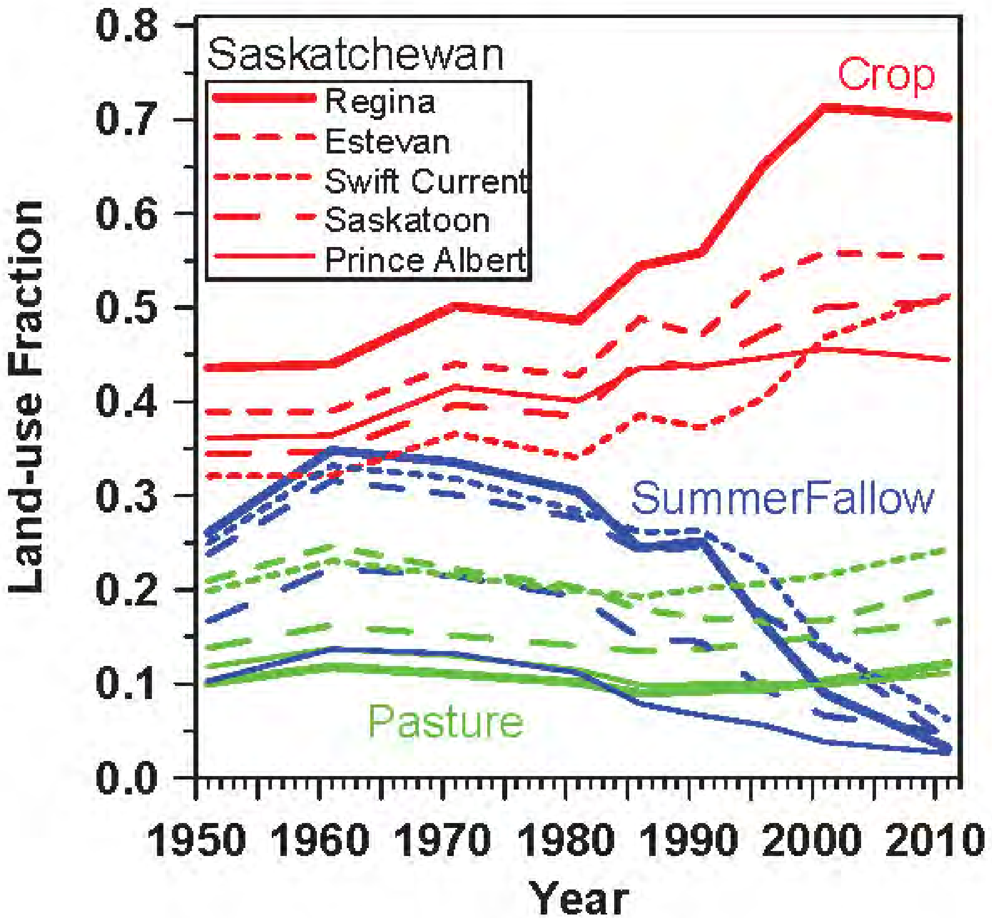
15 Prairie stations: 1953-2011



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

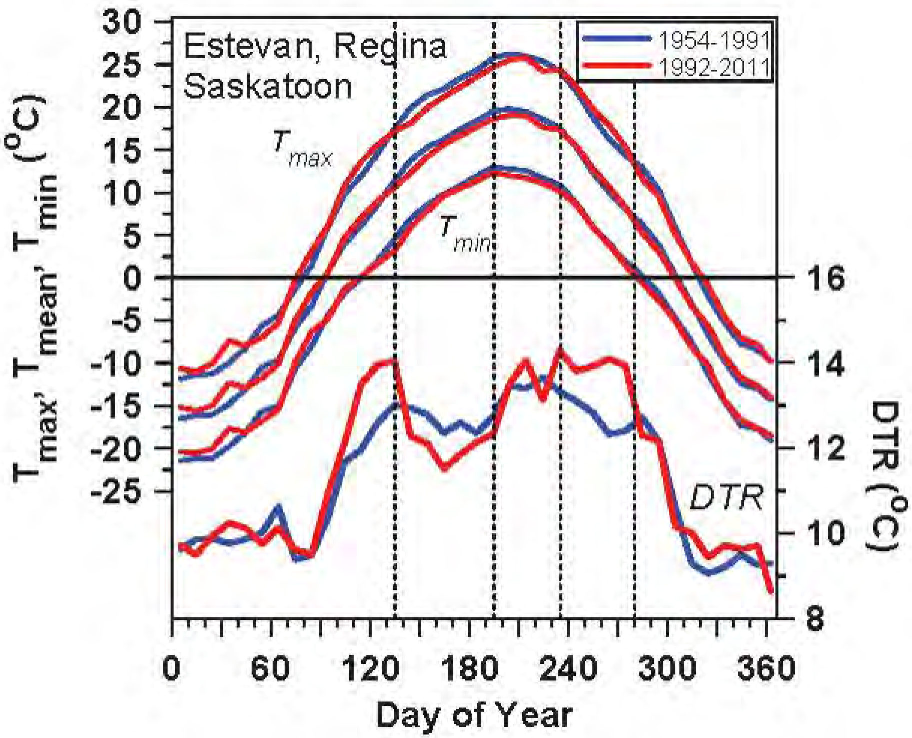
Change in Cropping (SK)

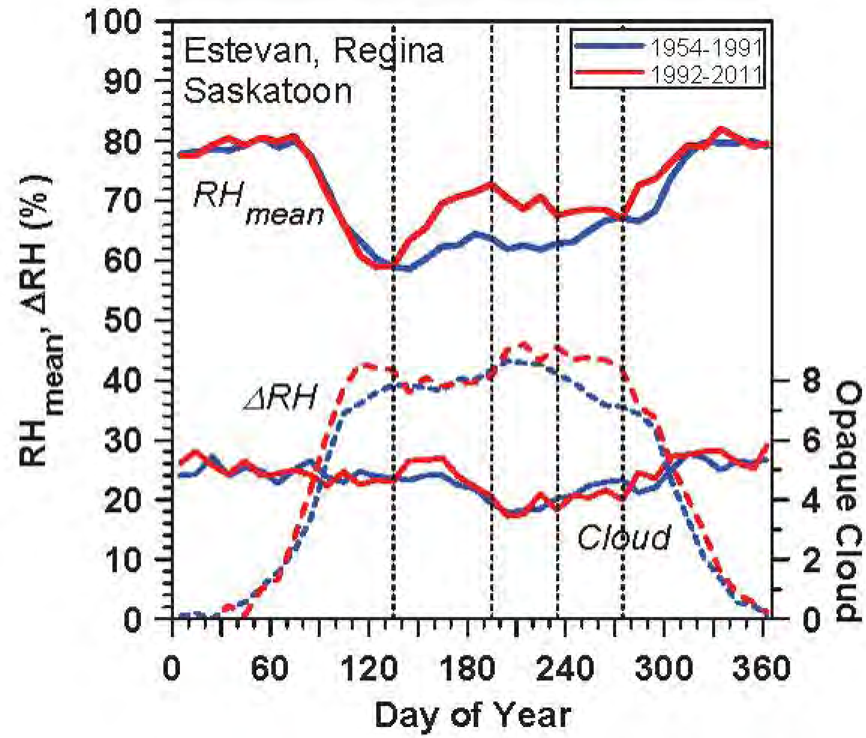
- **Ecodistrict mean for 50-km around station**
- **Saskatchewan:**
  - **25% drop in 'SummerFallow'**
  - **(no crops to save water)**
- ***Split at 1991 - has summer climate changed?***



Betts et al. 2013b

Three Station Mean in SK



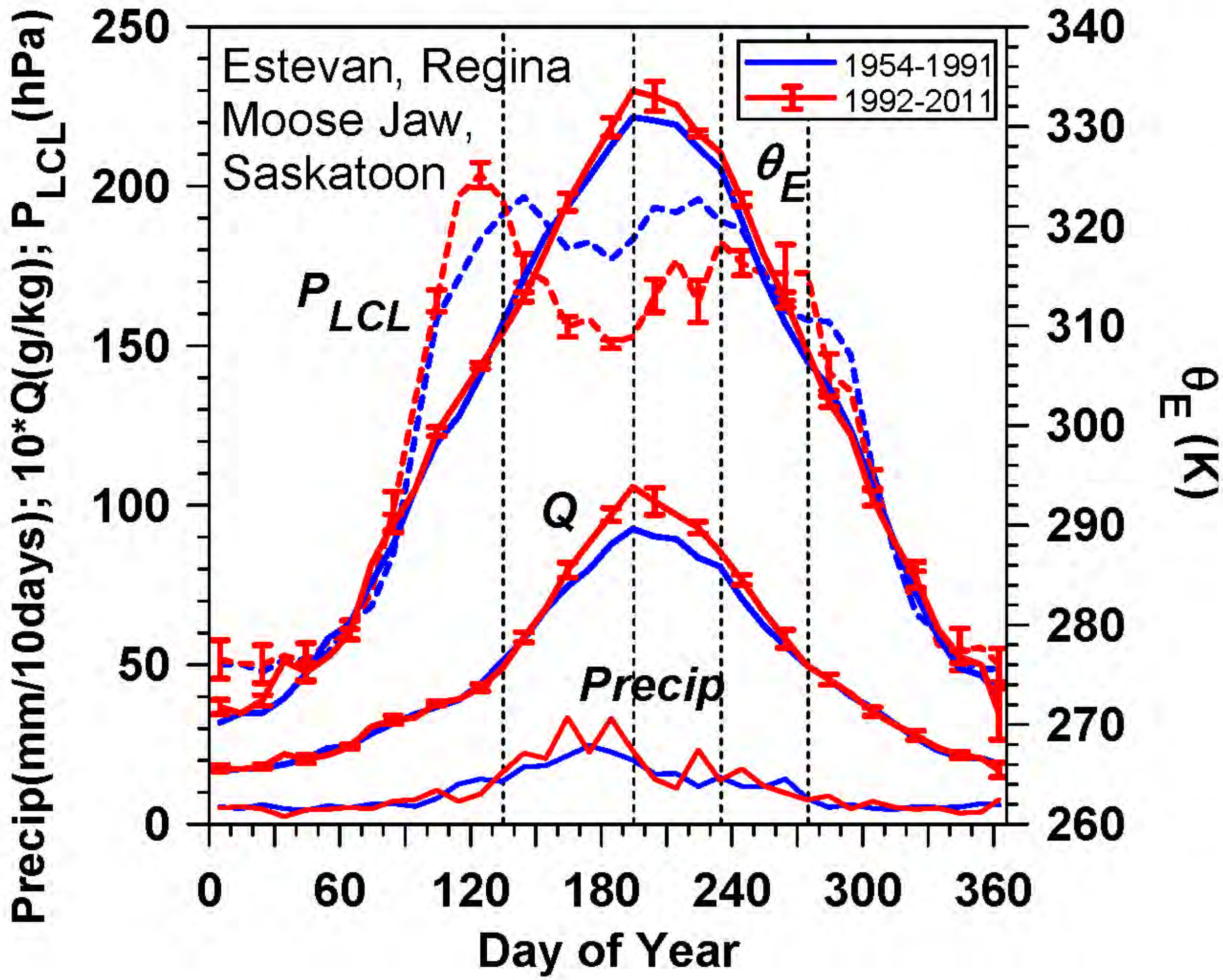


- **Growing season** **(winter warmer)**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal transitions**

Impact on Convective Instability

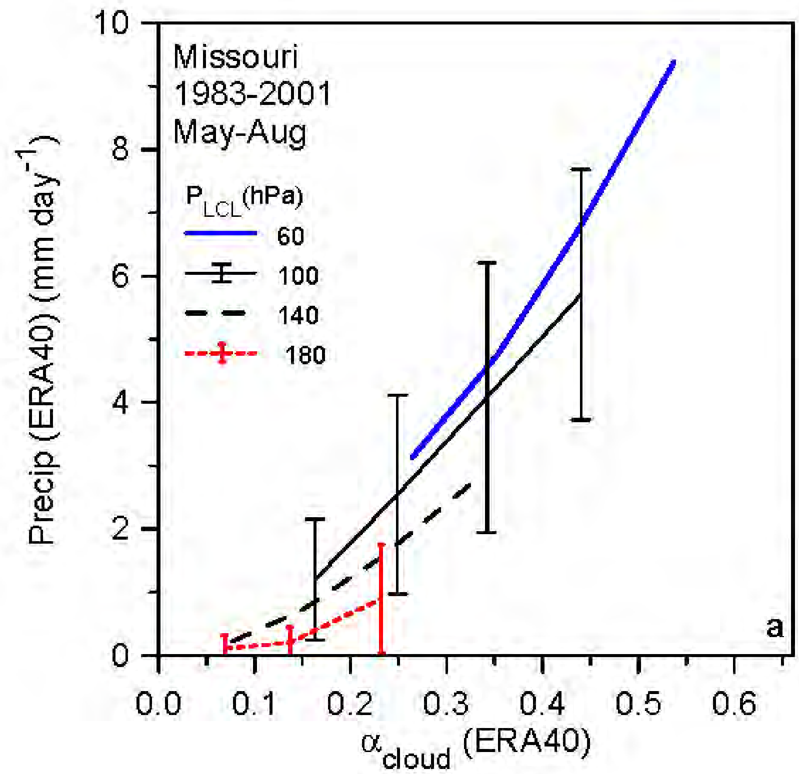
Growing season

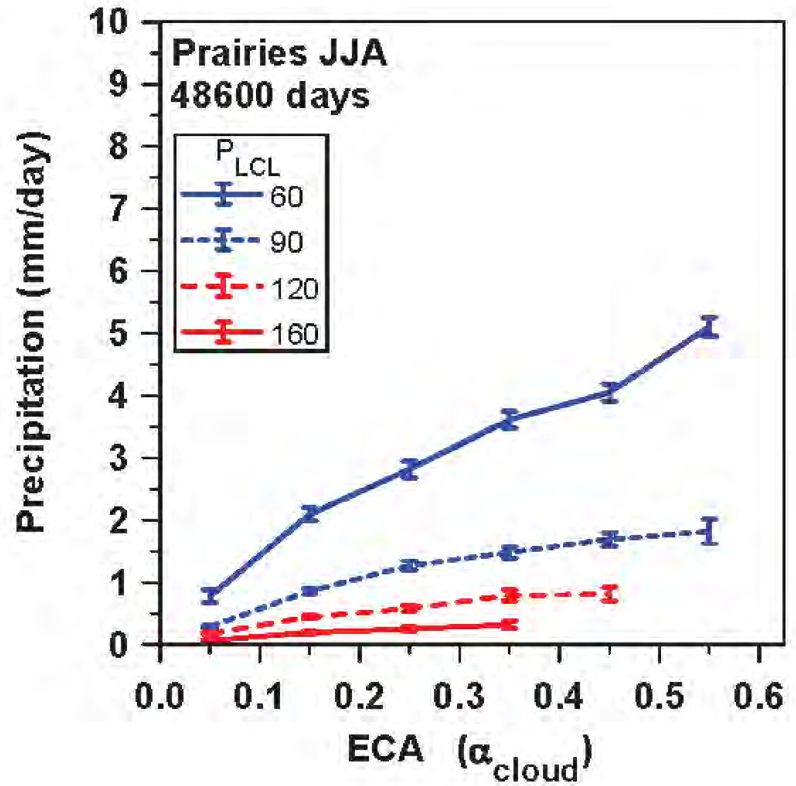
- **Lower LCL**
- **Higher θ_E**
- **More Precip**



Betts et al. 2013b

Precip. to SWCF in Real World?

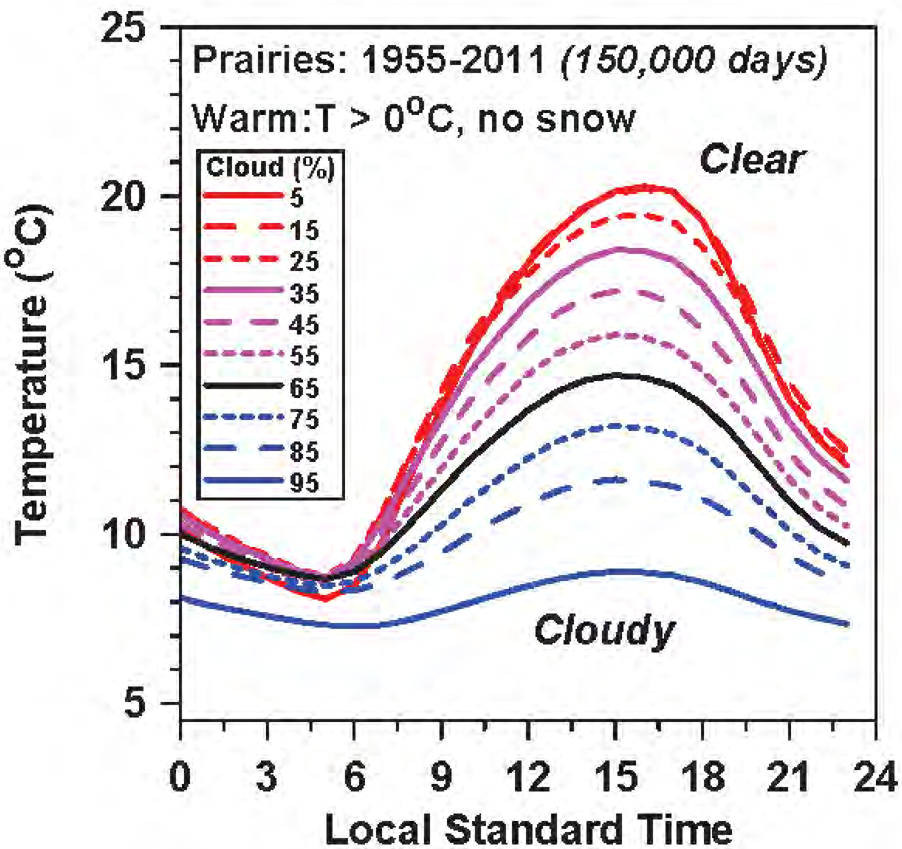


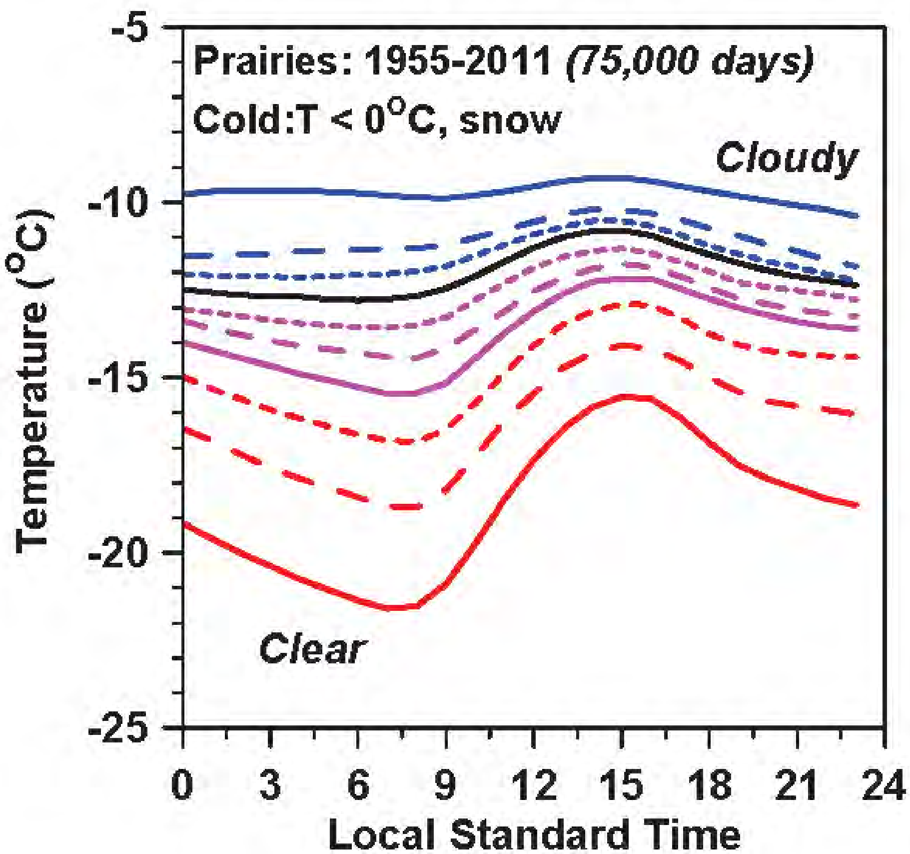


- **ERA40 Missouri basin means: MJJA (left)**
- **Canadian Prairie stations: JJA**
  - *Has greater cloud forcing for same precip. forcing*

Review

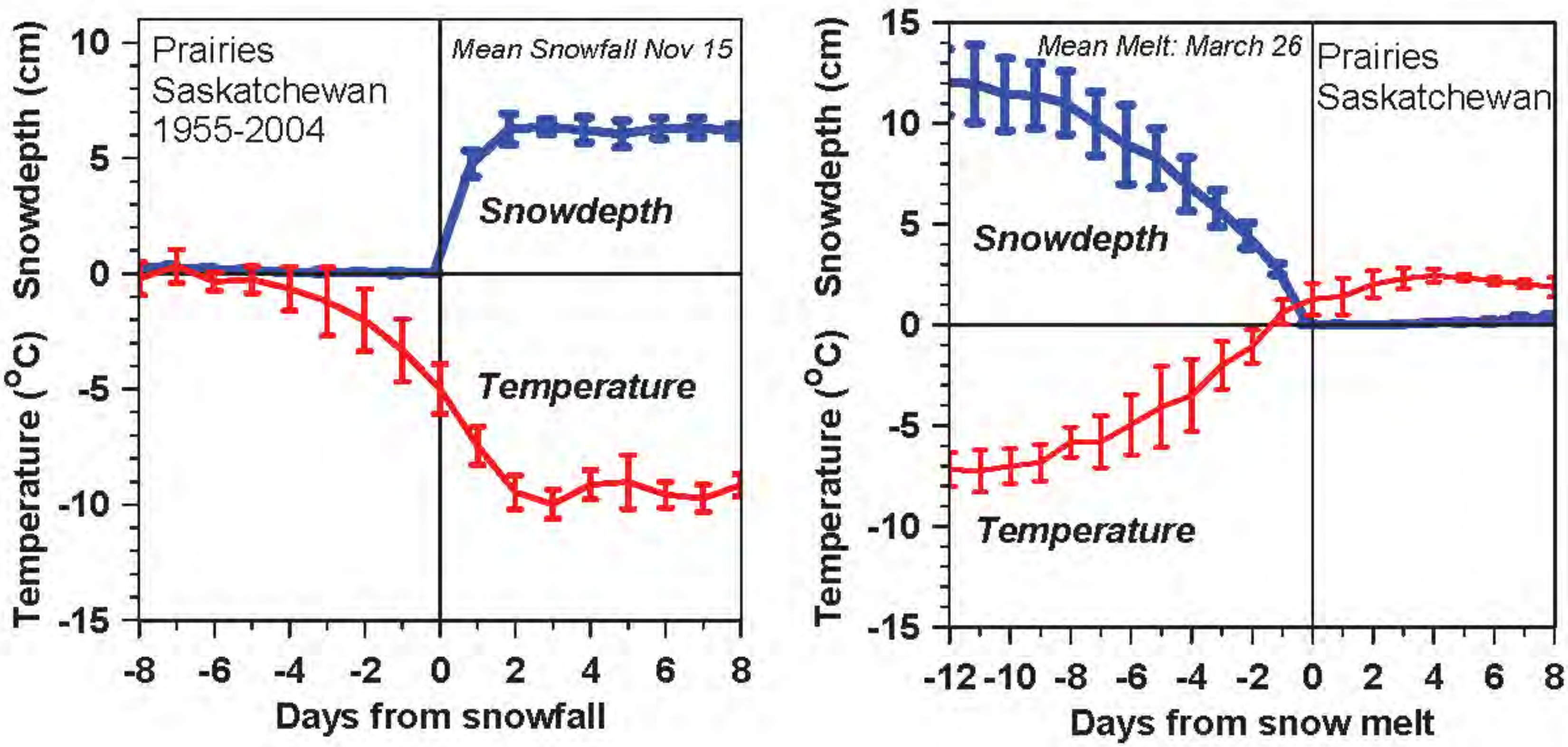
Warm & Cold Climates: T><0°C



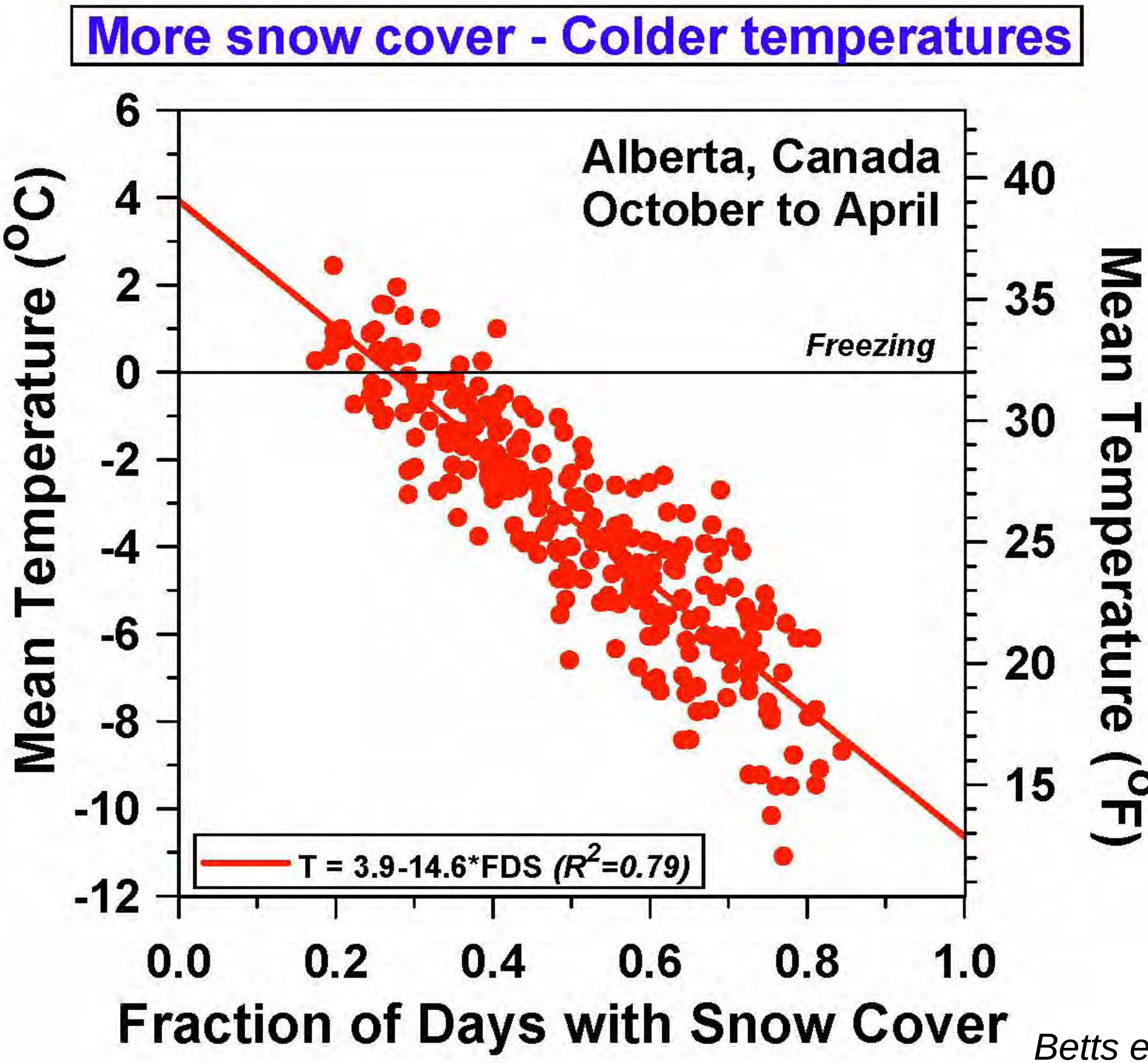


- **Warm >0°C:** **Clouds reflect sunlight**
- **Cold <0°C:** **Clouds are greenhouse & snow reflects sun**
- **T falls 10°C with snow -** ***Fast climate transition***

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***



Betts et al. 2014a

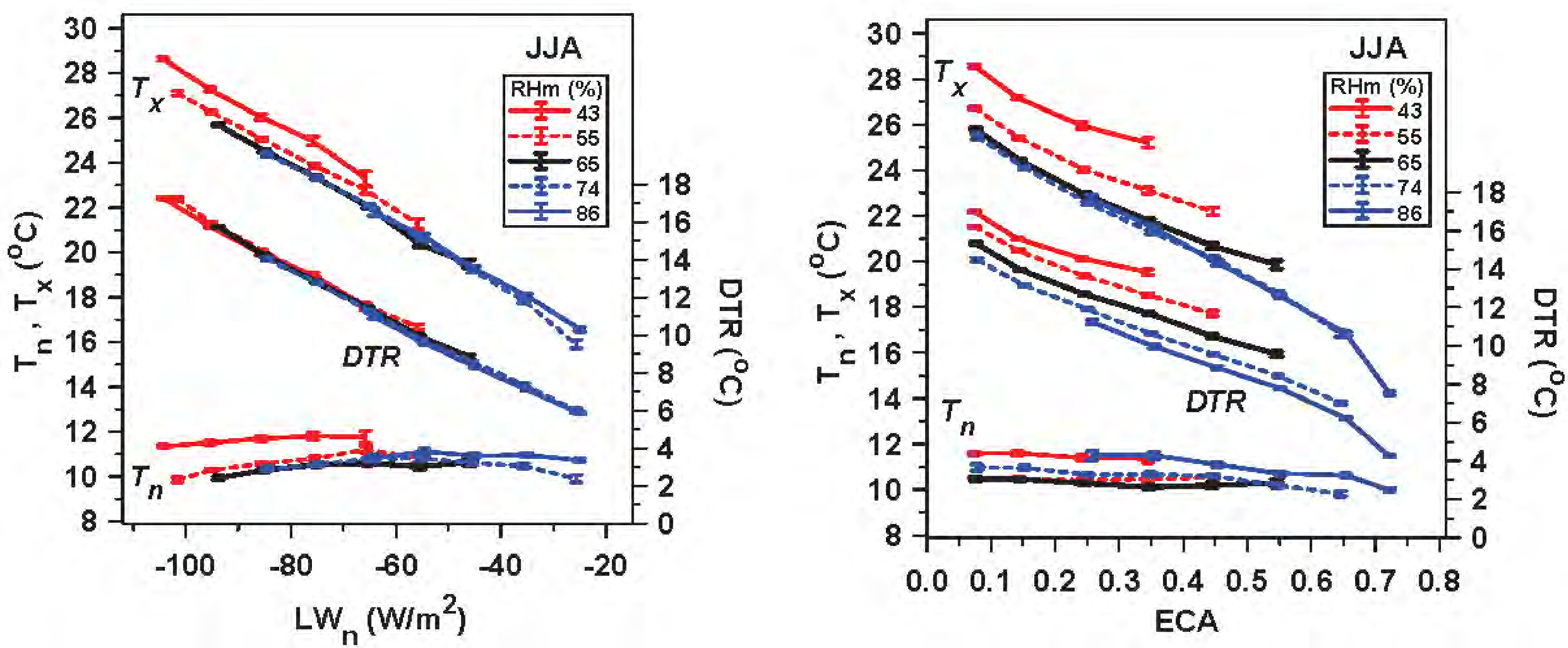
MJJA Growing Season

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

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**

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

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**
    - **Snow cover explains 80% of cold season T_{mean} variability**

- **Increased transpiration from crop change**
  - **Cooled and moistened summer climate**
  - **Lowered cloud-base and increased θ_E**
  - **(While winter climate has warmed)**

Papers at http://alanbetts.com

Conclusions

- **Hydrometeorology <u>requires</u>**
  - **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)***