Understanding land-atmosphere coupling

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Water in the Climate System

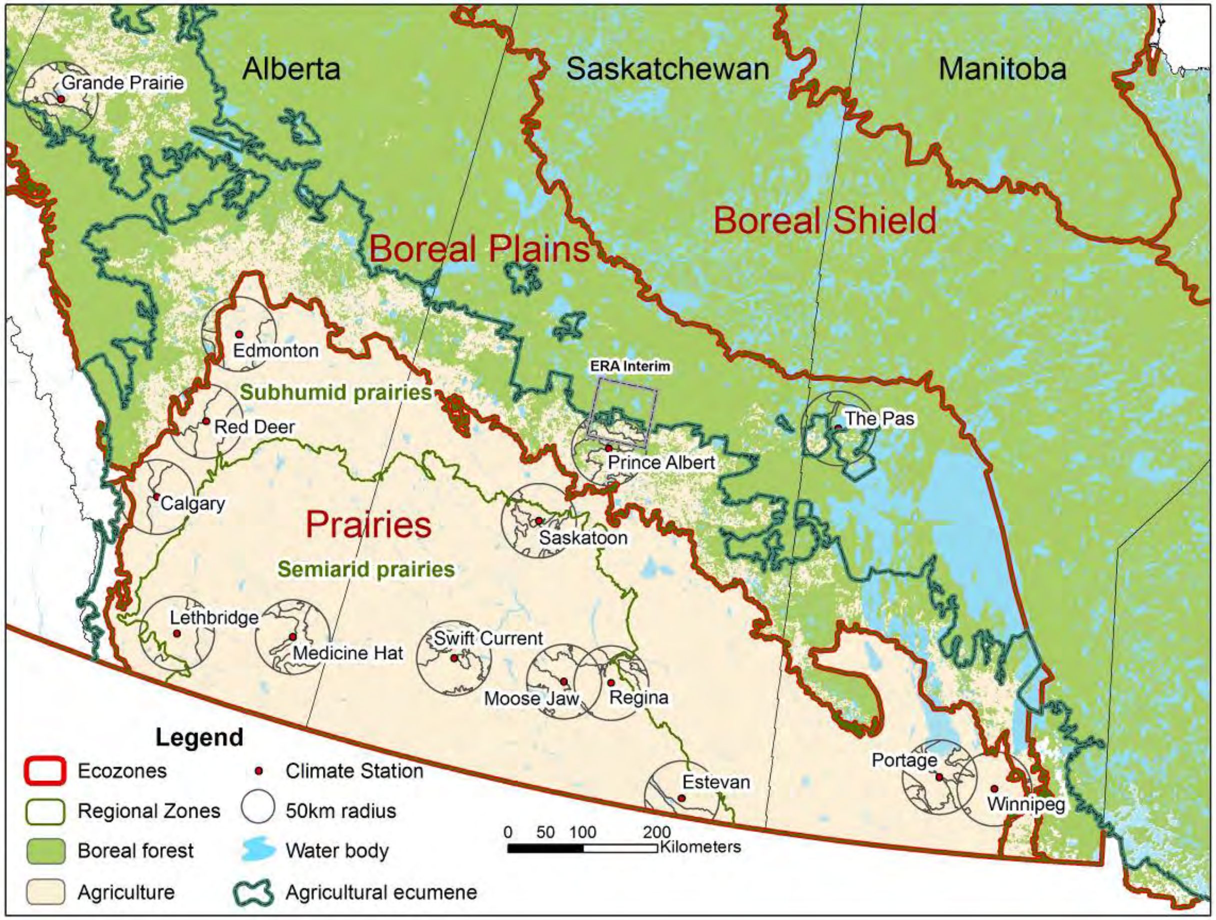
- Vapor, liquid and ice
  - Ocean and land
- Shortwave reflectivity of clouds and snow
  - Effective cloud albedo, surface albedo with snow
- Vapor longwave (Infared) absorption
  - Water vapor greenhouse effect
  - Clouds ‘black’ in Infrared
- Surface Energy balance
  - Net radiation = $\underline{\lambda E}$ + H + G
- Latent heat of phase changes
  - Evaporation: $\underline{\lambda E}$ (Precip, soil water, stomatal control)
  - LH release drives clouds and storms

Serendipity in Science

- **2012 Ray Desjardins at Agriculture-Canada asked for my help**

- **Preprocessed the Canadian Prairie data**
  - **From hourly to daily**
  - **Has opaque/reflective cloud observations**
  - ***That give radiative flux climatology***
- ***Transform our understanding***
  - ***Past hydromet based on Precip and T***
  - ***In fact half seasonal timescale variance comes from radiation (and most of daily variance)***

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

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 (2014), 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 (2014), Climate coupling between temperature, humidity, precipitation and cloud cover over the Canadian Prairies. (*J. Geophys. Res. Atmos*. 2014JD022010, minor rev)**

- Betts, A.K., R. Desjardins and A.C.M. Beljaars (2015): Land-surface-atmosphere coupling on daily timescales in the warm season. (in progress)

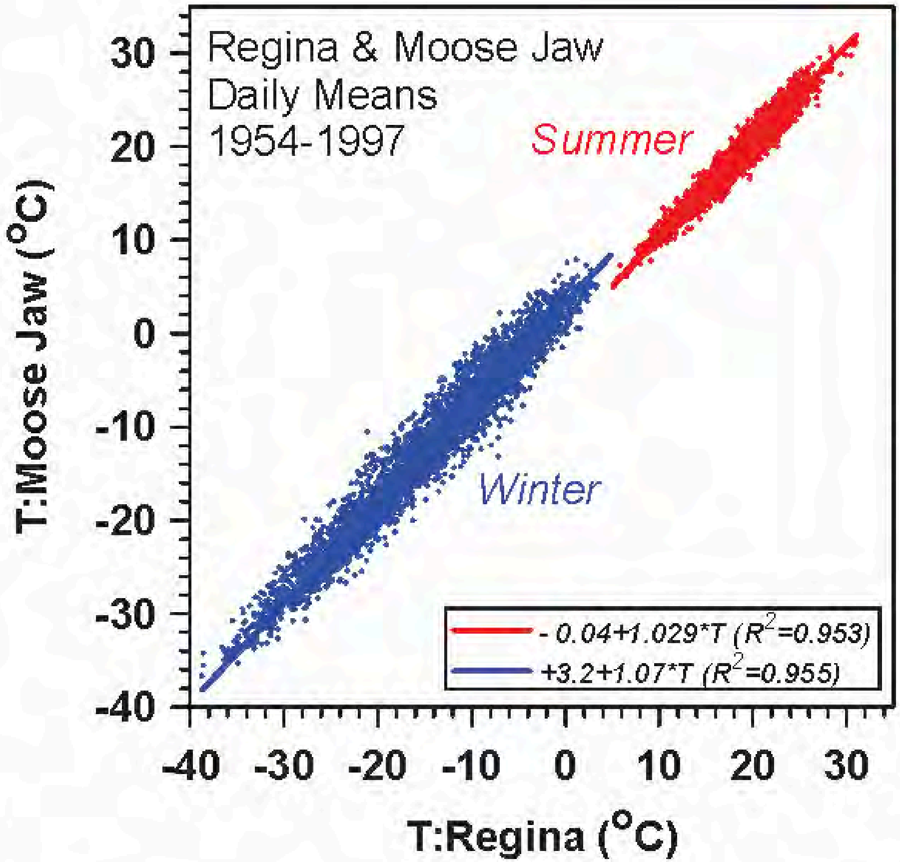
Methods: Analyze Coupled System

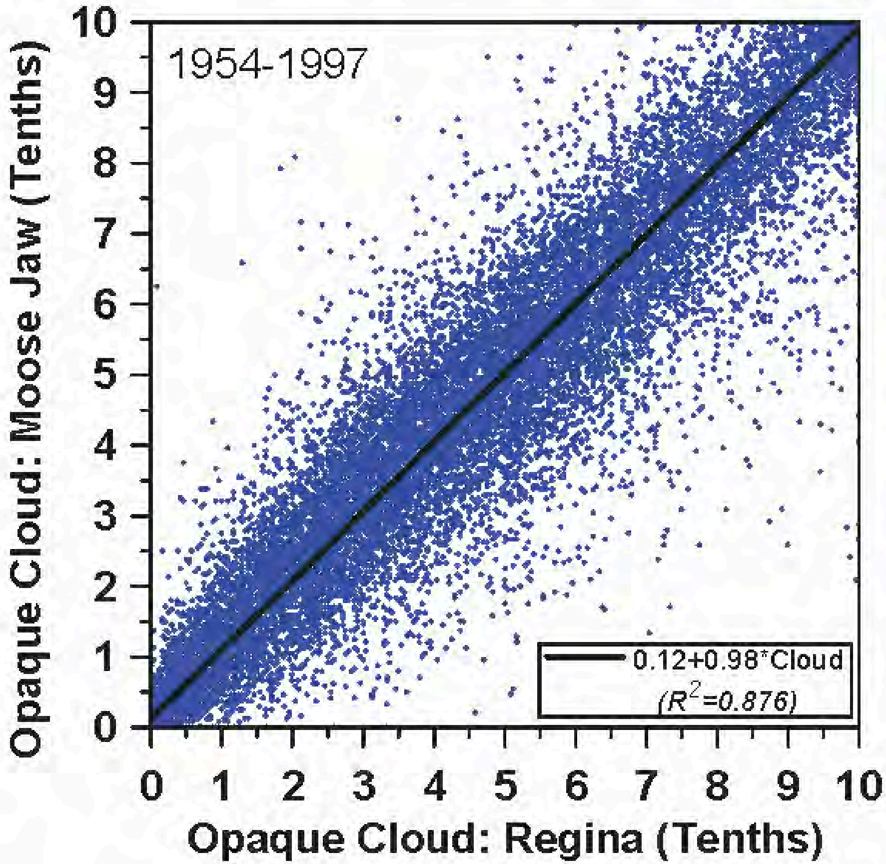
- *Seasonal diurnal climate by station/region*
- 220,000 days, excellent data (600 station-years)
  - Little analysis as not freely available
- Impact of reflective/opaque cloud on diurnal cycle in summer and winter
  - Calibrate "cloud radiative forcing"
- Change of seasonal climate with cropping
  - 'Summerfallow' to annual crops on 5MHa in 30 yrs
- Impact of snow transitions
  - First snow in fall; spring melt of snowpack
  - Winter climate and % days snow cover
- Climate coupling between T, RH, Precip and cloud: monthly to seasonal

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***
  - **$DTR = T_{max}-T_{min}$**
  - **$\Delta RH = RH_{tn} - RH_{tx}$**
- ***Almost no missing hourly data***
  - ***(until recent government cutbacks!)***

Compare Neighbors: 64 km

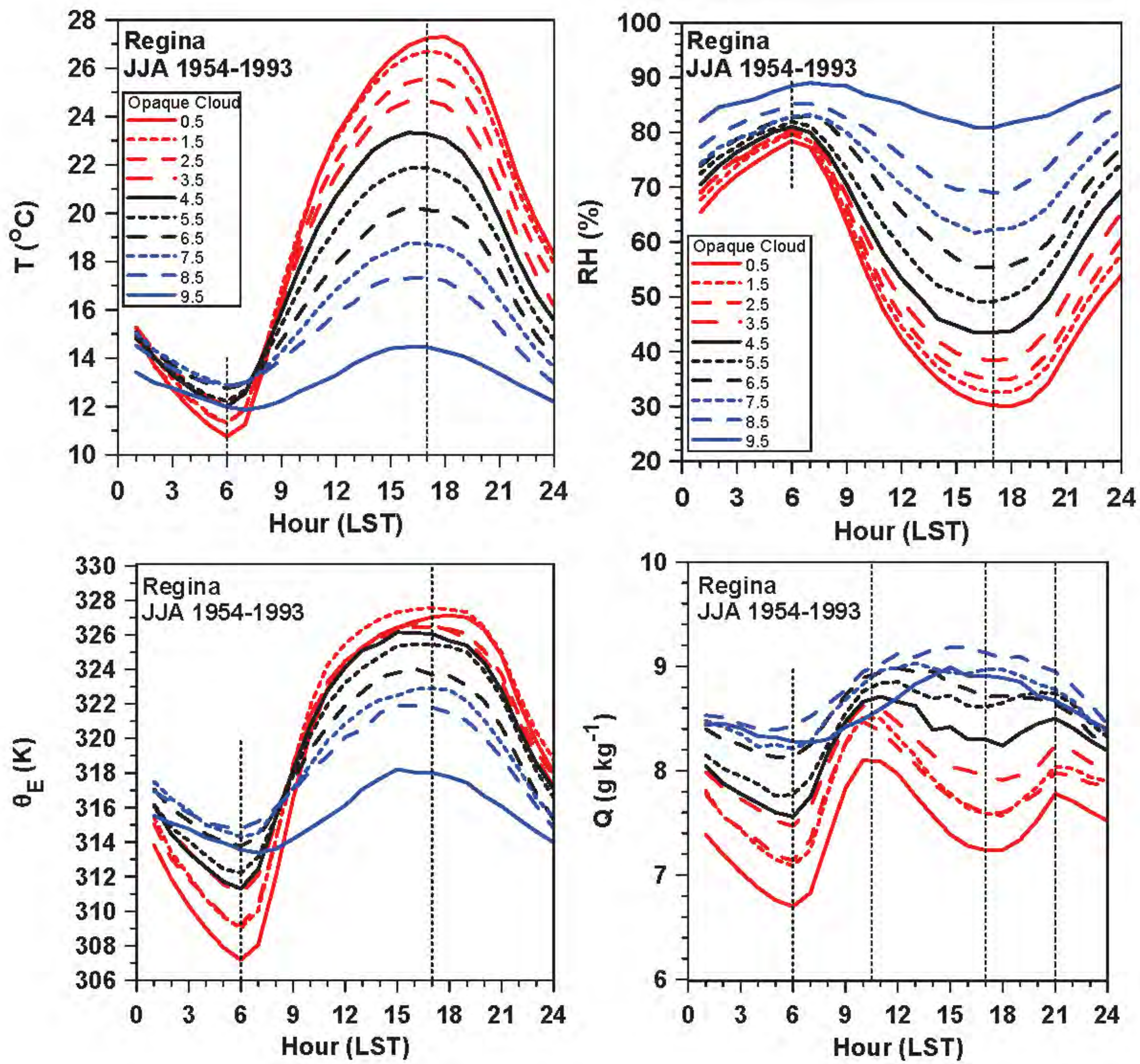




- Temp: 1 to 1: R^2 =0.95
- Opaque Cloud: 1 to 1: R^2 =0.88

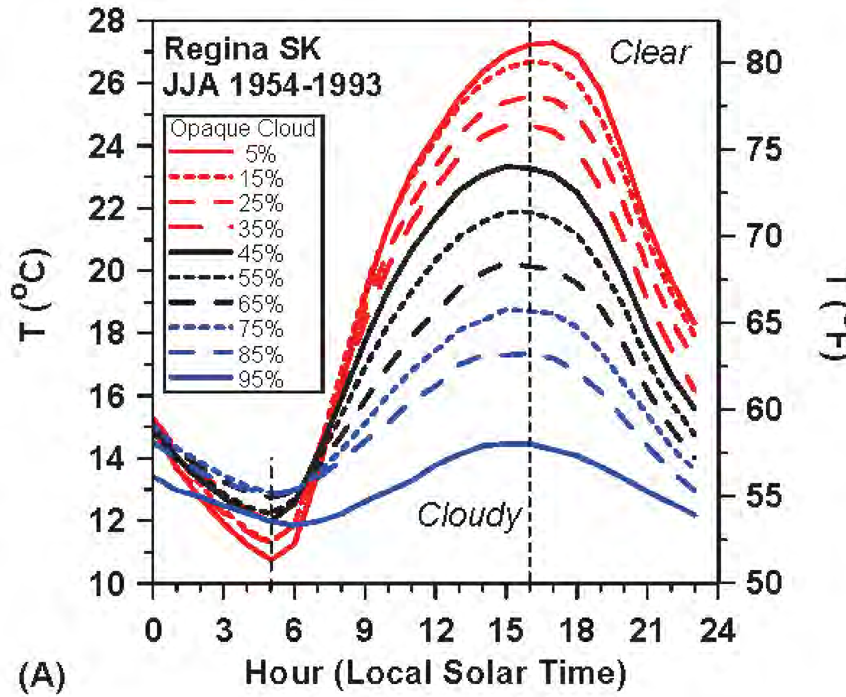
Clouds to Summer Diurnal Cycle

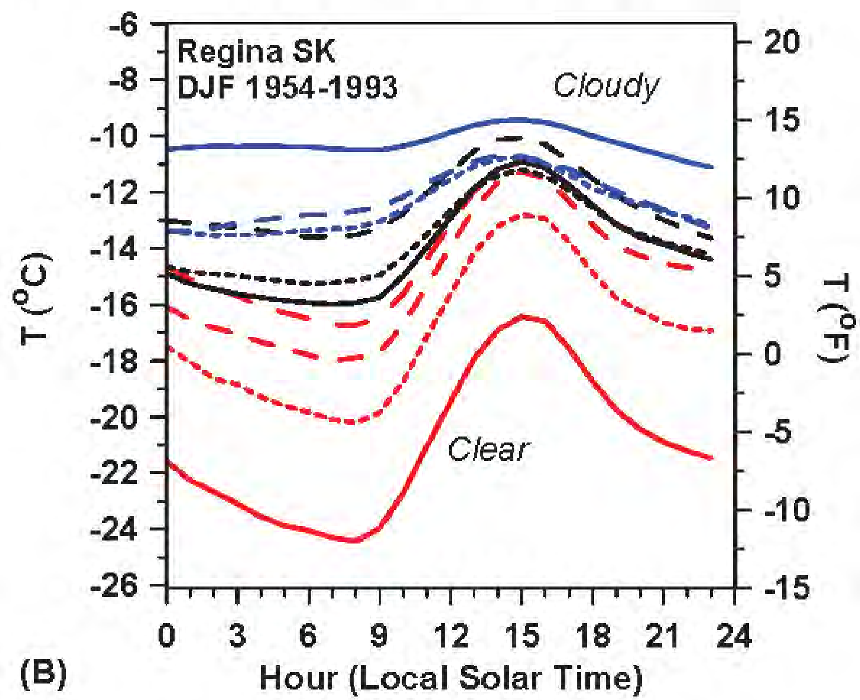
- ***40-yr climate***
- **T and RH are inverse**
- **Q has double maximum for BL transitions**
- **θ_E flatter**
- ***Overcast (rain) only outlier***



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***

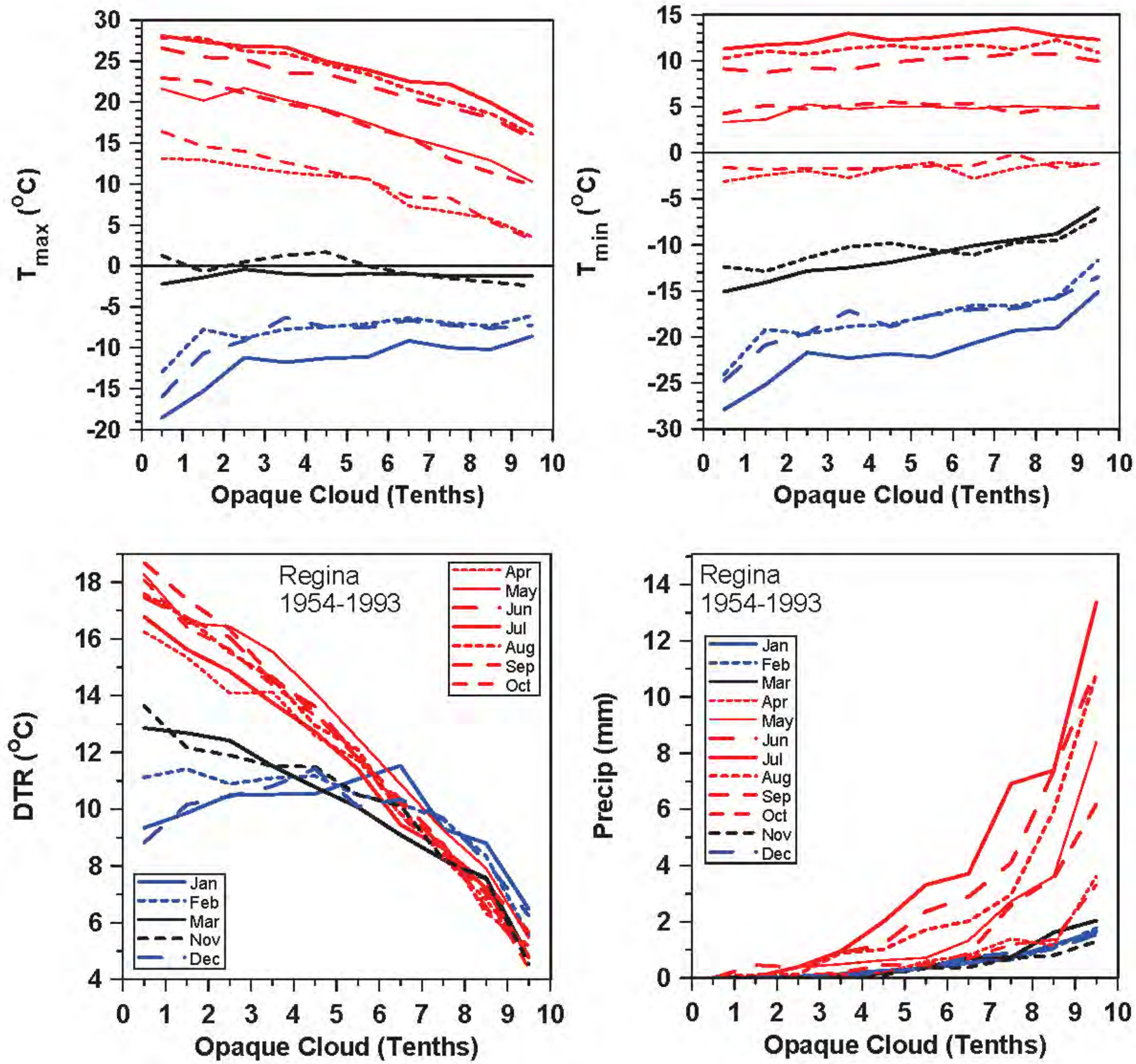




Betts et al. 2013

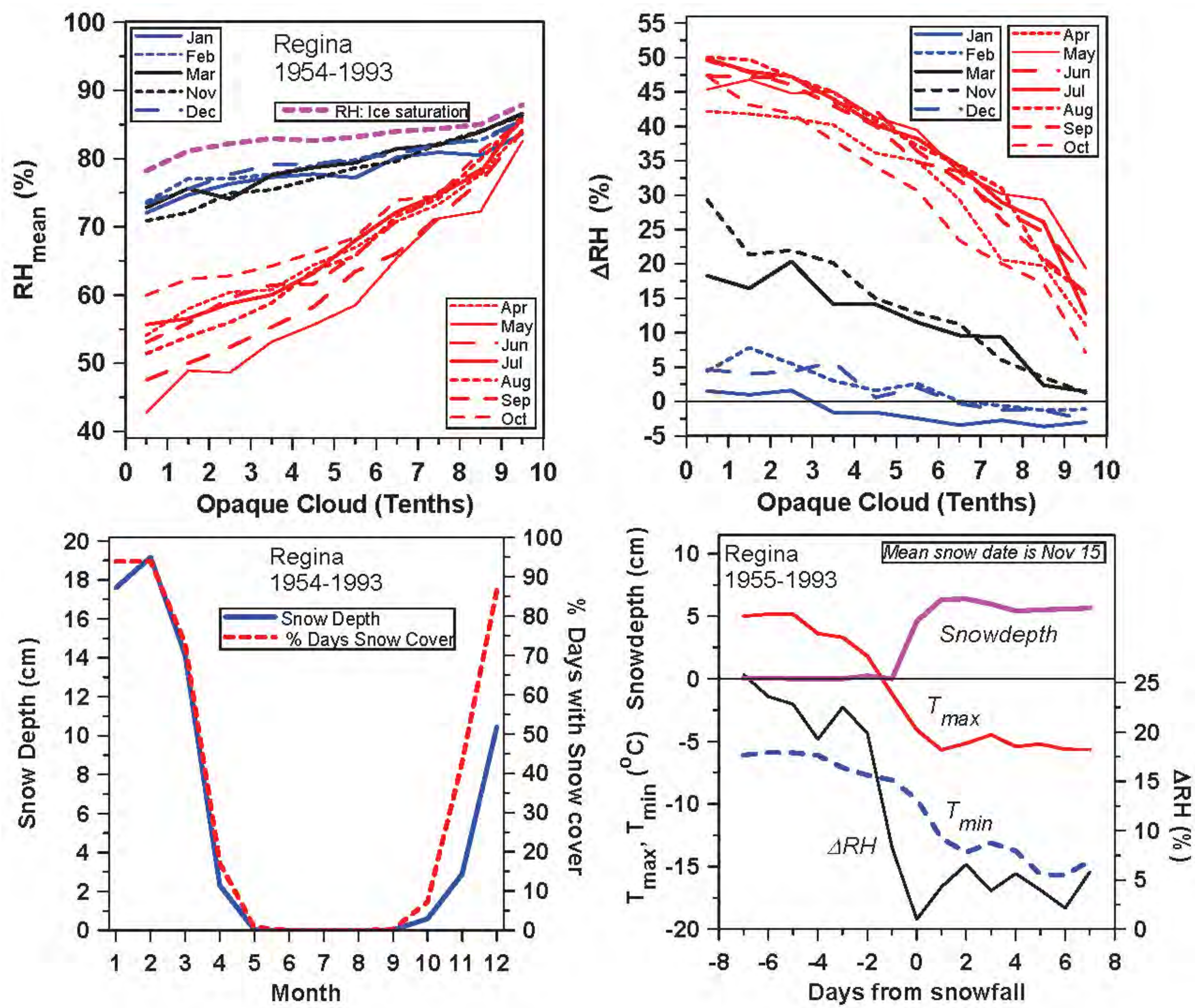
Annual Cycle: T_{max}, T_{min}, DTR, Precip

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

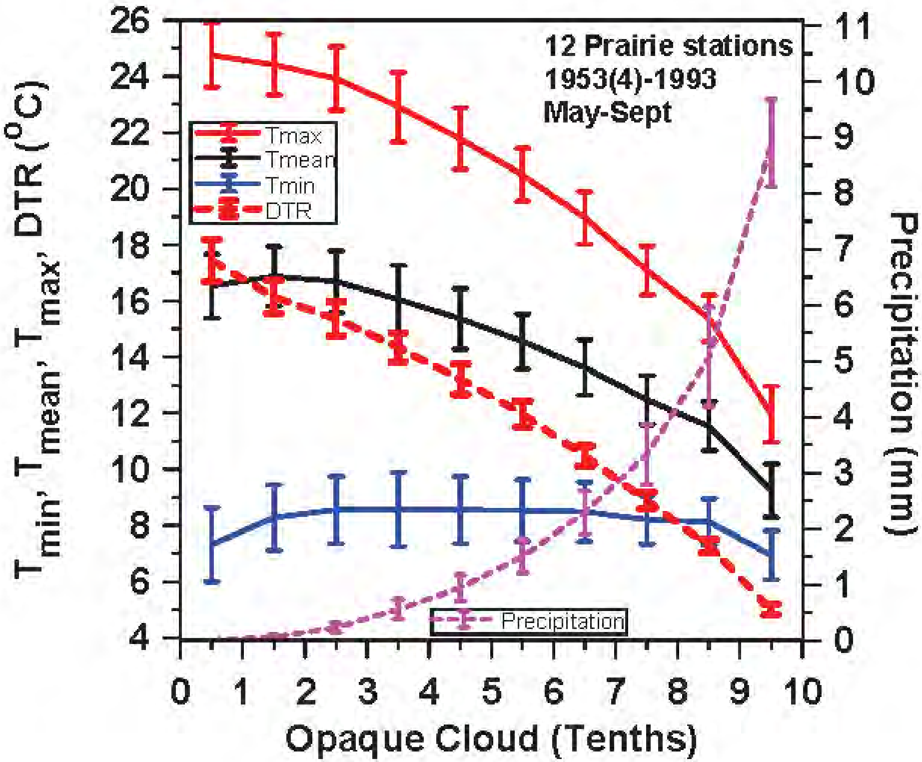


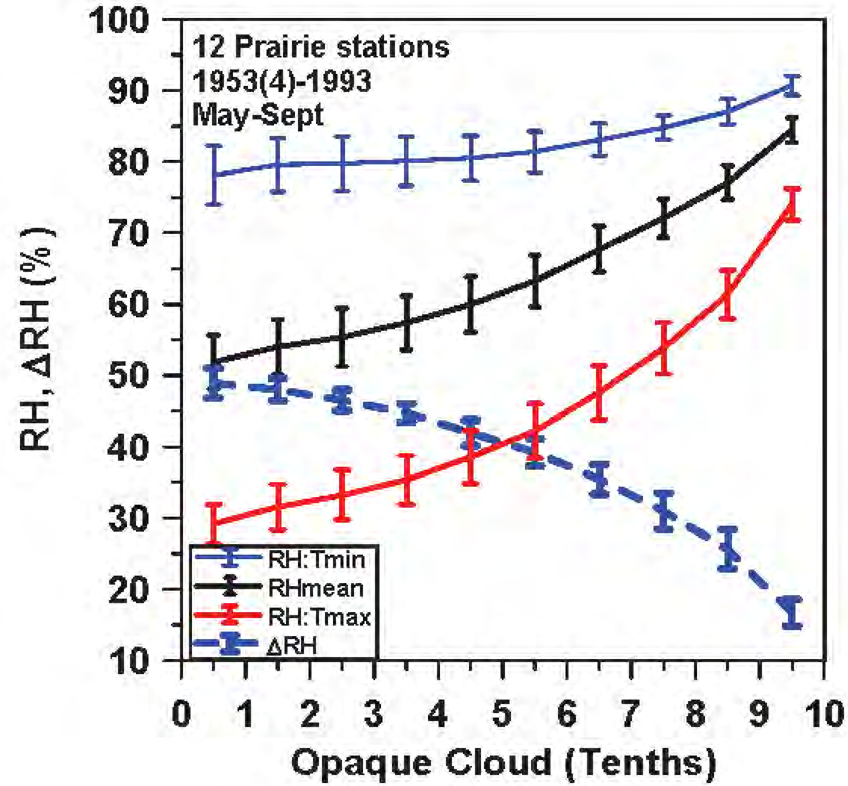
Annual Cycle: RH and ΔRH

- **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:** ***Uniform climatology***
- **<u>Tiny variability</u> in DTR and ΔRH**

Surface Radiation Budget

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

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

Define Effective Cloud Albedo (reflection)

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

  Clear sky

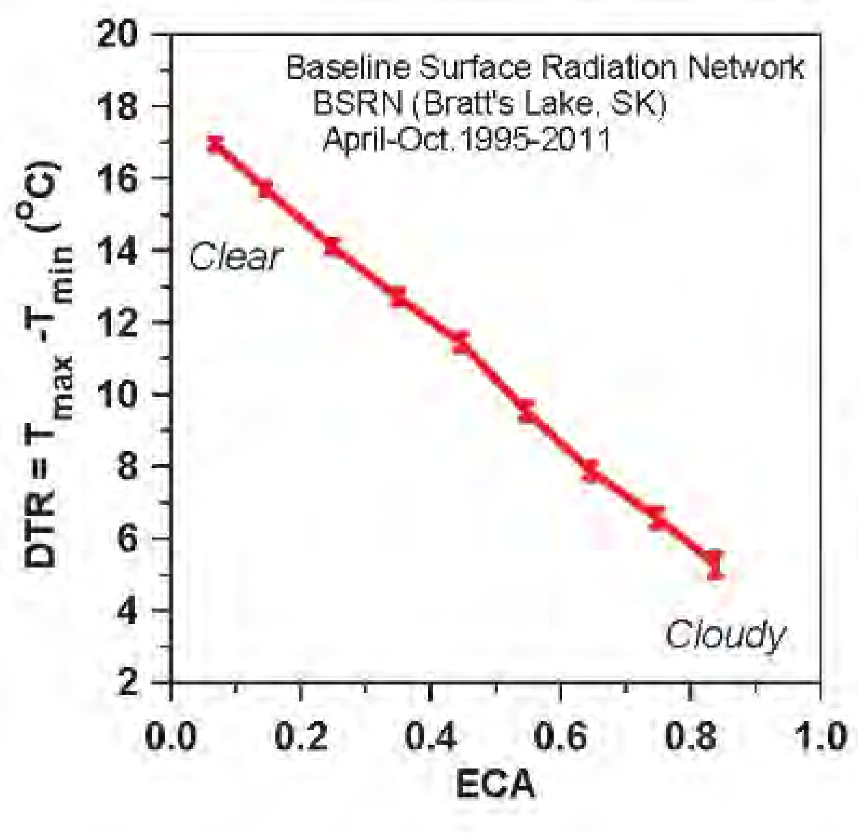
- $SW_{net} = (1 - \alpha_s)(1 - ECA)\ SW_{dn}(clear)$

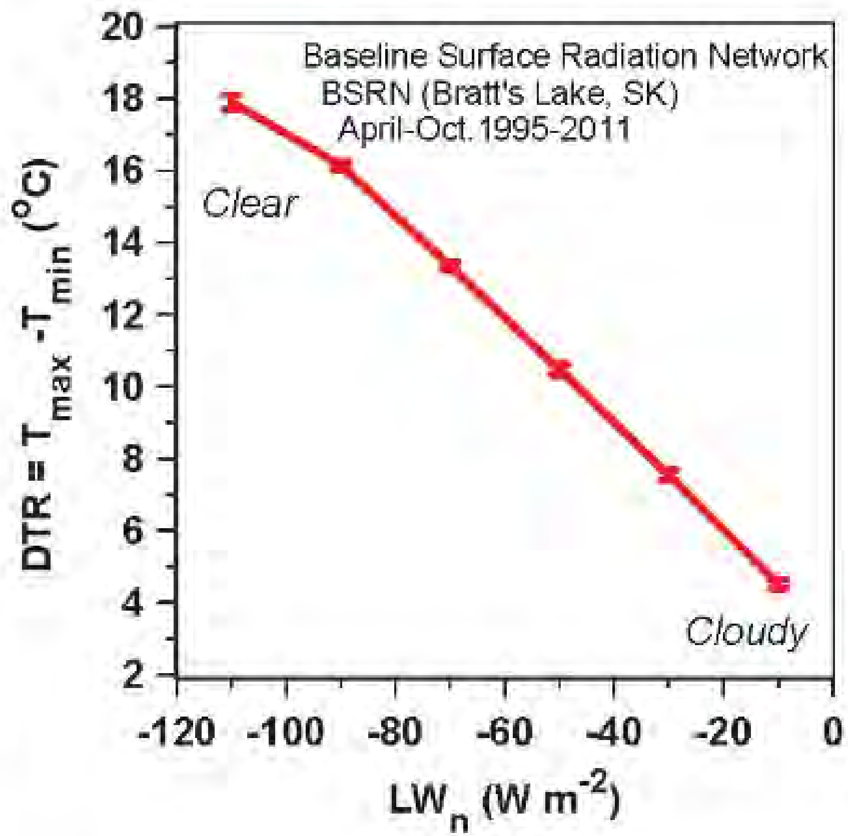
  Reflected by surface, clouds

  MODIS Calibrate Opaque Cloud data

Diurnal Temperature Range

Warms in daytime and cools at night





- **Daytime warming related to clouds: ECA**
- **Night-time cooling related to clouds: LW_{net}**

Warm Season Climate

- Sun warms surface; grass, trees – transpire (λE)
- Heating forms unstable boundary layer
- Clouds form at lifting condensation level, reflecting sunlight

Cold Season Climate

- **Low sun is reflected by snow**
- **Under clear sky, surface long-wave cooling**
- **Stable boundary layer forms**

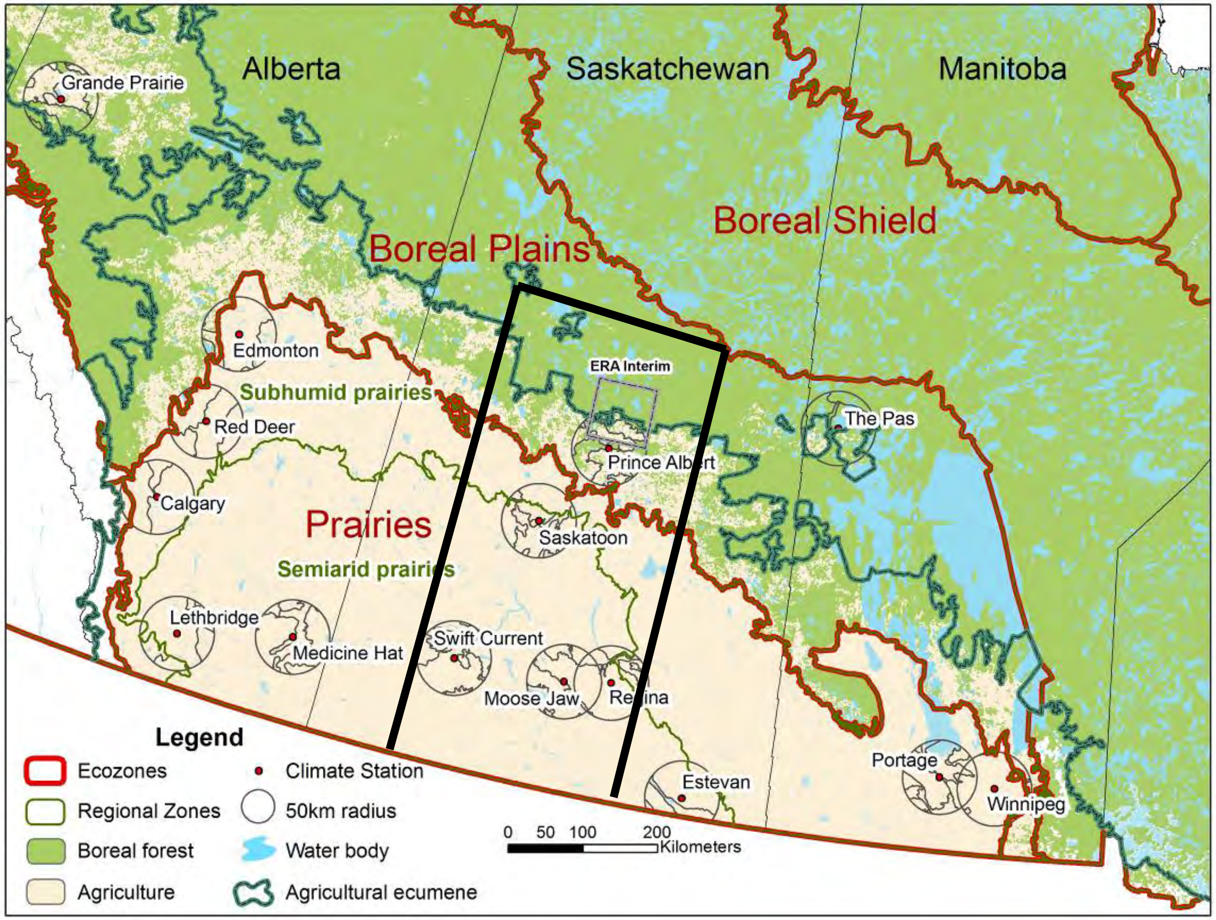
Impact of Snow on Climate

“*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’

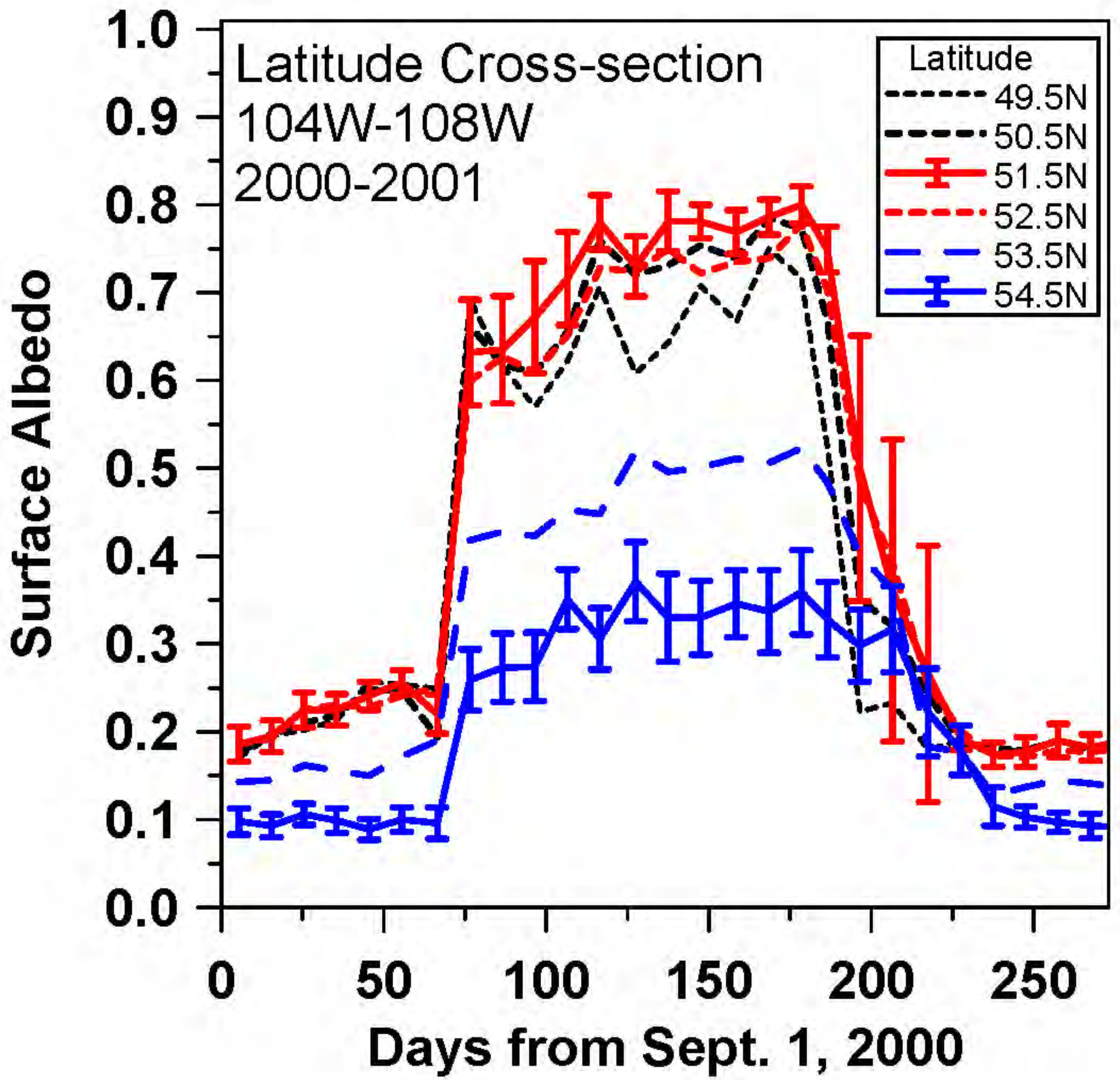
14 Prairie stations: 1953-2011



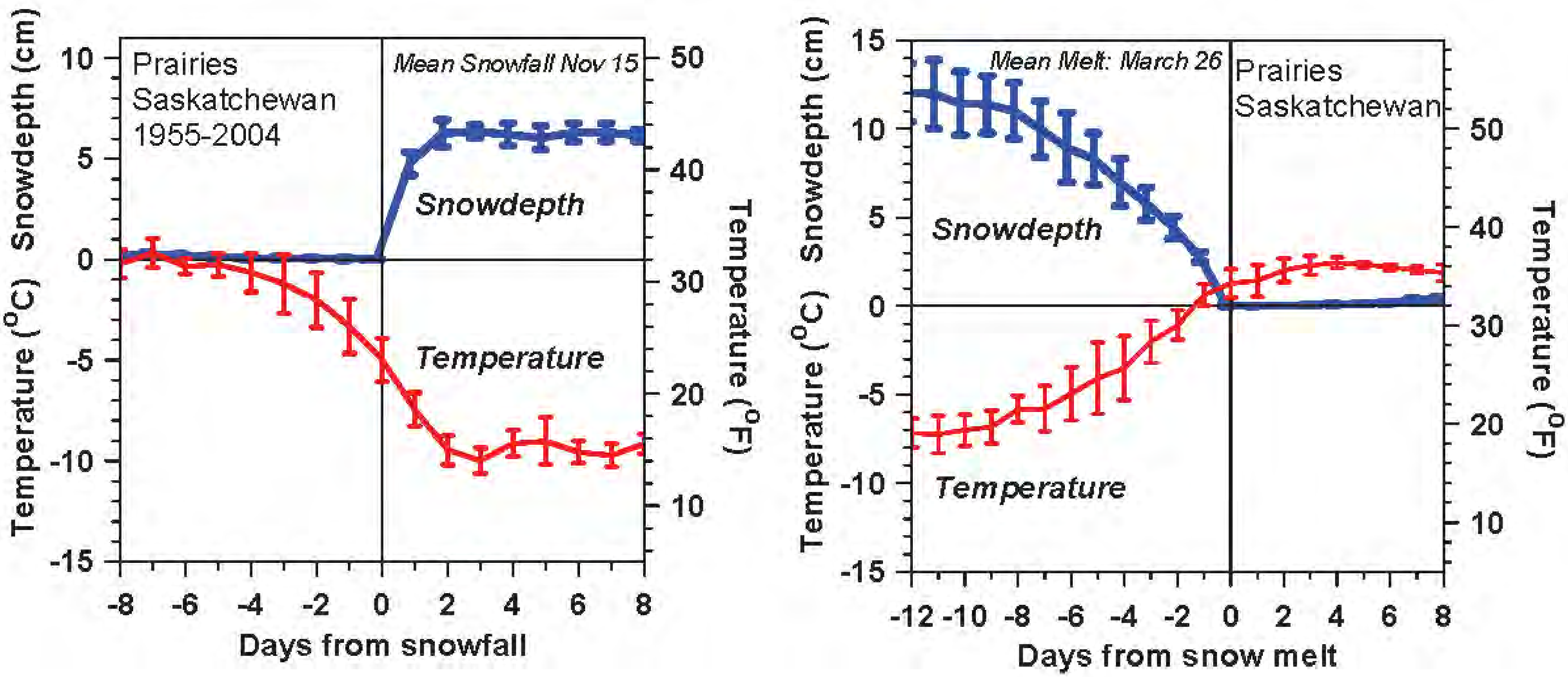
- Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})
- Daily precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

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*



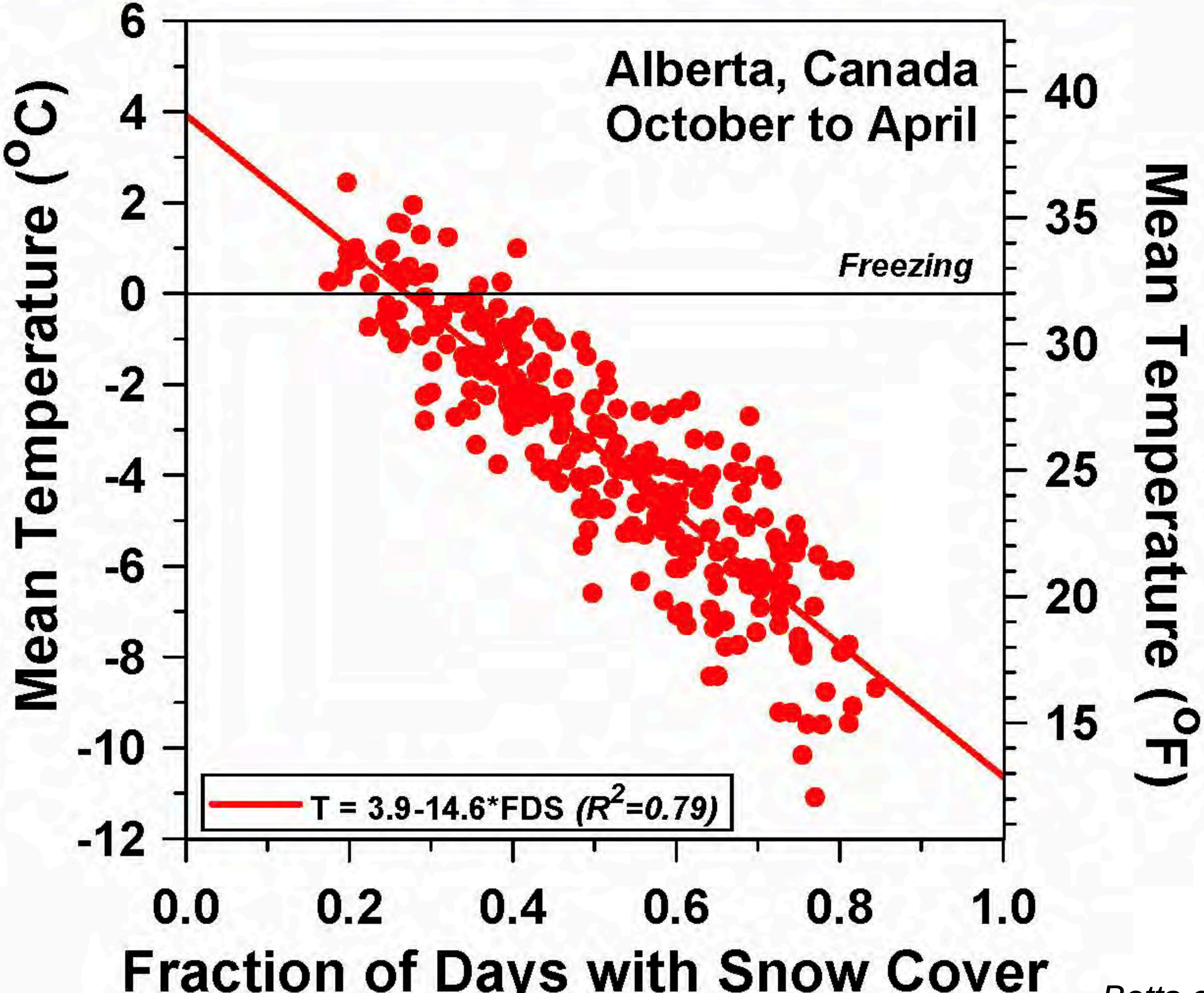
Snowfall and Snowmelt



- **Temperature falls 10C (18F) with first snowfall**
- **Similar change with snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – changes 'local climate'***

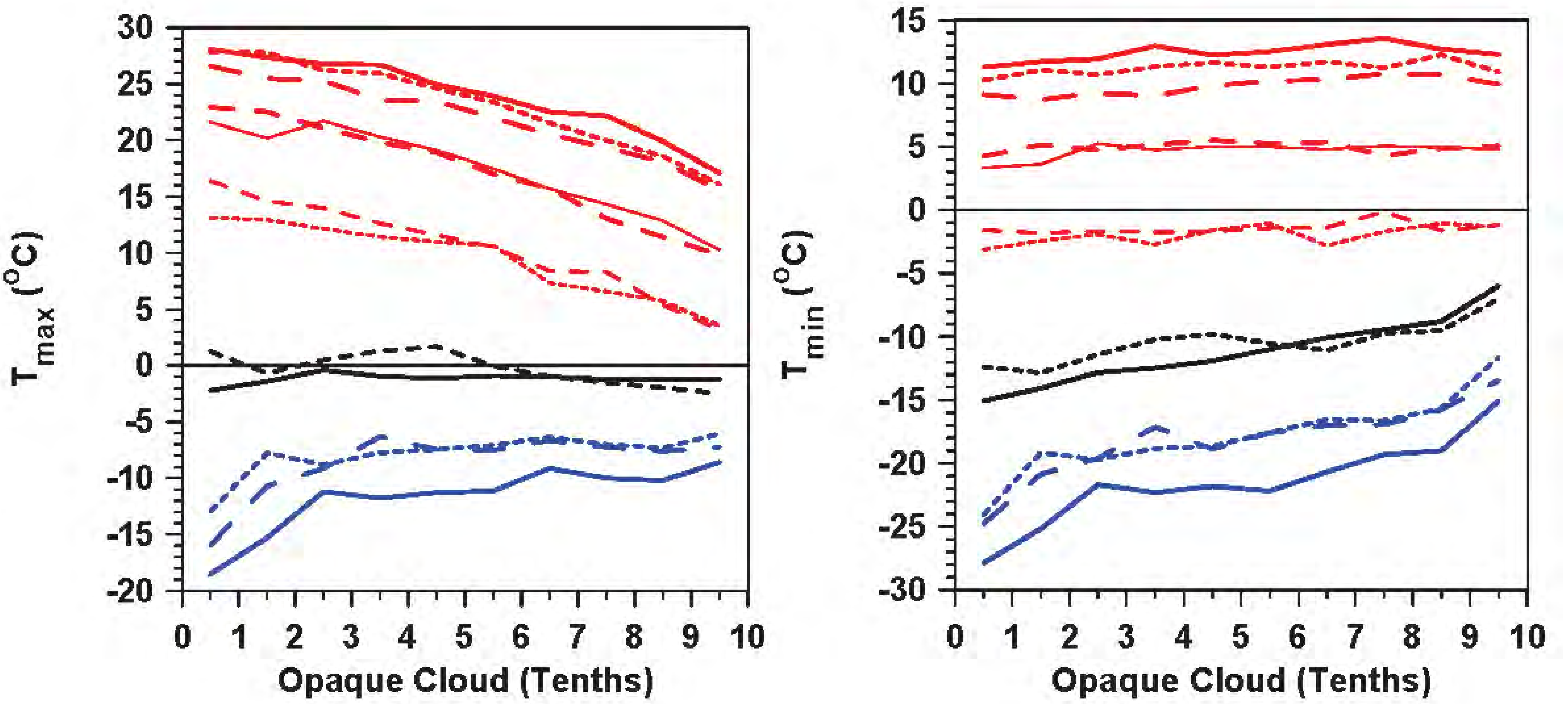
Betts et al. 2014

More snow cover - Colder temperatures



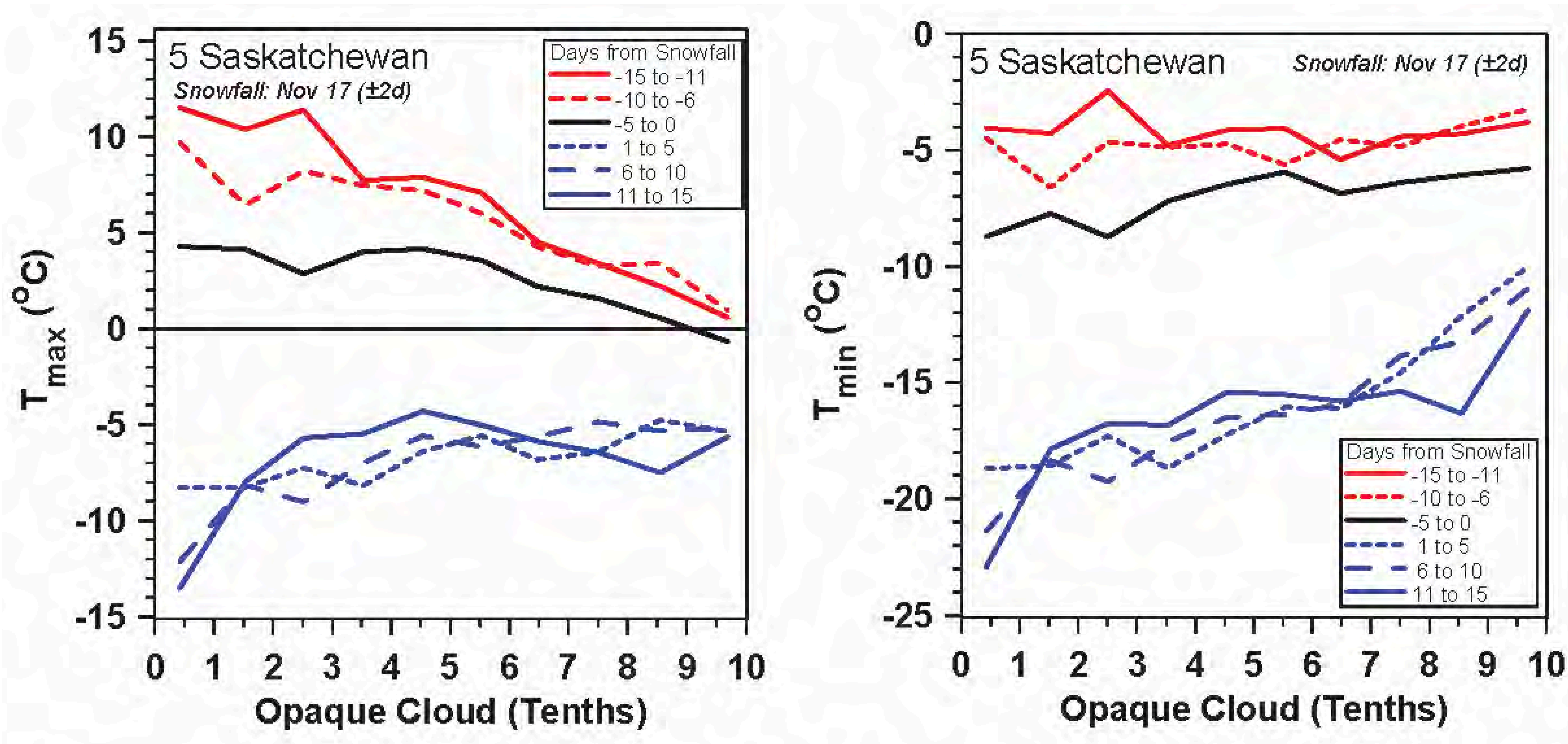
Betts et al. 2014

Recall: Annual Cycle: T_{max},T_{min}



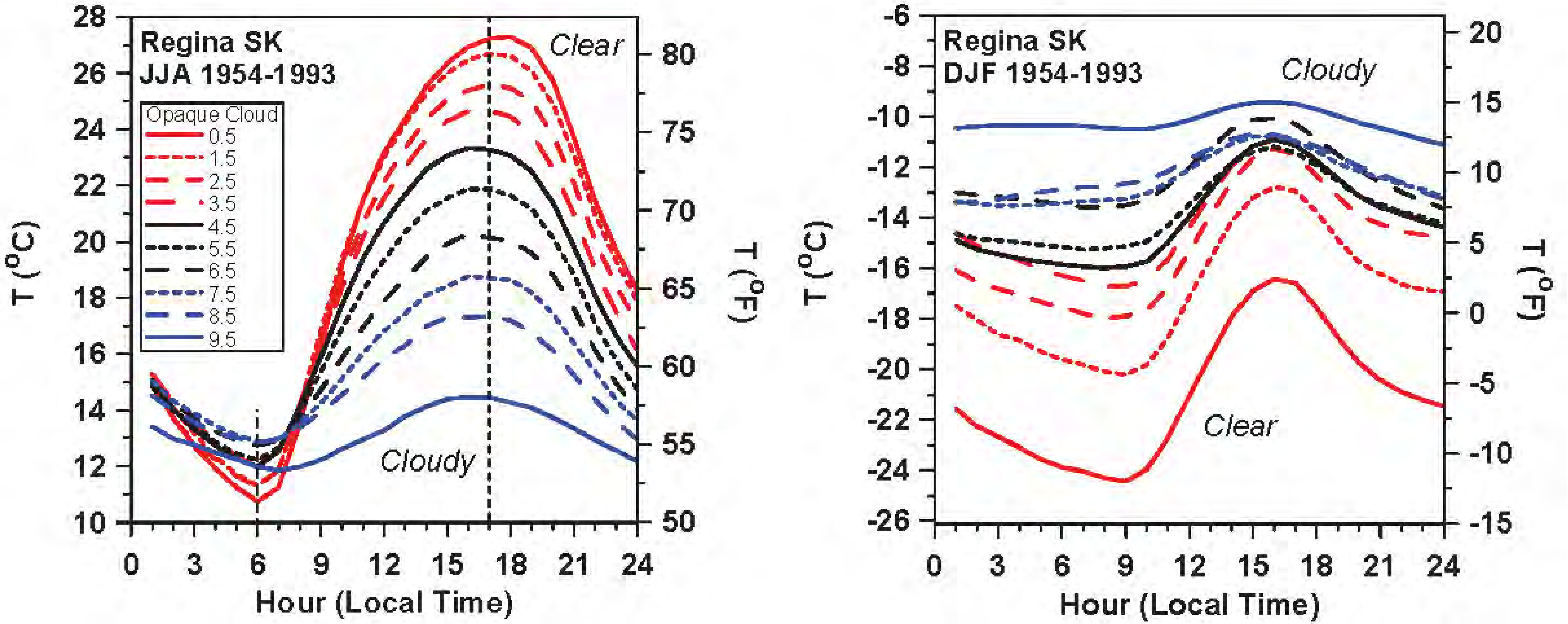
- Warm state: April – Oct
- Transitions: Nov, Mar when $T_{max} \approx 0^oC$
- Cold state: Dec – Feb

Snowfall is a 'Climate Switch'



- 5-day means: *red: no snow; blue: snow* (6000 days)
- With snow: T_{max}, T_{min} plunge
- Cloud coupling shifts in 5 days
- From 'Warm when clear' to 'Cold when clear'

Clouds: Summer & Winter Climate
Opposite Impact

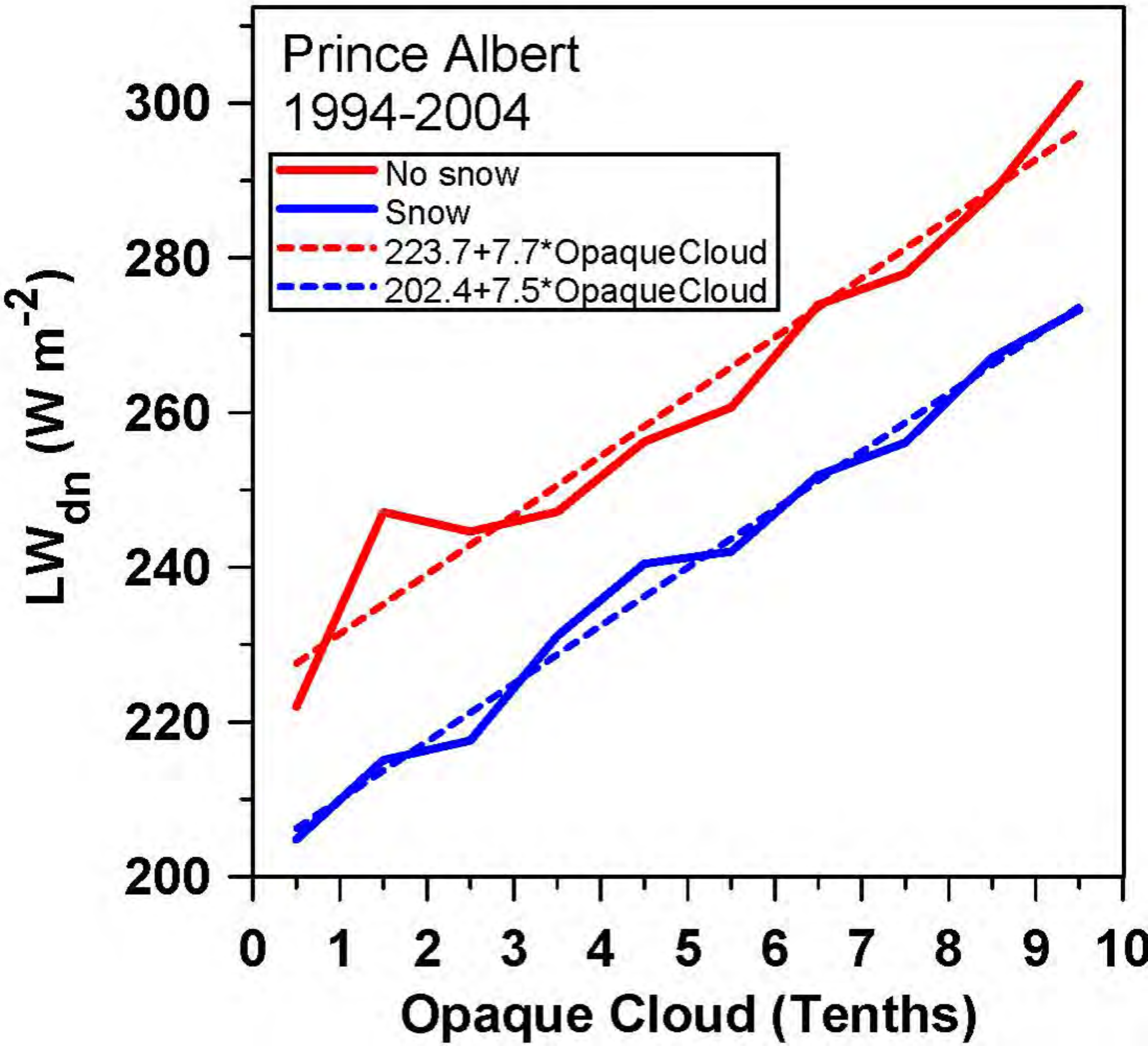


- **Summer: Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
  - **Convective boundary layer in daytime**
- **Winter: Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**
  - **Stable boundary layer**

Betts et al. 2013a

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/m^2
- LW_{dn} falls 15 W/m^2
- Total 49 W/m^2

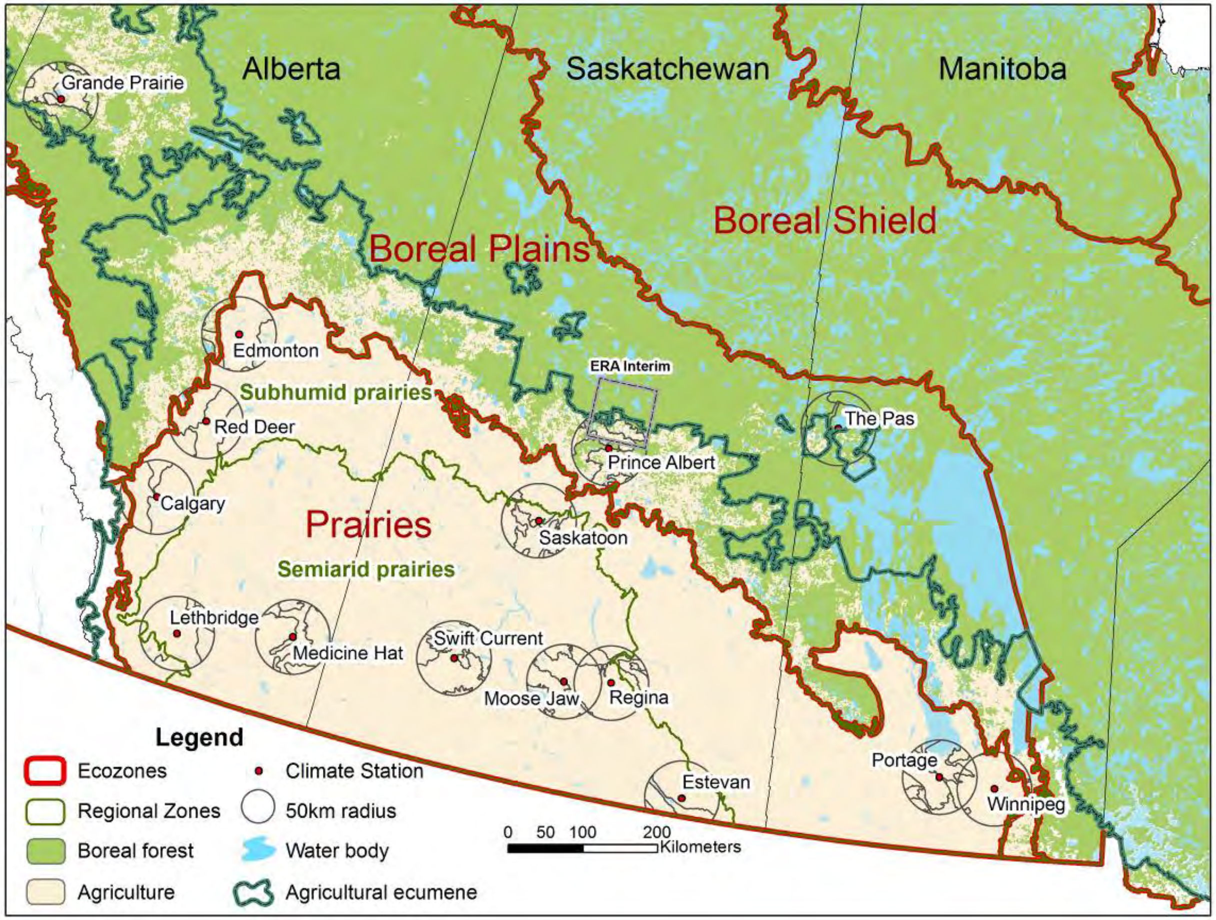
- Surface skin T falls: $\Delta T = -11K$ to balance

  (Stefan-Boltzman law: $\Delta(LW) = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)

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/subhumid 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



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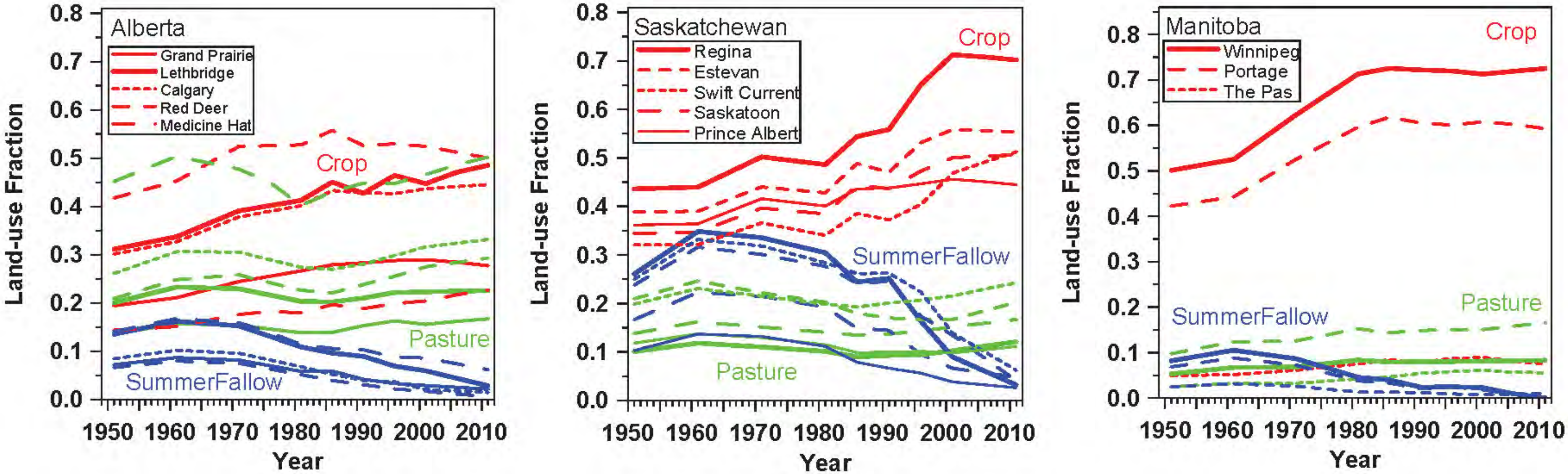
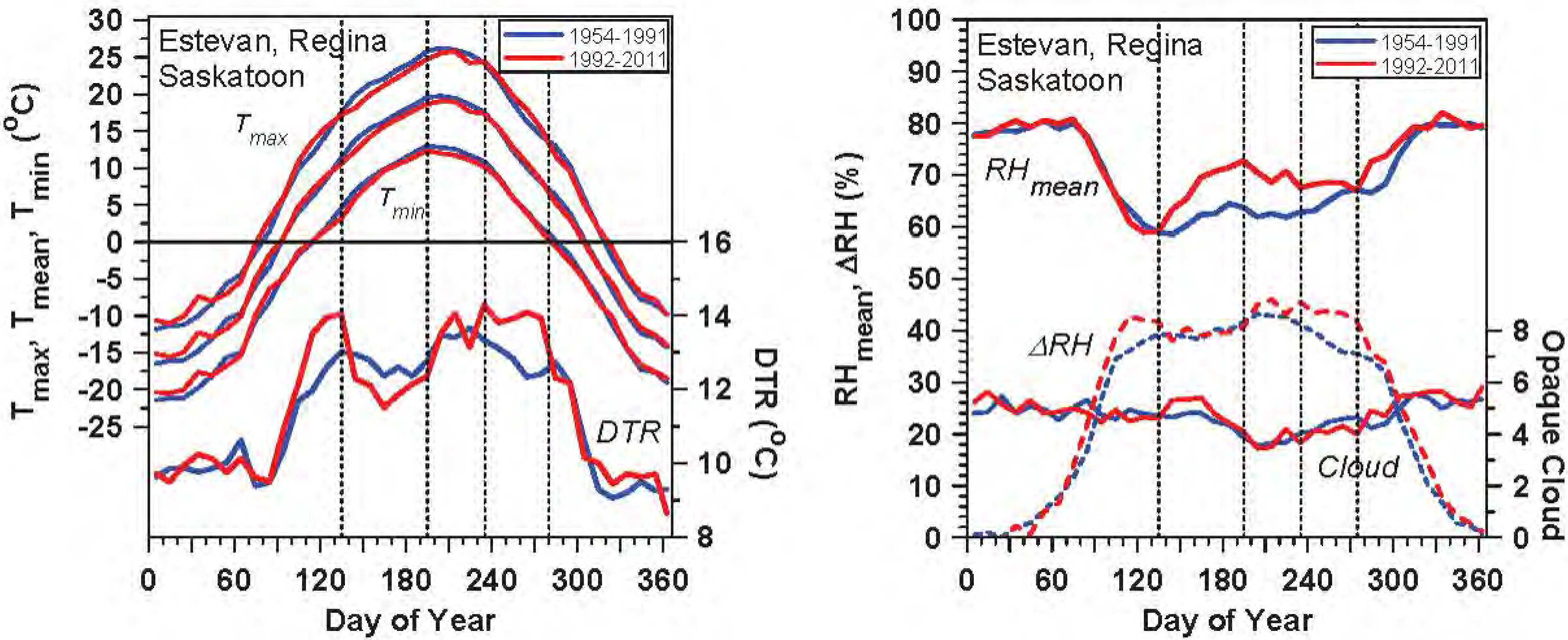
Change in Cropping



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

Three Station Mean in SK

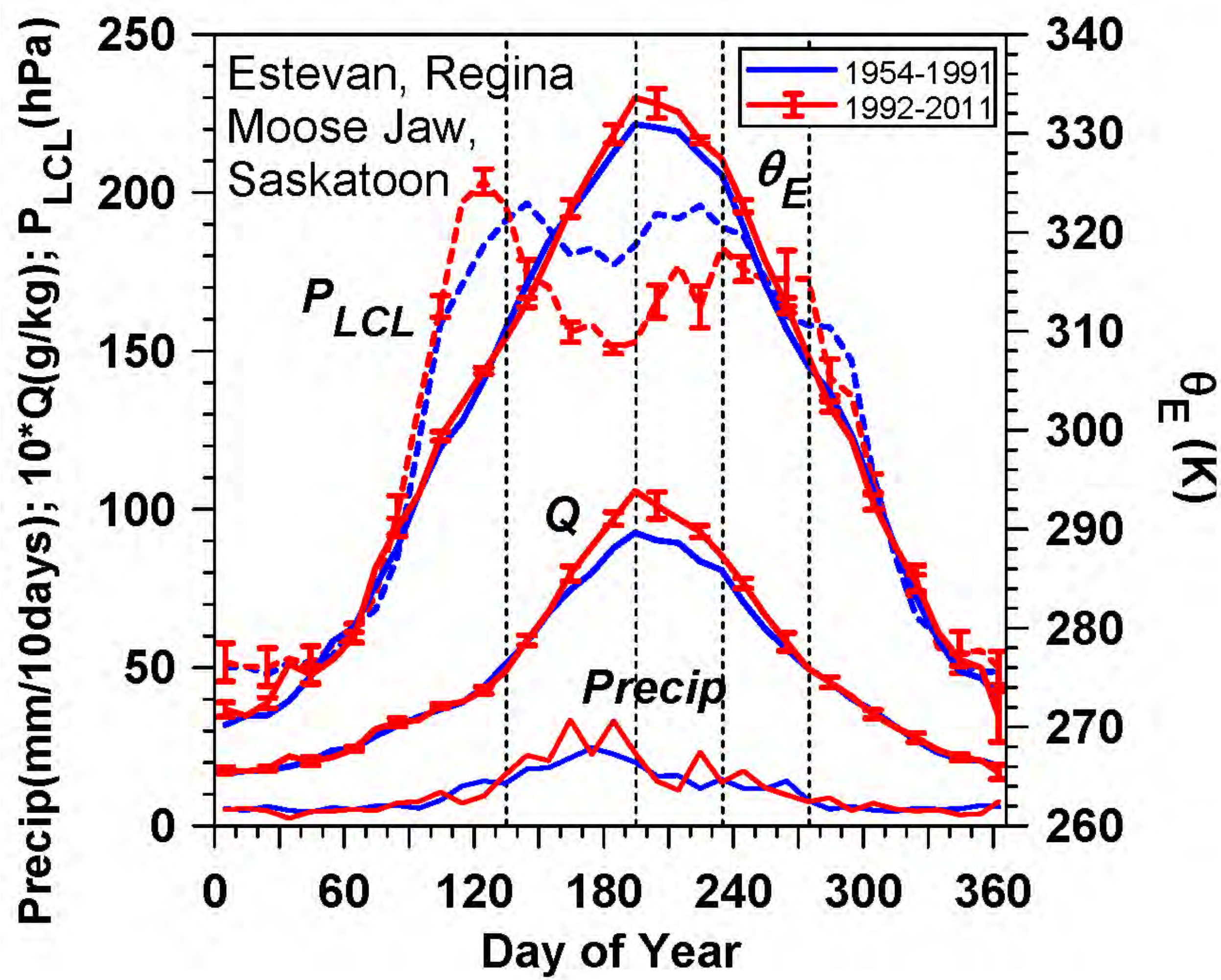


- **Winter climate warmer but growing season**
  - **T_{max} cooler; RH moister**
  - **DTR and ΔRH seasonal structure changes**

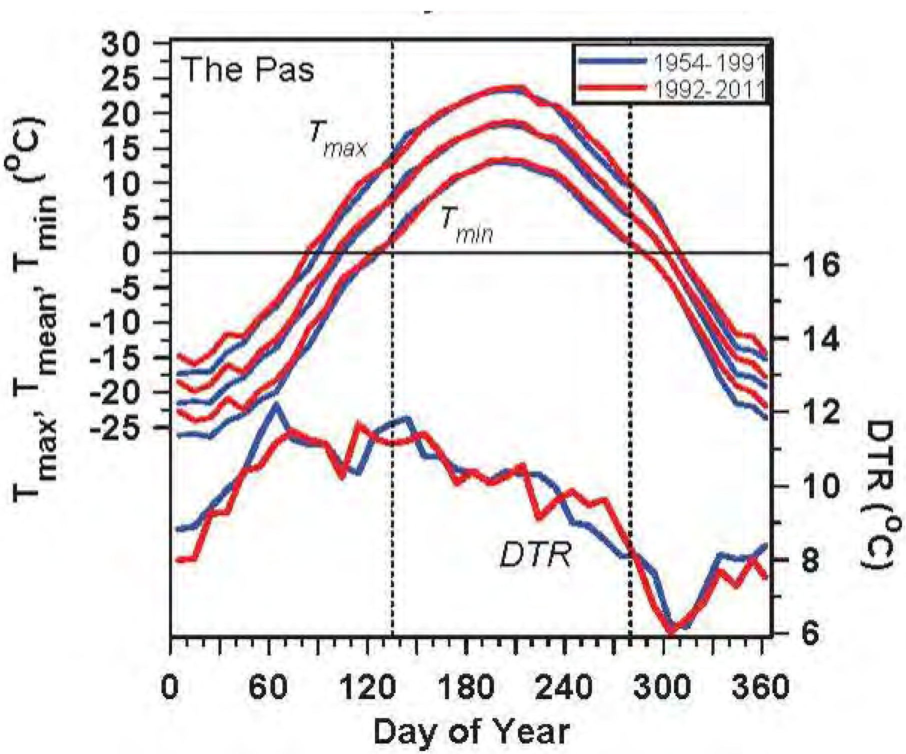
Impact on Convective Instability

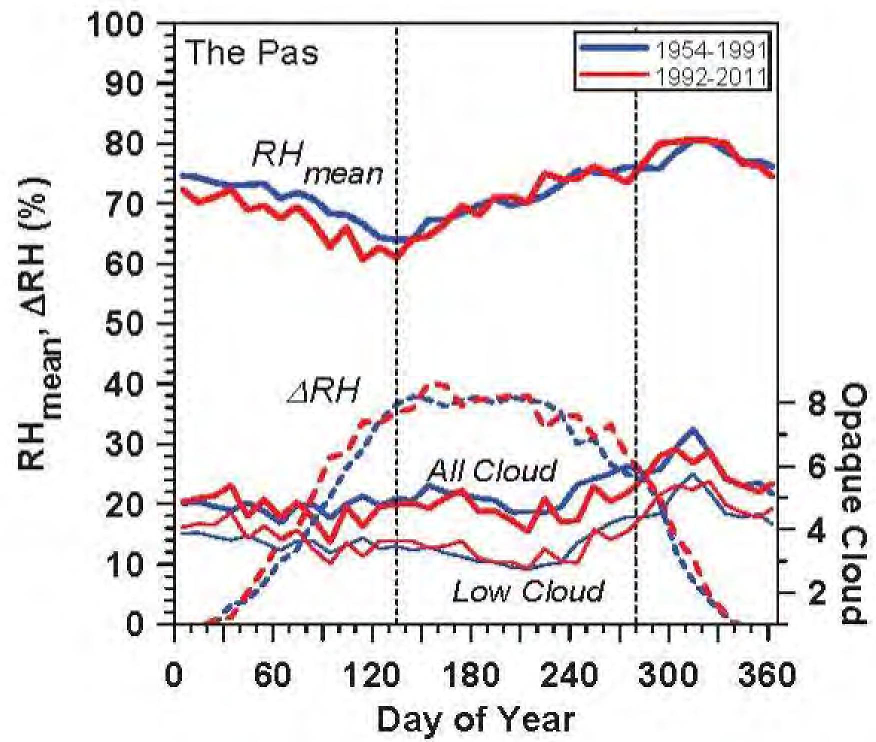
Growing season

- **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**
- **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**
- **Transpiration from crops changes climate**
  - **Cools and moistens summer climate**
  - **Lowers cloud-base and increases θ_E**
  - **(While winter climate has warmed)**

Papers at http://alanbetts.com

Monthly, Seasonal, 50-yr Climate

- Observables
- Opaque/reflective cloud → R_n
- Precipitation+ Drydown → Evaporation

- **50-yr timescale see separation**

  RH to precipitation and soil moisture

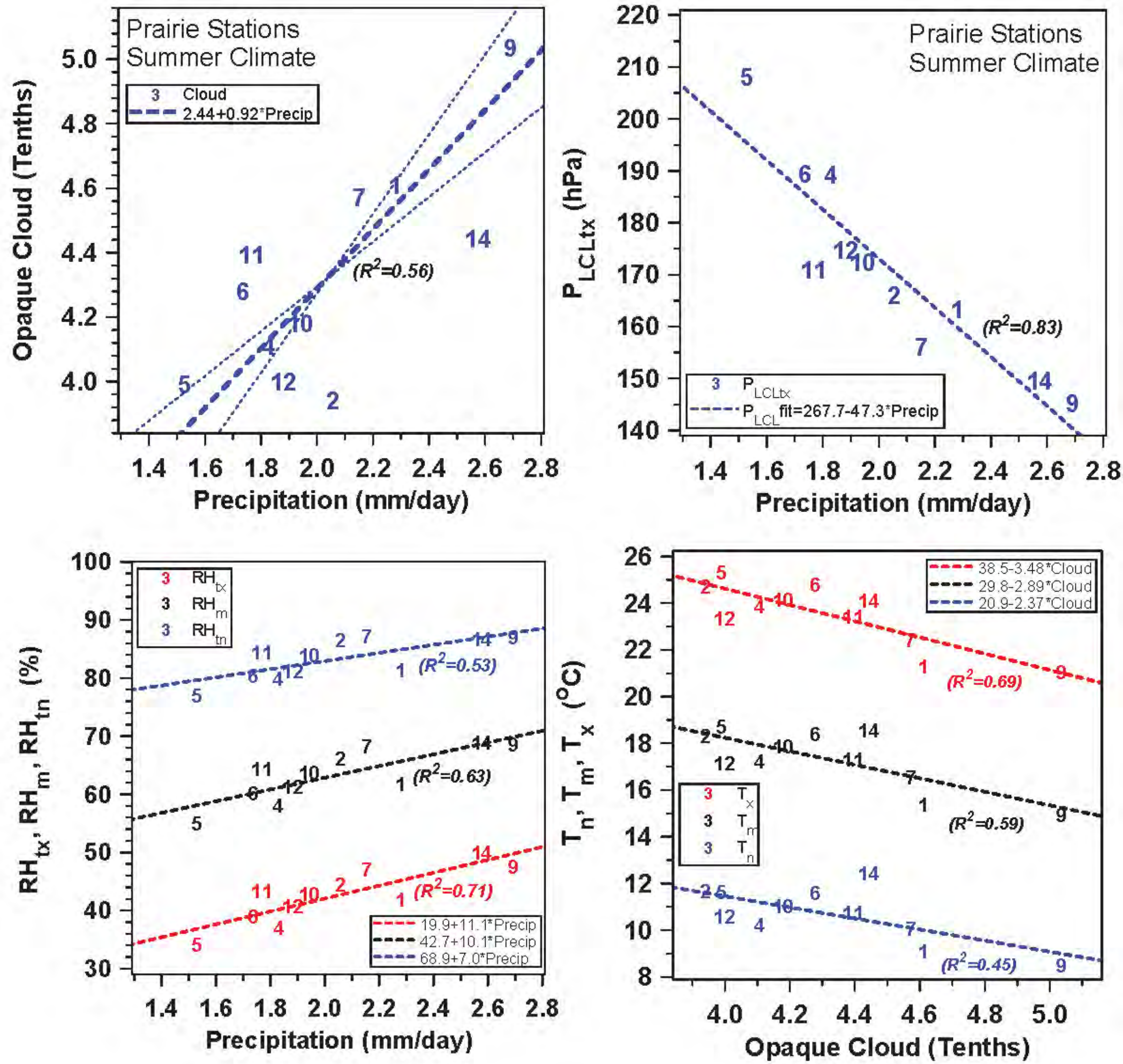
  T to opaque cloud and R_n

- ***Monthly, seasonal timescale blended***

- *Betts, A.K., R. Desjardins, D. Worth and B. Beckage (2014), Climate coupling between temperature, humidity, precipitation and cloud cover over the Canadian Prairies. JGR, 2014JD022511, (minor revision)*

11 stations: 53-yr JJA climate

- **Precip to *(R^2)***
  - Cloud (0.56)
  - P_{LCLtx} (0.83)
  - RH_{tx} (0.71)
- **Cloud to**
  - T_x (0.69)
- **Separation**
- ***Month: blend***
- ***Daily: cloud***



Monthly timescale: Regression

$\delta DTR = K + A^* \delta Precip(Mo\text{-}2) + B * \delta Precip(Mo\text{-}1) + C * \delta Precip + D * \delta OpaqueCloud$

(Month-2) (Month-1) (Month) (Month)

δDTR anomalies

	K	A	B	C	D	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**

Monthly timescale: Regression

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

δRH_{tx} anomalies

Month	K	A *(Mo-2)*	B*(Mo-1)*	C*(Mo)*	D	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	<u>0.66±0.11</u>	<u>1.23±0.13</u>	<u>2.42±0.16</u>	<u>4.08±0.20</u>	<u>0.73</u>	<u>0.53</u>	<u>0.56</u>
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

How good is the regression fit?

- **September**

  T_x ±1.4°C

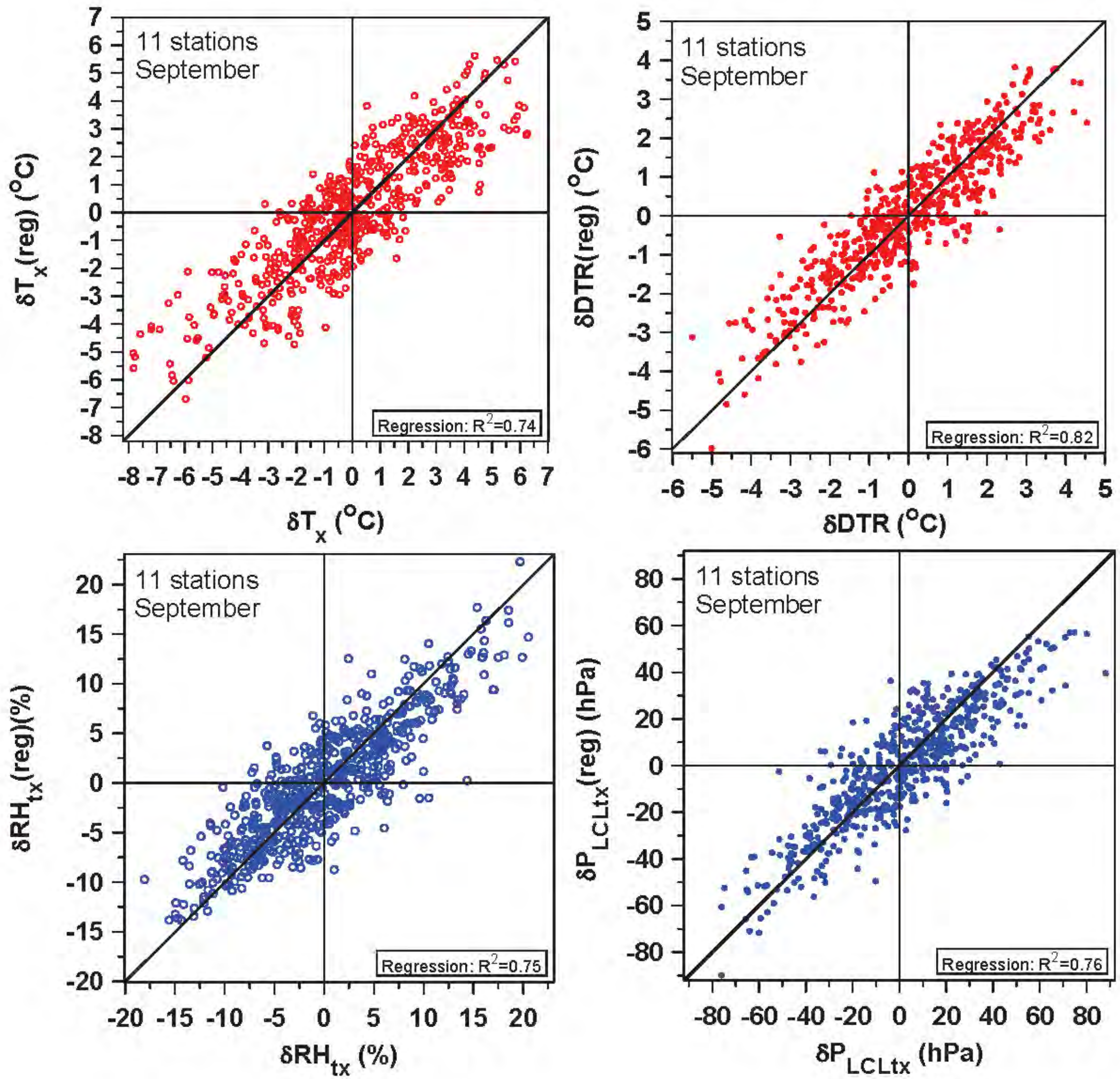
  DTR ±0.8°C

  RH_{tx} ±3.5%

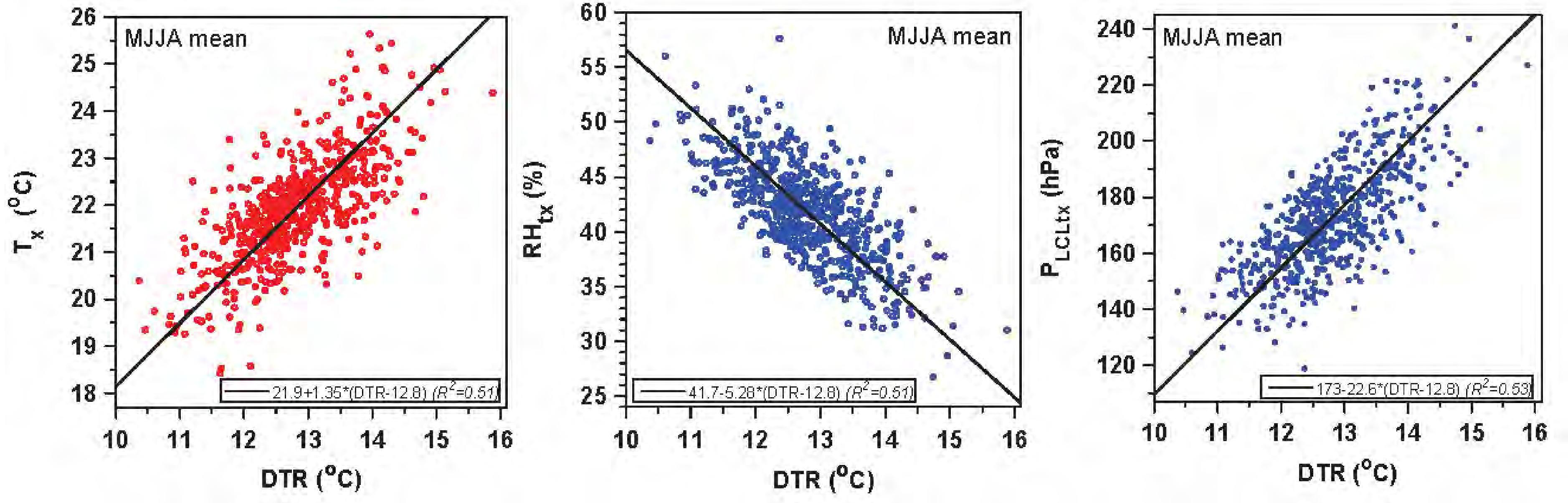
  P_{LCLtx} ±13hPa

- **Some extremes underestimated**

(586 station-yrs)



Diurnal coupling: MJJA mean



- **Internal coupling well-defined**
  - **Slopes less than 50-yr climate**

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**
$\delta RH_{tn\sigma}$	0±0.9	0.38±0.04	0.24±0.04	0.27	**4.52**
$\delta P_{LCLtx\sigma}$	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**

MJJA Surface Water Balance

$$E = P - R - \Delta TWS$$

where ΔTWS is change in Total Water Storage

$$P = P_m + \delta Precip(AMJJA)$$

where mean P_m = 1.94 mm/day

$R/P = 0.5$ *(assumed: rivers managed)*

$$\Delta TWS = \Delta TWS_m + F^*\delta Precip(MJJA)$$

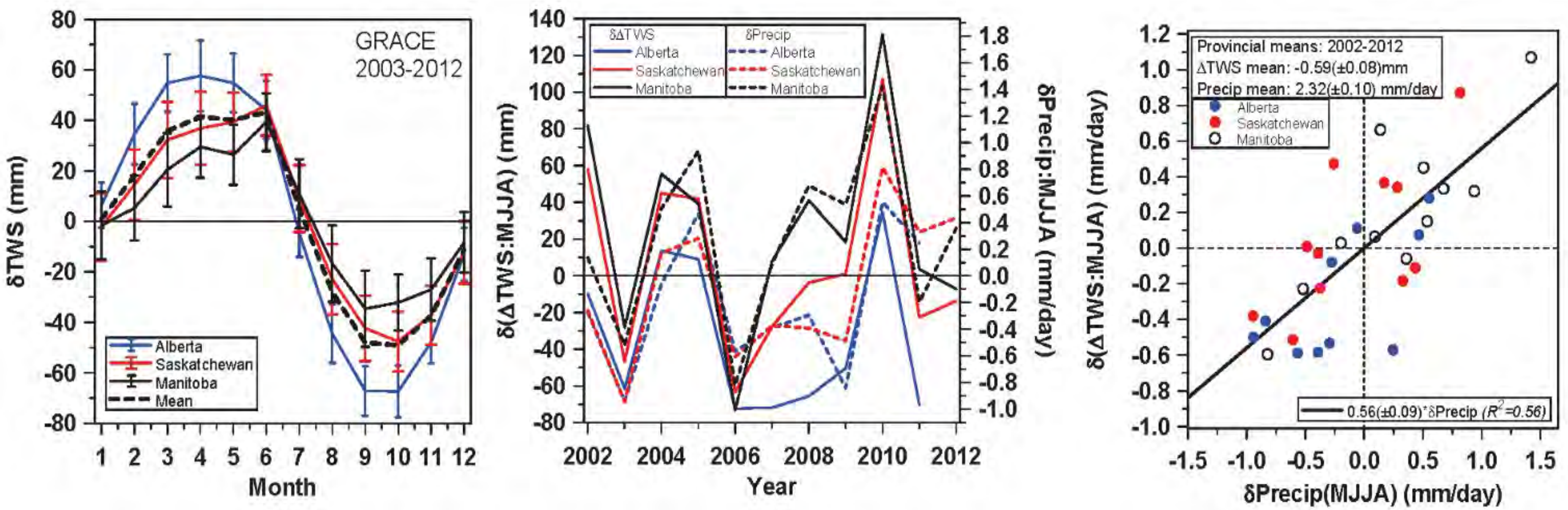
We estimate from GRACE data (2002-12)

ΔTWS_m= - 0.59(±0.08)mm/day (72mm/122 days)

F = +0.56(±0.09) (for AB, SK and MB)

(F is 56% damping of precipitation anomalies)

GRACE seasonal dry-down

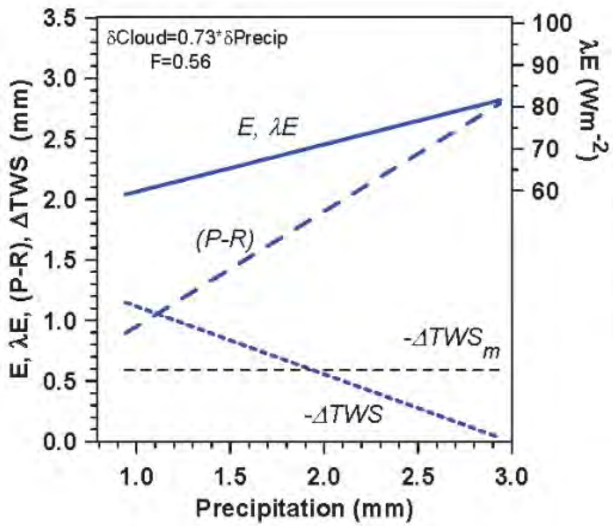


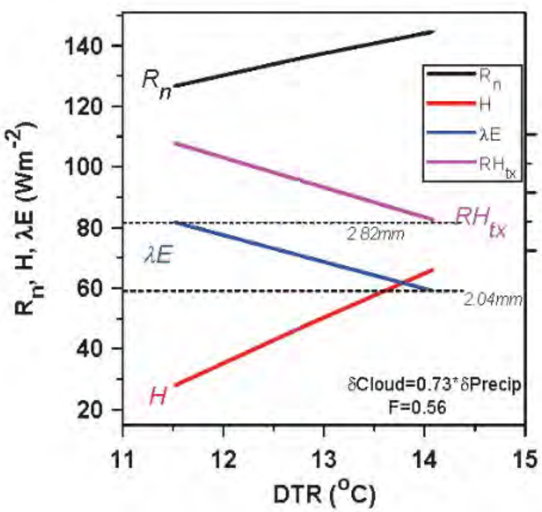
ΔTWS_m= - 0.59(±0.08)mm/day (73mm/123 days)

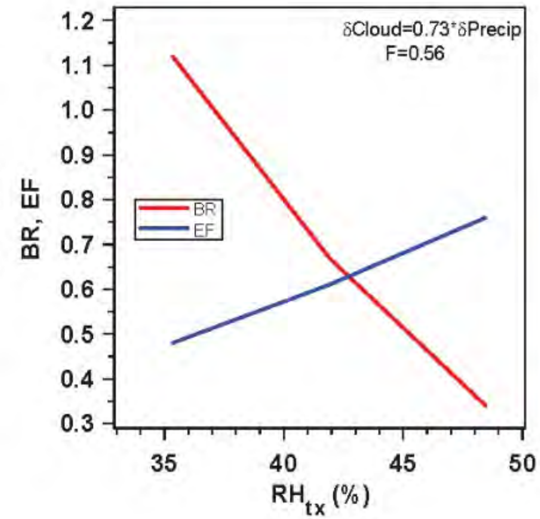
F = +0.56(±0.09) (for AB, SK and MB)

(F is 56% damping of precipitation anomalies)

Energy and Water “Budget”







- ***Cloud and precip. anomalies***
  - ***Give anomalies of DTR, RH_{tx} (and T_x..)***
  - ***Cloud gives R_n anomalies***
- ***Closures***
  - ***Climate coupling: cloud to precip. (0.73)***
  - ***GRACE estimate F = 0.56 gives E anomalies***
- ***Gives BR, EF anomalies***

Summary -2

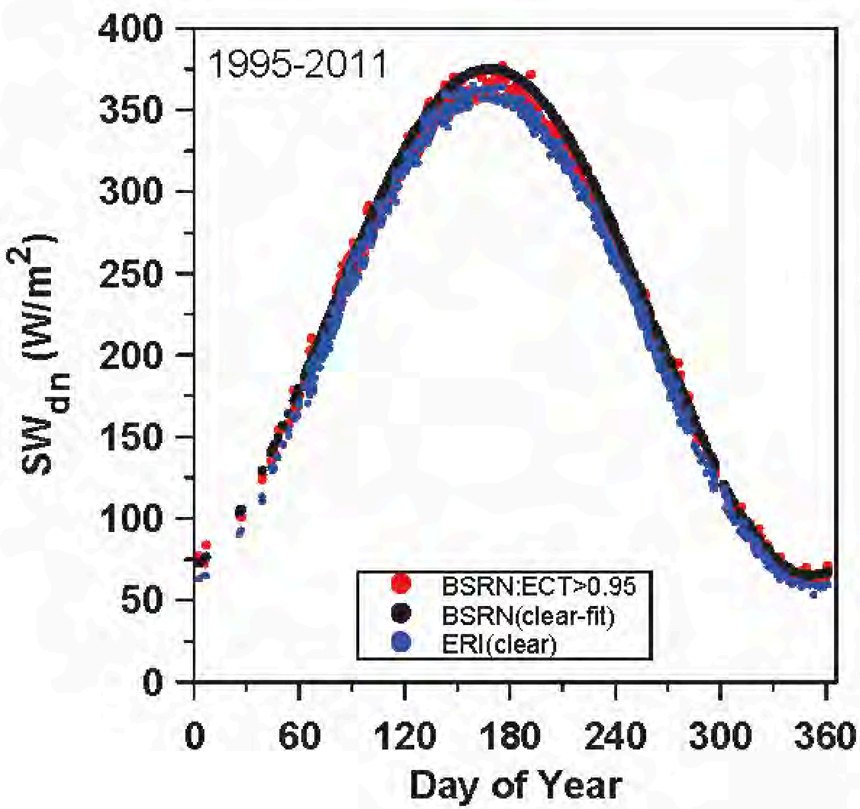
- ***High quality dataset with Opaque cloud***
  - ***Estimate SWCF, LWCF and R_n***
- **Map coupling of T, RH climate anomalies**
  - **To cloud on daily time-scale**
  - **To cloud and precip. on monthly/seasonal**
  - **MJJA: DTR, RH_x less dependent on cloud than T_x**
- **Dependence splits for 50-yr climate**
  - **T depends on cloud/radiation**
  - **RH and DTR depend on precip.**

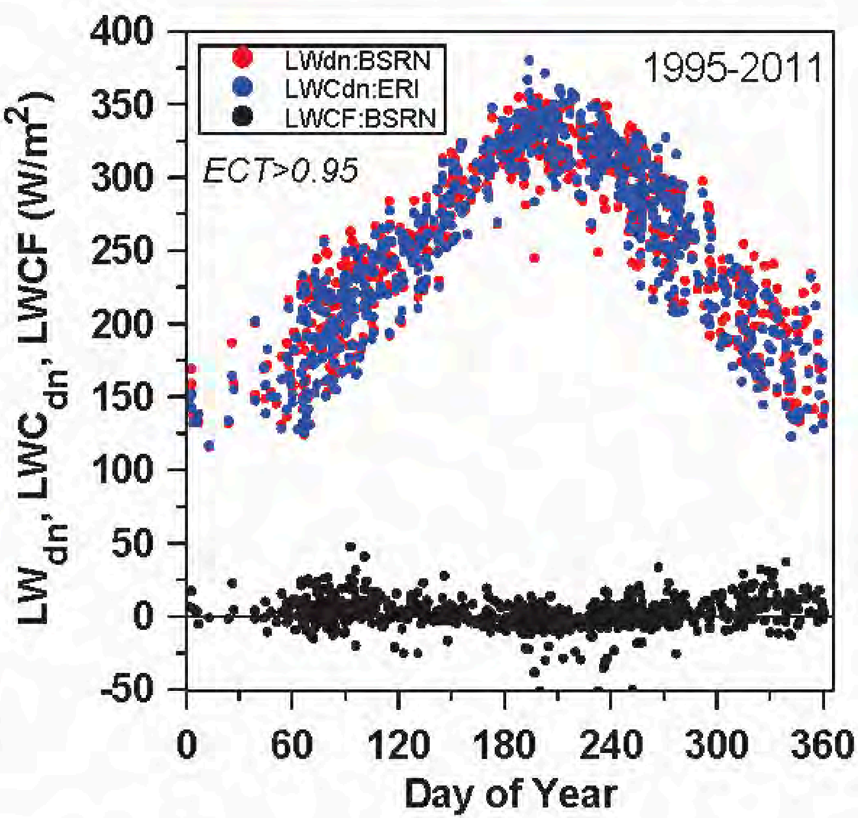
- ***Estimate evaporation using GRACE data to couple changes in TWS to precip. anomalies***

Land-surface-atmosphere coupling: daily timescales

- Revisit daily timescale
  - BSRN data for SW_{dn}, LW_{dn}
  - ERA-Interim for clear-sky fluxes
  - ECA, LW_n coupling to DTR and ΔRH
- Stratify by cloud and
  - RH
  - Wind
  - Precipitation anomalies

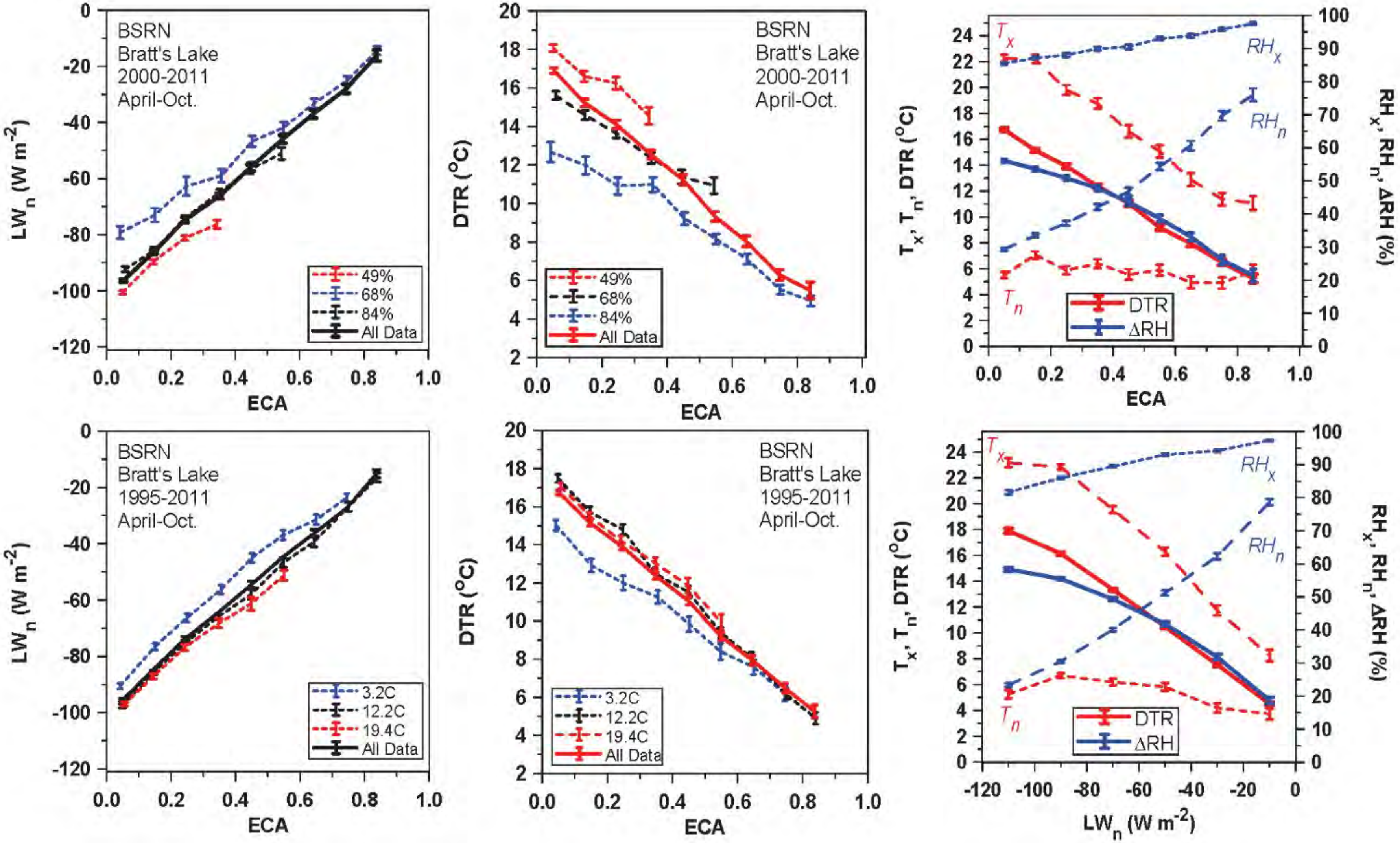
Comparison of BSRN and ERI
on clear days (>95% transmission)



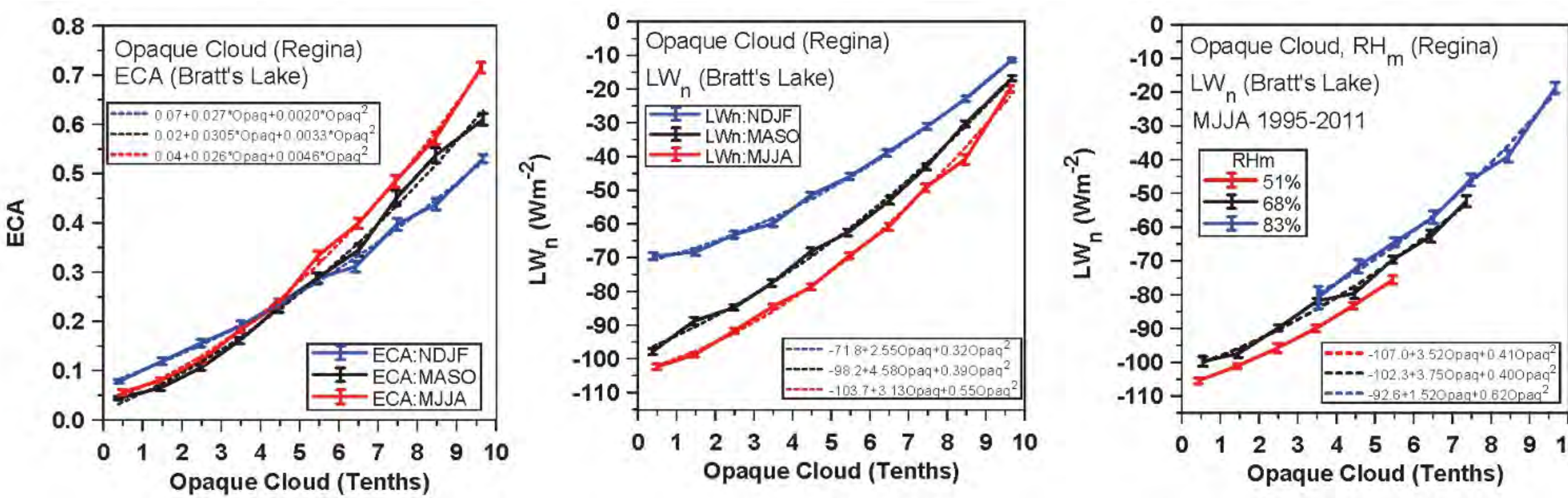


ERI SWC_{dn} biased low by 10-20 W/m^2 **ERI LW_{dn} unbiased**

Interdependence of ECA, LW_n, DTR, ΔRH



Calibrate Opaque Cloud to ECA and LW_n



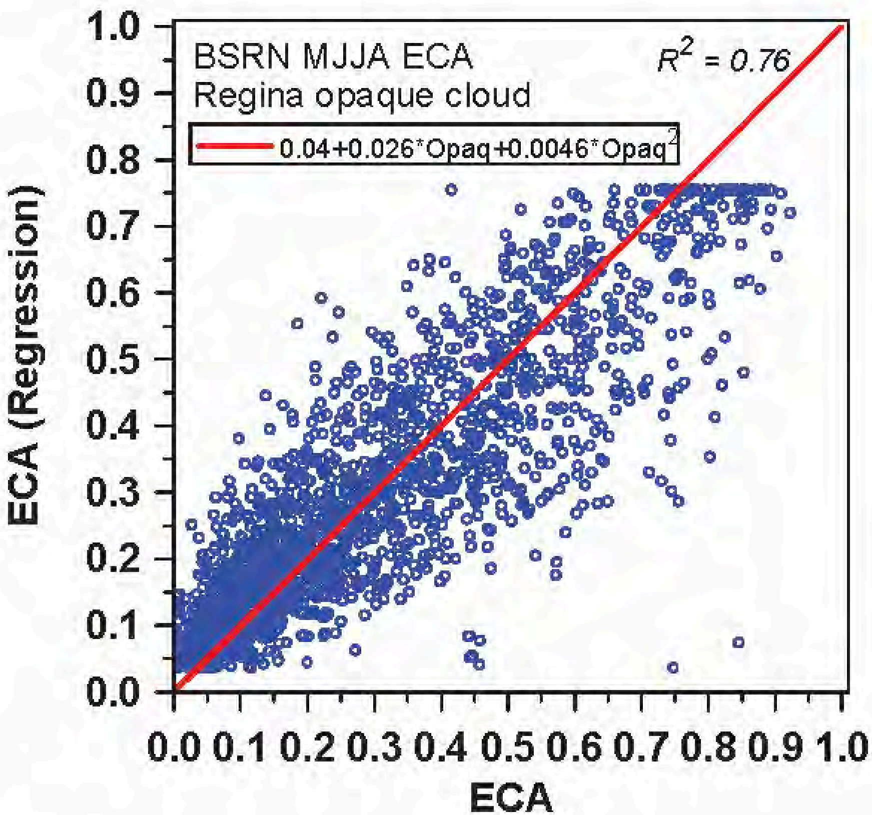
MJJA

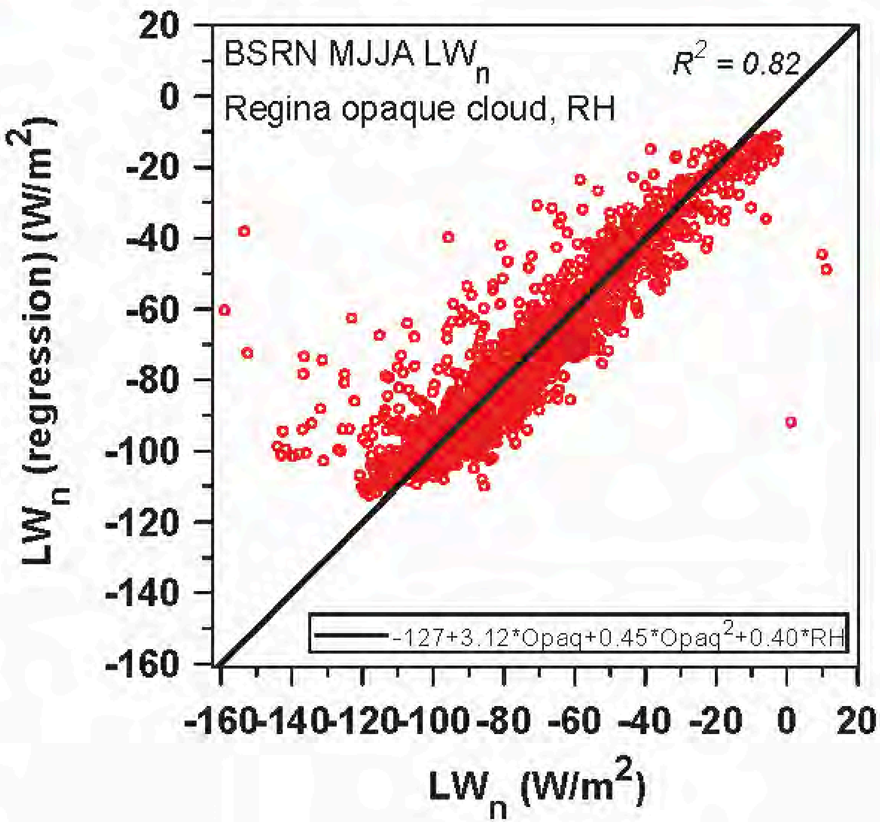
ECA = 0.04(±0.11) + 0.025(±0.003) OpaqueCloud + 0.0047(±0.0003) OpaqueCloud² ***(R^2=0.75)***

LW_n = -103(±9) + 3.5(±0.3)OpaqueCloud + 0.53(±0.03)OpaqueCloud² ***(R^2=0.88)***

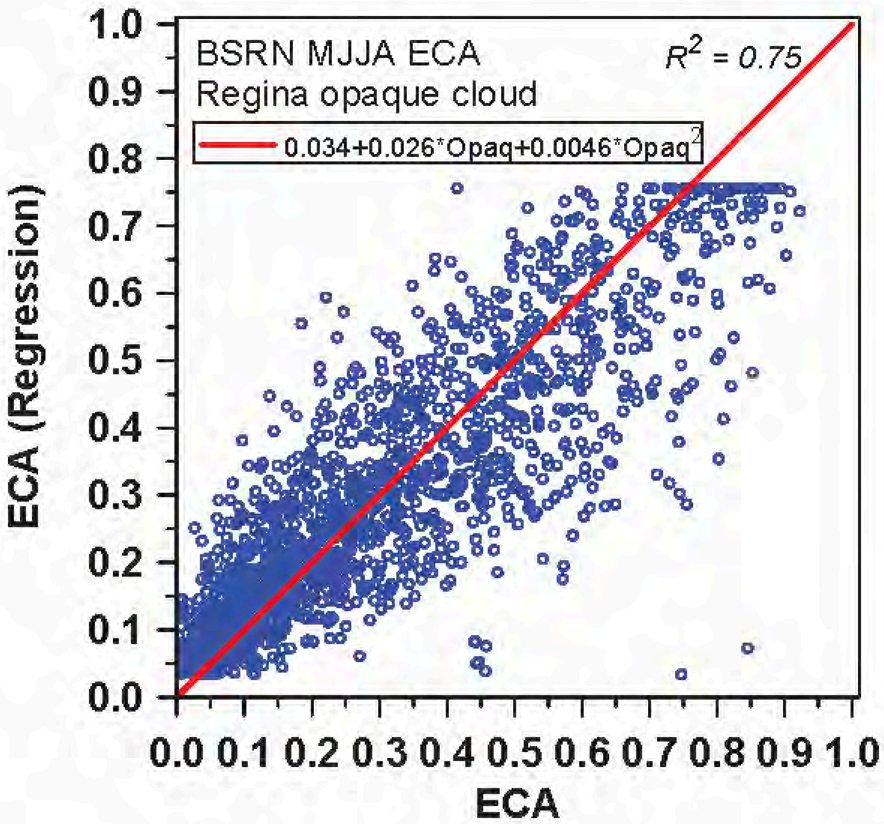
LW_n = -131(±7) + 3.1(±0.2)OpaqueCloud + 0.43(±0.02)OpaqueCloud² + 0.48(±0.02)RH_m ***(R^2=0.92)***

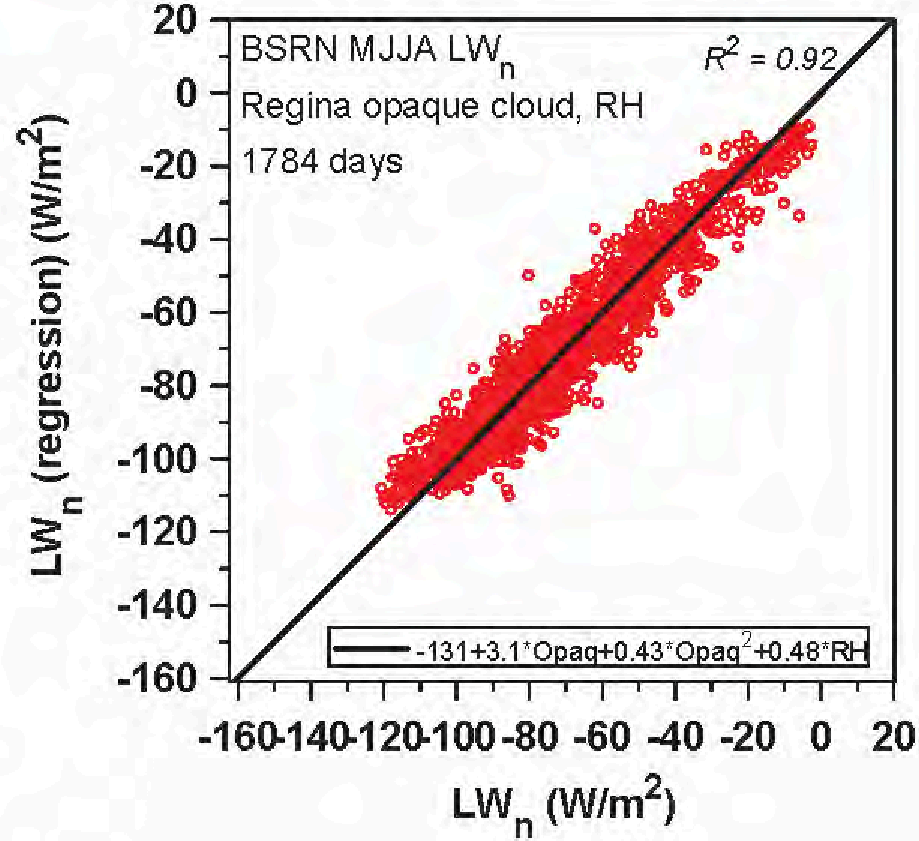
Regression fits to Opaque Cloud



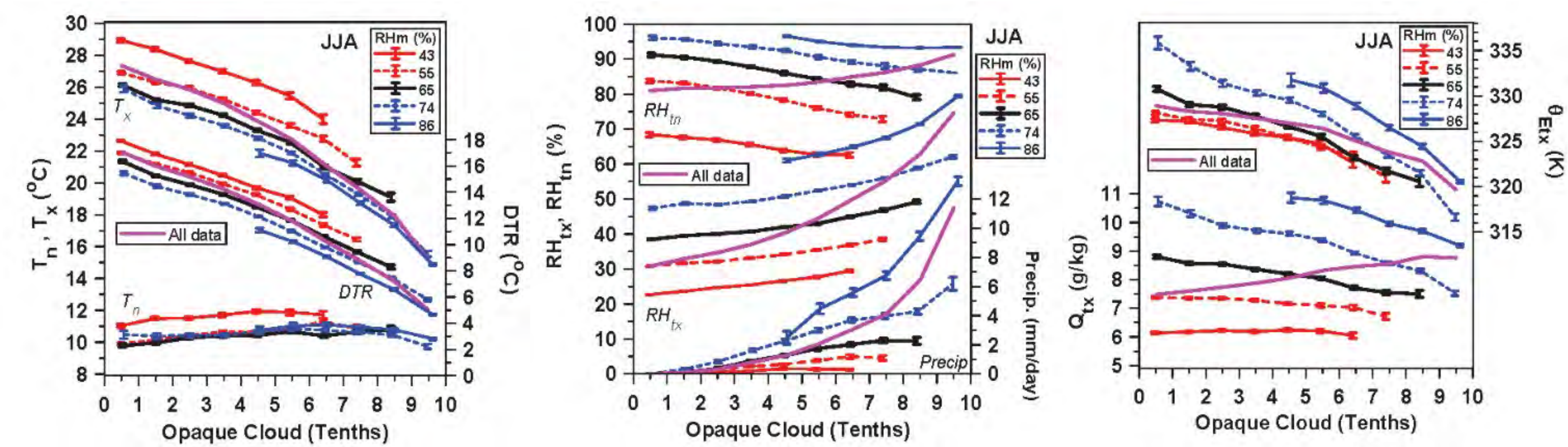


Fits to Opaque Cloud



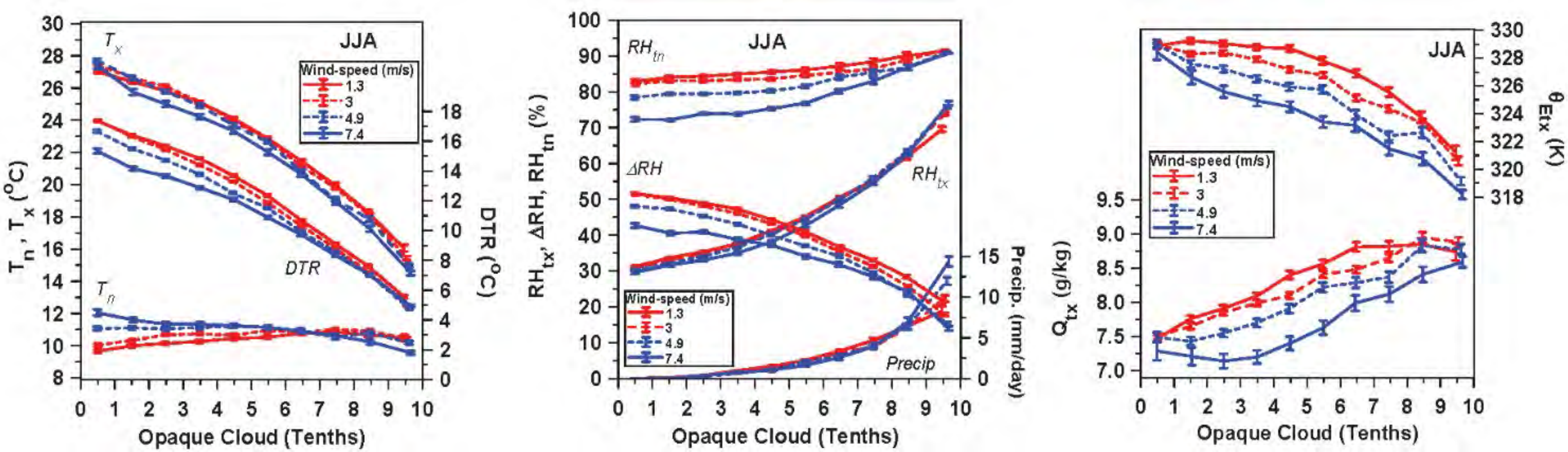


Partition: Cloud + RH



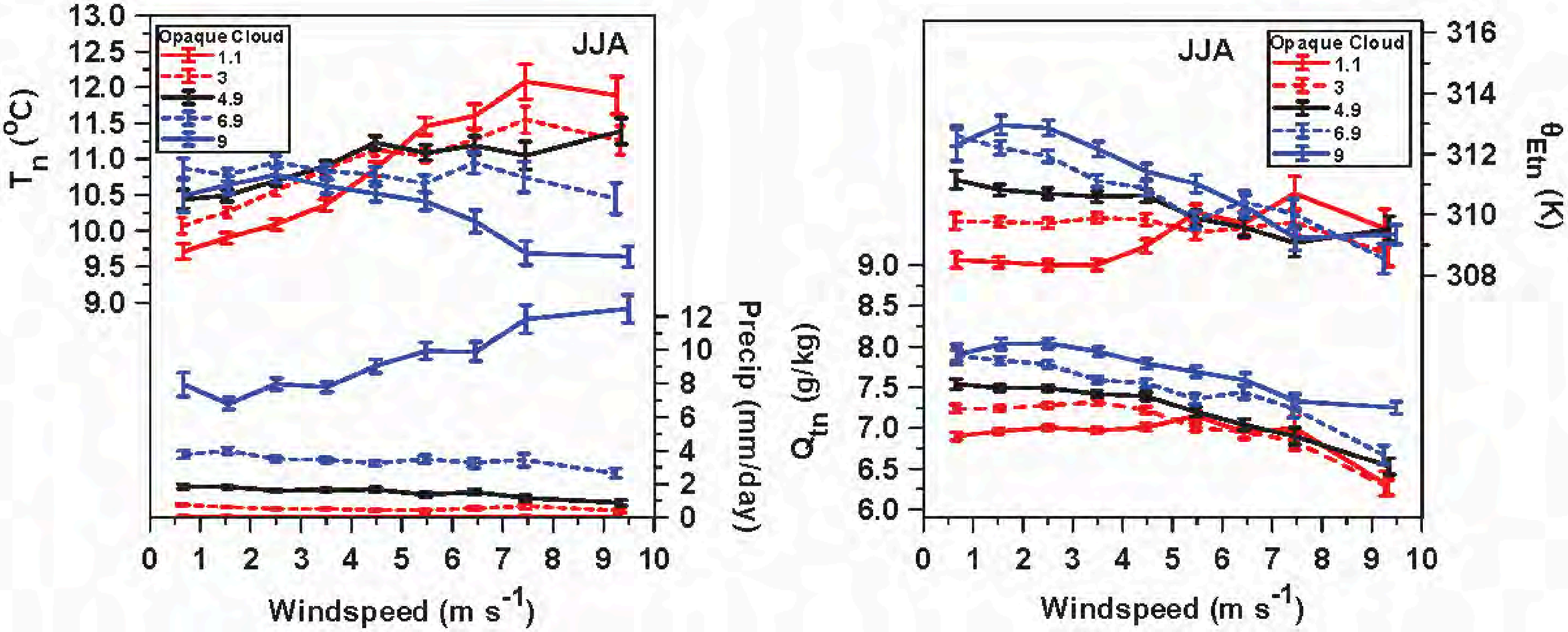
- **11 stations: 53600 days in June, July, August**
- **Low RH: warmer T_x and DTR; low precip.**
- **High RH: higher θ_{Etx}**

Partition: Cloud + Windspeed



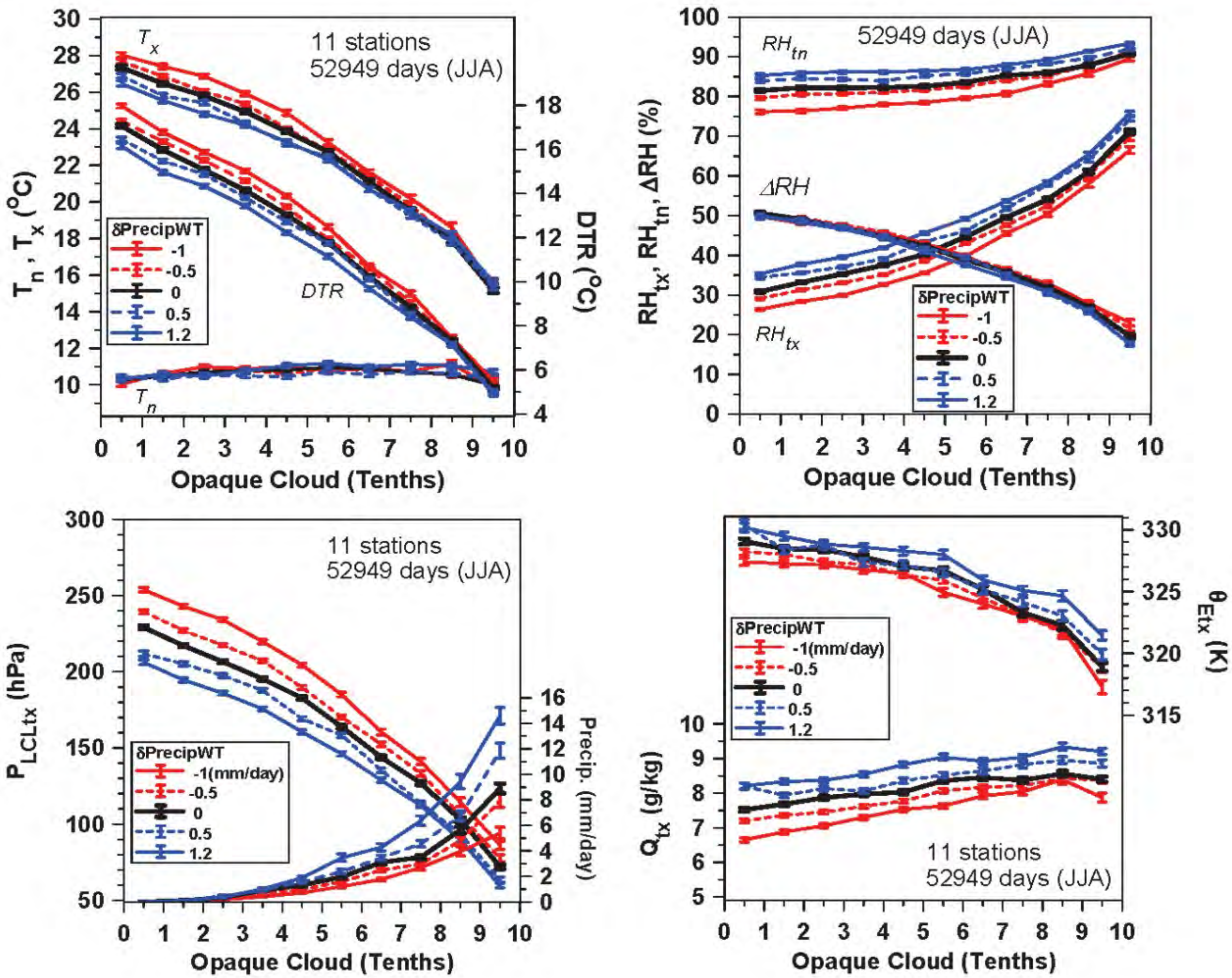
- 11 stations: 53600 days in June, July, August
- Low wind: lower T_n, higher DTR, RH_{tn}
- Low wind: higher Q_{tx}, θ_{Etx}

T_n: Windspeed and Cloud

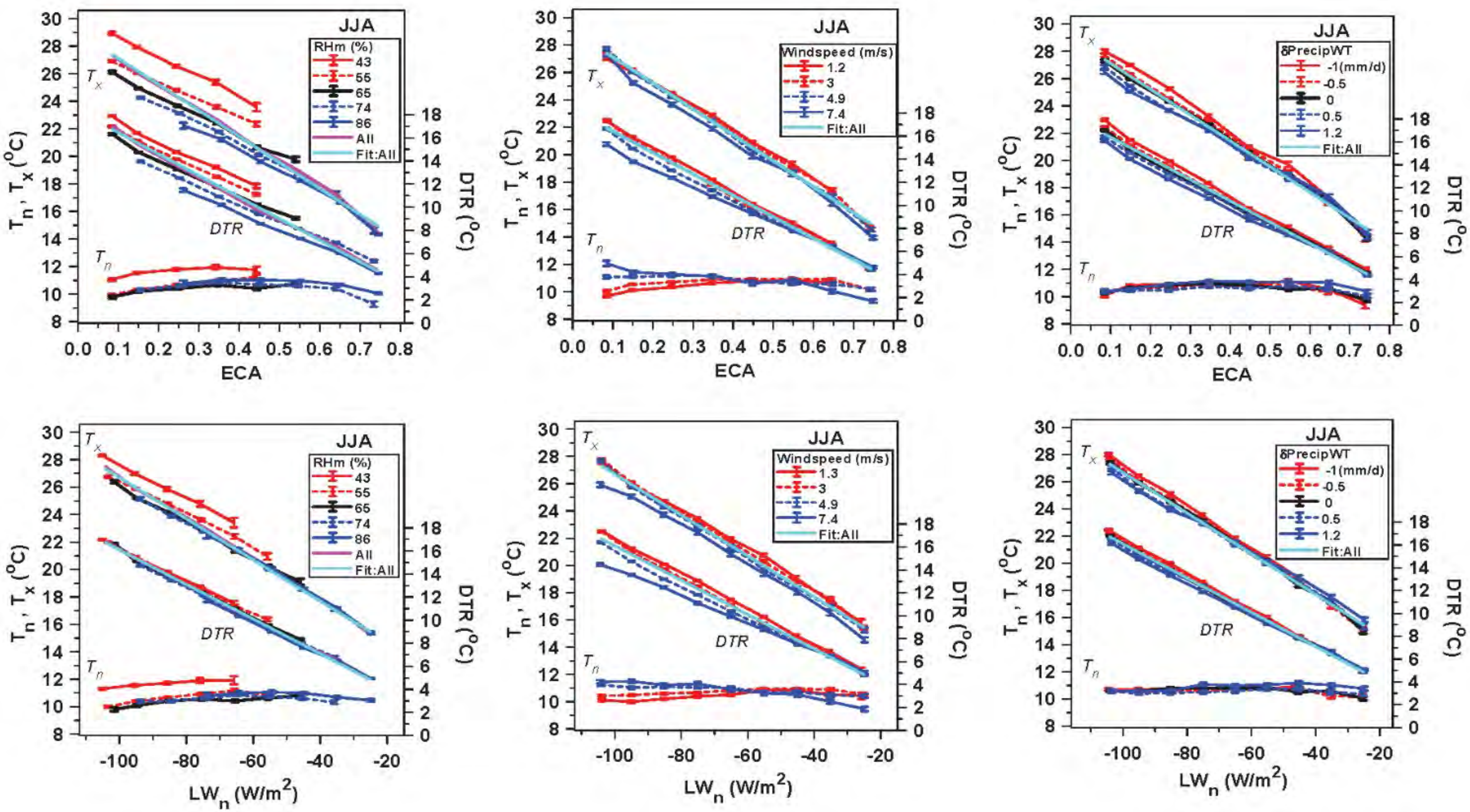


Slope of T_n with wind/cloud/LW_n

Partition: Cloud + δPrecipWT



Remap to ECA and LW_n

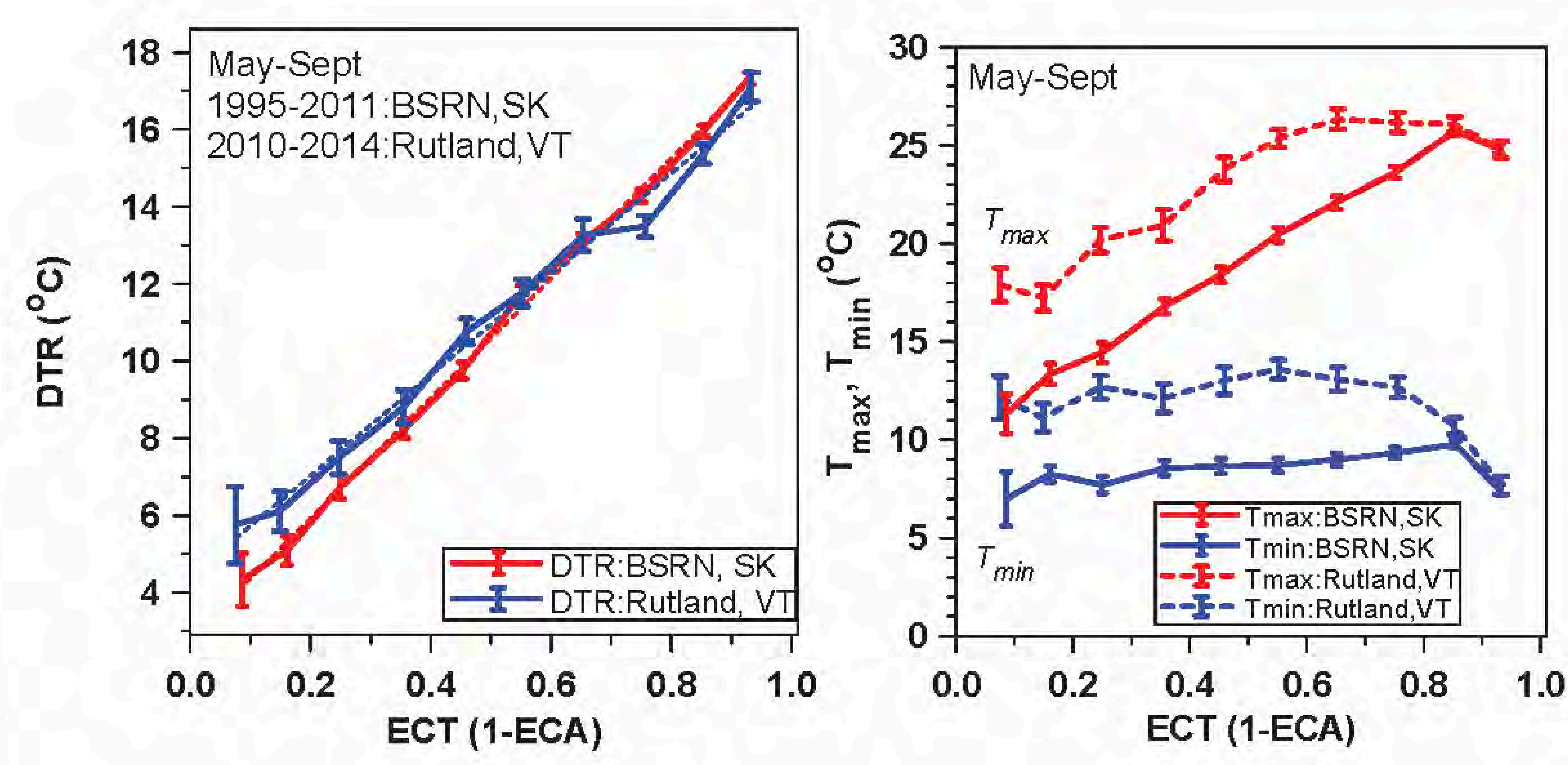


Summary - 3

- **Revisit daily timescale**
  - **BSRN data for SW_{dn}, LW_{dn}**
  - **ERA-Interim for clear-sky fluxes**
  - **ECA, LW_n coupling to DTR and ΔRH**
- **Stratify by cloud and**
  - **RH**
  - **Wind**
  - **Precipitation anomalies**

- ***Ongoing.. Work in progress***

DTR linear on ECT (1-ECA)



- **Prairie: Bratt's Lake (BSRN data)**
- **Solar array: Rutland VT** (Licor: LI-200SA)