Understanding land-atmosphere coupling

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Earth's climate sustains life

- **Burning fossil fuels is increasing greenhouse gases**
- **Climate is warming: ice is melting, extreme weather is increasing**
- **Water plays crucial amplifying role**

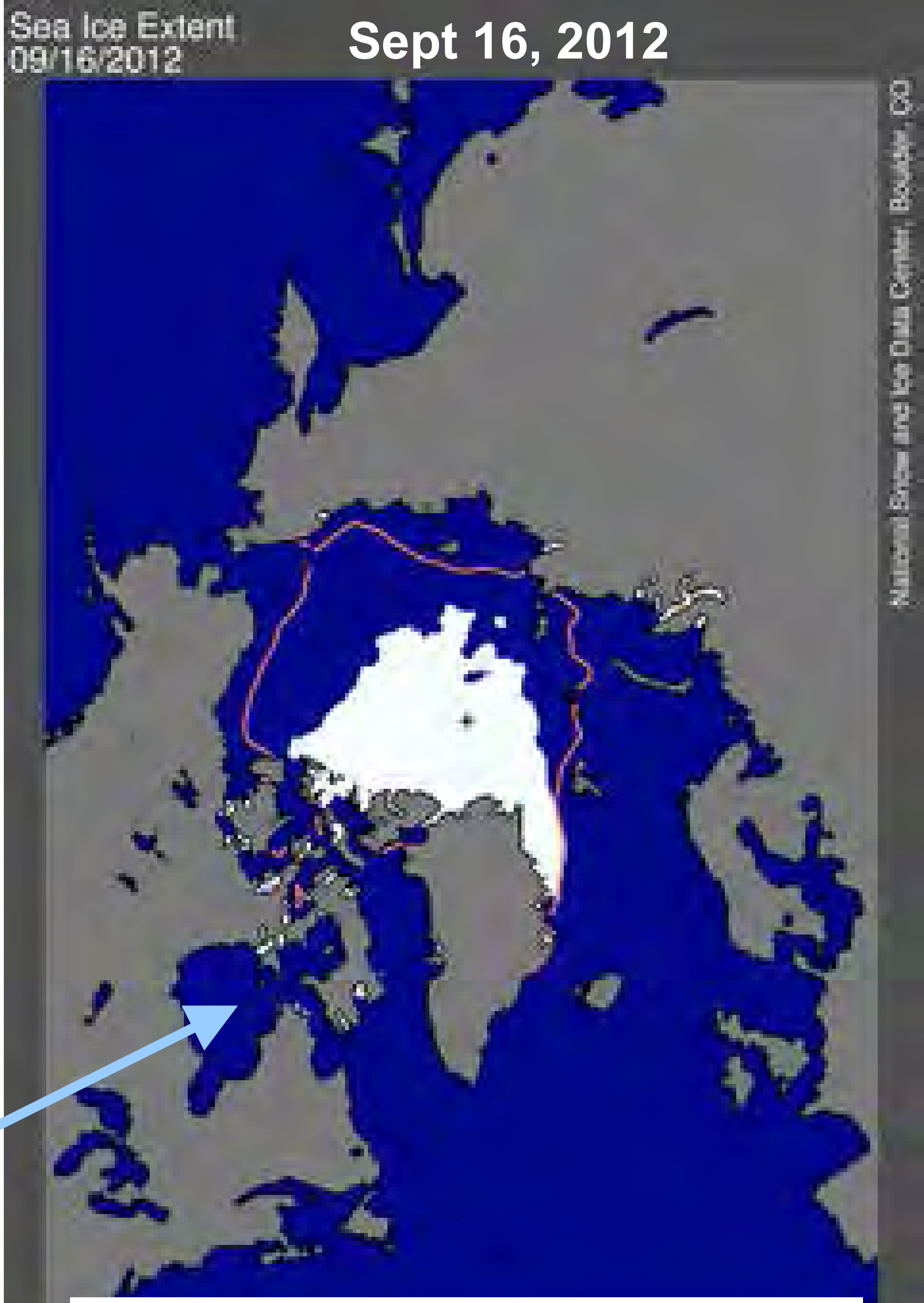
January 2, 2012: NASA

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

- **Half the Arctic Sea Ice Melted in 2012**
- **Open water in Oct. Nov. gives warmer Fall in Northeast**

> - ***Positive feedbacks:***
> - ***Less ice, less reflection of sunlight***
> - ***More evaporation, larger vapor greenhouse effect***
> - ***Same feedbacks as in our winters***

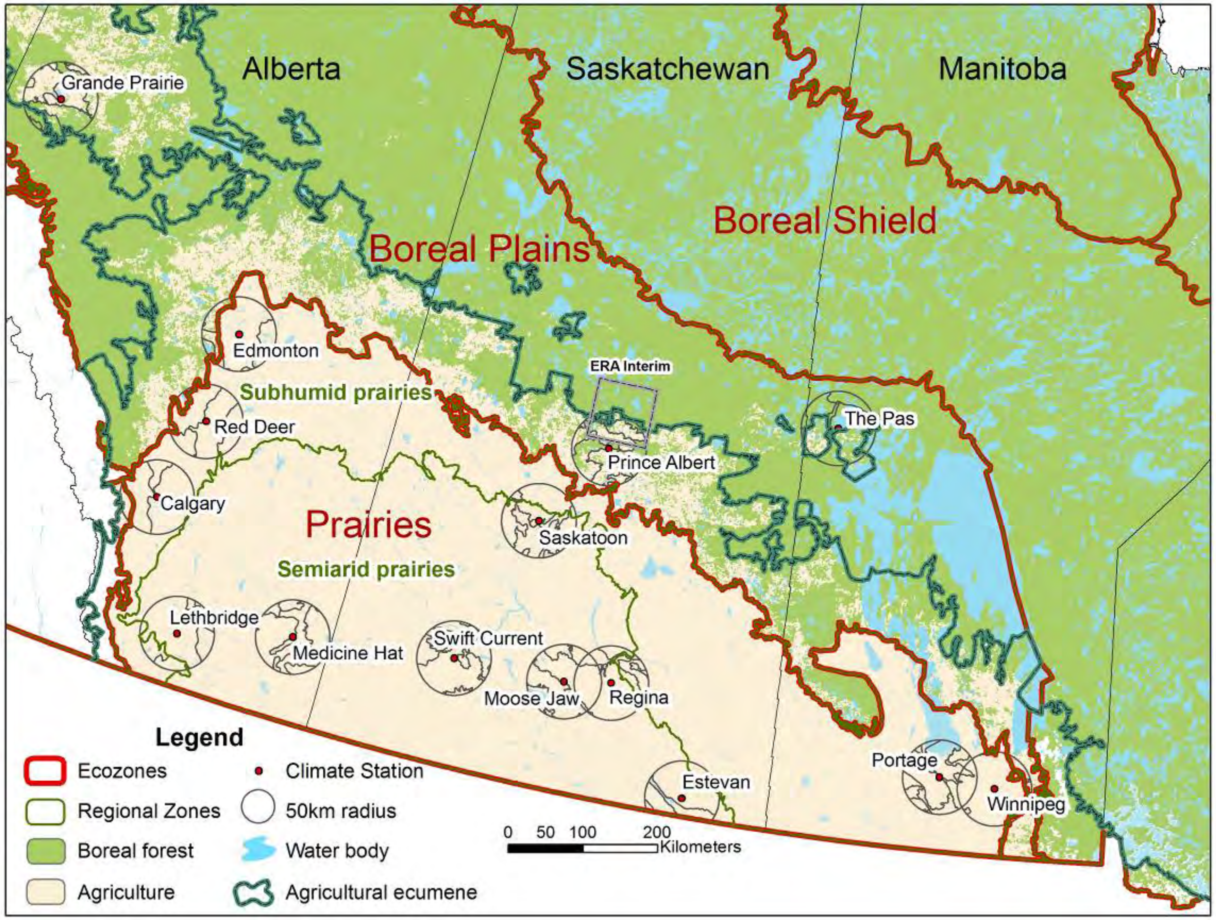


http://nsidc.org/arcticseaicenews/

Mysterious Ways of Science

- **2012 Ray Desjardins at Agriculture-Canada asked for my help**
  - **I said "Yes"**
- **Sent me all the Prairie data: preprocessed**
  - **Which is not readily available!**
  - **I found it contain cloud observations:**
  - ***That I did not know existed***
    - ***That give radiative flux climatology***
  - ***That transform our understanding***

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

Outline

Review of published papers (alanbetts.com)

- **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 (2014a)***

(+ many more)

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**

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

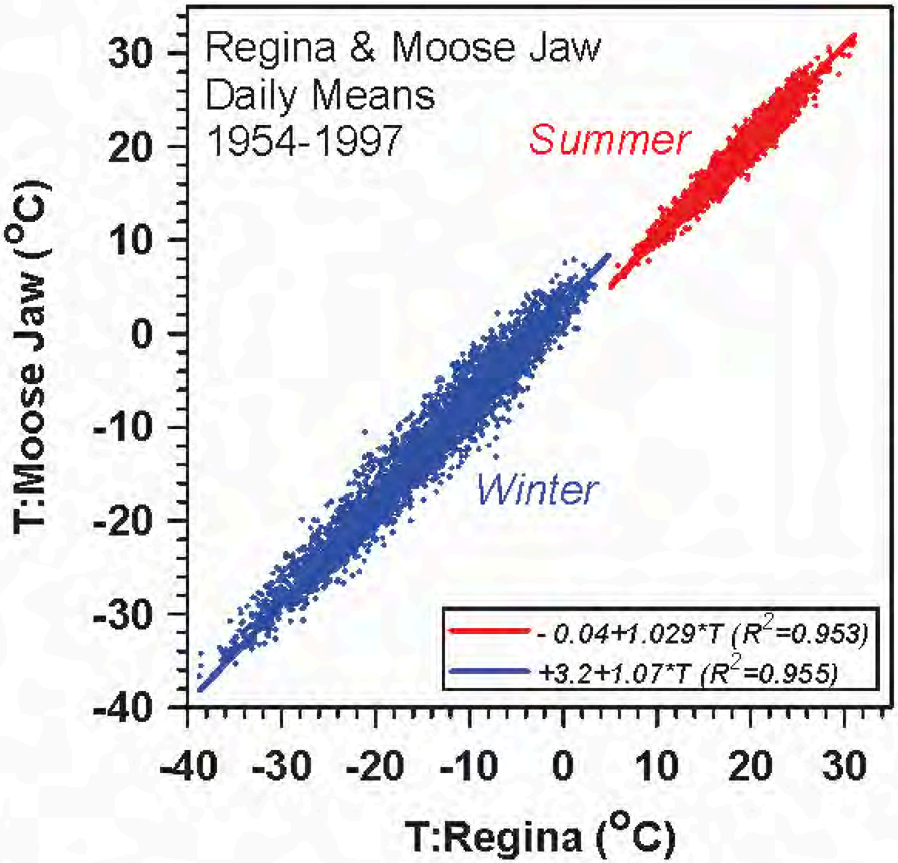
Methods: Analyze Coupled System

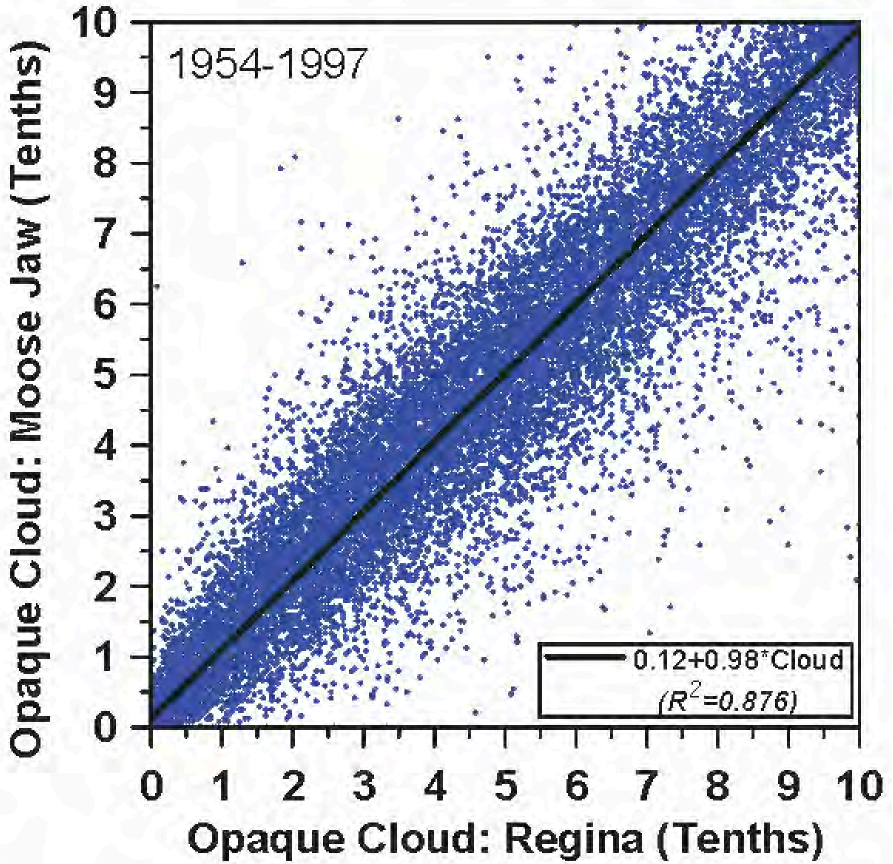
- *Seasonal diurnal climate by station/region*
- 220,000 days, excellent data (600 station-years)
  - Not freely available!
- Impact of reflective/opaque cloud on diurnal cycle in summer and winter
  - Calibrate “cloud radiative forcing”
- Change of seasonal climate with cropping
  - ‘Summerfallow’ to 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

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

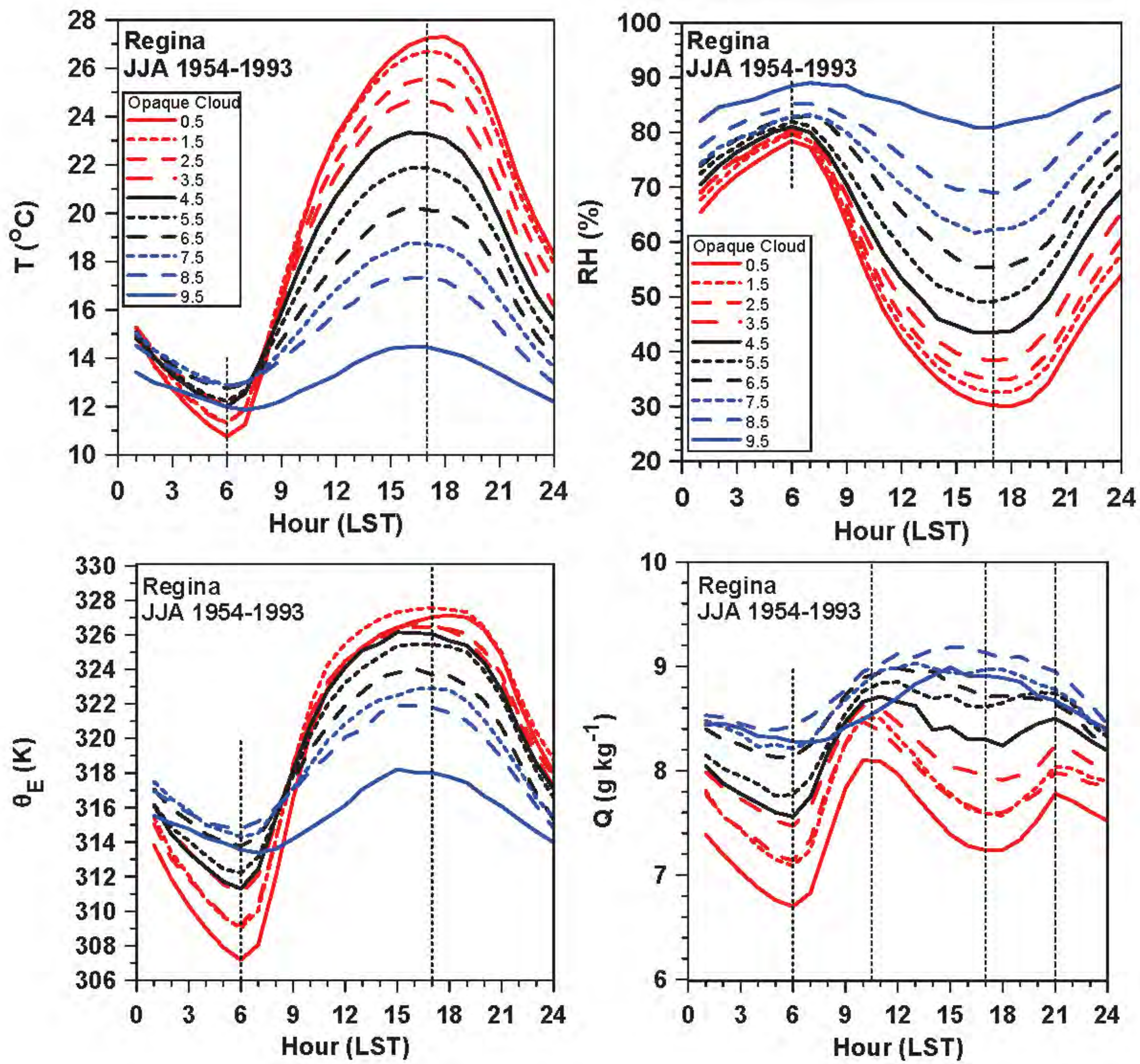




- **Temp: 1 to 1: R^2 =0.95**
- **Opaque Cloud: 1 to 1: R^2 =0.88**

Clouds to Summer Diurnal Cycle

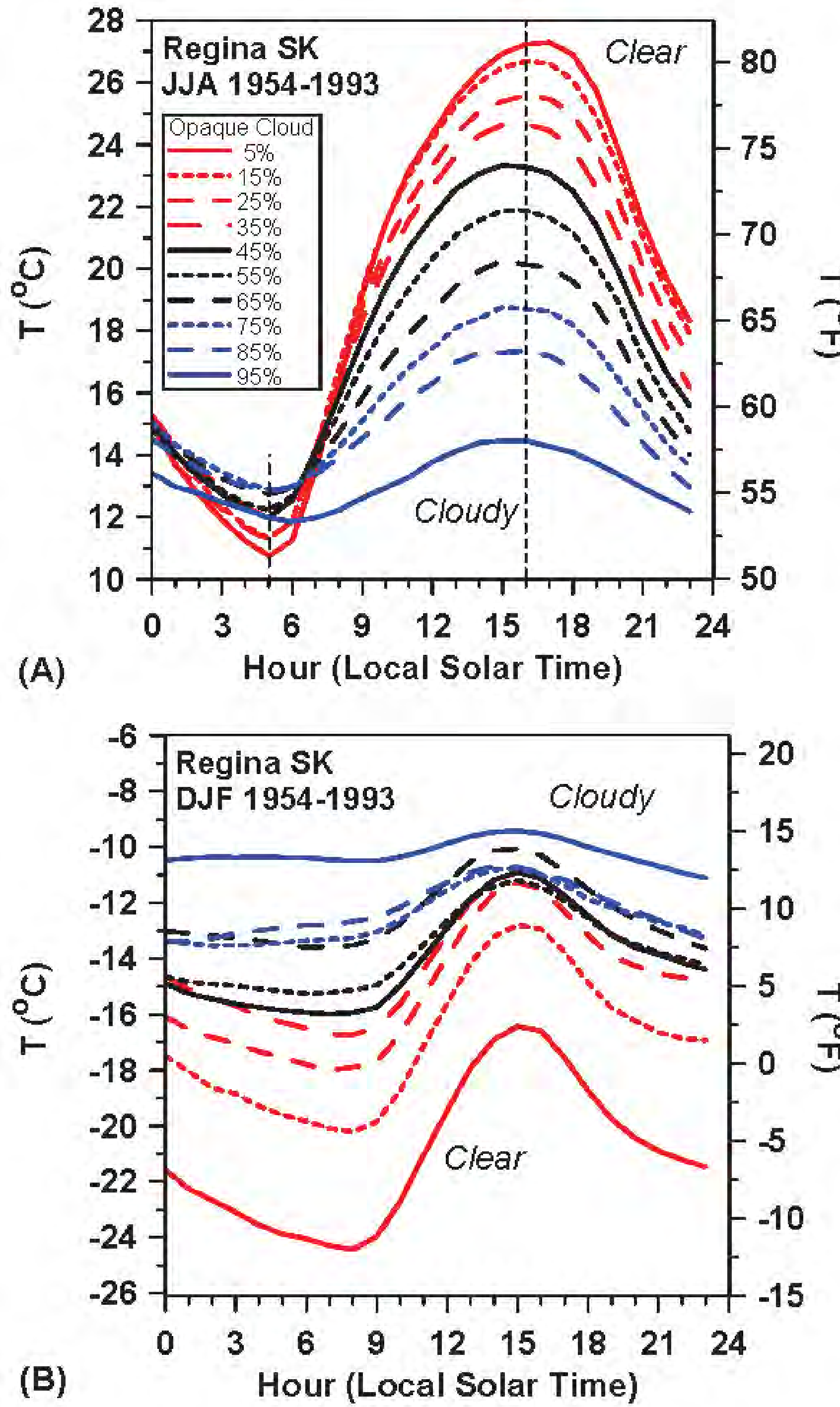
- ***40-yr climate***
- **T and RH are inverse**
- **Q has double maximum for BL transitions**
- **θ_E flatter**
- ***Overcast (rain) only outlier***



Cloud Impacts

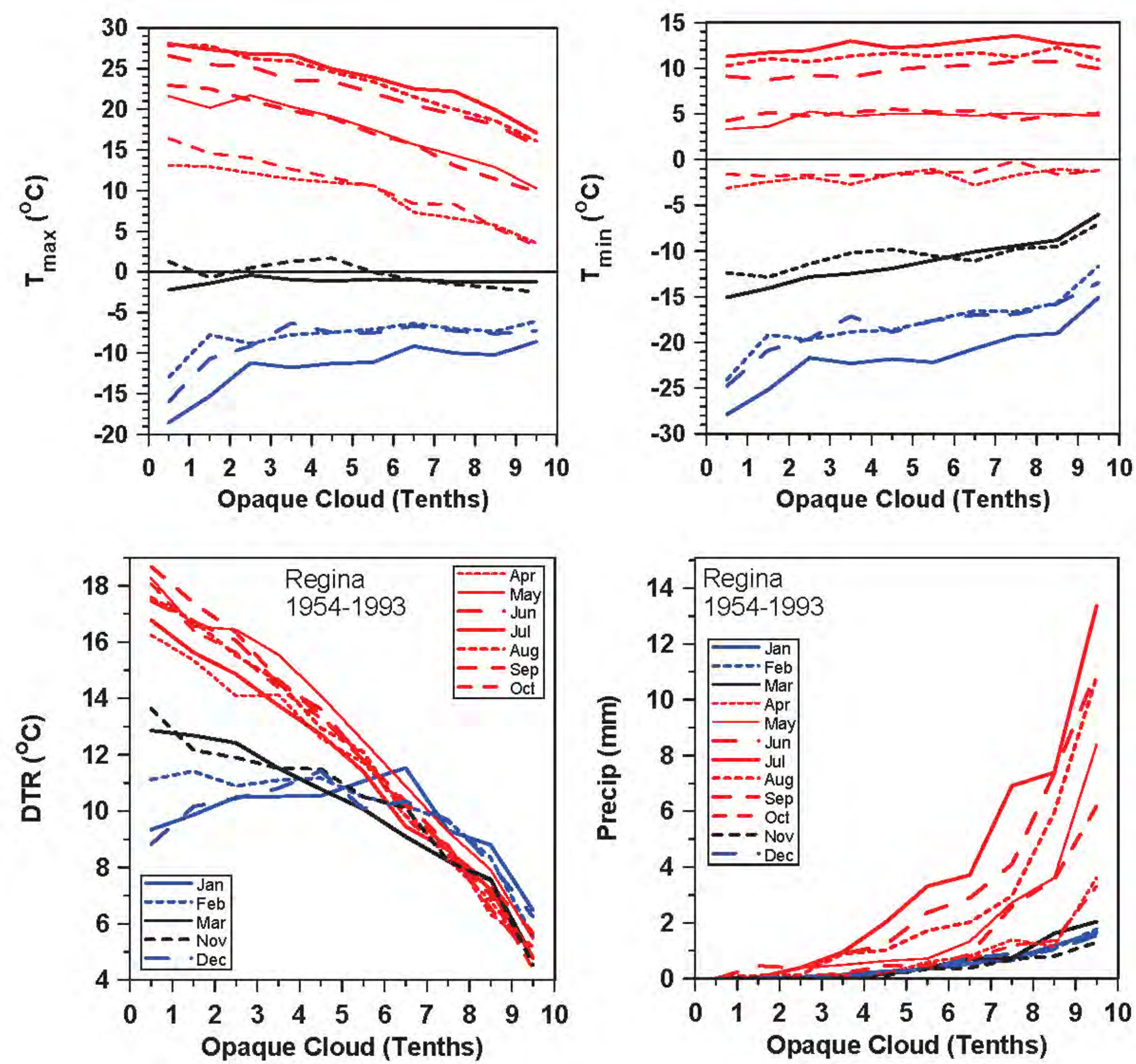
- **Summer: Clouds reflect sunlight**
  - **no cloud, hot days; only slightly cooler at night**
- **Winter: Clouds are greenhouse**
  - **snow reflects low sun**
  - **clear & dry sky, cold days, very cold nights**
- ***Fast transition with snow in 5 days***

Betts et al. 2013



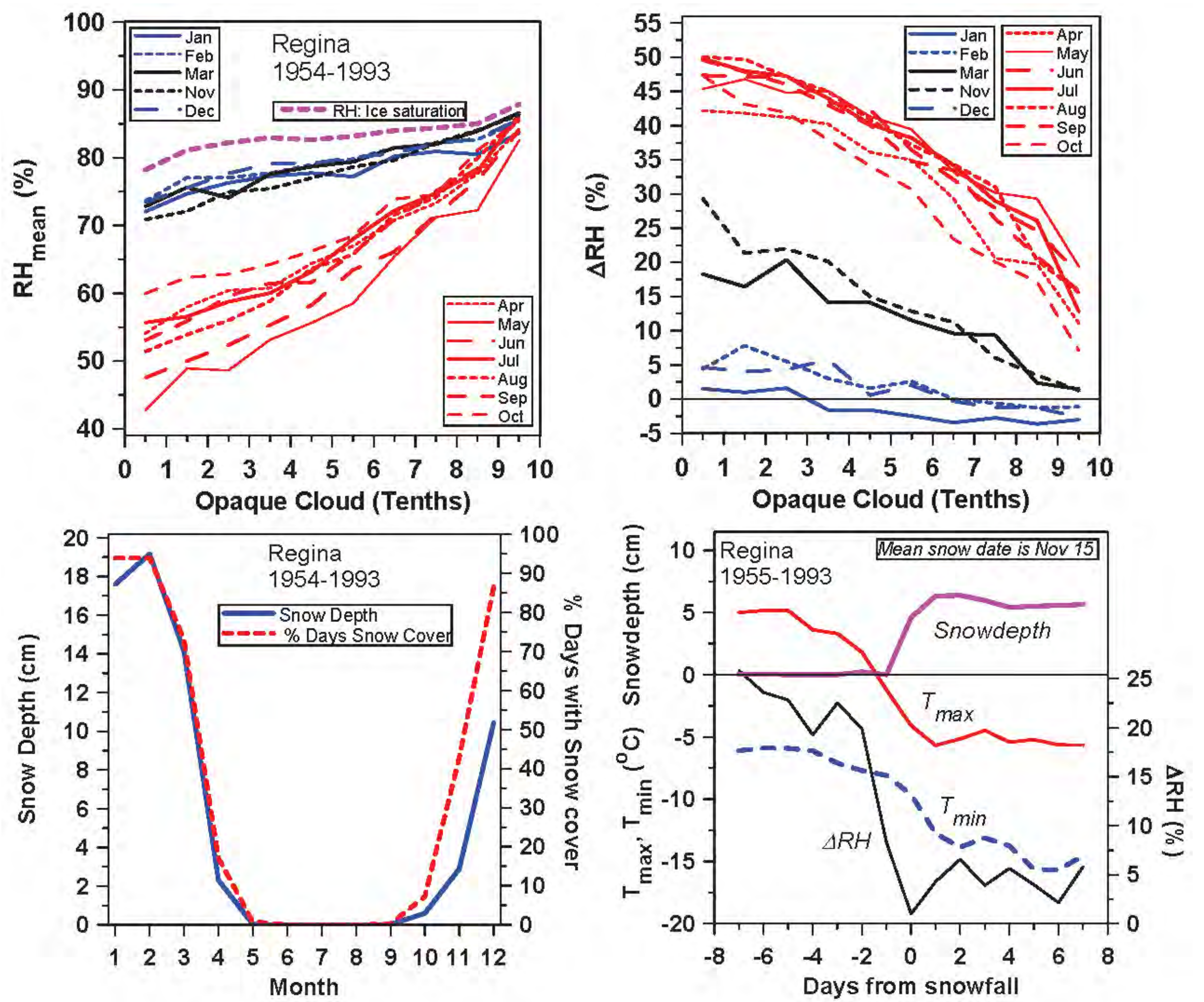
Annual Cycle: T_{max},T_{min}, DTR, Precip

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

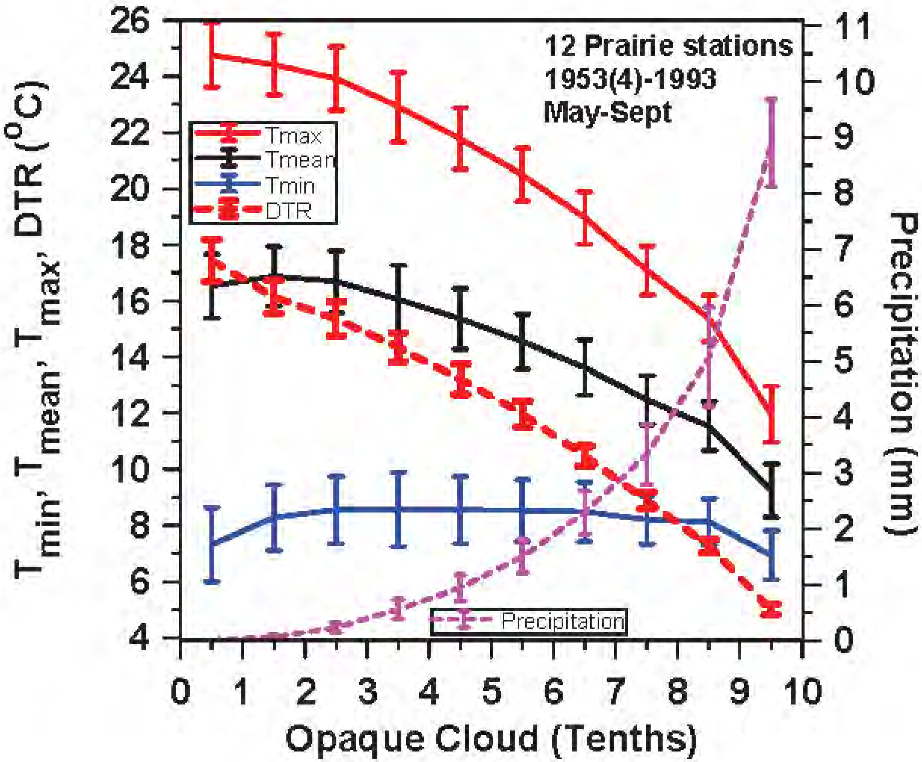


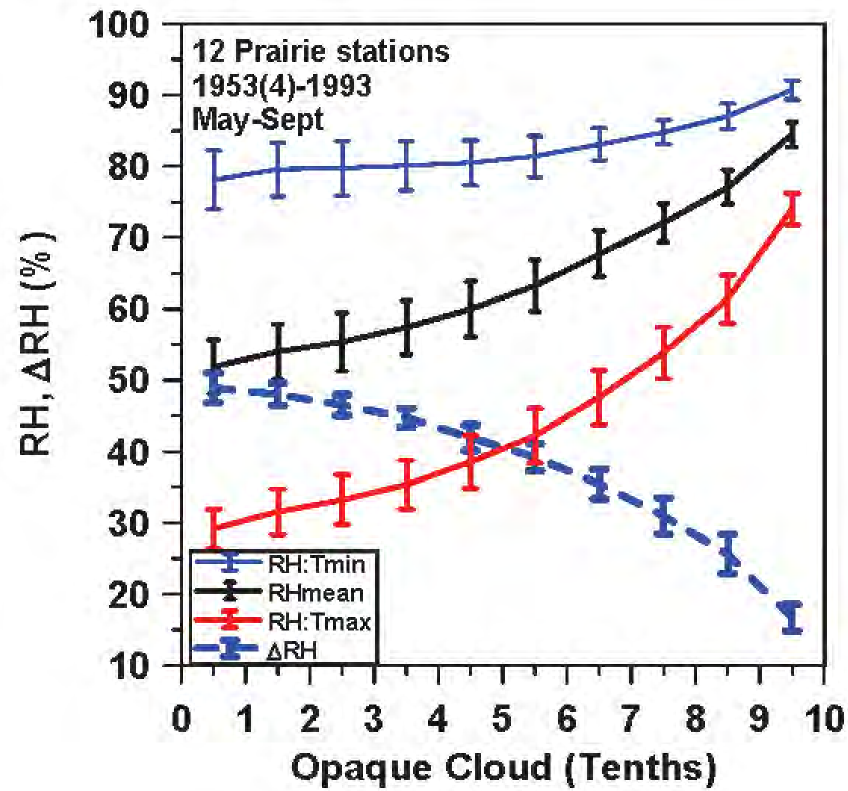
Annual Cycle: RH and ΔRH

- **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

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

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

Define Effective Cloud Albedo (reflection)

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

  Clear sky

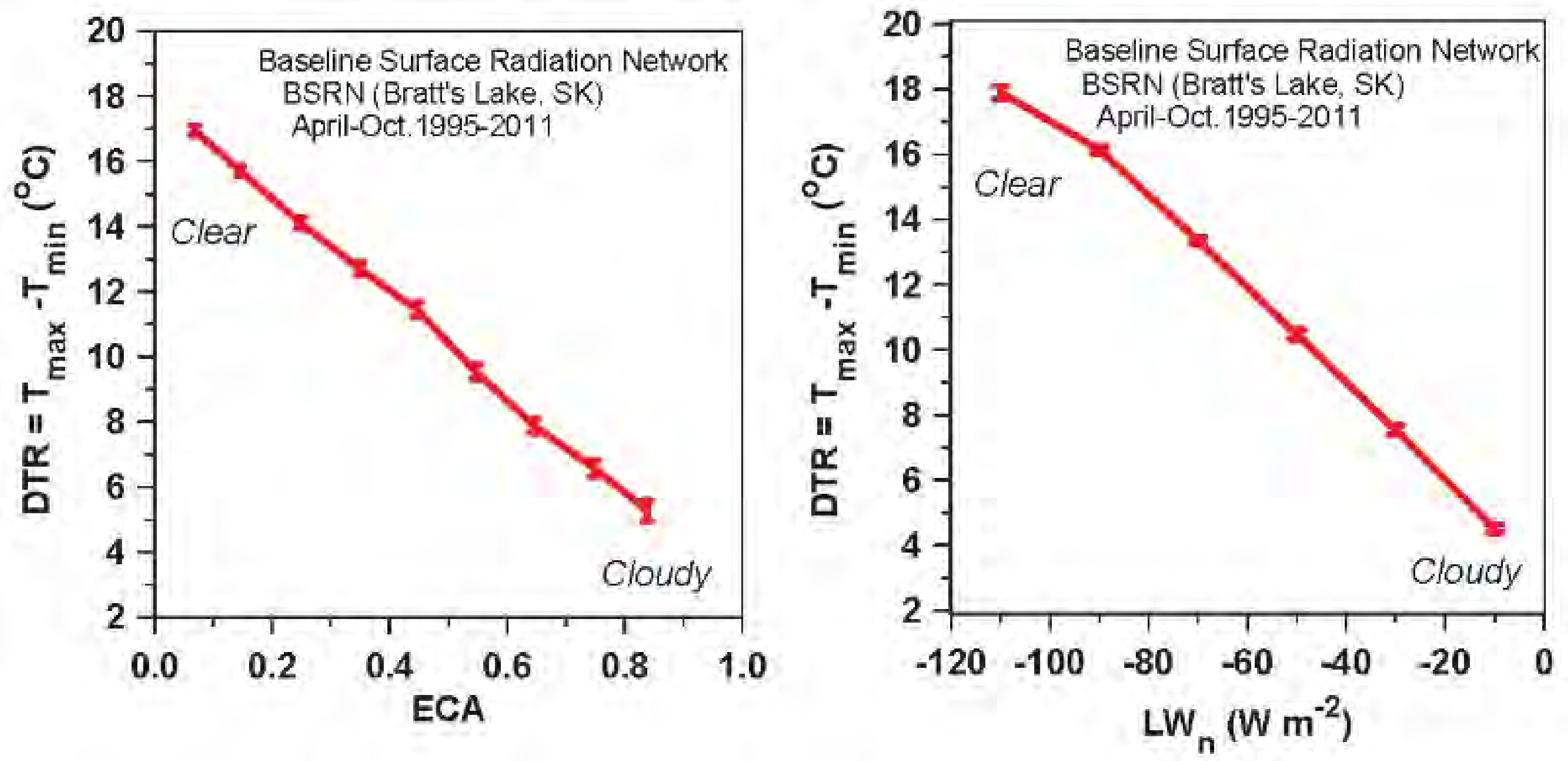
- $SW_{net} = (1 - \alpha_s)(1 - ECA)\ SW_{dn}(clear)$

  Reflected by surface, clouds

  MODIS Calibrate Opaque Cloud data

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**

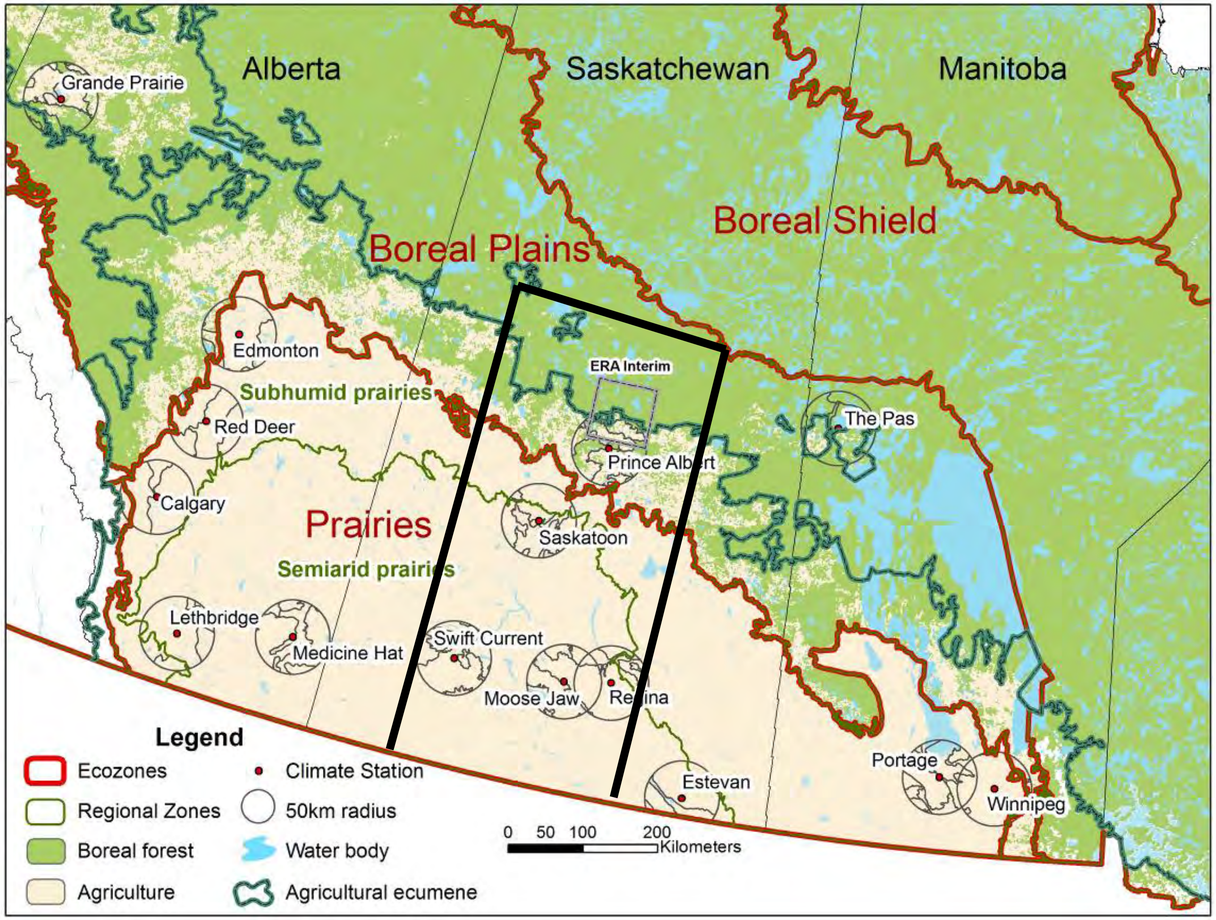
Impact of Snow on Climate

"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

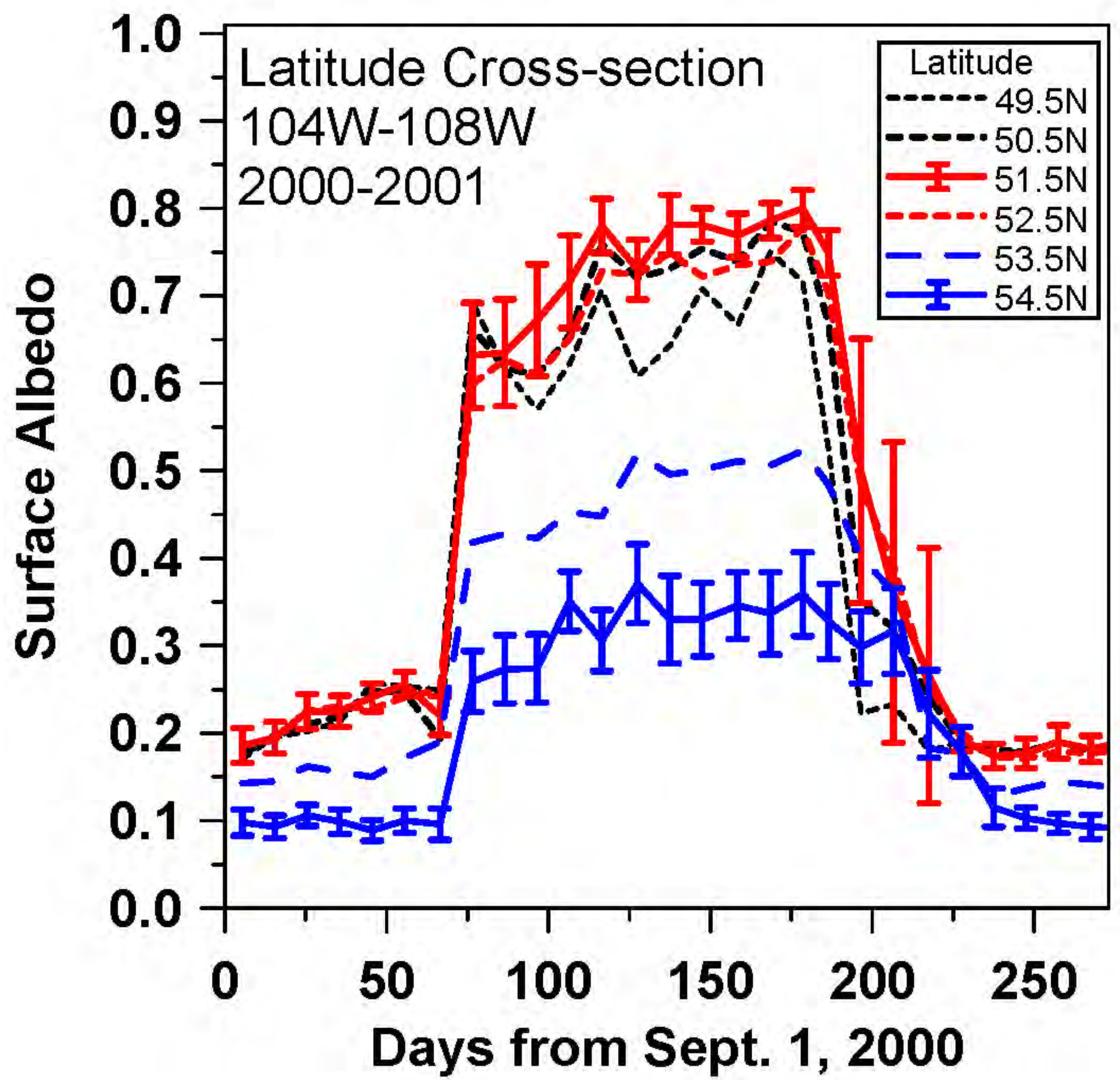


- Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})
- Daily precipitation and snowdepth
- Ecodistrict crop data since 1955
- Albedo data (MODIS/CCRS: 250m, after 2000)

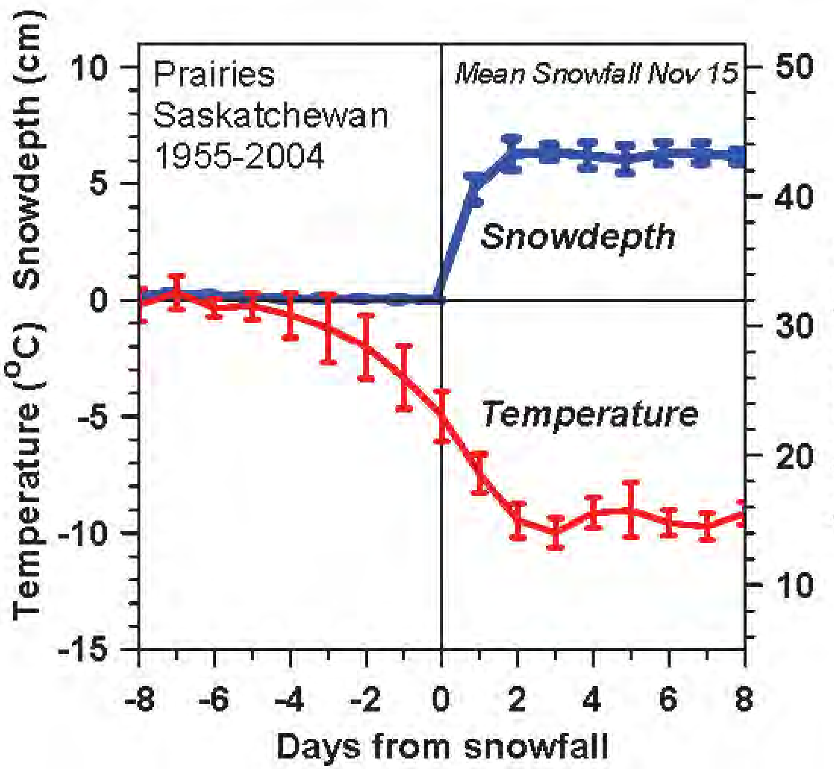
N-S Albedo through Winter

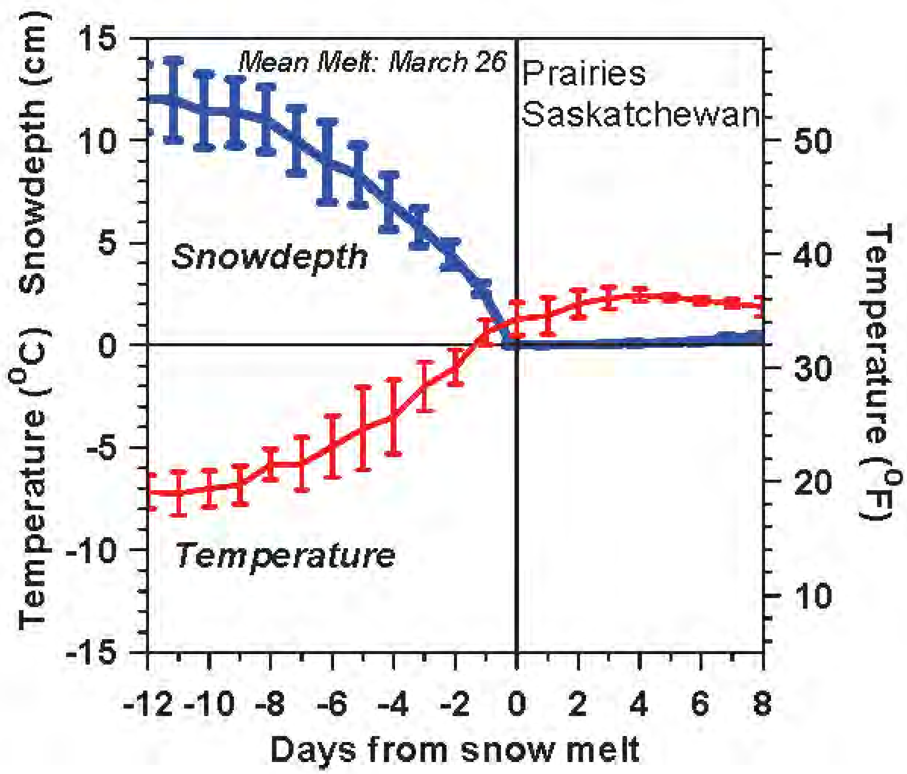
- **Prairies (SK)**
  α_s: 0.2 to 0.73
- **Boreal forest**
  α_s: 0.1 to 0.35

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



Snowfall and Snowmelt

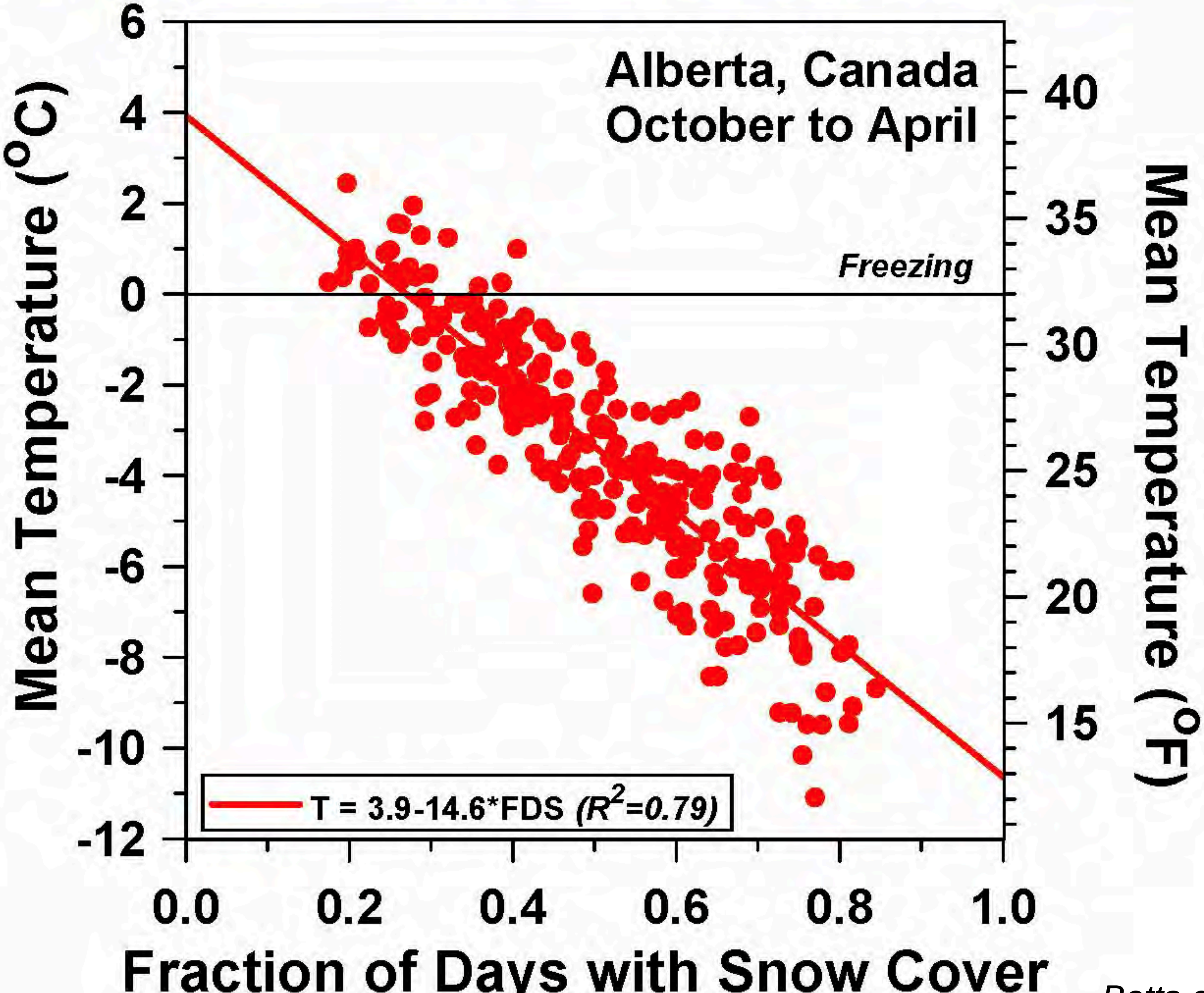




- **Temperature falls 10C (18F) with first snowfall**
- **Similar change with snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – changes 'local climate'***

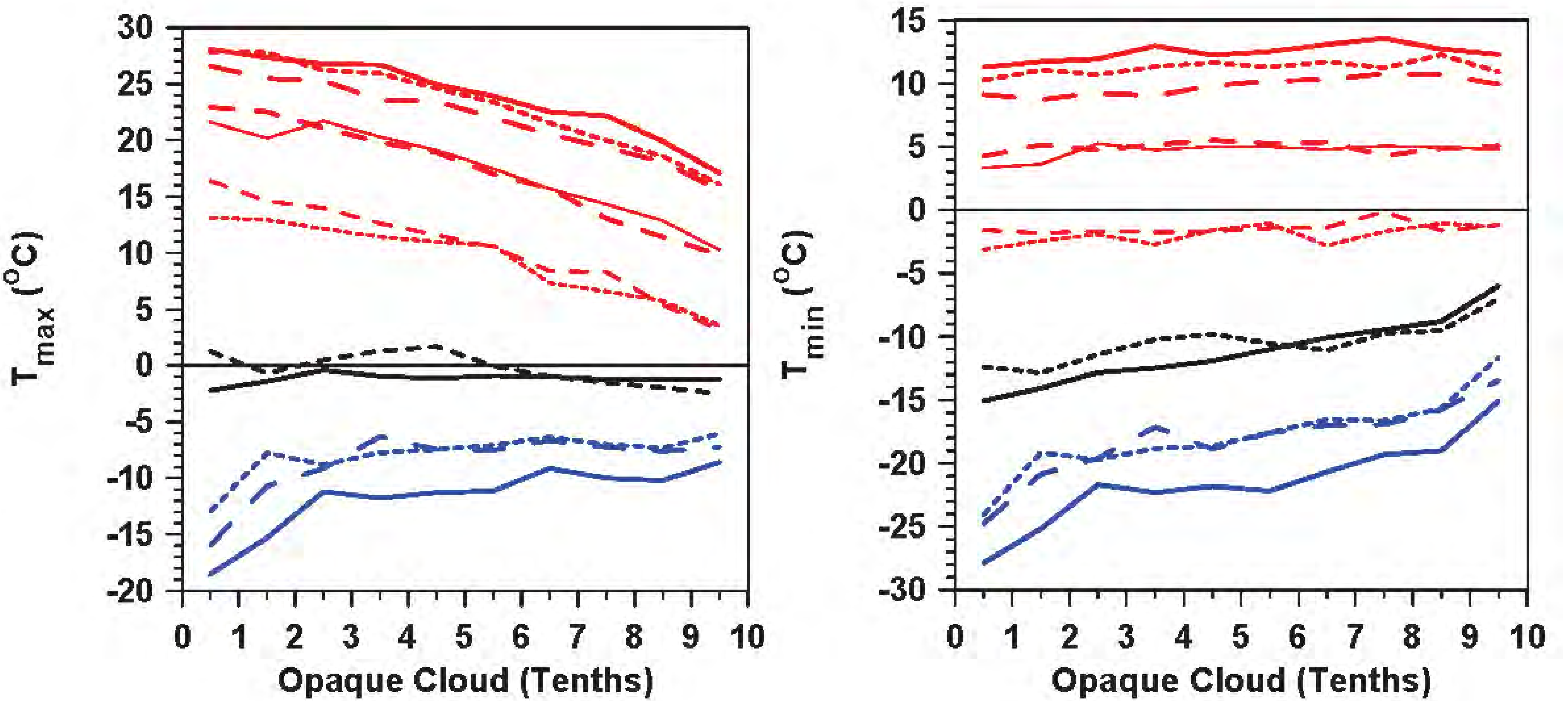
Betts et al. 2014

More snow cover - Colder temperatures



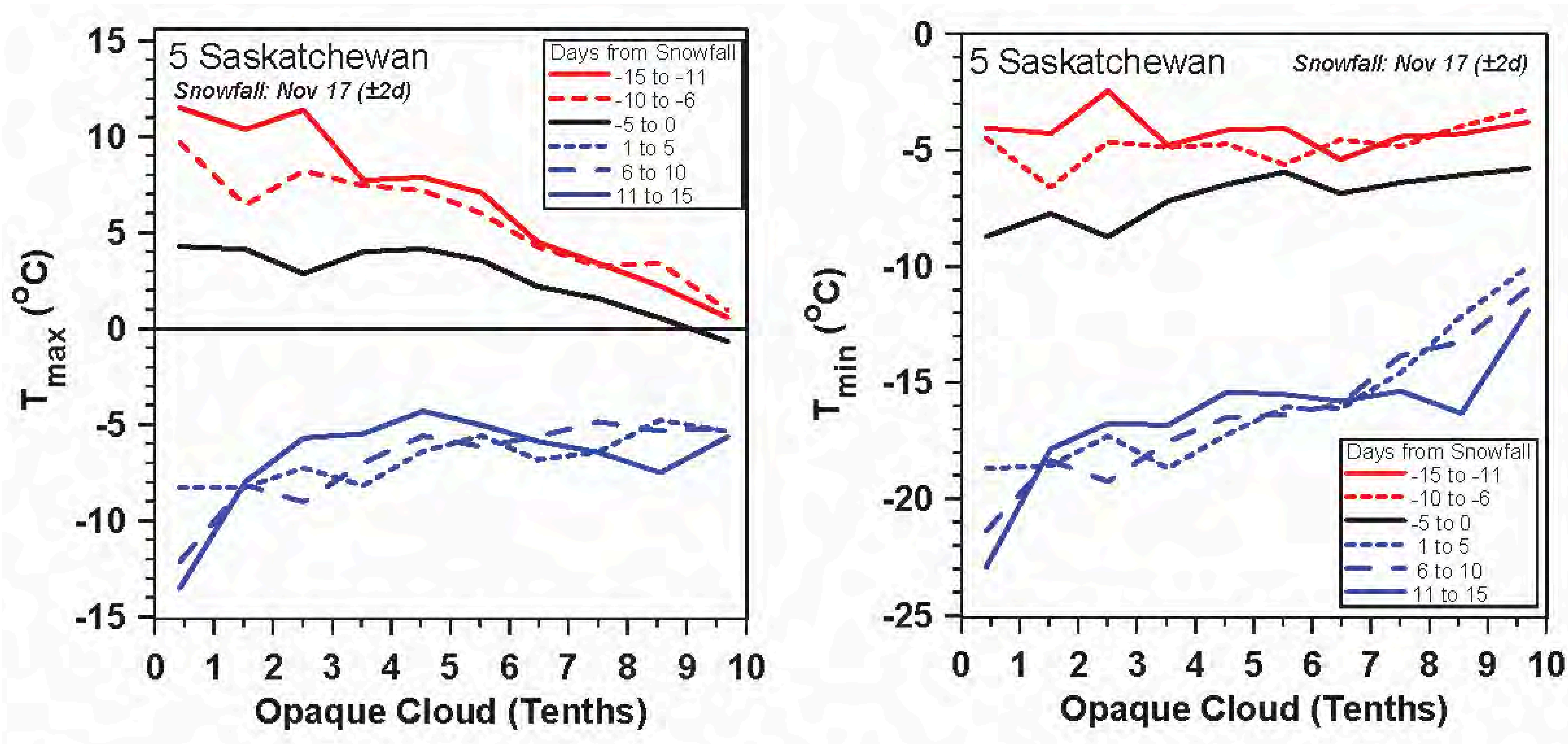
Betts et al. 2014

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



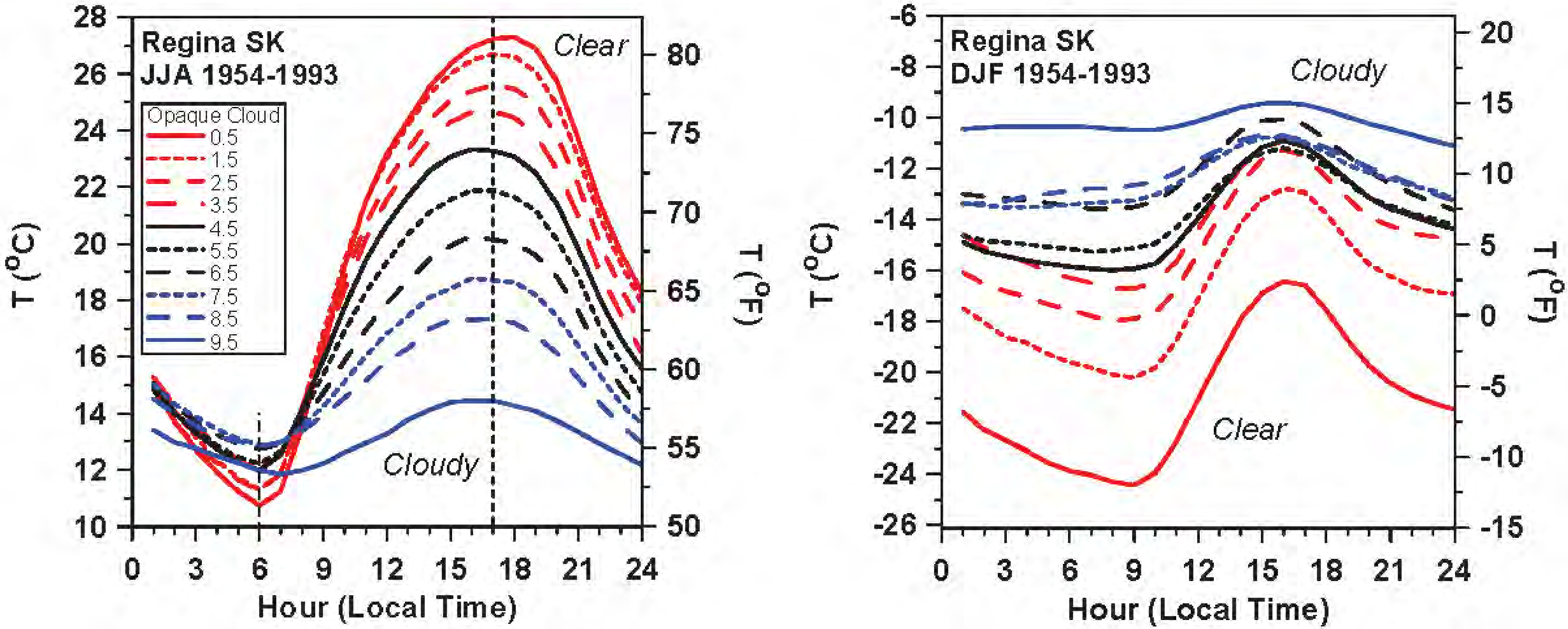
- **Warm state: April – Oct**
- **Transitions: Nov, Mar when $T_{max} \approx 0^oC$**
- **Cold state: Dec – Feb**

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

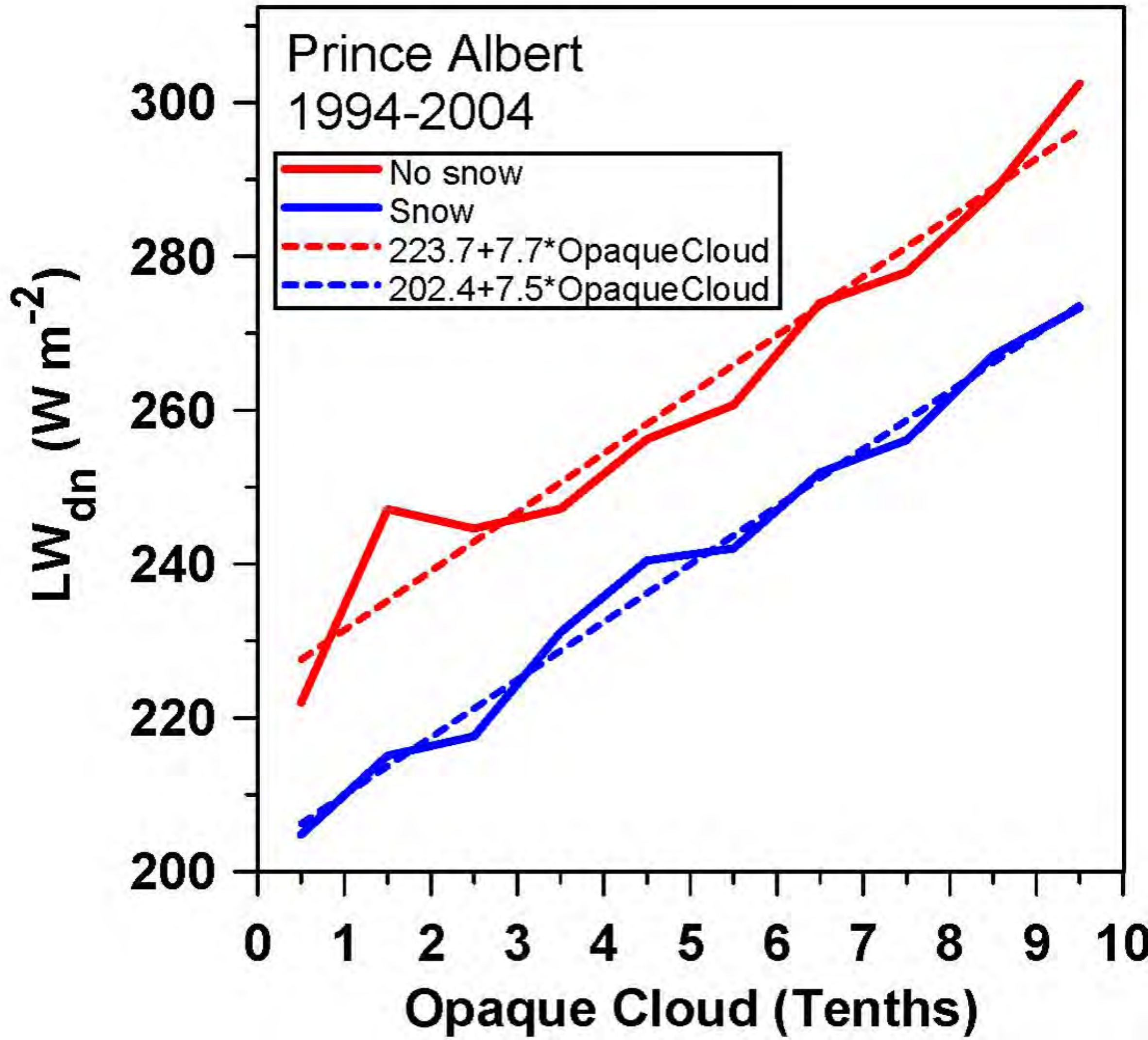


- **Summer:** **Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
  - **Convective boundary layer in daytime**
- **Winter:** **Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**
  - **Stable boundary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

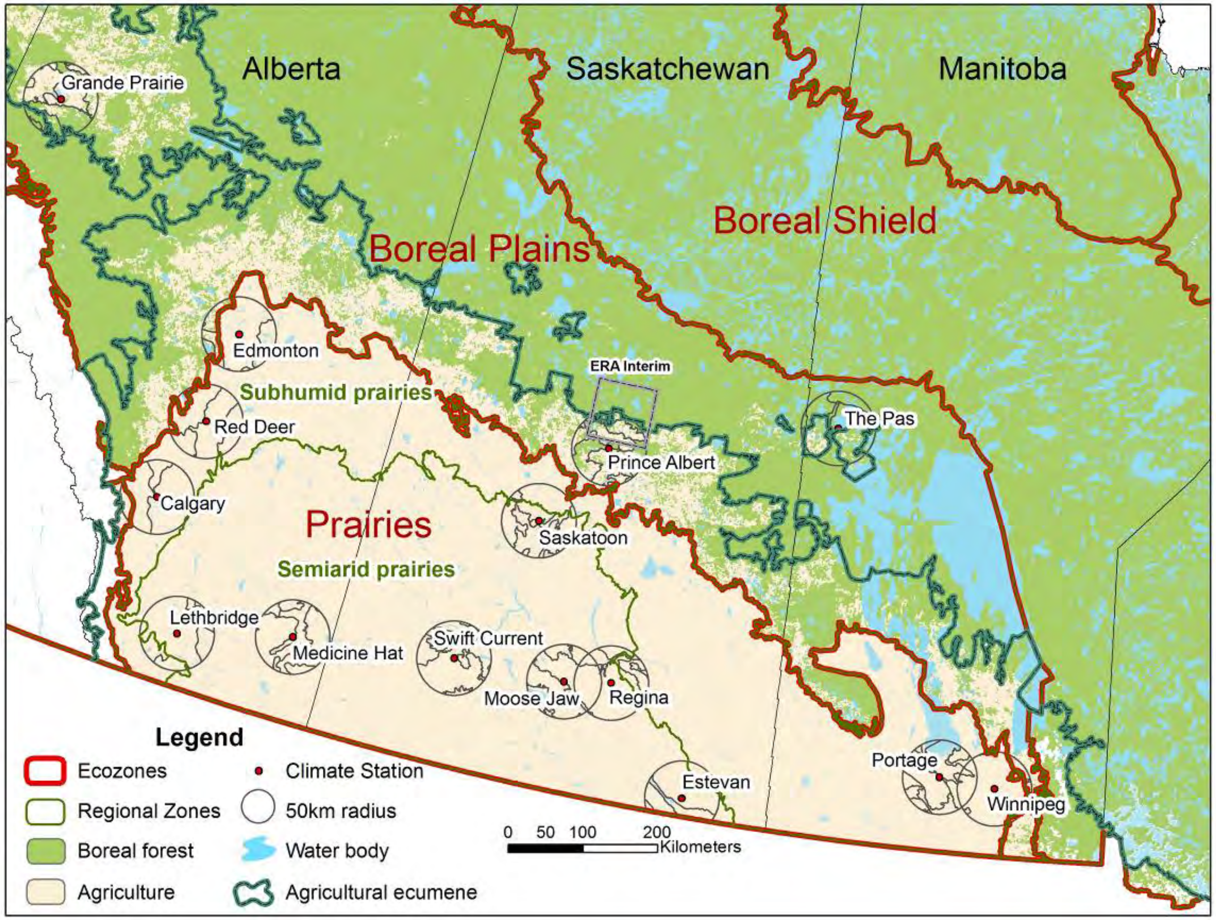
- Surface skin T falls: $\Delta T = -11K$ to balance

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

Annual crops and seasonal diurnal cycle

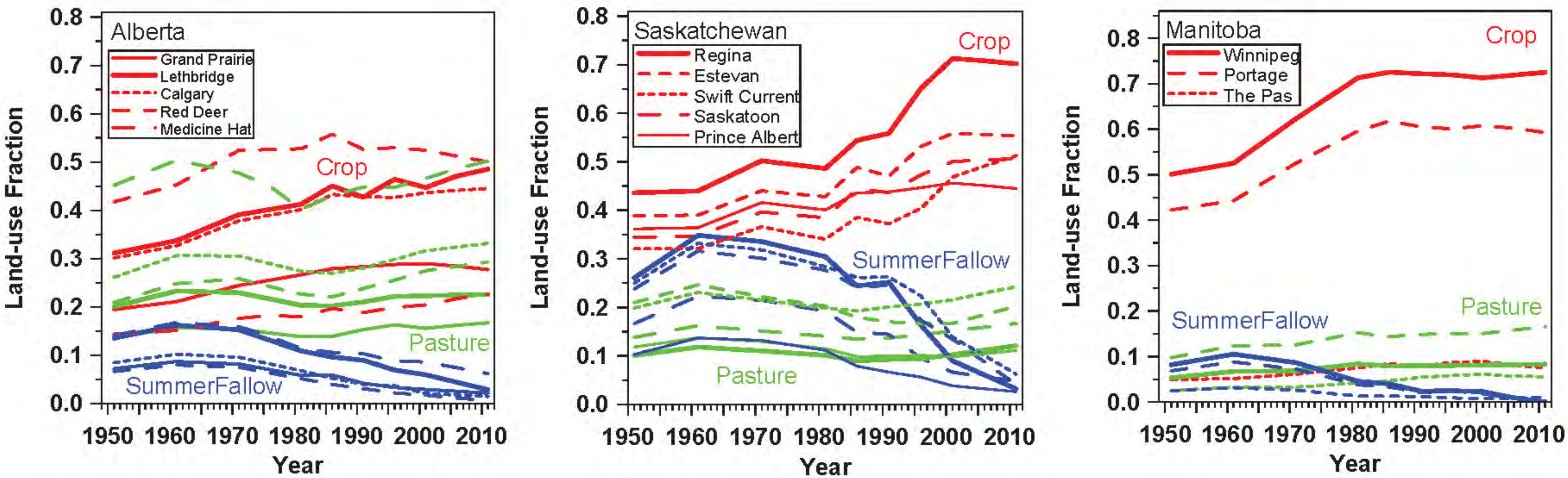
- Ecodistrict crop data since 1955
  - Ecodistricts mapped to soils
  - Typical scale: 2000 km^2 (500-7000)
- Ecozones
  - boreal plains ecozone
  - semiarid/subhumid prairie regional zones
- Shift from ‘Summerfallow’ (no crops) to annual cropping on 5 MHa (11 M acres)
  - *Large increase in transpiration: Jun-Jul*

13 Prairie stations: 1953-2011



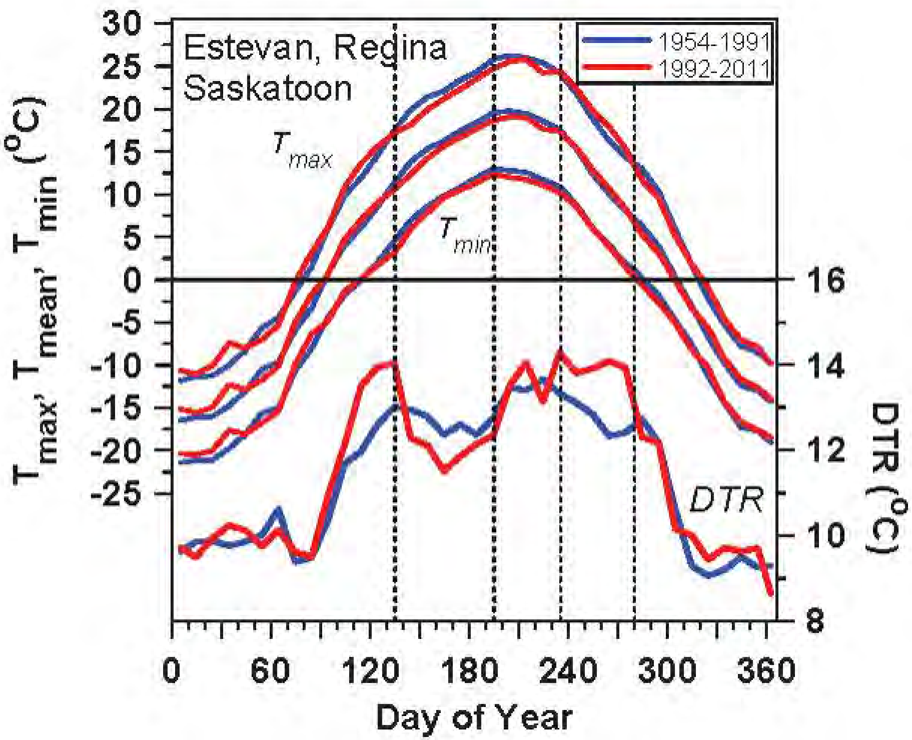
- **Hourly p, T, RH, WS, WD, Opaque Cloud by level, (SW_{dn}, LW_{dn})**
- **Daily precipitation and snowdepth**
- **Ecodistrict crop data since 1955**
- **Albedo data (MODIS/CCRS: 250m, after 2000)**

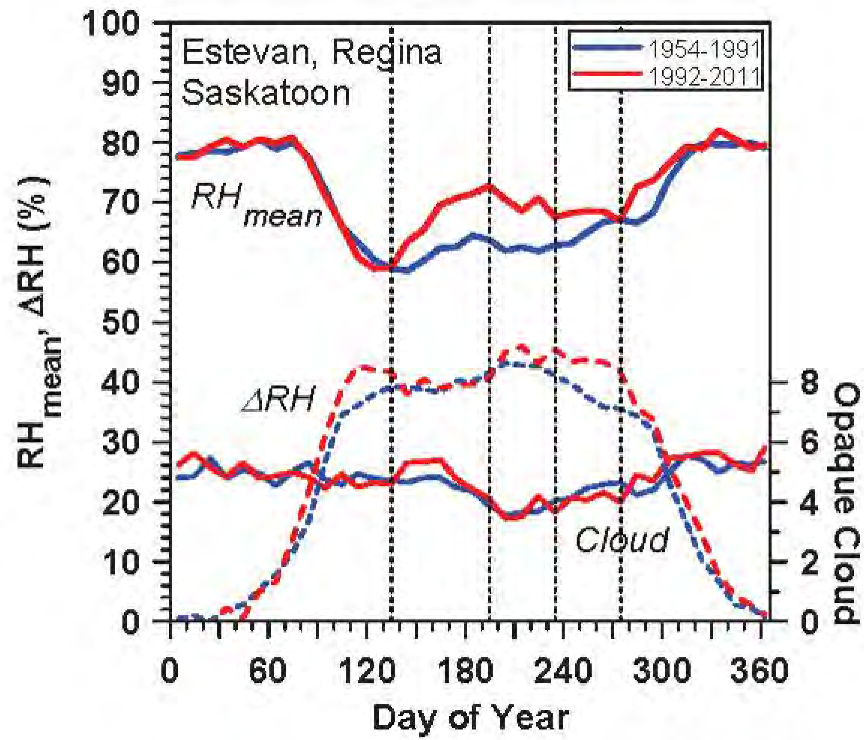
Change in Cropping



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

Three Station Mean in SK



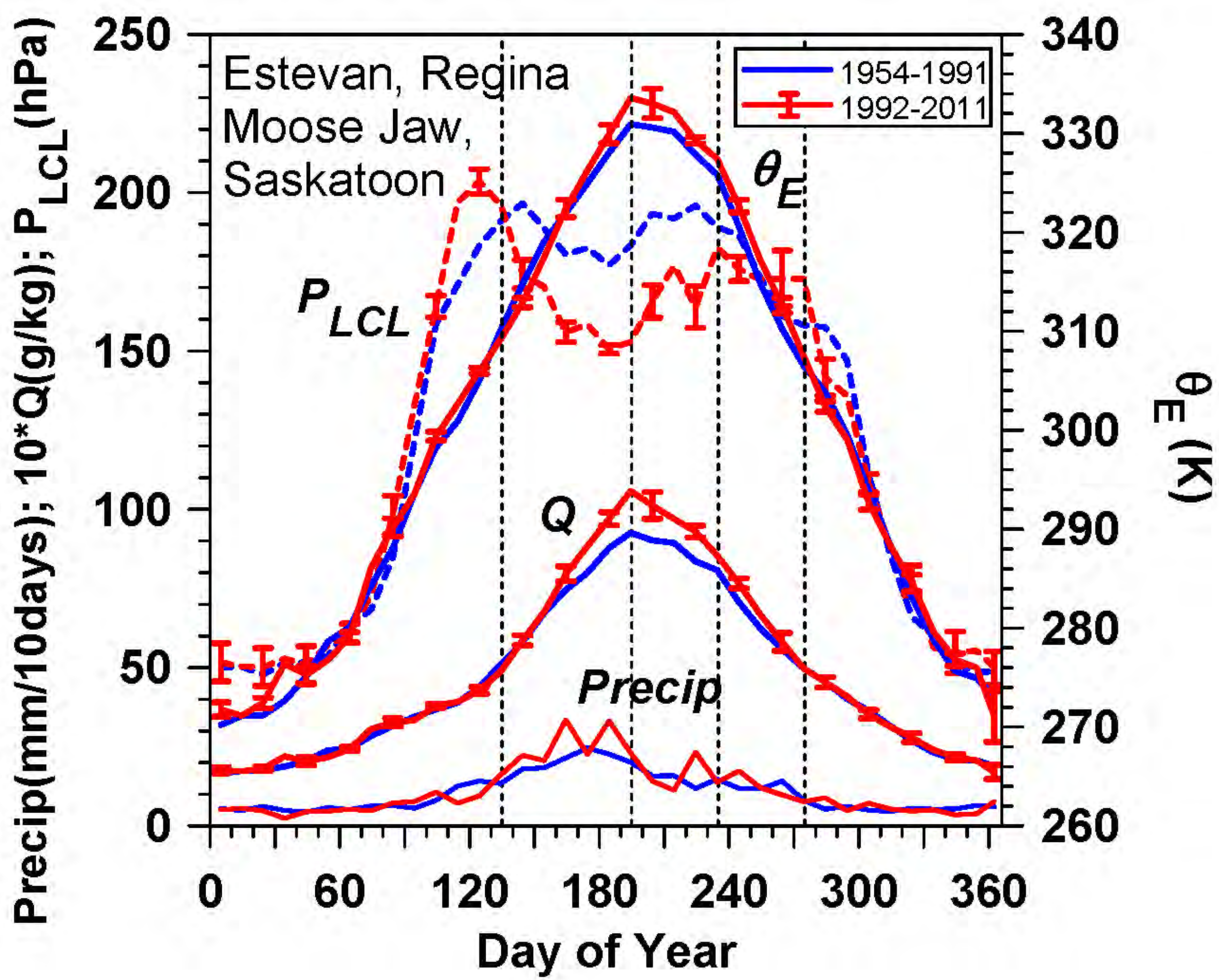


- Winter climate warmer but growing season
  - T_{max} cooler; RH moister
  - DTR and ΔRH seasonal structure changes

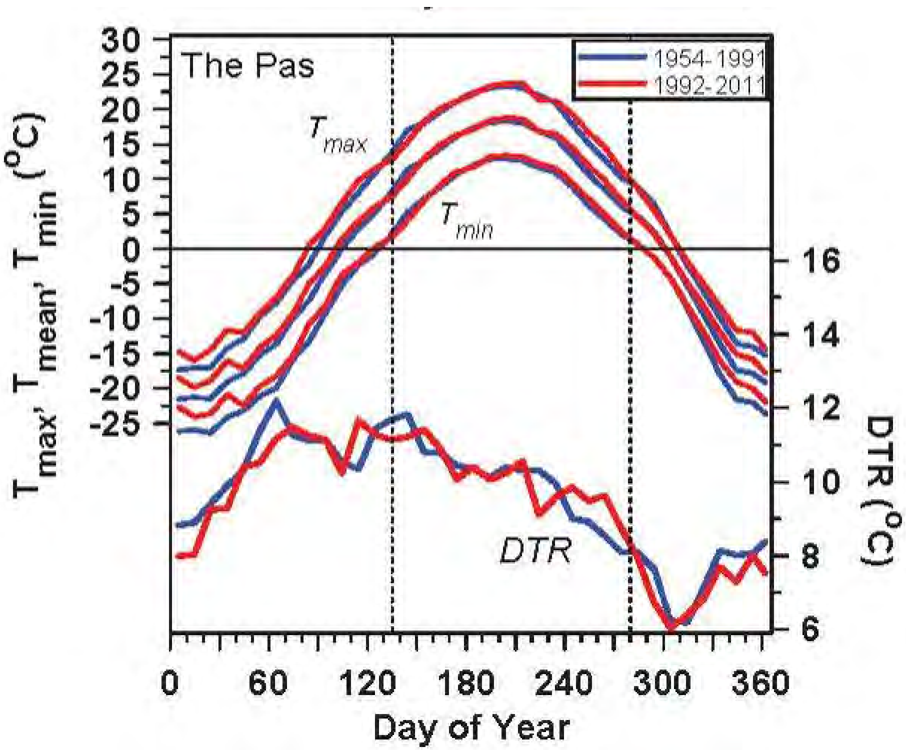
Impact on Convective Instability

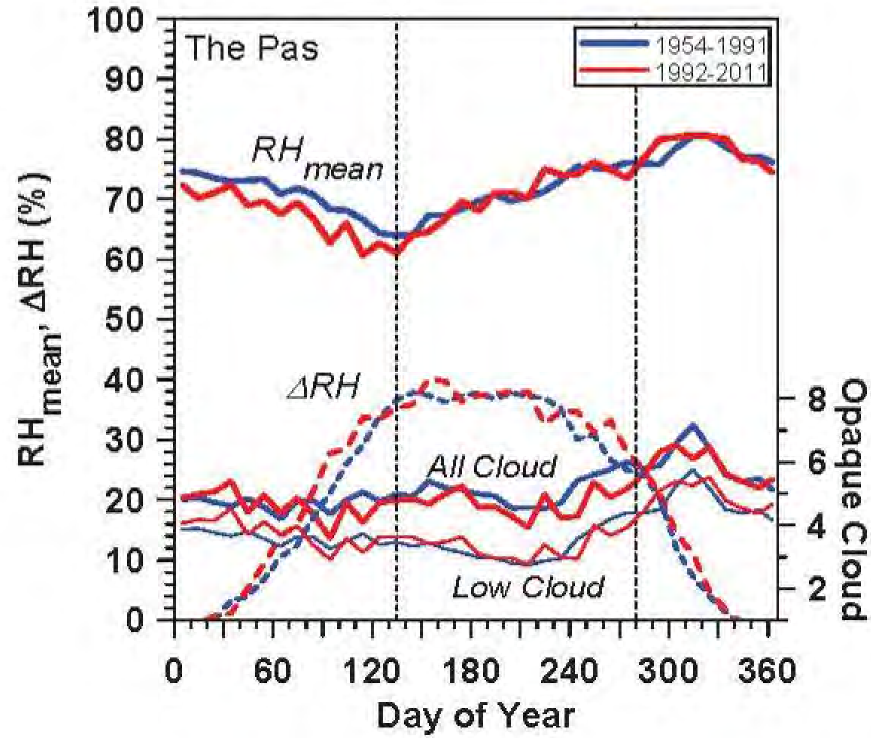
Growing season

- **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

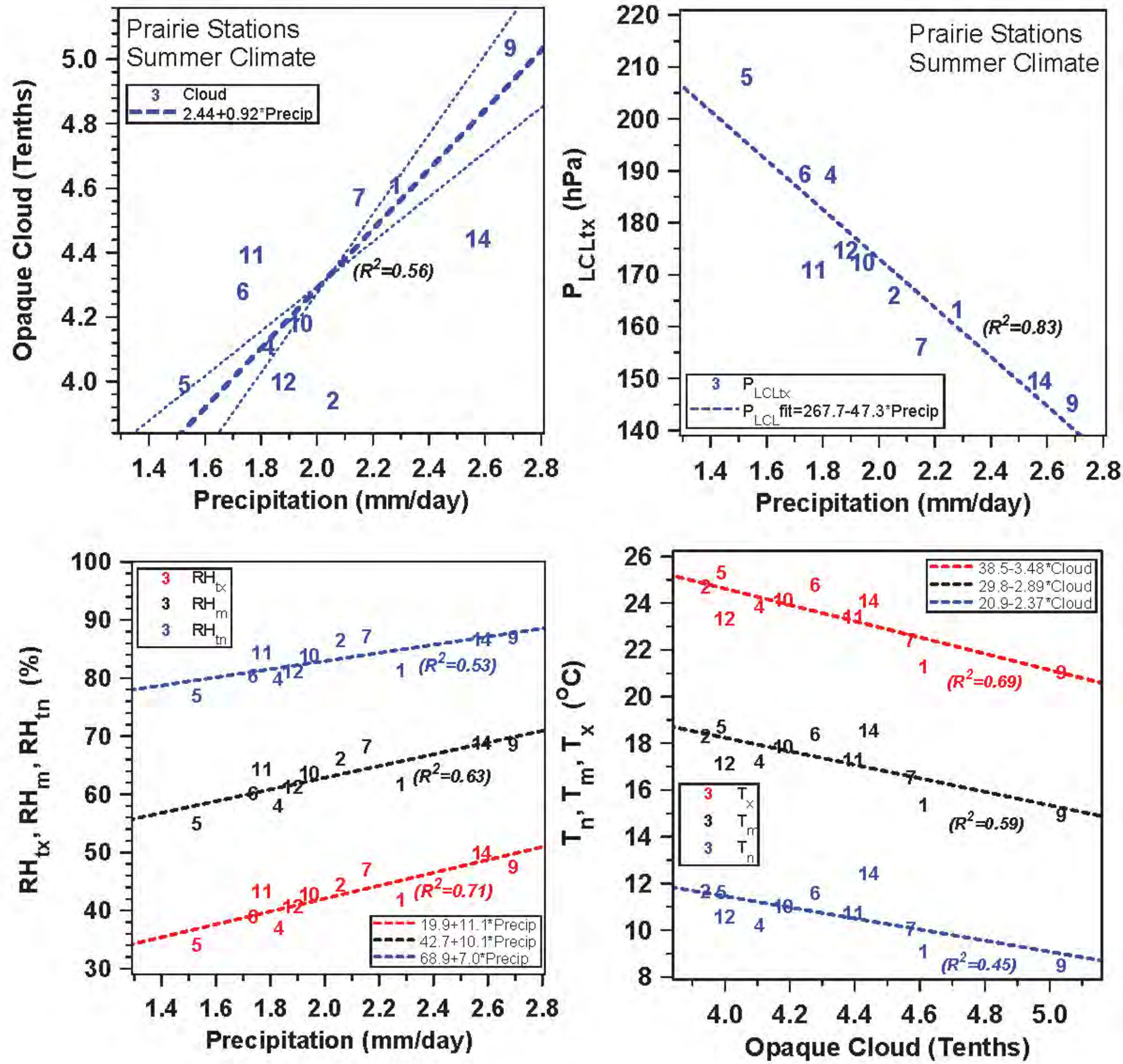
  T to opaque cloud and R_n

- ***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, in 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

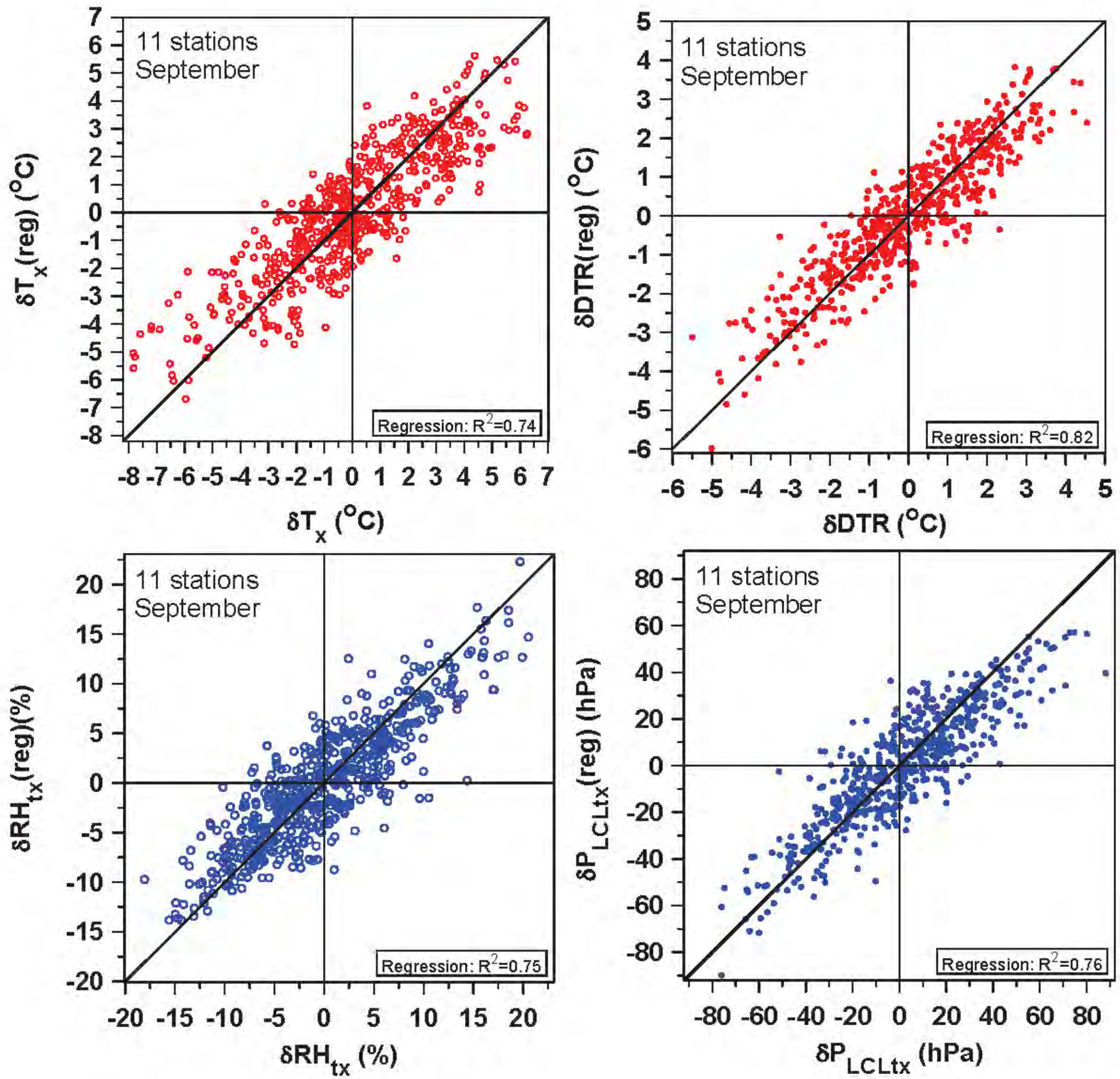
Month	K	A *(Mo-2)*	B*(Mo-1)*	C*(Mo)*	D	R^2 All	R^2 Precip	R^2 Cloud
May	**0±3.6**	**1.30±0.38**	**1.47±0.22**	**2.07±0.17**	**4.75±0.20**	**0.72**	**0.46**	**0.62**
Jun	**0±3.6**	**0.69±0.23**	**1.26±0.15**	**1.96±0.12**	**4.36±0.22**	**0.68**	**0.47**	**0.48**
July	**0±4.1**	**0.84±0.18**	**1.71±0.12**	**1.81±0.17**	**4.40±0.30**	**0.59**	**0.43**	**0.33**
Aug	**0±3.6**	**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**

How good is the regression fit?

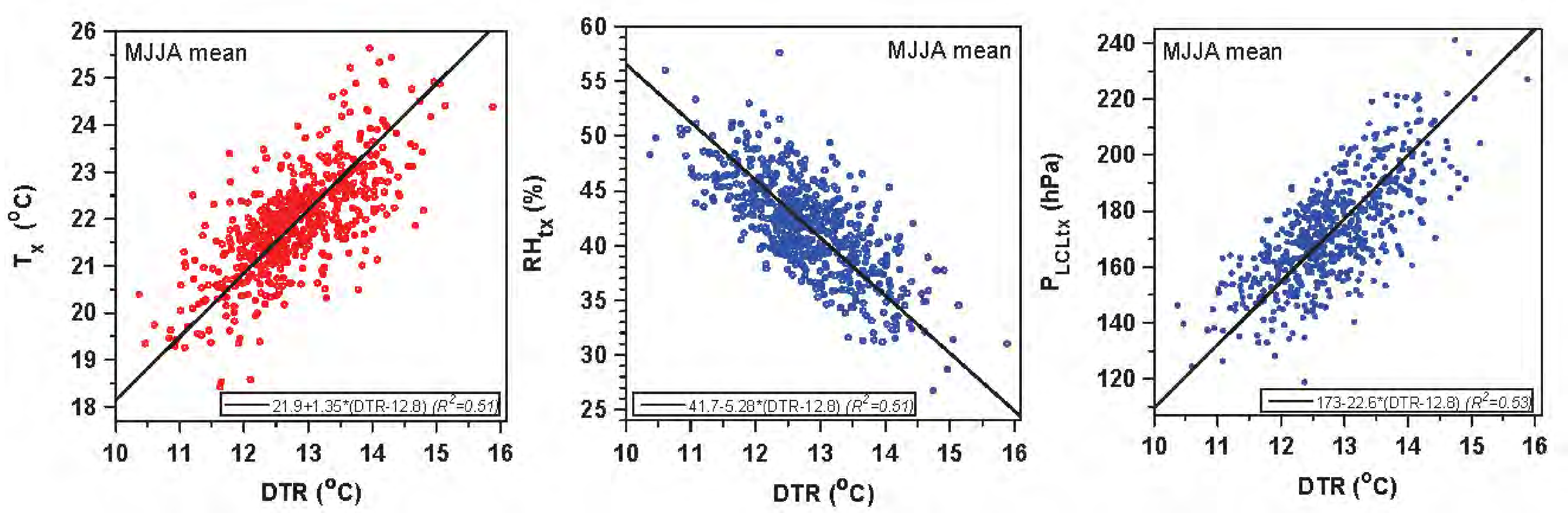
- **September**
  - T_x ±1.4°C
  - DTR ±0.8°C
  - RH_{tx} ±3.5%
  - P_{LCLtx} ±13hPa

- **Some extremes underestimated**

(586 station-yrs)



Diurnal coupling: MJJA mean



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

MJJA 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)***

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

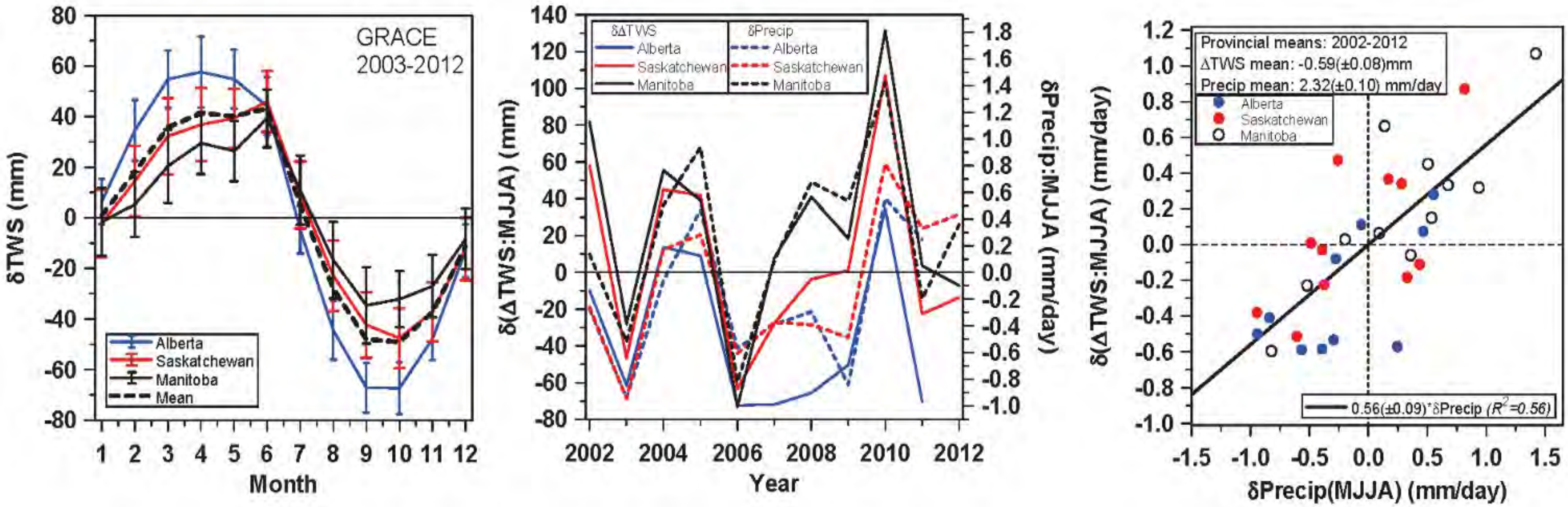
We estimate from GRACE data (2002-12)

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

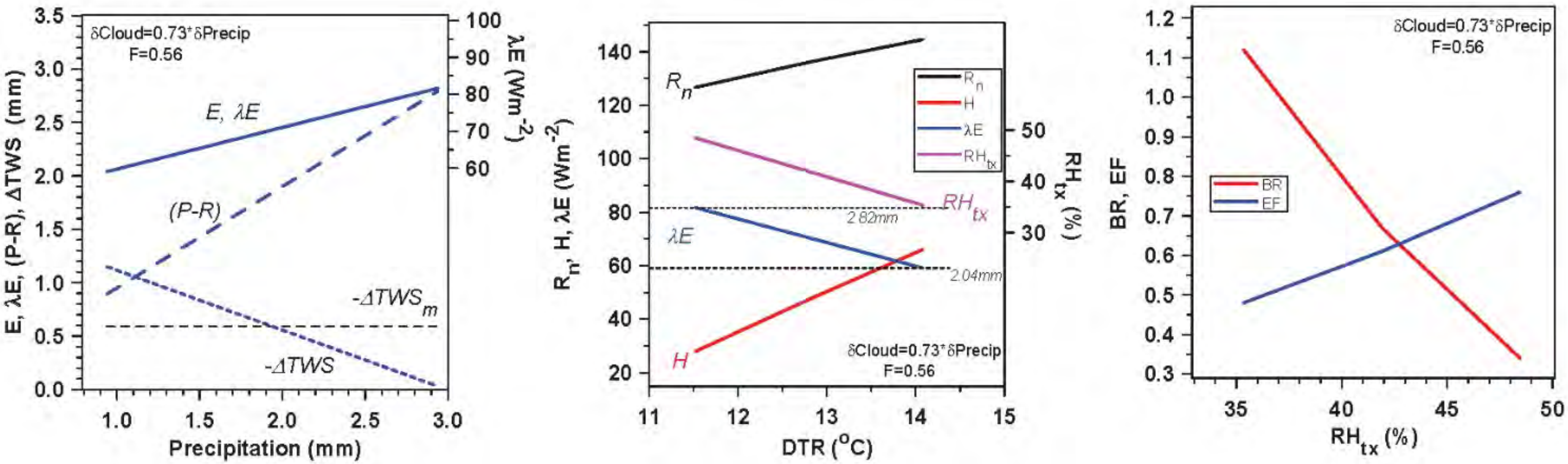


ΔTWS_m= - 0.59(±0.08)mm/day (73mm/123 days)

F = +0.56(±0.09) (for AB, SK and MB)

(F is 56% damping of precipitation anomalies)

Energy and Water "Budget"



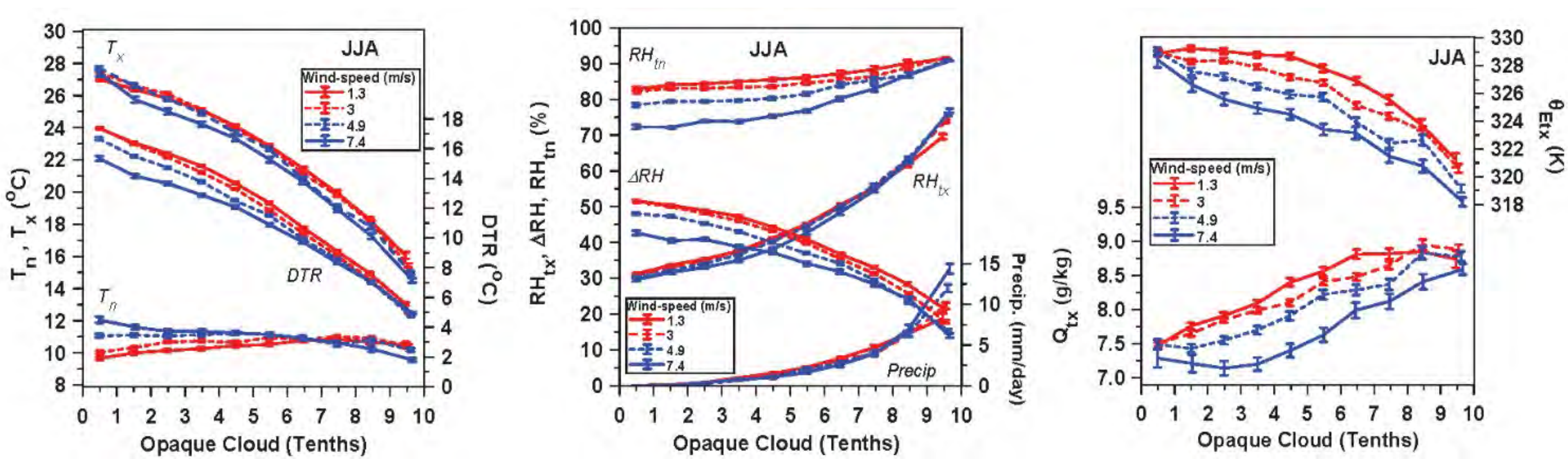
- ***Cloud and precip. anomalies***
  - ***Give anomalies of DTR, RH_{tx} (and T_x..)***
  - ***Cloud gives R_n anomalies***
- ***Closures***
  - ***Climate coupling: cloud to precip. (0.73)***
  - ***GRACE estimate F = 0.56 gives E anomalies***
- ***Gives BR, EF anomalies***

Summary (Part 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**
- **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*

Partition Further: Windspeed



- **11 stations: 53600 days in June, July, August**
- **See impact of low wind on DTR, $T_{n,}$ RH_{tn}**
- **See impact of low wind on θ_{Etx}**