Reinventing Hydrometeorology using Cloud and Climate Observations

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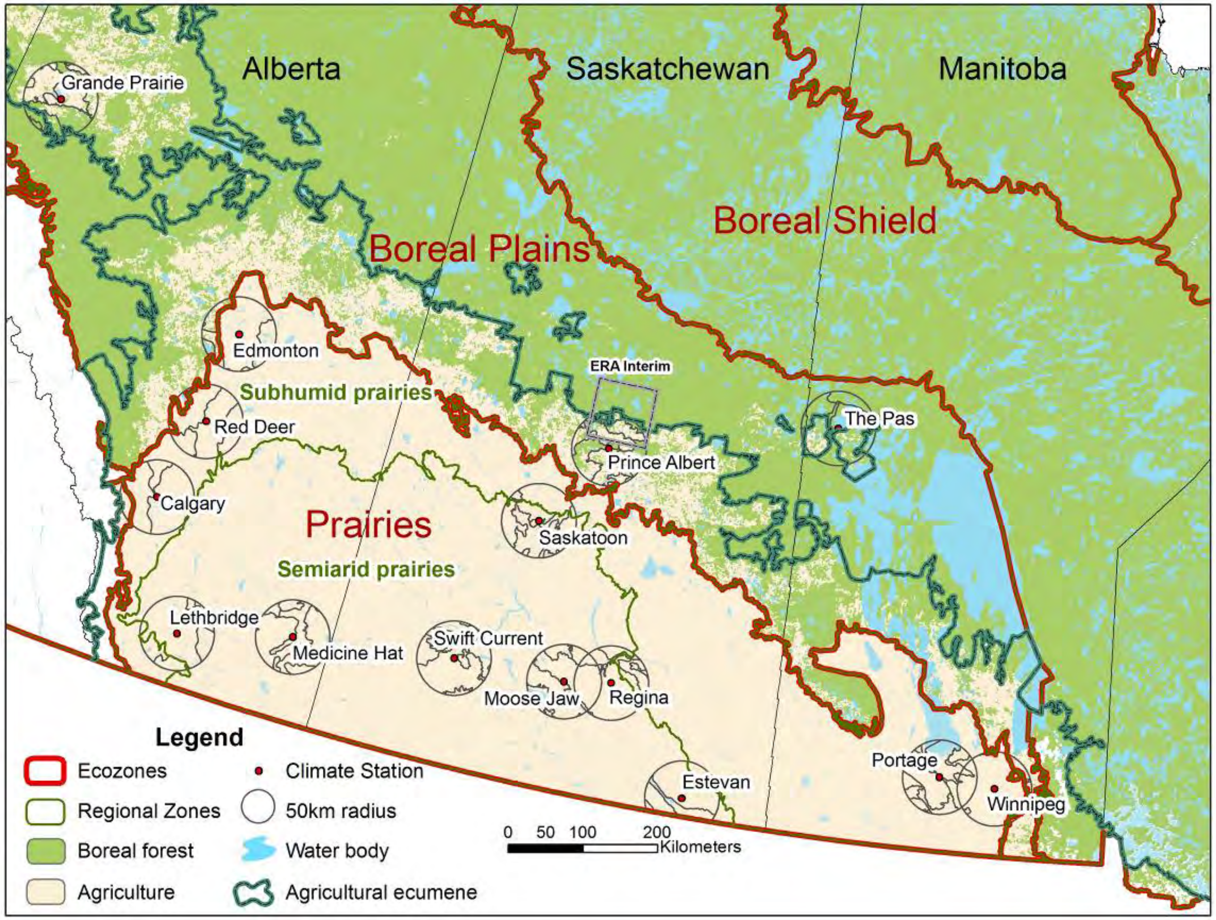
Reinventing Hydrometeorology

- *Betts (2004): Understanding hydrometeorology using global models. (Now Observations)*
- **Canadian Prairies: northern climate**
  - **Cold season hydrometeorology**
    - **Snow is a fast climate switch**
      - **Two distinct "climates" - above and below 0^oC**
      - **5-mo memory of cold season precipitation**
  - **Warm season hydrometeorology**
    - **T and RH have joint dependence on radiation and precipitation on monthly timescales**
    - **2-4 months precipitation memory**
    - **System Coupling parameters (observations)**

15 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; BSRN data**
- **Albedo data (MODIS/CCRS: 250m)**

http://alanbetts.com

- 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
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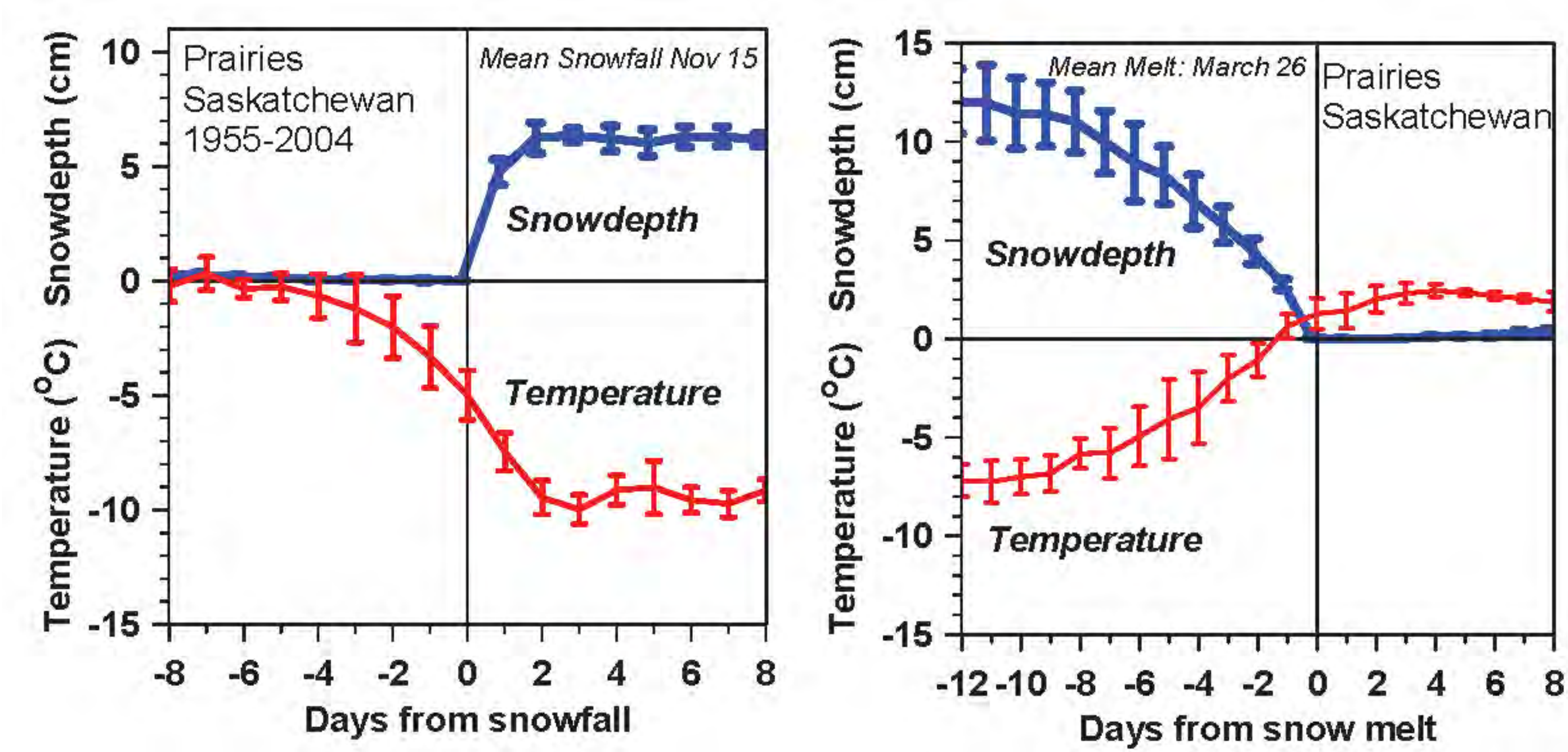
- Betts, AK and A.B. Tawfik (2016) Annual Climatology of the Diurnal Cycle on the Canadian Prairies. Front. Earth Sci. 4:1. doi: 10.3389/feart.2016.00001
- Betts, A. K., R. Desjardins and D. Worth (2016). The Impact of Clouds, Land use and Snow Cover on Climate in the Canadian Prairies. Adv. Sci. Res., 1, 1–6, doi:10.5194/asr-1-1-2016

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 approx. climate***
  - **$DTR = T_x - T_n$**
  - **$\Delta RH = RH_{tn} - RH_{tx}$**
- ***Full diurnal Cycle: ≡ monthly***
  - ***'True' diurnal ranges (Critical for winter)***
  - ***Energy imbalance of diurnal cycle***

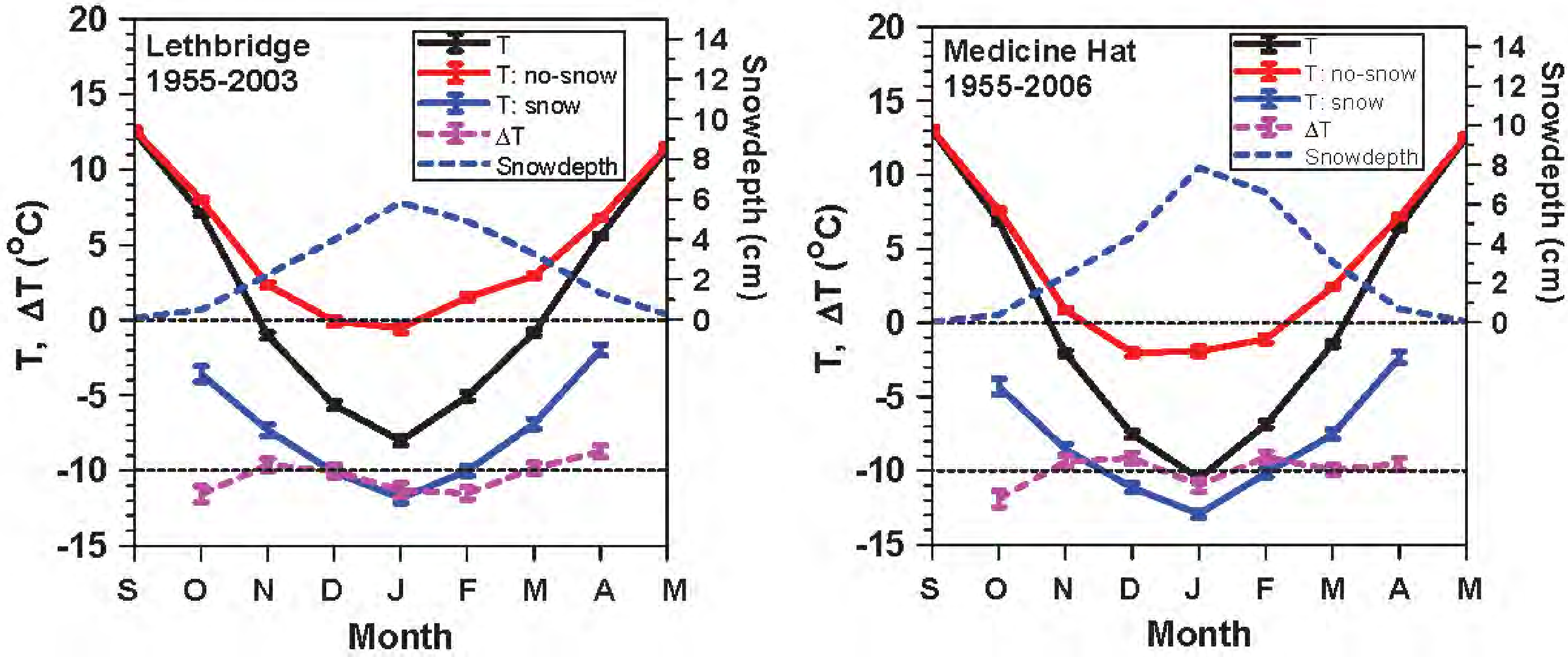
Snowfall and Snowmelt
Winter and Spring transitions



- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; shift to cold stable BL***
  - ***Local climate switch between warm and cold seasons***
  - ***Winter comes fast with snow***

Betts et al. 2014a

Impact of Snow on Climate



Separate mean climatology into days with no-snow and Snowdepth >0

ΔT = T:no-snow –T:snow = -10.2(±1.1)ºC

Betts et al. (2016)

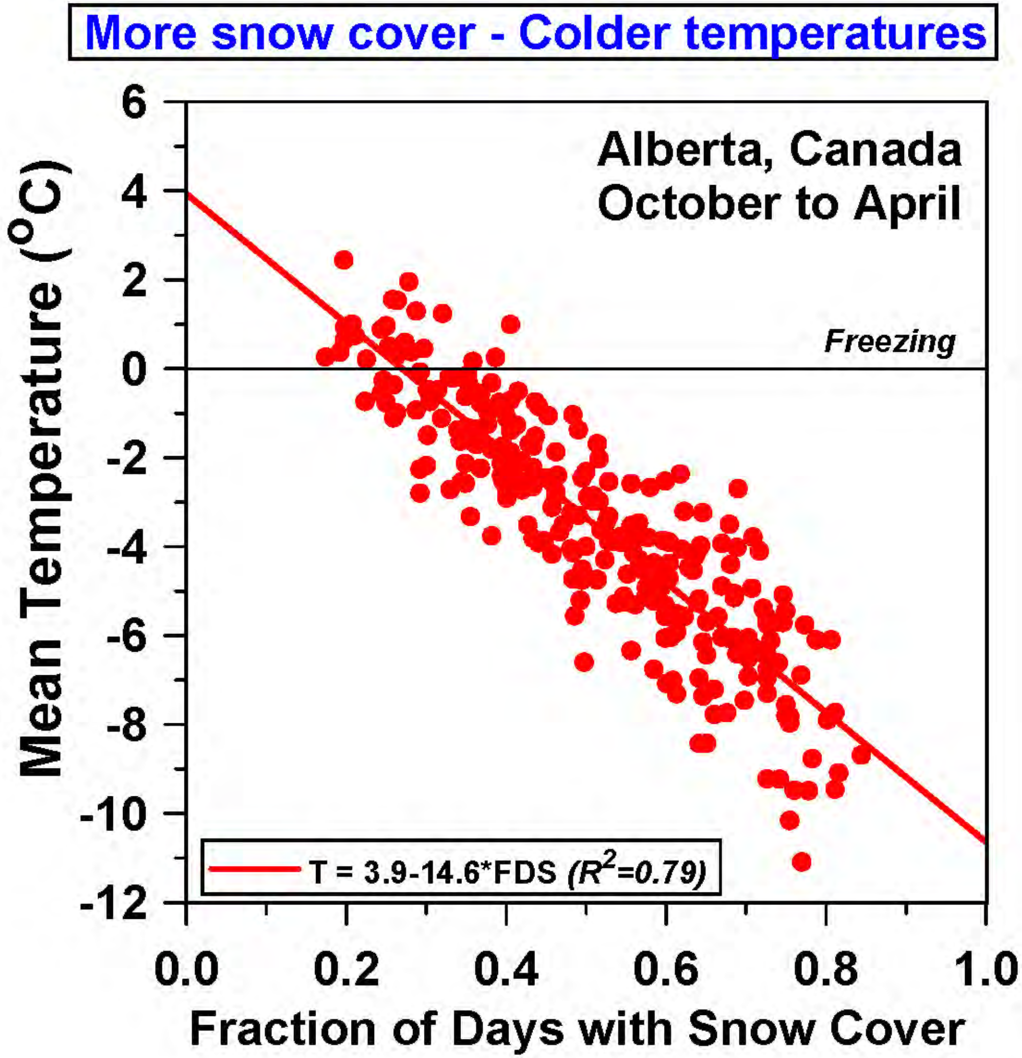
Interannual variability of T coupled to Snow Cover

- **Alberta: 79% of variance**
- **Slope T_m -14.7 (± 0.6) K**

10% fewer snow days

= 1.5K warmer

on Prairies



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)

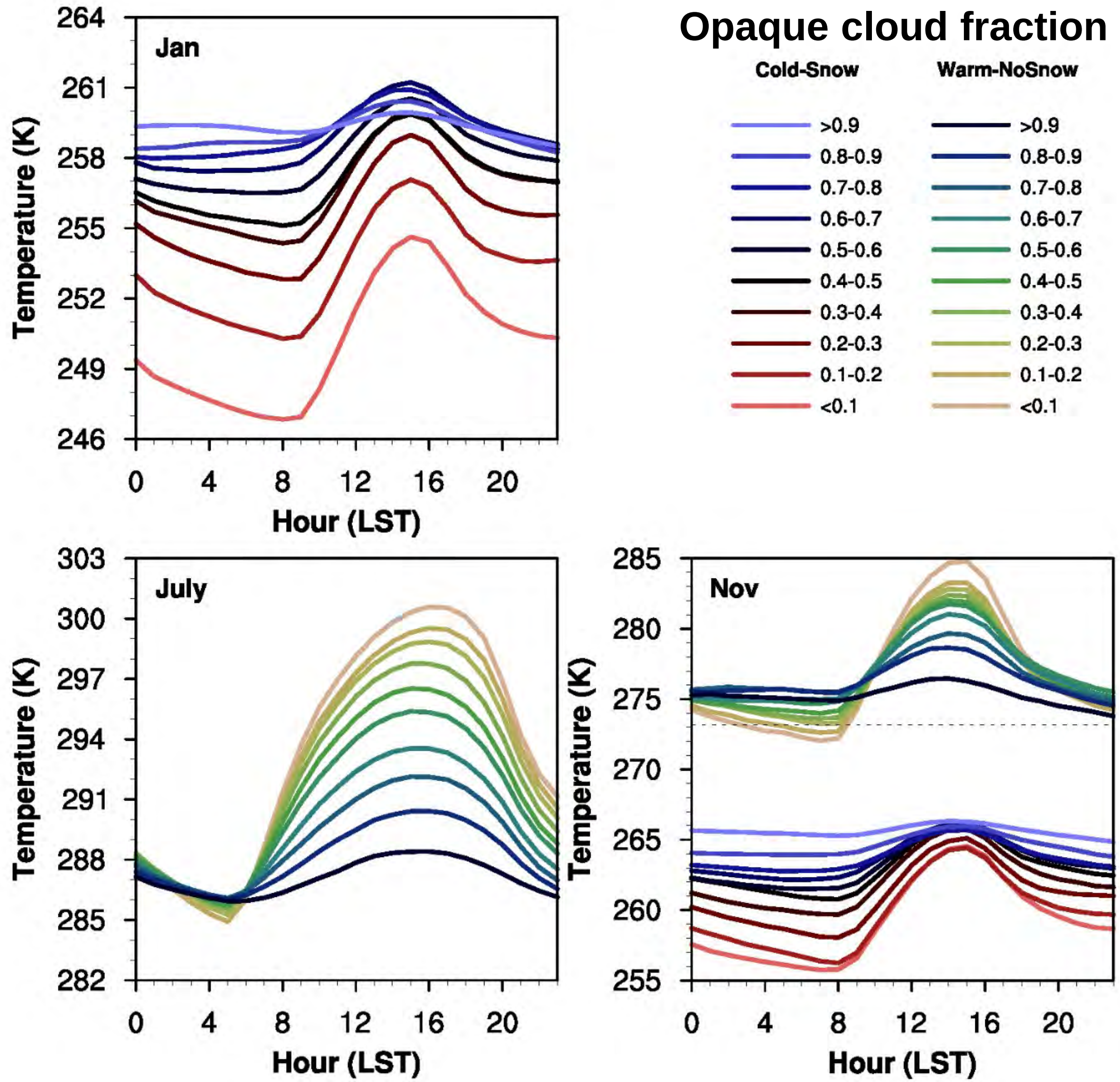
Diurnal cycle: Clouds & Snow

Canadian Prairies
660 station-years of data

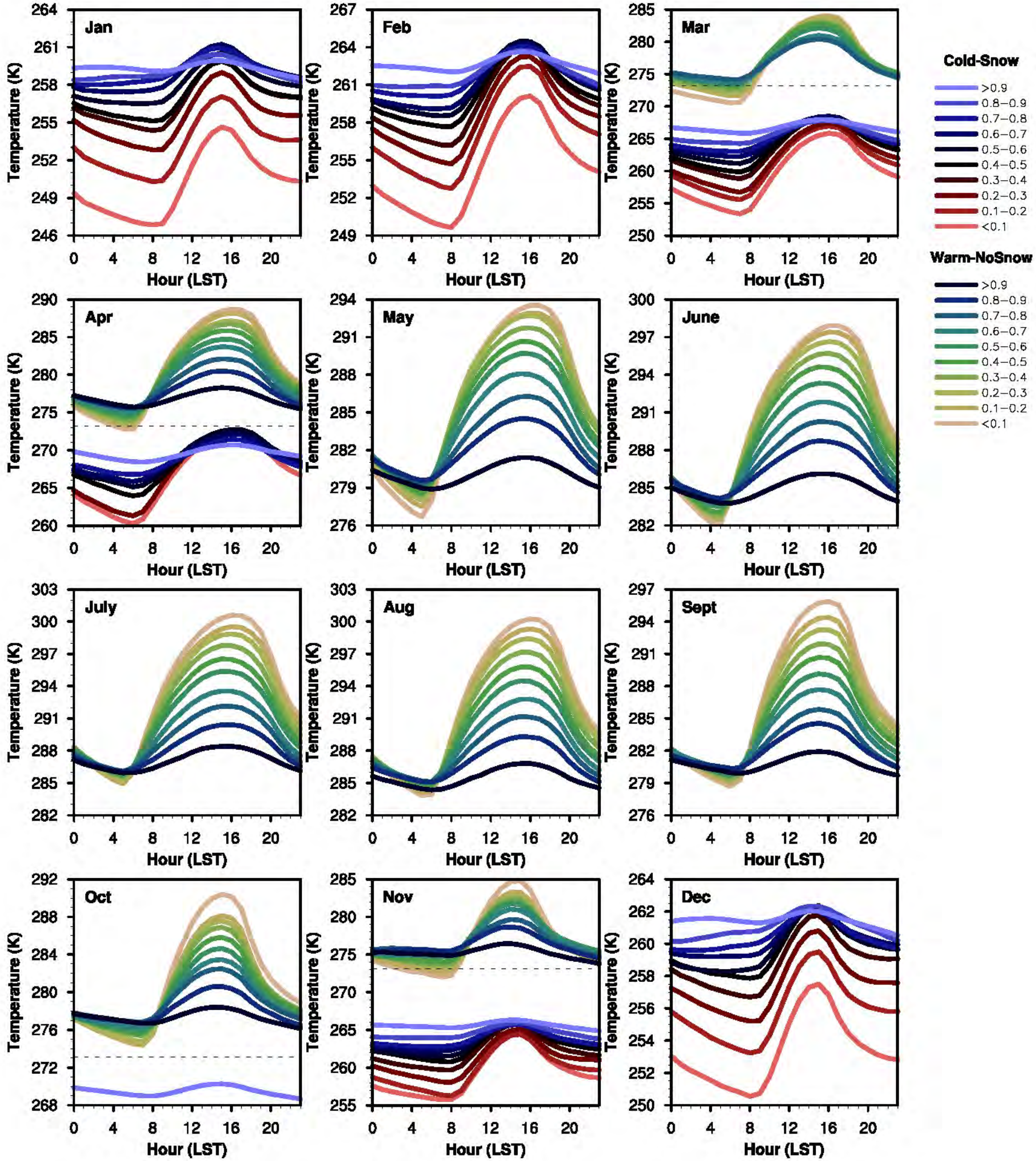
Winter climatology
- Colder when clear
- LWCF dominant with snow
- Stable BL

Summer climatology
- Warmer when clear
- SWCF dominant: no snow
- Unstable daytime BL

Transition months:
- Show both climatologies
- With 11K separation
- Fast transitions with snow
- Snow is "Climate switch"



Monthly diurnal climatology (by snow and cloud)



Impact of Snow

- **Distinct warm and cold season states**
- **Snow cover is the "climate switch"**
- **Prairies: $\Delta T = -10^{o}C$ (winter albedo = 0.7)**
- **Vermont: $\Delta T = -6^{o}C$ (winter albedo 0.3 to 0.4)**

- **Snow transforms BL-cloud coupling**
  - **No-snow 'Warm when clear' - convective BL**
  - **Snow 'Cold when clear' - stable BL**

Warm Season Climate: T>0ºC
(April – October with no snow)

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Cannot do coupling with just T & Precip !***

- ***Daily timescale is radiation driven***
  - ***Night LW_n; day SW_n (and EF)***
- ***Monthly timescale: Fully coupled***
- ***(Long timescales: separation)***

Betts et al. 2014b; Betts and Tawfik 2016)

Warm Season Diurnal Climatology

- **Averaging daily values (Conventional)**

  $DTR_D = T_{xD} - T_{nD}$

  $DRH_D = RH_{xD} - RH_{nD}$ **(rarely)**

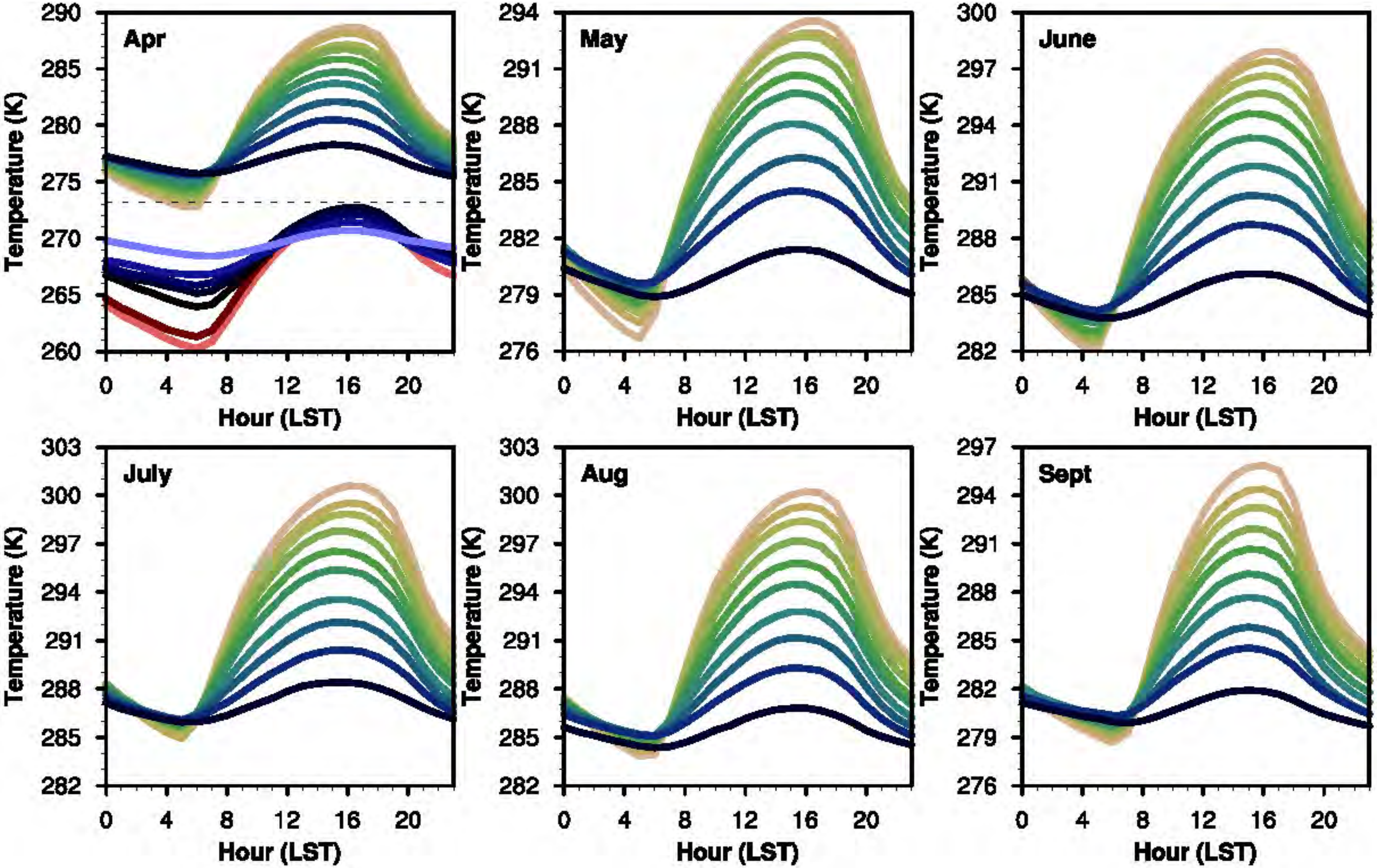
- **Extract mean diurnal ranges from composites** ***('True' radiatively-coupled diurnal ranges: damps advection)***

  $DTR_T = T_{xT} - T_{nT}$

  $DRH_T = RH_{xT} - RH_{nT}$

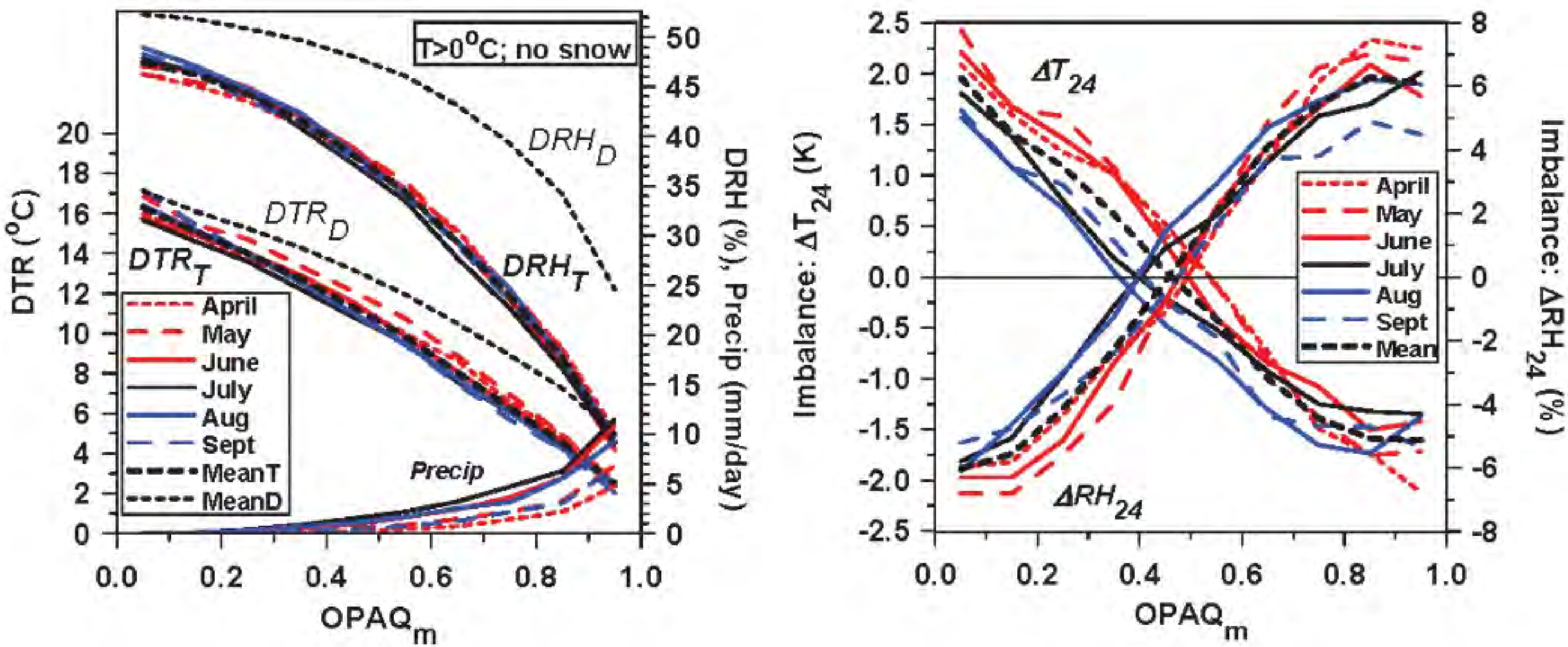
- **Q1: How are they related?** $DTR_T < DTR_D$

Monthly Diurnal Climatology



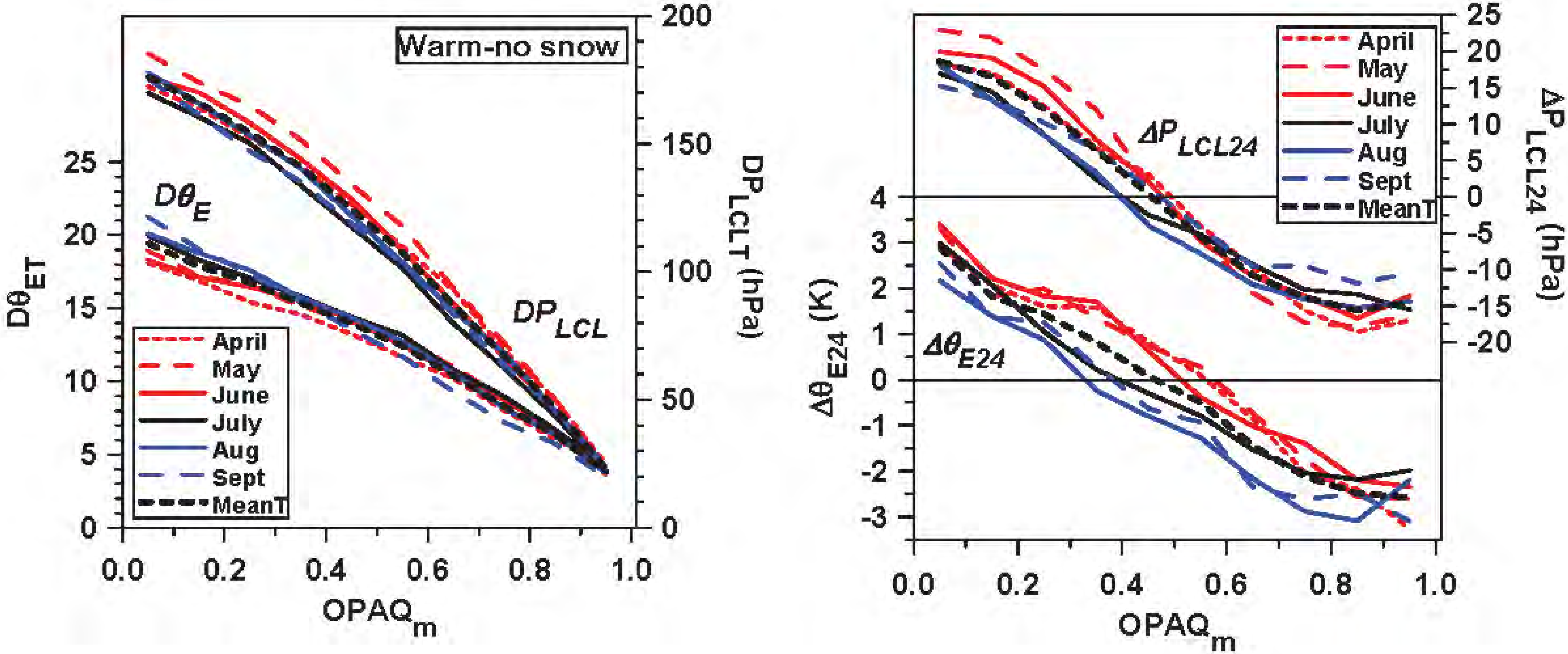
Q2: How much warmer is it at the end of a clear day?

Diurnal Ranges & Imbalances



- April to Sept: <u>same coupled structure</u>
- Q1: DTR_T, DRH_T < DTR_D, DRH_D <u>always</u>
- Q2: Clear-sky: warmer (+2°C), drier (-6%)

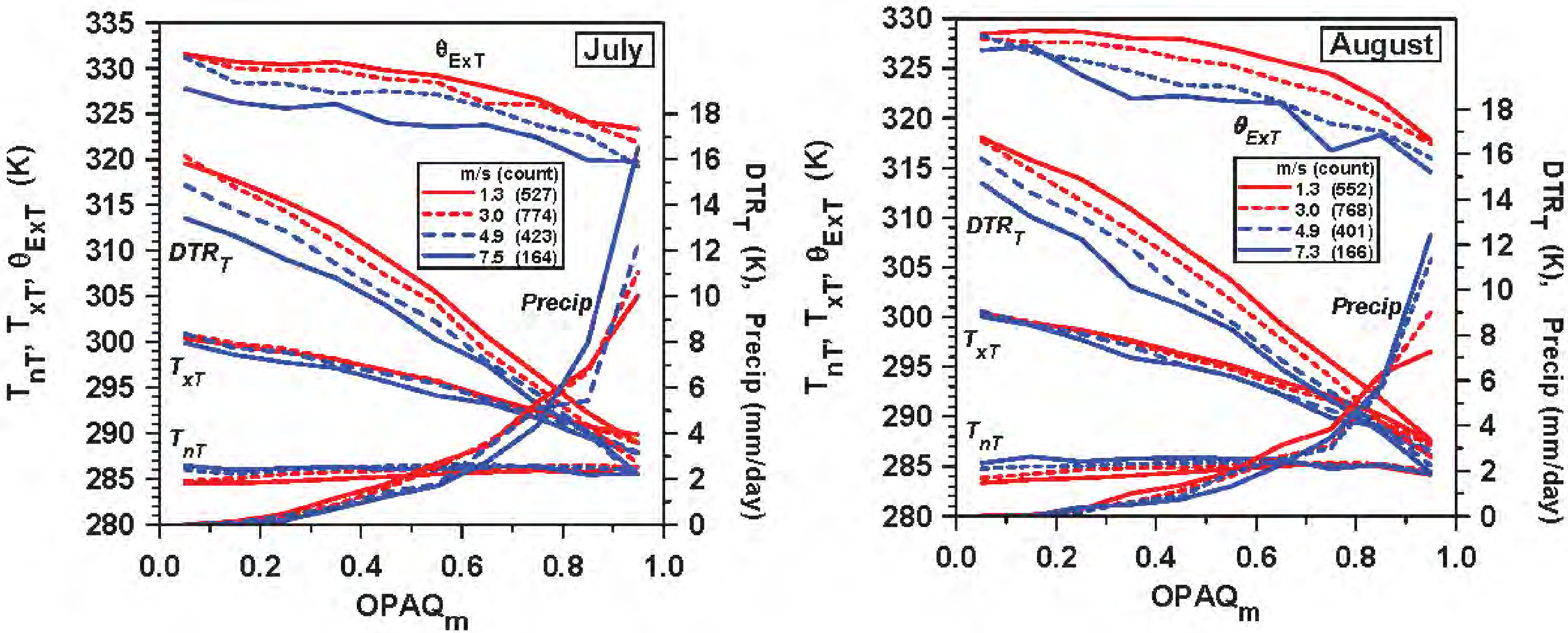
Diurnal Ranges & Imbalances



- **April to Sept: <u>same coupled structure</u>**
- **Clear-sky: θ_E (+3K), LCL higher (+18hPa)**

(Betts and Tawfik 2016)

Coupling to Wind



- **Low wind-speed: DTR increases**
  - **T_n falls; T_x, θ_{Ex} increase; (P_{LCLx} falls)**
  - **Precip. increases in mid-range**

(Betts and Tawfik 2016)

Warm Season Climate: T>0ºC

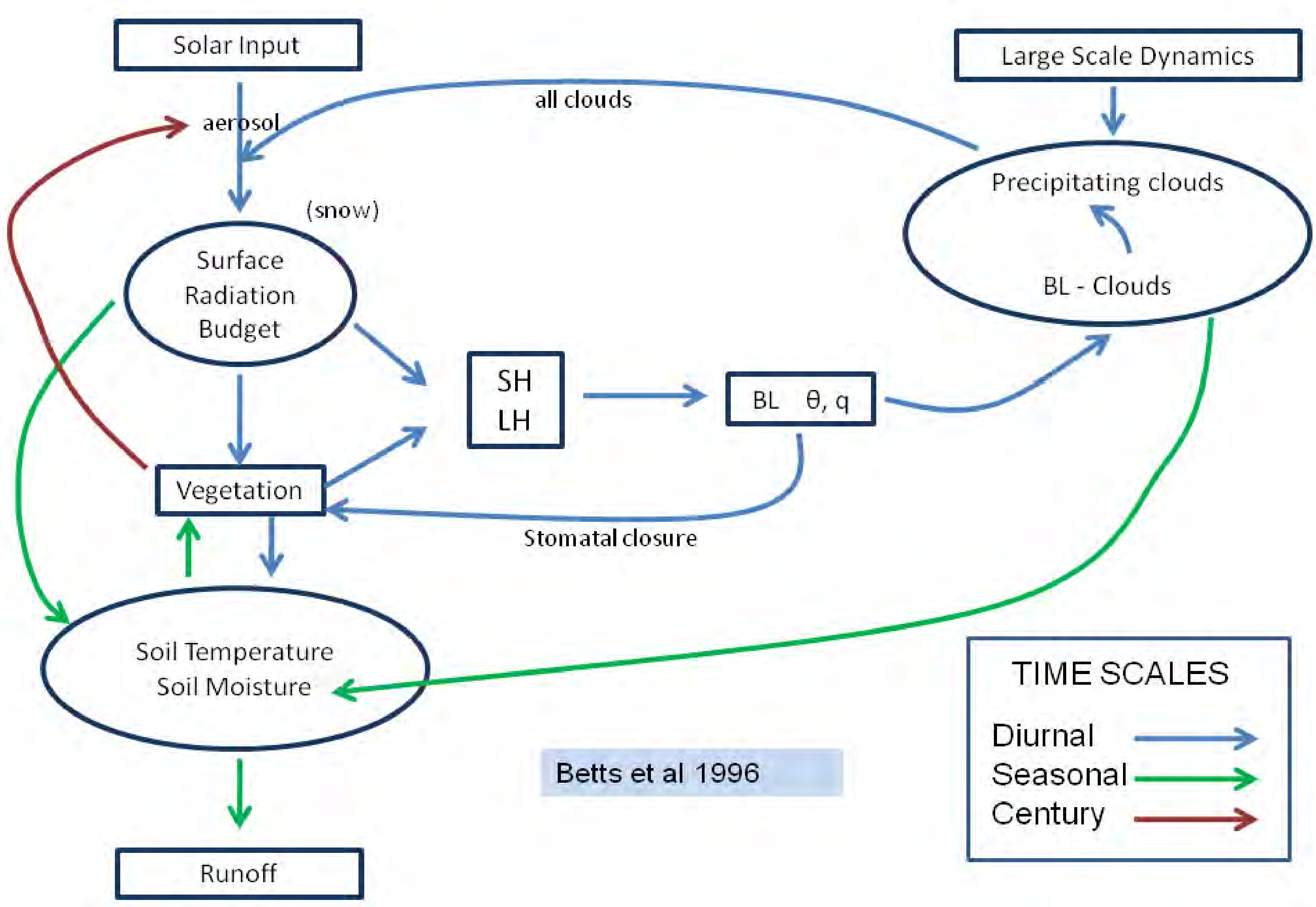
(May to September: no snow)

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Cannot do coupling with just T & Precip !***

- ***Monthly timescale: Fully coupled***
  - ***Use regression to couple anomalies***

Betts et al. 2014b

Fully coupled system



What are the <u>coupling coefficients</u> in the "real world"?

Monthly Regression on Cloud and lagged Precip. anomalies

- **Standardized monthly anomalies**
  - **opaque cloud (CLD)**
  - **precip. (PR-0, PR-1, PR-2): current, previous 2 to 5 months**

e.g.

δDTR = K + A*δCLD + B*δPR-0 + C*δPR-1 + D*δPR-2 ...

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

Soil moisture memory

April: ***memory of entire cold season (snow, soil ice) back to November freeze***

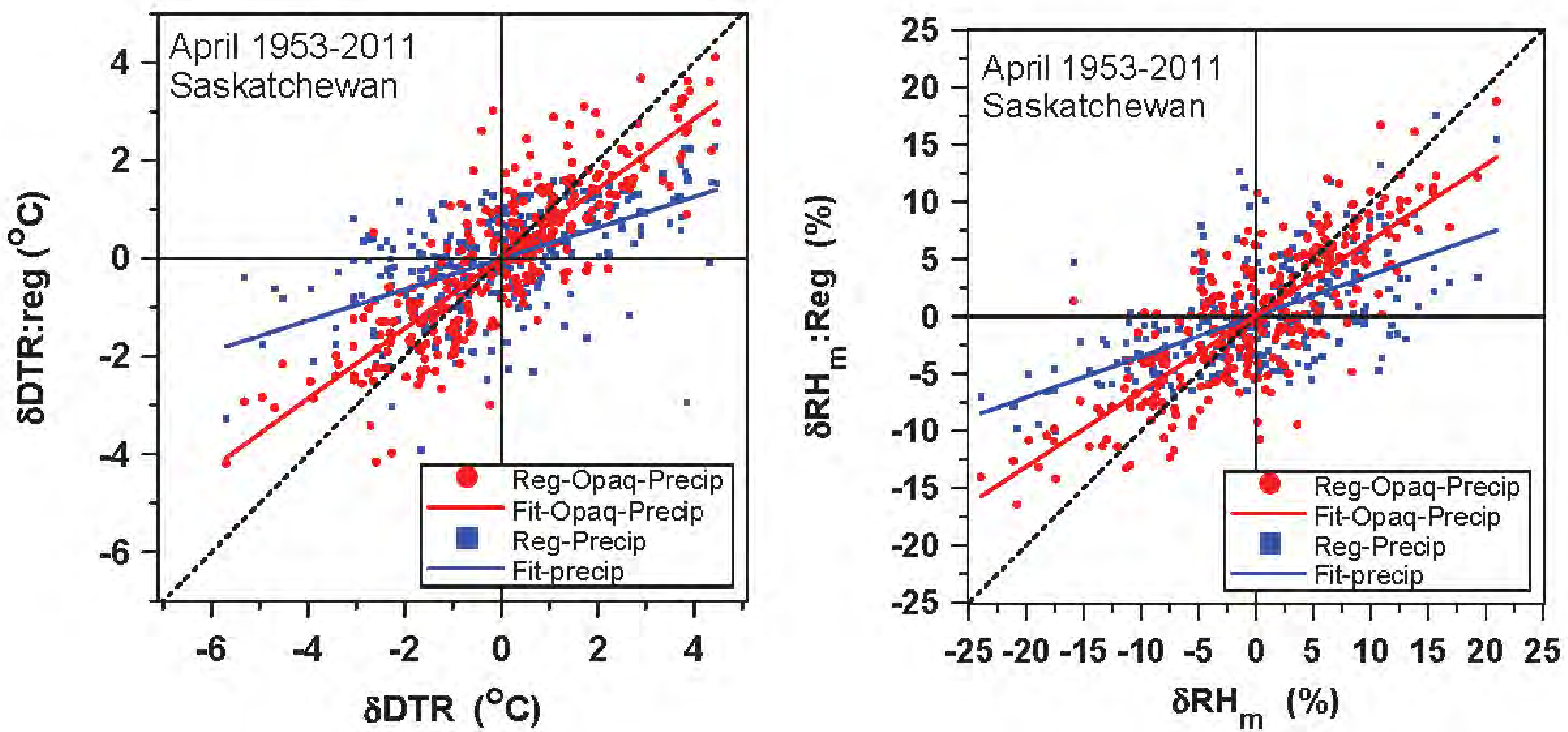
June, July: ***memory of moisture back to March***

April: Memory of Precip. to November

1953-2011: 12 stations (619 months)

Variable R^2 =	δDTR 0.67	δT_x 0.48	δRH_n 0.66	δP_{LCLx} 0.66
Cld-Apr	-0.52±0.02	-0.78±0.04	0.76±0.03	-0.93±0.04
PR-Apr	-0.04±0.01	0.00±0.03	0.14±0.02	-0.13±0.03
PR-Mar	-0.13±0.02	-0.25±0.04	0.25±0.03	-0.30±0.04
PR-Feb	-0.09±0.02	-0.15±0.05	0.19±0.04	-0.24±0.04
PR-Jan	-0.10±0.02	-0.20±0.04	0.19±0.03	-0.22±0.04
PR-Dec	-0.06±0.02	-0.07±0.05	0.20±0.04	-0.24±0.04
PR-Nov	-0.09±0.02	-0.14±0.04	0.08±0.03	-0.12±0.04

April Climate



- Regression on Opaq, Precip: $R^2 \approx 0.7$
- Regression on Winter Precip: $R^2 \approx 0.35$

Monthly timescale: Regression

1953-2011: 12 stations (615/month)

δDTR anomalies

Month	K	A *(CLD)*	B*(PR-0)*	C *(PR-1)*	D *(PR-2)*	R^2
May	0±0.02	-0.61±0.02	-0.27±0.02	-0.17±0.03	-0.06±0.05	0.74
Jun	0±0.02	-0.54±0.04	-0.22±0.02	-0.18±0.02	-0.05±0.03	0.68
July	0±0.02	-0.57±0.03	-0.24±0.02	-0.15±0.01	-0.12±0.02	0.68
Aug	0±0.02	-0.67±0.02	-0.26±0.02	-0.13±0.02	-0.03±0.02	0.80
Sept	0±0.02	-0.71±0.02	-0.30±0.02	-0.12±0.02	-0.03±0.02	0.84

Betts et al. 2014b, revisited

Monthly timescale: Regression

1953-2011: 12 stations (615/month)

Afternoon δRH_n anomalies

Month	K	A *(CLD)*	B*(PR-0)*	C *(PR-1)*	D *(PR-2)*	R^2
May	0±0.02	0.65±0.03	0.40±0.03	0.25±0.04	0.20±0.06	0.72
Jun	0±0.02	0.66±0.03	0.32±0.02	0.21±0.03	0.11±0.04 **	0.67
July	0±0.03	0.63±0.04	0.36±0.03	0.27±0.02	0.13±0.03 **	0.61
Aug	0±0.02	0.61±0.03	0.42±0.03	0.22±0.02	0.10±0.02	0.75
Sept	0±0.02	0.61±0.02	0.39±0.03	0.24±0.02	0.05±0.02	0.78

June, July weak memory back to March

Betts et al. 2014b, revisited

MJJAS merge: coupling coefficients

(±0.01)

T_x

CLD	**-1.01**
PR-0	-0.07
PR-1	-0.14
PR-2	-0.03
(R^2=0.62	

Maximum temp.
Falls strongly with cloud
Falls a little with precip.

T_m

CLD	**-0.70**
PR-0	0.03
PR-1	-0.08
PR-2	-0.02
(R^2=0.48)	

SWCF (negative)
No precip dependence

T_n

CLD	-0.36
PR-0	**0.17**
PR-1	0.0
PR-2	0.02
(R^2=0.16)	

Minimum temp.
Falls with cloud
Increases a little with precip.

DTR

CLD	**-0.65**
PR-0	**-0.24**
PR-1	-0.15
PR-2	-0.05
(R^2=0.76)	

Highest correlation
Falls strongly with cloud
Falls with precip. (memory)

1953-2011 (3081 months)
12 stations

MJJAS merge: coupling coefficients

Variable	Coefficients (±0.01)	Variable	Coefficients (±0.01)	Interpretation
T_x	**CLD -1.01** PR-0 -0.07 PR-1 -0.14 PR-2 -0.03 *(R^2=0.62)*	RH_n	**CLD 0.63** **PR-0 0.37** **PR-1 0.24** PR-2 0.10 *(R^2=0.71)*	***Minimum RH*** ***Increases with cloud*** ***Increases with precip (Memory)***
T_m	**CLD -0.70** PR-0 0.03 PR-1 -0.08 PR-2 -0.02 *(R^2=0.48)*	RH_m	CLD 0.54 PR-0 0.32 PR-1 0.25 PR-2 0.12 *(R^2=0.62)*	***Mean RH*** ***Increases with cloud*** ***Increases with precip (Memory)***
T_n	CLD -0.36 **PR-0 0.17** PR-1 0.0 PR-2 0.02 *(R^2=0.16)*	RH_x	CLD 0.36 **PR-0 0.20** PR-1 0.20 PR-2 0.11 *(R^2=0.35)*	***Maximum RH*** ***Increases with cloud*** ***Increases with precip (Memory)*** ***Saturation limits fall of T_n***
DTR	**CLD -0.65** **PR-0 -0.24** PR-1 -0.15 PR-2 -0.05 *(R^2=0.76)*	DRH	CLD -0.27 PR-0 -0.17 PR-1 -0.04 PR-2 0.01 *(R^2=0.31)*	***Diurnal range RH*** ***Decreases with cloud*** ***Decreases with precip***

1953-2011 (3081 months)
12 stations

MJJAS merge: coupling coefficients

T_x (±0.01)

CLD	**-1.01**
PR-0	-0.07
PR-1	-0.14
PR-2	-0.03
(R^2=0.62)	

T_m

CLD	**-0.70**
PR-0	0.03
PR-1	-0.08
PR-2	-0.02
(R^2=0.48)	

T_n

CLD	-0.36
PR-0	**0.17**
PR-1	0.0
PR-2	0.02
(R^2=0.16)	

DTR

CLD	**-0.65**
PR-0	**-0.24**
PR-1	-0.15
PR-2	-0.05
(R^2=0.76)	

RH_n (±0.01)

CLD	**0.63**
PR-0	**0.37**
PR-1	**0.24**
PR-2	0.10
(R^2=0.71)	

RH_m

CLD	0.54
PR-0	0.32
PR-1	0.25
PR-2	0.12
(R^2=0.62)	

RH_x

CLD	0.36
PR-0	**0.20**
PR-1	0.20
PR-2	0.11
(R^2=0.35)	

DRH

CLD	-0.27
PR-0	-0.17
PR-1	-0.04
PR-2	0.01
(R^2=0.31)	

Q_{Tx} (±0.02)

CLD	-0.10
PR-0	**0.48**
PR-1	**0.23**
PR-2	0.16
(R^2=0.21)	

Q_m

CLD	-0.12
PR-0	**0.39**
PR-1	**0.23**
PR-2	0.15
(R^2=0.20)	

Q_{Tn}

CLD	-0.10
PR-0	0.32
PR-1	0.16
PR-2	0.12
(R^2=0.15)	

θ_{Ex}

CLD	**-0.65**
PR-0	0.25
PR-1	0.10
PR-2	0.10
(R^2=0.26)	

P_{LCLx} (cloud-base)

CLD	**-0.80**
PR-0	**-0.41**
PR-1	**-0.32**
PR-2	-0.14
(R^2=0.70)	

DP_{LCL}

CLD	**-0.51**
PR-0	**-0.26**
PR-1	**-0.16**
PR-2	-0.05
(R^2=0.61)	

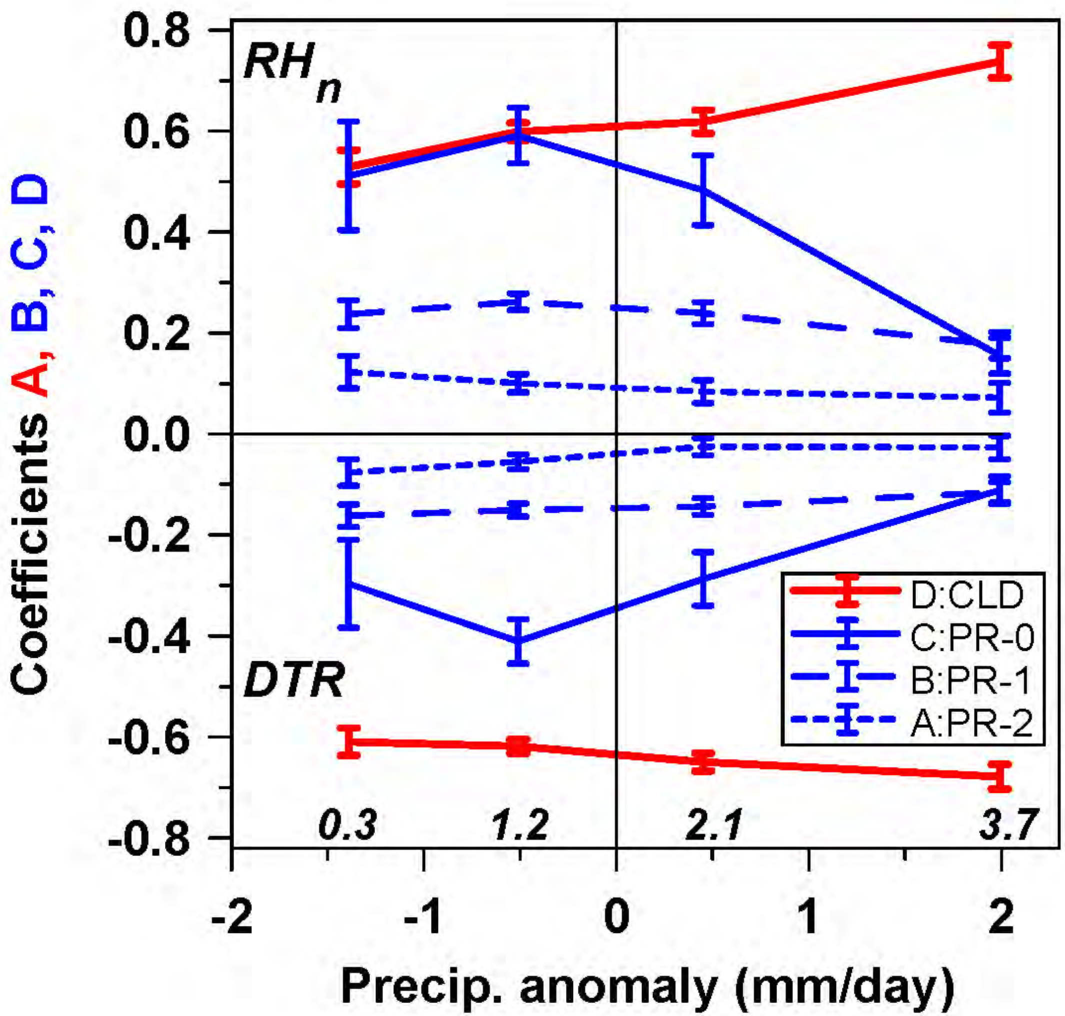
Q_{Tx}, Q_m → precip, little cloud
RH_n, T_x move inversely with cloud
P_{LCLx} part mirror of RH_n
T_m → cloud not precip
θ_{Ex} down/up with cloud/precip

1953-2011 (3081 months)
12 stations

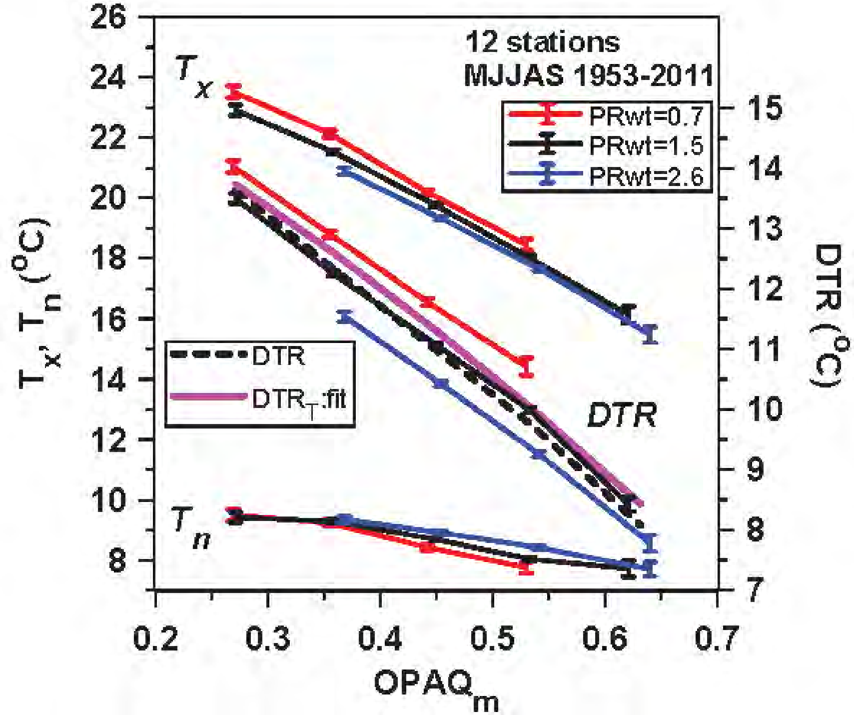
Dry to Wet Coefficient Change

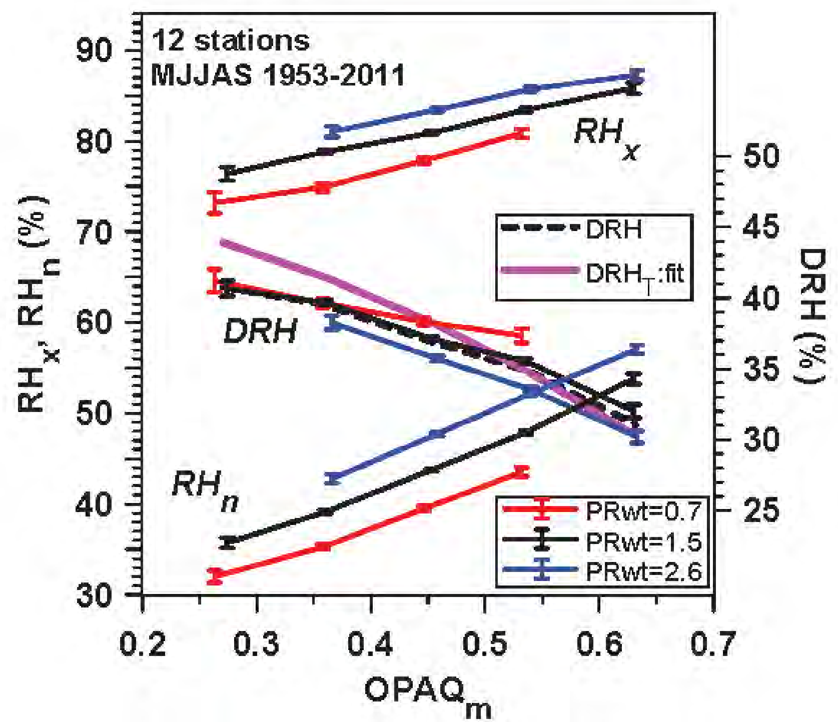
3081 months: split into precip (PR-0) SD ranges: < -1σ, -1 to 0, 0 to 1, >1σ (393, 1382, 887, 421 mos)

- **Asymmetric response**
- **Wet to dry conditions: dependence on precip. increases**
- **Except drought (0.3 mm/day)**
- **Consistent with uptake of water damping precip. anomalies (GRACE data)**



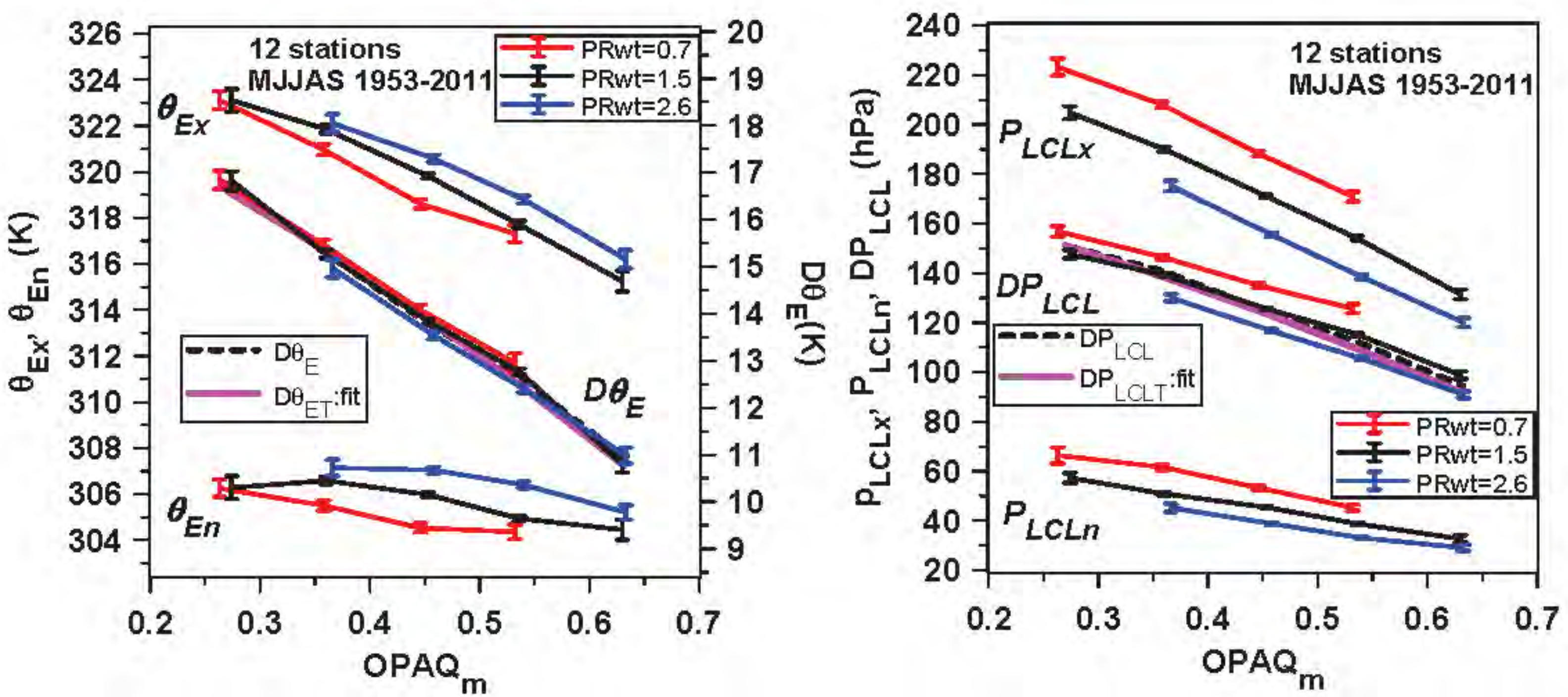
Monthly Climate of T, RH on Cloud and Precipitation





- **Sorted by cloud and weighted precip. anomalies**
  - **δPRwt = 0.61* δPR-0 + 0.39* δPR-1**
  - **DTR increases with decreasing cloud and precip.**
  - **Afternoon RH_n increases with cloud, precip.**

Afternoon maximum of θ_{Ex} and P_{LCLx} on Cloud and Precipitation



- Afternoon θ_{Ex} increases with weighted precip
- Afternoon cloud-base (P_{LCLx}) falls with precip
- Both favor convective instability

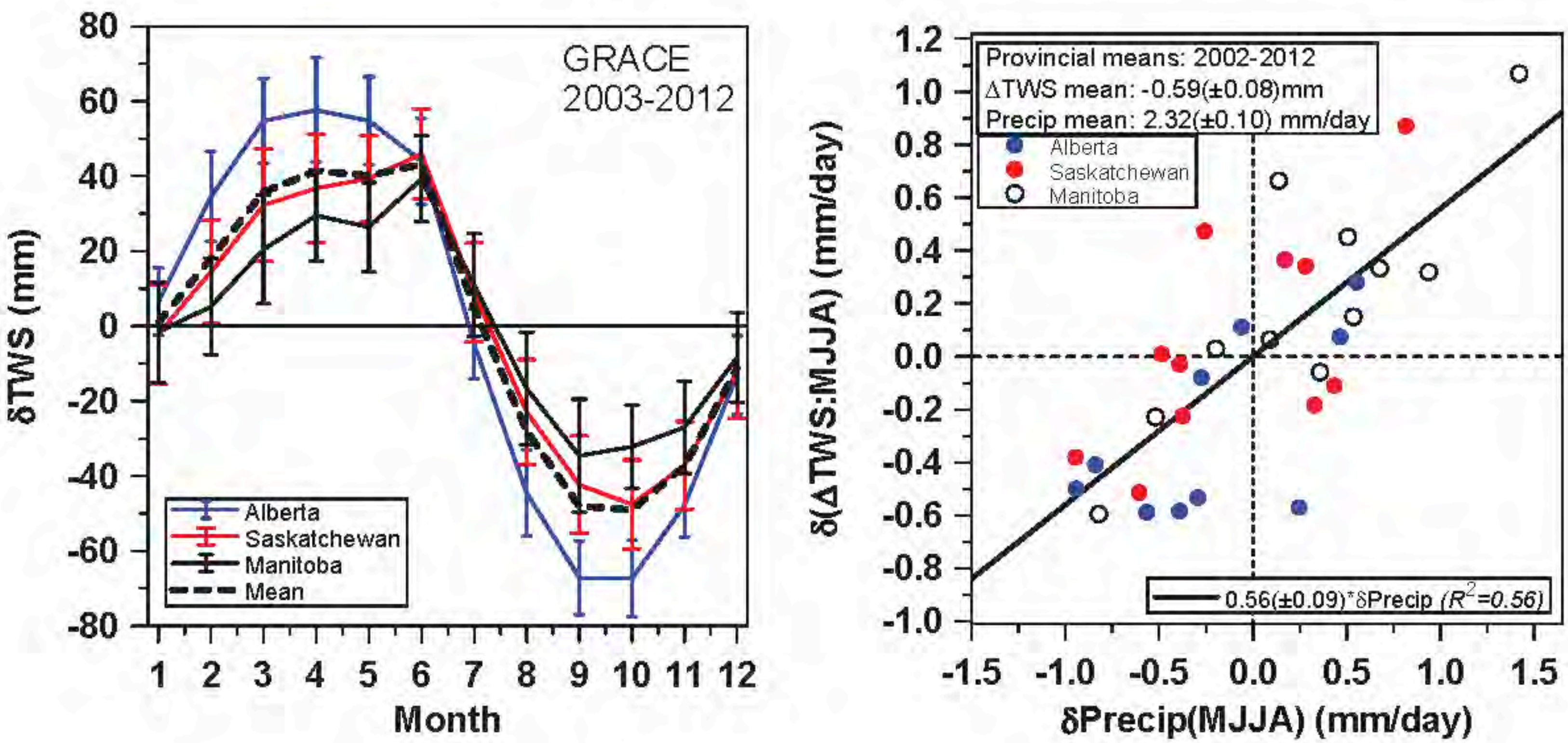
Monthly and daily bins

- Daily binning shows dependence of climate on cloud (radiation) and wind-speed
- Monthly anomaly analysis adds the lagged precipitation (soil moisture) dependence
  - RH, Q precip. memory goes back 2-5 months
- Asymmetric response to dry/wet precipitation anomalies
- <u>Observed coupling coefficients can be compared with model representations</u>

Warm Season Climate: T>0^{o}C

- ***Hydrometeorology***
  - ***<u>with Precipitation and Radiation</u>***
  - ***<u>Diurnal cycle of T and RH</u>***
  - ***Can't 'understand' climate with T & Precip.***
- ***<u>Monthly timescale coupling</u>***
  - ***T_m depends on radiation not precip.***
  - ***Q_m depends on precip. more than radiation***
  - ***DTR, RH_x, RH_m, θ_{Ex}, P_{LCLx}: coupled to both***
  - ***Sensitivity to precip. increases wet-to-dry, then falls with drought***

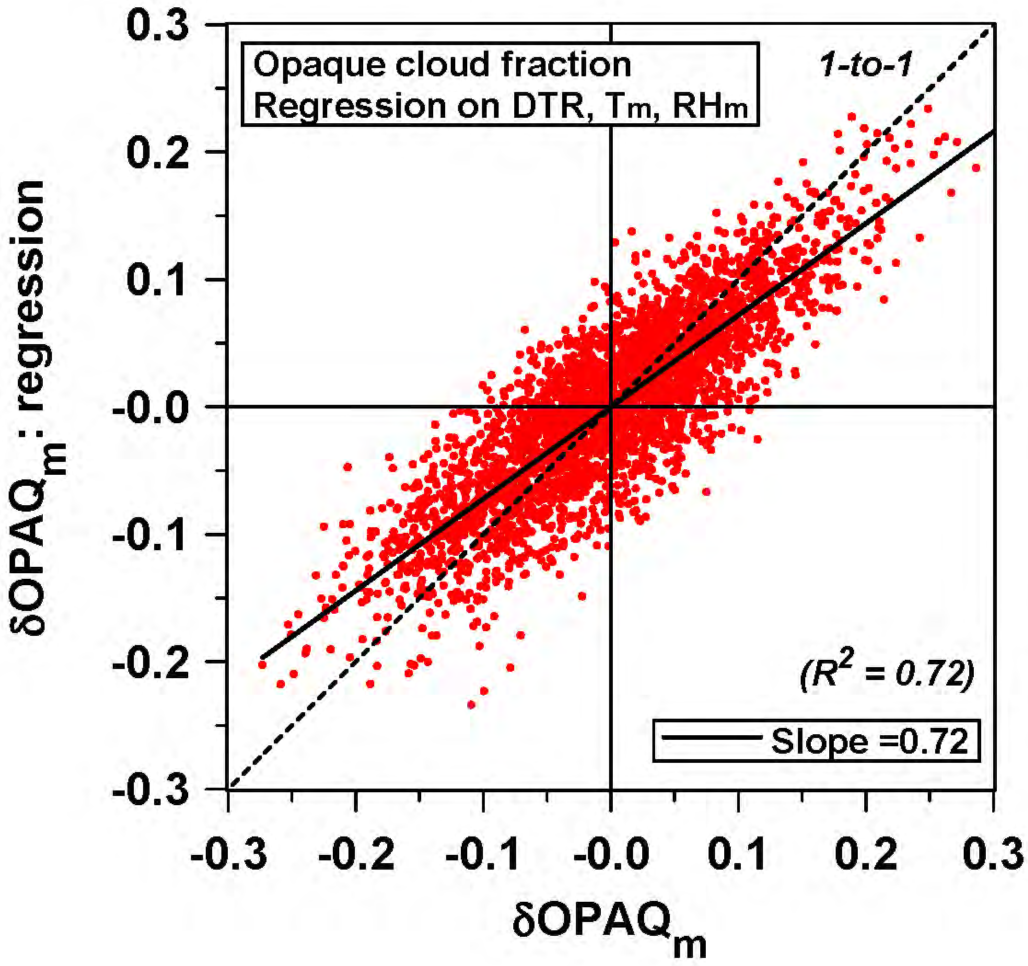
Seasonal Drydown damps Precip anomalies



- GRACE data shows seasonal change: Δ(Total Water Storage)
- δ(ΔTWS) damps 56% of precipitation anomalies

Betts et al. 2014b

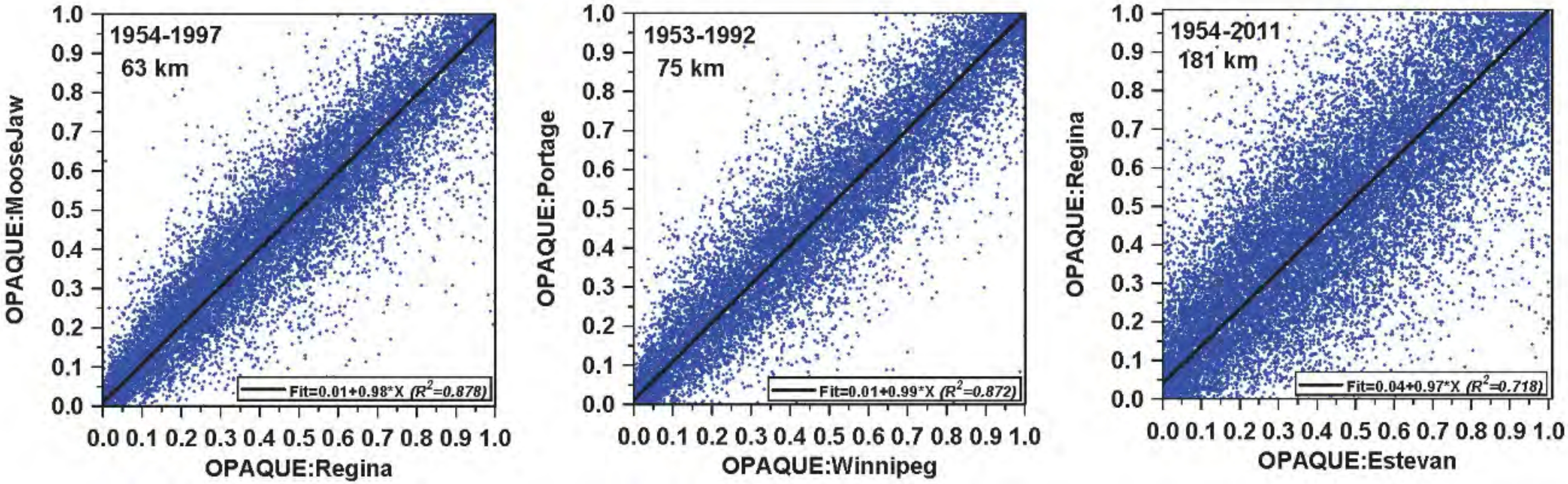
Cloud anomalies from Climate anomalies



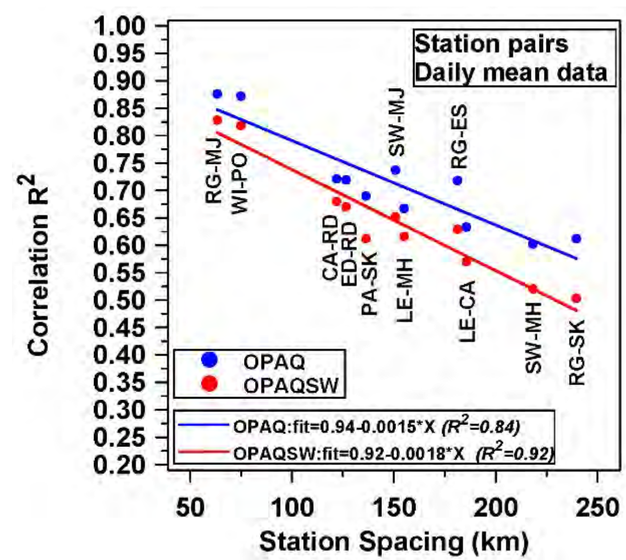
$\delta OPAQ_m$ to ±0.04

- $\delta OPAQ_{m\sigma}$:reg = $-0.64*\delta DTR_\sigma - 0.23*\delta T_{m\sigma} + 0.11*\delta RH_m$

Opaque Cloud (Observers)

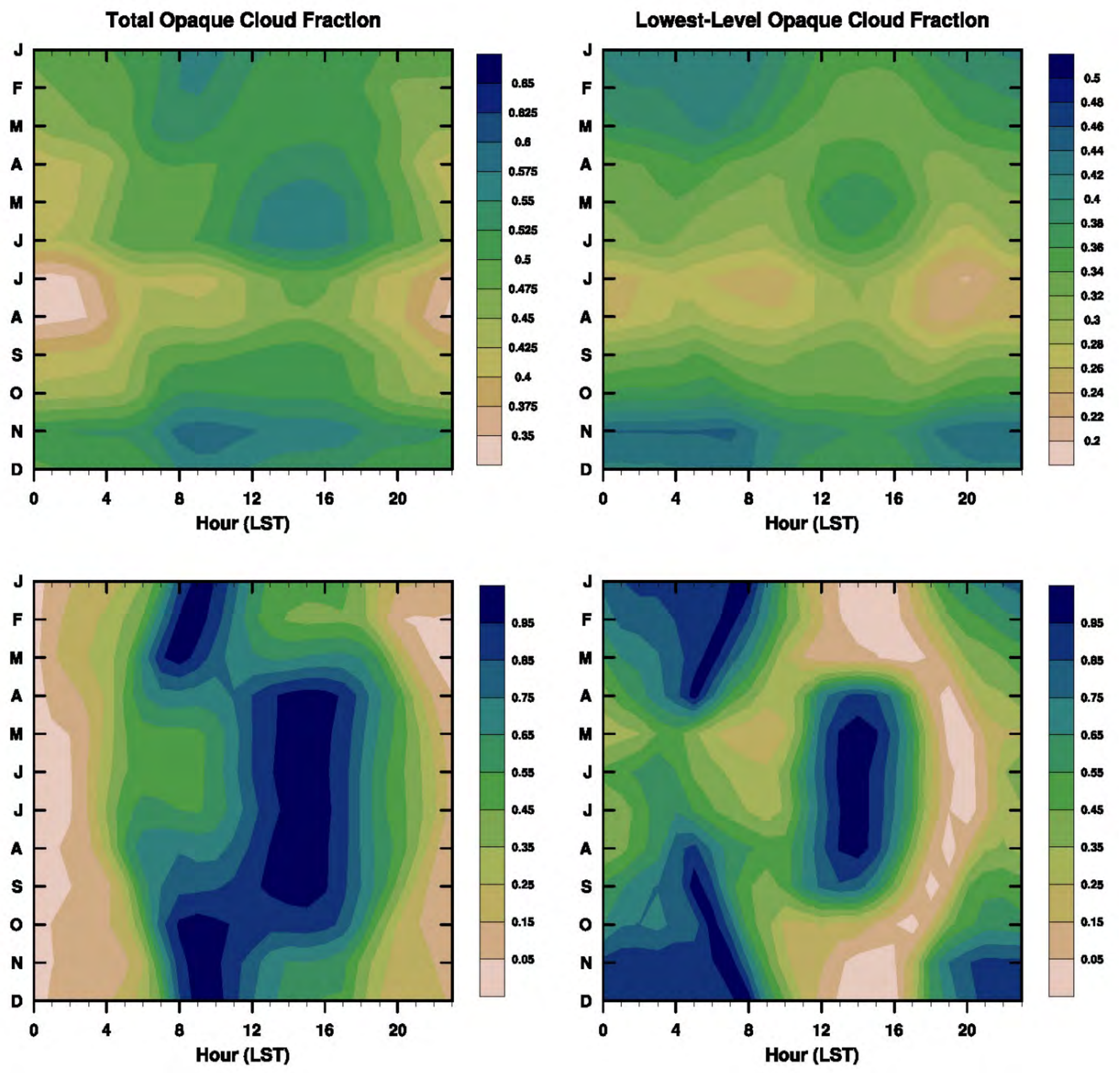


- **Daily means unbiased**
- **Correlation falls with distance**
- **Good data!**

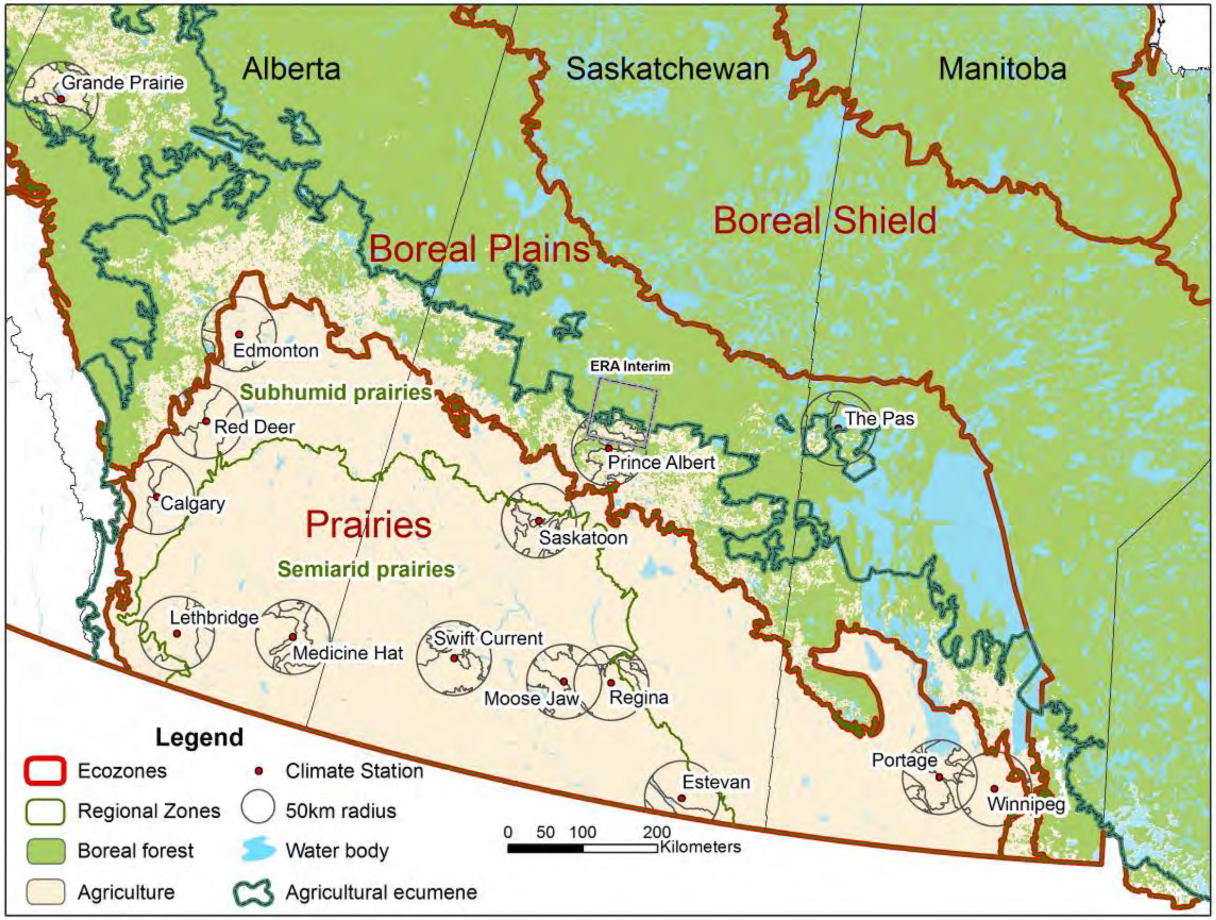


Annual/Diurnal Opaque Cloud

- **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 changes sign**



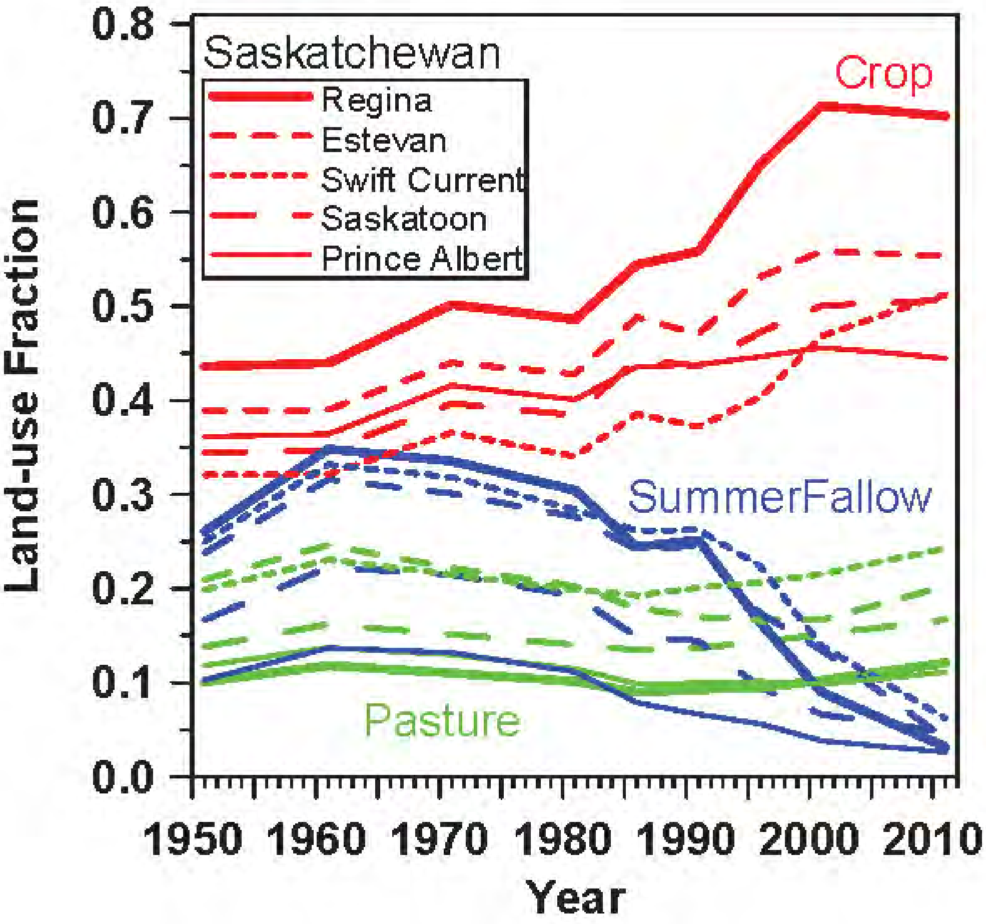
15 Prairie stations: 1953-2011



- ***How has changes in cropping changed the growing season climate?***

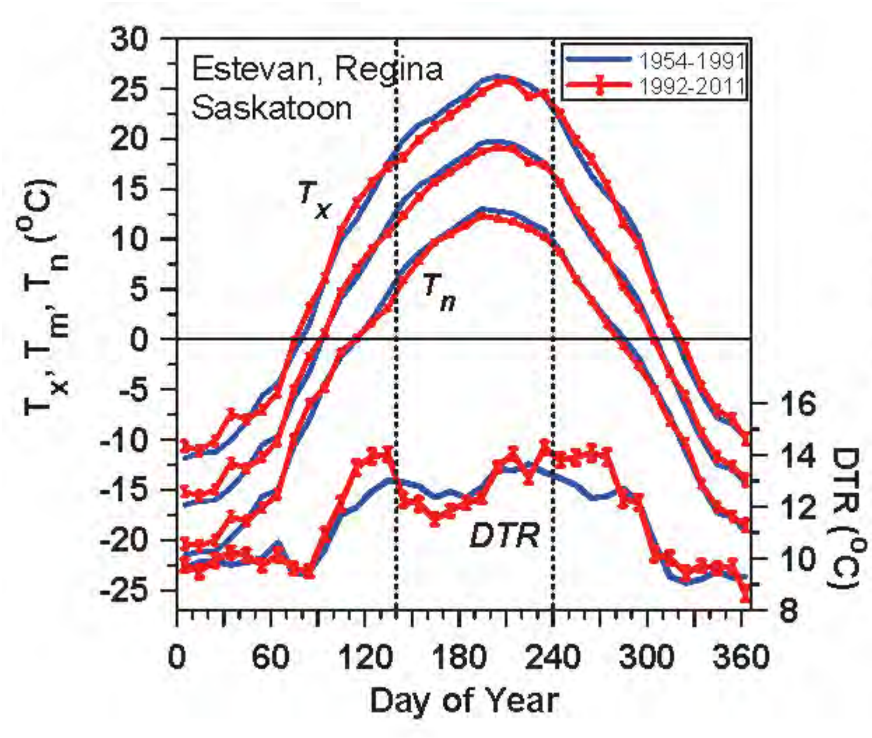
Change in Cropping (SK)

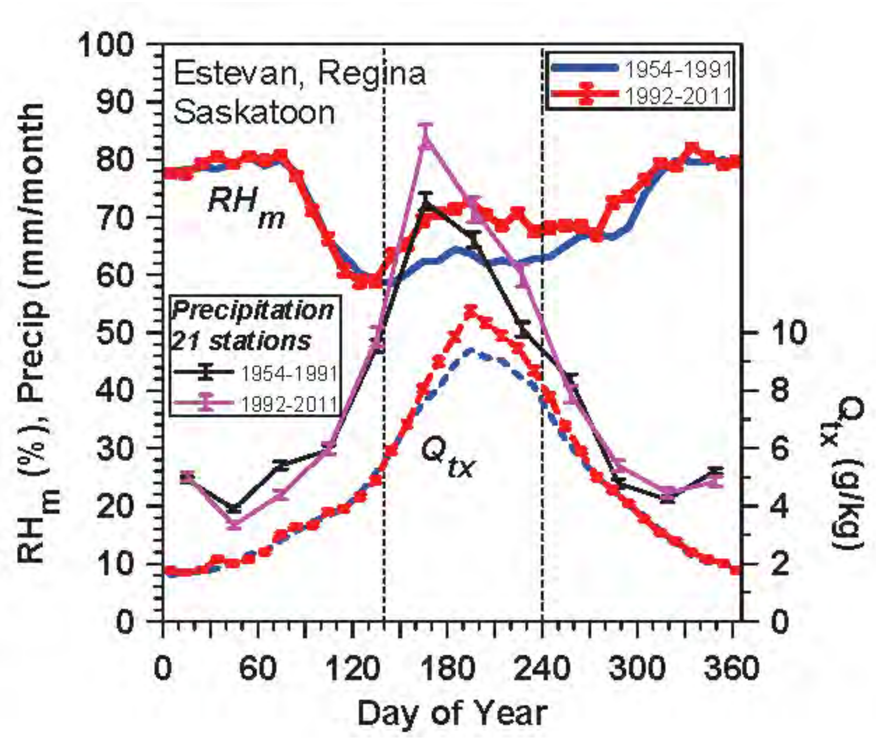
- **Ecodistrict mean for 50-km around station**
- **5 Mha drop (25%) in 'SummerFallow'**
  - **no crops: save water**
- ***Split at 1991 – Ask***
- ***Has summer climate changed?***



Betts et al. 2013b

Three Station Mean in SK



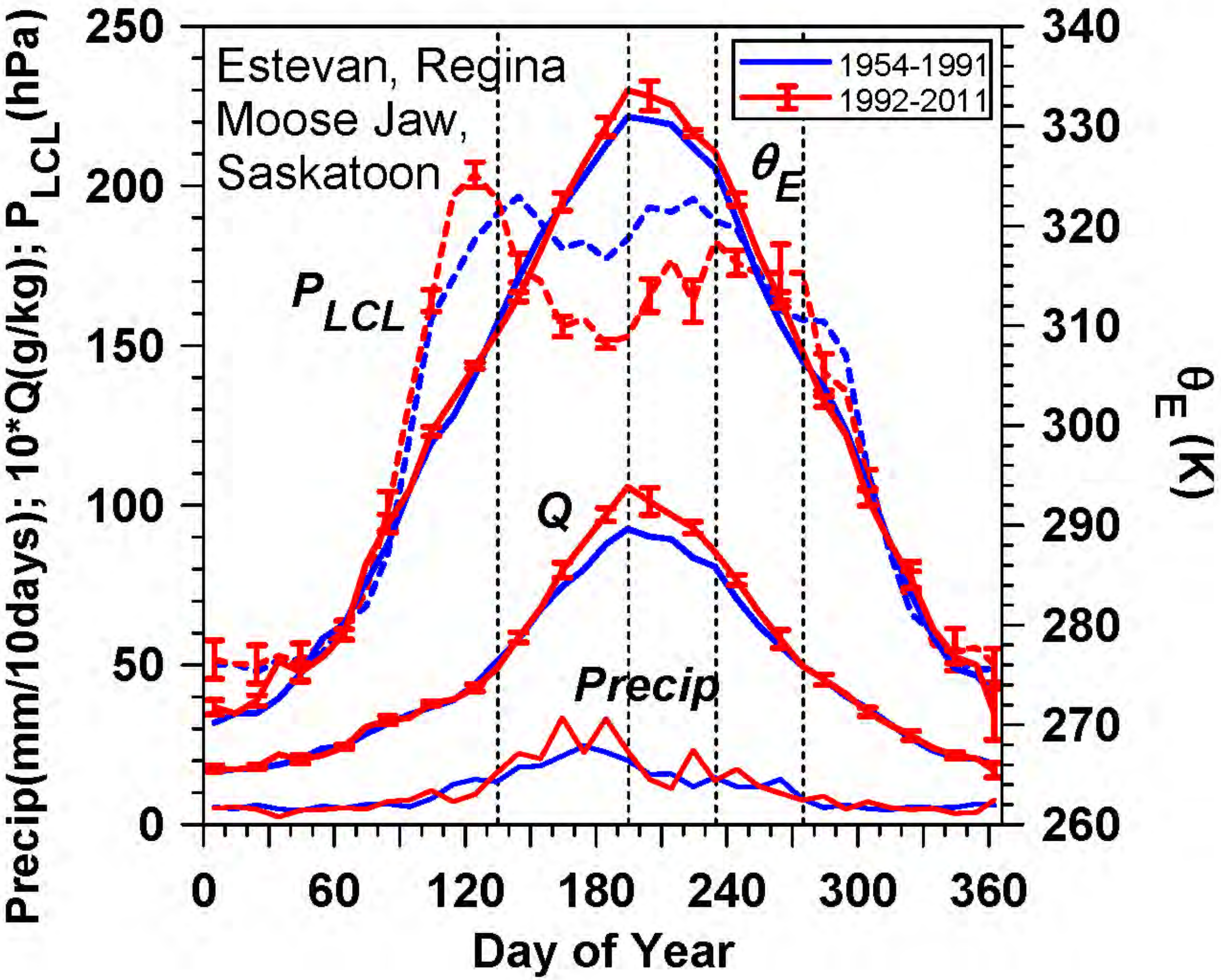


- **Growing season (Day of Year: 140-240)**
- **(T_x, T_m) cooler (-0.93±0.09, -0.82±0.07 °C)**
- **(RH_m, Q_{tx}) (+6.9±0.2%, +0.70±0.04 g/kg)**
- **Precipitation: +25.9±4.6 mm for JJA (+10%)**

Impact on Convective Instability

Growing season

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

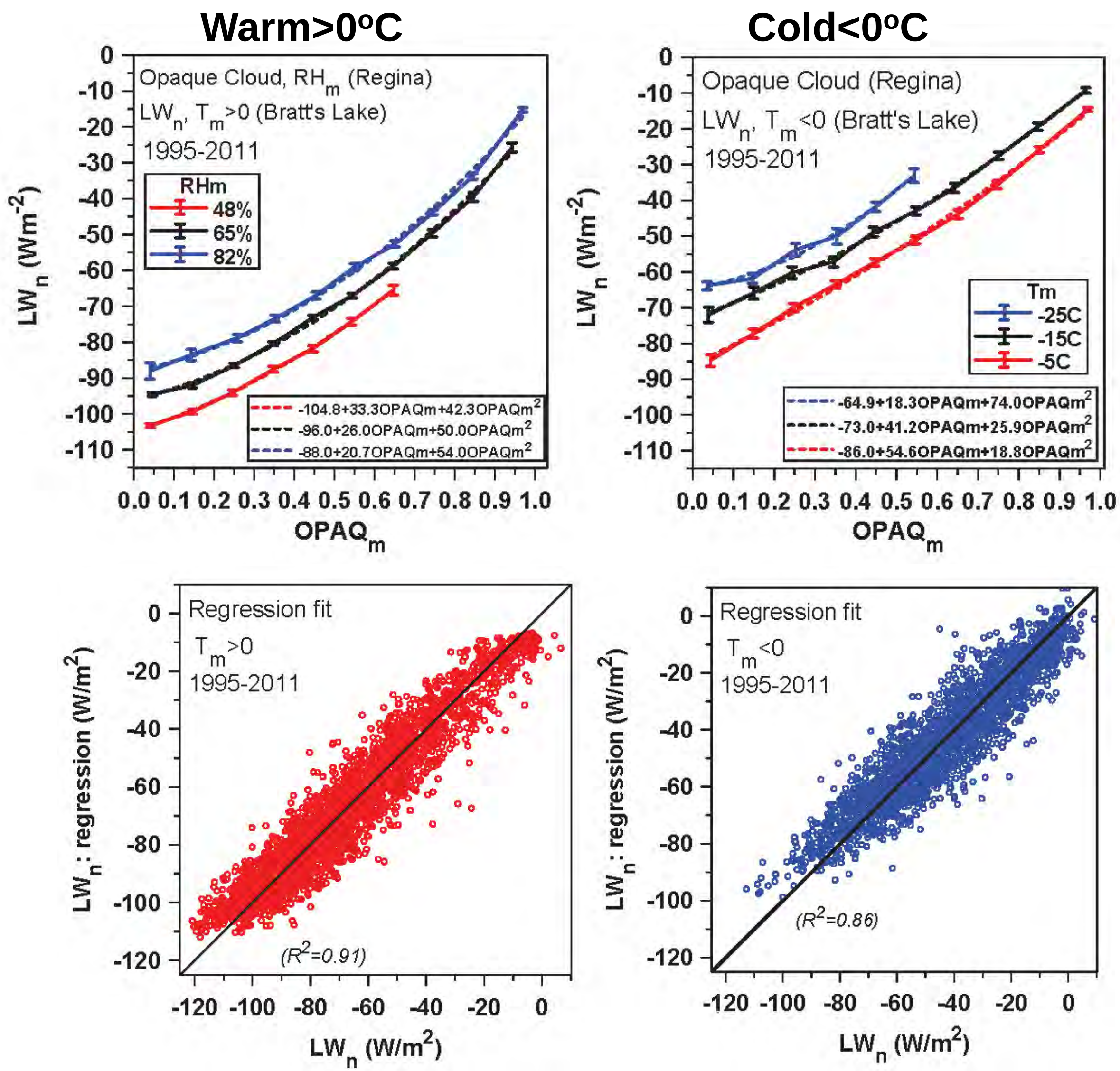


Betts et al. 2013b

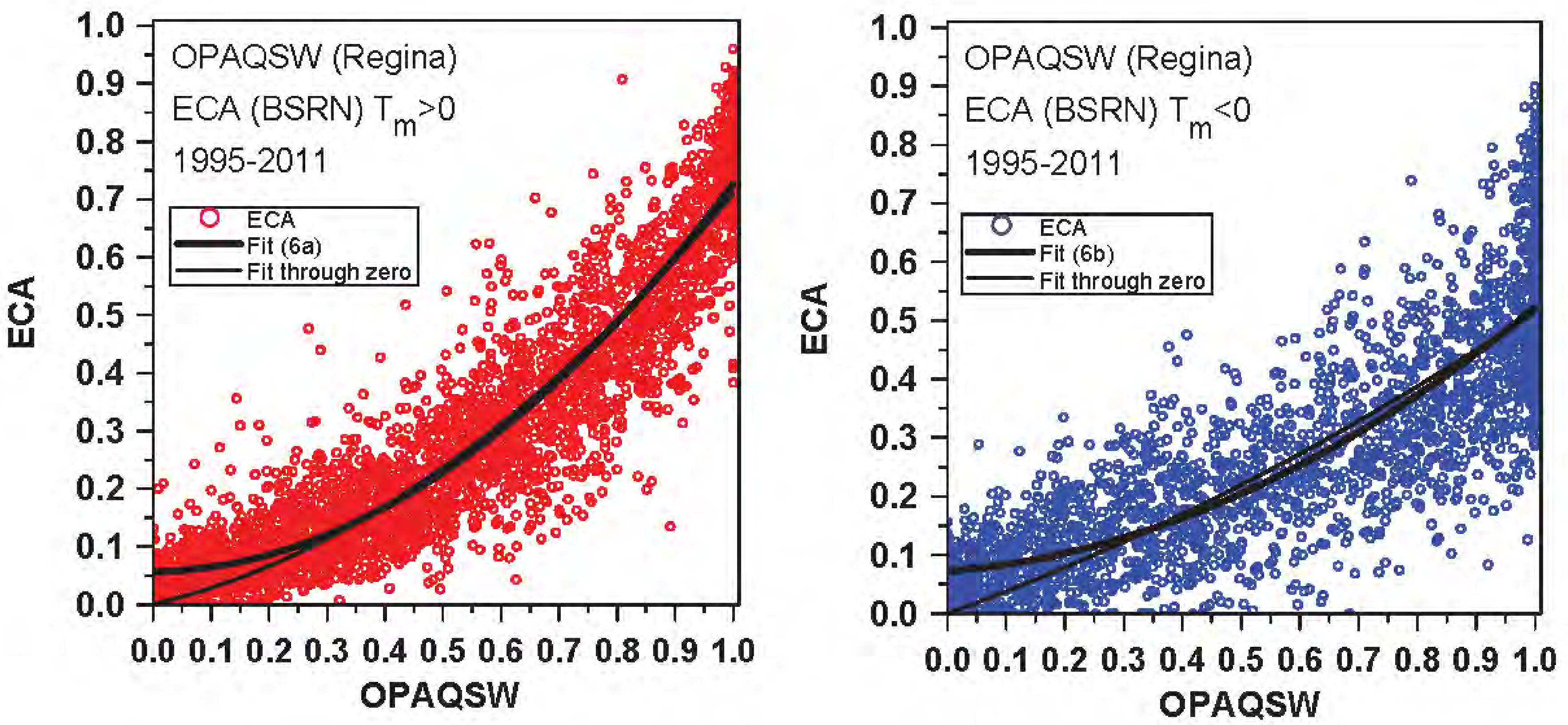
Use BSRN data to “calibrate” daily opaque/reflective Cloud at Regina

- **Daily mean opaque cloud $OPAQ_m$**
- ***LW cools but clouds reduce cooling***
- **Net LW: LW_n**
  - *T>0: RH dependence*
  - *T<0: T, TCWV also*
- ***Regression gives LW_n to ± 8W/m² for T_m>0 (R^2=0.91)***

(Betts et al. 2015)



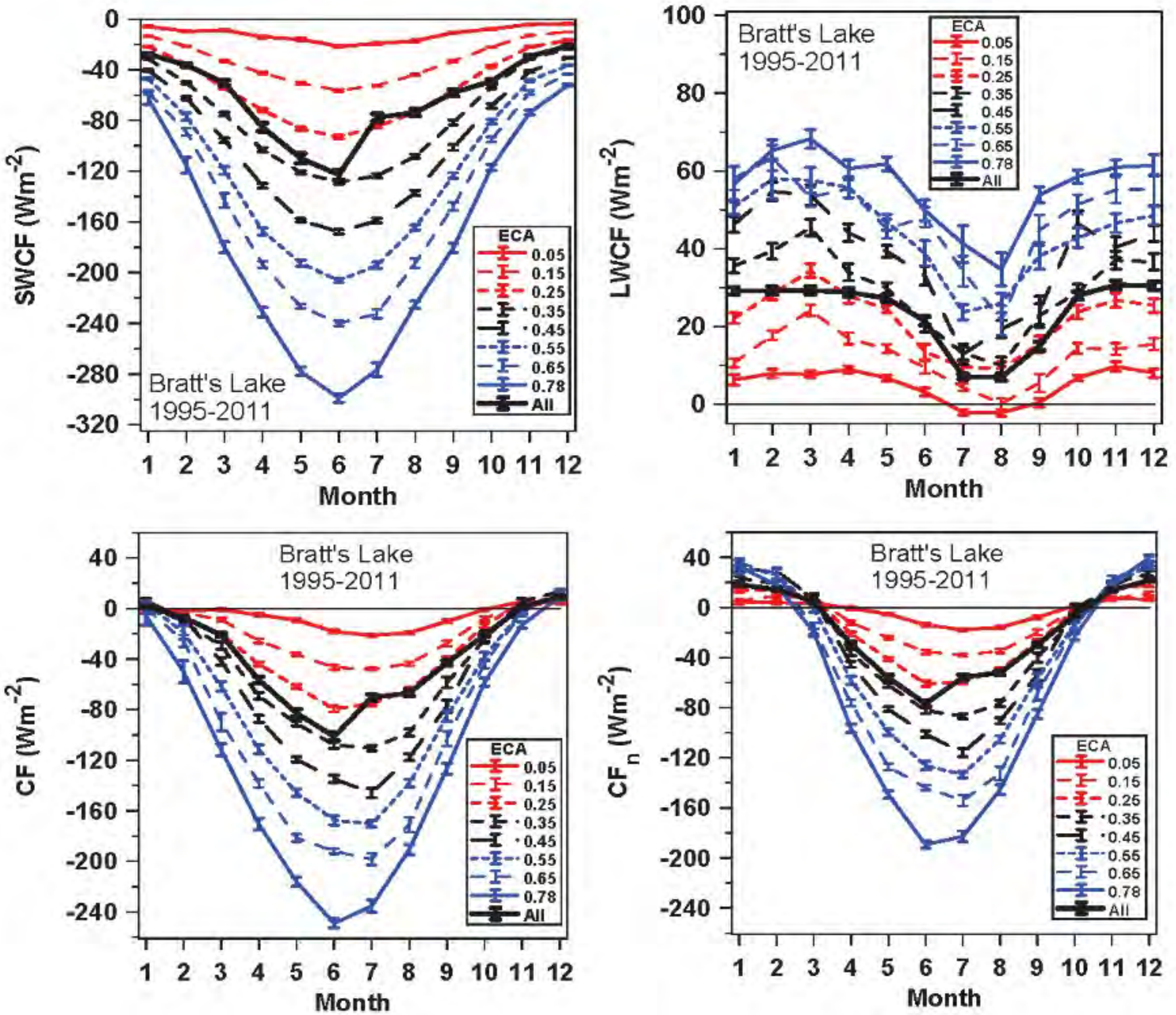
SW calibration



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

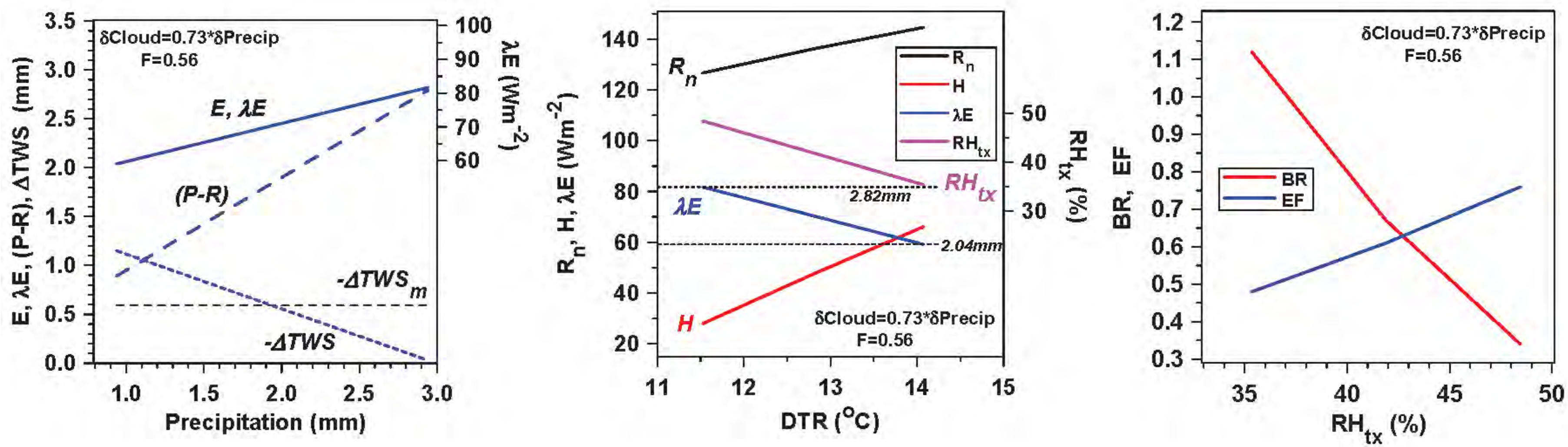
SW and LW Cloud Forcing
BSRN at Bratt's Lake, SK

- **"Cloud Forcing"**
  - ***Change from clear-sky flux***
- **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)

Growing Season Coupling between Energy and Water Budgets and Surface Climate



Betts et al. 2014b

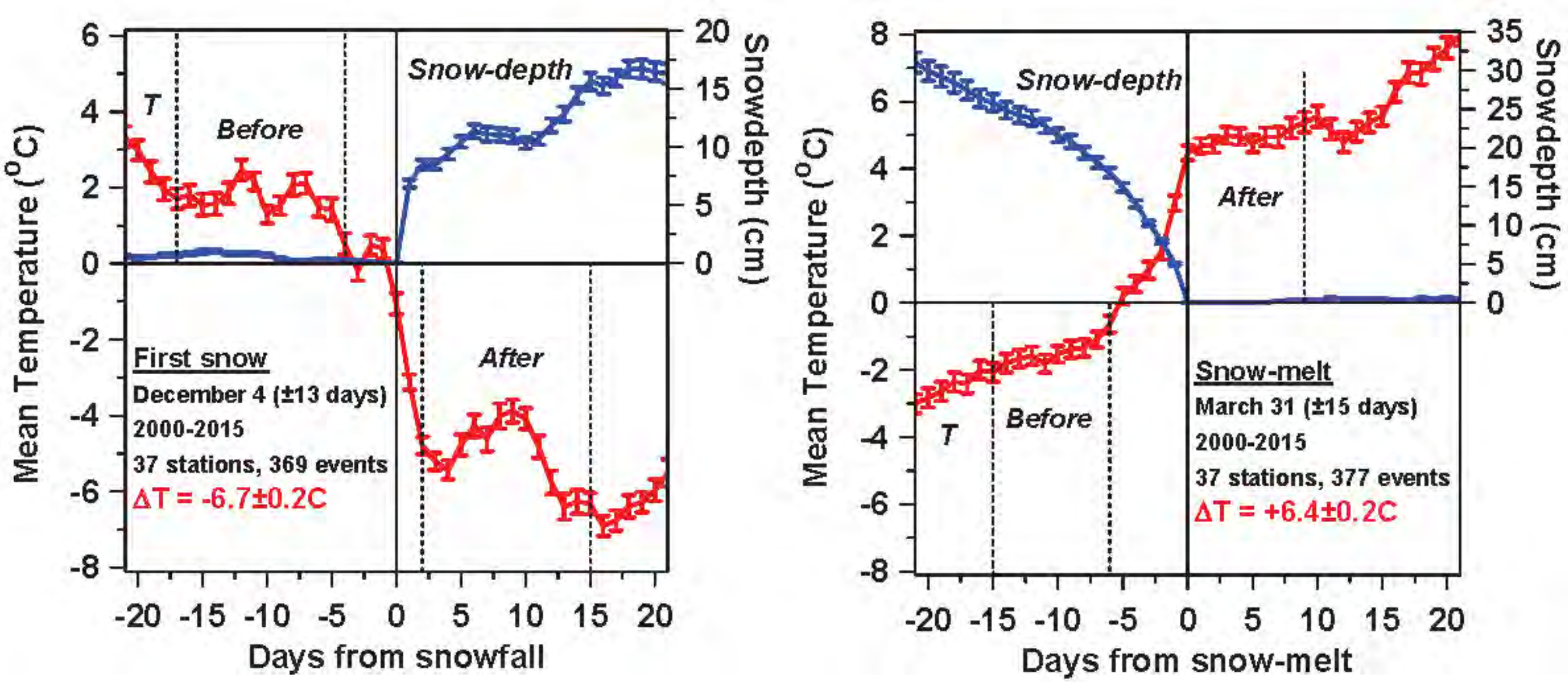
- **Total water storage (GRACE) coupled to precipitation variability (F=0.56)**
- **Climate cloud coupling: δCloud = 0.73 δPrecip**
- **R_n coupled to cloud variability**
- **Diurnal climate coupled to cloud and precipitation variability (regression)**

Warm and Cold Seasons

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

- Stable BL: LWCF +
- Cloud reduce LW loss
- Snow - reflects sunlight

Snowfall and Snowmelt
ΔT Vermont



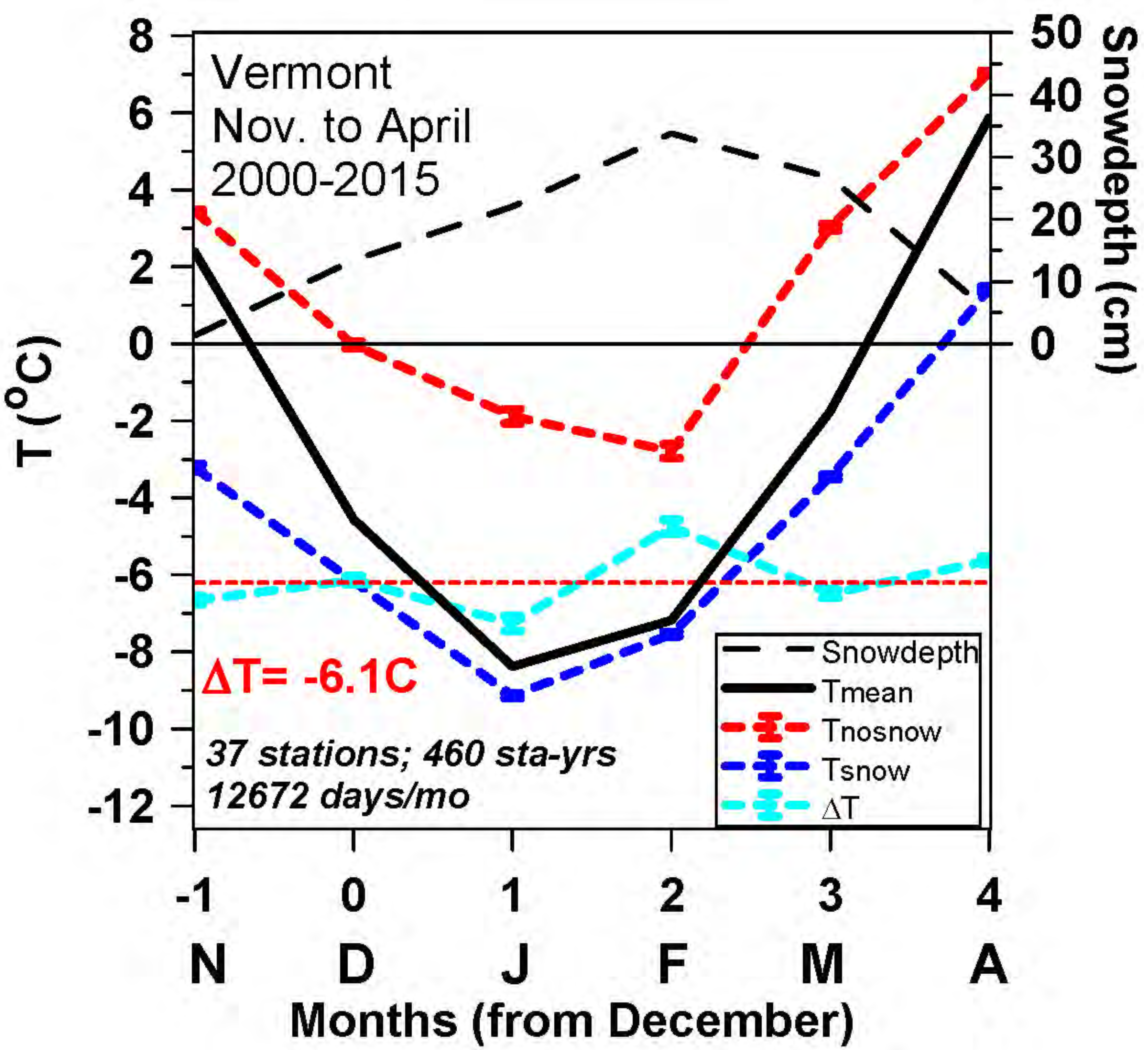
- **Temperature falls/rises 6.5 °C with first snowfall/snowmelt**
- **Albedo with snow less than Prairies**

Climatological Impact of Snow: Vermont

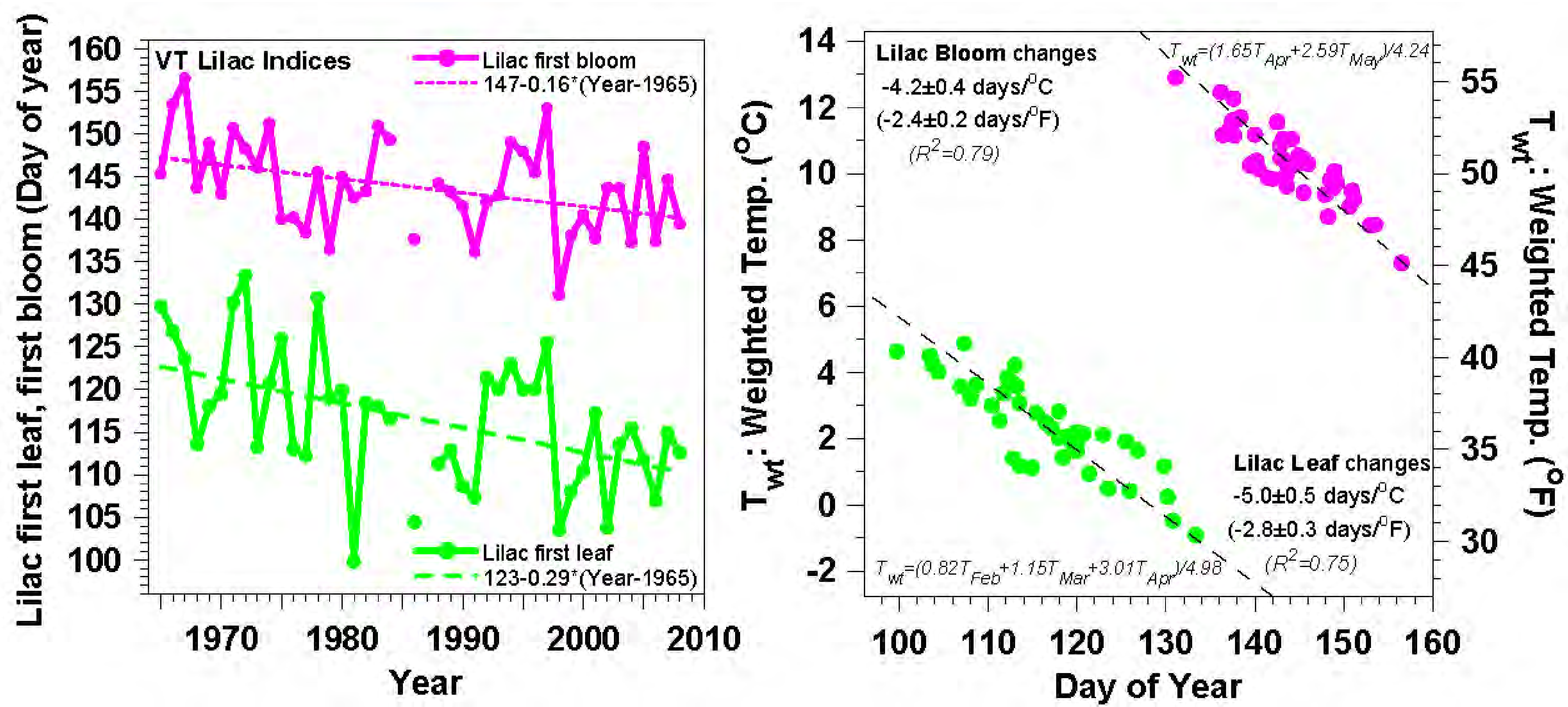
Separate mean climatology into days with no-snow and with snow

Difference ΔT= -6.1(±0.7)°C

Snow-free winters: warmer than snowy winters: +6°C



Coupling to Phenology -Lilacs



- **Leaf-out earlier by 3 days/decade (tracks ice-out)**
- **Leaf-out changes 5 days/°C**
- **Snow-free winters: +6°C * 5days = 30 days earlier**

Climate Processes

- *Solar seasonal cycle*
- *Temp., RH, Cloud, Precip. coupled*
- 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