Revisiting Hydrometeorology using Cloud and Climate Observations

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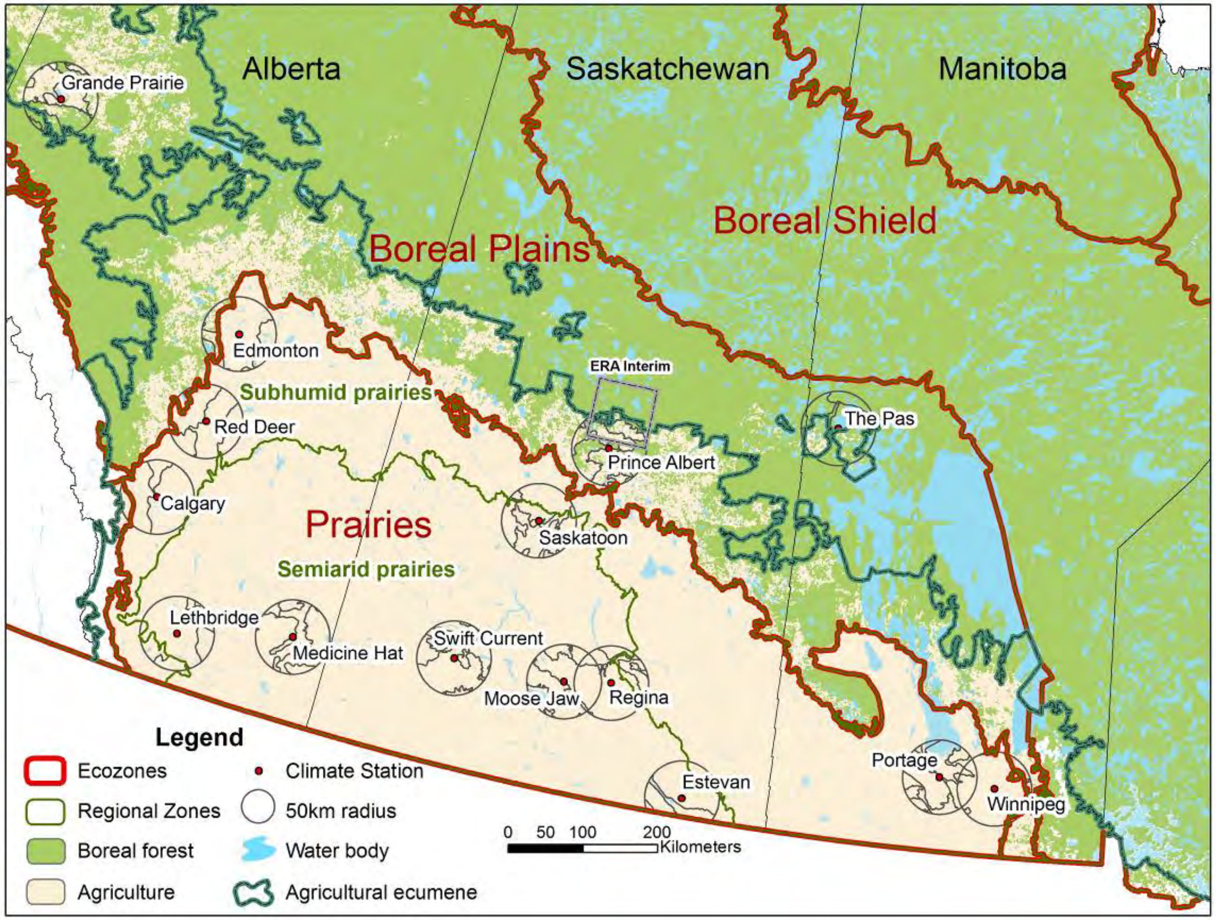
Reinventing Hydrometeorology

- *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^{o}C**
      - **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)

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- 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 (2013), 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. 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
- 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

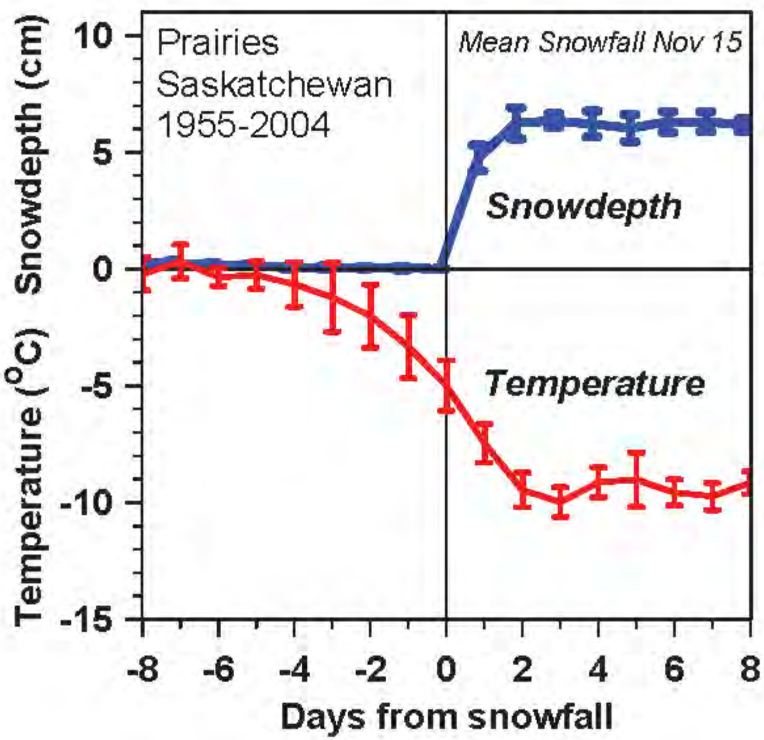
Diurnal Climate Dataset

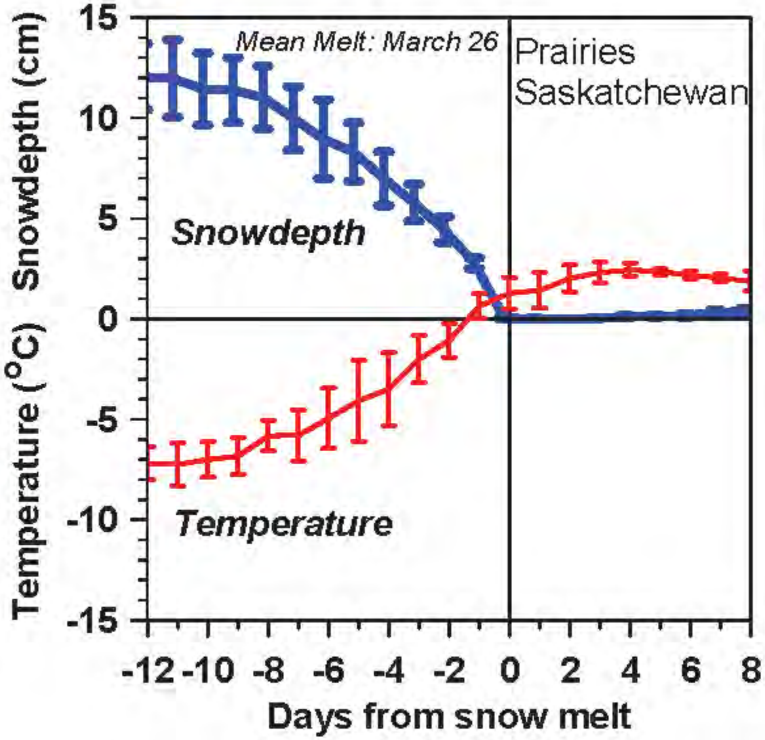
- **Reduce hourly data to**
  - **daily means: T_m , RH_m, $OPAQ_m$ etc**
  - **data at $T_{max/min}$: T_x and T_n**

- ***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

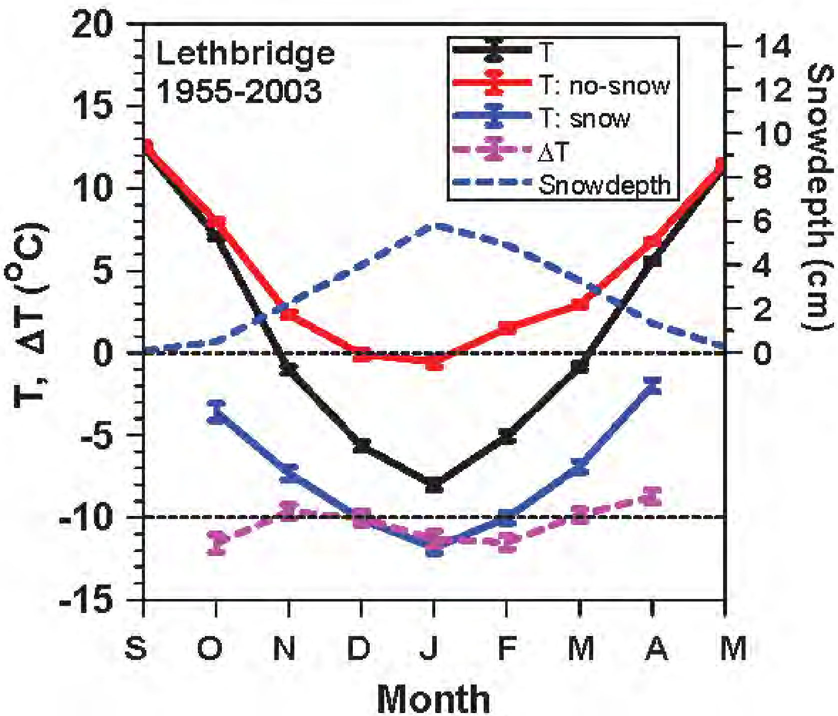


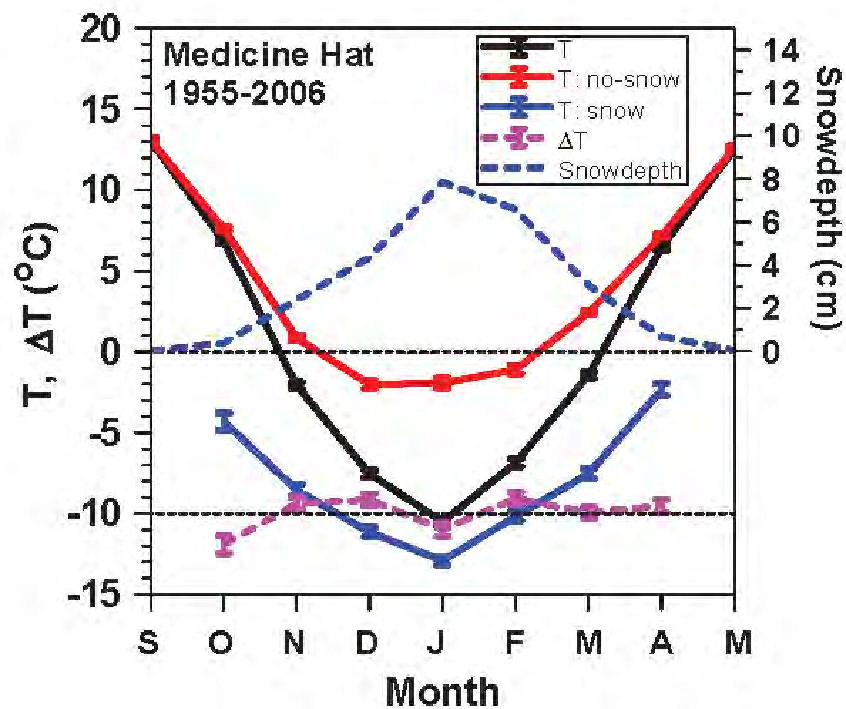


- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; shift to cold stable BL***
  - ***Local climate switch between warm and cold seasons***
  - ***Winter comes fast with snow***

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)°C

Betts et al. (2016)

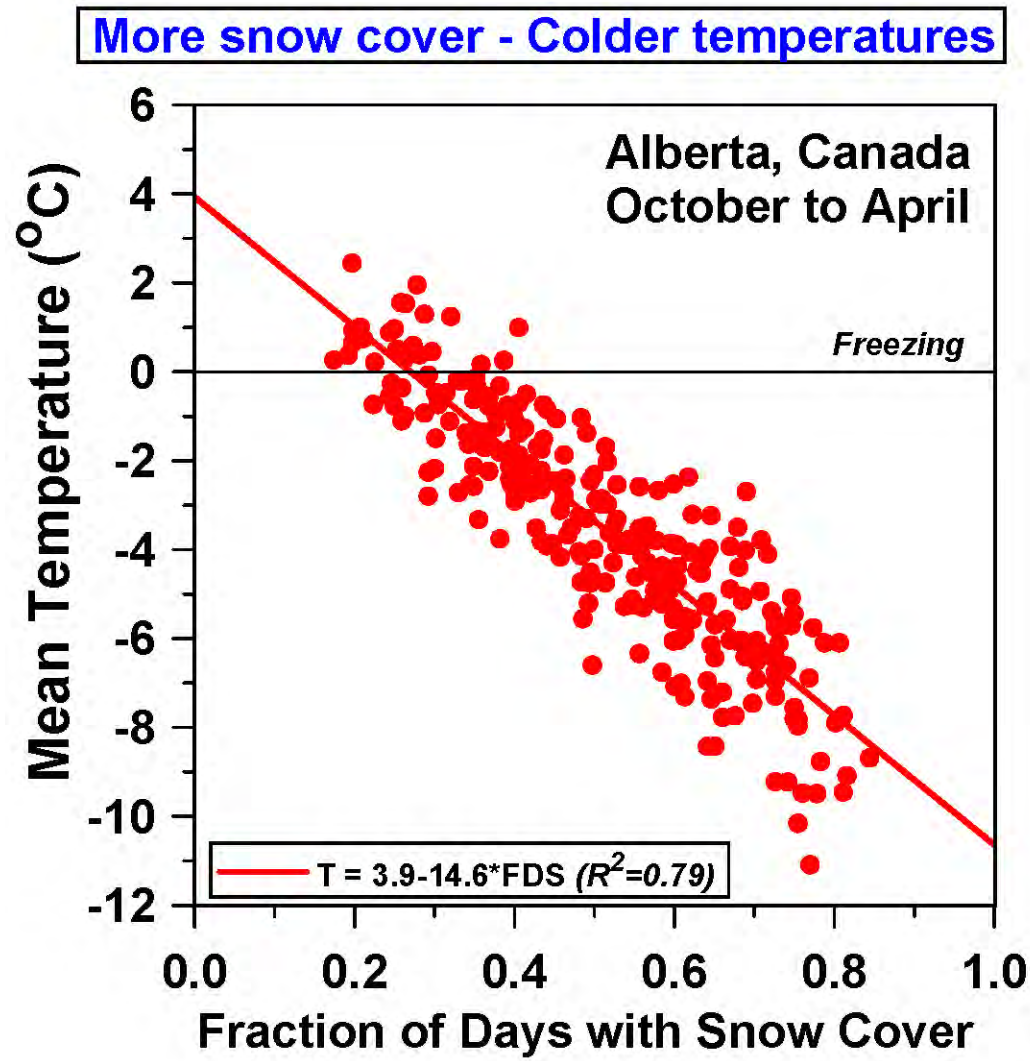
Interannual variability of T coupled to Snow Cover

- **Alberta: 79% of variance**
- **Slope T_m -14.7 ($\pm$ 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**

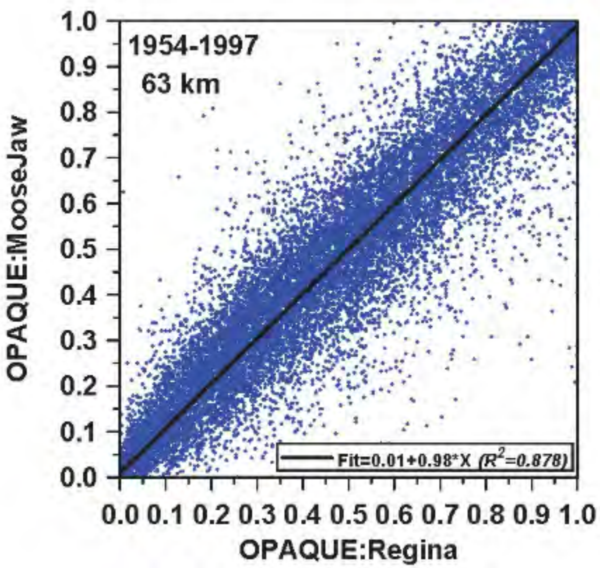
$$ECA = -SWCF/\ SW_{dn}(clear)$$

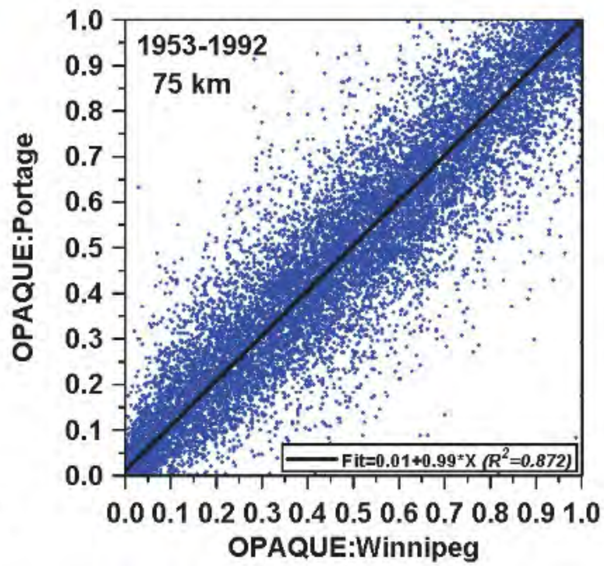
$$SW_n = (1 - \alpha_s)(1 - ECA)\ SW_{dn}(clear)$$

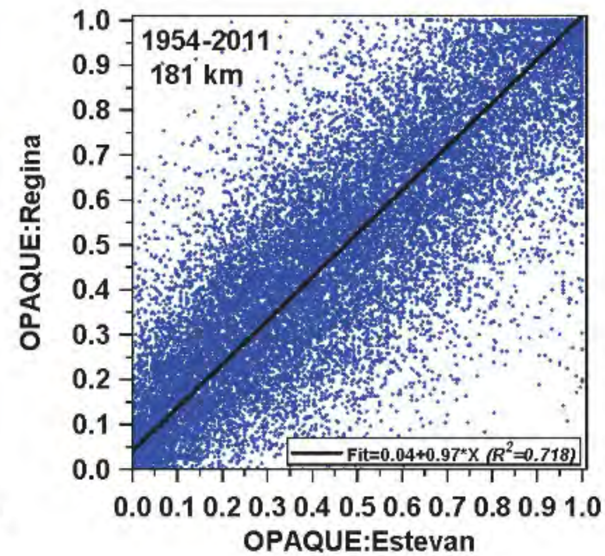
Reflected by surface, clouds

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

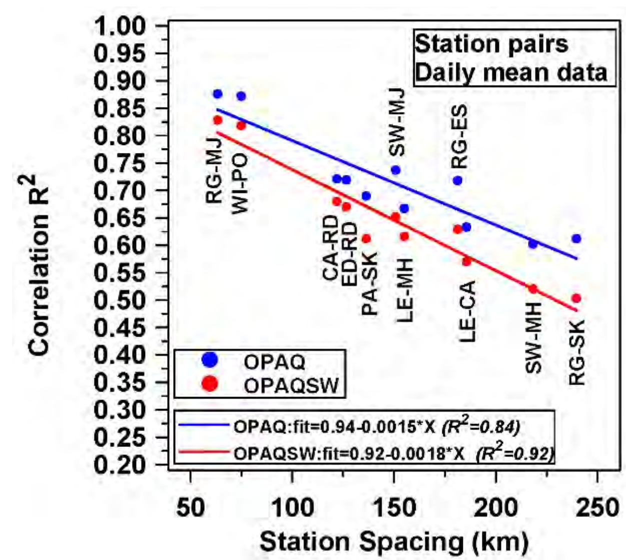
Opaque Cloud (Observers)





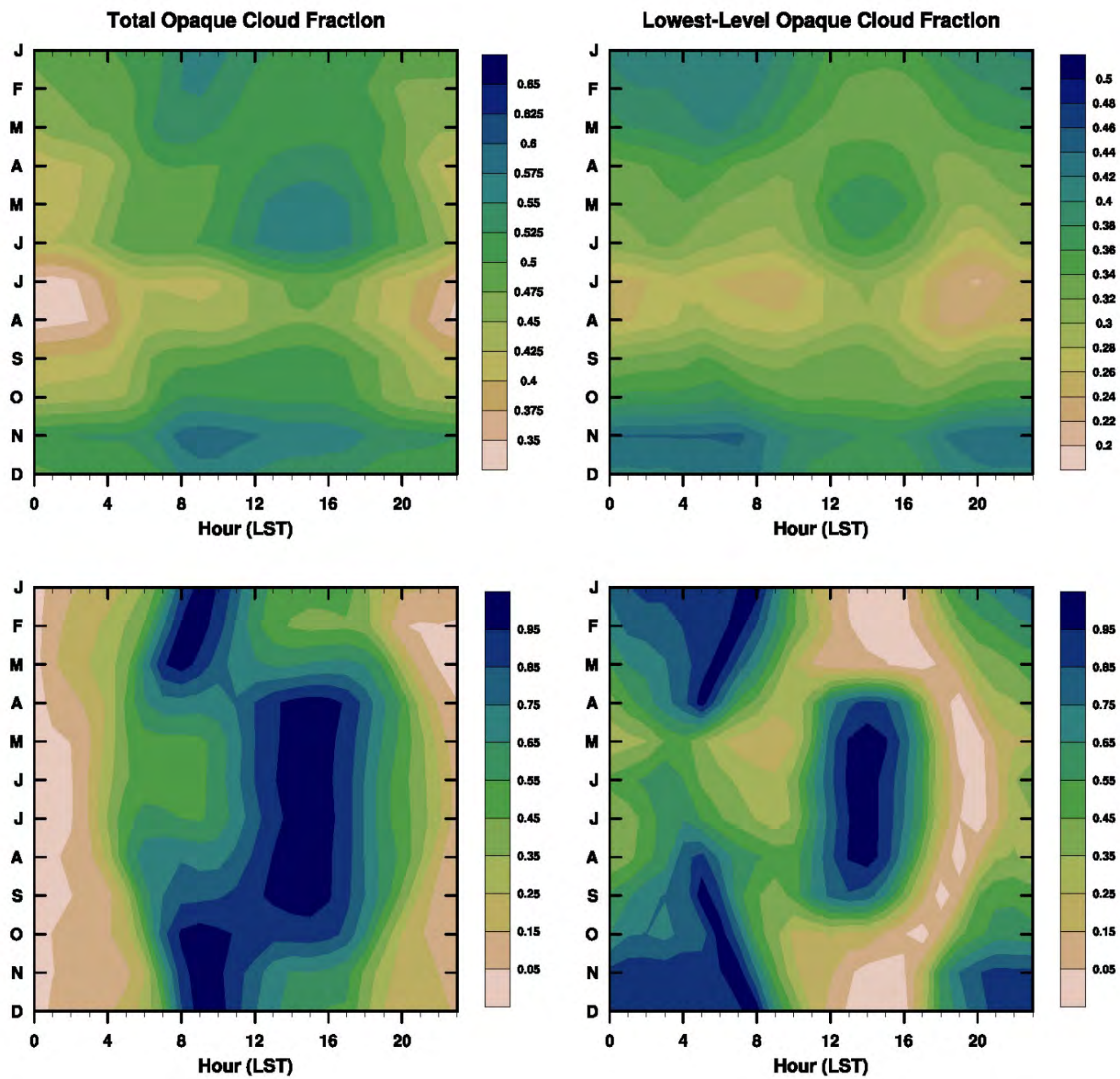


- **Daily means unbiased**
- **Correlation falls with distance**
- **Good data!**



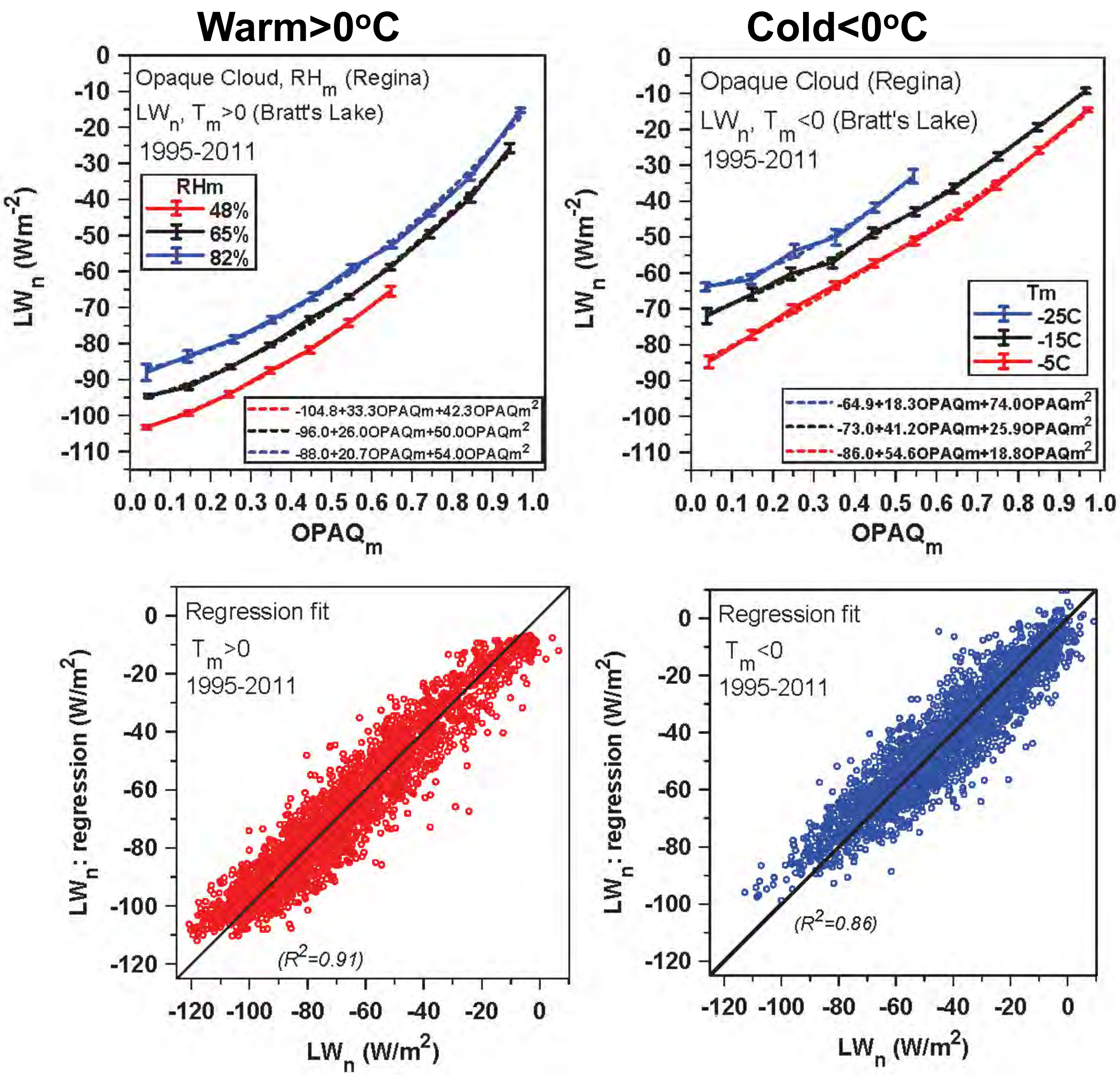
Annual/Diurnal Opaque Cloud

- 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



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)***

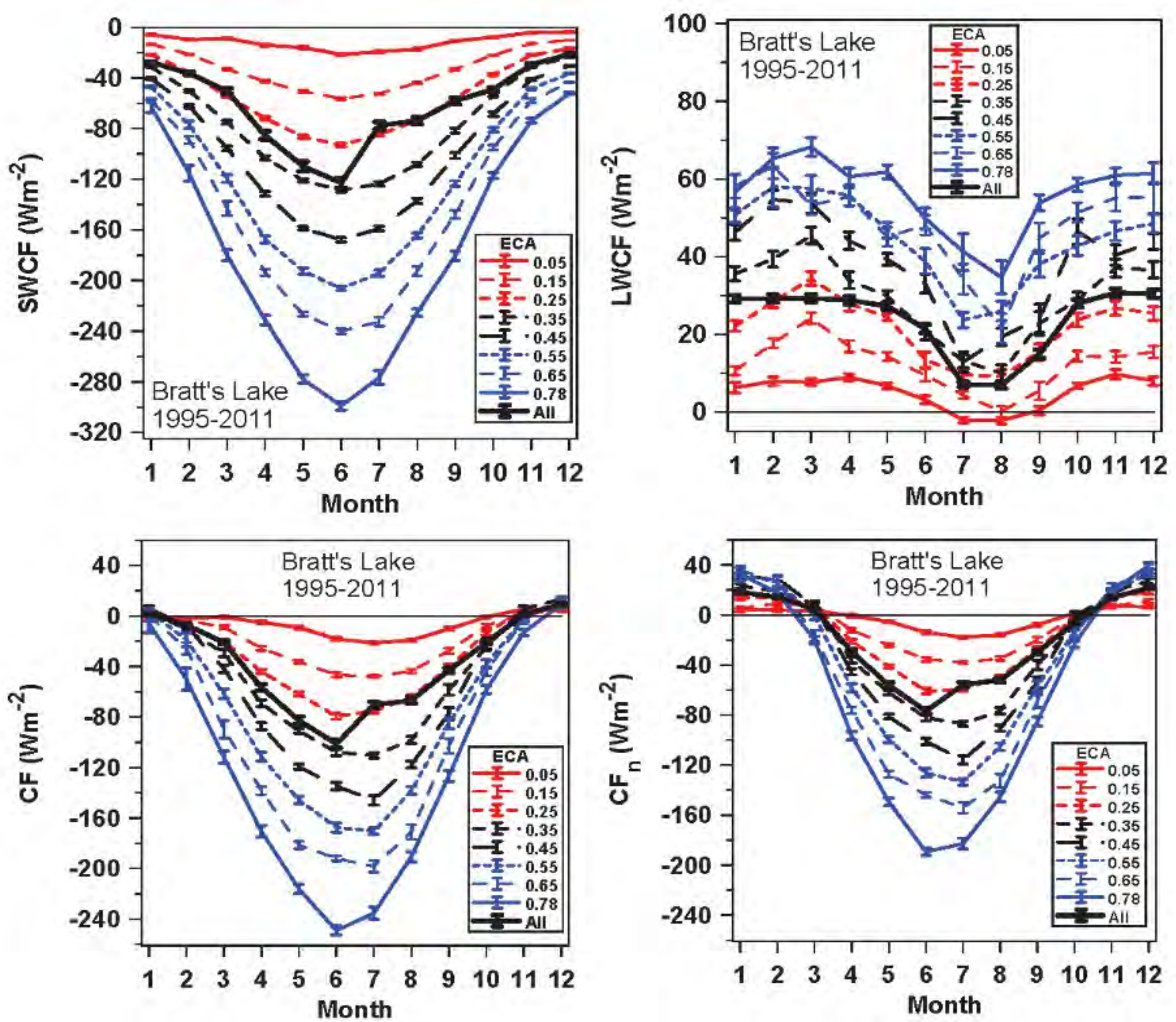


(Betts et al. 2015)

SW 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)



Diurnal cycle: Clouds & Snow

Canadian Prairies
660 station-years of data

Winter climatology

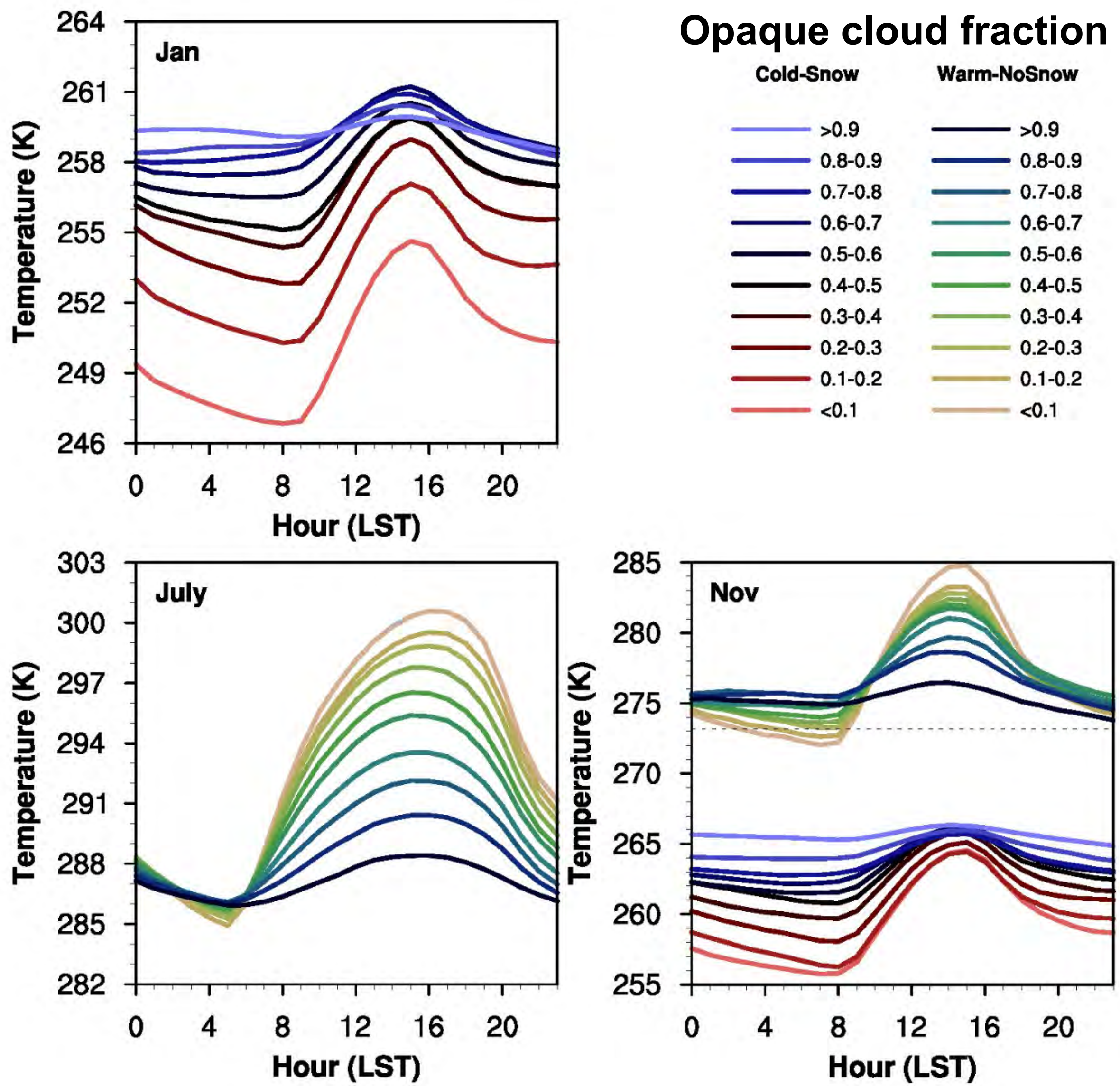
- Colder when clear
- LWCF dominant with snow
- Stable BL

Summer climatology

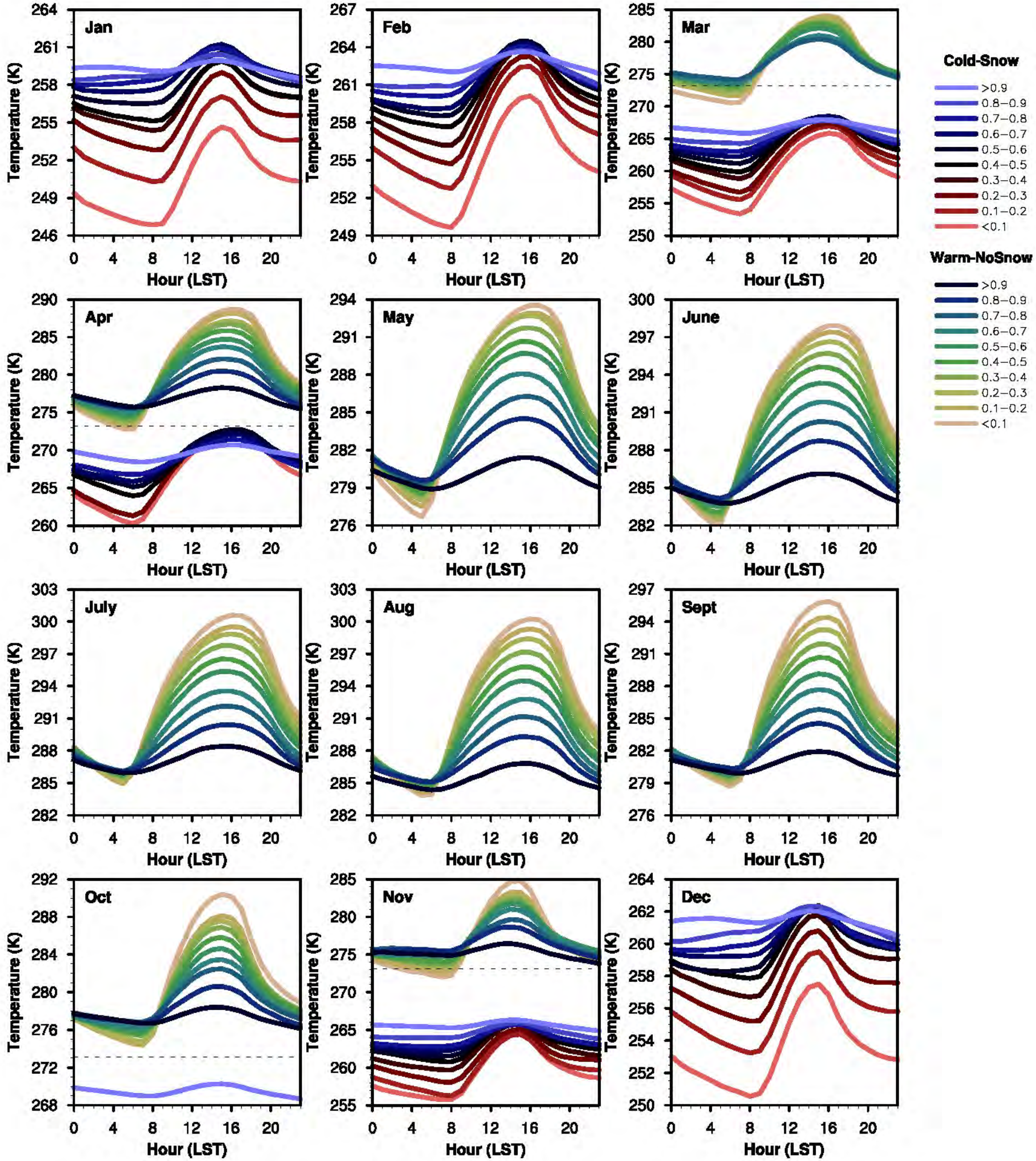
- Warmer when clear
- SWCF dominant: no snow
- Unstable daytime BL

Transition months:

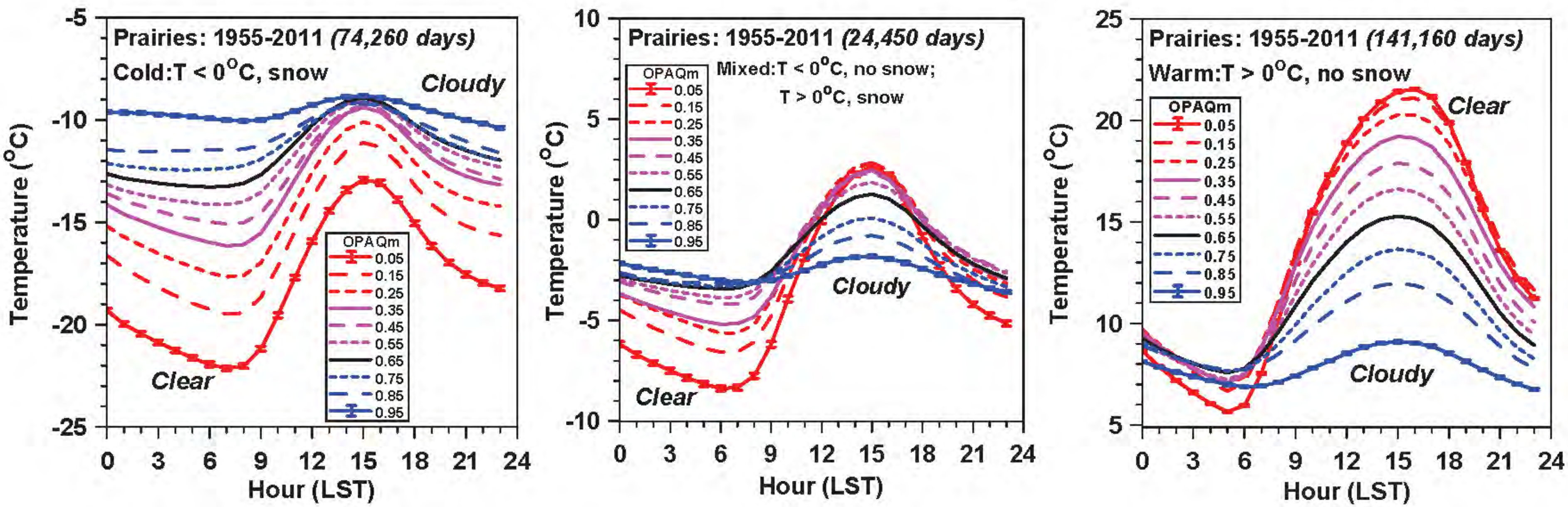
- Show both climatologies
- With 11K separation
- Fast transitions with snow
- Snow is “Climate switch”



Monthly diurnal climatology (by snow and cloud)



Merge all data
(650 years: 240,000 days)



Cold-Snow (31%) **Mixed (10%)** **Warm-NoSnow (59%)**

(Standard errors tiny)

Betts and Tawfik 2016)

Impact of Snow

- Distinct warm and cold season states
- Snow cover is the "climate switch"
- Prairies: ΔT = -10°C (winter albedo = 0.7)
- Vermont: ΔT = -6°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>0°C
(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)**

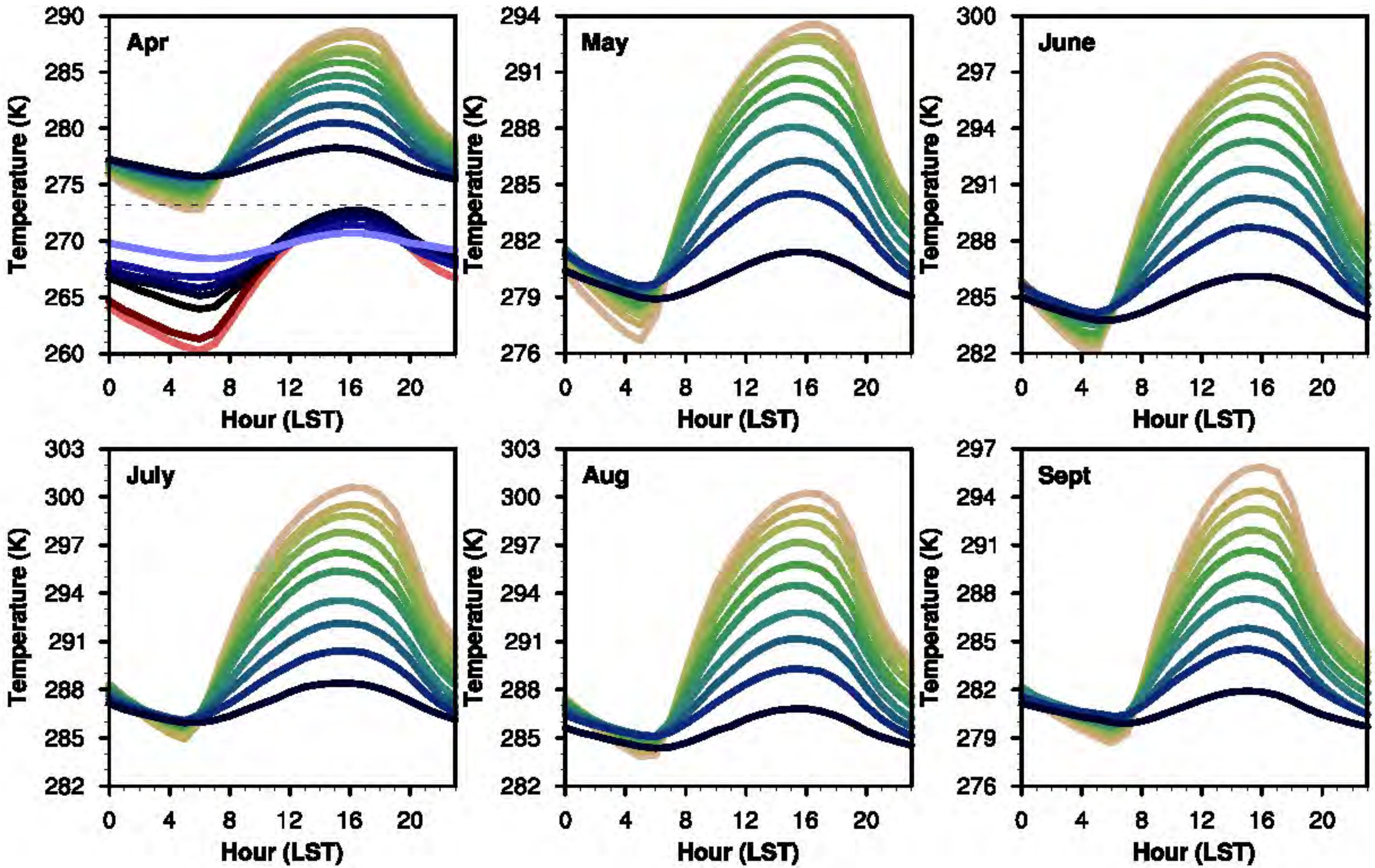
  $$DTR_D = T_{xD} - T_{nD}$$
  $$DRH_D = RH_{xD} – RH_{nD}$$ *(rarely shown)*

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

  $$DTR_T = T_{xT} - T_{nT}$$
  $$DRH_T = RH_{xT} – RH_{nT}$$

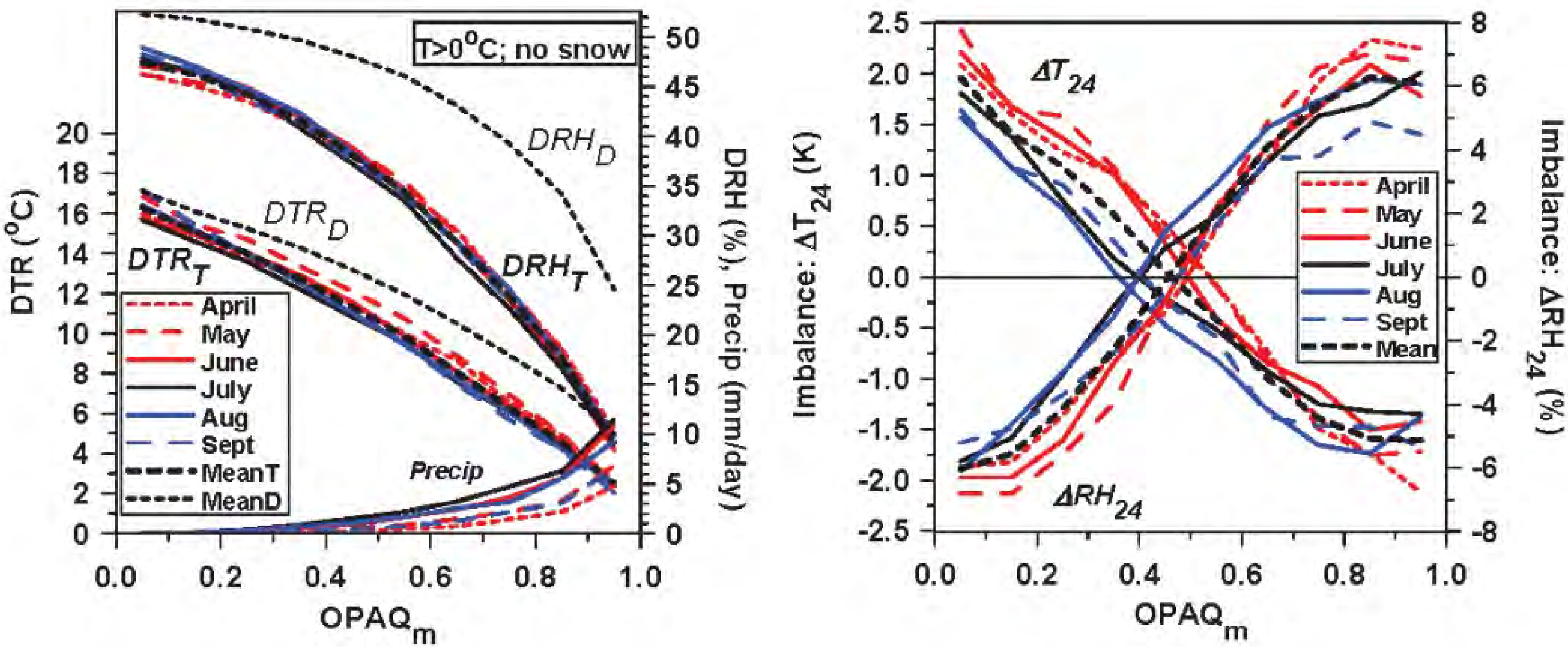
- **Q1: How are they related? $DTR_T < DTR_D$**

Monthly Diurnal Climatology



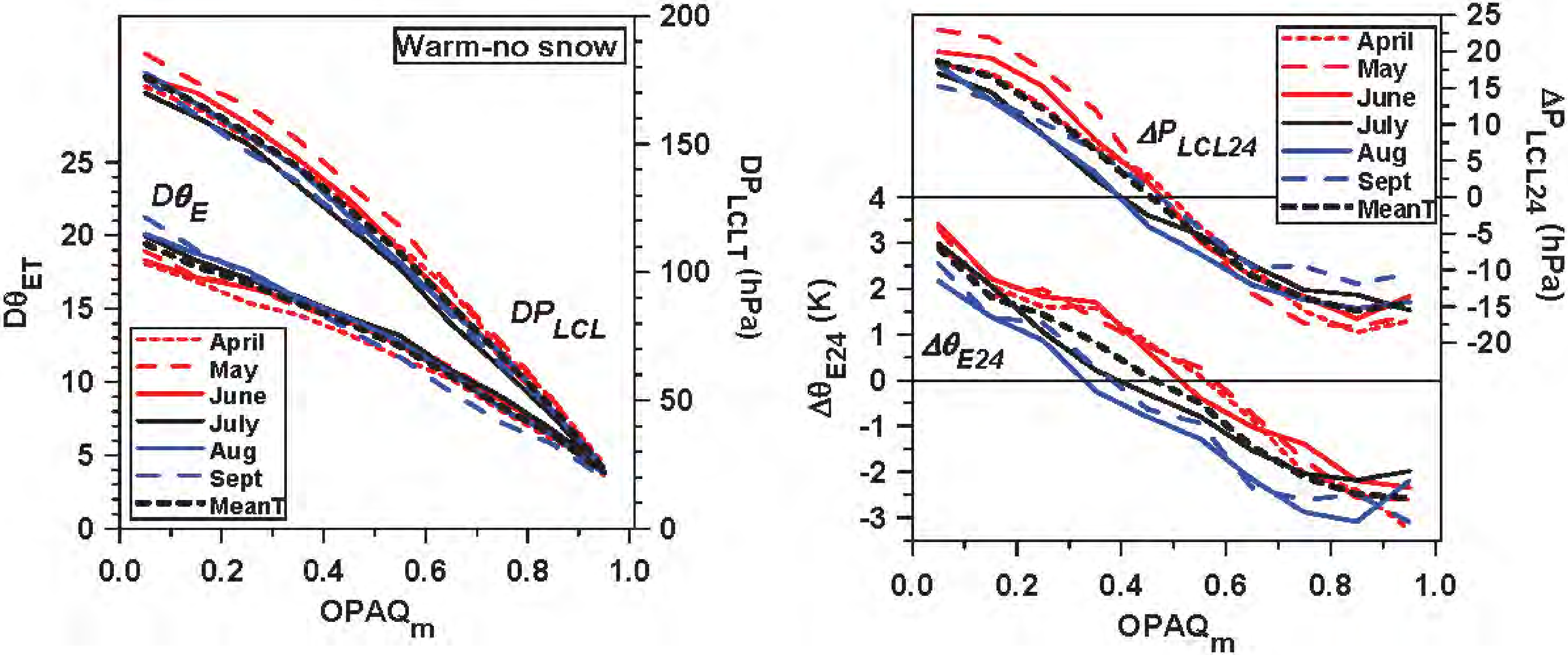
Q2: How much warmer is it at the end of a clear day?

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%)

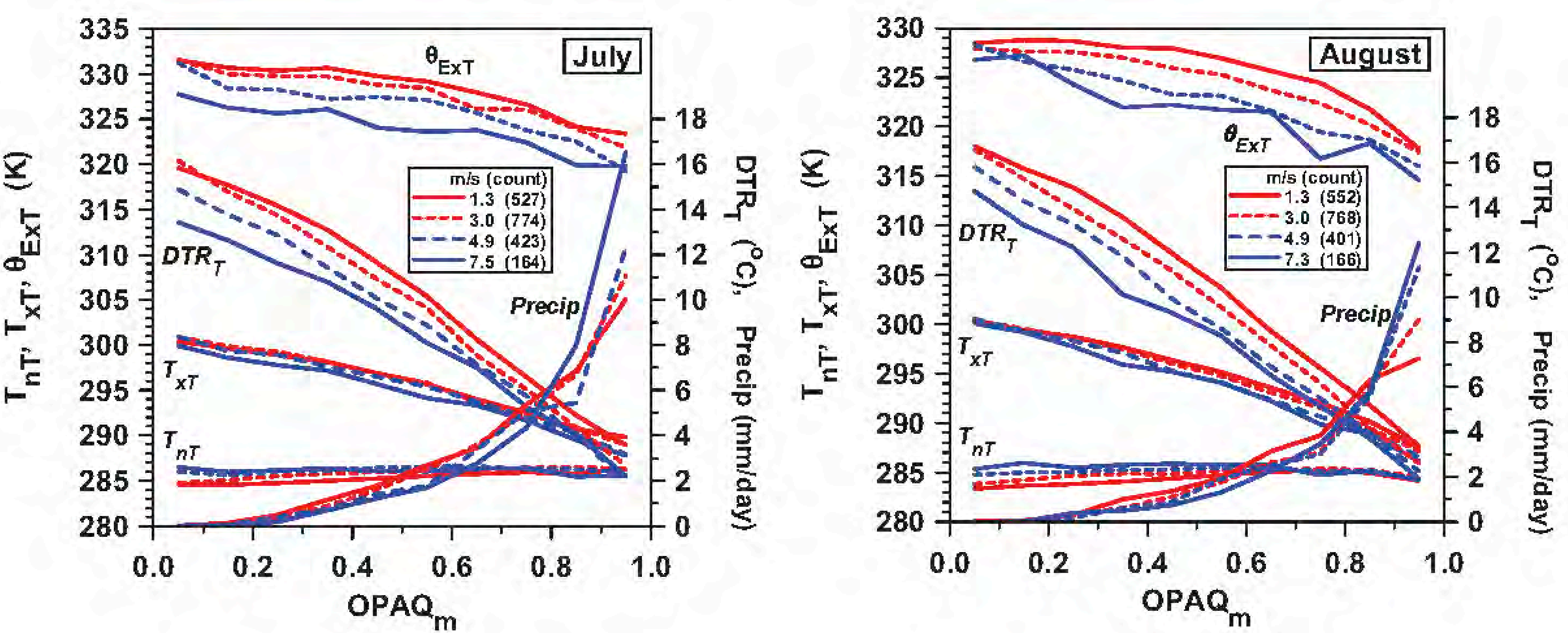
Diurnal Ranges & Imbalances



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

(Betts and Tawfik 2016)

Stratify by Cloud and 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)

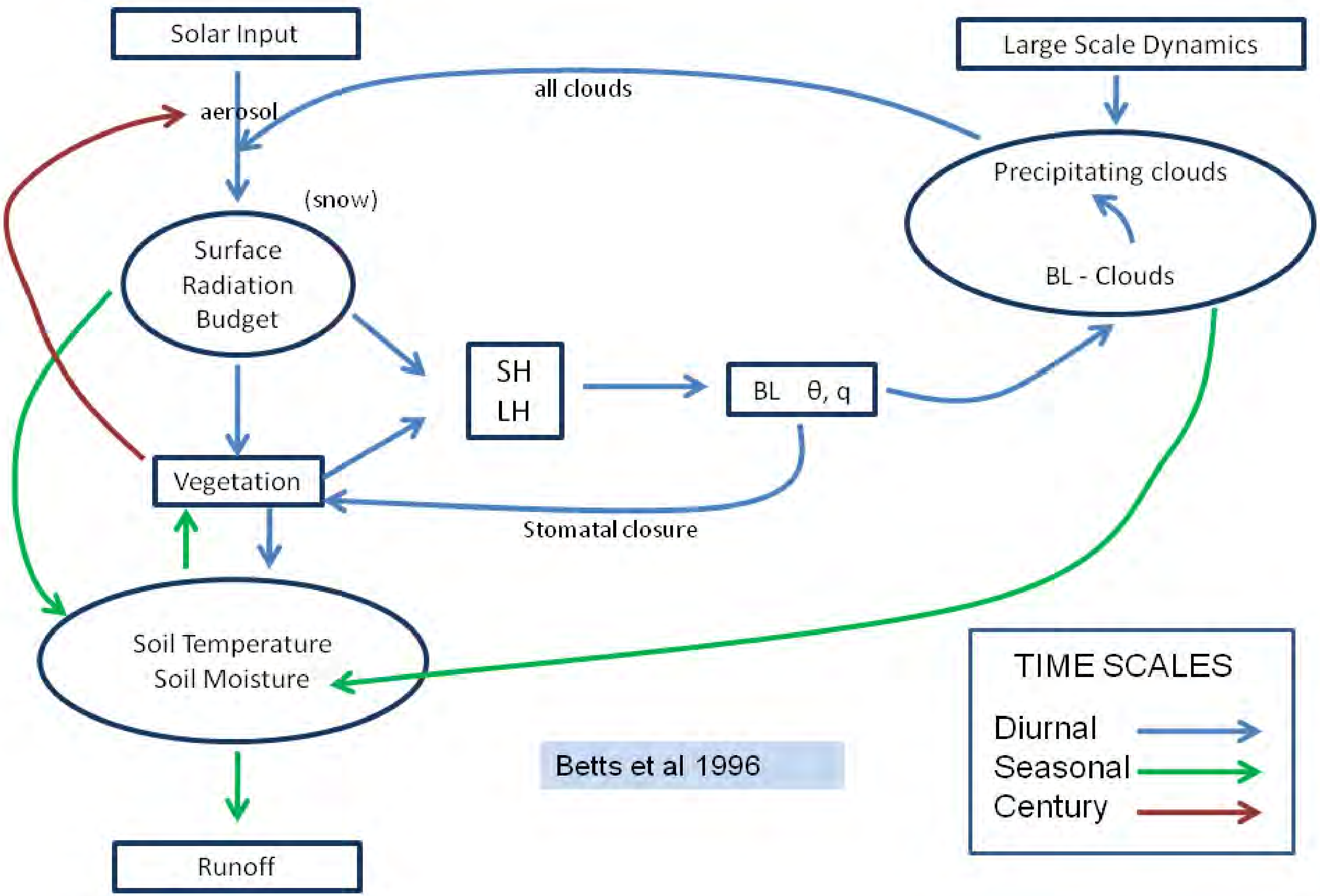
Warm Season Climate: T>0°C

(May to September: no snow)

- ***Hydrometeorology***
  - ***<u>with Precipitation and Radiation</u>***
  - ***<u>Diurnal cycle of T and RH</u>***
  - ***Cannot do <u>coupling</u> with just T & Precip !***
- ***<u>Monthly timescale: Fully coupled</u>***
  - ***Use regression to couple anomalies***

Betts et al. 2014b

Fully coupled system



Betts et al 1996

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

Monthly Regression on Cloud and lagged Precip. anomalies

- **Monthly anomalies (normalized by STD of means)**
  - **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***

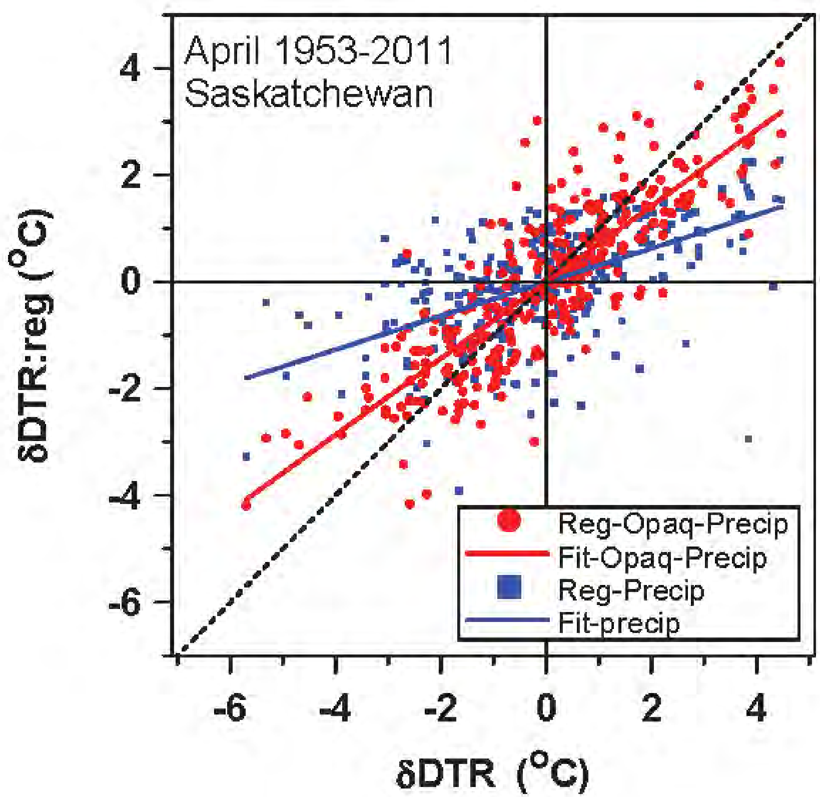
June, July, Aug: ***memory of moisture back to March***

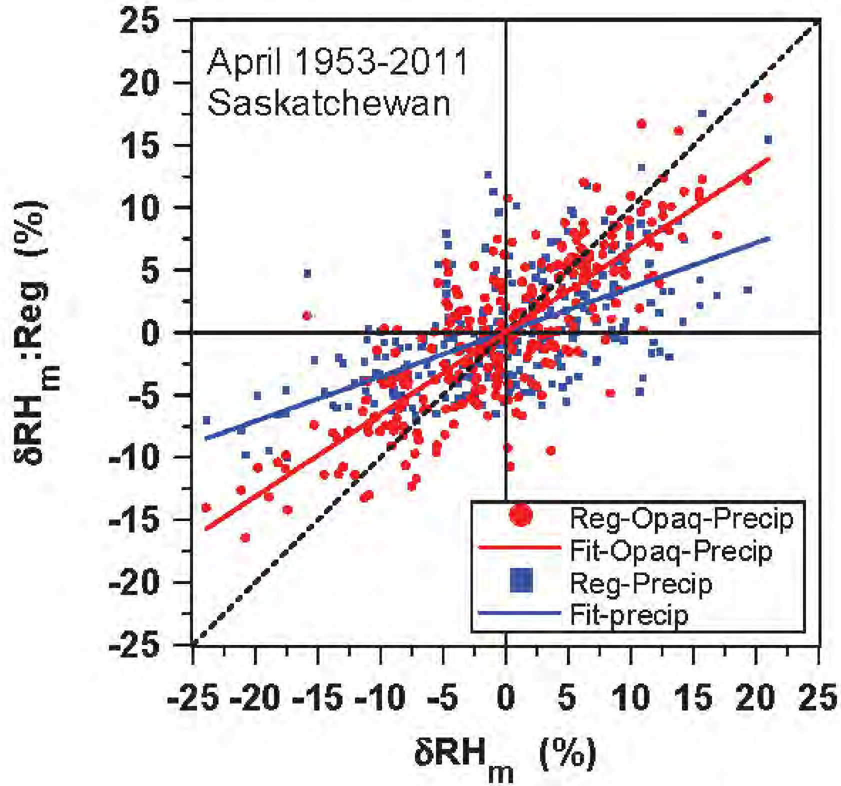
April: Memory of Precip. to November

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. Cloud, Precip: $R^2 \approx 0.7$**
- **Regression on Winter Precip: $R^2 \approx 0.35$**

Summer Precip Memory back to March

JULY 1953-2011: 12 stations (615 sta-years)

JULY R^2	δDTR 0.68	δRH_n 0.62	δP_{LCLx} 0.62	δQ_{Tx} 0.26
Cld-July	-0.58±0.03	0.63±0.04	-0.80±0.05	0.04±0.07
PR-July	-0.24±0.02	0.35±0.03	-0.42±0.04	0.40±0.05
PR-June	-0.15±0.01	0.27±0.02	-0.36±0.03	0.39±0.04
PR-May	-0.12±0.02	0.13±0.03	-0.20±0.04	0.24±0.06
PR-Apr	-0.05±0.03	0.10±0.05	-0.11±0.06	0.26±0.09
PR-Mar		0.16±0.07	-0.19±0.09	0.36±0.14

June, July, Aug have precip memory back to March

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

MJJA merge: coupling coefficients

(±0.015)

T_x

CLD	**-0.96**
PR-0	-0.07
PR-1	-0.16
PR-2	-0.01
(R^2=0.58)	

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

T_m

CLD	**-0.68**
PR-0	0.03
PR-1	-0.10
PR-2	-0.00
(R^2=0.44)	

SWCF (negative)
Little precip dependence

T_n

CLD	-0.34
PR-0	**0.17**
PR-1	-0.01
PR-2	0.04
(R^2=0.14)	

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

DTR

CLD	**-0.61**
PR-0	**-0.24**
PR-1	-0.15
PR-2	-0.06
(R^2=0.73)	

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

1953-2011 (2466 months)
12 stations

MJJA merge: coupling coefficients

	(±0.015)		(±0.015)	
T_x	**CLD -0.96**	RH_n	**CLD 0.64**	***Minimum RH***
	PR-0 -0.07		**PR-0 0.36**	***Increases with cloud***
	PR-1 -0.16		**PR-1 0.24**	***Increases with precip (Memory)***
	PR-2 -0.01		PR-2 0.12	
	(R^2=0.58)		*(R^2=0.69)*	
T_m	**CLD -0.68**	RH_m	CLD 0.57	***Mean RH***
	PR-0 0.03		PR-0 0.31	***Increases with cloud***
	PR-1 -0.10		PR-1 0.26	***Increases with precip (Memory)***
	PR-2 -0.00		PR-2 0.14	
	(R^2=0.44)		***(R^2=0.61)***	
T_n	CLD -0.34	RH_x	CLD 0.41	***Maximum RH***
	PR-0 0.17		**PR-0 0.19**	***Increases with cloud***
	PR-1 -0.01		PR-1 0.21	***Increases with precip (Memory)***
	PR-2 0.04		PR-2 0.12	***Saturation limits fall of T_n***
	(R^2=0.14)		*(R^2=0.36)*	
DTR	**CLD -0.61**	DRH	CLD -0.23	***Diurnal range RH***
	PR-0 -0.24		PR-0 -0.17	***Decreases with cloud***
	PR-1 -0.15		PR-1 -0.03	***Decreases with precip***
	PR-2 -0.06		PR-2 0.0	
	(R^2=0.73)		*(R^2=0.26)*	

1953-2011 (2466 months)
12 stations

MJJA merge: coupling coefficients

T_x (±0.015)

CLD	**-0.96**
PR-0	-0.07
PR-1	-0.16
PR-2	-0.01
(R^2=0.58)	

RH_n (±0.015)

CLD	**0.64**
PR-0	**0.36**
PR-1	**0.24**
PR-2	0.12
(R^2=0.69)	

Q_{Tx} (±0.02)

CLD	-0.01
PR-0	**0.49**
PR-1	**0.23**
PR-2	0.21
(R^2=0.25)	

θ_{Ex}

CLD	**-0.57**
PR-0	0.26
PR-1	0.09
PR-2	0.15
(R^2=0.21)	

T_m

CLD	**-0.68**
PR-0	0.03
PR-1	-0.10
PR-2	-0.00
(R^2=0.44)	

RH_m

CLD	0.57
PR-0	0.31
PR-1	0.26
PR-2	0.14
(R^2=0.61)	

Q_m

CLD	-0.07
PR-0	**0.40**
PR-1	**0.23**
PR-2	0.21
(R^2=0.22)	

P_{LCLx} (cloud-base)

CLD	**-0.82**
PR-0	**-0.41**
PR-1	**-0.33**
PR-2	-0.16
(R^2=0.68)	

T_n

CLD	-0.34
PR-0	**0.17**
PR-1	-0.01
PR-2	0.04
(R^2=0.14)	

RH_x

CLD	0.41
PR-0	**0.19**
PR-1	0.21
PR-2	0.12
(R^2=0.36)	

Q_{Tn}

CLD	-0.07
PR-0	0.33
PR-1	0.16
PR-2	0.16
(R^2=0.18)	

DP_{LCL}

CLD	**-0.50**
PR-0	**-0.26**
PR-1	**-0.16**
PR-2	-0.06
(R^2=0.58)	

DTR

CLD	**-0.61**
PR-0	**-0.24**
PR-1	-0.15
PR-2	-0.06
(R^2=0.73)	

DRH

CLD	-0.23
PR-0	-0.17
PR-1	-0.03
PR-2	0.0
(R^2=0.26)	

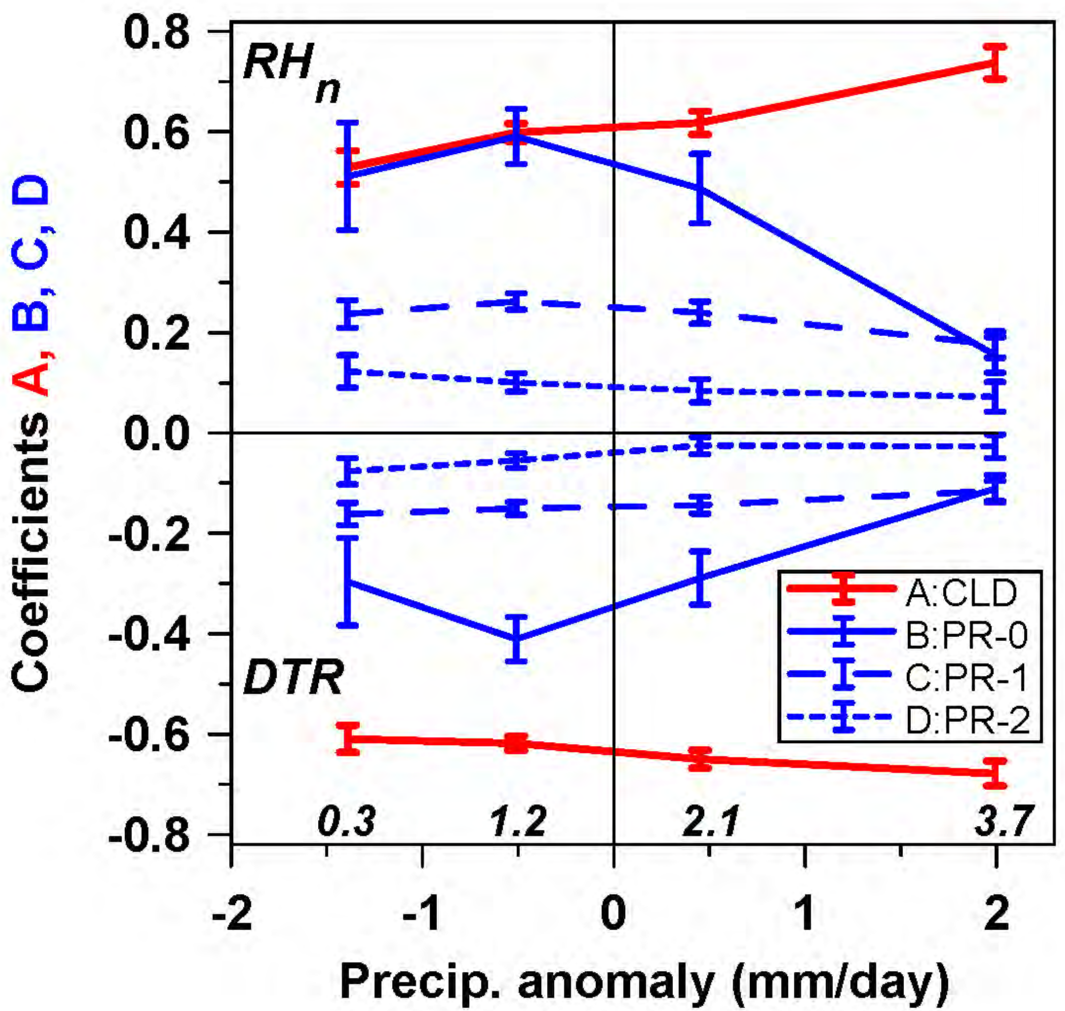
Q_{Tx}, Q_m → precip not cloud
RH_n, T_x move inversely with cloud
P_{LCLx} reflects RH_n , T_x
T_m → cloud not precip
θ_{Ex} down/up with cloud/precip

1953-2011 (2466 months)
12 stations

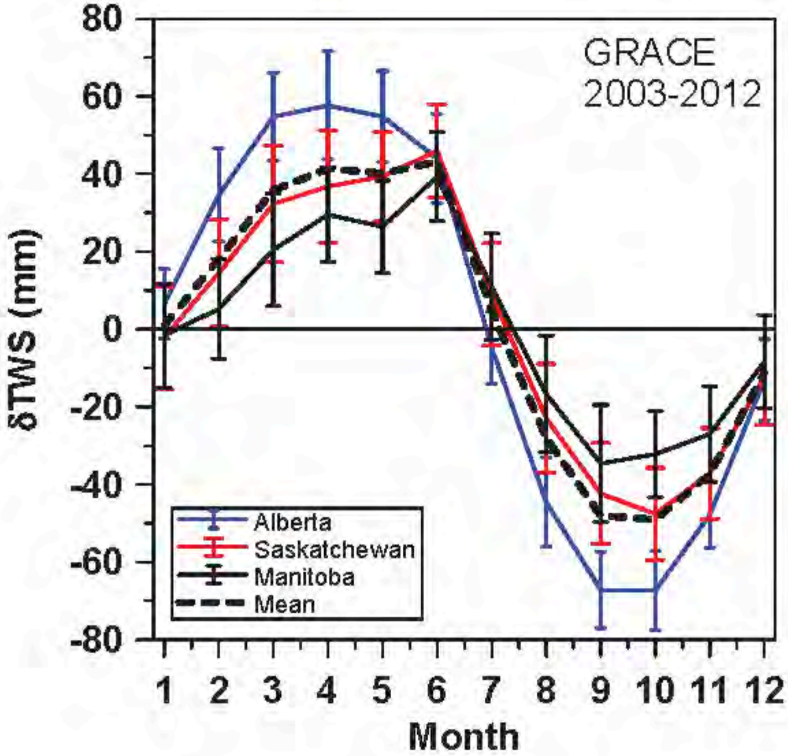
Dry to Wet Coefficient Change

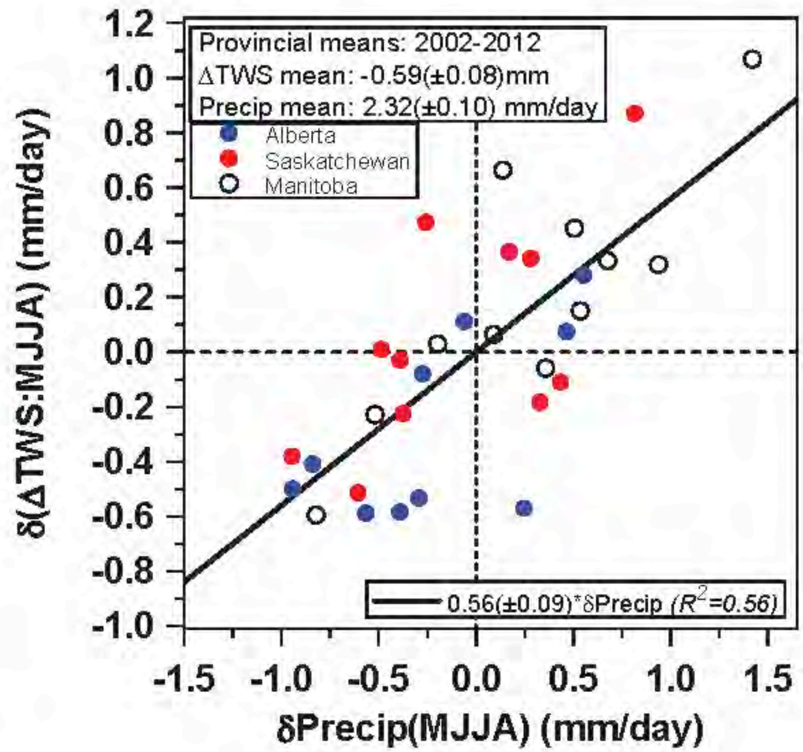
3081 months: split into precip (PR-0) SD ranges: < -1σ, -1 to 0, 0 to 1, >1σ (393, 1382, 885, 421 mos)

- **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)**



Seasonal Drydown damps Precip anomalies

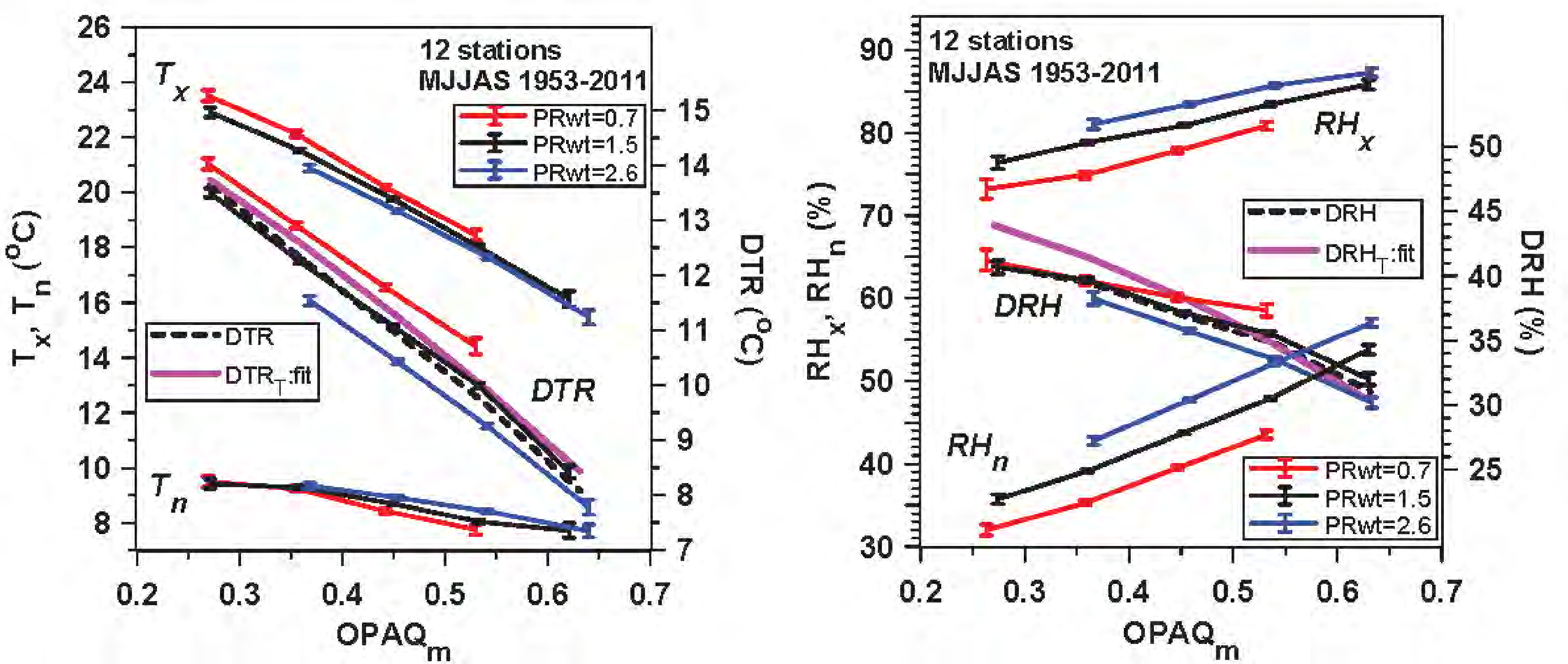




- **GRACE data shows seasonal change: Δ(Total Water Storage)**
- **δ(ΔTWS) damps 56% of precipitation anomalies**

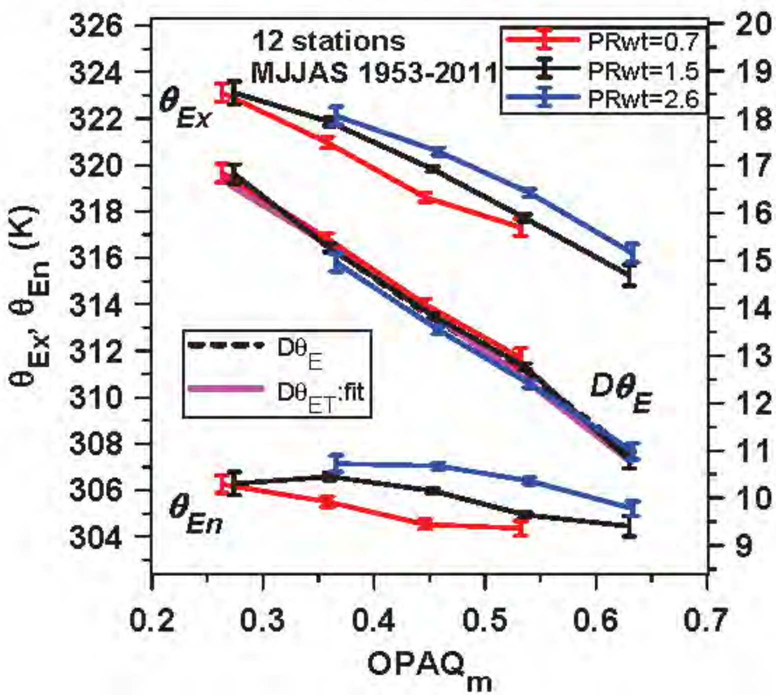
Betts et al. 2014b

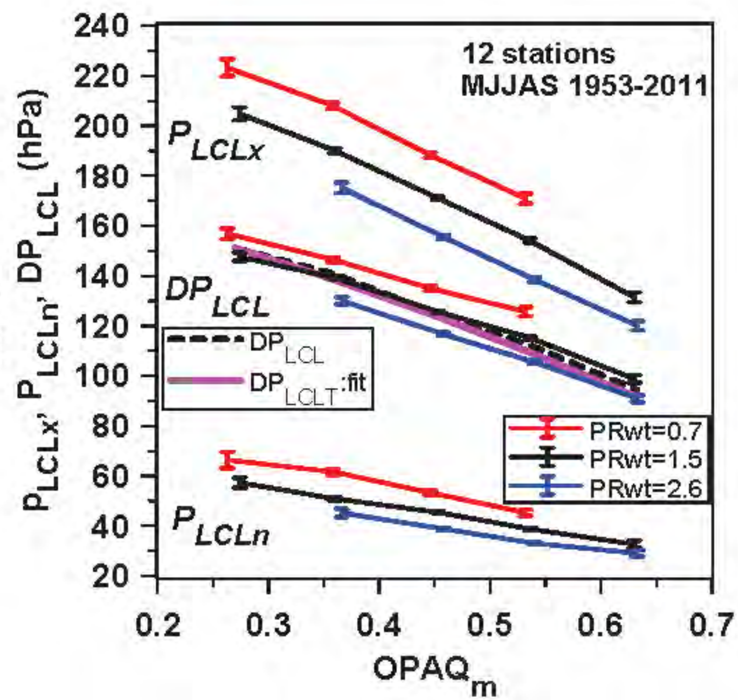
Monthly Climate of T, RH on Cloud and Precipitation



- Sorted by cloud and weighted precip. anomalies
  - δPRwt = 0.60* δPR-0 + 0.40* δPR-1
  - DTR increases with decreasing cloud and precip.
  - Afternoon RH_n increases with cloud, precip.

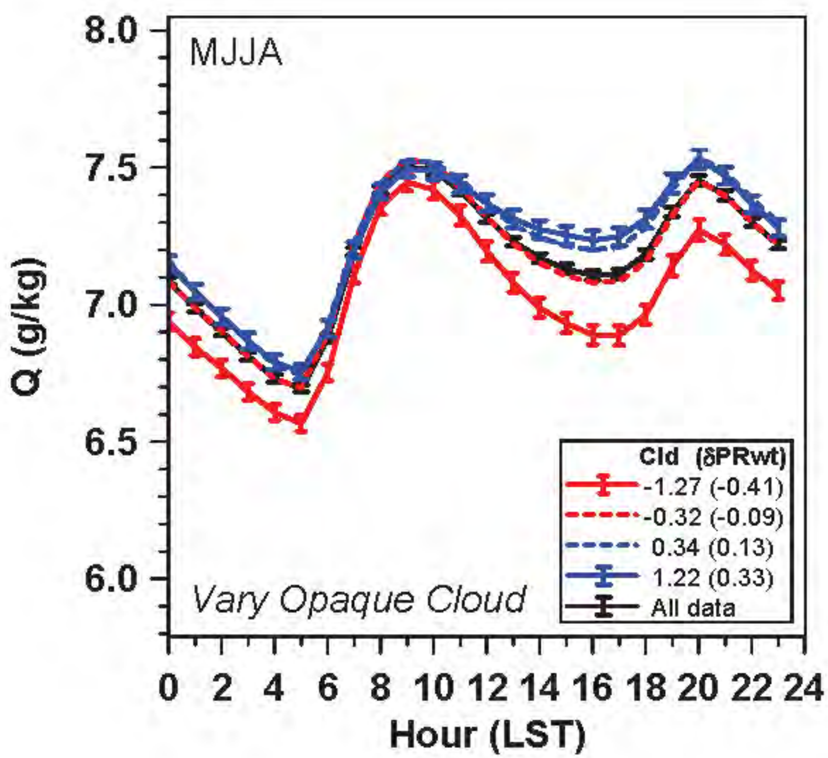
Afternoon maximum of θ_{Ex} and P_{LCLx} on Cloud and Precipitation

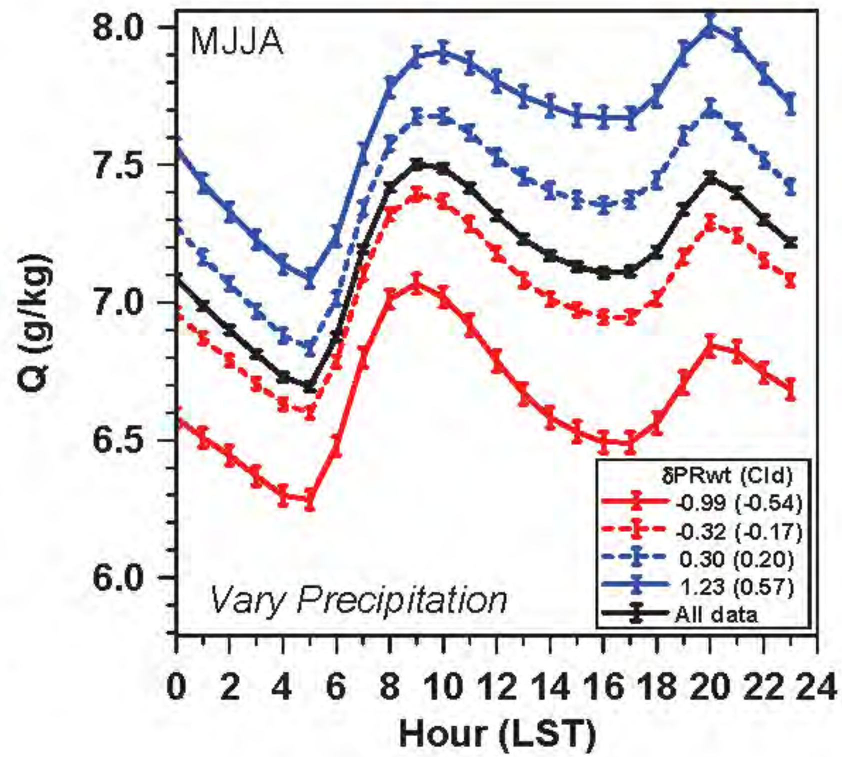




- Afternoon θ_{Ex} increases with weighted precip
- Afternoon cloud-base (P_{LCLx}) falls with precip
- Both favor convective instability

Diurnal Cycle of Q

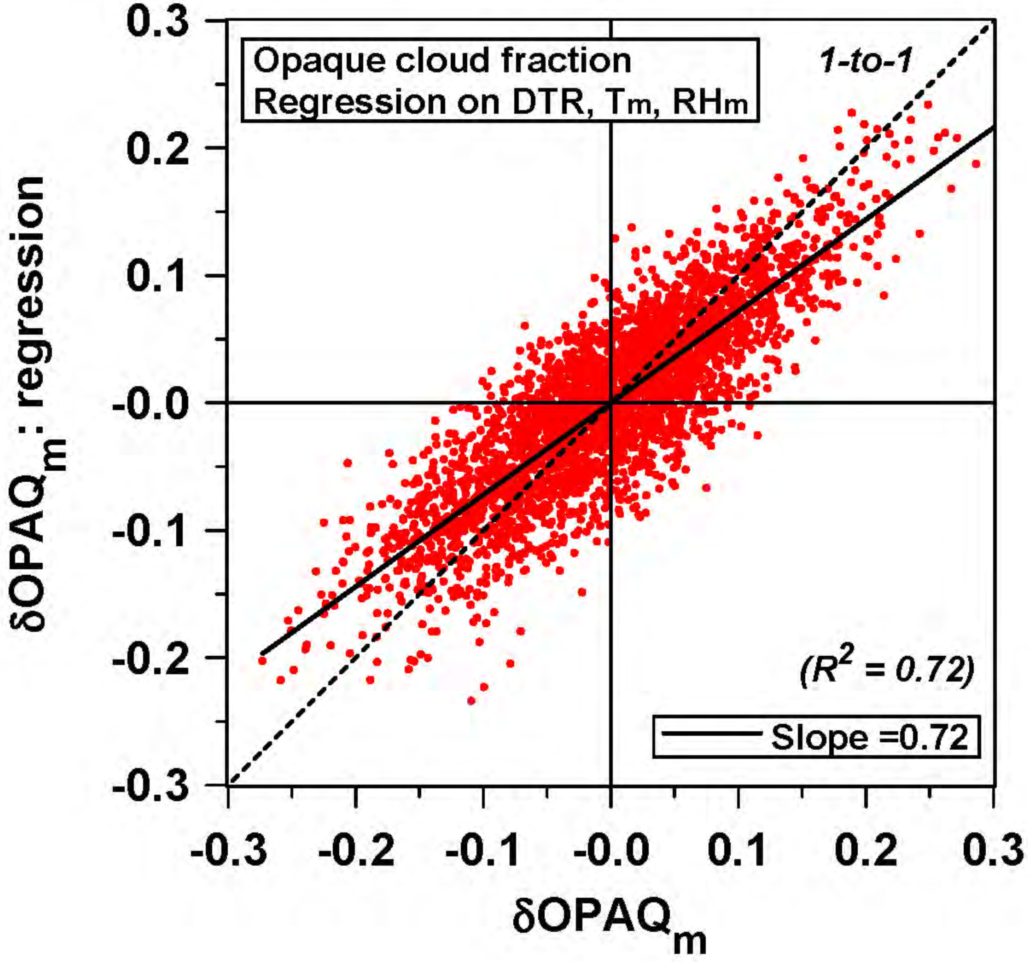




Binned by Opaque Cloud
Diurnal spread increases

Binned by Weighted Precipitation
Precip/evap shifts Q mean
Cloud and Precip coupled

Cloud anomalies from Climate anomalies



$\delta OPAQ_m$ to ±0.04

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

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 as long as 5 months
- Asymmetric response to dry/wet precipitation anomalies
- Observed coupling coefficients can be compared with model representations

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

- *Hydrometeorology*
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T and RH***
  - ***Can't 'understand' climate with T & Precip.***
- ***Monthly timescale coupling***
  - ***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***

http://alanbetts.com