Understanding Cloud-snow-climate coupling to PBL across timescales

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Contributions from many co-authors:

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NASA PBL Workshop

15 Prairie stations: 1953-2011

- *Hourly* surface meteorology
  - p, T, RH, WS, WD, *Opaque Cloud*
  - Calibrated to BSRN SW_{dn}, LW_{dn}
- *Daily* precip., snowdepth

- > 220,000 days
- Key stations: 99.9% days have no missing hours

  in first 40 years

References

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- 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, 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., A. Tawfik and R. Desjardins (2017), Revisiting hydrometeorology using cloud and climate observations. J. Hydrometeor., 18, 939-955., doi.org/10.1175/JHM-D-16-0203.1

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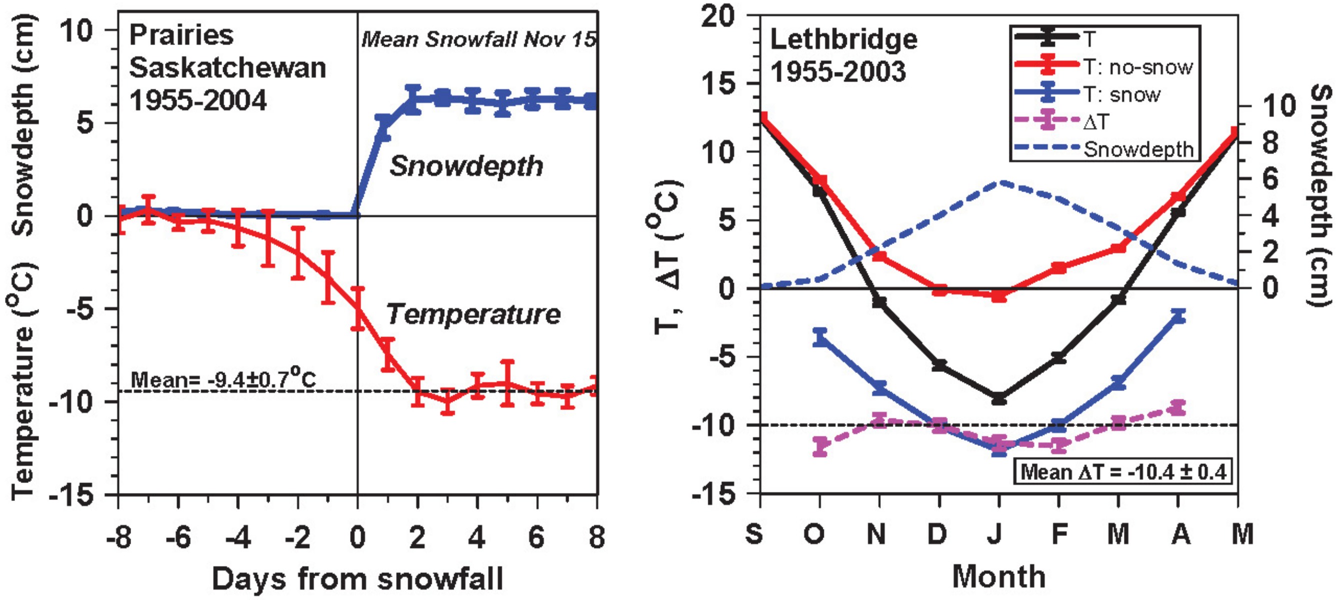
- Betts, A.K. and A.C.M. Beljaars (2017): Analysis of near-surface biases in ERA-Interim over the Canadian Prairies. J. Adv. Model. Earth Syst., 9, doi:10.1002/2017MS001025.
- Betts, A.K. and R.L. Desjardins (2018): Understanding Land-Atmosphere-Climate Coupling from the Canadian Prairie dataset. Environments 2018, 5, 129. doi.org/10.3390/environments5120129
- Betts, A.K., D.Z. Chan and R.L. Desjardins (2019), Near-surface biases in ERA5 over the Canadian Prairies. Front. Environ. Sci. doi: 10.3389/fenvs.2019.00129

Papers & this talk at
https://alanbetts.com/research

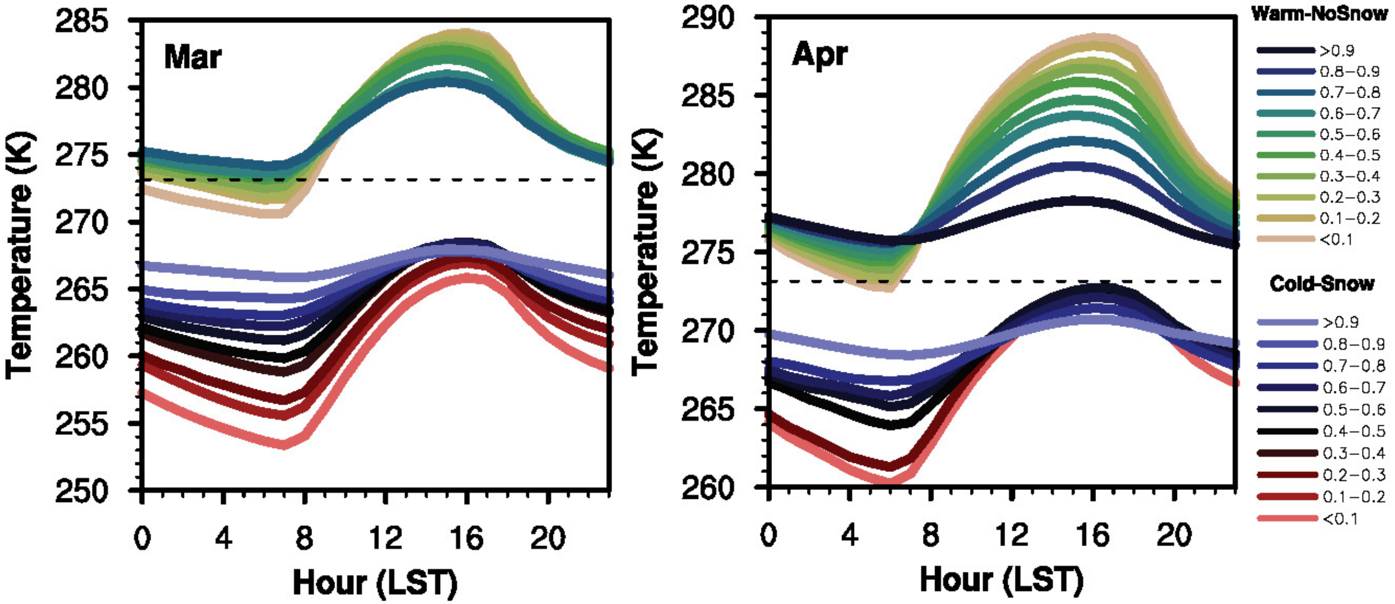
- **Prairie Data (15 stations: hourly, processed daily, docs) available as 90 meg Zip file at https://epscor.uvm.edu/owncloud/index.php/s/lWG2QuEobtsUsv5**

Snow and cloud coupling

- New snow
  T_m falls -9.4°C
- Partition days by snow cover
  ΔT_m -10.4°C



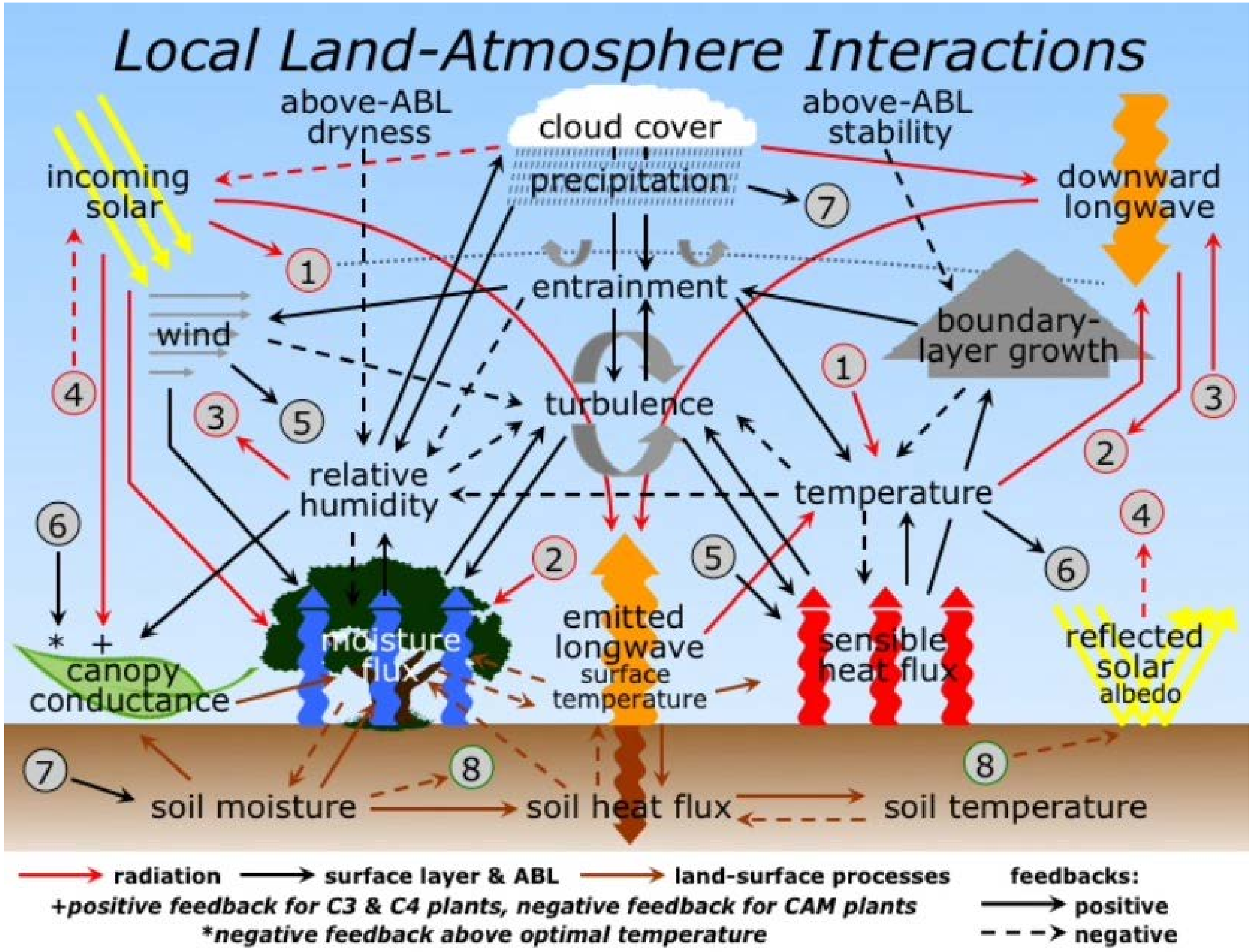
- *Two distinct regimes with & without snow (no overlap)*



- ***Tightly coupled diurnal climate system***
  - *Cloud-climate-radiation-precipitation coupling*
  - *Distinct warm and cold season climates*
  - *Snow cover is a “climate switch”*
  - *Wind & Synoptic forcing (advection; divergence)*

- **RH_n, P_{LCLx} and afternoon cloud-base all tightly coupled in warm season**
  - **Use as *reference climate equilibrium*, modified by cloud forcing, precipitation, wind & synoptic advection**

Compare Modeler's View

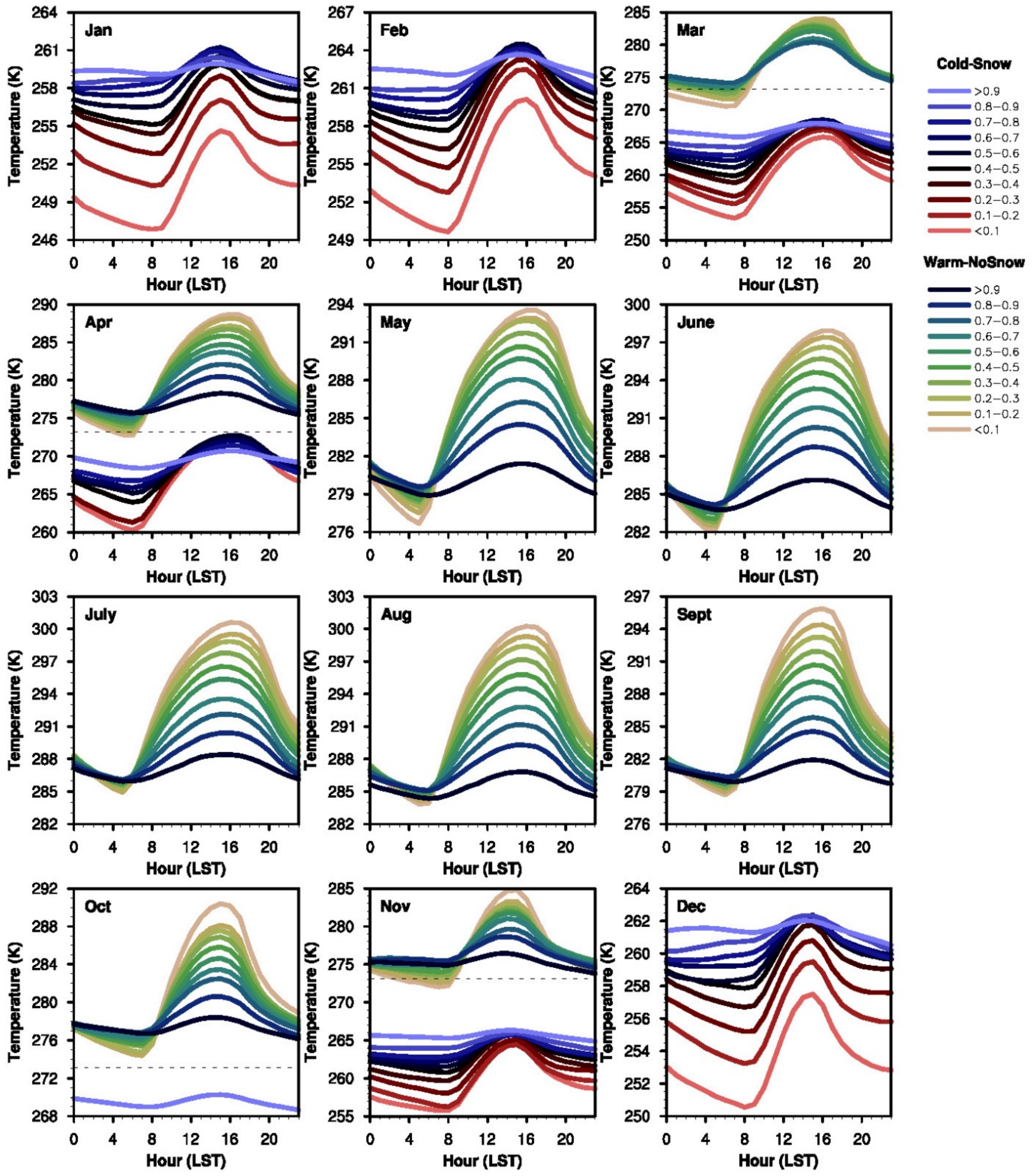


Monthly Diurnal Climatology
on opaque cloud

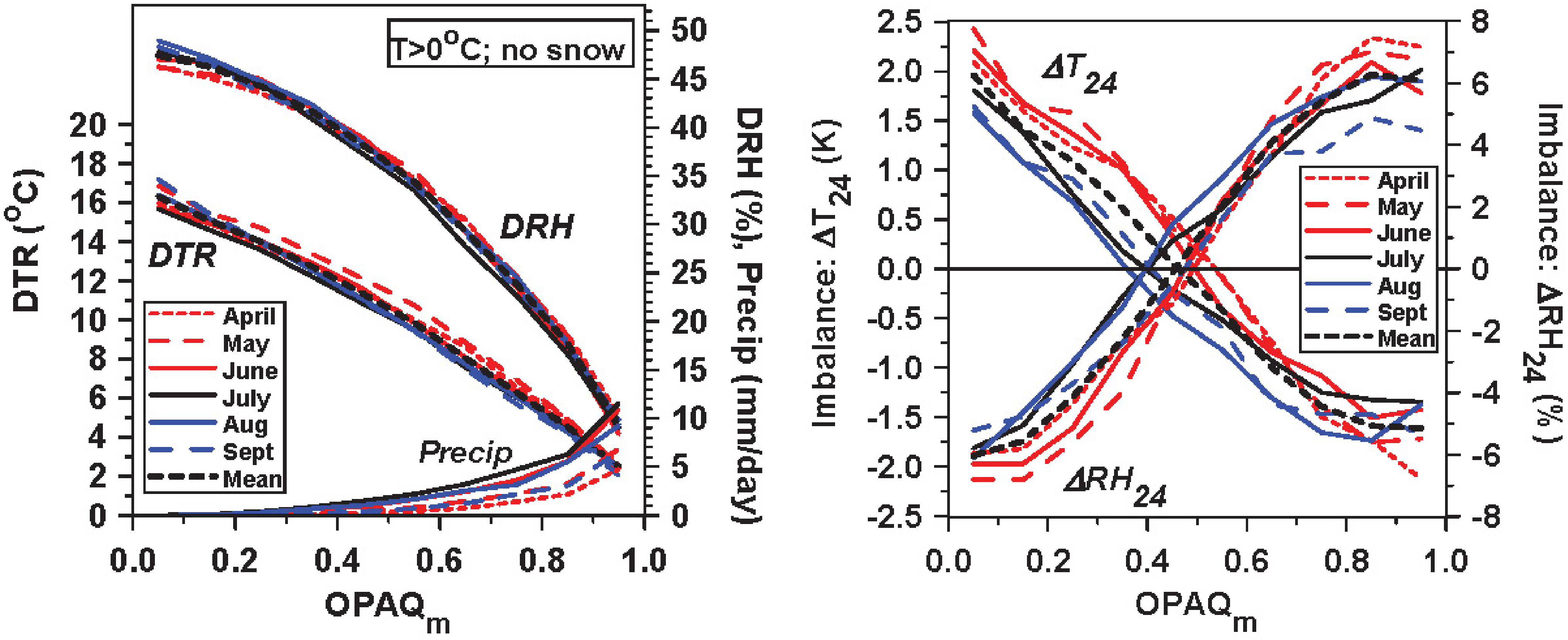
Distinct regimes:

Cold with & warm without snow cover

Warmer/cooler at end of clear/cloudy days



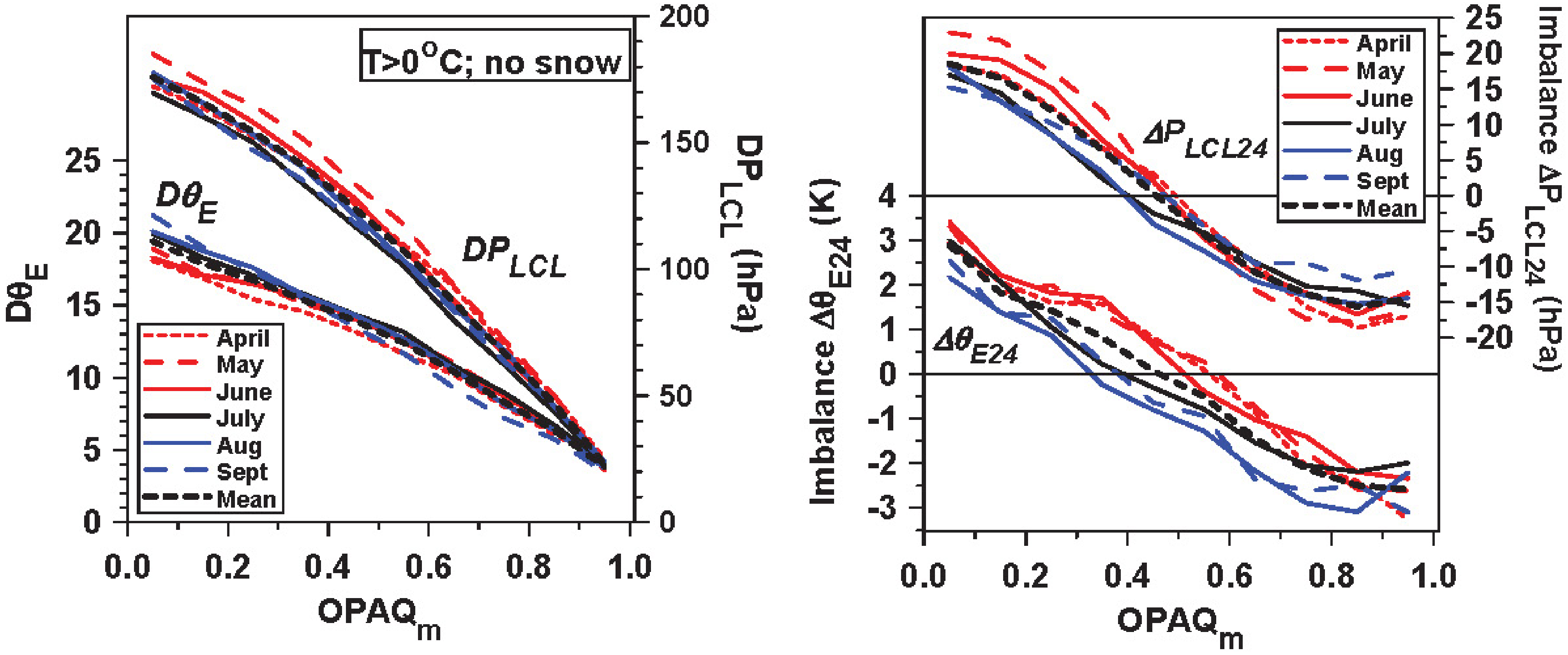
Diurnal Ranges & Imbalances



- April to Sept: <u>same coupled structure</u>
- Clear-sky: warmer (+2°C), drier (-6%)

(Betts and Tawfik 2016)

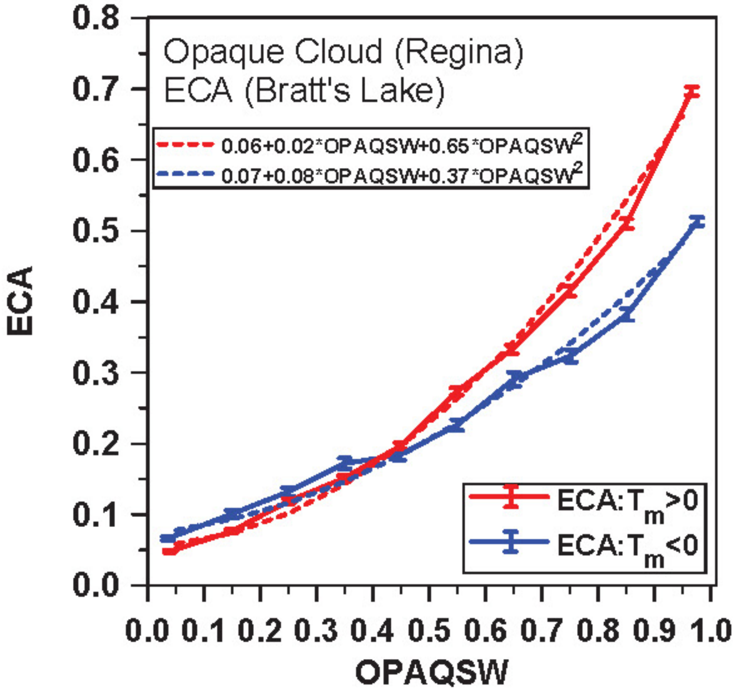
Diurnal Ranges & Imbalances

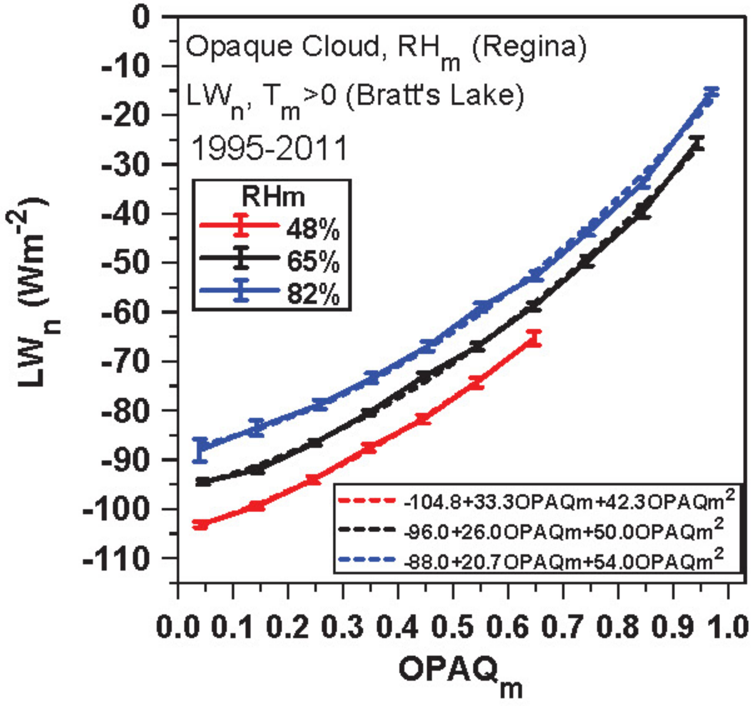


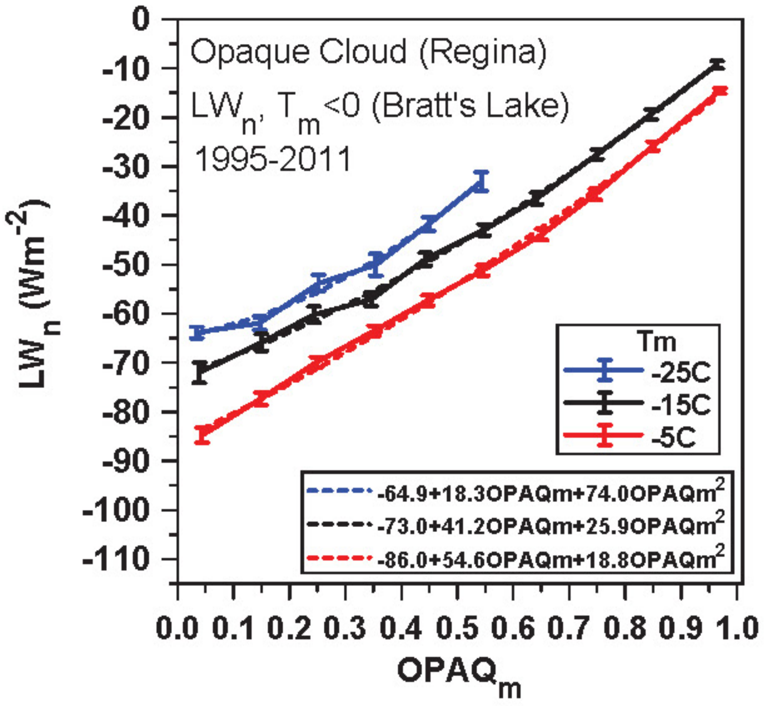
- April to Sept: <u>same coupled structure</u>
- Clear-sky: θ_E (+3K), LCL higher (+18hPa)

(Betts and Tawfik 2016)

BSRN calibration of OPAQ





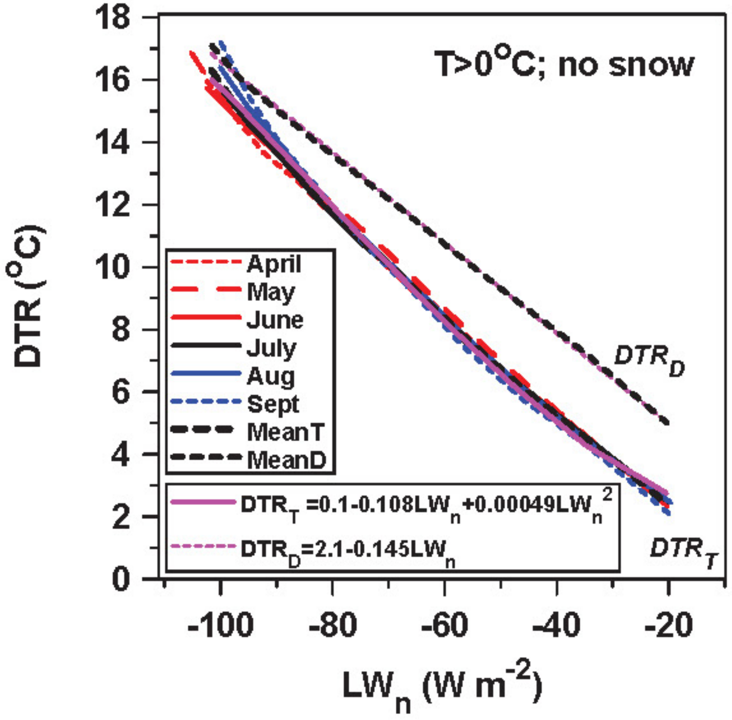


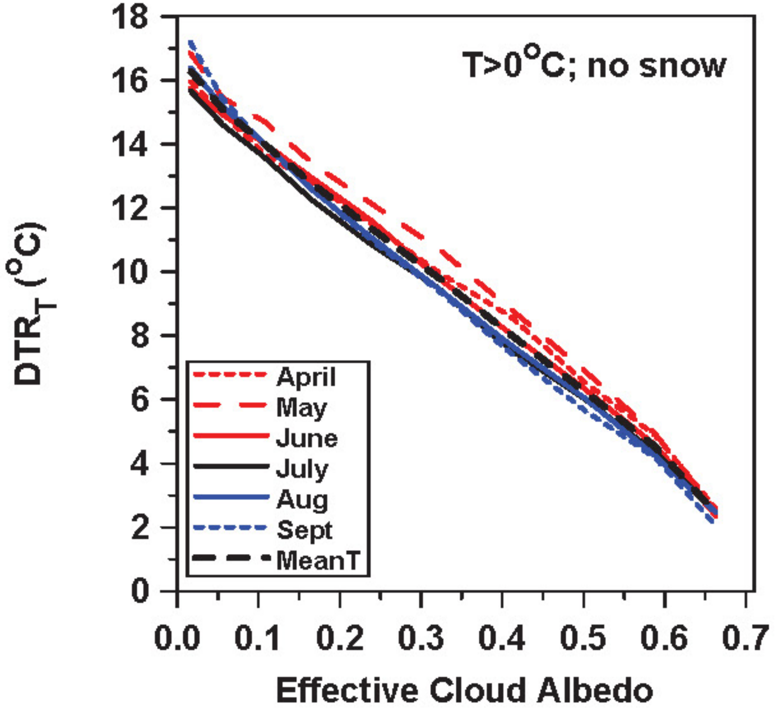
Effective Cloud Albedo warm; cold seasons

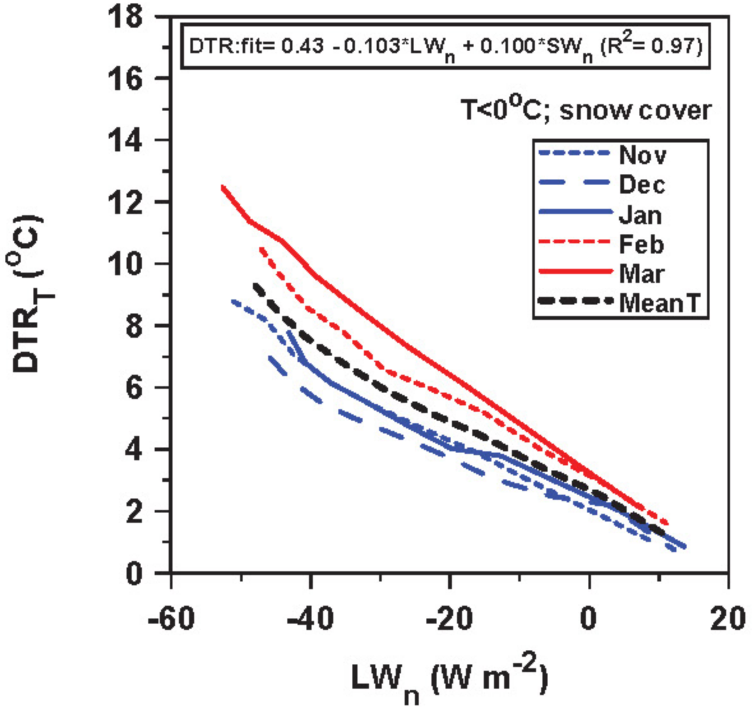
LW_n: warm season

LW_n: cold season

Convert Opaque Cloud to LW_n, ECA & SW_n using BSRN data



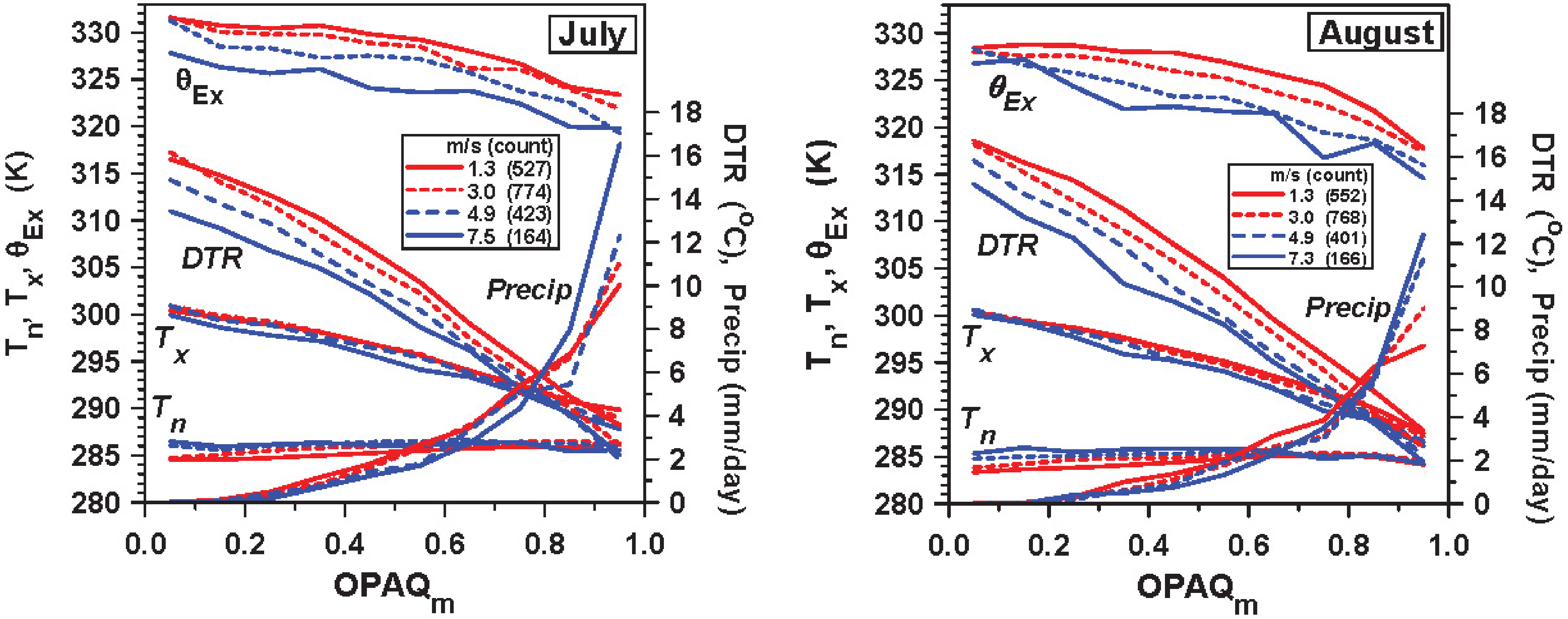




Warm Season DTR coupling is tight to both LW_n & ECA

Cold season DTR depends on LW_n & SW_n

Daily Coupling to Cloud and Windspeed



Decreasing wind: increasing DTR, θ_{Ex}, Precip.

(Betts and Tawfik 2016)

Warm Season Climate: T_m>0ºC
(May – October with no snow)

- ***Hydrometeorology***
  - ***with Precipitation and Radiation***
  - ***Diurnal cycle of T, RH, LCL & Q***
  - ***Climate is not just T & Precip !***

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

Betts et al. 2017;
Betts and Tawfik 2016)

Multiple 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**

δ<u>DTR</u> = A*δCLD + B*δPR-0 + C*δPR-1 + D*δPR-2 ...

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

Soil moisture memory

<u>June, July, Aug:</u> memory of moisture back to March

Summer Precip Memory back to March

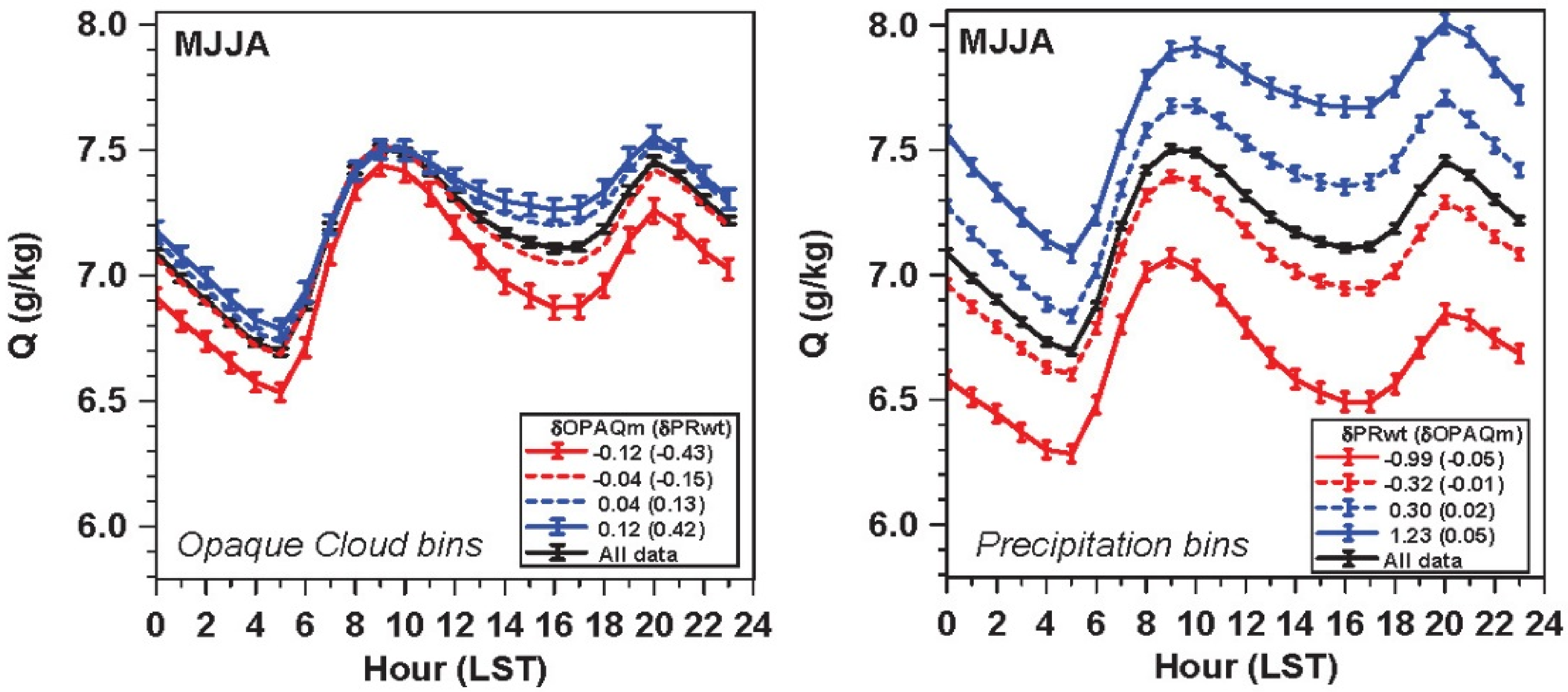
***JULY* 1953-2010: 12 stations (614 months)**

Bold: p<0.01
0.01<p<0.05
Italic: p>0.05
( ): p>0.1

JULY R^2	**δDTR** **0.68**	**δRH_n** **0.61**	**δP_{LCLx}** **0.62**	**δQ_{Tx}** **0.26**
Cloud-July	**-0.56±0.03**	**0.50±0.03**	**-0.63±0.04**	(0.03±0.04)
PR-July	**-0.31±0.02**	**0.37±0.03**	**-0.45±0.04**	**0.34±0.04**
PR-June	**-0.22±0.02**	**0.34±0.03**	**-0.44±0.04**	**0.38±0.04**
PR-May	**-0.12±0.02**	**0.11±0.03**	**-0.16±0.04**	**0.16±0.04**
PR-Apr	*-0.04±0.02*	0.06±0.03	*-0.06±0.03*	**0.12±0.04**
PR-Mar		0.06±0.03	-0.07±0.03	0.10±0.04

June, July, Aug have precip memory back to March

Diurnal cycle of mixing ratio Q

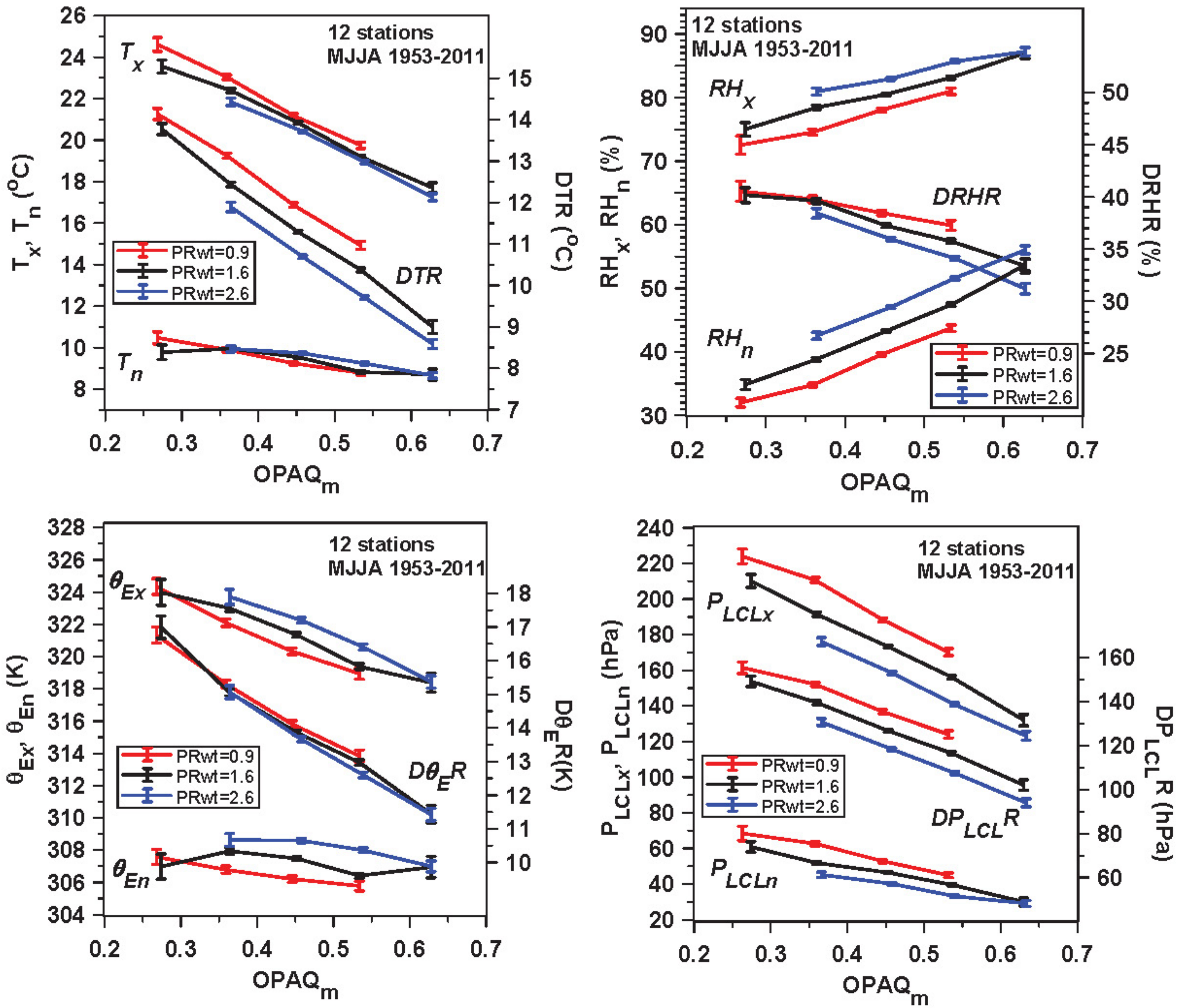


Dependence on cloud small; on precipitation large

MJJA on cloud and weighted Precipitation

PRwt
=0.6PR+0.4PR(Mo-1)

PRwt = 0.9
PRwt = 1.6 mm/d
PRwt = 2.6



Observational Conclusions

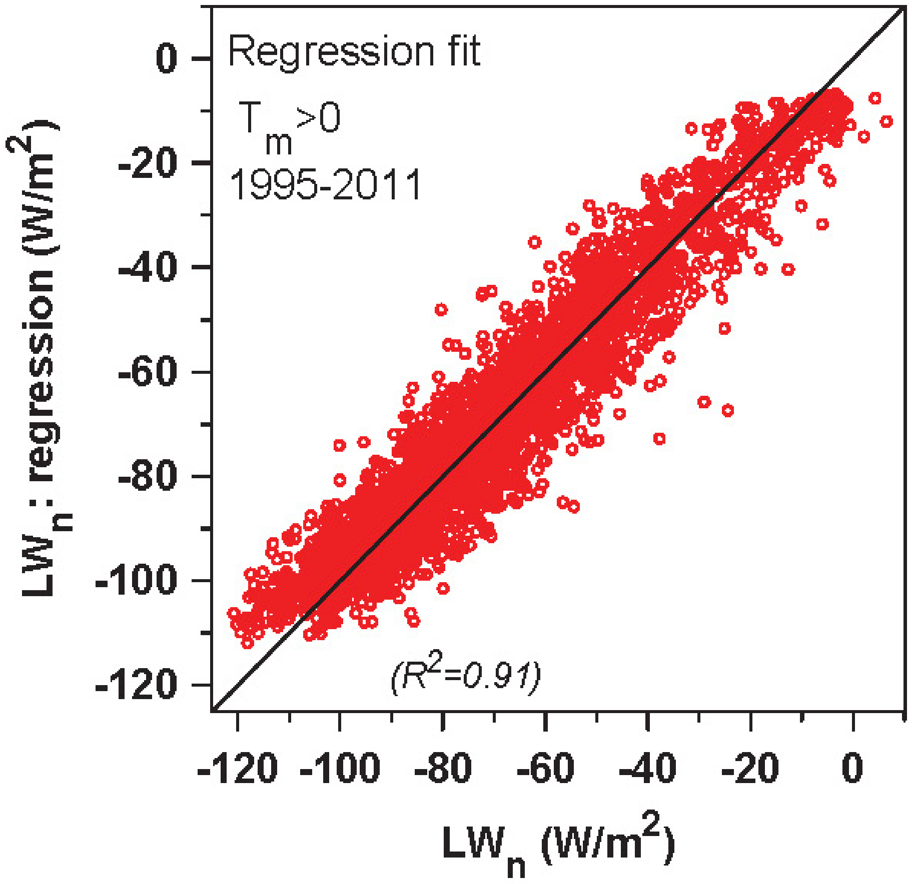
- **Excellent reference dataset with opaque cloud**
  - ***Clouds, BL and climate are tightly coupled on monthly timescale***
  - ***<u>Use structure of coupled solutions as reference</u>***
- ***<u>Cloud radiative forcing variability dominates diurnal and monthly timescales</u>***
  - **Coupled to 24h diurnal range & imbalances**
- **Low wind: greater DTR, θ_{Ex}, Precip. in summer**
- **Warm season precipitation memory back to March (early snowmelt)**
  - **Stronger for moisture variables than DTR**

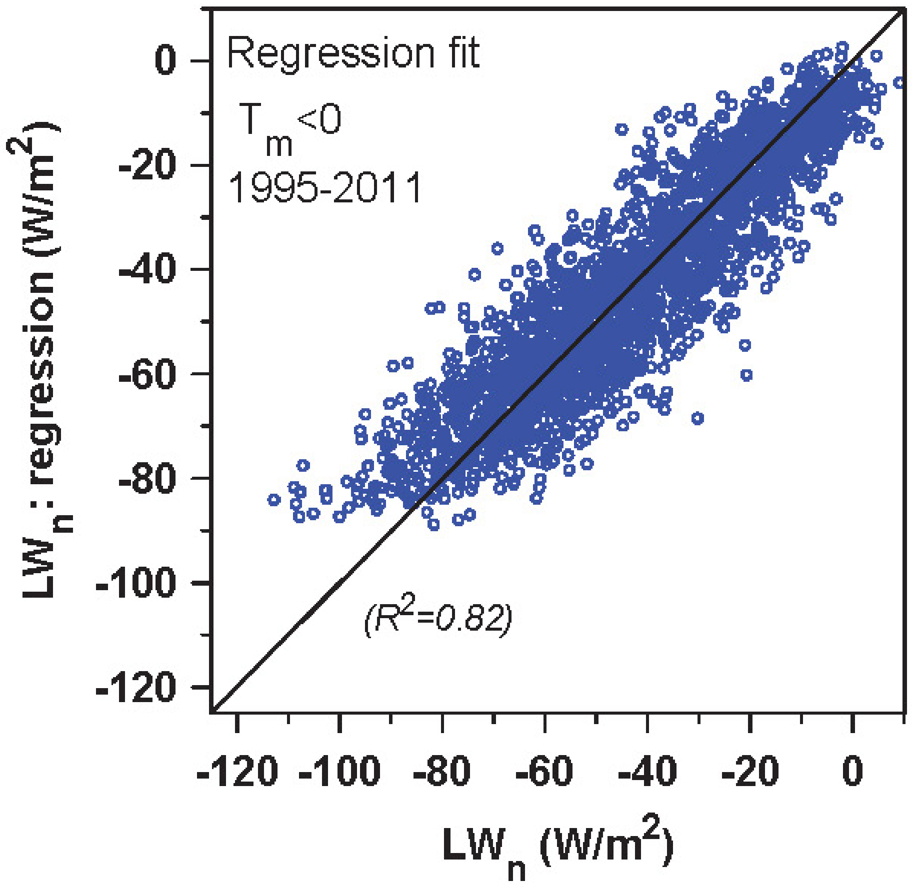
Data Needs

- **PBL: T, RH and wind structure**
  - ***High time resolution***
  - ***Radiative forcing of clouds on surface, PBL & troposphere***
  - ***Derive diurnal Surface Radiation Budget (SRB)***
  - ***Use structure of coupled solutions as reference***

  - ***Precipitation and advection – use global model products***
  - ***Soil moisture: use coupled land models***
  - ***Total Water Storage (TWS) – use GRACE satellite***

LW_n regression fit





Warm: $LW_n = -128.6(\pm 7.8) + 28.1(\pm 1.8)OPAQ_m + 44.6(\pm 1.8)OPAQ_m{}^2 + 0.49(\pm 0.01)RH_m$

Cold: $LW_n = -112.2(\pm 9.8) + 43.5(\pm 2.8)OPAQ_m + 26.8(\pm 2.5)OPAQ_m{}^2 + 0.29(\pm 0.02)RH_m - 1.02(\pm 0.03)T_m$

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 large composites *('True' radiatively-coupled diurnal ranges: damps advection)***

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

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

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

MJJA merge (2466 mos)

Variable	A ($\delta OPAQ_{m\sigma}$)	B ($\delta PR0_{\sigma}$)	C ($\delta PR1_{\sigma}$)	D ($\delta PR2_{\sigma}$)	E ($\delta PR3_{\sigma}$)	R^2
$\delta T_{x\sigma}$	-0.95±0.02	-0.07±0.02	-0.16±0.02			0.58
$\delta T_{m\sigma}$	-0.67±0.02	0.03±0.02	-0.10±0.02			0.43
$\delta T_{n\sigma}$	-0.34±0.02	0.18±0.02				0.13
δDTR_{σ}	-0.61±0.01	-0.26±0.01	-0.15±0.01	-0.05±0.01	-0.03±0.01	0.73
$\delta P_{LCLx\sigma}$	-0.76±0.02	-0.42±0.02	-0.31±0.01	-0.13±0.01	-0.05±0.01	0.68
$\delta P_{LCLm\sigma}$	-0.55±0.01	-0.30±0.01	-0.25±0.01	-0.12±0.01	-0.04±0.01	0.62
$\delta P_{LCLn\sigma}$	-0.30±0.01	-0.15±0.01	-0.16±0.01	-0.08±0.01	-0.03±0.01	0.36
$\delta DP_{LCL}R_{\sigma}$	-0.46±0.01	-0.27±0.01	-0.15±0.01	-0.05±0.01		0.58

April: Precip. Memory back to November

1953-2010: 12 stations (620 months)

Bold: p<0.01
0.01<p<0.05
Italic: p>0.05
( ): p>0.1

Variable	**δDTR**	**δT_x**	**δRH_n**	**δP_{LCLx}**
R^2 =	**0.67**	**0.47**	**0.65**	**0.66**
Cloud-Apr	**-0.52±0.02**	**-0.78±0.04**	**0.76±0.03**	**-0.93±0.04**
PR-Apr	**-0.06±0.02**	(0.01±0.04)	**0.20±0.03**	**-0.19±0.04**
PR-Mar	**-0.12±0.02**	**-0.22±0.04**	**0.23±0.03**	**-0.27±0.03**
PR-Feb	**-0.07±0.02**	**-0.12±0.04**	**0.16±0.03**	**-0.19±0.03**
PR-Jan	**-0.09±0.02**	**-0.19±0.04**	**0.17±0.03**	**-0.21±0.03**
PR-Dec	**-0.06±0.02**	(-0.06±0.04)	**0.16±0.03**	**-0.19±0.03**
PR-Nov	**-0.08±0.02**	**-0.13±0.04**	0.07±0.03	**-0.11±0.03**

April remembers Precip. back to freeze-up