Impacts on Numerical Weather Prediction and Climate Modeling

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"How FIFE and BOREAS Changed the World"

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Outline

- FIFE
  - Timeline
  - Research/dataset
  - Forecast model impacts
- BOREAS
  - Research
  - Forecast model impacts
  - ERA-40
- Ongoing model development
- Follow-on work: climate perspective

FIFE Timeline

- *1987: Call from Bob Grossman: "We need your help"*
- **1987: In Manhattan Kansas**
- **1990-1992: aircraft and surface BL budgets**
- **1992-3: *Mean time-series* from PAM and surface flux stations used to evaluate ECMWF model**
- **1992-3 winter: New ECMWF model cycle developed July 1993: parallel testing of 4-soil-layer model**
- **July 1993: Mississippi flood**
- **August 1993: New ECMWF model cycle operational**
- **Betts and Ball 1995: FIFE diurnal cycle climate**
- ***Data analysis took 5 years: ECMWF took 2 years***

Key FIFE papers (Citations-2016)

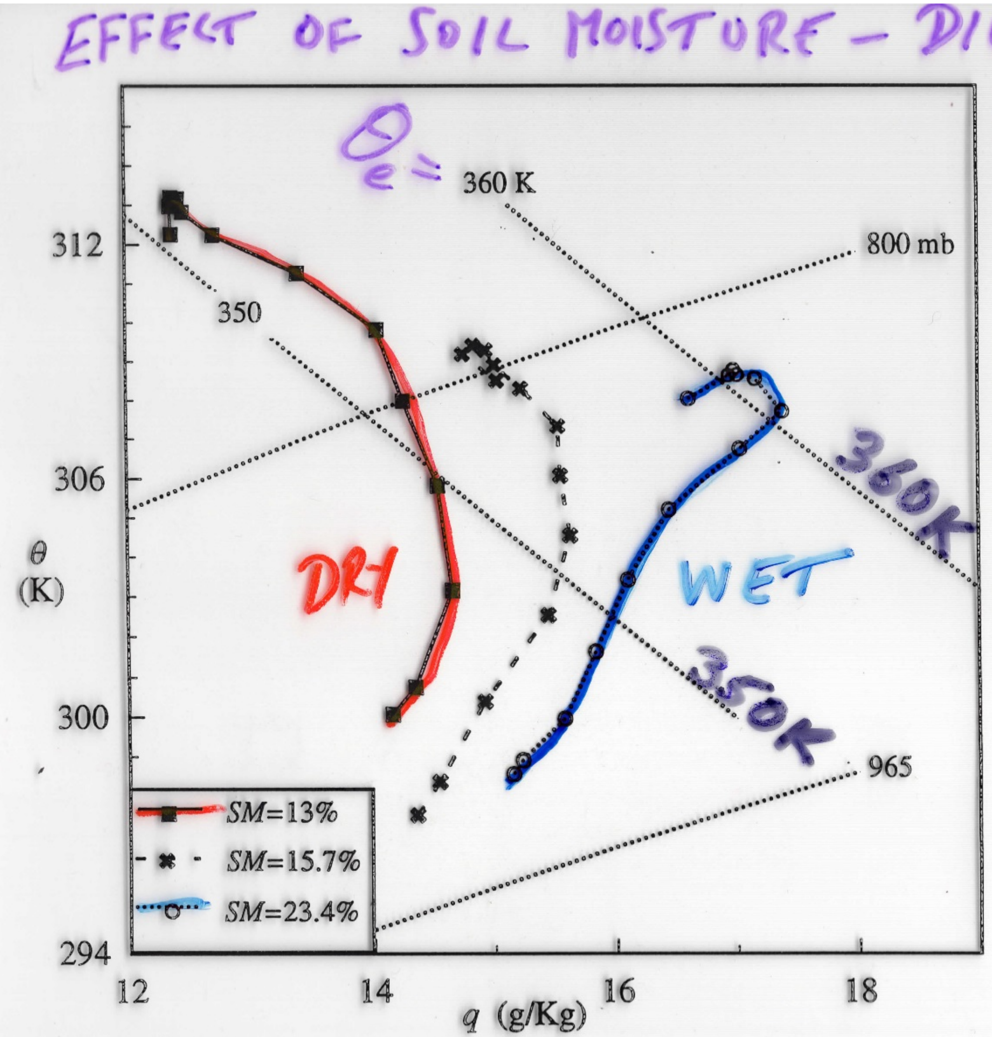
- **Betts, A.K., J.H. Ball, and A.C.M. Beljaars, 1993**: Comparison between the land surface response of the European Centre model and the FIFE-1987 data. QJRMS, 119, 975-1001. **(116)**
- **Betts, A.K. and J.H. Ball, 1995:** The FIFE surface diurnal cycle climate. J. Geophys. Res. 100, 25679-25693. **(127)**
- **Viterbo and Beljaars, 1995: An Improved Land Surface Parameterization Scheme in the ECMWF Model and Its Validation. J. Climate (481)**
- **Chen, F.,K. Mitchell, J. Schaake, Y. Xue, H-L. Pan, V. Koren, Q. Duan, and A. Betts, 1996**: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. J. Geophys. Res. **(796) (still 70/year)**
- **Betts, A. K., J.H. Ball, A.C.M. Beljaars, M.J. Miller and P. Viterbo, 1996**: The land-surface-atmosphere interaction: a review based on observational and global modeling perspectives. J. Geophys. Res. **(586) (still 40/year)**
- **Beljaars, A.C.M., P. Viterbo, M.J. Miller and A.K. Betts, 1996**: The anomalous rainfall over the United States during July 1993: sensitivity to land surface parameterization and soil moisture anomalies. Mon. Wea. Rev. **(445) (still 25/year)**
- **Betts, A.K., S-Y. Hong and H-L. Pan, 1996**: Comparison of NCEP/NCAR Reanalysis with 1987 FIFE data. . Mon. Wea. Rev. **(98)**
- **Betts, A.K., F.Chen, K. Mitchell, and Z.Janjic, 1997**: Assessment of land-surface and boundary layer models in 2 operational versions of the Eta Model using FIFE data. Mon. Wea. Rev. 125, 2896-2915. **(211)**
- **Betts A. K. and J. H. Ball, 1998**: FIFE surface climate and site-average dataset: 1987-1989. J. Atmos Sci , 55, 1091-1108. **(193) (still 8/year)**

"FIFE dataset"

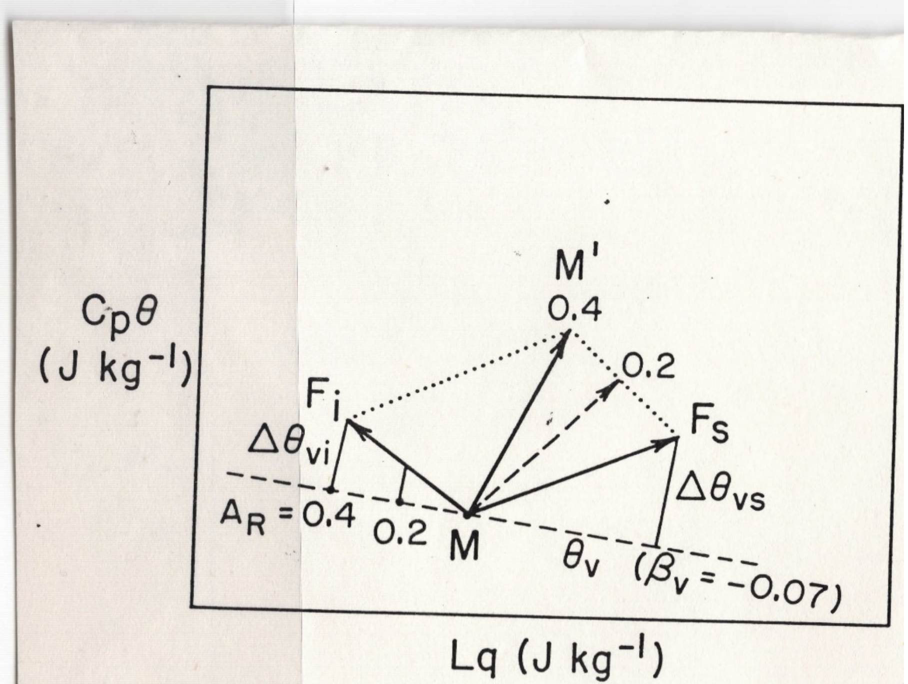
- ***Betts A. K. and J. H. Ball, 1998**: FIFE surface climate and **site-average dataset**: 1987-1989. J. Atmos Sci , 55, 1091-1108*
- **10 PAM sites and 10-22 Flux sites**
- **"The biggest difficulty in generating an interannual meteorological and radiation flux time series, averaged over the FIFE site, was cleaning up the data."**
- Range-filters and manual edit
- **Multi-site ensemble**
  - **mean + SD:σ**

John Ball

Vector representation of diurnal cycle



(Betts and Ball 1995, 1998))



(Betts 1992; Santanello et al. 2009)

ECMWF visit in summer 1992

Found Many Errors

- SW_{down} too high *(Clear-sky flux error)*
- Ground flux too high *(No skin layer)*
- No LH flux in October *(SM storage error)*
- T_{skin}-T_2 too small *(Z_{0m}/Z_{0h} error)*
- Diurnal cycle errors *(no BL entrainment)*
- BR rises rapidly on sequential dry days
  - T drifts too warm *(SM storage error)*
- ***We will fix them - find more!***
  - *Tony Hollingsworth*

4-layer model matched to FIFE

<u>*Viterbo and Beljaars, 1995*</u>

Comparison of results of the old model with FIFE observations, referred to above, suggested improvements in three areas of subsurface hydrology and evaporation:

a) **first, a mechanism is necessary to get precipitation rapidly into the ground where it can be stored;**

b) **second, sufficient storage is needed to represent several weeks of evaporation without rain;**

c) **third, seasonal and interannual memory of soil moisture anomalies needs deep predicted reservoirs.**

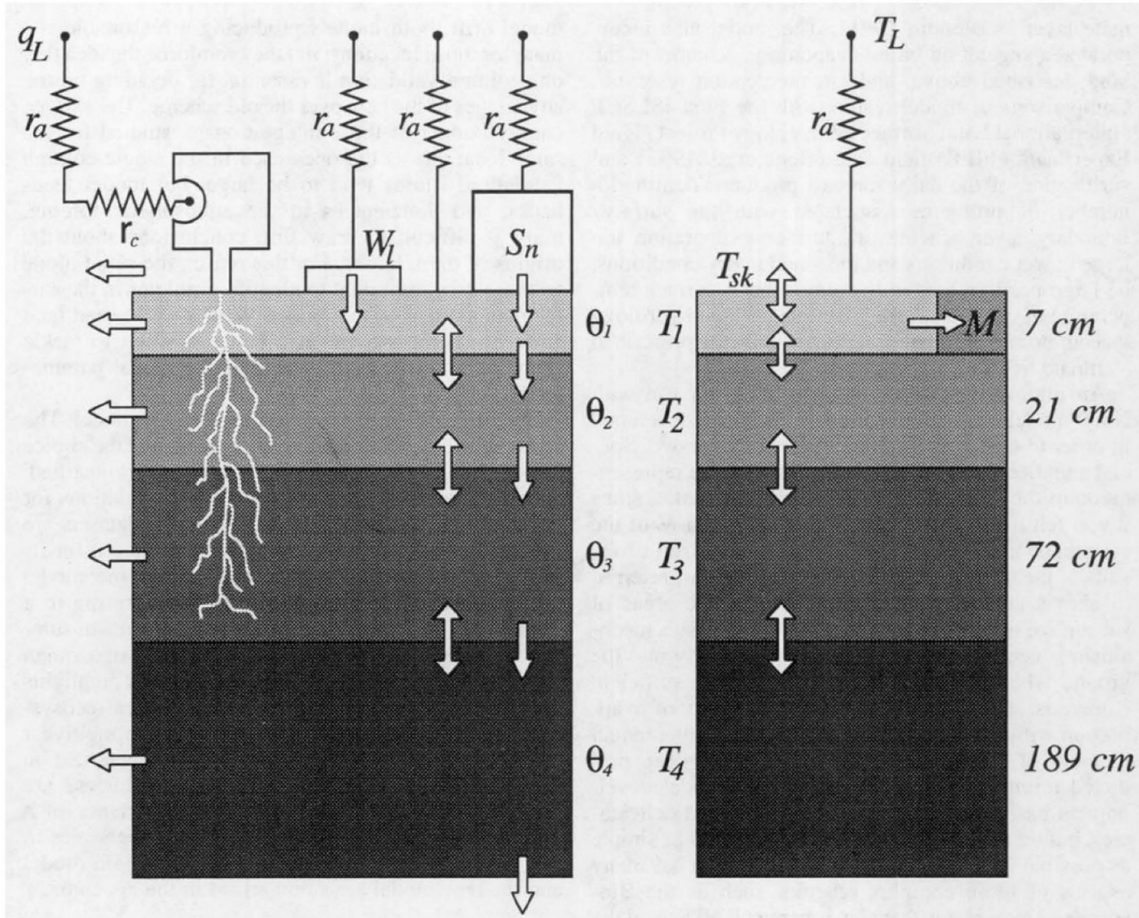
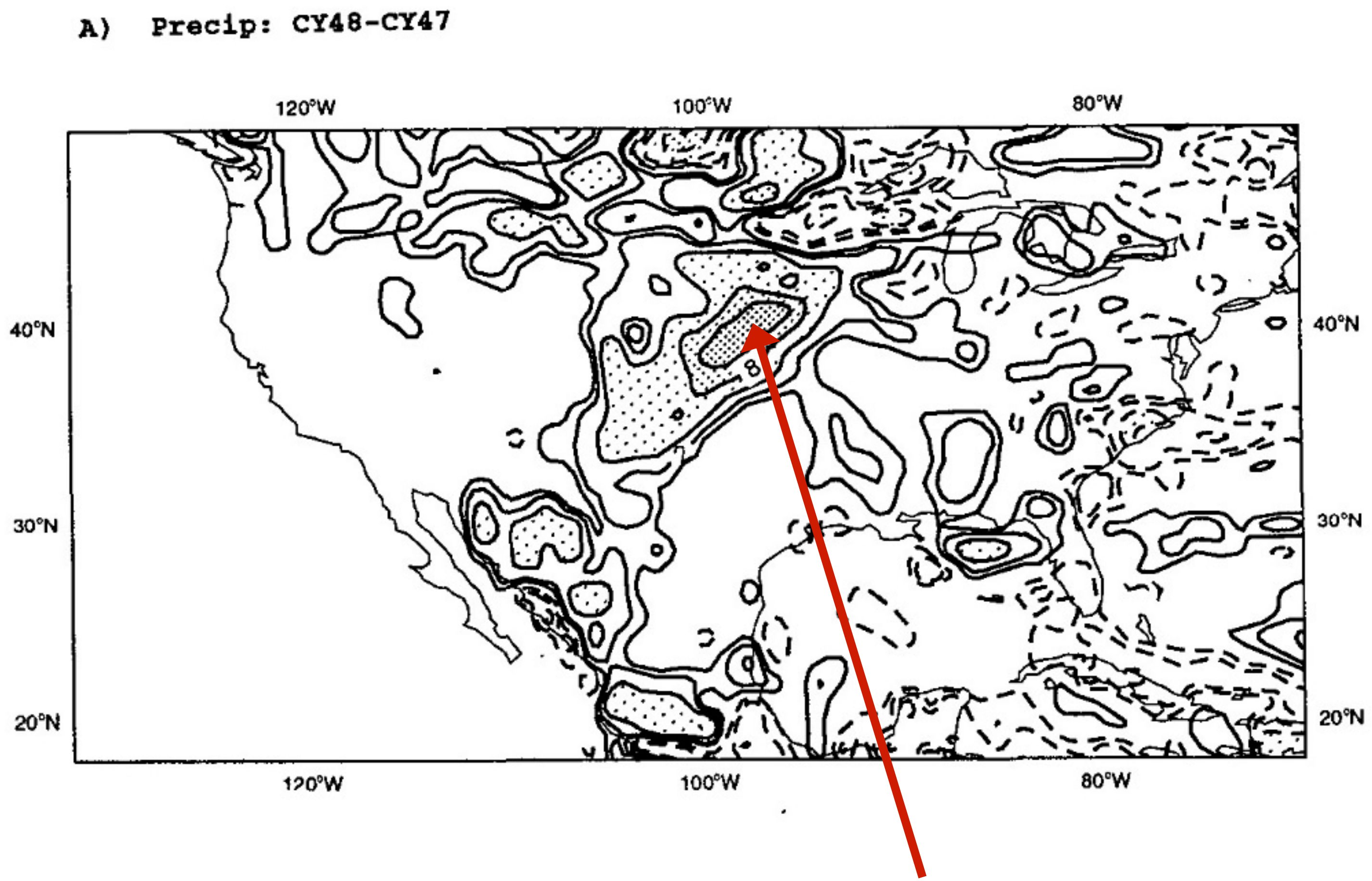


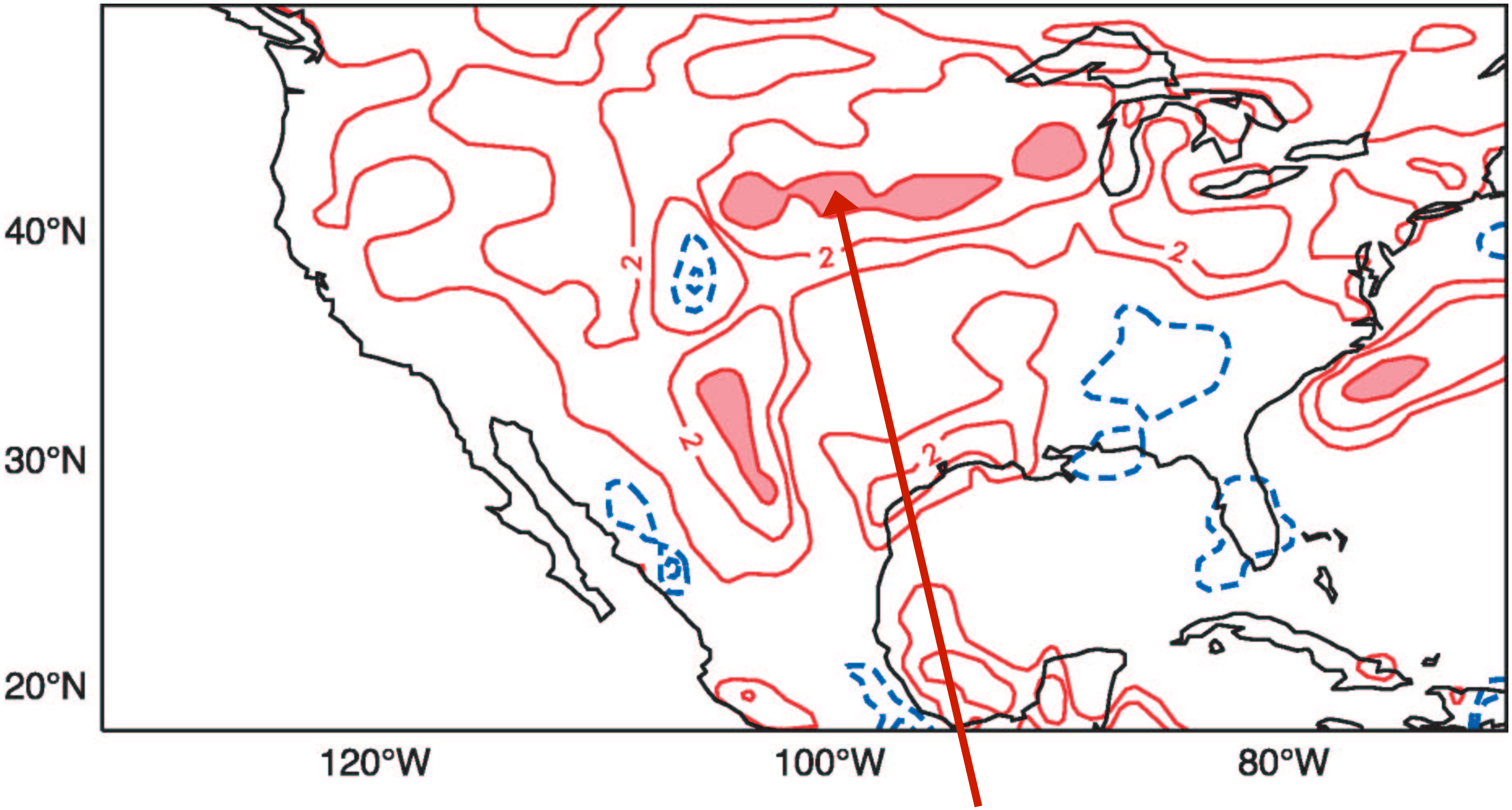
FIG. 1. Schematic description of the structure of the land surface model. Double arrows mean diffusivity processes, single arrows represent "drainagelike" terms (soil drainage, snow melting, and throughfall/top infiltration for the skin reservoir), horizontal arrows represent surface and subsurface runoff (bottom drainage is lost to the model and is therefore a runoff term). The bottom value of the resistance network for evaporation is $q_{sat}(T_{sk})$, except for the bare ground, where a relative humidity α is assumed [see Eq. (19)]. In the heat transfer panel, the snow mass replaces a portion of the first model layer (M), and the horizontal arrow represents heat exchanges due to melting.

Impact of model change on 48-72hr forecast precip. (July 9-25, 1993)



- **New model gave good 3-day <u>precipitation forecast</u> for Mississippi flood** <u>*Beljaars et al. 1996*</u>

July 1993 Forecast Difference: Wet or Dry soil on July 1,2,3

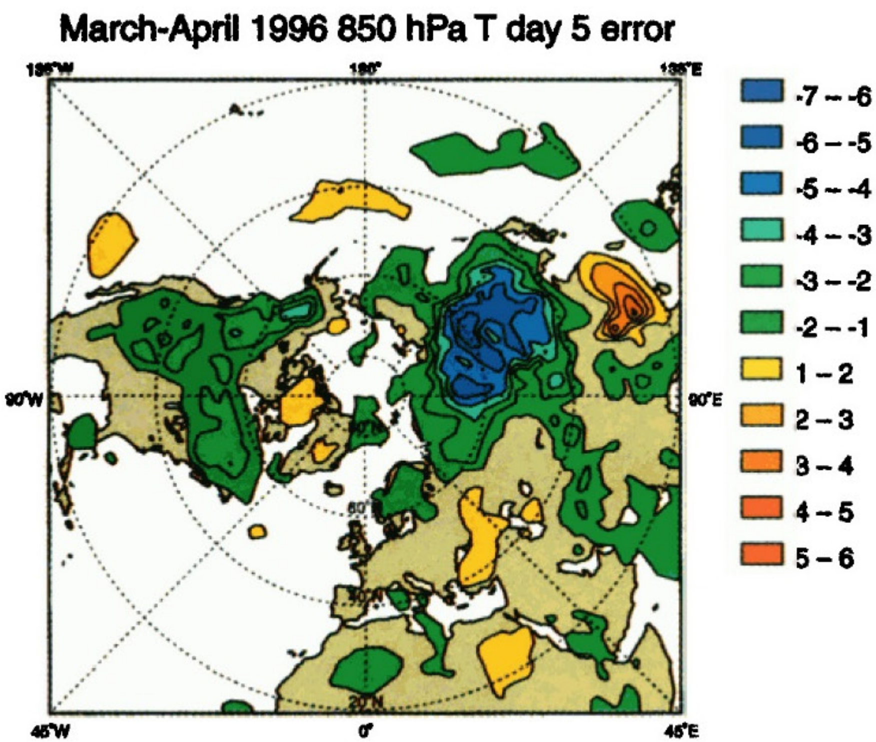


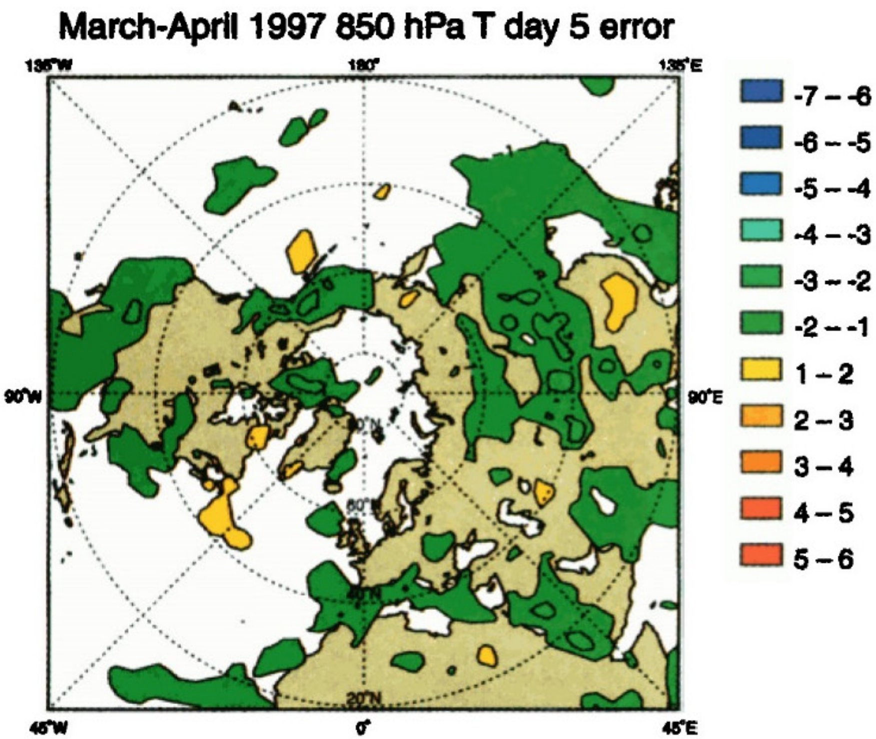
- Increase of forecast <u>monthly precipitation</u>: peaking at over **4 mm/day (>125 mm/month)** showed key role of soil moisture (global model)

BOREAS papers

- **Betts A. K., P. Viterbo, A.C.M. Beljaars, H-L. Pan, S-Y. Hong, M. L. Goulden and S.C. Wofsy, 1998**: Evaluation of the land-surface interaction in the **ECMWF and NCEP/NCAR reanalyses** over grassland (FIFE) and boreal forest (BOREAS). J. Geophys. Res., 103, 23079-23085. **(85)**
- **Betts, A. K., M. L. Goulden, and S.C. Wofsy, 1999**: Controls on evaporation in a boreal spruce forest. J. Climate, 12, 1601-1618. **(63)**
- **Betts A. K. and J. H. Ball, 1997**: Albedo over the boreal forest. J. Geophys. Res., 102, 28901-28910. **(388) (still 30/year)**
- **Viterbo, P. and A.K. Betts, 1999**: The impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. J. Geophys. Res., 104, 27803-27810. **(134)**
- **Van den Hurk, B.J.J.M., P. Viterbo, A.C.M. Beljaars and A. K. Betts, 2000**: Offline validation of the ERA40 surface scheme. ECMWF Tech Memo, 295, 43 pp. **(256)**
- **Betts, A. K., J. H. Ball, and J. H. McCaughey, (2001)**: Near-surface climate in the boreal forest. J. Geophys. Res., 106, 33529-33542, doi:10.1029/2001JD900047. **(50)**
- **Balsamo, G., P. Viterbo, A. Beljaars, B. van den Hurk, M. Hirschi, A.K. Betts and K. Scipal (2009)**, A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System., J. Hydrometeorol., 10, 623–643. **(285)**
- **Dutra, E., G. Balsamo, P. Viterbo et al (2010):** An Improved Snow Scheme for the ECMWF Land Surface Model: Description and Offline Validation. JHM, 11. **(104)**

Boreal forest snow-albedo error





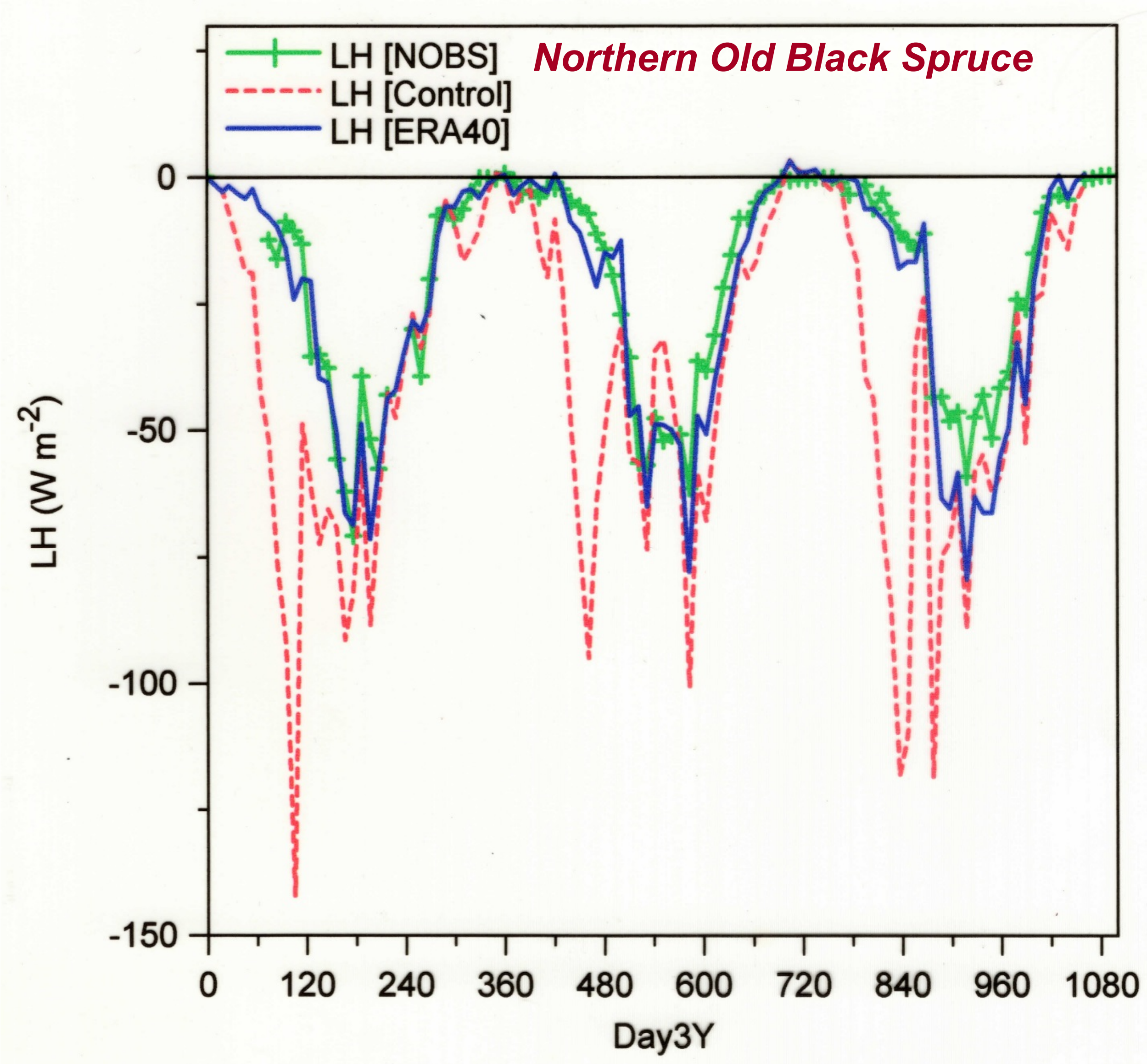
Reduction of boreal forest snow-albedo improved every single 5-day NH forecast for 850 hPa for March-April.

(Viterbo and Betts 1999)

Offline validation of ERA-40 surface scheme *(Van den Hurk et al. 2000)*

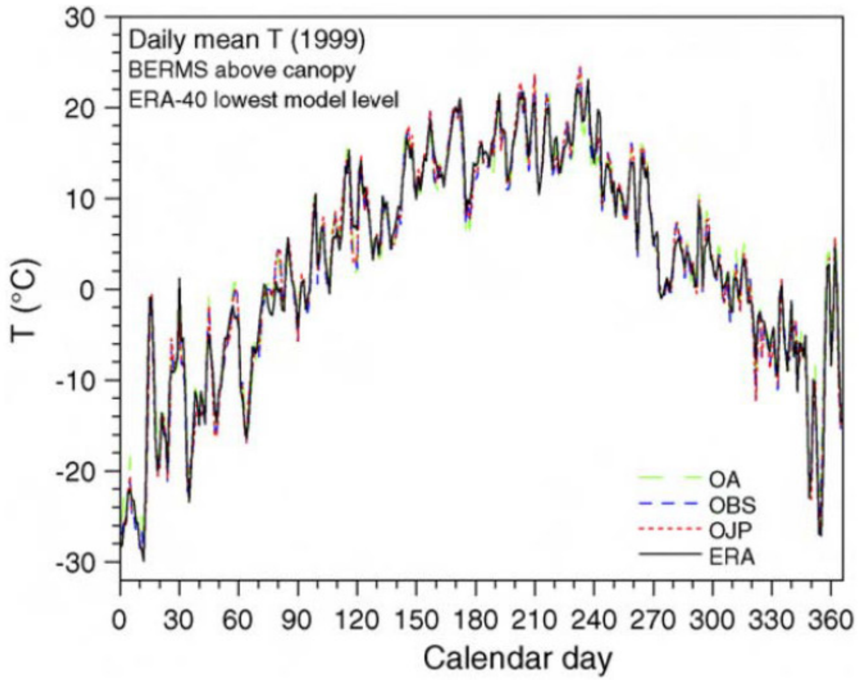
- New ECMWF tiled model
  - 8 tiles (bare soil, high vegetation, low vegetation, high vegetation with snow beneath, snow on low vegetation, interception layer, sea-ice, open water).
  - Coverage map of 18 vegetation types: land surface parameters vary per vegetation type.
  - A new set of environmental controls on canopy transpiration is introduced: including response to air humidity deficit; no water extraction from frozen soils
  - On top of the soil, a new single snow layer is introduced with prognostic equations for albedo and density, and separate energy balance equations for high and low vegetation tiles with snow.

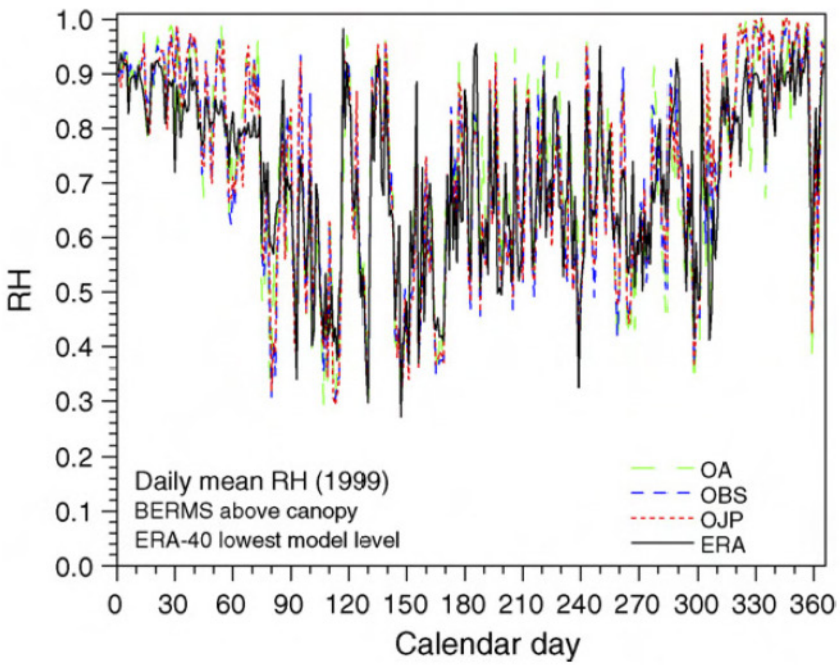
ERA-40 fluxes greatly improved!



BOREAS to BERMS

- **Betts, A.K., J. Ball, A. Barr, T. A. Black, J. H. McCaughey and P. Viterbo, (2006)**, Assessing land-surface-atmosphere coupling in the ERA-40 reanalysis with boreal forest data. AgForMet **(28)**
  - **Biases in ERA-40 of temperature and humidity are small**
  - Model has a high bias in evaporation
  - And a low bias of reflective cloud





Forecast to Climate Scale

Improved spring albedo, 2000-2008, from improved snow model. Multisite global calibration, including BERMS

(Dutra et al. 2010)

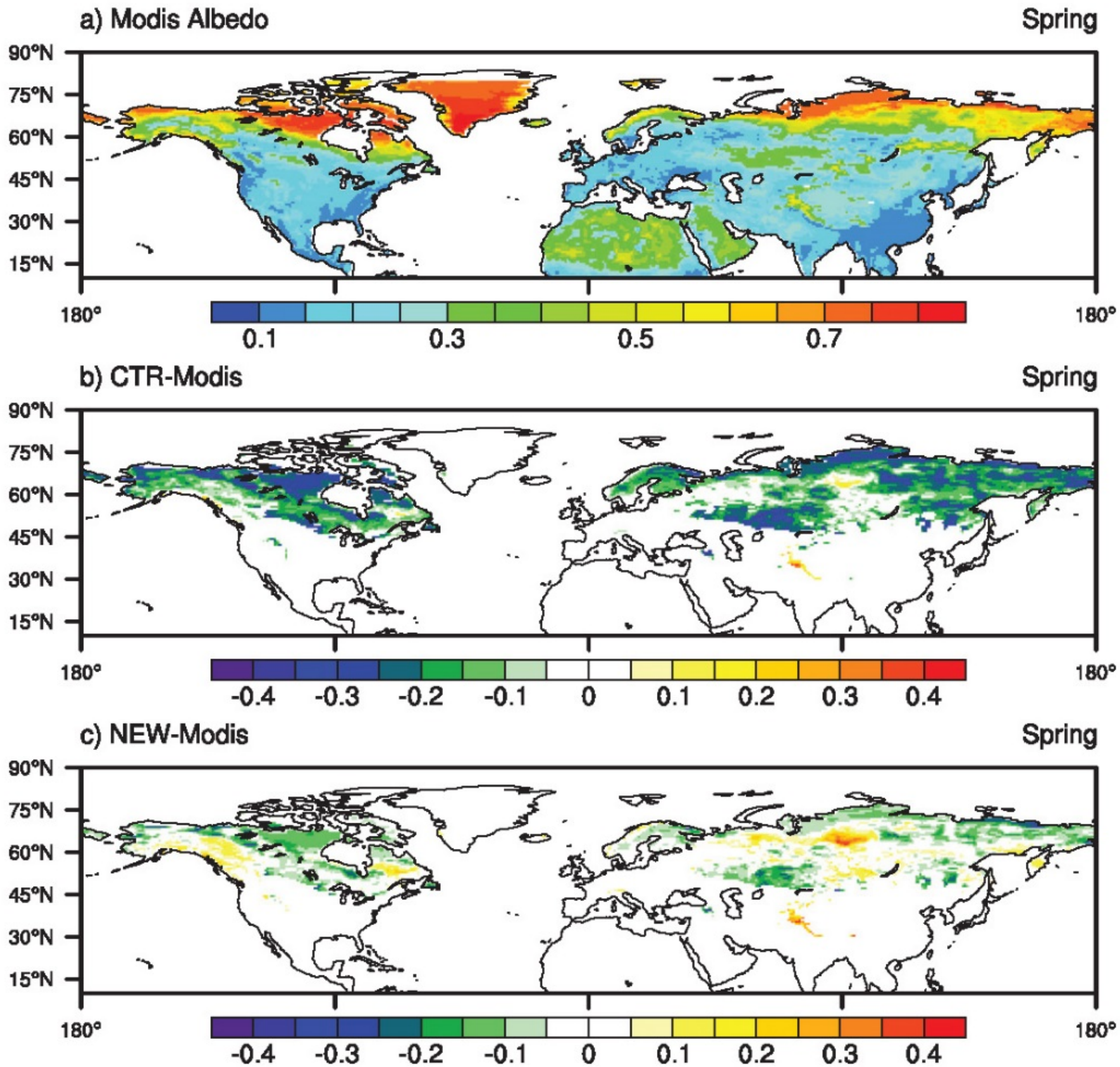


FIG. 12. (a) Mean observed maps of spring albedo by MODIS for the period 2000–08 and differences between simulated albedo and MODIS for (b) CTR and (c) NEW. The differences (b) and (c) show only snow-covered grid boxes with <50% MODIS missing data. Note the different color scales between panel (a) and panels (b) and (c).

Land Surface Model evolution

2000/06	2007/11	2009/03	2009/09		2010/11

- **TESSEL**

  Van den Hurk et al. (2000)
  Viterbo and Beljaars (1995),
  Viterbo et al (1999)

  Up to 8 tiles (binary Land-Sea mask)

  GLCC veg. (BATS-like)

  ERA-40 and ERA-I scheme

- **Hydrology-TESSEL**

  Balsamo et al. (2009)
  van den Hurk and
  Viterbo (2003)

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity &
  surface runoff revision

- **NEW SNOW**

  Dutra et al. (2010)

  Revised snow density

  Liquid water reservoir

  Revision of Albedo
  and sub-grid snow
  cover

- **NEW LAI**

  Boussetta et al. (2011)

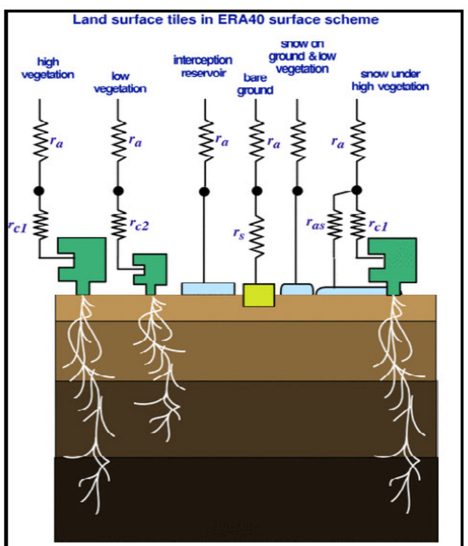
  New satellite-based

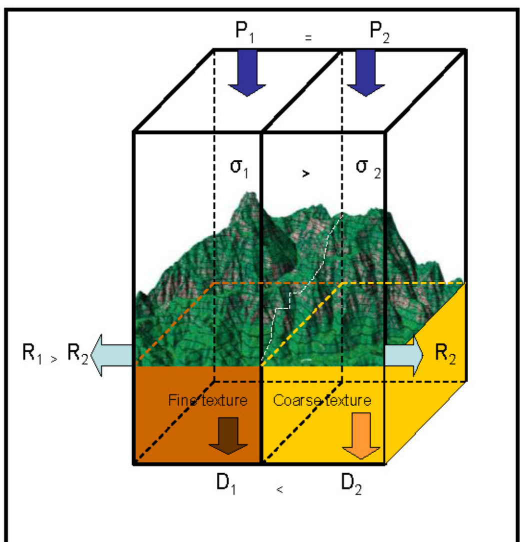
  Leaf-Area-Index

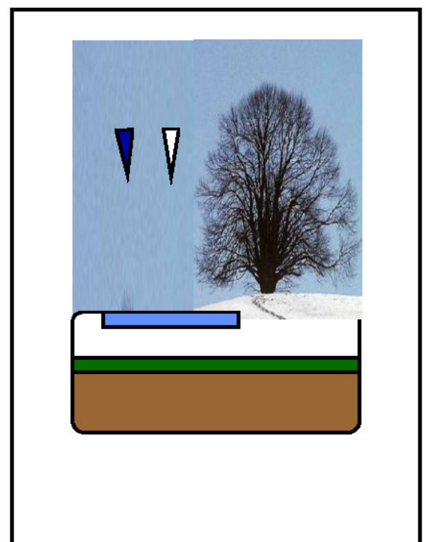
- **SOIL Evaporation**

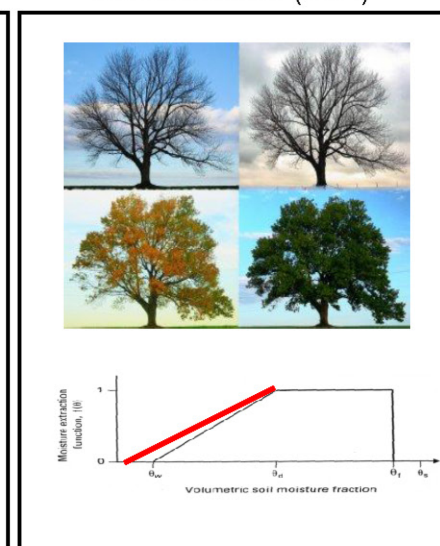
  Balsamo et al (2011) based on

  Mahfouf Noilhan (1991)









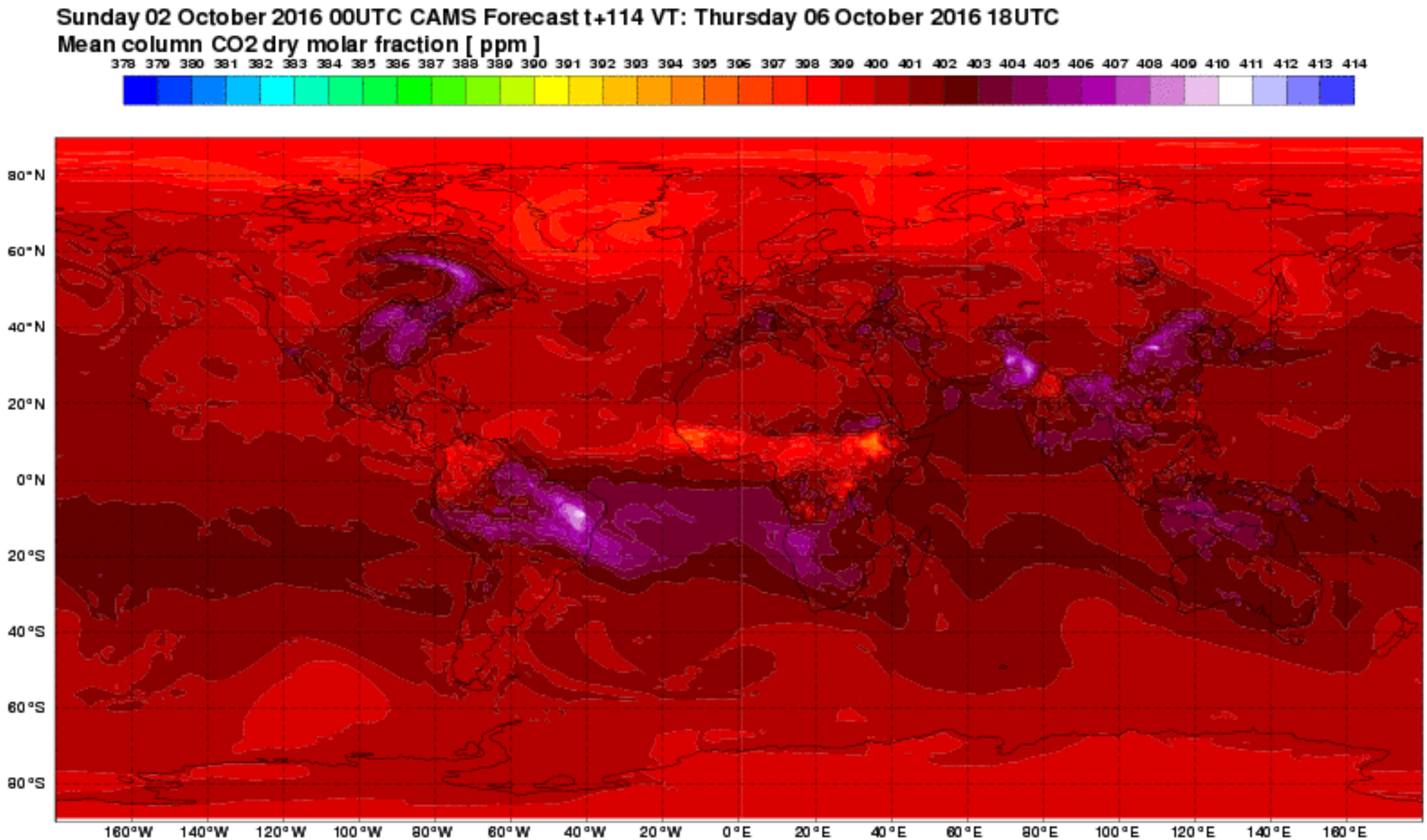
ECMWF operational model (2016)

- Many land-surface and BL improvements tested against FIFE/BOREAS (+other datasets)
- Major changes: 1993 to 2016
  - Horizontal resolution: 108km to 9km
  - Vertical resolution: 31 to 137 levels
- ERA-5 in production
  - Hourly, ¼ degree global reanalysis: 1979-2017on
  - Current operational model physics

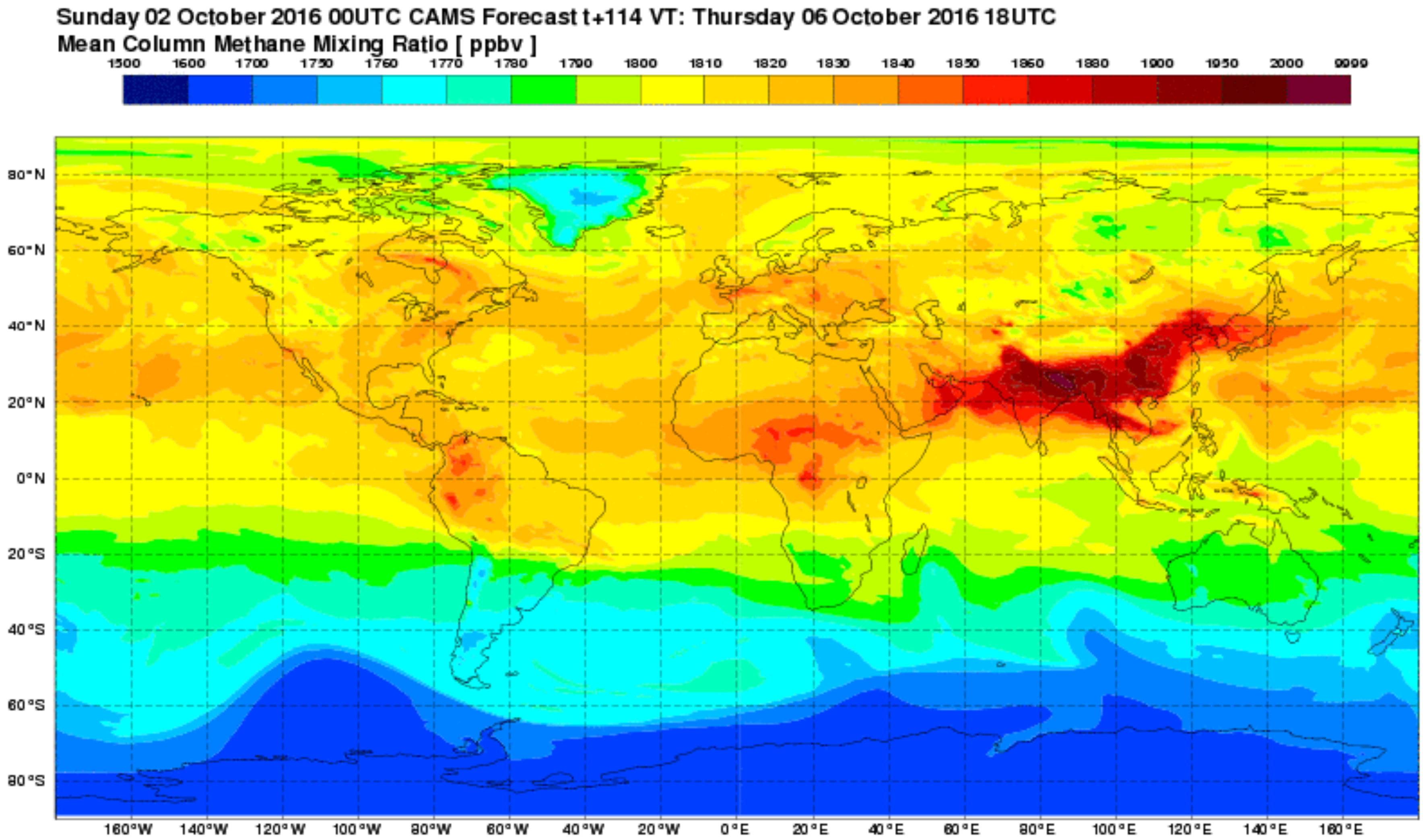
Fully coupled CO_2 analysis and forecast?

- **Boussetta, S., G. Balsamo, A. Beljaars et al. (2013):** Natural land carbon dioxide exchanges in the ECMWF integrated forecasting system: Implementation and offline validation. JGR
  - 34 sites including OA and OBS (BERMS)
  - The ECMWF land surface model has been extended to include a CO_2 module, relating photosynthesis to radiation, atmospheric CO_2, soil moisture, and temperature: with the option of deriving a canopy resistance from photosynthesis
- **Agustí-Panareda, A. et al. (2016):** A biogenic CO_2 flux adjustment scheme for the mitigation of large-scale biases in global atmospheric CO_2 analyses and forecasts. *Atmos. Chem. Phys., 16.*
  - Forecasting atmospheric CO_2 daily at the global scale with a good accuracy like it is done for the weather is a challenging task. However, it is also one of the key areas of development to bridge the gaps between weather, air quality and climate models. ***The challenge stems from the fact that atmospheric CO_2 is largely controlled by the CO_2 fluxes at the surface, which are difficult to constrain with observations.***

Global CO_2 forecasts



Global CH_4 forecasts



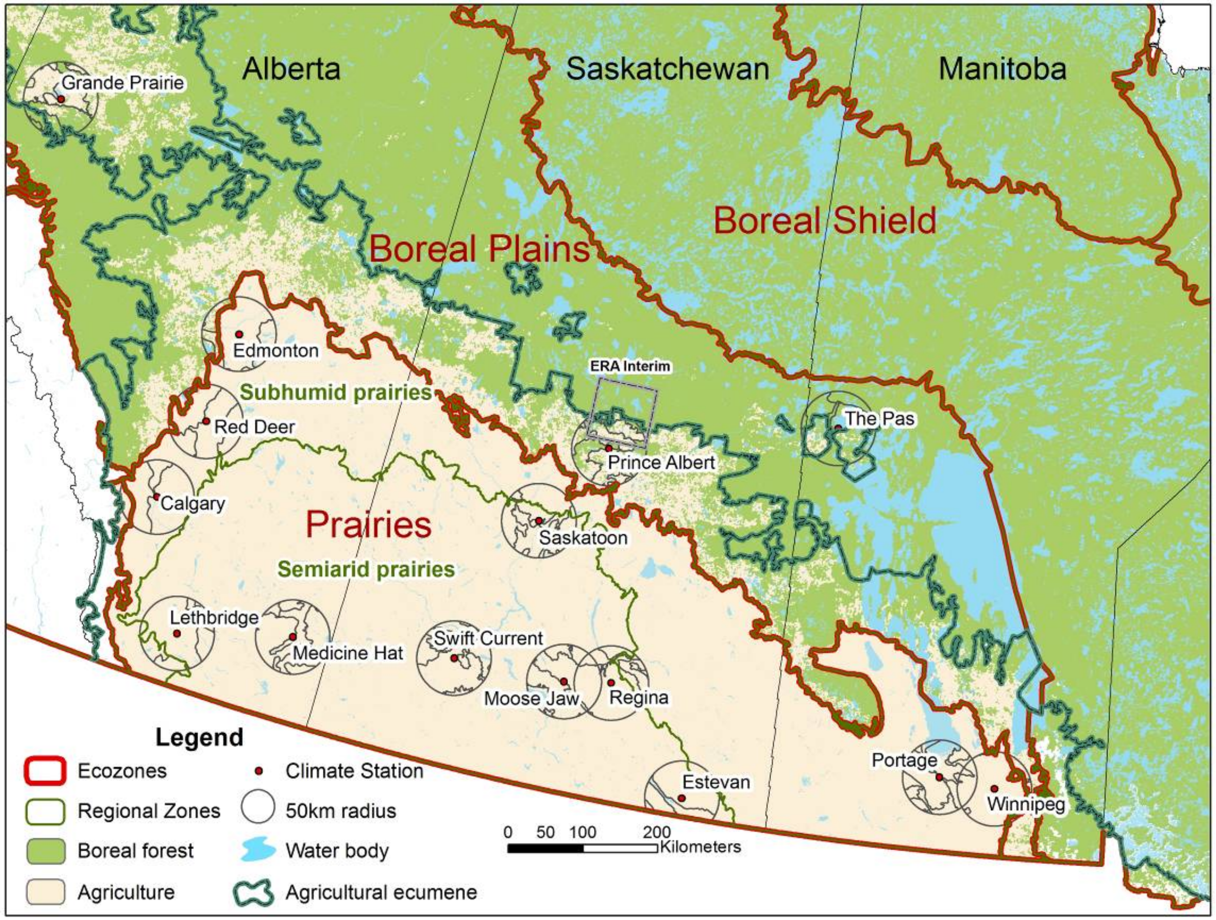
Kabat et al. (2004): Vegetation, Water, Humans and the Climate

Particularly well documented is the work by Betts and his co-workers on the FIFE data and more recently on BOREAS data to improve ECMWF and NCEP/NCAR models. Typical improvements include the soil hydrology, evaporation, soil heat flux and boundary layer parameterisations. Recently the impacts of frozen soil and snow have been assessed. The sum of these improvements has led to significant improvements in the skill of these forecast models (see Sect. A.4.5.2).

Ray Desjardins (2012)

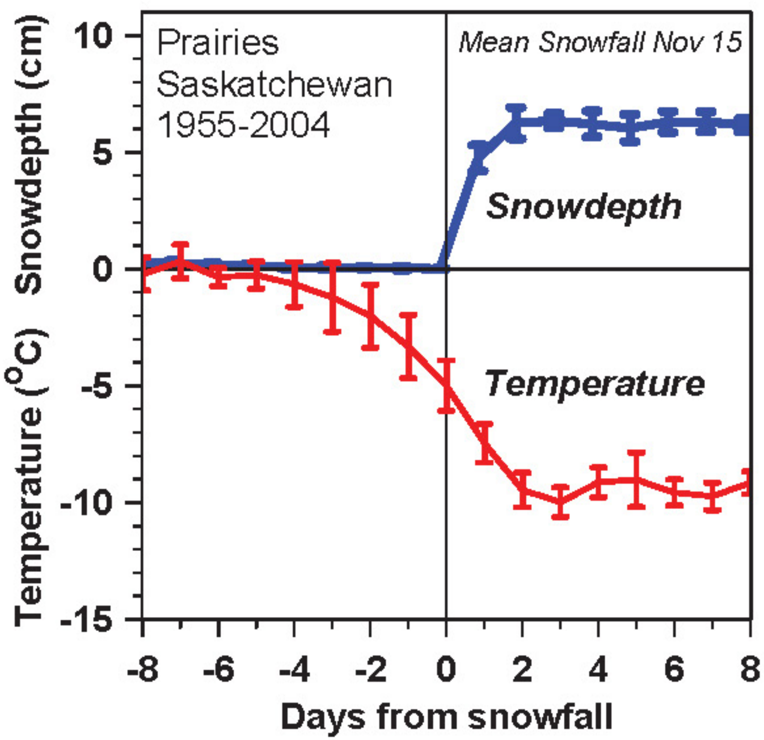
- ***Senior Scientist: AG-Canada***
  - ***TwinOtter flux aircraft in BOREAS***
- **"We need your help to understand the Prairie climate"**
  - **OK, if you access and preprocess the Environment Canada hourly data**
- **FIFE and BOREAS: open data access!**

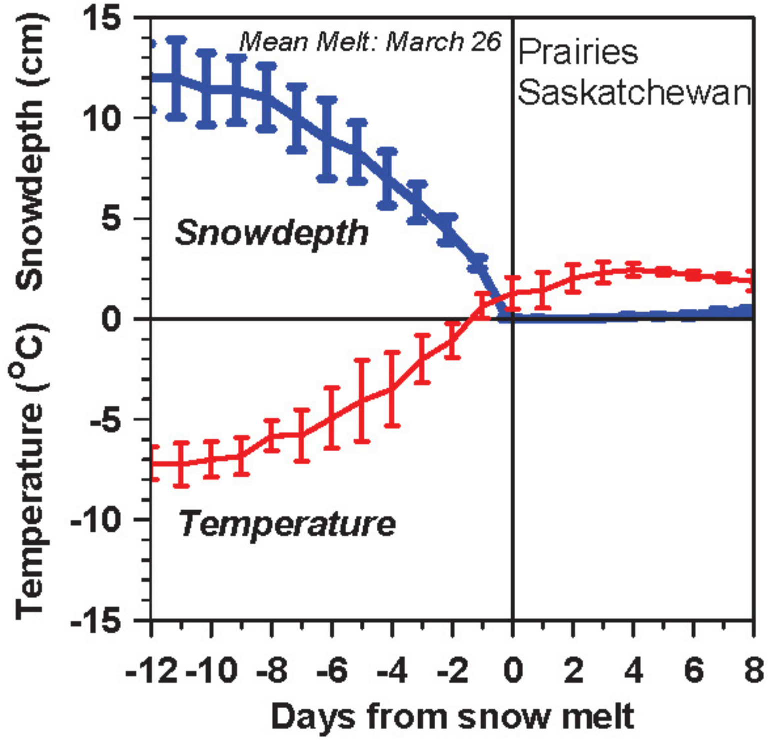
15 Prairie stations: 1953-2011



- *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)

Snowfall and Snowmelt
Winter and Spring transitions

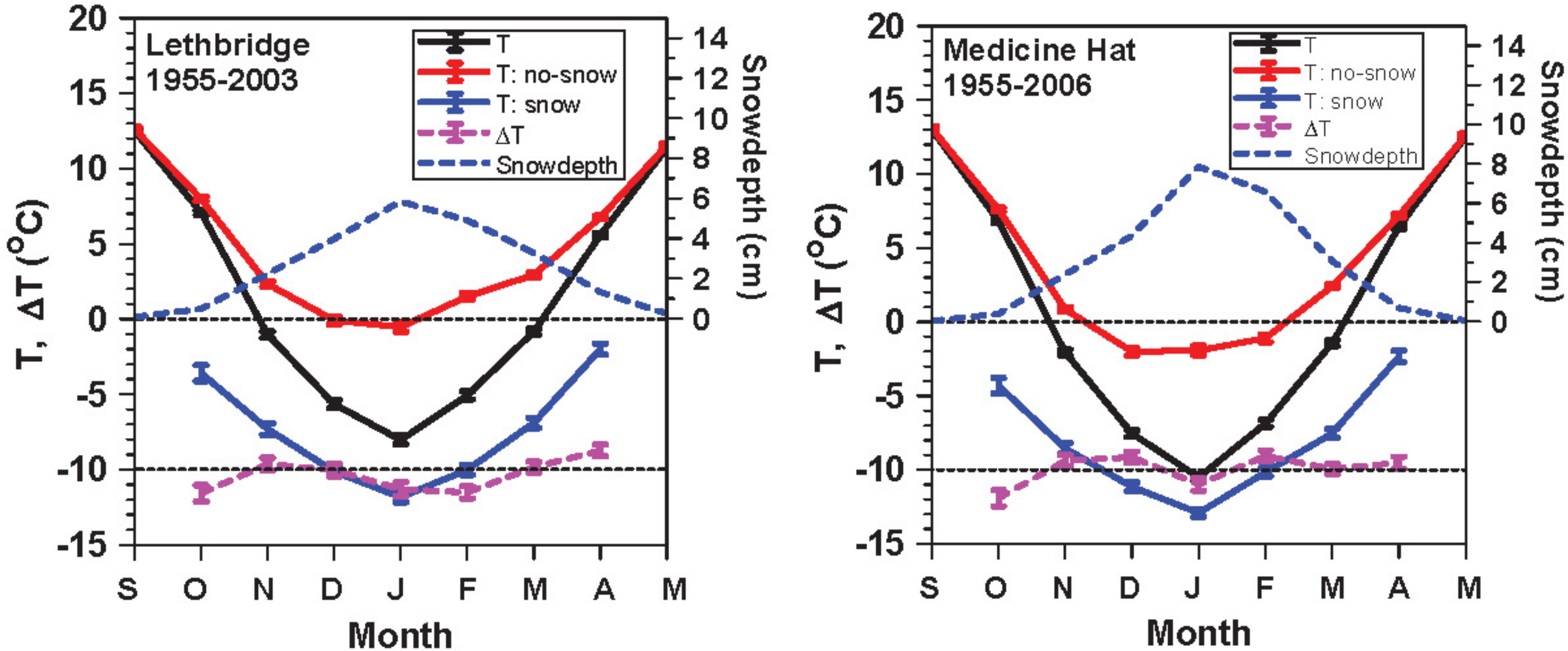




- **Temperature falls/rises about 10K with first snowfall/snowmelt**
- ***Snow reflects sunlight; shift to cold stable BL***
  - ***Local climate switch between warm and cold seasons***
  - ***Winter comes fast with snow***

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

- Two non-overlapping climates

Betts et al. (2016)

Interannual variability of T coupled to Snow Cover

- **Alberta: 79% of variance**
- **Slope T_m -14.6 (± 0.6) K**

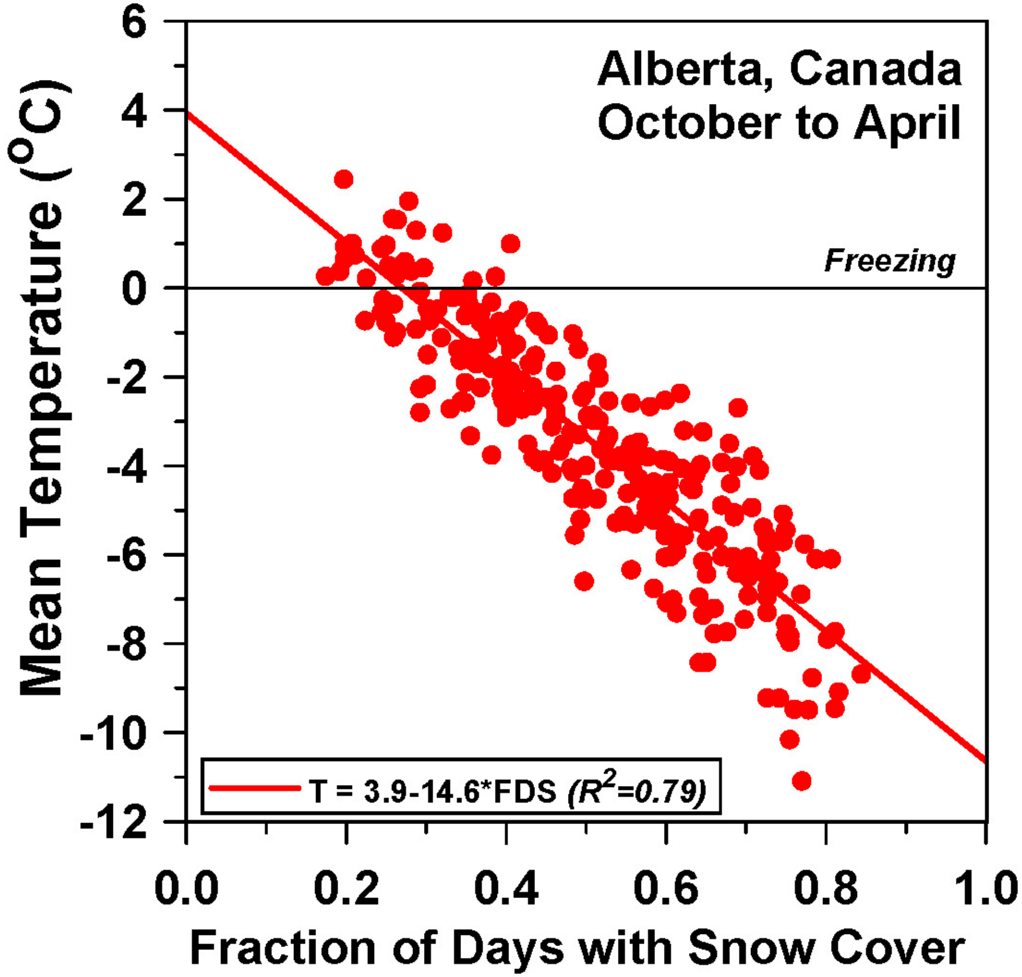
10% fewer snow days

= 1.5K warmer

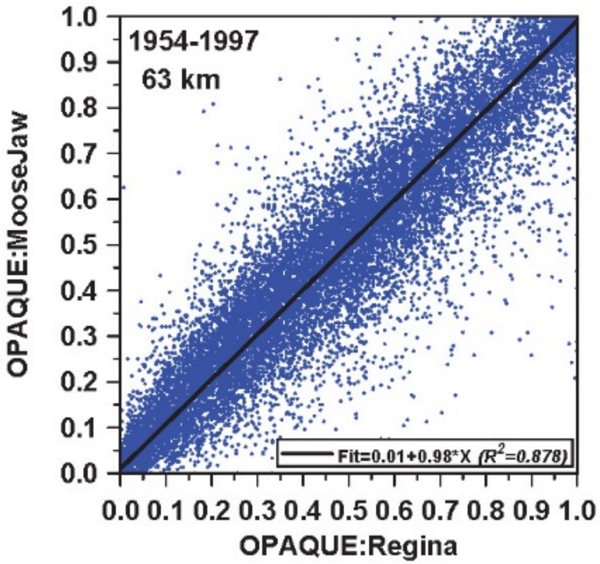
on Prairies

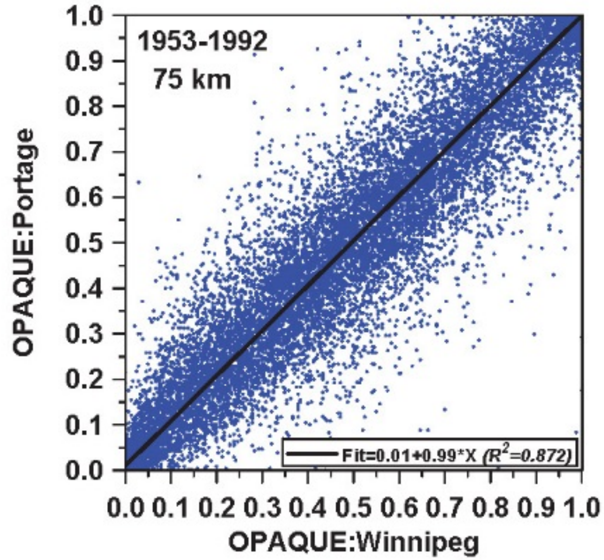
Think Climate Change!

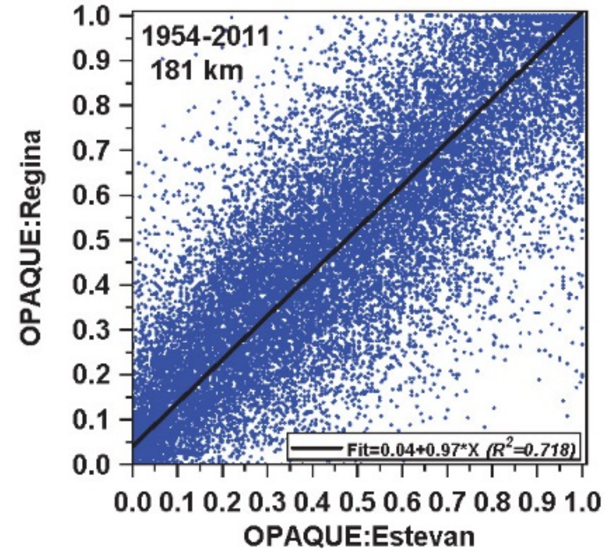
More snow cover - Colder temperatures



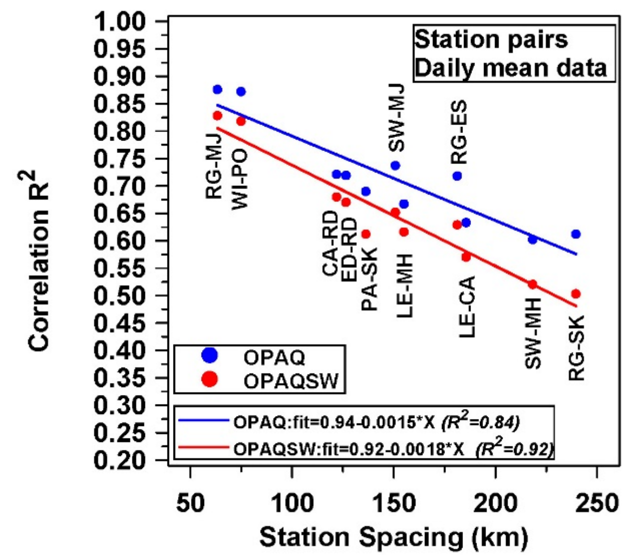
Opaque Cloud (Observers)







- **Daily means unbiased**
- **Correlation falls with distance - Good data!**
- **Calibrate to LW, SWCF**
  - **Using BSRN data**



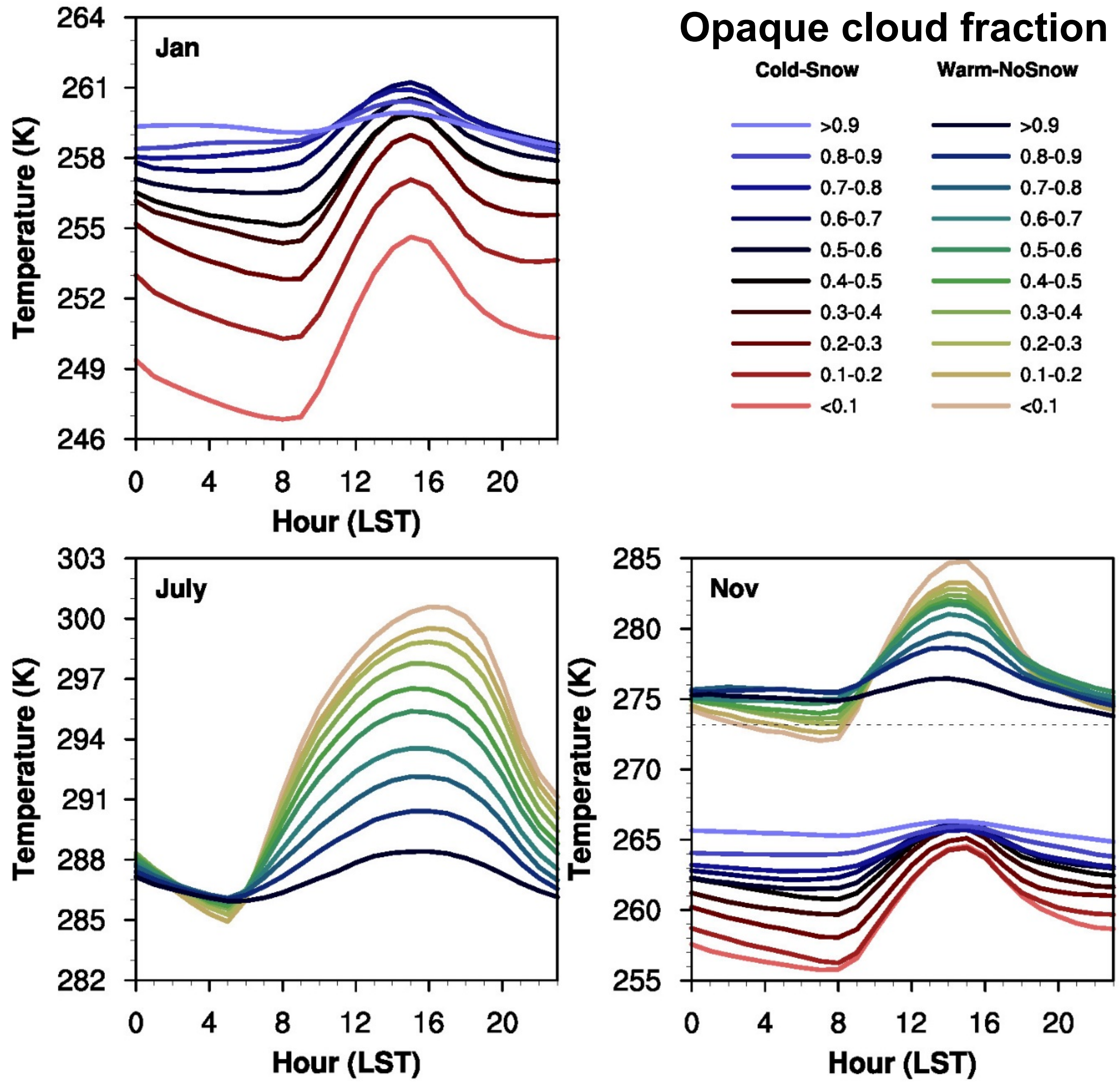
Diurnal cycle: Clouds & Snow

Canadian Prairies
660 station-years of data

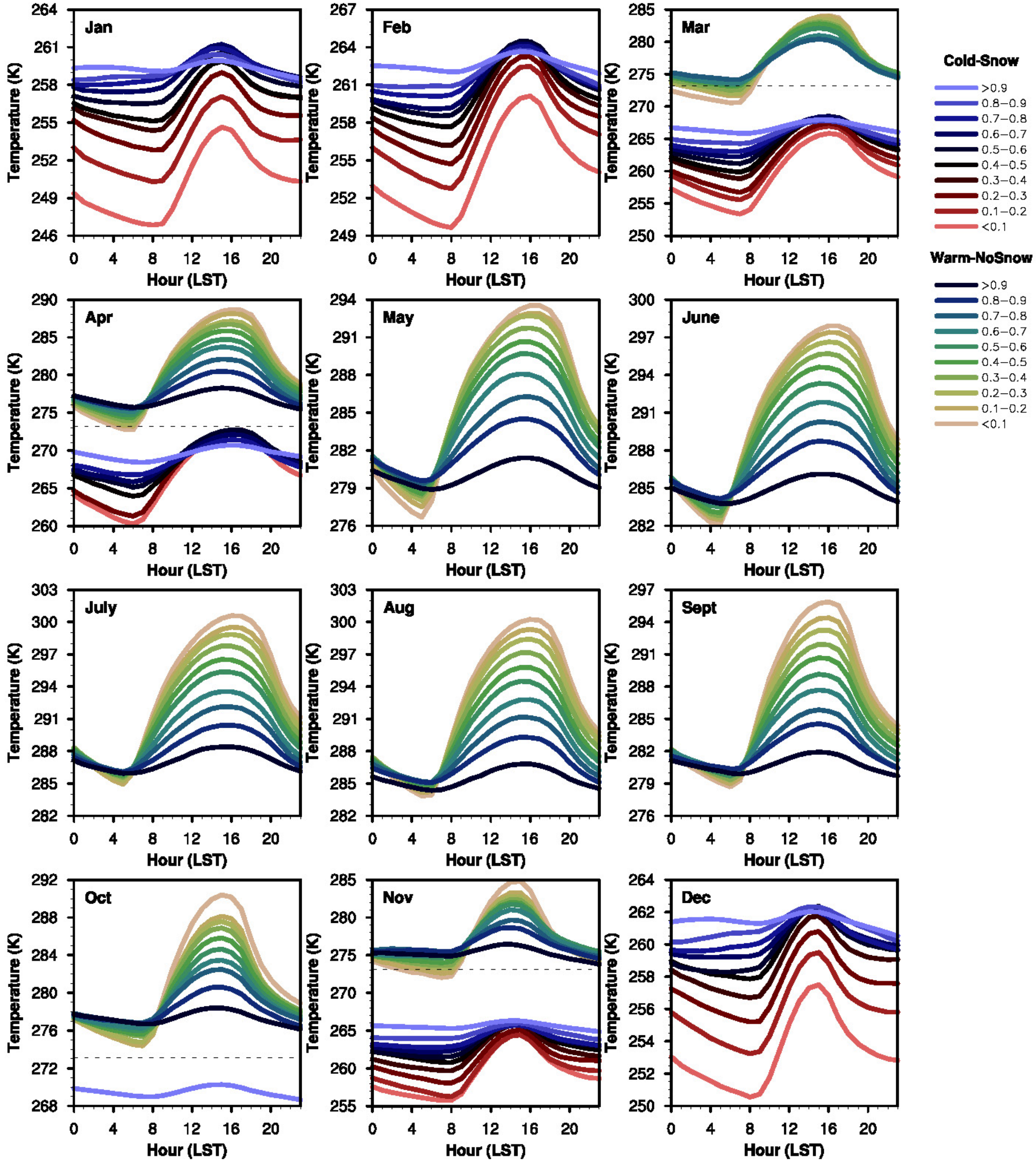
Winter climatology
- Colder when clear
- LWCF dominant with snow
- Stable BL

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)



Again two distinct climates

Impact of Snow

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

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**

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

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

Soil moisture memory

<u>April:</u> memory of entire cold season (snow, soil ice) back to November freeze

<u>June, July, Aug:</u> 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

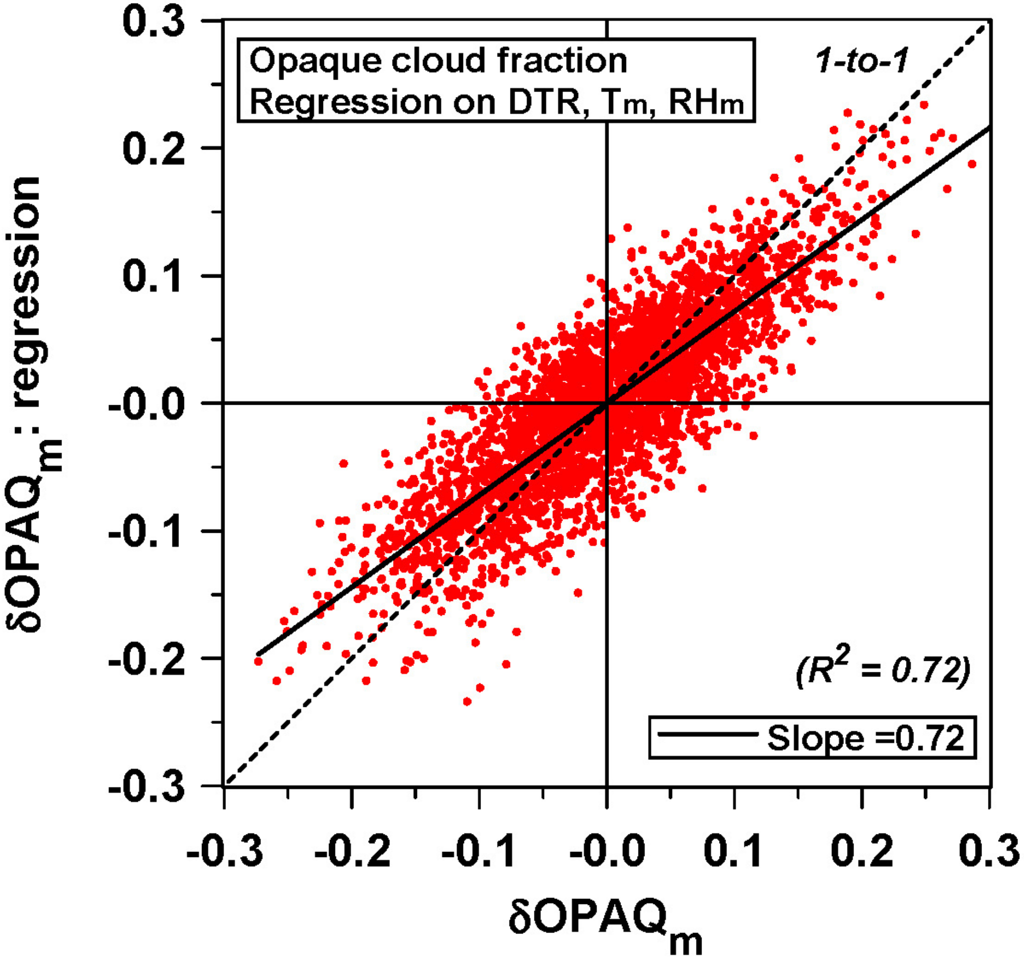
Summer Precip Memory back to March

***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

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

So?

- ***We need to revisit the boreal forest with these long-term Canadian hourly datasets – with hourly opaque cloud***

Climate Change?

- **Multi-model ensembles**
  - **More work on model biases still needed**
  - **Prairie data a new 60-year reference set**

- **Politics + ethics, not science, now the issue**
  - **Paris agreement step forward**
  - **China moving aggressively; planning to capture global renewable market; *systems engineering***
  - **Libertarian billionaires purchased Congress, but got a demagogue as candidate**
  - **Fictitious global conspiracy: collapse looming**

Conclusions

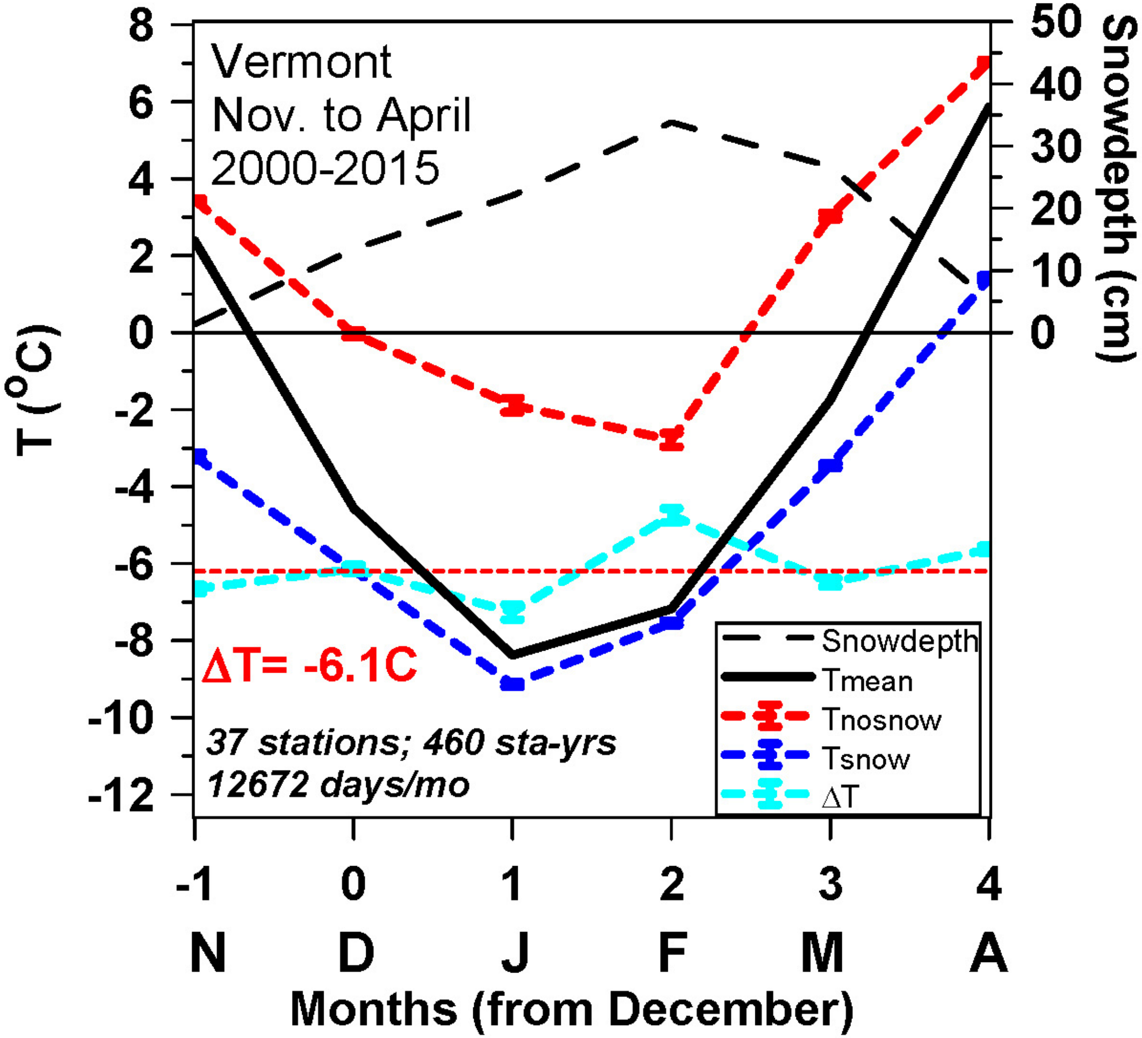
- **FIFE and BOREAS were transformative**
  - ***Their time-series of meteorology, radiation and surface fluxes, soil and vegetation data gave us ground truth for forecast models – up to seasonal scale***
  - ***The "FIFE dataset" was used to test every land-surface model for a decade: till global FLUXNET***
  - ***BOREAS/BERMS led to new forest models and several generations of snow models***
  - ***Understanding from forecast models still being transferred to Earth System Models.***

Climatological Impact of Snow: Vermont

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

<u>Difference ΔT= -6.1(±0.7)°C</u>

Snow-free winters: warmer than snowy winters: +6°C
(Extensive forest cover)



FIFE continues

- **Evans, J. P. et al. (2005):** Time series analysis of regional climate model performance. JGR
  - ‘Four regional climate models (RegCM2, MM5/BATS, MM5/SHEELS, and MM5/OSU) were intercompared on a fairly small domain covering a relatively homogenous area in Kansas, US, including the FIFE site.’
- **Rasmussen et al. (2012):** Spatial-Scale Characteristics of Precipitation Simulated by Regional Climate Models and the Implications for Hydrological Modeling. J. Hydromet
  - ‘On local scales, gridded precipitation observations and simulated precipitation are compared for the period of the 1987 FIFE campaign.’

Warm Season Diurnal Climatology

- **Averaging daily values (Conventional)**

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

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

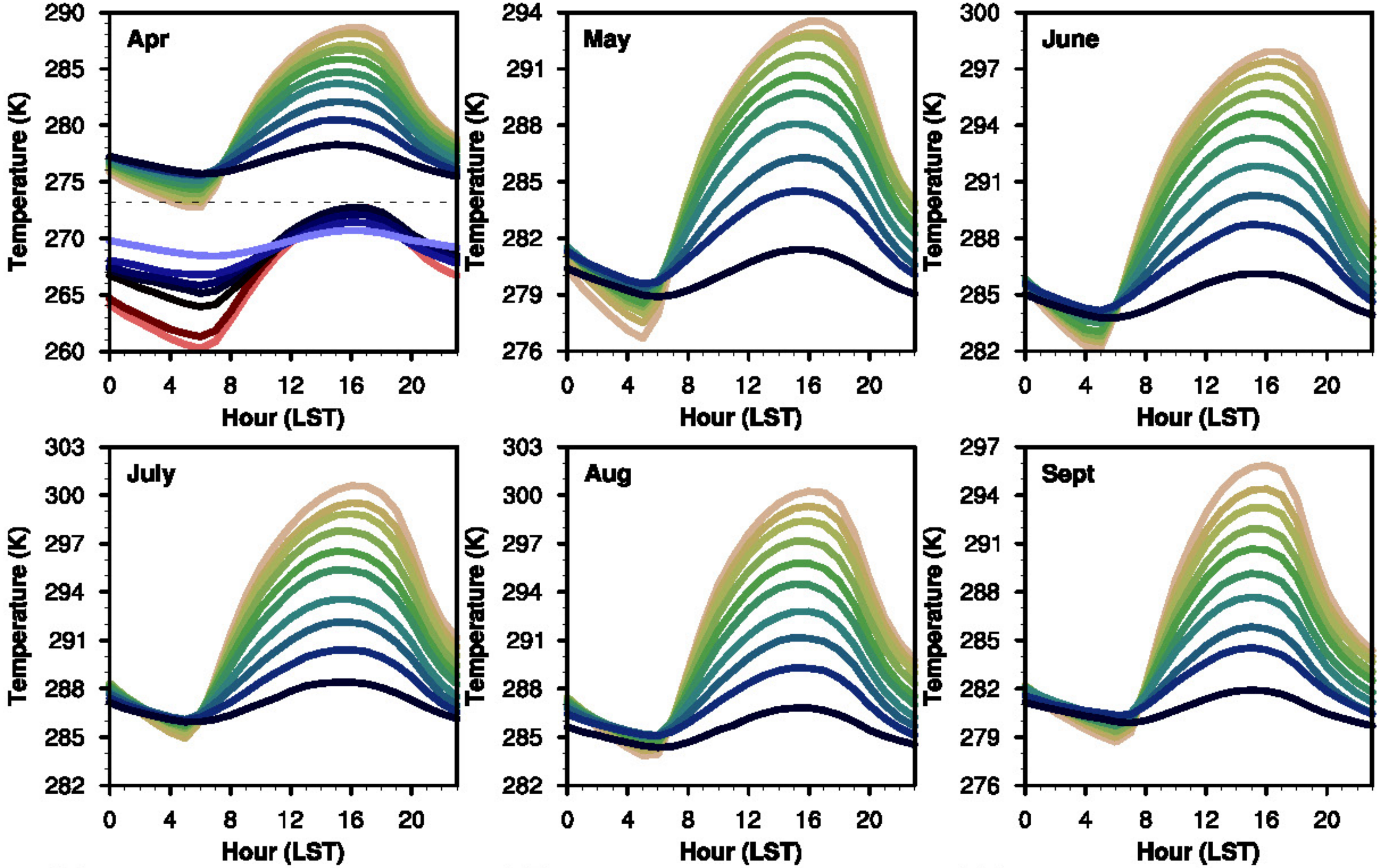
- **Extract mean diurnal ranges from composites** ***('True' radiatively-coupled diurnal ranges: damps advection)***

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

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

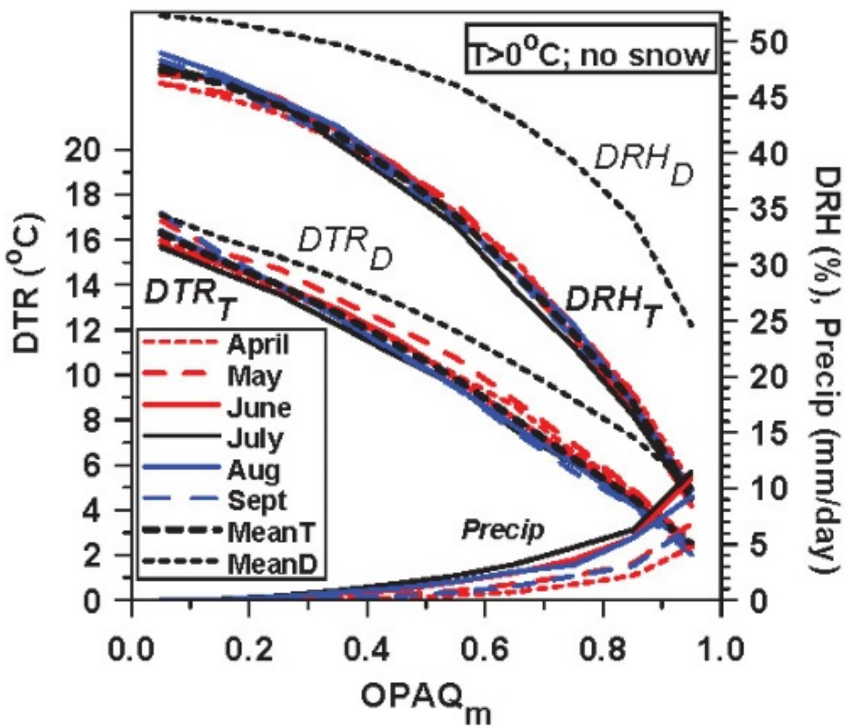
- **Q1: How are they related? $DTR_T < DTR_D$**

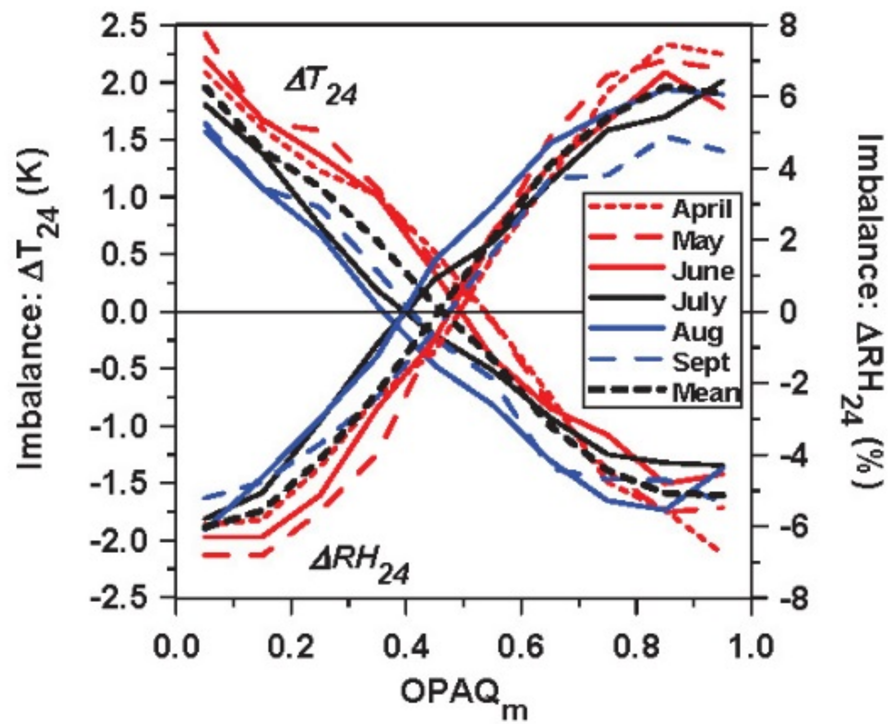
Monthly Diurnal Climatology



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

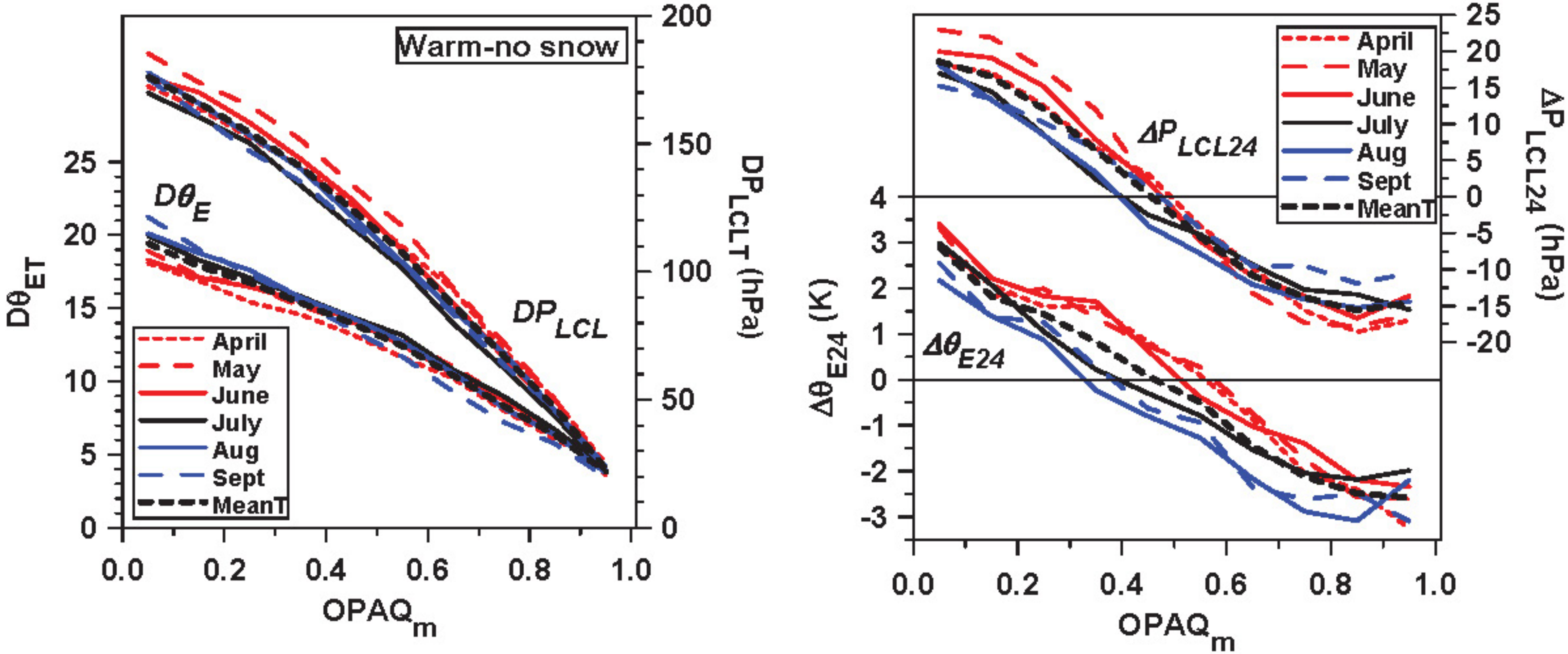
Diurnal Ranges & Imbalances





- 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%)

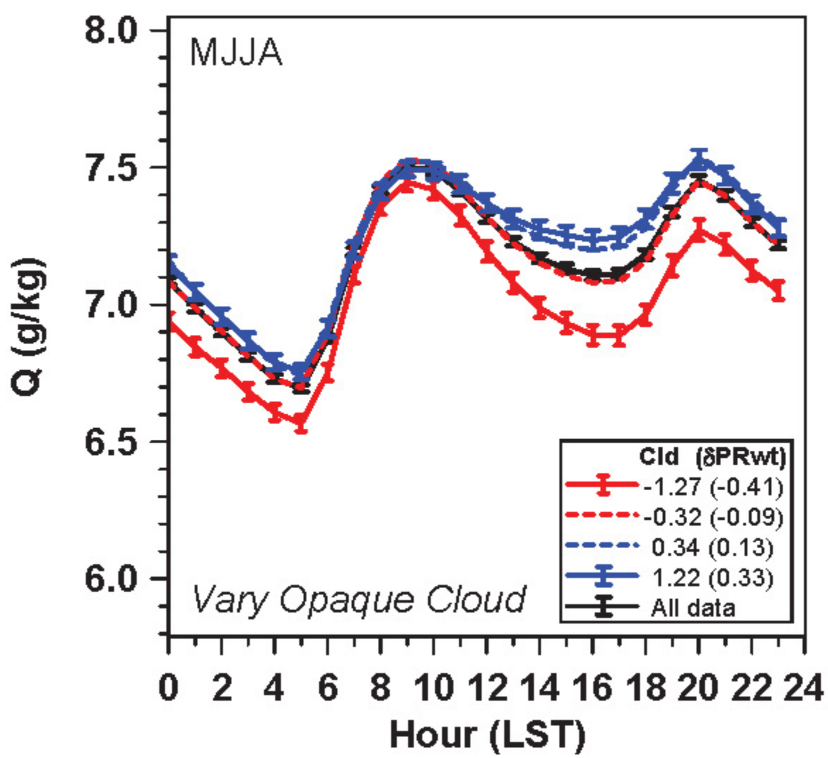
Diurnal Ranges & Imbalances

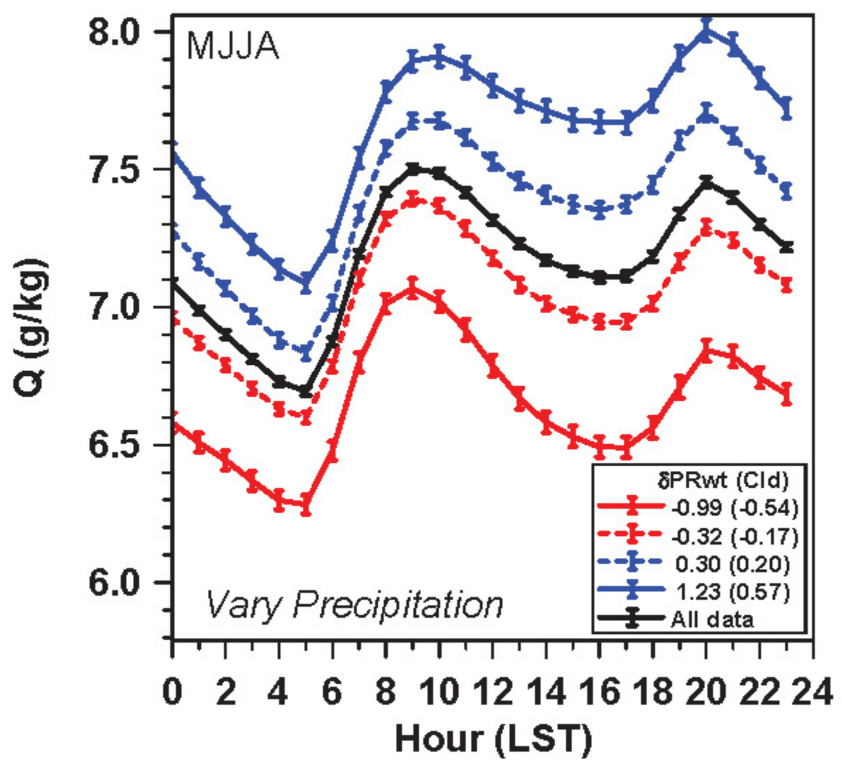


- April to Sept: <u>same coupled structure</u>
- Clear-sky: θ_E (+3K), LCL higher (+18hPa)

(Betts and Tawfik 2016)

Diurnal Cycle of Q

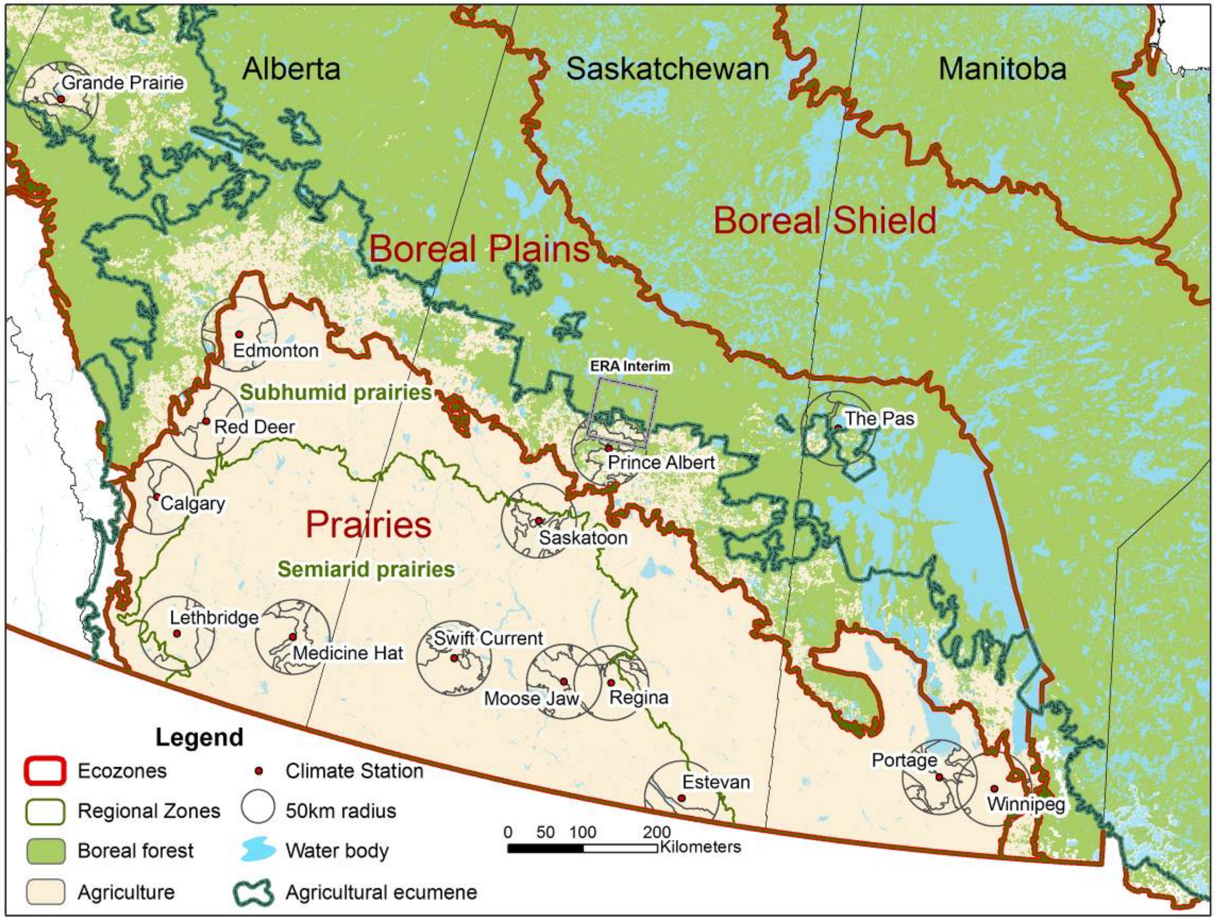




Binned by Opaque Cloud
Diurnal spread increases

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

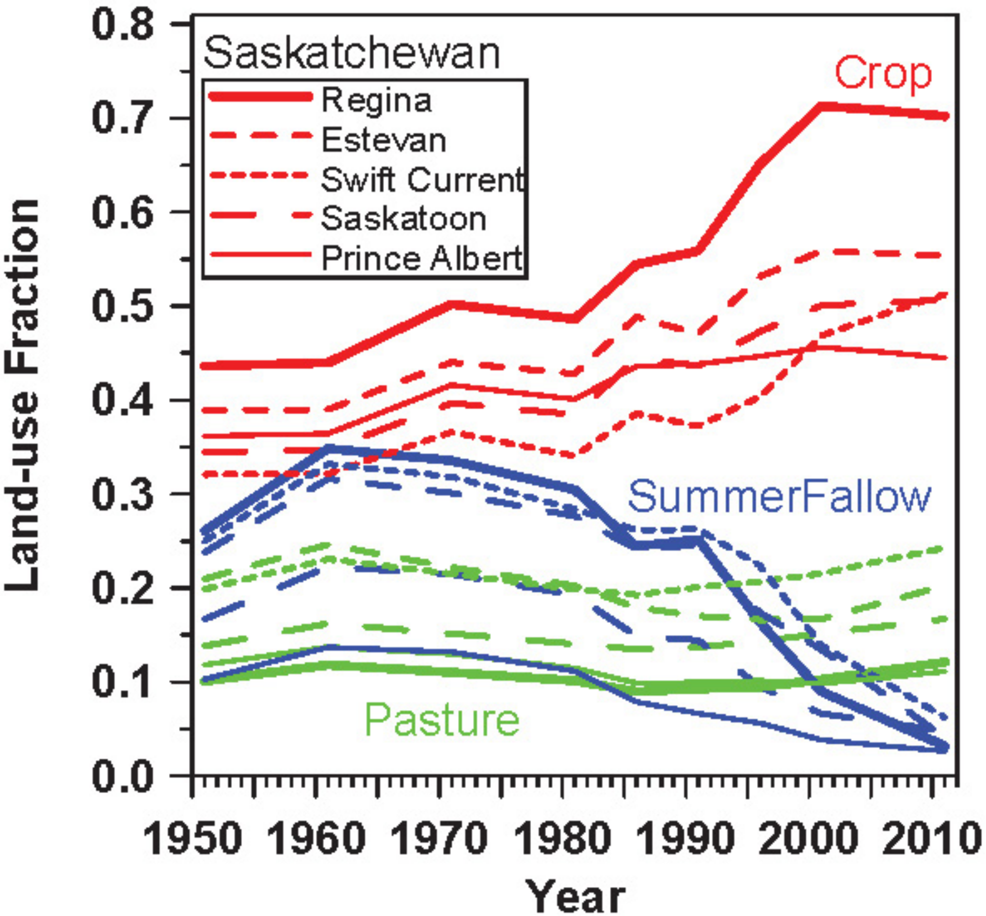
15 Prairie stations: 1953-2011



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

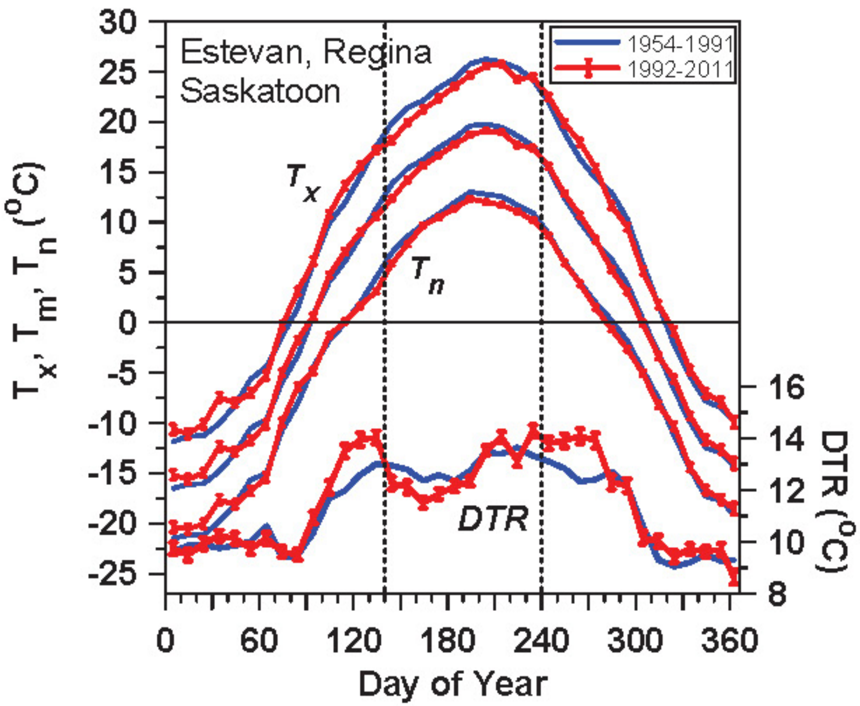
Change in Cropping (SK)

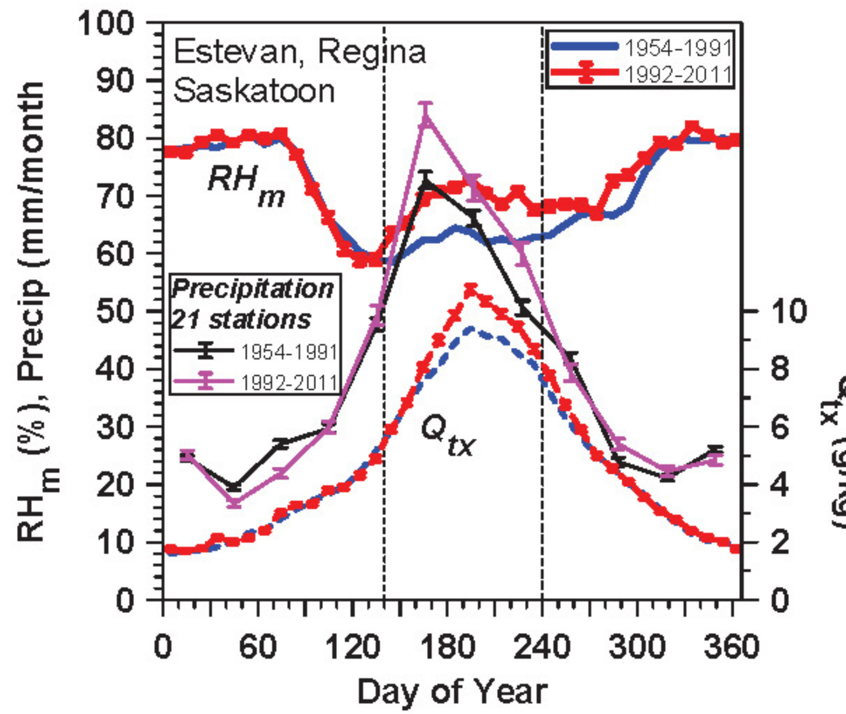
- **Ecodistrict mean for 50-km around station**
- **5 Mha drop (25%) in 'SummerFallow'**
  - **no crops: save water**
- ***Split at 1991 – Ask***
- ***Has summer climate changed?***



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%)