Land-cloud-climate coupling on the Canadian Prairies

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Land-Atmosphere Interactions
Valsavarenche, Valle d'Aosta, Italy
22 June - 1 July, 2015
Key Issues

• **Northern latitude climate**
  – Large seasonal cycle
    • Cold winters with snow
    • Snow is a fast climate switch
    • Two “climates” - above and below the freezing point of water

– **Summer hydrometeorology**
  • T and RH have joint dependence on radiation and precipitation on monthly timescales

– **Observational evaluation of models**
  • *Remarkable 55-yr hourly data set with opaque/reflective cloud observations*
Climate Processes

- **Solar seasonal cycle**
- **Precipitation**

- **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
15 Prairie stations: 1953-2011

- **Hourly** $p$, $T$, $RH$, $WS$, $WD$, **opaque/reflective cloud**
- **Daily** precipitation and snowdepth
References


• [http://alanbetts.com/research](http://alanbetts.com/research)
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 climate**
  - $DTR = T_x - T_n$
  - $\Delta RH = RH_{tn} - RH_{tx}$

- Almost no missing hourly data
  (until recent cutbacks)
Surface Radiation Budget

- $R_n = SW_n + LW_n$

- Define Effective Cloud Albedo
  
  \[ ECA = \frac{-SW_{CF}}{SW_{dn}(\text{clear})} \]

  \[ SW_n = (1 - \alpha_s)(1 - ECA) \cdot SW_{dn}(\text{clear}) \]

  Reflected by surface, clouds

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

- Daily means unbiased
- Correlation falls with distance
- Good data!
• **Annual means**
  – Interesting long-term variability
  – *Only Lethbridge has obvious bias after 1994*
Annual/D

- 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 Needs Clear-sky Fluxes:

- Compare ERA-Interim (ERI) and ‘clear’ BSRN days
  - $SW_{dn}(\text{clear})$: ERI biased low
  - Fit BSRN
  - $LW_{dn}(\text{clear})$: ERI unbiased
SW and LW Cloud Forcing

**BSRN at Bratt’s Lake, SK**

- **“Cloud Forcing”**
  - Change from clear-sky
- 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)
Use BSRN data to “calibrate” daily opaque/reflective Cloud at Regina

- **Daily mean opaque cloud** $\text{OPAQ}_m$

- **LW cools but clouds reduce cooling**

- **Net LW**: $\text{LW}_n$
  - $T>0$: depends on RH as well
  - $T<0$: depends on $T$ and TCWV

- **Regression gives** $\text{LW}_n$ to ± 8W/m² if $T_m>0$ ($R^2=0.91$)

(Betts et al. 2015)
SW calibration

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

- Unstable BL: SWCF
- Clouds at LCL
  - reflecting sunlight
- Stable BL: LWCF
- Snow
  - reflecting sunlight
Clouds: Cold & Warm Climates

- **250,000 days (Prairies: 650 station-years: 1953-2011)**
- **Freezing point of water changes everything**
- **Cold <0°C: Snow: Surface cools radiatively, clouds ‘blanket’**
  - **stable boundary layer**
- **Transition near freezing: >0°C: Snow; <0°C: No Snow**
- **Warm >0°C: No Snow: Surface solar heating, clouds reflect**
  - **Daytime unstable boundary layer**
RH and Pressure of LCL

- **Cold <0°C: Snow**
  - RH near saturation over ice
  - Prairie: 1955-2011 (75,000 days)
  - Cold: T < 0°C, snow

- **Transition**
  - Prairie: 1955-2011 (30,000 days)
  - Transition: T < 0°C, no snow; T > 0°C, snow

- **Warm >0°C: No Snow**
  - Prairie: 1955-2011 (150,000 days)
  - Warm: T > 0°C, no snow
Specific Humidity

- **Three Q regimes**
- **Cold <0°C**: Snow: *stable BL*, *no diurnal cycle*
- **Transition near freezing**: diurnal cycle
- **Warm >0°C**: *unstable BL*
  - Morning and late afternoon BL coupling/uncoupling
  - Clear is ‘drier’, while cloudy is cooler/drier/flat
Above/Below Freezing
Conserved Variables

SWCF

LWCF
Afternoon LCL is Cloud-base

- At $T_{\text{max}}$
- Lowest cloud-base (*ceilometer*)
- LCL (surface)
- Coupled convective boundary layer (*CBL*)
Winter Ice and Snow
Snowfall and Snowmelt

- Temperature falls 10°C with first snowfall
- And rises again with snowmelt
- "Fast transitions in ‘local climate’: a ‘climate switch’"
  - Snow reflects sunlight
  - Reduces evaporation and water vapor greenhouse
Mid-Nov. Snow Transition (Cloud partition)

- Ahead of snow Transition
- Warm >0°C: No Snow Transition
- Cold <0°C: Snow Transition
- Time sequence shows the three regimes
More snow cover - Colder temperatures

Alberta, Canada
October to April

Freezing

Mean Temperature (°C)

Fraction of Days with Snow Cover

\[ T = 3.9 - 14.6 \times \text{FDS} \ (R^2 = 0.79) \]

Betts et al. 2014a
Warm Season Climate: $T>0^\circ C$
(No snow: May – October)

- **Hydrometeorology**
  - with Precipitation and Radiation
  - Diurnal cycle of $T$ and RH
- **Daily timescale is radiation driven**
  - Night LW$_n$; day ECA/R$_n$ (and EF)
- **Monthly timescale: Fully coupled**
- (Long timescales: separation)

Betts et al. 2014b
**Monthly timescale: Regression**

\[ \delta DTR = K + A \cdot \delta \text{Precip}(\text{Mo}-2) + B \cdot \delta \text{Precip}(\text{Mo}-1) + C \cdot \delta \text{Precip} + D \cdot \delta \text{OpaqueCloud} \]

**\( \delta DTR \) anomalies**

<table>
<thead>
<tr>
<th>Month</th>
<th>K</th>
<th>A ((\text{Mo}-2))</th>
<th>B ((\text{Mo}-1))</th>
<th>C ((\text{Mo}))</th>
<th>D ((\text{Mo}))</th>
<th>(R^2) All</th>
<th>(R^2) Precip</th>
<th>(R^2) Cloud</th>
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<tbody>
<tr>
<td>May</td>
<td>0 ± 0.8</td>
<td>-0.37 ± 0.05</td>
<td>-0.37 ± 0.04</td>
<td>-1.10 ± 0.05</td>
<td>0.73</td>
<td>0.41</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>0 ± 0.7</td>
<td>-0.30 ± 0.03</td>
<td>-0.32 ± 0.02</td>
<td>-0.97 ± 0.04</td>
<td>0.69</td>
<td>0.42</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>0 ± 0.7</td>
<td>-0.20 ± 0.03</td>
<td>-0.25 ± 0.02</td>
<td>-0.33 ± 0.03</td>
<td>-1.10 ± 0.05</td>
<td>0.67</td>
<td>0.42</td>
<td>0.48</td>
</tr>
<tr>
<td>Aug</td>
<td>0 ± 0.7</td>
<td>-0.07 ± 0.02</td>
<td>-0.21 ± 0.03</td>
<td>-0.40 ± 0.03</td>
<td>-1.24 ± 0.04</td>
<td>0.79</td>
<td>0.46</td>
<td>0.71</td>
</tr>
<tr>
<td>Sept</td>
<td>0 ± 0.8</td>
<td>-0.22 ± 0.03</td>
<td>-0.49 ± 0.04</td>
<td>-1.27 ± 0.04</td>
<td>0.82</td>
<td>0.43</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>0 ± 0.8</td>
<td>-0.27 ± 0.03</td>
<td>-0.70 ± 0.07</td>
<td>-1.33 ± 0.04</td>
<td>0.77</td>
<td>0.37</td>
<td>0.70</td>
<td></td>
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</table>

*Betts et al. 2014b*
## Monthly timescale: Regression

\[ \delta \text{RH}_{tx} = K + A^* \delta \text{Precip}(\text{Mo-2}) + B^* \delta \text{Precip}(\text{Mo-1}) + C^* \delta \text{Precip} + D^* \delta \text{OpaqueCloud} \]

### Afternoon \( \delta \text{RH}_{tx} \) anomalies

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<tbody>
<tr>
<td>May</td>
<td>0 ± 3.6</td>
<td>1.30 ± 0.38</td>
<td>1.47 ± 0.22</td>
<td>2.07 ± 0.17</td>
<td>4.75 ± 0.20</td>
<td>0.72</td>
<td>0.46</td>
<td>0.62</td>
</tr>
<tr>
<td>Jun</td>
<td>0 ± 3.6</td>
<td>0.69 ± 0.23</td>
<td>1.26 ± 0.15</td>
<td>1.96 ± 0.12</td>
<td>4.36 ± 0.22</td>
<td>0.68</td>
<td>0.47</td>
<td>0.48</td>
</tr>
<tr>
<td>July</td>
<td>0 ± 4.1</td>
<td>0.84 ± 0.18</td>
<td>1.71 ± 0.12</td>
<td>1.81 ± 0.17</td>
<td>4.40 ± 0.30</td>
<td>0.59</td>
<td>0.43</td>
<td>0.33</td>
</tr>
<tr>
<td>Aug</td>
<td>0 ± 3.6</td>
<td>0.66 ± 0.11</td>
<td>1.23 ± 0.13</td>
<td>2.42 ± 0.16</td>
<td>4.08 ± 0.20</td>
<td>0.73</td>
<td>0.53</td>
<td>0.56</td>
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<td>Sept</td>
<td>0 ± 3.5</td>
<td>1.40 ± 0.13</td>
<td>2.10 ± 0.18</td>
<td>4.35 ± 0.16</td>
<td>4.58 ± 0.23</td>
<td>0.67</td>
<td>0.44</td>
<td>0.53</td>
</tr>
<tr>
<td>Oct</td>
<td>0 ± 4.3</td>
<td>1.28 ± 0.19</td>
<td>5.02 ± 0.39</td>
<td>4.58 ± 0.23</td>
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*Betts et al. 2014b*
Monthly Regression Fits

Regression

May

July

Sept

$\delta T_x$  $\delta DTR$  $\delta RH_{tx}$  $\delta P_{LCLtx}$
**MJJA Growing Season**

\[ \delta Y_\sigma = K_\sigma + B_\sigma \cdot \delta \text{Precip(AMJJA)}_\sigma + C_\sigma \cdot \delta \text{OpaqueCloud}_\sigma \]

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<th>Variable: ( \delta Y_\sigma )</th>
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<td>0±0.7</td>
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<td>0±0.8</td>
<td>-0.21±0.05</td>
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<td>0.38</td>
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<td>( \delta P_{LCLtx\sigma} )</td>
<td>0±0.6</td>
<td>-0.56±0.03</td>
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<td>0.61</td>
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<td>( \delta Q_{tx\sigma} )</td>
<td>0±0.9</td>
<td>0.50±0.04</td>
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Growing Season Coupling between Energy and Water Budgets and Surface Climate

- Total water storage (GRACE) coupled to precipitation variability (F=0.56)
- \( R_n \) coupled to cloud variability
- Climate cloud coupling: \( \delta \text{Cloud} = 0.73 \delta \text{Precip} \)
- Diurnal climate coupled to cloud and precipitation variability (regression)
Daily Timescale in Summer

• 11 Prairie stations: 1953-2011 (Betts et al. 2015)

• 54000 days: (standard error of mean small)

• Partition by cloud, sub-partition by
  – $RH_m$
  – Wind
  – (Day-night cloud asymmetry)
  – Precipitation anomalies
Daily Summer Climate Partitioned by Cloud and RH

- DTR increases with decreasing cloud and RH
  - Increasing $R_n$ (and falling soilwater)
- Upward shift to higher $\theta_{Etx}$ with increasing $R_{Hm}$
  - Despite falling $T_x$ because of $Q_x$ increase
Daily Summer Climate Partitioned by Cloud and Wind

- DTR increases with decreasing wind
  - Falling $T_n$ under clear skies at low windspeed
  - Increasing sunrise $RH_{tn}$ at low windspeed

- Higher $\theta_{Etx}$ with decreasing wind
  - Stronger superadiabatic layer?
DTR to $LW_n$: RH and Wind

- **DTR** depends **linearly** on $LW_n$  
  - cooling from afternoon $T_x$ to sunrise $T_n$
- **Increasing wind reduces DTR**
  - $T_x$ falls and $T_n$ increases

*Betts et al. 2015*
Compare ERA40 Madeira River (Amazon)

Canadian Prairie station data

versus ERA40 Madeira River basin mean

Not bad
Partition by Cloud & Precip. Anomalies

- Weighted precipitation anomalies as surrogate for soil moisture
- Cooler, moister, lower $P_{LCLtx}$, higher $\theta_{Etx}$ with increasing $\delta$PrecipWT
DTR to $LW_n$ and Precip

Summer, JJA: 54000 days

- **DTR depends linearly on $LW_n$** (daily $R^2 = 0.61$)
  - cooling from afternoon $T_x$ to sunrise $T_n$
- **DTR depends on ECA and RH$_m$**
  - $RH_m$ is ‘climate response’ to energy partition by soil moisture

(Betts et al. 2015)
15 Prairie stations: 1953-2011

- **Hourly** p, T, RH, WS, WD, **opaque/reflective cloud**
- **Daily** precipitation and snowdepth
Change in Cropping (SK)

- Ecodistrict mean for 50-km around station
- Saskatchewan:
  - 25% drop in ‘SummerFallow’
  - (no crops to save water)
- Split at 1991 - has summer climate changed?

Betts et al. 2013b
Three Station Mean in SK

- **Growing season** (winter warmer)
  - $T_{\text{max}}$ cooler; RH moister
  - DTR and $\Delta RH$ seasonal transitions
Impact on Convective Instability

Growing season

- Lower LCL
- Higher $\theta_E$
- More Precip

Betts et al. 2013b
Precip. to SWCF in Real World?

- ERA40 Missouri basin means: MJJA (left)
- Canadian Prairie stations: JJA
  - *Has greater cloud forcing for same precip. forcing*
Review
Warm & Cold Climates: T $\geq$ $0^\circ$C

- Warm >$0^\circ$C: Clouds reflect sunlight
- Cold <$0^\circ$C: Clouds are greenhouse & snow reflects sun
- T falls 10$^\circ$C with snow - *Fast climate transition*
Snowfall and Snowmelt

- Temperature falls 10°C with first snowfall
- And rises again with snowmelt
- Fast transitions in ‘local climate’: a ‘climate switch’
  - Snow reflects sunlight
  - Reduces evaporation and water vapor greenhouse
More snow cover - Colder temperatures

Alberta, Canada
October to April

Freezing

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DTR to $LW_n$ and ECA

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  - $RH_m$ is ‘climate response’ to energy partition by soil moisture

Summer, JJA: 54000 days

Betts et al. 2015
Summary

• 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
    • Snow cover explains 80% of cold season $T_{\text{mean}}$ variability

• Increased transpiration from crop change
  – Cooled and moistened summer climate
  – Lowered cloud-base and increased $\theta_E$
  – (While winter climate has warmed)

Papers at http://alanbetts.com
Conclusions

• **Hydrometeorology requires**
  – Precipitation and cloud/radiation
    • Cloud dominates on daily timescale
    • Both affect monthly to seasonal anomalies
  – Temperature and RH
    • Giving LCL and $\theta_E$: feedback to Precip

• **Canadian Prairie data**
  – Describe fully coupled Land-Atmos system
  – Invaluable for model evaluation

• [http://alanbetts.com/](http://alanbetts.com/) (5 papers)