Land-surface-snow-cloud Climate Coupling

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April 4, 2016
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
This talk

- **Northern latitude climate**
  - Large seasonal cycle
    - Cold winters with snow
    - Snow is a fast climate switch
    - Two separate “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
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
- Albedo data (MODIS/CCRS: 250m, after 2000)


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:*
  – ‘True’ diurnal ranges (*Critical for winter*)
  – Energy imbalance of diurnal cycle
Surface Radiation Budget

- $R_n = SW_n + LW_n$

- Define Effective Cloud Albedo

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

  Reflected by surface, clouds

  MODIS Calibrate Opaque Cloud data
  with Baseline Surface Radiation Network (BSRN)
Snow-No-snow Impact on Climate

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

$$\Delta T = T:\text{no-snow} - T:\text{snow} = -9.8(\pm 0.8)^\circ C$$

Betts et al. (2016)
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. 2014
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
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
Diurnal cycle: Clouds & Snow

**Canadian Prairies**
660 station-years of data

**Winter climatology**
- Colder when clear
- LWCF dominant with snow

**Summer climatology**
- Warmer when clear
- SWCF dominant: no snow

**Transition months:**
- Show both climatologies
- With 11K separation
- Fast transitions with snow
- Snow is “Climate switch”
Monthly diurnal climatology (by snow and cloud)
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
  - Net is CF
  - Add reflective snow, and CF goes +ve
- Regime change

(Betts et al. 2015)
Use BSRN data to “calibrate” daily opaque/reflective Cloud at Regina

- Daily mean opaque cloud OPAQ\textsubscript{m}
- LW cools but clouds reduce cooling
- Net LW: LW\textsubscript{n}
  - T>0: RH dependence
  - T<0: T, TCWV also
- Regression gives LW\textsubscript{n} to ± 8 W/m\textsuperscript{2} for T\textsubscript{m}>0 (R\textsuperscript{2}=0.91)

(Betts et al. 2015)
Snowfall and Snowmelt
\[\Delta T\] Canadian Prairies

- Temperature falls/rises 10K with first snowfall/snowmelt
  - *Local climate switch* between warm and cold seasons

*Betts et al. 2014*
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

\[ \Delta T \quad \text{Vermont} \]

- 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 $\Delta T = -6.1(\pm 0.7) ^\circ C$

Snow-free winters: warmer than snowy winters: $+6 ^\circ C$

Graph: Vermont Nov. to April 2000-2015

Snowdepth

- Snowdepth
- Tmean
- Tnosnow
- Tsnow
- $\Delta T$

37 stations; 460 sta-yr
12,672 days/mo

Months (from December)
**Coupling to Phenology - Lilacs**

- Leaf-out earlier by **3 days/decade** (tracks ice-out)
- Leaf-out changes **5 days/°C**
- **Snow-free winters:** $+6°C \times 5 \text{ days} = 30 \text{ days earlier}$
Impact of Snow

- Distinct warm and cold season states
- Snow cover is the “climate switch”
- **Prairies**: $\Delta T = -10^\circ C$ (winter albedo = 0.7)
- **Vermont**: $\Delta T = -6^\circ C$ (winter albedo 0.3 to 0.4)
  - VT Spring phenology change = 30 days

- Snow transforms BL cloud coupling
  - No-snow ‘Warm when clear’ - convective BL
  - Snow ‘Cold when clear’ - stable BL
Warm Season Climate: T>0\degree C
(April – October with no snow)

- **Hydrometeorology**
  - with *Precipitation and Radiation*
  - Diurnal cycle of \( T \) and \( RH \)
  - Cannot do climate 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? \( DTR_T < DTR_D \)
Q2: How much warmer is it at the end of a clear day?
Diurnal Ranges & Imbalances

- April to Sept: **same coupled structure**
- Q1: \(DTR_T, DRH_T < DTR_D, DRH_D\) **always**
- Q2: Clear-sky: warmer (+2°C), drier (-6%)
Warm Season Climate: T>0°C  
(April – October with no snow)

• **Hydrometeorology**
  – with *Precipitation and Radiation*
  – *Diurnal cycle of T and RH*
  – *Cannot do climate with just T & Precip!*

• **Monthly timescale: Fully coupled**
  – Use regression to couple anomalies

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

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

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

**δDTR anomalies**

<table>
<thead>
<tr>
<th>Month</th>
<th>K</th>
<th>A (Mo-2)</th>
<th>B (Mo-1)</th>
<th>C (Mo)</th>
<th>D (Mo)</th>
<th>R² All</th>
<th>R² Precip</th>
<th>R² Cloud</th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

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

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

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

<table>
<thead>
<tr>
<th>Month</th>
<th>K</th>
<th>A (Mo-2)</th>
<th>B (Mo-1)</th>
<th>C (Mo)</th>
<th>D (Mo)</th>
<th>( R^2 ) All</th>
<th>( R^2 ) Precip</th>
<th>( R^2 ) Cloud</th>
</tr>
</thead>
<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>
</tr>
<tr>
<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>0.75</td>
<td>0.45</td>
<td>0.63</td>
<td></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>
<td>0.67</td>
<td>0.44</td>
<td>0.53</td>
<td></td>
</tr>
</tbody>
</table>

*Betts et al. 2014b*
Monthly Regression Fits

Regression

May

July

Sept
MJJA Growing Season (Merge, Normalize by SD)
\[ \delta Y_\sigma = K_\sigma + B_\sigma \delta \text{Precip(AMJJA)}_\sigma + C_\sigma \delta \text{OpaqueCloud}_\sigma \]

<table>
<thead>
<tr>
<th>Variable: $\delta Y_\sigma$</th>
<th>$K_\sigma$</th>
<th>$B_\sigma$ (Precip)</th>
<th>$C_\sigma$ (Cloud)</th>
<th>$R^2_\sigma$</th>
<th>$\sigma(\delta Y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta T_{x\sigma}$</td>
<td>0±0.7</td>
<td>-0.33±0.03</td>
<td>-0.52±0.03</td>
<td>0.52</td>
<td>1.11 °C</td>
</tr>
<tr>
<td>$\delta T_{m\sigma}$</td>
<td>0±0.8</td>
<td>-0.21±0.05</td>
<td>-0.50±0.07</td>
<td>0.38</td>
<td>0.88 °C</td>
</tr>
<tr>
<td>$\delta DTR_\sigma$</td>
<td>0±0.6</td>
<td>-0.55±0.03</td>
<td>-0.39±0.03</td>
<td>0.62</td>
<td>0.83 °C</td>
</tr>
<tr>
<td>$\delta RH_{tx\sigma}$</td>
<td>0±0.6</td>
<td>0.56±0.03</td>
<td>0.35±0.03</td>
<td>0.60</td>
<td>4.35 %</td>
</tr>
<tr>
<td>$\delta RH_{m\sigma}$</td>
<td>0±0.7</td>
<td>0.51±0.03</td>
<td>0.33±0.03</td>
<td>0.50</td>
<td>4.61 %</td>
</tr>
<tr>
<td>$\delta P_{LCLtx\sigma}$</td>
<td>0±0.6</td>
<td>-0.56±0.03</td>
<td>-0.37±0.03</td>
<td>0.61</td>
<td>18.6 hPa</td>
</tr>
<tr>
<td>$\delta Q_{tx\sigma}$</td>
<td>0±0.9</td>
<td>0.50±0.04</td>
<td>0.03±0.04</td>
<td>0.26</td>
<td>0.58 g/kg</td>
</tr>
<tr>
<td>$\delta \theta_{Et\sigma}$</td>
<td>0±1.0</td>
<td>0.22±0.04</td>
<td>-0.31±0.04</td>
<td>0.09</td>
<td>1.95 K</td>
</tr>
</tbody>
</table>
• Total water storage (GRACE) coupled to precipitation variability (F=0.56)
• Climate cloud coupling: $\delta \text{Cloud} = 0.73 \delta \text{Precip}$
• $R_n$ coupled to cloud variability
• Diurnal climate coupled to cloud and precipitation variability (regression)
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?**
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)
- \((R_{H_m}, Q_{tx})\) (+6.9±0.2%, +0.70±0.04 g/kg)
- Precipitation: +25.9±4.6 mm for JJA (+10%)
Impact of Snow

- Distinct warm and cold season states
- Snow cover is the “climate switch”
- **Prairies**: $\Delta T = -10^\circ C$ (winter albedo = 0.7)
- **Vermont**: $\Delta T = -6^\circ C$ (winter albedo 0.3 to 0.4)
  - VT Spring phenology change = 30 days
- Snow transforms BL-cloud coupling
  - No-snow ‘Warm when clear’ - convective BL
  - Snow ‘Cold when clear’ - stable BL

Papers at [http://alanbetts.com](http://alanbetts.com)
Warm Season Climate: $T > 0^\circ C$

- **Hydrometeorology**
  - with *Precipitation* and *Radiation*
  - *Diurnal cycle of* $T$ *and* RH
  - Can’t ‘understand climate’ with $T$ & Precip.

- **Monthly/seasonal timescale: coupled**
  - But $T_x$, $T_m$ depend more on cloud/radiation
  - $RH_x$, $RH_m$, DTR depend more on precip.

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Betts et al. 2014b