Reinventing Hydrometeorology using Cloud and Climate Observations

Alan K. Betts

akbetts@aol.com
http://alanbetts.com

Co-authors:
Ray Desjardins, Devon Worth
Agriculture and Agri-Food Canada
Ahmed Tawfik
NCAR

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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°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)


Diurnal Climate Dataset

• Reduce hourly data to
  – daily means: $T_m, RH_m, OPAQ_m$ etc
  – data at $T_{\text{max/min}}$: $T_x$ and $T_n$

• Diurnal cycle approx. climate
  – $DTR = T_x - T_n$
  – $\Delta RH = RH_{tn} - RH_{tx}$

• Full diurnal Cycle: $\equiv$ 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

$$\Delta T = T:\text{no-snow} - T:\text{snow} = -10.2(\pm 1.1){}^\circ\text{C}$$

Betts et al. (2016)
Interannual variability of T coupled to Snow Cover

- Alberta: 79% of variance
- Slope $T_m \cdot 14.7 (\pm 0.6) K$

10% fewer snow days
= 1.5K warmer
on Prairies
Surface Radiation Budget

• \( R_n = SW_n + LW_n \)

• Define Effective Cloud Albedo

\[
ECA = - \frac{SWCF}{SW_{dn}(clear)}
\]

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

Reflected by surface, clouds

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

• 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)

• 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: **same coupled structure**
- Q1: \( \text{DTR}_T, \text{DRH}_T < \text{DTR}_D, \text{DRH}_D \) **always**
- Q2: Clear-sky: warmer (+2°C), drier (-6%)
Diurnal Ranges & Imbalances

- April to Sept: same coupled structure
- Clear-sky: $\theta_E (+3K)$, LCL higher (+18hPa)

(Betts and Tawfik 2016)
Coupling to Wind

- Low wind-speed: DTR increases
  - $T_n$ falls; $T_x$, $\theta_{Ex}$ 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**
  – with *Precipitation and Radiation*
  – Diurnal cycle of *T and RH*
  – Cannot do coupling with just *T & Precip*!

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

Betts et al. 2014b
What are the **coupling coefficients** in the “real world”?
Monthly Regression on Cloud and lagged Precip. anomalies

- Standardized monthly anomalies
  - opaque cloud (CLD)
  - precip. (PR-0, PR-1, PR-2): current, previous 2 to 5 months

\[ \delta DTR = K + A \delta \text{CLD} + B \delta \text{PR-0} + C \delta \text{PR-1} + D \delta \text{PR-2} \ldots \]

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

**Soil moisture memory**

- **April:** memory of entire cold season (snow, soil ice) back to November freeze
- **June, July:** memory of moisture back to March
April: Memory of Precip. to November

1953-2011: 12 stations (619 months)

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\delta DTR$</th>
<th>$\delta T_x$</th>
<th>$\delta RH_n$</th>
<th>$\delta P_{LCLx}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R$^2 =$</td>
<td>0.67</td>
<td>0.48</td>
<td>0.66</td>
<td>0.66</td>
</tr>
<tr>
<td>Cld-Apr</td>
<td>-0.52±0.02</td>
<td>-0.78±0.04</td>
<td>0.76±0.03</td>
<td>-0.93±0.04</td>
</tr>
<tr>
<td>PR-Apr</td>
<td>-0.04±0.01</td>
<td>0.00±0.03</td>
<td>0.14±0.02</td>
<td>-0.13±0.03</td>
</tr>
<tr>
<td>PR-Mar</td>
<td>-0.13±0.02</td>
<td>-0.25±0.04</td>
<td>0.25±0.03</td>
<td>-0.30±0.04</td>
</tr>
<tr>
<td>PR-Feb</td>
<td>-0.09±0.02</td>
<td>-0.15±0.05</td>
<td>0.19±0.04</td>
<td>-0.24±0.04</td>
</tr>
<tr>
<td>PR-Jan</td>
<td>-0.10±0.02</td>
<td>-0.20±0.04</td>
<td>0.19±0.03</td>
<td>-0.22±0.04</td>
</tr>
<tr>
<td>PR-Dec</td>
<td>-0.06±0.02</td>
<td>-0.07±0.05</td>
<td>0.20±0.04</td>
<td>-0.24±0.04</td>
</tr>
<tr>
<td>PR-Nov</td>
<td>-0.09±0.02</td>
<td>-0.14±0.04</td>
<td>0.08±0.03</td>
<td>-0.12±0.04</td>
</tr>
</tbody>
</table>
April Climate

- Regression on Opaq, Precip: $R^2 \approx 0.7$
- Regression on Winter Precip: $R^2 \approx 0.35$
Monthly timescale: Regression

1953-2011: 12 stations (615/month)

δDTR anomalies

<table>
<thead>
<tr>
<th>Month</th>
<th>K</th>
<th>A (CLD)</th>
<th>B (PR-0)</th>
<th>C (PR-1)</th>
<th>D (PR-2)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0±0.02</td>
<td>-0.61±0.02</td>
<td>-0.27±0.02</td>
<td>-0.17±0.03</td>
<td>-0.06±0.05</td>
<td>0.74</td>
</tr>
<tr>
<td>Jun</td>
<td>0±0.02</td>
<td>-0.54±0.04</td>
<td>-0.22±0.02</td>
<td>-0.18±0.02</td>
<td>-0.05±0.03</td>
<td>0.68</td>
</tr>
<tr>
<td>July</td>
<td>0±0.02</td>
<td>-0.57±0.03</td>
<td>-0.24±0.02</td>
<td>-0.15±0.01</td>
<td>-0.12±0.02</td>
<td>0.68</td>
</tr>
<tr>
<td>Aug</td>
<td>0±0.02</td>
<td>-0.67±0.02</td>
<td>-0.26±0.02</td>
<td>-0.13±0.02</td>
<td>-0.03±0.02</td>
<td>0.80</td>
</tr>
<tr>
<td>Sept</td>
<td>0±0.02</td>
<td>-0.71±0.02</td>
<td>-0.30±0.02</td>
<td>-0.12±0.02</td>
<td>-0.03±0.02</td>
<td>0.84</td>
</tr>
</tbody>
</table>

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

**1953-2011: 12 stations (615/month)**

**Afternoon $\delta RH_n$ anomalies**

<table>
<thead>
<tr>
<th>Month</th>
<th>$K$</th>
<th>$A$ (CLD)</th>
<th>$B$ (PR-0)</th>
<th>$C$ (PR-1)</th>
<th>$D$ (PR-2)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0±0.02</td>
<td>0.65±0.03</td>
<td>0.40±0.03</td>
<td>0.25±0.04</td>
<td>0.20±0.06</td>
<td>0.72</td>
</tr>
<tr>
<td>Jun</td>
<td>0±0.02</td>
<td>0.66±0.03</td>
<td>0.32±0.02</td>
<td>0.21±0.03</td>
<td>0.11±0.04 **</td>
<td>0.67</td>
</tr>
<tr>
<td>July</td>
<td>0±0.03</td>
<td>0.63±0.04</td>
<td>0.36±0.03</td>
<td>0.27±0.02</td>
<td>0.13±0.03 **</td>
<td>0.61</td>
</tr>
<tr>
<td>Aug</td>
<td>0±0.02</td>
<td>0.61±0.03</td>
<td>0.42±0.03</td>
<td>0.22±0.02</td>
<td>0.10±0.02</td>
<td>0.75</td>
</tr>
<tr>
<td>Sept</td>
<td>0±0.02</td>
<td>0.61±0.02</td>
<td>0.39±0.03</td>
<td>0.24±0.02</td>
<td>0.05±0.02</td>
<td>0.78</td>
</tr>
</tbody>
</table>

**June, July weak memory back to March**

Betts et al. 2014b, revisited
MJJAS merge: coupling coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Influence</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_x</td>
<td>CLD</td>
<td>-1.01</td>
<td>±0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-0</td>
<td>-0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-1</td>
<td>-0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-2</td>
<td>-0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_m</td>
<td>CLD</td>
<td>-0.70</td>
<td>±0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-0</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-1</td>
<td>-0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-2</td>
<td>-0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_n</td>
<td>CLD</td>
<td>-0.36</td>
<td>±0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-0</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-1</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-2</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTR</td>
<td>CLD</td>
<td>-0.65</td>
<td>±0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-0</td>
<td>-0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-1</td>
<td>-0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PR-2</td>
<td>-0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

**SWCF (negative)**
No precip dependence

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

1953-2011 (3081 months)
12 stations
### MJJAS merge: coupling coefficients

#### Minimum RH

<table>
<thead>
<tr>
<th>Variable</th>
<th>CLD</th>
<th>PR-0</th>
<th>PR-1</th>
<th>PR-2</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_x )</td>
<td>-1.01</td>
<td>-0.07</td>
<td>-0.14</td>
<td>-0.03</td>
<td>0.62</td>
</tr>
<tr>
<td>( T_m )</td>
<td>-0.70</td>
<td>0.03</td>
<td>-0.08</td>
<td>-0.02</td>
<td>0.48</td>
</tr>
<tr>
<td>( T_n )</td>
<td>-0.36</td>
<td>0.17</td>
<td>0.0</td>
<td>0.02</td>
<td>0.16</td>
</tr>
<tr>
<td>DTR</td>
<td>-0.65</td>
<td>-0.24</td>
<td>-0.15</td>
<td>-0.05</td>
<td>0.76</td>
</tr>
</tbody>
</table>

**Increases with cloud**

**Increases with precip (Memory)**

**\( (\pm 0.01) \)**

#### Mean RH

<table>
<thead>
<tr>
<th>Variable</th>
<th>CLD</th>
<th>PR-0</th>
<th>PR-1</th>
<th>PR-2</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( RH_n )</td>
<td>0.63</td>
<td>0.37</td>
<td>0.24</td>
<td>0.10</td>
<td>0.71</td>
</tr>
<tr>
<td>( RH_m )</td>
<td>0.54</td>
<td>0.32</td>
<td>0.25</td>
<td>0.12</td>
<td>0.62</td>
</tr>
<tr>
<td>( RH_x )</td>
<td>0.36</td>
<td>0.20</td>
<td>0.20</td>
<td>0.11</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Increases with cloud**

**Increases with precip (Memory)**

**\( (\pm 0.01) \)**

#### Maximum RH

<table>
<thead>
<tr>
<th>Variable</th>
<th>CLD</th>
<th>PR-0</th>
<th>PR-1</th>
<th>PR-2</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( RH_n )</td>
<td>-0.27</td>
<td>-0.17</td>
<td>-0.04</td>
<td>0.01</td>
<td>0.31</td>
</tr>
<tr>
<td>( RH_m )</td>
<td>-0.14</td>
<td>-0.08</td>
<td>-0.02</td>
<td>-0.01</td>
<td>0.31</td>
</tr>
<tr>
<td>( RH_x )</td>
<td>-0.07</td>
<td>-0.03</td>
<td>-0.04</td>
<td>-0.01</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Increases with cloud**

**Increases with precip (Memory)**

**Saturation limits fall of \( T_n \)**

**Diurnal range RH**

**Decreases with cloud**

**Decreases with precip**

\( 1953-2011 \) (3081 months)

12 stations
# MJJAS merge: coupling coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_x )</td>
<td>( \text{CLD} -0.10 )</td>
<td>0.48</td>
</tr>
<tr>
<td>( R_{n} )</td>
<td>( \text{CLD} 0.63 )</td>
<td>0.71</td>
</tr>
<tr>
<td>( Q_{Tx} )</td>
<td>( \text{CLD} -0.10 )</td>
<td>0.21</td>
</tr>
<tr>
<td>( \theta_{Ex} )</td>
<td>( \text{CLD} -0.65 )</td>
<td>0.26</td>
</tr>
<tr>
<td>( T_m )</td>
<td>( \text{CLD} -0.70 )</td>
<td>0.48</td>
</tr>
<tr>
<td>( R_{m} )</td>
<td>( \text{CLD} 0.54 )</td>
<td>0.62</td>
</tr>
<tr>
<td>( Q_{m} )</td>
<td>( \text{CLD} -0.12 )</td>
<td>0.20</td>
</tr>
<tr>
<td>( P_{LCLx} )</td>
<td>( \text{CLD} -0.80 )</td>
<td>0.70</td>
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<tr>
<td>( T_n )</td>
<td>( \text{CLD} -0.36 )</td>
<td>0.16</td>
</tr>
<tr>
<td>( R_{x} )</td>
<td>( \text{CLD} 0.36 )</td>
<td>0.35</td>
</tr>
<tr>
<td>( Q_{Tn} )</td>
<td>( \text{CLD} -0.10 )</td>
<td>0.15</td>
</tr>
<tr>
<td>( D_{P_{LCL}} )</td>
<td>( \text{CLD} -0.51 )</td>
<td>0.61</td>
</tr>
</tbody>
</table>

1953-2011 (3081 months)
12 stations

\( Q_{Tx}, Q_{m} \rightarrow \text{precip, little cloud} \)
\( R_{n}, T_x \) move inversely with cloud
\( P_{LCLx} \) part mirror of \( R_{n} \)
\( T_m \rightarrow \text{cloud not precip} \)
\( \theta_{Ex} \) down/up with cloud/precip
Dry to Wet Coefficient Change

3081 months: split into precip (PR-0) SD ranges: < -1σ, -1 to 0, 0 to 1, >1σ (393, 1382, 887, 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)
Monthly Climate of T, RH on Cloud and Precipitation

- Sorted by cloud and weighted precip. anomalies
  - $\delta PR_{wt} = 0.61 \times \delta PR-0 + 0.39 \times \delta PR-1$
  - DTR increases with decreasing cloud and precip.
  - Afternoon RH$_n$ increases with cloud, precip.
Afternoon maximum of $\theta_{Ex}$ and $P_{LCLx}$ on Cloud and Precipitation

- Afternoon $\theta_{Ex}$ increases with weighted precip
- Afternoon cloud-base ($P_{LCLx}$) falls with precip
- Both favor convective instability
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 goes back 2-5 months
- Asymmetric response to dry/wet precipitation anomalies
- Observed coupling coefficients can be compared with model representations
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 timescale coupling**
  - $T_m$ depends on radiation not precip.
  - $Q_m$ depends on precip. more than radiation
  - $DTR$, $RH_x$, $RH_m$, $\theta_{Ex}$, $P_{LCLx}$: coupled to both
  - Sensitivity to precip. increases wet-to-dry, then falls with drought

http://alanbetts.com
Seasonal Drydown damps Precip anomalies

- GRACE data shows seasonal change: $\Delta$ (Total Water Storage)
- $\delta(\Delta TWS)$ damps 56% of precipitation anomalies

Betts et al. 2014b
Cloud anomalies from Climate anomalies

\[ \delta \text{OPAQ}_m \sigma: \text{reg} = -0.64 \cdot \delta \text{DTR}_\sigma - 0.23 \cdot \delta T_{m\sigma} + 0.11 \cdot \delta \text{RH}_m \]

\[ \delta \text{OPAQ}_m \sigma \text{ to } \pm 0.04 \]
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
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%)
Impact on Convective Instability

Growing season

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

Betts et al. 2013b
Use BSRN data to “calibrate” daily opaque/reflective Cloud at Regina

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

- $\text{LW}$ cools but clouds reduce cooling

- Net LW: $\text{LW}_n$
  - $T>0$: RH dependence
  - $T<0$: $T$, TCWV also

- Regression gives $\text{LW}_n$ to $\pm 8\text{W/m}^2$ for $T_m>0$ ($R^2=0.91$)

(Betts et al. 2015)
SW calibration

- **Contrast simple quadratic fit with fit through zero**
- **Uncertainty at low opaque cloud end**
  - Thin cirrus not opaque
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<sub>n</sub>**
  - Net is CF<sub>n</sub>
  - Add reflective snow, and CF<sub>n</sub> goes +ve
- **Regime change**

(Betts et al. 2015)
Growing Season Coupling between Energy and Water Budgets and Surface Climate

- 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)

Betts et al. 2014b
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

$\Delta T$ 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: $+6^\circ C$
**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 * 5 days = 30 days earlier
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