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 $T_m = -14.7 \pm 0.6$ K

10% fewer snow days = 1.5K warmer on Prairies

More snow cover - Colder temperatures

Alberta, Canada October to April
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)
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
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 $\text{LW}$: $\text{LW}_n$
  - $T>0$: 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)
"Cloud Forcing" — Change from clear-sky flux
- SWCF — Cool
- 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)
**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)
Merge all data
(650 years: 240,000 days)

Cold-Snow (31%)

Mixed (10%)

Warm-NoSnow (59%)
(Standard errors tiny)

Betts and Tawfik 2016)
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: $T > 0^\circ \text{C}$
(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 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: same coupled structure
- Q1: $DTR_T$, $DRH_T < DTR_D$, $DRH_D$ 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)
Stratify by Cloud and 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: \( T > 0^\circ C \)
(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

- Monthly anomalies (normalized by STD of means)
  - opaque cloud (CLD)
  - precip. (PR-0, PR-1, PR-2): current, previous 2 to 5 months

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

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

  Soil moisture memory

**April:** memory of entire cold season (snow, soil ice) back to November freeze

**June, July, Aug:** 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>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>

$R^2 = 0.67$

$\delta DTR$ = 0.67, $\delta T_x$ = 0.48, $\delta RH_n$ = 0.66, $\delta P_{LCLx}$ = 0.66

1953-2011: 12 stations (619 months)
April Climate

- Regression on Opaq. Cloud, Precip: $R^2 \approx 0.7$
- Regression on Winter Precip: $R^2 \approx 0.35$
### Summer Precip Memory back to March

**JULY** 1953-2011: 12 stations (615 sta-years)

<table>
<thead>
<tr>
<th>JULY</th>
<th>R²</th>
<th>δDTR</th>
<th>δRHₙ</th>
<th>δP_{LCLx}</th>
<th>δQₜₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.68</td>
<td>0.62</td>
<td>0.62</td>
<td>0.26</td>
</tr>
<tr>
<td>Cld-July</td>
<td>-0.58±0.03</td>
<td>0.63±0.04</td>
<td>-0.80±0.05</td>
<td>0.04±0.07</td>
<td></td>
</tr>
<tr>
<td>PR-July</td>
<td>-0.24±0.02</td>
<td>0.35±0.03</td>
<td>-0.42±0.04</td>
<td>0.40±0.05</td>
<td></td>
</tr>
<tr>
<td>PR-June</td>
<td>-0.15±0.01</td>
<td>0.27±0.02</td>
<td>-0.36±0.03</td>
<td>0.39±0.04</td>
<td></td>
</tr>
<tr>
<td>PR-May</td>
<td>-0.12±0.02</td>
<td>0.13±0.03</td>
<td>-0.20±0.04</td>
<td>0.24±0.06</td>
<td></td>
</tr>
<tr>
<td>PR-Apr</td>
<td>-0.05±0.03</td>
<td>0.10±0.05</td>
<td>-0.11±0.06</td>
<td>0.26±0.09</td>
<td></td>
</tr>
<tr>
<td>PR-Mar</td>
<td></td>
<td>0.16±0.07</td>
<td>-0.19±0.09</td>
<td>0.36±0.14</td>
<td></td>
</tr>
</tbody>
</table>

**June, July, Aug have precip memory back to March**
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
### MJJA merge: coupling coefficients

<table>
<thead>
<tr>
<th></th>
<th>$T_x$ (±0.015)</th>
<th>$T_m$</th>
<th>$T_n$</th>
<th>DTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLD</td>
<td>-0.96</td>
<td>-0.68</td>
<td>-0.34</td>
<td>-0.61</td>
</tr>
<tr>
<td>PR-0</td>
<td>-0.07</td>
<td>0.03</td>
<td>0.17</td>
<td>-0.24</td>
</tr>
<tr>
<td>PR-1</td>
<td>-0.16</td>
<td>-0.10</td>
<td>-0.01</td>
<td>-0.15</td>
</tr>
<tr>
<td>PR-2</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.04</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

**$T_x$ Max. Temp.:**
- Falls strongly with cloud
- Falls a little with precip.

**$T_m$ SWCF (negative):**
- Little precip dependence

**$T_n$ Min. Temp.:**
- Falls with cloud
- Increases a little with precip.

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

1953-2011 (2466 months)
12 stations
# MJJA merge: coupling coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>R²</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tₓ</td>
<td>CLD -0.96, PR-0 -0.07, PR-1 -0.16, PR-2 -0.01 (±0.015)</td>
<td>0.44</td>
<td><strong>Minimum RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory)</td>
</tr>
<tr>
<td>Tₘ</td>
<td>CLD -0.68, PR-0 0.03, PR-1 -0.10, PR-2 -0.00 (±0.015)</td>
<td>0.44</td>
<td><strong>Mean RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory)</td>
</tr>
<tr>
<td>Tₙ</td>
<td>CLD -0.34, PR-0 0.17, PR-1 -0.01, PR-2 0.04 (±0.015)</td>
<td>0.14</td>
<td><strong>Maximum RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory) &lt;br&gt;<em>Saturation limits fall of Tₙ</em></td>
</tr>
<tr>
<td>DTR</td>
<td>CLD -0.61, PR-0 -0.24, PR-1 -0.15, PR-2 -0.06 (±0.015)</td>
<td>0.73</td>
<td><strong>Diurnal range RH</strong>&lt;br&gt;Decreases with cloud&lt;br&gt;Decreases with precip</td>
</tr>
<tr>
<td>RHₙ</td>
<td>CLD 0.64, PR-0 0.36, PR-1 0.24, PR-2 0.12 (±0.015)</td>
<td>0.69</td>
<td><strong>Minimum RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory)</td>
</tr>
<tr>
<td>RHₘ</td>
<td>CLD 0.57, PR-0 0.31, PR-1 0.26, PR-2 0.14 (±0.015)</td>
<td>0.61</td>
<td><strong>Mean RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory)</td>
</tr>
<tr>
<td>RHₓ</td>
<td>CLD 0.41, PR-0 0.19, PR-1 0.21, PR-2 0.12 (±0.015)</td>
<td>0.36</td>
<td><strong>Maximum RH</strong>&lt;br&gt;Increases with cloud&lt;br&gt;Increases with precip (Memory)</td>
</tr>
<tr>
<td>DRH</td>
<td>CLD -0.23, PR-0 -0.17, PR-1 -0.03, PR-2 0.0 (±0.015)</td>
<td>0.26</td>
<td><strong>Diurnal range RH</strong>&lt;br&gt;Decreases with cloud&lt;br&gt;Decreases with precip</td>
</tr>
</tbody>
</table>

1953-2011 (2466 months)<br>12 stations
1953-2011 (2466 months)
12 stations

Q_{Tx}, Q_m \rightarrow precip not cloud
RH_n, T_x move inversely with cloud
P_{LCLx} reflects RH_n, T_x
T_m \rightarrow cloud not precip
θ_{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, 885, 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)
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*
Monthly Climate of T, RH on Cloud and Precipitation

- Sorted by cloud and weighted precip. anomalies
  - $\delta PR_{wt} = 0.60 \times \delta PR-0 + 0.40 \times \delta PR-1$
  - 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
Diurnal Cycle of Q

Binned by Opaque Cloud
Diurnal spread increases

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

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

\[ \delta \text{OPAQ}_m \text{ to } \pm 0.04 \]
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 as long as 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