Coupling Climate to Clouds, Land-use, Precipitation and Snow

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Water in the Climate System

• Vapor, liquid and ice
  – Ocean and land

• Latent heat of phase changes
  – LH release drives clouds and storms
  – Precip, soil moisture, stomatal control
    \[ EF = \frac{\lambda E}{(R_n - G)} \]

• Vapor IR absorption (WV greenhouse)
  – Clouds ‘black’ in IR

• SW reflectivity of clouds and snow
  – Effective cloud albedo, surface albedo
14 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)
## Prairie Station Locations

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station ID</th>
<th>Province</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
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Outline

Part 1: Review of published papers

• Clouds and Diurnal Cycle over seasons
  – Betts et al (2013a)

• Annual crops and seasonal diurnal cycle
  – Betts et al (2013b)

• Winter snow transitions and climate
  – Betts et al (2014a)

Part 2: Work in progress

• Betts et al. 2014b: Warm season coupling of temperature and humidity to precipitation and cloud cover

Papers at http://alanbetts.com
References


Methods: Analyze Coupled System

• **Seasonal diurnal climate by station/region**
• **220,000 days of excellent data (600 years)**
• **Composite by daily mean opaque cloud**
  – Calibrate SWCF, LWCF against radiation data
• **Change of seasonal climate with cropping**
  – ‘Summerfallow’ to annual crops on 5MHa in 30 yrs
• **Composite across snow transitions**
  – First snow in fall; spring melt of snowpack
  – Winter climate and % days snow cover
• **Link T, RH to precipitation and cloud cover on monthly and seasonal timescales**
Clouds and Diurnal Climate

- Reduce hourly data to
  - daily means: $T_{\text{mean}}$, $RH_{\text{mean}}$ etc
  - data at $T_{\text{max}}$ and $T_{\text{min}}$

- **Diurnal cycle climate**
  - $\text{DTR} = T_{\text{max}} - T_{\text{min}}$  
    
  - $\Delta RH = RH_{tn} - RH_{tx}$

- Almost no missing hourly data (until recent government cutbacks!)
Compare Neighbors: 64 km

- Daily means
- T: $R^2 > 0.95$
- DTR: 1 to 1
- RH poorly correlated in winter
- Opaque Cloud 1 to 1
Calibration of Opaque Cloud to Effective Cloud Albedo (ECA)

- $SW_{dn}$ data
  - Lethbridge, Swift Current, The Pas, Winnipeg
  - 82 station-years

- Tight relationship
  - OpaqueCloud to ECA
  - NDJF a little flatter
Clouds to Summer Diurnal Cycle

- 40-yr climate
- T and RH are inverse
- Q has double maximum for BL transitions
- $\theta_E$ flatter
- Overcast (rain) only outlier
Cloud Impacts

- **Summer**: Clouds reflect sunlight
  - no cloud, hot days; only slightly cooler at night
- **Winter**: Clouds are greenhouse
  - snow reflects low sun
  - clear & dry sky, cold days, very cold nights
- **Fast transition with snow in 5 days**

Betts et al. 2013
Annual Cycle: $T_{\text{max}}, T_{\text{min}}, \text{DTR}, \text{Precip}$

- **Warm state:** April – Oct
- **Cold state:** Dec – Feb
- **Transitions:** Nov, Mar
  \[ T_{\text{max}} \approx 0 \, ^\circ\text{C} \]
- **Actually occur in <5 days**
Annual Cycle: RH and $\Delta$RH

- **Warm state:** April – Oct
- **Cold state:** Dec – Feb
- **Transitions:** Nov, Mar
  $T_{\text{max}} \approx 0^\circ\text{C}$

- **Transition**
  - *in <5 days with snow*
Prairie Warm Season Climate

- 12 stations: *Uniform climatology*
- *Tiny variability* in DTR and ΔRH
RH is linked to LCL

- RH increases with cloud
- Cloud-base LCL decreases
- Afternoon LCL 550 - 2350m
Afternoon LCL is Cloud-base

- At $T_{\text{max}}$
- Lowest cloud-base (*ceilometer*)
- LCL (surface)
- Coupled CBL
Surface Radiation Budget

\[ R_{\text{net}} = SW_{\text{net}} + LW_{\text{net}} \]
\[ = (SW_{dn} - SW_{up}) + (LW_{dn} - LW_{up}) \]

Define Effective Cloud Albedo (reflection)

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

Clear sky

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

Reflected by surface, clouds

MODIS Calibrate Opaque Cloud data
Fit ECA and \( \text{LW}_{\text{net}} \) to Opaque Cloud

NDJF: \( \text{ECA} = 0.1056 + 0.0404 \text{ Cloud} + 0.00158 \text{ Cloud}^2 \)
SO-MA: \( \text{ECA} = 0.0588 + 0.0365 \text{ Cloud} + 0.00318 \text{ Cloud}^2 \)
MJJA: \( \text{ECA} = 0.0681 + 0.0293 \text{ Cloud} + 0.00428 \text{ Cloud}^2 \)

Gives \( \text{SW}_{\text{net}} \) from \( \text{SW}_{\text{dn}} \text{(clear)} \) and albedo \( \alpha_s \)

NDJF: \( \text{LW}_{\text{net}} = -63.0 + 3.14 \text{ Cloud} + 0.193 \text{ Cloud}^2 \)
SO-MA: \( \text{LW}_{\text{net}} = -91.5 + 4.43 \text{ Cloud} + 0.267 \text{ Cloud}^2 \)
MJJA: \( \text{LW}_{\text{net}} = -100.1 + 4.73 \text{ Cloud} + 0.317 \text{ Cloud}^2 \)
Diurnal Temperature Range

- Warms in daytime and cools at night
- Daytime Driver: $R_{\text{netD}}$
- Nighttime driver: $LW_{\text{net}}$

(Betts JGR 2006)
Impact of Snow on Climate

“Winter transitions”

- Composite about snow date
  - First lying snow in fall
  - Final snow-pack melt in spring
- Gives mean climate transition with snow
  - 13 stations with 40-50 years of data
- **Snow cover and winter climate**
- **Snow cover cools surface 10-14K**
  - Snow cover is a fast “climate switch”
  - Shift to ‘LW cloud forcing’ from ‘SW cloud forcing’
    - Shift to ‘Cold when clear’ from ‘Warm when clear’
14 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)
N-S Albedo through Winter

- Prairies (SK)  
  $\alpha_s$: 0.2 to 0.73

- Boreal forest  
  $\alpha_s$: 0.1 to 0.35

- MODIS: 10day, 250m, avg. to 50x50km to latitude bands
  - CCRS product
Snowfall and Snowmelt
Winter and Spring transitions

- Temperature falls/rises about 10K with first snowfall/snowmelt
- **Snow reflects sunlight; reduces evaporation and water vapor greenhouse – loss of snow warms ‘local climate’**
  - Same feedbacks that are speeding Arctic ice melt in summer
  - **Local climate switch** between warm and cold seasons

Betts et al. 2014
Fall Snow Transition Climatology

- $T_x$, $T_m$, $T_n$ fall about 10K
- Cloud peaks with snow; increases $\approx 10\%$
- Snow date: Nov 15 ± 3 days
Snow-melt Transition Climatology

- SW Alberta: T increase about 11K
- Saskatchewan: T increase about 10K
- 3 northern stations: increase 10K, slower
- Melt date: March 12–April 11
Snow Cover: Winter Climatology

- Alberta: 79% of variance
- Slopes
  - $T_x$ = $-16.0 (\pm 0.6)$ K
  - $T_m$ = $-14.7 (\pm 0.6)$ K
  - $T_n$ = $-14.0 (\pm 0.7)$ K

10% fewer snow days

= $1.5K$ warmer
Coupling to Cloud Cover Across Snowfall

- **Mid-November**
- **5-day means (6000 days)**
  - *red: no snow*
  - *blue: snow*
- **With snow**
  - $T_x$, $T_n$ plunge
- **Cloud coupling shifts in 5 days**
  - from ‘Warm when clear’
  - to ‘Cold when clear’
  - “SWCF to LWCF”
Clouds: Summer & Winter Climate

**Opposite Impact**

- **Summer:** Clouds reflect sunlight (soil absorbs sun)
  - no cloud, hot days; only slightly cooler at night
  - Convective boundary layer in daytime
- **Winter:** Clouds are greenhouse (snow reflects sun)
  - clear & dry sky, cold days and very cold nights
  - Stable boundary layer

Betts et al. 2013a
Role of $LW_{dn}$ in Surface Radiation

- Snow reduces vapor flux
- Atmosphere cooler and drier
  - Less water vapor greenhouse
  - $-22 \text{ W/m}^2$
- Offset by 10% cloud increase with snow
Surface Radiation Balance

• Across snow transition
  – Surface albedo $\alpha_s$ increases: 0.2 to 0.73
  – $LW_{dn}$ decreases
  – Opaque cloud increases

• $SW_{\text{net}}$ falls 34 W/m²
• $LW_{dn}$ falls 15 W/m²
• Total 49 W/m²

• Surface skin $T$ falls: $\Delta T = -11K$ to balance
  (Stefan-Boltzman law: $\Delta LW = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)
Annual crops and seasonal diurnal cycle

• Ecodistrict crop data since 1955
  – Ecodistricts mapped to soils
  – Typical scale: 2000 km² (500-7000)

• Ecozones
  – boreal plains ecozone
  – semiarid/subumid prairie regional zones

• Shift from ‘Summerfallow’ (no crops) to annual cropping on 5 MHa (11 M acres)
  – Large increase in transpiration: Jun-Jul
13 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)
Change in Cropping

- Ecodistrict mean for 50-km around station
- Saskatchewan: 25% drop ‘SummerFallow’
- *Split at 1991- has summer climate changed?*
Three Station Mean in SK

- Growing season
  - $T_{\text{max}}$ cooler; RH moister
  - DTR and $\Delta$RH seasonal structure changes
Impact on Convective Instability

Growing season

- Lower LCL
- Higher $\theta_E$
- More Precip
Contrast Boreal Forest

- No RH, DTR signal
Summary (Part 1)

• High quality dataset with Opaque cloud
• Understand cloud coupling to climate
• Transpiration from crops changes climate
  – Cools and moistens summer climate
  – Lowers cloud-base and increases $\theta_E$
• 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

Papers at http://alanbetts.com
Transformative Concepts

- Snow as climate switch

- **Opaque/reflective cloud**
  - SWCF, LWCF $\rightarrow R_n$

- Diurnal climate analysis of T, RH
  - Dominated by cloud/$R_n$
  - **BUT**: Radiation only analysis
  - Because no soil moisture $\rightarrow$ EF
Monthly, Seasonal, 50-yr Climate

• **Opaque/reflective cloud** → $R_n$

• **Precipitation** linked to
  – Evaporation, soil moisture, EF

• **Separate land-surface coupling?**
  – YES, 50-yr climate coupling is
    – RH to precipitation and soil moisture
    – T to opaque cloud and $R_n$

• *Monthly timescale blended*
11 stations: 53-yr JJA climate

- Precip to \((R^2)\)
  - Cloud \((0.56)\)
  - \(P_{\text{LCLtx}}\) \((0.83)\)
  - \(RH_{\text{tx}}\) \((0.71)\)

- Cloud to
  - \(T_x\) \((0.69)\)

- Separation

- Month: blend

- Daily: cloud
Diurnal cycle tightly coupled

- $\Delta RH$ to DTR
- 2.77 %/K
  ($R^2 = 0.90$)
## Monthly timescale: Regression

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

<table>
<thead>
<tr>
<th>Month</th>
<th>K</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>(R^2) All</th>
<th>(R^2) Precip</th>
<th>(R^2) Cloud</th>
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<tr>
<td>May</td>
<td>0±0.83</td>
<td>-0.35±0.05</td>
<td>-0.37±0.04</td>
<td>-1.10±0.05</td>
<td>0.69</td>
<td>0.39</td>
<td>0.62</td>
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<td>Jun</td>
<td>0±0.70</td>
<td>-0.30±0.03</td>
<td>-0.32±0.02</td>
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<td>0.42</td>
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<td>July</td>
<td>0±0.73</td>
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<td>-0.25±0.02</td>
<td>-0.32±0.03</td>
<td>-1.10±0.05</td>
<td>0.67</td>
<td>0.42</td>
<td>0.48</td>
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<td>Aug</td>
<td>0±0.74</td>
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<td>-0.21±0.03</td>
<td>-0.40±0.03</td>
<td>-1.24±0.04</td>
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<td>Sept</td>
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<td>Oct</td>
<td>0±0.78</td>
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<td>-0.70±0.07</td>
<td>-1.33±0.04</td>
<td>0.78</td>
<td>0.37</td>
<td>0.70</td>
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Monthly timescale: Regression

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

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<tr>
<th>Month</th>
<th>( K )</th>
<th>A (Mo-2)</th>
<th>B (Mo-1)</th>
<th>C (Mo)</th>
<th>D</th>
<th>( R^2 ) All</th>
<th>( R^2 ) Precip</th>
<th>( R^2 ) Cloud</th>
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<tr>
<td>May</td>
<td>0.0±3.6</td>
<td>1.13±0.38</td>
<td>1.41±0.23</td>
<td>2.01±0.17</td>
<td>4.67±0.20</td>
<td><strong>0.70</strong></td>
<td>0.43</td>
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<tr>
<td>Jun</td>
<td>0.0±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><strong>0.68</strong></td>
<td>0.47</td>
<td>0.48</td>
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<tr>
<td>July</td>
<td>0.0±4.1</td>
<td>0.84±0.18</td>
<td>1.72±0.12</td>
<td>1.80±0.17</td>
<td>4.42±0.30</td>
<td><strong>0.59</strong></td>
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<td>0.33</td>
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<tr>
<td>Aug</td>
<td>0.0±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><strong>0.73</strong></td>
<td><strong>0.53</strong></td>
<td><strong>0.56</strong></td>
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<tr>
<td>Sept</td>
<td>0.0±3.5</td>
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<td>2.10±0.18</td>
<td>4.35±0.16</td>
<td><strong>0.75</strong></td>
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<tr>
<td>Oct</td>
<td>0±4.3</td>
<td>1.30±0.19</td>
<td>5.06±0.38</td>
<td>4.61±0.22</td>
<td><strong>0.67</strong></td>
<td>0.44</td>
<td>0.53</td>
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Monthly anomalies (MJJA: 2346 months)

- Less cloudy and less rain (this month and last)
  - $\delta T_x$ warmer (cloud mostly) \( (R^2 = 0.55) \)
  - $\delta DTR$ larger (both) \( (R^2 = 0.72) \)
  - $\delta RH$ drier (both) \( (R^2 = 0.68) \)
How good is the regression fit?

- **September**
  - $T_x \pm 1.4^\circ C$
  - DTR $\pm 0.8^\circ C$
  - $RH_{tx} \pm 3.5\%$
  - $P_{LCLtx} \pm 13$ hPa

- Some extremes underestimated

(586 station-yrs)
MJJA Mean: Regression Fit

Growing Season Means

\[ \delta \text{Precip(AMJJA)} = 0.25 \delta \text{Precip(April)} + \delta \text{Precip(MJJA)} \]
Diurnal coupling: MJJA mean

- Internal coupling well-defined
  - Slopes ≈ 60% of 50-yr climate
MJJA Surface Water Balance

\[ E = P - R - \Delta SM \]

\[ (R/P \approx 0.05: (P-R) = 0.95P) \]

\[ RH_x \text{ depends on } \delta \text{Precip(AMJJA)} \]

\[ P = P_m + \delta \text{Precip(AMJJA)} \]

\[ \Delta SM = \Delta SM_m + F*\delta \text{Precip(AMJJA)} \]

where \( P_m = 1.92 \text{ mm/day} \)

\[ \Delta SM_m = -0.61 \text{ mm/day (75mm/122 days)} \]

(Just an estimate)

But \( F \) is unknown

– change of \( \Delta SM \) with precipitation anomalies
– damps impact of precipitation anomalies
Energy and Water “Budget”

- **Start with cloud and precip. anomalies**
  - Gives anomalies of $T$, $RH$
  - Gives $R_n$ anomalies

- **Close with assumptions**
  - Climate coupling of cloud to precip. (0.73)
  - $F = 0.6$: soil water extraction heavily damped by precip. anomalies
Summary (Part 2)

• **High quality dataset with Opaque cloud**
  – Estimate SWCF, LWCF and $R_n$

• **Map coupling of T, RH climate anomalies**
  – To cloud on daily time-scale
  – To cloud and precip. on monthly/seasonal

• **Dependence splits for 50-yr climate**
  – T depends on cloud/radiation
  – RH and DTR depend on precip.

• **Estimate evaporation anomalies**
  – Feedback to daily timescale

*Papers at [http://alanbetts.com](http://alanbetts.com)*
Summer Diurnal Cycle Climate

- Climate emerges from daily variability
- Cloud increases, precipitation increases
- $T_{\text{max}}$, DTR increase, $T_{\text{min}}$ flat
- $\text{RH}_{\text{mean}}$ increases, $\Delta RH$ decreases
Diurnal Climate Change

- Annual cycle in Saskatchewan
- DTR change
- $\text{RH}_\text{mean}$ up
- Cloud peak
6 Stations in Saskatchewan

- $T_x, T_m, T_n$ fall about 10K
- $\Delta RH$ falls to <10%, afternoon RH rises
- Cloud increases 10% (peaking with snow)
- Snow date: Nov 15 ± 15 days
Snow Cover: Fall and Spring Climatology

- Fraction of days with snow cover drives much of interannual T variability
- More in spring than fall
- T- Slopes: -11, -8, -11, -11
**Daily Mean Climate vs Long-term Diurnal Mean**

- **Definitions**
  - \( \text{DTR} = T_x - T_n \)
  - \( \Delta \text{RH} = RH: T_x - RH: T_n \)

Monthly mean diurnal cycle

- \( \text{DTR}_h = T_{xh} - T_{nh} \)
- \( \Delta \text{RH}_h = RH_{xh} - RH_{nh} \)

Radiatively forced signal small in winter compared to daily advection
Daily Mean Climate vs Monthly Diurnal Mean Climate

- Daily variability in winter large
- Monthly variability small: $DTR_h$ quasi-linear
\[ T_{bias} = \frac{(T_{\text{max}} + T_{\text{min}})}{2} - T_{\text{mean}} \]

- Opposite in warm and cold season