Coupling Climate to Clouds, Precipitation and Snow

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14 Prairie stations: 1953-2011

- **Hourly** $p, T, RH, WS, WD, \textbf{Opaque Cloud}$ 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>
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<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

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

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

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

• [Betts *et al*. 2014b: Coupling of temperature and humidity to precipitation and cloud cover in the growing season]

Papers at [http://alanbetts.com](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

• Composite across **snow transitions**
  – First snow in fall; spring melt of snowpack
  – Winter climate and % days snow cover
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**
  - $\text{DTR} = T_{\text{max}} - T_{\text{min}} = (T_x - T_n)$
  - $\Delta RH = RH:T_x - RH:T_n$

- *Almost no missing hourly data* (until recent government cutbacks!)

Compare Neighbors: 64 km

T: \((R^2=0.95)\)

Opaque Cloud: 1 to 1 \((R^2=0.88)\)
Clouds to Summer Diurnal Cycle

- **40-yr climate**
- **T and RH** are inverse
- **Q** has double maximum for BL transitions
- **θ_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 ΔRH

- **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
Diurnal Temperature Range

- **Wars in daytime and cools at night**
- **Daytime Driver:** $R_{netD}$
- **Nighttime driver:** $LW_{net}$

(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
- **Albedo** data (MODIS/CCRS: 250m, after 2000)
N-S Albedo through Winter

- Prairies (SK) \( \alpha_s: 0.2 \text{ to } 0.73 \)
- Boreal forest \( \alpha_s: 0.1 \text{ to } 0.35 \)
- 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 $\pm$ 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
  - $T_x = -16.0 (\pm 0.6) \text{ K}$
  - $T_m = -14.7 (\pm 0.6) \text{ K}$
  - $T_n = -14.0 (\pm 0.7) \text{ K}$

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 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$_{net}$ falls 34 W/m$^2$
• LW$_{dn}$ falls 15 W/m$^2$
• Total 49 W/m$^2$

• Surface skin $T$ falls: $\Delta T = -11K$ to balance
  (Stefan-Boltzman law: $\Delta LW = \Delta(\sigma T^4) = 4\sigma T^3 \Delta T$)
Summary

- **High quality dataset with Opaque cloud**
- Understand cloud coupling to climate
- 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 BL
    - To ‘Cold when clear’ - stable BL

Papers at [http://alanbetts.com](http://alanbetts.com)
Transformative Concepts

• Snow as climate switch

• **Opaque/reflective cloud** \( \rightarrow \) \( R_n \)

• Separation of land-surface coupling
  – RH to precipitation and soil moisture
  – T to opaque cloud and \( R_n \)
Surface Radiation Budget

\[ R_{\text{net}} = \text{SW}_{\text{net}} + \text{LW}_{\text{net}} = (\text{SW}_{\text{dn}} - \text{SW}_{\text{up}}) + (\text{LW}_{\text{dn}} - \text{LW}_{\text{up}}) \]

Define Effective Cloud Albedo (reflection)

\[ \text{ECA} = \frac{(\text{SW}_{\text{dn}}(\text{clear}) - \text{SW}_{\text{dn}})}{\text{SW}_{\text{dn}}(\text{clear})} \]

Clear sky

\[ \text{SW}_{\text{net}} = (1 - \alpha_s)(1 - \text{ECA}) \text{SW}_{\text{dn}}(\text{clear}) \]

Reflected by surface, clouds

\text{MODIS} \quad \text{Calibrate Opaque Cloud data}
11 stations: 55-yr MJJA climate

- Precip to
  - Cloud (0.47)
  - LCL (0.79)
  - RH: $T_x$ (0.68)

- Cloud to
  - $T_x$ (0.68)

- Month: blend
- Daily: cloud
Monthly anomalies (MJJA: 2346 months)

- Less cloudy and less rain (this month and last)
  - $\delta T_x$ warmer (cloud mostly) \hspace{1cm} (R$^2 = 0.55$)
  - $\delta$DTR larger (both) \hspace{1cm} (R$^2 = 0.72$)
  - $\delta$RH drier (both) \hspace{1cm} (R$^2 = 0.66$)