Coupling of Diurnal Climate to Clouds, Land-use and Snow

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UW Madison
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1969: Barbados to Venezuela

BOMEX to VIMHEX
PhD student, London,
“Cumulus Convection”
Vermont Winter 2006

- Snow reflects sunlight, except where trees shadow
- Cold; little evaporation, clear sky; earth cools to space
- **2012 warm winter, snow melts** → **positive feedback**
- “Understanding Climate Change” “Advise Vermont”
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: 250m, after 2000)
# Prairie Station Locations

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

• **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 (2014)
References


• Betts, A.K., R. Desjardins, D. Worth, Shusen Wang and Junhua Li (2014), Coupling of winter climate transitions to snow and clouds over the Prairies (JGR 2013JD021168 submitted)
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
    - Sub-stratify by RH
- Change of seasonal climate with **cropping**
  - Summerfallow to annual crops on 5MHa in 30 yrs
  - Comparison with ERA-Interim grid-box
  - Drydown after precipitation events
- Composite across **snow transitions**
  - First snow in fall; spring melt of snowpack
  - Winter climate and % snow cover
Clouds and Diurnal Climate

• Reduce hourly data to daily mean, \( T_{\text{mean}} \) + data at \( T_{\text{max}} \) and \( T_{\text{min}} \)

• **Definitions: Diurnal cycle climate**
  - \( \text{DTR} = T_{\text{max}} - T_{\text{min}} = (T_x - T_n) \)
  - \( \Delta \text{RH} = \text{RH}:T_x - \text{RH}:T_n \)

• Almost no missing data (*until government cutbacks!*), reject a day if <23h data
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
Clouds to Summer Diurnal Cycle

- **40-yr climate**
- **T and RH are inverse**
- **Q has double maximum for BL transitions**
- **θ_E flatter**
- **Overcast only outlier**
Diurnal Cycle of Cloud Cover

- Noon peak for >6/10s
- Afternoon broken Cu for <6/10
Clouds: Summer & Winter Climate

Opposite Impact

• **Summer:** Clouds reflect sunlight (soil absorbs sun)
  – no cloud, hot days; barely cooler at night - *SWCF*

• **Winter:** Clouds are greenhouse (snow reflects sun)
  – clear & dry sky, cold days and very cold nights - *LWCF*

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

- **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 $T_{\text{max}} \approx 0^\circ$C
  - Transition – *in <5 days with snow*
Prairie Warm Season Climate

- 12 stations: small variability
- Variability in DTR and $\Delta$RH tiny
- Structure same as Regina
Surface Radiation Budget

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

- \( SWCF = SW_{\text{dn}} - SW_{\text{dn}}(\text{clear}) \)
  
  *Fit clear days or calculate*

Define Effective Cloud Albedo

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

- \( SW_{\text{net}} = (1 - \alpha_s)(1 - ECA) \cdot SW_{\text{dn}}(\text{clear}) \)
  
  *Reflected by surface, clouds*

*MODIS Calibrate Opaque Cloud data*
Calibration of Opaque Cloud to ECA-Effective Cloud Albedo

- Tight relationship: ECA to Opaque Cloud
- NDJF a little flatter
Fit ECA and 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 \( SW_{\text{net}} \) from \( SW_{\text{dn(clear)}} \) 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

- **Daytime Driver:** \( R_{\text{netD}} \)
- **Nighttime driver:** \( LW_{\text{net}} \)
- *Fully coupled diurnal system in warm season*
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/subhumid prairie regional zones

• Shift from ‘Summerfallow’ (no crops) to annual cropping on 5 MHa (11 M acres)
  – Large increase in transpiration: Jun-Jul
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: 250m, after 2000)
Change in Cropping

- Ecodistrict mean for 50-km around station
- Saskatchewan: 25% drop SummerFallow
- **Split at 1991- has summer climate changed?**
Diurnal Climate Change

- Annual cycle in Saskatchewan
- DTR change
- $\text{RH}_{\text{mean}}$ up
- Cloud peak
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
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
  – Shift to LWCF control from SWCF
  – Snow cover is a fast “climate switch”
October 2011– March 2012

• Warmest 6 months on record
• My garden frozen only 67 days
• No permanent snow cover west of Green Mtns
• Contrast snowy winter 2010-11
Snowfall and Snowmelt
Winter and Spring transitions

- Temperature falls 9K with first snowfall
- Rise with snowmelt is similar
- 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

Betts et al. 2014
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
Fall Snow Transition Climatology

- $T_x$, $T_m$, $T_n$ fall about 10K
- $\Delta RH$ falls to 10%, afternoon RH rises
- Cloud increases 10% (peaking with snow)
- Snow date: Nov 15 ± 3 days
Snow-melt Transition Climatology

- SW Alberta: $T_x, T_m, T_n$ increase about 11K
- Saskatchewan: increase about 10K
- 3 northern stations: increase 10K, slower
- Melt date: March 12–April 11
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
Snow Cover: Cold Season Climate

- **Alberta:** 79% of variance

- **Slopes**
  - $T_x$ -16.0K
  - $T_m$ -14.7K
  - $T_n$ -14.0K
Coupling to Cloud Cover Across Snowfall

- Mid-November
- 5-day means
  - red: no snow
  - blue: snow
- With snow $T_x, T_n$ plunge
- Cloud coupling shifts: 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
- **Winter:** Clouds are greenhouse (snow reflects sun)
  - clear & dry sky, cold days and very cold nights

*Betts et al. 2013*
N-S Albedo through Winter

- **Prairies**
  - $\alpha_s$: 0.2 to 0.73

- **Boreal forest**
  - $\alpha_s$: 0.1 to 0.35

- **MODIS**: 10day, 250m, avg. to 50x50km to latitude bands
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
  - $LW_{dn}$ 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: -11K to balance
Summary

• High quality dataset with Opaque cloud
• Understand cloud coupling to climate
• Transpiration from crops changes climate
  – Cools and moistens summer
  – Lowers cloud-base and increases $\theta_E$
  – Feedback increases precipitation
• Distinct warm and cold season states
  – Sharp transitions with snow cover: $\alpha_s = 0.7$
  – From SWCF dominated, with coupled CBL
  – To LWCF dominated, with stable BL
  – Snow cover is a “climate switch”

Papers at http://alanbetts.com
Outline Revisited

- **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 (2014)*

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Daily Mean Climate vs Long-term Diurnal Mean

• **Definitions**
  
  • $DTR = T_x - T_n$
  • $\Delta RH = RH_x - RH_n$

Monthly mean diurnal cycle

• $DTR_h = T_{xh} - T_{nh}$
• $\Delta RH_h = RH_{xh} - RH_{nh}$

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
\[ T_{\text{bias}} = \left( T_{\text{max}} + T_{\text{min}} \right)/2 - T_{\text{mean}} \]

- Opposite in warm and cold season