AN ANALYSIS OF SNOWPACK LOSSES DUE TO SUBLIMATION AT HUBBARD BROOK EXPERIMENTAL FOREST

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Outline

• Introduction
• Previous studies
• Research Question
• Methods
• Results
  • Sublimation losses 2007-2012
  • Seasonal and Daily Variability
  • Sensitivity Analysis
  • Sublimation losses 1986-2011
• Discussion
• Conclusions
• Outreach
This phenomena is understudied in the northeast.
Bailey et al. 2003

\[ P = Q + ET \]

Where

- \( P \) = Precipitation = 1,326 mm year\(^{-1}\)
- \( Q \) = Runoff = 833 mm year\(^{-1}\)
- \( ET \) = Evapotranspiration = 493 mm year\(^{-1}\)

http://www.geotimes.org/aug03/feature_hubbard.html
What causes Snow Water Equivalent (SWE) losses due to sublimation?

- Sublimation was driven by an imbalance between saturation vapor pressure in the immediate vicinity of an ice surface (Neumann et al. 2009)
- Sublimation has a significant effect on the water balance in an alpine area where wind induced transport is frequent and efficient (Strasser et al. 2007)
- Sublimation most correlated with wind speed and specific humidity (Hood et al. 1999)
Wind Induced Transport

- In Germany: 70% of annual snowfall was sublimated by wind transport along a high ridge.
Eddy Covariance Technique

- Molotch et al. 2007
- Niwot Ridge- Colorado
- 40 day study
  - Below canopy: 0.41 mm day$^{-1}$
  - Above canopy: 0.71 mm day$^{-1}$
- Sub canopy sublimation is dependent on the partitioning of sensible and latent heat fluxes in the canopy.
Aerodynamic Profile Method

- Niwot Ridge- Colorado
- Hood et al. 1999
- Aerodynamic profile method
  - Uses observations from 2 heights above snowpack
- Seasonal study
  - Net snow accumulation: 1308 mm year\(^{-1}\)
  - Summer time precipitation: 203 mm year\(^{-1}\)
  - Total SWE loss due to sublimation: 193 mm year\(^{-1}\)
Aerodynamic Profile Method

- November - Sublimation losses most correlated with wind speed
- February - Sublimation losses most correlated with specific humidity
Aerodynamic Profile Method

Hood et al. 1999
-15% of seasonal water budget
-13% of annual water budget
Bulk Profile Method

• Fassnacht 2010
  • Uses one set of observations above the snowpack.
• Average monthly precipitation: 88.9 mm month\(^{-1}\)
• Average monthly sublimation 22.7 mm month\(^{-1}\)
Research Questions

• What is the magnitude of snowpack losses due to sublimation losses at Hubbard Brook Experimental Forest during the most recent winters?
  • 2007-2012

• How have these calculated sublimation losses changed historically?
  • 1986-2011
Data Sources

• NRCS- National Resources Conservation Service
  • SCAN- Soil Climate Analysis Network
  • Average daily and hourly
    • Temperature (T)
    • Relative Humidity (RH)
    • Wind Speed ($U_a$)
    • Atmospheric Pressure (P)
    • Soil Moisture

• HBEF- Hubbard Brook Experimental Forest
  • Averaged daily
    • Vapor pressure
    • Temperate
    • Wind Speed
    • SWE depth

• NCDC- National Climatic Data Center
  • Average Daily
    • Atmospheric Pressure
Study Site

- Northern Research Station of the USDA Forest Service
- 3,160 hectares.
- SCAN site: 451 meters above sea level.
- Surround forest:
  - Sugar maple (*Acer saccharum*),
  - American beech (*Fagus grandifolia*),
  - Yellow birch (*Betula alleghaniensis*)
    - (Bailey et al. 2003).
Methods

- A bulk profile method was used to calculate a mass transport from the snowpack
  - Required 1 set of observations from above the snow surface
- T, U_a, RH, and P were used to calculate: e_b, e_o, and ρ_a
- Fassnacht 2010

\[
FE = \frac{0.623 \rho_a k_o^2}{P} \frac{u_a e_b - e_o}{\ln\left(\frac{z_a}{z_o}\right) \ln\left(\frac{z_b}{z_o}\right)}
\]

Where:
- FE = Mass transport from snowpack
- \(\rho_a\) = Density of air
- \(k_o\) = Von Karmon constant
- \(P\) = Atmospheric pressure
- \(u_a\) = Wind speed
- \(z_a\) = Height of wind speed obs.
- \(z_b\) = Height of vapor pressure obs.
- \(z_o\) = Roughness length
- \(e_b\) = Vapor pressure of ambient air
- \(e_o\) = Saturated vapor pressure

FE is then multiplied by the latent heat of sublimation ~2850 kJ/ kg
Methods

• SCAN Site- Winters of 2007-2012
  • Daily averaged data, and hourly data
• A sensitivity analysis was performed on $T$, $e_b$, $U_a$, $Z_O$, and $P$.
  • Increase and decrease variables by 10%, 25%, and 50%.
• HBEF and NCDC winters of 1986-2011
  • Using a hypsometric equation to estimate the pressure differences between HBEF and KCON.
Methods

• Hypsometric Equation (Bluestein 1992)

\[ P_1 = \frac{e^{(R_d \cdot T_v)}}{g \cdot P_2} (z_2 - z_1) \]

Where:
\[ P_1 = \text{P at HBEF} \]
\[ R_d = \text{Gas constant} \]
\[ T_v = \text{Virtual temperature at HBEF} \]
\[ z_2 = \text{Elevation at HBEF} \]
\[ z_1 = \text{Elevation at KCON} \]
\[ P_2 = \text{P at KCON} \]
## Results

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Sublimating Days</th>
<th>Sum of loss per winter (daily mean obs) [mm]</th>
<th>Mean Loss per day due to Sublimation [mm/day]</th>
<th>Winter Precipitation [mm/ winter]</th>
<th>Max snowpack SWE [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>91</td>
<td>59.2</td>
<td>0.65</td>
<td>508</td>
<td>137.2</td>
</tr>
<tr>
<td>2008</td>
<td>55</td>
<td>45.1</td>
<td>0.81</td>
<td>497</td>
<td>284.5</td>
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<tr>
<td>2009</td>
<td>111</td>
<td>71.6</td>
<td>0.64</td>
<td>470</td>
<td>203.2</td>
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<tr>
<td>2010</td>
<td>81</td>
<td>64.7</td>
<td>0.79</td>
<td>518</td>
<td>88.9</td>
</tr>
<tr>
<td>2011</td>
<td>113</td>
<td>83.7</td>
<td>0.75</td>
<td>552</td>
<td>200.6</td>
</tr>
<tr>
<td>2012</td>
<td>90</td>
<td>59.6</td>
<td>0.66</td>
<td>494</td>
<td>139.7</td>
</tr>
</tbody>
</table>

Recall at HBEF: P = 1,326 mm year\(^{-1}\)  
Q = 833 mm year\(^{-1}\)  
ET = 493 mm year\(^{-1}\)
Winter 2007

SWE Loss: 11 mm
Calculated Loss: 10.5 mm
Winter 2011

Snowpack SWE
Loss Due to Sublimation
Soil Moisture Percentage

SWE Loss: 12 mm
Calculated Loss: 9.5 mm
<table>
<thead>
<tr>
<th>Year</th>
<th>Maximum Sublimation Loss [mm/day]</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>6.24</td>
<td>April 1</td>
</tr>
<tr>
<td>2008</td>
<td>3.74</td>
<td>Jan 31</td>
</tr>
<tr>
<td>2009</td>
<td>2.25</td>
<td>Mar 26</td>
</tr>
<tr>
<td>2010</td>
<td>3.92</td>
<td>Mar 5</td>
</tr>
<tr>
<td>2011</td>
<td>3.74</td>
<td>Feb 27</td>
</tr>
<tr>
<td>2012</td>
<td>4.88</td>
<td>Mar 31</td>
</tr>
</tbody>
</table>
## Sensitivity Analysis

Increase and decrease variables by 10%, 25%, and 50%

<table>
<thead>
<tr>
<th>Variable</th>
<th>+50%</th>
<th>+25%</th>
<th>+10%</th>
<th>Initial</th>
<th>-10%</th>
<th>-25%</th>
<th>-50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>16.4</td>
<td>8.81</td>
<td>3.61</td>
<td>--</td>
<td>3.93</td>
<td>10.2</td>
<td>20.2</td>
</tr>
<tr>
<td>e_b</td>
<td>67.9</td>
<td>47.8</td>
<td>21.7</td>
<td>--</td>
<td>24.5</td>
<td>61.2</td>
<td>122.6</td>
</tr>
<tr>
<td>w</td>
<td>41.9</td>
<td>20.9</td>
<td>8.42</td>
<td>--</td>
<td>8.42</td>
<td>20.9</td>
<td>41.9</td>
</tr>
<tr>
<td>z_o</td>
<td>12.2</td>
<td>6.41</td>
<td>2.72</td>
<td>--</td>
<td>2.81</td>
<td>7.31</td>
<td>16.1</td>
</tr>
</tbody>
</table>
Sensitivity Analysis

- \( T \)
- \( U_a \)
- \( Z_o \)
- \( e_b \)
Historical Daily Variation

Mann-Kendall:
\[ \tau = -0.226 \]
2-sided p-value \( \leq 0.00 \)

Slope = 0.02 mm day\(^{-1}\) year\(^{-1}\) for the 23 year period.
Historical Daily Variation

Calculated Water Loss due to Sublimation [mm/day]

- Range of values from 0 to 6
Historical Annual Variation

Mann-Kendall:
\[ \tau = -0.76 \]
2-sided p-value < 0.00
Slope = -1.33 mm winter\(^{-1}\) year\(^{-1}\) for the 23 year period.
Discussion

- Water Budget implications
- Downward Trend
- Comparison with other studies
- Changing Winters
Water Budget

• According to recent studies at HBEF, approximately 61% of annual precipitation leaves runoff and 39% leaves the system as evapotranspiration (Campbell et al. 2007)

• Annual Water Budget (Oct 2010- Oct 2011).
  • 1450 mm of annual precipitation
  • 84 mm of sublimation \( \rightarrow \) 5.5%

• Seasonal Water Budget (First snow accumulation- final melt)
  • 550 mm of winter precipitation
  • 84 mm of sublimation \( \rightarrow \) 15.2%
  • On average (2007-2012) about 12%
Downward Trend - Temperature

Sen Slope = 0.00 °C winter\(^{-1}\) year\(^{-1}\)
for the 23 year period
Downward Trend - Wind speed

No Statistical Change to Wind Speed!
Downward Trend - Vapour Pressure

Sen Slope = 0.14 kPa winter$^{-1}$ year$^{-1}$ for the 23 year period
Downward Trend- RH

Sen Slope = 0.75 % winter$^{-1}$ year$^{-1}$ for the 23 year period

Or about 20% increase since 1986
Downward Trend - Vapour Pressure Deficit

Sen Slope = 0.02 kPa day\(^{-1}\) year\(^{-1}\) for the 23 year period
Comparison with other studies

• HBEF- 2007-2012
  • Mean sublimation loss: 64 mm winter$^{-1}$
    • 12% of winter water budget
  • Mean sublimation loss: 0.71 mm day$^{-1}$
  • Mean sublimation days: 85 days

• Niwot Ridge- Hood et al 1999
  • Net Sublimation: 195 mm winter$^{-1}$
    • 15% of winter water budget

• Niwot Ridge- Molotch et al. 2007
  • Mean sublimation loss: 0.71 mm day$^{-1}$
  • Total (40 day study): 53 mm winter$^{-1}$

• Syracuse, NY Fassnacht 2004
  • Mean sublimation loss: 22 mm month$^{-1}$
  • Losses account for nearly 30% of monthly precipitation
Loss due to Sublimation [mm/year]

Conclusions

- Sublimation winters of 2007-2012
  - Average of 64 mm winter$^{-1}$
  - Average of 0.71 mm day$^{-1}$

- Sublimation winters of 1986-2011
  - Average of 103 mm winter$^{-1}$
  - Average of 1.21 mm day$^{-1}$

- Downward Trend explained by:
  - Increase in $e_o$ since 1986
  - Decrease in wind speed since 1986
Outreach

- Work will be submitted to the Journal of Hydrometeorology.
- New watershed hydrology blog
  - [http://jpmolloy.blogs.plymouth.edu/](http://jpmolloy.blogs.plymouth.edu/)

**CFE- Watershed Hydrology Lab**

*a neutron walks into a bar and asks how much for a drink. the bartender replies "for you no charge"*
Acknowledgements

• Thanks to:
  • My friends and family for their support through this process.
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  • Committee Members
    • Eric Hoffman
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    • Jennifer Jacobs
  • Advisor
    • Mark Green
Works Cited

- Hood, Eran, Mark Williams, and Don Cline. 1999. “Sublimation from a Seasonal Snowpack at a Continental, Mid-latitude Alpine Site.” *Hydrological Processes* 13 (September 1): 1781–1797.
Questions