New Perspectives on Blowing Snow Transport, Sublimation, and Layer Thermodynamic Structure over Antarctica

American Geophysical Union

Steve Palm¹,², Vinay Kayetha¹,², Yuekui Yang² and Rebecca Pauly¹,²

¹Science Systems and Applications Inc., Lanham MD
²Goddard Space Flight Center, Greenbelt, MD
Outline

- The importance of blowing snow
- The structure of blowing snow layers
- Dropsonde measurements through blowing snow layers
- Climatology of blowing snow over Antarctica
- Blowing snow sublimation and transport
- What’s missing and errors
- Summary
Why Study Blowing Snow?

- Mass balance of ice sheets
- Atmospheric moisture/hydrology
- Paleoclimate
- Atmospheric chemistry
- Regional radiation budget
- Model improvement
- Human impact
- Altimetry range delay
Typical Blowing Snow Layer Structure as Revealed by Lidar

- Larger undulations are ~ 14 km
- Small “cells” are roughly 2 km
- Larger undulations are ~ 14 km

Columbus, OH to Dallas, TX:
- 250 m
- 400 m
- 1500 km
- 210 km
- 420 km
Temperature and Moisture Structure

![Graph showing temperature and relative humidity from 05:53 to 05:55 on 12 Oct 2010. The graph displays temperature in °C and relative humidity (%) as functions of height (m) and distance along the track (km). The location of the sonde is marked, and the time of sonde position is 12:42:50. There are also graphs showing wind direction (Degrees) and potential temperature (K).]
Toward a Blowing Snow Climatology
For Antarctica

- Blowing Snow is very frequent in all months but December and January
- Large areas of > 50% frequency April through September
- Localized year to year variability, but overall frequency pattern is very stable

Intra-annual Average 2006 - 2016

Inter-annual variability 2006 - 2016
Ice Sheet Mass Balance and Blowing Snow

Ice Sheet Mass Balance Equation:

\[ S = \int_{\text{year}} (P - E - M - \sqrt{Q_t} - Q_s)dt \]

- \( S \) - Accumulation or reduction of mass
- \( P \) - Precipitation
- \( E \) - Evaporation and surface sublimation
- \( M \) - Melt runoff
- \( Q_t \) - Blowing snow divergence (transport)
- \( Q_s \) - Blowing snow sublimation

**Importance of \( Q_s \)**

- A large atmospheric water vapor source in high latitudes.
- Together with \( Q_t \), a significant term in the mass balance of ice sheets.
- Magnitudes largely unknown due to lack of observations

To compute \( Q_s \) directly, we need knowledge of

blowing snow particle size, number density,

and air temperature and humidity
Sublimation of Blowing Snow: A Major Source of High-Latitude Atmospheric Moisture

How do we get sublimation from CALIPSO backscatter profiles?

\[
N(z) = \frac{(\beta(z) - \beta_m(z))S}{2\pi r(z)^2} \quad \text{Particle number density (m}^{-3}\text{)}
\]

\[
q_b(z) = \frac{4\pi \rho_{\text{ice}} r(z)^3 N(z)}{3 \rho_{\text{air}}} \quad \text{Blowing snow mixing ratio (kg/kg)}
\]

\[
S_b(z) = \frac{q_b(z)Nu(q_v(z)/q_{is}(z) - 1)}{2\rho_{\text{ice}} r(z)^2 (F_k(z) + F_d(z))} \quad \text{Blowing snow sublimation (s}^{-1}\text{)}
\]

\[
Q_s = \rho_{\text{air}} \int_{z=0}^{z_{\text{top}}} S_b(z)dz \quad \text{Column integrated blowing snow sublimation (kg m}^{-2}\text{ s}^{-1})
\]

\[
B(z): \text{CALIPSO average attenuated backscatter profile}
\]
\[
S: \text{extinction/backscatter (25)}
\]
\[
R(z): \text{average particle radius (10 - 40\mu m)}
\]
\[
q_v: \text{water vapor mixing ratio}
\]
\[
q_{is}: \text{saturation mixing ratio wrt ice}
\]
\[
F_k: \text{heat conduction term (m s kg}^{-1}\text{)}
\]
\[
F_d: \text{heat diffusion term (m s kg}^{-1}\text{)}
\]

\[
Nu: \text{Nusselt number:}
\]
\[
Nu = 1.79 + 0.606 \text{Re}^{0.5}
\]
\[
\text{Re} = 2r(z)\nu_b / \nu
\]
Sublimation of Blowing Snow: Results

(a) The average April through October blowing snow frequency for the period 2007-2015.

(b) The average annual blowing snow sublimation for the same period as in (a).

Sublimation rate is highly dependent on temperature and humidity.
Sublimation of Blowing Snow: Direct Observation vs Parameterization

CALIPSO Direct Observation
2007 – 2015
Average

De´ry, S. J., and M. K. Yau, 2002
### Table 2. The total transport (Gt yr\(^{-1}\)) from continent to ocean for various regions in Antarctica for 2007 – 2015.

<table>
<thead>
<tr>
<th>Year</th>
<th>East Antarctica</th>
<th>West Antarctica</th>
<th>135E – 160E</th>
<th>80W – 120W</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2.52</td>
<td>1.29</td>
<td>1.72</td>
<td>0.82</td>
</tr>
<tr>
<td>2008</td>
<td>2.20</td>
<td>1.43</td>
<td>1.21</td>
<td>0.90</td>
</tr>
<tr>
<td>2009</td>
<td>2.63</td>
<td>1.27</td>
<td>1.51</td>
<td>0.78</td>
</tr>
<tr>
<td>2010</td>
<td>2.26</td>
<td>1.15</td>
<td>1.38</td>
<td>0.73</td>
</tr>
<tr>
<td>2011</td>
<td>2.04</td>
<td>1.04</td>
<td>1.13</td>
<td>0.64</td>
</tr>
<tr>
<td>2012</td>
<td>2.49</td>
<td>1.21</td>
<td>1.41</td>
<td>0.73</td>
</tr>
<tr>
<td>2013</td>
<td>2.54</td>
<td>1.41</td>
<td>1.26</td>
<td>0.83</td>
</tr>
<tr>
<td>2014</td>
<td>2.55</td>
<td>1.02</td>
<td>1.49</td>
<td>0.67</td>
</tr>
<tr>
<td>2015</td>
<td>2.76</td>
<td>1.38</td>
<td>1.58</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Avg</strong></td>
<td><strong>2.44</strong></td>
<td><strong>1.24</strong></td>
<td><strong>1.41</strong></td>
<td><strong>0.75</strong></td>
</tr>
</tbody>
</table>

### Table 1. The year average sublimation per year (average off all grid boxes) and the integrated sublimation over the Antarctic continent (north of 82S).

<table>
<thead>
<tr>
<th>Year</th>
<th>Average Sublimation (mm swe)</th>
<th>Integrated Sublimation (Gt yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006*</td>
<td>28.3</td>
<td>255</td>
</tr>
<tr>
<td>2007</td>
<td>56.8</td>
<td>514</td>
</tr>
<tr>
<td>2008</td>
<td>49.2</td>
<td>446</td>
</tr>
<tr>
<td>2009</td>
<td>45.3</td>
<td>409</td>
</tr>
<tr>
<td>2010</td>
<td>42.9</td>
<td>388</td>
</tr>
<tr>
<td>2011</td>
<td>47.6</td>
<td>431</td>
</tr>
<tr>
<td>2012</td>
<td>44.4</td>
<td>402</td>
</tr>
<tr>
<td>2013</td>
<td>47.7</td>
<td>432</td>
</tr>
<tr>
<td>2014</td>
<td>41.5</td>
<td>376</td>
</tr>
<tr>
<td>2015</td>
<td>41.3</td>
<td>374</td>
</tr>
<tr>
<td>2016*</td>
<td>33.2</td>
<td>301</td>
</tr>
<tr>
<td><strong>AVG</strong></td>
<td><strong>43.5</strong></td>
<td><strong>393.4</strong></td>
</tr>
</tbody>
</table>

*2006 and 2016 consist of only 7 and 9 months of observations, respectively.
What are the Errors in Sublimation Calculation?

- Particle density computation relies on knowledge of extinction to backscatter ratio and particle radius
- Errors in the MERRA-2 temperature and moisture data
- Not correcting for possible attenuation above and within the blowing snow layer
- Failure to detect all blowing snow layers and spatial coverage limitations
Summary and Conclusions

• Blowing snow occurs over 50% of the time in winter over much of Antarctica
• Layers are on average 150 m thick but can reach 400-500 m
• The thermal and moisture structure within the layer is well mixed, due to wind shear driven turbulence
• The sublimation process does not saturate the layer
• Continent-wide integrated sublimation is roughly twice as high as prior model estimates (393 Gt yr$^{-1}$ vs 193)
• The amount of snow blown off the Antarctic continent is significant (3.68 Gt yr$^{-1}$)
Thank You for your Attention!

For further information please see:


Blowing Snow data available from the author upon request
Soon to be available from the NASA Langley atmospheric data center
Blowing Snow Transport ($Q_t$) off Continent

**Importance:**

- Mass Balance
- Sea Ice Thickness
- Ocean Freshening

CALIPSO BLSN Detections
Blowing Snow Storm and Transport

Solid Colored: October 13
Dashed Colored: October 14
Solid Black: October 15
2009

MODIS

CALIPSO

Surface Wind Speed

10 m Wind (m/s)