Satellite Observations of Blowing Snow in Polar Regions: Implications for Mass Balance, Atmospheric Chemistry and Moisture Budget

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Outline

• Motivation
• How do we detect blowing snow from satellite?
• Blowing snow frequency, 2006–2015
• Blowing snow transport and sublimation
• Blowing snow and atmospheric chemistry
• Take home points
• Future work
Motivation

• No prior measurements of blowing snow covering all of Antarctica, the Arctic and Greenland

• Important for:
  – Mass balance of ice sheets
  – Atmospheric water vapor and chemistry
  – Paleoclimatology
  – Model improvement and validation
  – Regional radiation budget
  – Lidar altimetry error
Satellite Detection of Blowing Snow from CALIPSO

Backscatter (km$^{-1}$sr$^{-1}$)

Surface Wind Speed

~ 900 km

14 October 2009 06:13 UTC

MODIS RGB = 2.1, 2.1, 0.84 μm
Satellite Detection of Blowing Snow using MODIS

- At 2.1 μm, small particles are more reflective
- BLSN stands out from the underlying snow and ice surface
- Limited to sunlit scenes
Toward a Blowing Snow Climatology for Antarctica

- 10 years of data indicate no temporal trend in average winter frequency over large areas.
- But inter-annual variability can be large as can smaller regional variability.
- Large regions experience blowing snow 60 to 70% of the time

Mar – Sep Average
Ice Sheet Mass Balance and Blowing Snow

Ice Sheet Mass Balance Equation:

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

- **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.
Blowing Snow Transport ($Q_t$) off Continent

**Importance:**

- Mass Balance
- Sea Ice Thickness
- Ocean Freshening

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CALIPSO BLSN Detections
Blowing Snow Storm and Transport

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

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MODIS

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CALIPSO

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Surface Wind Speed

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10 m Wind (m/s)
There are a few “hot spots” where blowing snow is frequently transported off the continent (arrows) and areas over sea ice where blowing snow acts to move snow from place to place – mainly over the Ross and Weddell Seas (white circles).
Blowing Snow Sublimation ($Q_s$): A Lack of Observations Necessitates Parameterization

Blowing snow sublimation ($Q_s$) parameterization – Dery and Yau, 2002:

$$Q_s = (a_0 + a_1 \xi + a_2 \xi^2 + a_3 \xi^3 + a_4 U_{10} + a_5 \xi U_{10} + a_6 \xi U_{10} + a_7 U_{10}^2 + a_8 \xi U_{10}^2 + a_9 U_{10}^3) / U'$$

$$U' = \frac{(1 - U_t / U_{10})^{2.59}}{(1 - 6.975 / U_{10})^{2.59}}$$

$$\xi = \frac{(RH_i - 1)}{2 \rho_{ice} (F_k (T) + F_d (T))}$$

$$U_t = 6.975 + 0.0033(T + 27.27)^2$$

Sublimation of Blowing Snow: A Major Source of Atmospheric Moisture

How do we get sublimation from CALIPSO backscatter profiles?

\[ N(z) = \frac{(\beta(z) - \beta_m(z))S}{2\pi r^2} \]

Particle number density \((m^{-3})\)

\[ q_b(z) = \frac{4\pi \rho_{ice} r^3 N(z)}{3\rho_{air}} \]

Blowing snow mixing ratio \((kg/kg)\)

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

Blowing snow sublimation \(s^{-1}\)

\[ Q_s = \rho_{air} \int_{z=0}^{z_{top}} S_b(z)dz \]

Column integrated blowing snow sublimation \(kg \, m^{-2} \, s^{-1}\)

B(z): CALIPSO average attenuated backscatter profile
S: extinction/backscatter (25)
r: average particle radius \((30\mu m)\)

q_v: water vapor mixing ratio
q_{is}: saturation mixing ratio wrt ice

F_k: heat conduction term \((m \, s \, kg^{-1})\)
Nu = 1.79 + 0.606 Re^{0.5}
Re = \frac{2\nu r_v \nu}{\rho_{air} r^2}

F_d: heat diffusion term \((m \, s \, kg^{-1})\)

Nu: Nusselt number:
Parameterization of blowing snow sublimation does not work!

Figure 5. The mean annual blowing snow sublimation rate (mm swe) for the period 1979–1993 in the Southern Hemisphere.

De´ry, S. J., and M. K. Yau, 2002

365/5*0.5*(1.5 mm swe) = 54 mm

Blowing Snow over Sea Ice: A Possible Source of Sea Salt Aerosol

July 2, 2013 00:34:00 – 00:35:14

BLOWSEA July 2, 2013 UTC

Polarstern Mean 29m
Wind: 9.5m/s

Polarstern
Particle Density (m⁻³)
@29m

July 2, 2013 00:34:00 – 00:35:14

Height (m)
Blowing Snow over Sea Ice is Correlated with Bromine Bursts

March 12  
March 13  
March 14
CALIPSO Blowing Snow Retrievals are used for Model Validation and Improvement

- Models can be used to supplement observations
- Observations can be used to improve and validate models
- Good blowing snow models can be used in ICESat-2 data analysis

Model Validation Lenaerts, et al., 2012
Take Home Points

• Blowing snow occurs more than 50% of the time over large areas of Antarctica for 8 months of the year.
• Transport and sublimation of blowing snow play an important role in ice sheet mass balance
• Blowing snow over sea ice may be catalyst for bromine bursts seen in polar spring
• On an annual basis, current estimates of blowing snow sublimation over at least some parts of Antarctica may be nearly an order of magnitude too low.
Where From Here?

- Improve blowing snow detection algorithm by including depolarization and color ratio.
- Add blowing snow to the Level 2 CALIPSO data product.
- Improve and extend sublimation analysis over CALIPSO timeframe to obtain monthly and annual sublimation.
Blowing snow sublimation computed from CALIPSO data is of comparable magnitude to the model parameterized values, but the model has the spatial distribution completely wrong.
Blowing snow sublimation ($Q_s$) parameterization – Dery and Yau, 2002:

$$Q_s = (a_0 + a_1 \xi + a_2 \xi^2 + a_3 \xi^3 + a_4 U_{10} + a_5 \xi U_{10} + a_6 \xi^2 U_{10} + a_7 U_{10}^2 + a_8 \xi U_{10}^2 + a_9 U_{10}^3)$$

$$\xi_{fr} = \frac{(RH_i - 1)}{2 \rho_{ice} (F_k(T) + F_d(T))}$$
Blowing snow sublimation computed from CALIPSO data is of comparable magnitude to the model parameterized values, but the model has the spatial distribution completely wrong.
How do we get Sublimation from CALIPSO Backscatter Profiles?

\[ N(z) = \frac{(\beta(z) - \beta_m(z))S}{2\pi r^2} \]

\[ q_b(z) = \frac{4\pi \rho_{ice}r^3 N(z)}{3\rho_{air}} \]

\[ q_b(z) = \frac{2\rho_{ice}r\sigma(z)}{3\rho_{air}} \]

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

\[ S_b(z) = \frac{\sigma(z)Nu(q_v(z)/q_{is}(z)-1)}{3\rho_{air}r(F_k(z)+F_d(z))} \]

\[ Q_s = \rho_{air} \int_{z=0}^{z_{top}} S_b(z)dz \]

Particle number density (m\(^{-3}\))

Blowing snow mixing ratio (kg / kg)

Blowing snow sublimation (s\(^{-1}\))

Column integrated blowing snow sublimation (kg m\(^{-2}\) s\(^{-1}\))

B(z): CALIPSO average attenuated backscatter profile
S: extinction/backscatter (25)
r: average snow particle radius (30µm)
q_v: water vapor mixing ratio
q_{is}: saturation mixing ratio wrt ice
F_k: heat conduction term (m s kg\(^{-1}\))
F_d: heat diffusion term (m s kg\(^{-1}\))

Nu: Nusselt number:

Re = \frac{2rv_b}{v}
Blowing snow sublimation ($Q_s$) parameterization – Dery and Yau, 2002:

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\[ \xi = \frac{(RH_i - 1)}{2 \rho_{\text{ice}} (F_k(T) + F_d(T))} \]

\[ U' = \frac{(1 - U_t / U_{10})^{2.59}}{(1 - 6.975 / U_{10})^{2.59}} \]

\[ U_t = 6.975 + 0.0033(T + 27.27)^2 \]
First Dropsonde Data through a Blowing Snow Storm:
October 12, 2010, 12:42

(a) Potential temperature
(b) Relative humidity wrt ice
(c) Dew point (blue) and air temperature (black)
(d) Wind speed (red, m/s) and direction (black)
Particle Number Retrieval from Lidar Measurement of Extinction ($\sigma$)

$z_r = 29.0 \text{ m}$
$N_r = 2.0 \times 10^4 \text{ m}^{-3}$
$\omega = 0.13 \text{ m/s}$
$u_* = 0.30 \text{ m/s}$
$r = 70 \mu\text{m}$
$S = 25$