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

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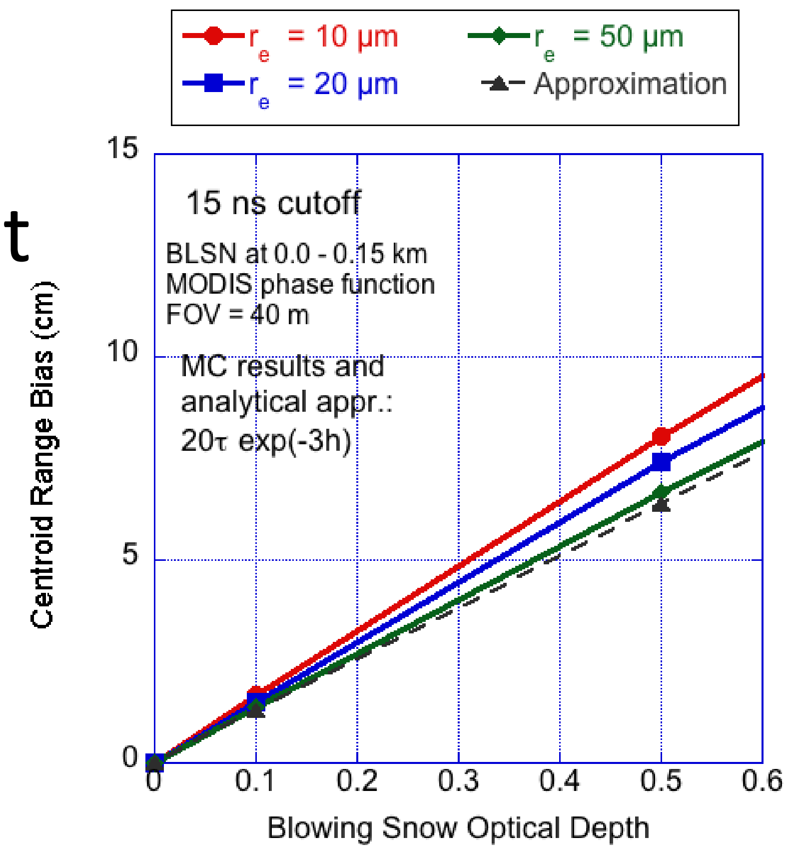
Outline

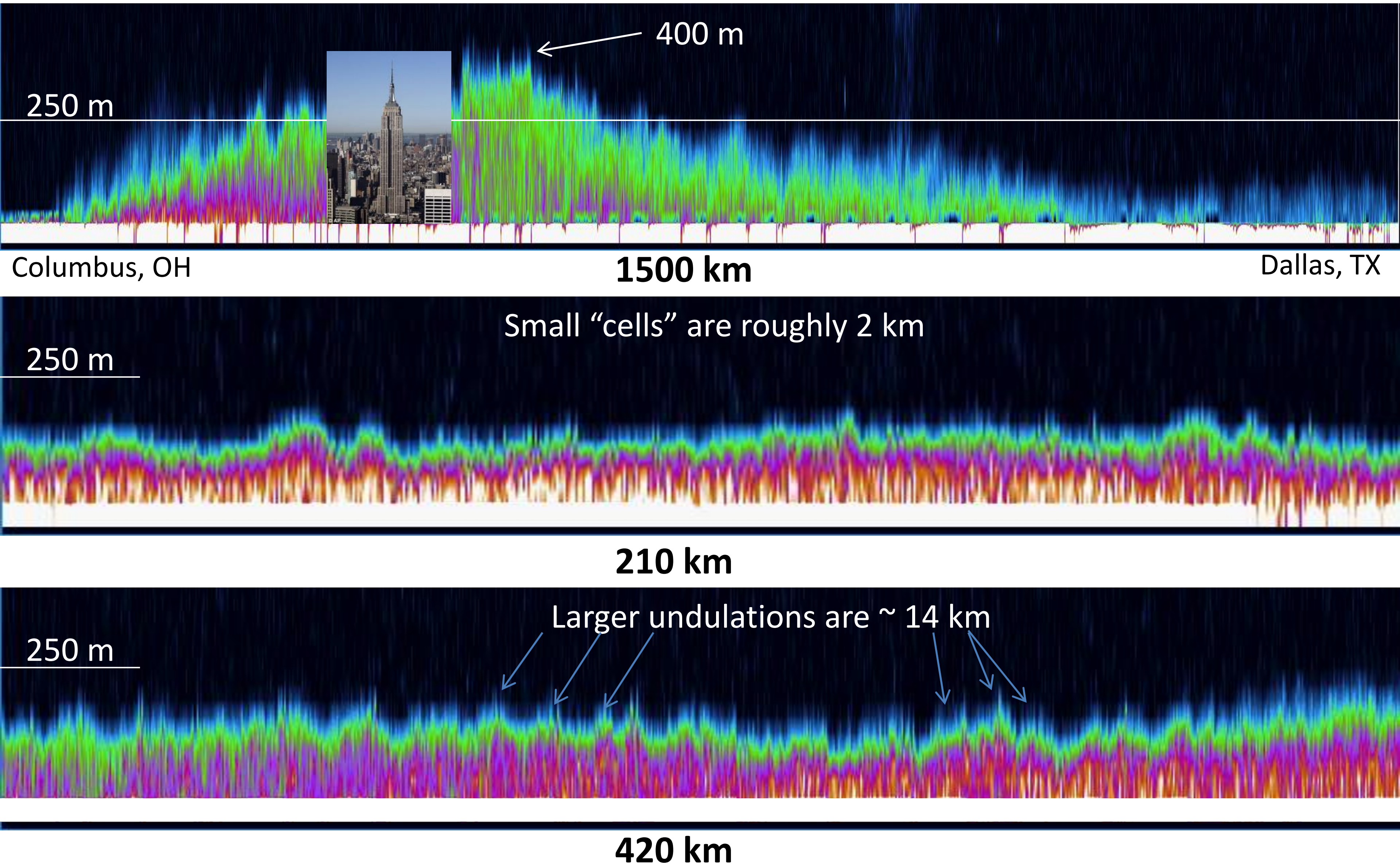
- The importance of blowing snow
- The structure of blowing snow layers
- Dropsonde measurements through blowing snow layers
- Climatology of blowing snow over Antarctica
- Blowing snow sublimation and transport
- What’s missing and errors
- Summary

Why Study Blowing Snow?

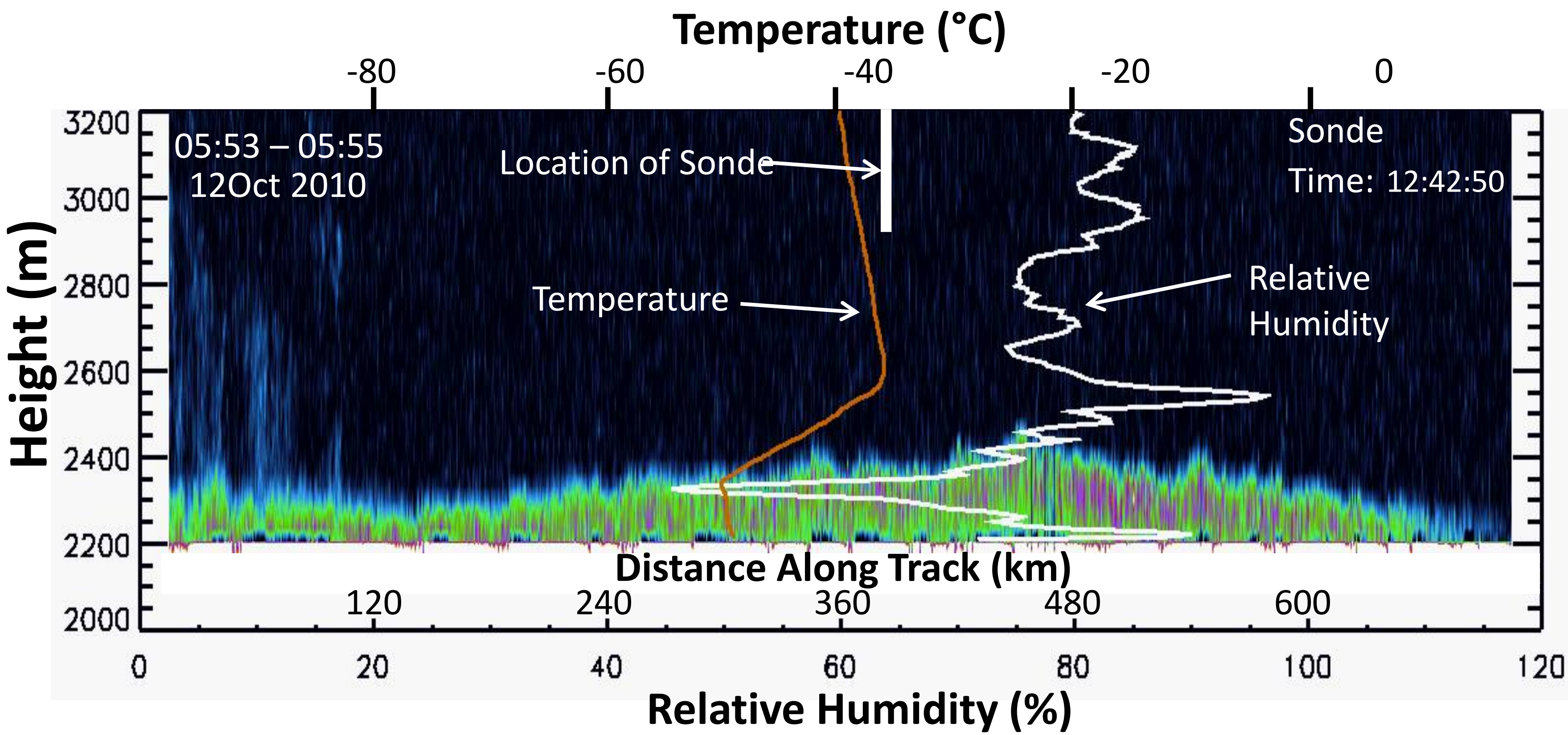
- Mass balance of ice sheets
- Atmospheric moisture/hydrology
- Paleoclimate
- Atmospheric chemistry
- Regional radiation budget
- Model improvement
- Human impact
- Altimetry range delay

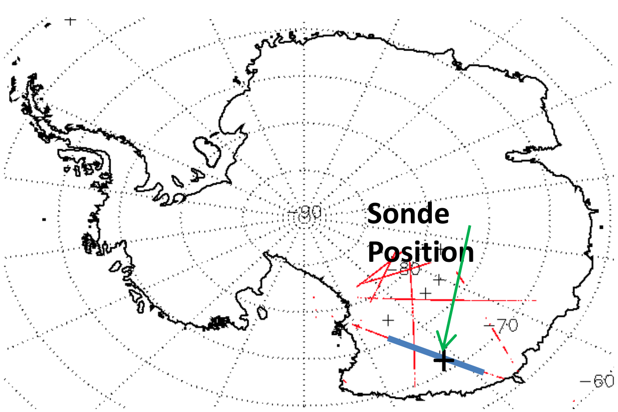


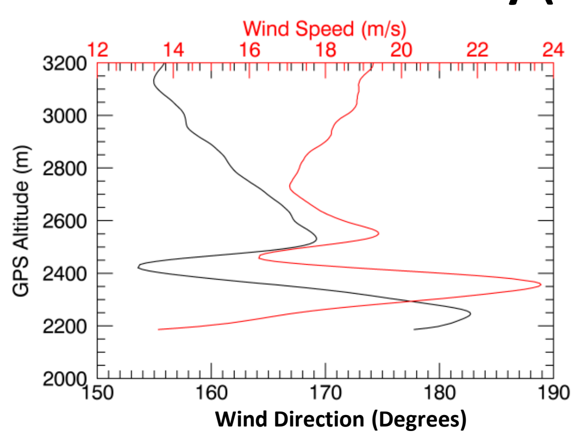
Typical Blowing Snow Layer Structure as Revealed by Lidar

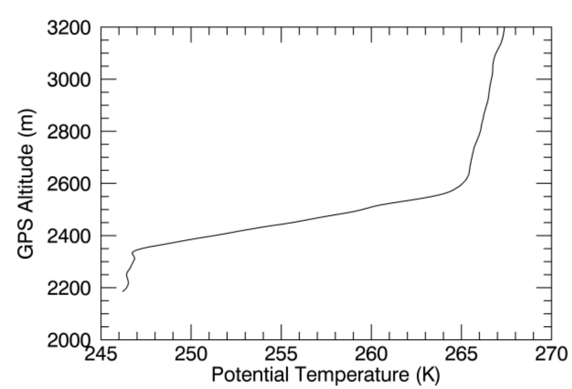


Temperature and Moisture Structure





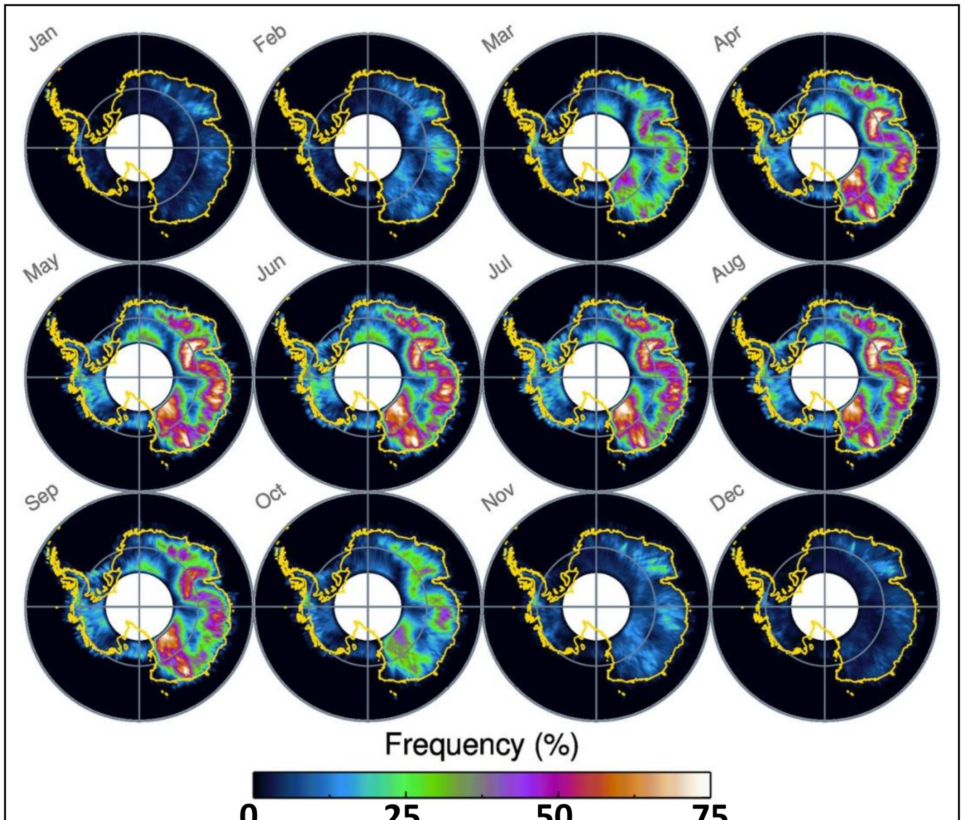




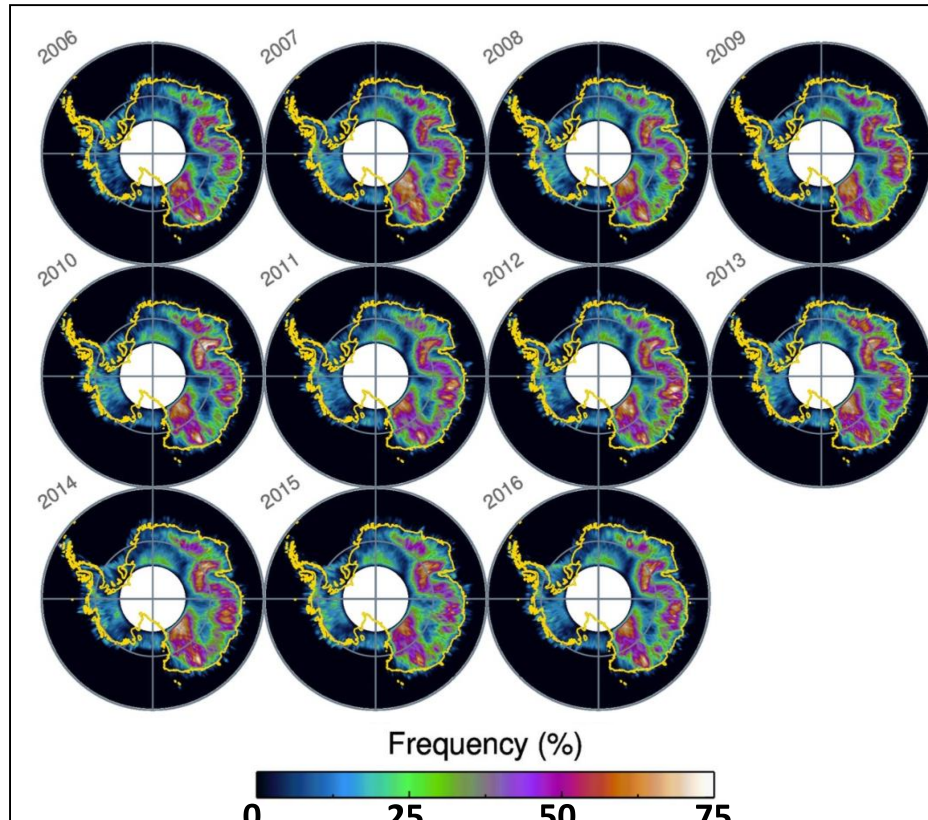
Toward a Blowing Snow Climatology For Antarctica

- 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:

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

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

Sublimation of Blowing Snow: A Major Source of High-Latitude Atmospheric Moisture

How do we get sublimation from CALIPSO backscatter profiles?

$$N(z) = \frac{(\beta(z) - \beta_m(z))S}{2\pi r(z)^2}$$ *Particle number density (m^{-3})*

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

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

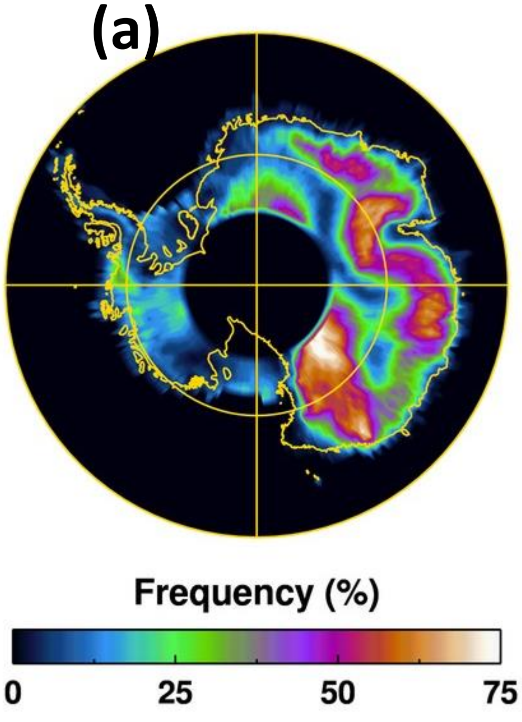
B(z): CALIPSO average attenuated backscatter profile
S: extinction/backscatter (25)
R(z): average particle radius (10 - 40µm)
q_v: water vapor mixing ratio
q_{is}: saturation mixing ratio wrt ice
F_k: heat conduction term (m s kg^{-1})
F_d: heat diffusion term (m s kg^{-1})
Nu: Nusselt number:

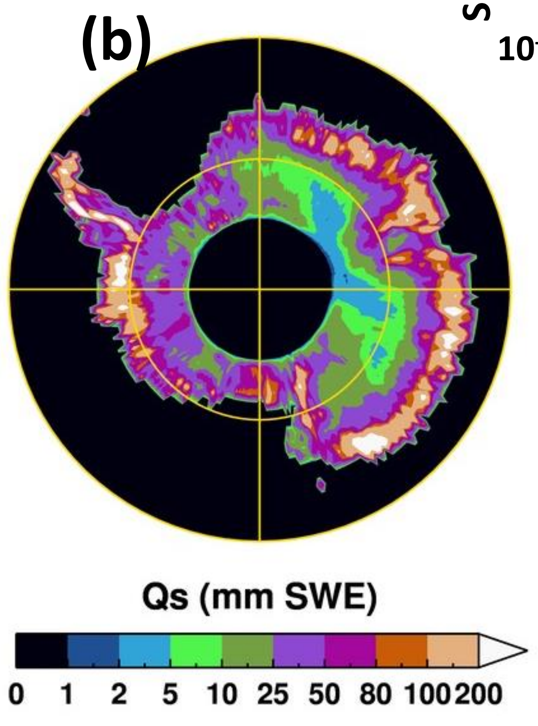
$$Nu = 1.79 + 0.606\,\mathrm{Re}^{0.5}$$
$$\mathrm{Re} = 2r(z)v_b / \nu$$

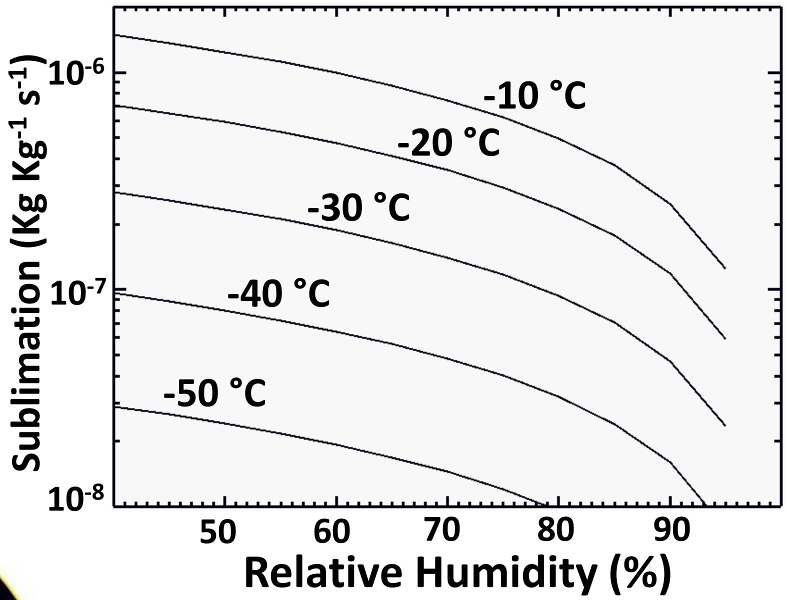
Sublimation of Blowing Snow: Results

(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).





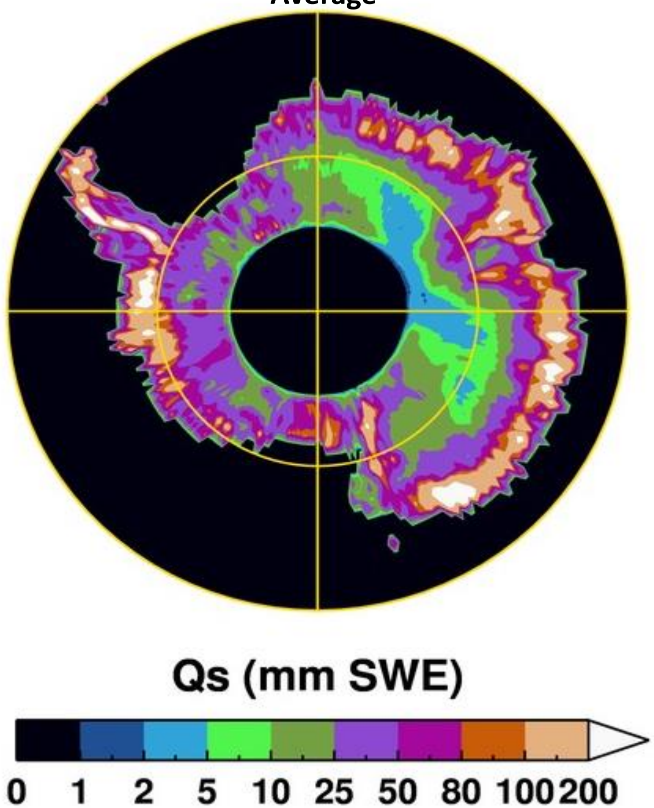


Sublimation rate is highly dependent on temperature and humidity

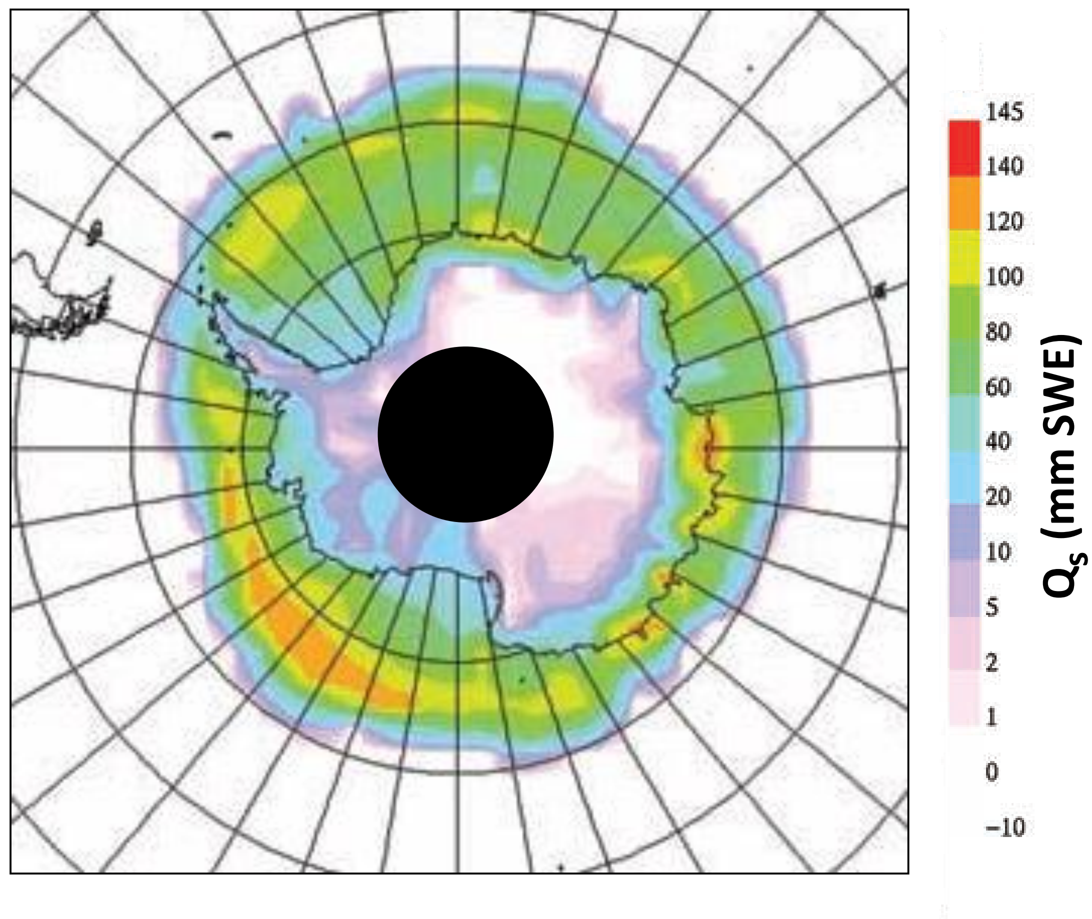
Sublimation of Blowing Snow: Direct Observation vs Parameterization

CALIPSO Direct Observation

2007 – 2015
Average



De´ry, S. J., and M. K. Yau, 2002



Blowing Snow Sublimation and Transport

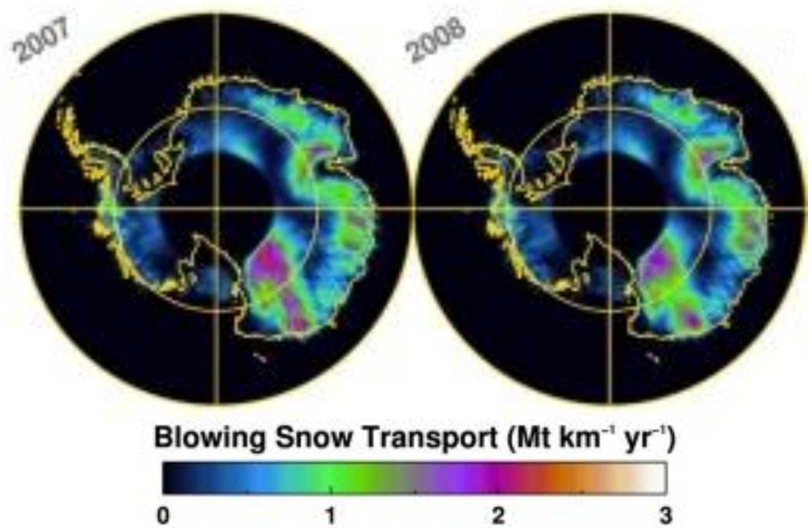


Table 2. The total transport (Gt yr^{-1}) from continent to ocean for various regions in Antarctica for 2007 – 2015.

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

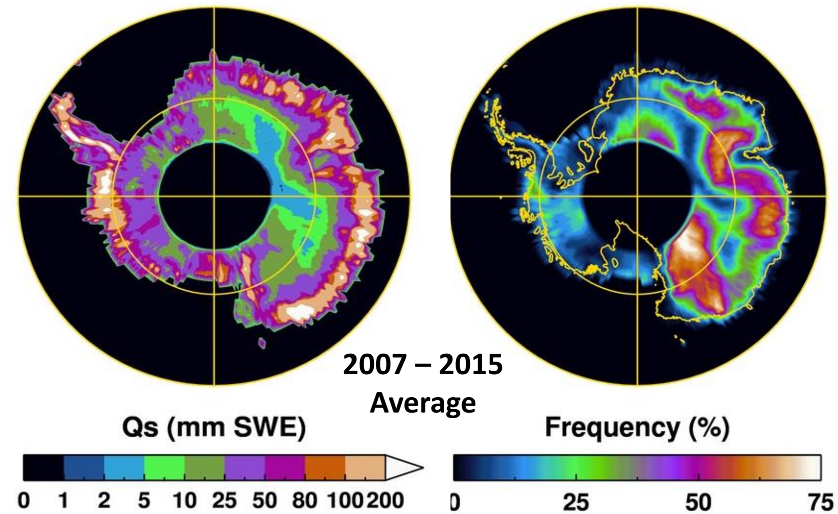


Table 1. The year average sublimation per year (average off all grid boxes) and the integrated sublimation over the Antarctic continent (north of 82S).

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

*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:

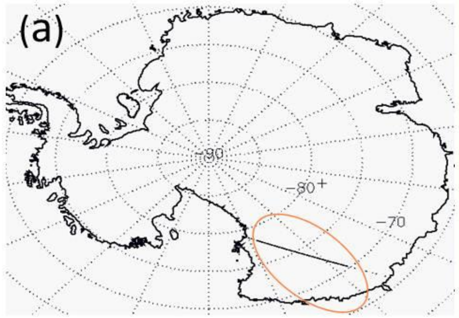
Palm, S. P., Kayetha, V., Yang, Y., and Pauly, R.: **Blowing Snow Sublimation and Transport over Antarctica from 11 Years of CALIPSO Observations**, *The Cryosphere* ,**11**, 2555–2569, 2017 https://doi.org/10.5194/tc-11-2555-2017

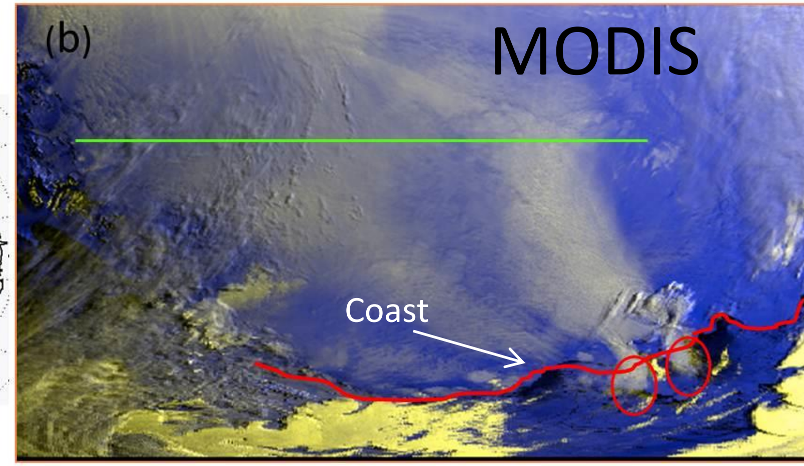
Blowing Snow data available from the author upon request
Soon to be available from the NASA Langley atmospheric data center

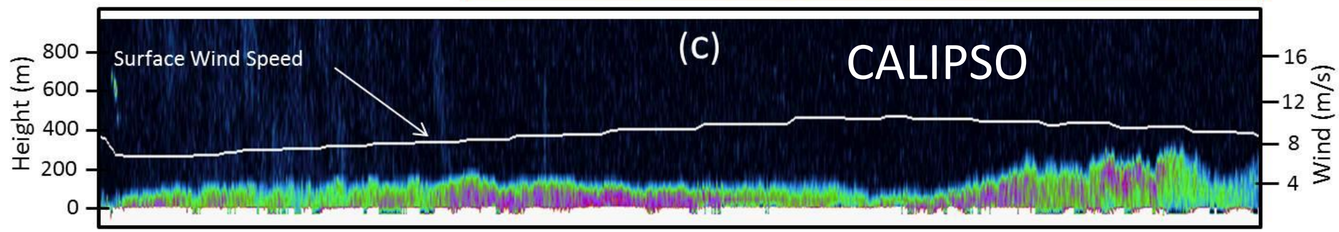
Blowing Snow Transport (Q_t) off Continent

Importance:

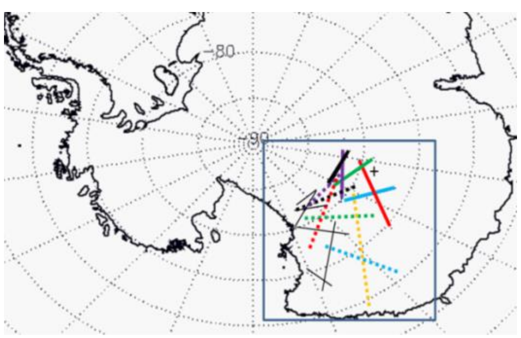
- Mass Balance
- Sea Ice Thickness
- Ocean Freshening



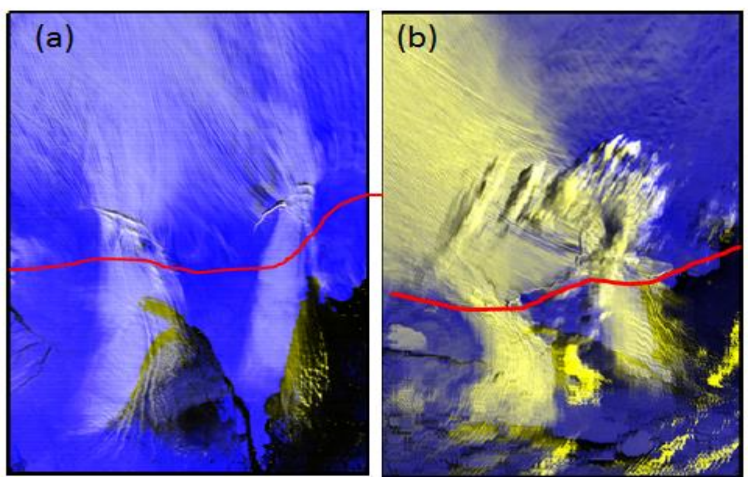


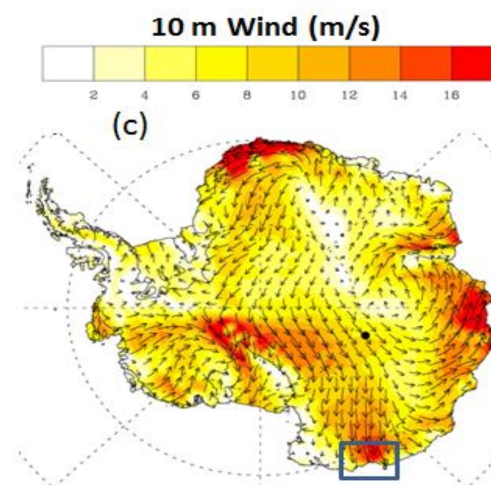


CALIPSO BLSN Detections
Blowing Snow Storm and Transport



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





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