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

CALIPSO-CloudSat Ten-Year Progress Assessment and Path Forward Workshop
June 8-10, 2016 Paris, France

Steve Palm[1], Rebecca Pauly[1] and Yuekui Yang[2]

[1]Science Systems and Applications Inc.
[2]Universities Space Research Association, Columbia, MD

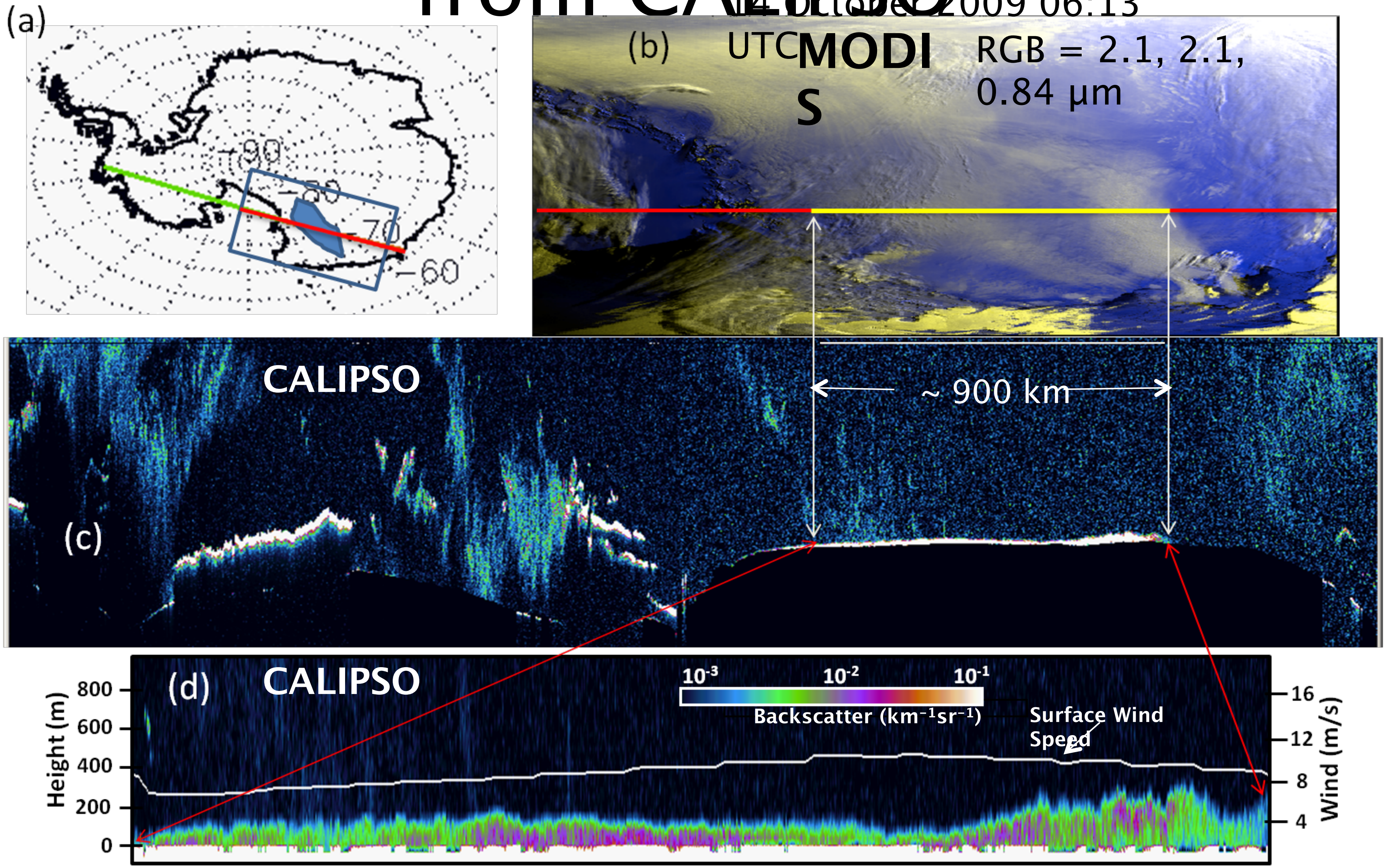
Outline

- 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

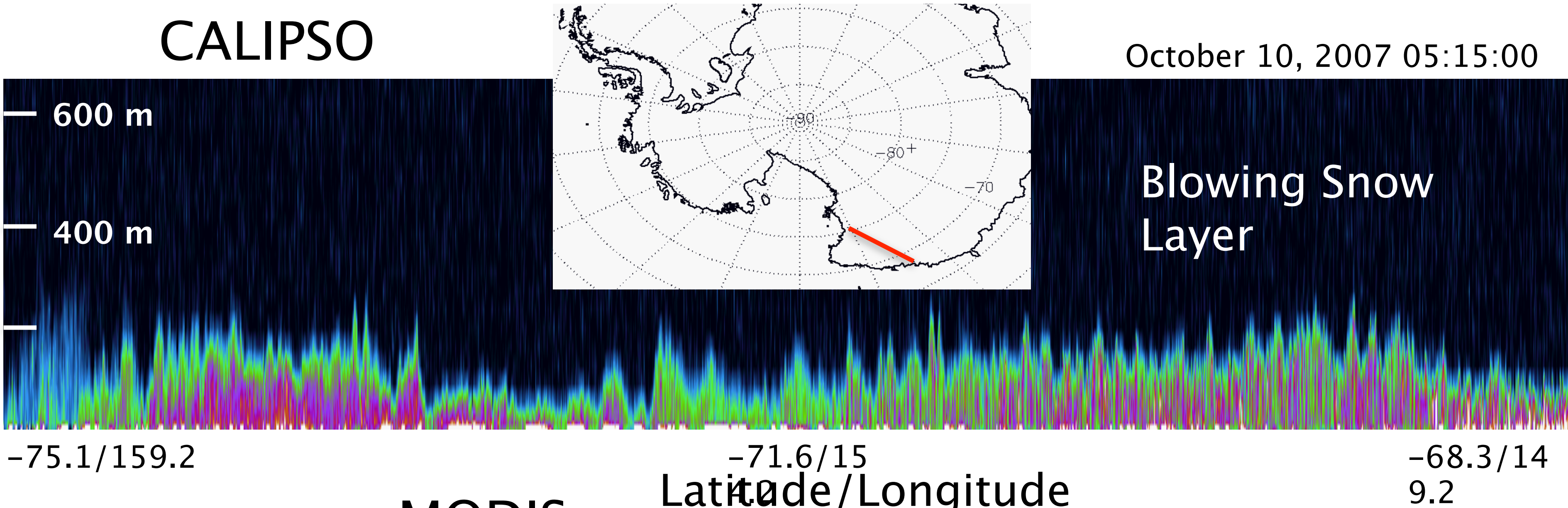
- No prior measurements of blowing snow covering all of Antarctica, the Arctic and Greenland
- Important for:
  - Mass balance of ice sheets
  - Atmospheric water vapor and chemistry
  - Paleoclimatology
  - Model improvement and validation
  - Regional radiation budget
  - Lidar altimetry error

Satellite Detection of Blowing Snow from CALIPSO

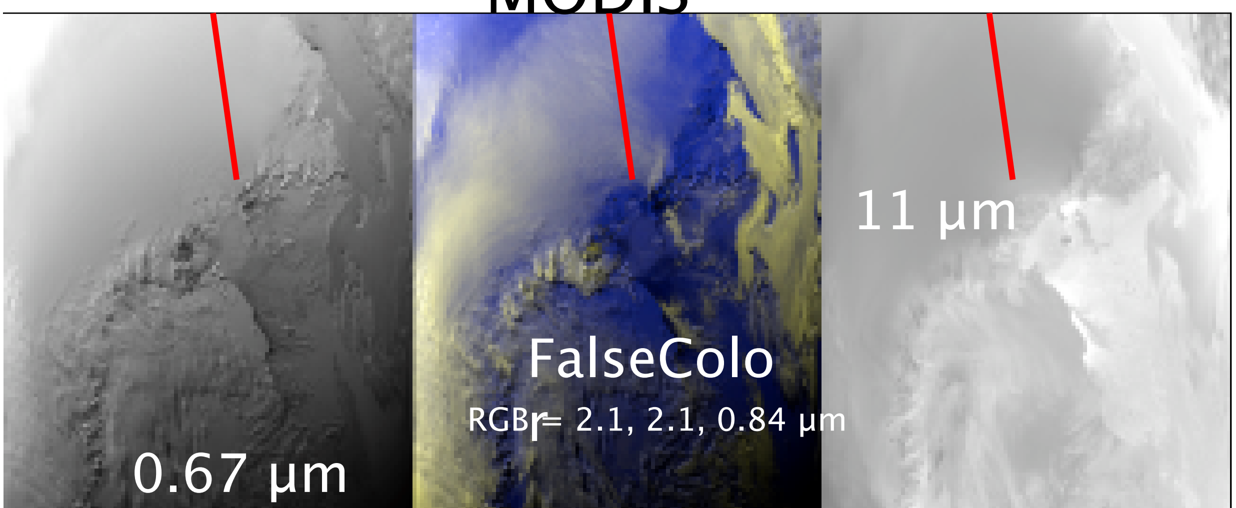


Satellite Detection of Blowing Snow using MODIS

CALIPSO



MODIS

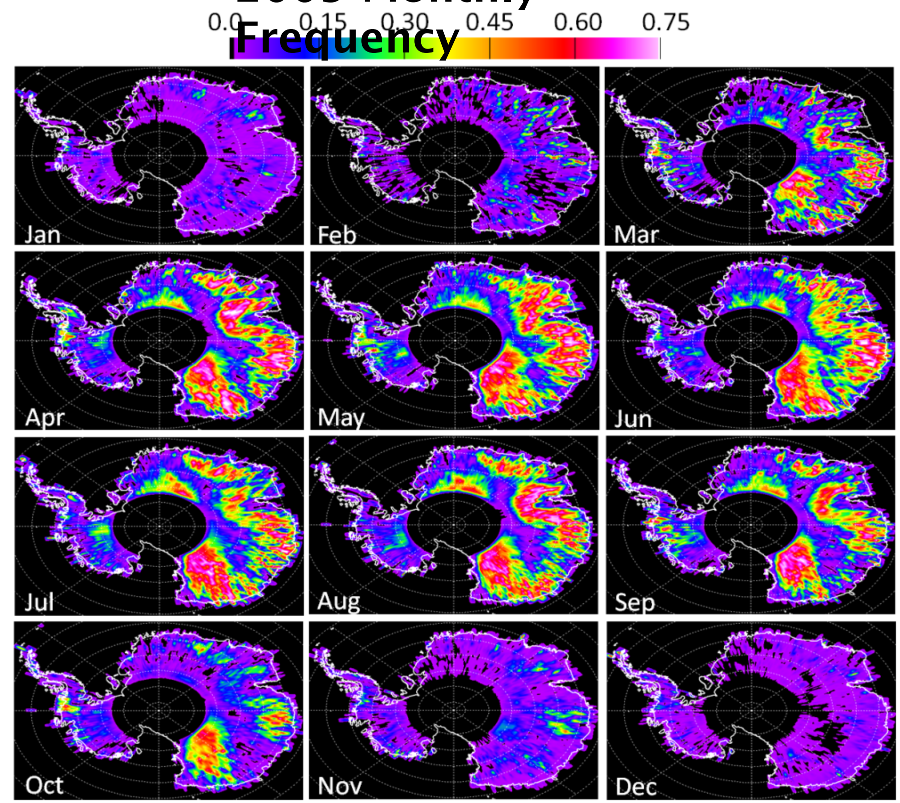


- At 2.1 µm, small particles are more reflective
- BLSN stands out from the underlying snow and ice surface
- Limited to sunlit scenes

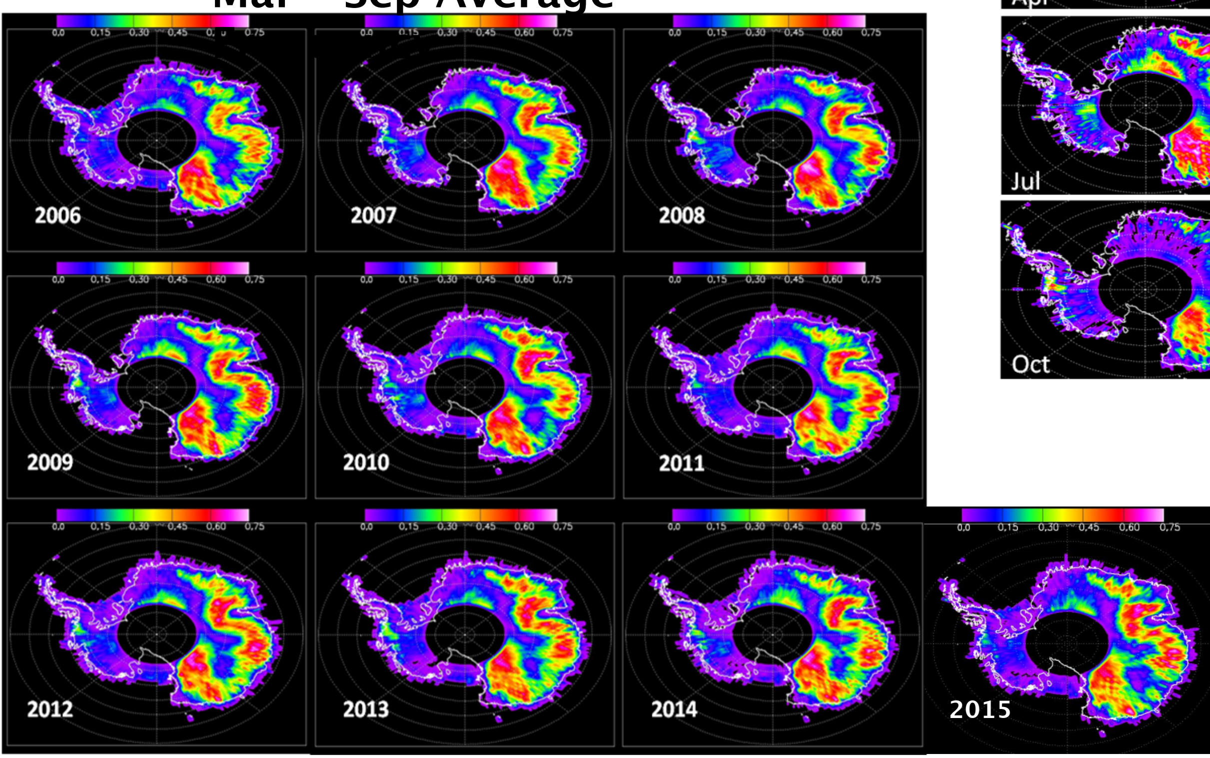
Toward a Blowing Snow Climatology for Antarctica

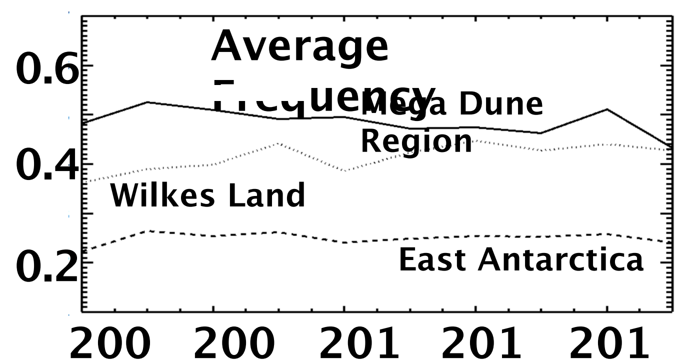
- 10 years of data indicate no temporal trend in average winter frequency over large areas.
- But inter-annual variability can be large as can smaller regional variability.
- Large regions experience blowing snow 60 to 70% of the time

2009 Monthly Frequency



Mar – Sep Average





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*

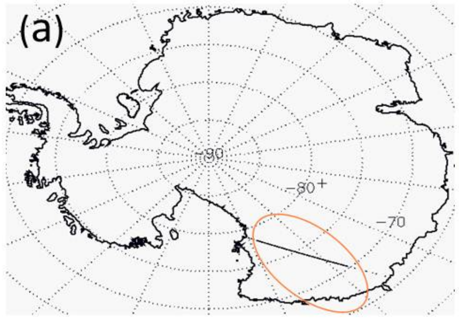
- A large atmospheric water vapor source in high latitudes.
- Together with Q_t, a significant term in the mass balance of ice sheets.
- Magnitudes largely unknown due to lack of observations

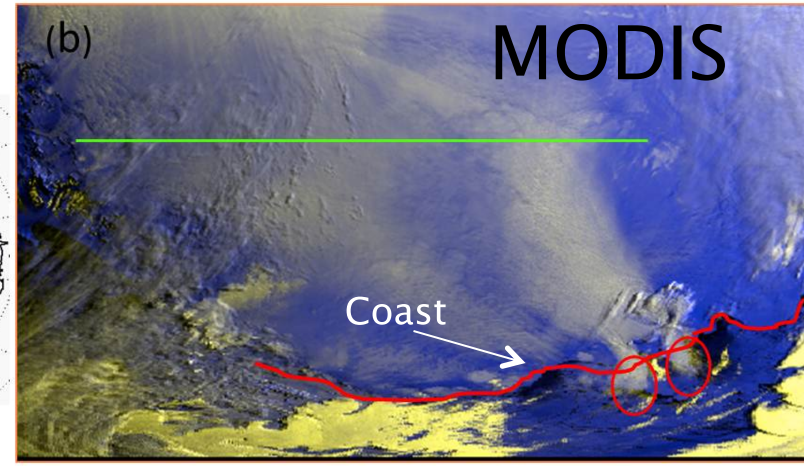
To compute Q_s directly, we need knowledge of blowing snow particle size, number density, and air temperature and humidity

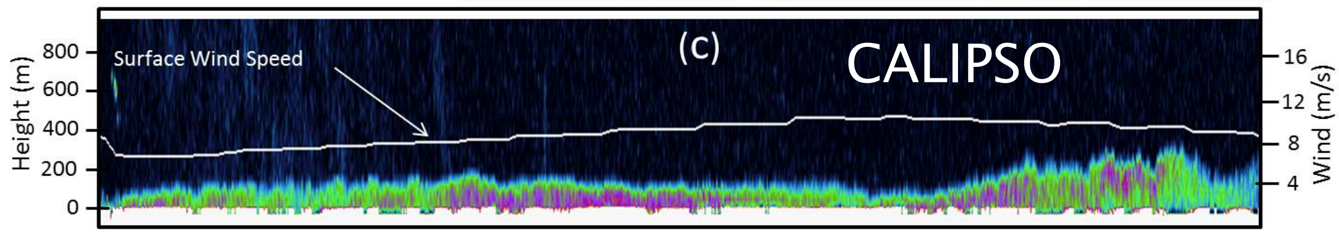
Blowing Snow Transport (Q_t) off Continent

Importance:

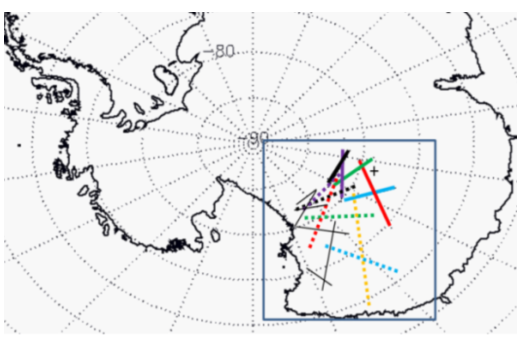
- Mass Balance
- Sea Ice Thickness
- Ocean Freshening



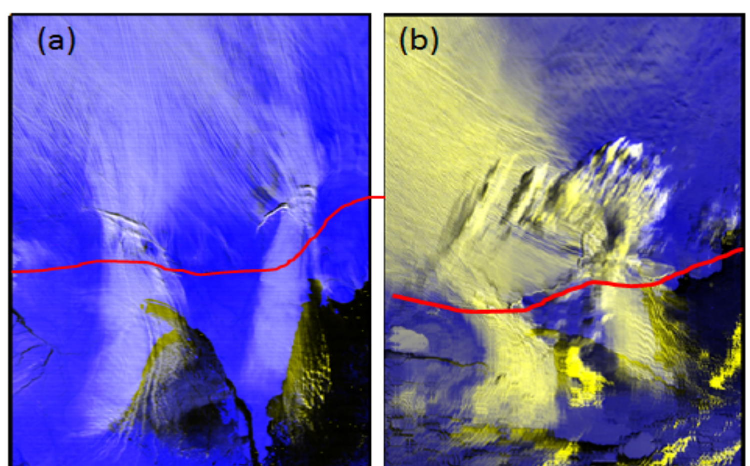


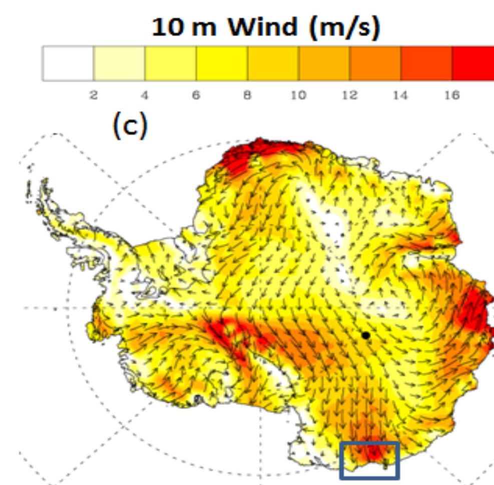


CALIPSO BLSN Detections
Blowing Snow Storm and Transport

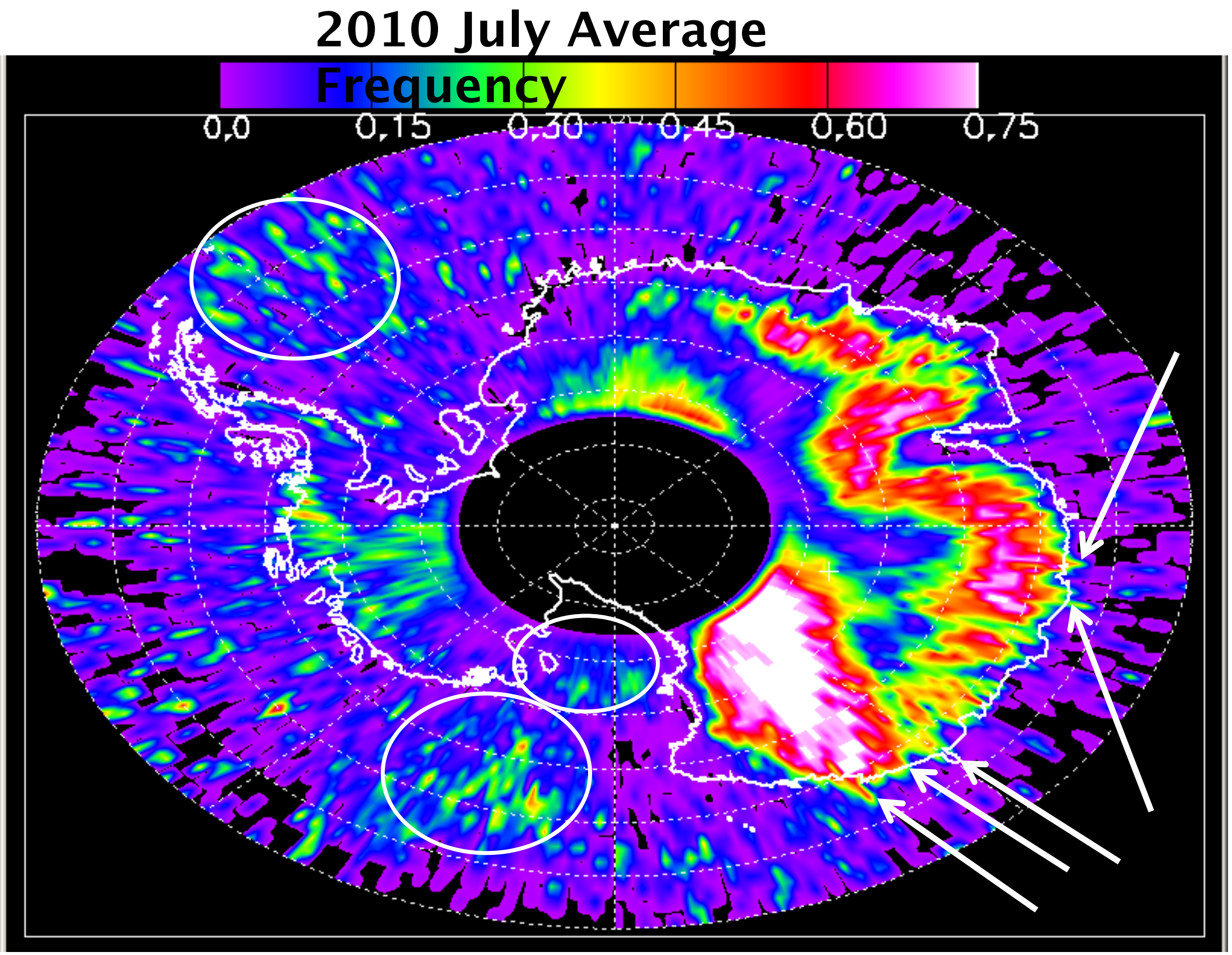


Solid Colored: October 13
Dashed Colored: October 14
Solid Black: October 15
2009





Blowing Snow Over Sea Ice



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:

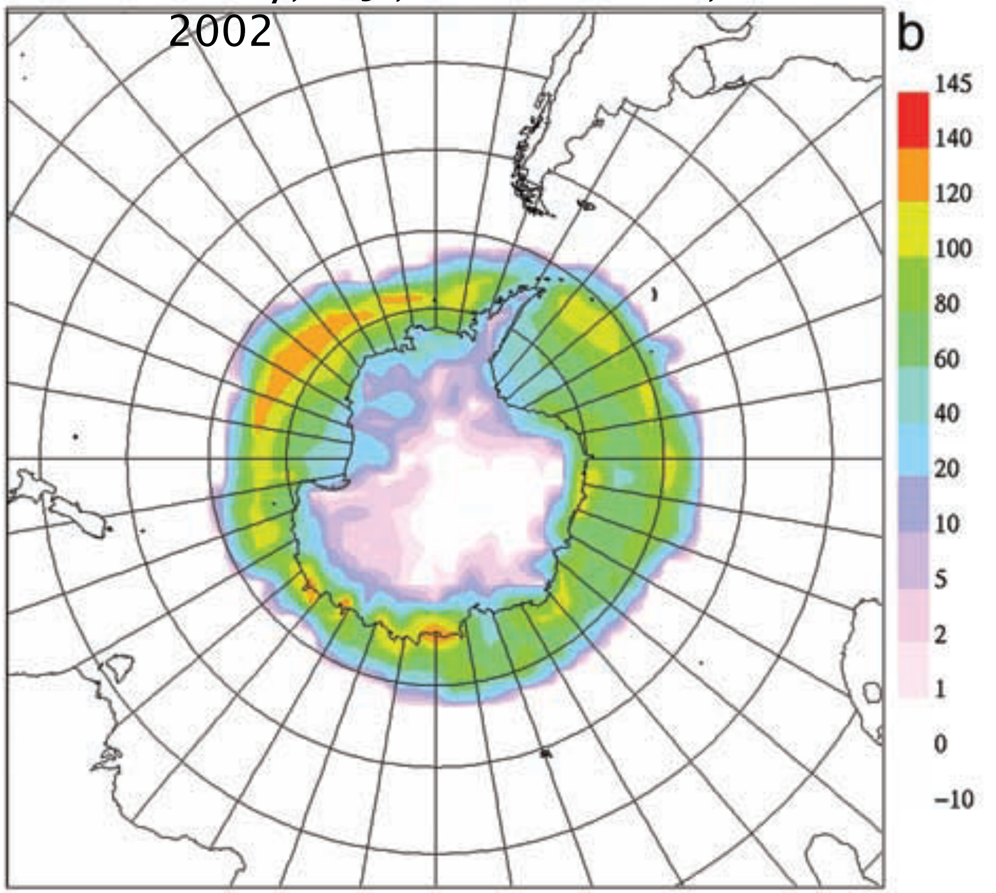
$$Q_s = (a_0 + a_1\xi + a_2\xi^2 + a_3\xi^3 + a_4U_{10} + a_5\xi U_{10} + a_6\xi U_{10} + a_7U_{10}^2 + a_8\xi U_{10}^2 + a_9U_{10}^3)/U'$$

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

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

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

De´ry, S. J., and M. K. Yau, 2002



De´ry, S. J., and M. K. Yau, Large-scale mass balance effects of blowing snow and surface sublimation, *J. Geophys. Res.,* 107(D23), 4679,

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})

$$Q_s = \rho_{air} \int_{z=0}^{Z_{top}} S_b(z) dz$$

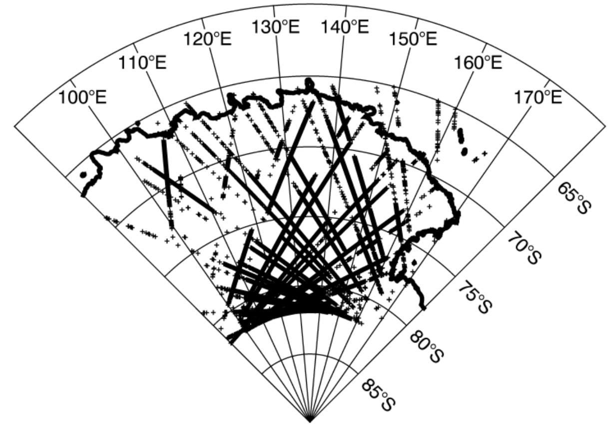
Column integrated blowing snow sublimation (kg m^{-2} s^{-1})

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

$$Nu = 1.79 + 0.606 \mathrm{Re}^{0.5}$$

$$\mathrm{Re} = 2 r v_b / \nu$$

Parameterization of blowing snow sublimation does not work!



De´ry, S. J., and M. K. Yau, 2002

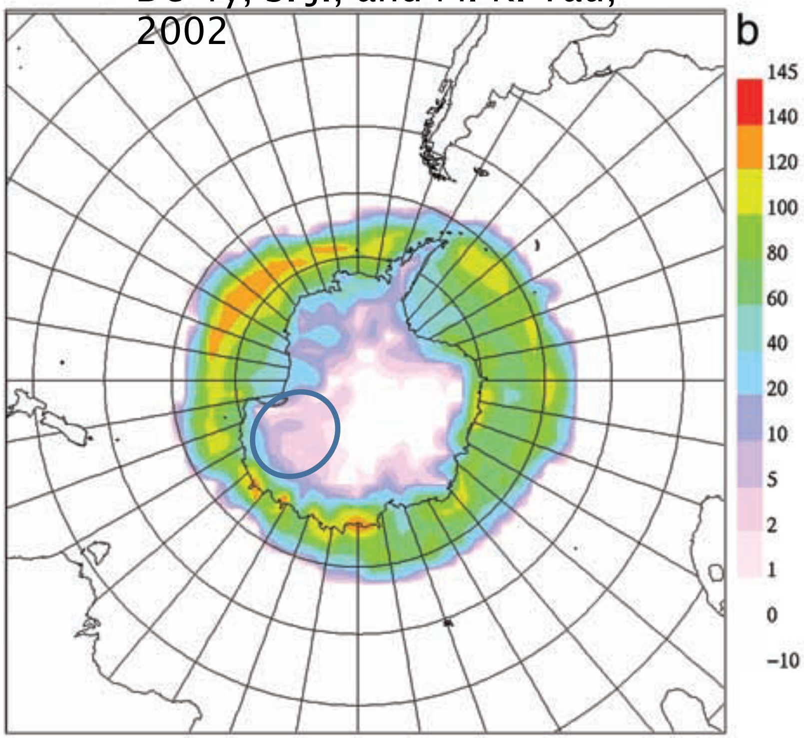
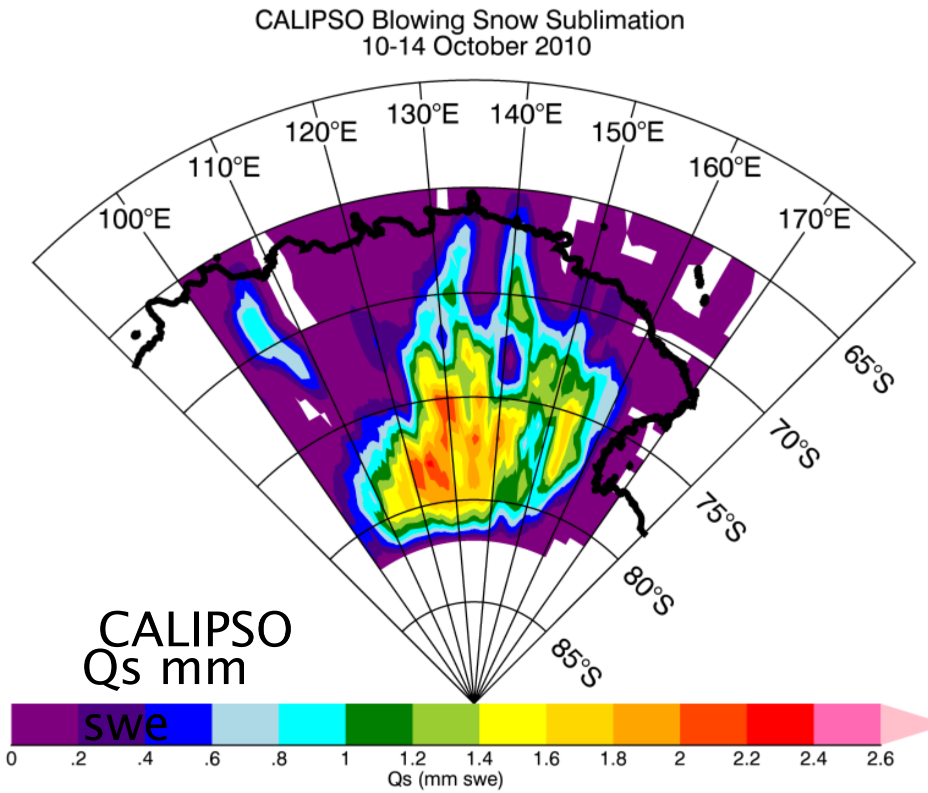


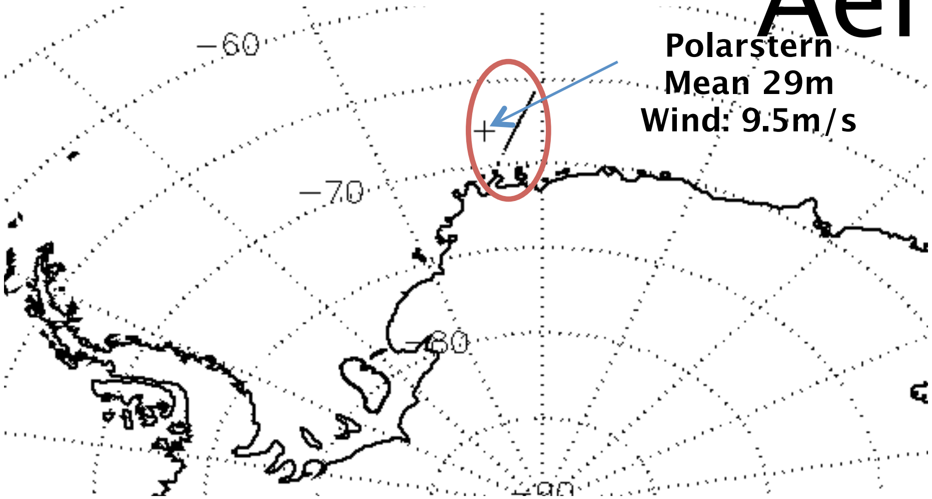
Figure 5. The mean annual blowing snow sublimation rate (mm swe) for the period 1979–1993 in the Southern Hemisphere.

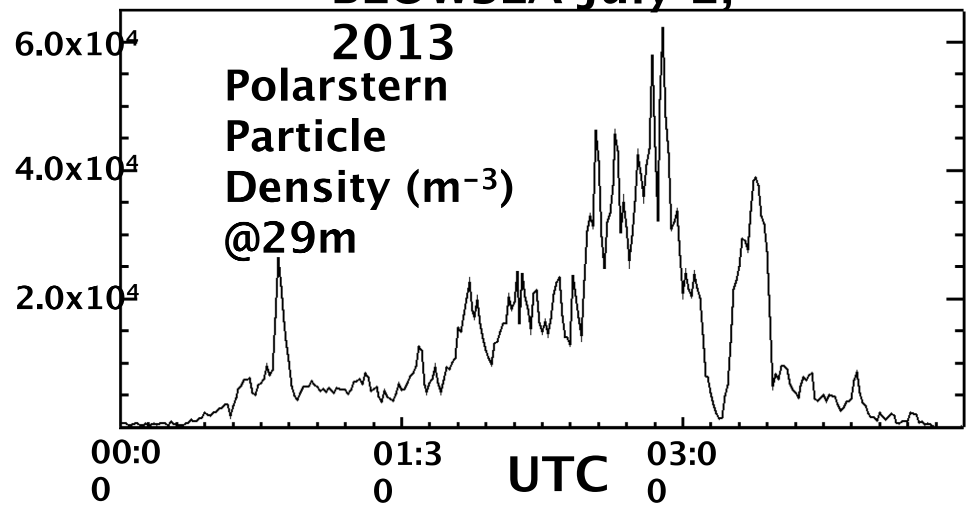
365/5*0.5*(1.5 mm swe) = 54 mm

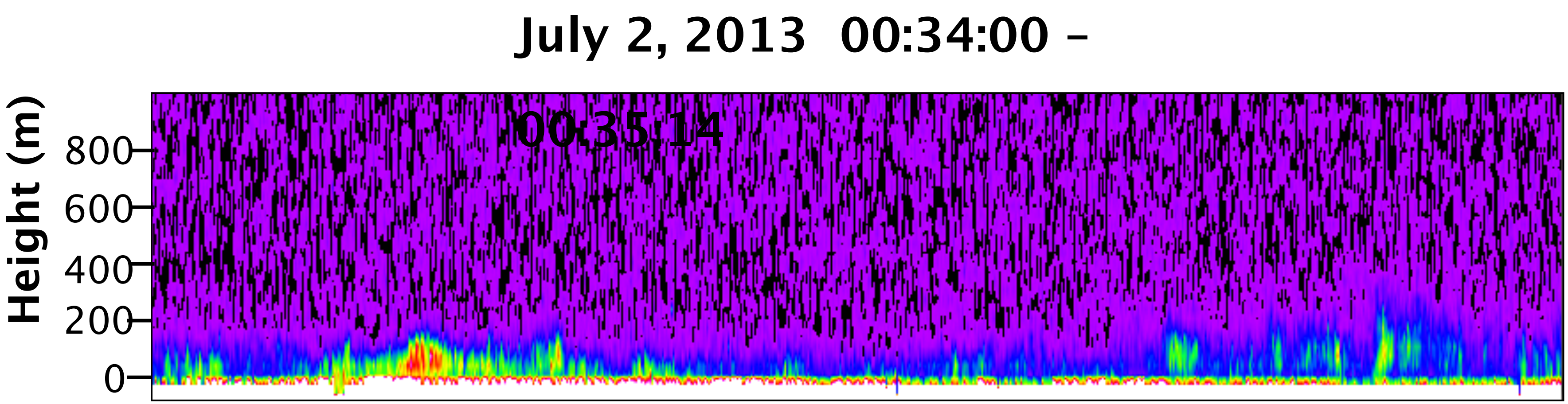


De´ry, S. J., and M. K. Yau, Large-scale mass balance effects of blowing snow and surface sublimation, *J. Geophys. Res.*, 107(D23), 4679, doi: 10.1029/2001JD001251, 2002

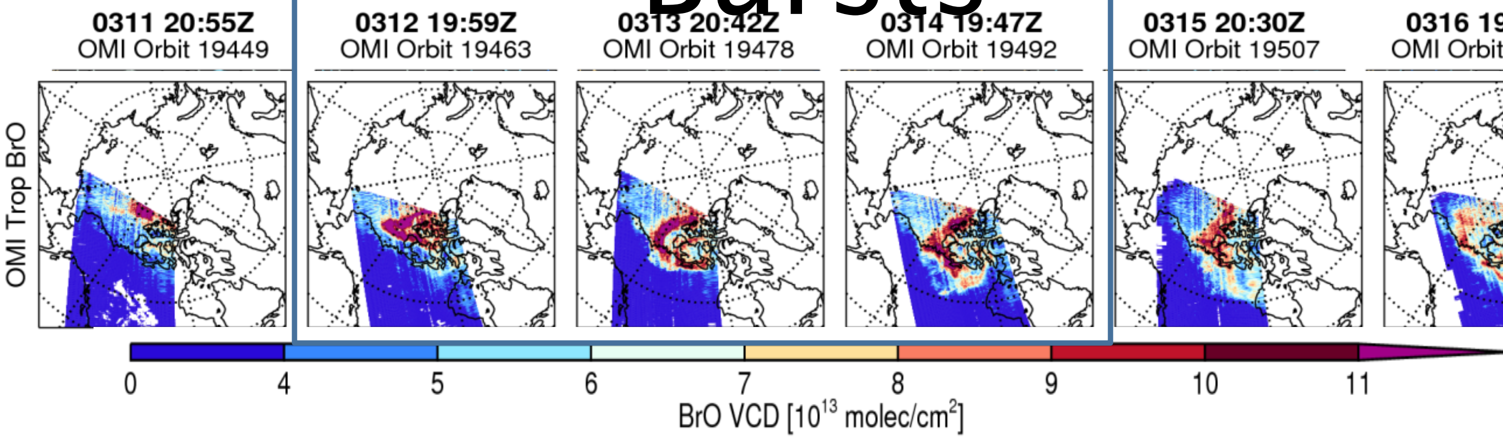
Blowing Snow over Sea Ice: A Possible Source of Sea Salt Aerosol

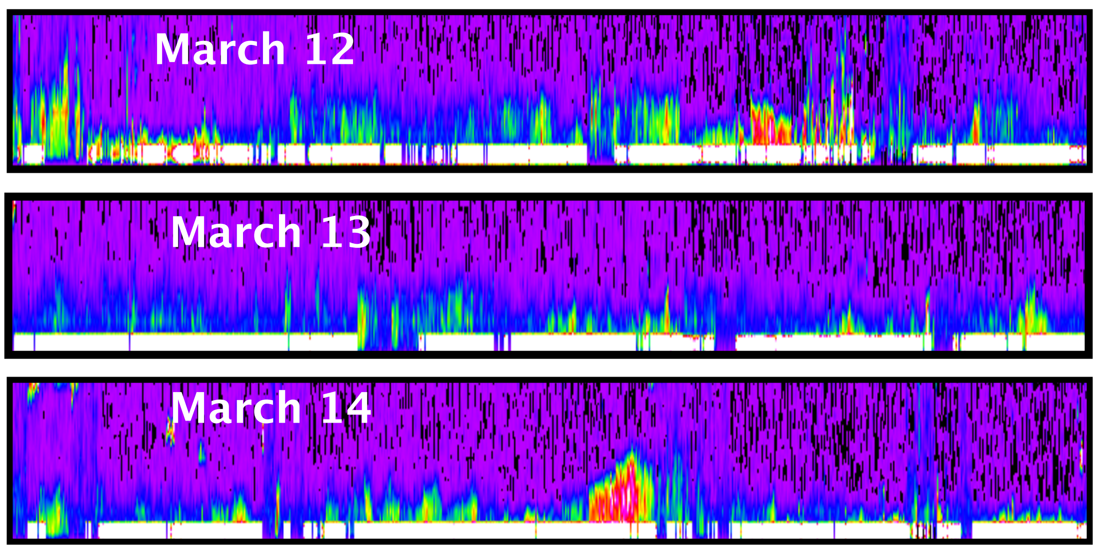


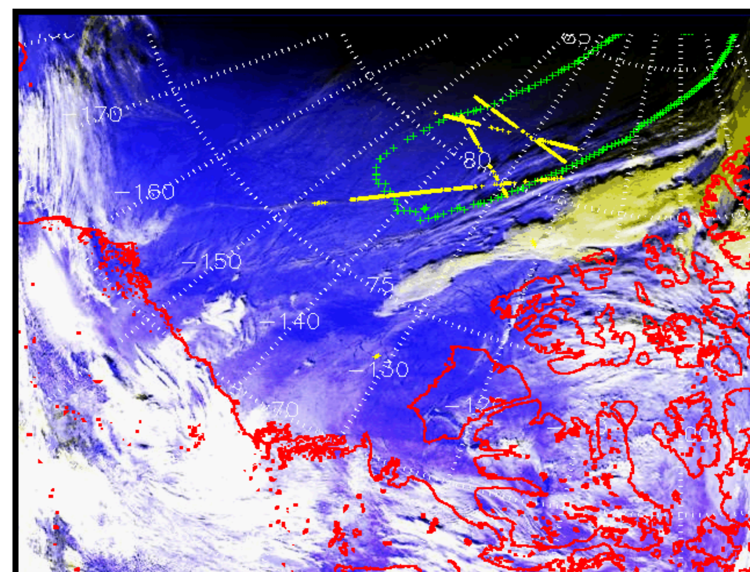




Blowing Snow over Sea Ice is Correlated with Bromine Bursts



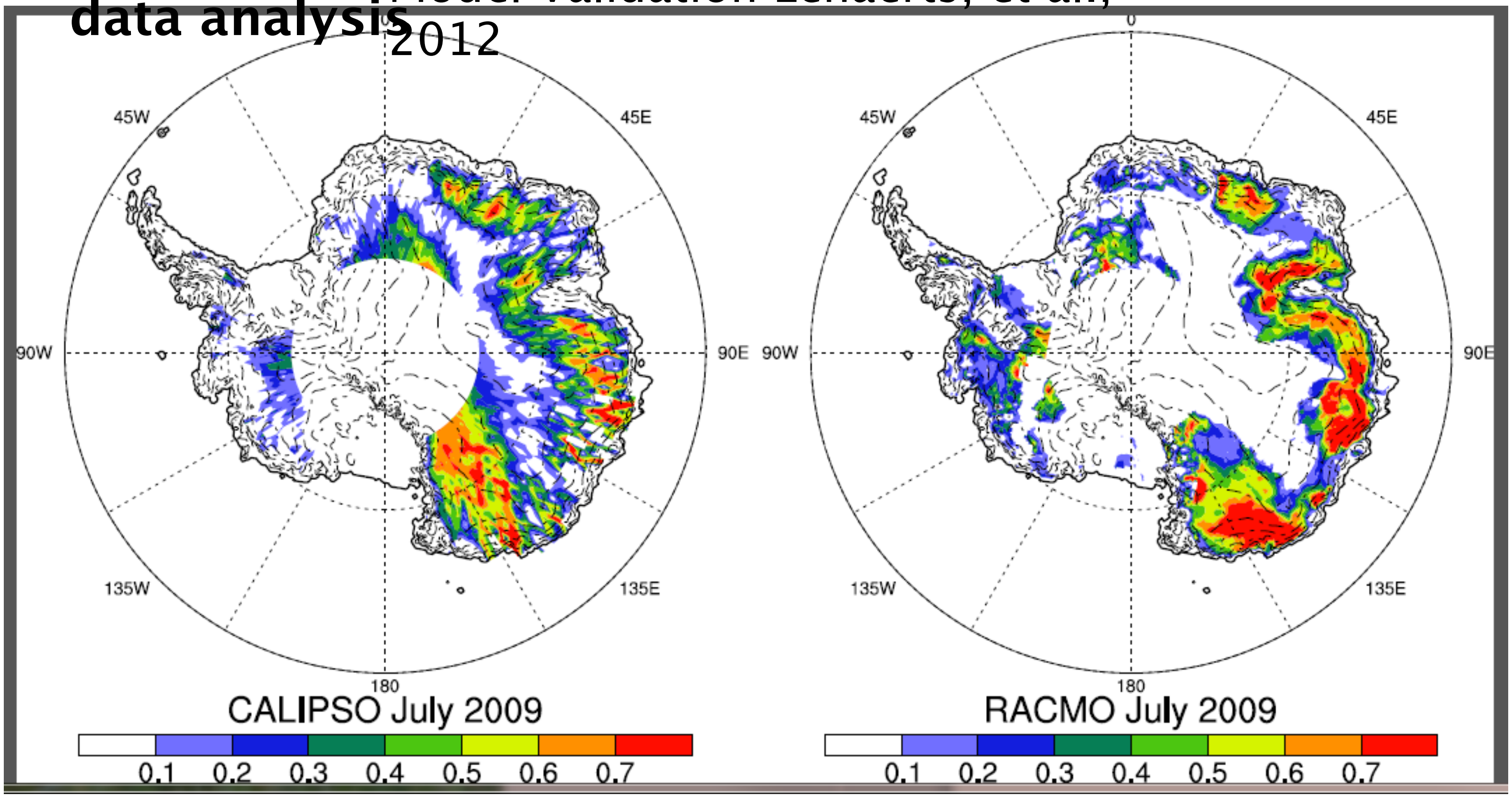




CALIPSO Blowing Snow Retrievals are used for Model Validation and Improvement

- 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

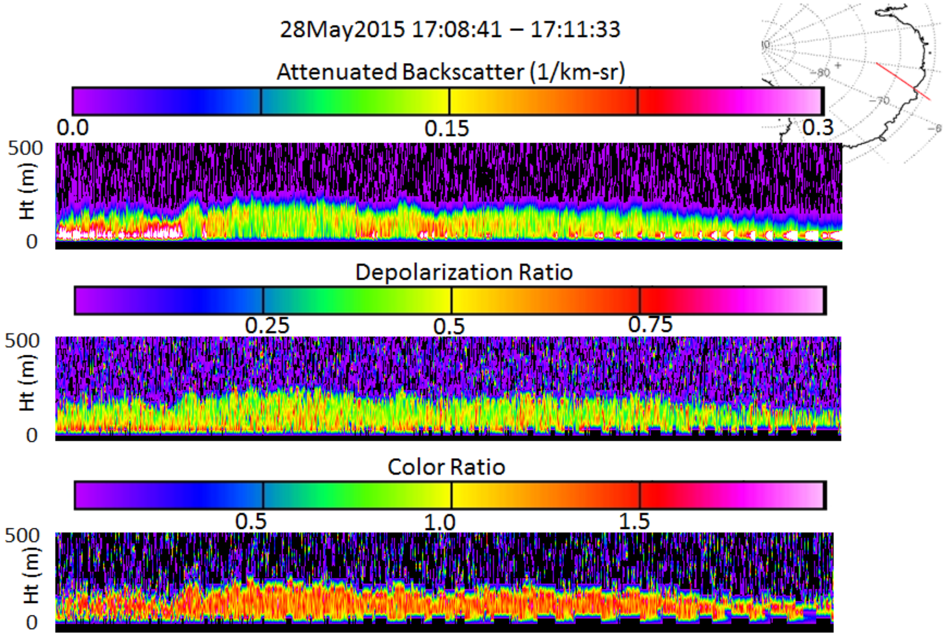


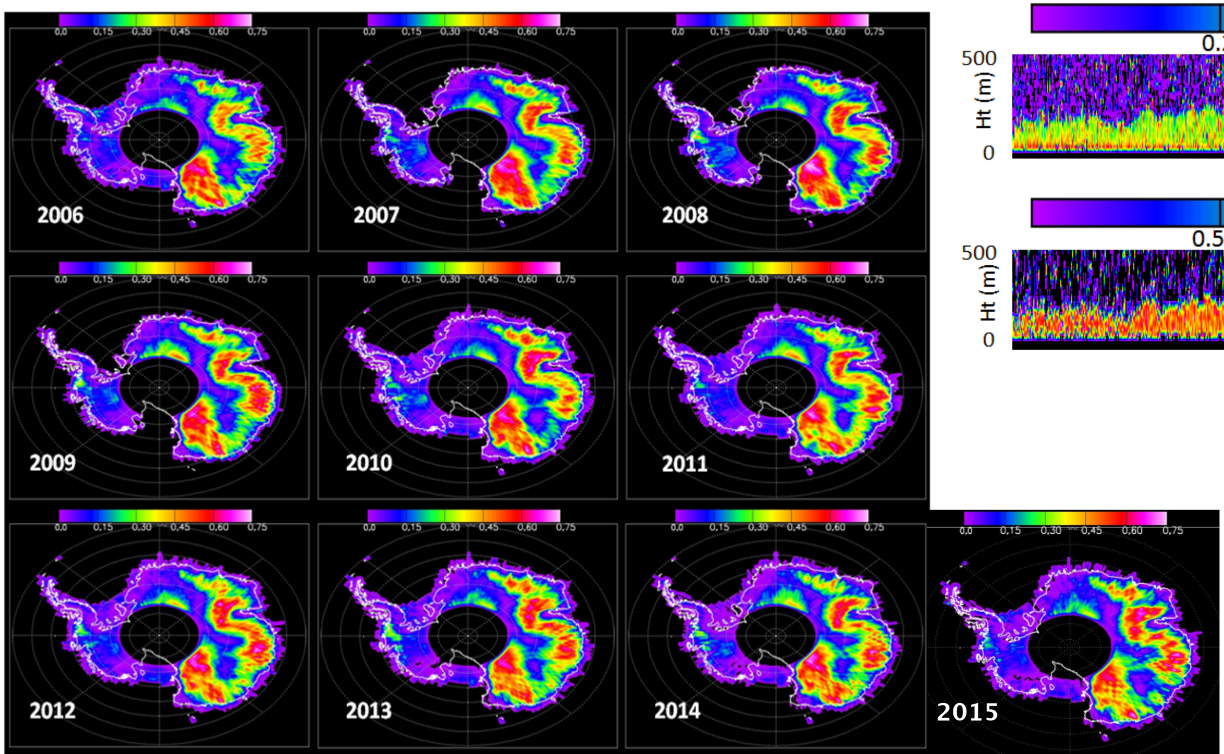
Take Home Points

- 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





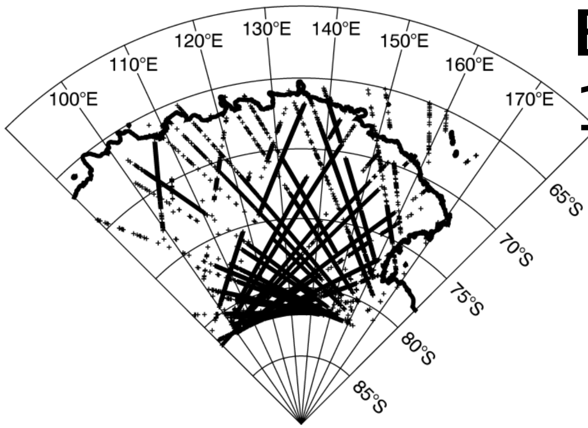
CALIPSO

2016, 2017, 2018?

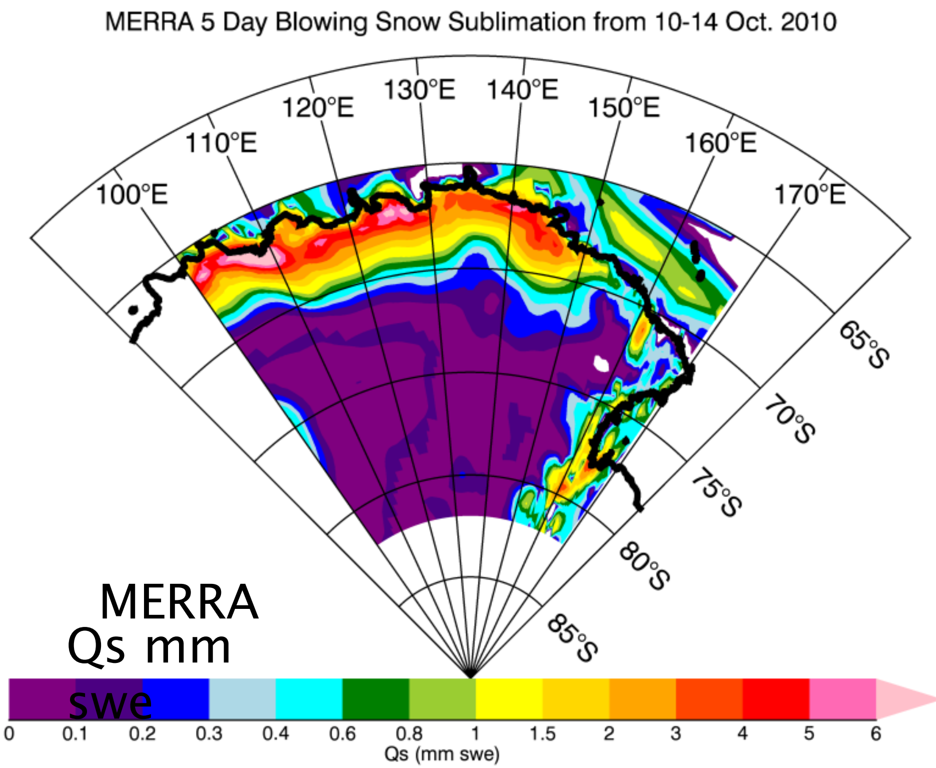
ICESat-2

2018 – 2021

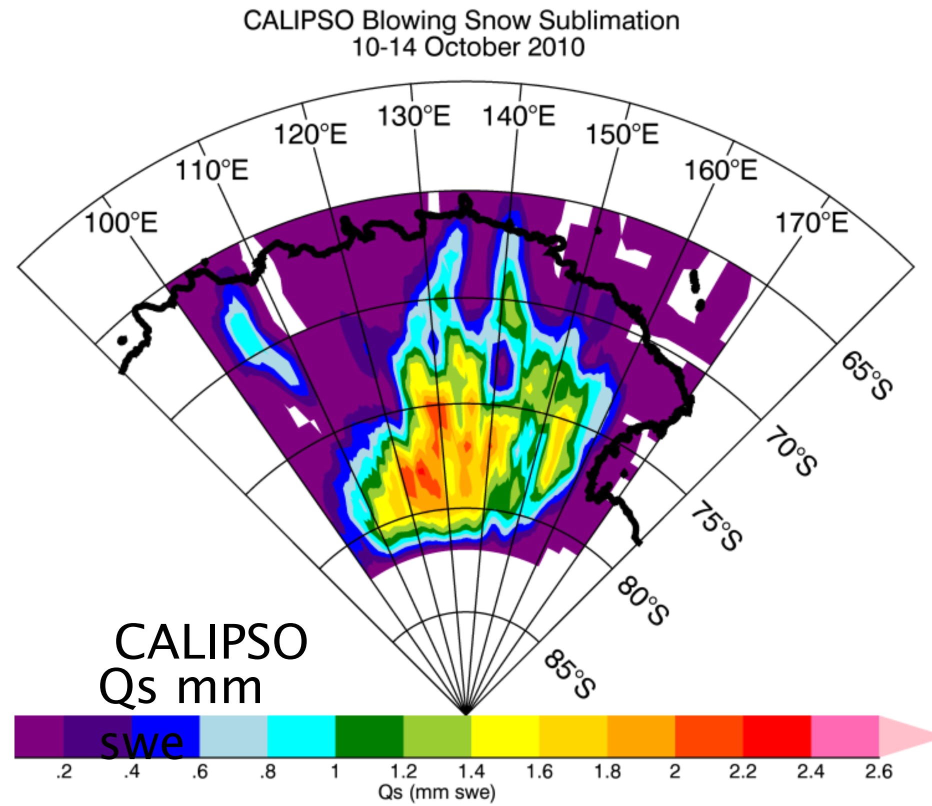
Blowing Snow Sublimation, October 10–14, 2010



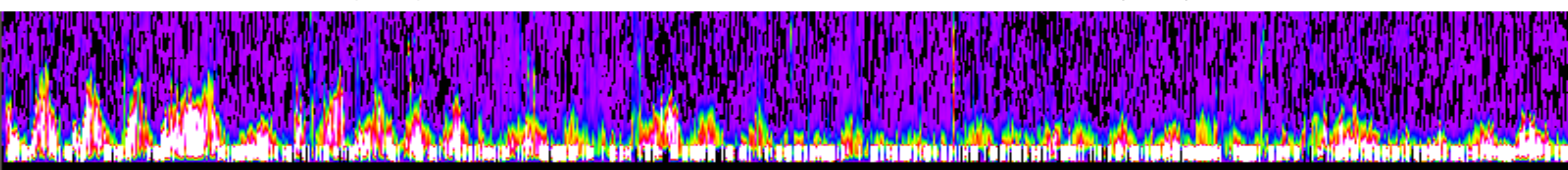
Blowing snow sublimation computed from CALIPSO data is of comparable magnitude to the model parameterized values, but the model has the spatial distribution completely wrong.

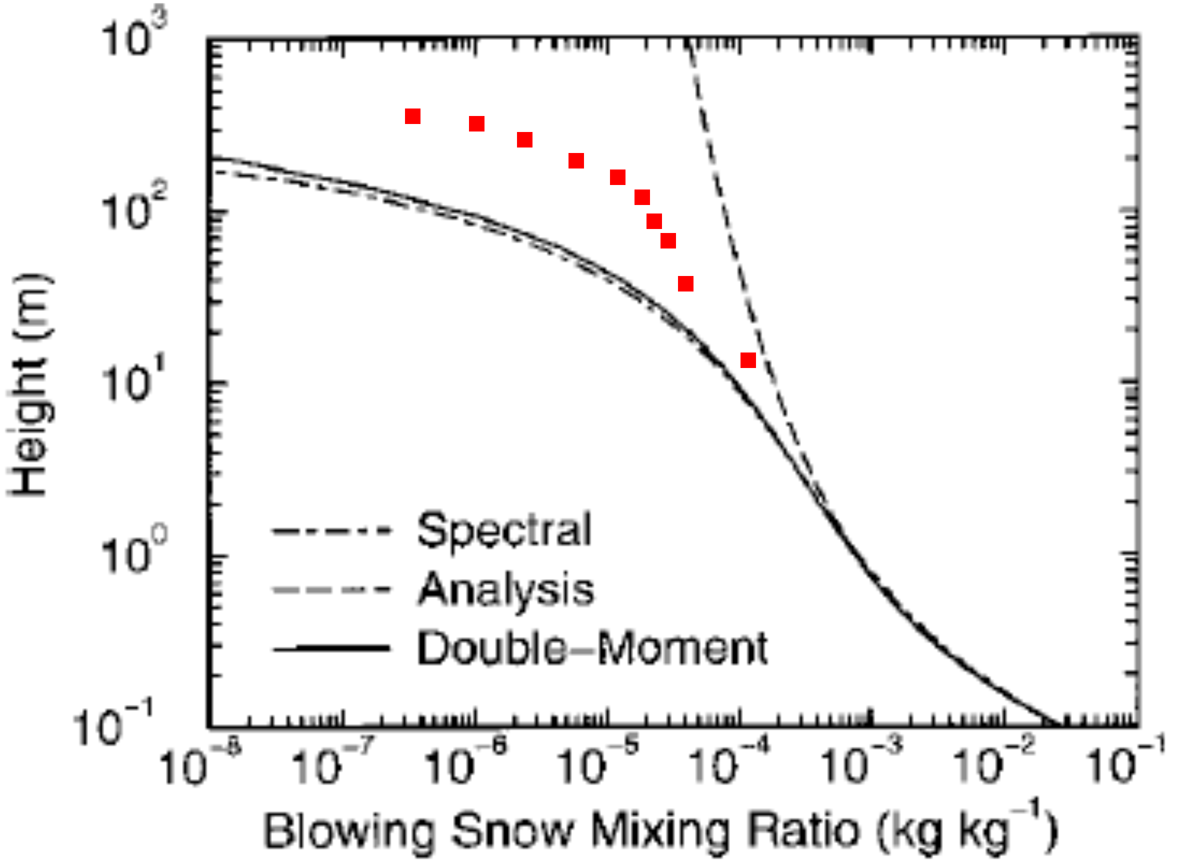


MERRA
Qs mm swe



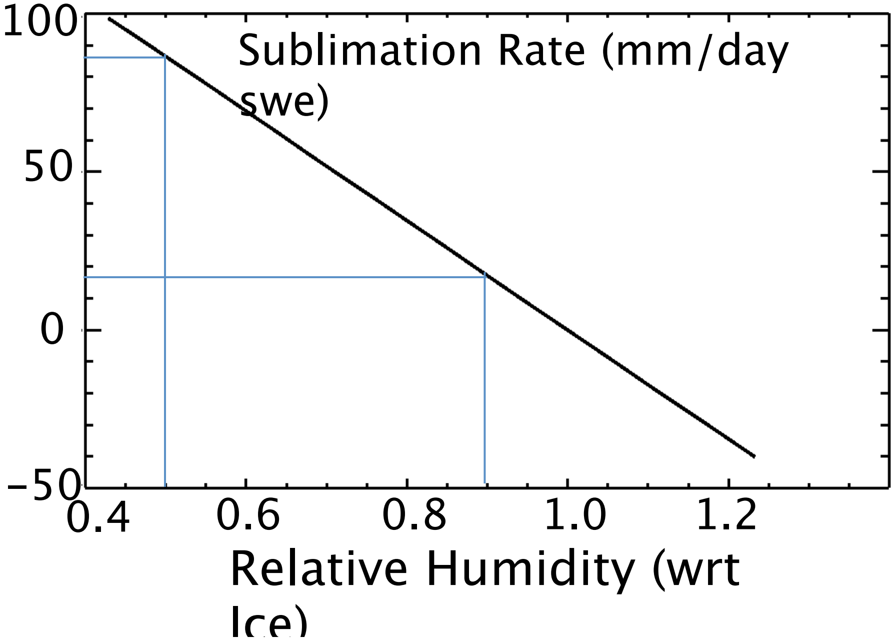
CALIPSO
Qs mm swe





Height (m)
Blowing Snow Mixing Ratio (kg kg^{-1})
Spectral
Analysis
Double–Moment

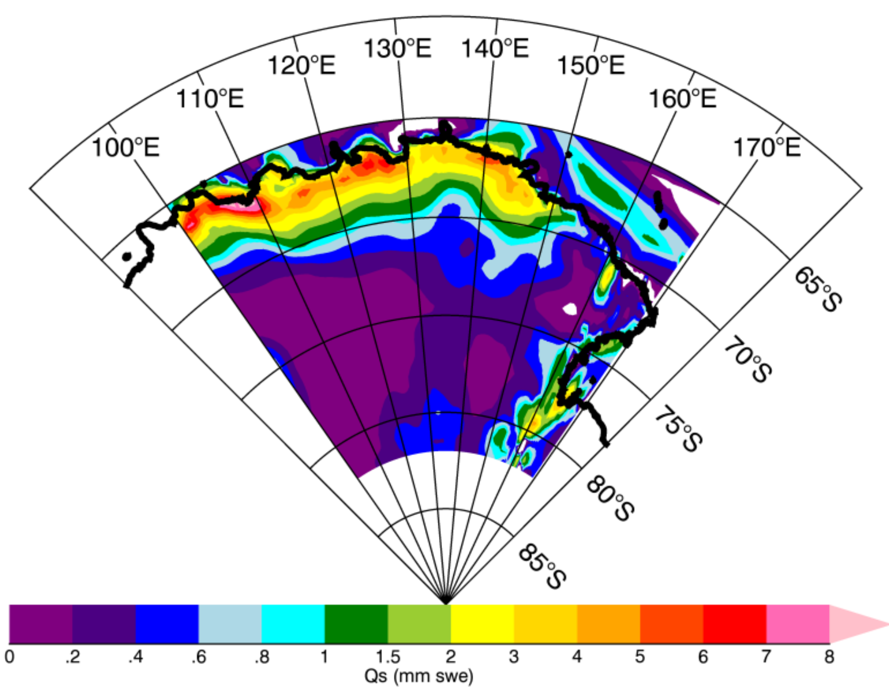
Blowing snow sublimation (Q_s) parameterization – Dery and Yau, 2002:



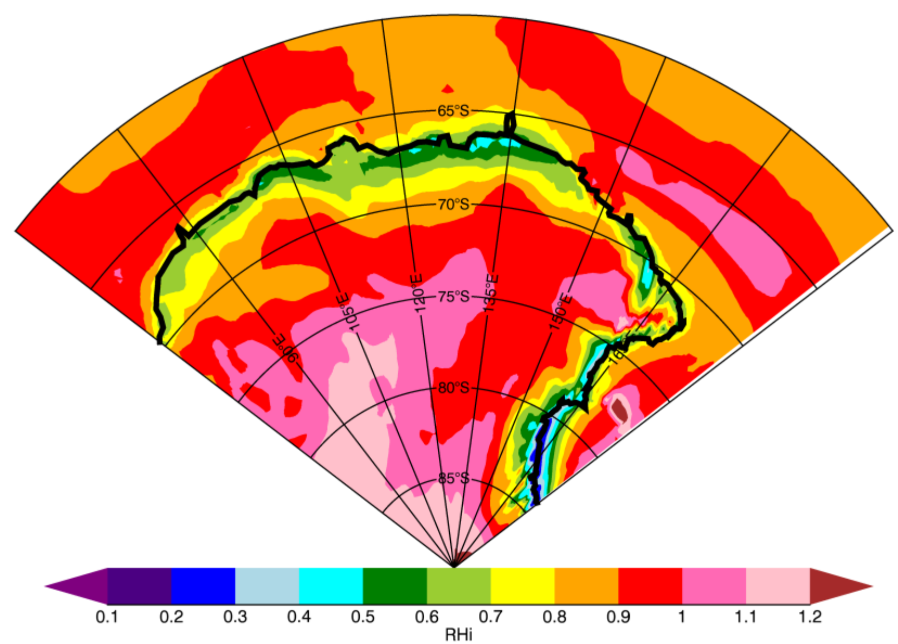
$$Q_s = (a_0 + a_1\xi + a_2\xi^2 + a_3\xi^3 + a_4 U_{10} + a_5\xi U_{10} + a_6\xi^2 U_{10} + a_7 U_{10}^2 + a_8\xi U_{10}^2 + a_9 U_{10}^3)$$

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

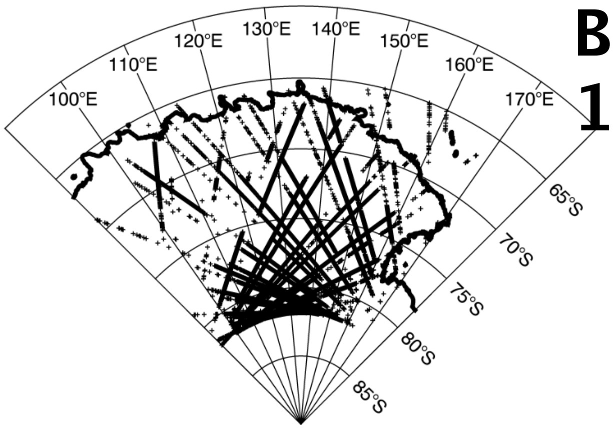
MERRA 5 Day Blowing Snow Sublimation from 10-14 Oct. 2010



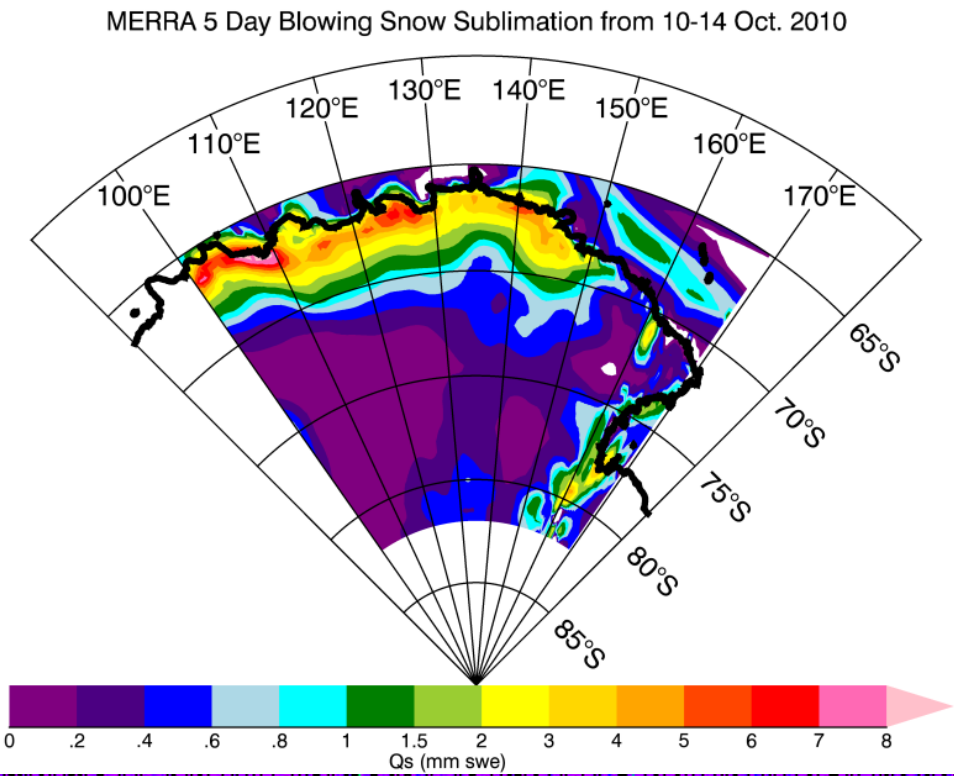
MERRA 5 Day Mean RHi 10-14 Oct. 2010

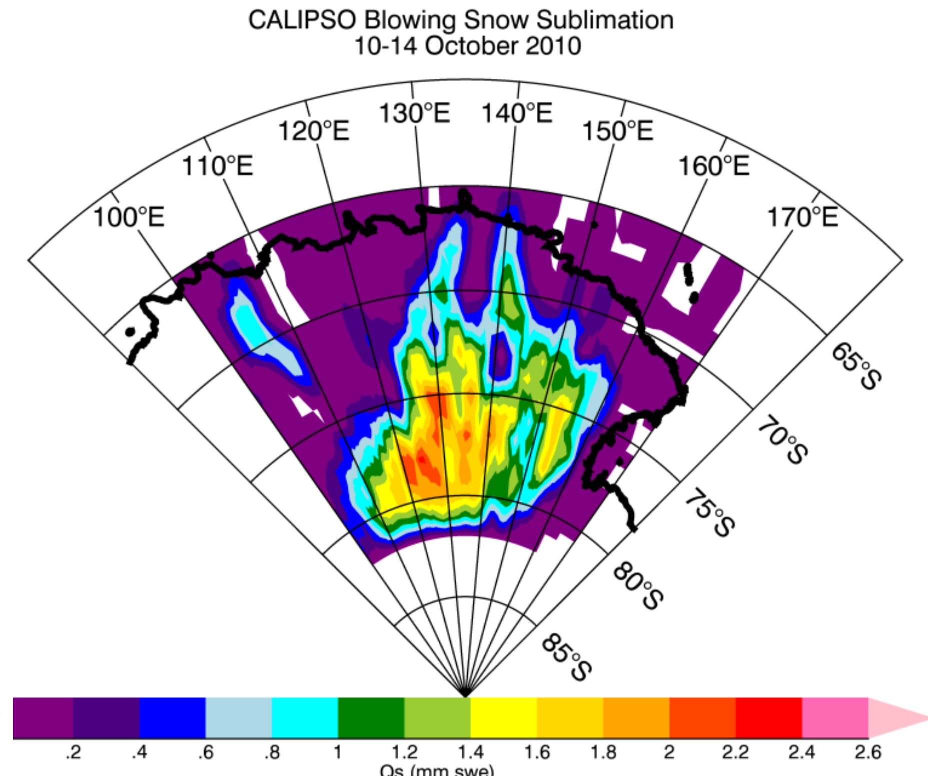


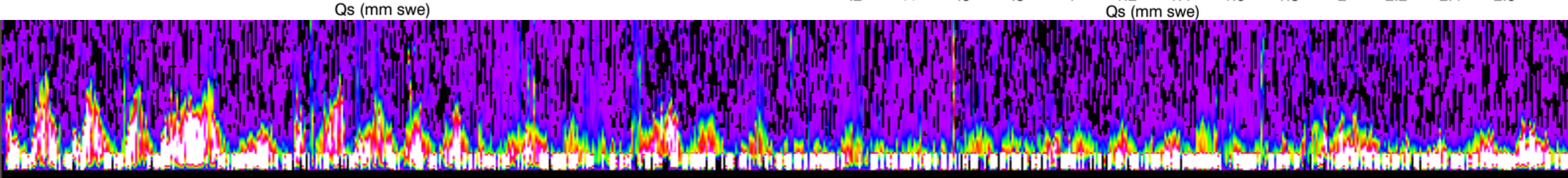
Blowing Snow Sublimation, October 10–14, 2010



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?

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

Particle number density (m^{-3})

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

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

Blowing snow mixing ratio (kg / kg)

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

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

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 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:

$$Nu = 1.79 + 0.606\,Re^{0.5}$$

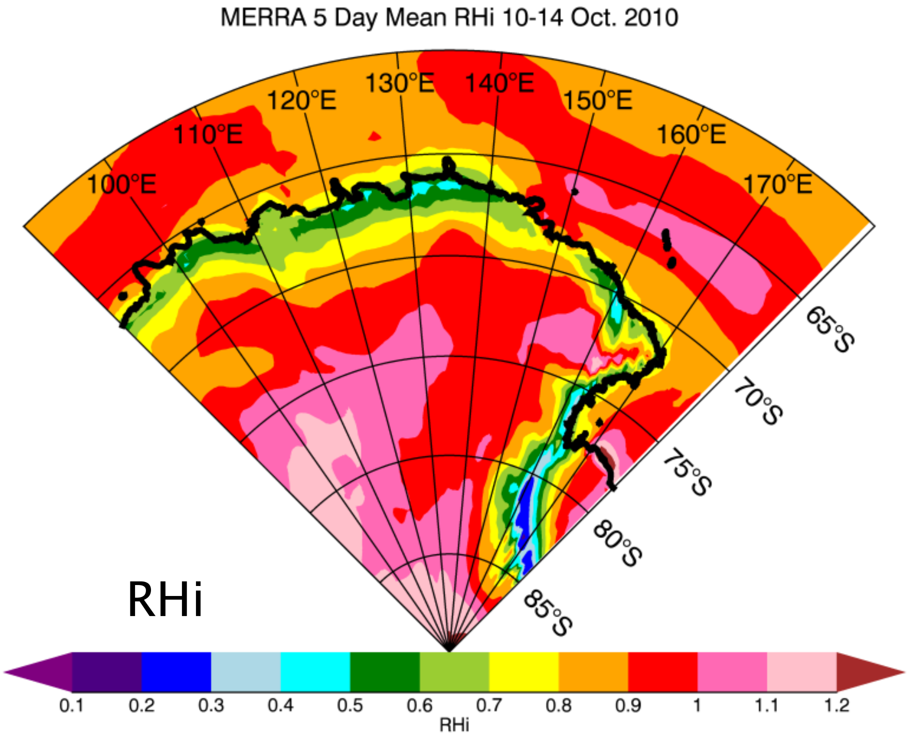
$$Re = 2rv_b/\nu$$

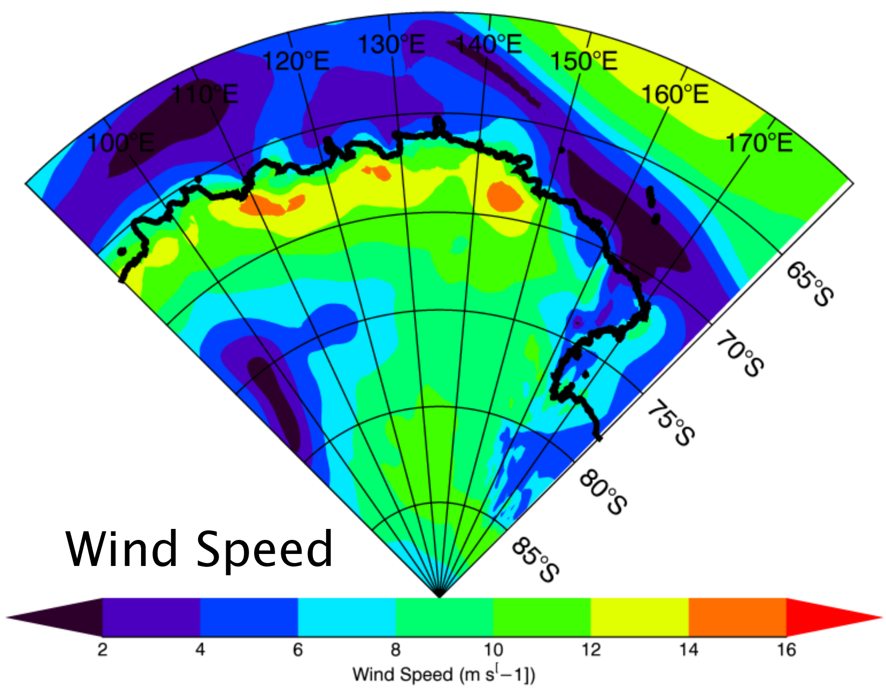
Blowing snow sublimation (Q_s) parameterization – Dery and Yau, 2002:

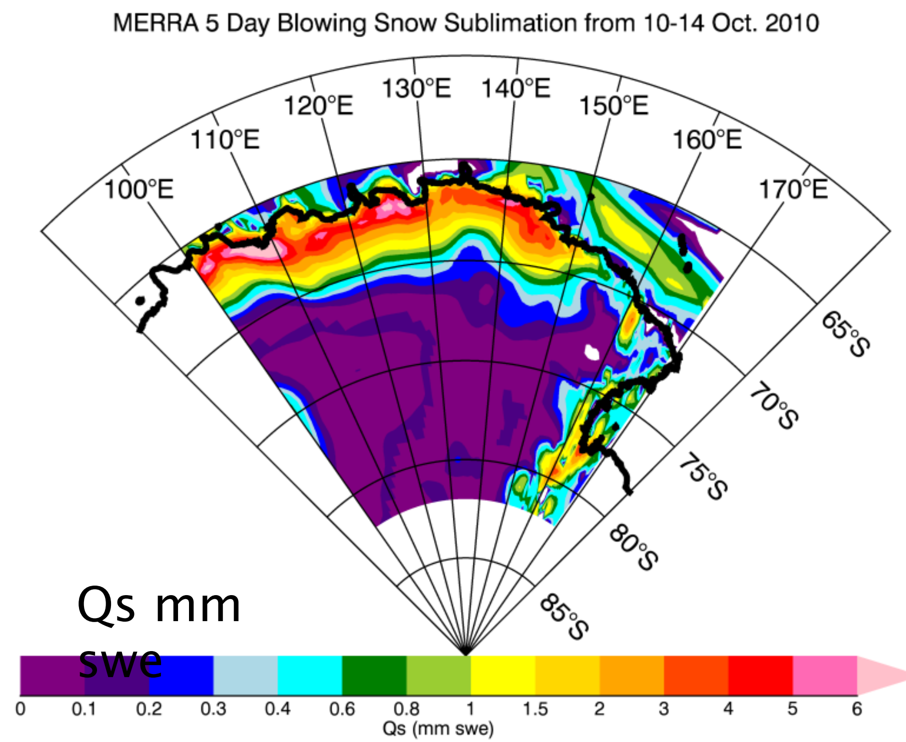
$$Q_s = (a_0 + a_1\xi + a_2\xi^2 + a_3\xi^3 + a_4 U_{10} + a_5 \xi U_{10} + a_6 \xi^2 U_{10} + a_7 U_{10}^2 + a_8 \xi U_{10}^2 + a_9 U_{10}^3) / U'$$

$$\xi = \frac{(RH_i - 1)}{2\rho_{ice}(F_k(T) + F_d(T))} \qquad U' = \frac{(1 - U_t / U_{10})^{2.59}}{(1 - 6.975 / U_{10})^{2.59}}$$

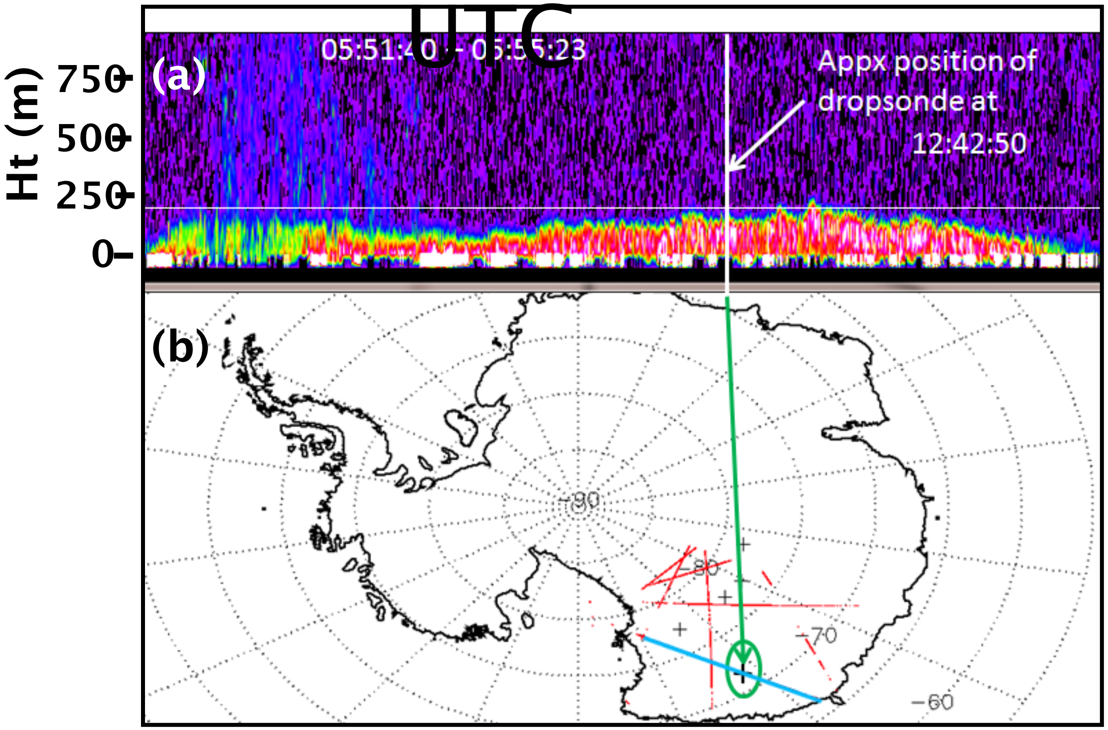
$$U_t = 6.975 + 0.0033(T + 27.27)^2$$

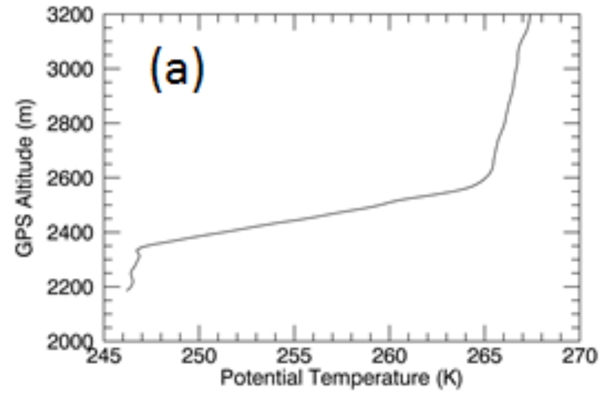


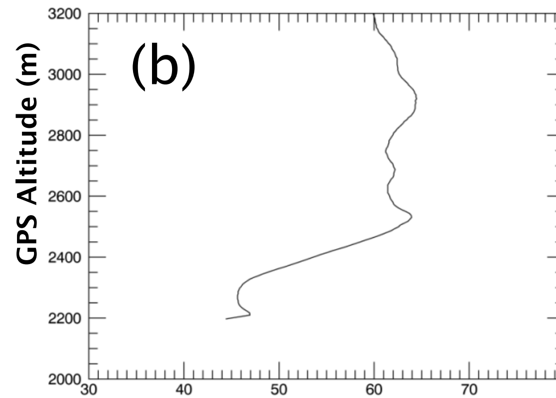


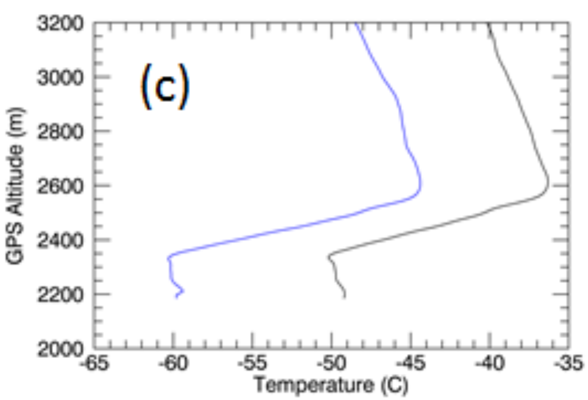


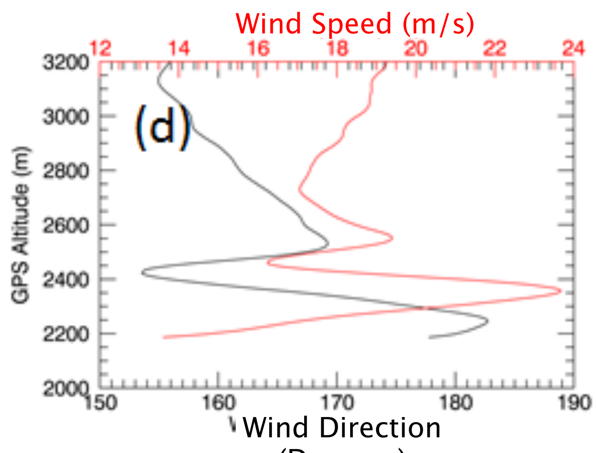
First Dropsonde Data through a Blowing Snow Storm: October 12, 2010, 12:42 UTC











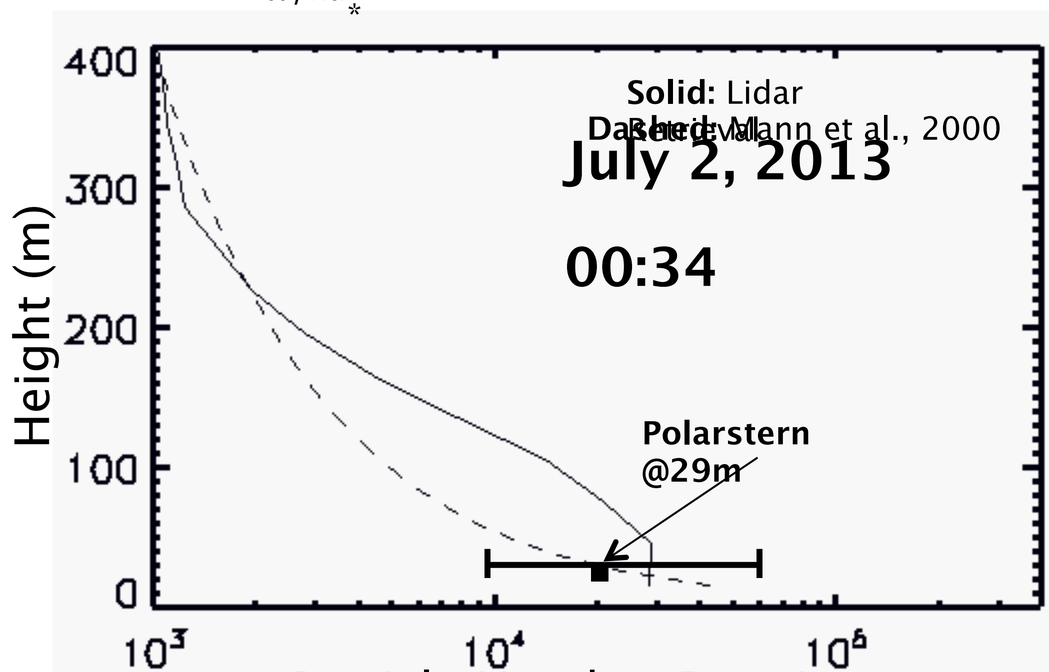
(a) Potential temperature
(b) Relative humidity wrt ice
(c) Dew point (blue) and air temperature (black)
(d) Wind speed (red, m/s) and direction (black)

Particle Number Retrieval from Lidar Measurement of Extinction (σ)

z_r = 29.0 m
N_r = 2.0e4 m^{-3}
ω = 0.13 m/s
u_* = 0.30 m/s r = 70 μm
S = 25

Lidar: $N(z) = \sigma/(2\pi r^2)$

[1]**Mann et al:** $N(z) = N_r(z/z_r)^{-\omega/ku_*}$



Particle Number Density (m^{-3})

[1]*Mann, G.W., P.S. Anderson and S.D. Mobbs, 2000,* ***Profile measurements of blowing snow at Halley, Antarctica*** *.JGR, 105*