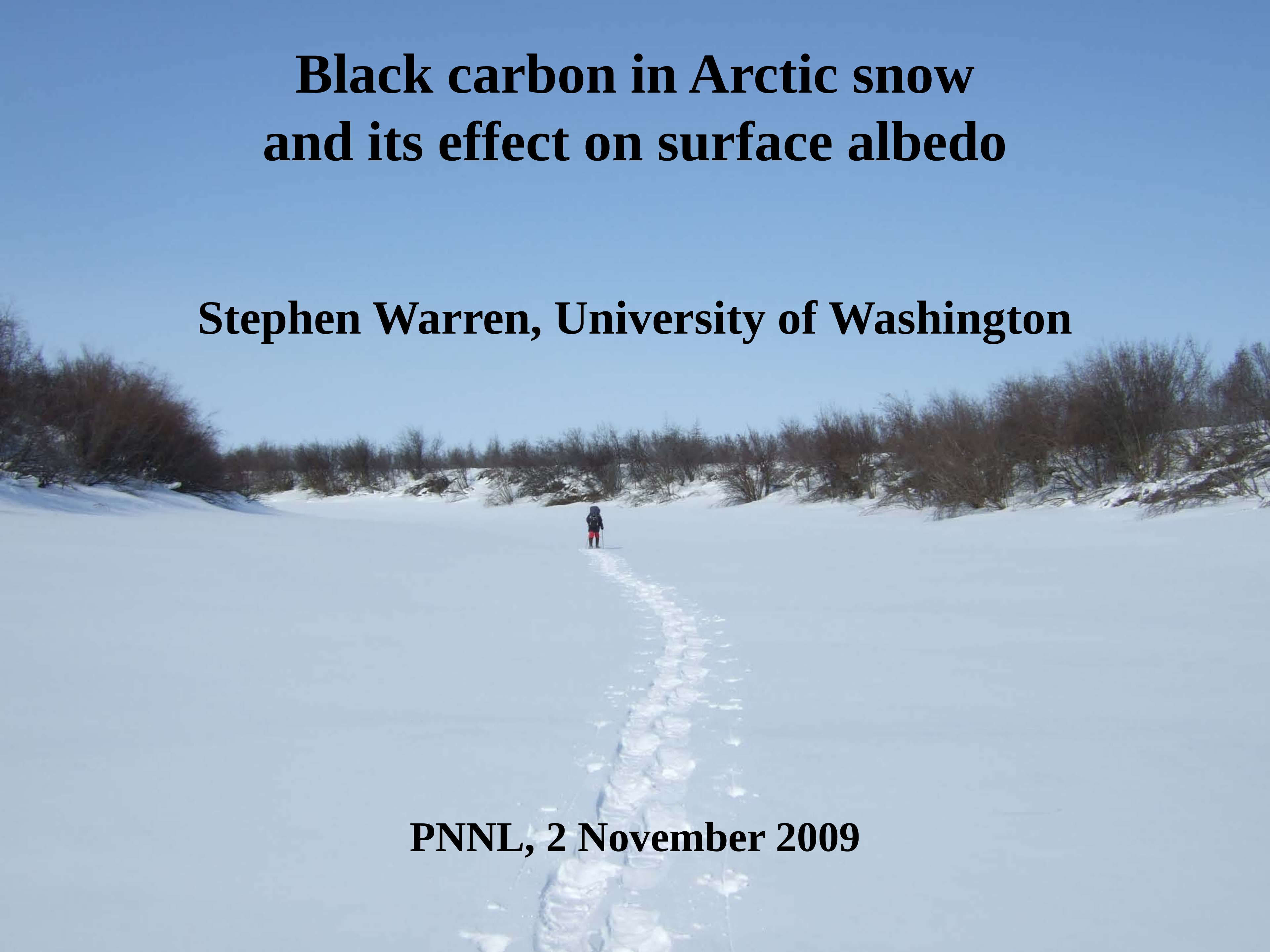
# Black carbon in Arctic snow and its effect on surface albedo

Stephen Warren, University of Washington

PNNL, 2 November 2009



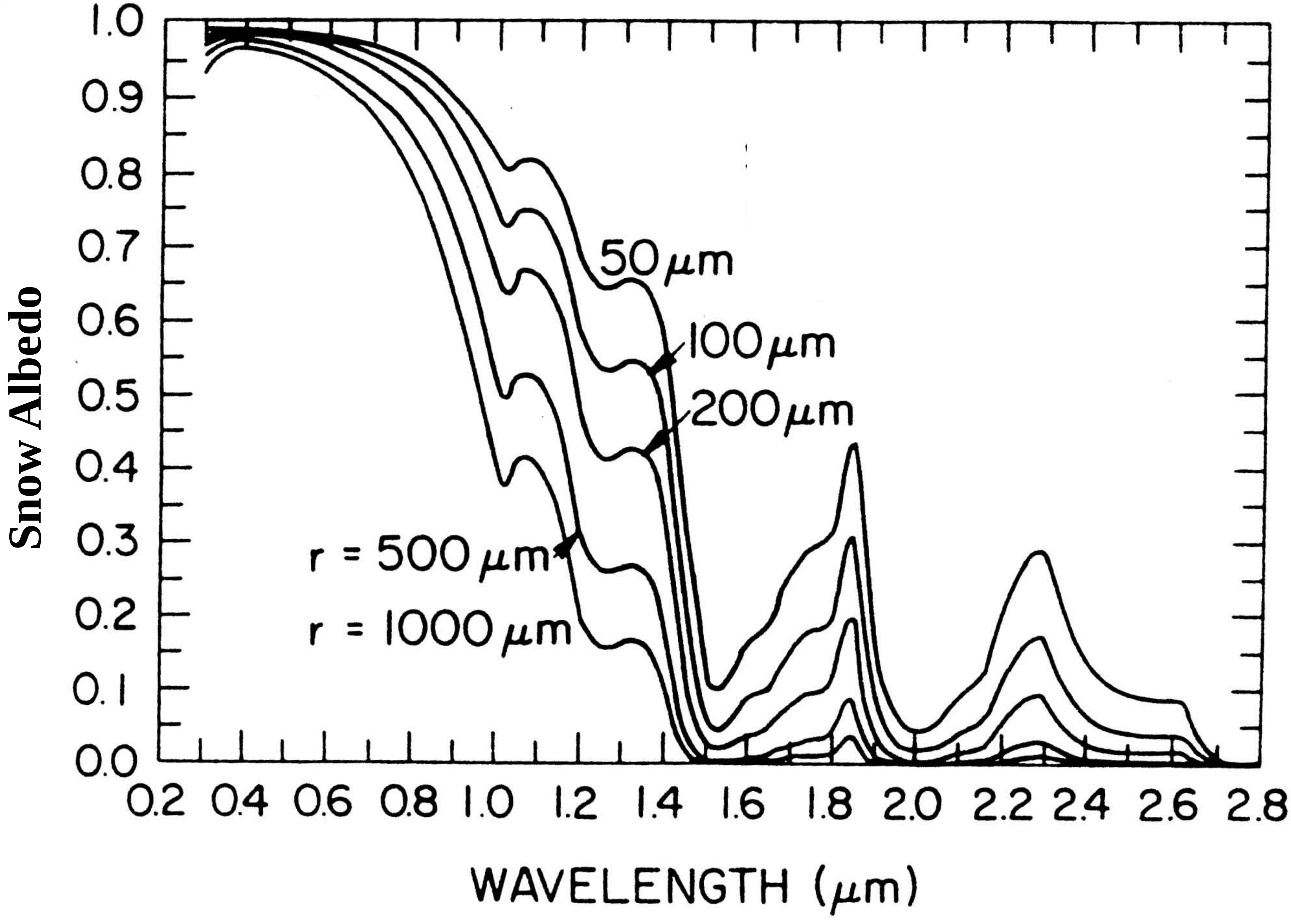
# Co-workers

**Thomas Grenfell, Sarah Doherty,**
**Dean Hegg, Antony Clarke, Richard Brandt**

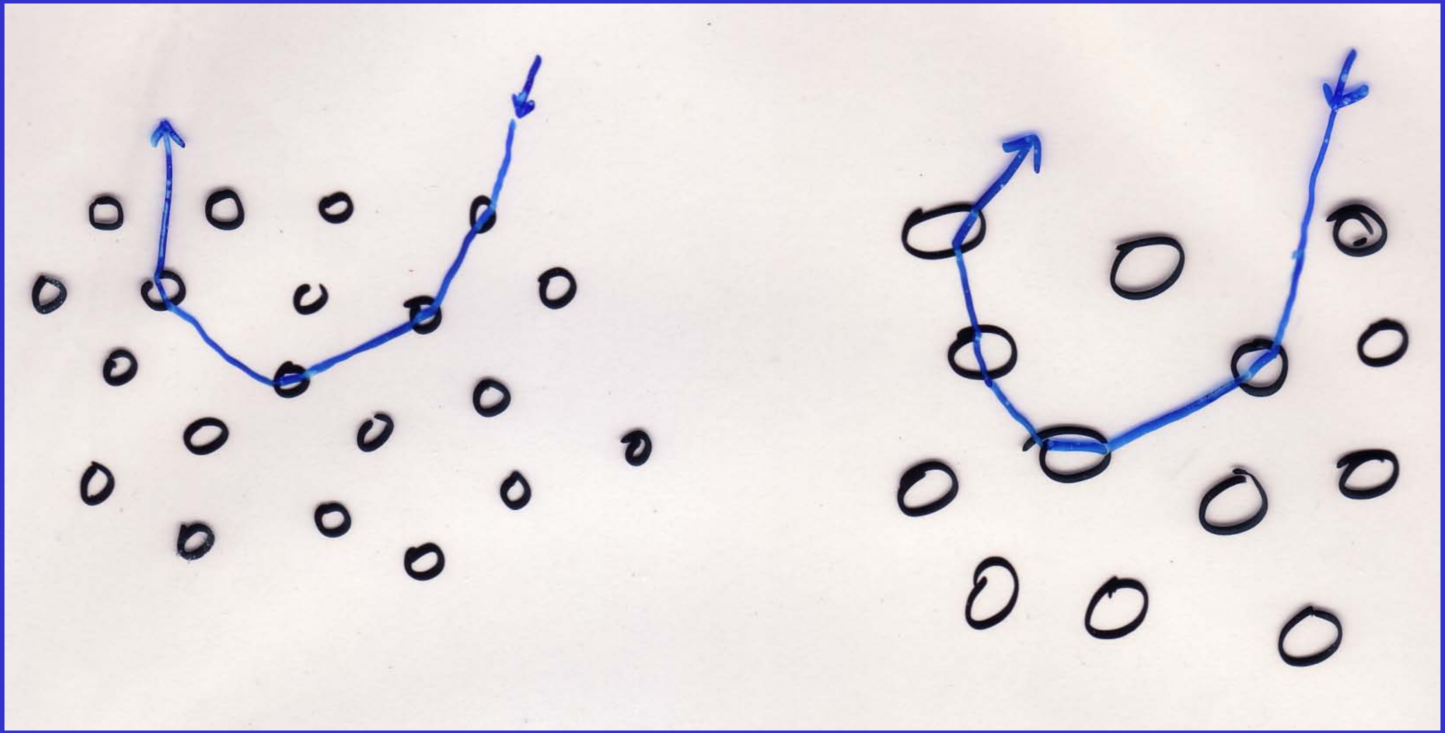
# What affects snow albedo?

*Snow grain size (age)*
Variation of grain size with depth
Snow depth (& vegetation in thin snow)
Sun angle
Impurities

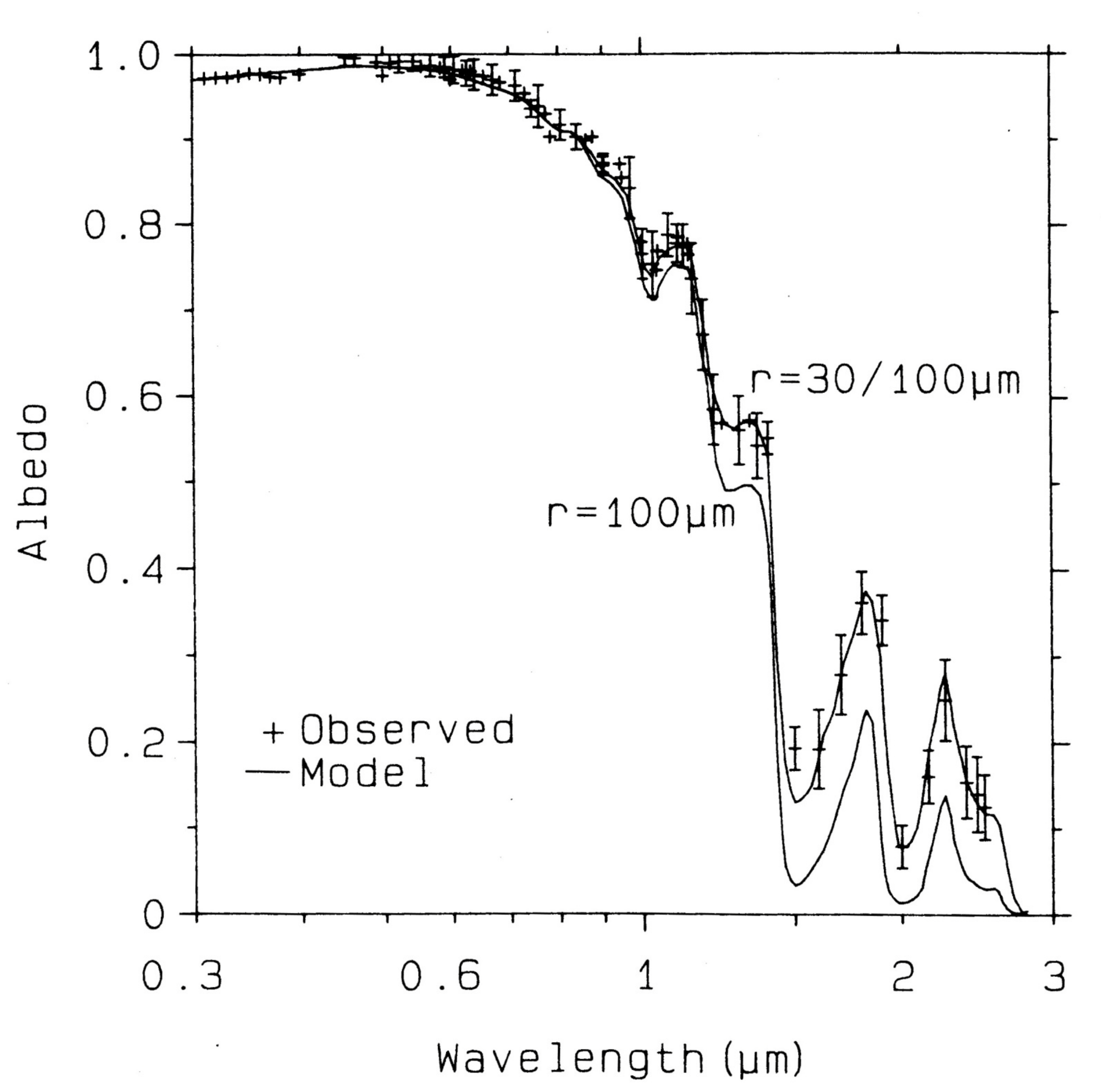
# Effect of snow grain size (Wiscombe & Warren 1980)



# Interaction of sunlight with snow



To get the same number of refraction events, the distance traveled through ice is greater in coarse-grained snow.  Therefore, coarse-grained snow has lower albedo.




Grenfell,
Warren,
Mullen (1994)

South Pole

# What affects snow albedo?

Snow grain size (age)
Variation of grain size with depth
*Snow depth* (& vegetation in thin snow)
Sun angle
Impurities

# Tundra of northern Yakutia, April 2008

Tundra of northern Yakutia, April 2008

*A surface-albedo calculation in a climate model should use a frequency-distribution of snow depth.  Albedo computed from the average snow depth will be too high.*

What affects snow albedo?

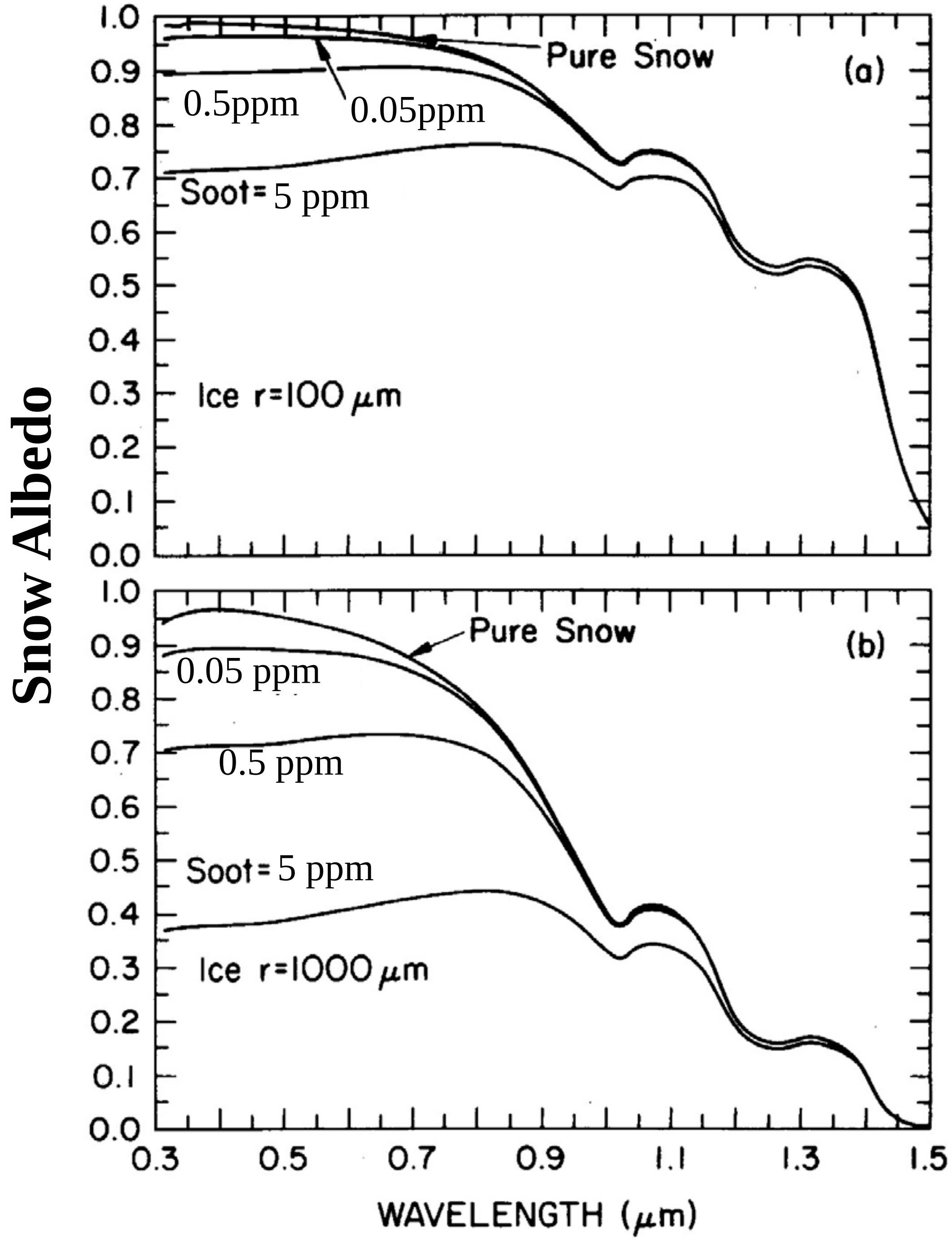
Snow grain size (age)
Variation of grain size with depth
Snow depth (& vegetation in thin snow)
Sun angle
*Impurities*

## *Why are impurities so effective at reducing snow albedo?*

Because absorption by ice is very weak at visible wavelengths: ice is nearly transparent.

*Absorptive impurities:*

- Black carbon (soot)
- Brown carbon (organics)
- Soil dust




Warren & Wiscombe 1980

# Reduction of snow albedo $\alpha$

***(1) by snow aging*** $\Delta\alpha = 12\%$

| | *new snow* | *old melting snow* |
|---|---|---|
| grain radius: | 100 µm | 1000 µm |
| broadband albedo: | 83% | 71% |

***(2) by addition of black carbon (BC)*** (20 ppb):

$\Delta\alpha \approx 0.5\%$ for r = 100 µm

$\Delta\alpha \approx 1.6\%$ for r = 1000 µm

***Typical values of BC in Arctic snow (ppb):***

| | |
|---|---|
| Greenland | 2-3 |
| Canada | 10 |
| Siberia | 20-25 |

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|---|---|
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| Canada | 10 |
| Siberia | 20-25 |

*Snow grain size is more important than soot content, and it is harder to predict.*

*Atmospheric Environment* Vol. 19, No. 12, pp. 2045–2053, 1985
Printed in Great Britain.

# SOOT IN THE ARCTIC SNOWPACK: A CAUSE FOR PERTURBATIONS IN RADIATIVE TRANSFER

ANTONY D. CLARKE* and KEVIN J. NOONE

Environmental Engineering and Science Program, Civil Engineering Department, University of Washington, Seattle, Washington 98195, U.S.A.

(*First received* 5 *November* 1984, *in final form* 22 *April* 1985 *and received for publication* 17 *July* 1985)

# Soot in snow 1983-4 (Clarke & Noone) Most amounts are 5-50 ppb.

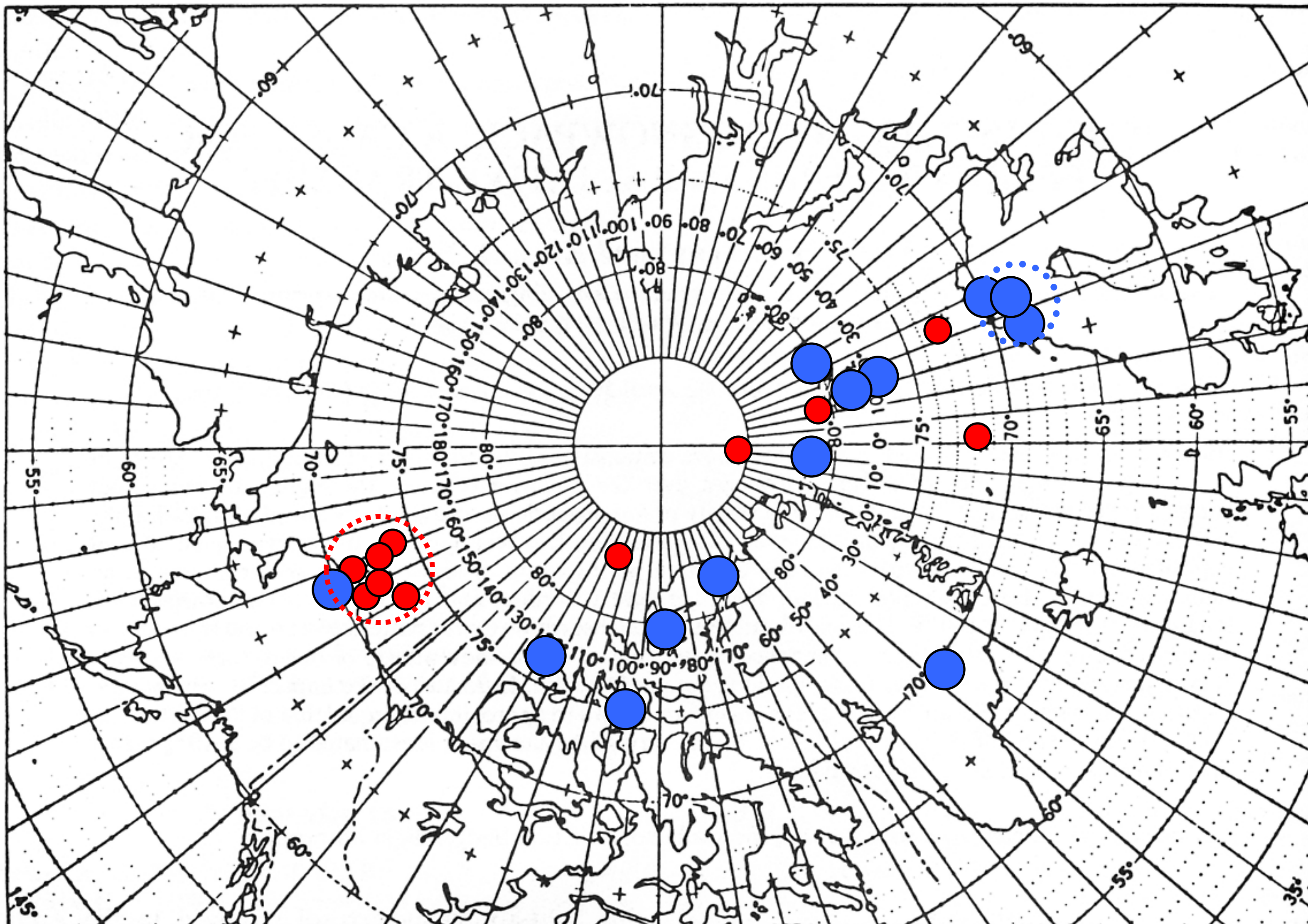


Fig. 1. Map of Arctic sampling locations for the University of Washington atmospheric (●) aircraft samples and snowpack (●) samples for 1983 and 1984.

1983

5-50 ppb of black carbon could reduce snow albedo by 0-4%.

Clarke & Noone’s average of all 60 samples was 25 ppb, implying albedo reduction of ~2%.

Now, 20 years after *Clarke & Noone (1985)*, there is renewed interest in dirty snow.

# Soot climate forcing via snow and ice albedos

**James Hansen*†‡ and Larissa Nazarenko*†**

*National Aeronautics and Space Administration Goddard Institute for Space Studies and †Columbia University Earth Institute, 2880 Broadway, New York, NY 10025

Contributed by James Hansen, November 4, 2003

**Plausible estimates for the effect of soot on snow and ice albedos (1.5% in the Arctic and 3% in Northern Hemisphere land areas) yield a climate forcing of +0.3 W/m$^2$ in the Northern Hemisphere. The "efficacy" of this forcing is ≈2, i.e., for a given forcing it is twice as effective as $CO_2$ in altering global surface air temperature. This indirect soot forcing may have contributed to global warming of the past century, including the trend toward early springs in the Northern Hemisphere, thinning Arctic sea ice, and melting land ice and permafrost. If, as we suggest, melting ice and sea level rise define the level of dangerous anthropogenic interference with the climate system, then reducing soot emissions, thus restoring snow albedos to pristine high values, would have the double benefit of reducing global warming and raising the global temperature level at which dangerous anthropogenic interference occurs. However, soot contributions to climate change do not alter the conclusion that anthropogenic greenhouse gases have been the main cause of recent global warming and will be the predominant climate forcing in the future.**

aerosols | air pollution | climate change | sea level

bonaceous mixtures can be ambiguous (12, 13). BC is commonly defined in an operational sense as the absorbing component of carbonaceous aerosols, which may result in some humic-like or other organic material contributing to estimated BC absorption. We employ this operational definition, because the practical question concerns the impact of soot on snow/ice albedo, and for this it matters little whether the carbon is elemental or in other carbonaceous aerosols.

We compile empirical data on BC amount in snow and compare calculated effects on snow albedo with field data. We then use these data to specify plausible albedo changes for climate simulations. We calculate the forcings due to specified albedo changes, carry out equilibrium climate simulations for these forcings, calculate the efficacy of snow/ice albedo forcing relative to $CO_2$, and carry out transient climate simulations for 1880–2000. Finally, we discuss potential implications.

**Soot in Snow.** Be thou as chaste as ice, as pure as snow, thou shalt not escape calumny (Shakespeare, *Hamlet*). Perceptions persist about the purity of fresh snow, but measurements tell another story.

*Proc. Nat. Acad. Sci.* 2004

Soot in snow is hard to detect visually.

30 km east of Vorkuta, Russia
*370 ppb*

Greenland Ice Sheet
*2 ppb*

Debris-covered ice in ablation zone of Greenland Ice Sheet. Silt and sand.

## *Where and when does variation of snow albedo matter for climate?*

Whenever large areas of snow are exposed to significant solar energy (snow albedo is less important in winter and in boreal forest)

***Arctic snow***

- Tundra in spring
- Sea ice in spring (covered with snow)
- Greenland Ice Sheet in both spring and summer

***Non-Arctic snow***

- Great Plains of North America
- Steppes of Asia: Kazakhstan, Mongolia, Xinjiang, Tibet

***Sea ice***

- Arctic ocean in summer

(*Mountain glaciers* are too small to be important for climate, but they are important for hydrology)

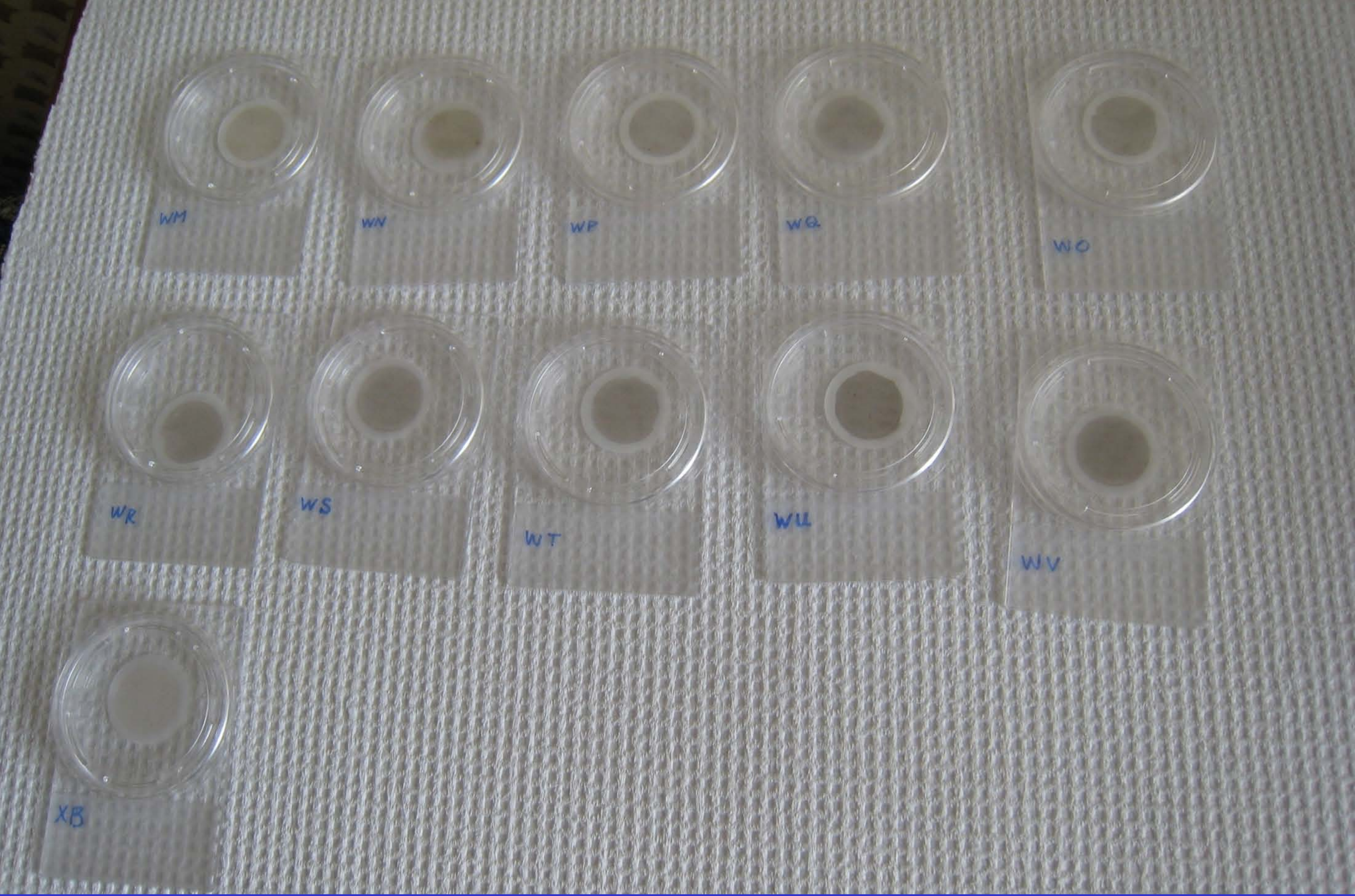
## Summary of strategy

(1600 snow samples, only a few albedo measurements)

Climatic effect of BC on snow albedo is expected to be at most a few percent, and snow albedo depends on several other variables. *Therefore we do not directly measure the albedo reduction. Instead:*

(1) Collect snow samples, melt and filter them. Analyze the filters photometrically for
- (a) BC concentration
- (b) fraction of absorption due to other ("brown") constituents (organic carbon, soil dust).

(2) Use the BC amount together with snow grain size in a radiative-transfer model to *compute* albedo reduction.

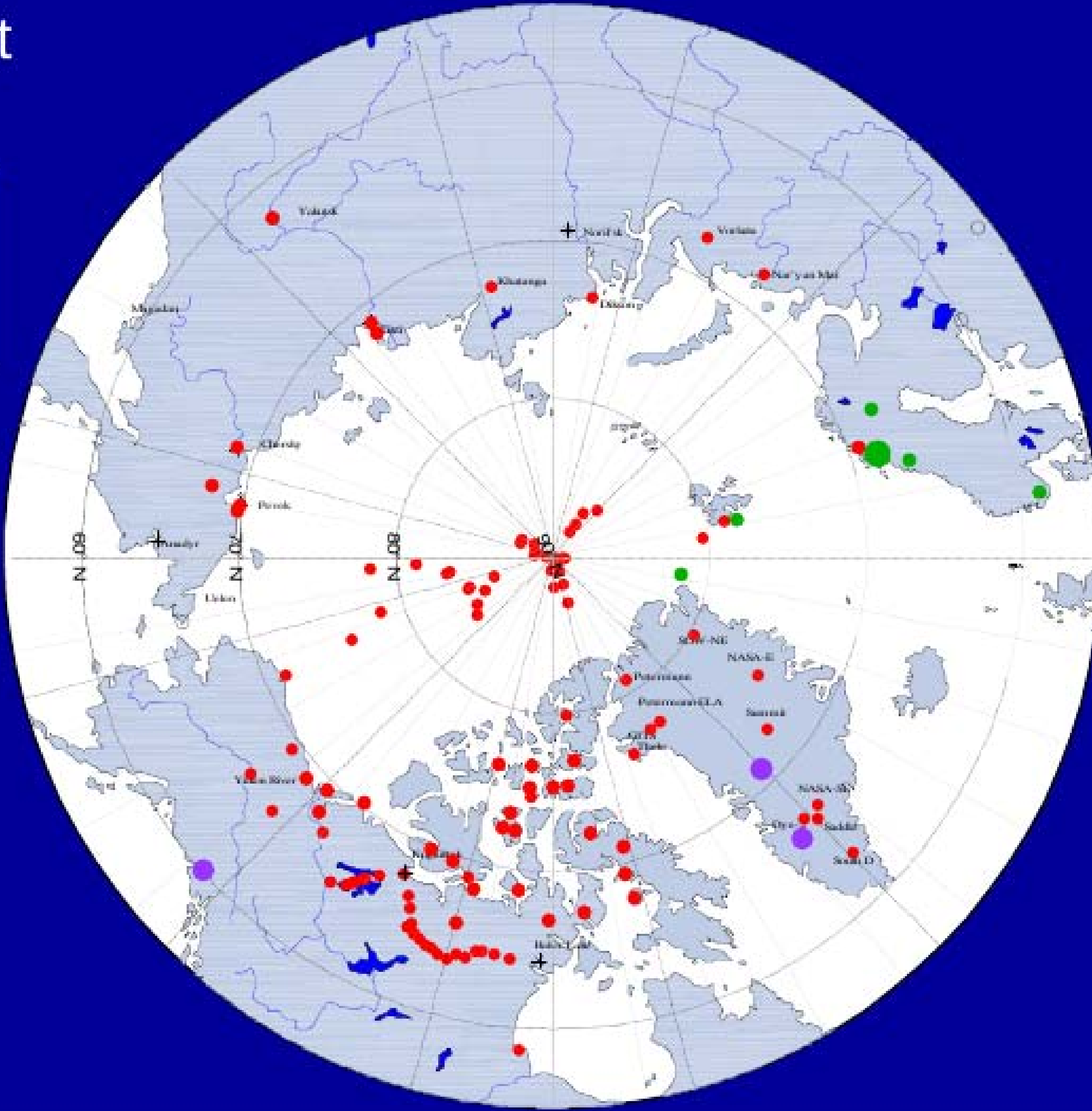

WM
WN
WP
WQ
WO
WR
WS
WT
WU
WV
XB

# Measurement Sites

thermo-optical

photometric

SP2 ice cores



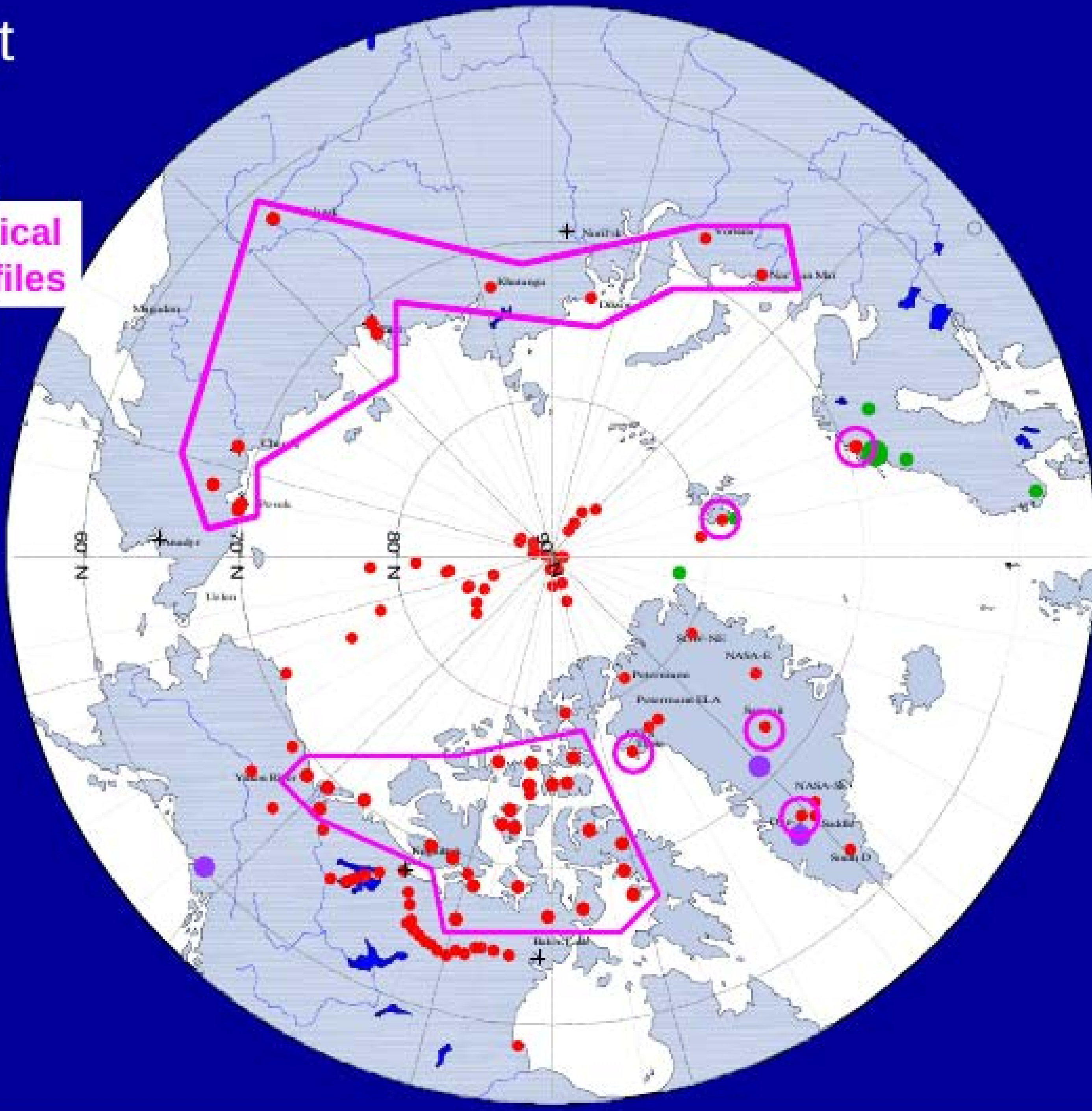
# Measurement Sites

thermo-optical

photometric

vertical profiles

SP2 ice cores



***Other methods to measure BC:***

Thermo-Optical (controlled combustion)

Single-particle soot photometer (SP2)

***Advantages of filter method:***

It's a measure of absorption, which is closely related to absorption in the snow.

Filtering can be done anywhere; no need to bring large quantities of snow back to Seattle

# Filter apparatus at Ny-Alesund, Svalbard


Inuvik, Canada

Northeast Greenland


Northeast Greenland

Absorption coefficient $k_{abs}$ ($m^2$/g snow)

$$k_{abs} = \frac{\text{(absorption cross-section of particles on the filter)}}{\text{(amount of meltwater passed through the filter)}}$$

$k_{abs} = B_a\, C$

$B_a$ mass absorption cross-section ($m^2$/g BC)

$C$ concentration (g BC/g snow)

*Our BC amounts are calibrated relative to filters with Monarch-71 soot, which has $B_a \approx 6\ m^2/g$.*

# How do we verify the modeling of albedo reduction? (*or bypass the model!*)

Direct measurement of albedo-reduction is unlikely to be feasible in nature, because of vertical variation of snow grain size and soot content, and because natural soot content is small.

## How do we verify the modeling of albedo reduction? (*or bypass the model!*)

Direct measurement of albedo-reduction is unlikely to be feasible in nature, because of vertical variation of snow grain size and soot content, and because natural soot content is small.

Therefore artificial snowpacks are needed, with uniform grain size and large uniform soot content (ppm not ppb), to get a large signal on albedo.

*In cold-room laboratory:*

Charlie Zender

Tom Kirchstetter (LBL)

*Outdoors:*

Richard Brandt

*Advantages of an outdoor experiment:*

Uniform illumination across snowpack

Wide sample to avoid edge-effects (light emerges from snow horizontally distant from where it entered)

Albedo measurement is possible (instead of BRDF)

*Advantages of an outdoor experiment:*

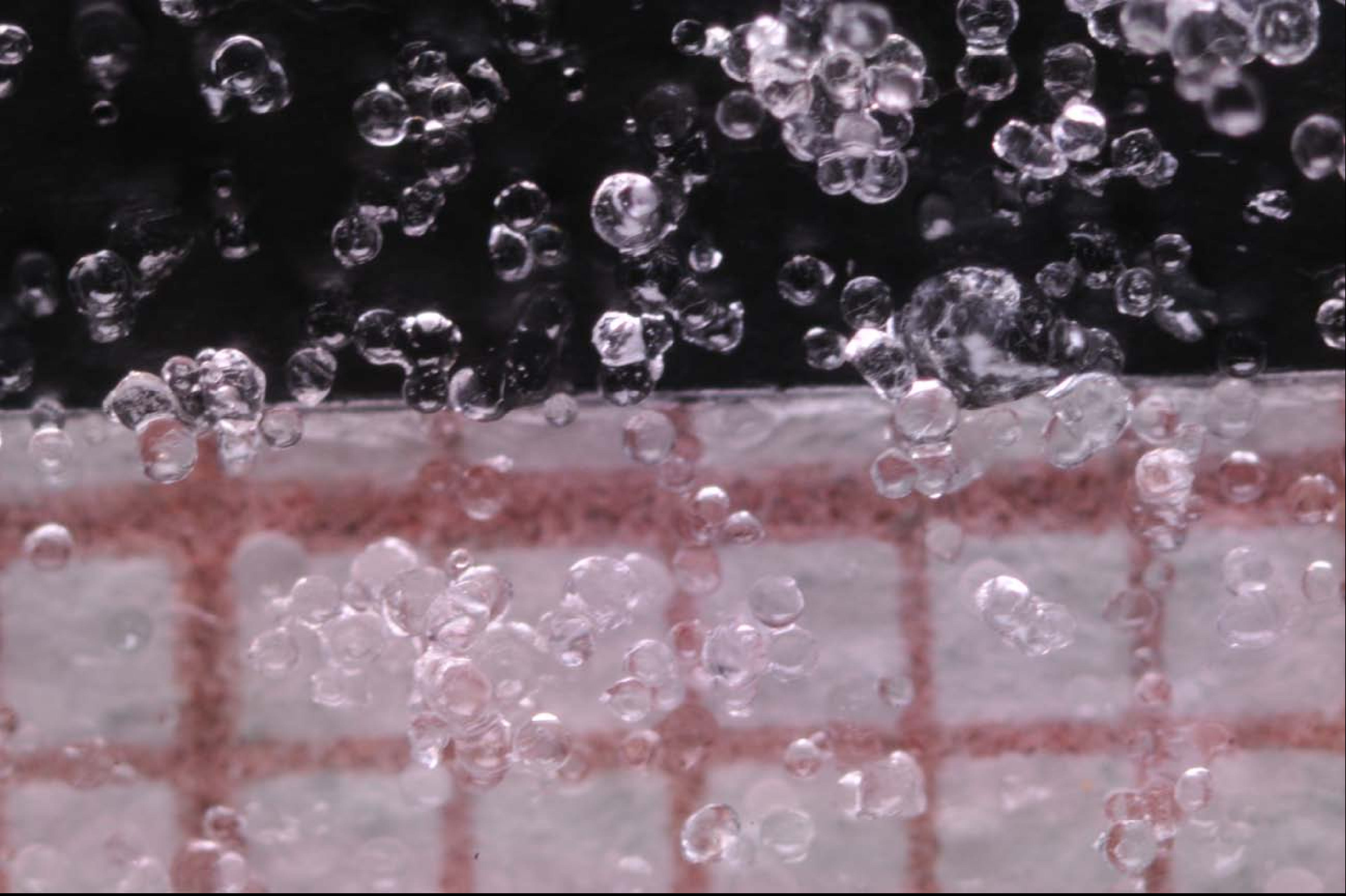
Uniform illumination across snowpack

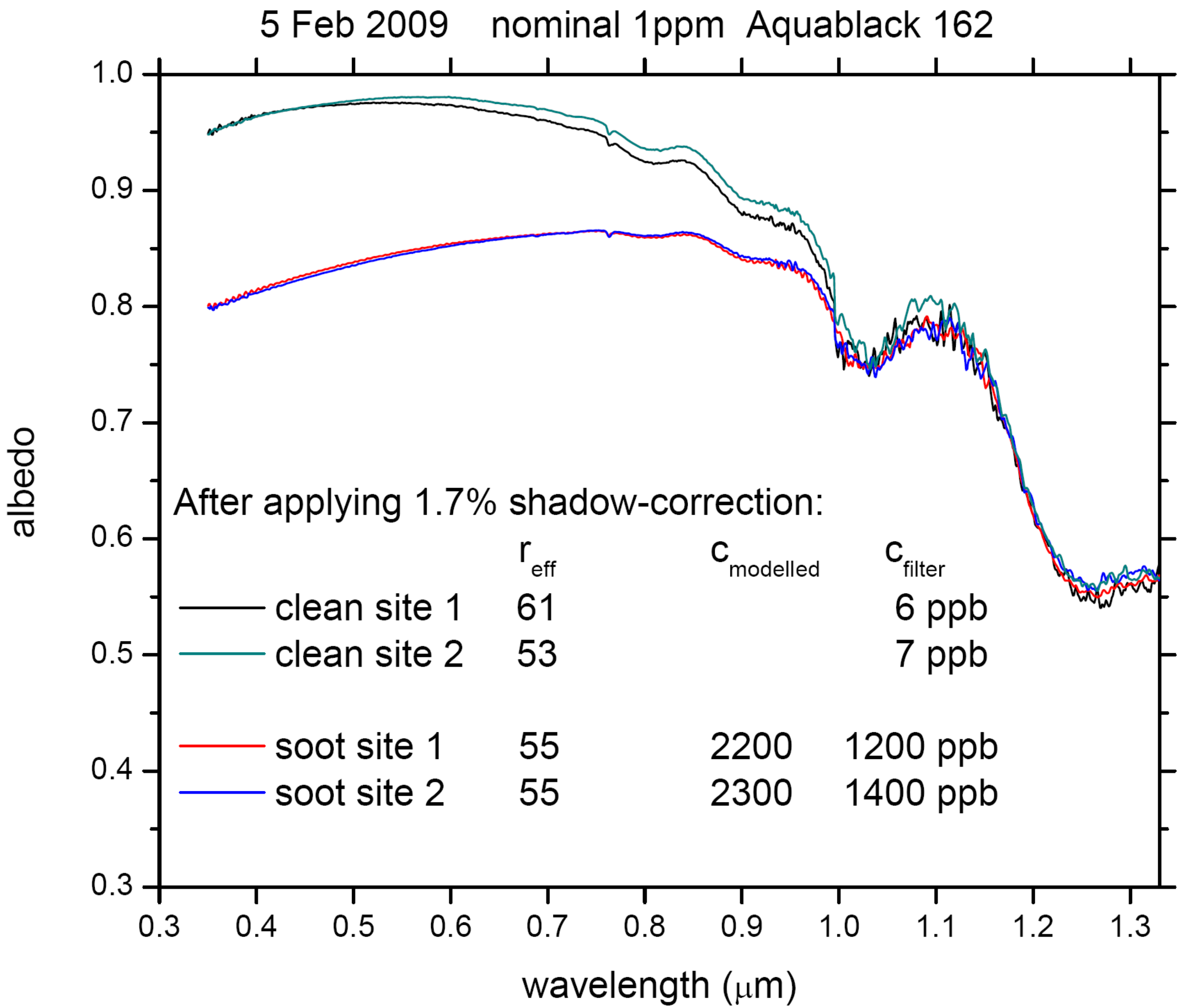
Wide sample to avoid edge-effects (light emerges from snow horizontally distant from where it entered)

Albedo measurement is possible (instead of BRDF)


Ingersoll Rand

1 ppm means 3 grams of soot in 3 tons of snow





5 Feb 2009 nominal 1ppm Aquablack 162
albedo
wavelength (μm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
After applying 1.7% shadow-correction:
$r_{eff}$ $c_{modelled}$ $c_{filter}$
clean site 1 61 6 ppb
clean site 2 53 7 ppb
soot site 1 55 2200 1200 ppb
soot site 2 55 2300 1400 ppb

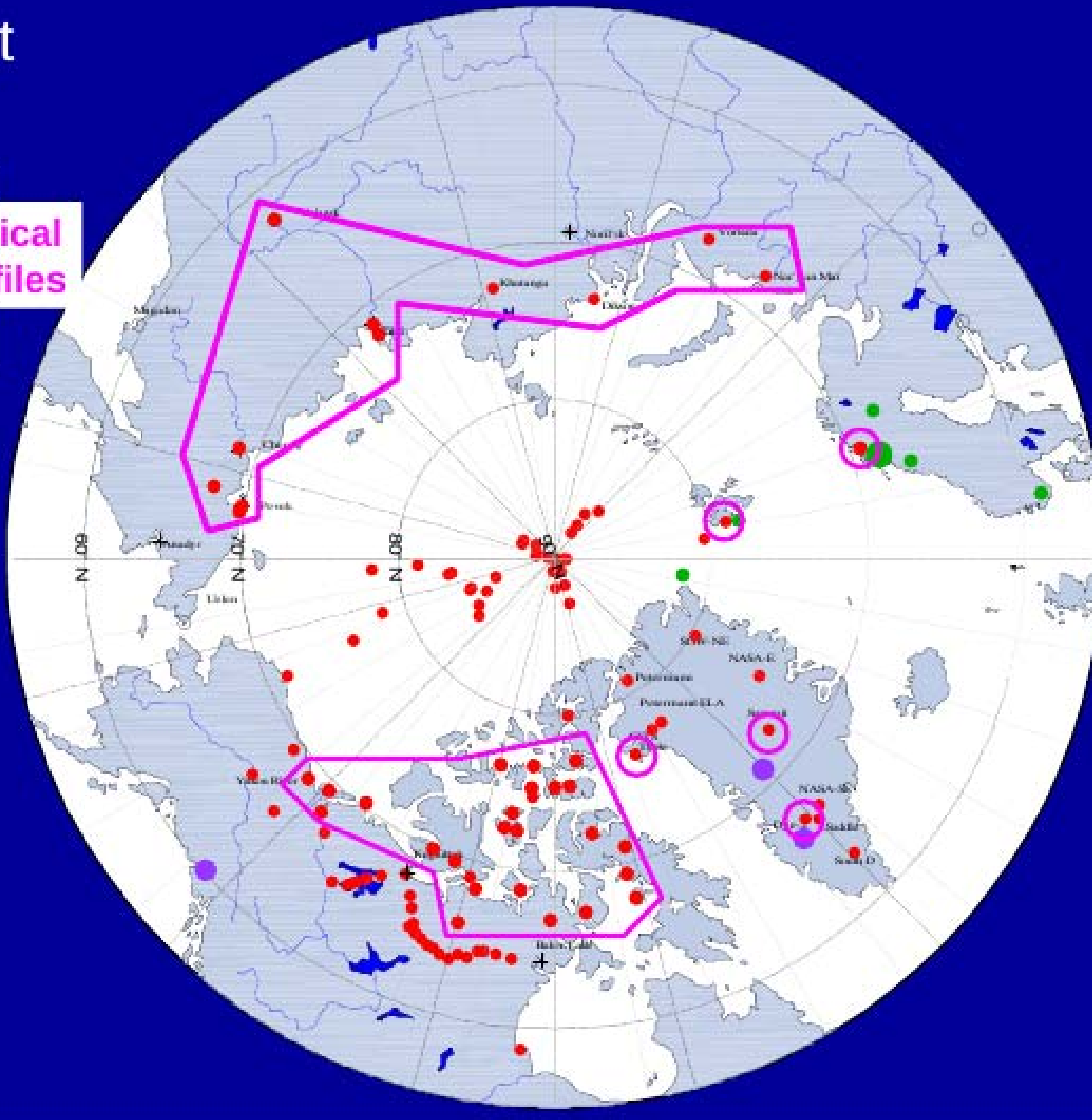
# Measurement Sites

thermo-optical

photometric

SP2 ice cores

vertical profiles

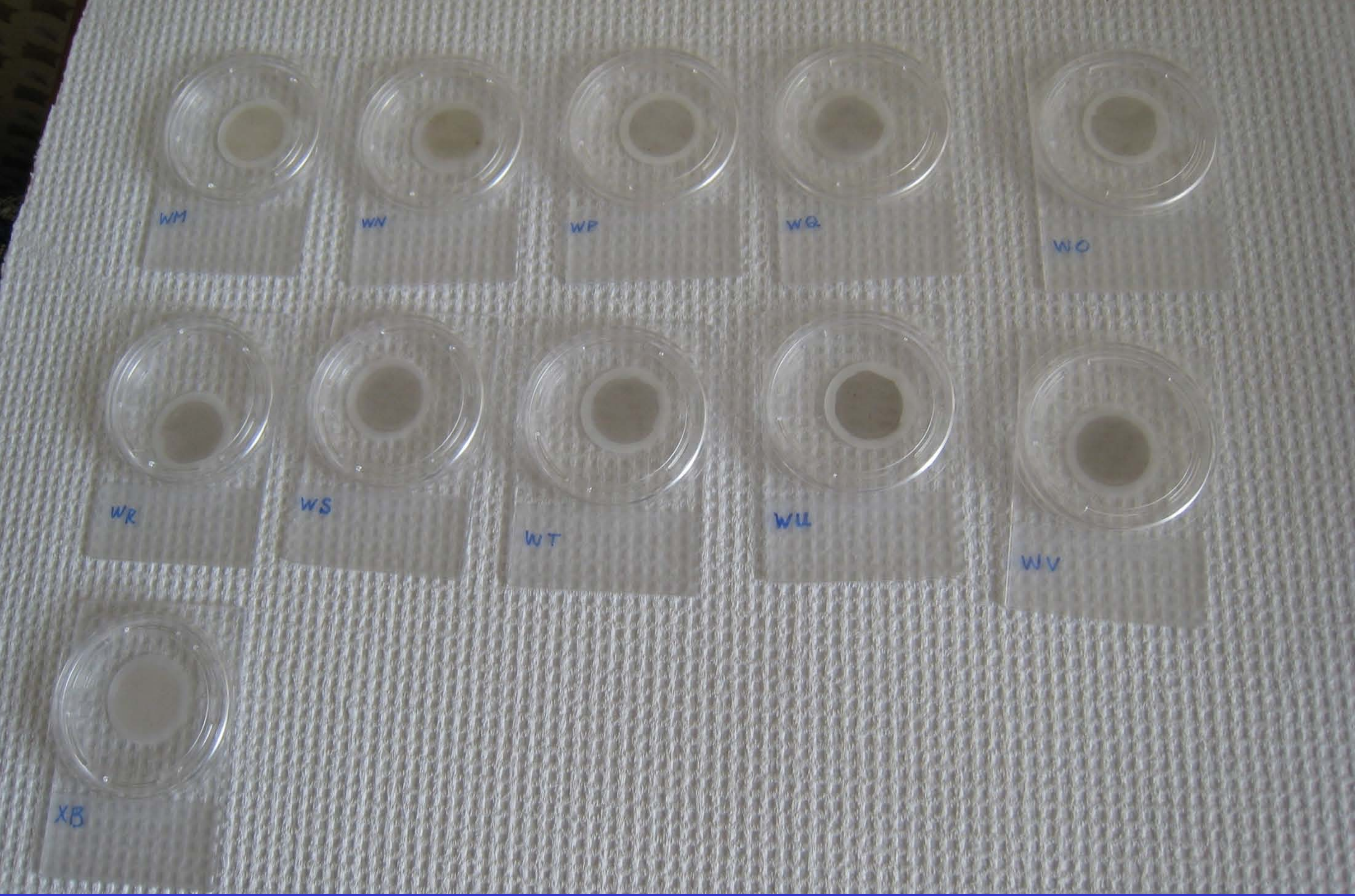



Driving on the Laptev Sea, near the Lena Delta

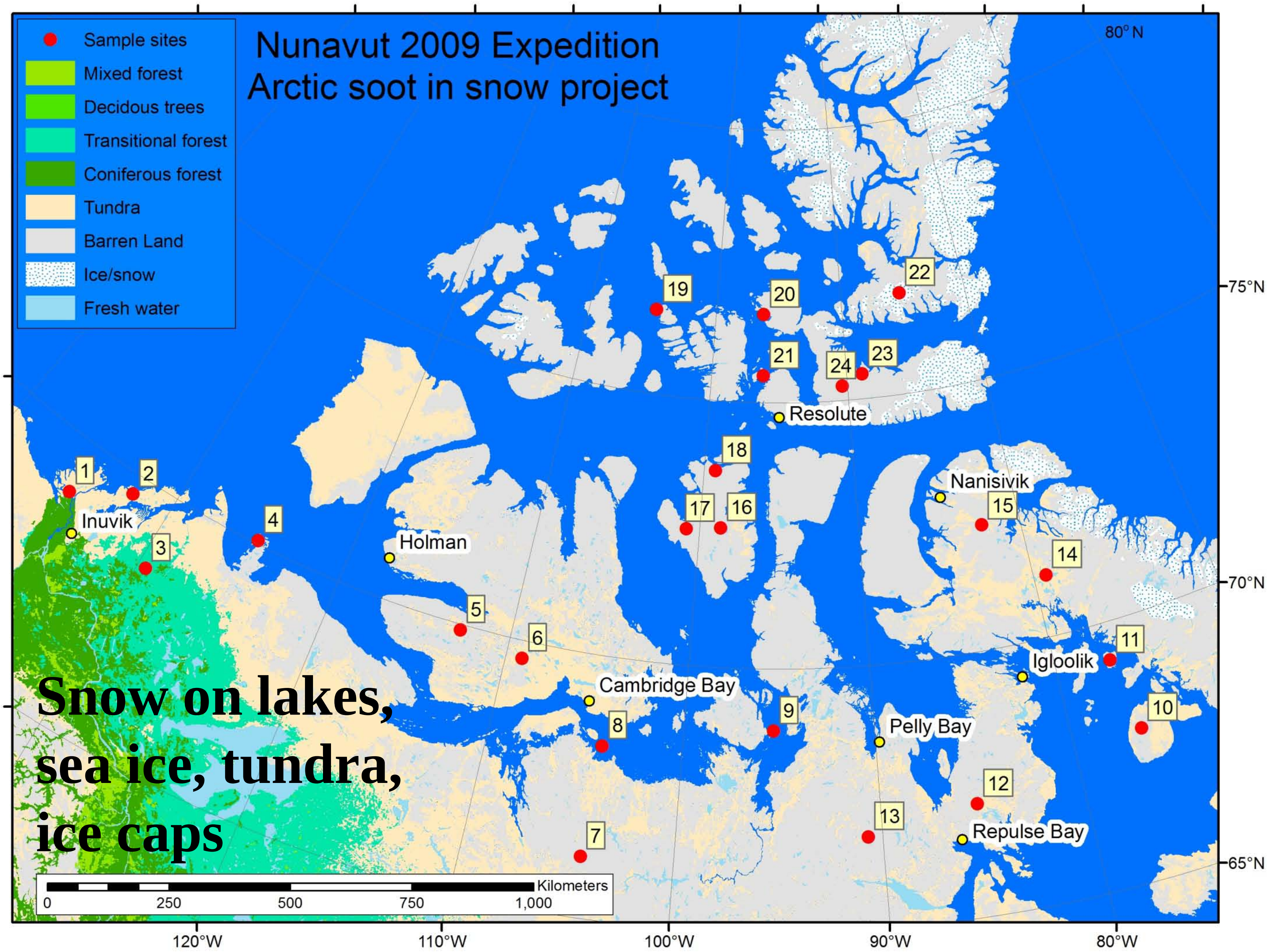
# 60 km west of Cherskiy, in the Kolyma lowland

# On the Lena River west of Tiksi (Yakutia)


Snowmelt-filtering lab
in Tiksi hotel




Filters from snow near Tiksi


Nunavut 2009 Expedition
Arctic soot in snow project
Sample sites
Mixed forest
Decidous trees
Transitional forest
Coniferous forest
Tundra
Barren Land
Ice/snow
Fresh water
Inuvik
Holman
Cambridge Bay
Resolute
Nanisivik
Igloolik
Pelly Bay
Repulse Bay
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
80° N
75°N
70°N
65°N
120°W
110°W
100°W
90°W
80°W
0
250
500
750
1,000
Kilometers
Snow on lakes,
sea ice, tundra,
ice caps

Eastern Siberia, Spring 2008

350 snow samples in 2 months

Arctic Canada, Spring 2009

306 snow samples in 2 weeks

Southwest Devon Island


Sea ice

Thick snow on sea ice

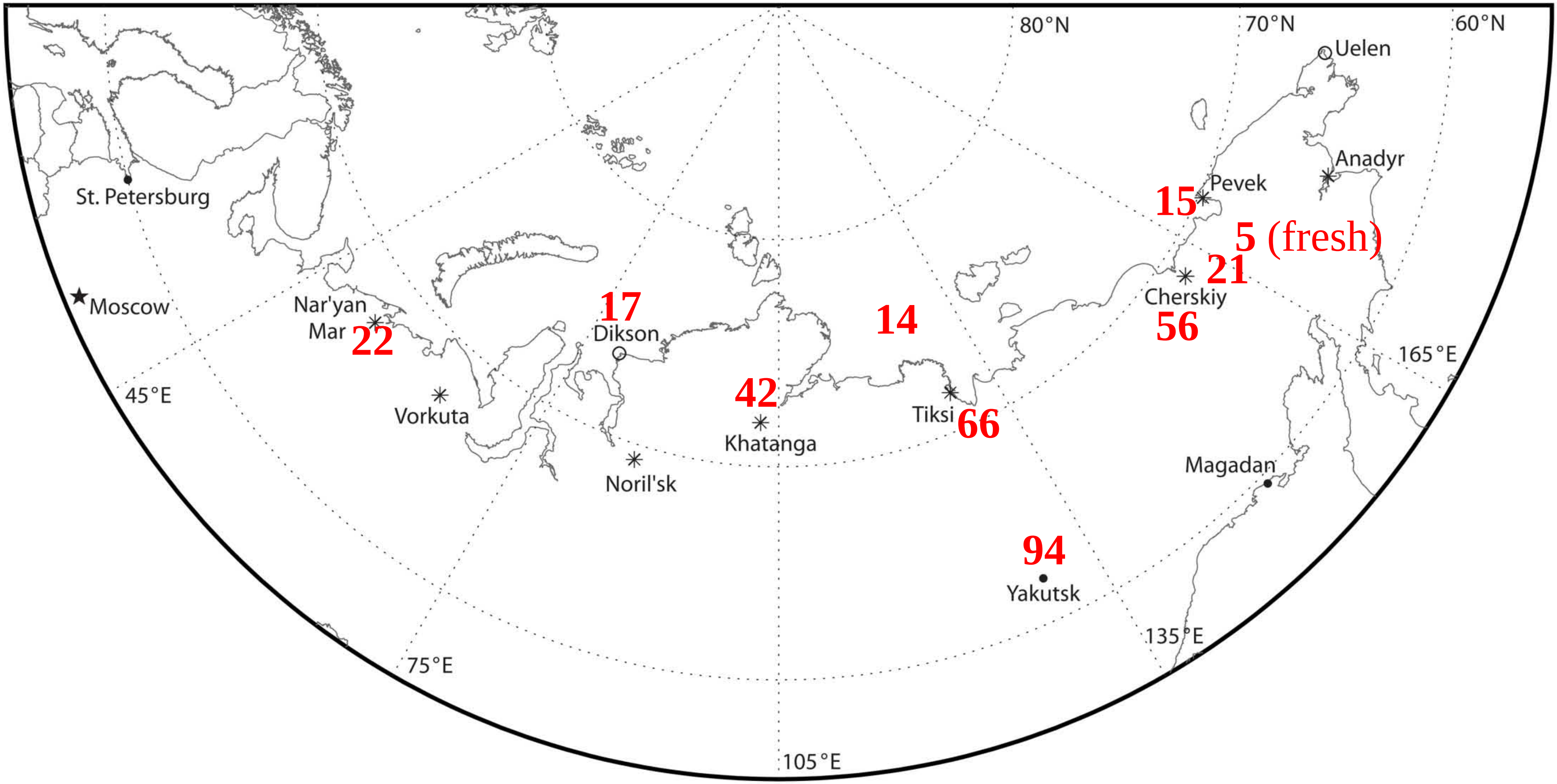
Thin snow on sea ice


Nasco

# BC concentrations (ng/g *or* ppb)

| LOCATION | MEDIAN |
|---|---|
| Russia, 2007 (western) | 33 |
| Russia, 2008 (eastern) | 20 |
| Canada, 2007 (subarctic) | 15 |
| Canada, 2009 (arctic) | 9 |

| LOCATION | MEDIAN |
|---|---|
| Barrow (Alaska), 2008 | 12 |
| Greenland, AWS | 3 |
| Greenland, Dye-2 | 2 |
| North Pole Vicinity, 2008 | 6 |
| Svalbard, 2007 | 11 |
| | |

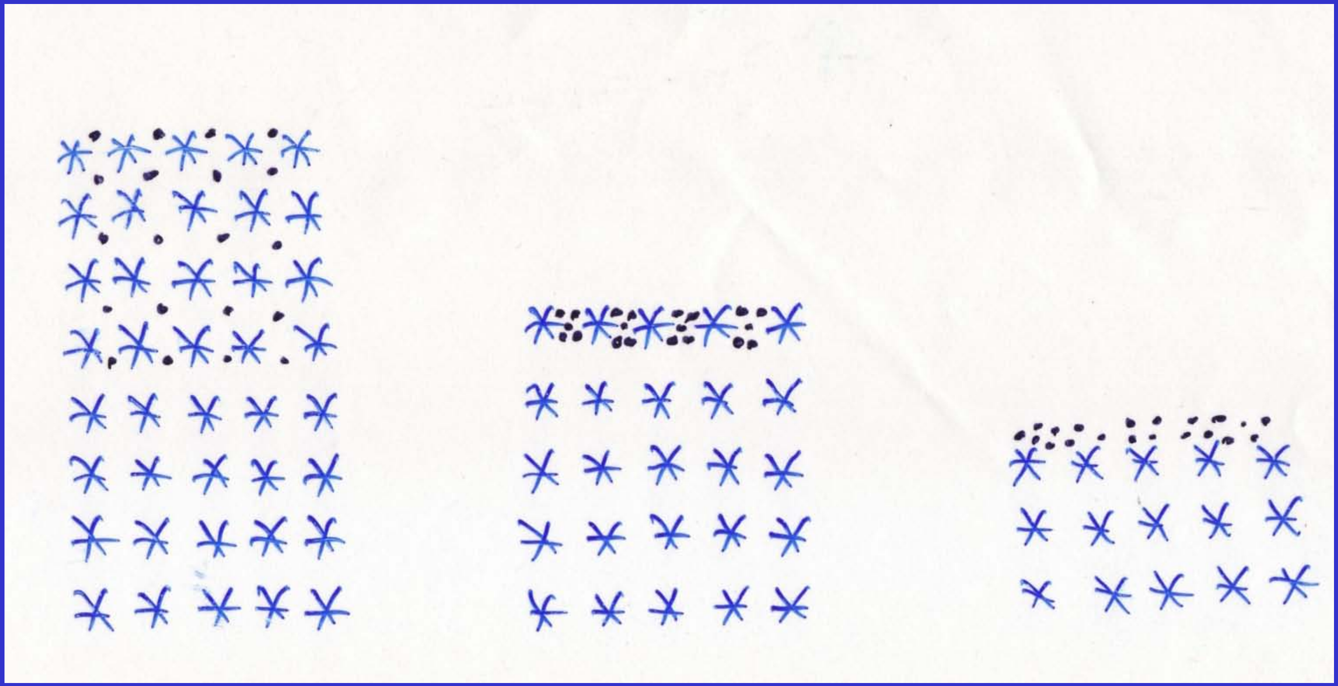



# Arctic Russia March-May 2007, 2008

~500 snow samples; median ***surface*** *(0-10 cm)* values plotted here (ppb).

(Cherskiy: **56** ppb surface, **20** ppb subsurface. Heavy snowfall in autumn, sublimation in winter leaves BC at surface.)

# Do particles get left behind at the surface as the snow melts?



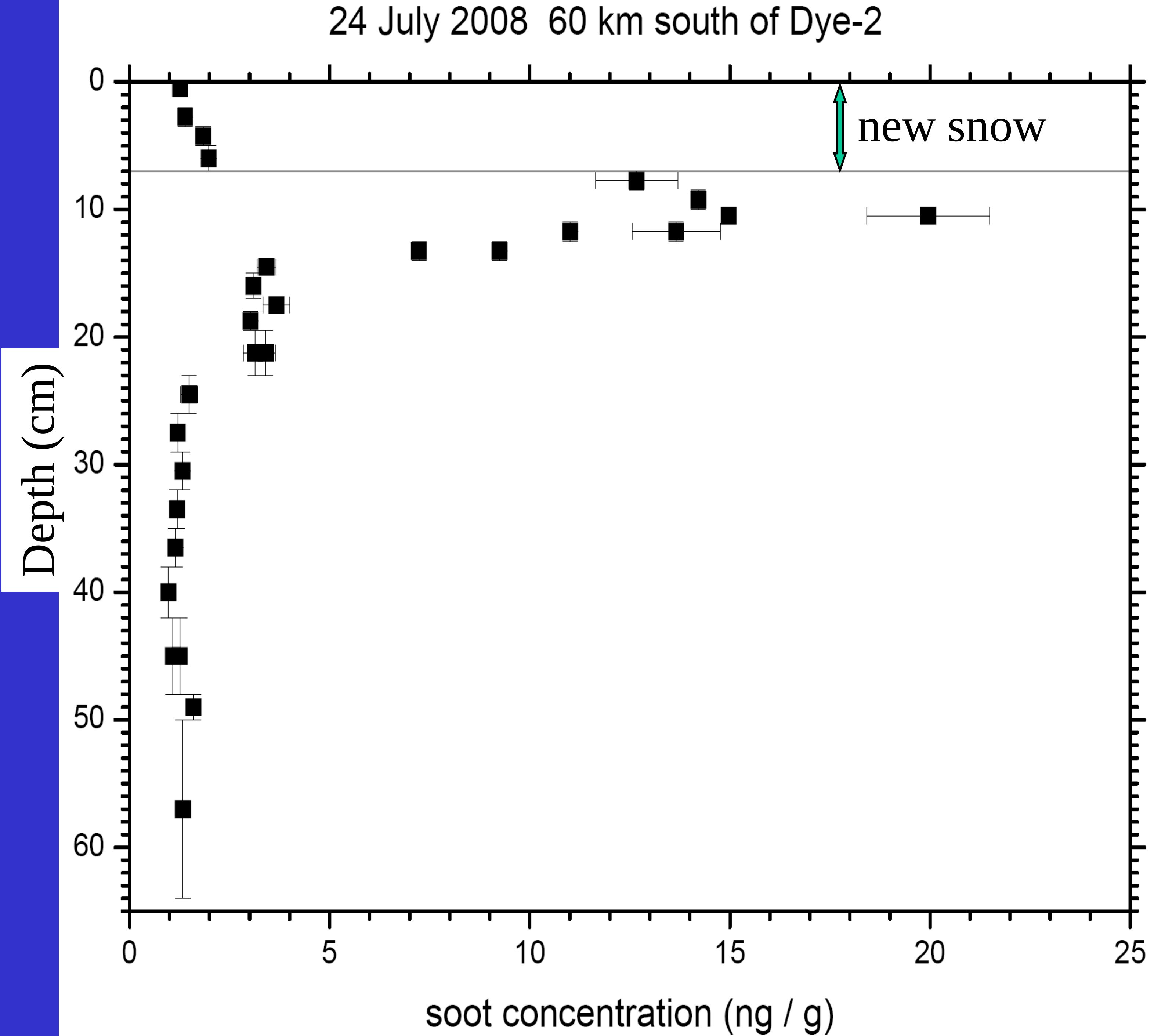
# Percolation zone of southern Greenland July 2008

60 km south (upwind) of Dye-2 station

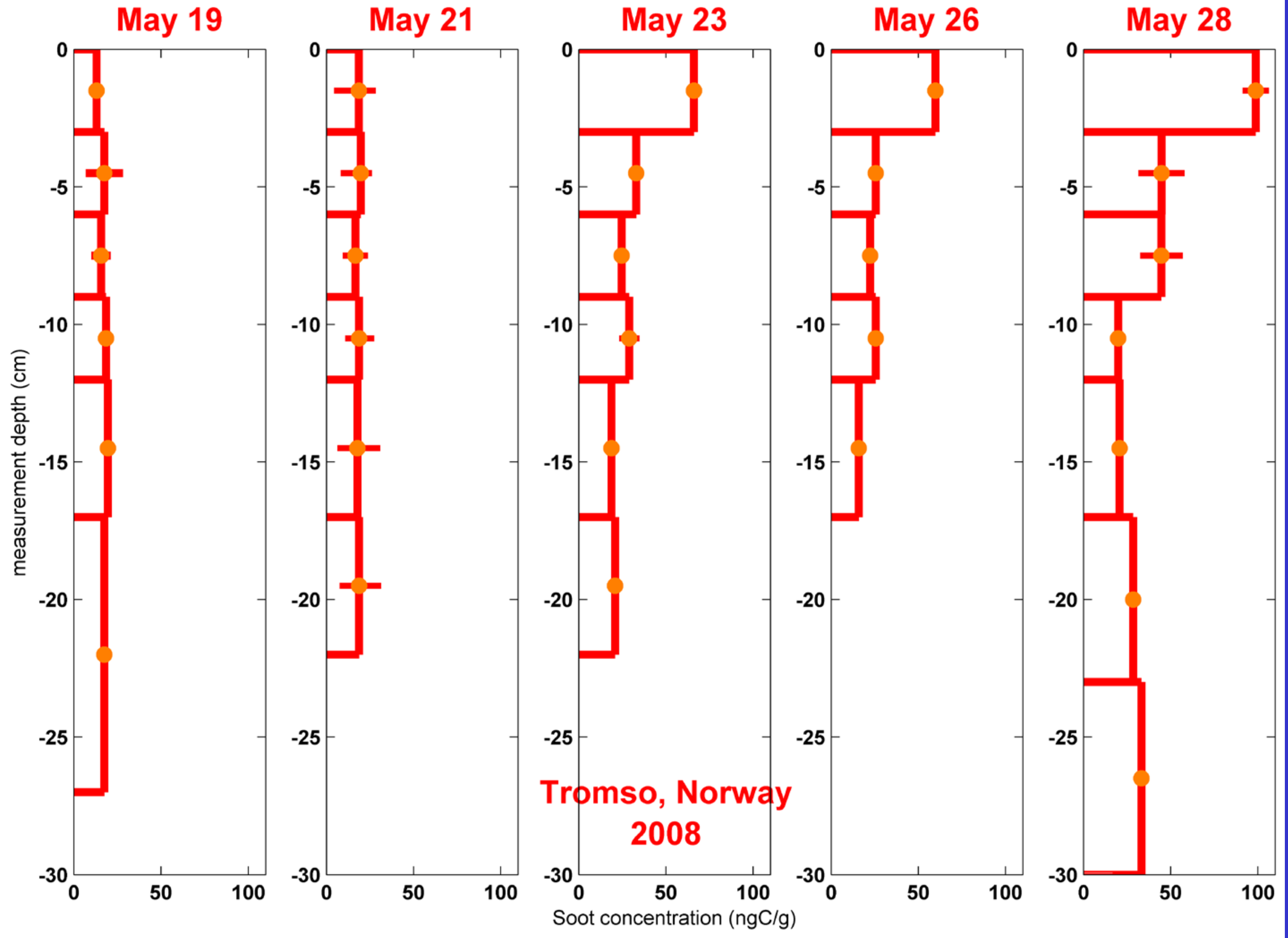
~1 m annual snowfall, ~2 ppb soot

~50 cm melts in July.  But 7 cm new snow at end of July.


Ziploc




(not yet corrected for under-catch by filter; need to multiply by 1.1)





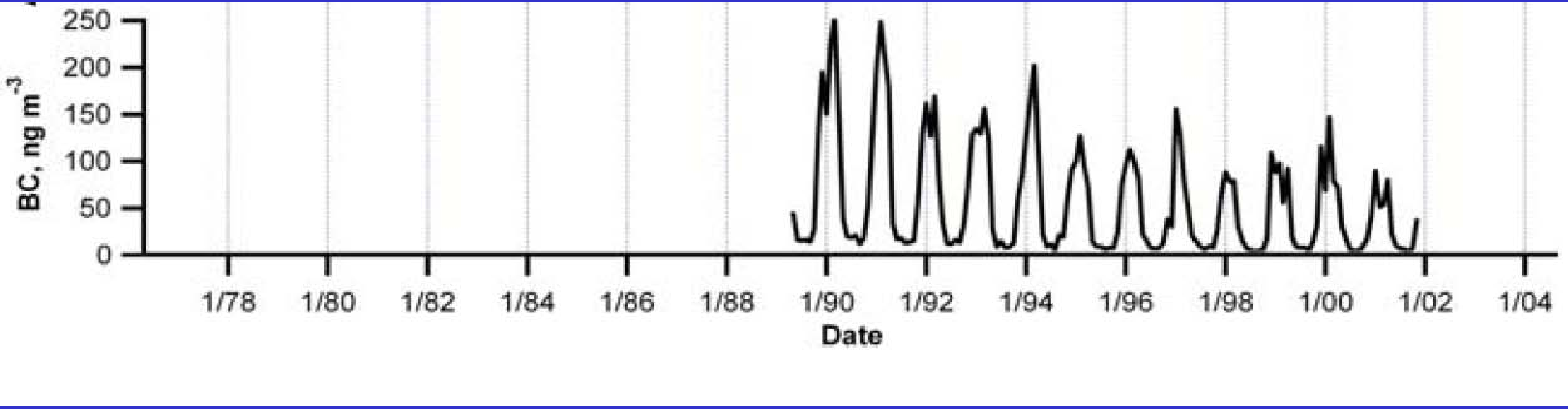

Sanja Forsström (Norwegian Polar Institute)

# Has the Arctic become cleaner or dirtier in 25 years?

Median values of BC in snow (ppb):

| | Clarke & Noone<br>60 samples<br>1983-1984 | Our values<br>1600 samples<br>2005-2009 |
|---|---|---|
| Greenland | 2 | 2-3 |
| Canada | 21 | 12 |
| Alaska | 15 | 12 |
| Arctic Ocean | 32 | 6 |
| Svalbard | 22 | 14 |

(Difference in photometer accounts for factor 1.6, based on Arctic filters from 1984 remeasured with integrating sandwich.)




Black carbon in air at Alert, Canada (83 N, 62 W)

Patricia Quinn et al., *Tellus* 2007

# Summary

- BC in snow is not detected visually.

- Variation in albedo due to variation of snow grain size is much larger than albedo reduction due to BC (and grain size is harder to predict).

- *Greenland* has the lowest BC values in the Arctic (~2 ppb). This value was also found by Clarke & Noone, Petr Chylek et al., Joe McConnell et al.

Median BC values from *Canada* (12 ppb) and *the Arctic Ocean* (6 ppb) are lower now than were reported in 1984.

Highest soot amounts now are in *Arctic Russia*, which was not sampled in 1984.

- Don’t just use median values; BC becomes concentrated at the surface by sublimation, and perhaps also in melting snow.

# Summary (2)

- Our values of BC may be too high (dust; SP2, T/O comparisons in progress)

- Experiments on artificial snowpacks are underway to check the radiative-transfer modeling.

- Arctic snow is often thin and patchy, so albedo may be determined more by snow thickness than by impurities.

- BC in snow is not the cause of rapid Arctic warming of the last 25 years.

## Measurements:

BC content

Albedo change

## Modeling:

Radiative forcing

Climate response

# Global, annual-mean RF estimates

- *Hansen and Nazarenko* (2004): +0.16 W/m$^2$
  - **Superseded by recent estimates from Koch/GISS**
- *Jacobson* (2004): +0.06 W/m$^2$
  - TOA forcing from (early) Bond fossil fuel+biofuel BC
  - Equilibrium warming: +0.06 K
- *Flanner et al* (2007, 2009): +0.04 W/m$^2$
  - TOA forcing from (2004) Bond fossil fuel+biofuel BC
  - Equilibrium warming: +0.12 K
- *Koch et al* (2009): +0.03 W/m$^2$ (all present sources)
  - 1995 – 1890 change from all BC in snow/ice: +0.01 W/m$^2$
  - Equilibrium warming: +0.18 K
- *Rypdal et al* (2009): +0.03 W/m$^2$
  - Emissions from *Cofala et al* (2007)
- *All have efficacies larger than 1*

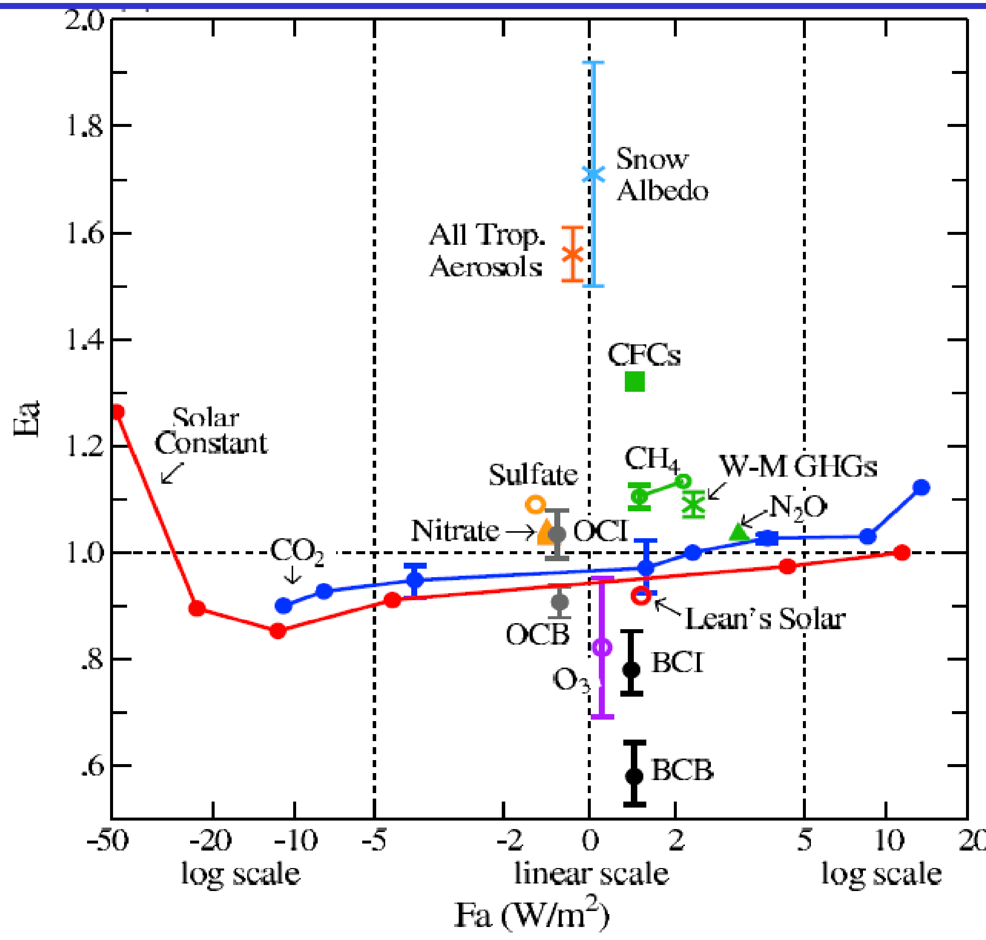
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, D18104, doi:10.1029/2005JD005776, 2005

## Efficacy of climate forcings

J. Hansen,[1,2] M. Sato,[2] R. Ruedy,[3] L. Nazarenko,[2] A. Lacis,[1,4] G. A. Schmidt,[1,4] G. Russell,[1] I. Aleinov,[2] M. Bauer,[2] S. Bauer,[2] N. Bell,[2] B. Cairns,[5] V. Canuto,[1] M. Chandler,[2] Y. Cheng,[3] A. Del Genio,[1,4] G. Faluvegi,[2] E. Fleming,[6] A. Friend,[7] T. Hall,[1,5] C. Jackman,[6] M. Kelley,[7] N. Kiang,[1] D. Koch,[2,8] J. Lean,[9] J. Lerner,[2] K. Lo,[3] S. Menon,[10] R. Miller,[1,5] P. Minnis,[11] T. Novakov,[10] V. Oinas,[3] Ja. Perlwitz,[5] Ju. Perlwitz,[2] D. Rind,[1,4] A. Romanou,[1,4] D. Shindell,[1,4] P. Stone,[12] S. Sun,[1,12] N. Tausnev,[3] D. Thresher,[4] B. Wielicki,[11] T. Wong,[11] M. Yao,[3] and S. Zhang[2]

Received 7 January 2005; revised 3 June 2005; accepted 27 June 2005; published 28 September 2005.

$$E_i = \frac{\Delta T_s / F_i}{\Delta T_s / F(CO_2)}$$




Soot in snow has the greatest efficacy of all climate forcings considered, because:

(1) Peak of soot fallout (Spring) coincides with onset of snowmelt

(2) Melting snow has lower albedo than cold snow

(3) Earlier melt exposes dark underlying surface

(4) Stable atmosphere prevents rapid heat exchange with free troposphere, concentrates warming at surface.

## *Efficacy for soot in snow*

1.8 (Hansen et al. 2005)

**3.2 (Flanner, Zender, Randerson, and Rasch, 2007)**

(1) Albedo reduction causes temperature increase, grain-size growth, reduced albedo.
(2) Soot causes greater albedo reduction in coarse-grained snow
(3) Melting concentrates soot at the surface.

***Global annual mean forcing by soot in snow:***

$F = 0.17 \text{ W m}^{-2}$; $F_e = 0.30 \text{ W m}^{-2}$ (Hansen & Nazarenko 2004)

**$F = 0.05 \text{ W m}^{-2}$; $F_e = 0.16 \text{ W m}^{-2}$ (Flanner et al. 2007)**

Modeling questions:

How is BC removed from the atmosphere into snow?

How does uncertainty in snow grain size propagate to uncertainty in BC's reduction of albedo?

How does sub-grid-scale heterogeneity of snow depth and snow cover affect BC's ability to reduce snow albedo?

What radiative forcing results from a change in surface albedo?

To what extent is snow hidden by
(a) Trees
(b) Clouds

# The forward model process (Doherty and Flanner)