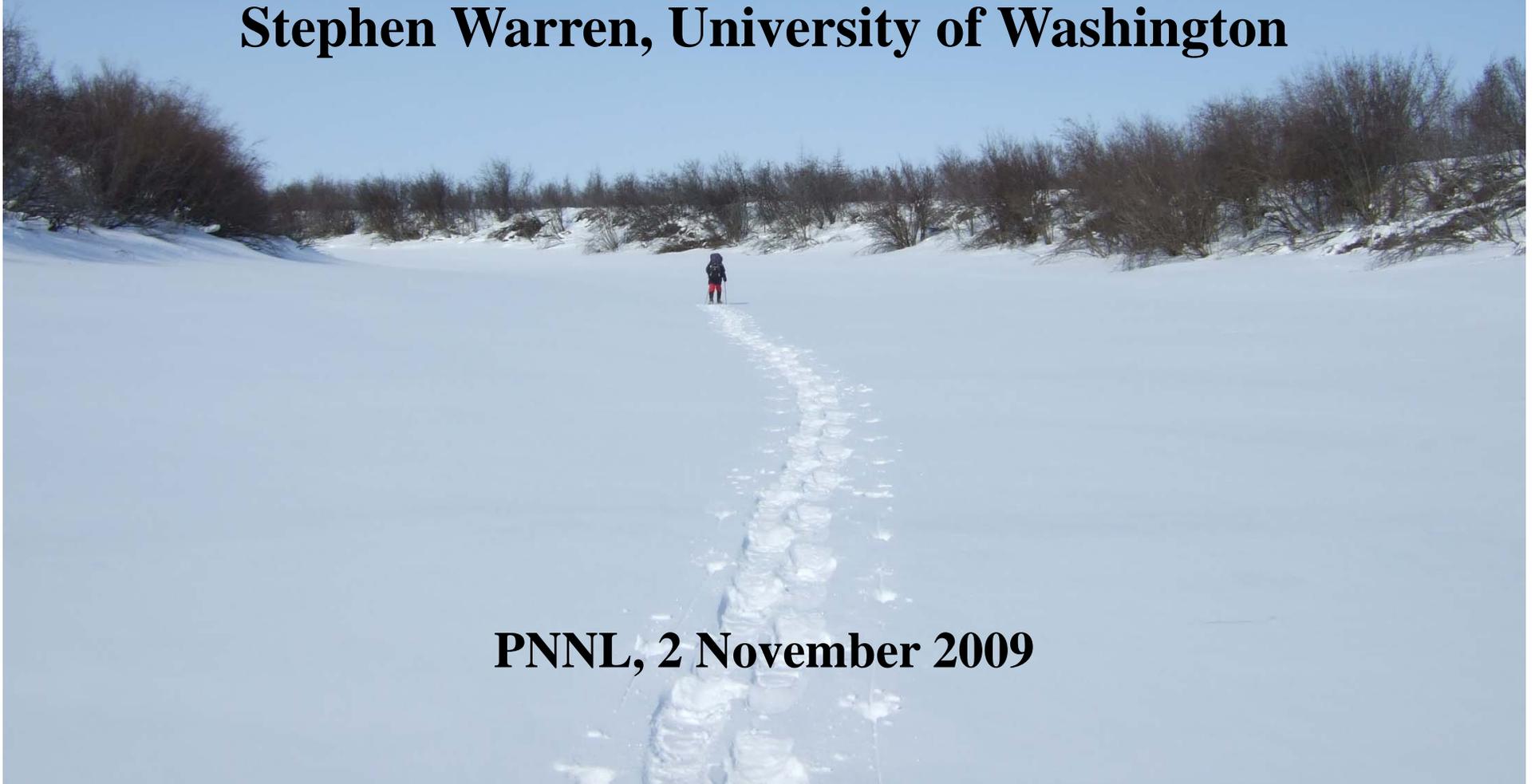


Black carbon in Arctic snow and its effect on surface albedo

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

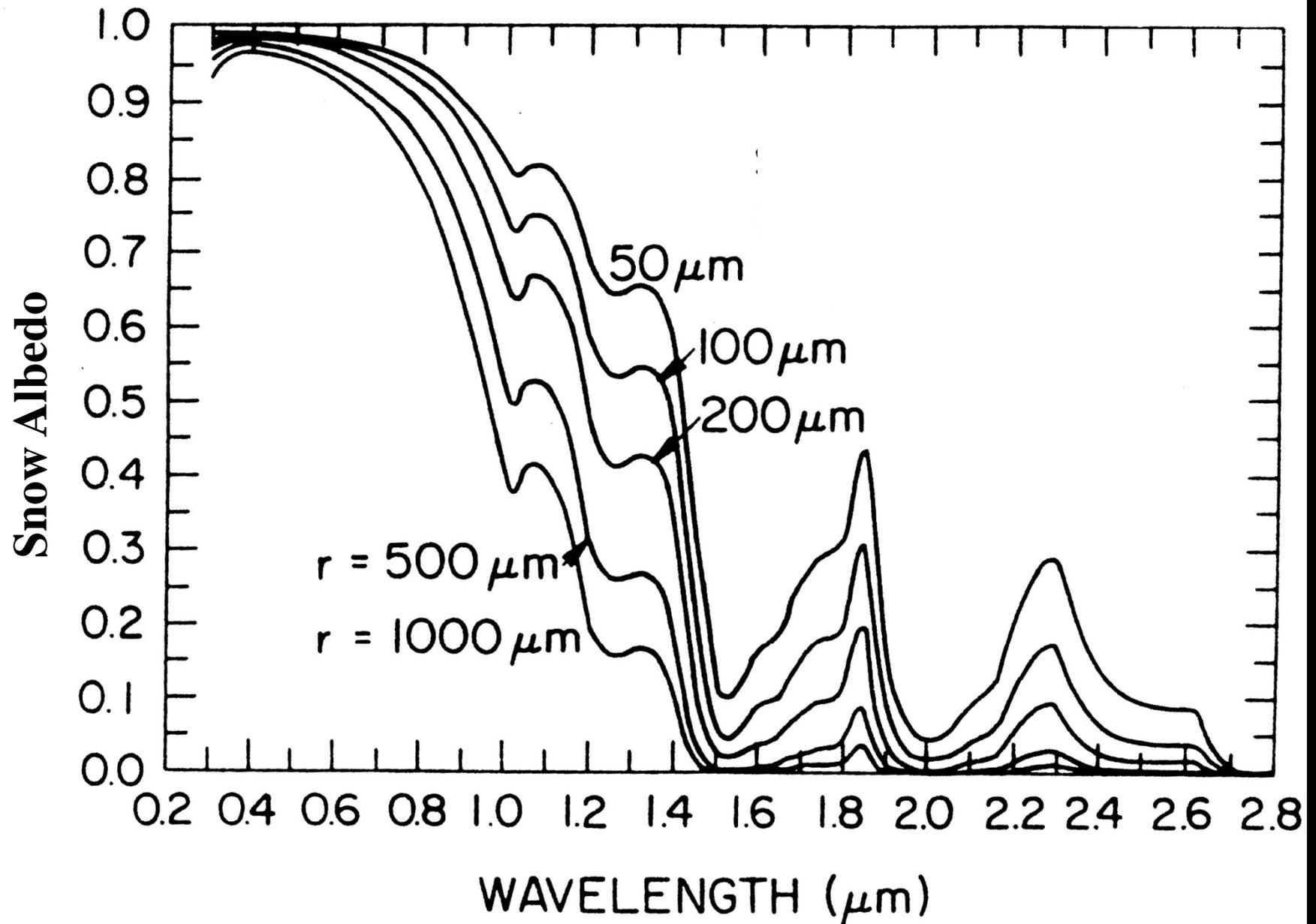
Snow depth (& vegetation in thin snow)

Sun angle

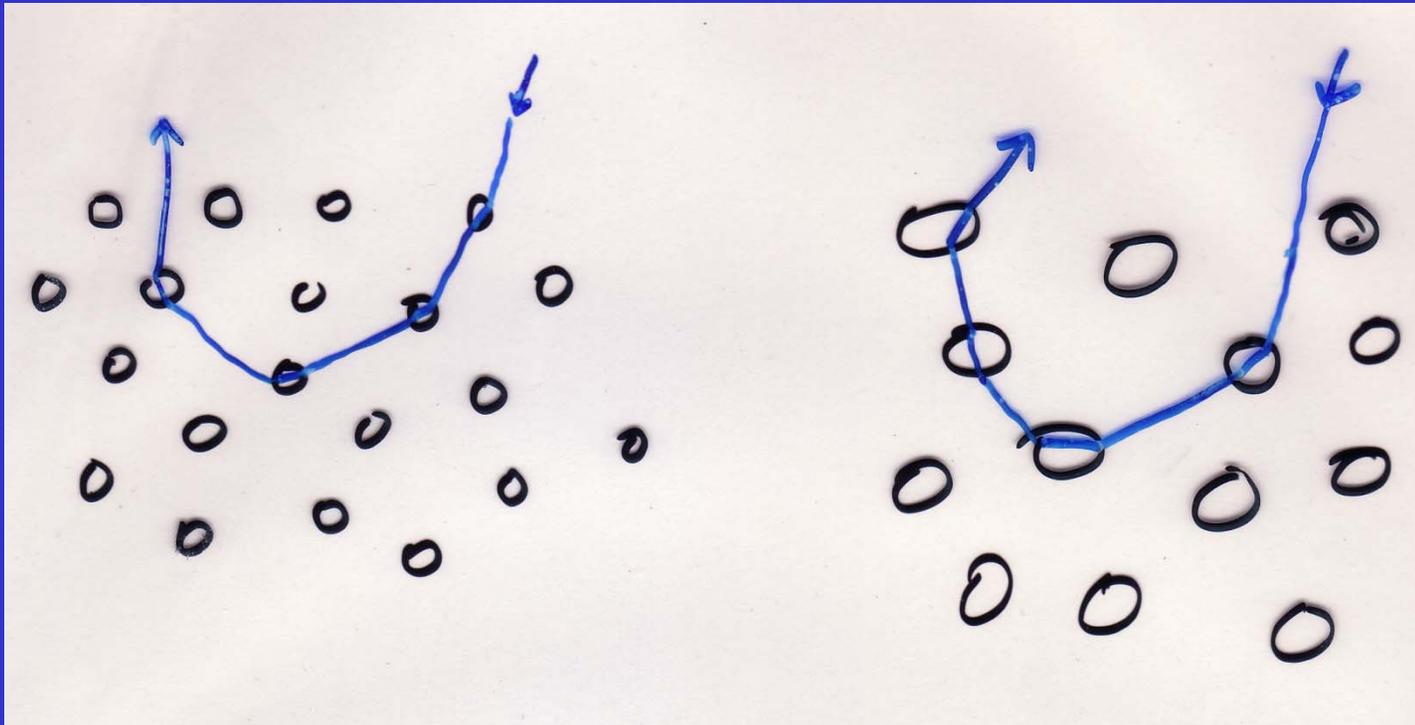
Impurities



Effect of snow grain size (Wiscombe & Warren 1980)



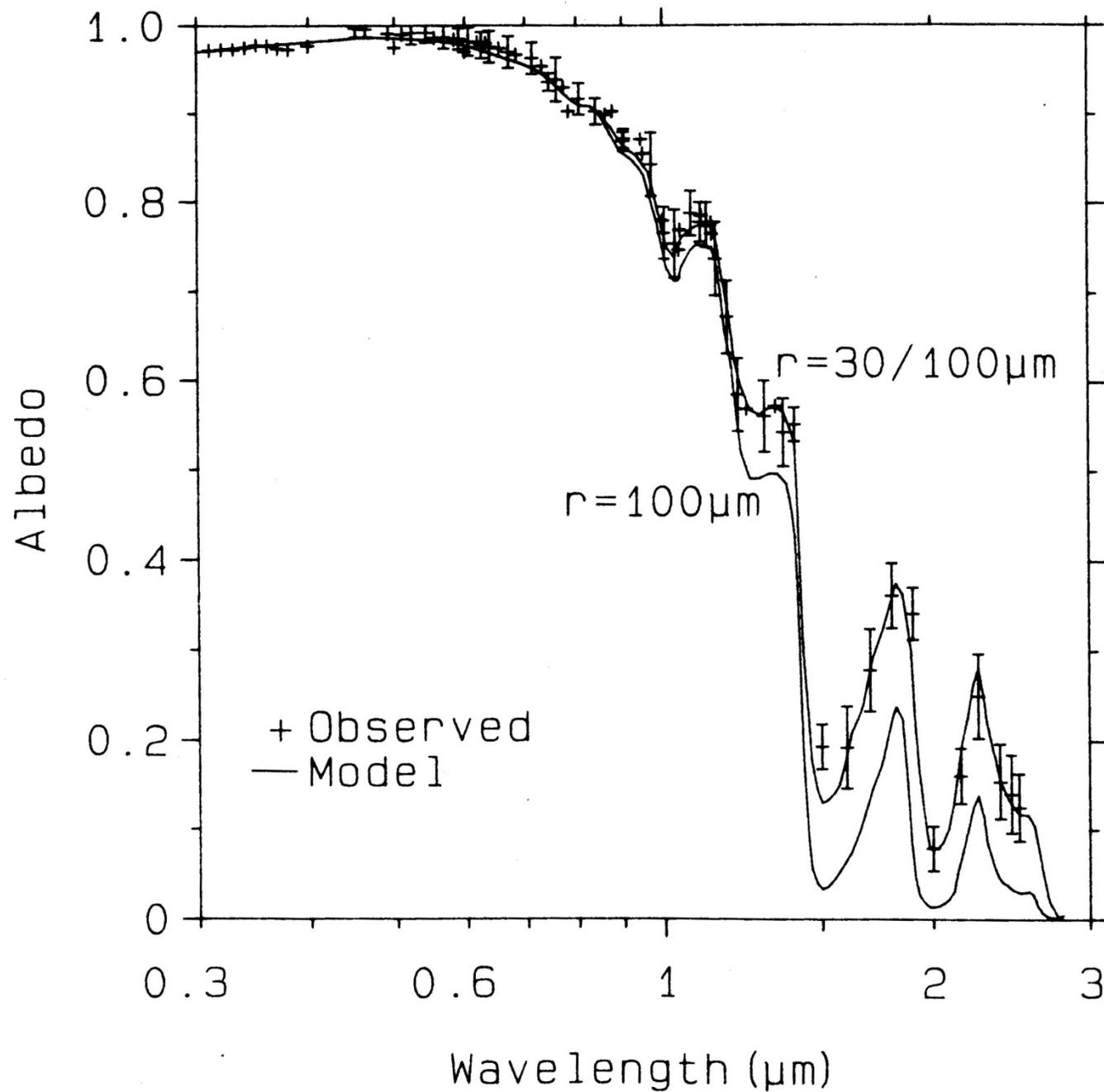
Interaction of sunlight with snow



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)

View 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.

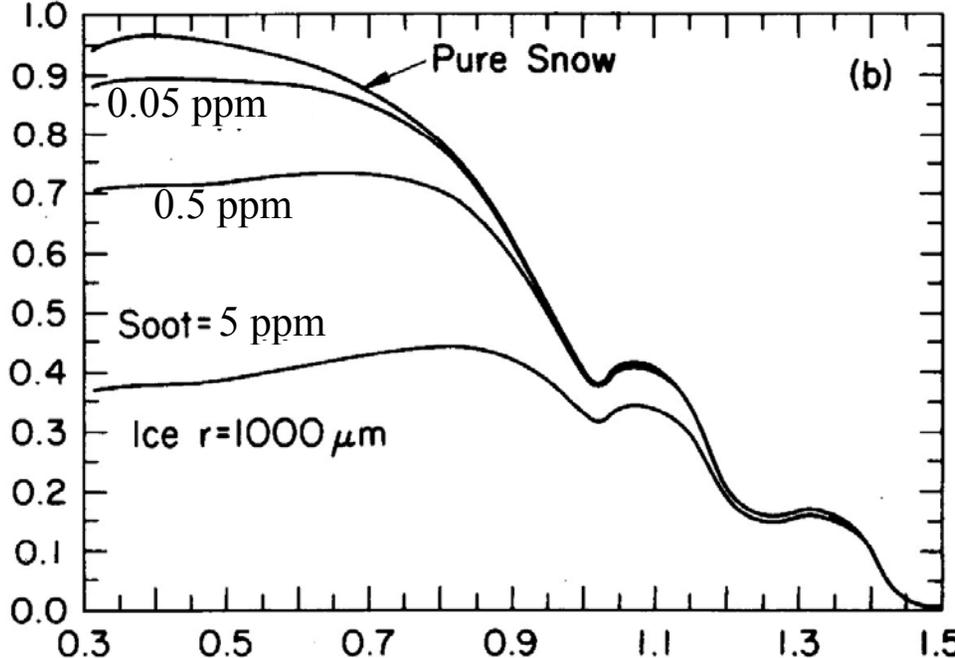
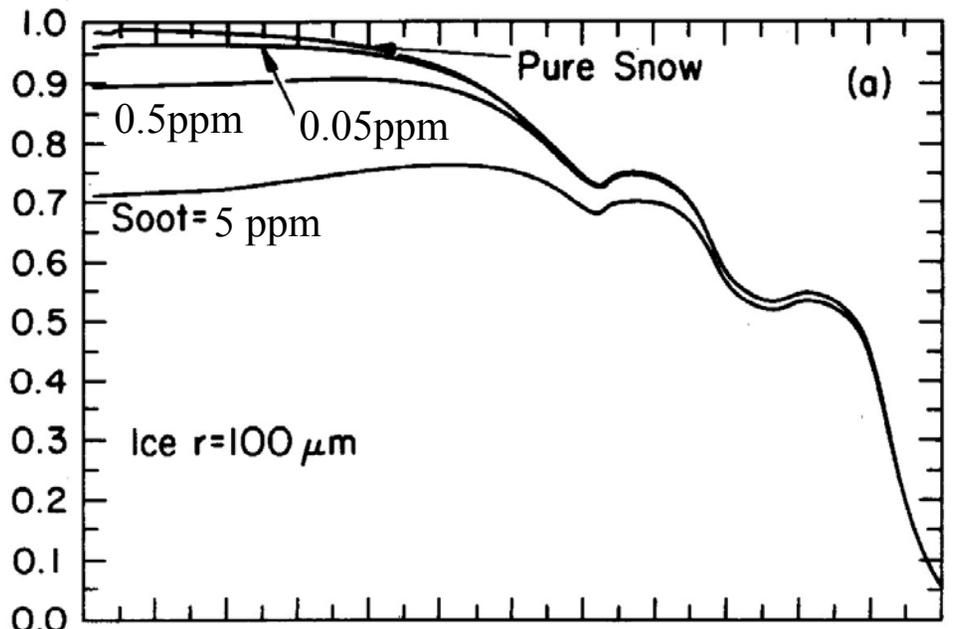
Absorptive impurities:

- Black carbon (soot)

- Brown carbon (organics)

- Soil dust

Snow Albedo



Warren &
Wiscombe
1980

Reduction of snow albedo α

by snow aging $\Delta\alpha = 12\%$

	<i>new snow</i>	<i>old melting snow</i>
grain radius:	100 μm	1000 μm
broadband albedo:	83%	71%

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

$\Delta\alpha \approx 0.5\%$ for $r = 100 \mu\text{m}$

$\Delta\alpha \approx 1.6\%$ for $r = 1000 \mu\text{m}$

typical values of BC in Arctic snow (ppb):

Greenland	2-3
Canada	10
Siberia	20-25

Reduction of snow albedo α

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typical values of BC in Arctic snow (ppb):

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Canada	10
Siberia	20-25

*Small 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.

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

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

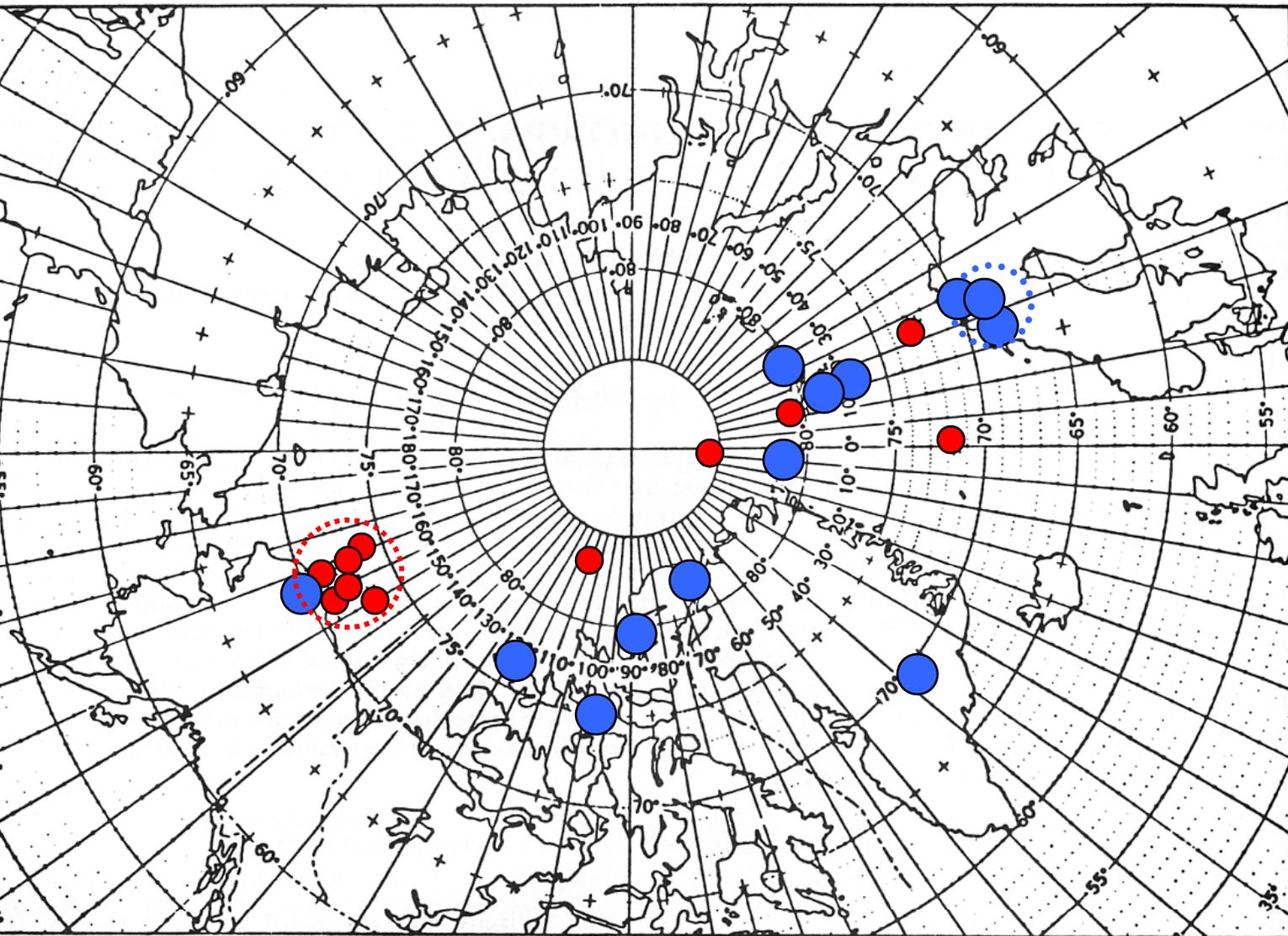


Fig. 1. Map of Arctic sampling locations for the University of Washington atmospheric (●) aircraft samples and snowpack

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

Marke & 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.

climate forcing via snow and ice albedos

James Hansen*^{†‡} and Larissa Nazarenko*[†]

*NASA Goddard Space Administration Goddard Institute for Space Studies and [†]Columbia University Earth Institute, 2880 Broadway, New York, NY 10025

Presented by James Hansen, November 4, 2003

Estimates for the effect of soot on snow and ice albedos (Arctic and 3% in Northern Hemisphere land areas) indicate a net forcing of +0.3 W/m² in the Northern Hemisphere. The efficacy of this forcing is ≈2, i.e., for a given forcing it is twice as effective as CO₂ in altering global surface air temperature. This forcing may have contributed to global warming of the late 20th century, including the trend toward early springs in the Northern Hemisphere, thinning Arctic sea ice, and melting land ice. If, as we suggest, melting ice and sea level rise are signs of dangerous anthropogenic interference with the climate system, then reducing soot emissions, thus restoring snow and ice albedo to pristine high values, would have the double benefit of reducing global warming and raising the global temperature level above the dangerous anthropogenic interference threshold. However, continued emissions of greenhouse gases have been the main cause of global warming and will be the predominant climate forcing in the 21st century.

Global warming | air pollution | climate change | sea level rise

Carbonaceous 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 CO₂, 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.



east of Vorkuta, Russia
370 ppb



Greenland Ice Sheet
2 ppb



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

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

Never 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

Arctic snow

Great Plains of North America

Steppes of Asia: Kazakhstan, Mongolia, Xinjiang, Tibet

Ice

Arctic ocean in summer

Mountain glaciers are too small to be important for climate, but they

Summary of strategy

600 snow samples, only a few albedo measurements)

Dynamic 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:*

Collect snow samples, melt and filter them. Analyze

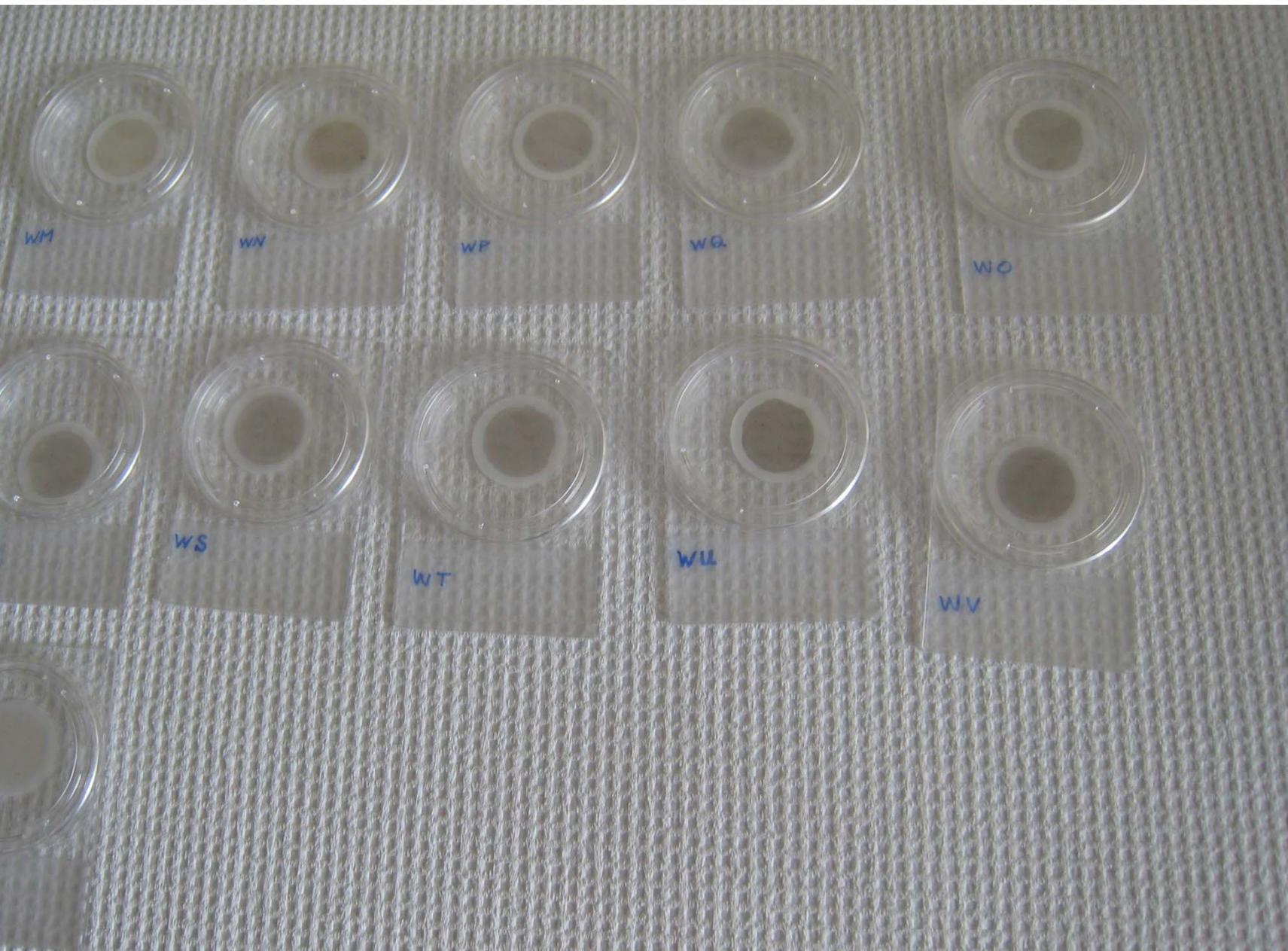
the filters photometrically for

a) BC concentration

b) fraction of absorption due to other (“brown”) constituents (organic carbon, soil dust).

Use the BC amount together with snow grain size in a

radiative transfer model to compute albedo reduction



Other methods to measure BC:

Thermo-Optical (controlled combustion)

Single-particle soot photometer (SP2)

Advantages of filter method:

is 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

apparatus at Ny-Alesund, Svalbard









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

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



$$k_{\text{abs}} = B_a C$$

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 $B \approx 6 \text{ m}^2/\sigma_{33}$

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.

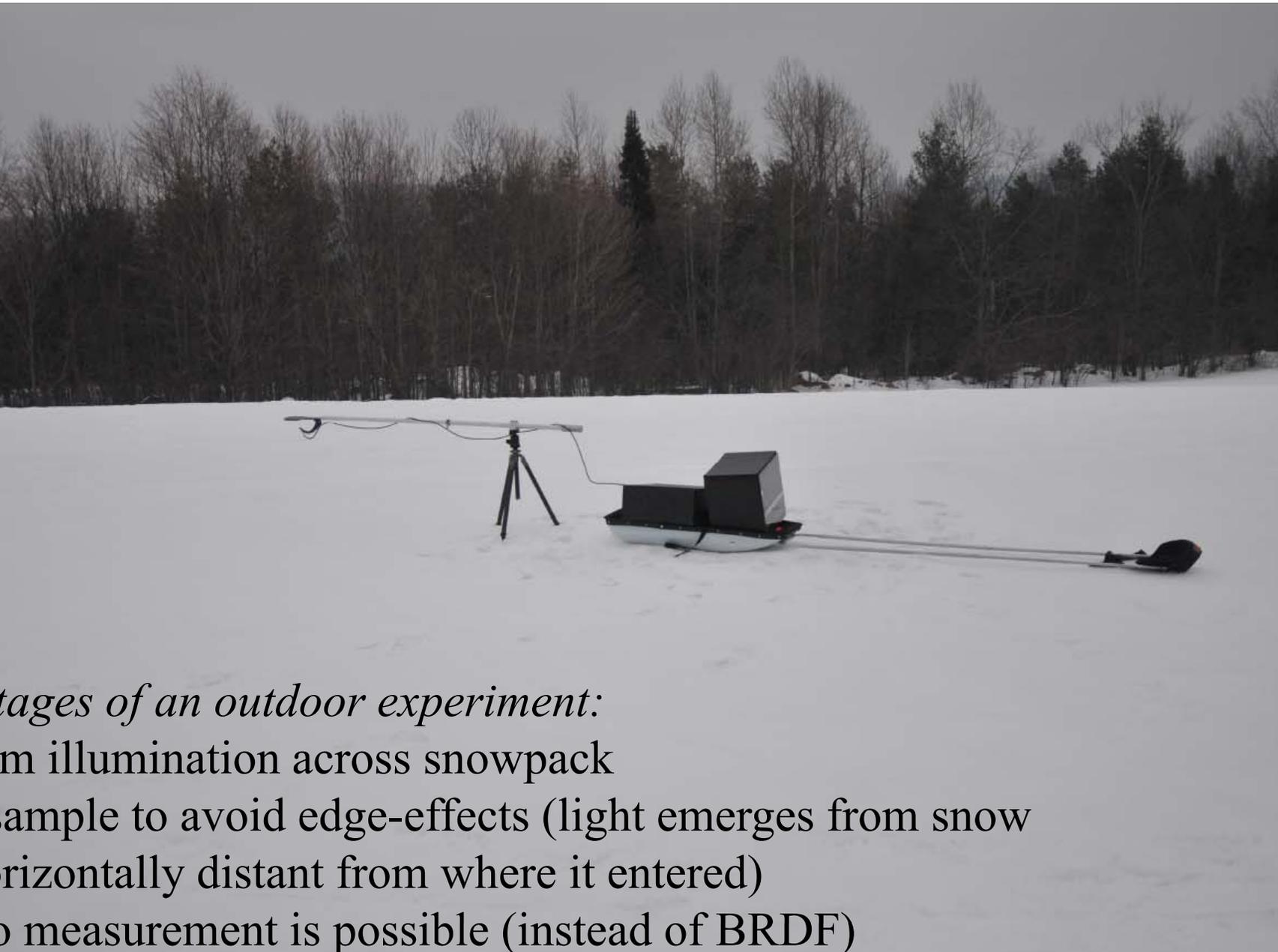
Cold-room laboratory:

Charlie Zender

Tom Kirchstetter (LBL)

Outdoors:

Richard Brandt

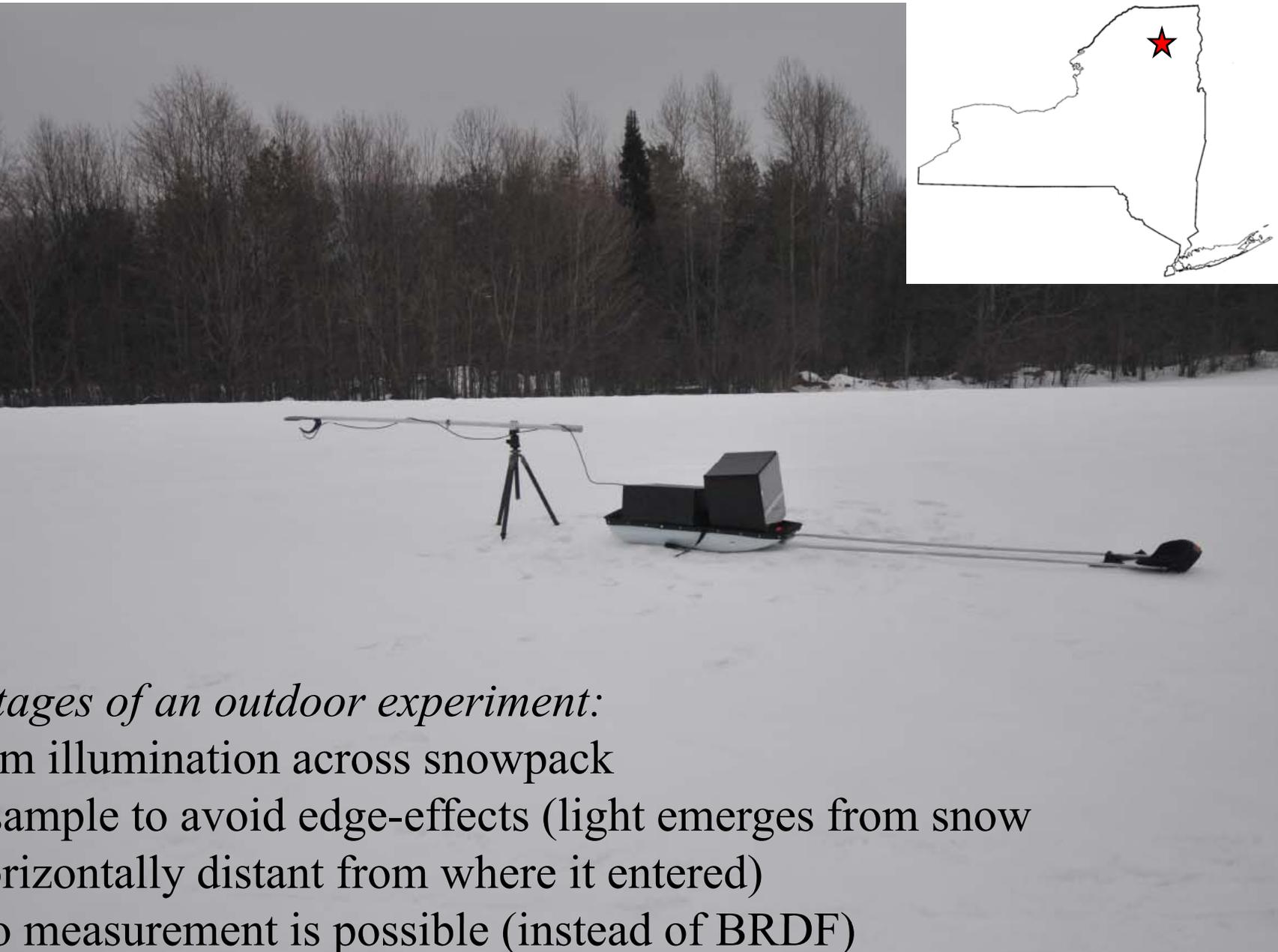


Advantages of an outdoor experiment:

Uniform illumination across snowpack

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

Direct measurement is possible (instead of BRDF)



Advantages of an outdoor experiment:

Uniform illumination across snowpack

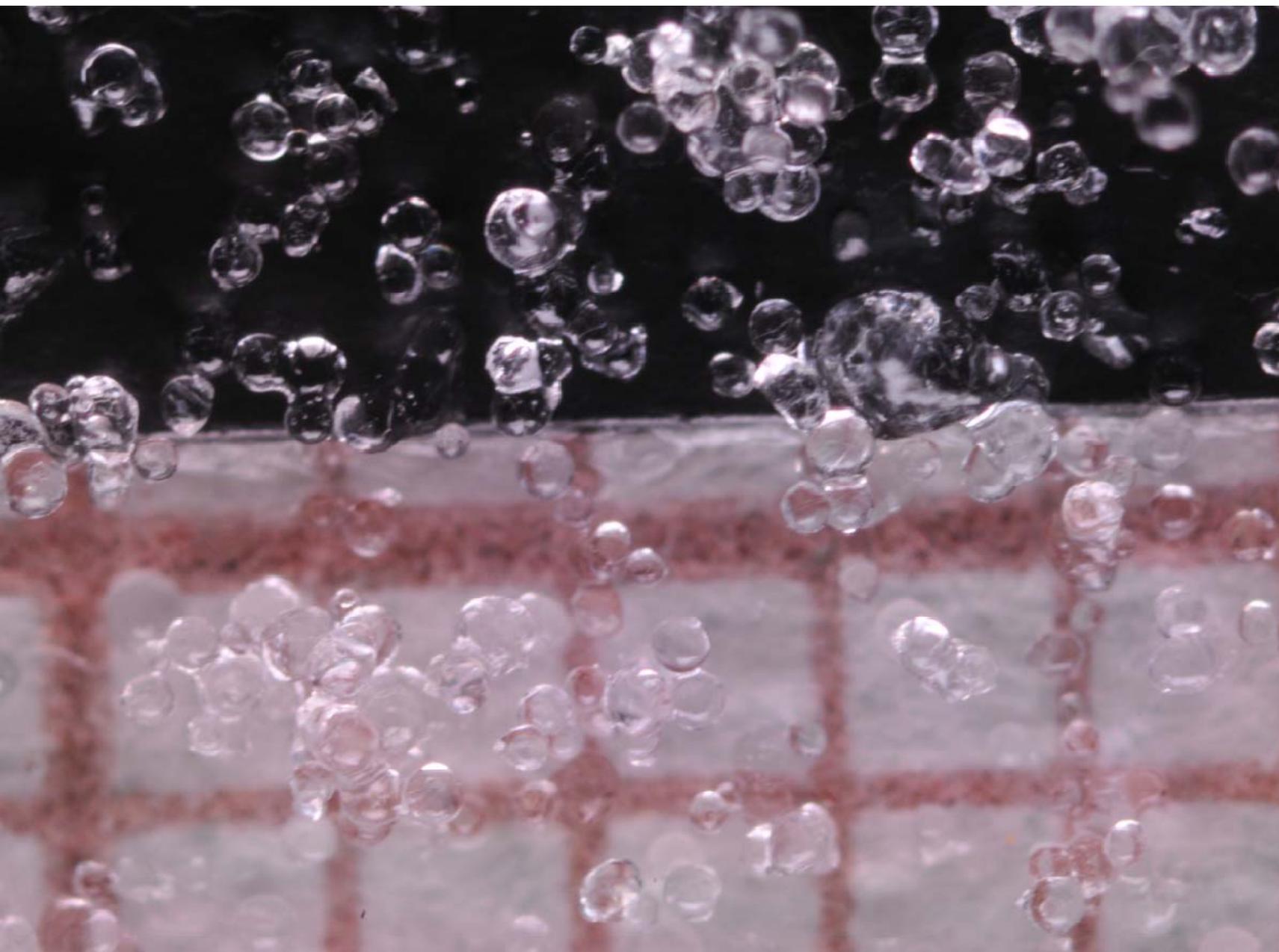
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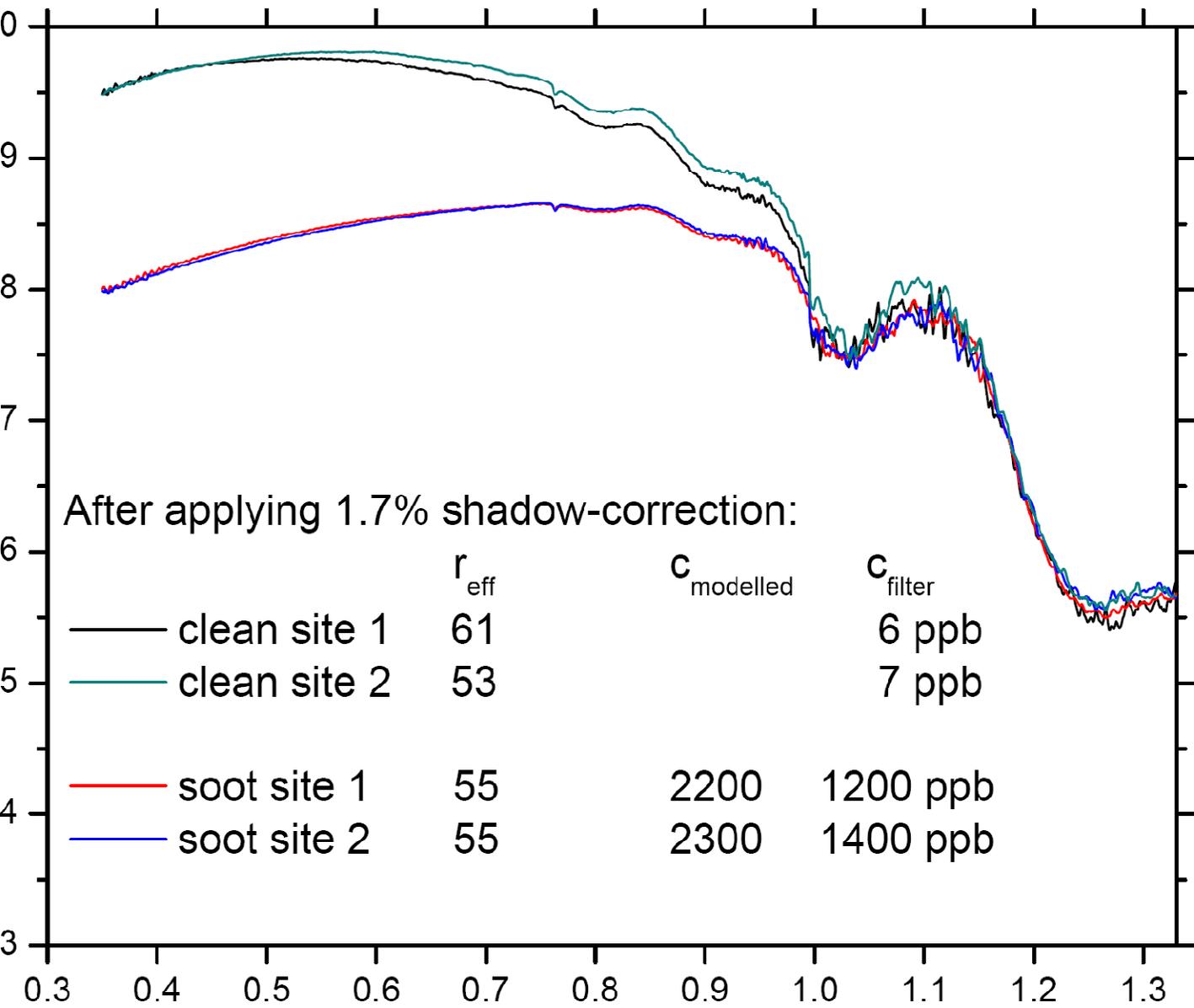








5 Feb 2009 nominal 1ppm Aquablack 162



Measurement

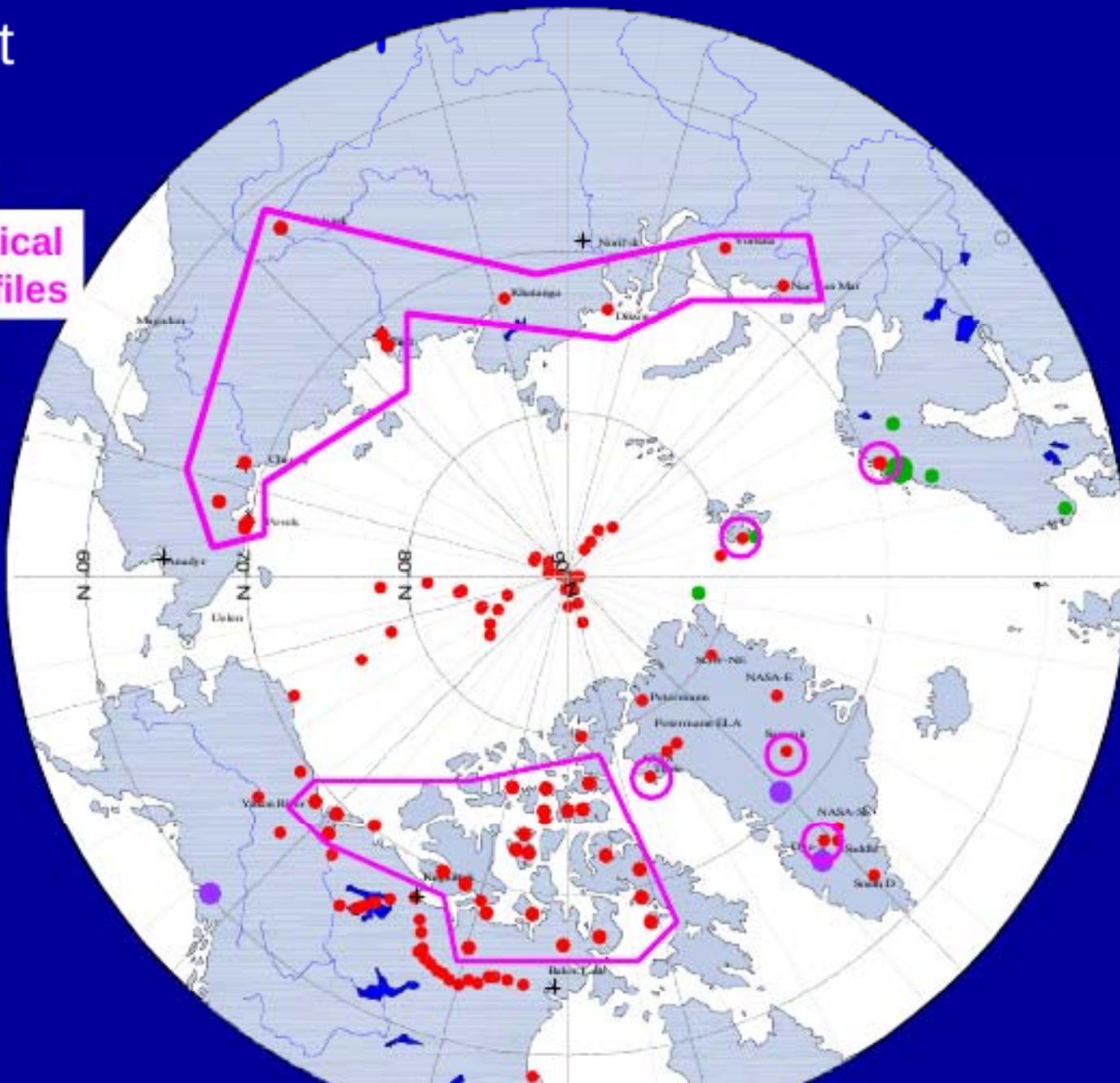
S

laser-optical

metric

ice cores

vertical profiles





Driving on the Laptev Sea, near the Lena Delta

km west of Cherskiy, in the Kolyma lowland

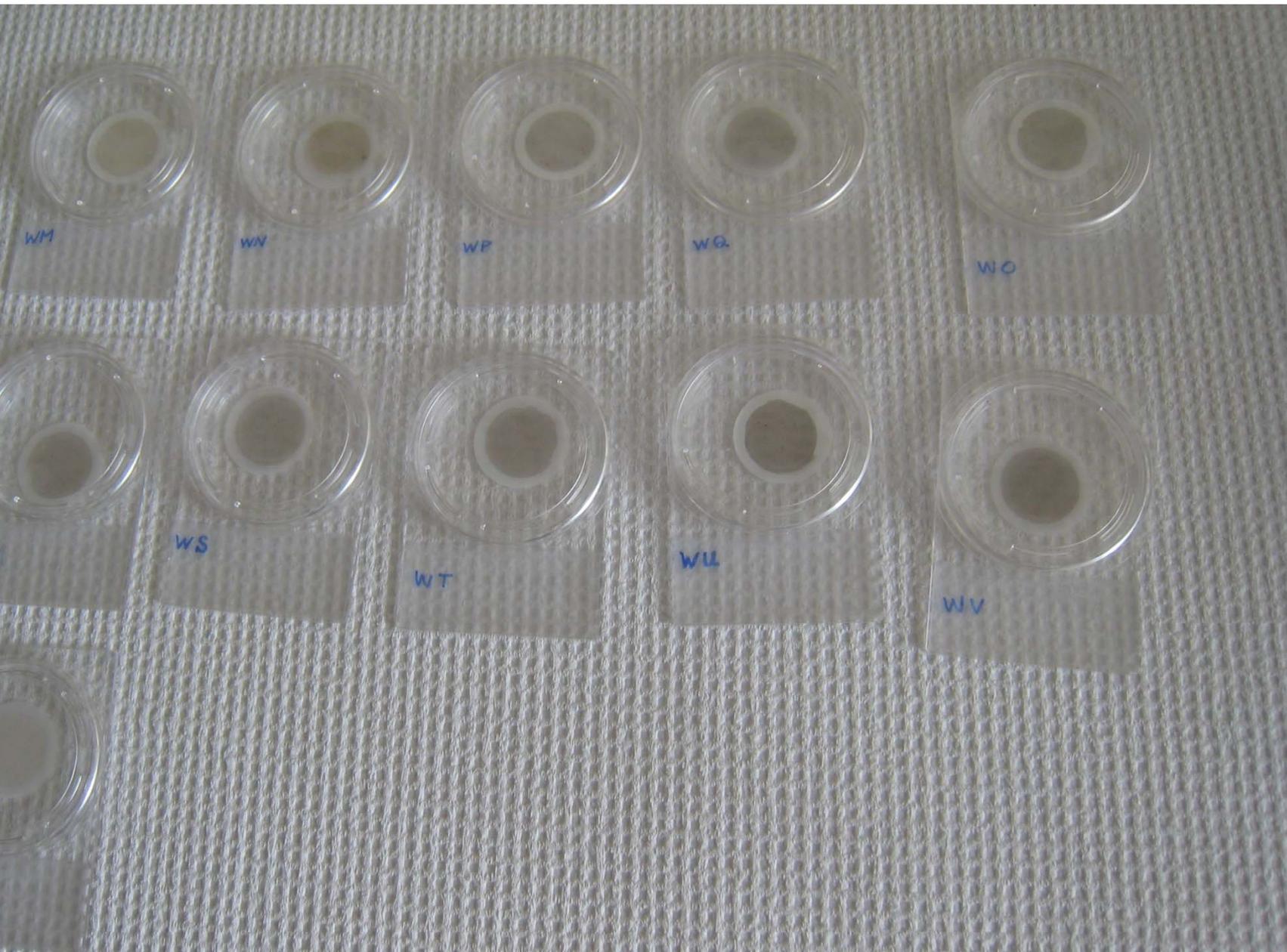


the Lena River west of Tiksi (Yakutia)



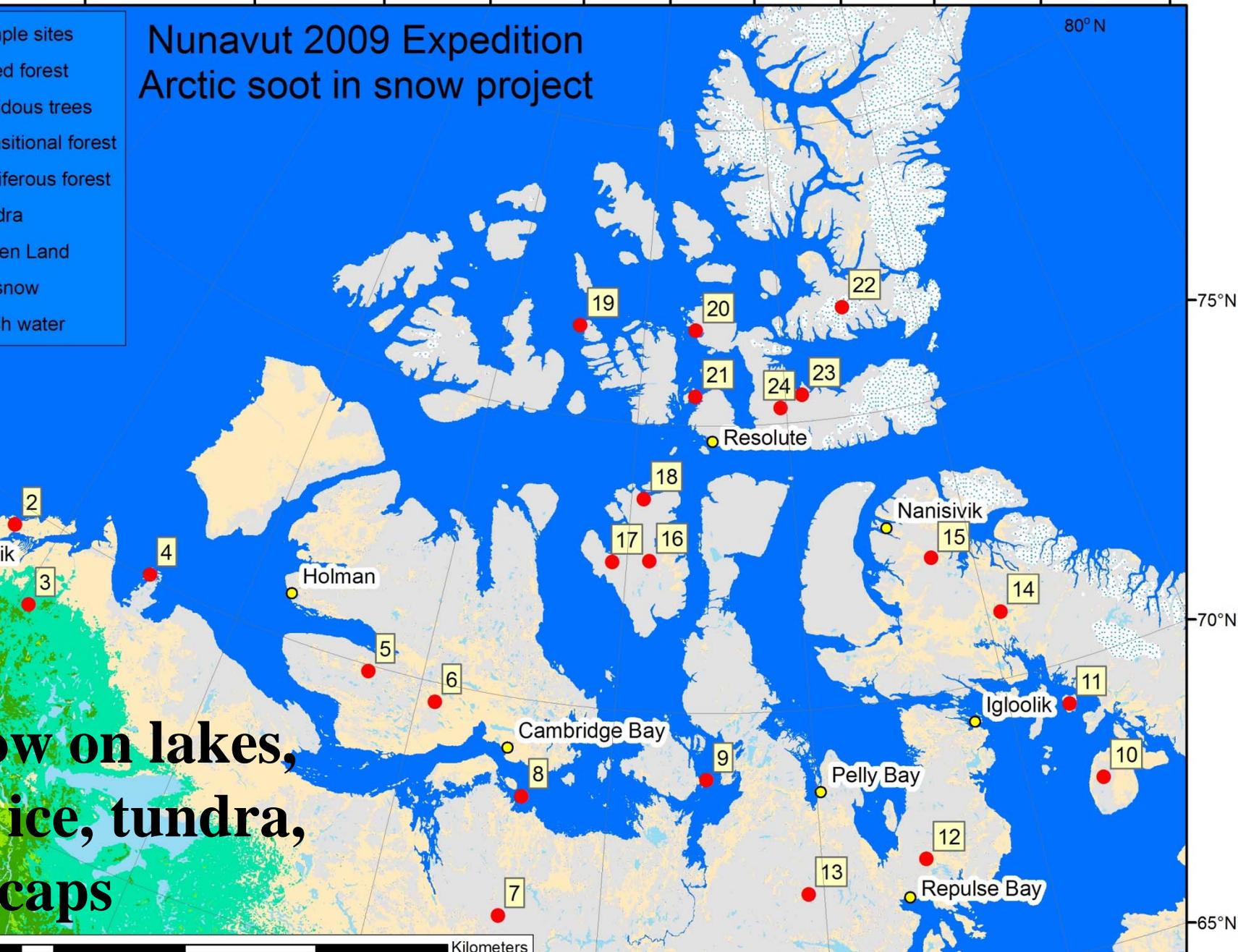
Snowmelt-filtering lab in Tiksi hotel





Filters from snow near Tiksi

Nunavut 2009 Expedition Arctic soot in snow project



ow on lakes,
ice, tundra,
caps

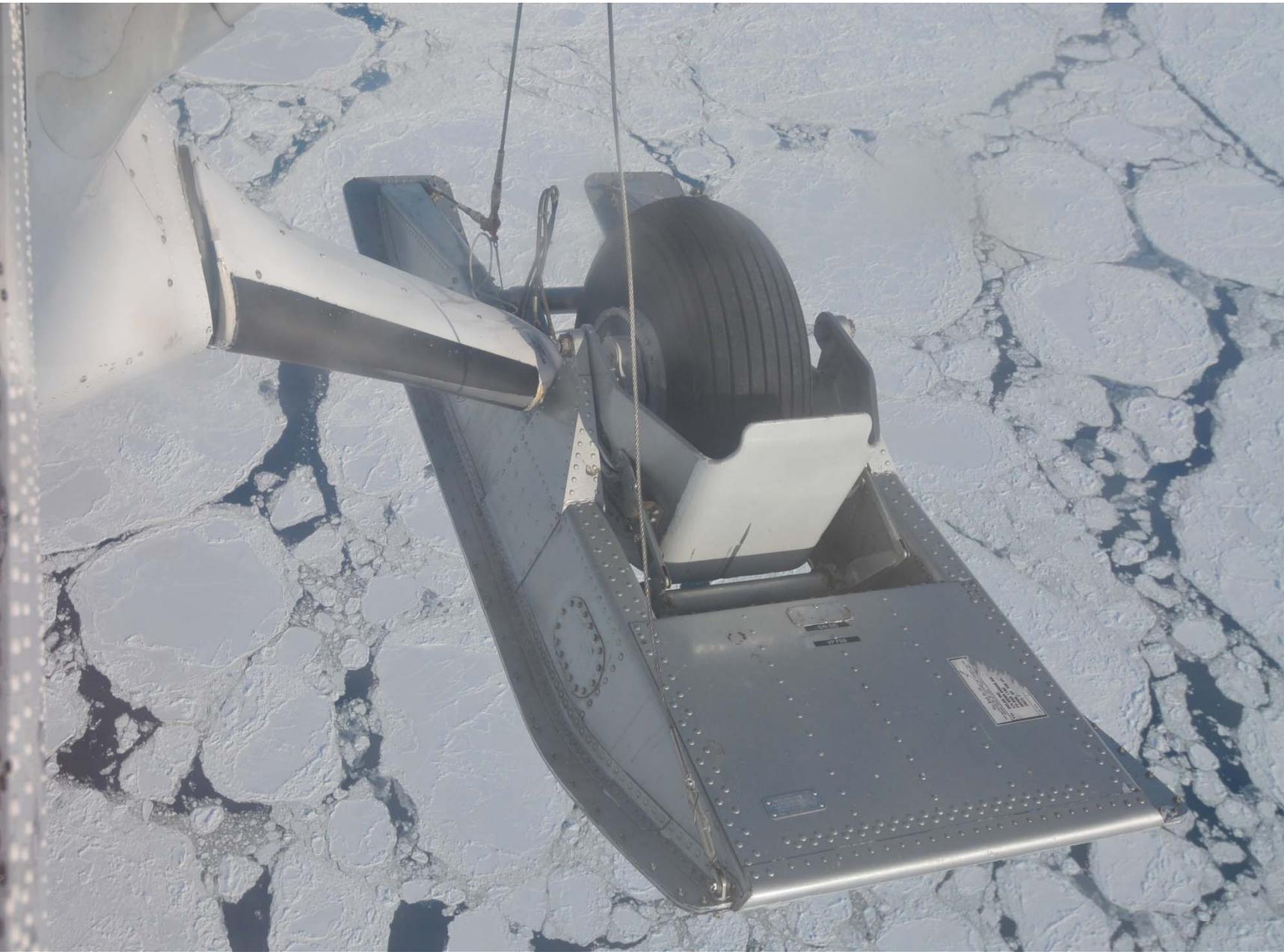
Eastern Siberia, Spring 2008

350 snow samples in 2 months

Arctic Canada, Spring 2009

306 snow samples in 2 weeks





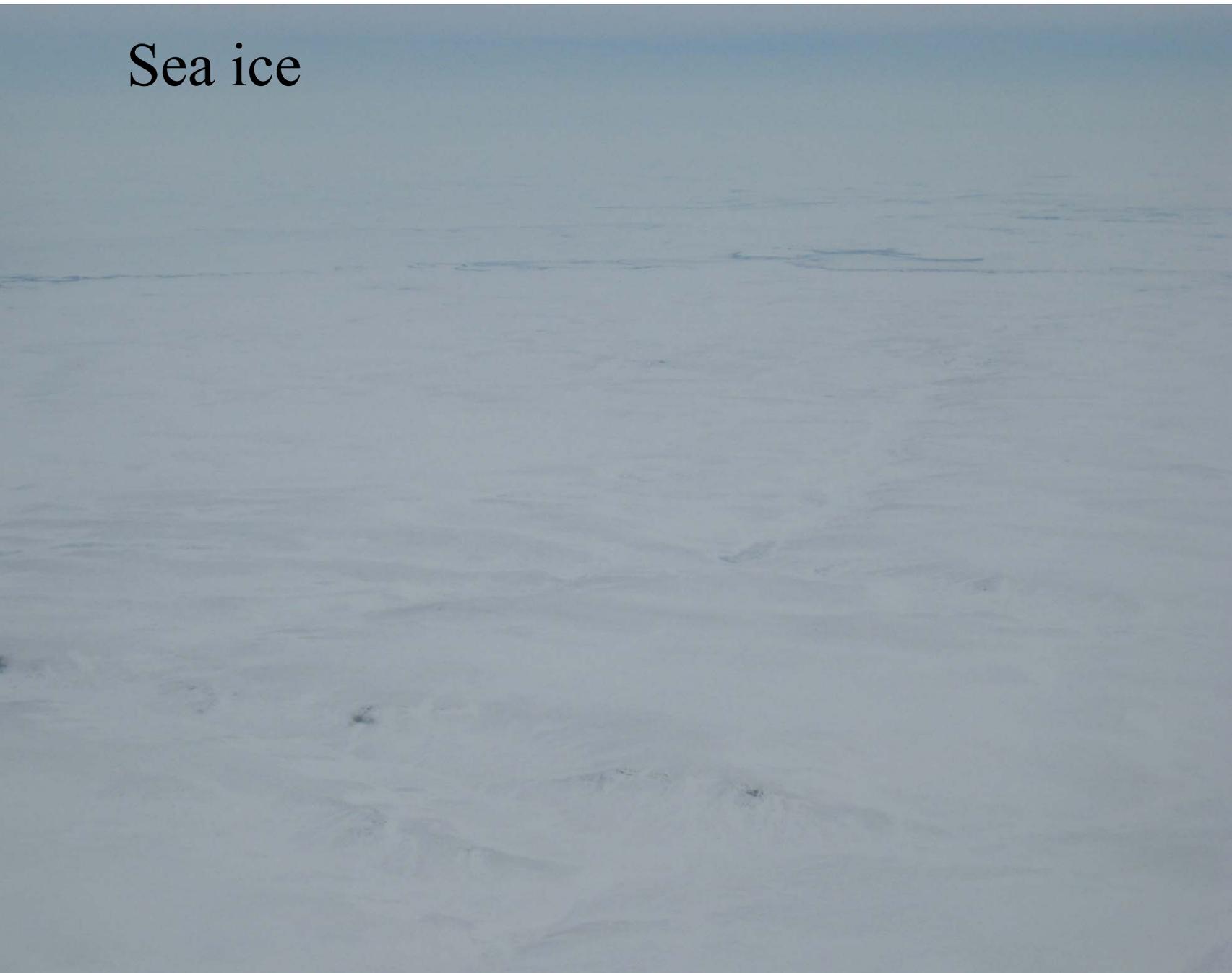






Southwest Devon Island

Sea ice





Thick snow on sea ice

Thin snow on sea ice



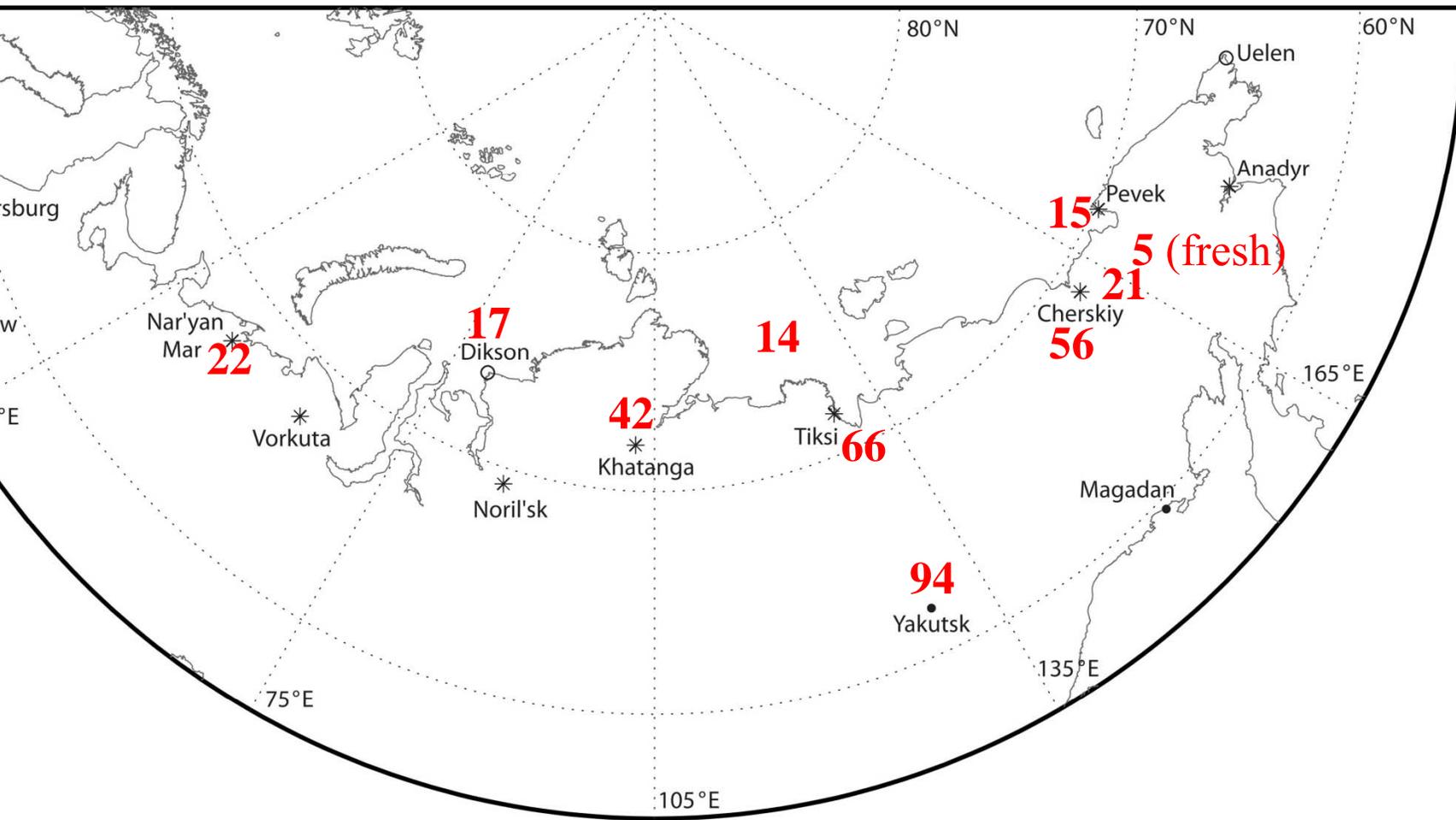






BC concentrations (ng/g *or* ppb)

LOCATION	MEDIAN	LOCATION	MEDIAN
Russia, 2007 (western)	33	Barrow (Alaska), 2008	12
Russia, 2008 (eastern)	20	Greenland, AWS	3
Canada, 2007 (subarctic)	15	Greenland, Dye-2	2
Canada, 2009 (arctic)	9	North Pole Vicinity, 2008	6
		Svalbard, 2007	11

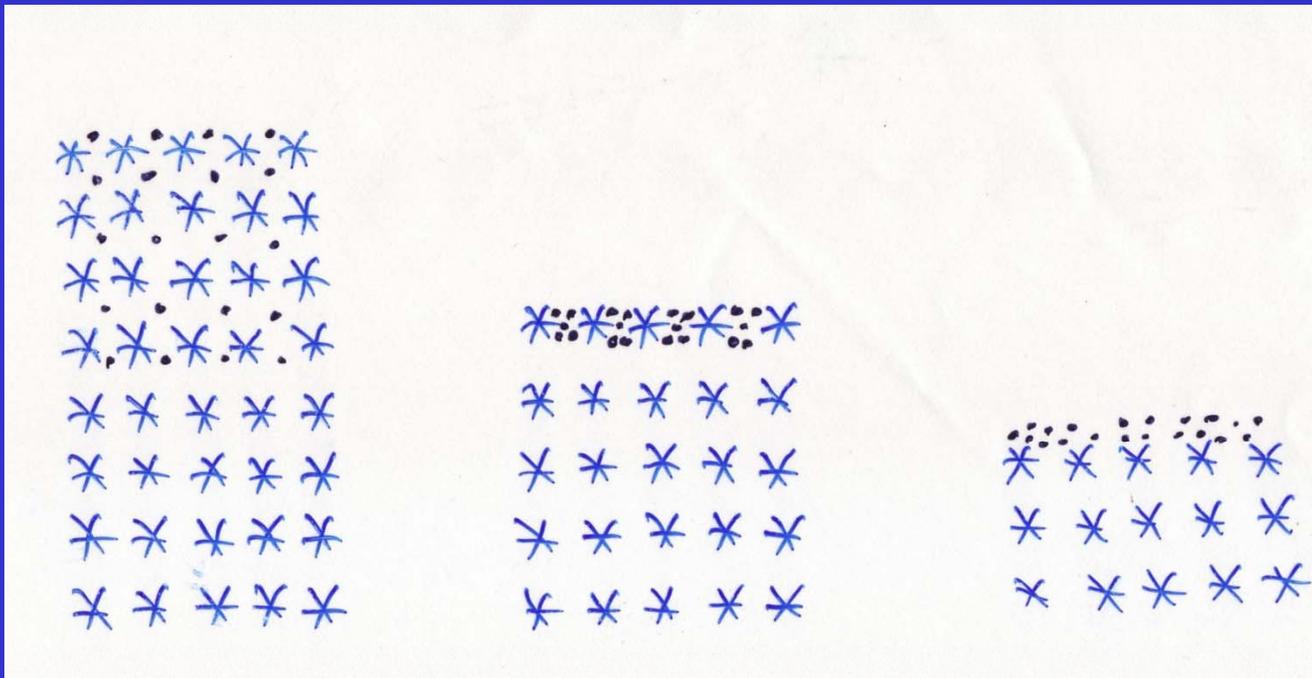


Arctic Russia March-May 2007, 2008

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

Cherskiy: 56 ppb surface, 20 ppb subsurface. Heavy snowfall in

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



reculation zone of southern Greenland July 2008



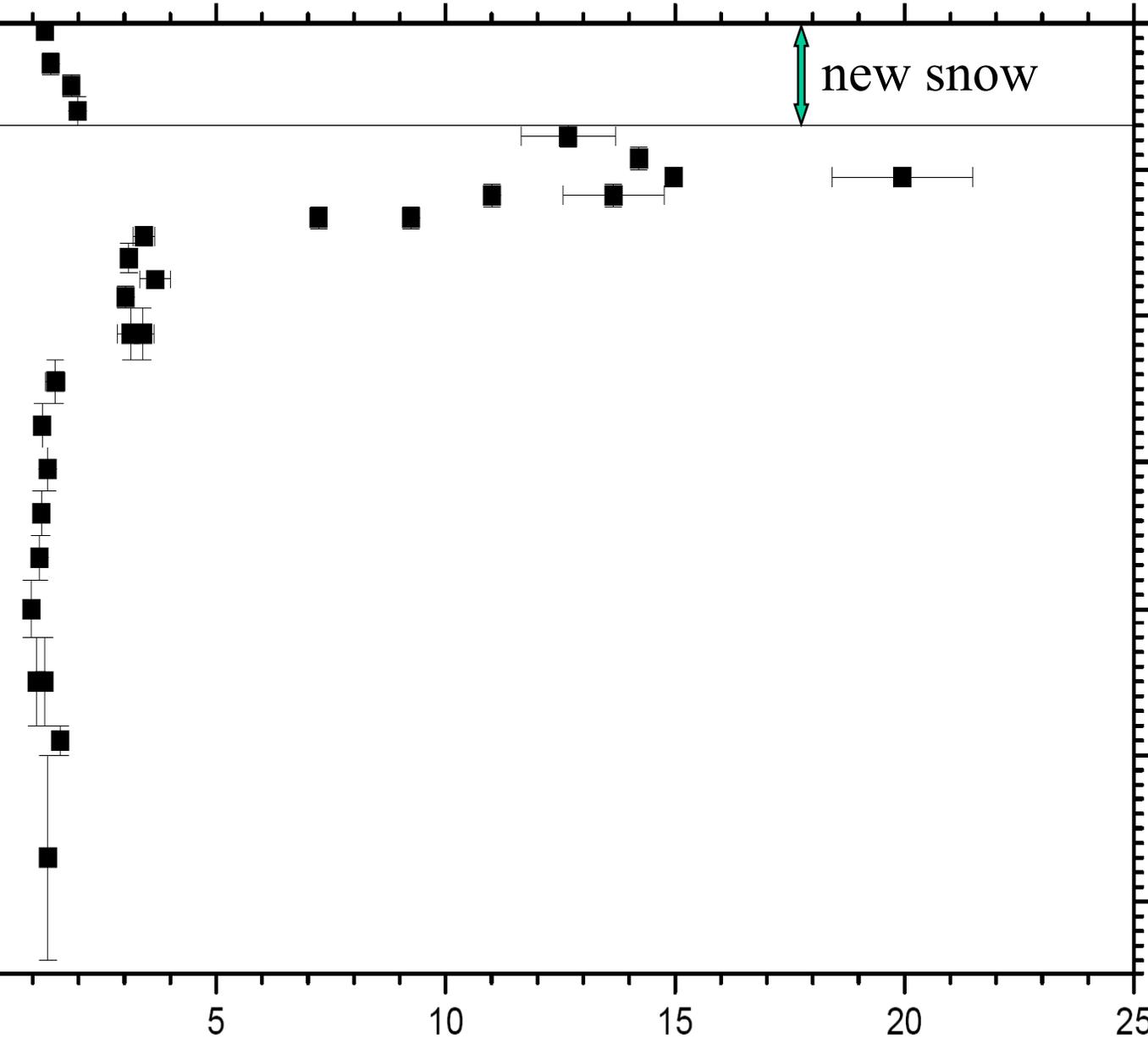
km south (upwind) of Dye-2 station
m annual snowfall, ~2 ppb soot

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

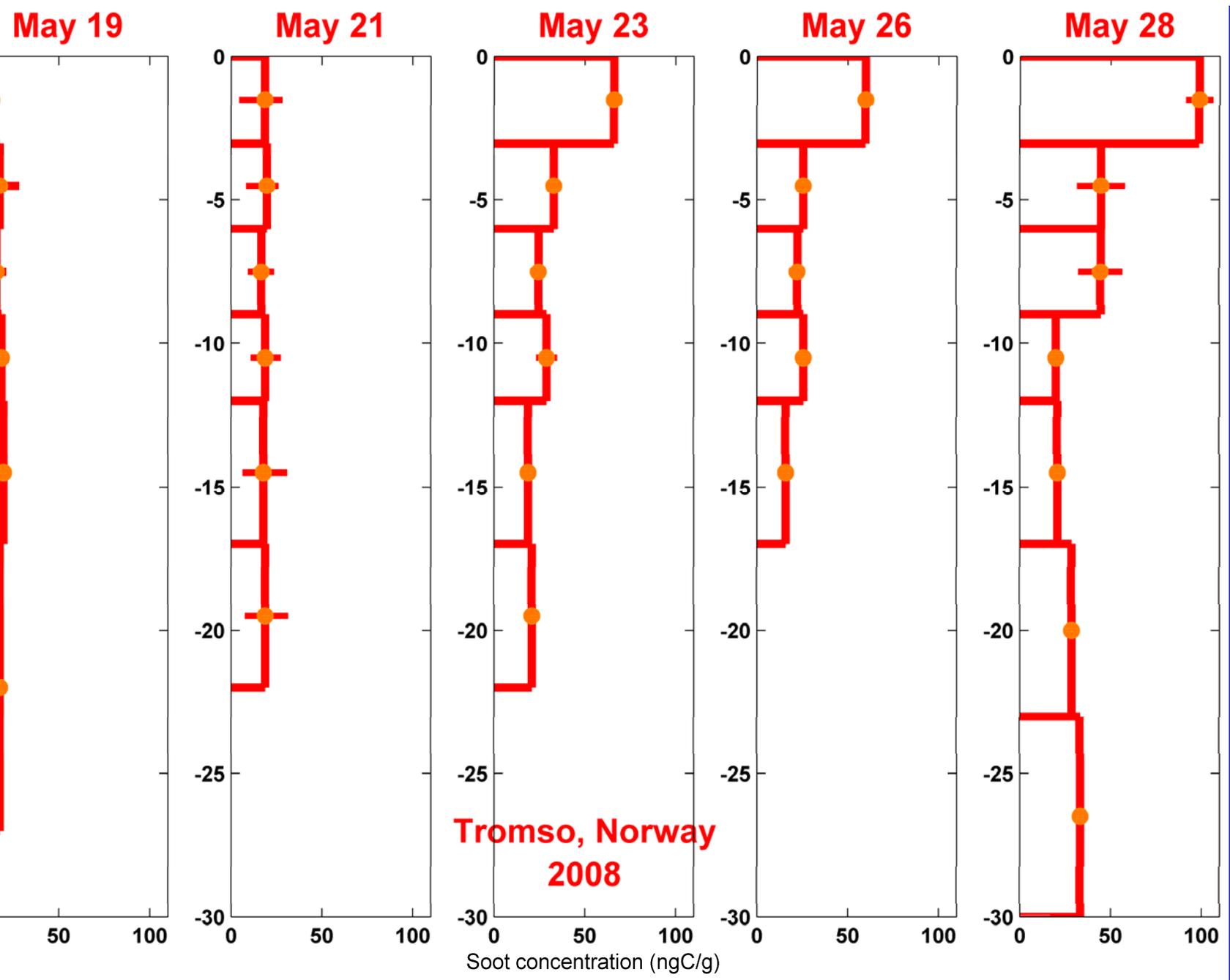




24 July 2008 60 km south of Dye-2



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

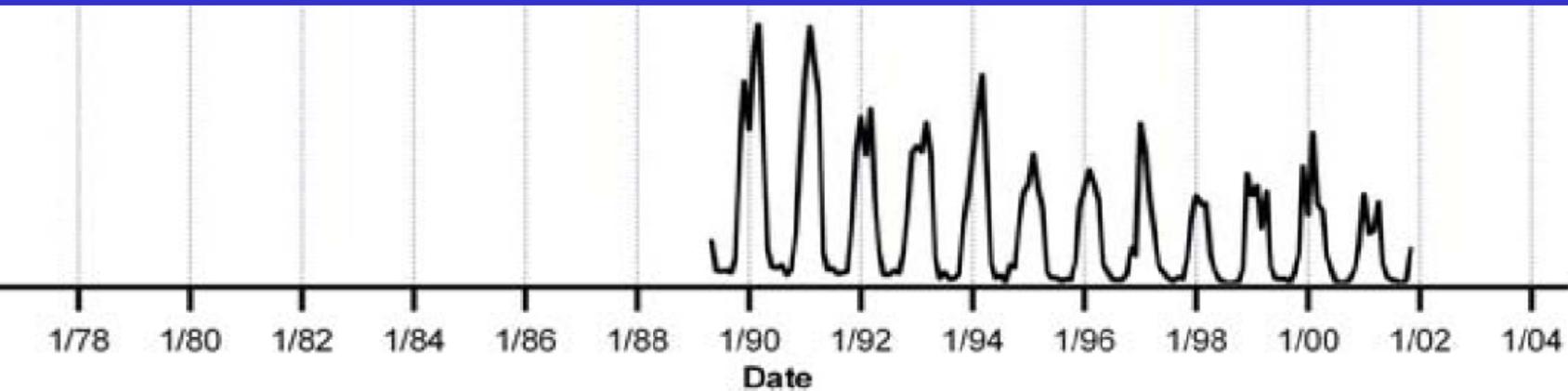


the Arctic become cleaner or dirtier in 25 years?

Median values of BC in snow (ppb):

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

Difference in photometer accounts for factor 1.6, based on Arctic



Black carbon in air
Alert, Canada
(62° 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* (10 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

Manabe and Nazarenko (2004): +0.16 W/m²

Superseded by recent estimates from Koch/GISS

McRobson (2004): +0.06 W/m²

TOA forcing from (early) Bond fossil fuel+biofuel BC

Equilibrium warming: +0.06 K

Manabe et al (2007, 2009): +0.04 W/m²

TOA forcing from (2004) Bond fossil fuel+biofuel BC

Equilibrium warming: +0.12 K

Koch et al (2009): +0.03 W/m² (all present sources)

1995 – 1890 change from all BC in snow/ice: +0.01 W/m²

Equilibrium warming: +0.18 K

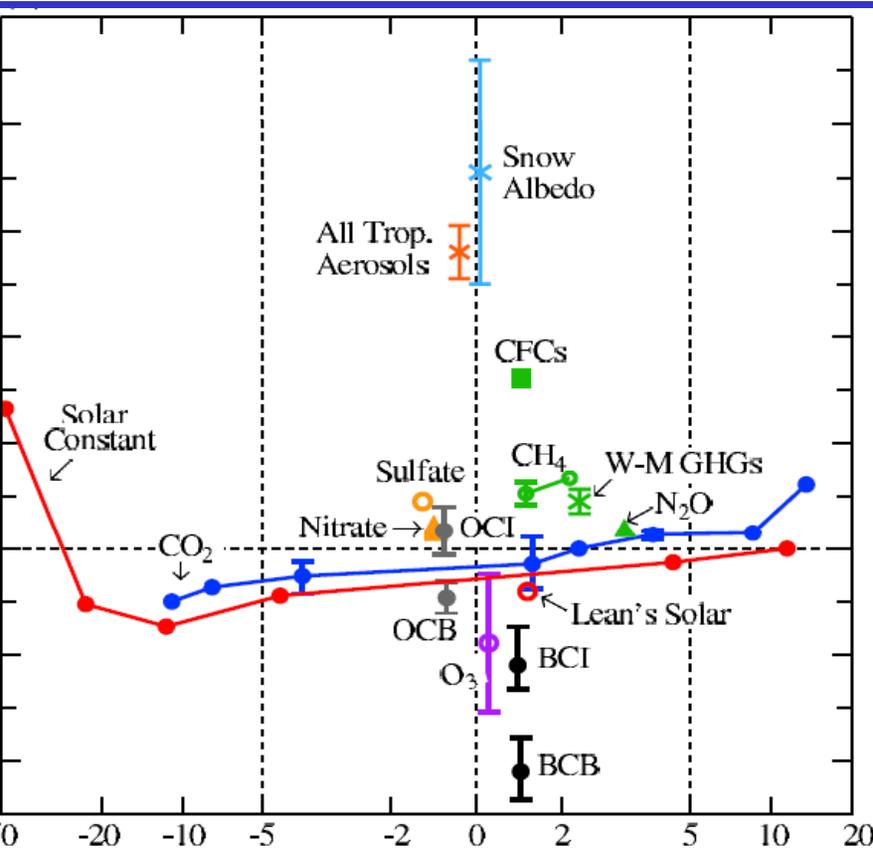
Myrland et al (2009): +0.03 W/m²

Emissions from *Cofala et al (2007)*

of climate forcings

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

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

Efficiency for soot in snow

(Hansen et al. 2005)

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

Albedo reduction causes temperature increase, grain-size growth, reduced albedo.

Soot causes greater albedo reduction in coarse-grained snow

Melting concentrates soot at the surface.

Global annual mean forcing by soot in snow:

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

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

ling questions:

is BC removed from the atmosphere into snow?

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

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

radiative forcing results from a change in surface
bedo?

what extent is snow hidden by

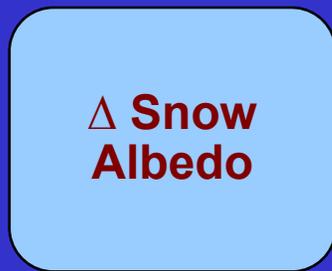
ees

The forward model process (Doherty and Flanner)



(Recent measurements helping with items in red)

Complications
grain size,
BC absorptivity
snow thickness,
other impurities



Complications
and sea-ice
response, etc.
snow aging
response



Complications
clouds,
vegetation masking,
snow fraction

to continue
heavily on