Overview of Radiation and Arctic Aerosol Interactions with LCLUC

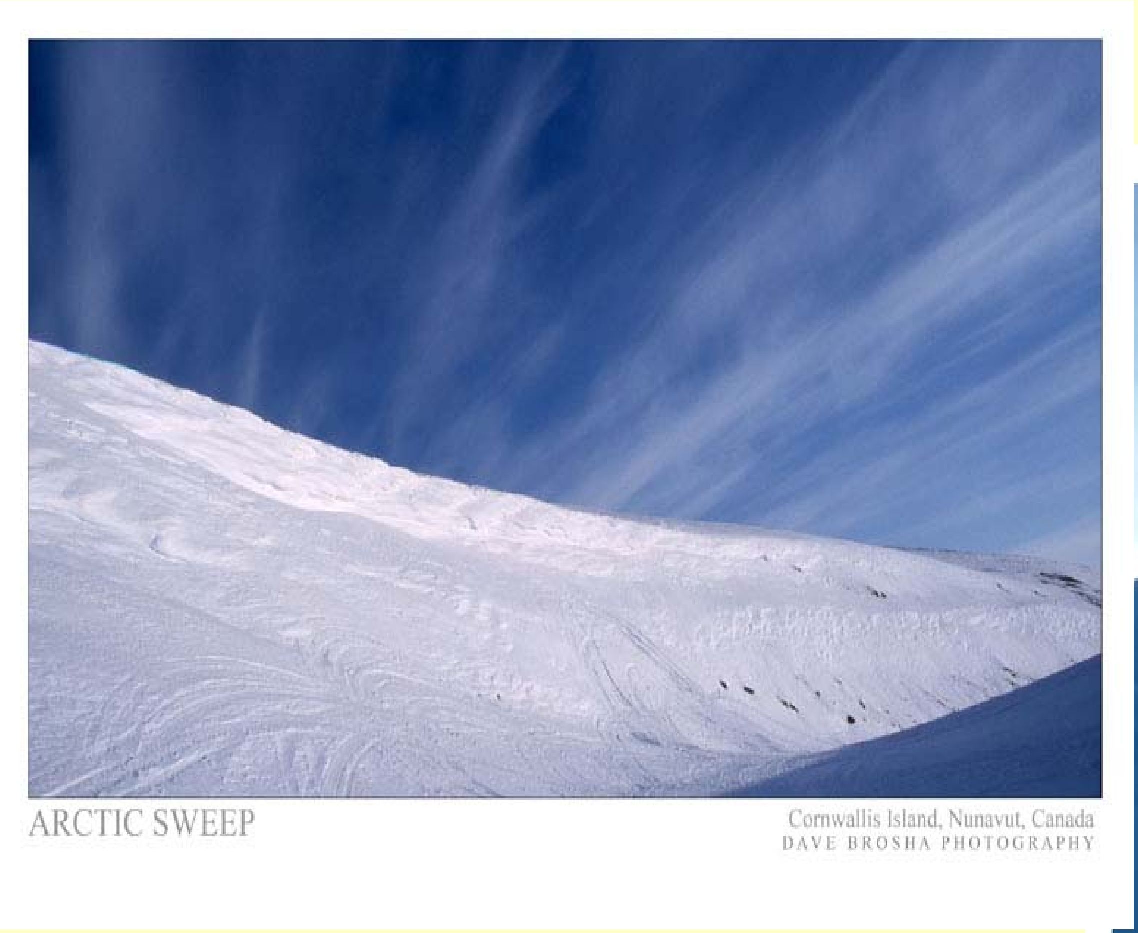
Irina N. Sokolik

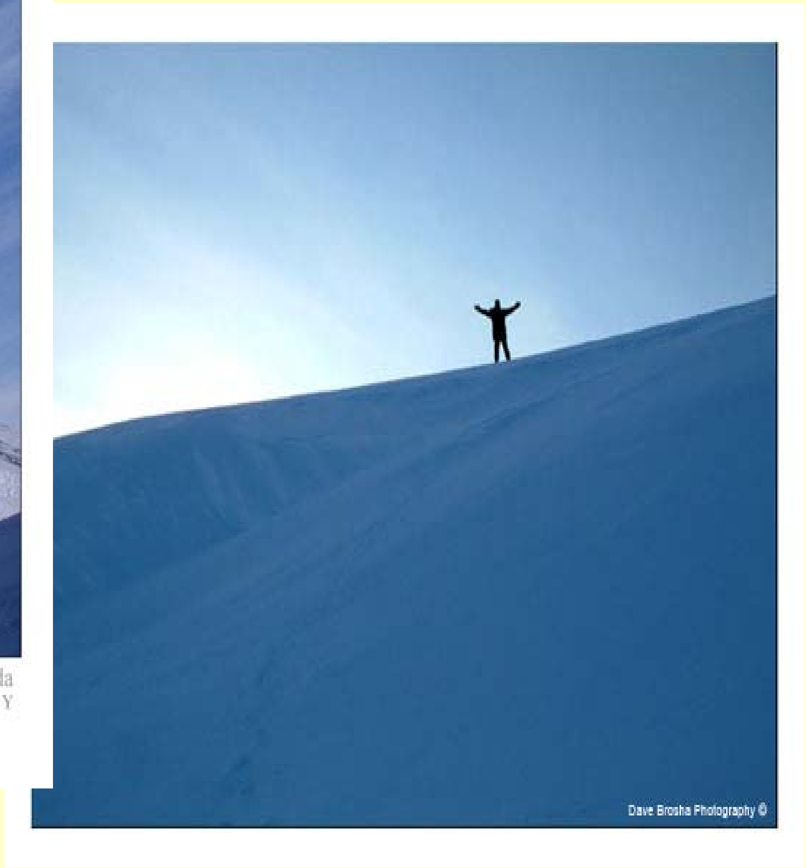
School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA, USA

Where are aerosols in the Arctic?

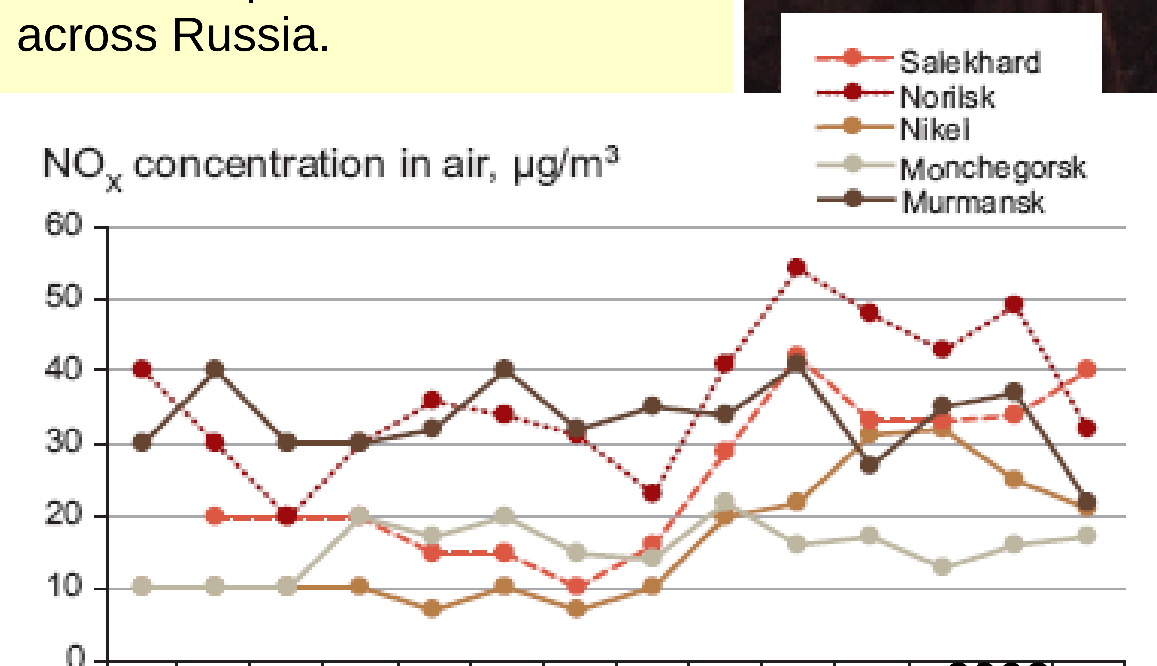




Local sources of anthropogenic aerosols in the Arctic

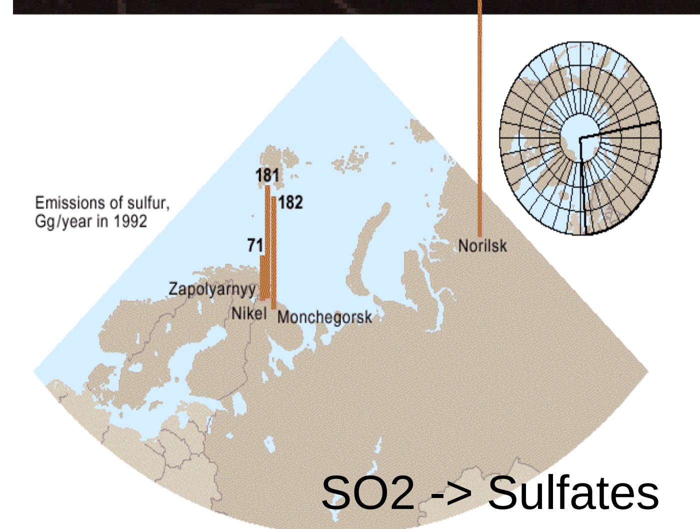
- The only significant industrial urban centers within the Arctic are located in Russia.

- Increasing NO_x concentrations in several Northern Russia cities reflects the increasing number of private vehicles all across Russia.



2003

1990



SO2 -> Sulfates

Soot (BC)

Local natural and anthropogenic sources of aerosols in the Arctic

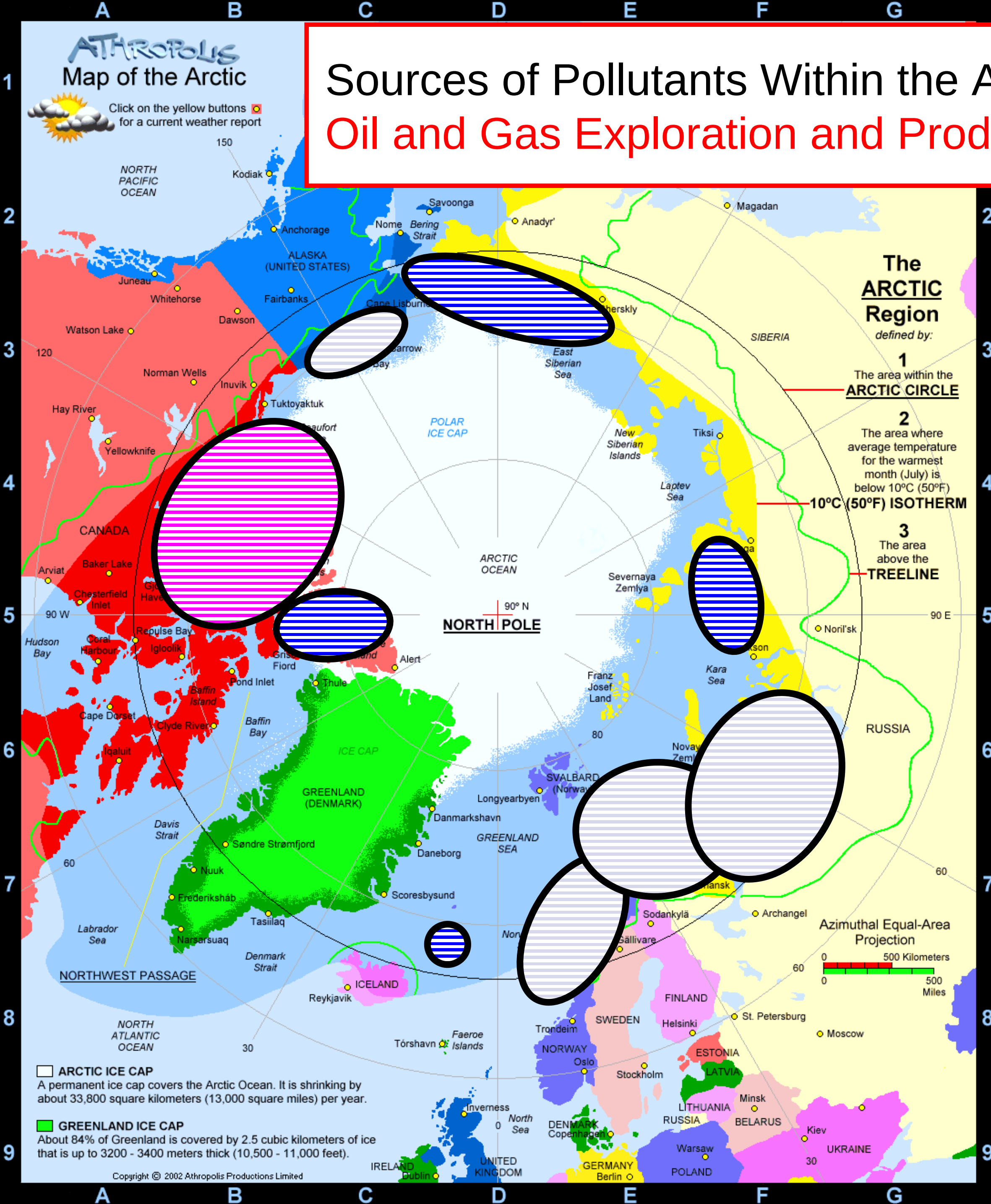
- ***Natural***:
  - sulfates (gas-to-particle conversion of DMS emitted from sea-water)
  - sea-salt (emitted from sea-water)
  - organics (emission from vegetation)
  - some crustal particulates (from snow-free land surfaces)
  - carbonaceous (OC and BC (soot) from wild fires)
  - volcanic aerosols

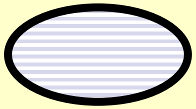
- ***Anthropogenic*** sulfates, nitrates and carbonaceous:
  - industrial cities (e.g., metal smelters in Norilsk, Nikel)
  - local use of fossil fuels
  - oil production industries
  - shipping

Local sources are projected to increase in the future

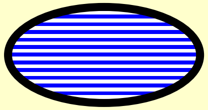
Sources of Pollutants Within the Arctic

Oil and Gas Exploration and Production

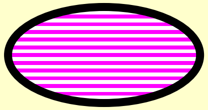




Main areas of oil and gas production in the Arctic today



Extensive oil and gas exploration occurring today



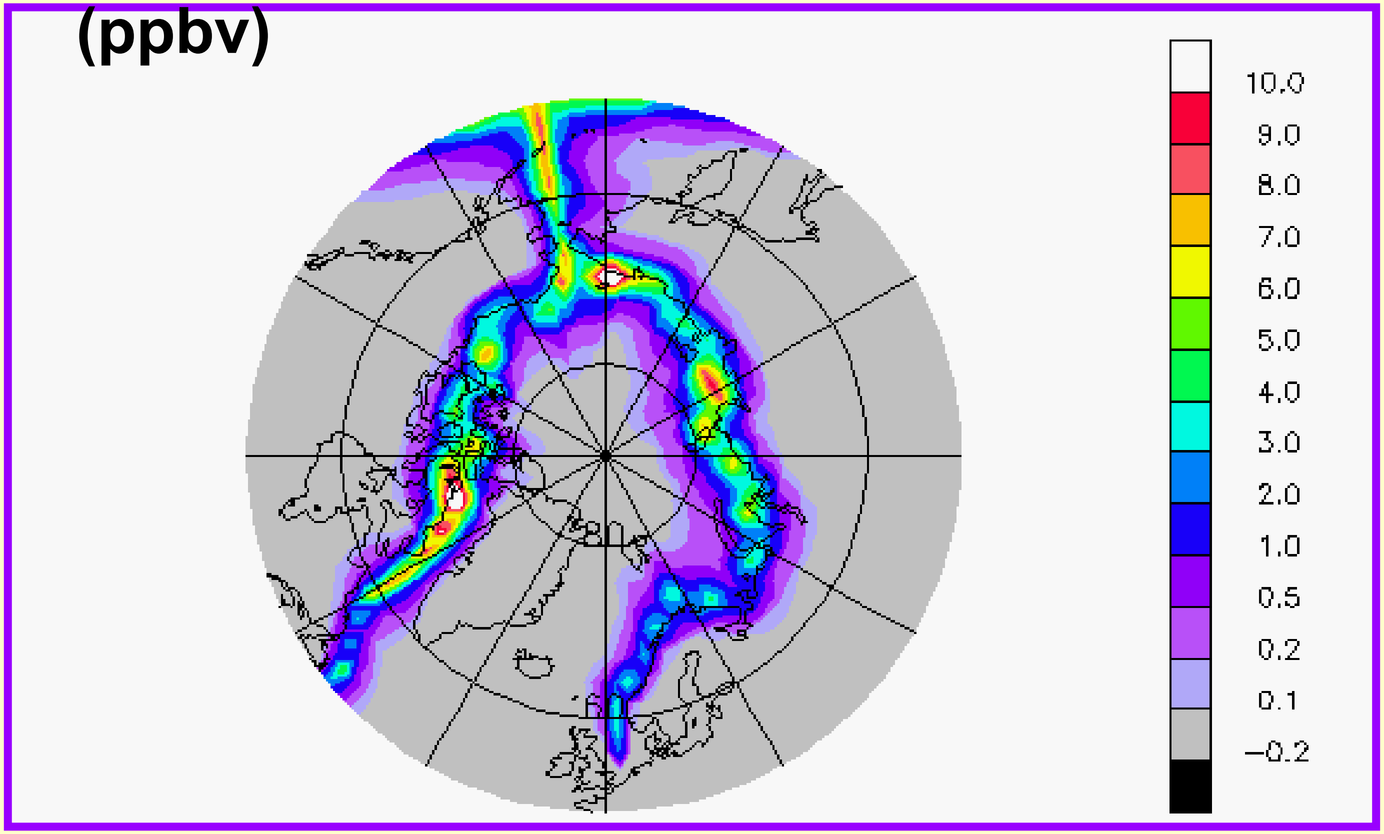
Extensive petroleum reserves

Emissions are not well quantified but include CO_2, NO_x, SO_x, CH_4 and non-methane VOCs.

The Arctic is estimated to contain at least 25% of the world's undiscovered petroleum resources.

The use of oil and gas resources in the Arctic is expected to increase as the ice-free season increases and ice cover decreases.

Change in the NOx distribution in the Arctic resulting from ships calculated by the MOZART model (July 2050 - July 2000)

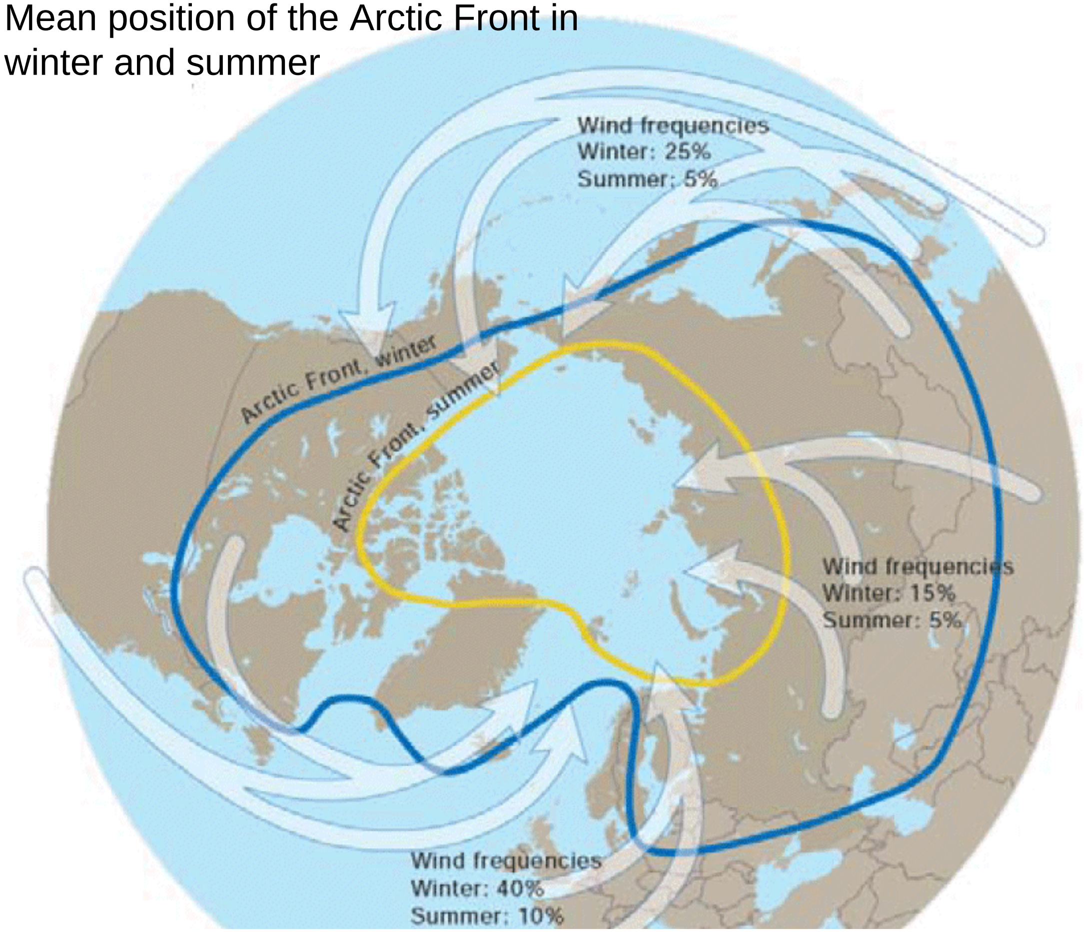


Granier et al. (2007):

- Increases in NO_x from 2000 to 2050: up to 10 ppbv
- Increases in O_3 from 2000 to 2050: up to 30 ppbv
- Increases in Black Carbon from 2000 to 2050: up to 0.1 ppbv (50 ng m^{-3})

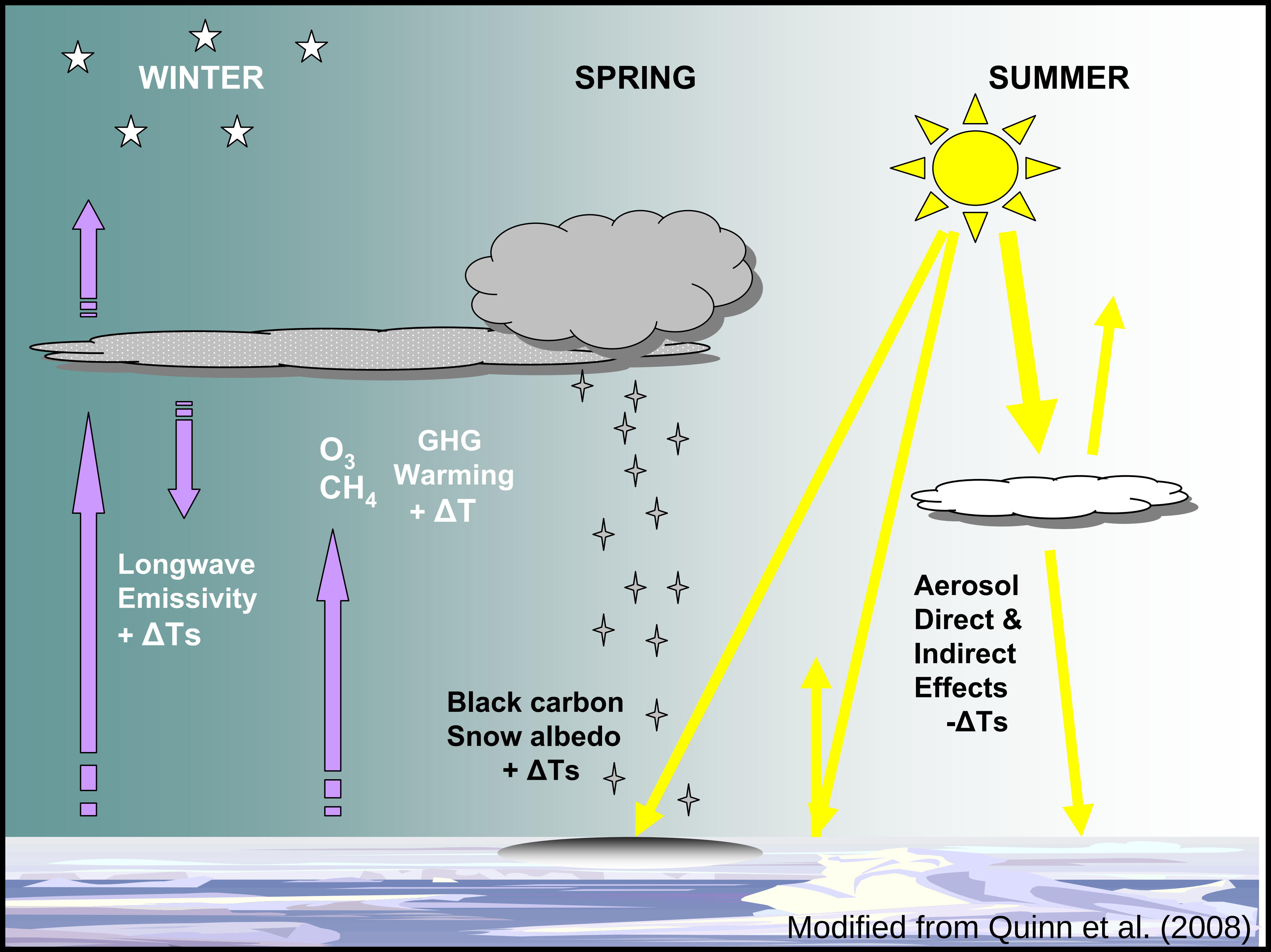
Long-range transport of aerosols to the Arctic: "Arctic Haze"

Mean position of the Arctic Front in winter and summer

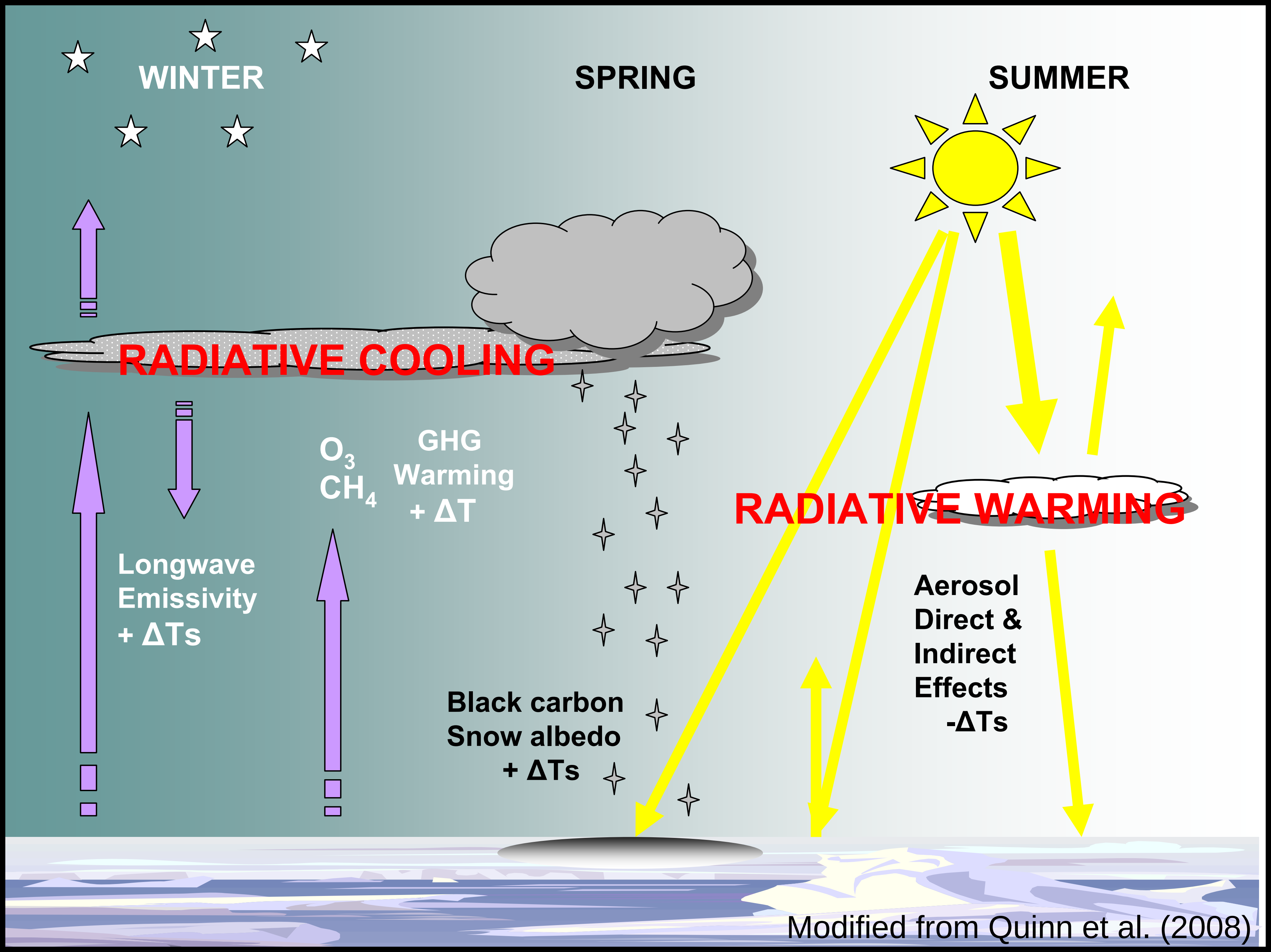


- **Winter/spring accumulation of pollution originated at lower latitudes (but to the north of the Arctic Front)**
- **First reports by pilots in the 50s, measurements from the 70s**
- **Northern Eurasia and Northern West Europe are major source regions to the BL in the Arctic due to:**
  - **extension of Arctic front to near 40°N large**
  - **pollution sources**

Understanding of aerosol impacts on the Arctic system requires a knowledge of sources dynamics (LCLUC) in Northern Eurasia, changes in general circulation and climate variability and change.

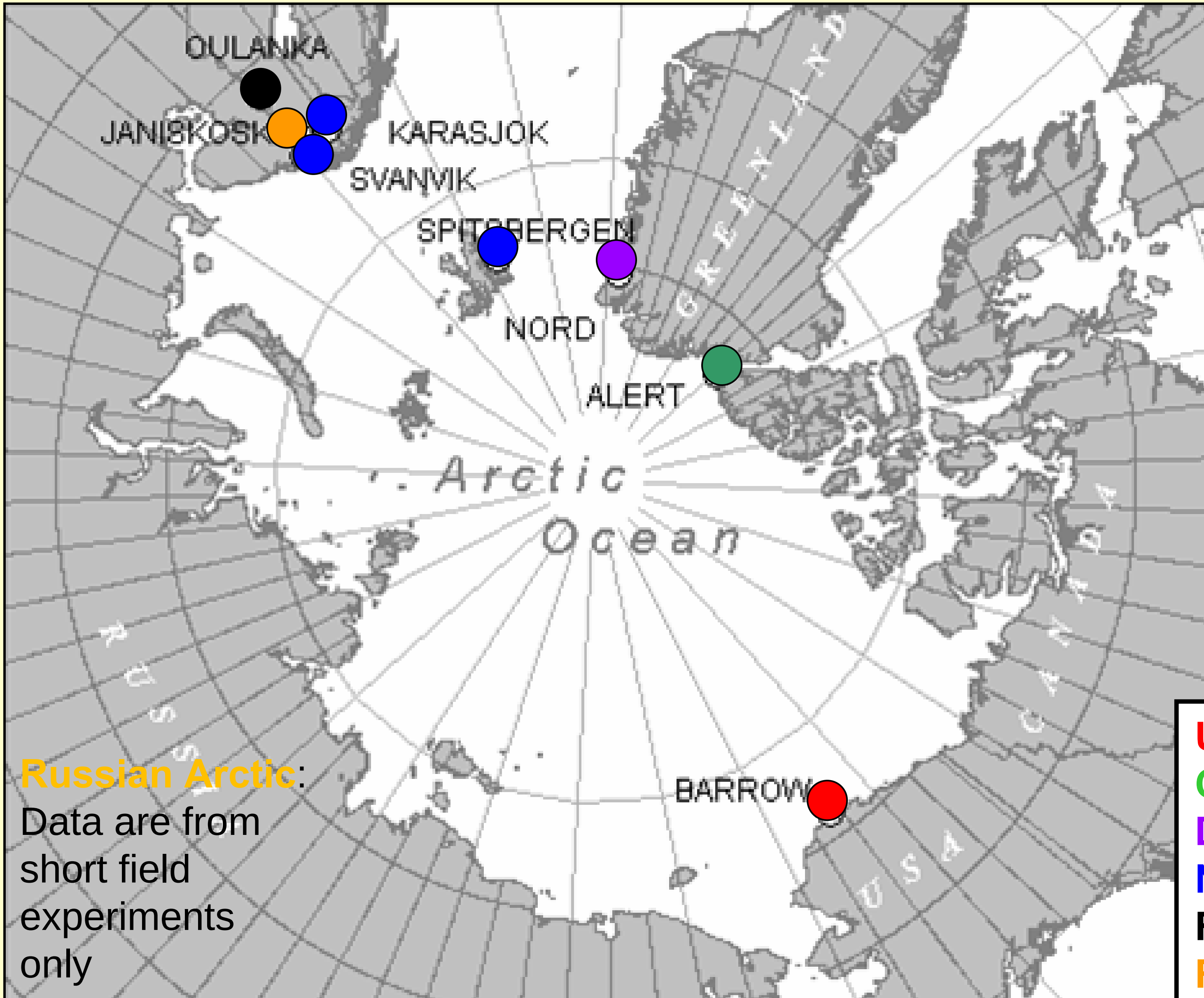


WINTER
SPRING
SUMMER
Longwave
Emissivity
+ ΔTs
O3
CH4
GHG
Warming
+ ΔT
Black carbon
Snow albedo
+ ΔTs
Aerosol
Direct &
Indirect
Effects
-ΔTs
Modified from Quinn et al. (2008)



WINTER
SPRING
SUMMER
RADIATIVE COOLING
RADIATIVE WARMING
O_3
CH_4
GHG Warming + ΔT
Longwave Emissivity + ΔTs
Black carbon Snow albedo + ΔTs
Aerosol Direct & Indirect Effects -ΔTs
Modified from Quinn et al. (2008)

Locations of Long-term Arctic Aerosol Monitoring Stations

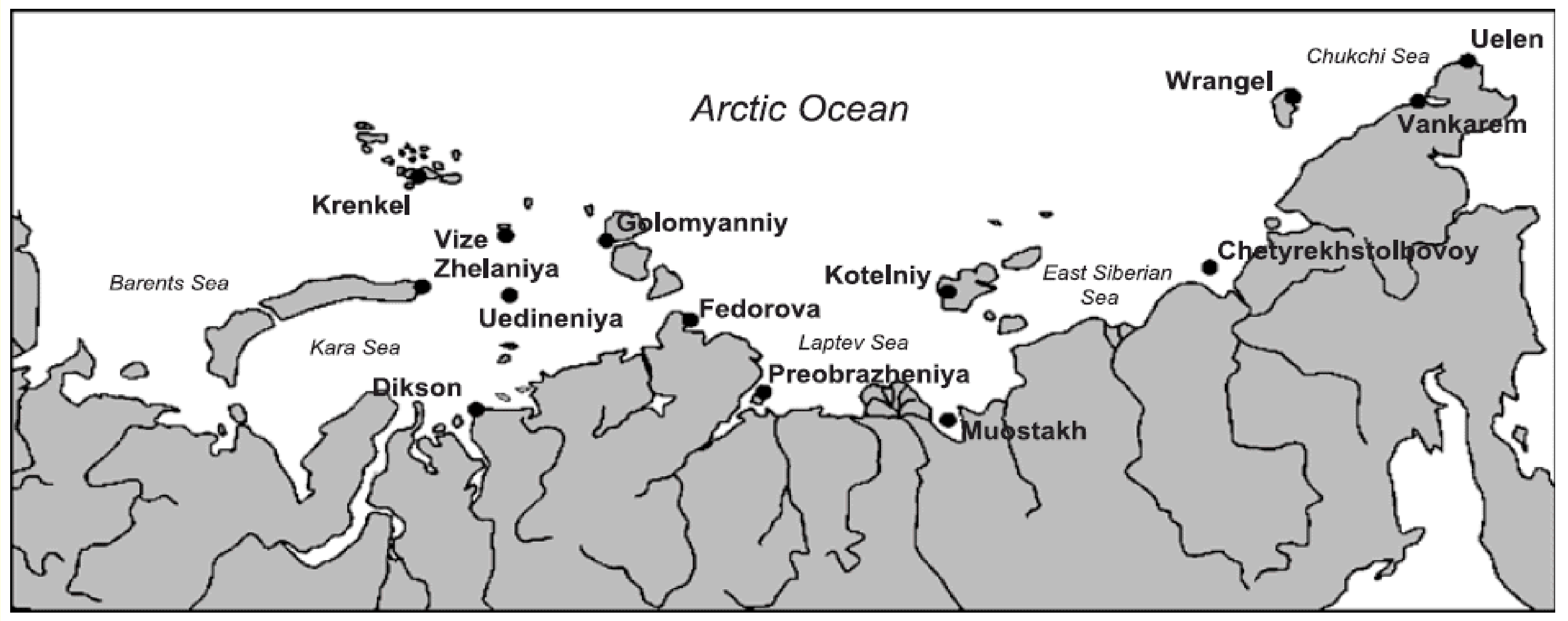


Russian Arctic: Data are from short field experiments only

US
Canada
Denmark
Norway
Finland
Russia

Locations of actinometric stations in the Russian Arctic

Operated from the 50-60s until 1993

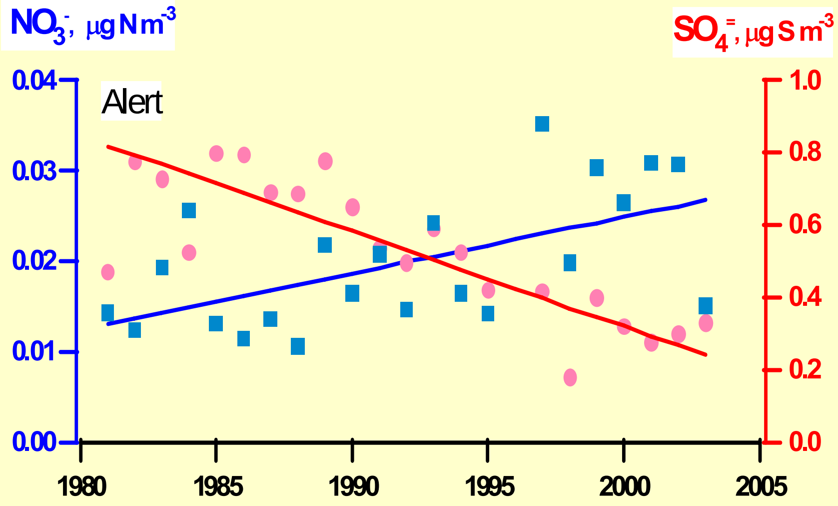


Measurements of SW and LW total and diffuse radiation

Retrieved aerosol optical depth

Observed long-term aerosols trends in the Northern American Arctic

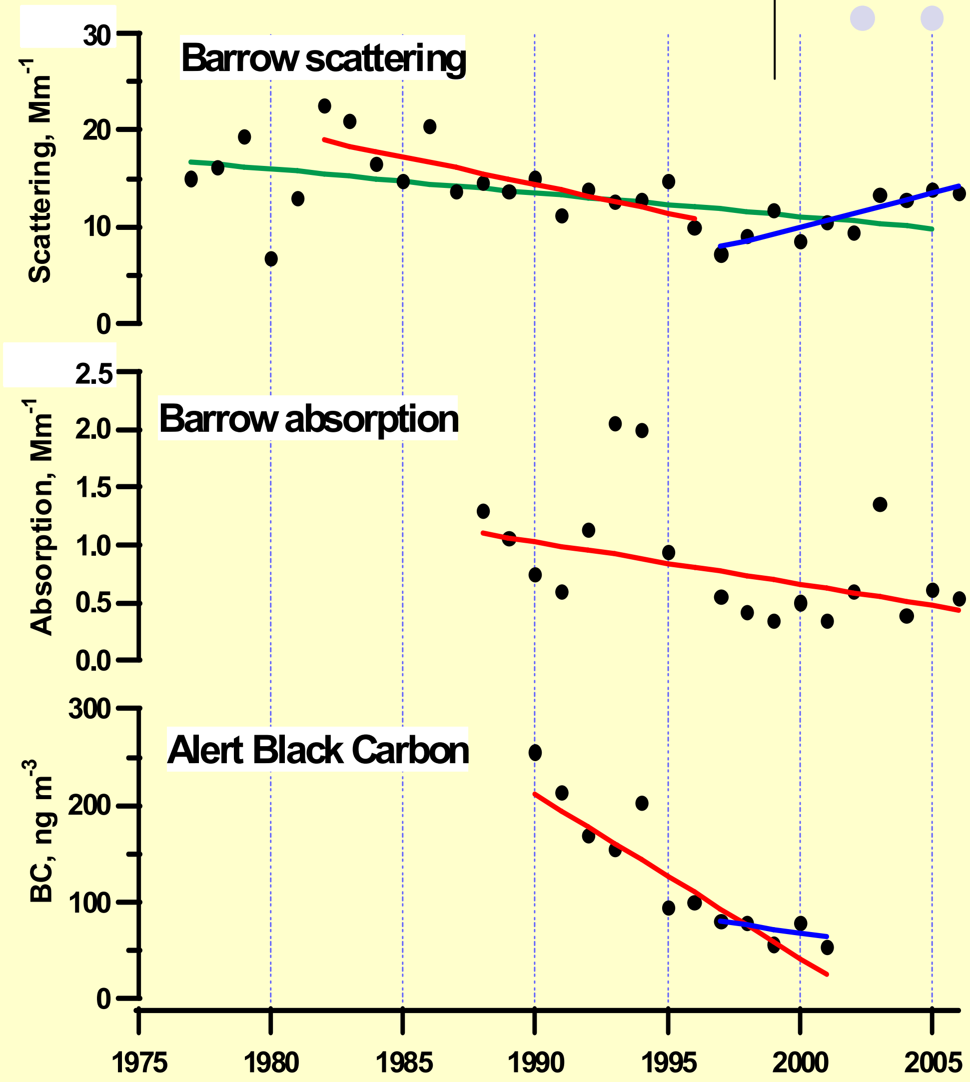
Long -term trends in nitrates and sulfates at Alert, Canada (monthly means for Aprils)



Sources: **Diesel and gasoline engines**
Fertilizer

Coal fired power plants

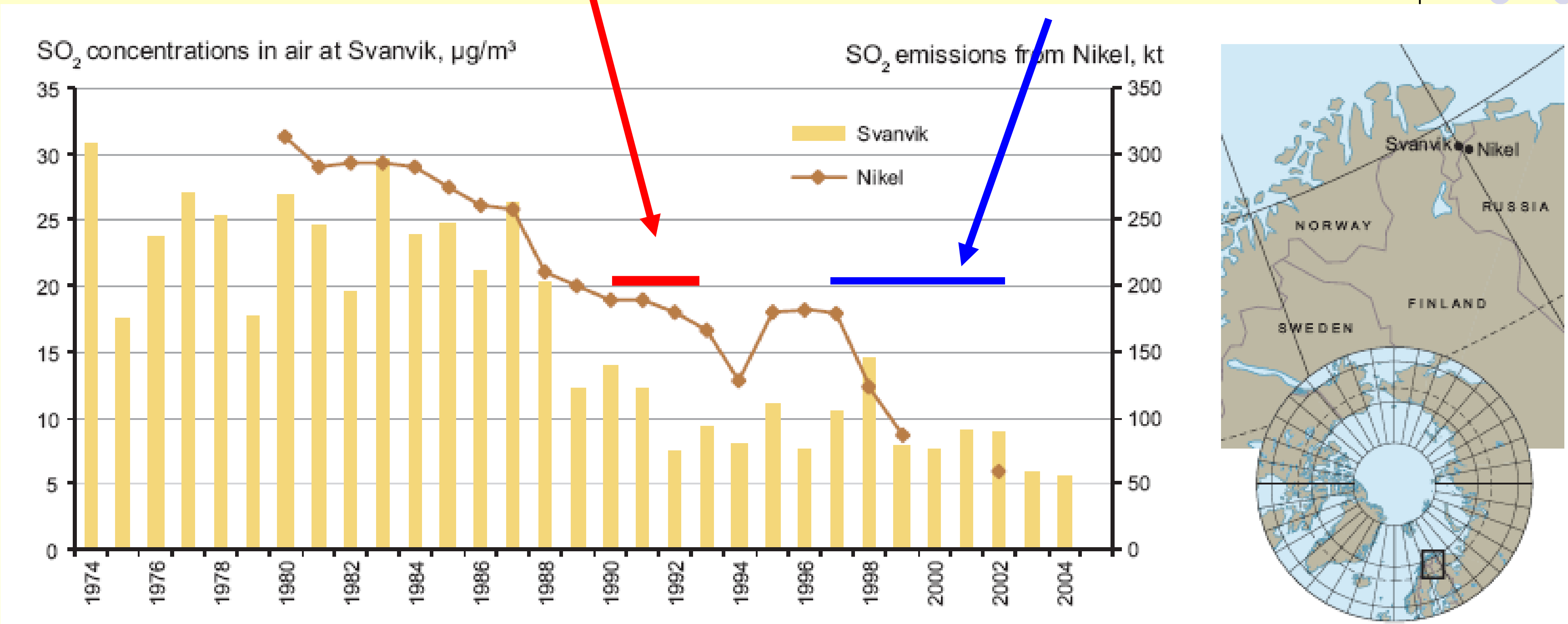
Quinn et al., *Tellus,* 2006.



Observed long-term aerosols trends in Finland

Decrease due to break up of the Soviet Union (Quinn et al.)

Decrease due to introduction of emission control technologies

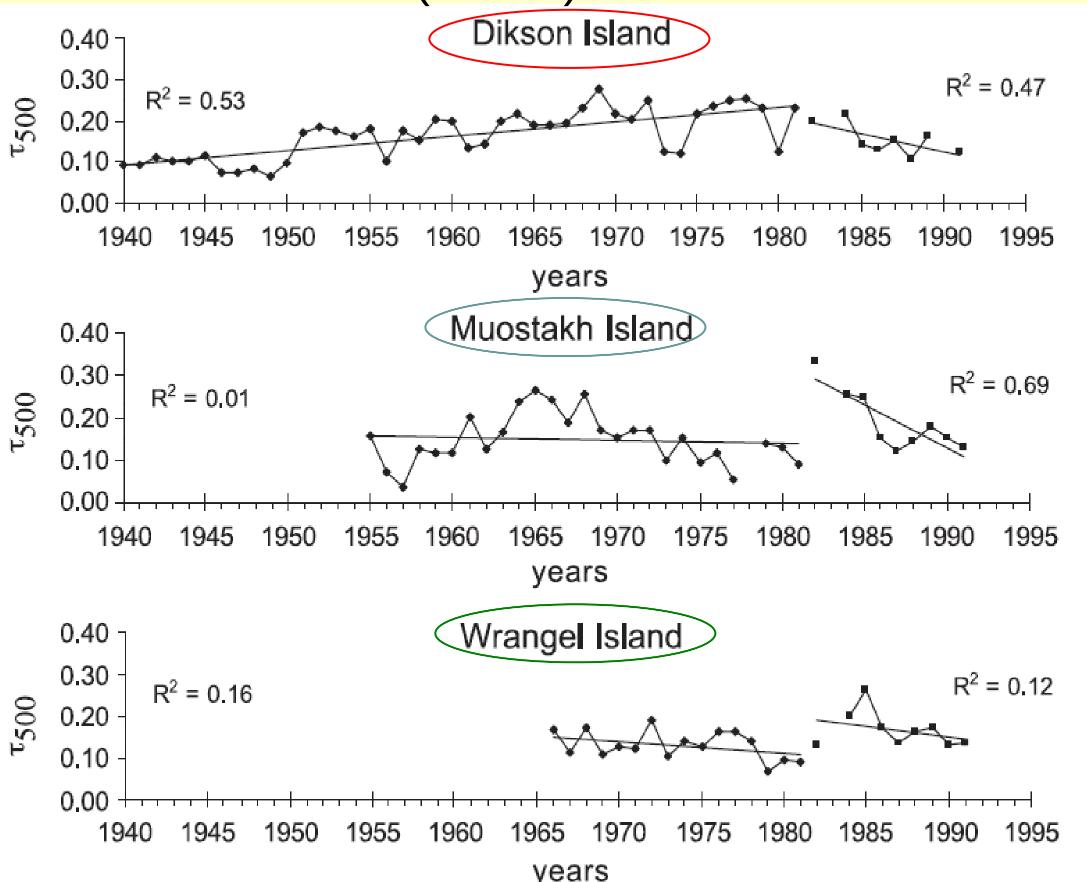


Time series of SO_2 emissions from the non-metal ferrous Smelter at Nikel

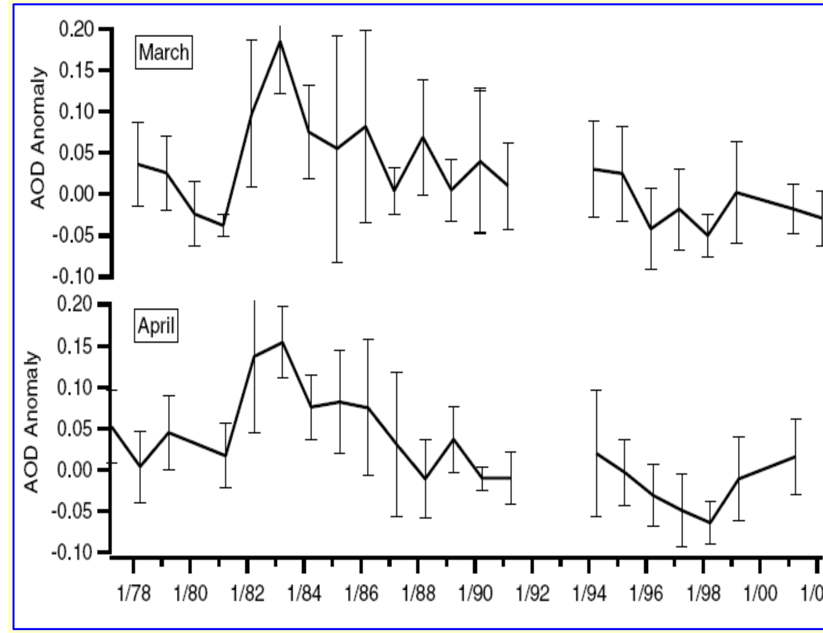
Yellow bars = Norwegian monitoring station - Svanvik
Brown dots = Nikel emissions.

Trends in aerosol optical depth in the Arctic

Russian Arctic (March)

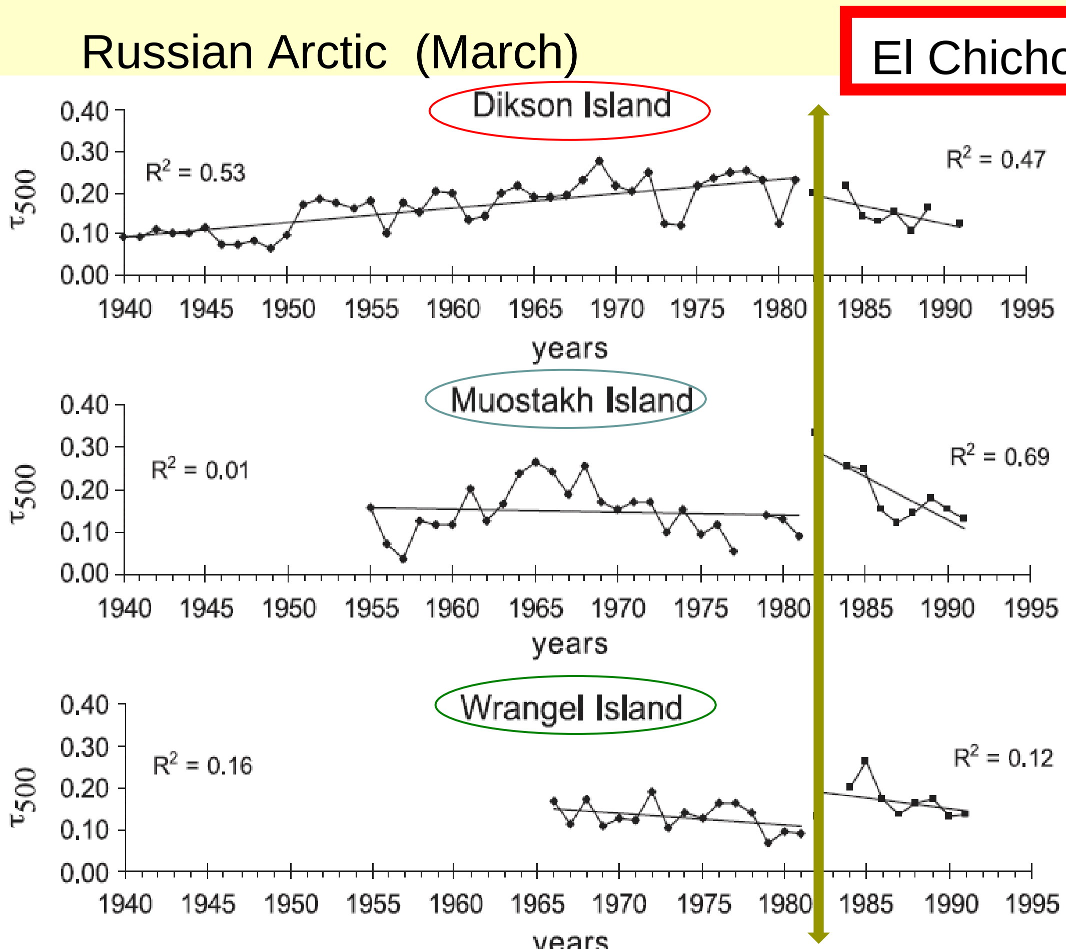


Barrow, Alaska

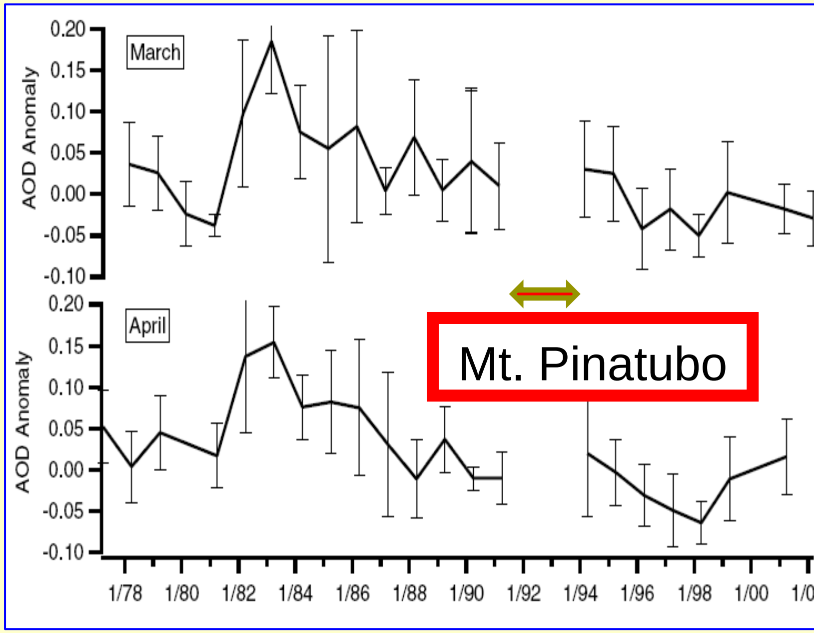


Trends in aerosol optical depth in the Arctic

Russian Arctic (March)



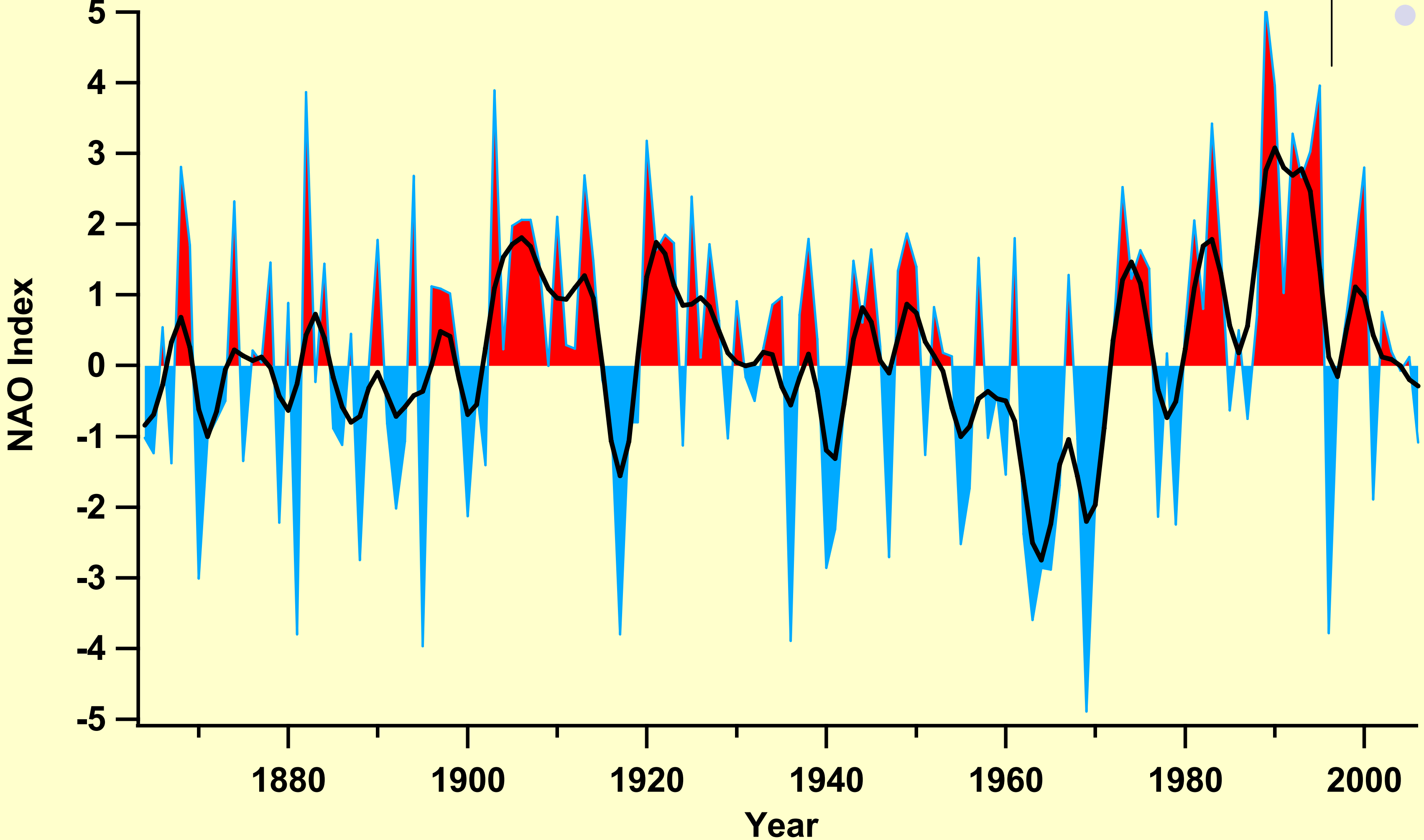
Barrow, Alaska



Complex distribution of trends:
A combination of sources dynamics and variability in transport and removal (precipitation)

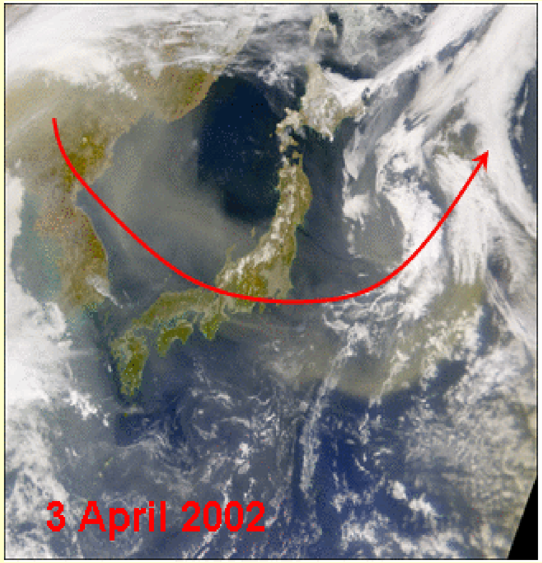
Winter (Dec – Mar) Index of the North Atlantic Oscillation (NAO)

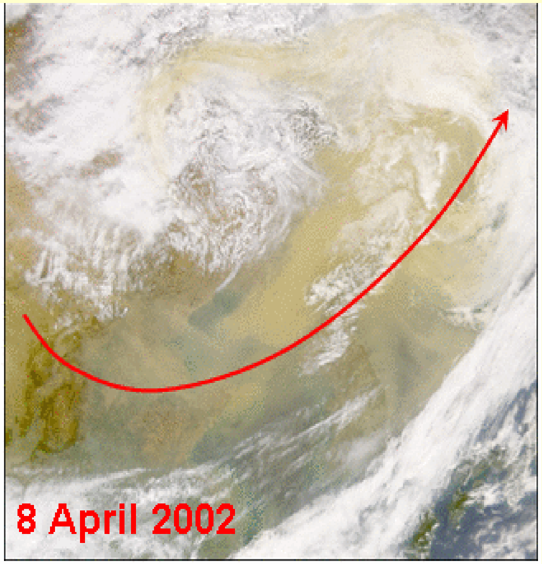
Based on the normalized sea level pressure difference between Lisbon and Reykjavik



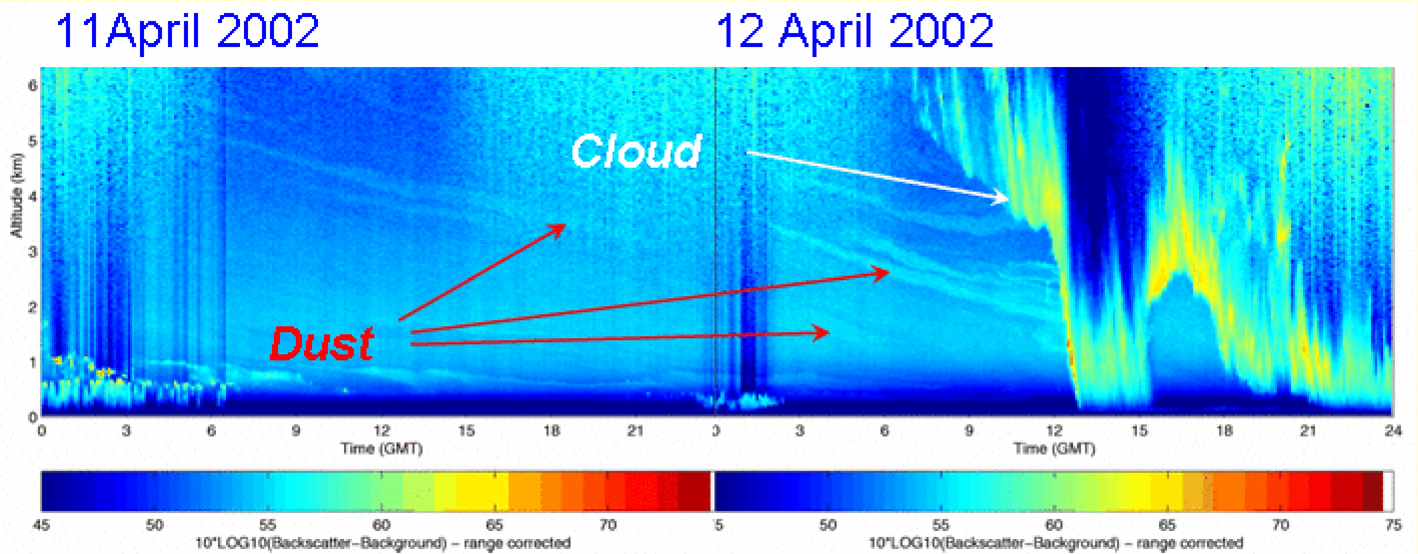
Positive values lead to stronger than average westerlies over the middle latitudes

Transport of Asian dust to Alaska





Frequency and intensity of dust outbreaks to the Arctic remain unknown

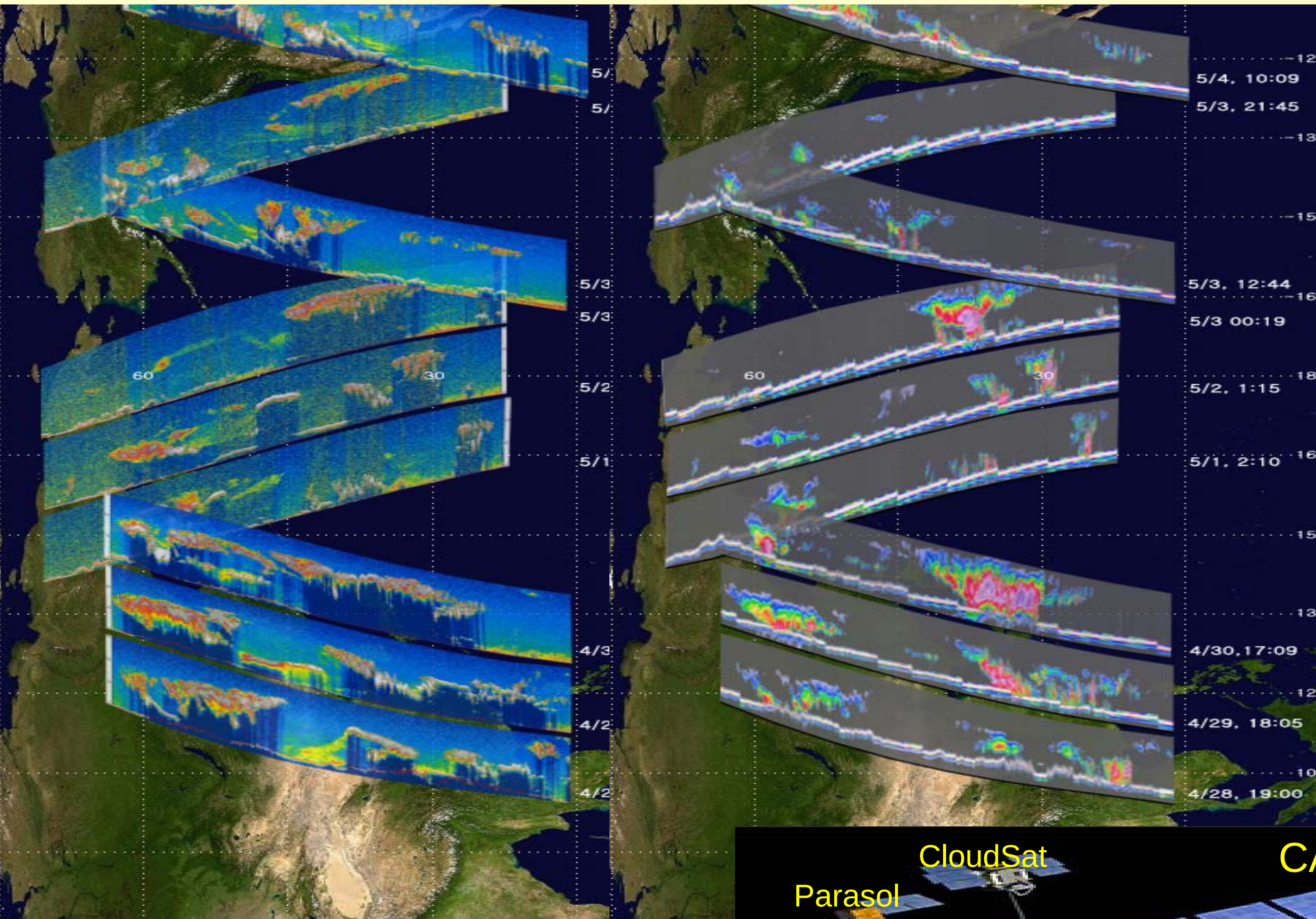


DOE/ARM North Slope, Alaska

Transport of Asian dust from CALIPSO

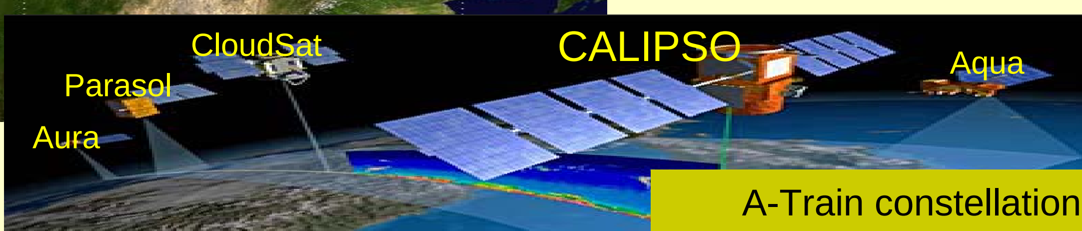
CALIPSO

CloudSat



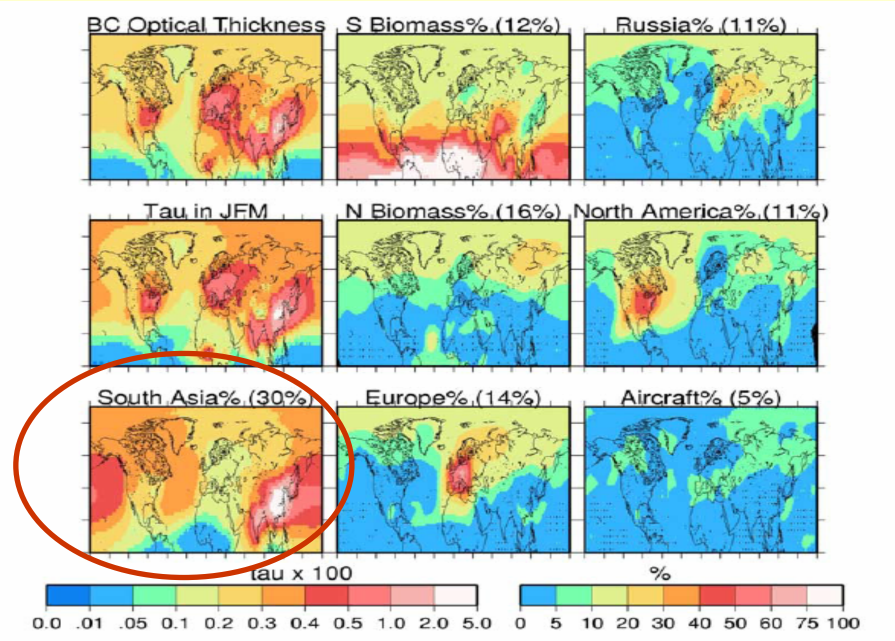
Vertical distribution is a key factor in controlling radiative impacts of aerosols, aerosol-cloud-precipitation interactions and aerosol removal/deposition that affects aerosol transport

Choi, Sokolik, and Winker(2007)



A-Train constellation

Transport of soot to the Arctic



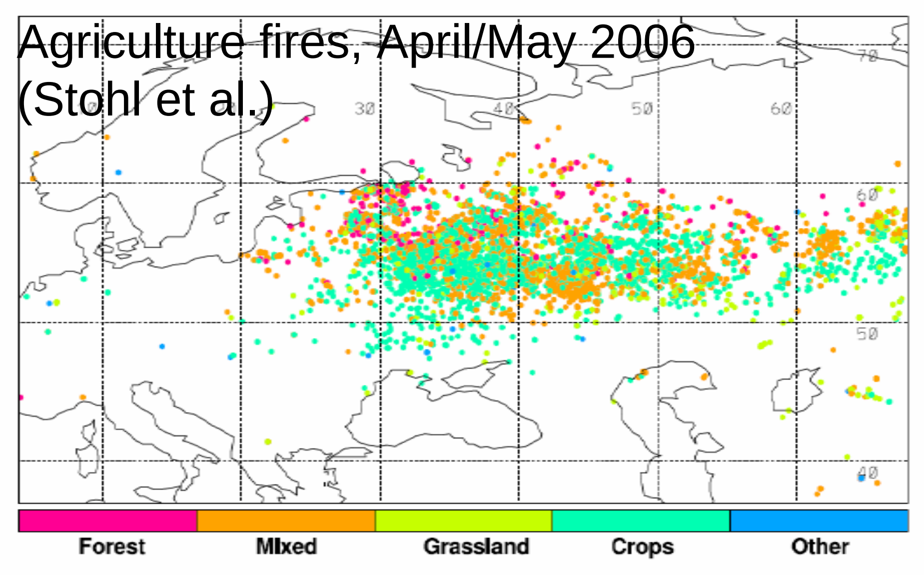
Where are the sources of BC?

Koch and Hansen (2005):

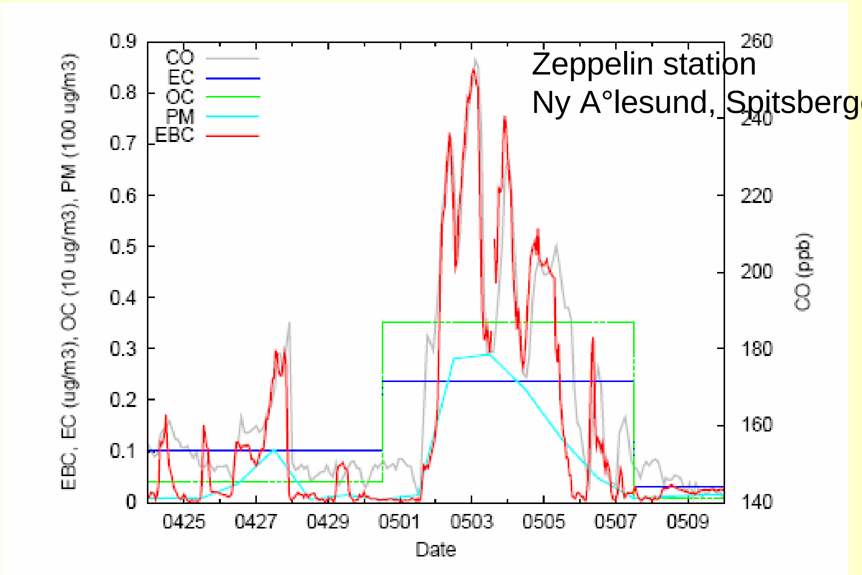
Industrial and biofuel combustion in Southern Asia are a major source of BC in the Arctic

Stohl et al. (2006, 2007):

Western Europe and Northern Eurasia are the main sources of BC



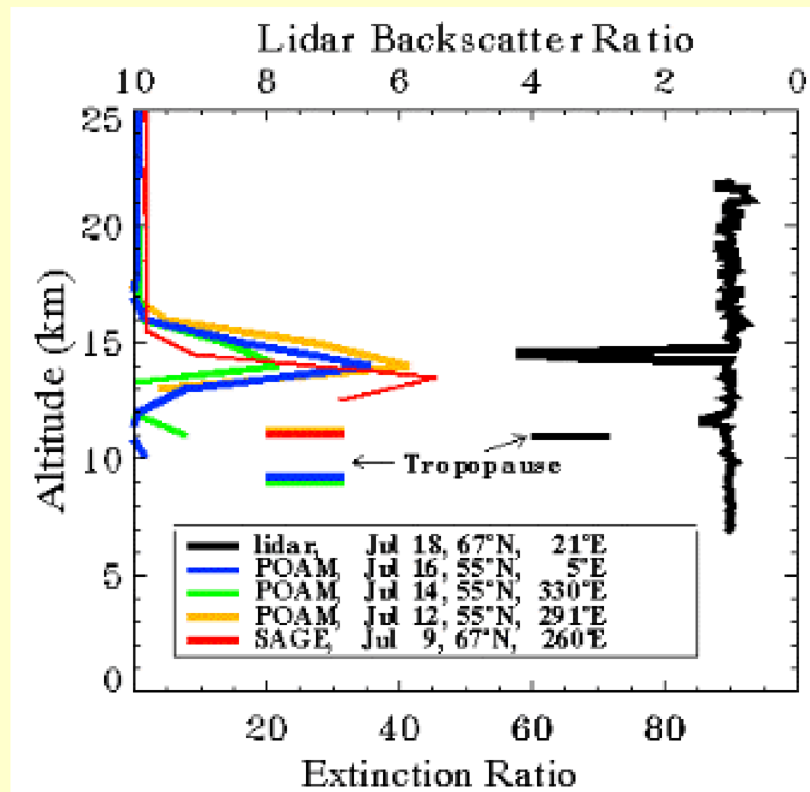
Agriculture fires, April/May 2006 (Stohl et al.)



Zeppelin station Ny A°lesund, Spitsbergen

"Non-accounted" summer transport of smoke to the Arctic

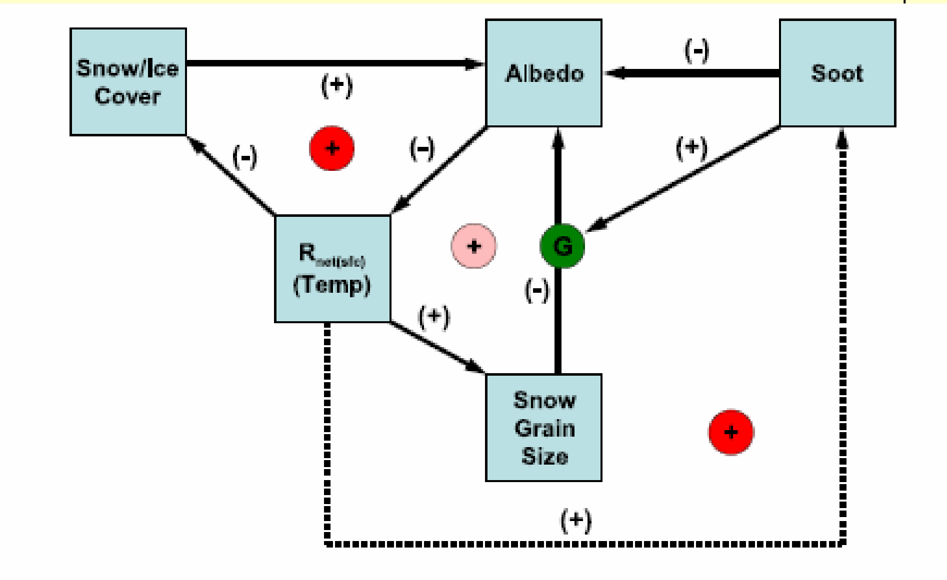
Importance of pyro-convective smoke clouds



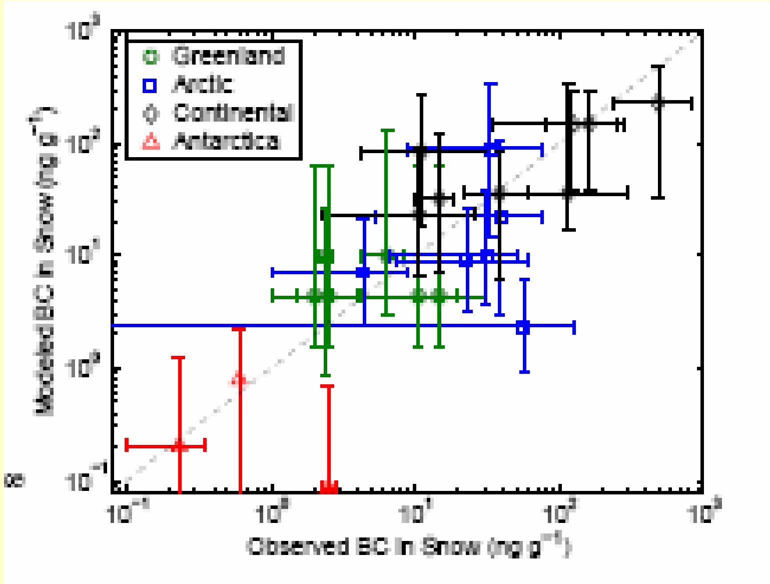
Aerosol effect on surface albedo

Deposition of BC onto snow (ice) surfaces:

- ice-albedo feedback amplification
- anthropogenic soot may have caused one quarter of last century's observed warming (Hansen et al.)
- significant reductions in Northern hemisphere albedo and sea-ice extent (Jacobson, 2004)
- contribute to melting

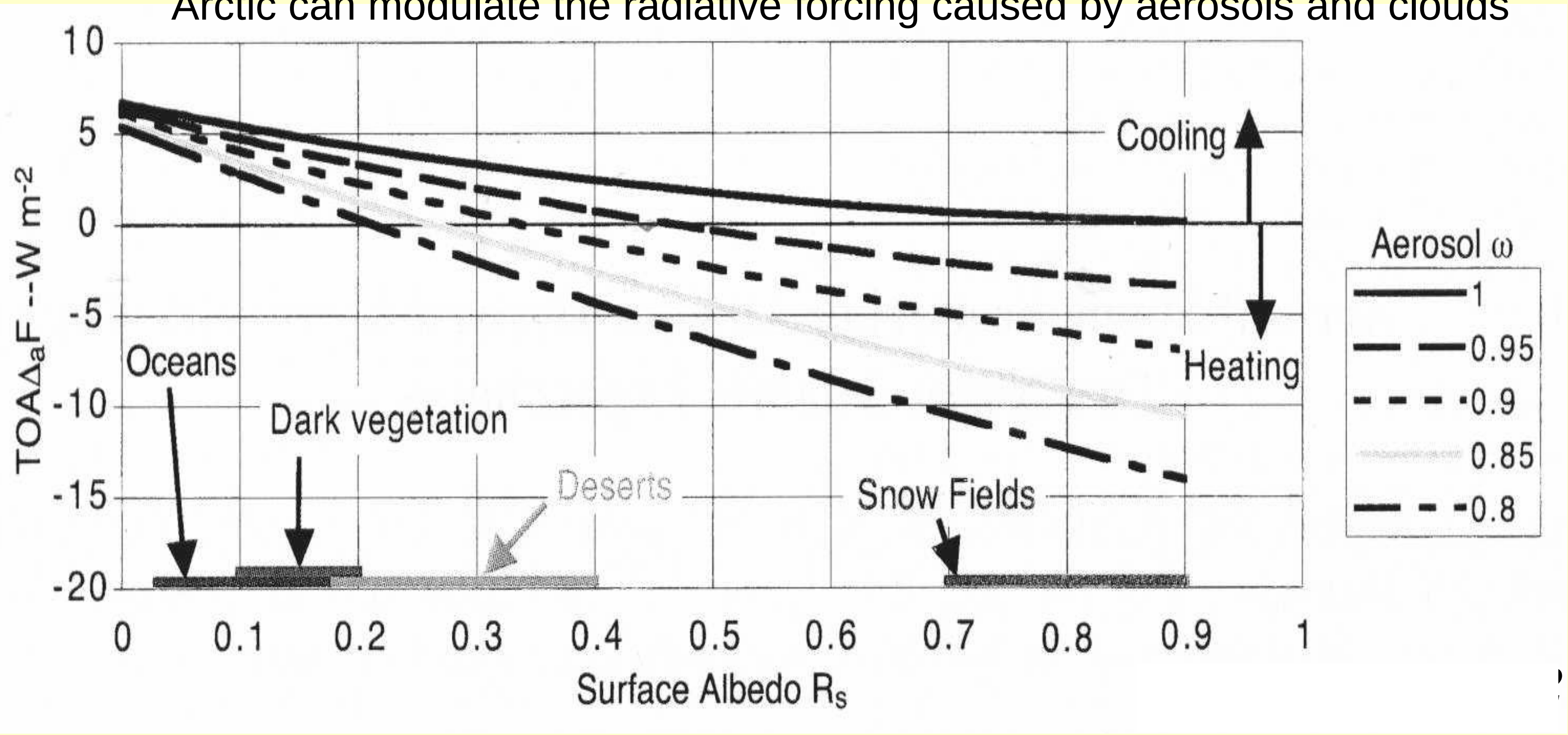


Estimates are extremely sensitive to accurate treatment of snowpack aging and soot optical properties as well as modeled predicted soot deposition (Zender et al.)



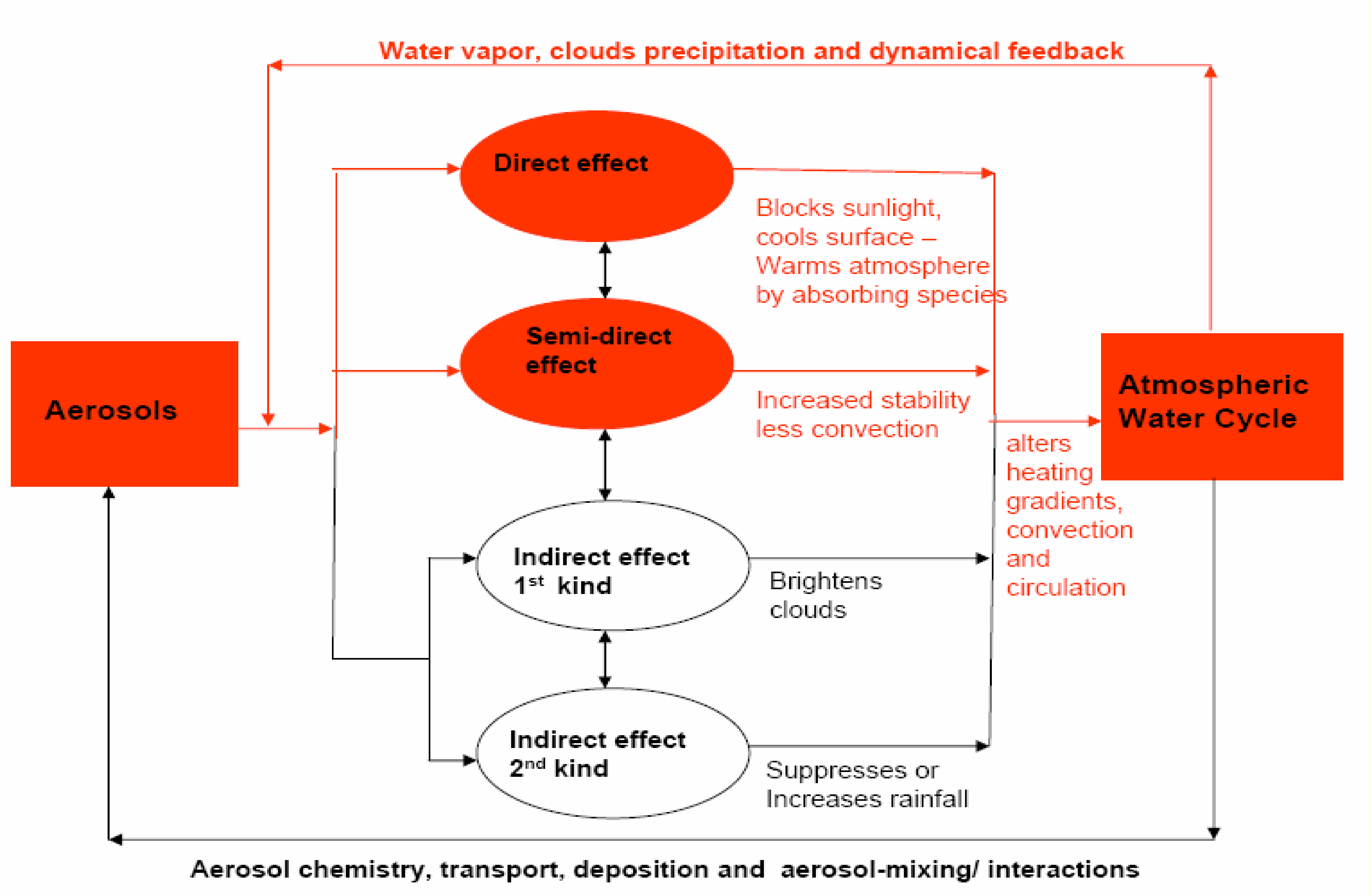
Effects of surface albedo on radiative forcing of aerosols

Changes in vegetation cover, land snow cover and sea-ice extent in the Arctic can modulate the radiative forcing caused by aerosols and clouds



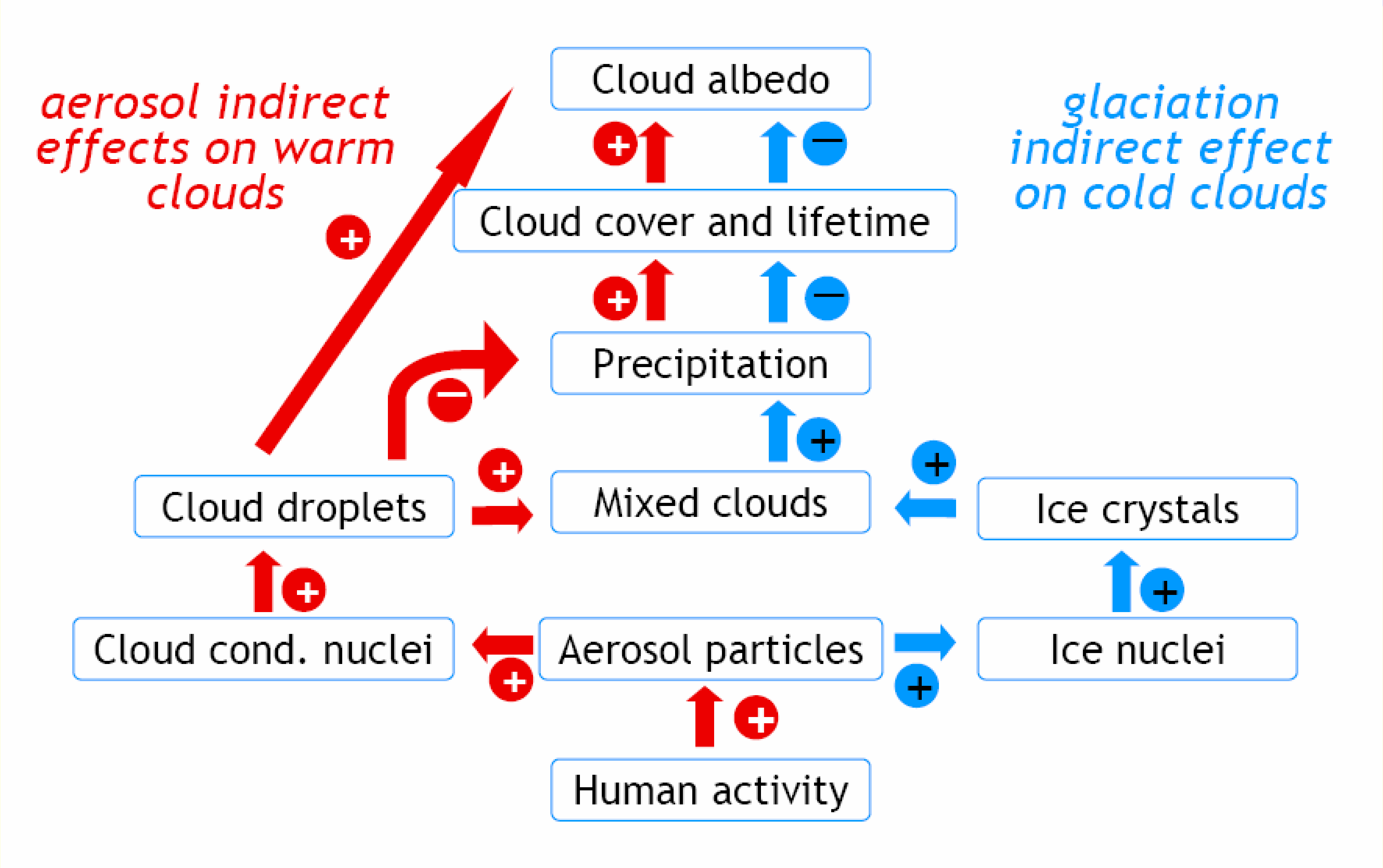
mixed vegetation-snow surfaces

Aerosol - clouds interactions



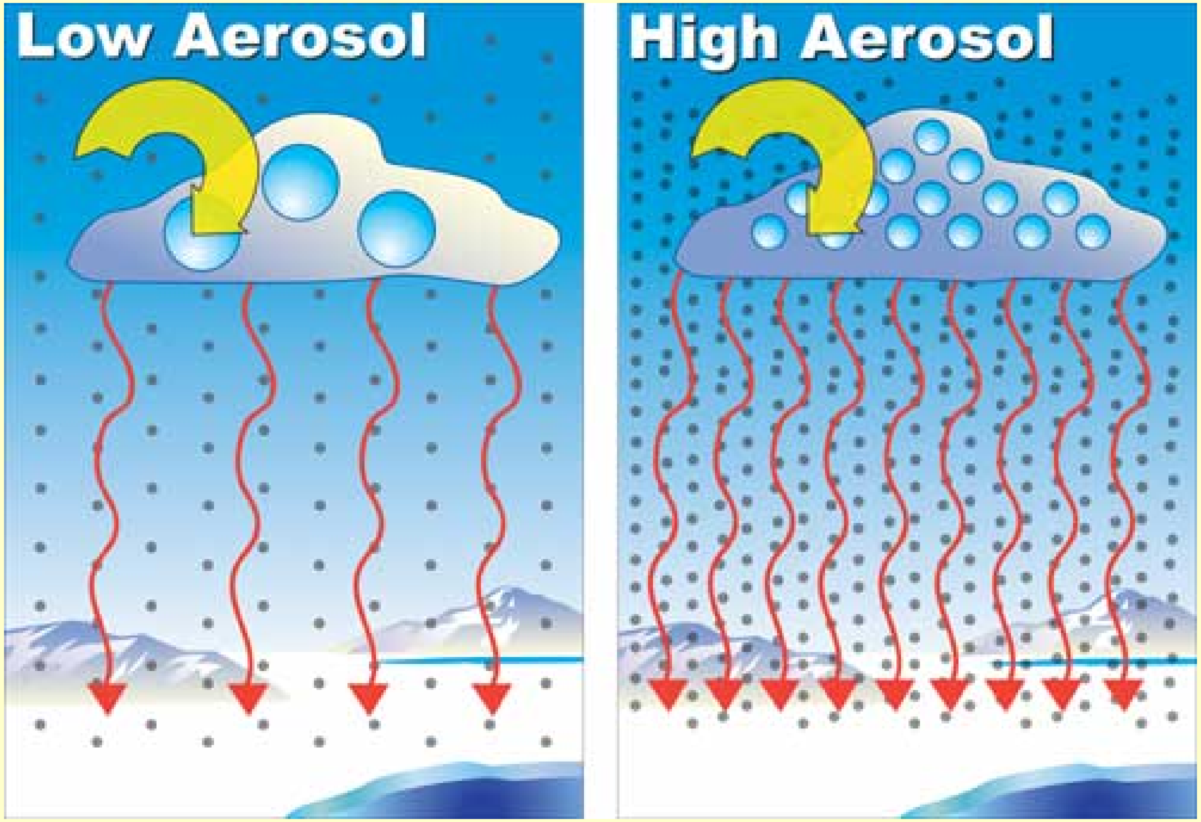
“Classical view”:

Second indirect effect -> precipitation (warm and cold clouds)



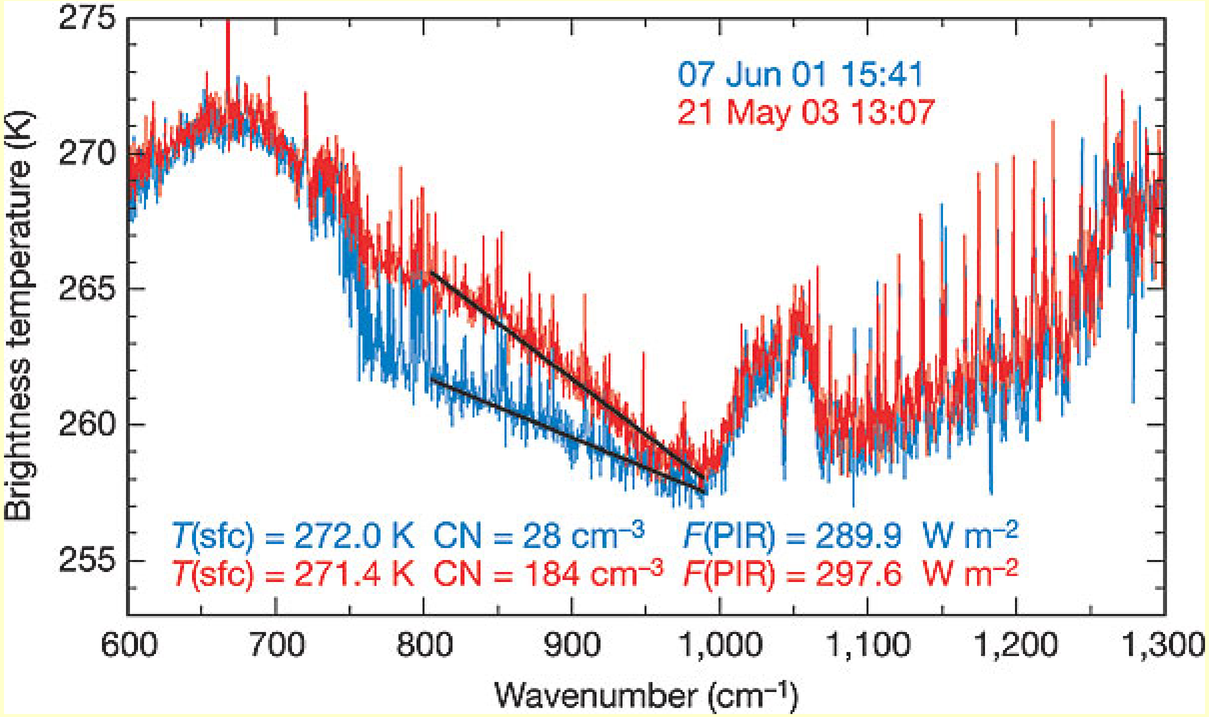
Enhanced aerosol amounts can make clouds emit more thermal energy to the surface

(Lubin and Vogelmann, 2006, *Nature*)



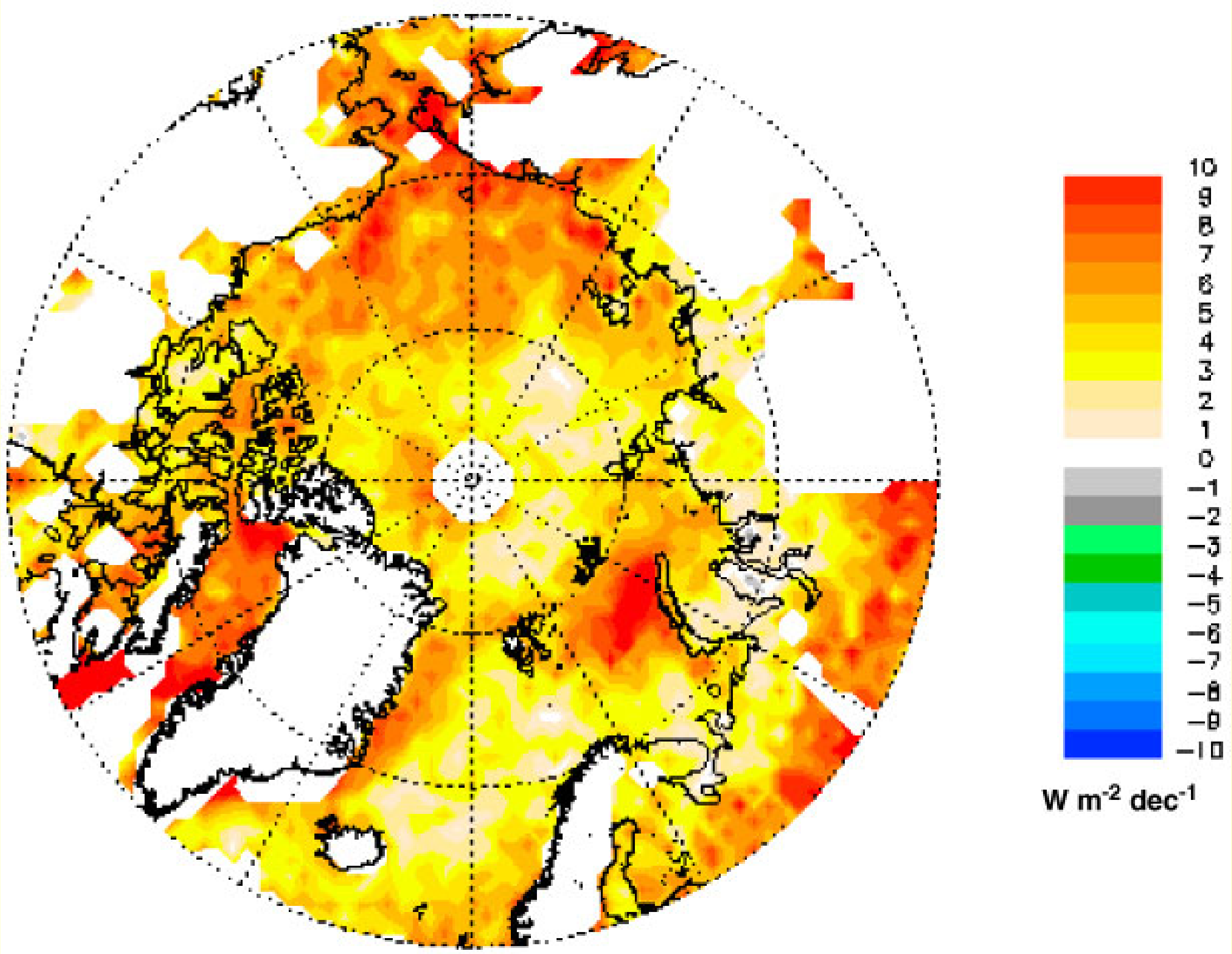
Smaller sizes of drops in polluted clouds

Enhanced aerosol amounts can make clouds emit more thermal energy to the surface (Lubin and Vogelmann, 2006, *Nature*)



Downwelling emission spectra measured by the NSA AERI beneath two clouds with very different condensation nuclei (CN) concentrations.

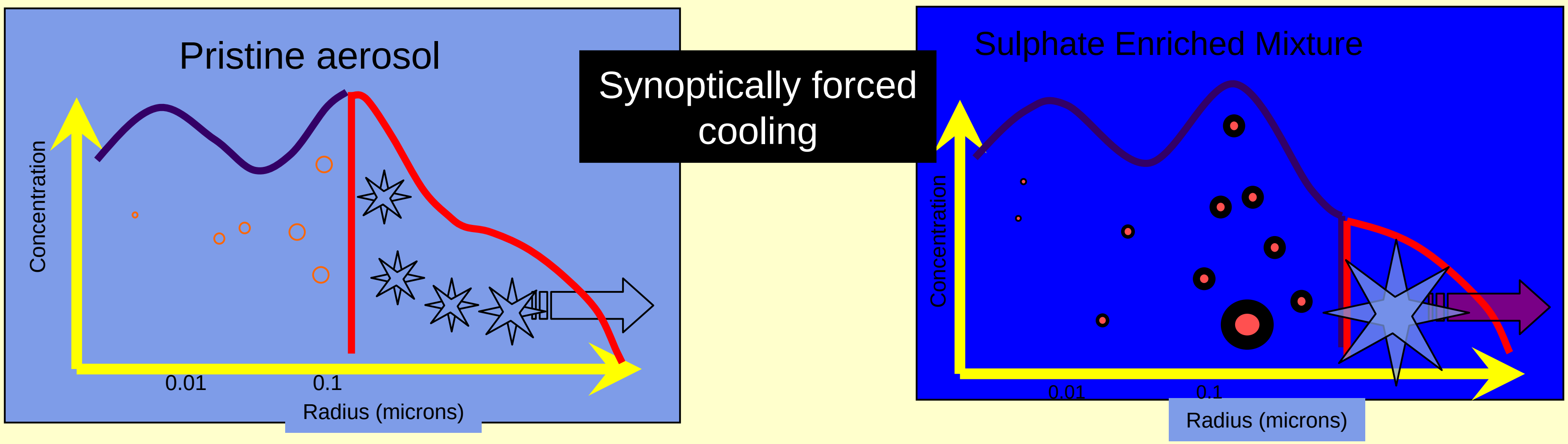
Trends in downwelling surface LW radiation
Francis and Hunter (2007)



Dehydration-Greenhouse Feedback (DGF)

Blanchet et al.

•Sulphuric acid coating is observed on aerosol - laboratory observations this indicate coated aerosols inhibit ice nuclei activity by orders of magnitude

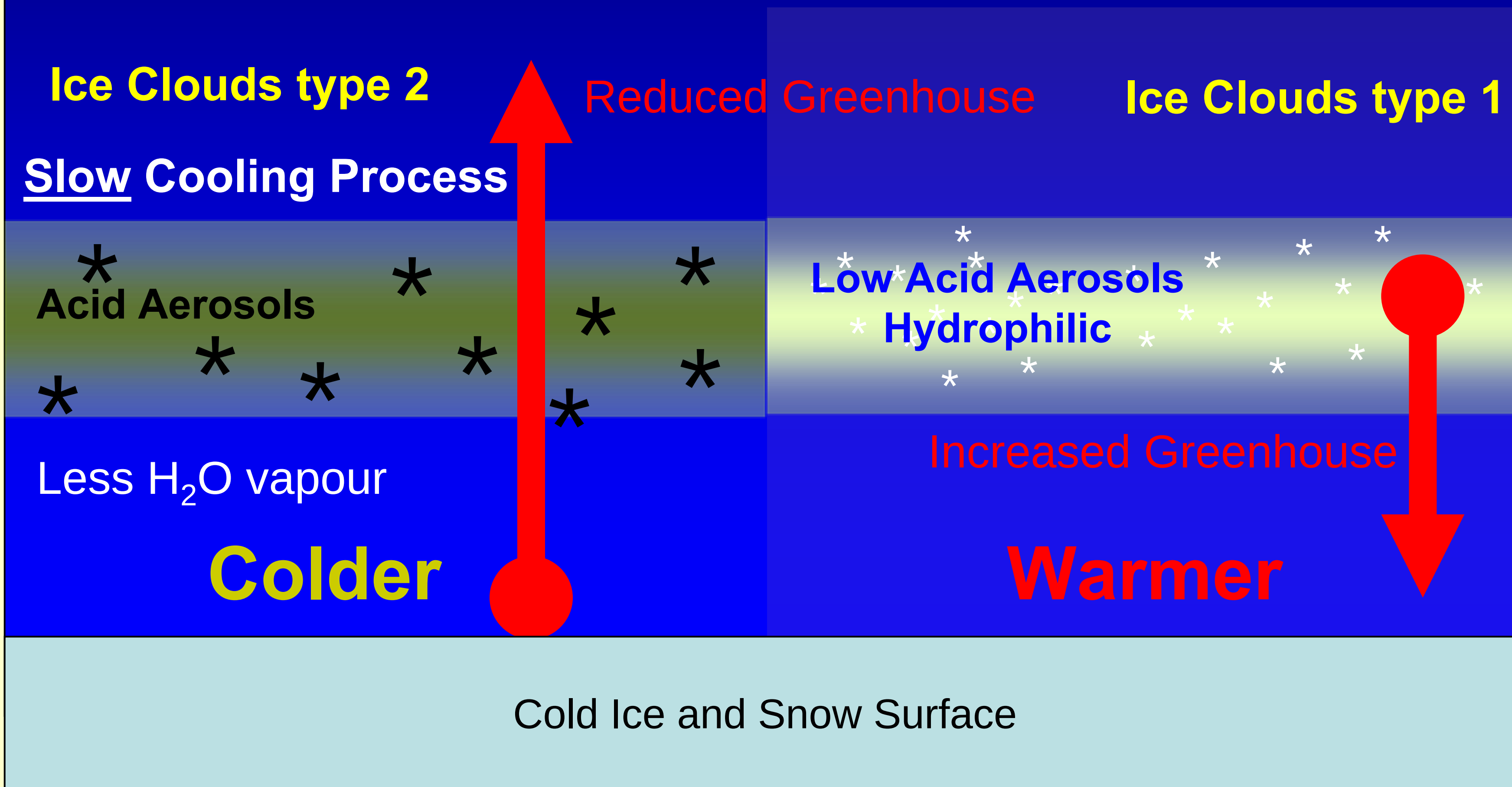


- Numerous small ice crystals
- Long cloud lifetime
- Greenhouse warming
- Radar: no or weak return
- Lidar: observed backscatter
- Thin Ice Cloud ***type 1***

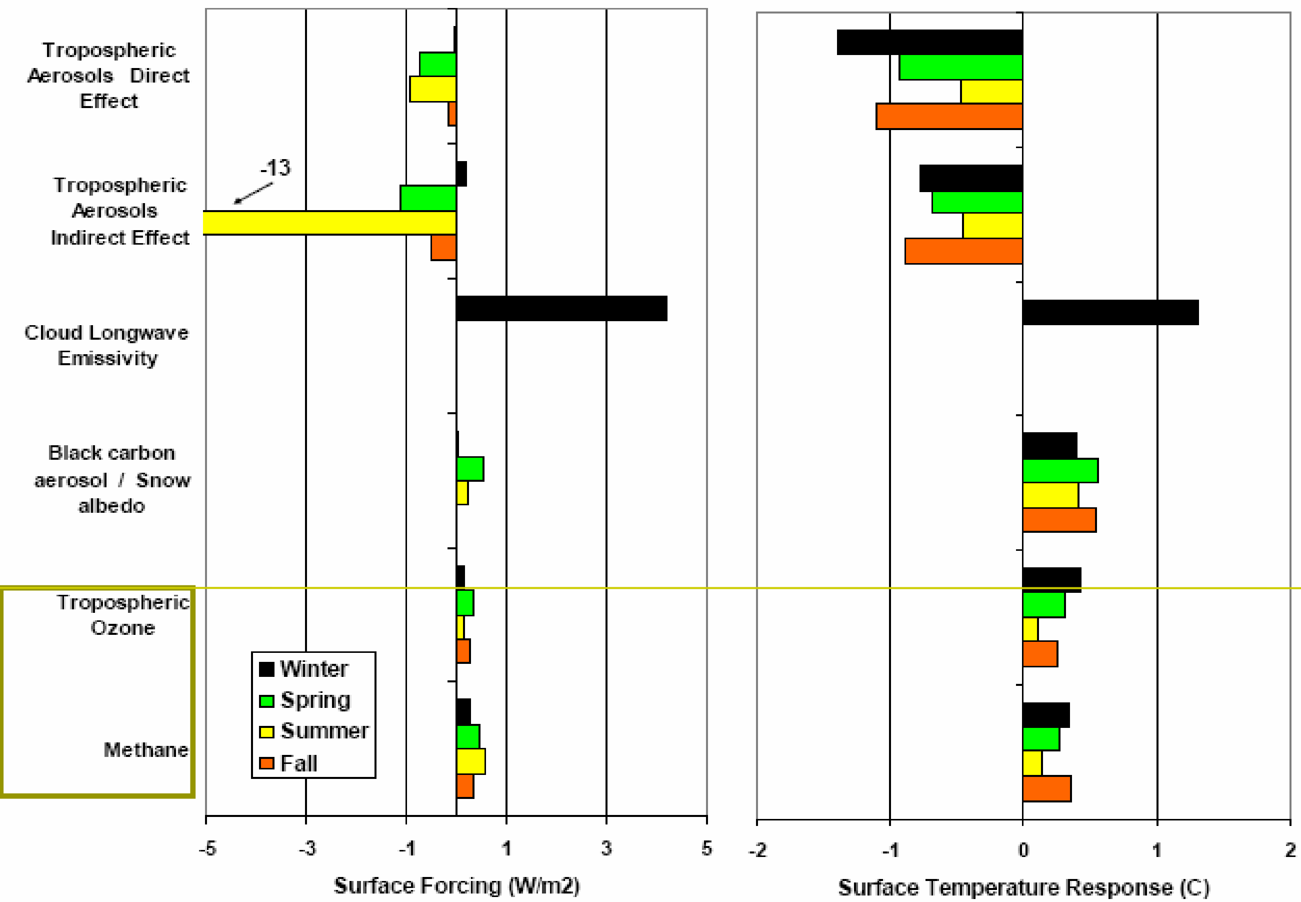
- Fewer but larger ice crystals
- Precipitate and dehydrate
- Reduced Greenhouse & cooling
- Radar: visible
- Lidar: Visible
- Thin Ice Cloud ***type 2***

Dehydration-Greenhouse Feedback (DGF)

Clouds forming on acidic ice nuclei precipitate more effectively, dehydrate the air, reduce greenhouse effect and cool the surface



Aerosol surface forcings and surface temperature response



GHGs

Seasonally mean forcing and responses simulated with NASA GISS ModelE GCM

Quinn et al.(2008)

Comparison of Seasonality & Magnitude of Forcing and Surface Temperature Response for Short-lived Pollutants in the Arctic

Quinn et al.(2008)

Forcing Agent	Season	F_S W m^{-2}	F_{TOA} W m^{-2}	F_{TOA-S} W m^{-2}	ΔT_s[a] °C
Tropospheric Aerosols - Direct Effect[b]					
Total* – Fossil+Bio Fuel *$SO_4^{=}$ + OC + BC	Winter	-0.04	0.08	0.11	-1.4[c]
	Spring	-0.72	0.92	1.6	-0.93[c]
	Summer	-0.93	0.11	1.0	-0.47[c]
	Fall	-0.14	0.08	0.23	-1.1[c]
Tropospheric Aerosols - Indirect Effects					
Total* – Fossil+Bio Fuel Cloud albedo + cloud cover SW, LW, SW+LW *$SO_4^{=}$ + OC + BC	Winter	-0.04, 0.24, 0.2[d]	0.07, -0.1, -0.03[e]	0.11, -0.34, -0.23	-0.77[f]
	Spring	-3.0, 1.9, -1.1	0, 0.1, 0.1	3.0, -1.8, 1.2	-0.68[f]
	Summer	-12.2, -0.5, -13	6.6, -0.5, 6.1	19, 0, 19	-0.45[f]
	Fall	-0.4, -0.1, -0.5	0.49, -0.9, -0.41	0.89, -0.8, 0.09	-0.89[f]
Cloud longwave emissivity	Winter	+3.3 to 5.2[g]			1 to 1.6
Black carbon - Snow Albedo[h]					
BC – Fossil+Bio Fuel	Winter	0.02			0.37
	Spring	0.53			0.51
	Summer	0.21			0.21
	Fall	0.002			0.49
Tropospheric Ozone – GHG warming + SW absorption[i]					
O_3 – Fossil+Bio Fuel and Biomass burning	Winter		0.13		0.43
	Spring		0.34		0.31
	Summer		0.14		0.11
	Fall		0.24		0.26
Methane – GHG warming[j]					
Methane	Winter		0.29		0.34
	Spring		0.45		0.27
	Summer		0.55		0.15
	Fall		0.34		0.35

Seasonal Offset in Forcing and Response

Summary

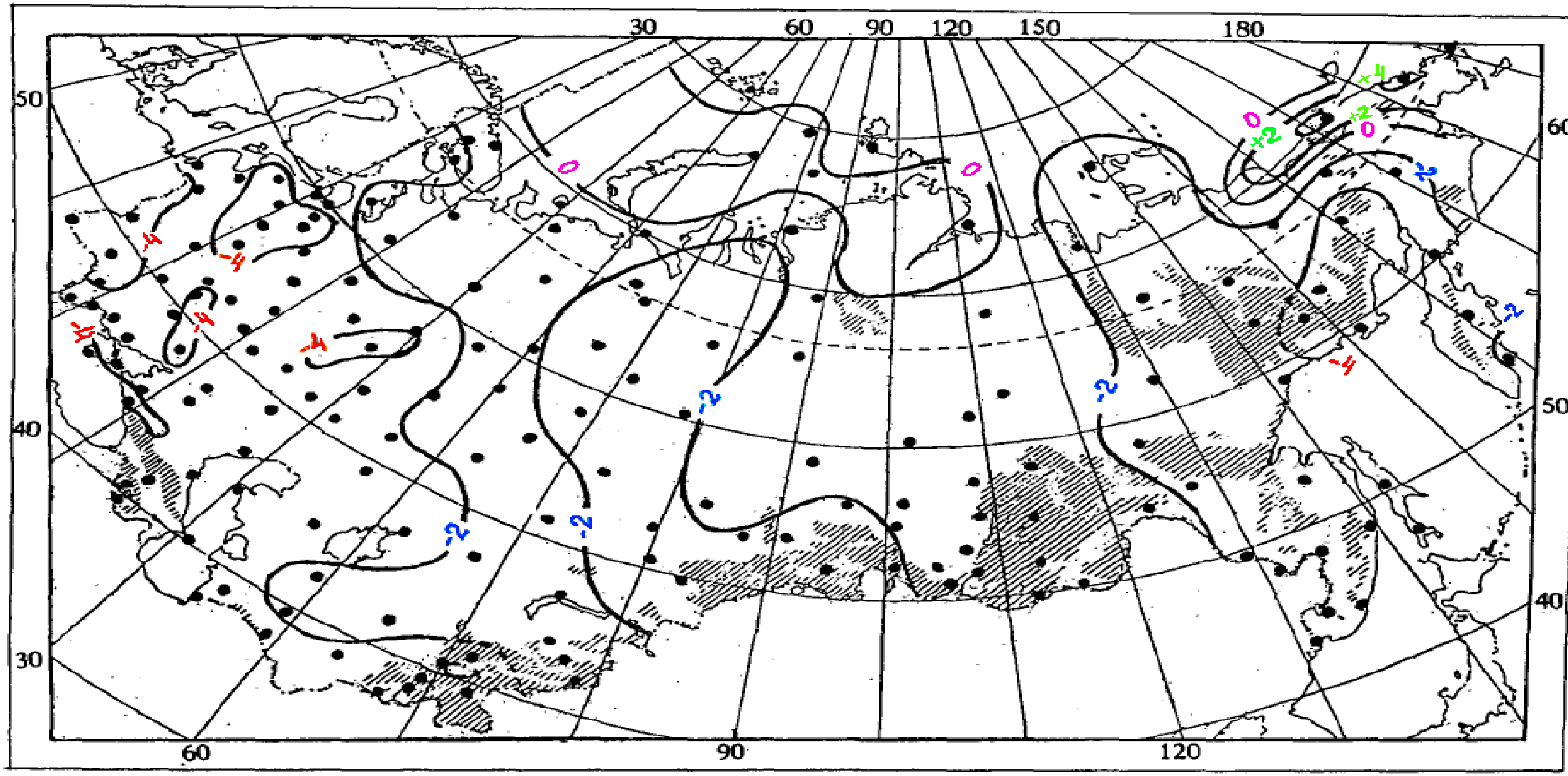
- Arctic aerosols may be contributing to the accelerated rates of warming observed in the Arctic. However, there are large uncertainties in assessments because of the inability of models to describe accurately many of the complex processes and feedbacks involved, as well as a paucity of observational data.
- A key question remains as to the role that aerosol, clouds and associated feedbacks play in modulating GHG warming in the Arctic
- By affecting radiation, clouds and surface albedo, aerosols are linked to the radiation-climate feedback processes such as snow/ice-albedo feedbacks, water vapor feedback and cloud-radiation feedbacks that all have been known for some time to be of importance for the Arctic climate.
- Complex spatial trends of aerosol across the Arctic imply the heterogeneous related forcing and complex responses
- A combination of changes in sources (especially, LCLUC in Northern Eurasia), transport (atmospheric circulation) and precipitation (aerosol removal) is emerging as a key factor that controls the presence of aerosols in the Arctic and hence aerosol-induced impacts upon the Arctic system

EXTRA

Global "dimming" paradigm:
aerosol-induced reduction in downward surface solar radiation

Trend (%/10YR)

Data of global (direct+diffuse) solar radiation from 160 FSU actinometric stations, 1960 – 1990; Abakumova et al. (1996)



!!!! Net effect of {Aerosols +clouds +H_2O} + surface albedo

The Spectrum of our Knowledge

From Ground-based Sensors (Shupe et al)

← Certain "Known" Unknown

Phase Classification

Phase balance (layer)

Aerosol profile

Ice Re

Phase balance (resolved)

IWC/IWP

Cloud Boundaries

LWP

LWC No assumption

LWC (adiabatic)

Liquid Re (thin clouds)

Liquid Re (Thick clouds)

Ice optical depth

Radiative Forcing

Liquid optical depth

Heating Rate

Liquid extinction (thick)

Ice extinction

Vertical Velocity

Liquid extinction (thin)

Turbulent dissipation rate

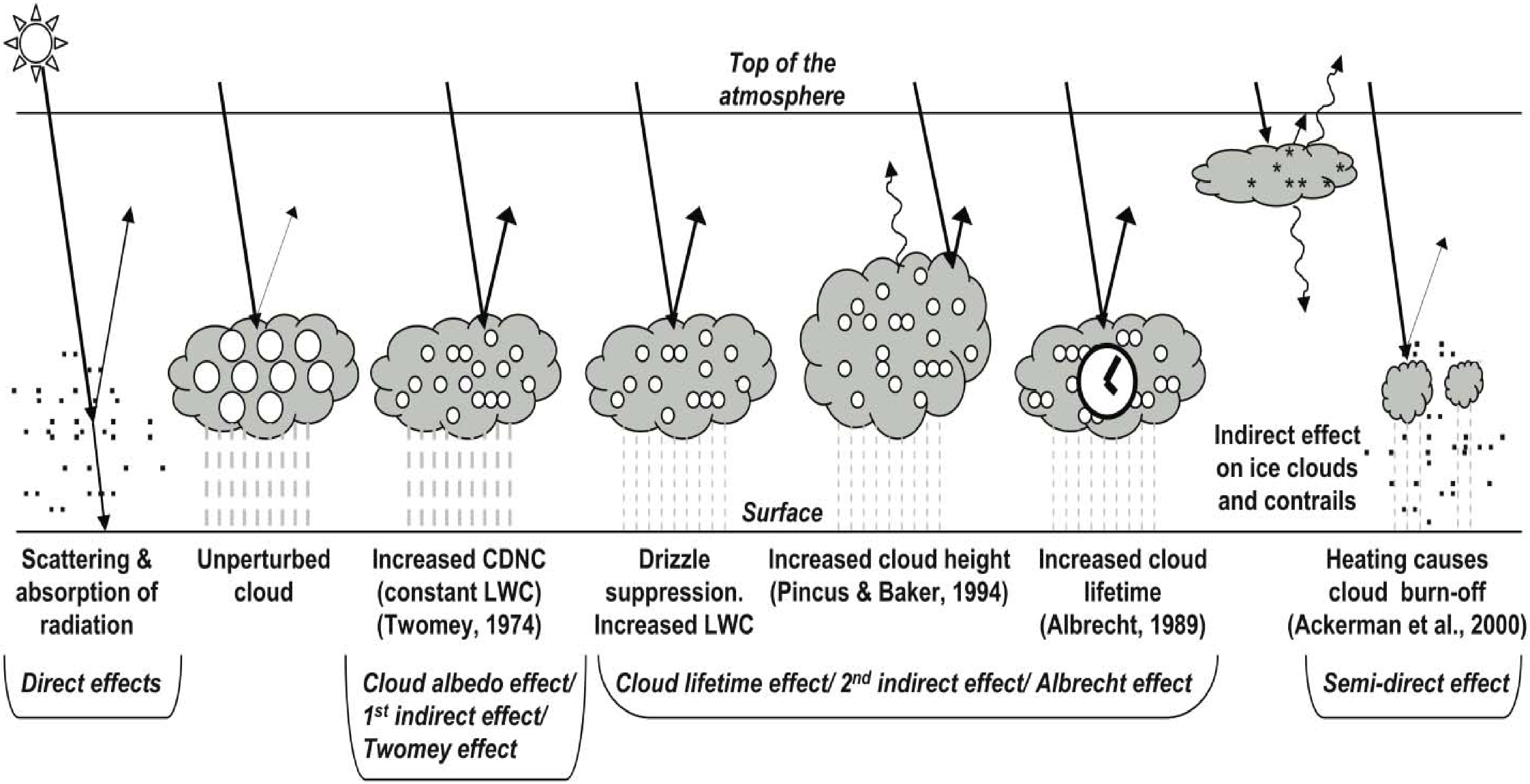
Need new methods

Need further validation

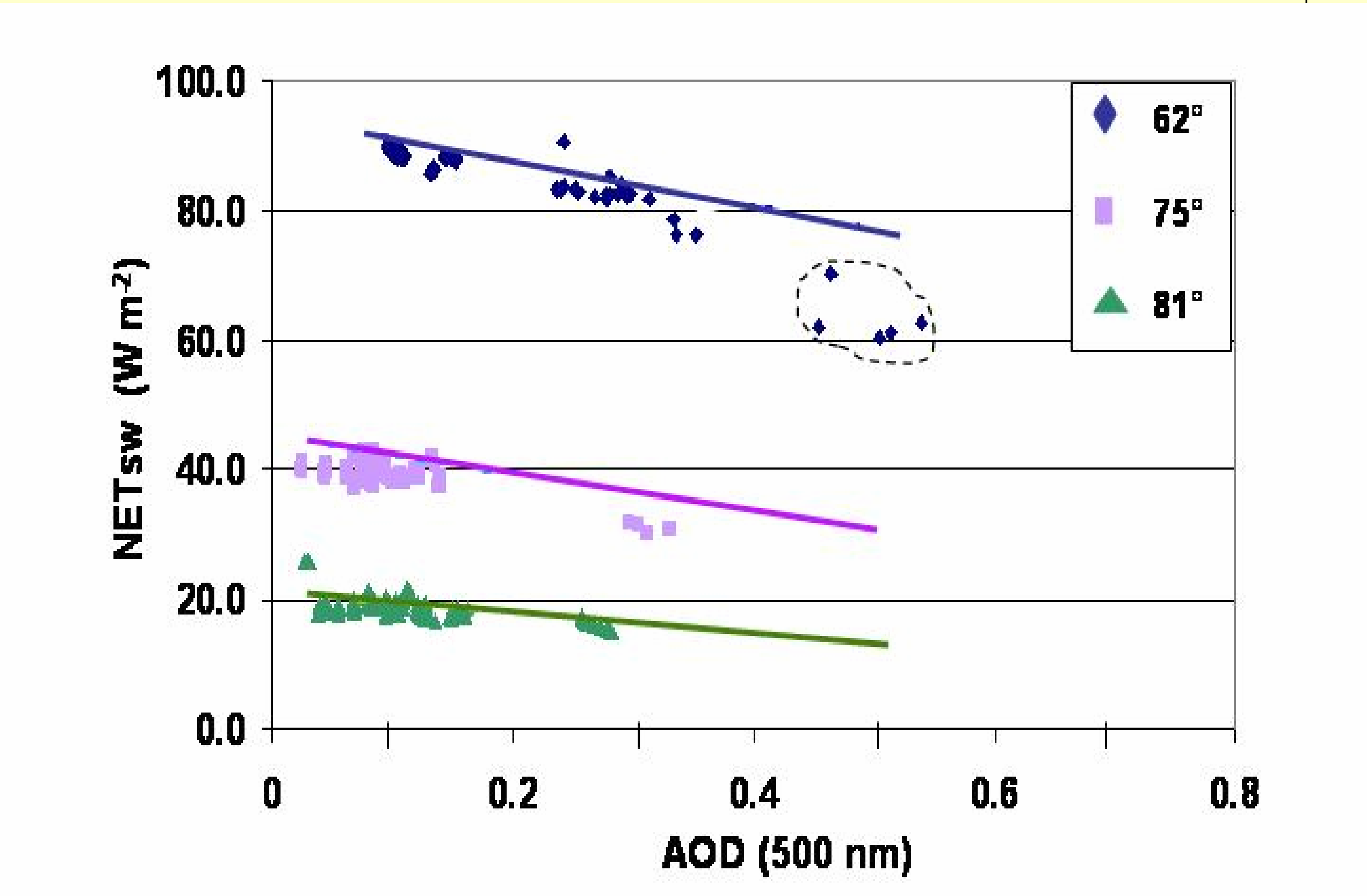
Direct radiative impacts of aerosols specifics of the Arctic region

IMPACT	IMPORTANCE
Top of the atmosphere (TOA) radiative forcing (SW plus LW)	affects energy balance of the Earth's climate system
Radiative forcing at the surface (SW plus LW)	affects surface temperature and surface-atmosphere exchange processes, ecosystem functioning
Radiative heating/cooling (SW plus LW)	affects temperature profile, cloud lifetime, and atmospheric dynamics thermodynamics
Actinic flux (UV)	affects photolysis rates and photochemistry (e.g., O3)
Changes in surface albedo (via deposition of soot and dust on surfaces) (SW)	affects surface energy budget, land surfaces and oceans

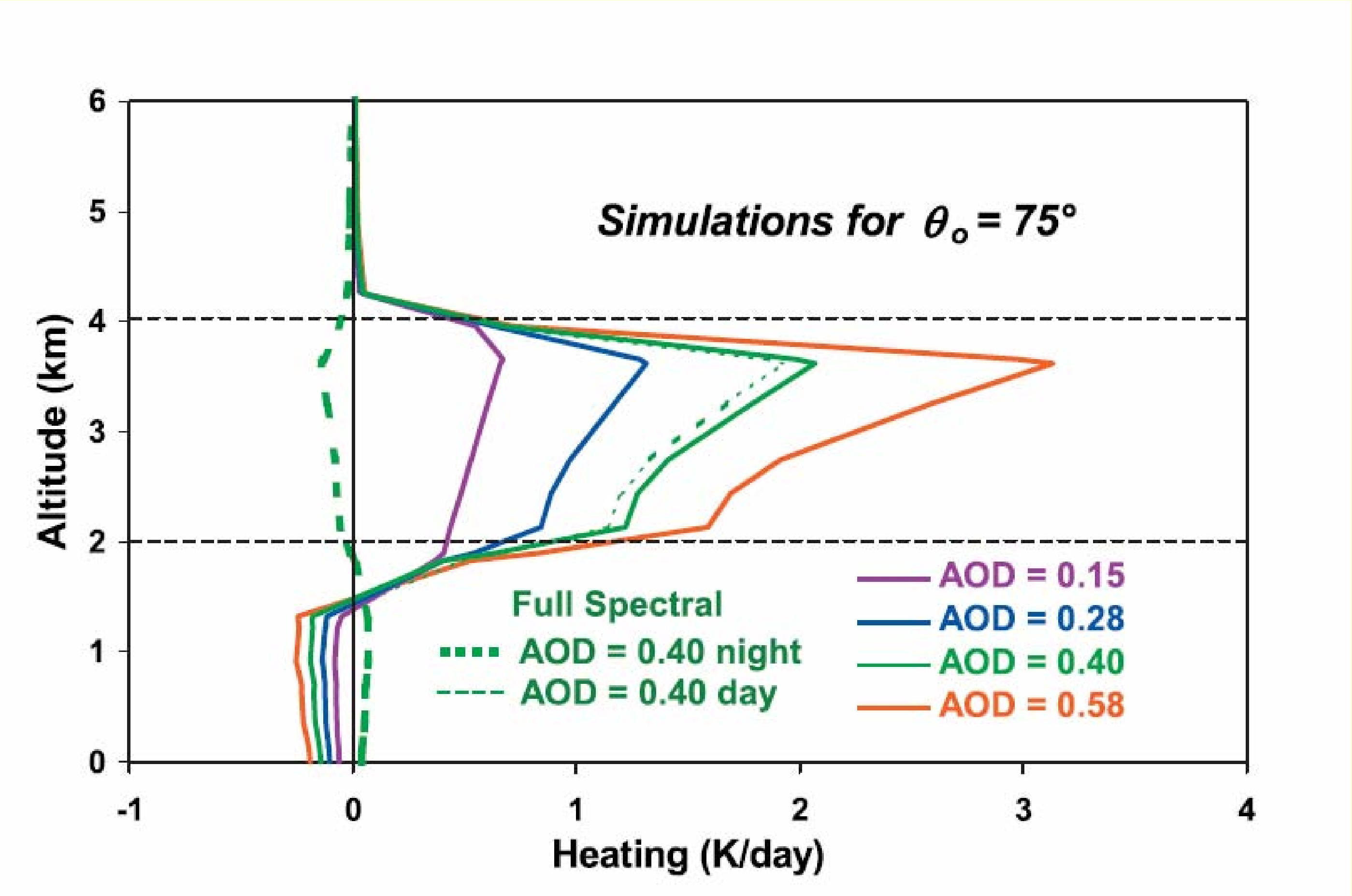
Linking aerosol and precipitation through direct and indirect effects



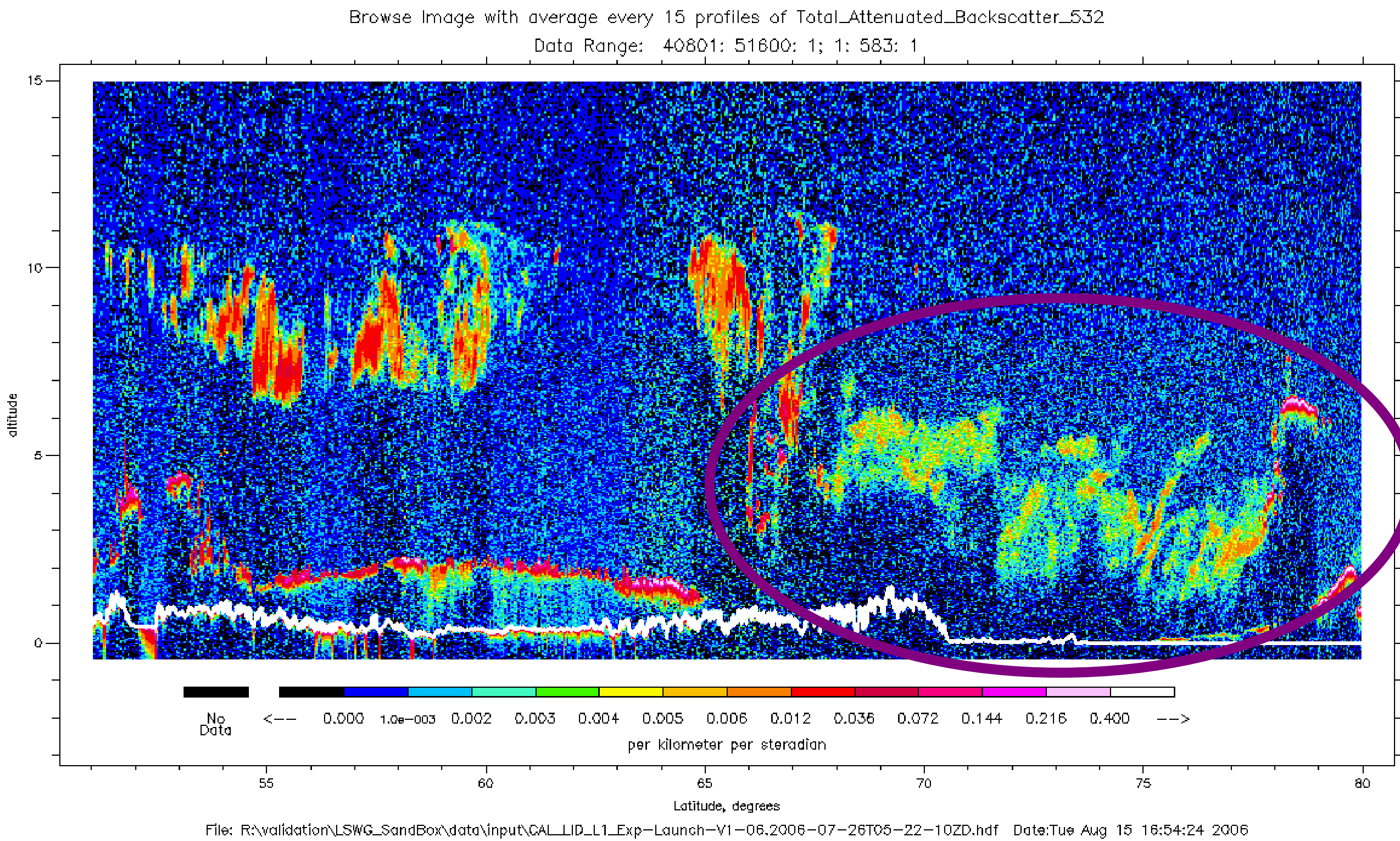
Comparison of measured and simulated surface net shortwave irradiance as a function of visible (500 nm) aerosol optical depth during an Asian dust event at Barrow Observatory, April 2002. Symbols represent one-minute measurements and solid lines the results from MODTRAN™ fitted using linear regression for zenith angles indicated at the upper right. The circled (suspect) points were not used in the 62° analysis for purposes of computing *DARF* empirically (Stone et al.)



Heating/cooling – Asian dust at Barrow

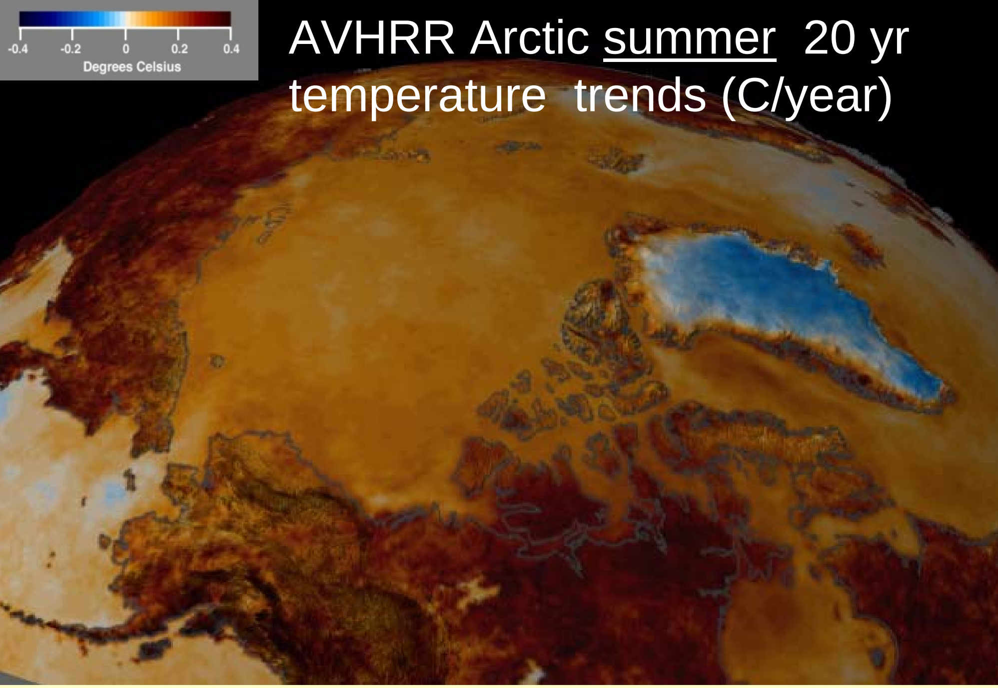


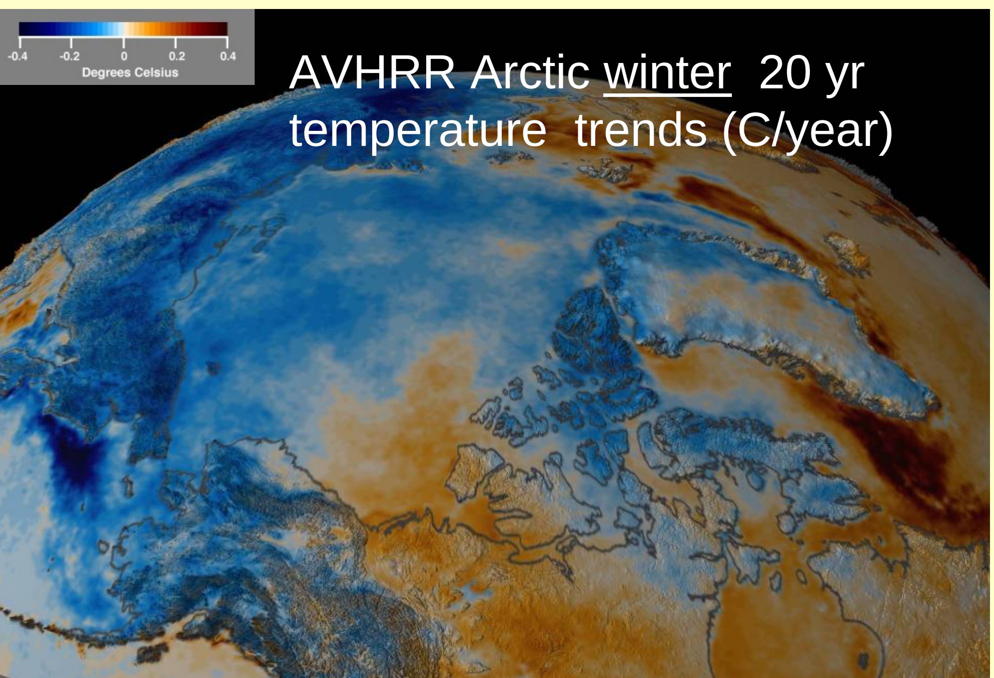
First Views of CALIPSO data



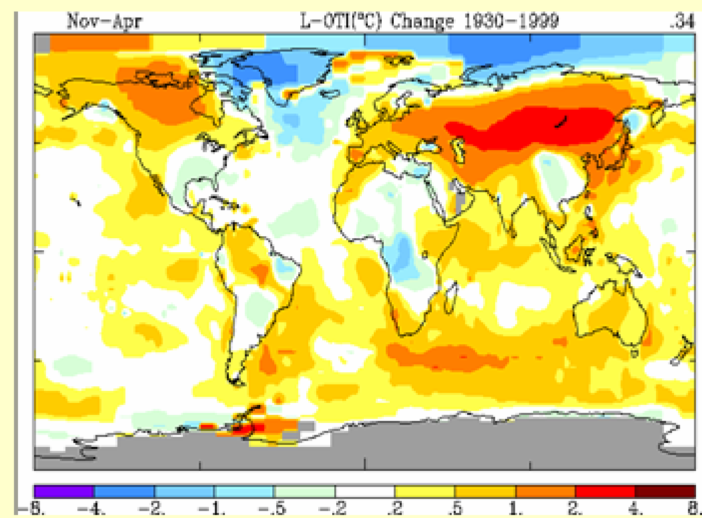
CALIPSO captures both the maximum altitude of the smoke plume at about 6 km and the vertical smoke structure, as it evolves over time.

Hints at Aerosol-precipitation effects on the climate change of the Arctic





70 year observed trend
Hansen, GISS



Specifics of aerosol- radiation interactions in the Arctic

- The deficit of Arctic energy is central to the Globe
- The radiative balance in the Arctic very sensitive to changes of atmospheric composition
- Prolong Polar night – importance of LW (aerosols and clouds work like GHGs)
- Because of bright surfaces, even relatively small amounts of absorbing species (such as soot and dust) cause warming
- Changes in

- Important to know: Arctic –wide distribution of aerosol types (composition as a function of size) and their abundance