



Effects of Human Activities on the Arctic Climate **and** Environment

CEMP Workshop, Ely NV, July 2009



Joe McConnell



- **Arctic climate is changing rapidly**
- **As documented in ice cores, humans have had a significant impact on Arctic climate and the Arctic environment for at least 150 years**

Outline

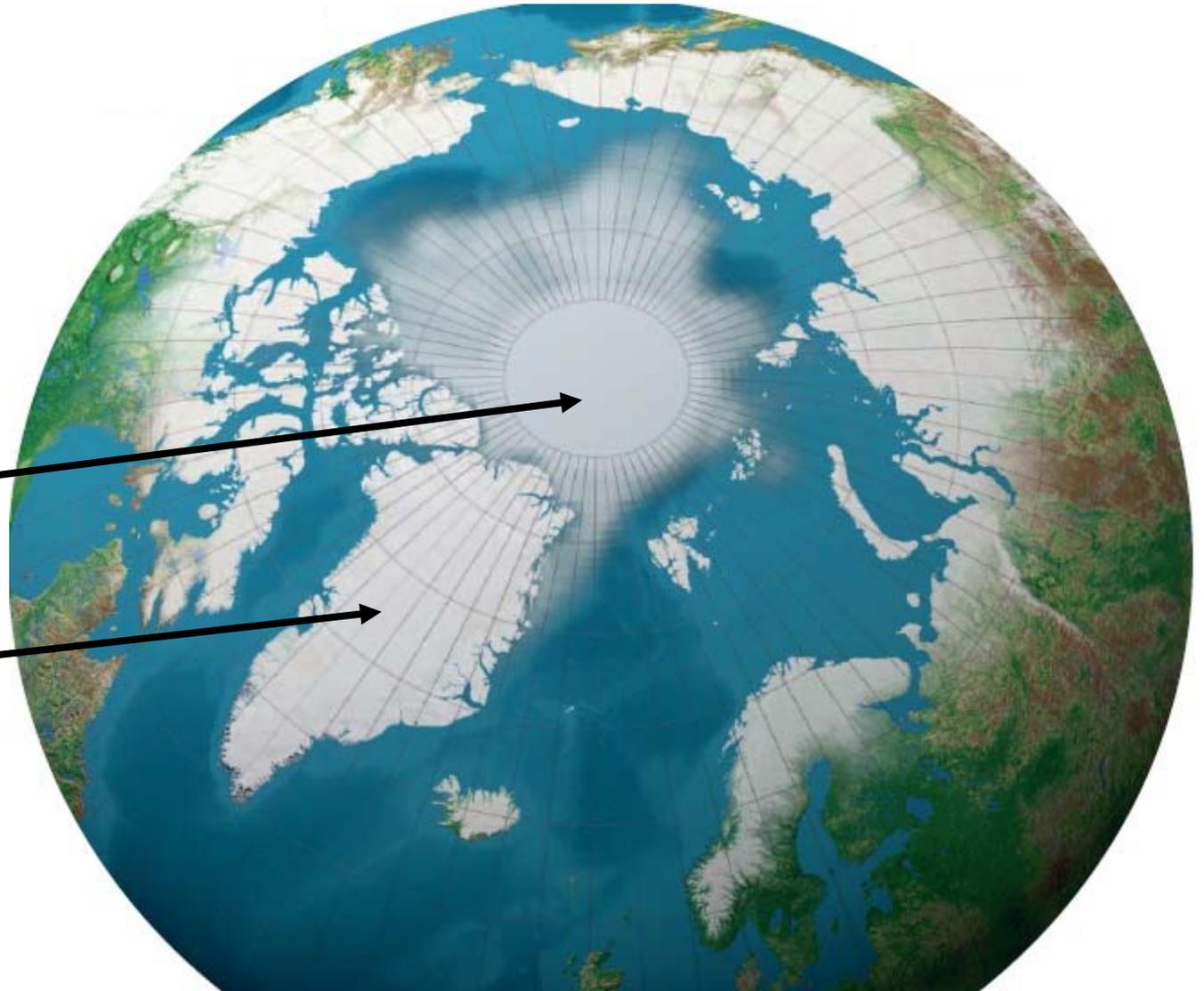
- **What is the role of the Arctic in global climate and how is Arctic climate changing today?**
- **What is the glaciochemical archive and why is it so valuable for understanding climate and environmental change?**
- **How do we sample the archive with ice cores?**
- **DRI's unique ice core analytical system**
- **Recently published results from Greenland**

Where is the Arctic?

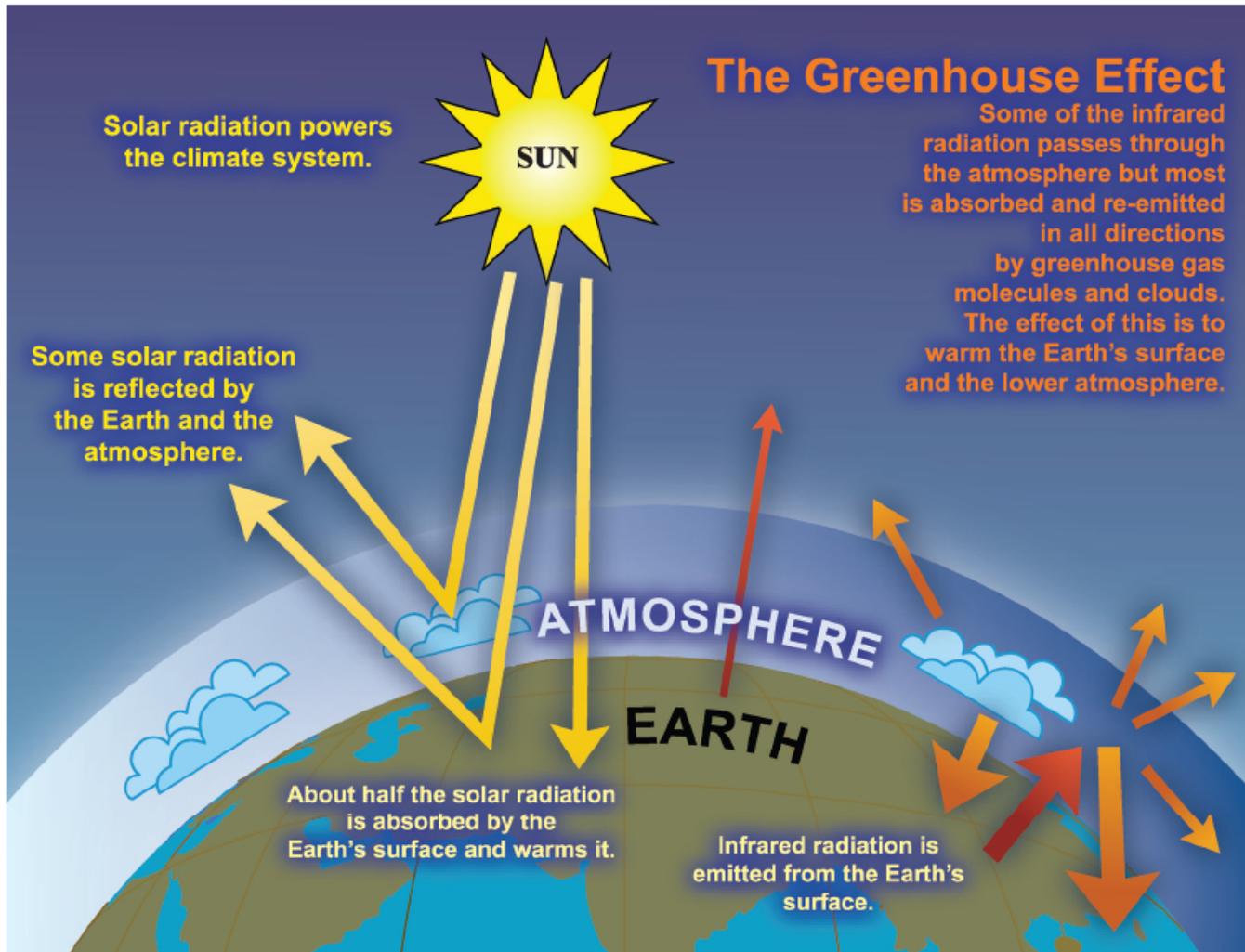
Permafrost

Permanent and
seasonal sea ice

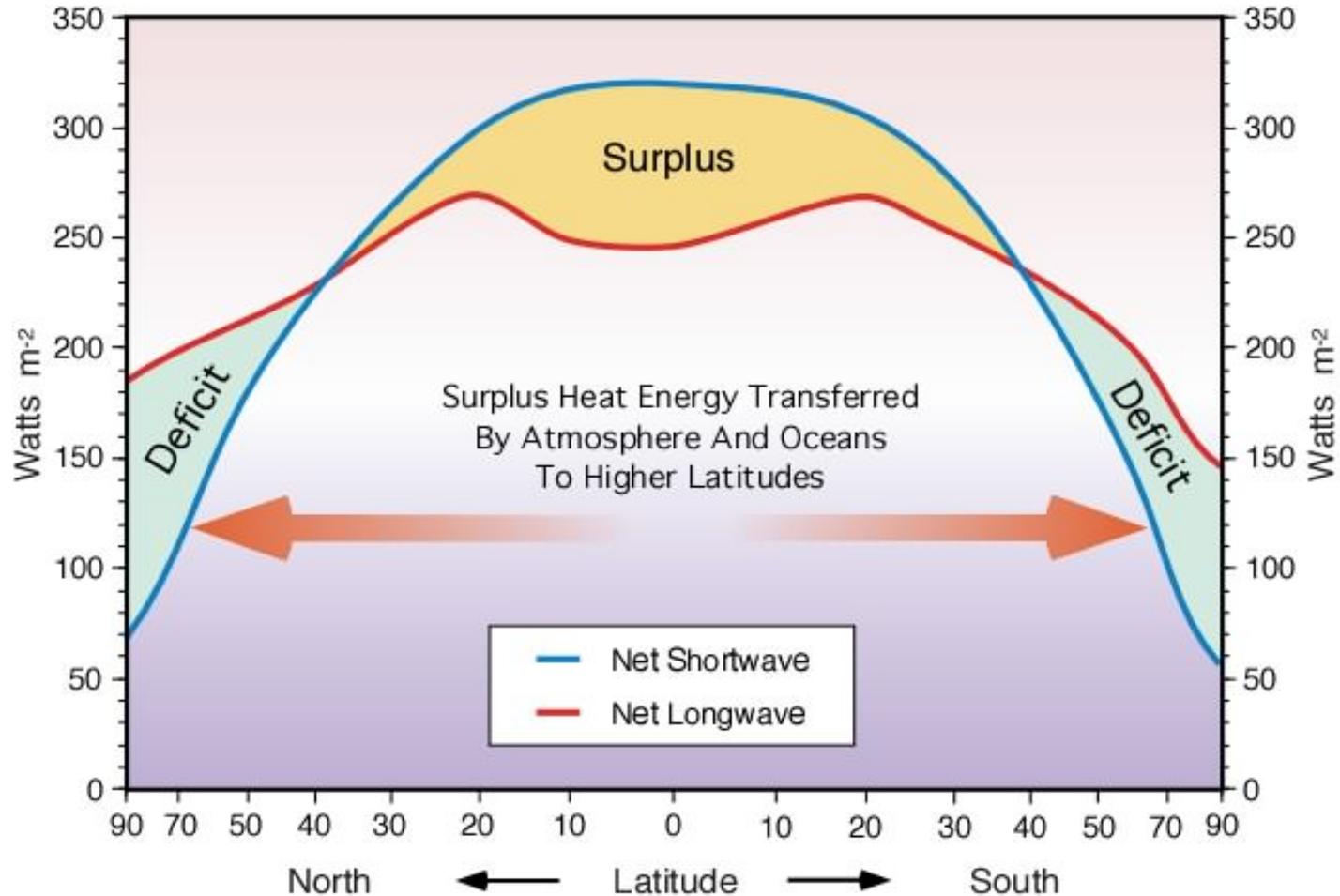
Glaciers and
ice sheets



What drives global climate? The “Greenhouse Effect”



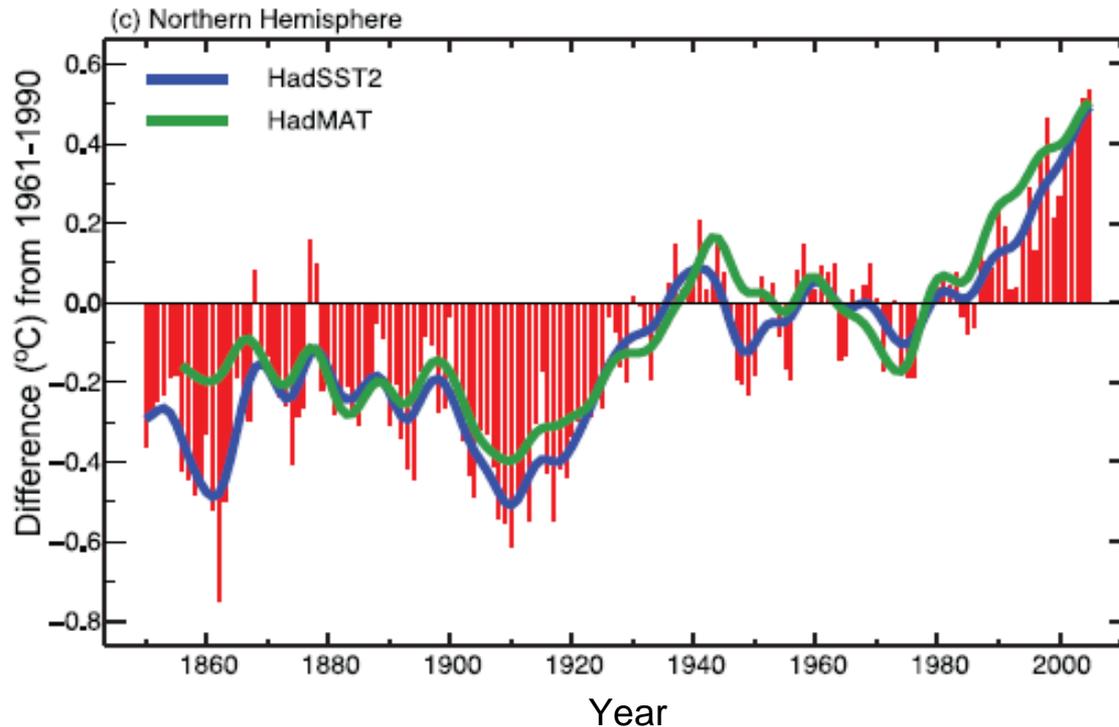
The Polar Regions play a key role in global energy balance



Source: PhysicalGeography.net

How is the Arctic changing today?

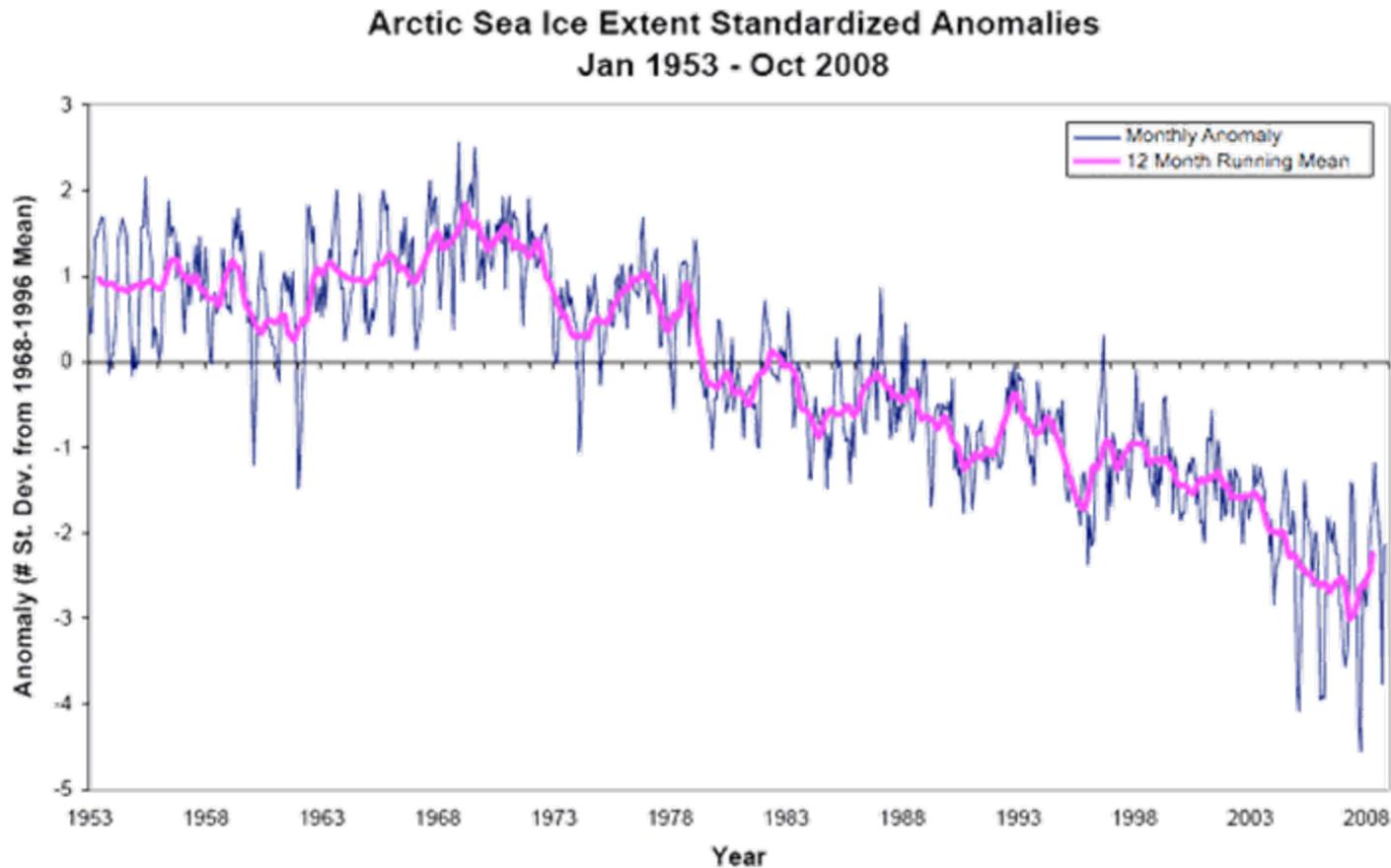
Air temperatures are rising!



Source: IPCC, 2007

How is the Arctic changing today?

Sea ice extent expands and shrinks each year but overall trend is strongly downward!



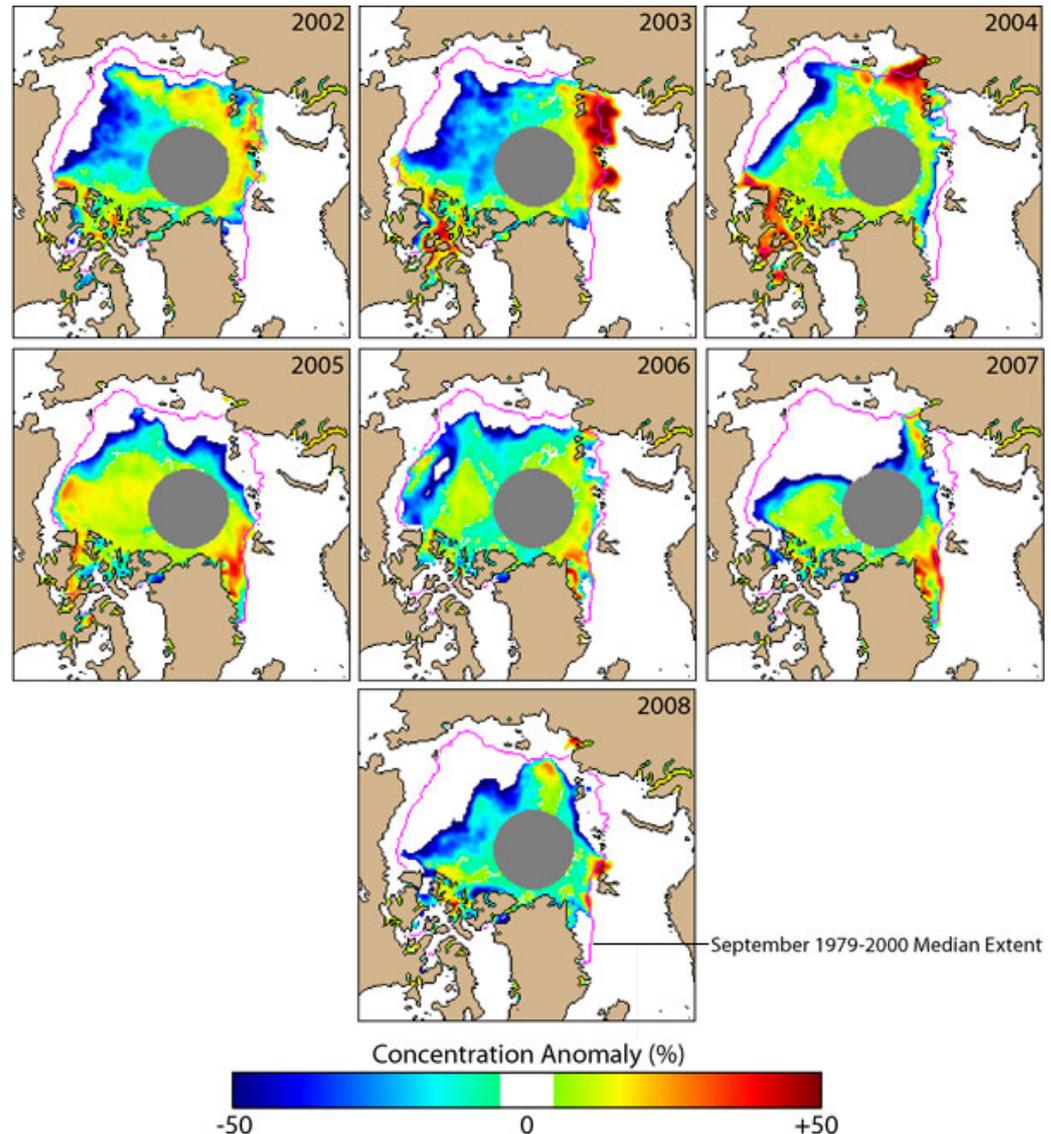
Source: <http://nsidc.org/>

How is the Arctic changing today?

Permanent sea ice is melting!

Sea ice conditions for the month of September, 2002 through 2008

Source: <http://nsidc.org/>



Loss of permanent sea ice predicted by 2030 (or earlier!)

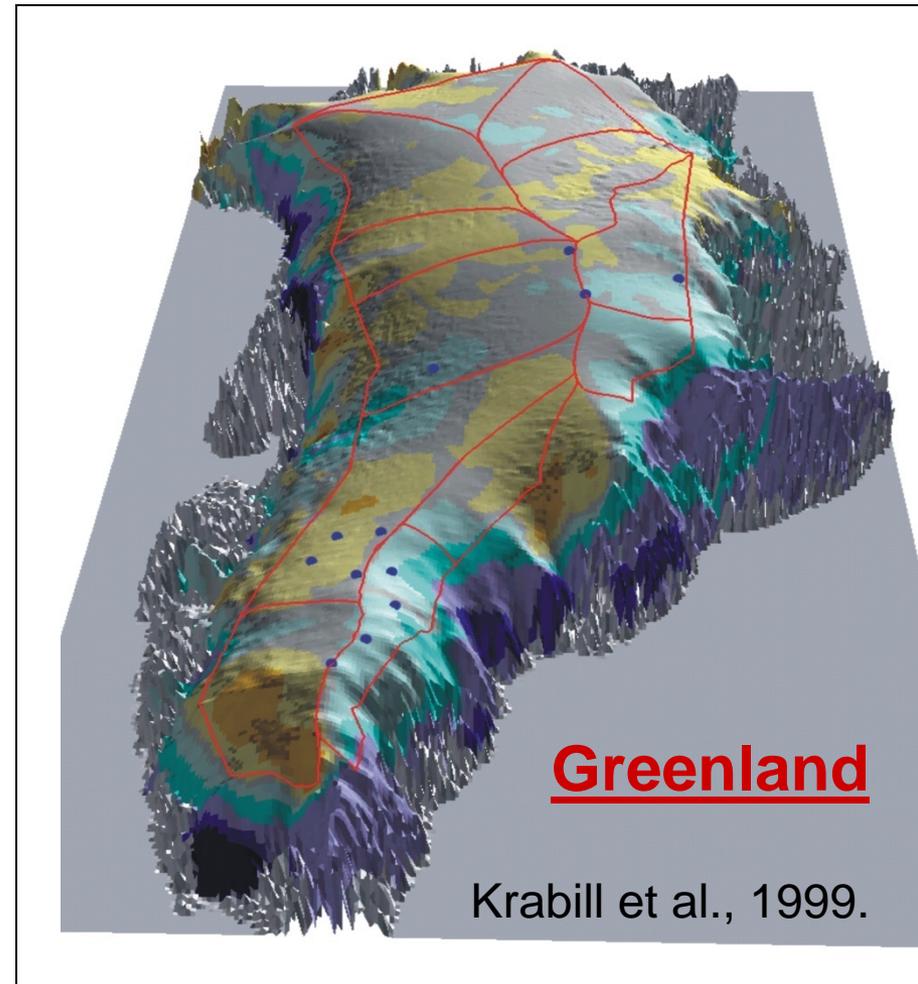
How is the Arctic changing today?



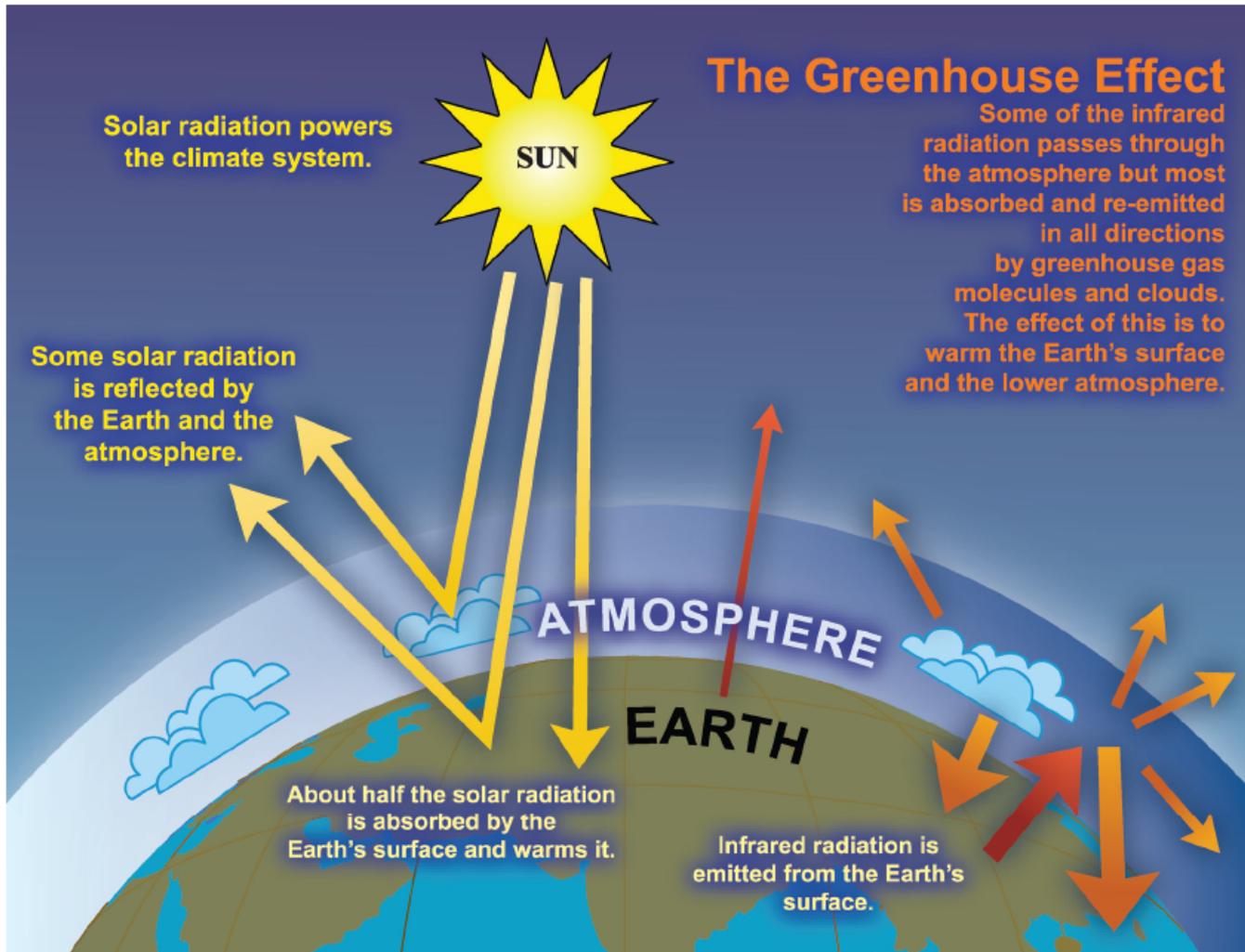
Edges of Greenland ice sheet are melting and flowing faster toward the sea!

1993 to 1999 changes in Greenland ice sheet thickness from repeated altimetry measurements

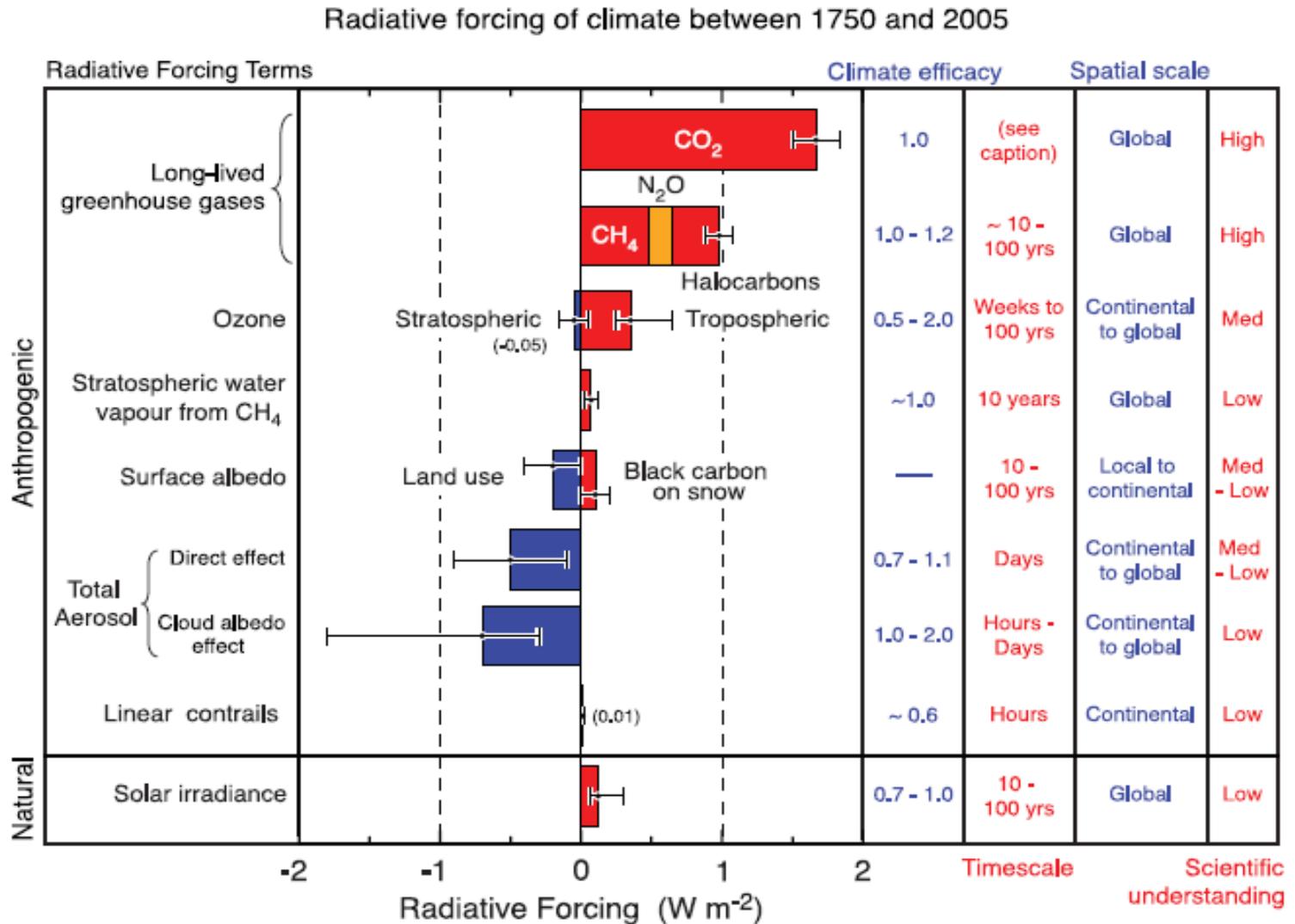
Warm colors = up
Cold colors = down



How have drivers of climate changed during recent centuries?



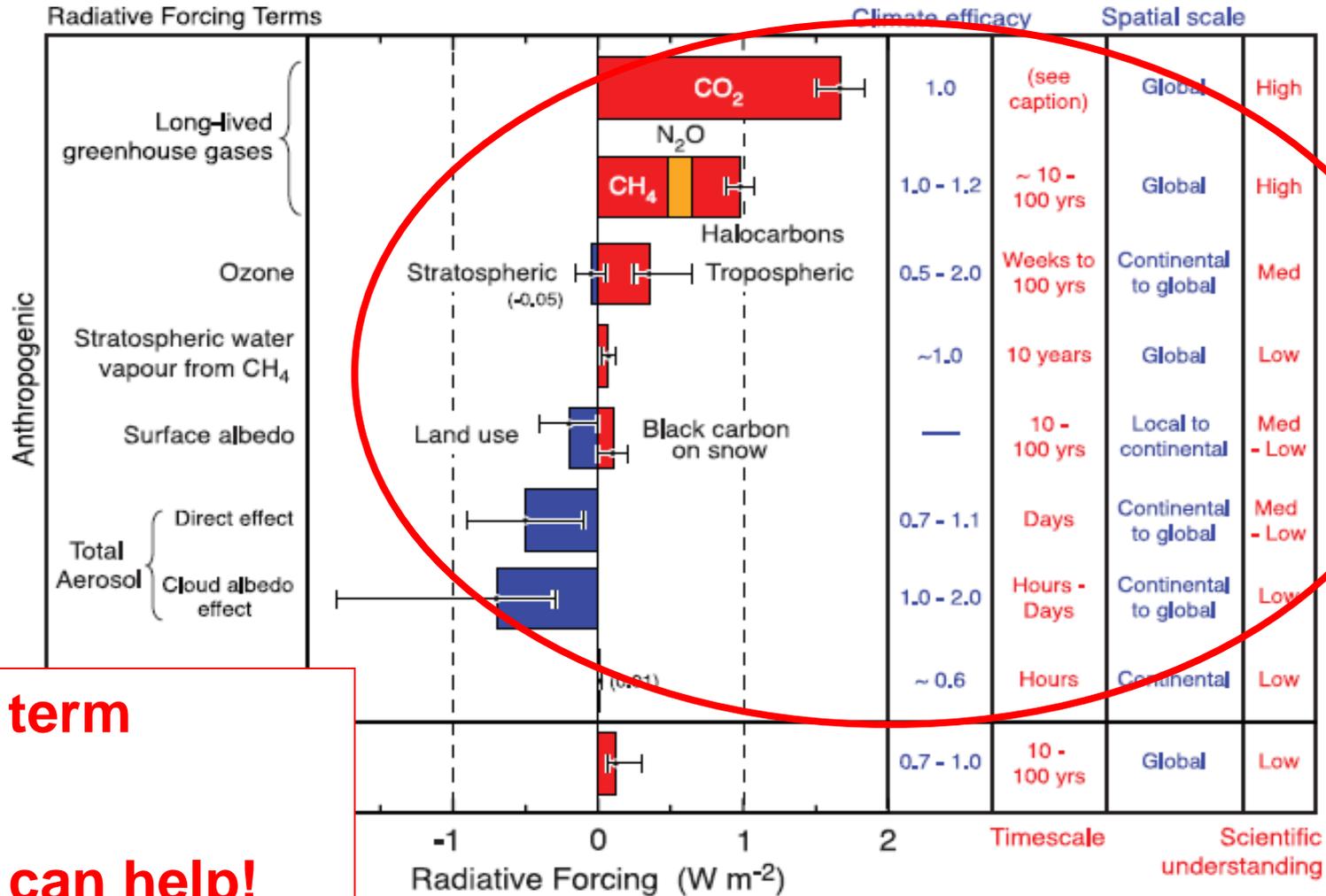
Attribution of radiative forcing of climate (1750 – 2005)



Source: IPCC, 2007

Attribution of radiative forcing of climate (1750 – 2005)

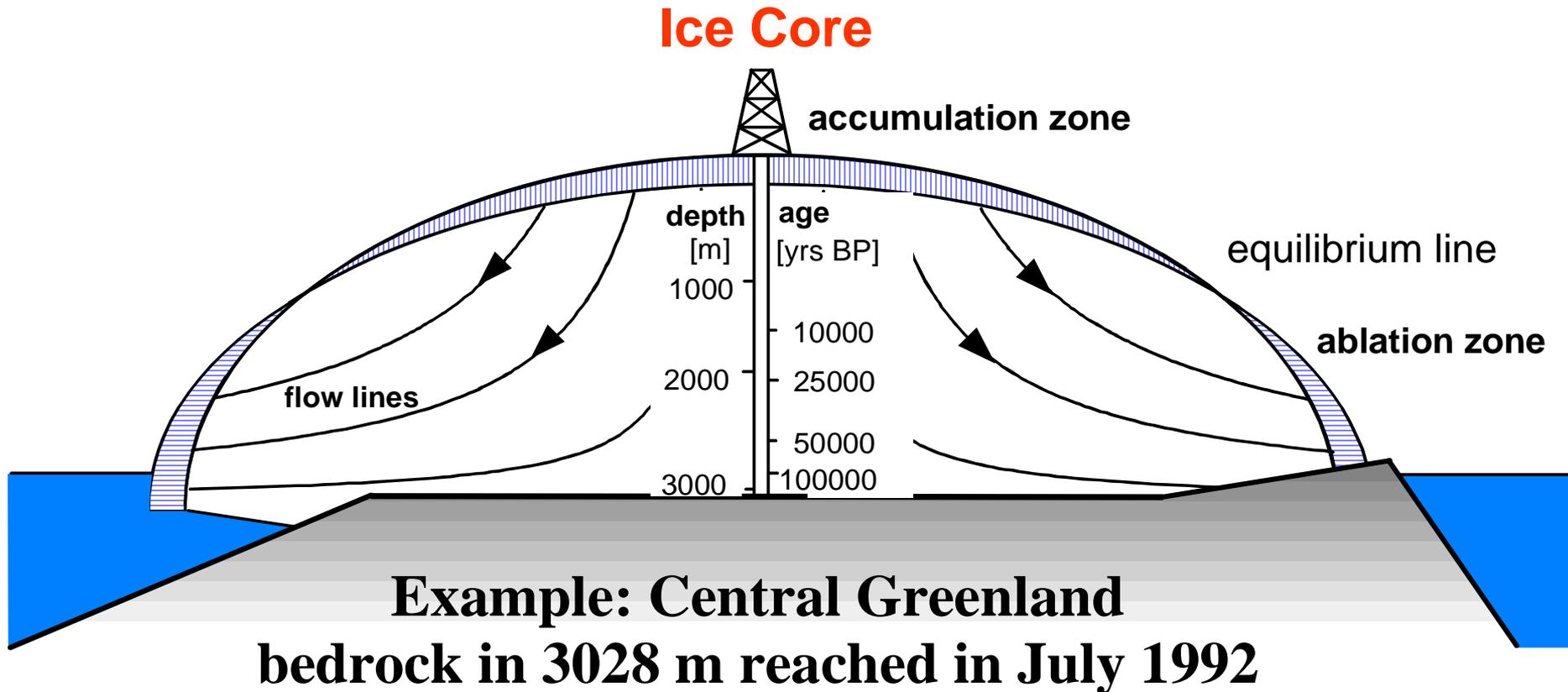
Radiative forcing of climate between 1750 and 2005



Few long term records.

Ice cores can help!

Forming the glaciochemical archive of the environment

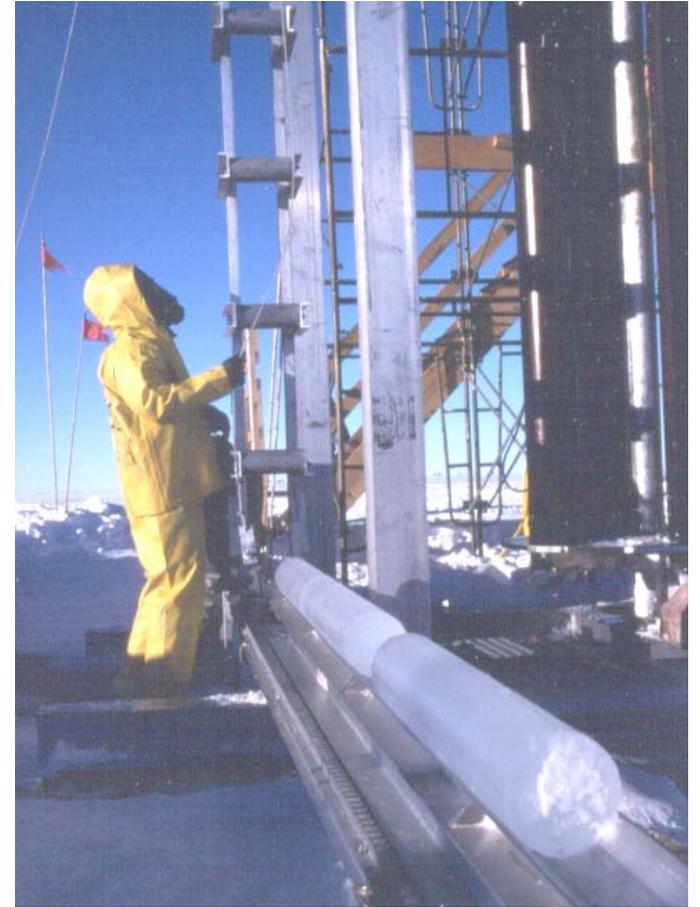


Courtesy of B. Stauffer

Sampling the Archive

Deep (Millennial-Scale) Ice Coring

Deep Coring at Siple Dome,
West Antarctica



Photos: K. Taylor

Sampling the Archive

Intermediate (Century-Scale) Ice Coring



Photos: L. Long

Sampling the Archive

Shallow (Decade-Scale) Ice Coring

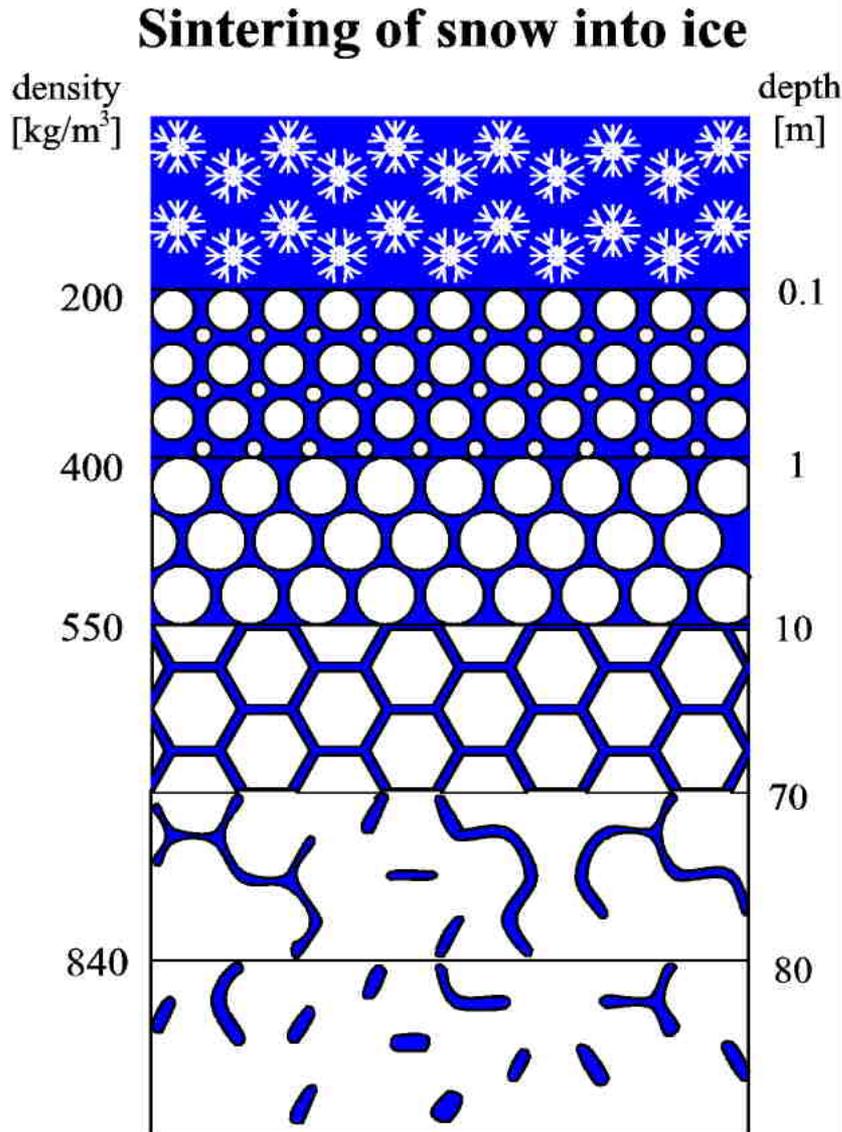


“Commuter” Coring
Home in time for dinner!!

Why are ice cores records so valuable?

- **Most direct paleo???** records
 - **Actual (not proxy) atmospheric & precipitation chemical properties**
 - **Span decades to centuries to millennia**
 - **High temporal resolution (monthly to annual)**
 - **Spatial resolution (arrays)**
 - **Point to regional scale information (long range transport implicit)**

Components of the Archive



- **Net snowfall**
- **Gases trapped in the pore spaces**
- **Water isotopes**
- **Soluble & insoluble impurities in the ice lattice**

Why care about net snowfall?

Ice Sheets ↑ Sea Level ↓ or Ice sheets ↓ Sea Level ↑

Mass balance = inputs – outputs

Inputs: snowfall (ice cores, precipitation models)

Outputs: sublimation, ice berg calving, melt

Greenland + Antarctica = 81 m (~260 ft) sea level

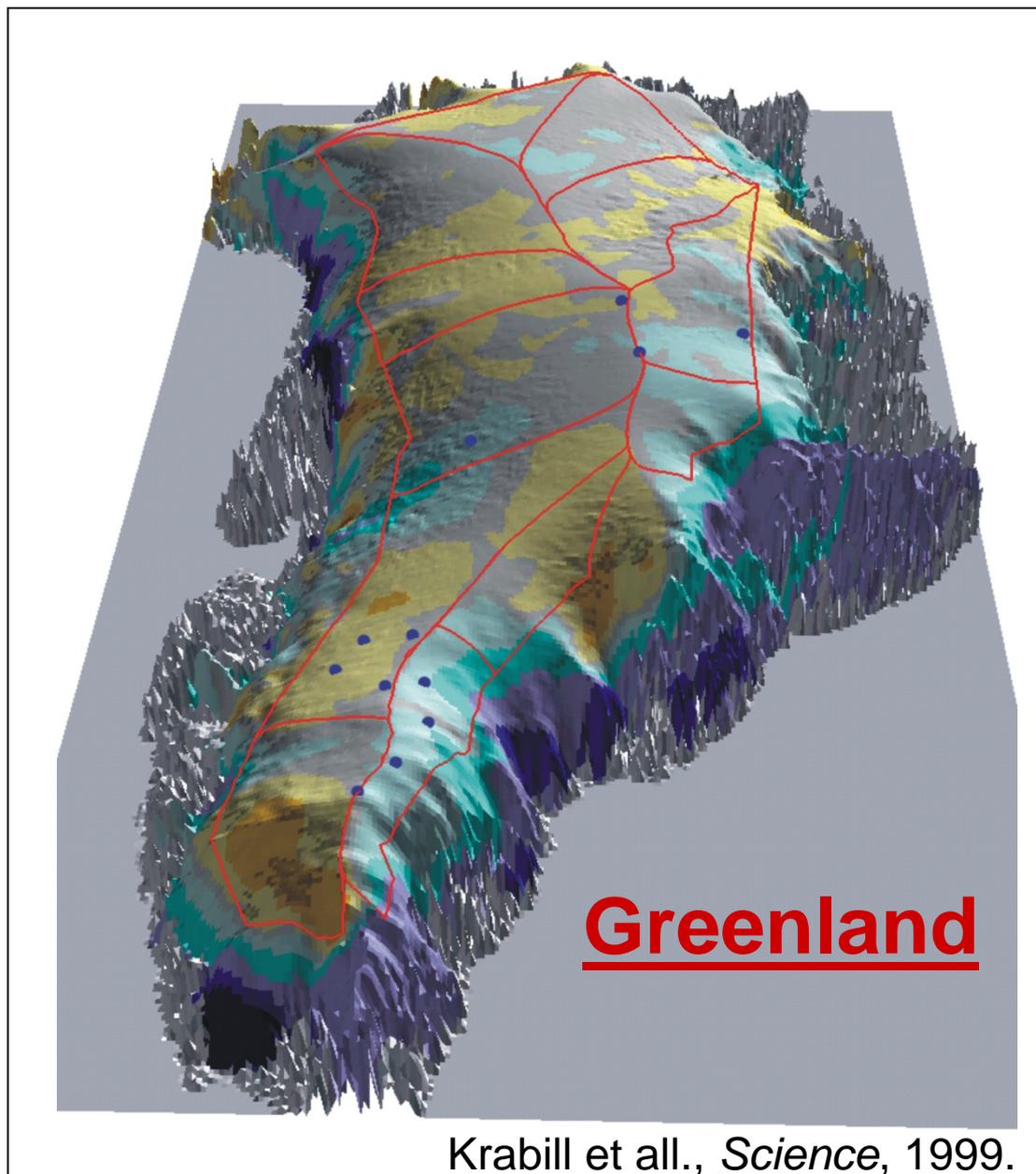
**Question: Will ice sheets grow
or shrink under global warming?**



Change in elevation from 1993 to 1998 measured by repeat airborne laser altimetry

Warm colors = up

Cold colors = down



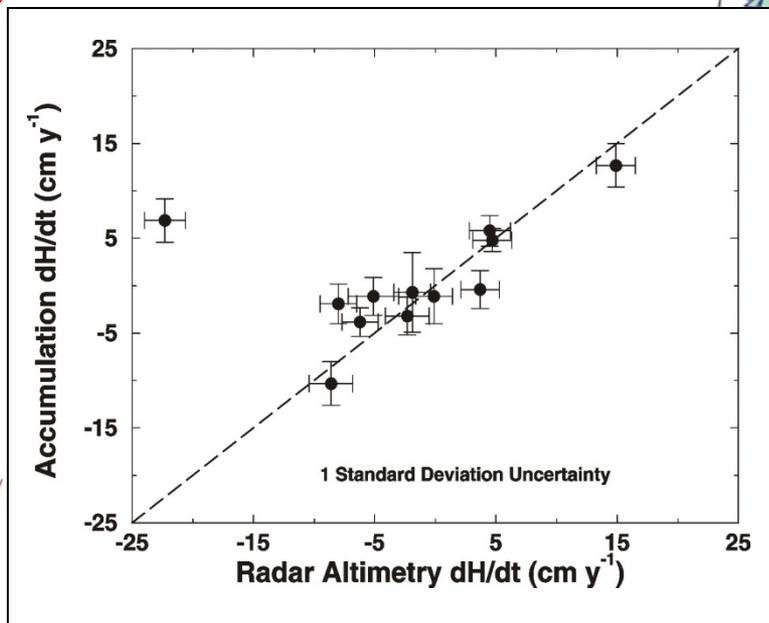
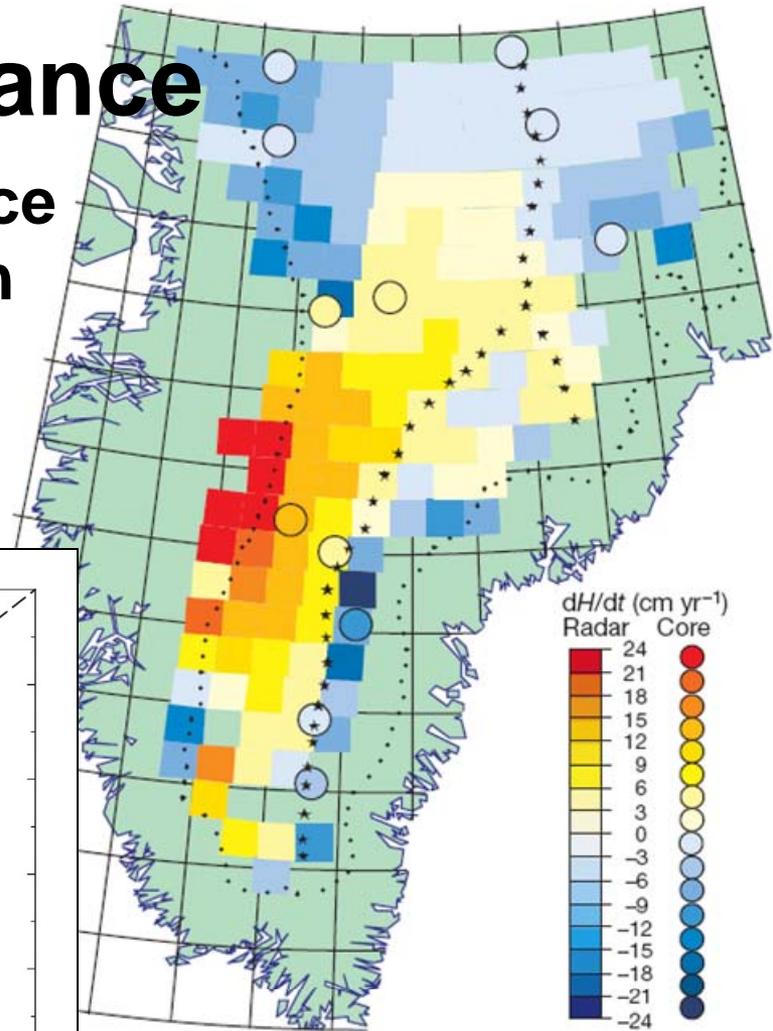
Krabill et al., *Science*, 1999.

Ice Cores & Ice Sheet Mass Balance

1978-1988 Elevation Change

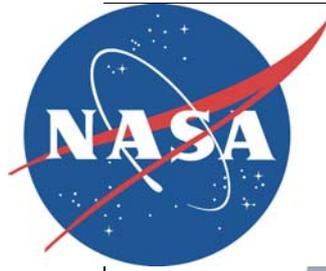
Net (P-E) snowfall is half of ice sheet mass balance equation

Short-term snowfall rate variability masks long term change



McConnell et al., *Nature*, 2000.

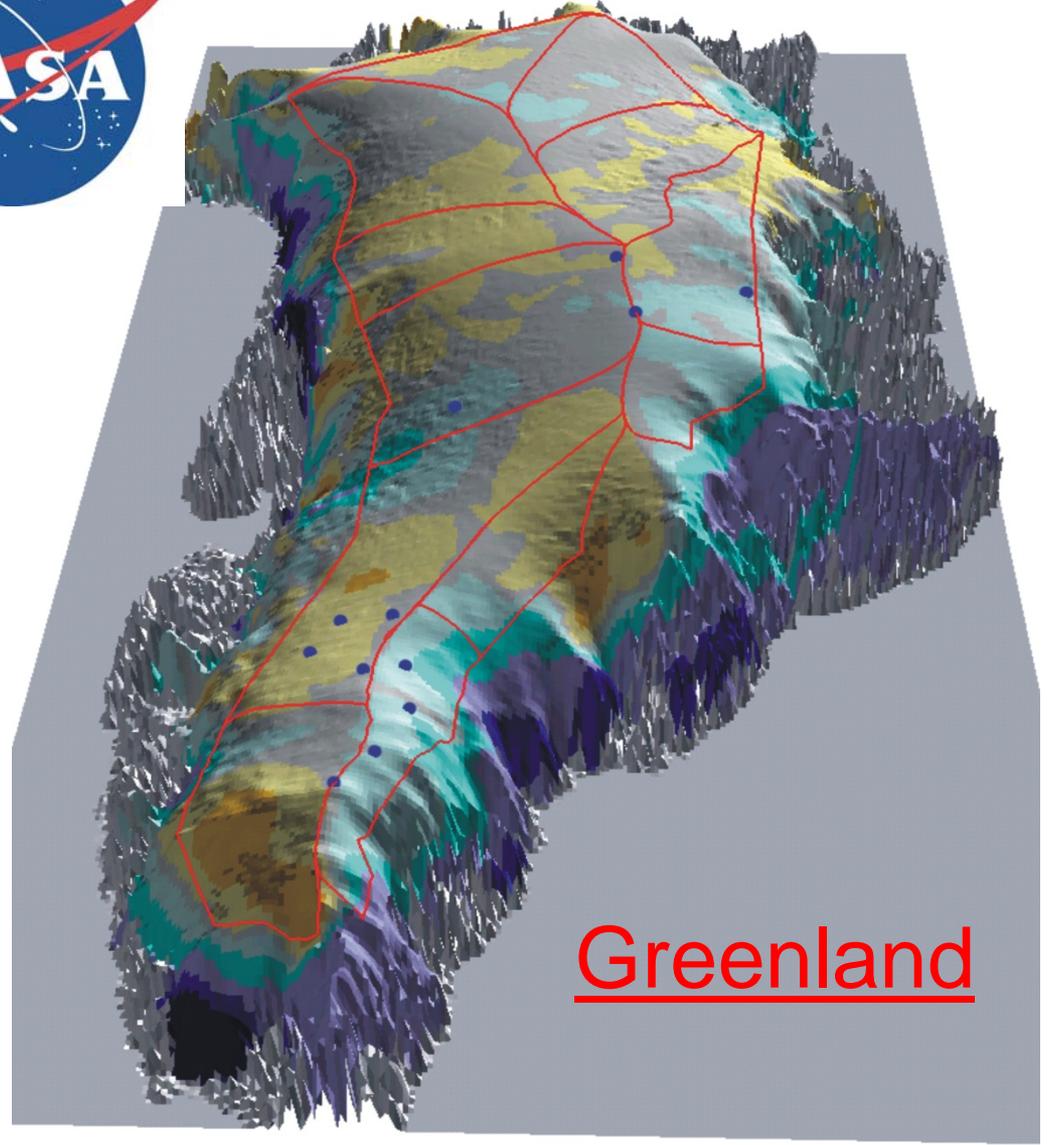




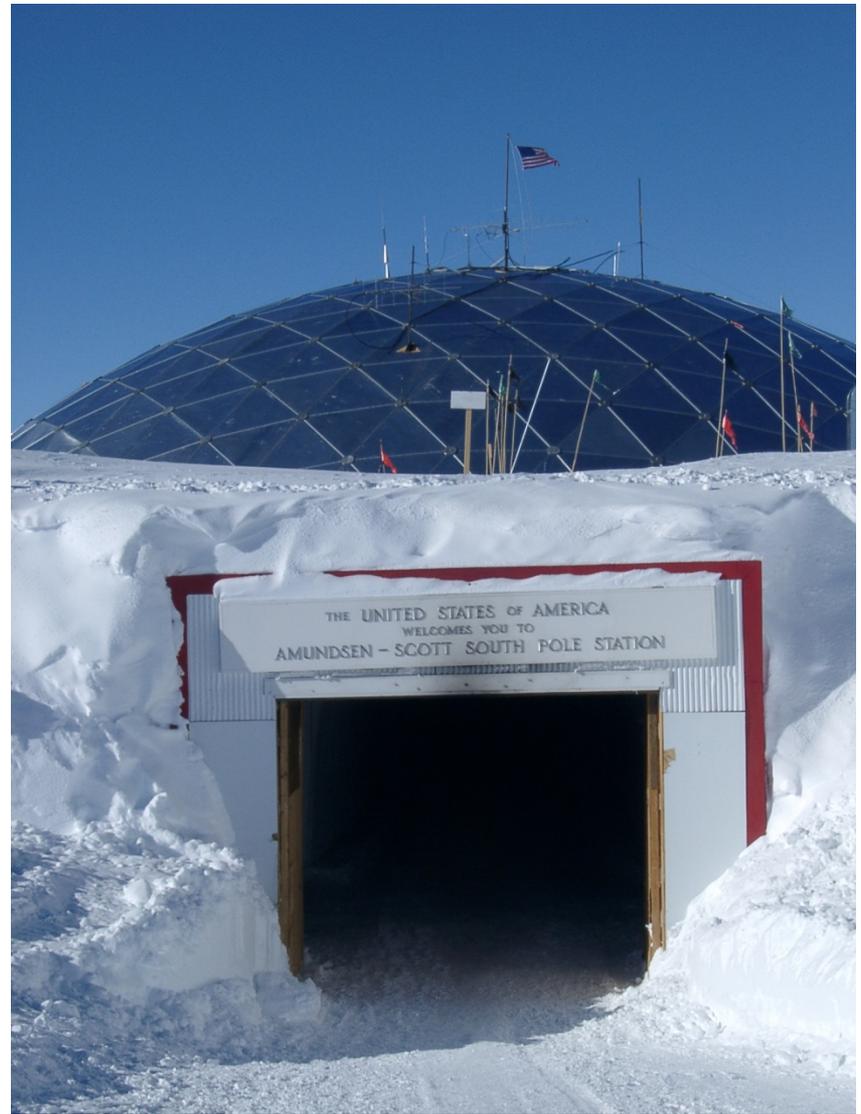
Margins are melting rapidly.

Center is in balance or rising slightly.

**Best Estimate:
+0.20 mm/yr SL**



Greenland



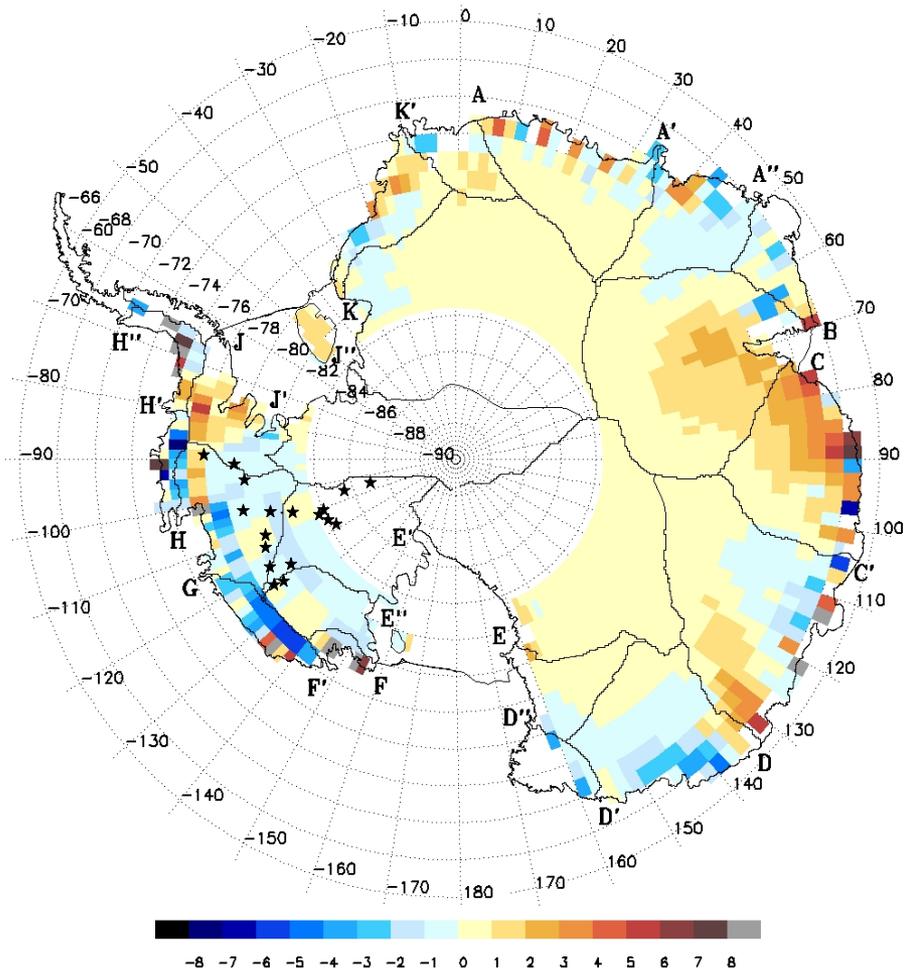
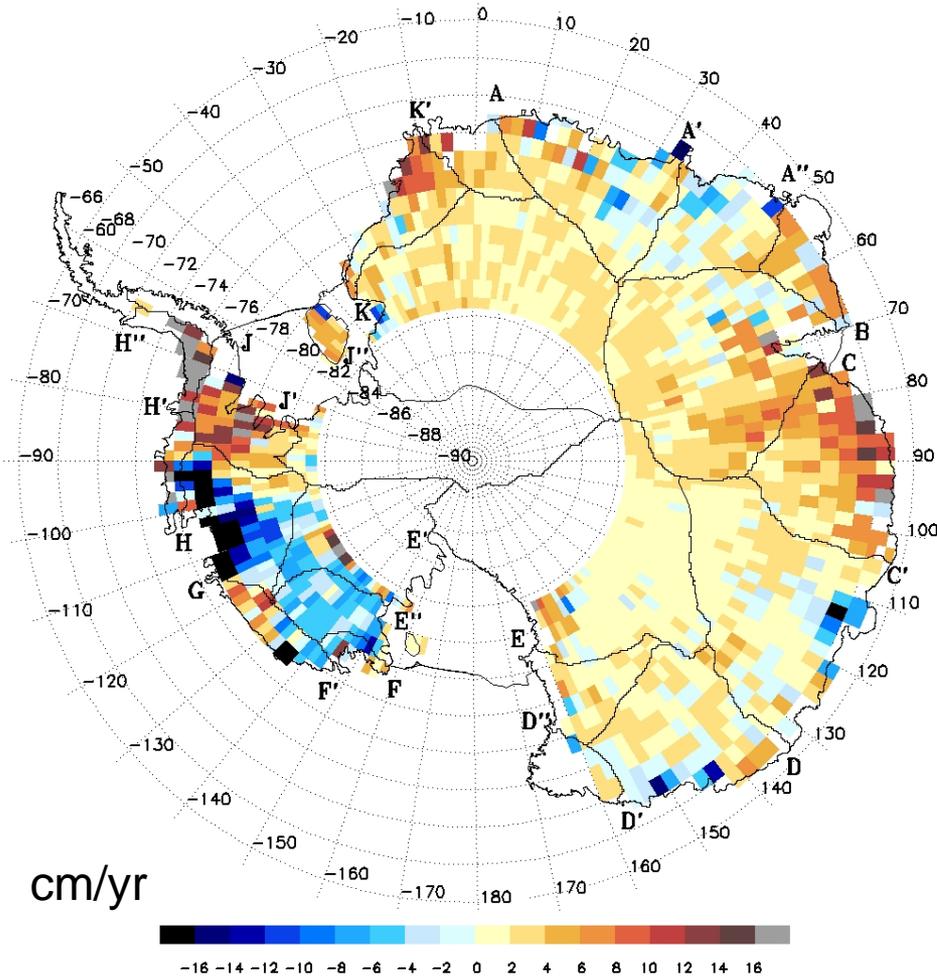
**What about
Antarctica???**

Remember that it is huge!

1992 – 2003 Elevation Change from Satellites

Observed

Precipitation-Driven



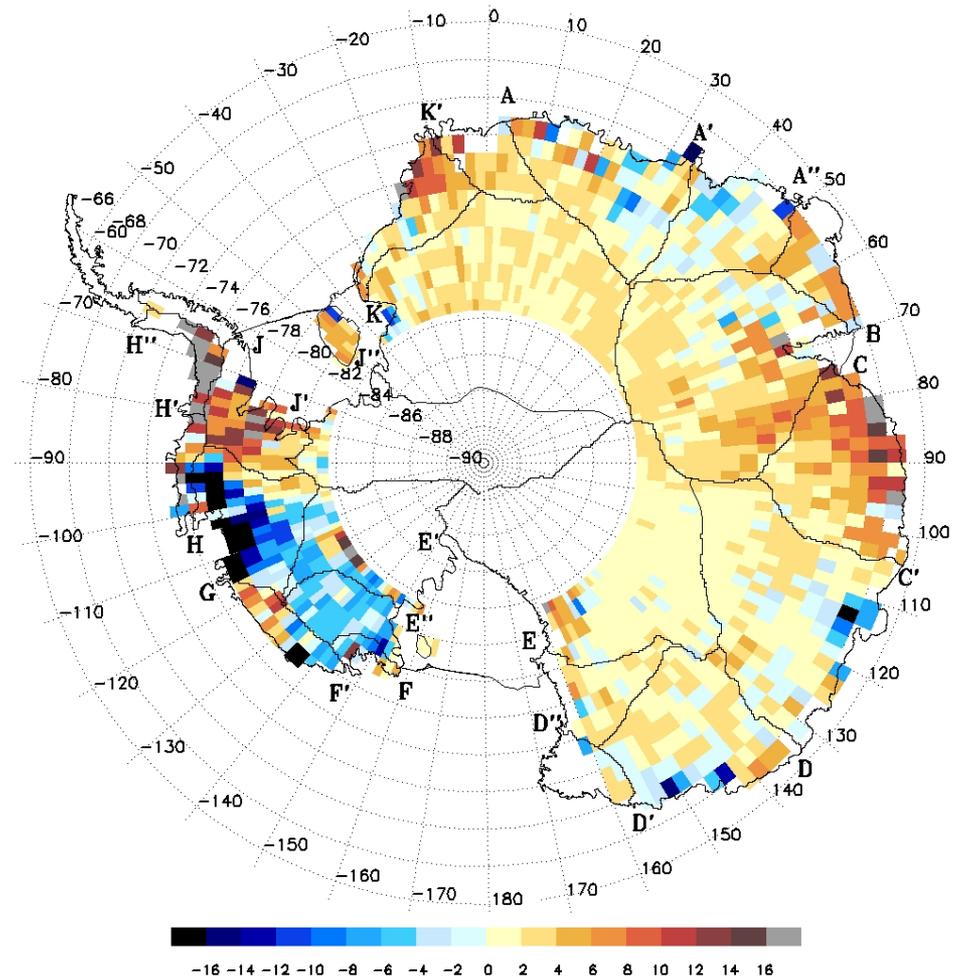
Davis et al., *Science*, 2005.

1992 – 2003 Elevation Change from Satellites

West Antarctica
shrinking rapidly.

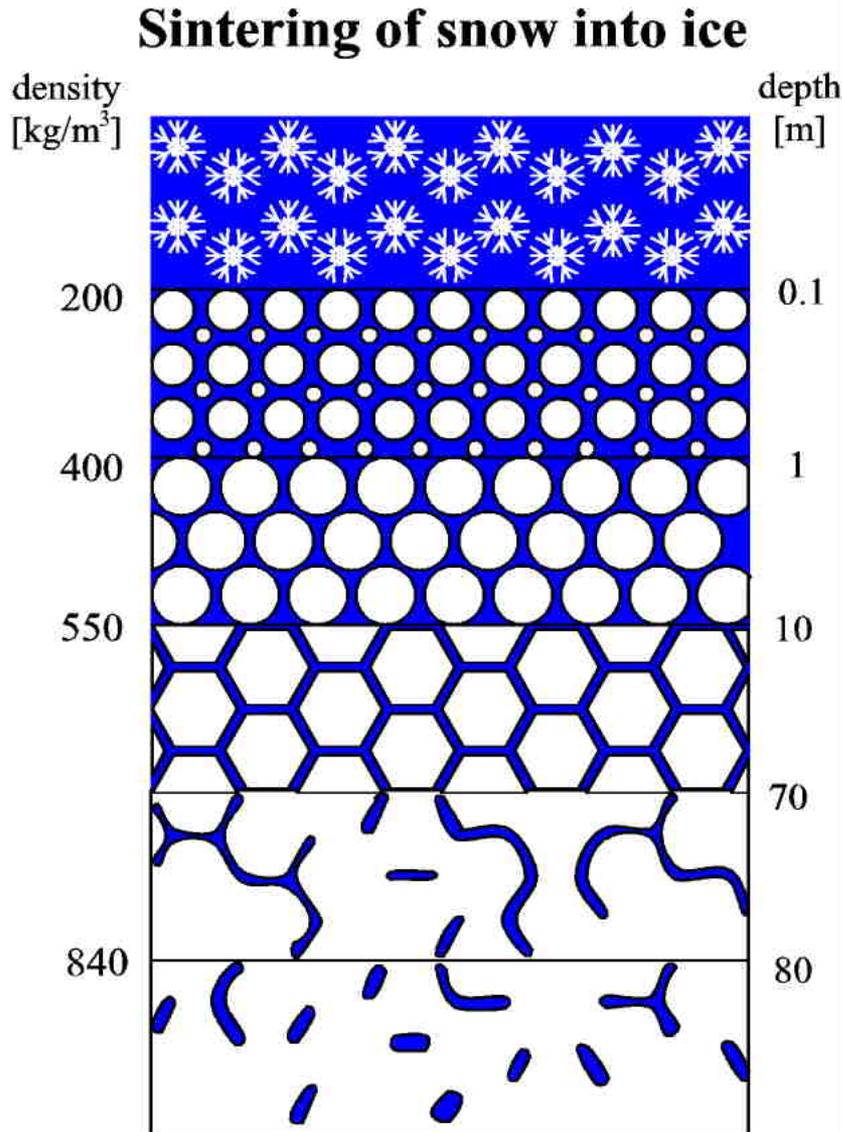
East Antarctica is
rising slowly
(Warmer air means
more precipitation).

**Best Estimate:
-0.02 mm/yr SL**

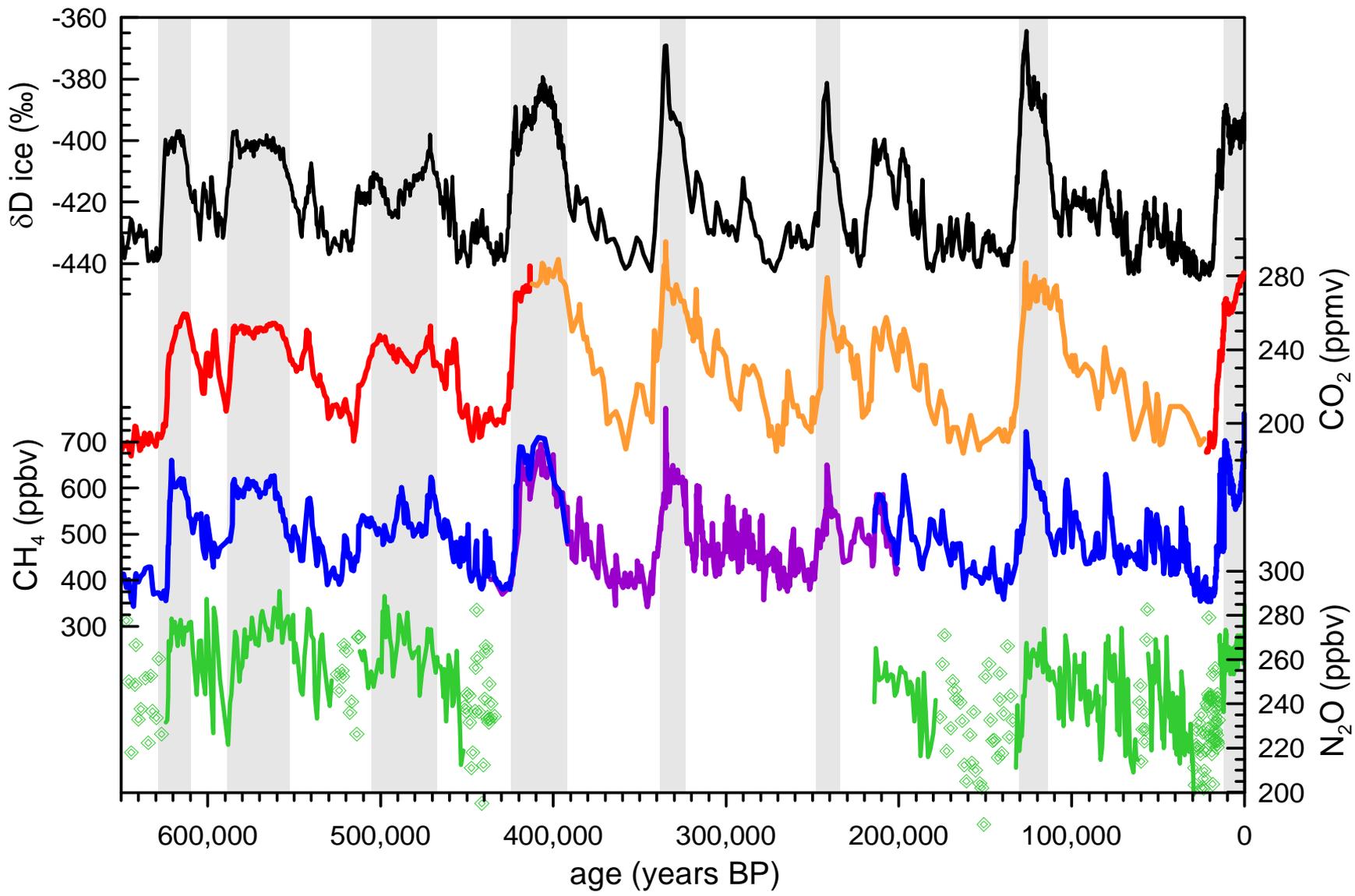


Davis et al., *Science*, 2005.

Components of the Archive



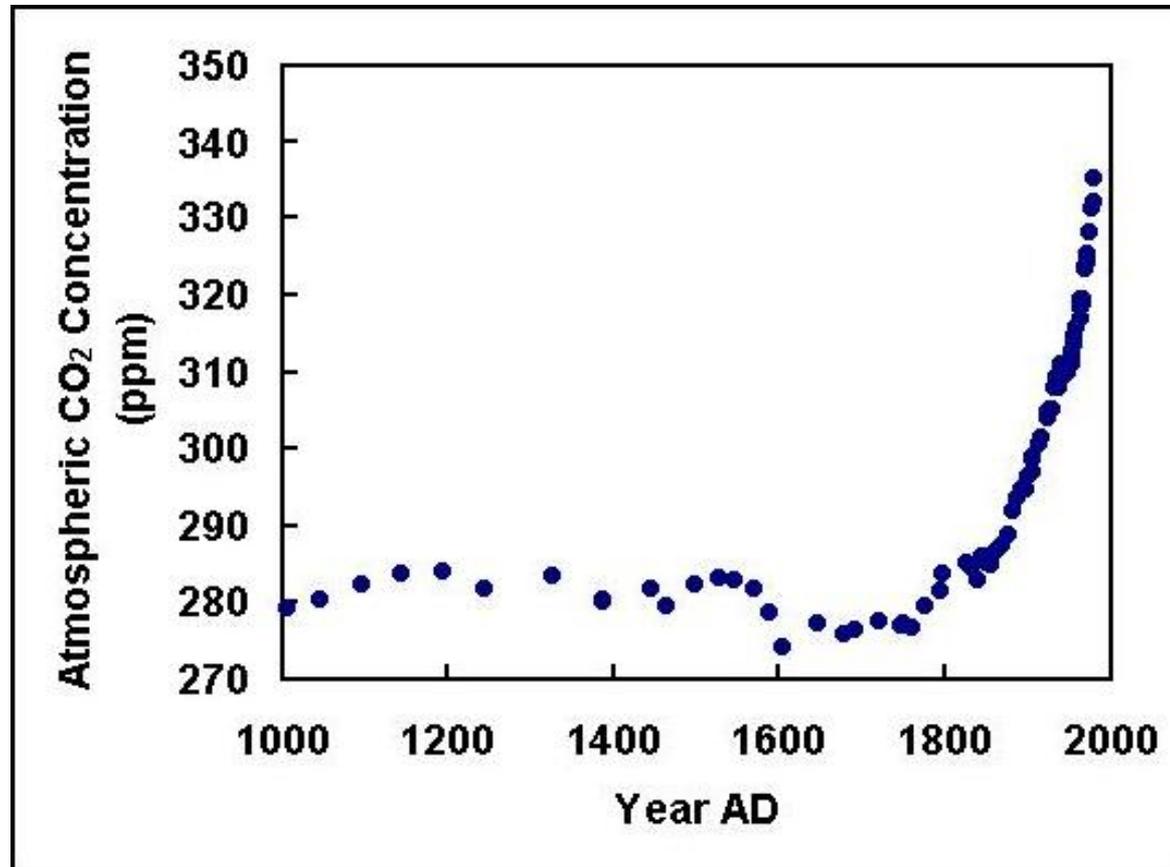
- Net snowfall
- Gases trapped in the pore spaces
- Water isotopes
- Soluble & insoluble impurities in the ice lattice



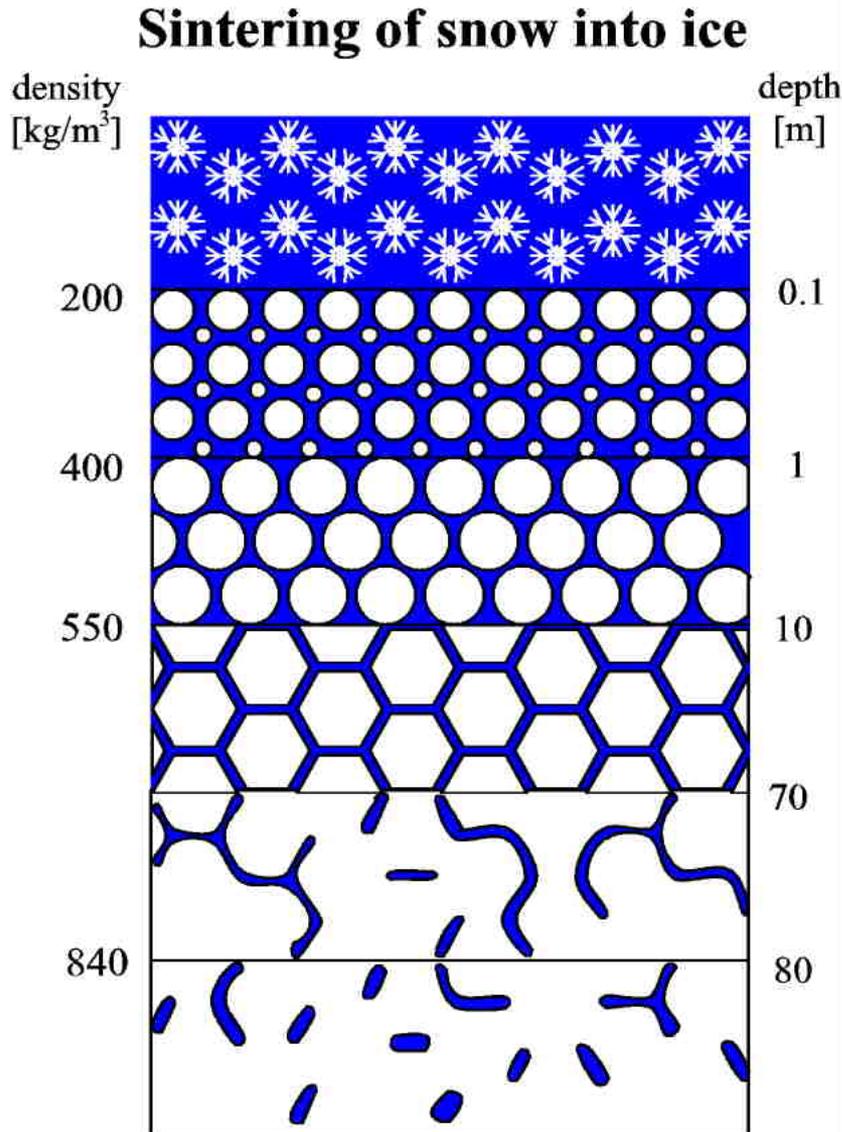
2009



The last 1000 years of atmospheric carbon dioxide from ice cores



Components of the Archive



- Net snowfall
- Gases trapped in the pore spaces
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- Soluble & insoluble impurities in the ice lattice

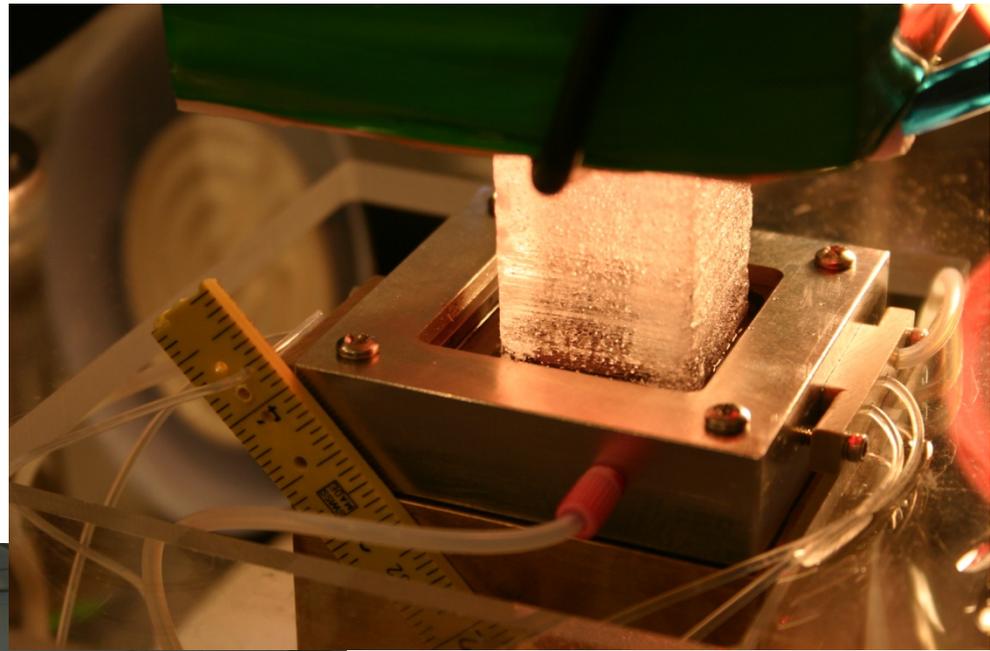
**The challenge is to analyze
the ice core record
to maximize
geophysical information**



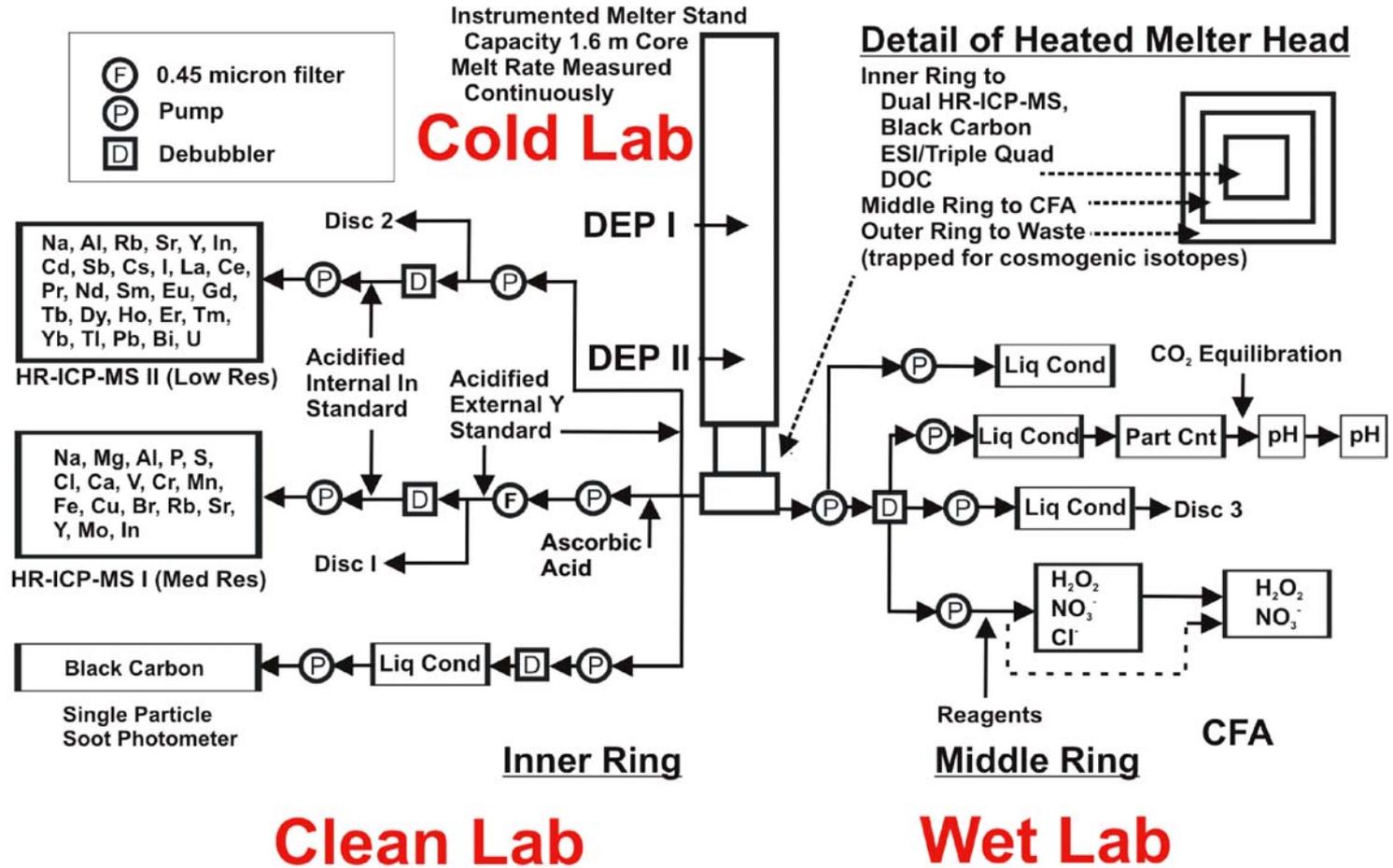


Firn Core

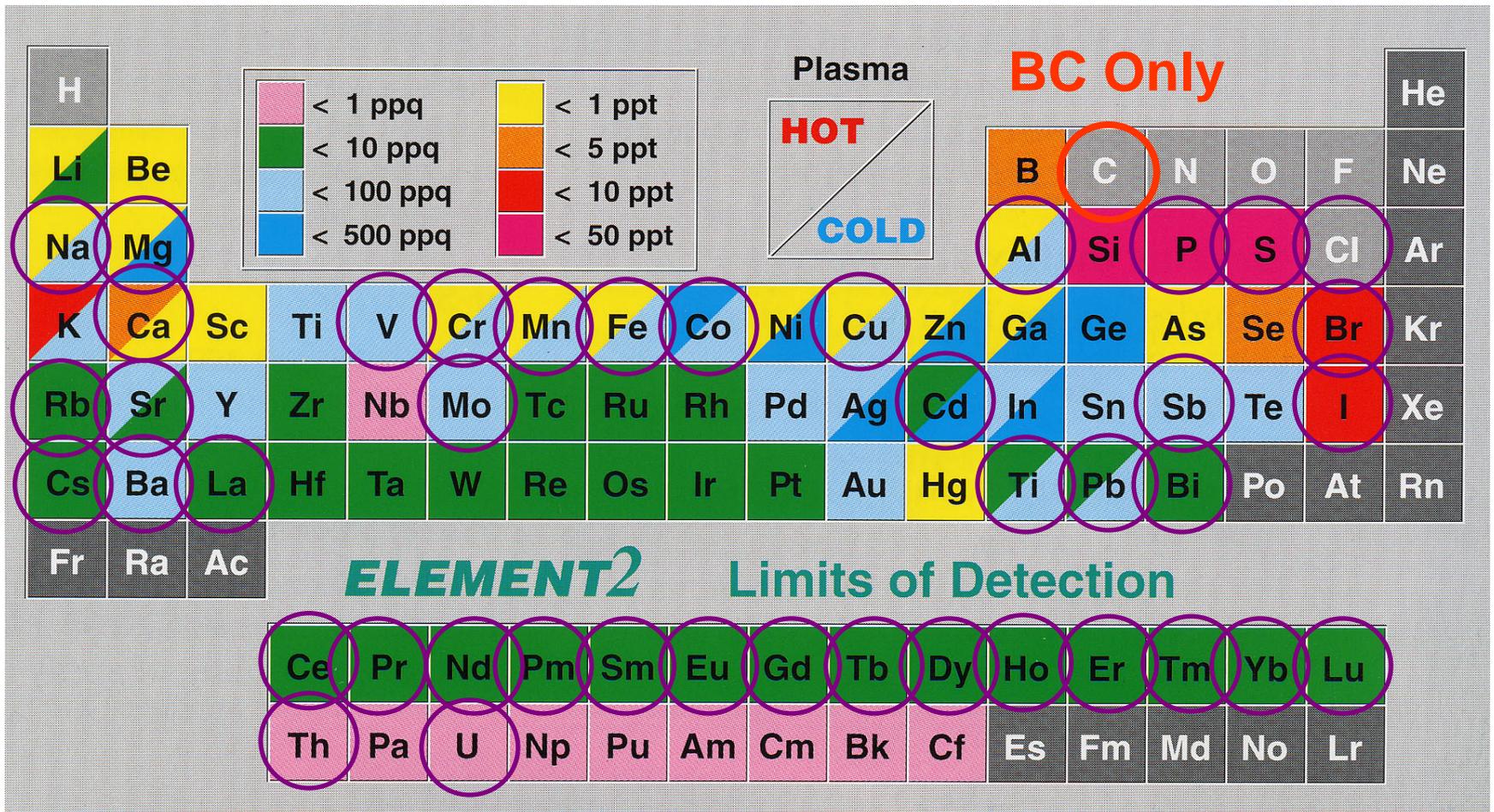
**DRI's unique
analytical system for
high-resolution,
continuous ice core
measurements**



CFA-TED/BC Schematic



~5 sec dt ~ 5 mm dz

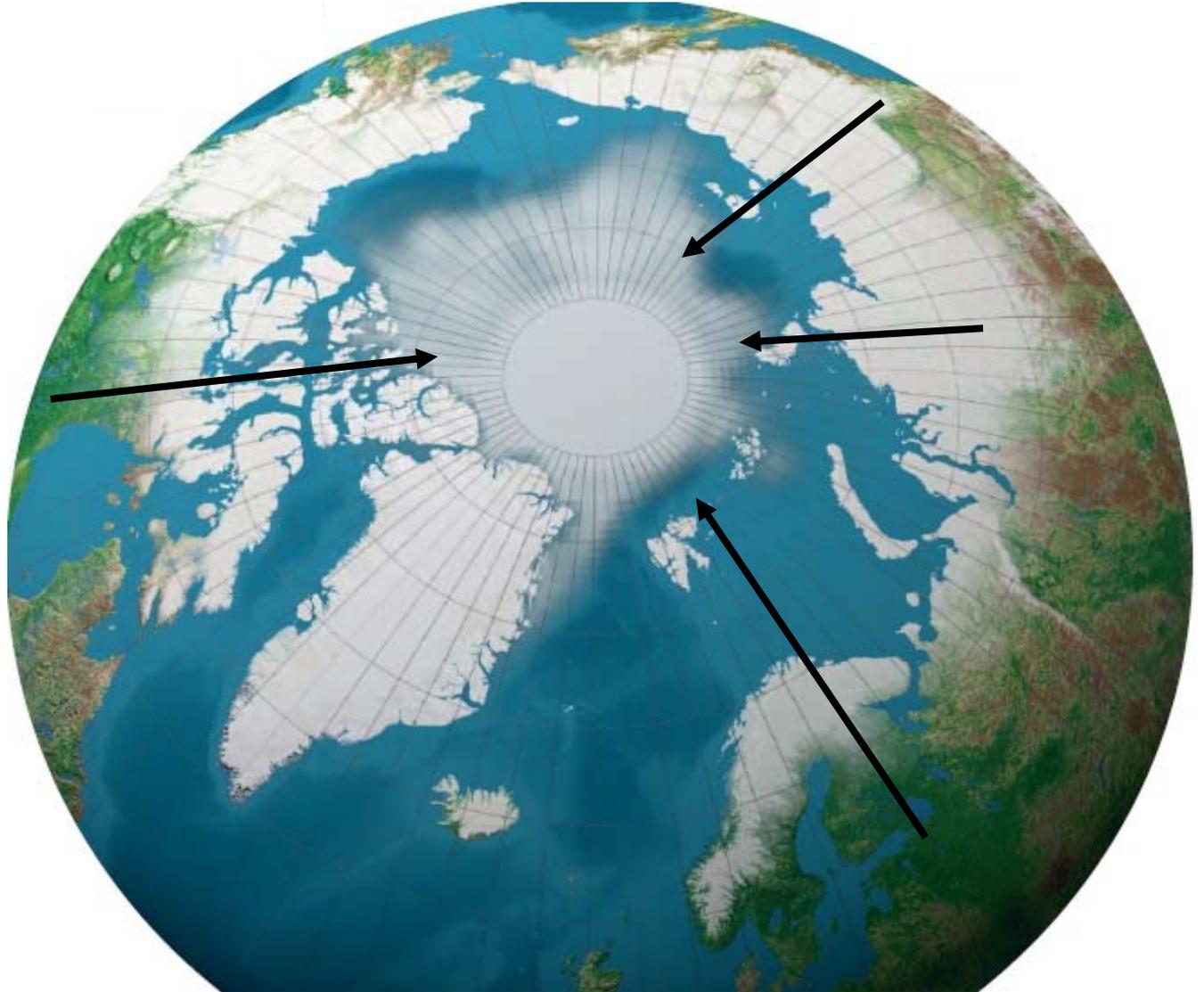


Currently measured at DRI in ice cores

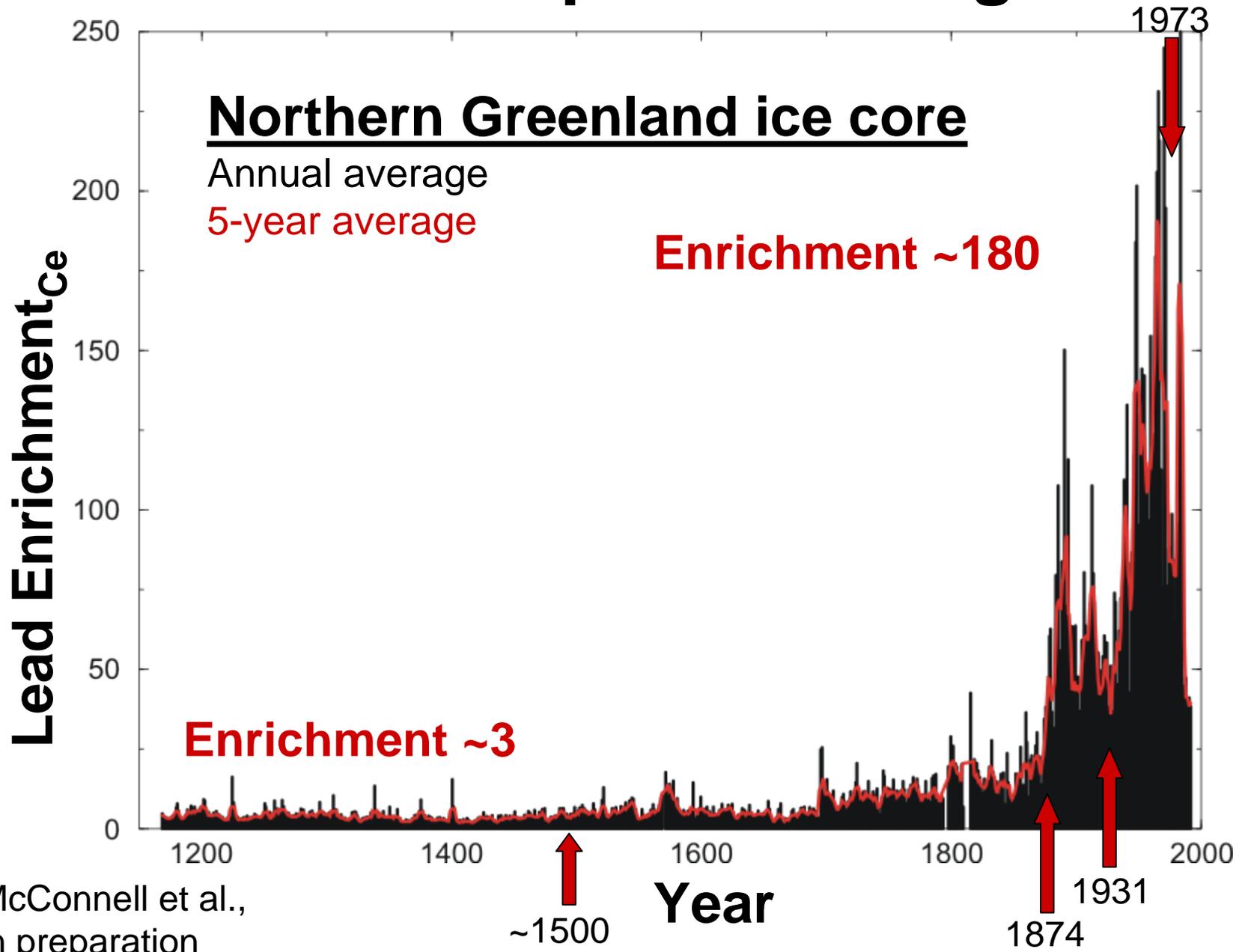
○ using ICPMS ○ using SP2-based analyzer

Where does Arctic pollution come from?

Emissions in the warm mid-latitudes are transported in the atmosphere and deposited in the cold high latitudes.



When did Arctic pollution begin?

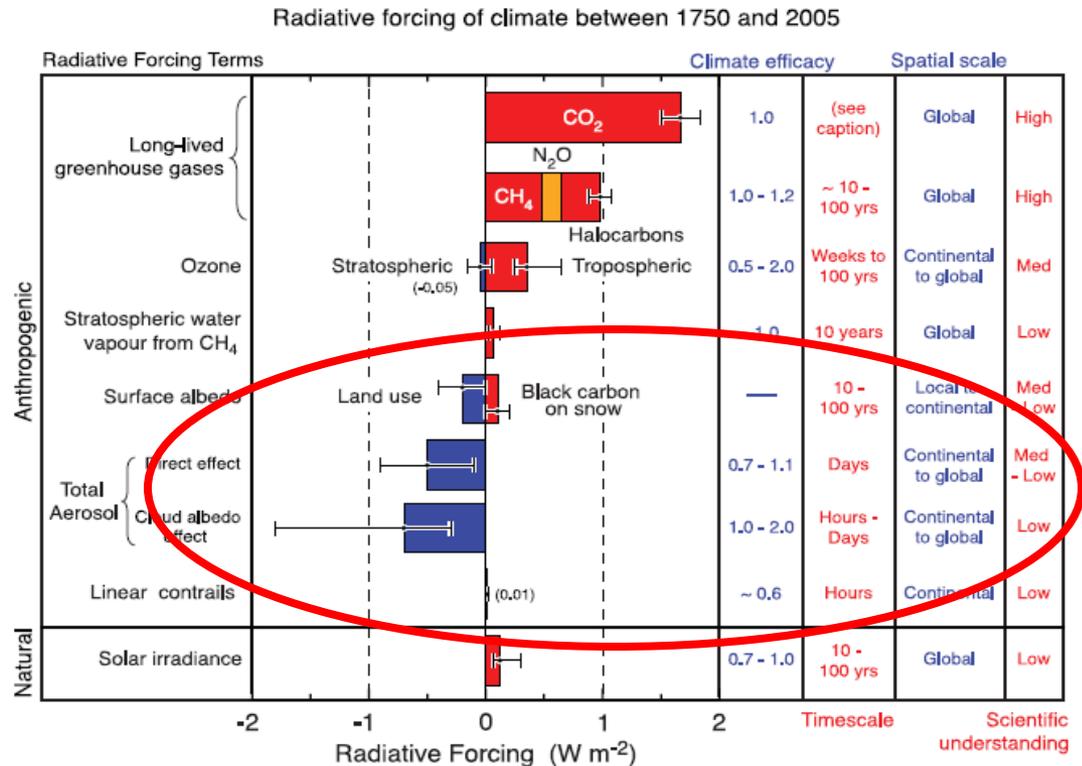


What is the role of pollution in Arctic climate change?

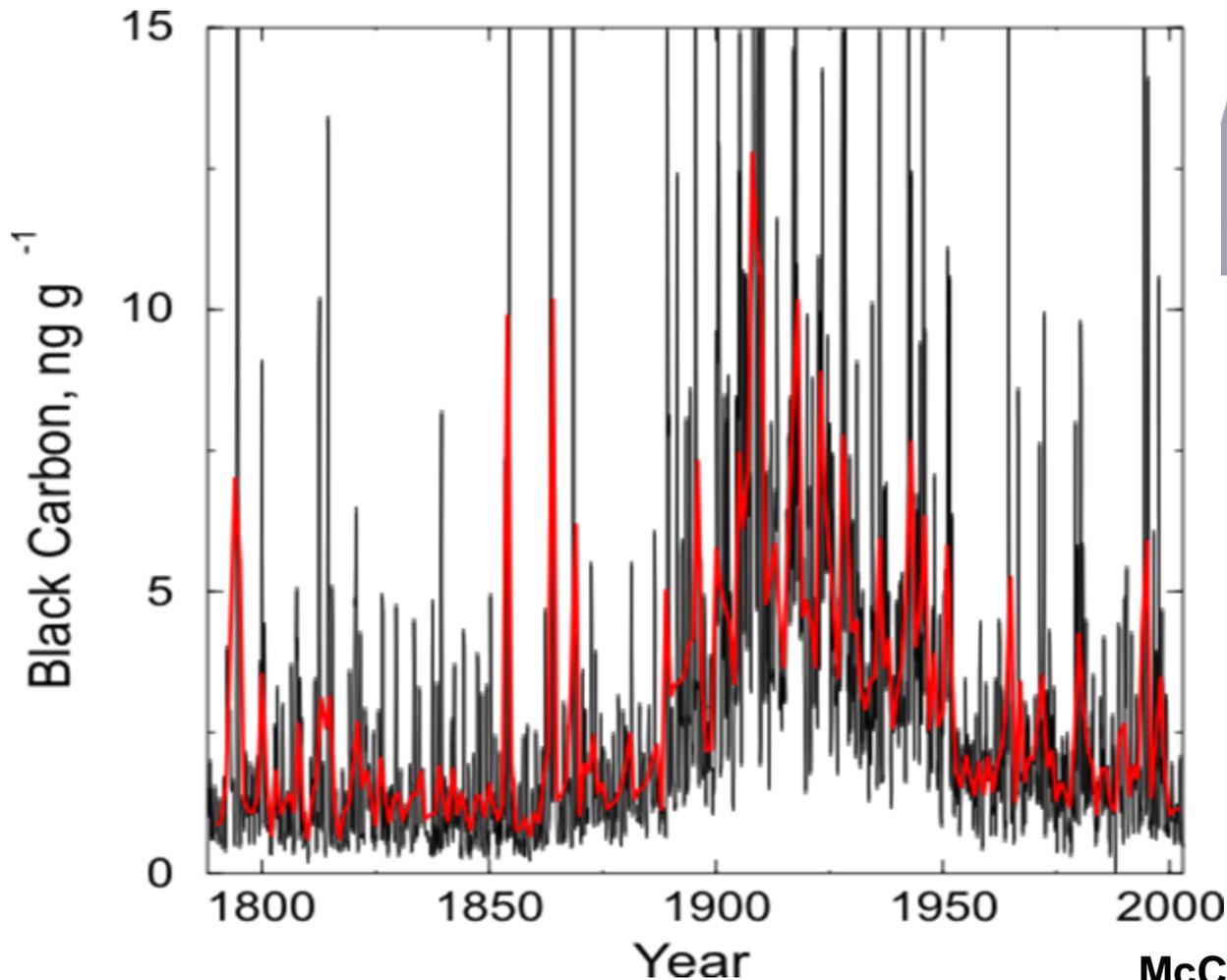
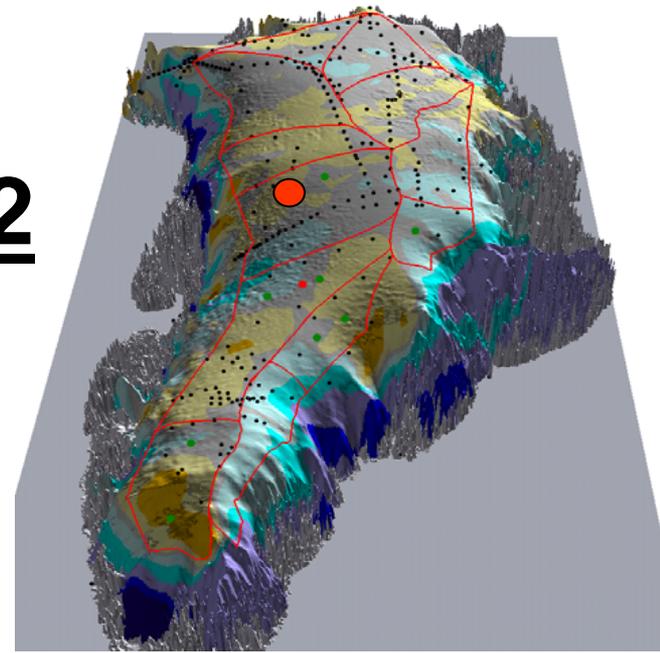
Few long term records

Ice cores can help!

Consider Black Carbon (a.k.a. soot)



Case Study: BC in Greenland 1788-2002

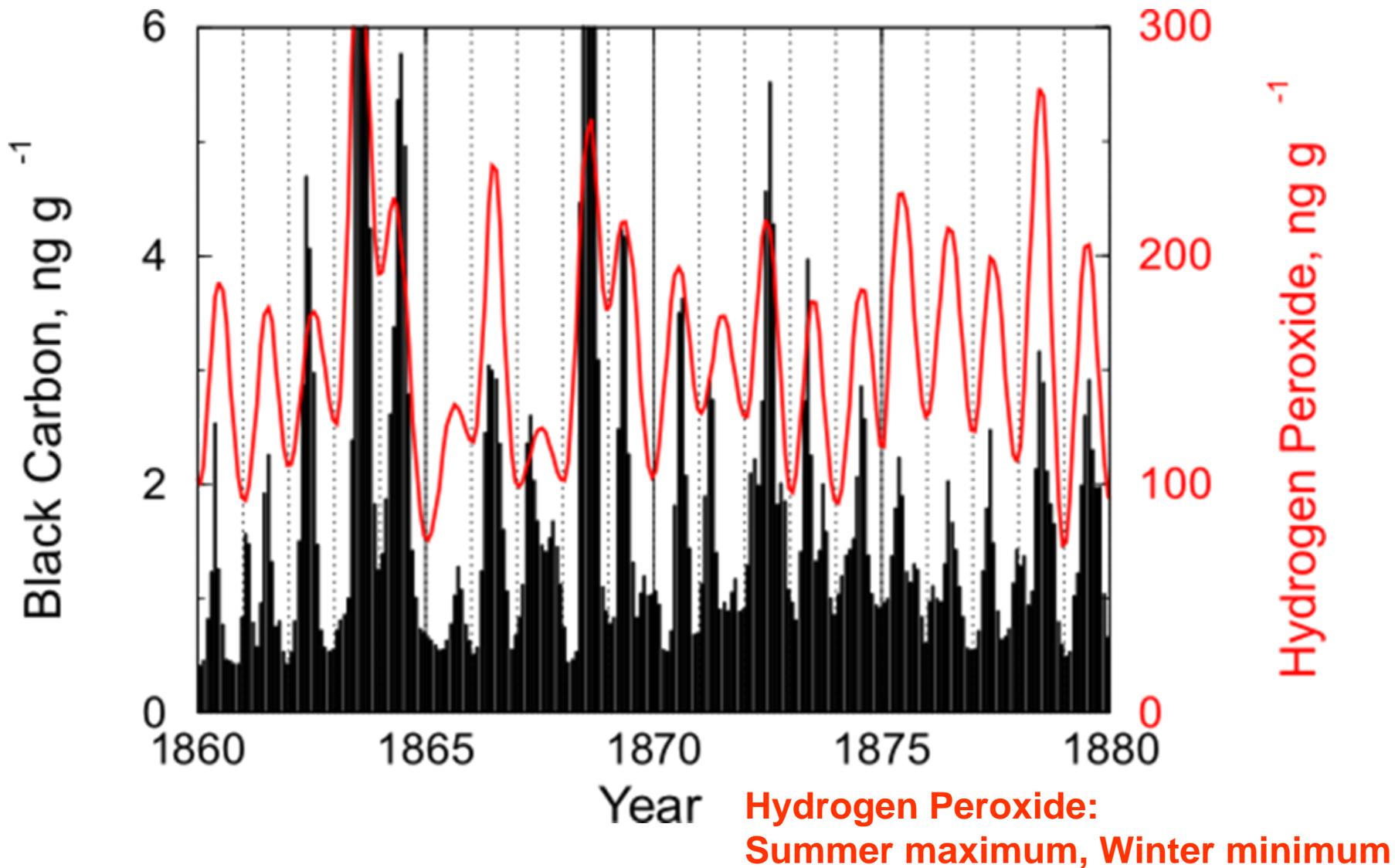


Annual
Monthly

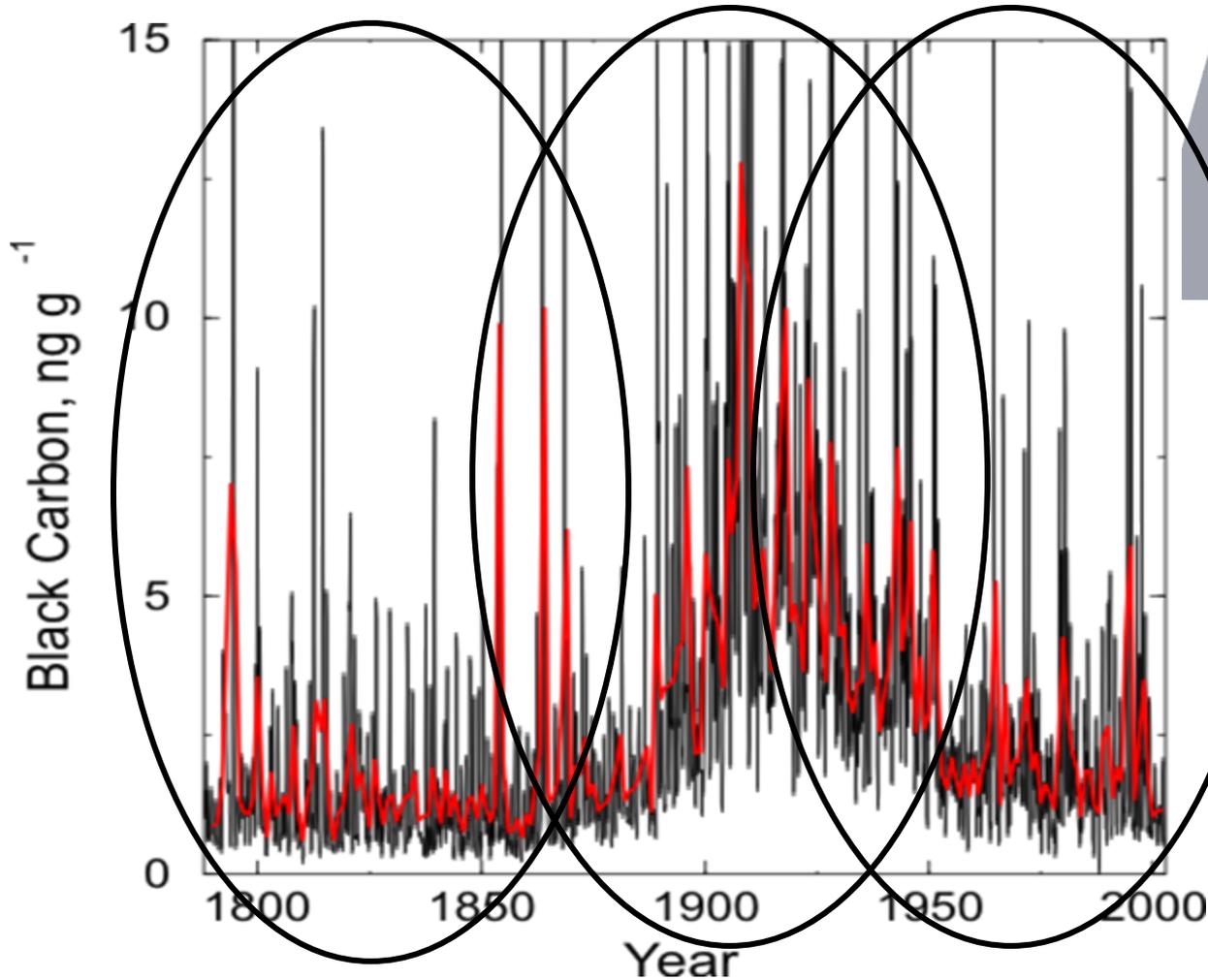
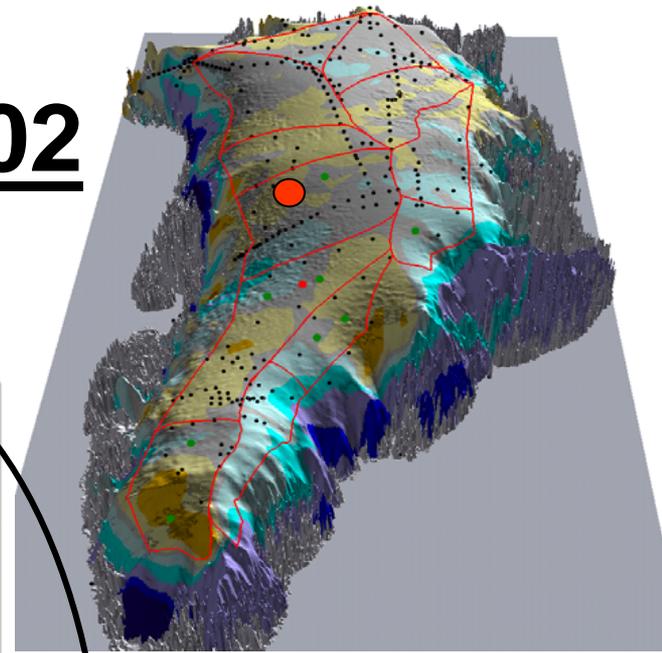
~30 samples y⁻¹

McConnell et al., *Science*, 2007.

High Resolution Measurements



BC in Greenland 1788-2002



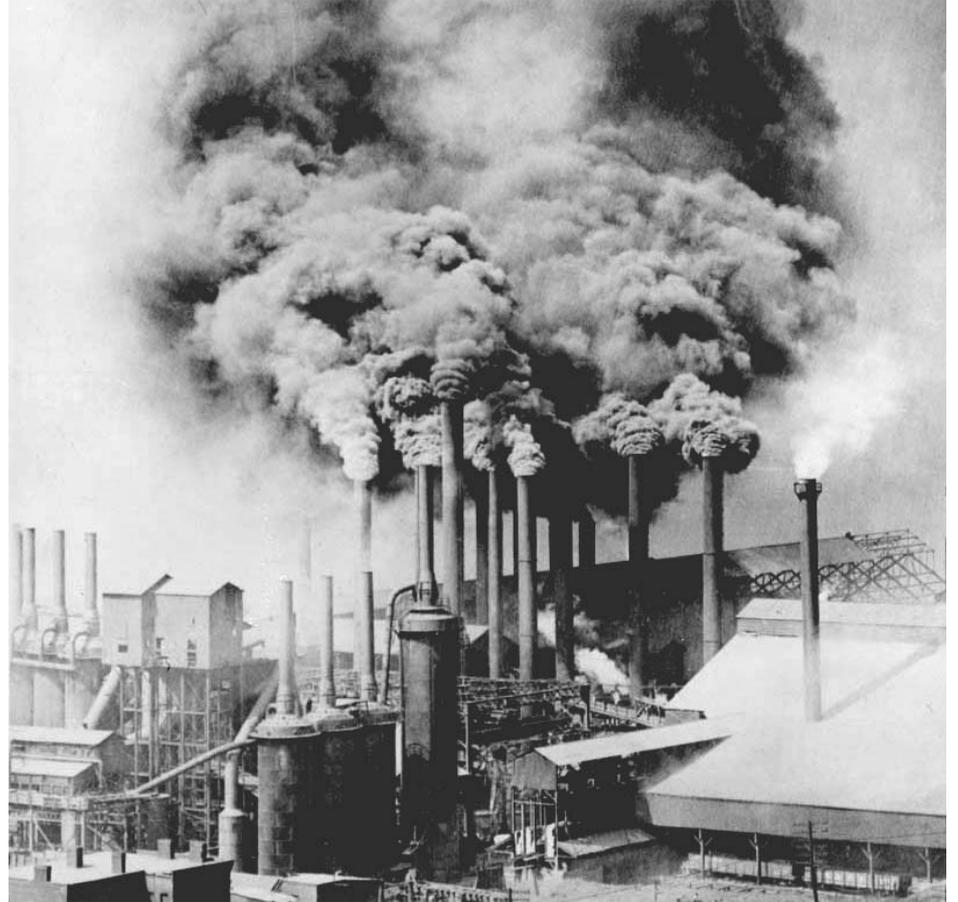
Annual
Monthly

~30 samples y^{-1}

Vanillic Acid as a tracer of biomass burning emissions



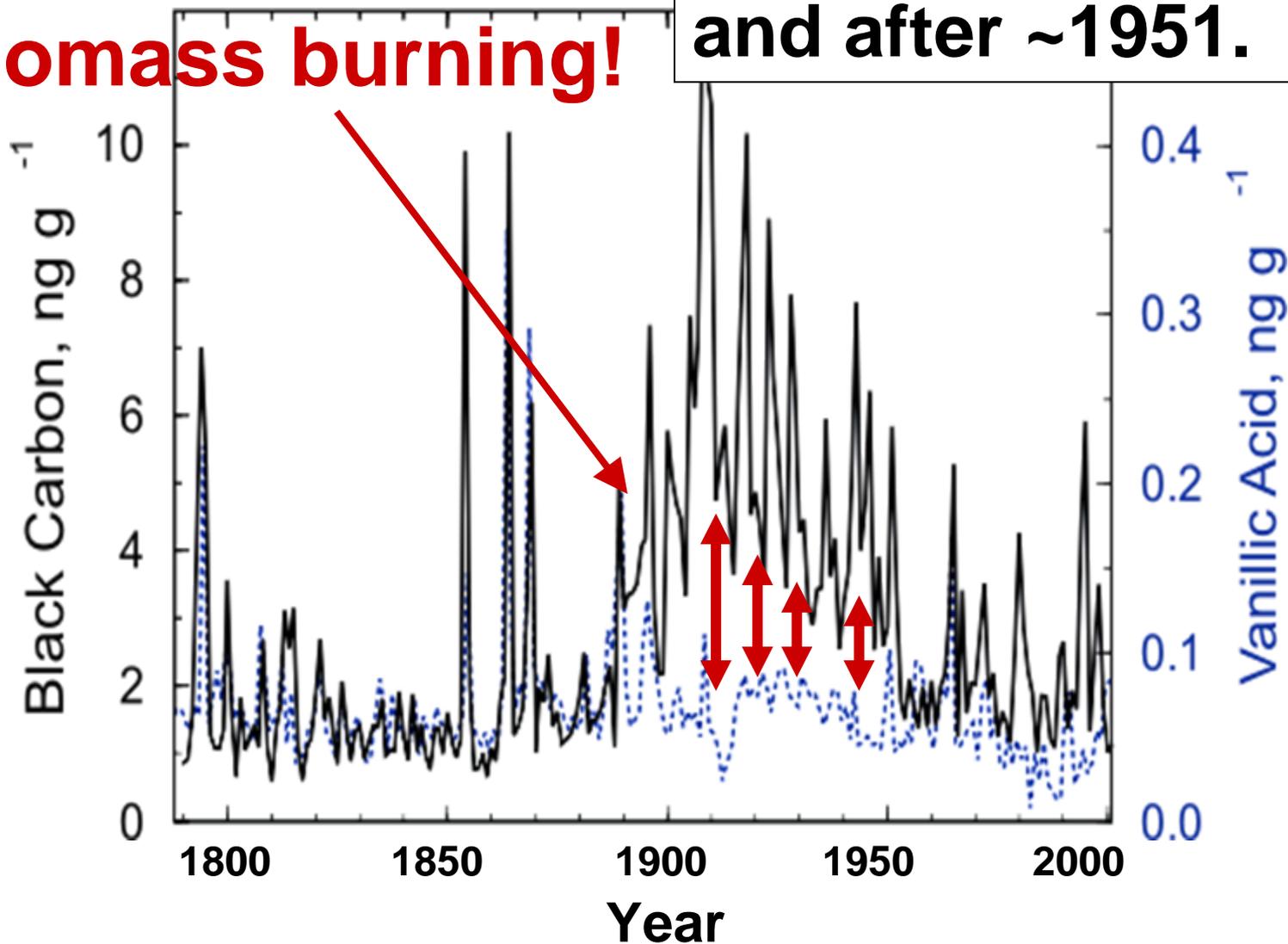
Photo courtesy
of A. Stohl



Non-sea salt sulfur as a tracer of industrial emissions

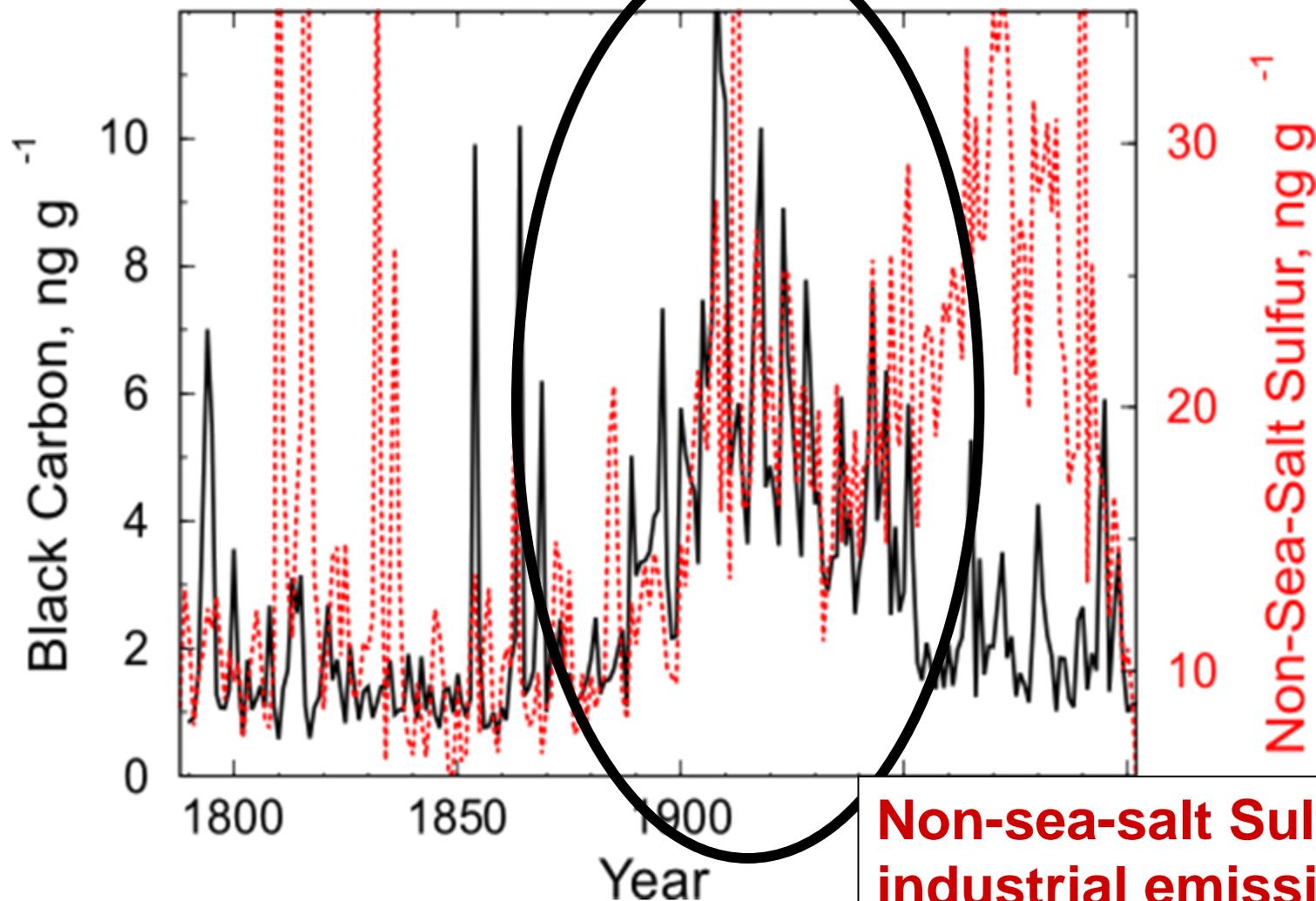
**Not from
biomass burning!**

**Biomass burning
dominated 1788~1860
and after ~1951.**



Annual: 0.67 ($p < 0.0001$)
Winter: 0.74 ($p < 0.0001$)
Summer: 0.59 ($p < 0.0001$)

Coal burning dominated ~1850 to 1951

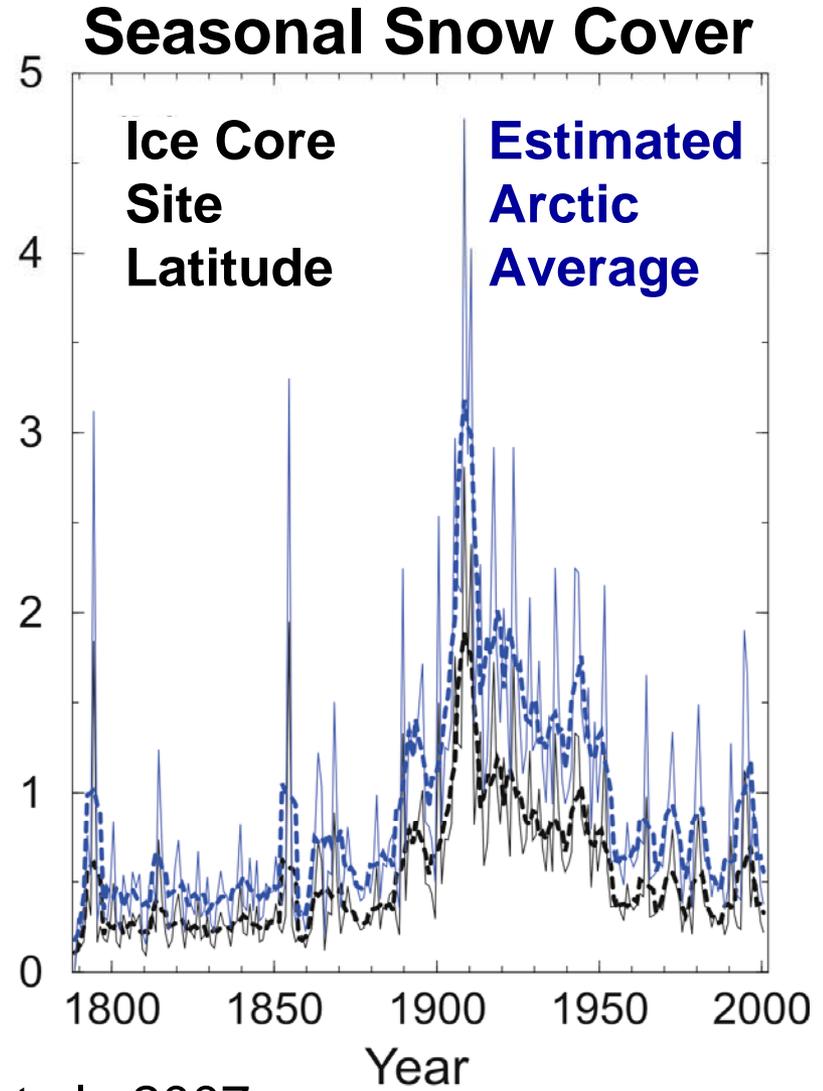
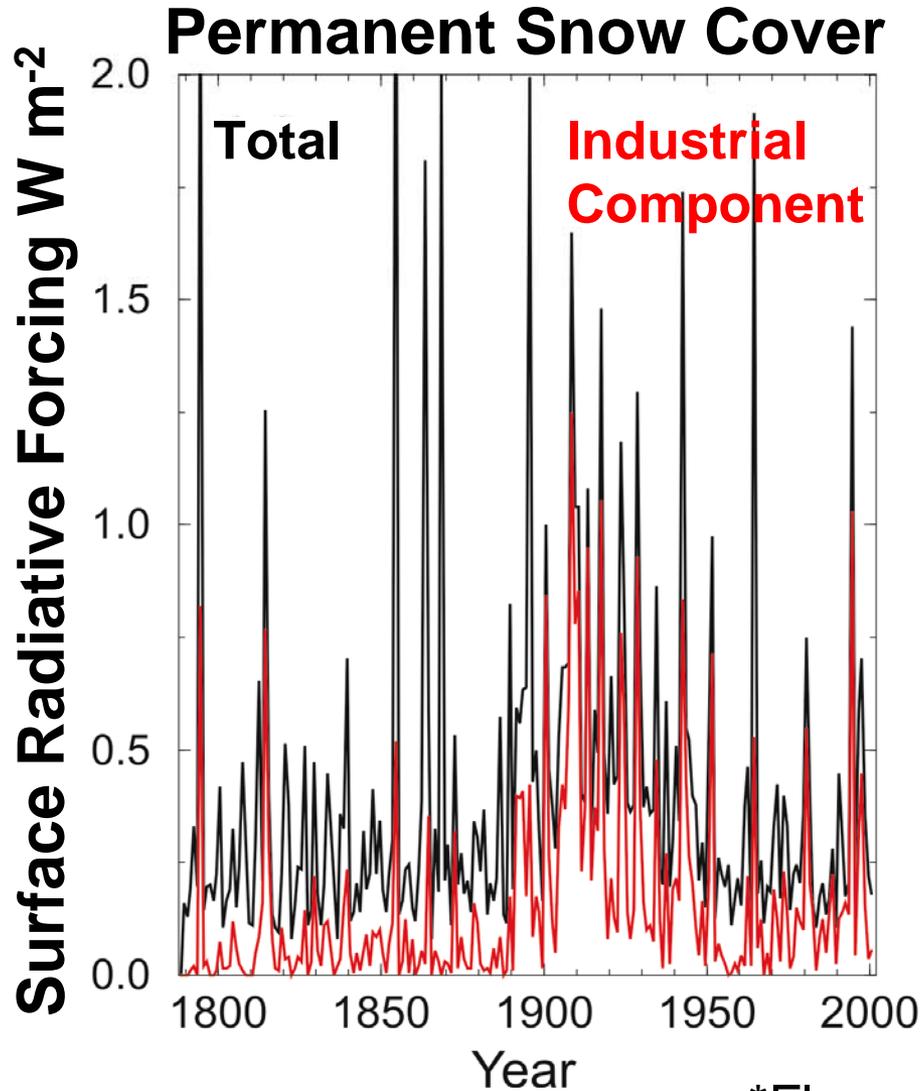


**Non-sea-salt Sulfur from
industrial emissions**

BC (Soot) First Conclusions

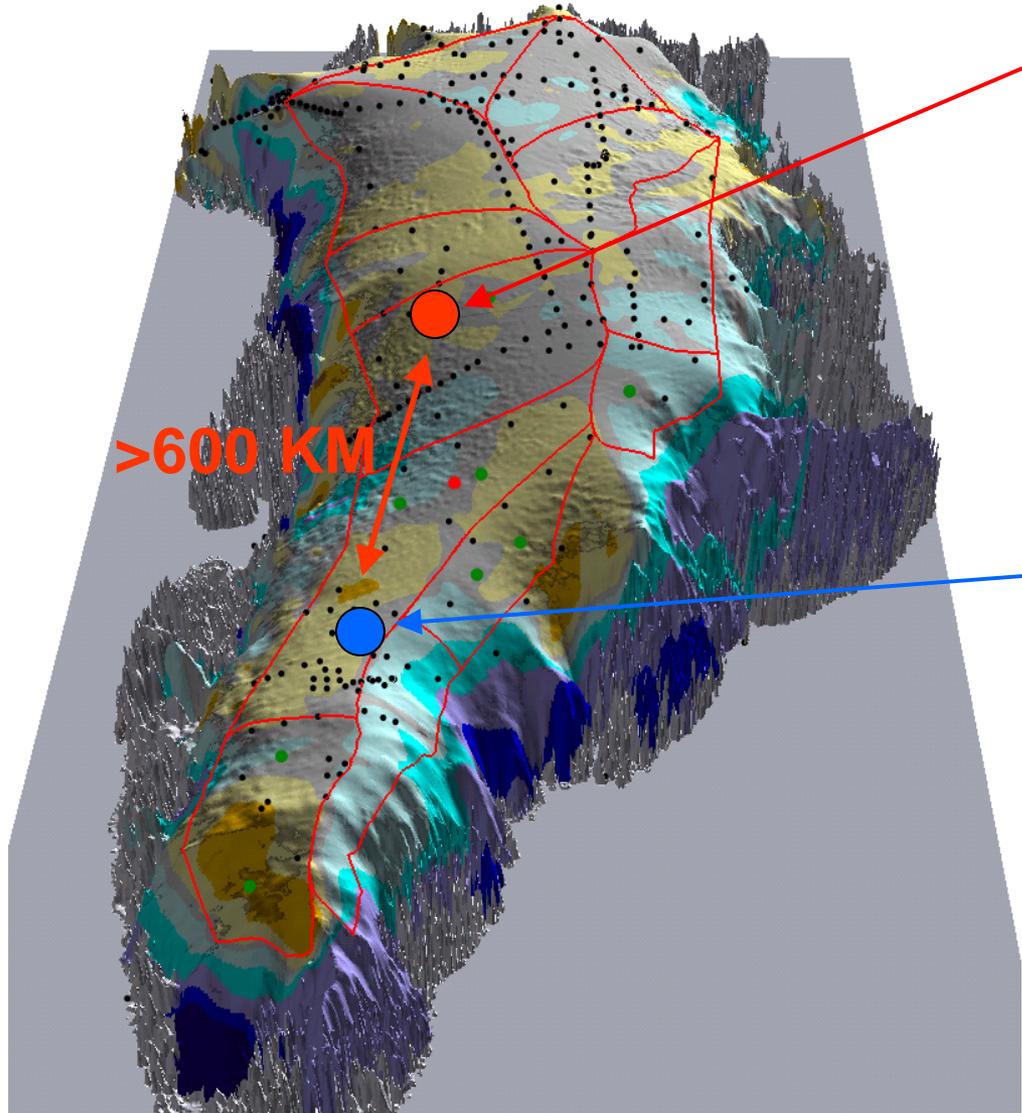
- BC in central Greenland is highly seasonal
- BC comes from boreal forest fires & industrial emissions
- Pre-Industrial and for all summers: Primary source is burning in conifer-rich boreal forest
- From ~1850 to 1951, N American (?) industrial emissions resulted ~2 to ~4 fold increase (~10 fold in winter (five years from 1906 to 1910))
- BC drop in ~1951 linked to change in fuel type in N America (?) (Novakov et al., 2003; Bond et al., 2007), burning technology improvements & possibly fire suppression
- **What is the impact on radiative forcing?**

Early Summer Radiative Forcing from Black Carbon in Snow from Model*



*Flanner et al., 2007

What about at other Arctic sites influenced by different sources?



D4 ice core

**High Elevation
(>3000 m)**

Cold (no melt)

**High snowfall
(440 kg m⁻² y⁻¹)**

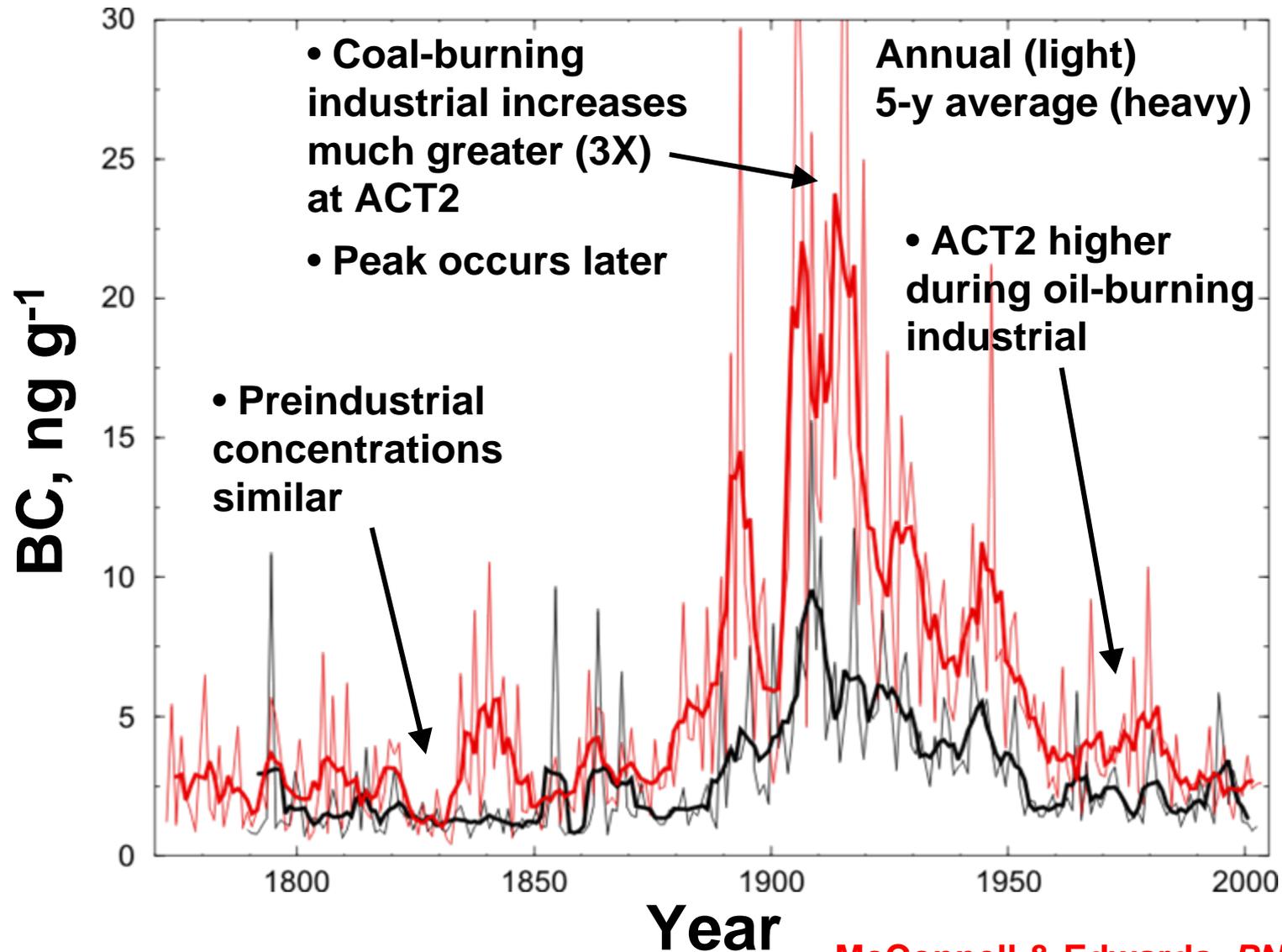
ACT2 ice core

**High Elevation
(~2400 m)**

Surface melting

**High snowfall
(368 kg m⁻² y⁻¹)**

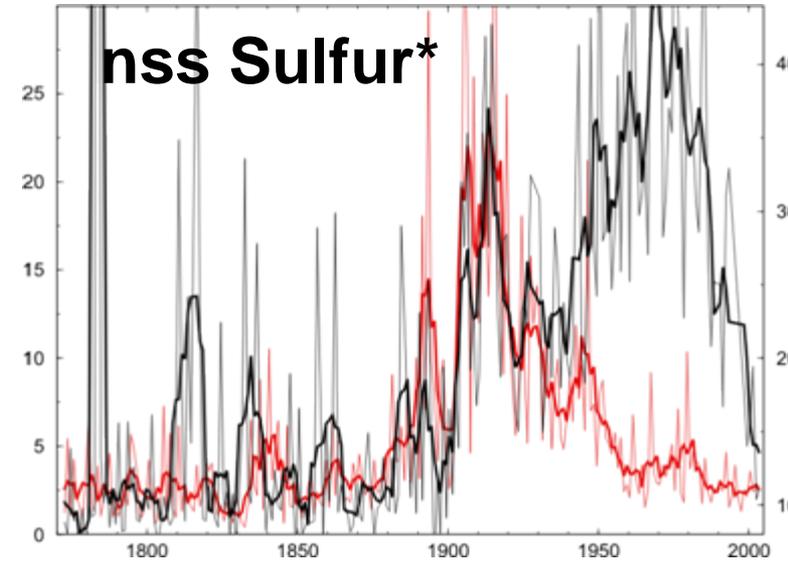
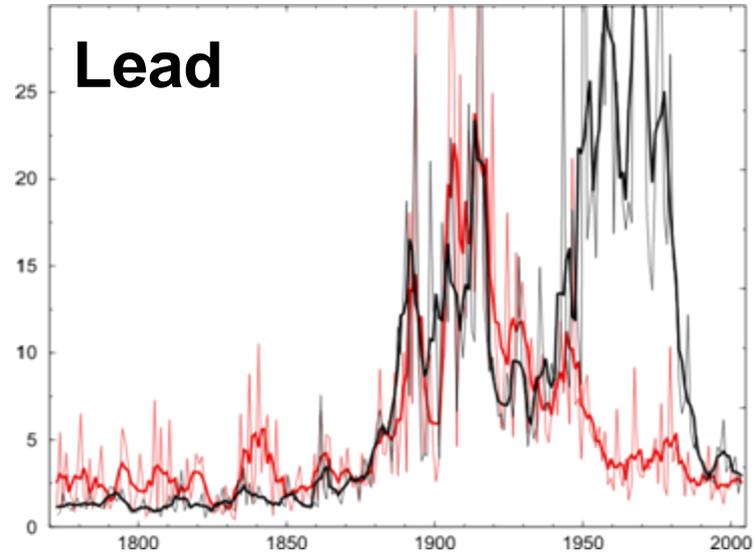
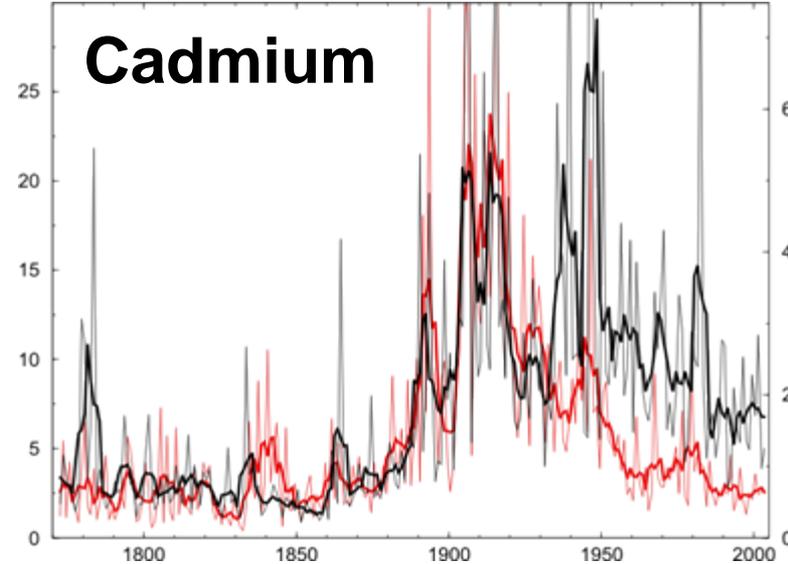
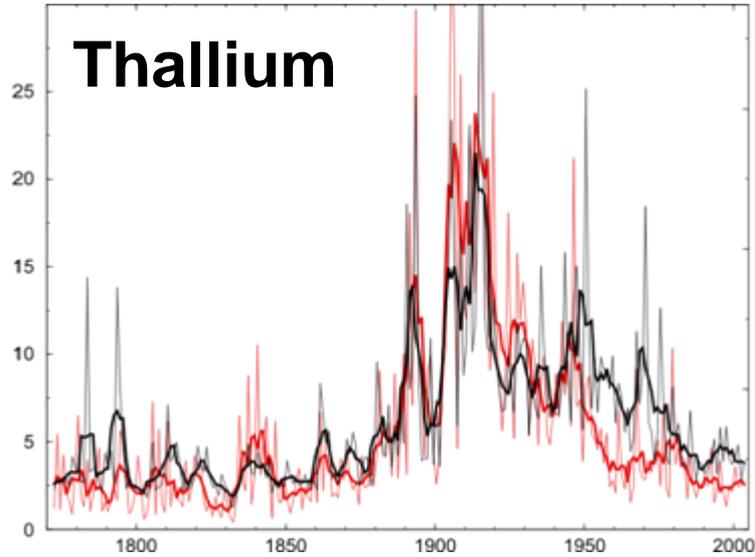
BC at D4 (Greenland) & ACT2 (Greenland)



McConnell & Edwards, *PNAS*, 2008.

BC source tracers (toxic heavy metals)

BC Concentration, ng g⁻¹

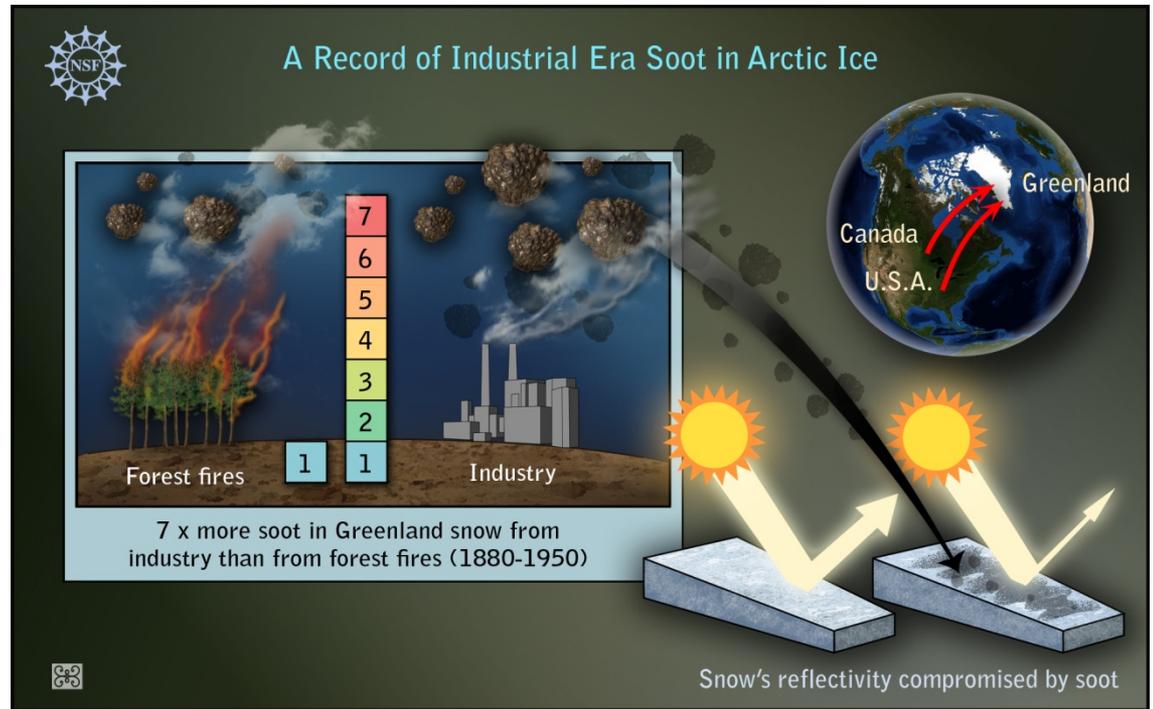
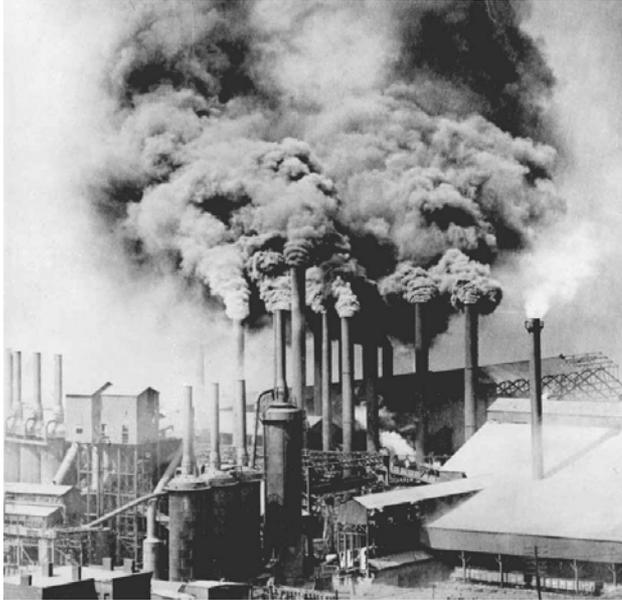


Concentration, pg g⁻¹ (ng g⁻¹)*

Year

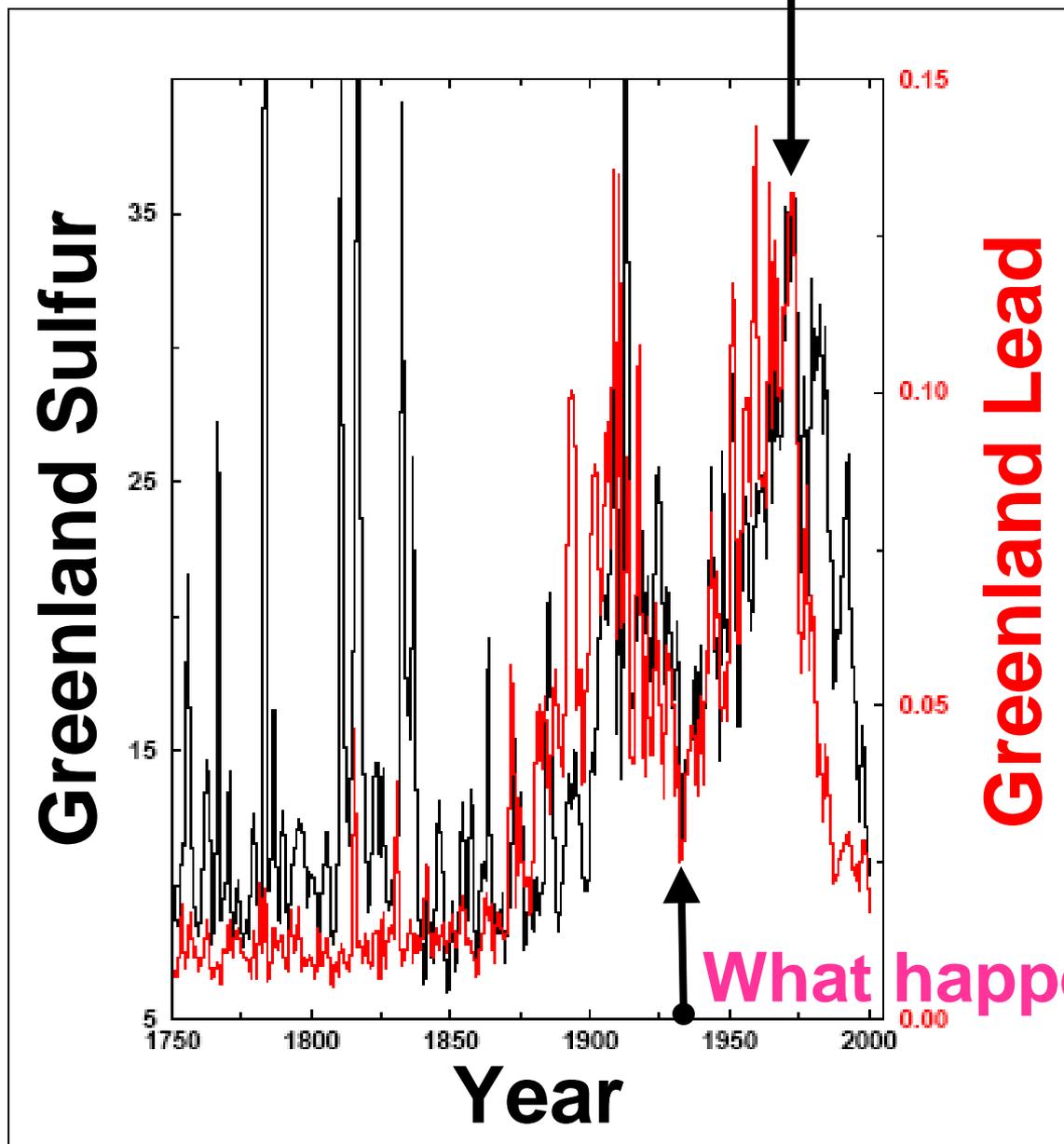
McConnell & Edwards, *PNAS*, 2008.

Conclusions



- Humans have had a very significant impact on Arctic pollution & radiative forcing for centuries.
- Can we slow Arctic warming? Role of short-lived pollutants.
- High-resolution ice cores records (especially spatial arrays) can help elucidate changes, sources, & transport pathways

What happened here?



What happened here?

Thanks!

