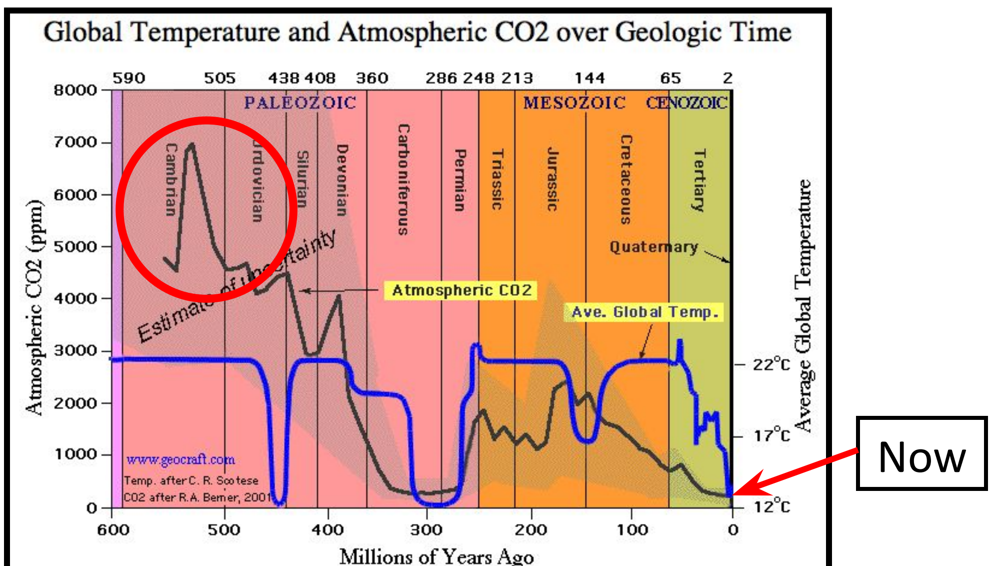
Methods

Looking back 600 million years

Atmospheric Carbon Dioxide was likely 18 times today's concentration, during the Cambrian period when life's diversity was at its greatest expansion (red circle). It was 4 times the current level when the dinosaurs were killed by an asteroid. The only other extended time CO2 was low, (like today) was a period 300 million years ago.



Late Carboniferous to **Early Permian** time (315 mya -- 270 mya) is the only time period in the last 600 million years when **both** atmospheric **CO2** and **temperatures** were as low as they are today (**Quaternary Period**).

In the big picture we are now in a **low** CO_2 period. The 20^{th} century increase shows as an insignificant dot at this scale.

Do we risk **runaway greenhouse warming** if our CO_2 concentration gets too high? CO2 has been scarce the last 2 million years. Also, it has never significantly driven temperature before. Venus may have runaway greenhouse warming, but its CO_2, at 96.5% is 2,500 **times** the level of CO_2 in the earth's atmosphere.

Looking Back 1800 years

A CO_2 Measurement Proxy
From stomatal density in fossil pine needles

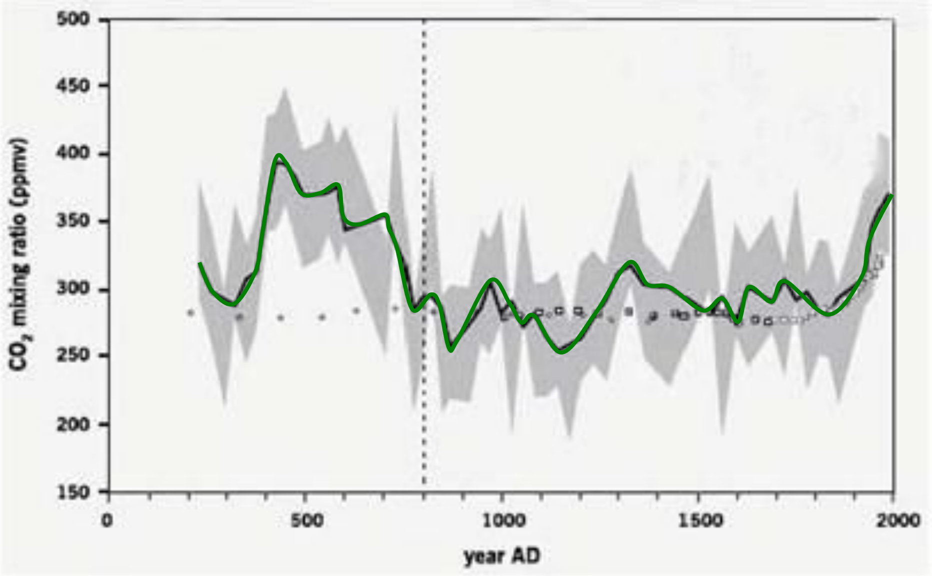
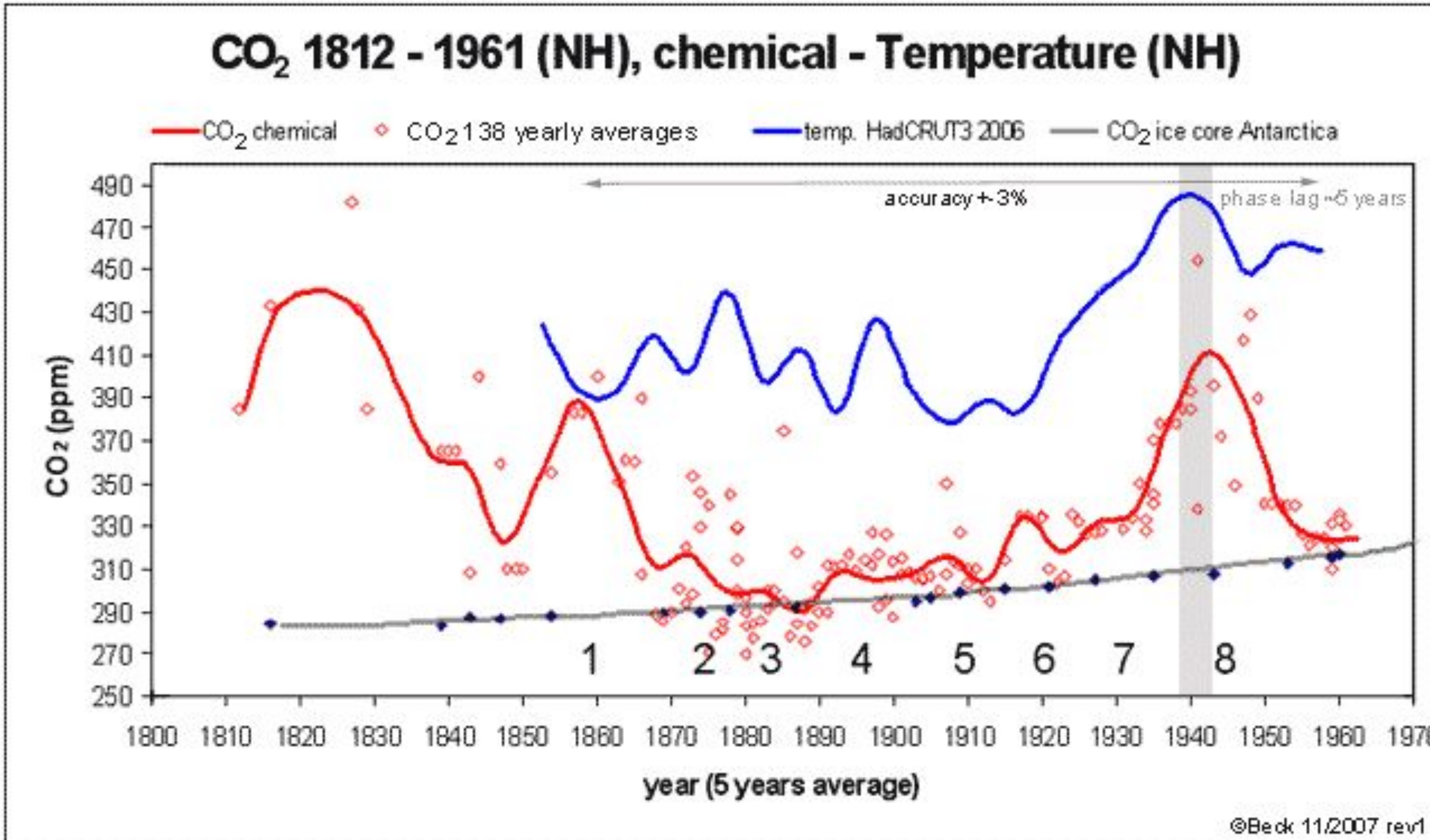


FIG 2 - Reconstruction of paleo-atmospheric carbon dioxide levels for the last 1800 years inferred from stomatal density in fossil pine needles (Tsuga heterophylla), northwestern USA (after Kouwenberg, 2005, Figure 5.4). Black line: three-point running average, based on 305 needles per data point; grey shading: error estimate. Open diamonds and squares indicate, respectively, measurements from the Taylor Dome and Law Dome ice cores, Antarctica. The ice core data represent generalised averages, and appear not to preserve the decadal-centennial changes in atmospheric carbon dioxide indicated by the stomatal measurements.

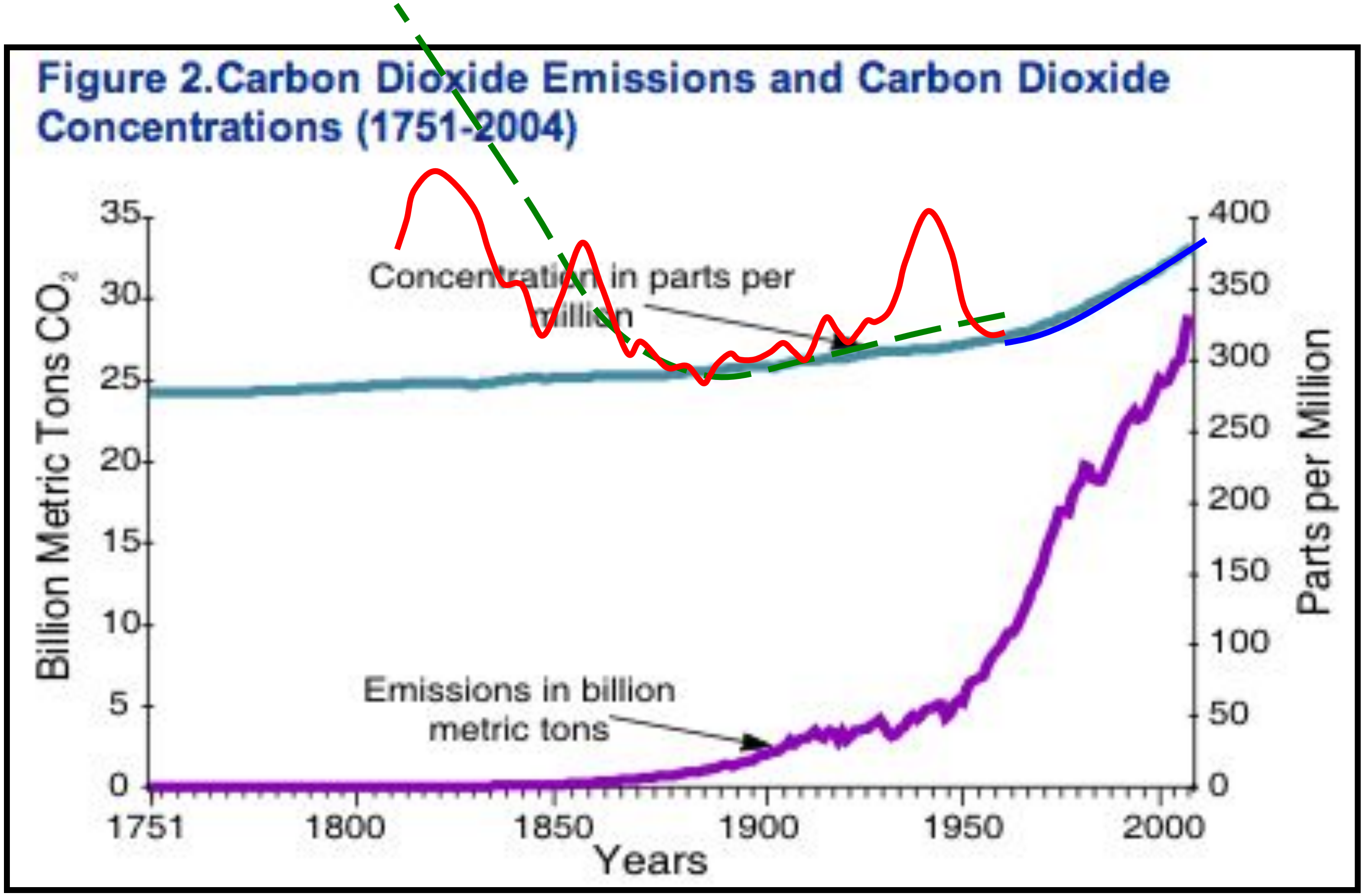
Another CO2 Measurement Method

Chemical method: data for 1810 to 1962 period.



The ‘Basic’ CO2 Chart

Now takes on a different look



Green dashed - Fairing of early, directly-measured CO2

Red - chemical method

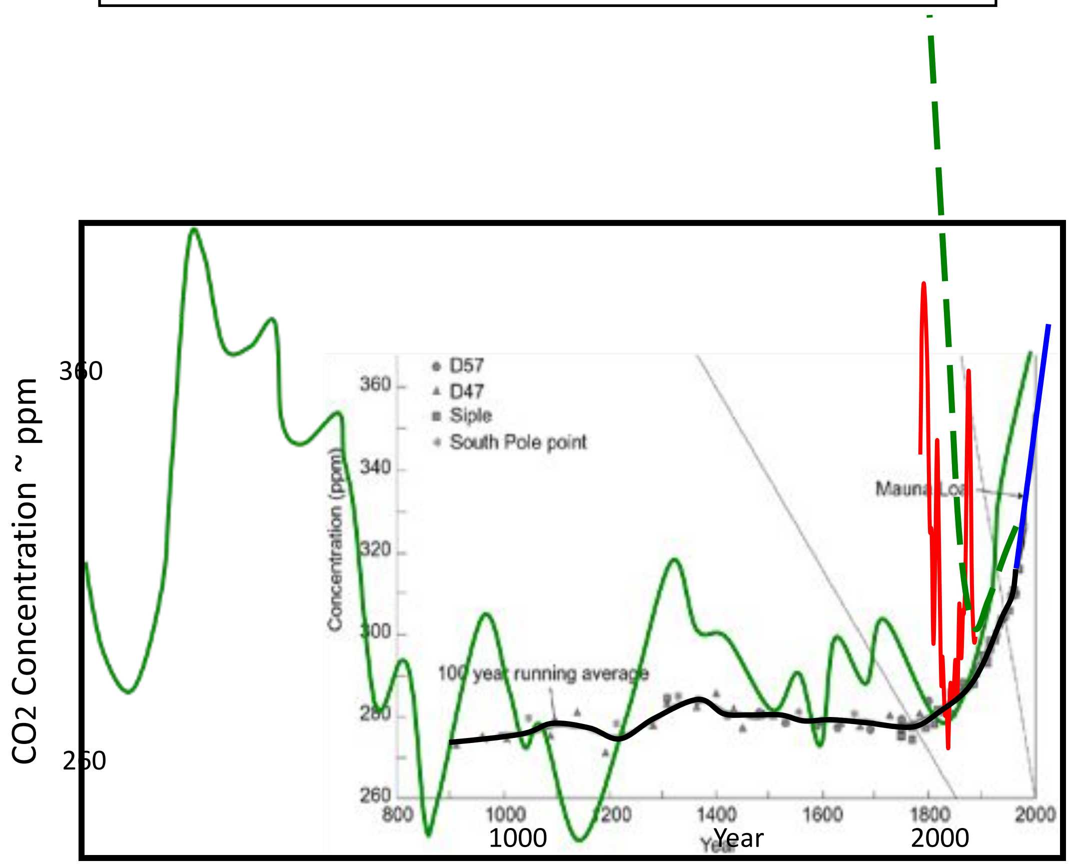
Blue - Mauna Loa modern measurements

Summary: CO_2 Data for the last 1800 years

Data from early & modern measurements, Ice core, chemical and pine needles.

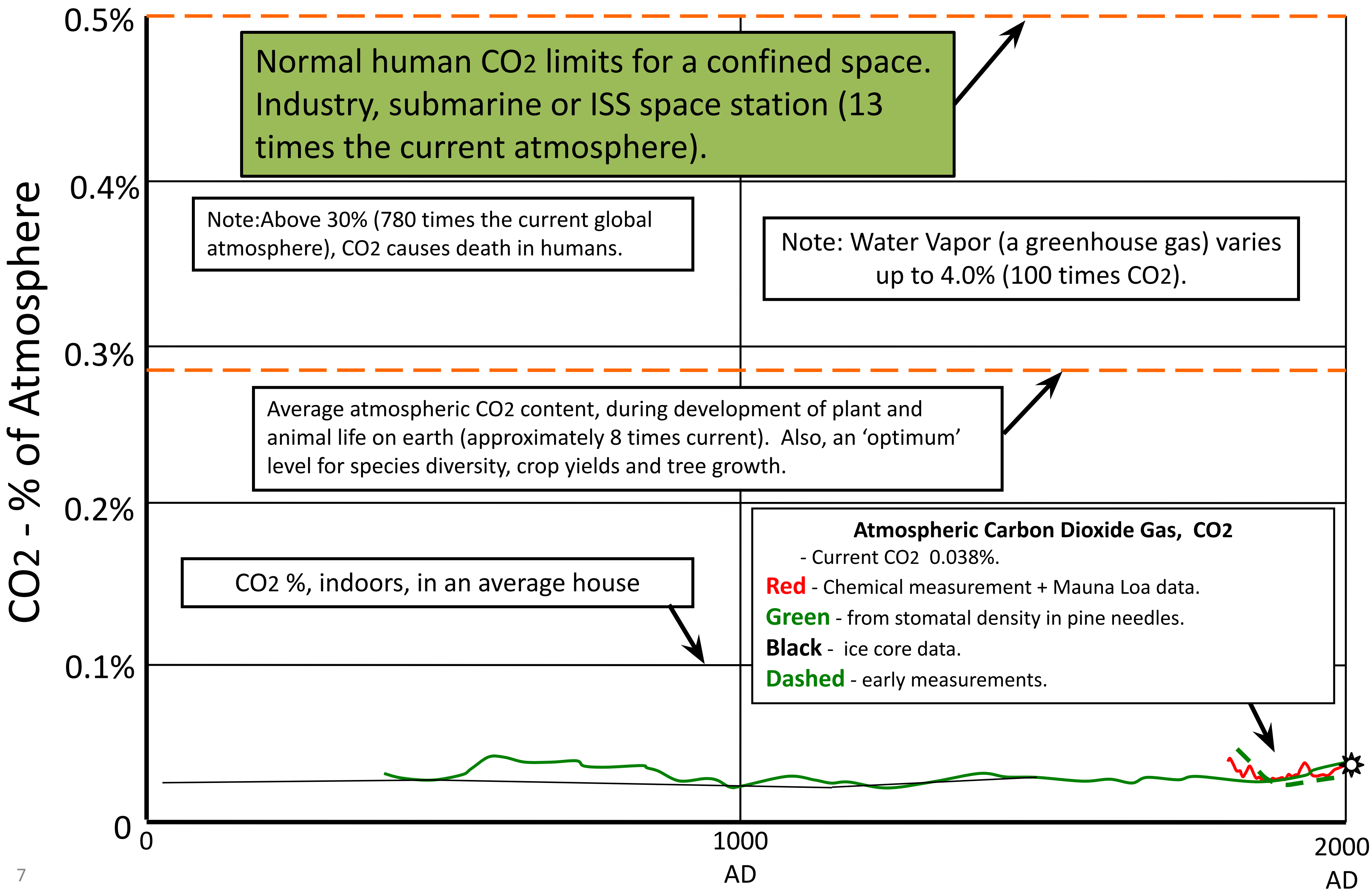
Dashed green - early direct measurements
Green - stomatal density in fossil pine needles
Black - ice cores, 4 locations
Red - chemical method
Blue - modern, Mauna Loa direct measurements

This chart **informs** illustrates (five data sources) the significant scatter seen in the various methods for CO_2 historical data.



Now, to put Atmospheric CO_2 in Perspective

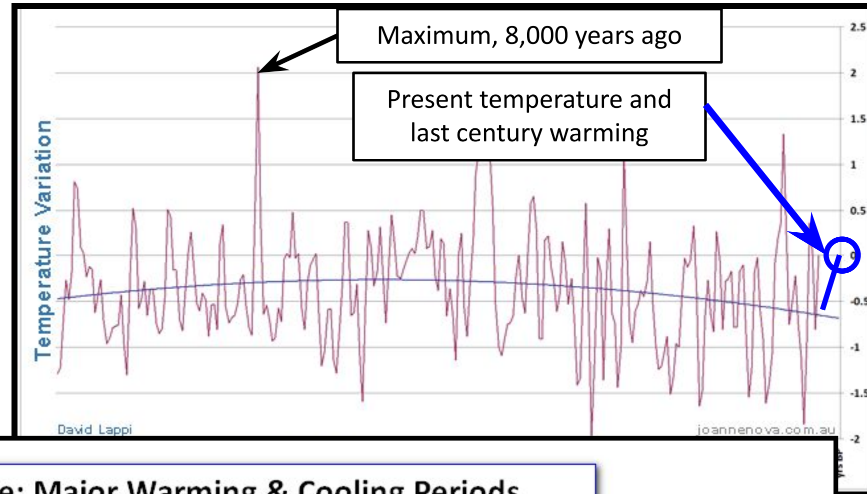
This shows CO_2 in its proper role as a trace gas, not something that has to be immediately eliminated.



The Greenland ice core data show it has been consistently warmer for the last 11,000 years.

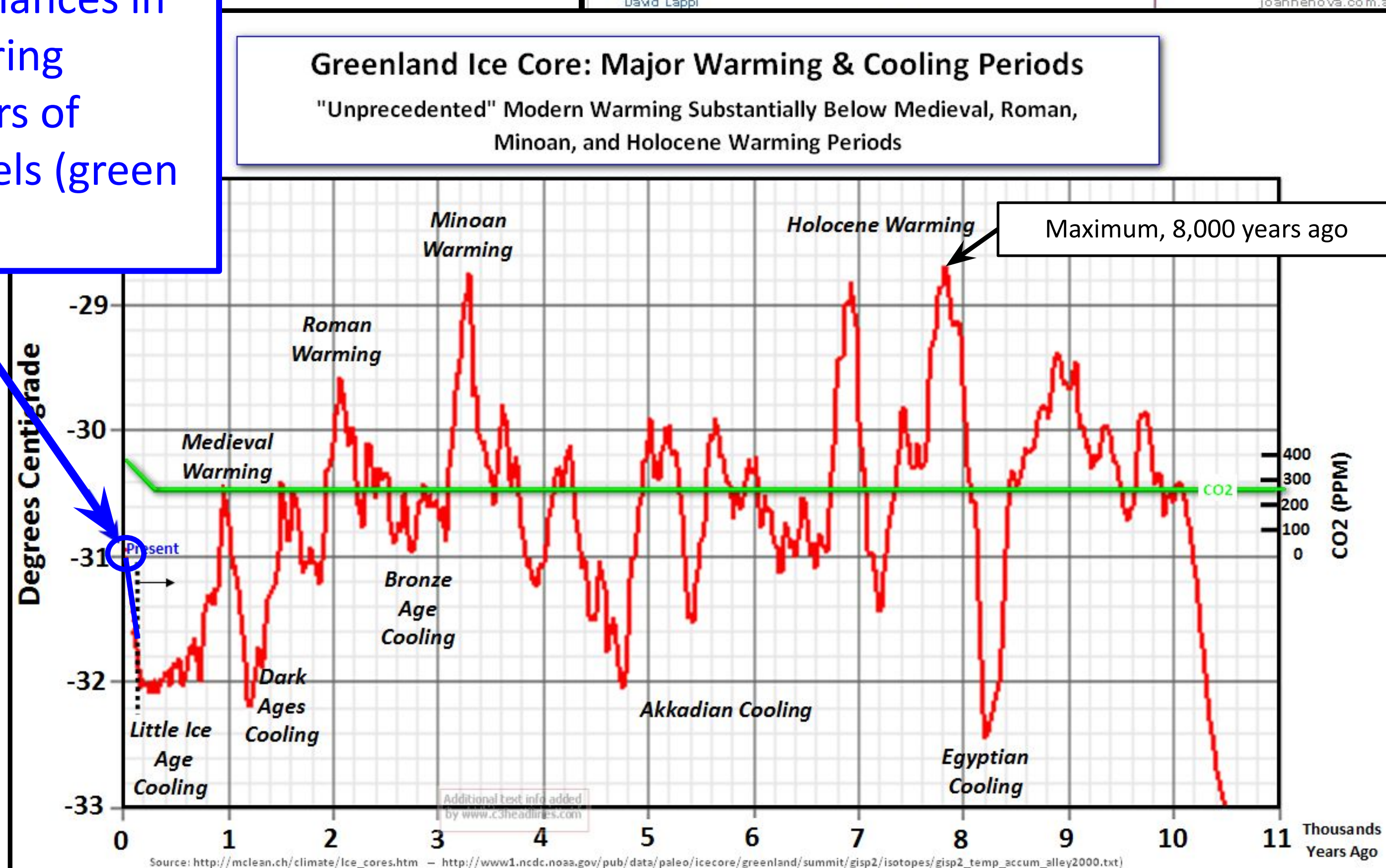
Today's climate is not even close to being the "warmest on record".

Russian Vostok ice cores, Antarctica

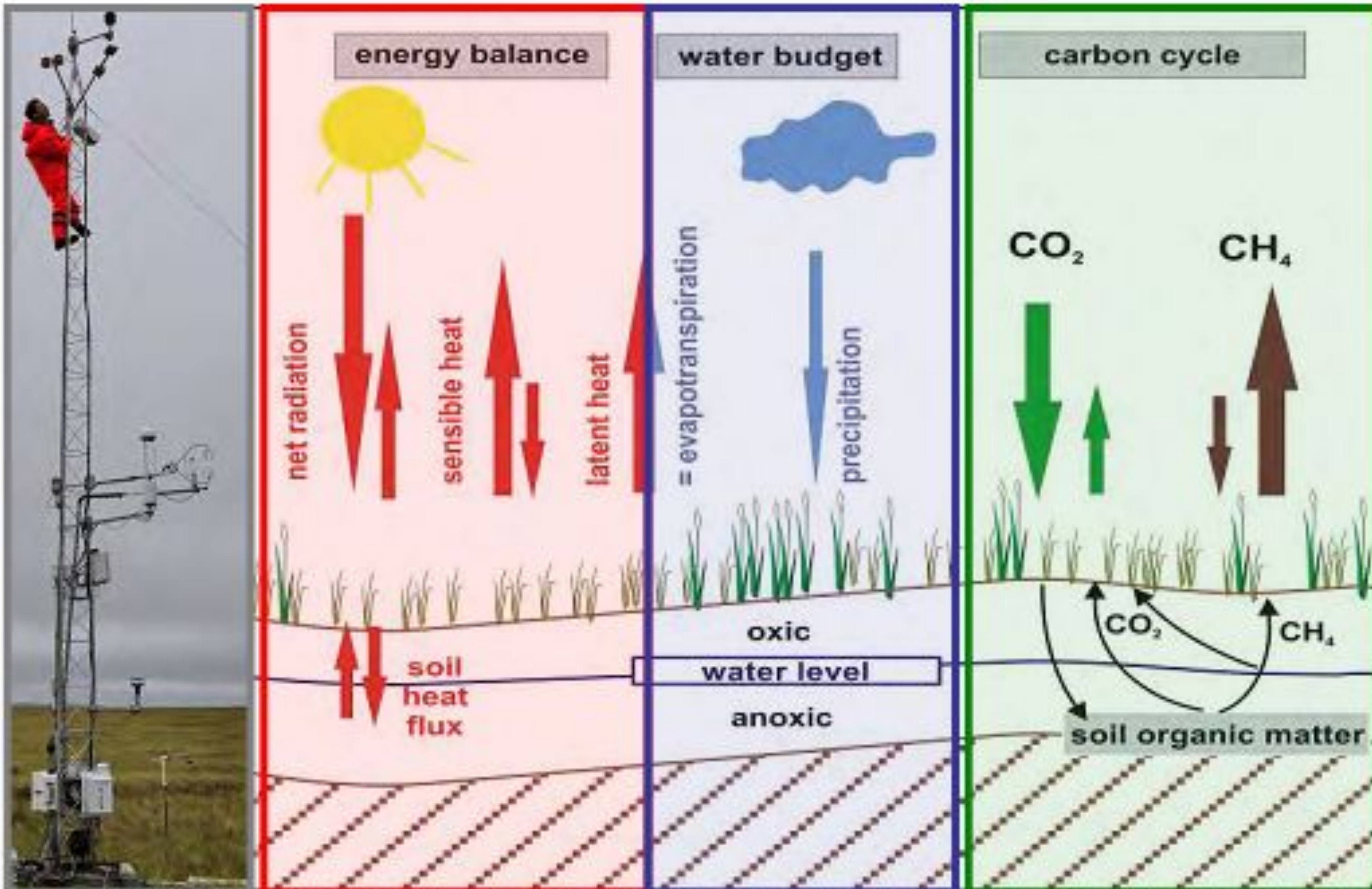


Note the wild variances in temperatures during thousands of years of constant CO2 levels (green data).

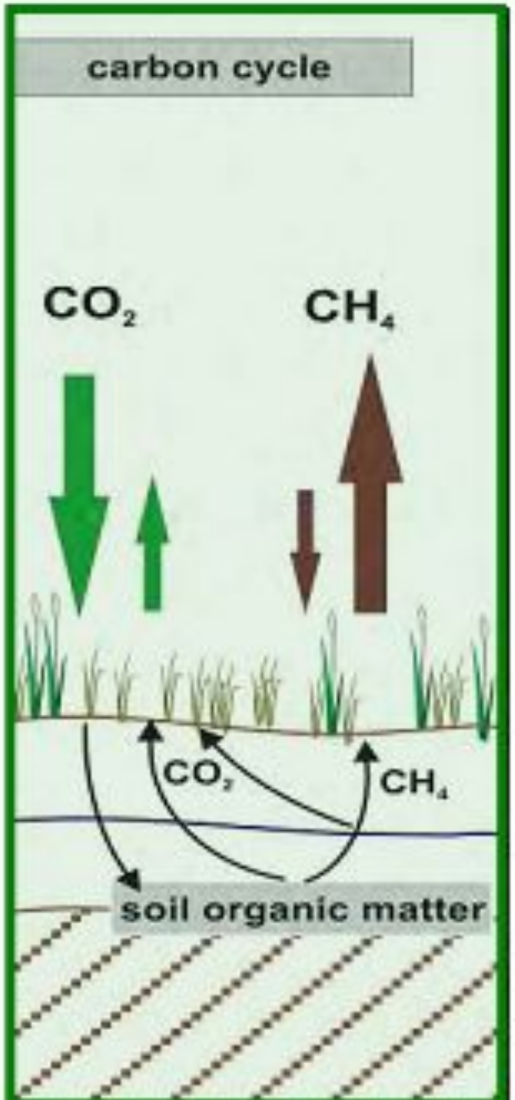
Present temperature and last century warming



From: http://www.c3headlines.com/



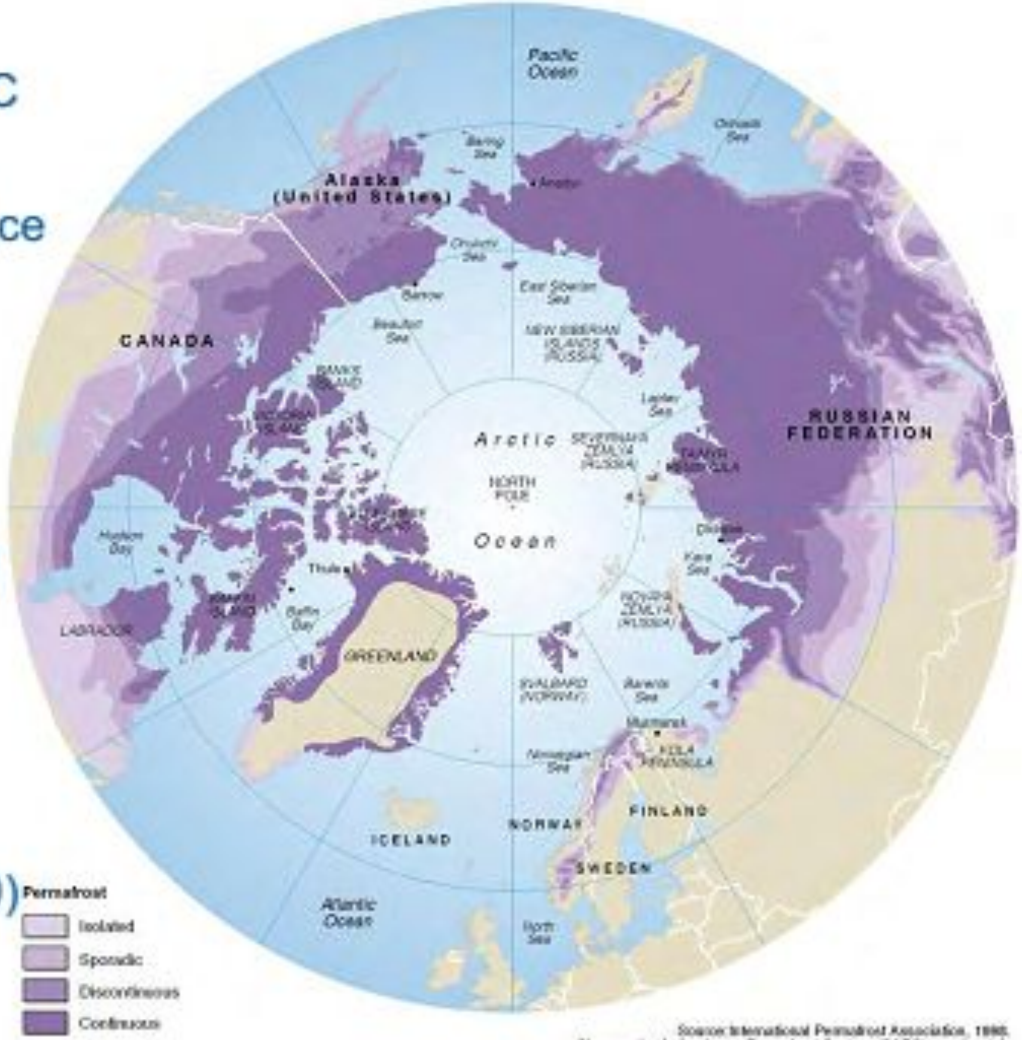
Source: Modified from Kutzbach



Source: Modified from Kutzbach

- Carbon pools (total amount: 75 Mio Gt)
    - Hydrosphere: 38.000 Gt (ocean)
    - Atmosphere: 765 Gt (IPCC 2007) + 3Gt/a
    - Pedosphere (soil): 1500 Gt*
    - Vegetation: 560 Gt
    - *Latest estimate for permafrost alone: 1670 Gt
- Carbon dioxide (CO2)
    - Photosynthesis removes CO2 from atmosphere
    - Respiration releases CO2 into atmosphere
        - Ca. 50 % of the photosynthesized C
- Methane (CH4)
    - Primarily release into atmosphere

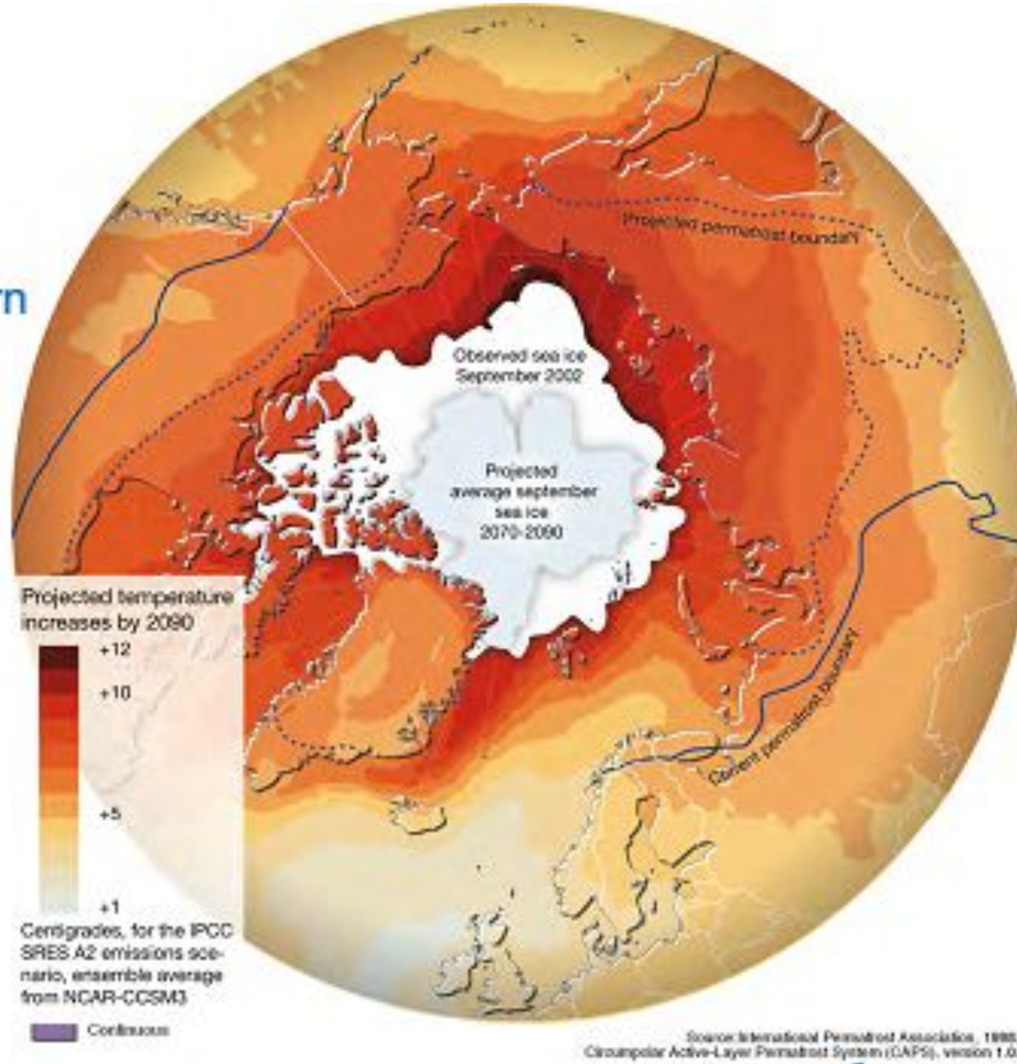
- Soils / sediment / rocks
  - ≥ 2 consecutive years < 0 °C
- ~24 % of the northern land surface
  - N-America: ~ 6,2 Mio km²
  - Eurasia: ~ 16,7 Mio km²
- Thickness up to > 1500 m
  - Seasonal thaw (active layer) few decimeters to meter
- Warming since 1960s
  - East Siberia: ~ 1,3 °C
  - Alaska: ~ 2-3 °C (since 1980)



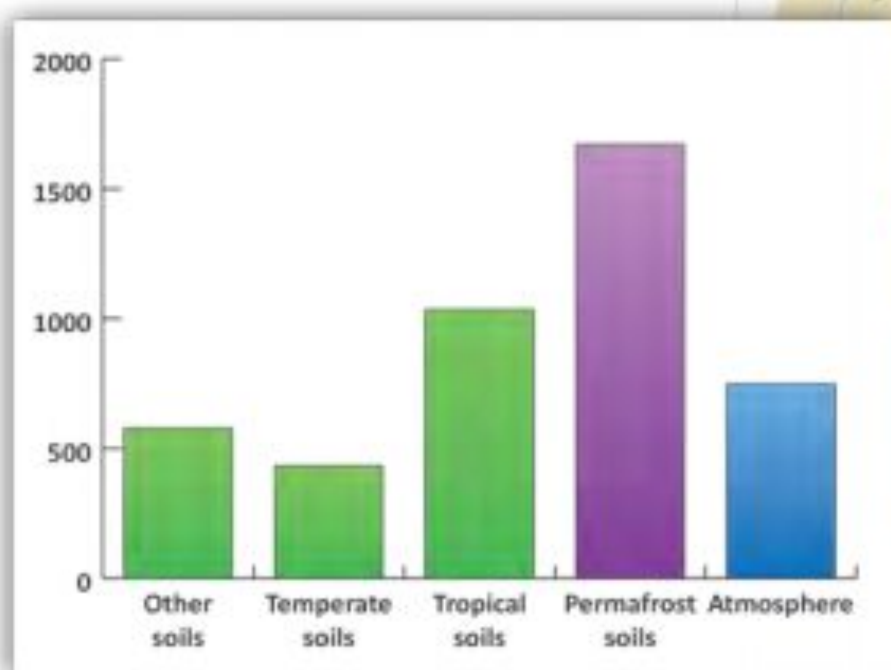
Source: International Permafrost Association, 1998. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.

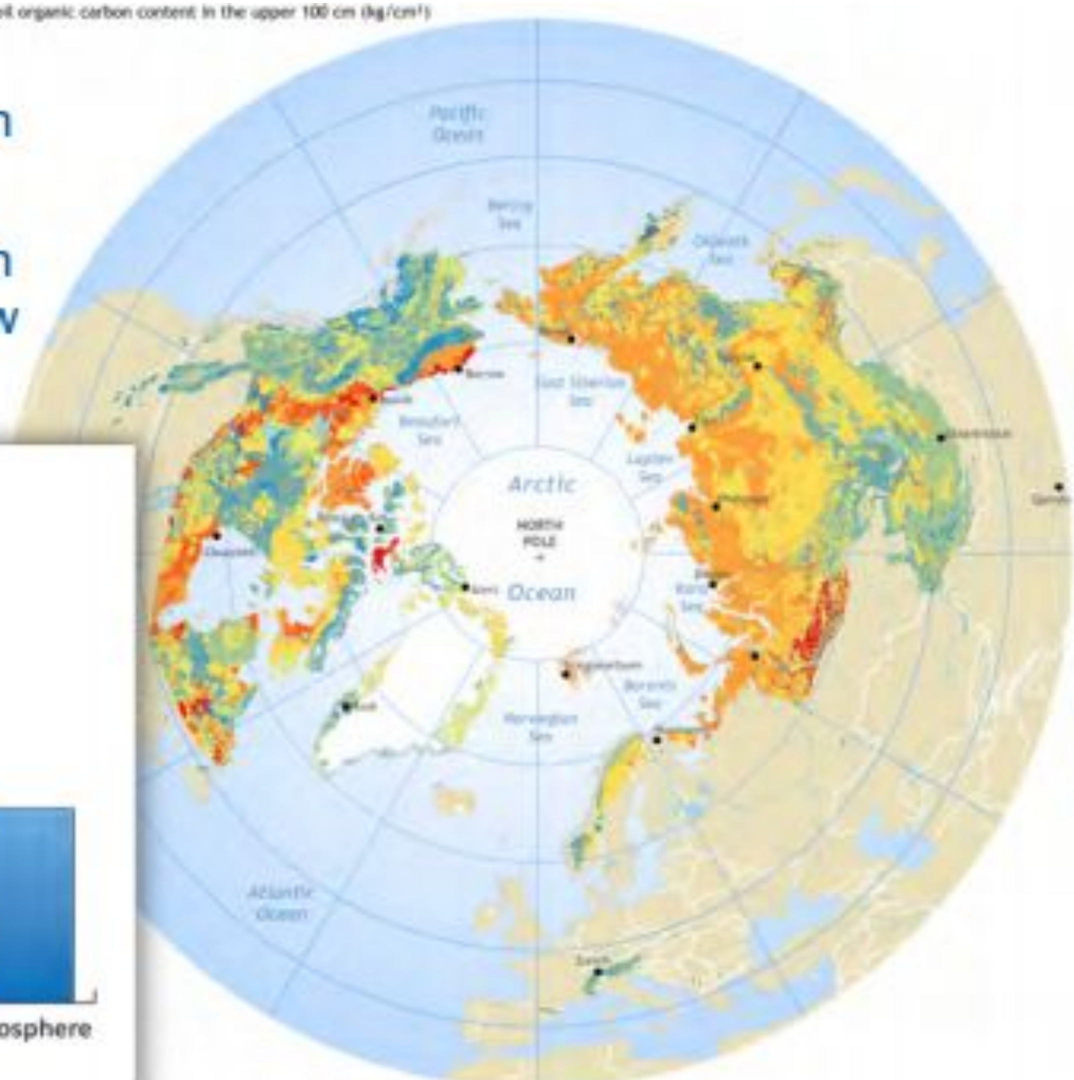
- Is happening right now!
- Predictions for permafrost:
  - Northward retreat of southern border
  - Deeper active layer
  - Enhanced release of greenhouse gases
- Predictions for sea ice:
  - Retreat
  - Strong effect on radiation

→ Positive feedback on climate



- Large amounts of organic carbon
- Large amounts of organic carbon in areas already undergoing thaw

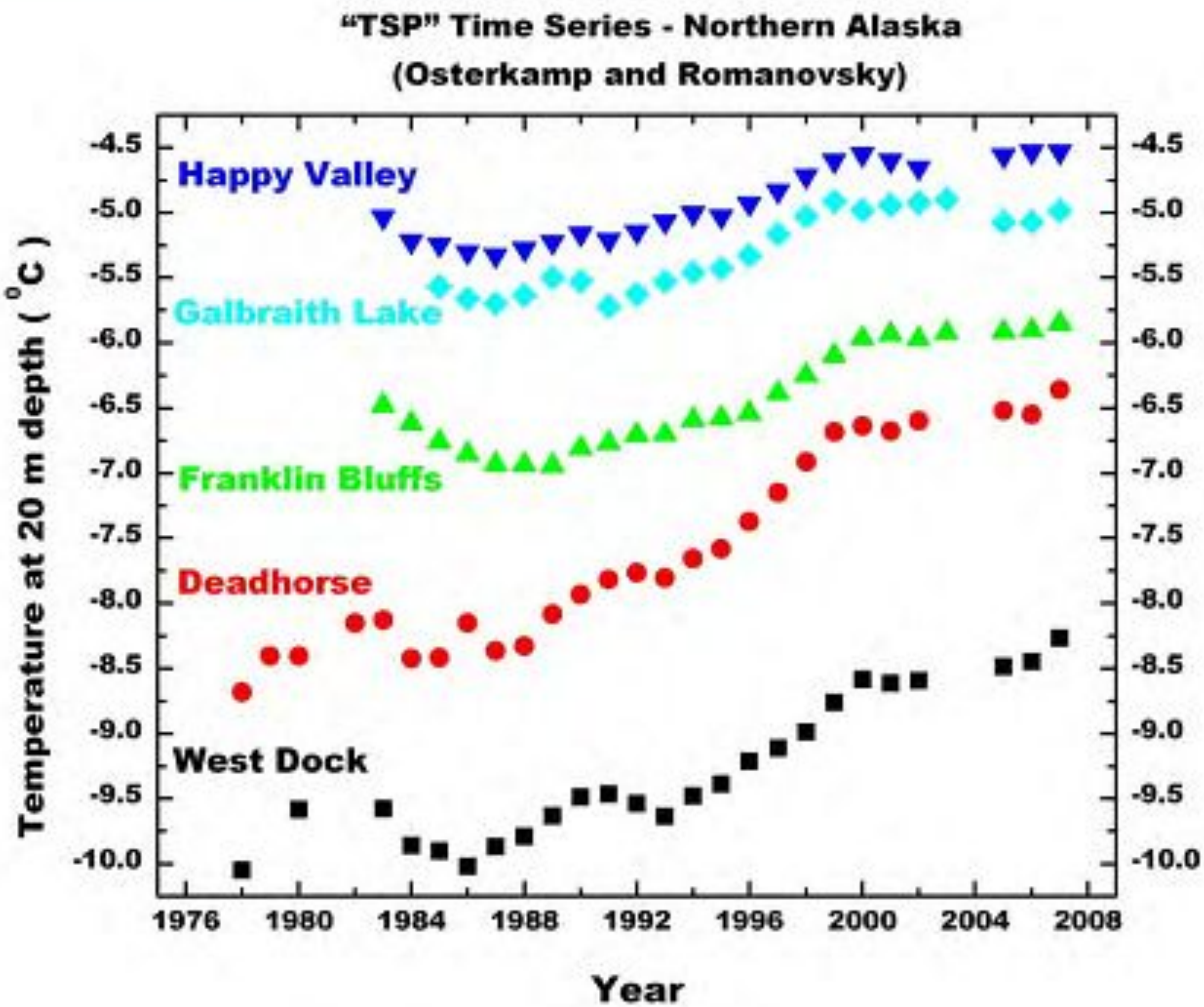




after Tarnocai et al., 2009

GFZ

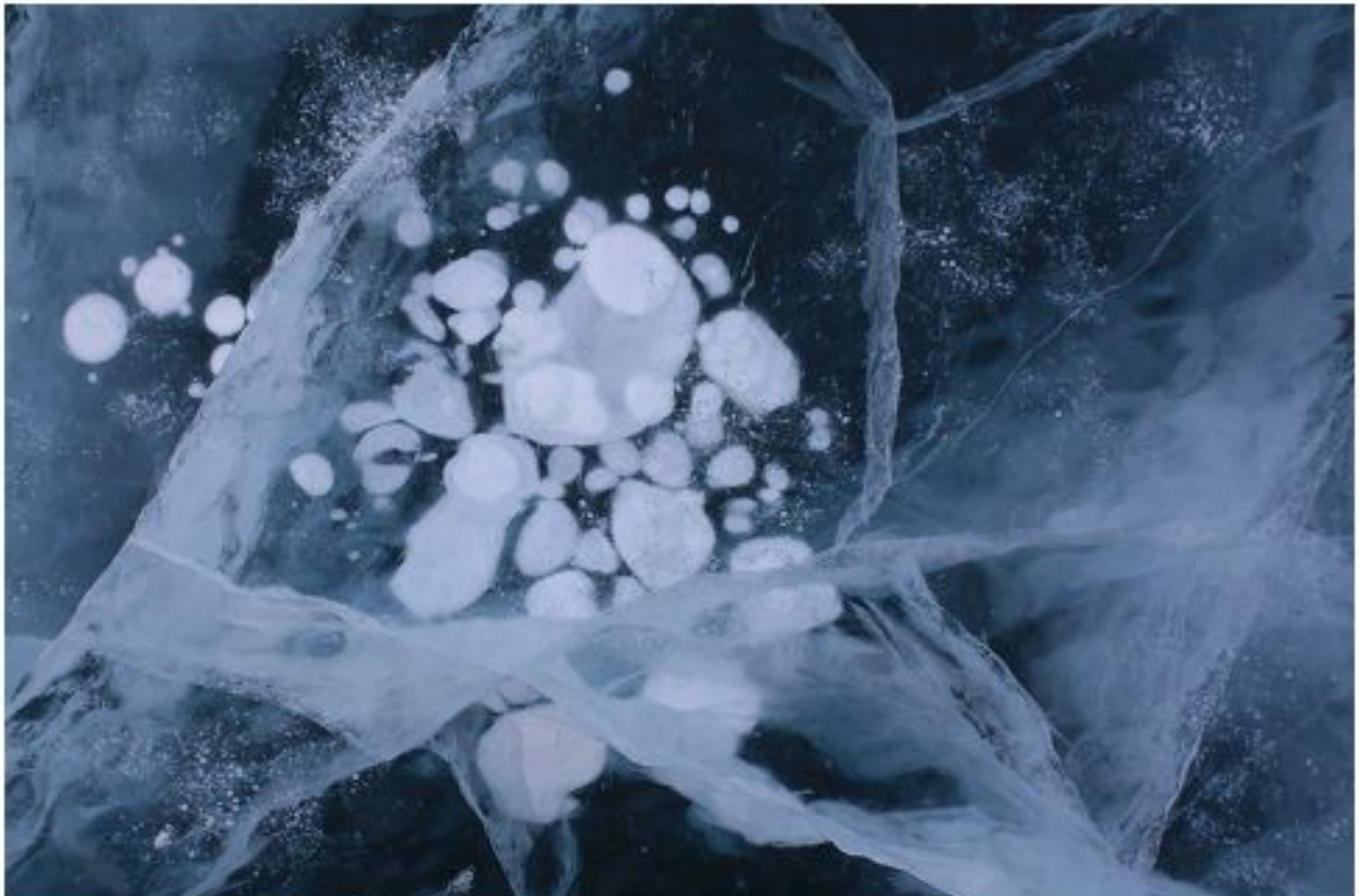
Warming of the permafrost



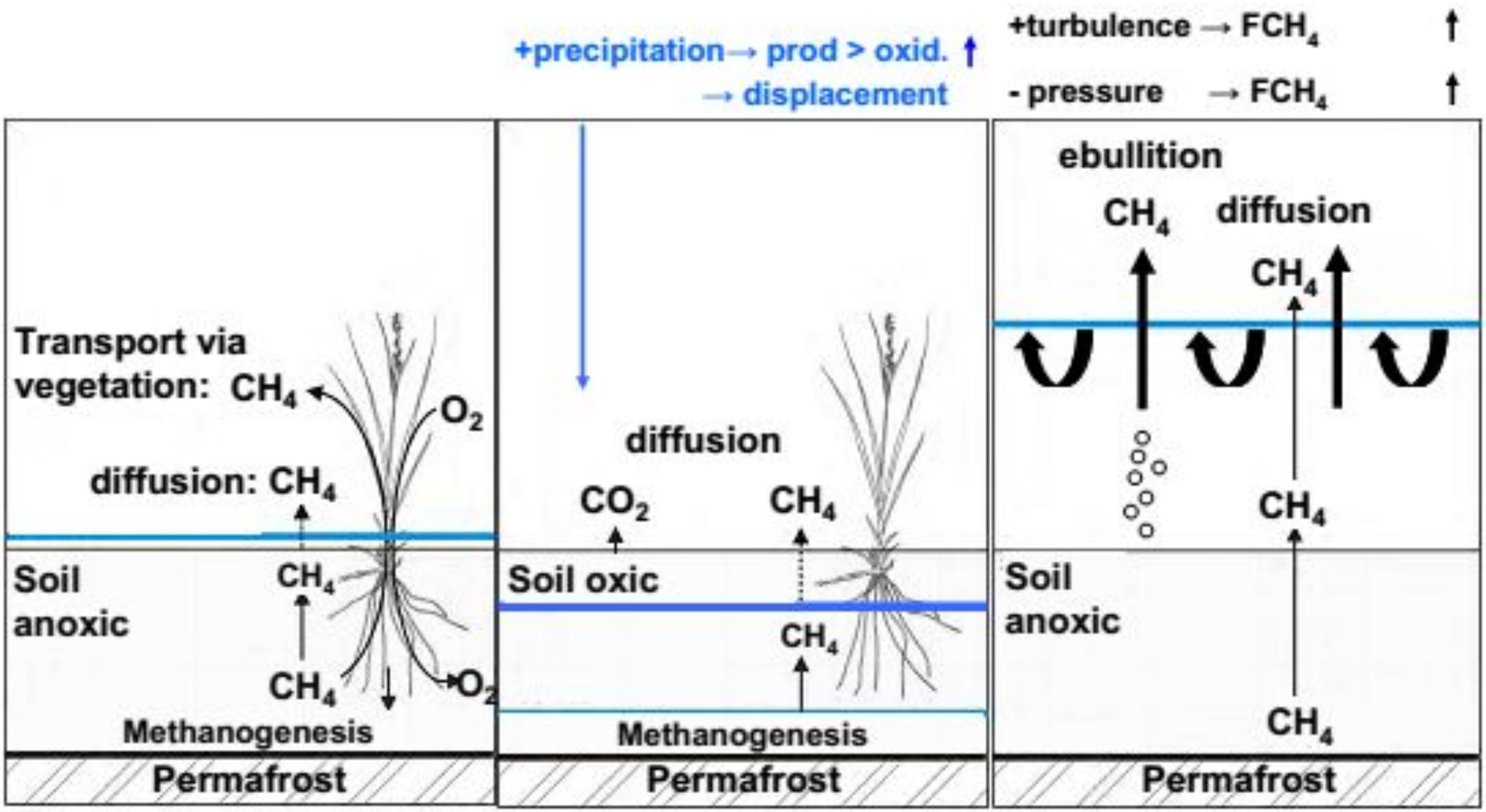
Carbon storage in Yedoma ice complex

Photo: K. Piel

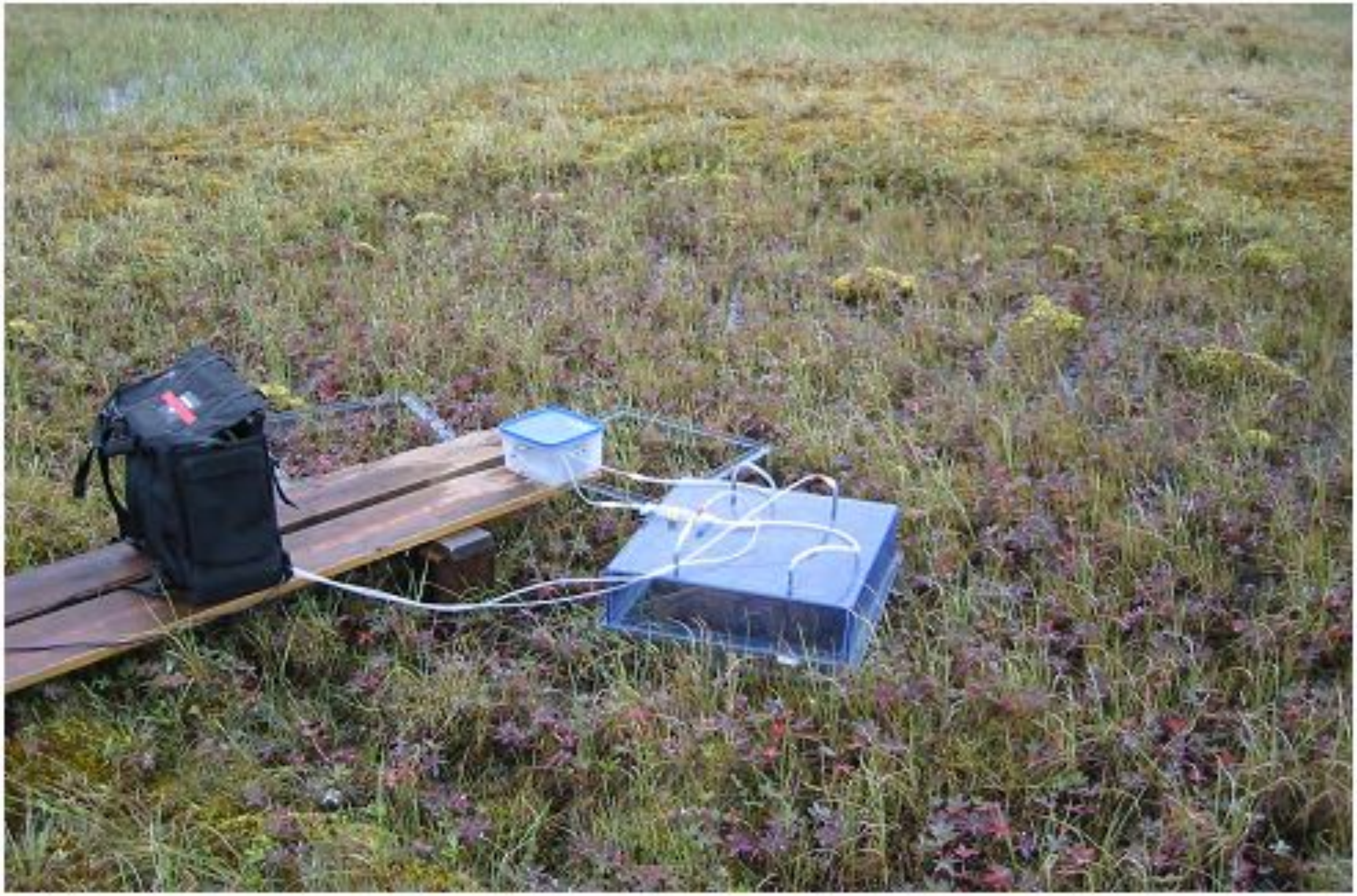
Carbon mobilization in thaw lakes



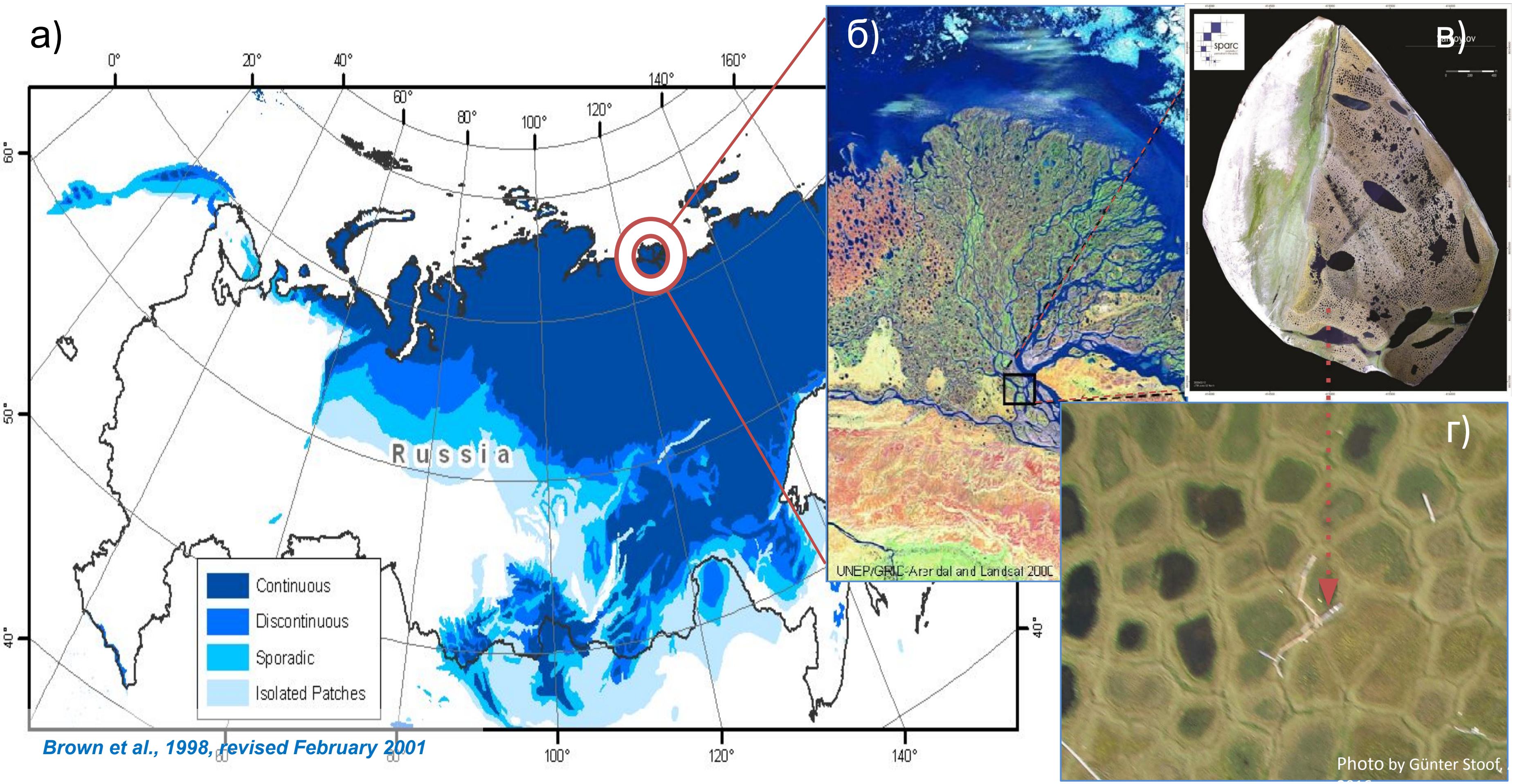
Pathways


+precipitation→ prod > oxid.
→ displacement
+turbulence → FCH_4
- pressure → FCH_4
Transport via vegetation: CH_4
O_2
diffusion: CH_4
CH_4
Soil anoxic
CH_4
O_2
Methanogenesis
Permafrost
diffusion
CO_2
CH_4
Soil oxic
CH_4
Methanogenesis
Permafrost
ebullition
CH_4
diffusion
CH_4
CH_4
Soil anoxic
CH_4
Permafrost

Methods: closed chambers

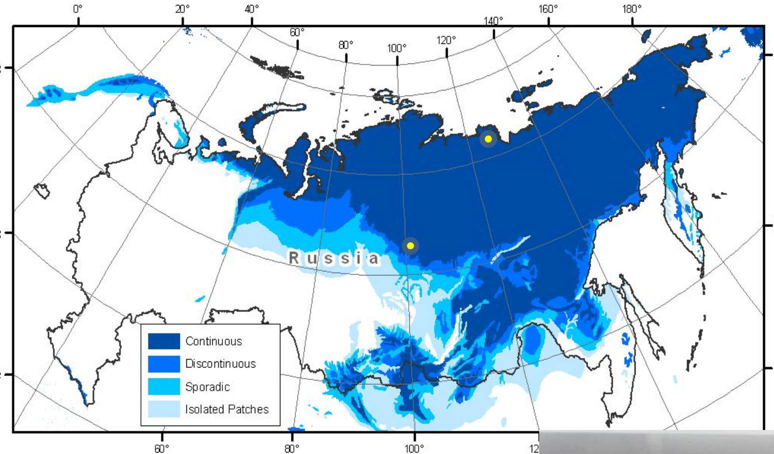


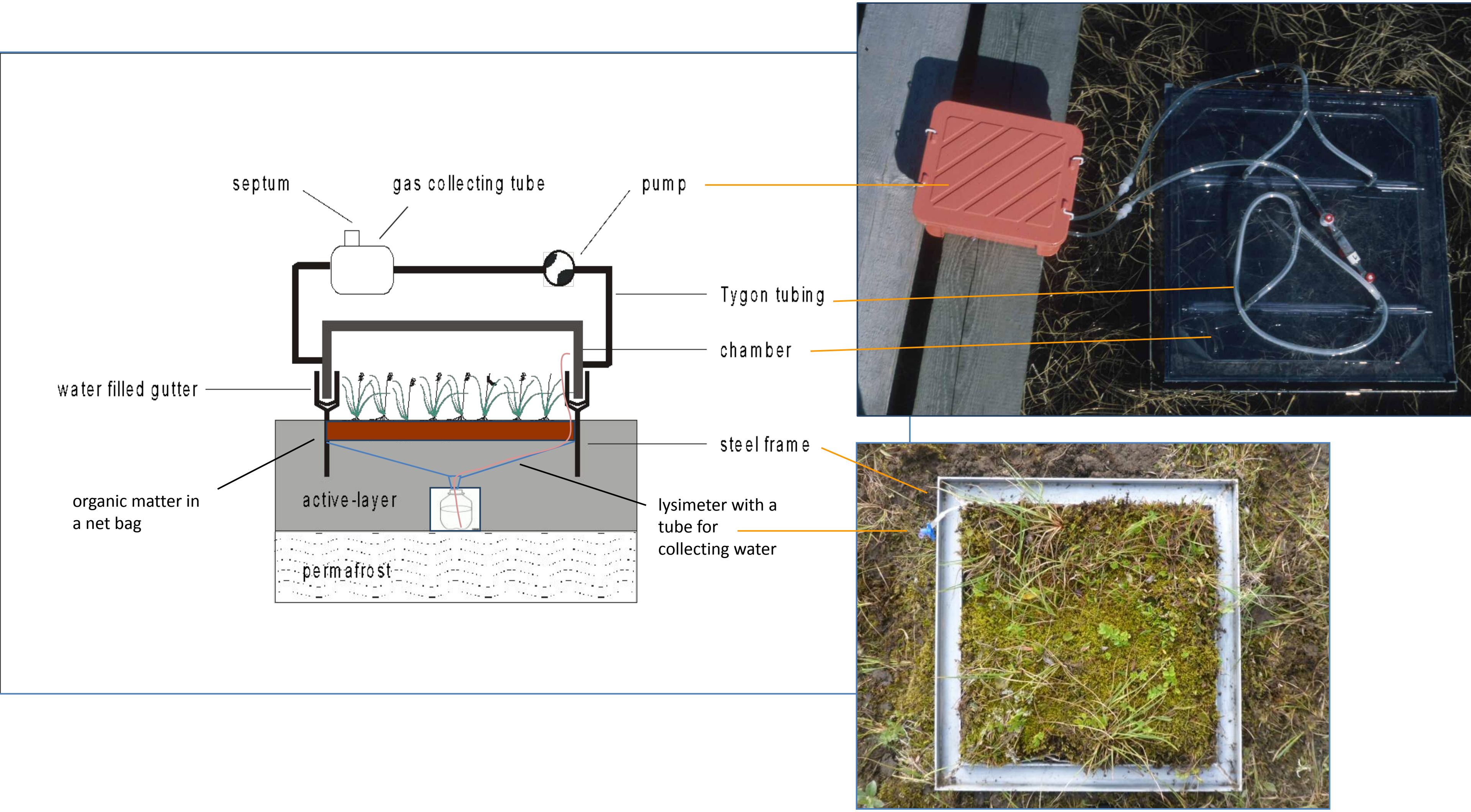
Sachs et al. (2010), *Global Change Biol.*

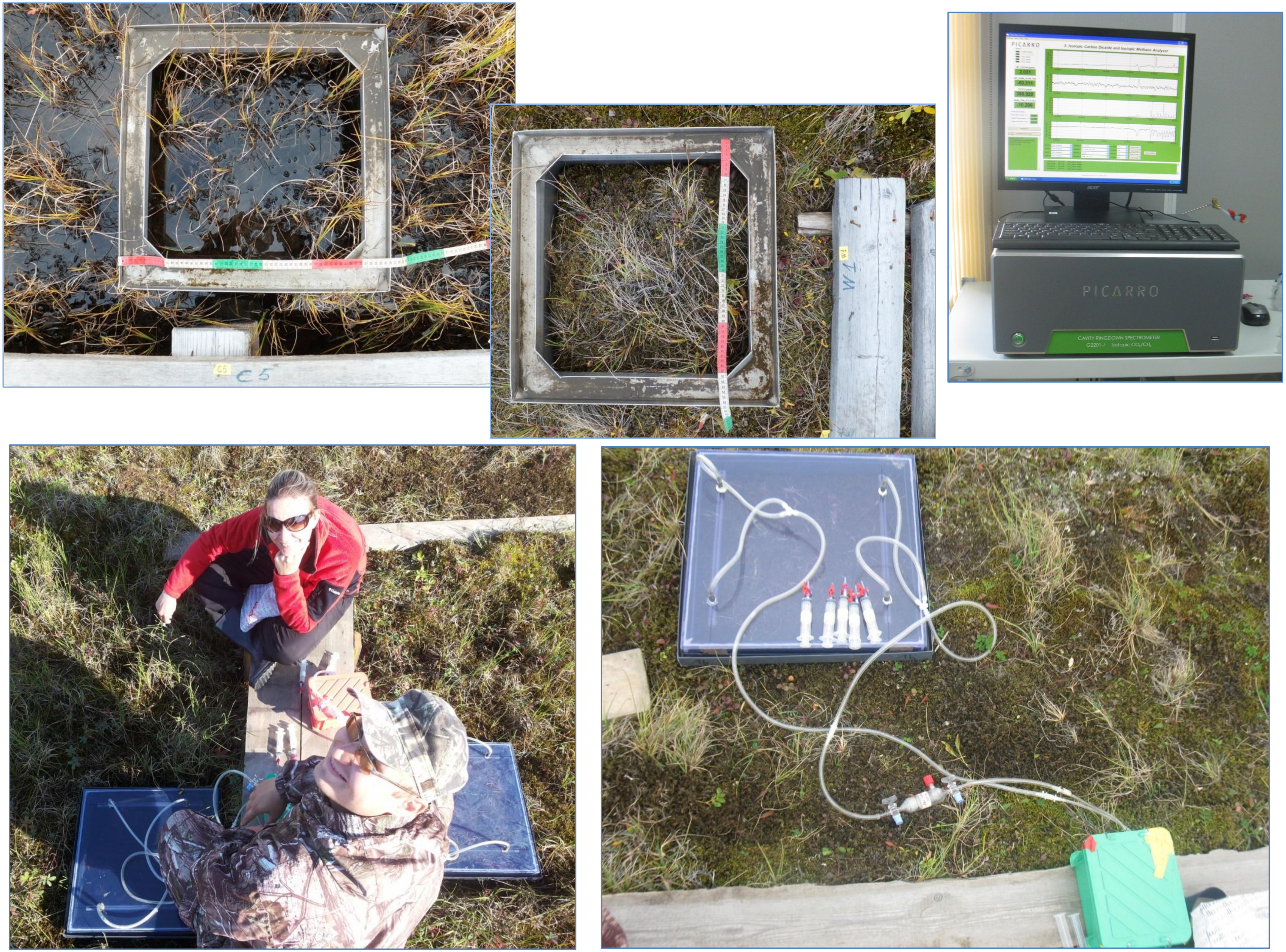


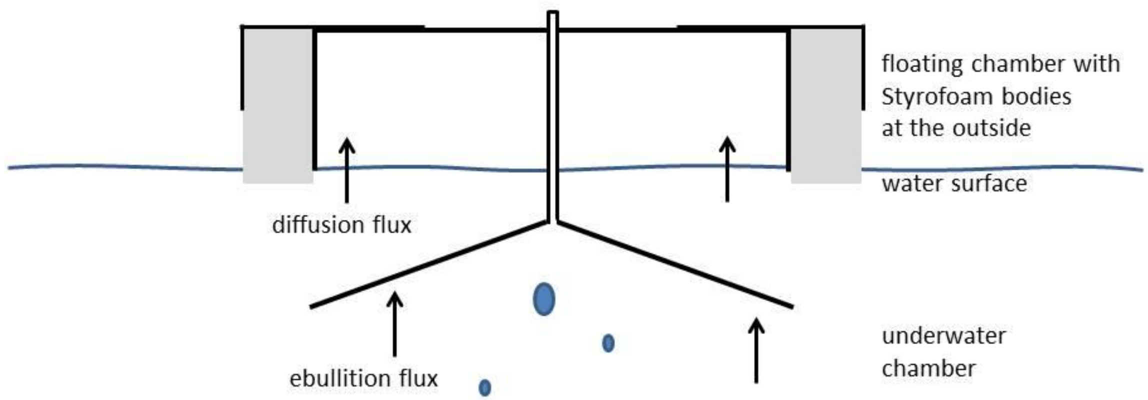
а)
0°
20°
40°
60°
80°
100°
120°
140°
160°
60°
50°
40°
Russia
Continuous
Discontinuous
Sporadic
Isolated Patches
Brown et al., 1998, revised February 2001
б)
UNEP/GRID-Arendal and Landsat 2000
в)
sparc
г)
Photo by Günter Stoof,

Ivakhov V. (photos and chamber)




septum
gas collecting tube
pump
Tygon tubing
chamber
water filled gutter
steel frame
organic matter in
a net bag
active-layer
lysimeter with a
tube for
collecting water
permafrost

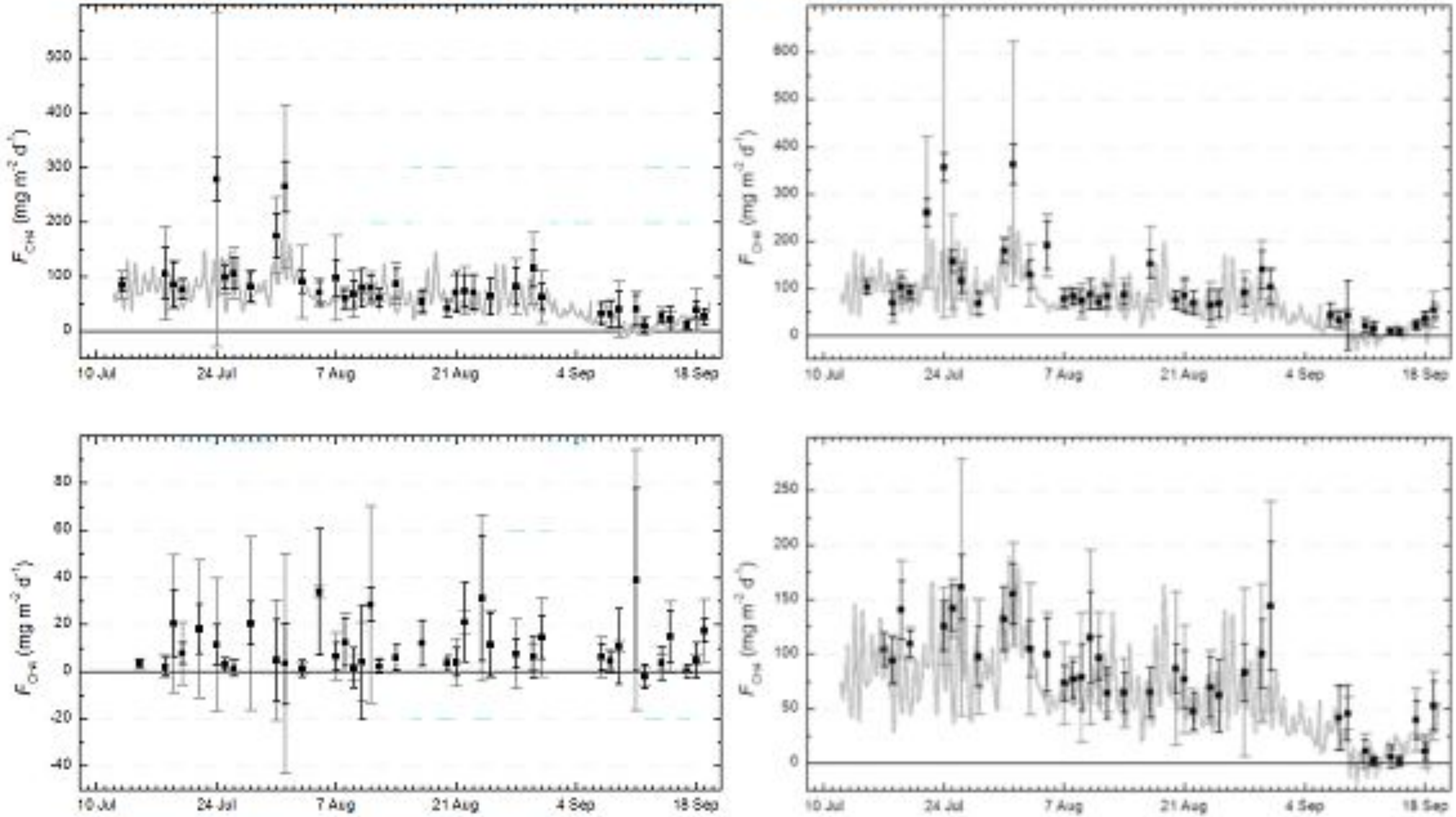

C5
PICARRO
CAVITY RINGDOWN SPECTROMETER
G2201-i Isotopic CO2/CH4



Cross section through the floating emission chambers with the underwater chambers for trapping gas bubbles rising from the ponds bottom.

Methods: closed chambers

- Not continuous, small footprint, spatially explicit



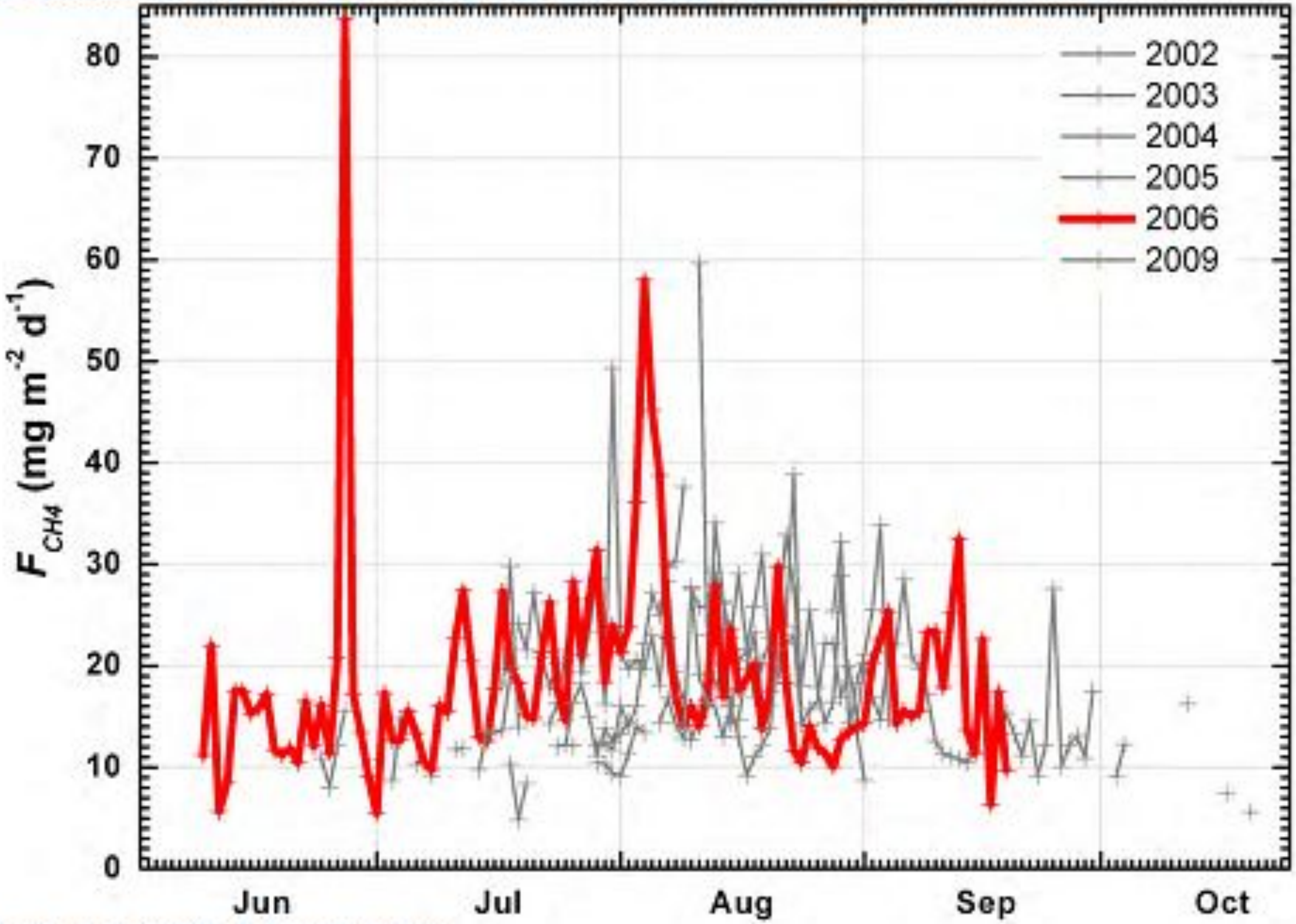
Sachs et al. (2010), *Global Change Biol.*

Methods: Eddy Covariance

Sachs et al. (2008) *J. Geophys. Res.*

Methods: Eddy Covariance

- continuous, integrated across ha-km², high temporal resolution



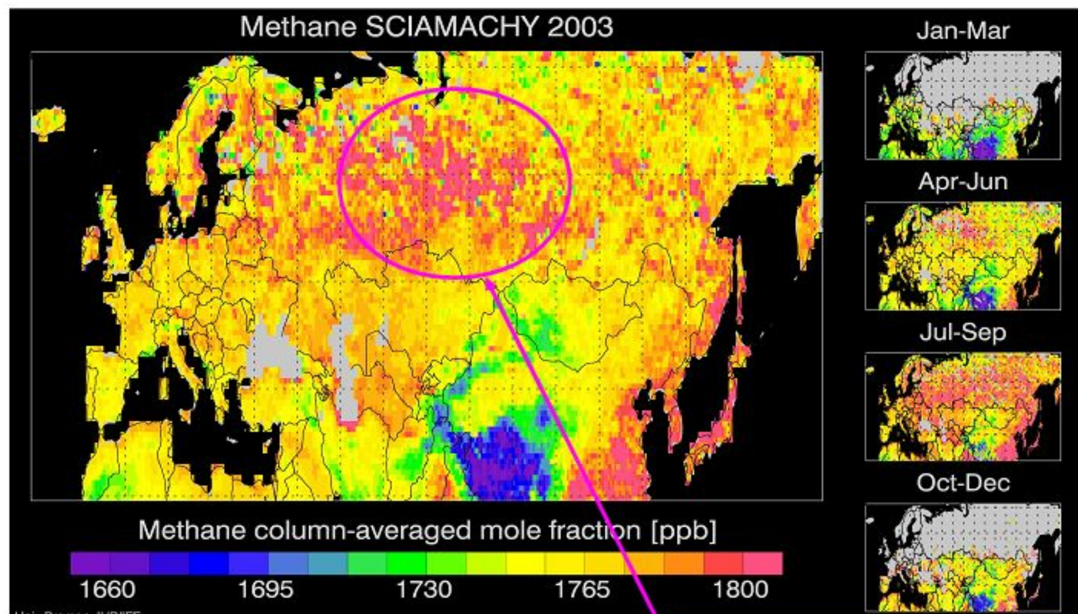
Sachs et al. (2008) *J. Geophys. Res.*

Methods:

Chamber

Eddy covariance

Satellite retrievals of methane concentration



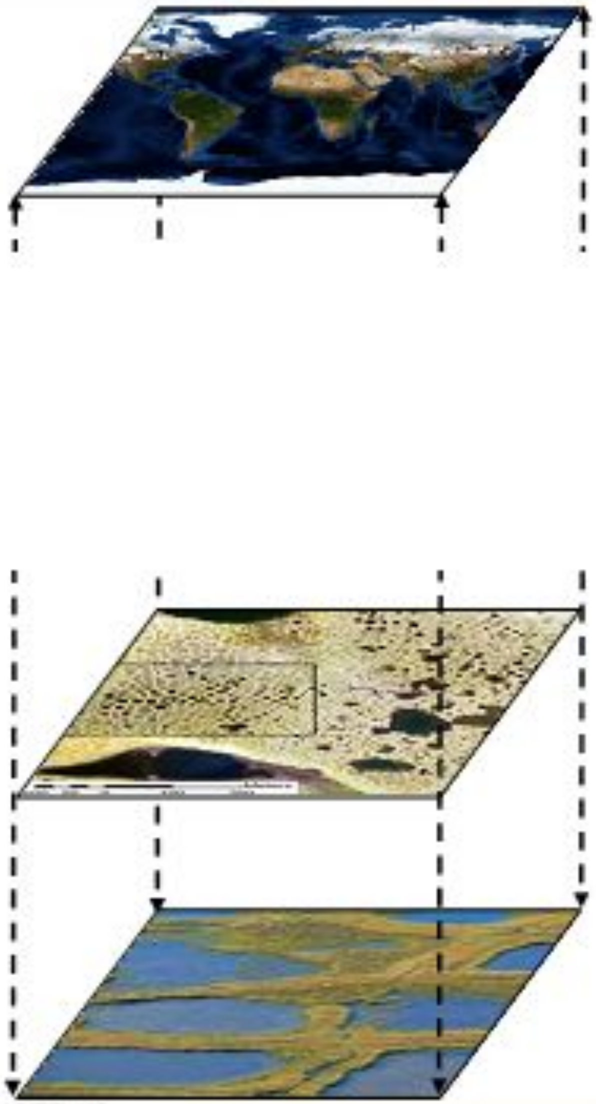
Maximum of methane concentration over Western Siberia indicates high surface emissions

Satelite

Aircraft

1) **SCIAMACHY**
(SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY, http://envisat.esa.int)
2) **GOSAT** (Greenhouse gases Observing SATellite, http://www.gosat.nies.go.jp/index_e.html)
3) **AIRS** (Atmospheric Infrared Sounder, http://airs.jpl.nasa.gov/)

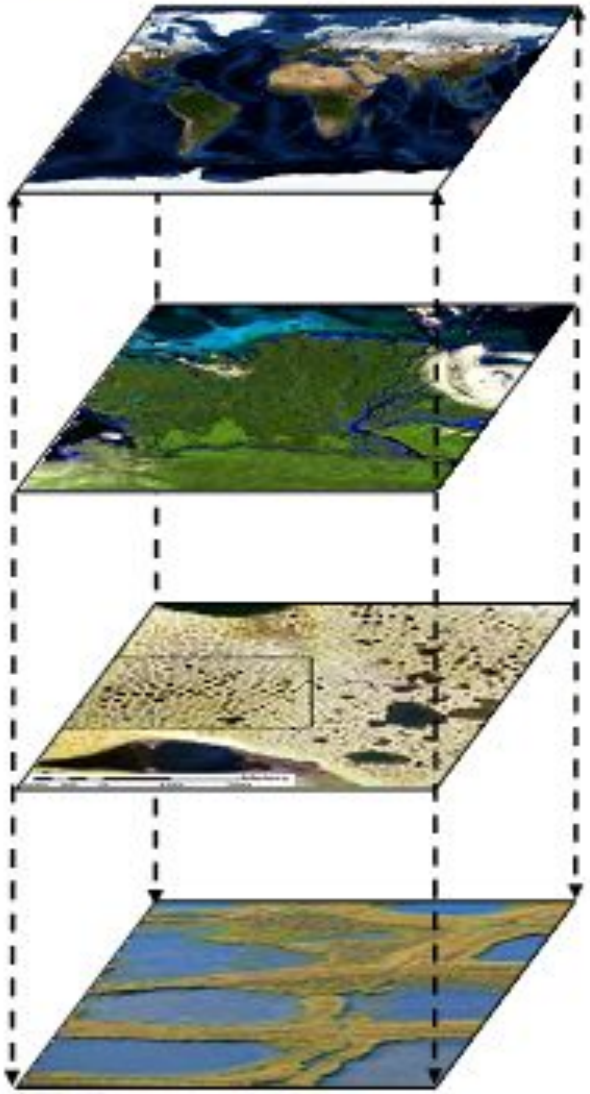
Problem: measurement gap



- Global: large uncertainties
  Arctic bottom-up: 32-112 $TgCH_4/a$
  Arctic top-down: 15-50 $TgCH_4/a$
  (McGuire et al. 2009)

- Heterogeneity of sources and sinks:
  - Location biases?
  - Difficult to extrapolate
  - Requires high-resolution classifications + lots of data
  - Expensive and not feasible in large and remote areas

Problem: measurement gap



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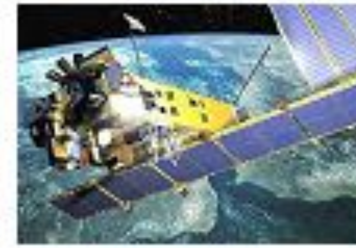
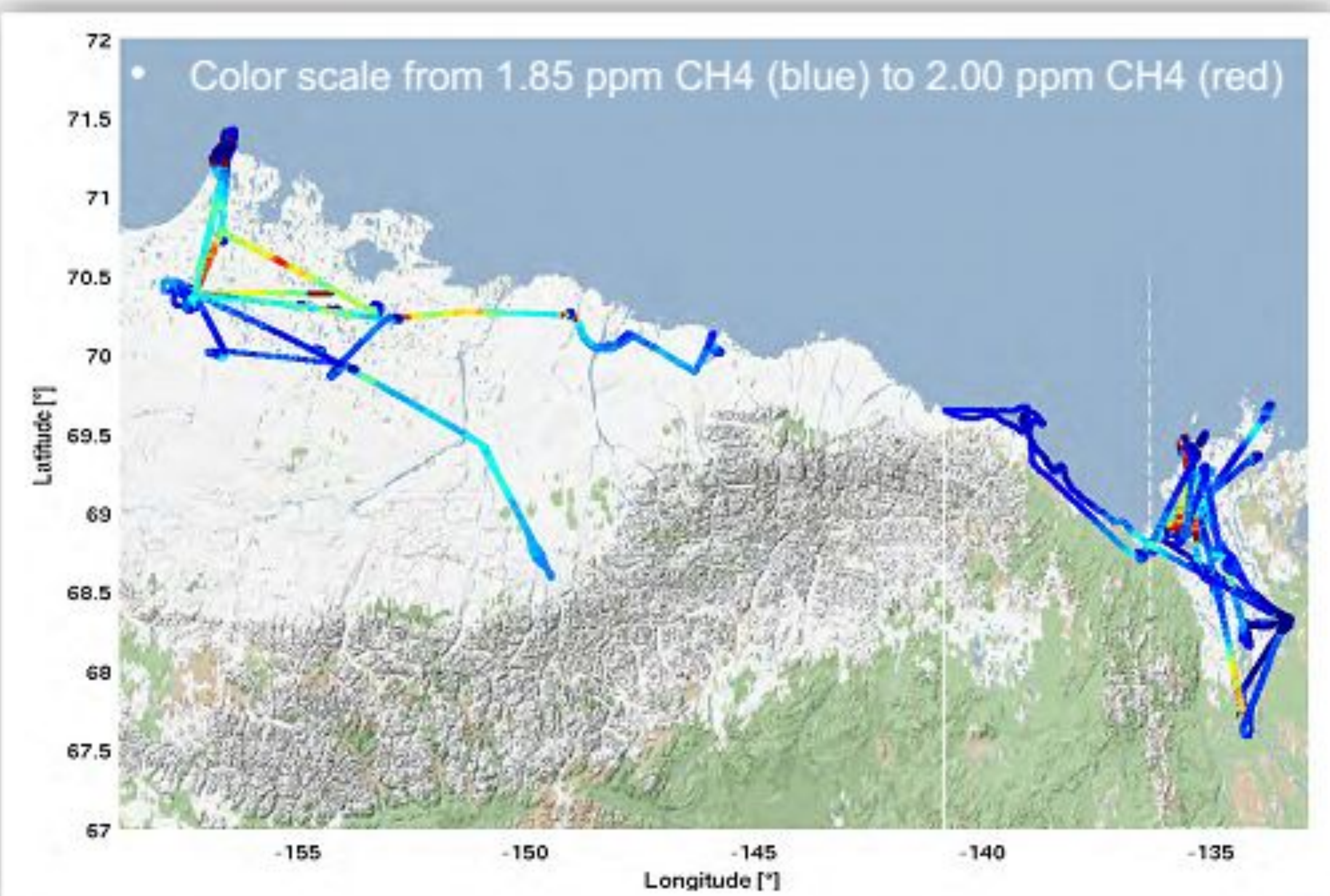


- Closing the gap:
  Airborne measurements of methane (AIRMETH)

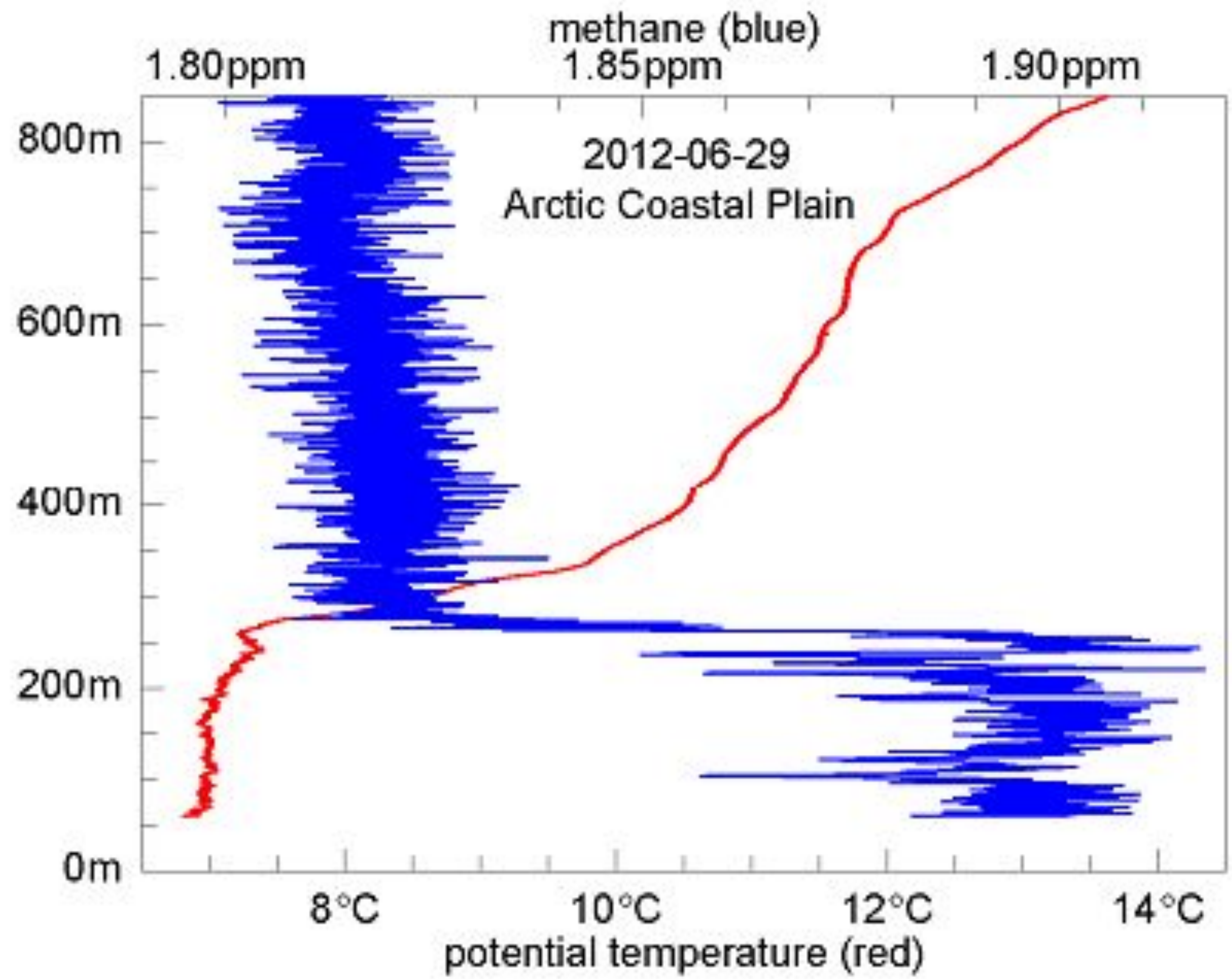
- Heterogeneity of sources and sinks:
  - Location biases?
  - Difficult to extrapolate
  - Requires high-resolution classifications + lots of data
  - Expensive and not feasible in large and remote areas

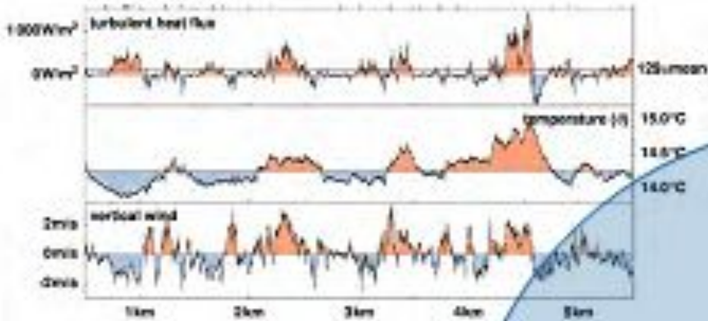
Airborne platforms

Study areas in Alaska and Canada 2012

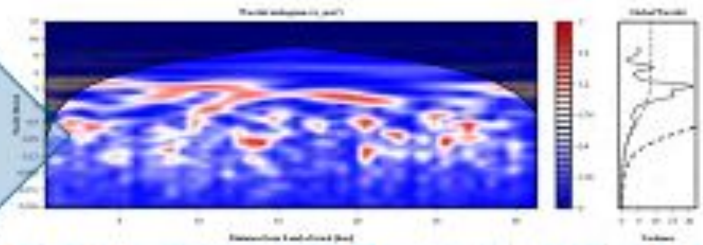


Profiles for boundary layer height





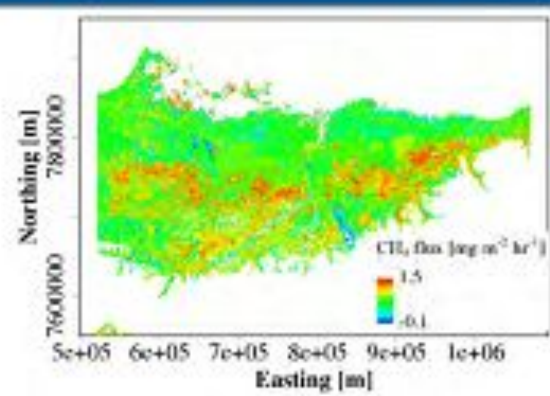
1. Low level flights
- 3D location, attitude, wind vector
- Temperature, pressure, humidity, CH4

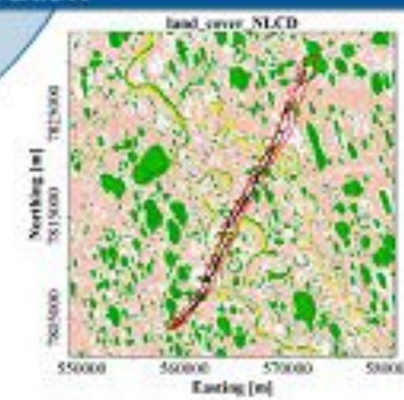


2. Time-frequency (wavelet) analysis
- Spatially resolved turbulence statistics
- Spatially resolved fluxes (H, LE, CH4)

4. Machine learning (BRT)
- In: Meteorology, surface properties
- Out: Environmental Response Function

3. Footprint modeling
- Spatially resolved contributions of land cover, LST, NDVI, EVI etc. to each flux observation



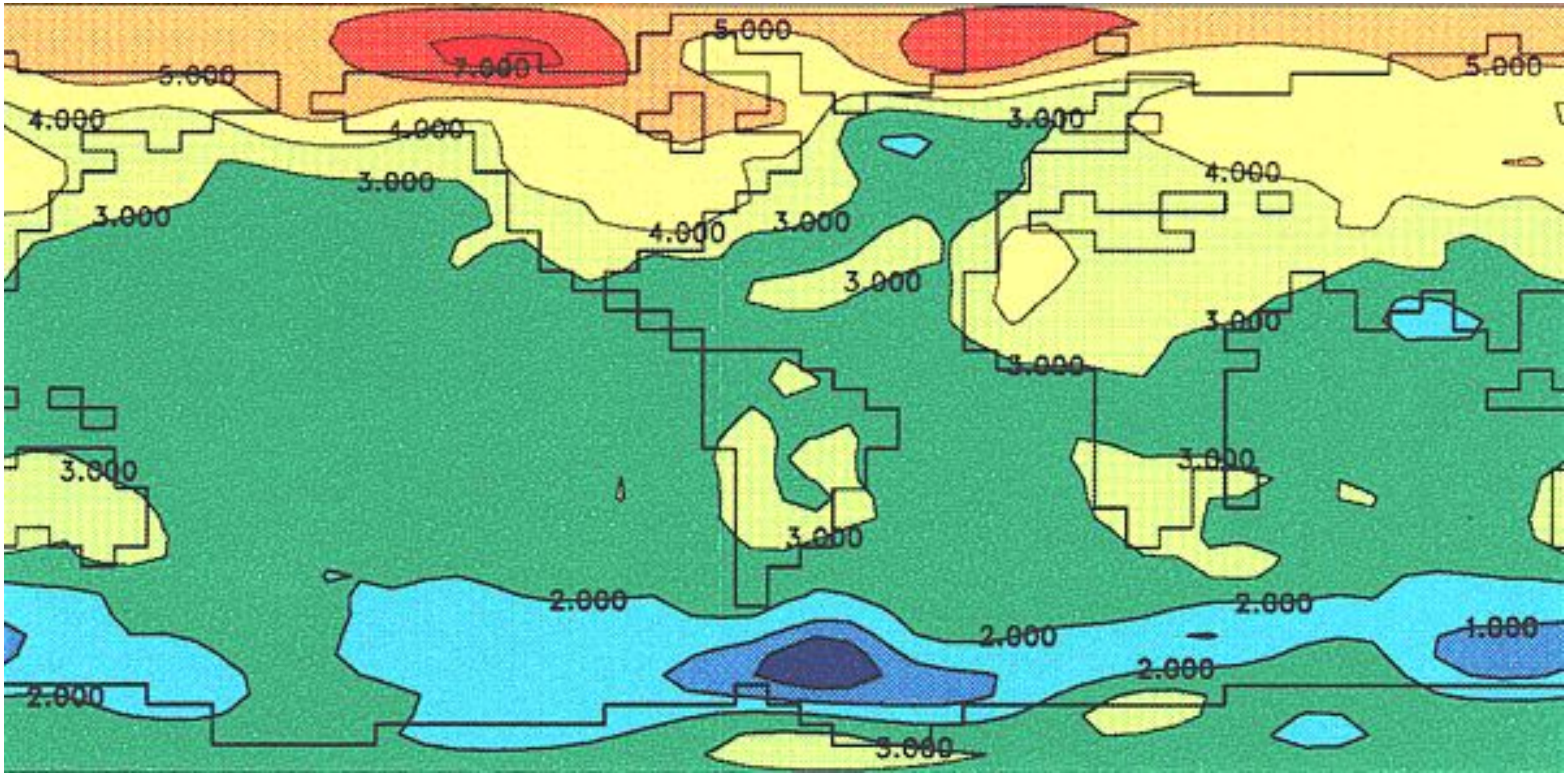


Questions

1. Why are CH_4 and N_2O more effective greenhouse gases than CO_2?
2. Which GHG are more important in permafrost ecosystems?
3. Do all aerosol particles lead to atmospheric cooling? Why?
4. The effect of warming will not be uniform everywhere. Why higher latitudes are more sensitive?
5. Describe all possible feedbacks of temperature increasing in continuous permafrost region.
6. If a gas (ore a substance) were found to have significant anthropogenic emissions, what would you want to know about it before assessing if it could be a greenhouse gas?

The degree of warming will not be uniform everywhere

higher latitudes are more sensitive



Source: IPCC