A Century of Arctic Climate Change: An Abisko Perspective

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200 km north of the Arctic Circle

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Abisko Scientific Research Station

Unique environmental record-meteorological monitoring (1913 to present)

Aerial Photo: Nils Åke Andersson, others by Keith Larson

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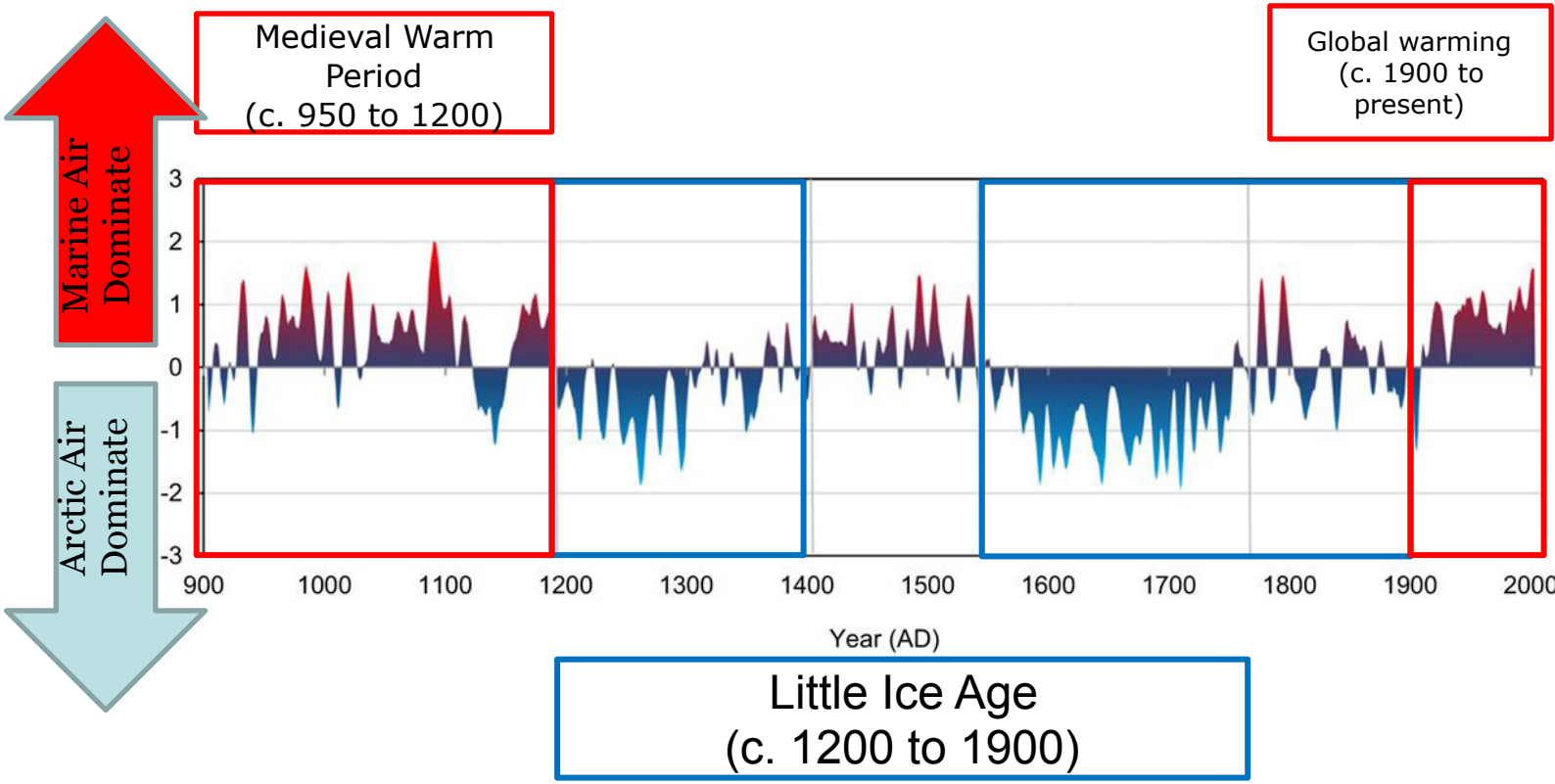
Abisko long-term climate regimes



No evidence for globally coherent warm and cold periods during the preindustrial era

Loader et al. 2013, Neukom et al. 2019

How do we know about the past climate before we built weather stations?

Photo: Scott Wilson

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Weather and climate is written is wood

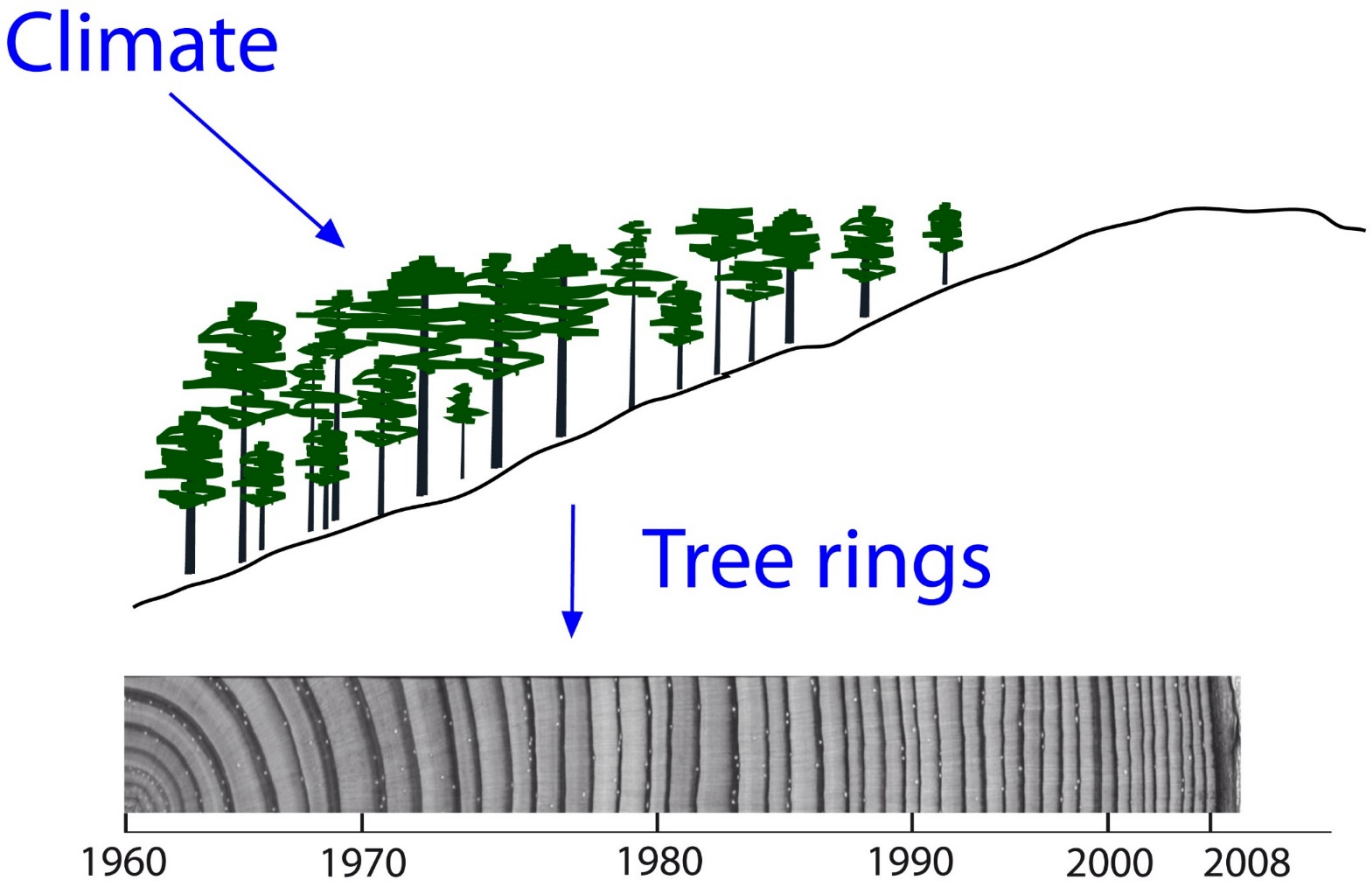

Photo: Håkan Grudd

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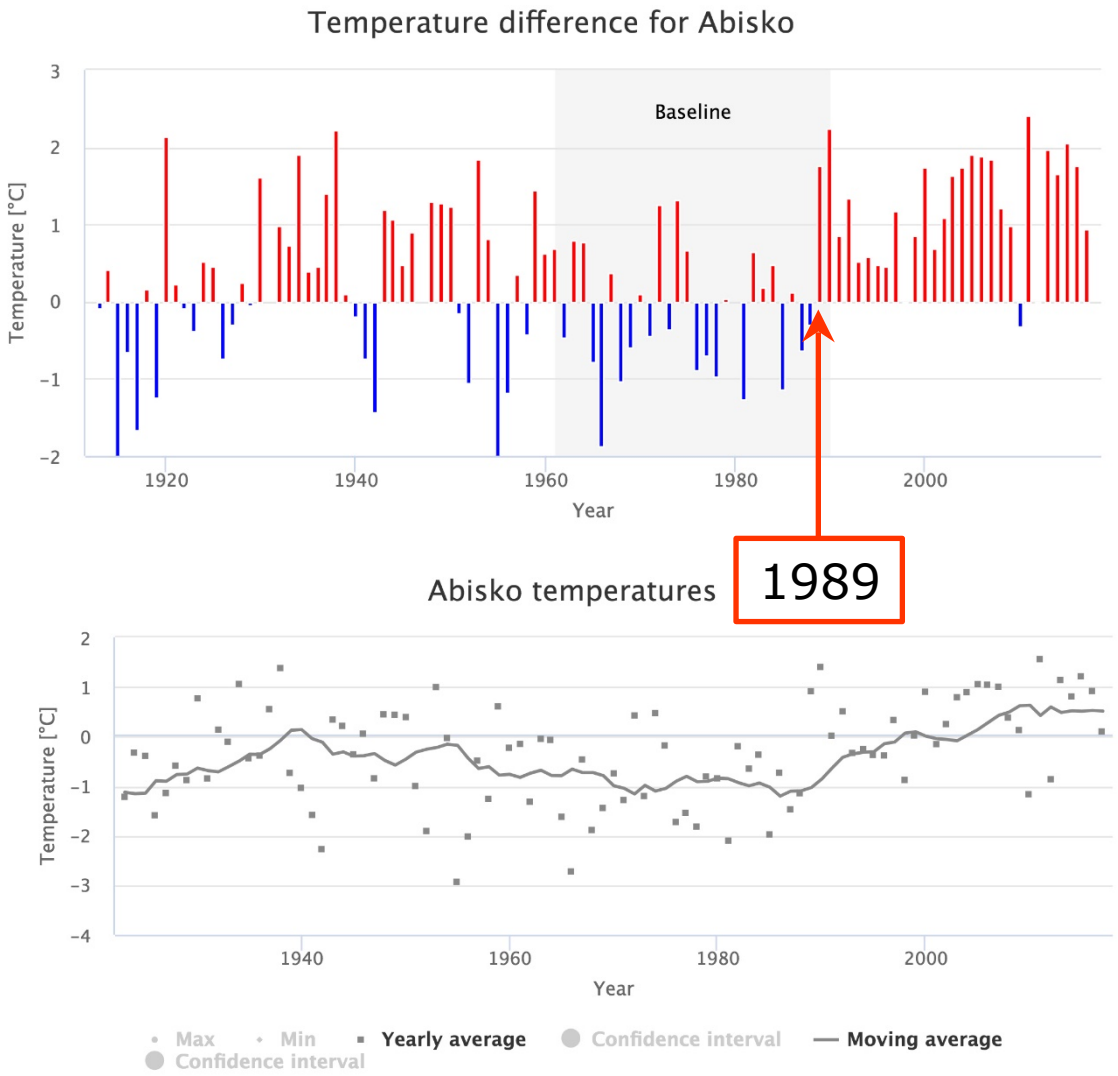
How far back can we go?

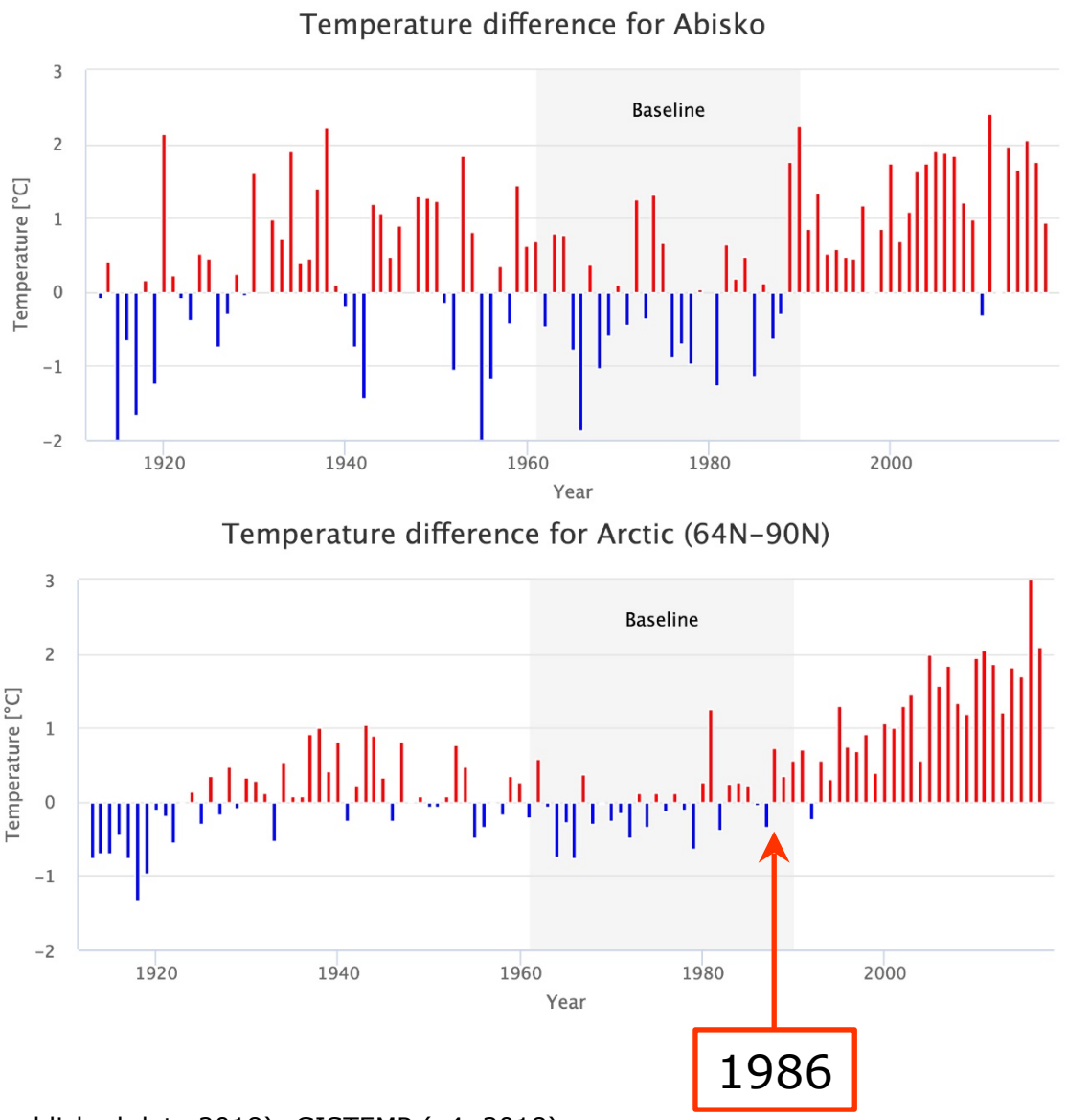
Photo: Håkan Grudd

Arctic warming



ANS (unpublished data 2018)

Arctic Warming



ANS (unpublished data 2018); GISTEMP (v4, 2018)

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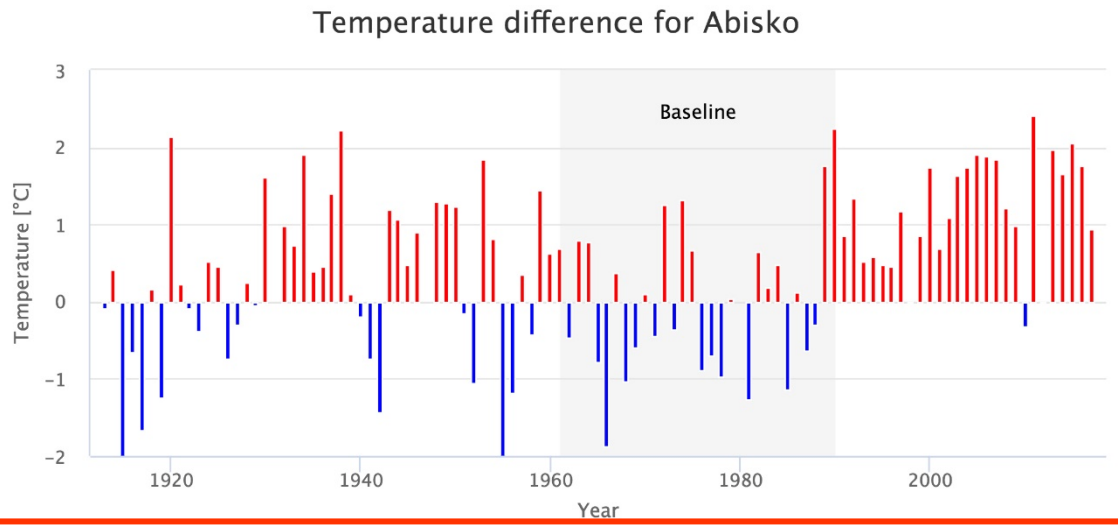
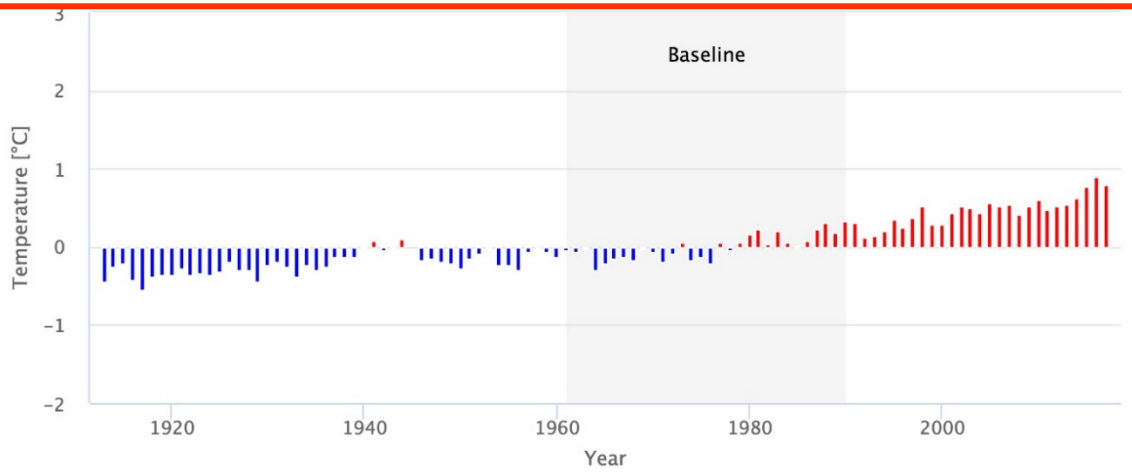
Arctic amplification



Arctic temperatures are rising at twice the global rate



ANS (unpublished data 2018); GISTEMP (v4, 2018)

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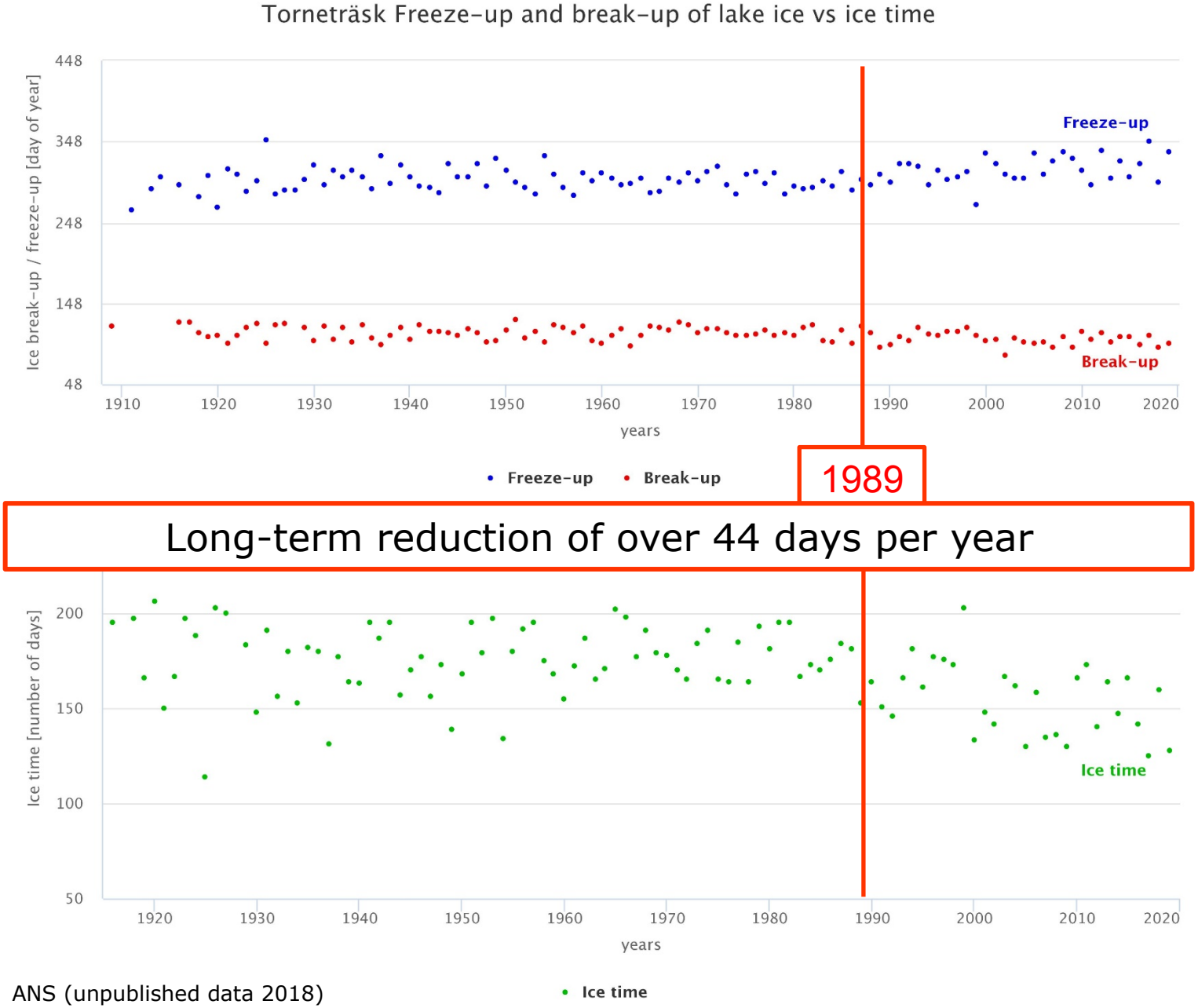
Torneträsk Ice Cover – Sweden's Sea Ice



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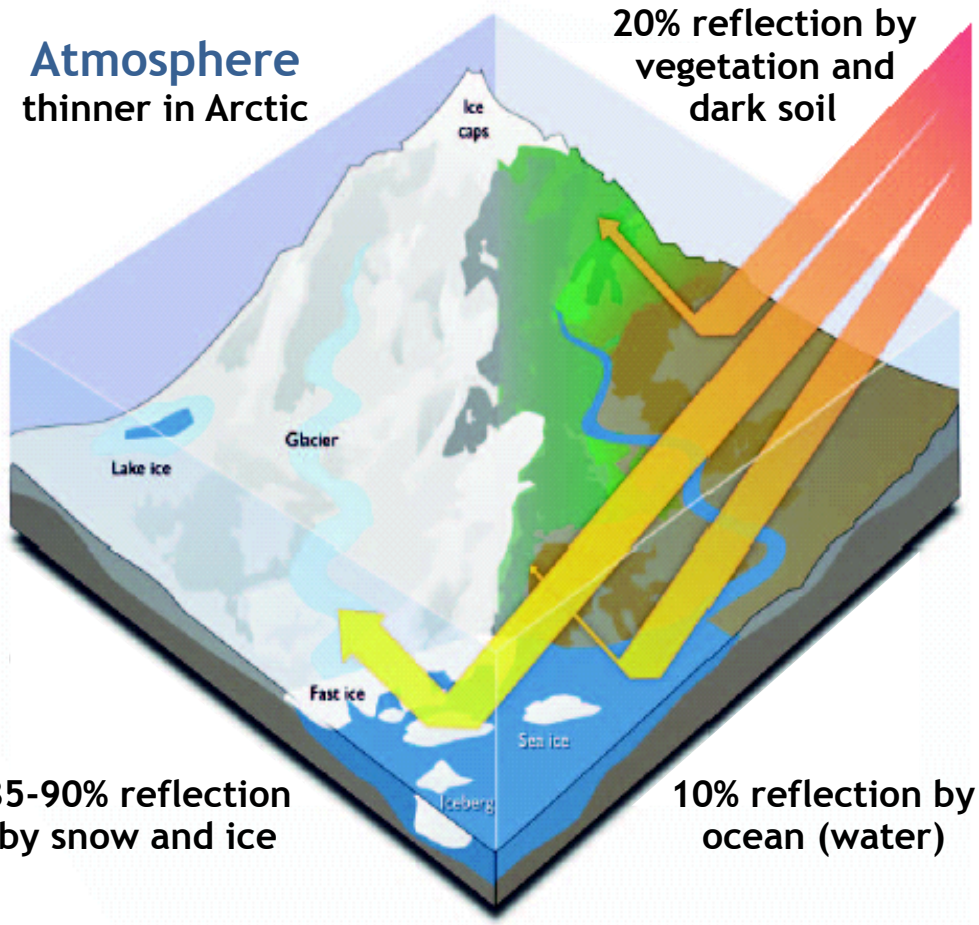
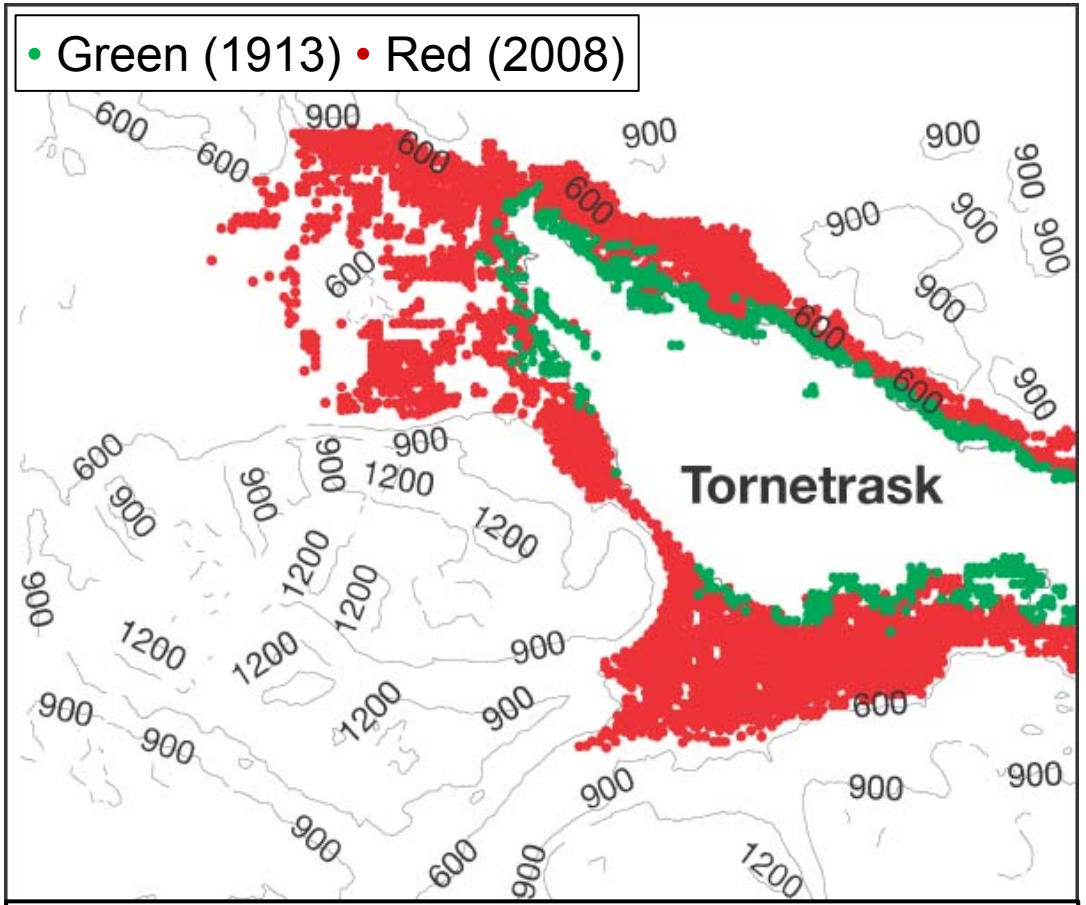
Accelerated warming of the Arctic



- Melting of snow and ice
- greater absorption of heat
- warming of thinner atmosphere
- Positive feedback!

Arctic Climate Impact Assessment (2004)

When is the warming occurring?



Comparison of the area around Abisko above 0°C mean annual temperature between 1913 and 2008.

Yang, Z., et al. *Met. Apps* **19,** 454–463 (2012)

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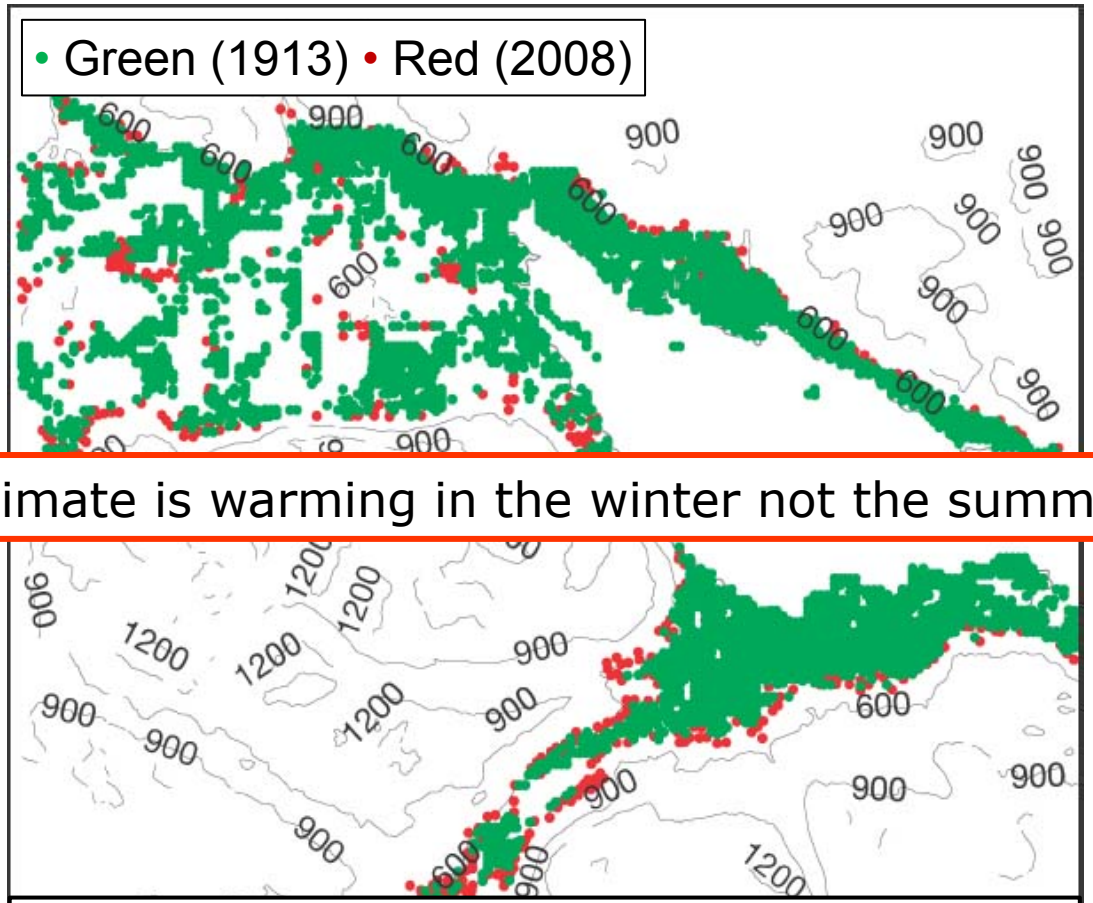
Warming across the year?

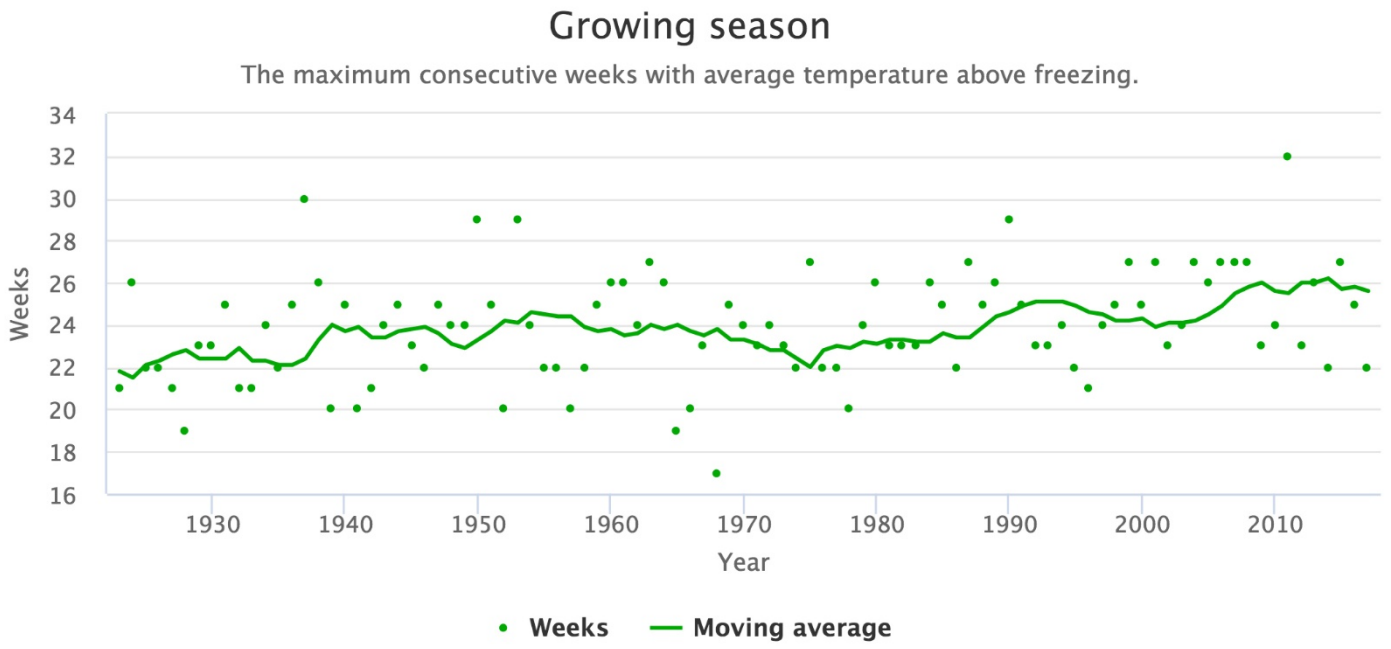


The climate is warming in the winter not the summer…

Comparison of the area around Abisko above 10°C in July (warmest month) between 1913 and 2008.

Yang, Z., et al. *Met. Apps* **19,** 454–463 (2012)

Growing season change from 1913 to 2017



4 weeks longer over the last 100 years

* Mean weekly temperature above 0°C (Körner 2012)

ANS (unpublished data 2018)

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Species shifting their distributions

Approximately 230 m, 30 m elev.

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How do climate changes impacts?

- natural climate gradients
  - temperature
  - precipitation
- experiments

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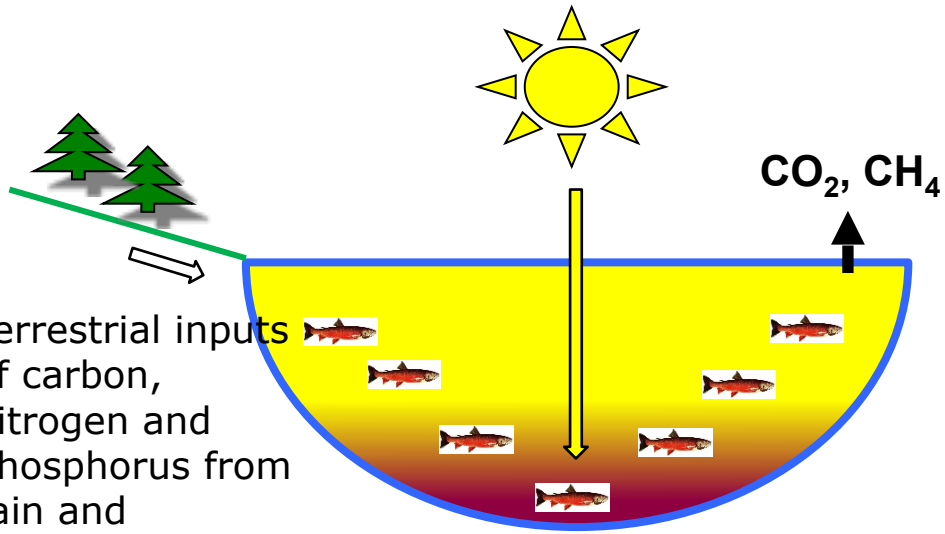
Case Study 1: Climate change induced regime shifts in northern lake ecosystems



Terrestrial inputs of carbon, nitrogen and phosphorus from rain and snowmelt runoff

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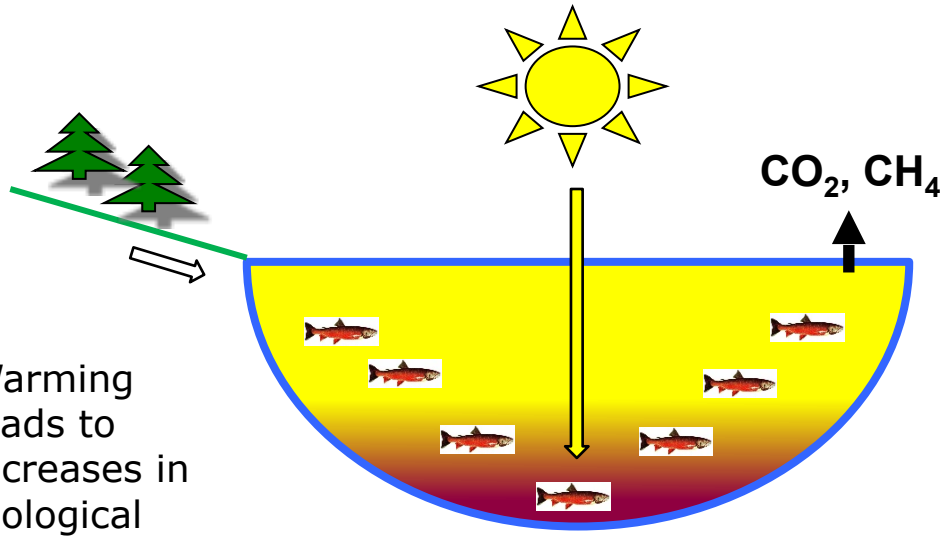
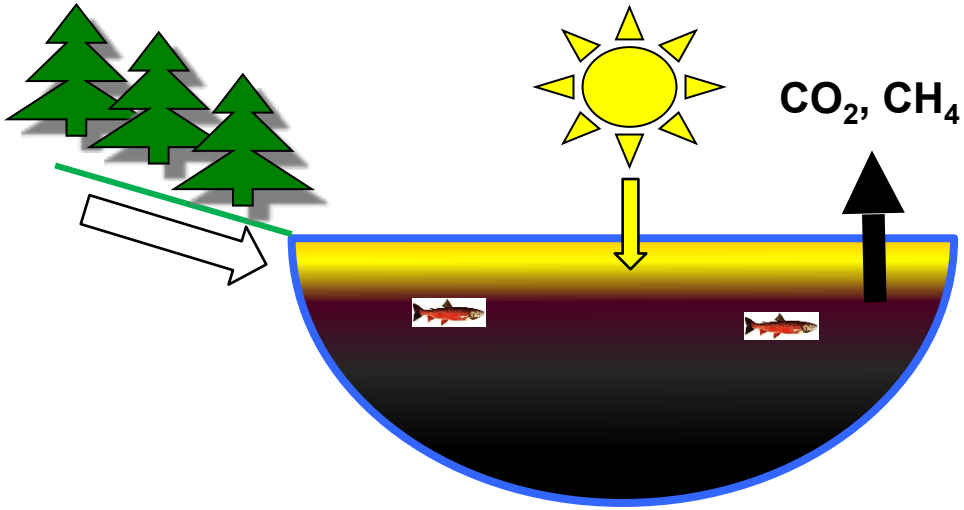
Results: Climate change induced regime shifts in northern lake ecosystems



Warming leads to increases in biological productivity



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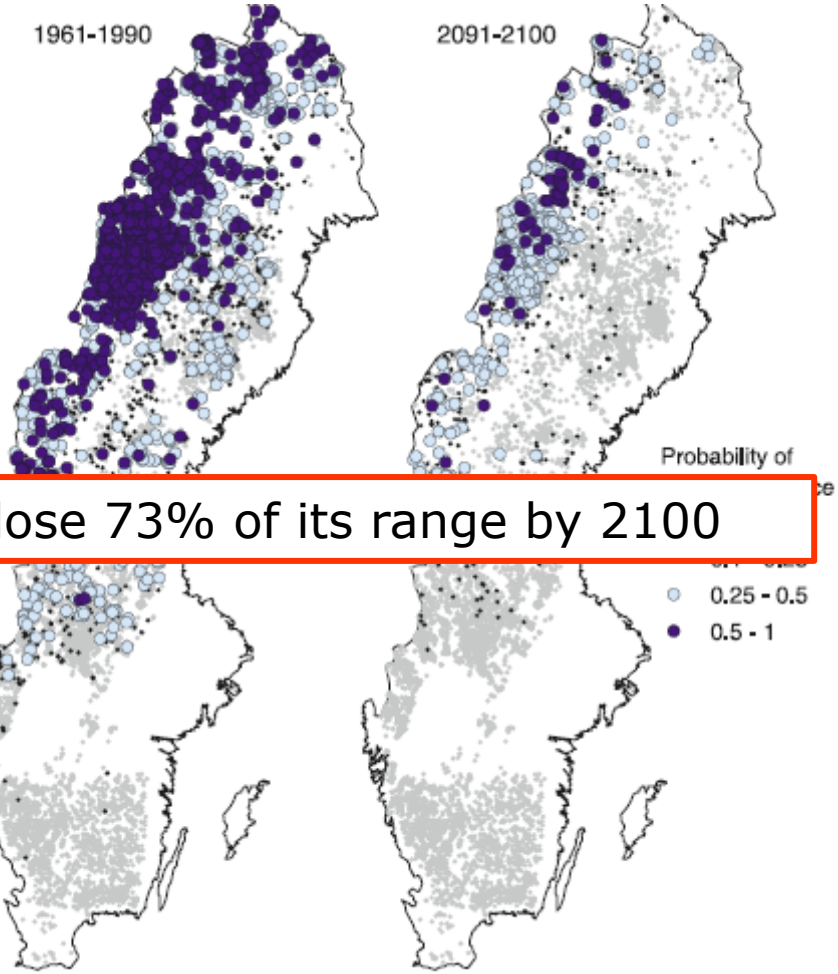
Results: Warming leads to changes in fish communities

Arctic Char
Röding
(*Salvelinus alpinus*)



Arctic char predicted to lose 73% of its range by 2100

Northern Pike
Gädda
(*Esox lucius*)

Hein et al. (2012)

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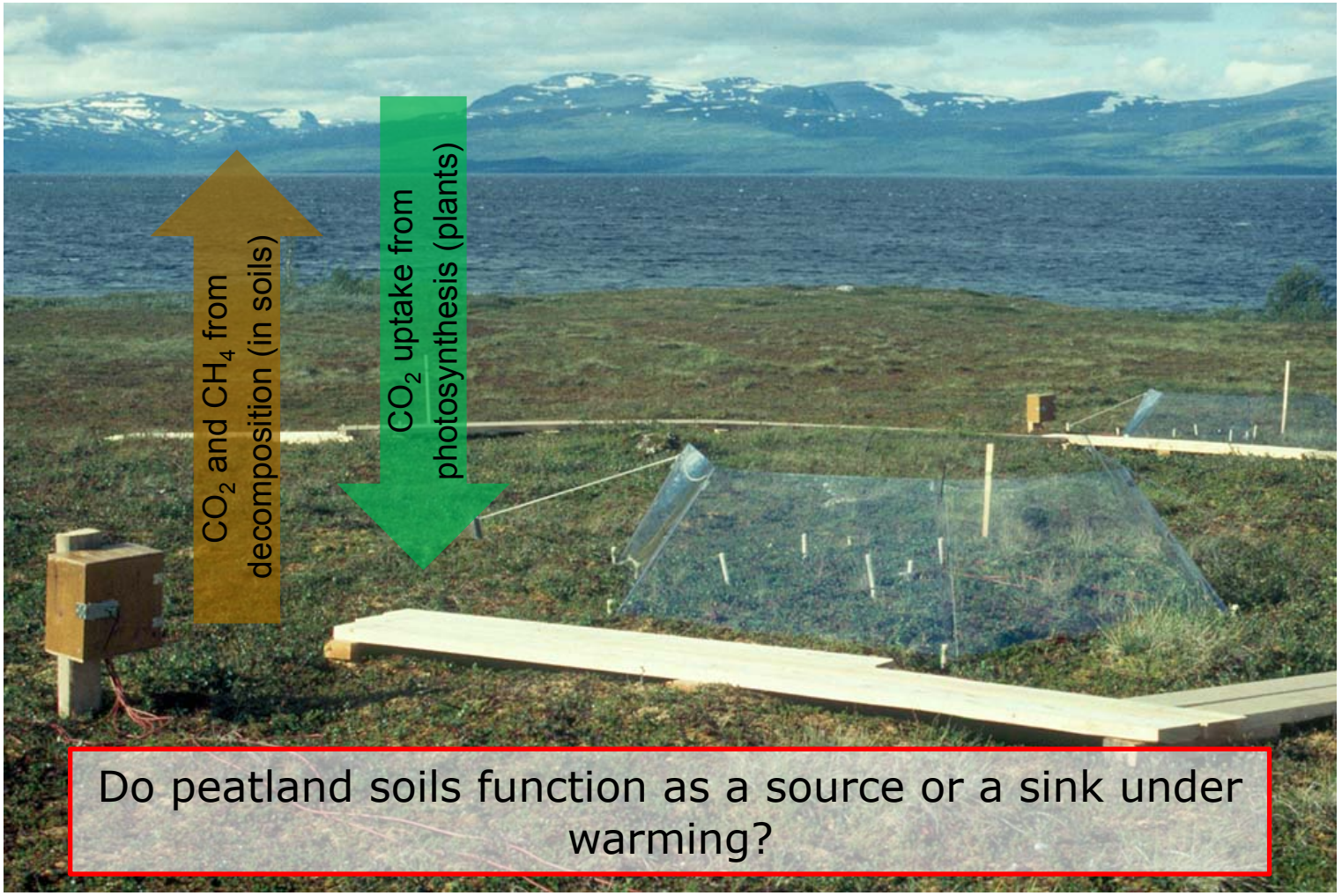
Experiment Study 1: How does increasing temperatures effect carbon emissions?



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How do open-top chambers work?

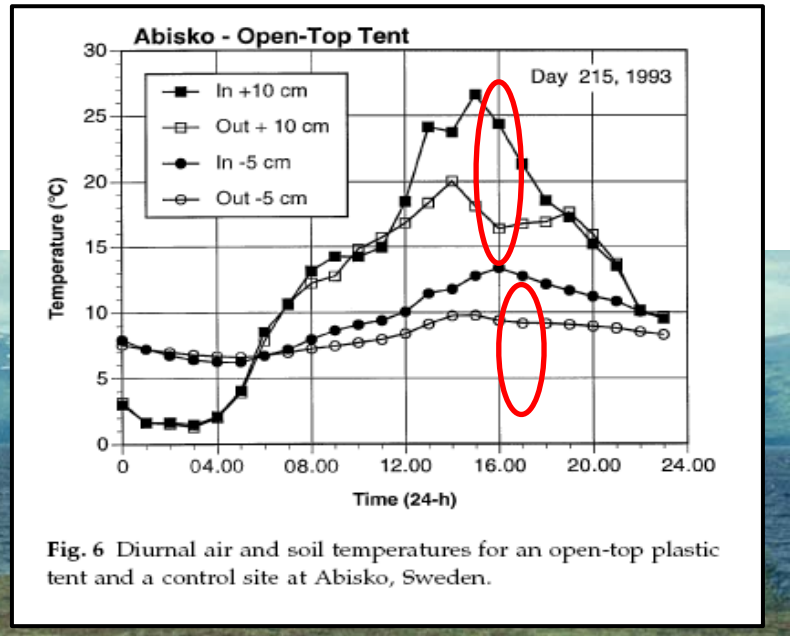

Fig. 6 Diurnal air and soil temperatures for an open-top plastic tent and a control site at Abisko, Sweden.

Passive warming

Trap solar radiation

Block wind

Air Temperature

Soil Temperature

Spring:
0.3-1.0˚C
Summer:
0.2-0.9˚C

Spring:
0.3-0.6˚C
Summer:
0.1-1.2˚C

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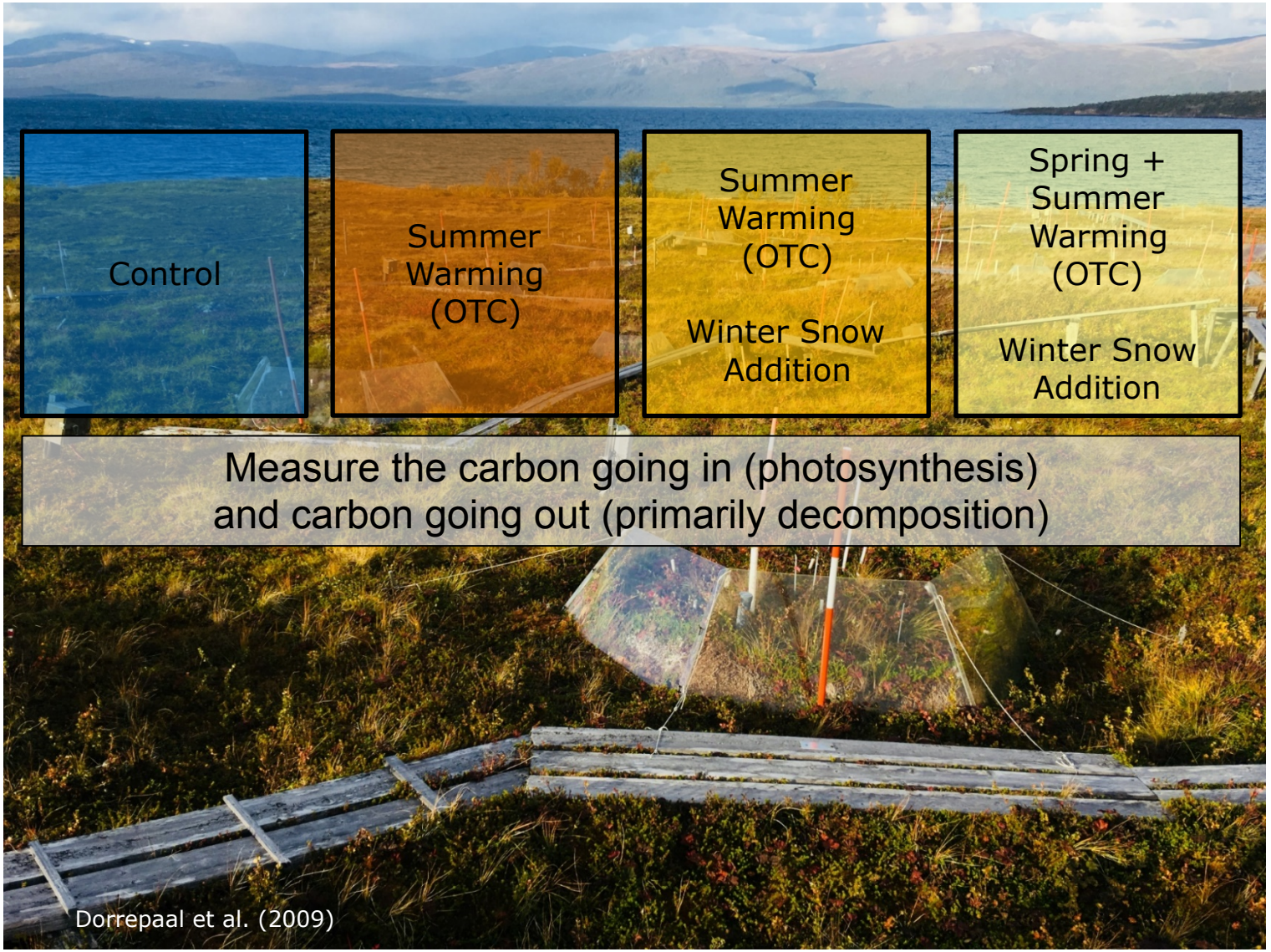
Experimental design



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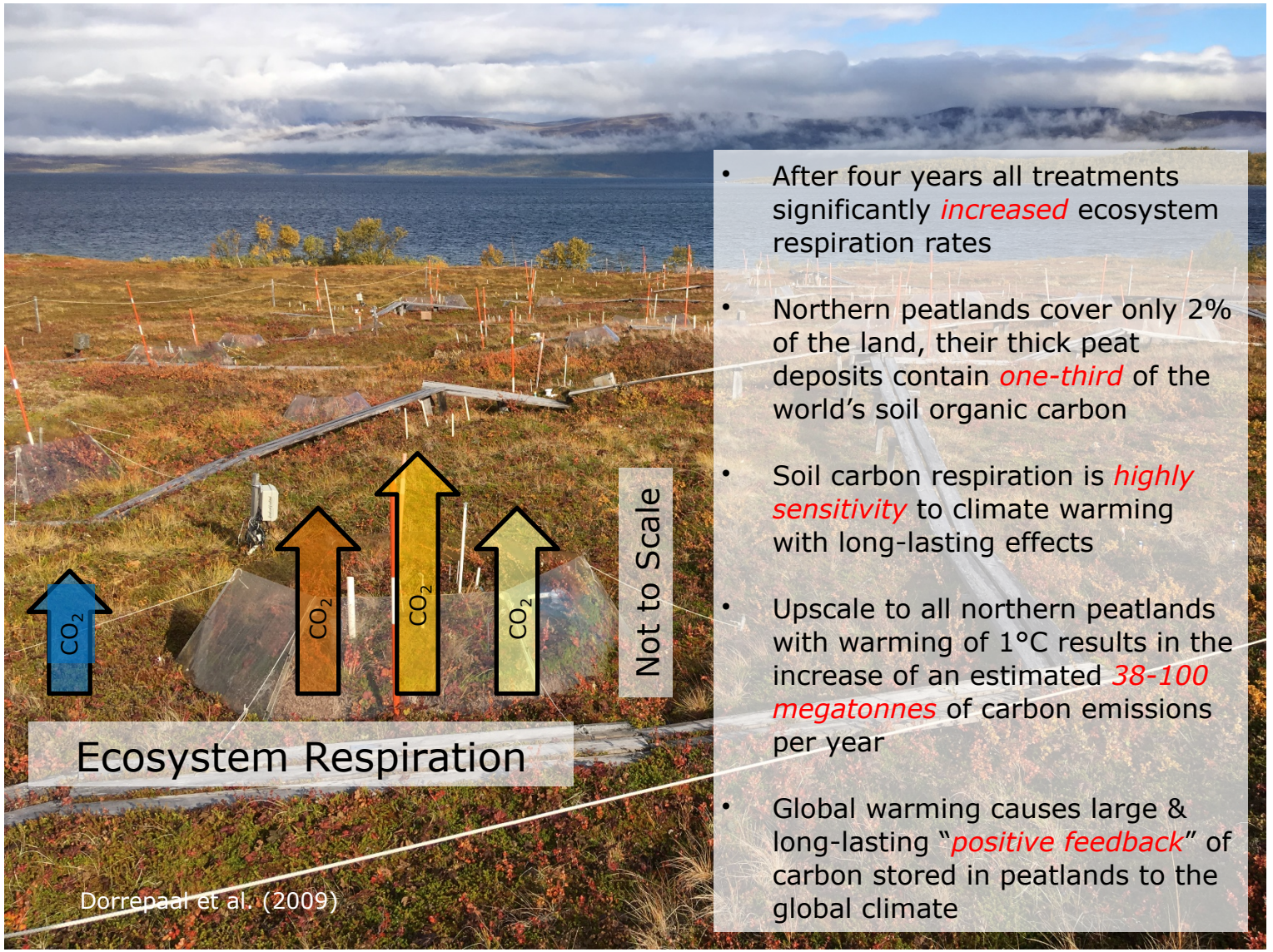
Results: Increased net ecosystem respiration



- After four years all treatments significantly *increased* ecosystem respiration rates
- Northern peatlands cover only 2% of the land, their thick peat deposits contain *one-third* of the world's soil organic carbon
- Soil carbon respiration is *highly sensitivity* to climate warming with long-lasting effects
- Upscale to all northern peatlands with warming of 1°C results in the increase of an estimated *38-100 megatonnes* of carbon emissions per year
- Global warming causes large & long-lasting "*positive feedback*" of carbon stored in peatlands to the global climate

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Experiment Study 2: Effects of increasing snow depth on permafrost

Aerial view of permafrost mire

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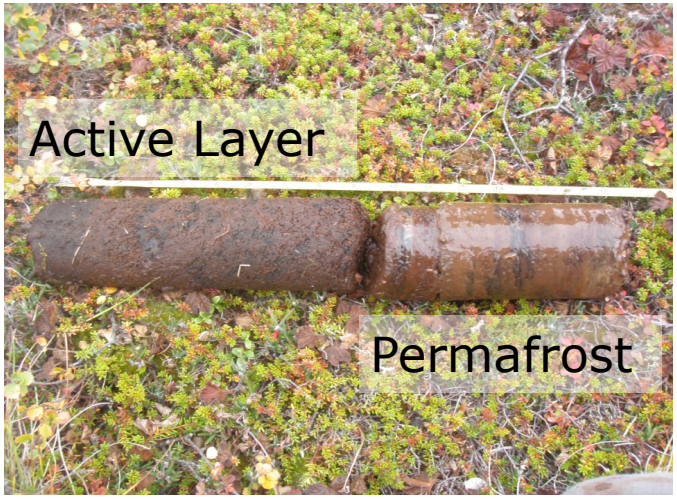
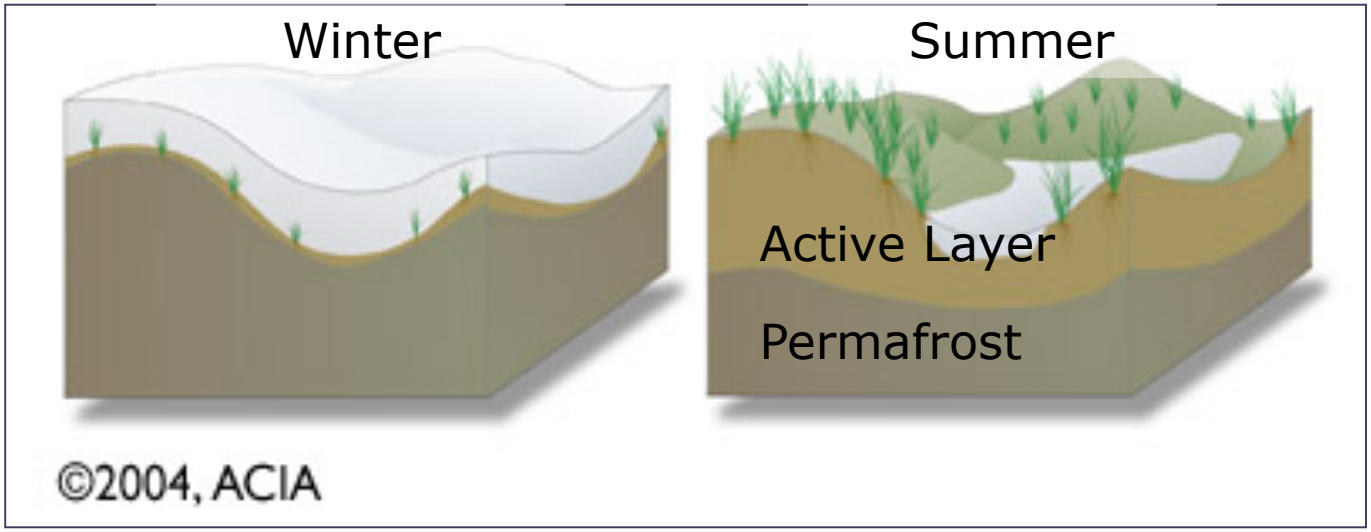
Active layer: the top layer of permafrost that thaws each year during the warm season and freezes again in winter





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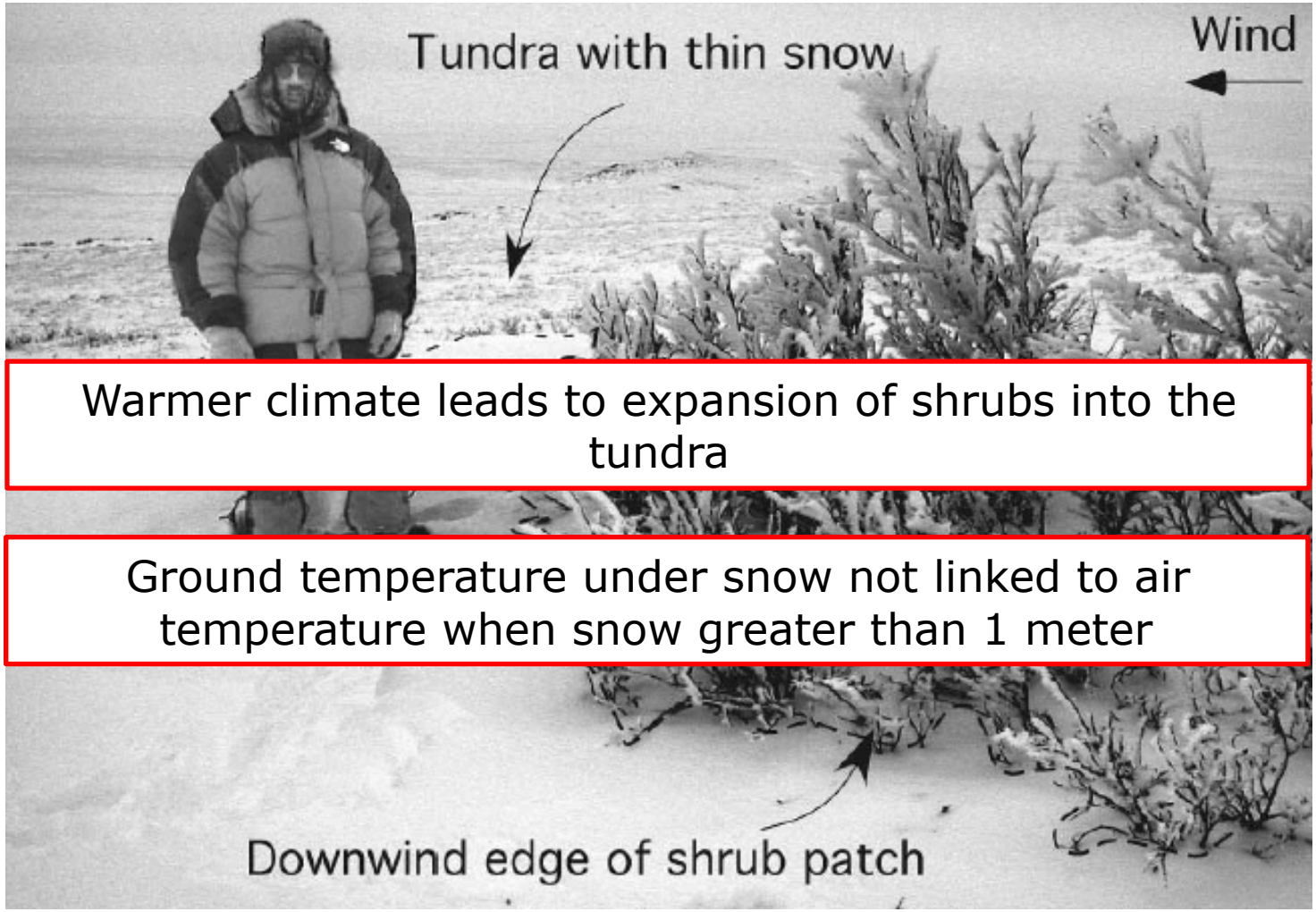
Warming increases biological productivity



Warmer climate leads to expansion of shrubs into the tundra

Ground temperature under snow not linked to air temperature when snow greater than 1 meter

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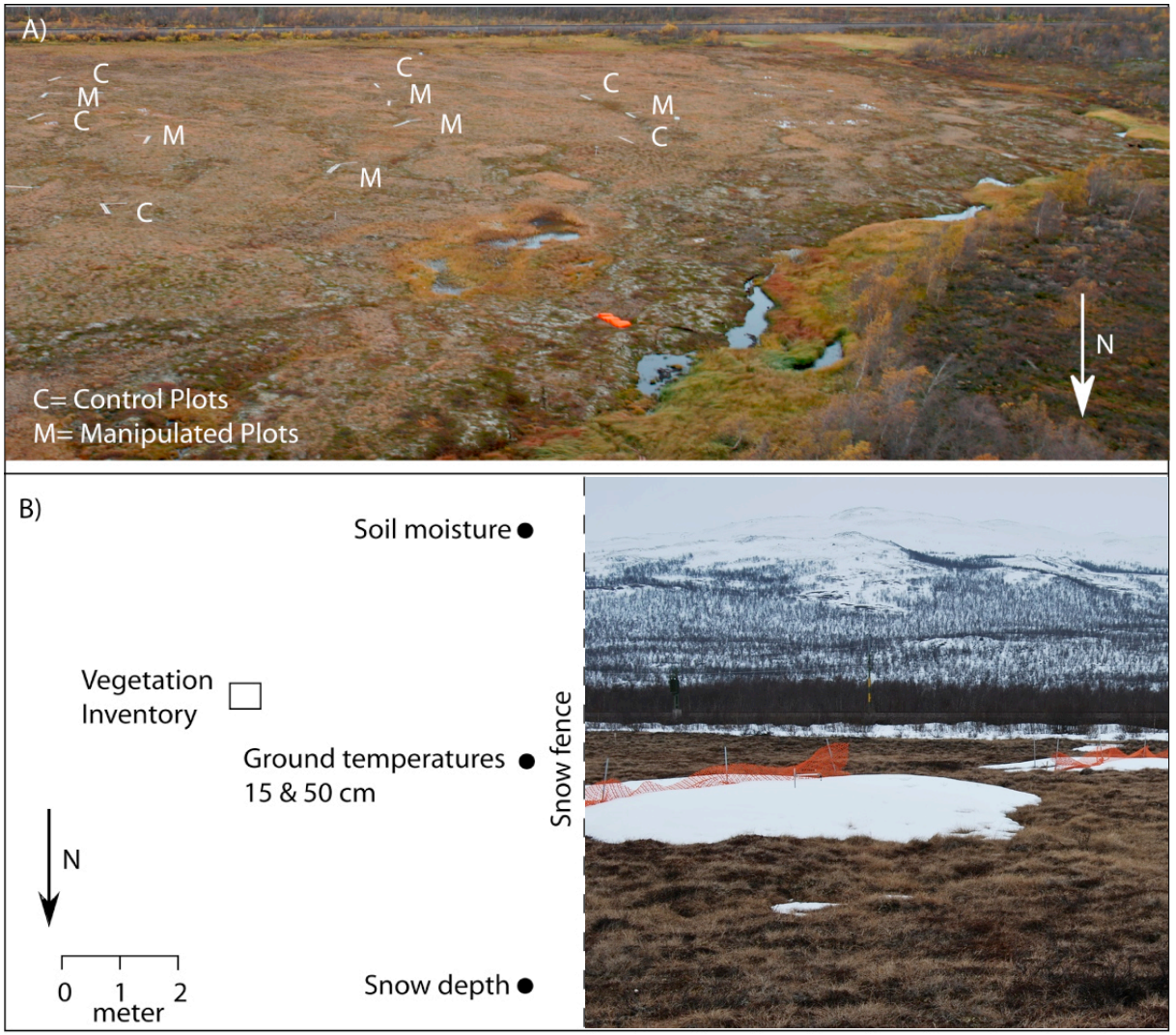
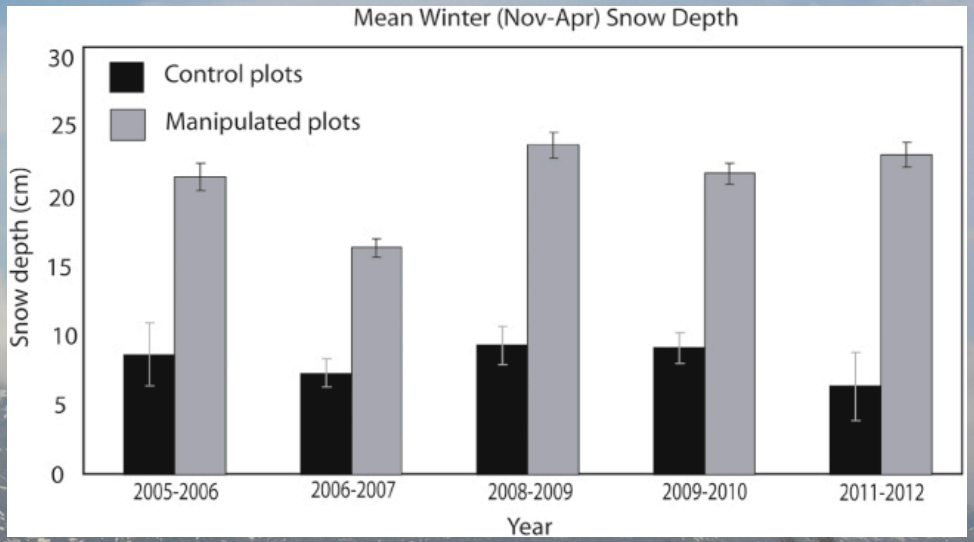
Snow fence experimental design



Johansson et al. (2013)

Snow depth increases



Johansson et al. (2013)

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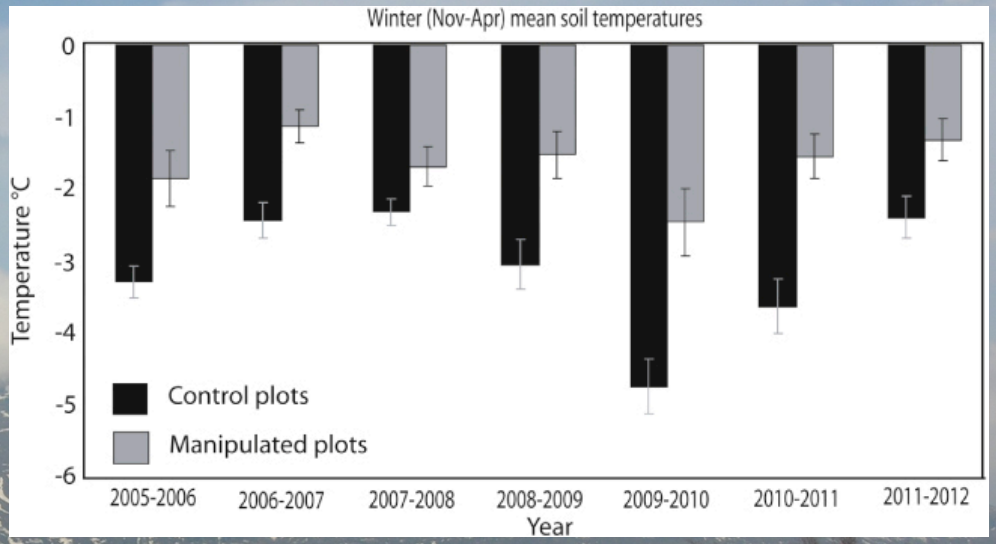
Below ground temperatures decreases



Below ground temperatures increased 1.5 C

Johansson et al. (2013)

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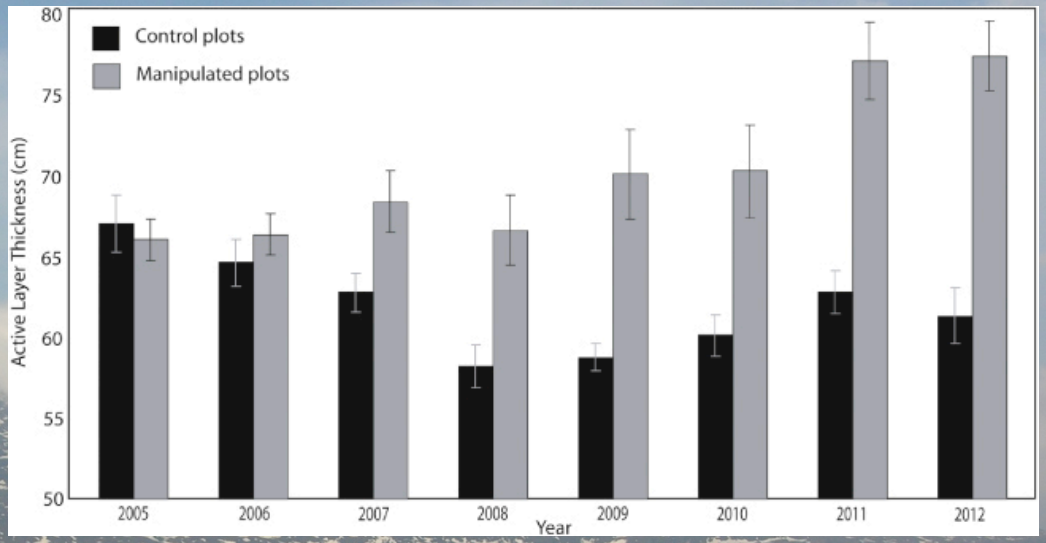
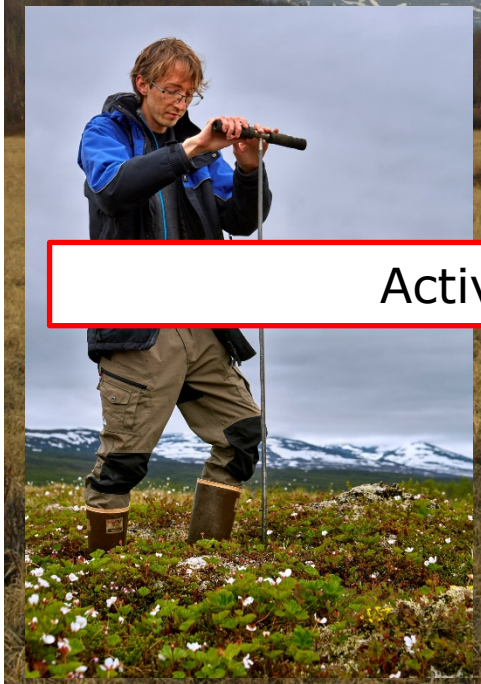
Active layer depth increases





Active layer depth increased 20%

Johansson et al. (2013)

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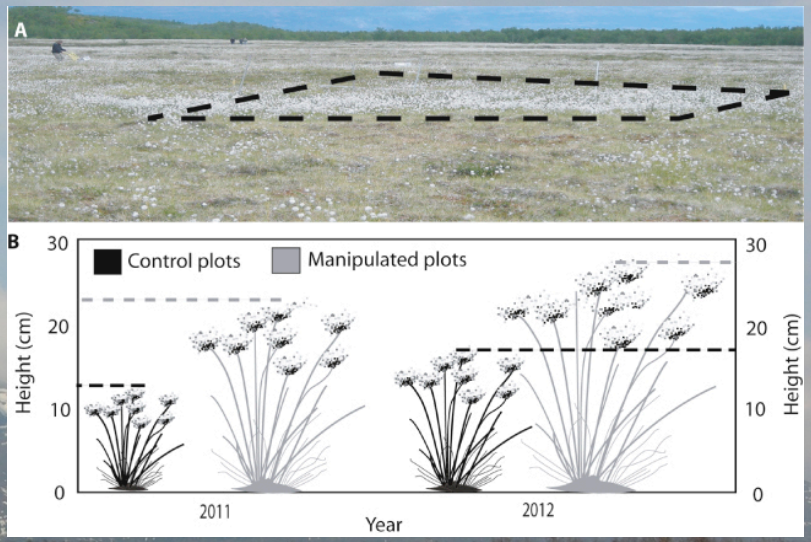
Increasing biological productivity



Johansson et al. (2013)

Surface subsidence leads to thaw ponds

Surface subsidence as much as 35 cm

Johansson et al. (2013)

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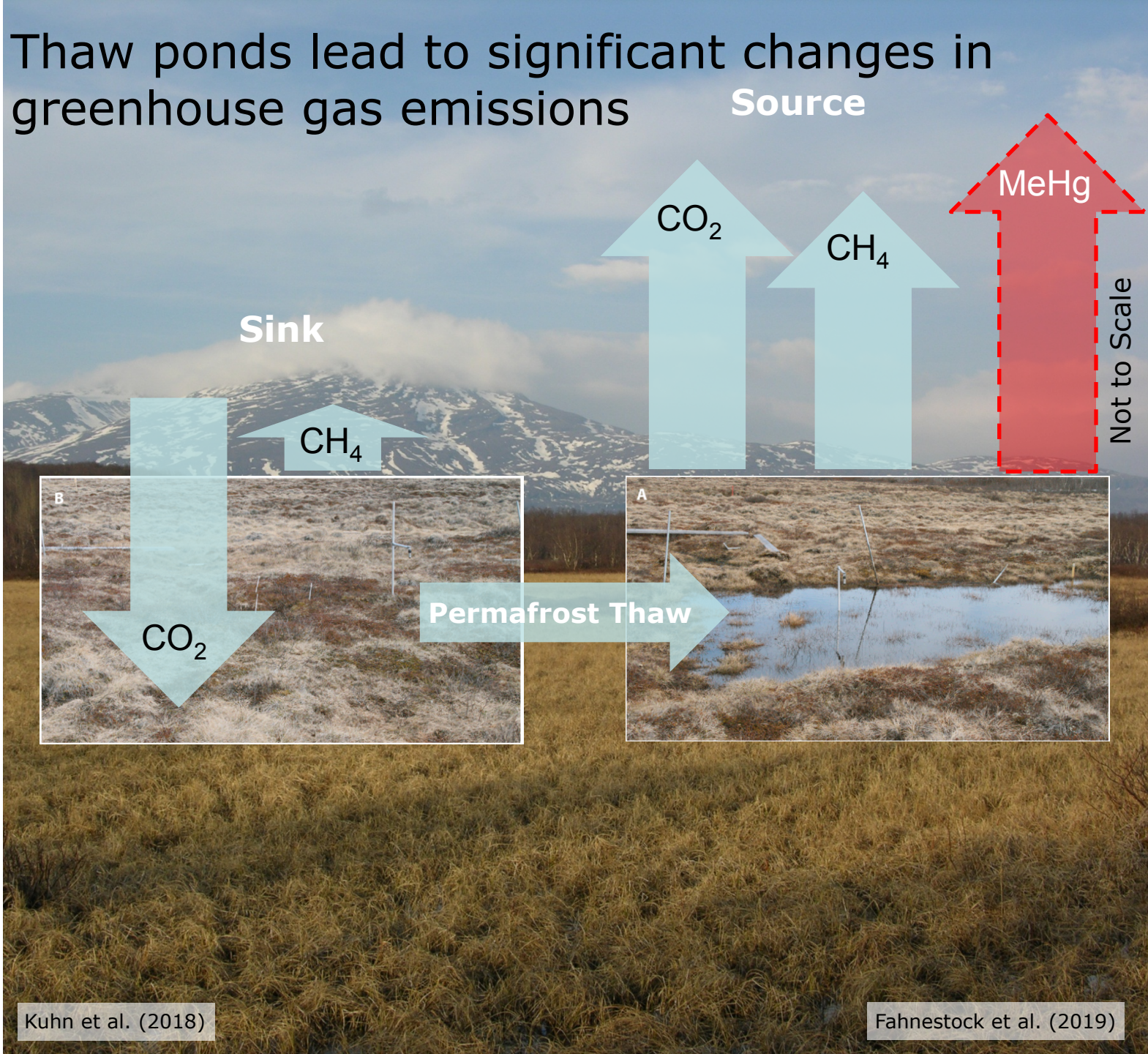
Thaw ponds lead to significant changes in greenhouse gas emissions



Kuhn et al. (2018)

Fahnestock et al. (2019)

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Feedbacks from the Arctic: Permafrost

24% of the terrestrial soils in the Northern Hemisphere or 12% globally

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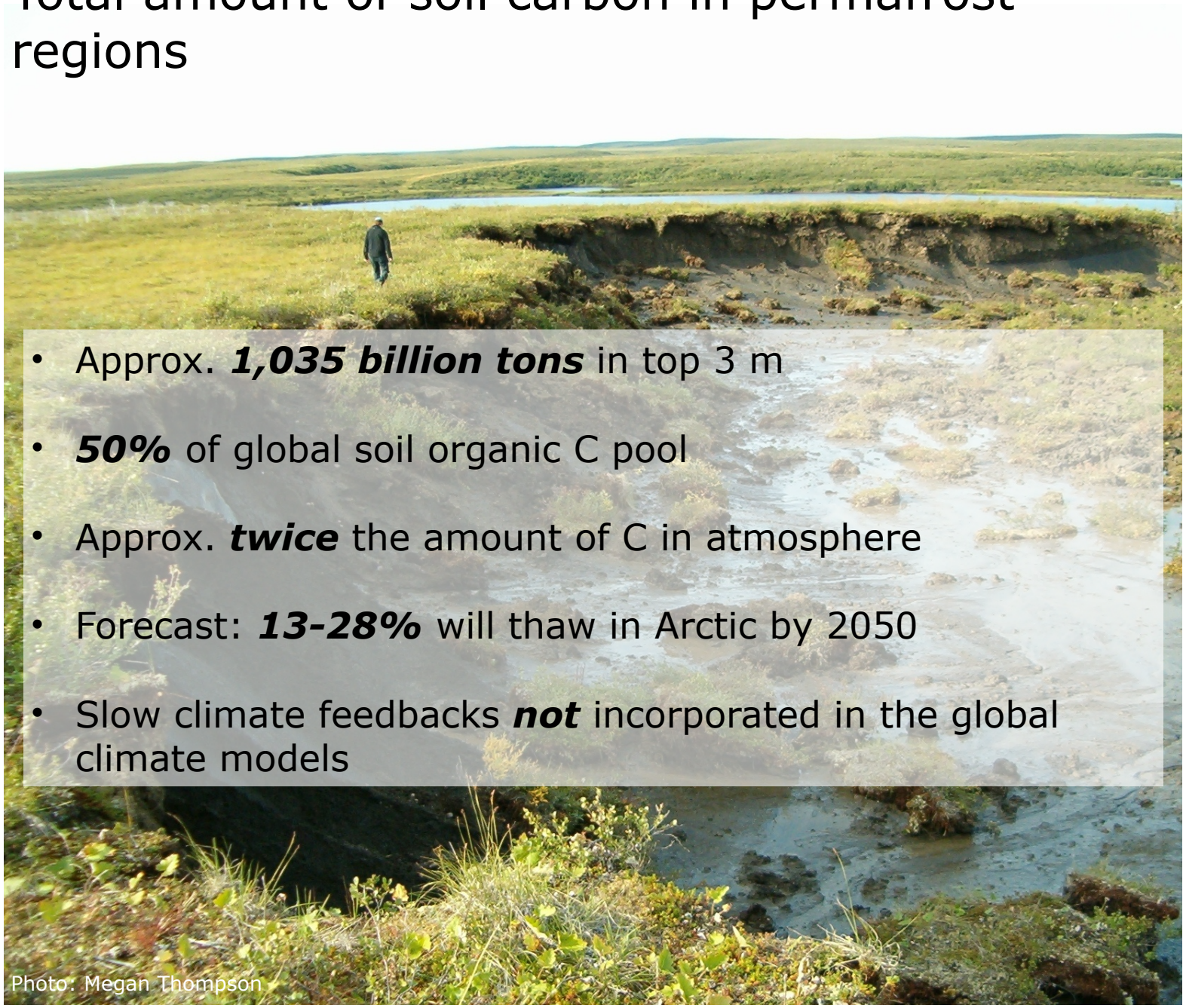
Total amount of soil carbon in permafrost regions



- Approx. ***1,035 billion tons*** in top 3 m
- ***50%*** of global soil organic C pool
- Approx. ***twice*** the amount of C in atmosphere
- Forecast: ***13-28%*** will thaw in Arctic by 2050
- Slow climate feedbacks ***not*** incorporated in the global climate models

Photo: Megan Thompson

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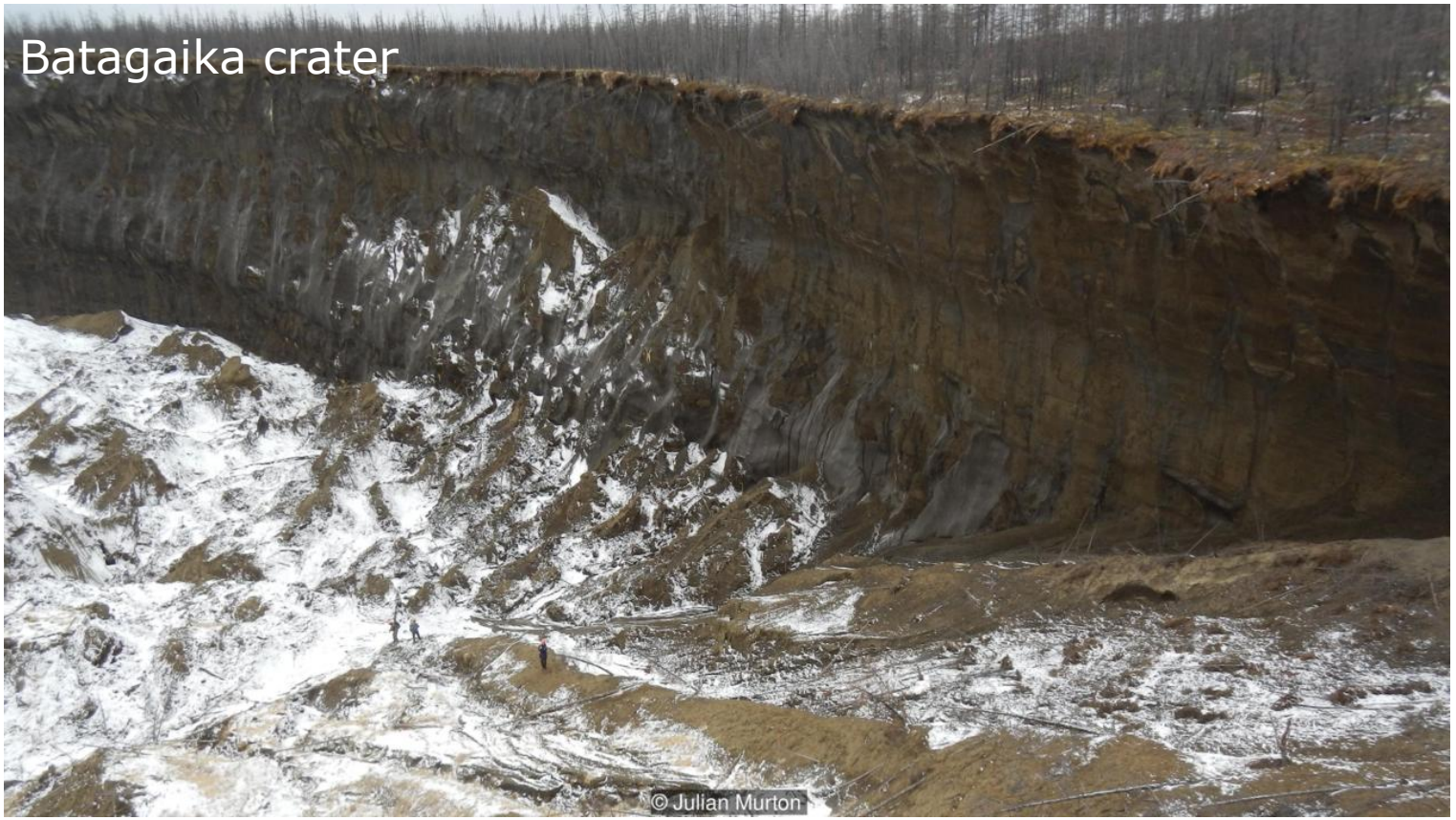
Permafrost crater in Siberia



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Permafrost crater in Siberia

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The Arctic region gives off more heat to space than it absorbs from outside, which helps cool the planet.

The Arctic functions as the earth's cooling system

Changes in the Arctic climate are significant globally!

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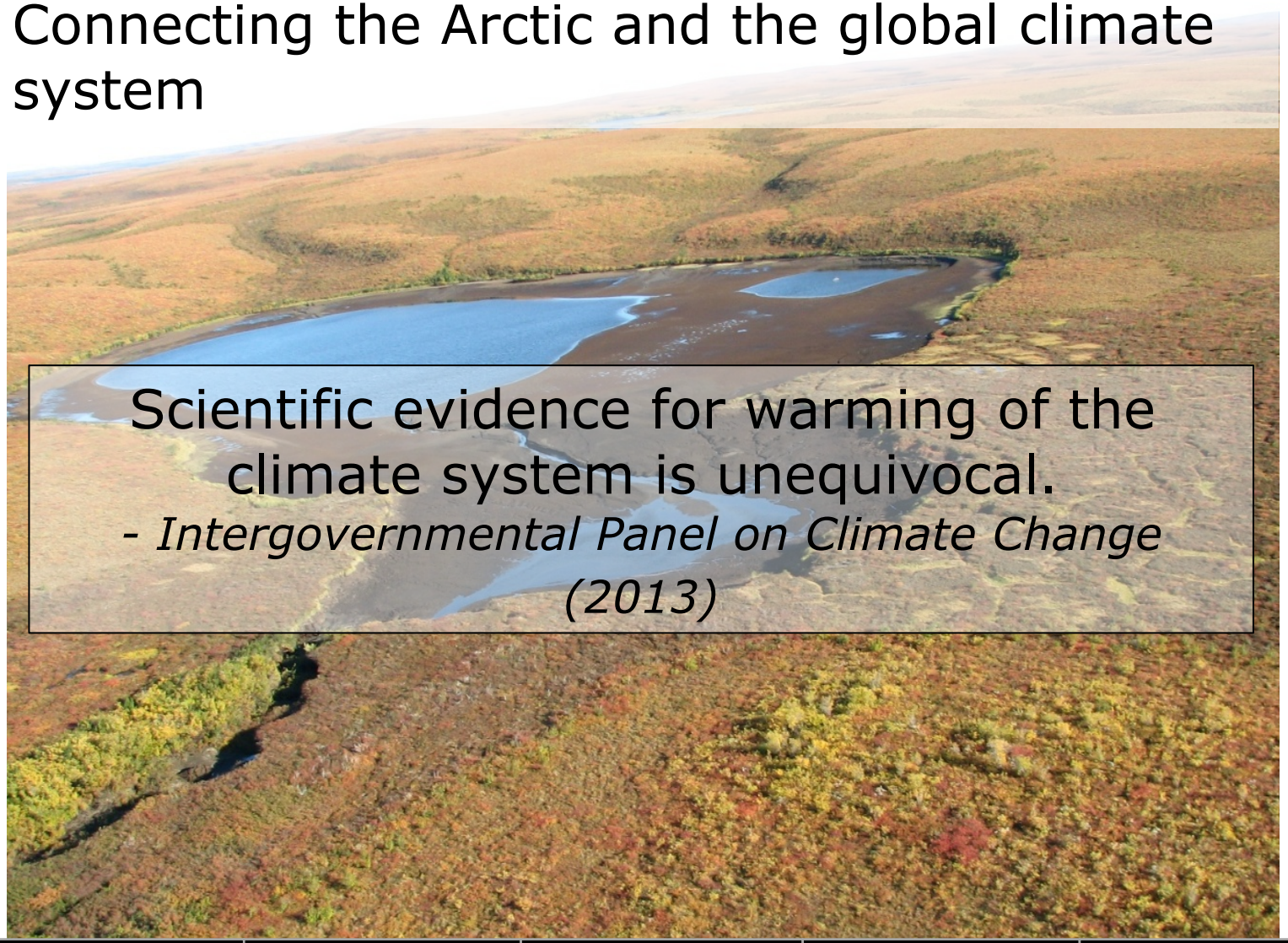
Connecting the Arctic and the global climate system

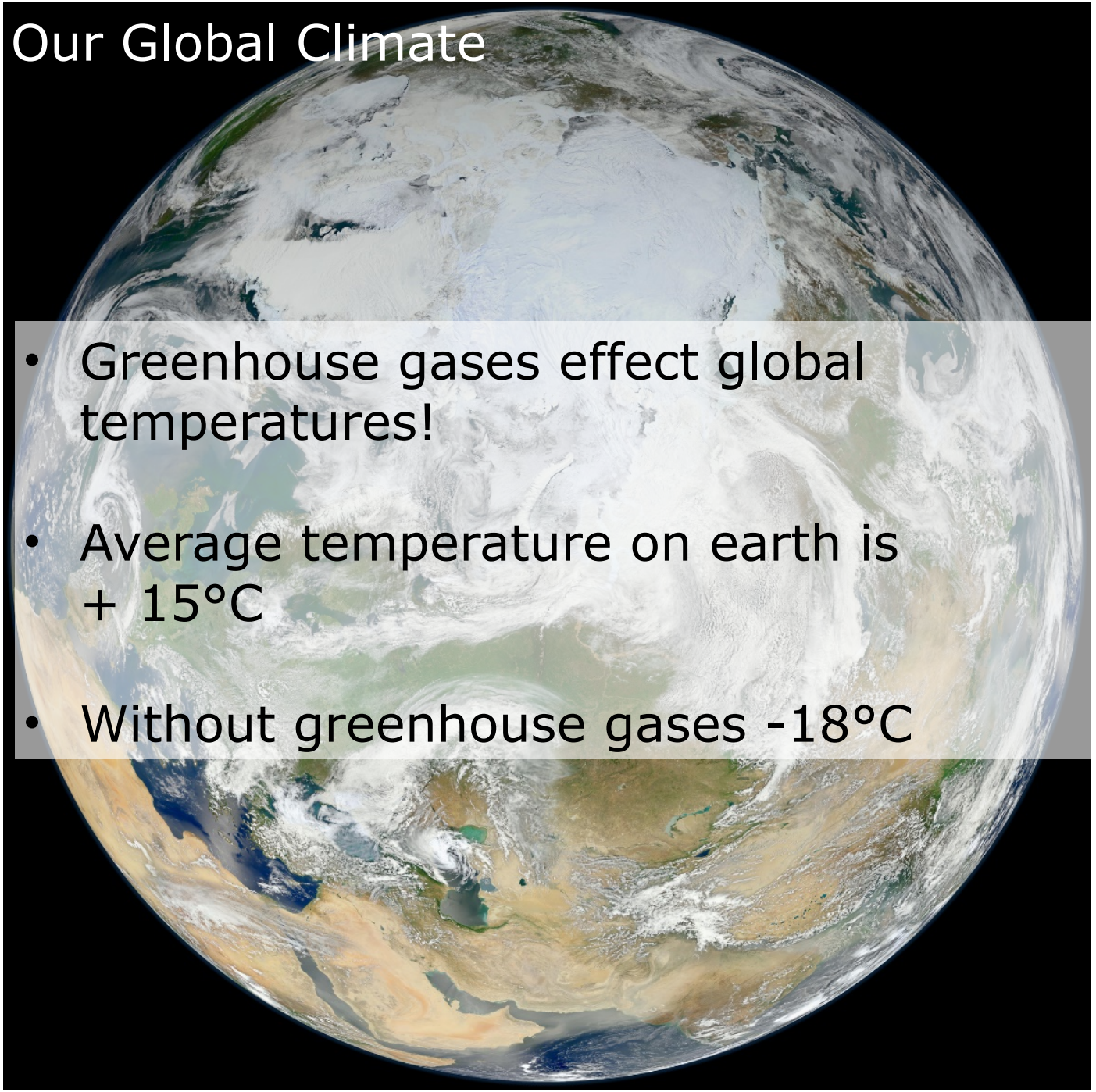


Scientific evidence for warming of the climate system is unequivocal.

- Intergovernmental Panel on Climate Change (2013)

Carbon Dioxide	Global Temperature	Arctic Temperature	Arctic Ice Minimum	Ice Sheets	Sea Level
↑411.7	↑1.1 °C	↑1.8°C	↓12.8	↓413.0	↑3.3
Parts per million	Since 1880	Last 30 years	Percent per decade	Gigetonnes per year	mm per year

Our Global Climate



- Greenhouse gases effect global temperatures!
- Average temperature on earth is + 15°C
- Without greenhouse gases -18°C

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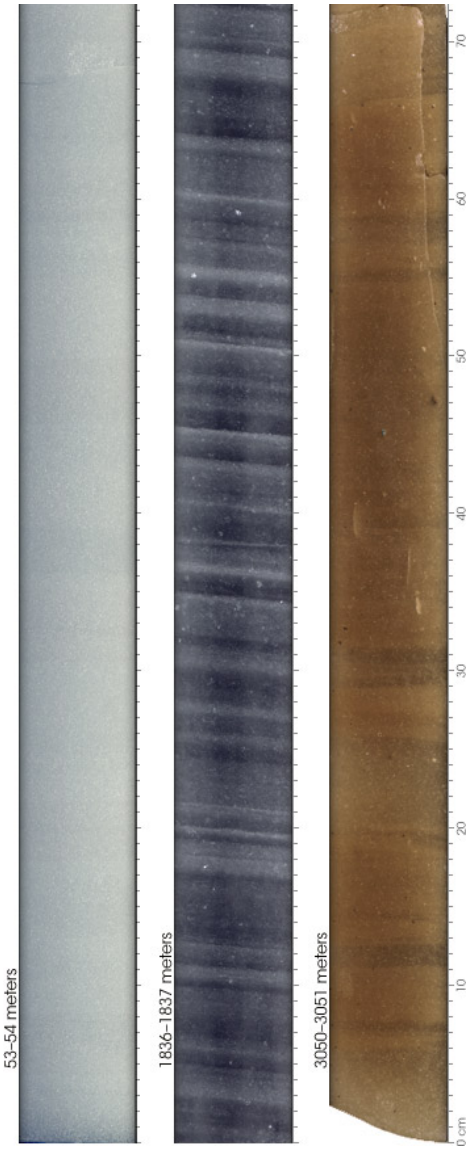
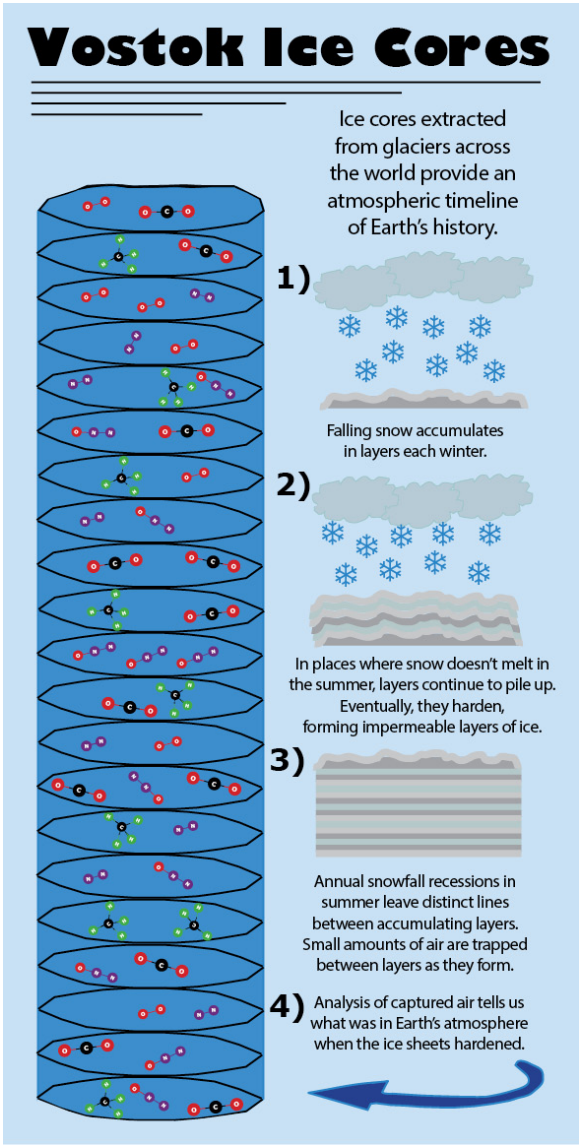
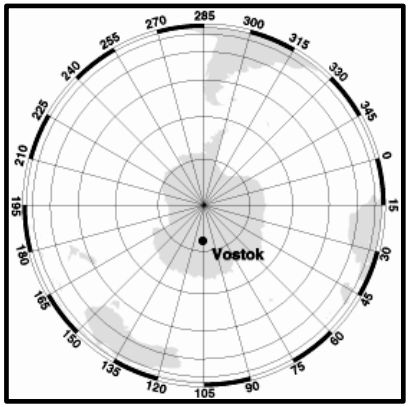
How do we understand past climate changes?

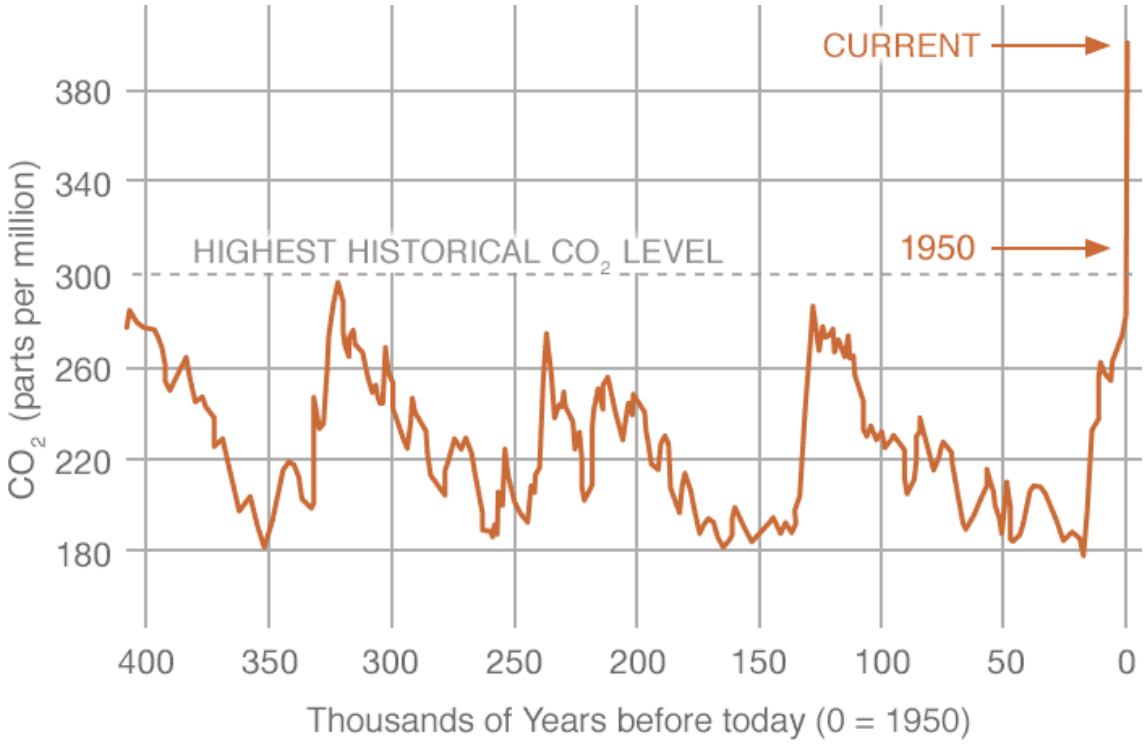


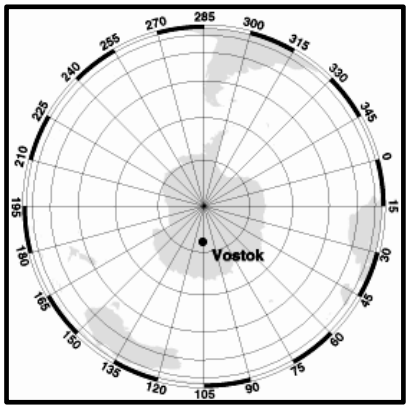


Vostok, Antarctica
78°28' S, 106°48'E
3488 m amsl



What does history tell us using the Vostok Ice Core?





Vostok, Antarctica
78°28' S, 106°48'E
3488 m amsl

Source: NASA (2016)

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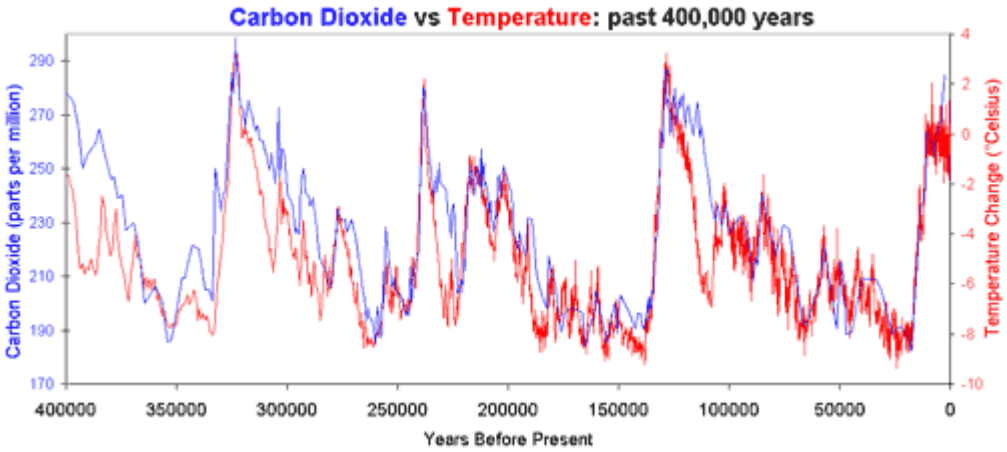
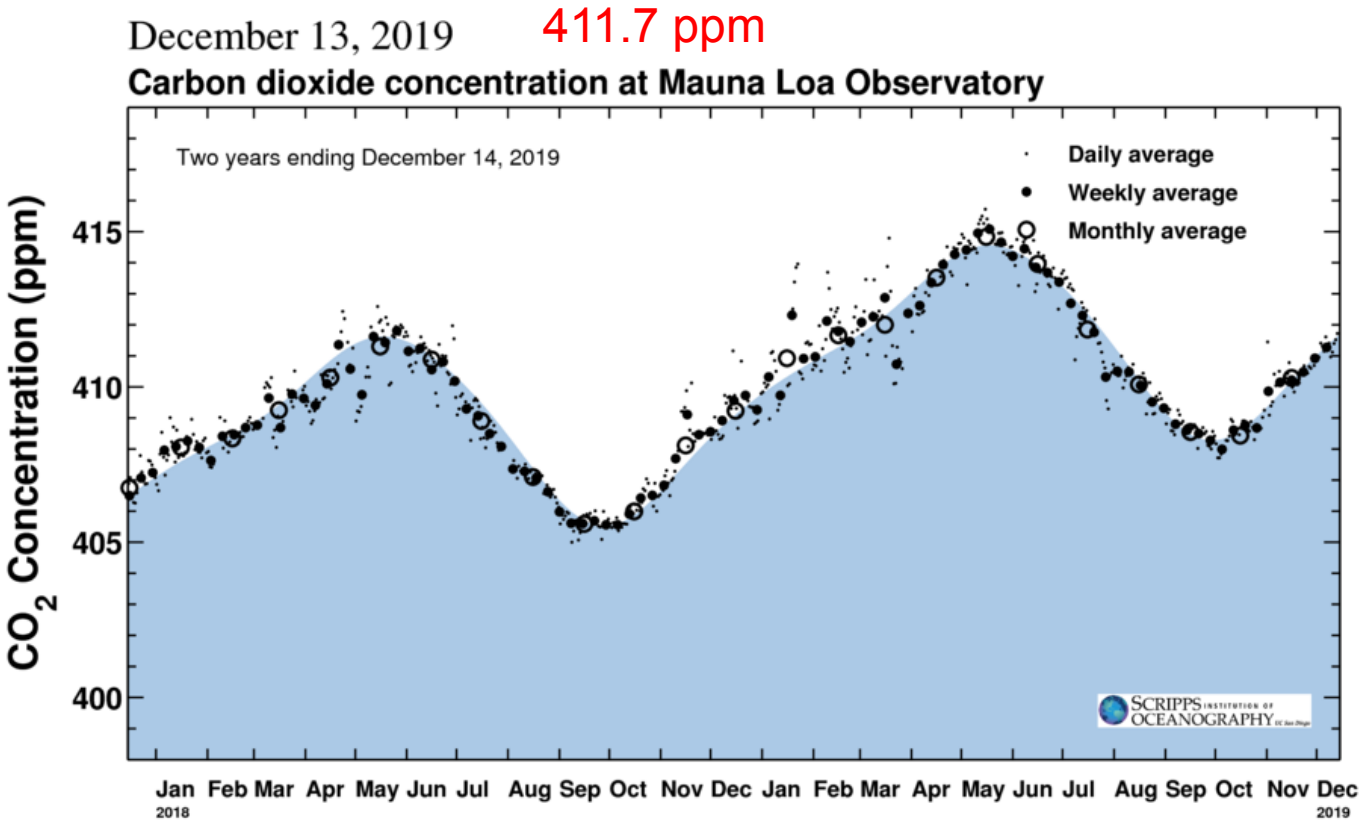
Why does temperature lag CO_2 atmospheric concentrations?



- Deglaciation (warming) is not initiated by CO_2 but by orbital cycles
- CO_2 amplifies warming which is not explained only by orbital cycles
- CO_2 spreads warming throughout the planet

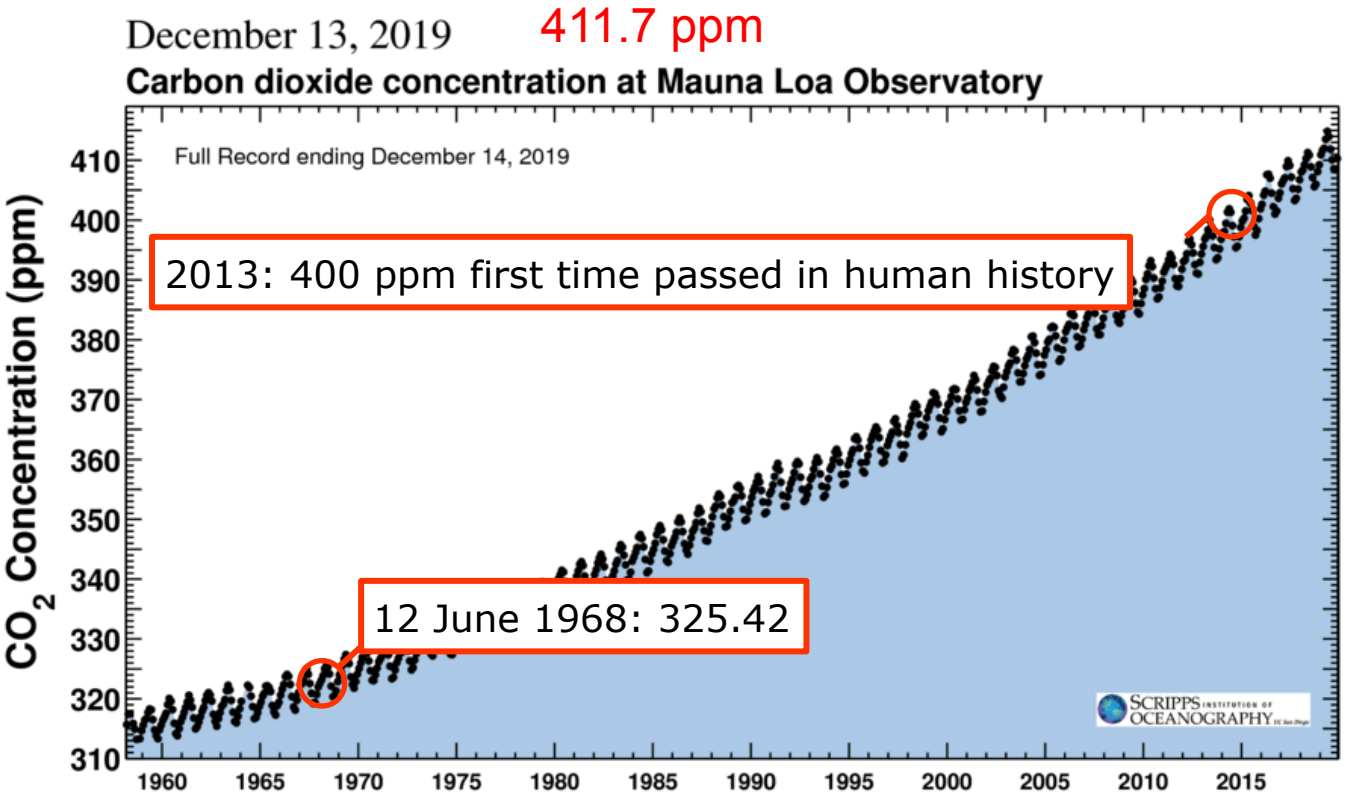
Current Atmospheric CO_2



"We were witnessing for the first time nature's withdrawing CO_2 from the air for plant growth during the summer and returning it each succeeding winter."

- Charles David Keeling (1998)

Recent Atmospheric CO_2



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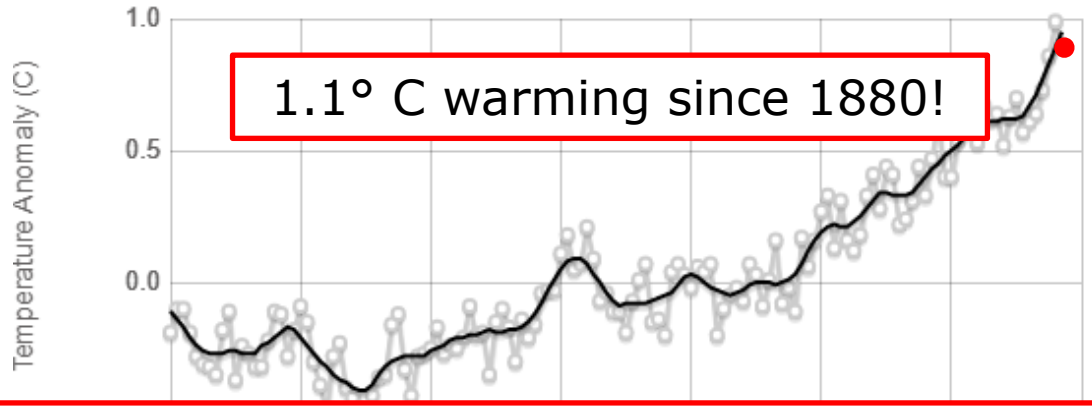
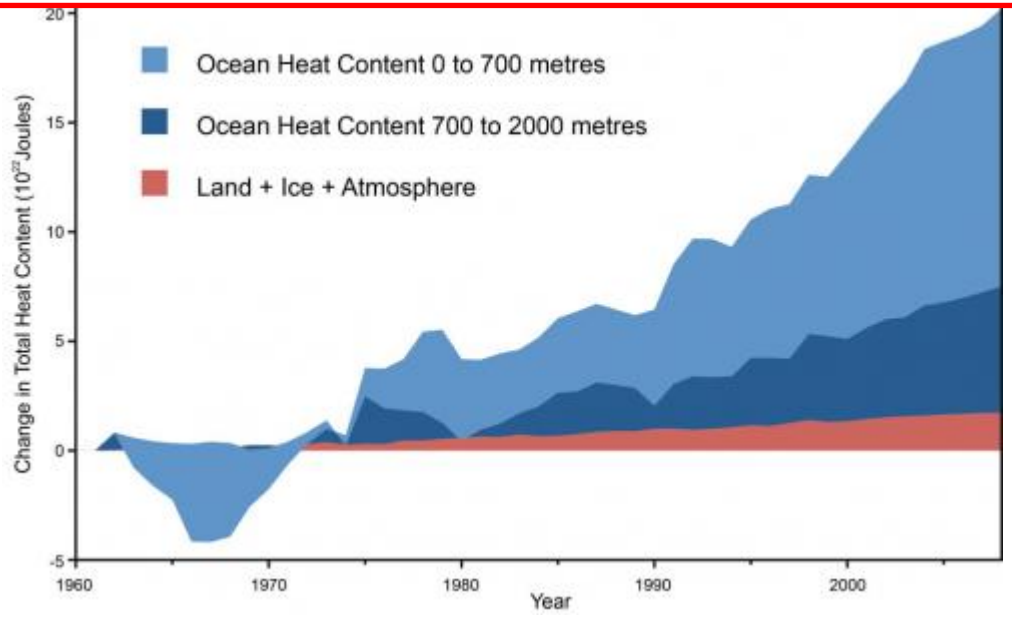
NASA's global temperature record



The oceans have taken up over 90% of the warming and approximately 1/3 of carbon dioxide released since the pre-industrial period



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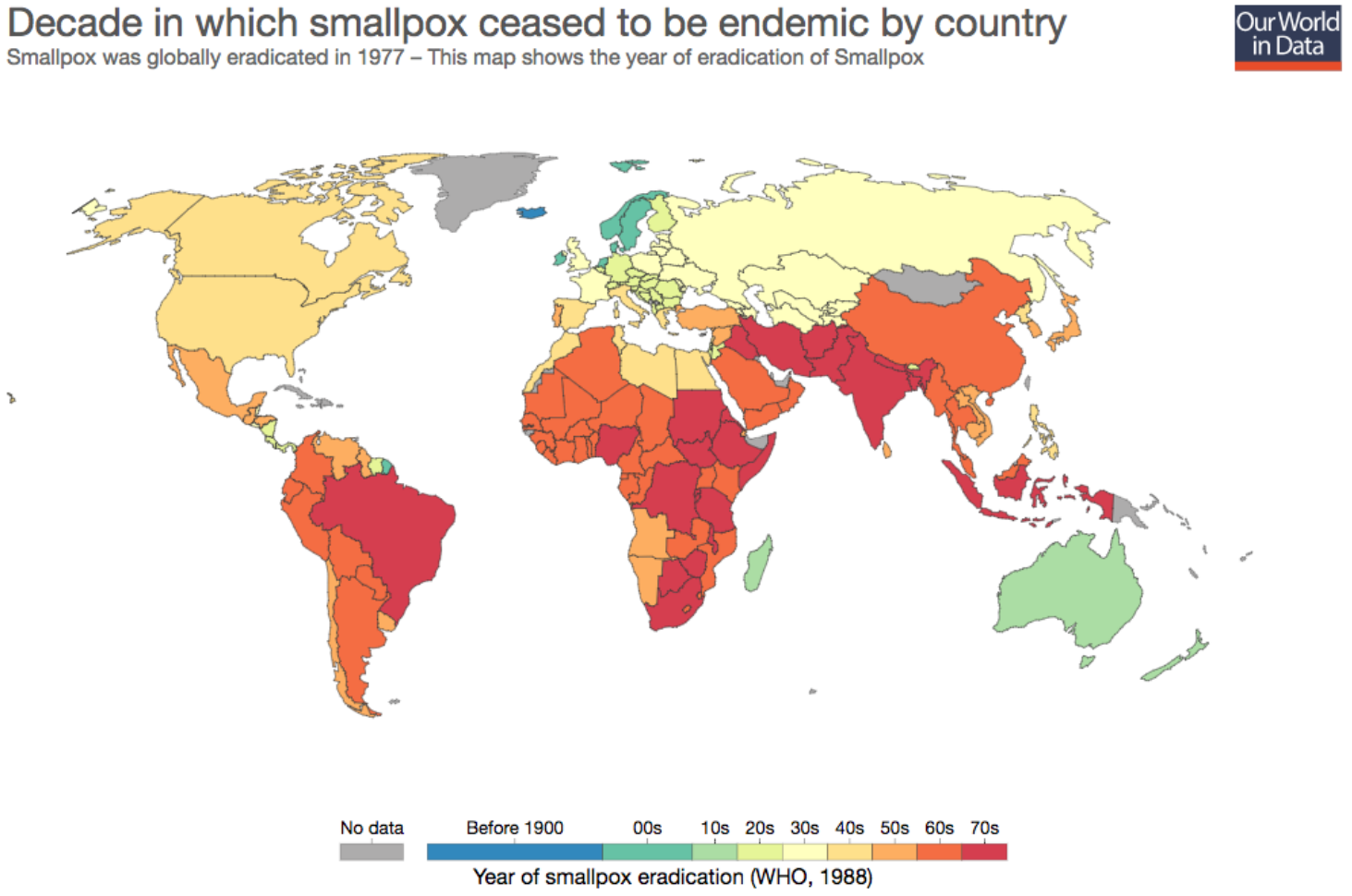
How do we tackle big problems?

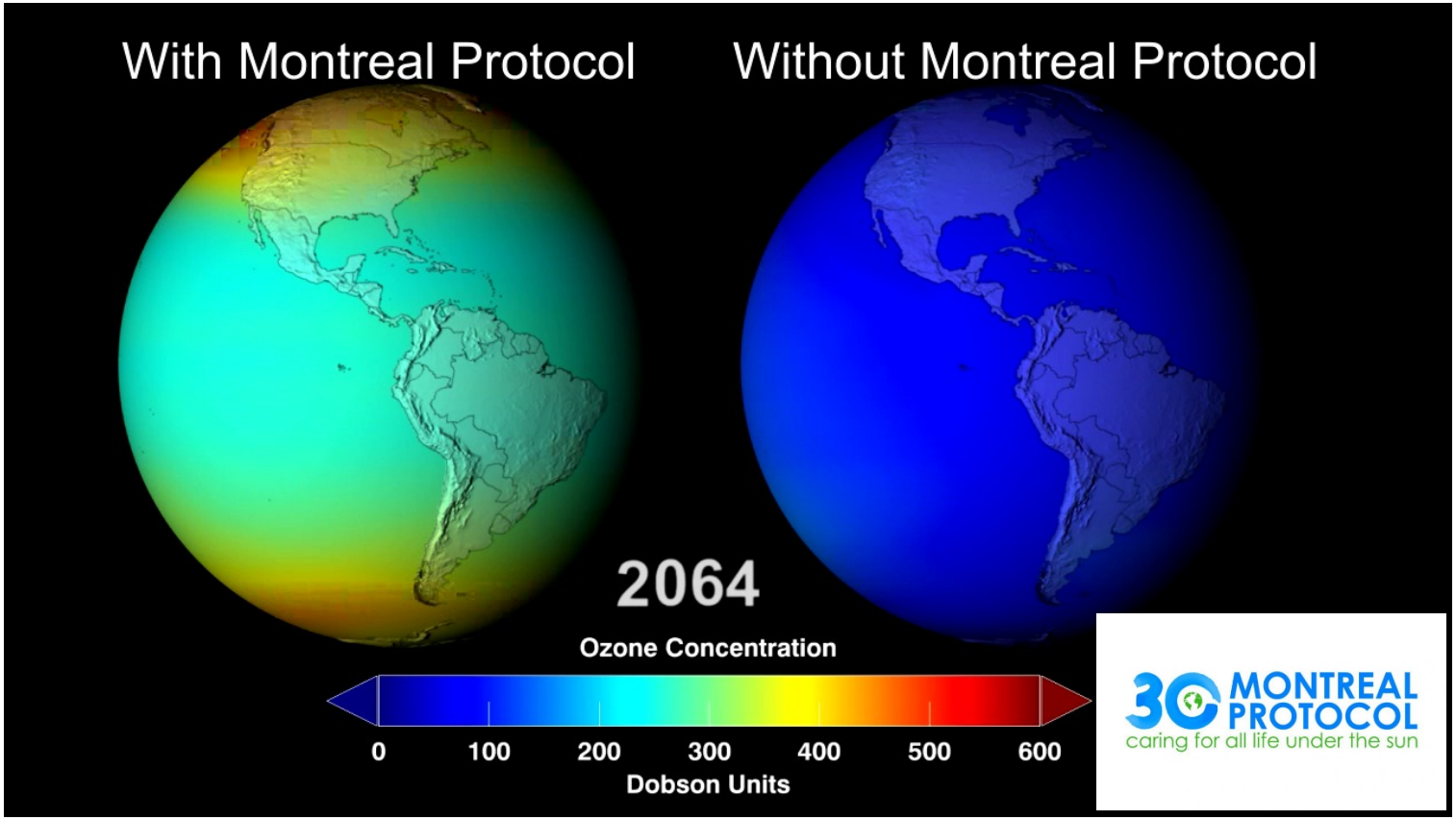
Scientific Evidence → Global Collaboration



- The first successful vaccine to be developed, Edward Jenner in 1796
- 192 years between first vaccination and eradication (1988)

How do we tackle big problems?

Scientific Evidence → Global Collaboration



- The first universally ratified treaties in United Nations history.
- 14 years between research discovery in 1973 and the international agreement in 1987.

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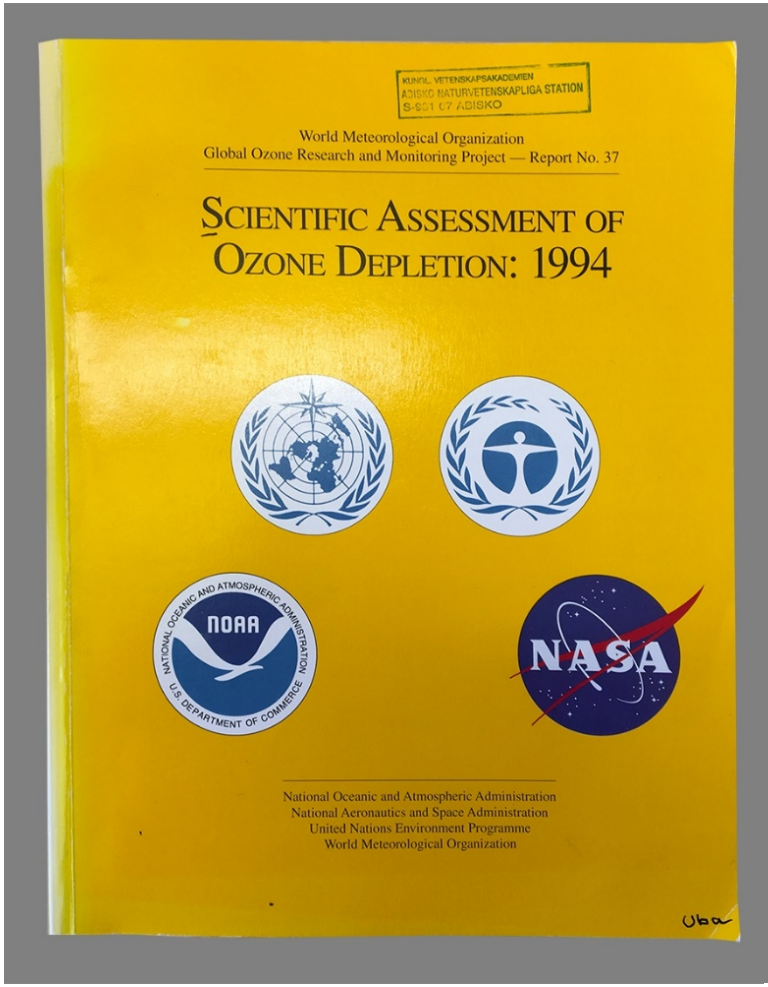
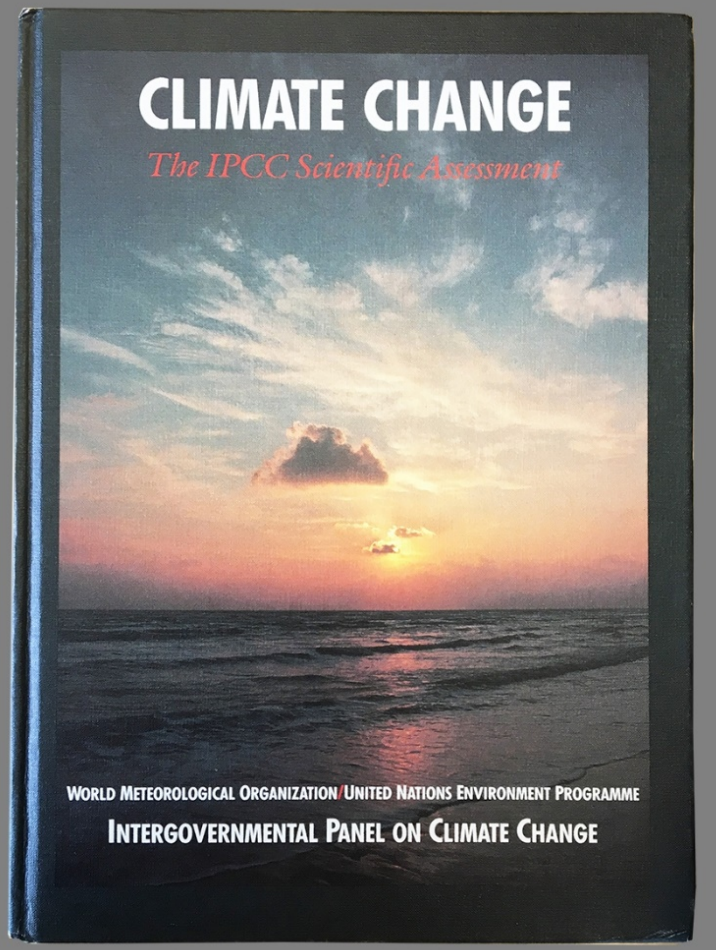
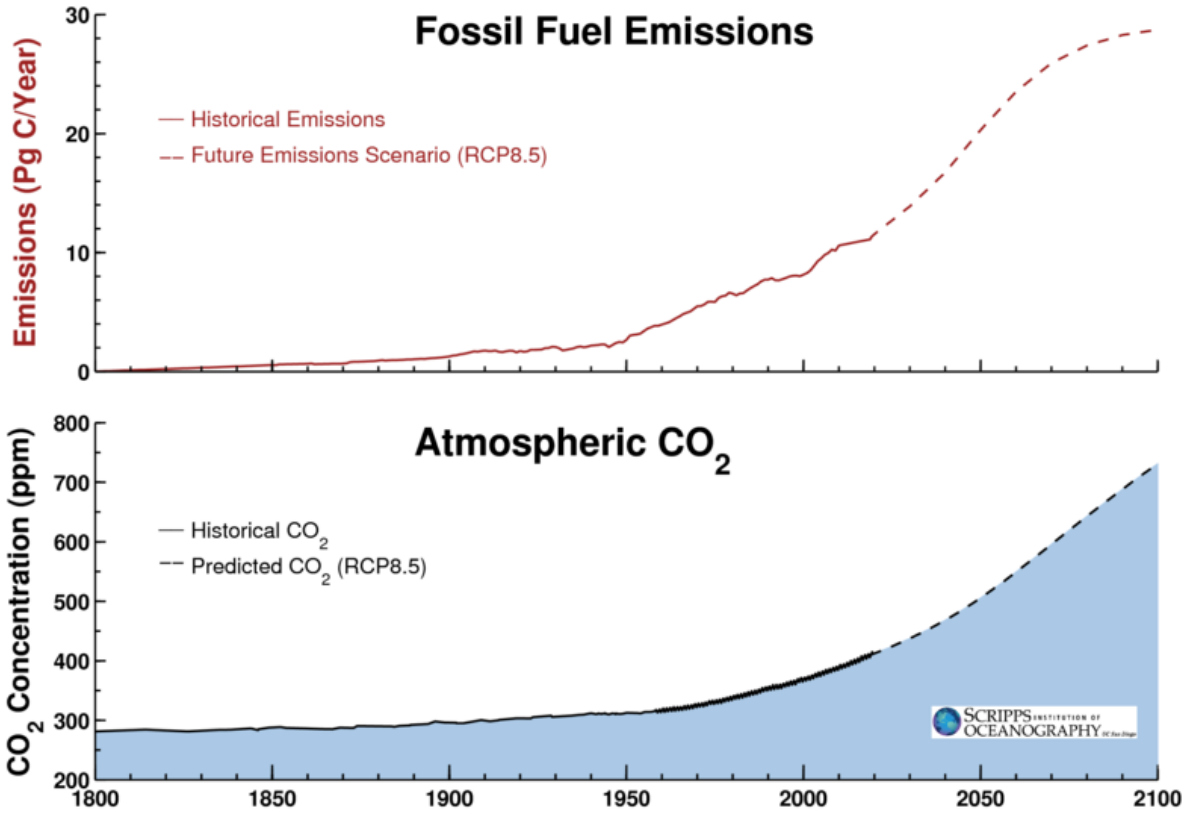
Lack of compelling narratives





Our current trajectory



Estimated emissions in 2019: 36.8 billion tons

**emissions have grown by 62% since international climate negotiations began in 1990 to address the problem*

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Climate Action / Lack of Action

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Lack of Action

Environmental Research Letters

EDITORIAL

Global energy growth is outpacing decarbonization

R B Jackson[1], C
B Zheng[5]

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Stanford, CA 94305
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[3] CICERO Center for
[4] Global Carbon Proj
[5] Laboratoire des Scie

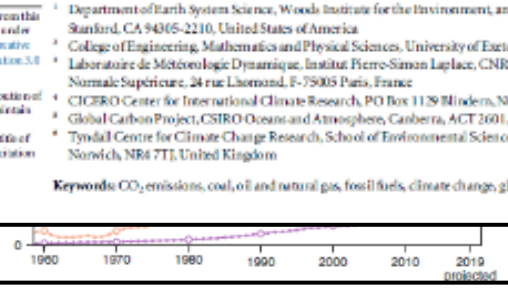
comment

Carbon dioxide emissions continue to grow amidst slowly emerging climate policies

A failure to recognize the factors behind continued emissions growth could limit the world's ability to shift to a pathway consistent with 1.5 °C or 2 °C of global warming. Continued support for low-carbon technologies needs to be combined with policies directed at phasing out the use of fossil fuels.

G. P. Peters, R. M. Andrew, J. G. Canadell, P. Friedlingstein, R. B. Jackson, J. I. Korsbakken, C. Le Quéré and A. Peregon

Global fossil CO_2 emissions gr
at 0.9% per year in the 1990s
accelerated to 3.0% per year
2000s, but have returned to a slower
rate of 0.9% per year since 2010, wit
pronounced slowdown from 2014 t
Despite modest declines in emission
the United States and the European
(EU) over the past decade, the grow
in emissions in China, India and mo
developing countries has dominated
emission trends over the past 20 yea
Global Carbon Budget projection[1] s
that global fossil CO_2 emissions will
by 0.6% (range −0.2% to 1.5%) in 20
with emissions projected to decline
United States and the EU28, but projected to
increase in China, India and the rest of the
world (Fig. 1a).



PERSPECTIVE

Persistent fossil fuel growth threatens the Paris Agreement and planetary health

R B Jackson[1], P Friedlingstein[2,3], R M Andrew[4], J G Canadell[5], C Le Quéré[6] and G P Peters[4]

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OPEN ACCESS

4 December 2019

Keywords: CO_2 emissions, coal, oil and natural gas, fossil fuels, climate change, global warming, energy

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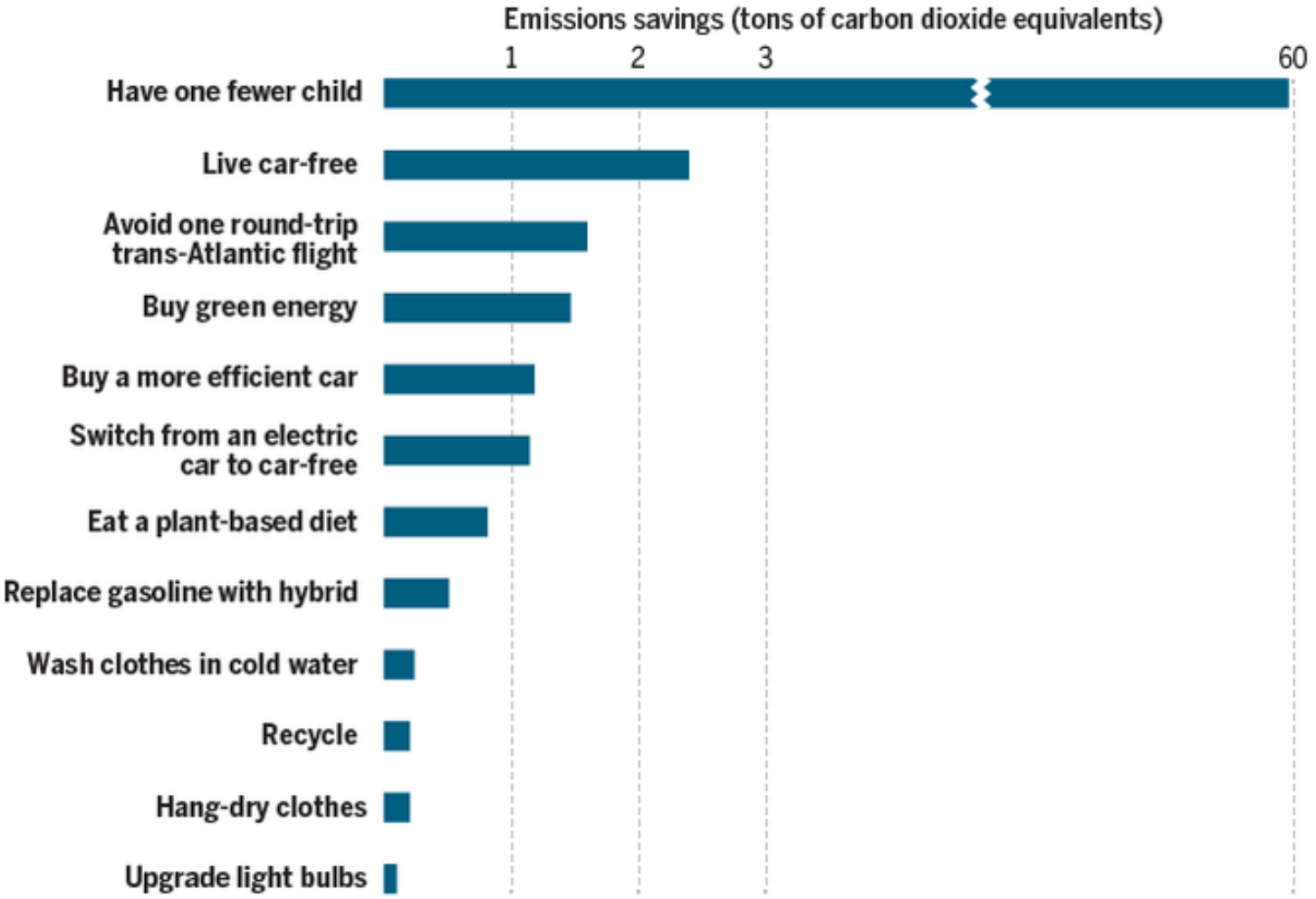
How do we make sense of this?



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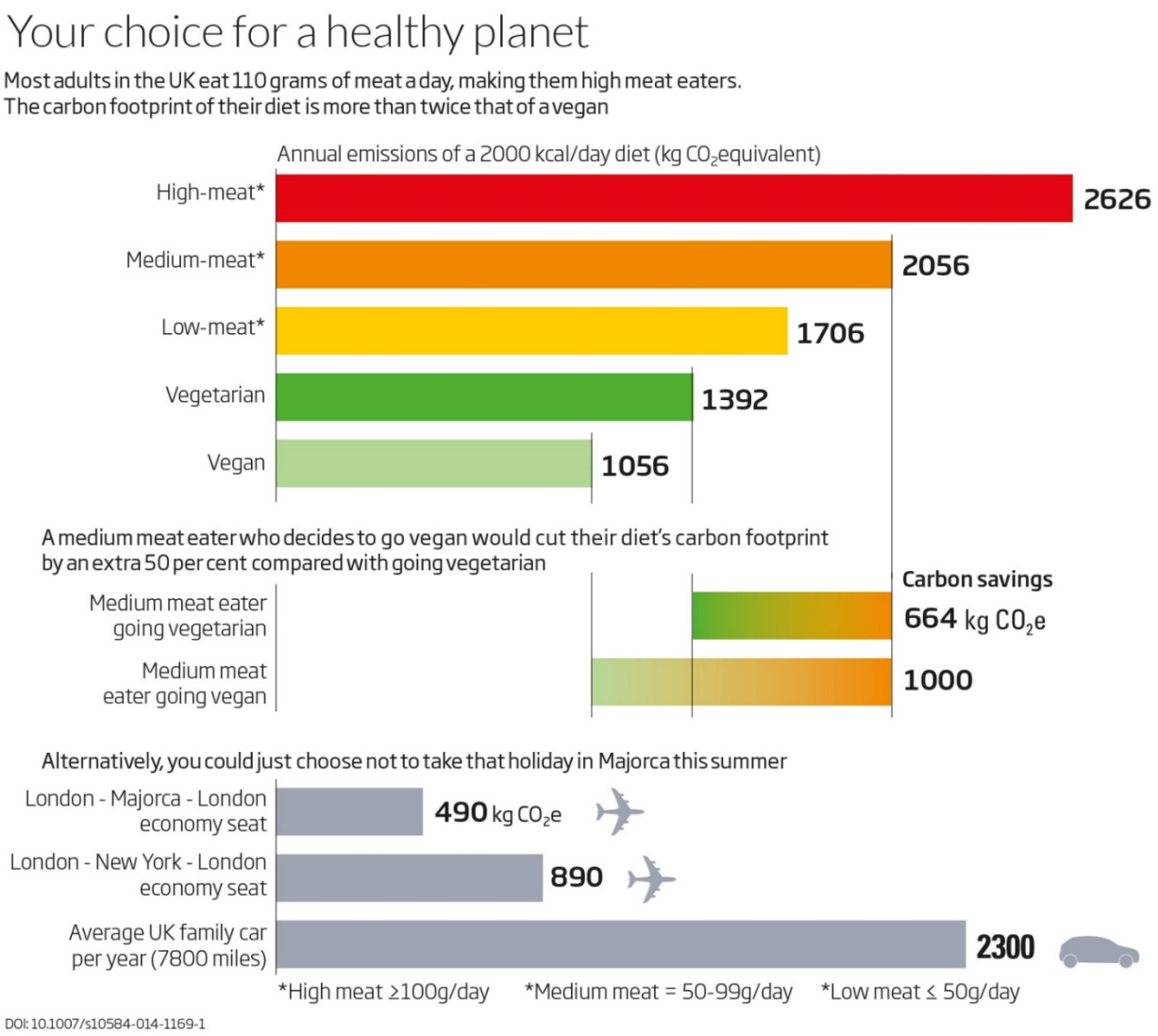
How do we make sense of this?



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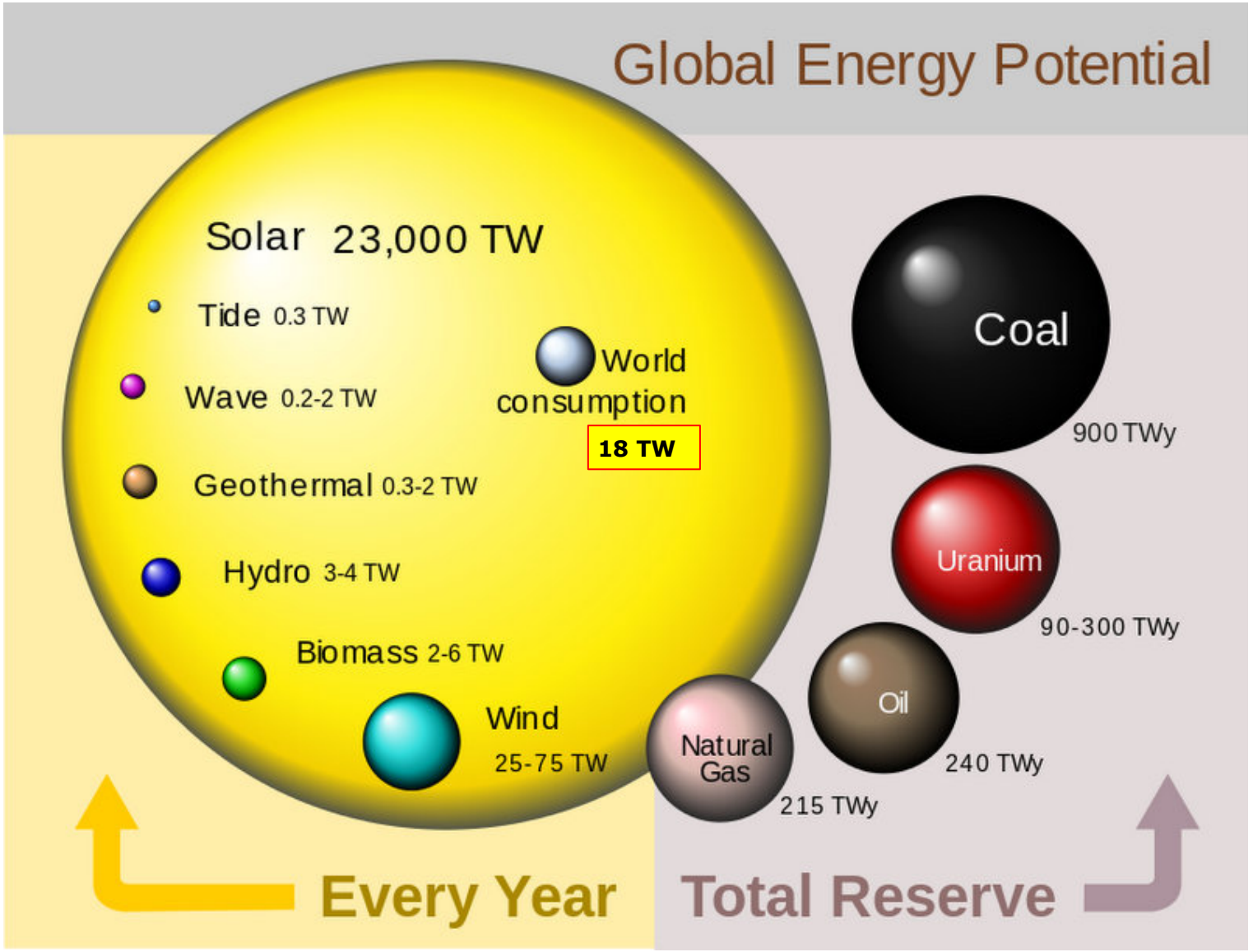
A path to renewal “clean” energy



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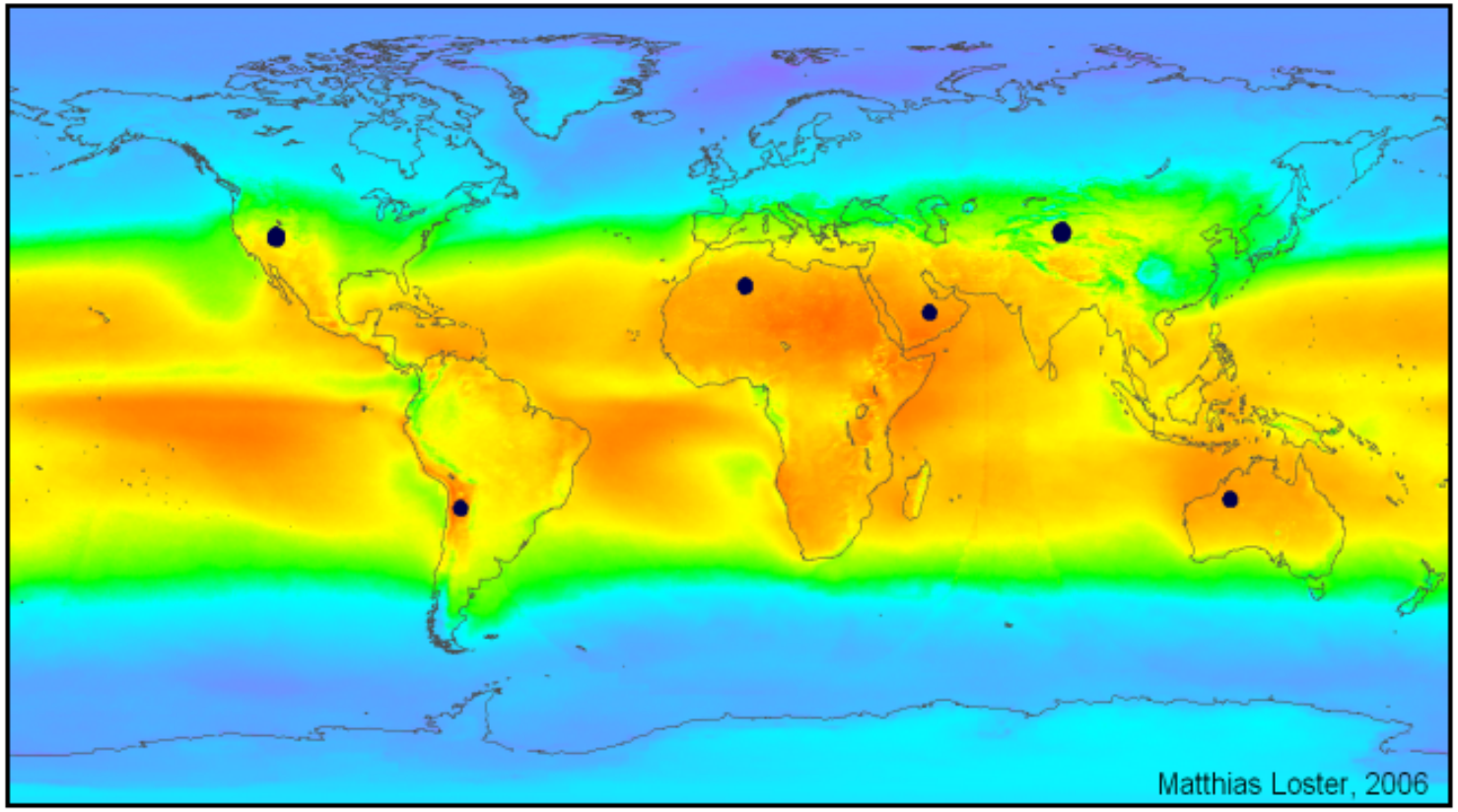
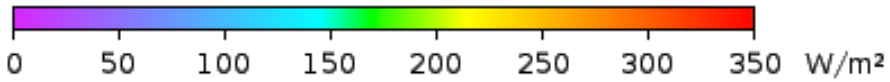
A path to renewal “clean” energy





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A path to renewal “clean” energy

theguardian

UK world sport football opinion culture business lifestyle fashion environment tech travel all sections

home › environment › climate change wildlife energy pollution

Renewable energy
Global warning

Reasons to be cheerful: a full switch to low-carbon energy is in sight

Climate change optimism is justified - a complete transition from carbon to solar and wind power looks practical and affordable within a generation

Colle des Mées solar farm in Alpes-de-Haute-Provence is the biggest in France and consists of 112,780 panels and represents 100 MW of power. Photograph: Jean-Paul Pelissier/Reuters

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The solar future is here!

How Tesla's big battery is bringing Australia's gas cartel to heel

South Australia's big gamble on grid-scale battery storage may pay for itself in just a year if it continues to prevent massive price spikes

● **Giles Parkinson is editor of RenewEconomy**

On Sunday 14 January something very unusual happened.

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Population: 5 (non-human)
Number of species: unknown

"We are running out of space, and the only places to go to are other worlds."
— Stephen Hawking

Taken by NASA Mars Maven Mission 2014

02 January 2019

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If you were to really *internalize* that we are the first generation to see the effects of climate change…

and the last generation to be able to do anything about it…

would you change your life?

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Young people are the most politically liberated force globally right now.

You have less to lose than any other generation, and everything to gain.

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References

Arctic Climate Impact Assessment. 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, United Kingdom.

Dorrepaal, E., S. Toet, R. S. P. van Logtestijn, E. Swart, M. J. van de Weg, T. V. Callaghan, and R. Aerts. 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. Nature 460:616–619.

Fahnestock, M. F., J. G. Bryce, C. K. McCalley, M. Montesdeoca, S. Bai, Y. Li, C. T. Driscoll, P. M. Crill, V. I. Rich, and R. K. Varner. 2019. Mercury reallocation in thawing subarctic peatlands. Geochemical Perspectives Letters:33–38.

GISTEMP Team. 2019. GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies.

Grudd, H., K. R. Briffa, W. Karlén, T. S. Bartholin, P. D. Jones, and B. Kromer. 2002. A 7400-year tree-ring chronology in northern Swedish Lapland: natural climatic variability expressed on annual to millennial timescales. The Holocene 12:657–665.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade. 2006. Global temperature change. Proceedings of the National Academy of Sciences 103:14288–14293.

Hein, A. M., C. Hou, and J. F. Gillooly. 2012. Energetic and biomechanical constraints on animal migration distance. Ecology Letters 15:104–110.

Hugelius, G., J. Strauss, S. Zubrzycki, J. W. Harden, E. a. G. Schuur, C.-L. Ping, L. Schirrmeister, G. Grosse, G. J. Michaelson, C. D. Koven, J. A. O'Donnell, B. Elberling, U. Mishra, P. Camill, Z. Yu, J. Palmtag, and P. Kuhry. 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences 11:6573–6593.

Jackson, R. B., C. L. Quéré, R. M. Andrew, J. G. Canadell, J. I. Korsbakken, Z. Liu, G. P. Peters, and B. Zheng. 2018. Global energy growth is outpacing decarbonization. Environmental Research Letters 13:120401.

Jackson, R. B., P. Friedlingstein, R. M. Andrew, J. G. Canadell, C. L. Quéré, and G. P. Peters. 2019. Persistent fossil fuel growth threatens the Paris Agreement and planetary health. Environmental Research Letters 14:121001.

Johansson, M., T. V. Callaghan, J. Bosiö, H. J. Åkerman, M. Jackowicz-Korczynski, and T. R. Christensen. 2013. Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden. Environmental Research Letters 8:035025.

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References (continued)

Jones, A. G., J. Scullion, N. Ostle, P. E. Levy, and D. Gwynn-Jones. 2014. Completing the FACE of elevated CO2 research. Environment International 73:252–258.

Jones, N. 2013. Troubling milestone for CO2. Nature Geoscience 6:589–589.

Körner, C. 2012. Alpine treelines: functional ecology of the global high elevation tree limits. First edition. Springer, Basel.

Kuhn, M., E. J. Lundin, R. Giesler, M. Johansson, and J. Karlsson. 2018. Emissions from thaw ponds largely offset the carbon sink of northern permafrost wetlands. Scientific Reports 8:9535.

Lenssen, N. J. L., G. A. Schmidt, J. E. Hansen, M. J. Menne, A. Persin, R. Ruedy, and D. Zyss. 2019. Improvements in the GISTEMP Uncertainty Model. Journal of Geophysical Research (Atmospheres) 124:6307.

Loader, N. J., G. H. F. Young, H. Grudd, and D. McCarroll. 2013. Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation. Quaternary Science Reviews 62:97–113.

Neukom, R., N. Steiger, J. J. Gómez-Navarro, J. Wang, and J. P. Werner. 2019. No evidence for globally coherent warm and cold periods over the preindustrial Common Era. Nature 571:550–554.

Oechel, W. C., S. Cowles, N. Grulke, S. J. Hastings, B. Lawrence, T. Prudhomme, G. Riechers, B. Strain, D. Tissue, and G. Vourlitis. 1994. Transient nature of CO 2 fertilization in Arctic tundra. Nature 371:500–503.
von Schuckmann, K., M. D. Palmer, K. E. Trenberth, A. Cazenave, D. Chambers, N. Champollion, J. Hansen, S. A. Josey, N. Loeb, P.-P. Mathieu, B. Meyssignac, and M. Wild. 2016. An imperative to monitor Earth's energy imbalance. Nature Climate Change 6:138–144.

Peters, G. P., R. M. Andrew, J. G. Canadell, P. Friedlingstein, R. B. Jackson, J. I. Korsbakken, C. L. Quéré, and A. Peregon. 2019. Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. Nature Climate Change:1–4.

Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov. 2009. Soil organic carbon pools in the northern circumpolar permafrost region: SOIL ORGANIC CARBON POOLS. Global Biogeochemical Cycles 23:n/a-n/a.

Turetsky, M. R., B. W. Abbott, M. C. Jones, K. W. Anthony, D. Olefeldt, E. A. G. Schuur, C. Koven, A. D. McGuire, G. Grosse, P. Kuhry, G. Hugelius, D. M. Lawrence, C. Gibson, and A. B. K. Sannel. 2019. Permafrost collapse is accelerating carbon release. Nature 569:32–34.

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References (continued)

Yang, Z., E. Hanna, T. V. Callaghan, and C. Jonasson. 2012. How can meteorological observations and microclimate simulations improve understanding of 1913–2010 climate change around Abisko, Swedish Lapland? Meteorological Applications 19:454–463.

Zimov, S. A., E. A. G. Schuur, and F. S. Chapin. 2006. Permafrost and the Global Carbon Budget. Science 312:1612–1613.