Biogeochemical impacts of Arctic expansion: past and future

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Age of Permafrost

- Permafrost remaining from the last ice age (c. 115,000 – c. 11,700 years ago) and prior glaciations
- Rapid thaw in the last 50 years is changing structural dynamics of the tundra, releasing GHG and permafrost components
- ‘Yedoma’ can be 100,000 of years old and hundreds of meters deep- exposed by thermokarst development
- May contain viable microbes from the Cenozoic to modern times
- 2% carbon by mass, but 80-90% ice

Miner et al. 2021 *Nature Climate Change, Solicited review*

Permafrost thaw

- Thaw mechanisms governing the release of paleo-organisms into the modern environment
  - Gradual thaw
  - Abrupt thaw: Thermokarst ponds, lakes and collapsed ground, wildfires, water penetration and ground water expansion

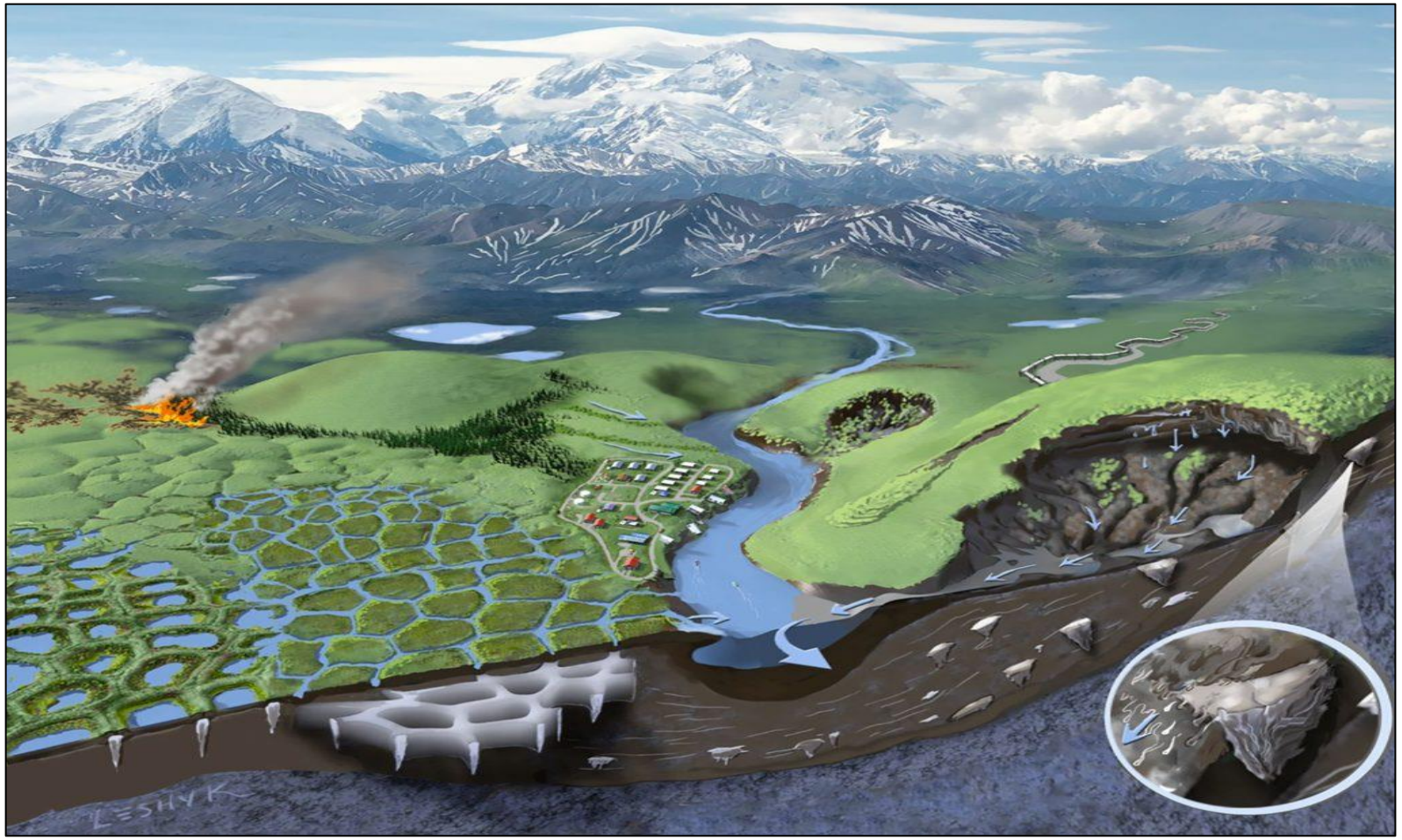
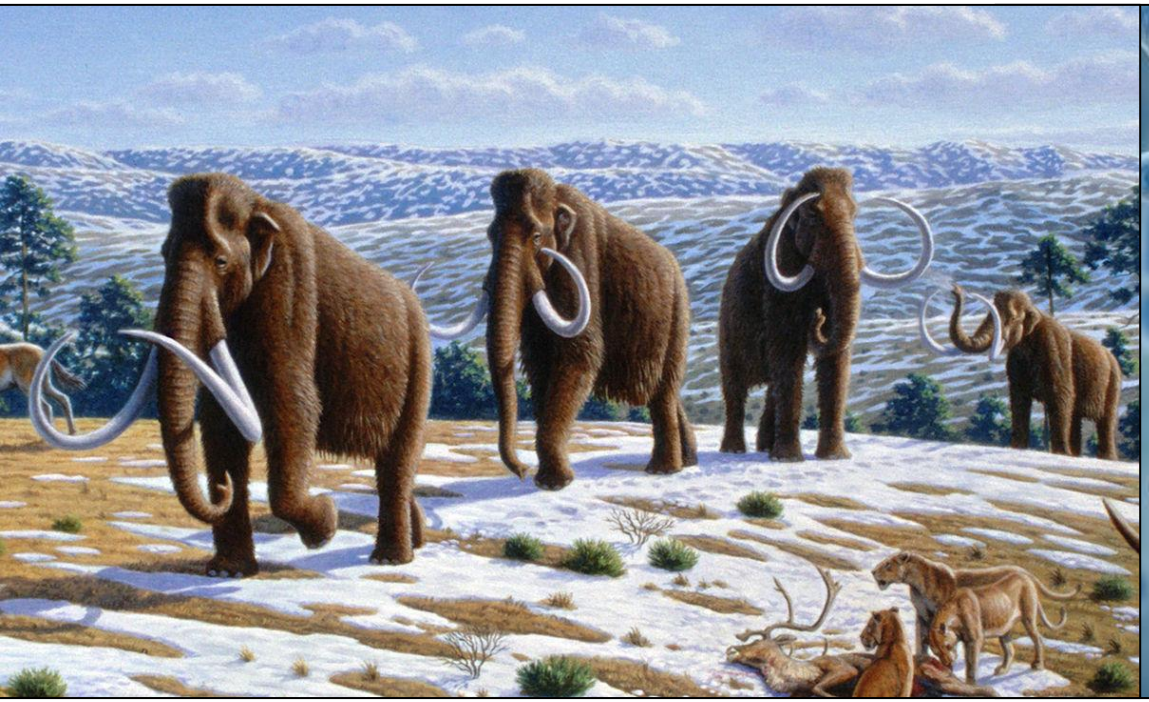


Figure: Schuur et al. 2018

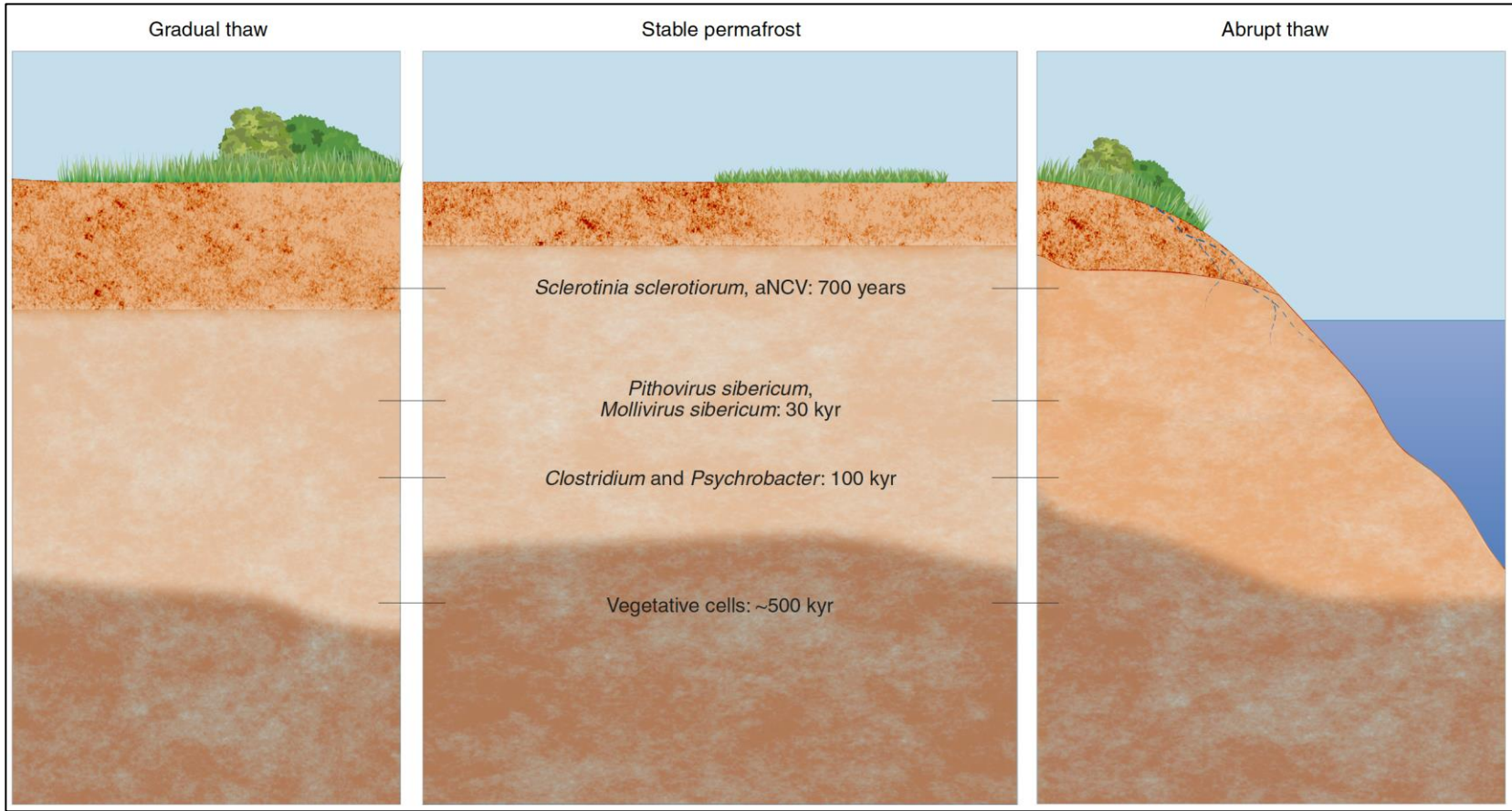
Permafrost microbes



Images: Wikicommons

Permafrost microbes

- Cold-adapted generalist microbes with lipid membranes still viable (extremophiles)
  - Cold methane seeps: ancient bacteria phylotypes related to *Loktanella, Gillisia, Halomonas,* and *Marinobacter* spp.
  - Brine lenses (100k-120kyr): *Clostridium* and *Psychrobacter*
  - Permafrost substrate (30kyr): intact virus species including Mimiviruses, Pandoraviruses, *Pithovirus sibericum, Mollivirus sibericum*
- Unknow bacteria, viruses and microbes
  - Up to 1 million years old
  - ‘Methuselah’ microbes



Miner et al 2021, Nature Climate Change

Permafrost microbes

- The Plague, Black Death, Small Pox and unknown viruses including new ”Alaskapox”
- Antibiotic resistance in some species
  - bacteria resistant to chloramphenicol, streptomycin, kanamycin, gentamicin, tetracycline, spectinomycin, and neomycin have been recovered (15-290kyr)
- Other potential ‘eradicated’ diseases

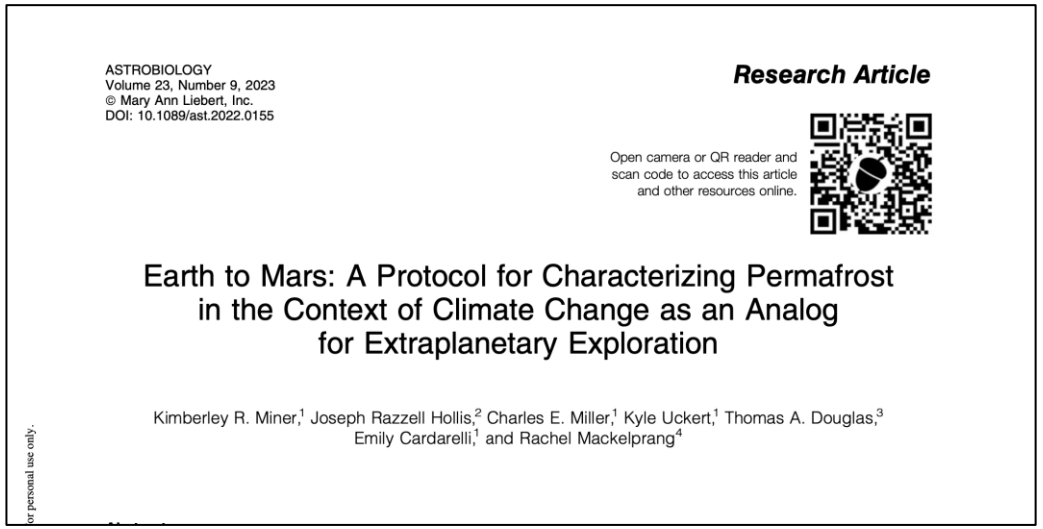
Images: Wikicommons

Potential Impacts

- Anthrax release in Siberia suspected in death of 200 reindeer and a child in 2016
- Graves of Smallpox victims excavated in 2016, 2019
- Microbes from 700-yr old Caribou cloned into modern plant in 2014
- Exploration of microbiome in unprotected labs ongoing
- Exposure can expand with tourism travel to the Arctic

Microbes in permafrost and space

- Find, characterize and index the permafrost microbiome, developing a greater understanding of niches supporting life
- Sampled permafrost from 10-130,000 years old in Alaska
- Proof of concept in Greenland, on the Mars Perseverance a similar instrument (SHERLOC) with same laser system
- Identifying ancient, extremophile organisms on Earth may make successful recovery from similar extraplanetary environments possible



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Research Article

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Earth to Mars: A Protocol for Characterizing Permafrost in the Context of Climate Change as an Analog for Extraplanetary Exploration

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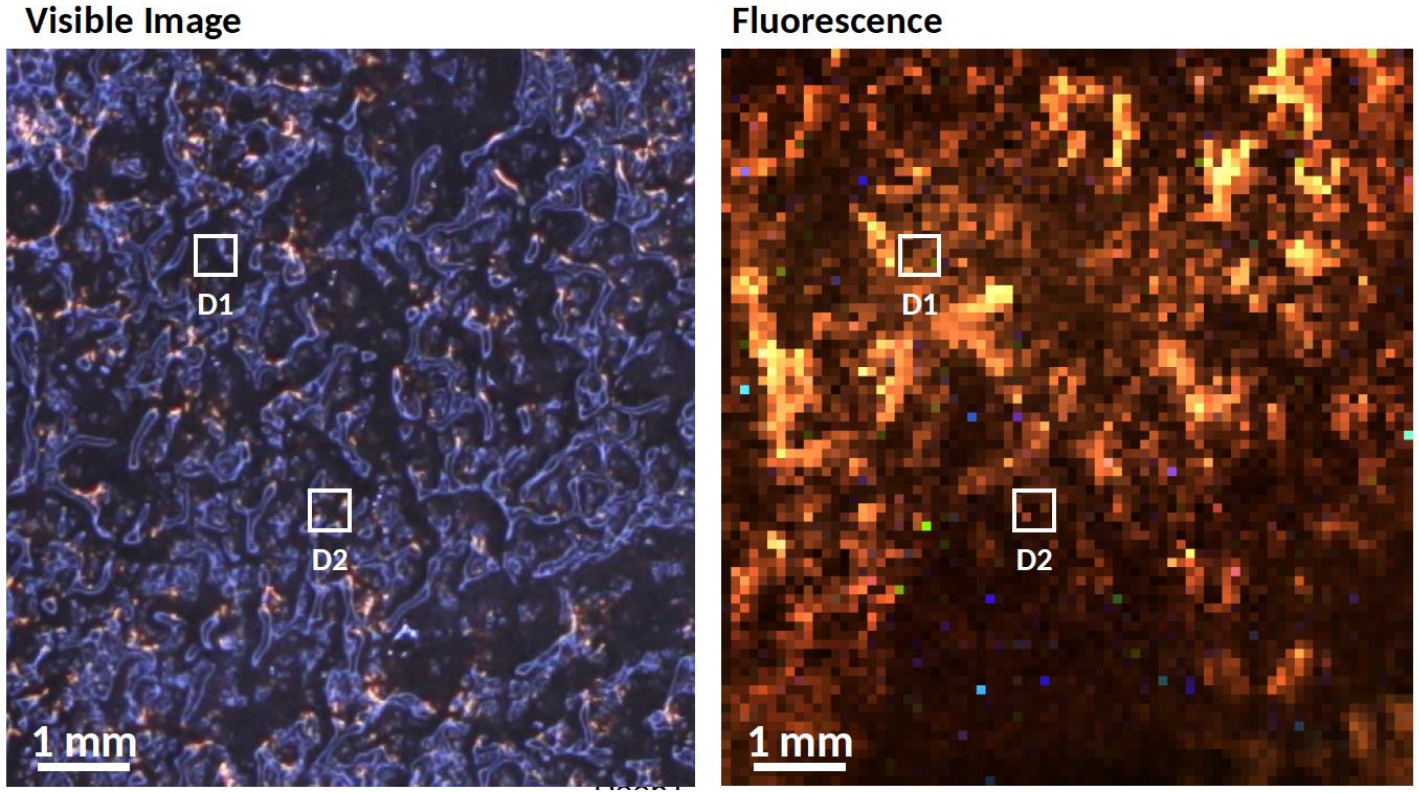


Anthropogenic contamination

Images: Wikicommons, NYT

Anthropogenic Contamination: The ‘Grasshopper Effect’

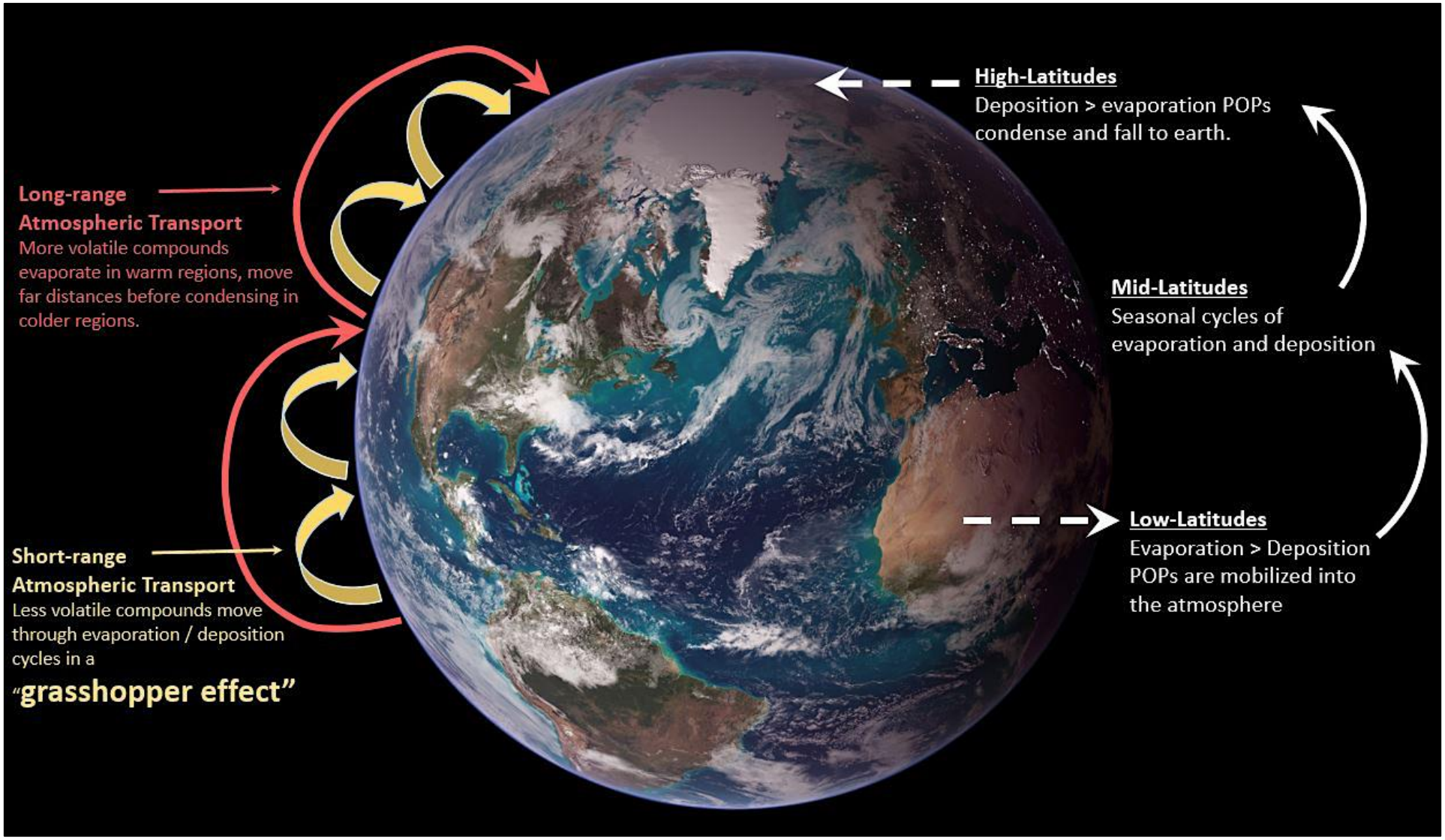


Figure: Pointus et al. 2016

Other mechanisms for contamination

- Melt and thaw of ice and permafrost
- Release during industrial use (storage and seepage)
- Nuclear materials mined, utilized or stored in the Arctic
- Release from accidents, global transport or shipwrecks
- Oil drilling, transport and infrastructure leaks

Images: Wikicommons WAPO

Persistent Organic Pollutants (POPs) and metals

- Organic chemicals including DDT, HCH, PCBs deposited atmospherically
  - 2019, 2020 studies show human risk from fish consumption
  - High concentrations- DDT (10 ng/L) , PCB (~4.5 ng/L), and HCH (~20 ng/L) in glacier ice and permafrost
- Heavy metals Arsenic (As), Cd, Nickel (Ni), and Mercury (Hg) from mine tailings and atmospheric deposition
  - One open pit mine: Cd (1 – 4 mg/kg), Ni (1000 – 1500 mg/kg), and Hg (40-120 mg/kg)
- Bioaccumulation in fish may see an increase of up to 222% by 2300
  - *Glaucous Gull* species show high levels of Hg (4.9 ug/g), PCB (3326 ng/g), and DDT (2367 ng/g)

Images: Wikicommons, NYT

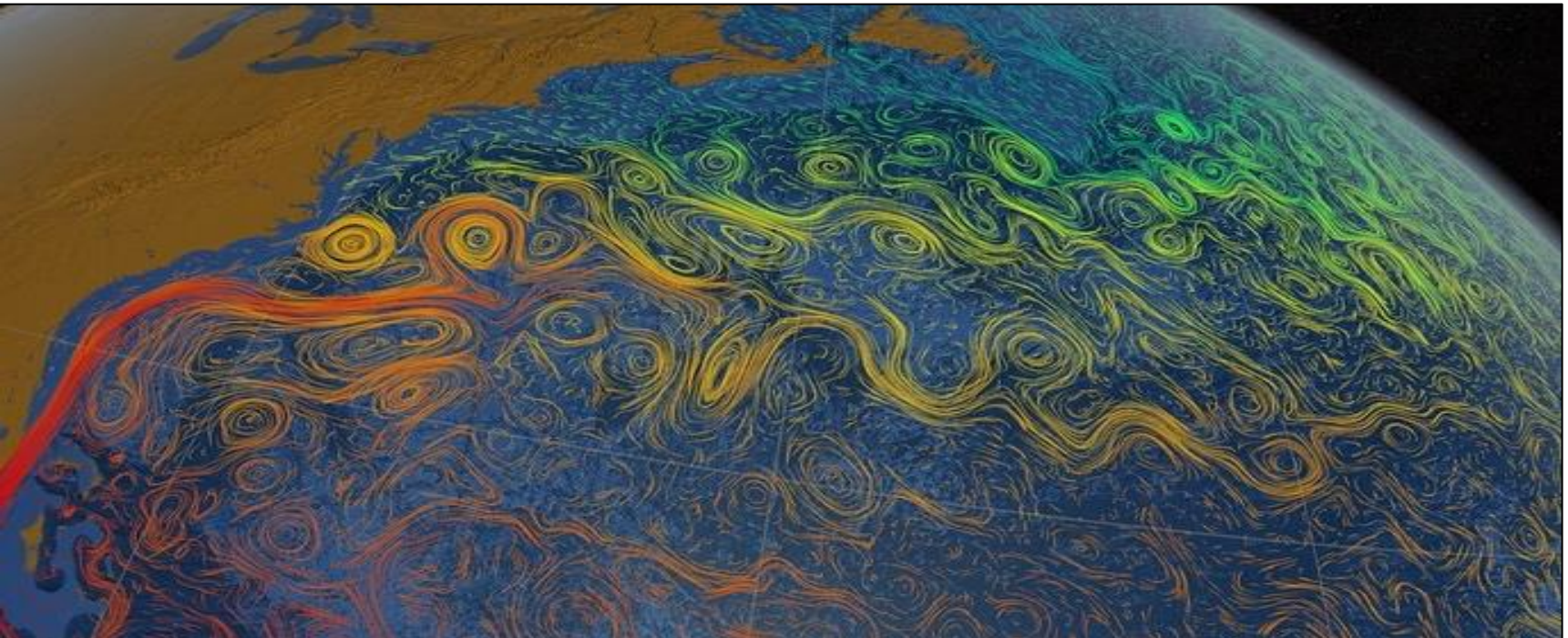
Nuclear waste

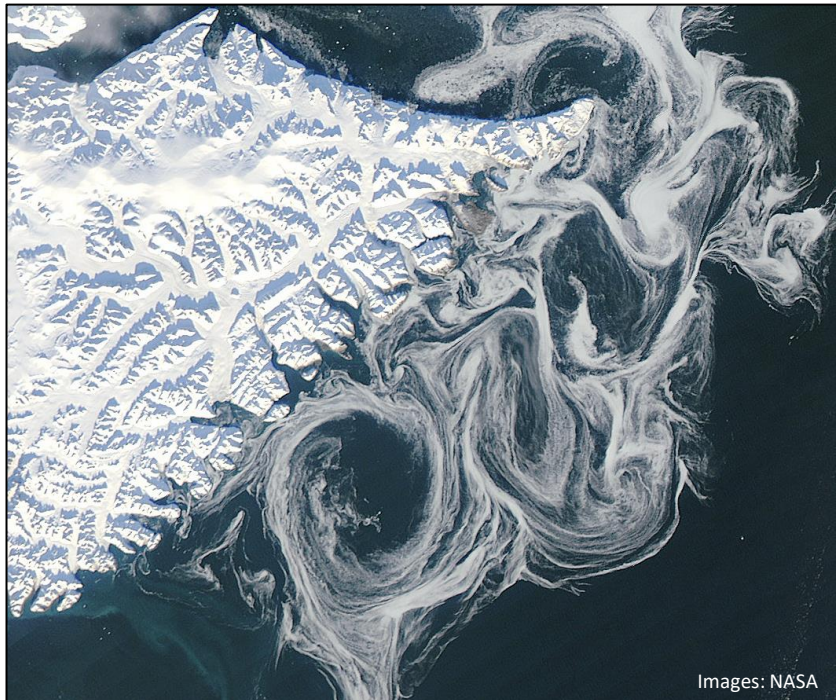
- 1955-1990, the Soviet Union conducted 130 nuclear weapons tests in the Novaya Zemlya Archipelago
  - 224 separate explosive devices, releasing ~265 megatons of nuclear energy
  - Kara Sea sediments contain up to 11,000 Bq/kg of Plutonium, 3-4x larger than the background
  - Sunken ships excluded from cleanup account for ~8860 TBq of radiation
- Camp Century: radioactivity of ~1.2×10^{9} Bq including physical waste, diesel fuel & PCBs, and sewage
- 1968 Thule bomber crash >4.6×10^{12} Bq of Uranium and Plutonium on Greenland ice sheet

Images: Wikicommons, NYT

Could Arctic hazards transport globally?

- Potential introduction of old bacteria, viruses, and microbial life into land and ocean
- Atmospheric remobilization of chemicals and toxins stored in the Arctic
- The ‘greening’ of the Arctic and changing hydrology
- A possible route for microbial contamination in freshwater

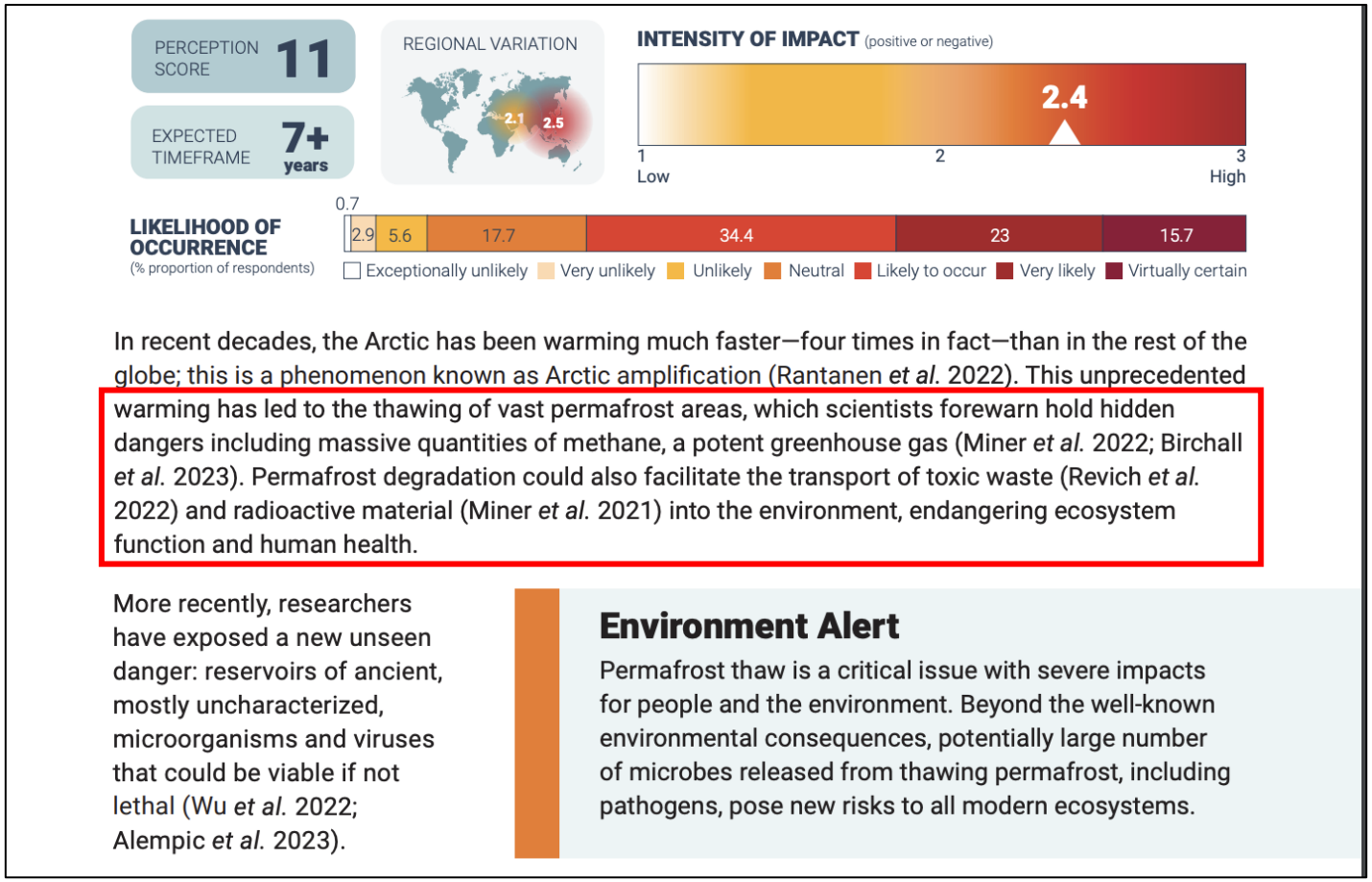




Images: NASA

Earth Science to Action

- UNEP scoping policy report released in 2024 cites JPL Arctic research
- Basic research that is integrated into decision making is an example of Earth Science to Action- a new NASA initiative in applied science

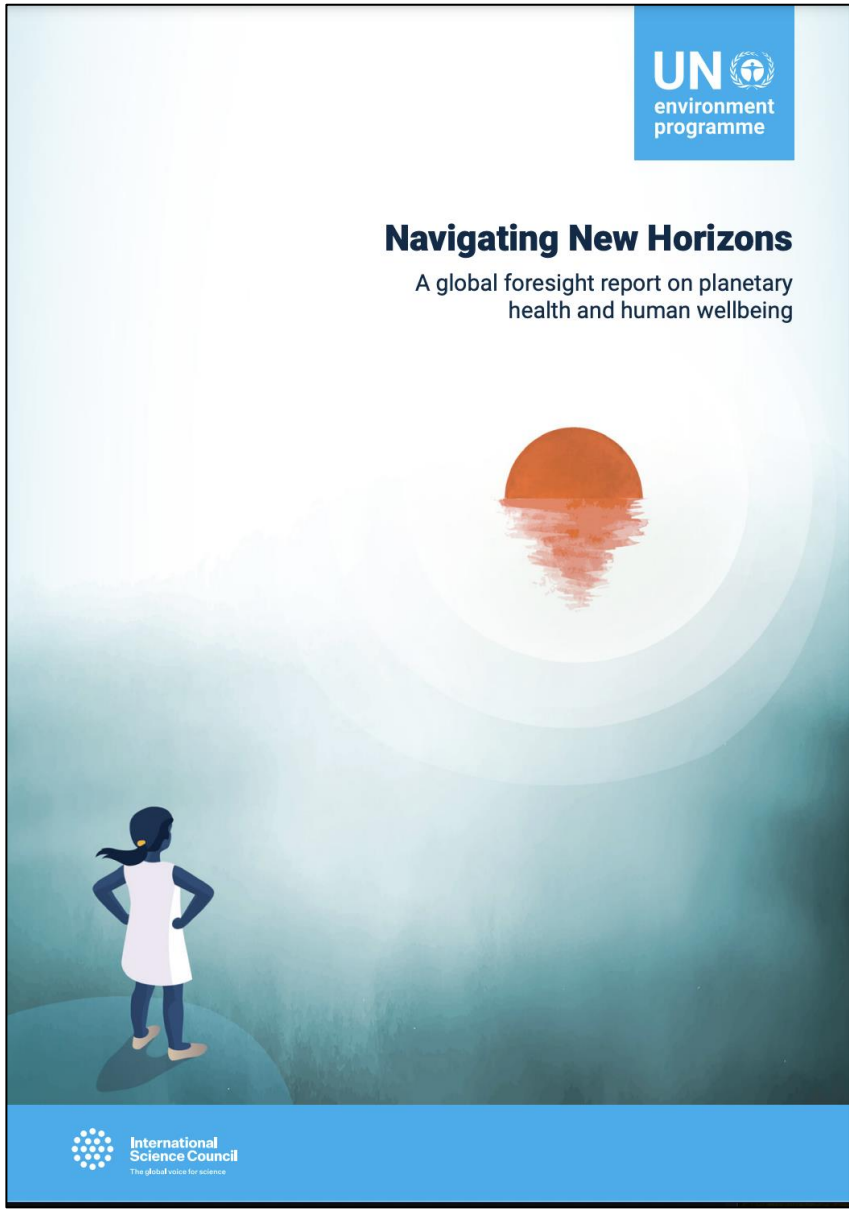


In recent decades, the Arctic has been warming much faster—four times in fact—than in the rest of the globe; this is a phenomenon known as Arctic amplification (Rantanen *et al.* 2022). This unprecedented warming has led to the thawing of vast permafrost areas, which scientists forewarn hold hidden dangers including massive quantities of methane, a potent greenhouse gas (Miner *et al.* 2022; Birchall *et al.* 2023). Permafrost degradation could also facilitate the transport of toxic waste (Revich *et al.* 2022) and radioactive material (Miner *et al.* 2021) into the environment, endangering ecosystem function and human health.

More recently, researchers have exposed a new unseen danger: reservoirs of ancient, mostly uncharacterized, microorganisms and viruses that could be viable if not lethal (Wu *et al.* 2022; Alempic *et al.* 2023).

Environment Alert

Permafrost thaw is a critical issue with severe impacts for people and the environment. Beyond the well-known environmental consequences, potentially large number of microbes released from thawing permafrost, including pathogens, pose new risks to all modern ecosystems.



Next Steps

- NASA-ESA Arctic Methane Challenge Summer School
- Ongoing modeling and AI work, combining satellite and in-situ monitoring
- Identifying emerging Arctic vulnerabilities across scales

Questions?

Figure: Victor Leshyk

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Next steps: microbes in permafrost and in space

- Goal: To find, characterize and index the permafrost microbiome, developing a greater understanding of niches supporting life
- Sampling permafrost from 10-130,000 years old in Alaska
- Proof of concept in Greenland & on the Mars Perseverance a similar instrument (SHERLOC) with same laser system
- **If we can identify ancient, extremophile organisms on Earth, successful recovery from similar extraplanetary environments may be possible**

SHERLOC

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