SAND2022-7671C

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Mapping Arctic Marine Greenhouse Gas Emissions for Use as a Source Term in Global Climate and Earth System Models

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William K. Eymold, Michael A. Nole, Benjamin Wagman, Thomas M. Marchitto

ESCO 2022

Advanced Computational Methods for Climate Modeling and Analysis

SAND2022-xxxx

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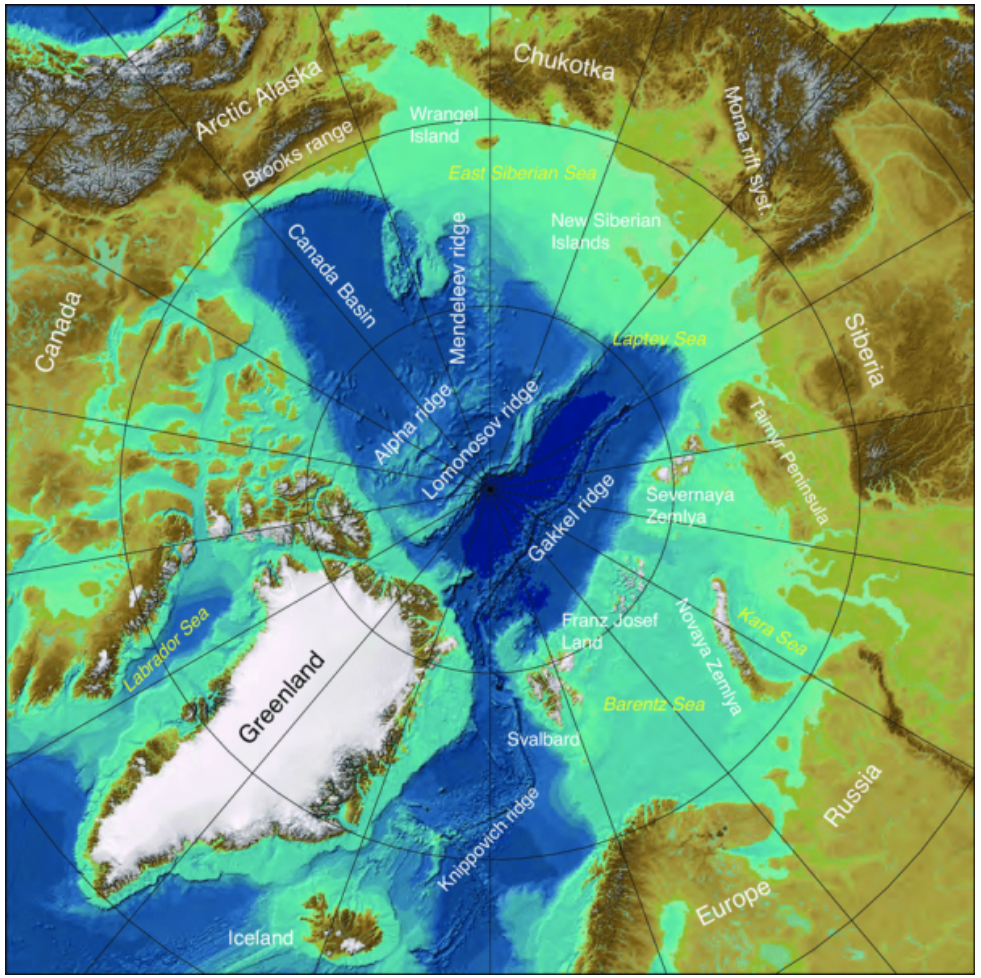
The Ice Age Arctic 18,000 Years Ago

Sea level was ~130 m lower and large portions of the shallow continental shelf were exposed as land.

The Bering Land Bridge

National Geographic

International Bathymetric Chart of the Arctic Ocean (IBCAO) of Jakobsson et al. (2008)



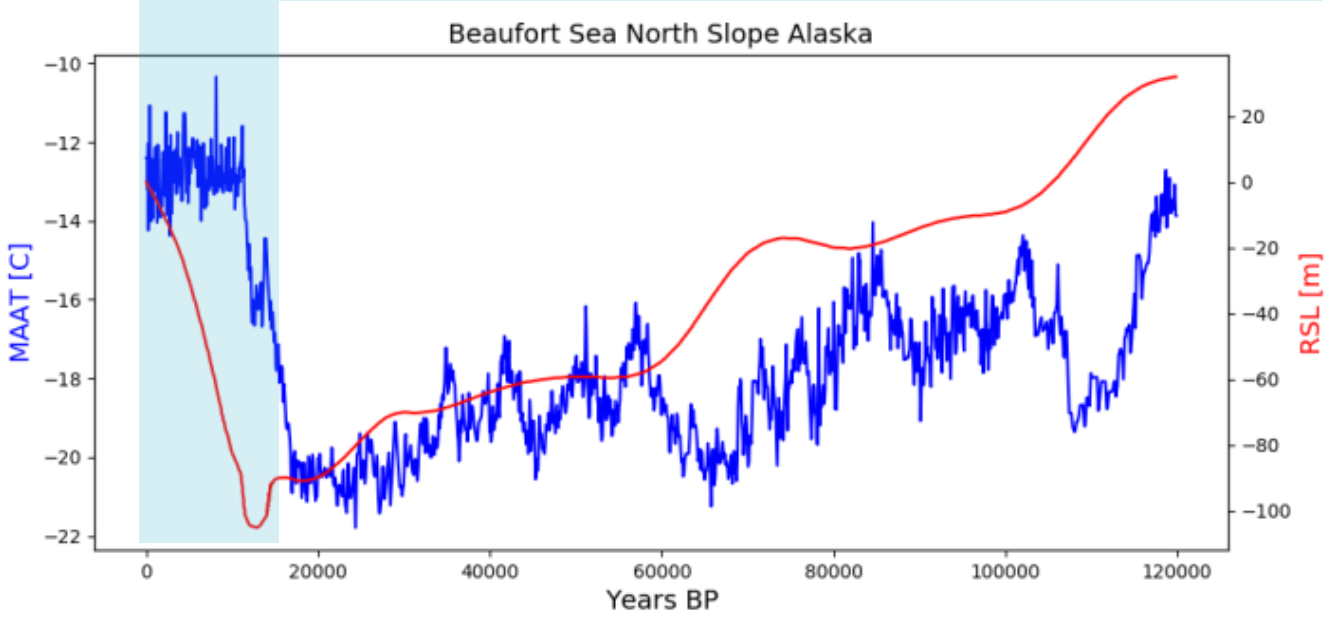
Modern Day Bathymetry

The Ice Age Arctic Warms Up

(natural, not anthropogenic)

Sea level has risen quickly as a result of warming.

Permafrost that formed on the exposed shelves was submerged, and is still thawing today!



Data comes from:
- Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok Ice Core, Antarctica, Nature, 399, 429–436.
- Zhang, T., T. E. Osterkamp, and K. Stamnes (1996), Some characteristics of the climate in Northern Alaska, U.S.A., Arctic Alpine Res., 28(4), 509–518.
- Peltier, W. R. (2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) Model and GRACE, Annu. Rev. Earth Planet. Sci., 32, 111–149.
- Kendall, R. A., J. X. Mitrovica, and G. A. Milne (2005), On post-glacial sea level—II. Numerical formulation and comparative results on spherically symmetric models, Geophys. J. Int., 161, 679–706.

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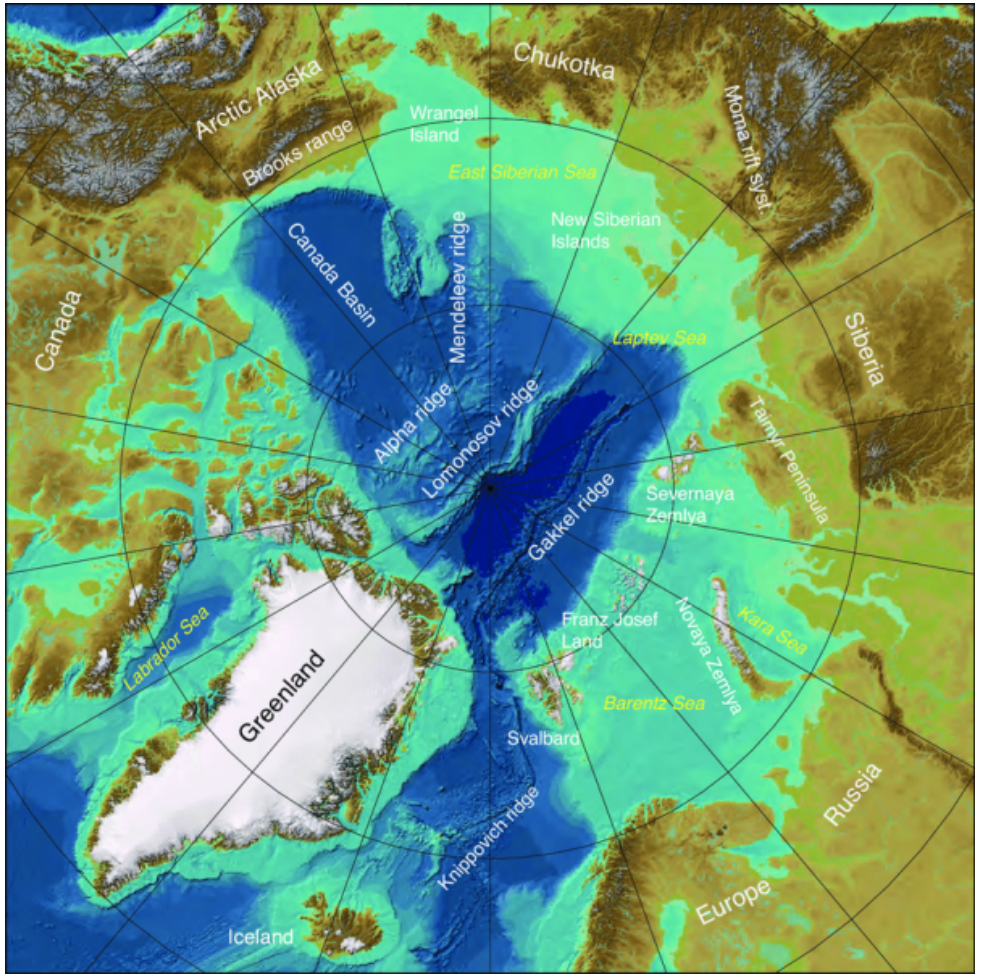
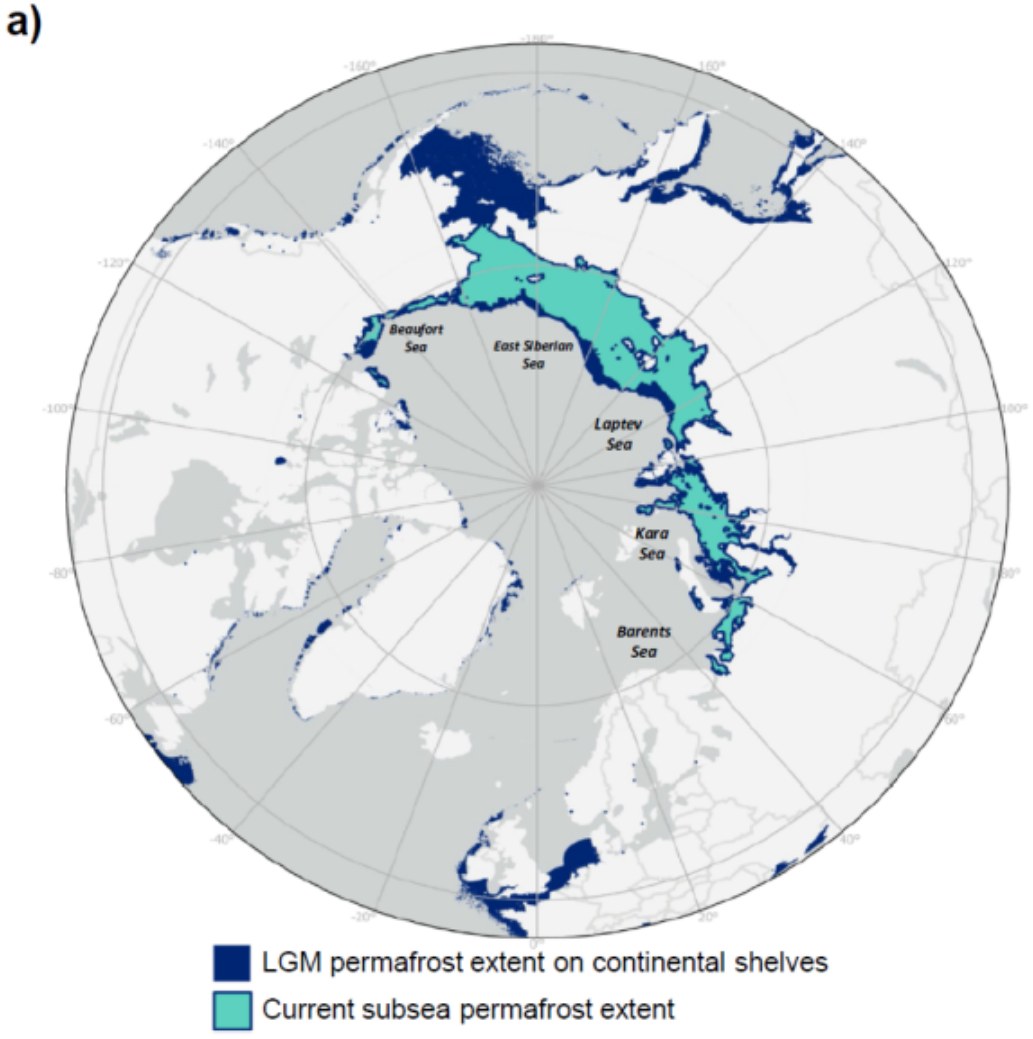
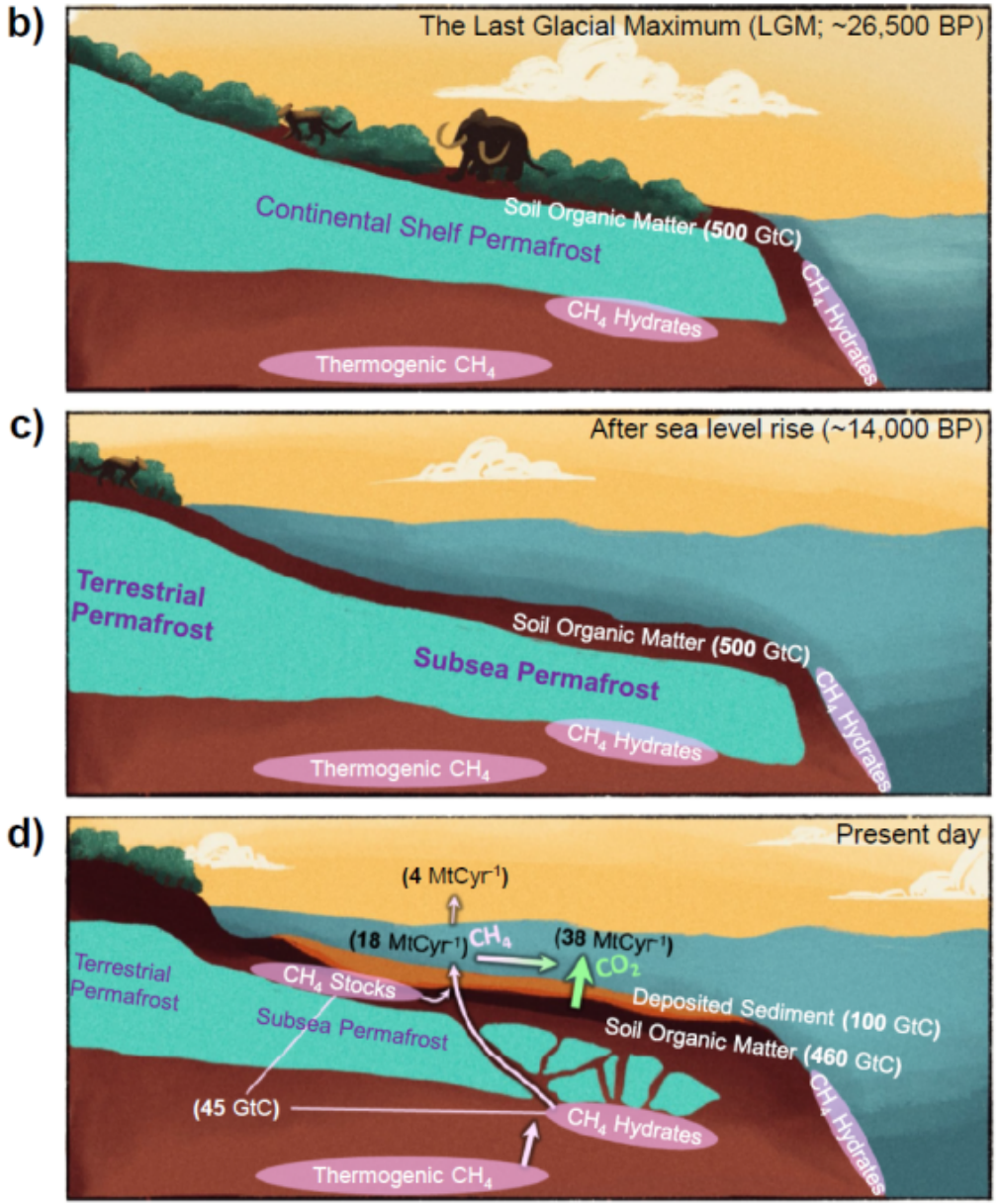


Modern Day Bathymetry

Submarine Permafrost

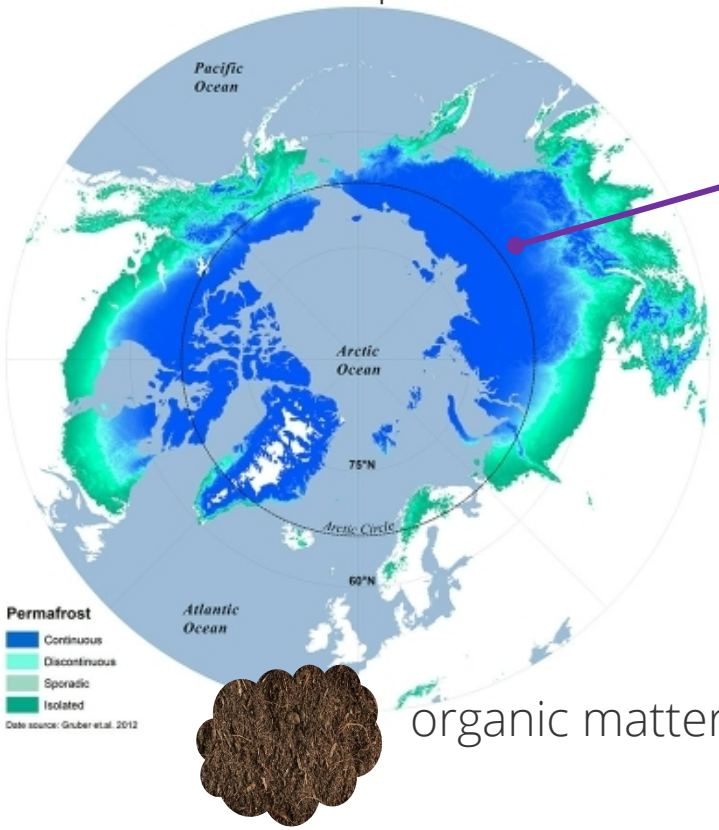




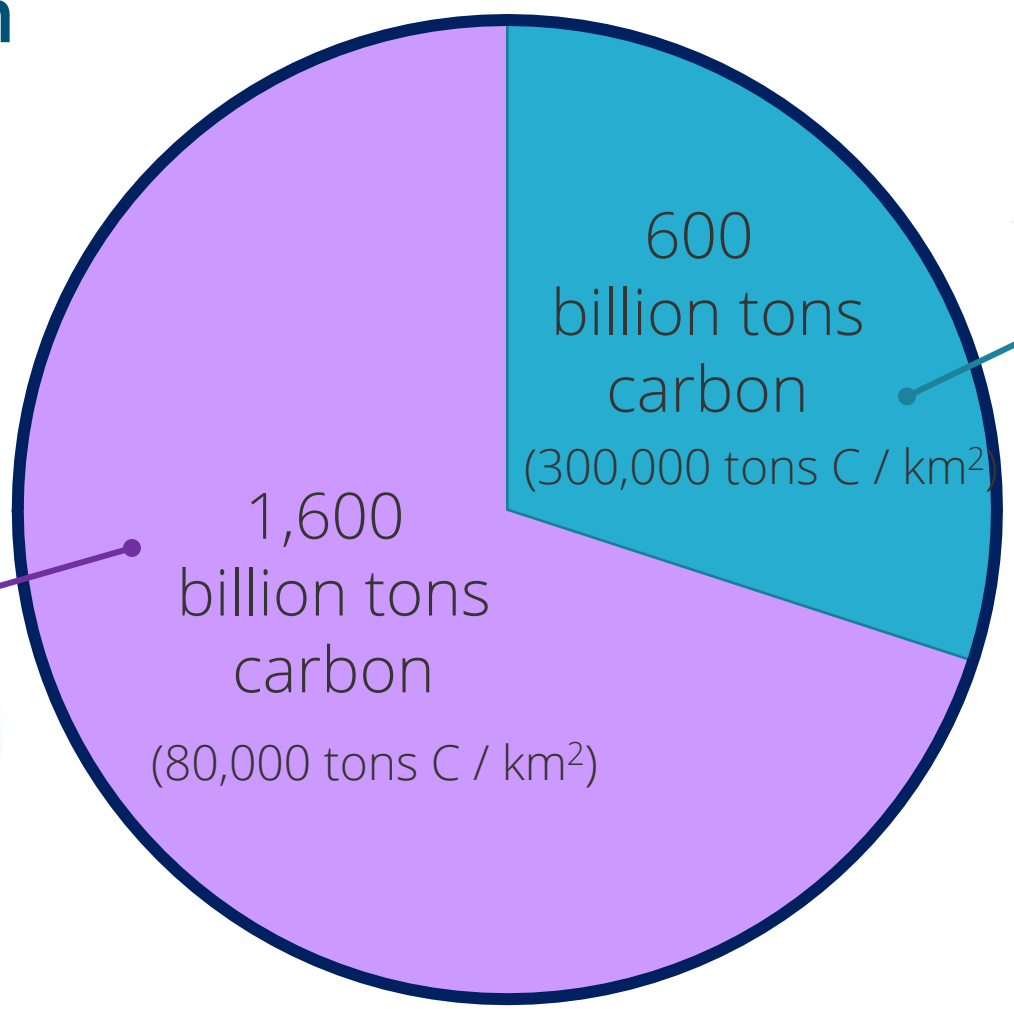
Sayedi et al. (2020), Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment, *Environmental Research Letters*, https://doi.org/10.1088/1748-9326/abcc29.

Permafrost is Carbon-Rich

Terrestrial permafrost

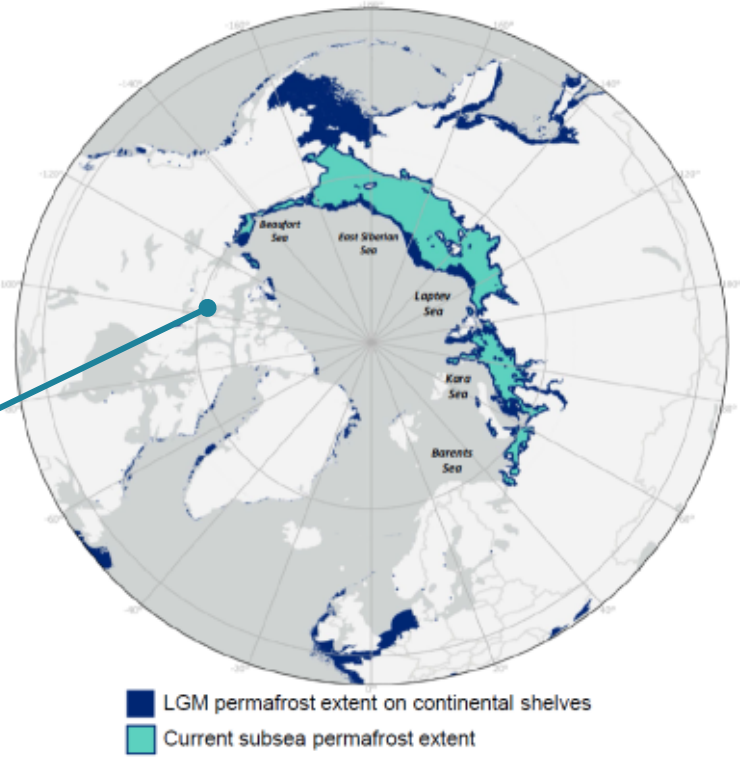


organic matter



How much carbon is stored?

Submarine permafrost



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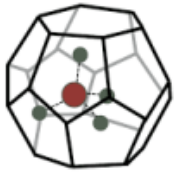
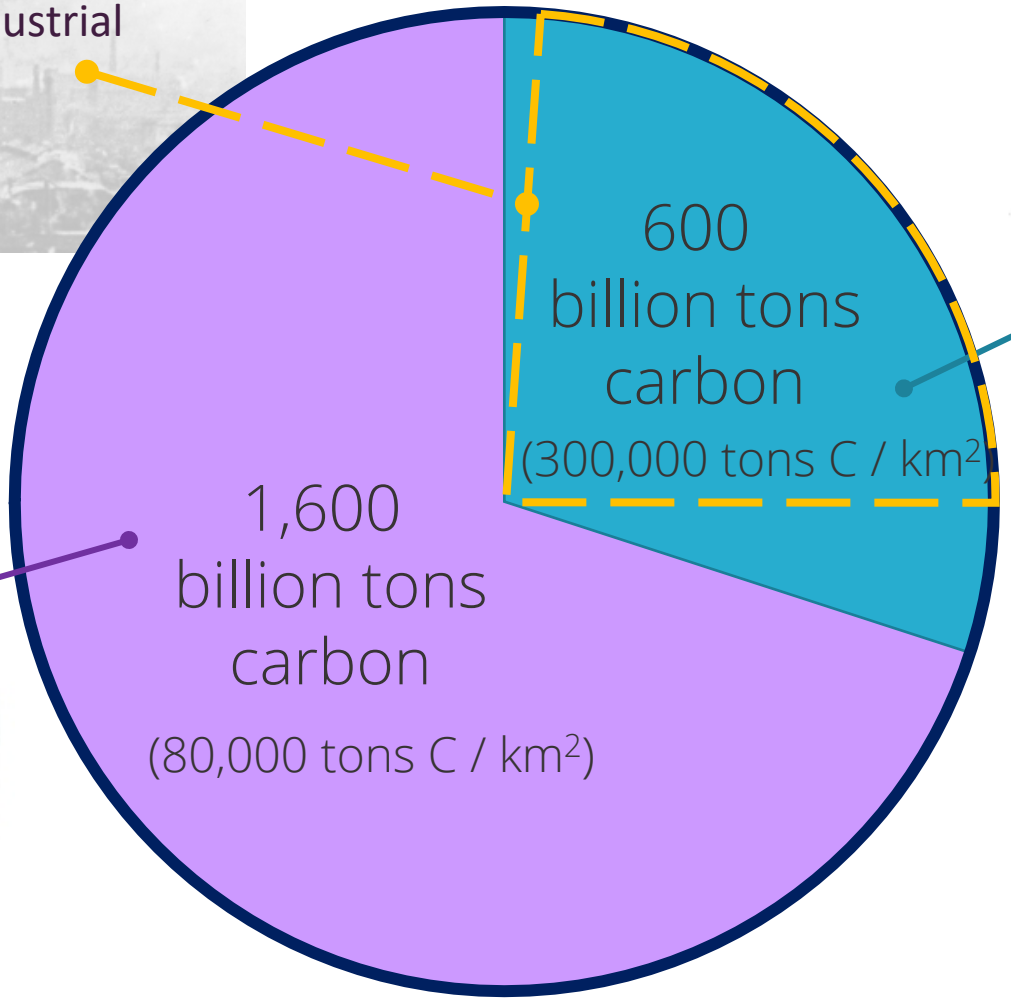


methane hydrate

Humans have released about **500 billion tons** of carbon into the atmosphere since the Industrial Revolution.

How much carbon is stored?



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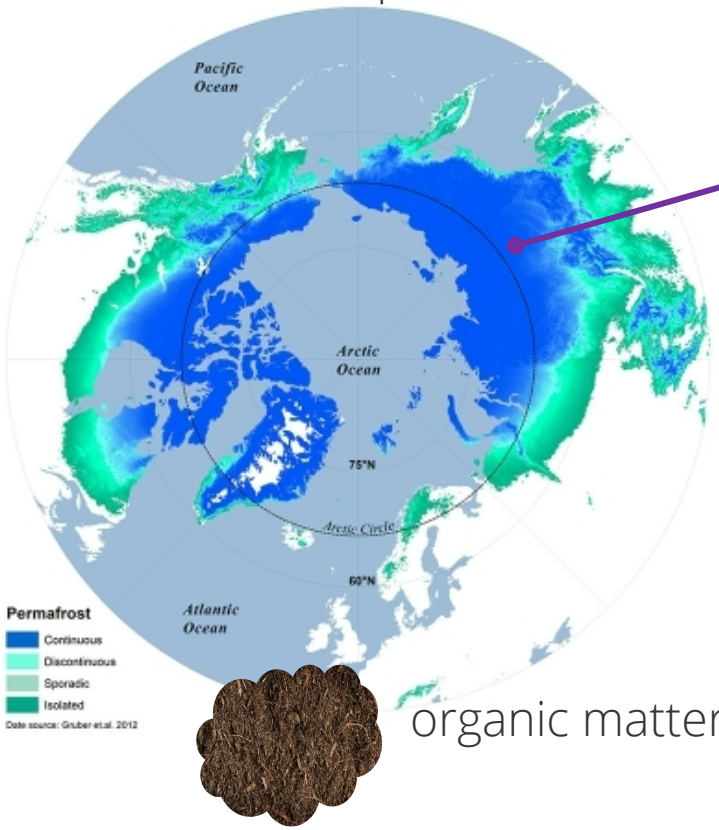

organic matter

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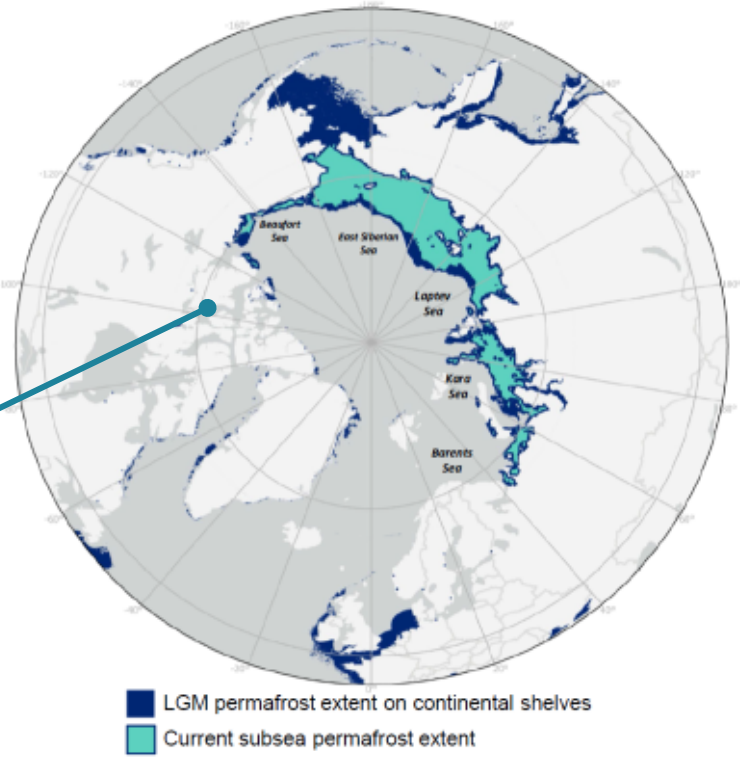

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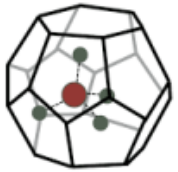

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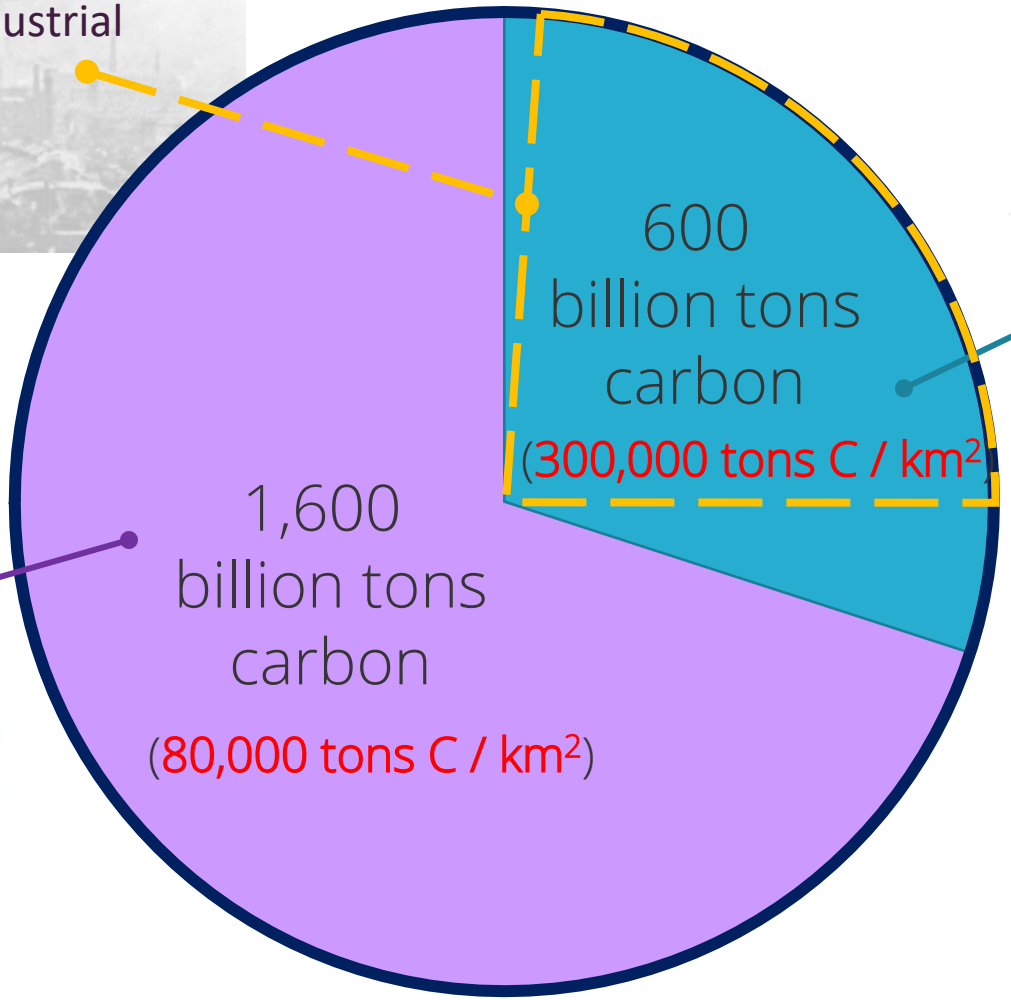

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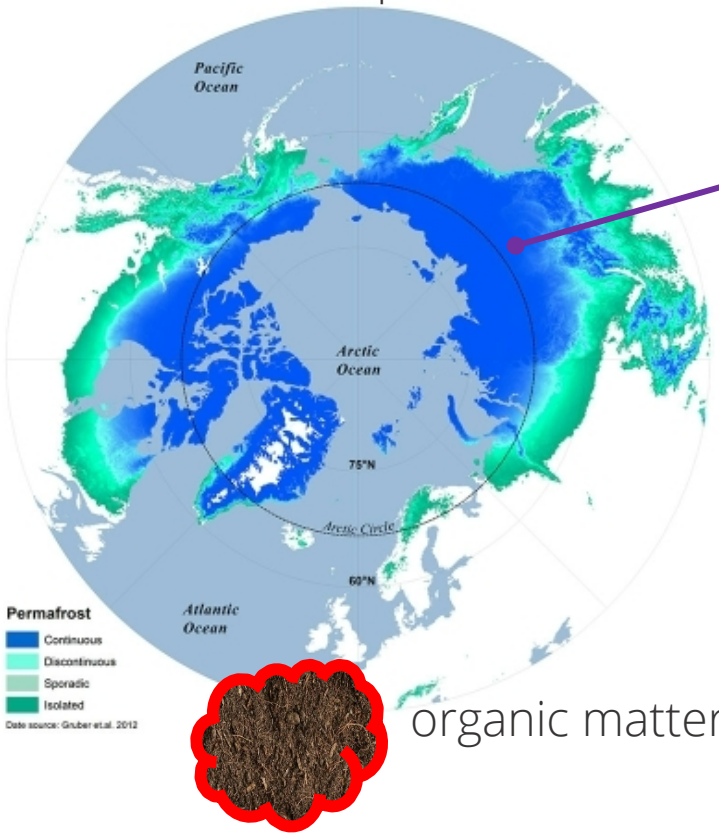


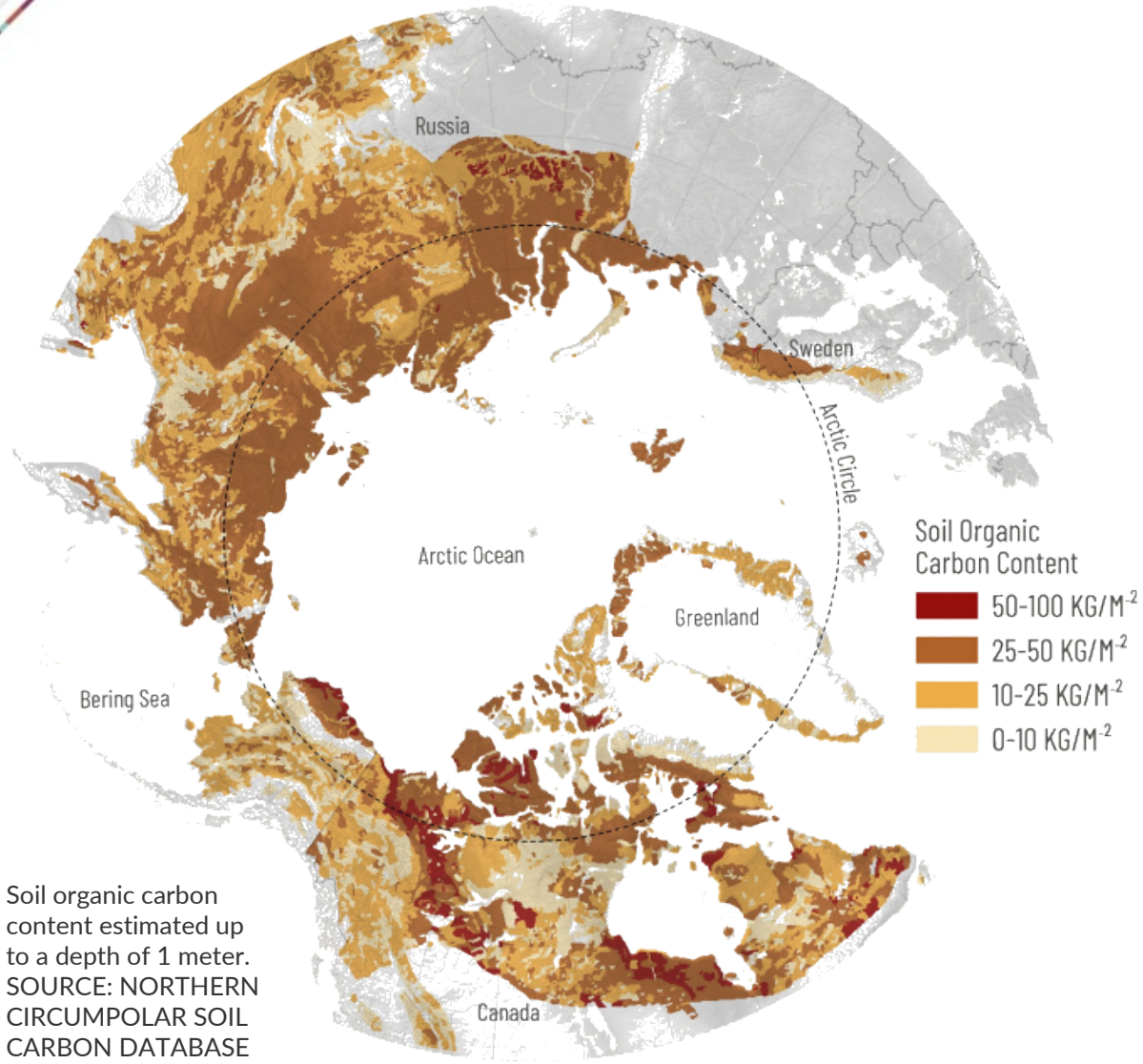
organic matter

Submarine permafrost

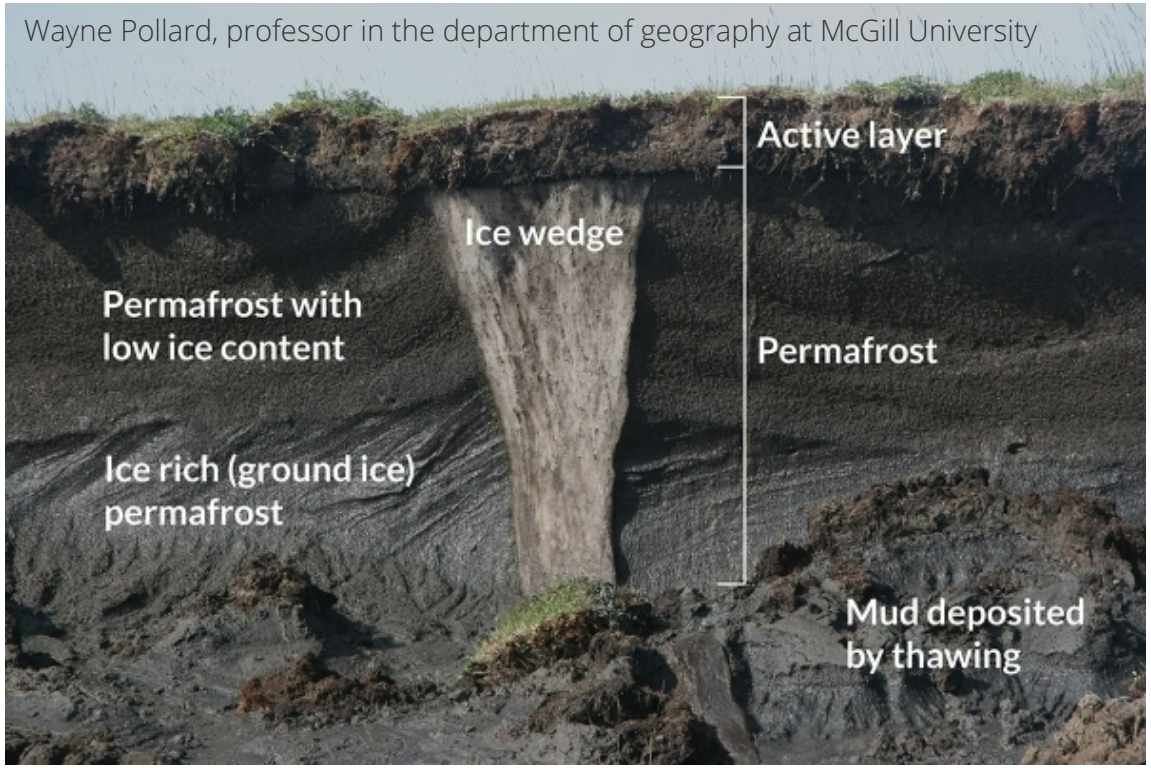
organic matter

methane hydrate

Permafrost-Associated Carbon Stocks

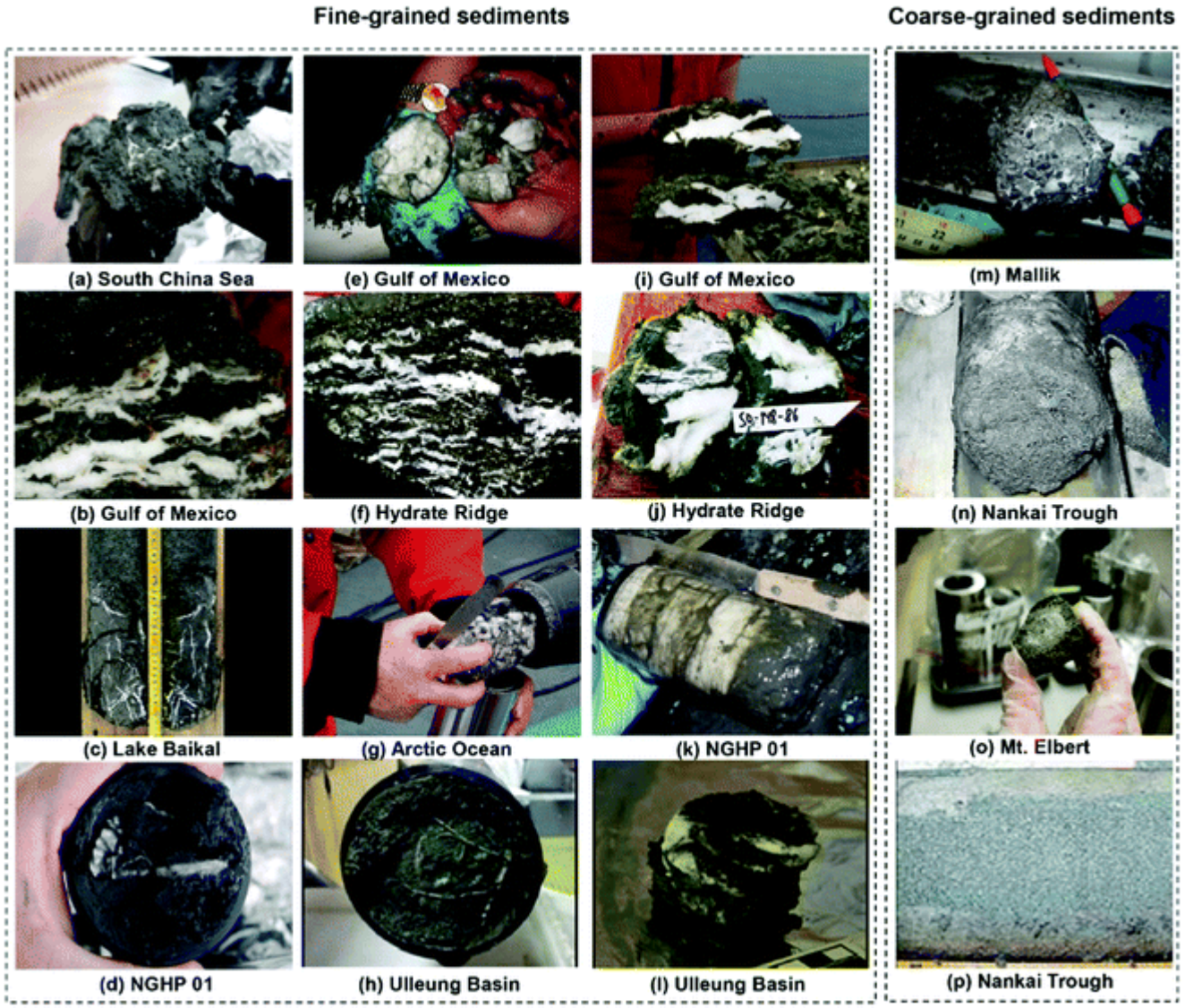


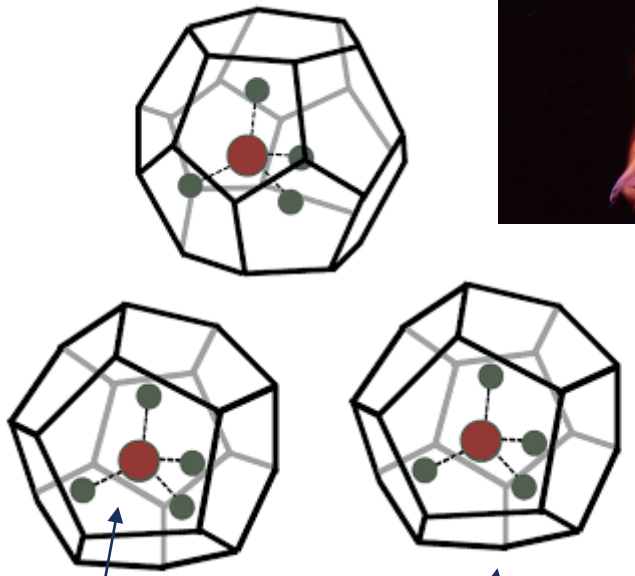
Soil organic carbon content estimated up to a depth of 1 meter. SOURCE: NORTHERN CIRCUMPOLAR SOIL CARBON DATABASE PERMAFROST CARBON NETWORK



Experts estimate that the submarine permafrost domain contains 560 gigatons carbon (GtC; 170–740, 90% confidence interval) in organic matter and 45 GtC (10–110) in CH_4.

Permafrost-Associated Methane Gas Hydrate



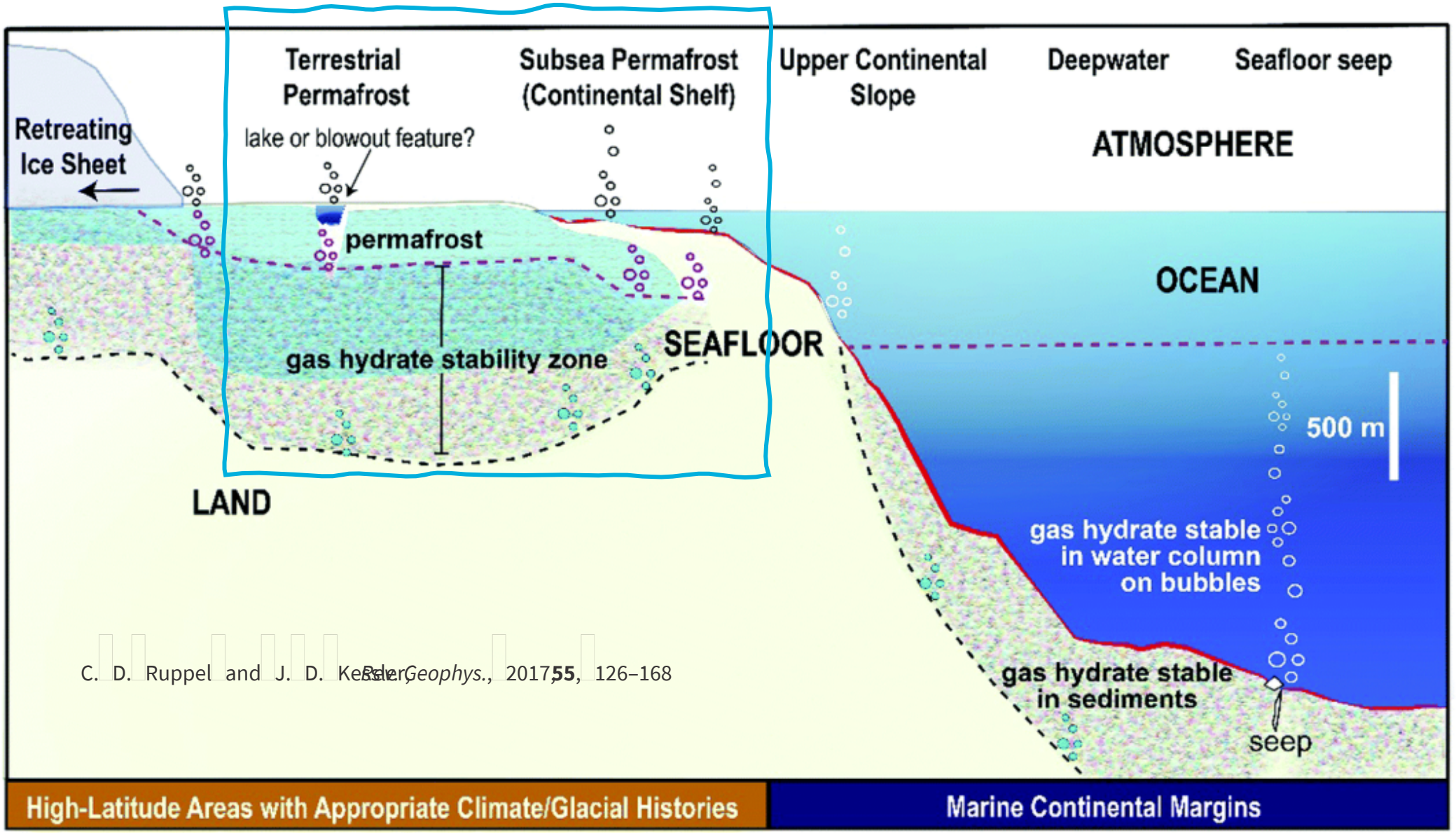


Methane gas

Ice crystal

1L hydrate at depth holds equivalent of 170L methane gas at STP.

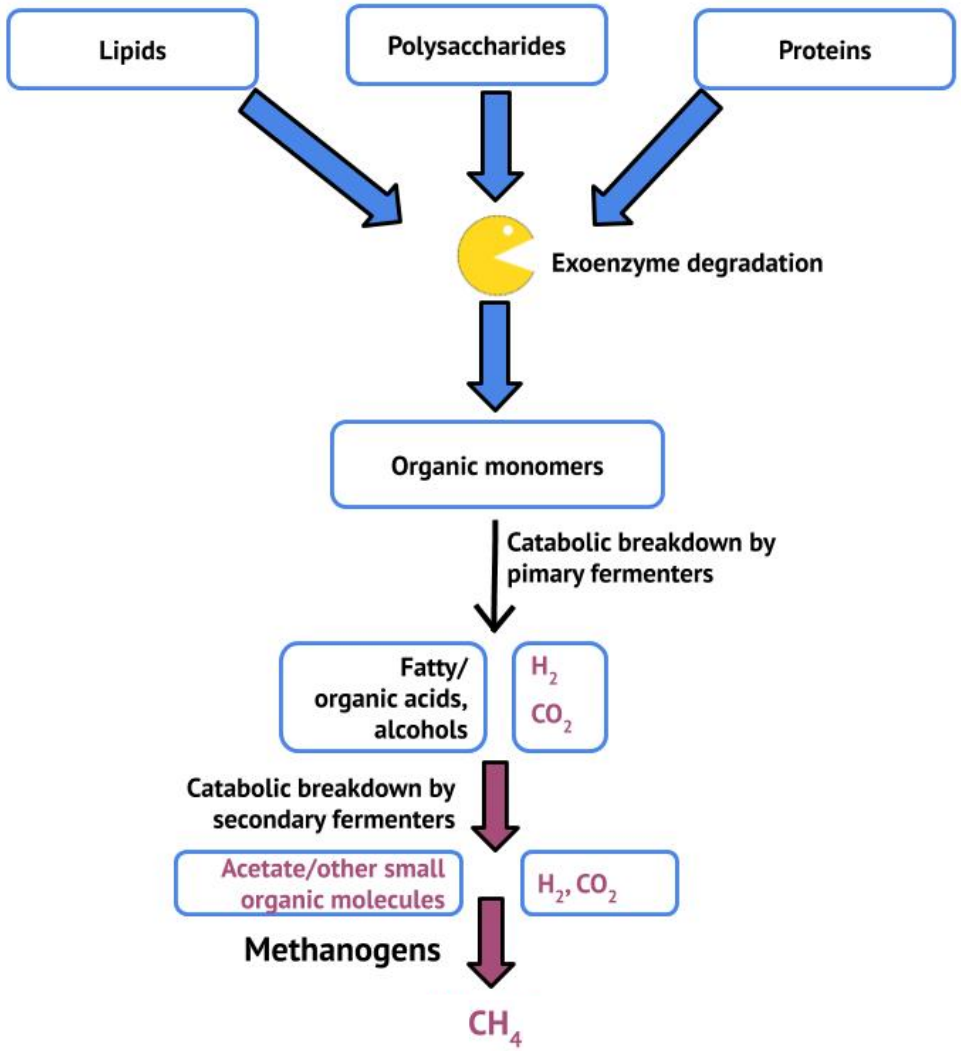
Permafrost-Associated Methane Gas Hydrate

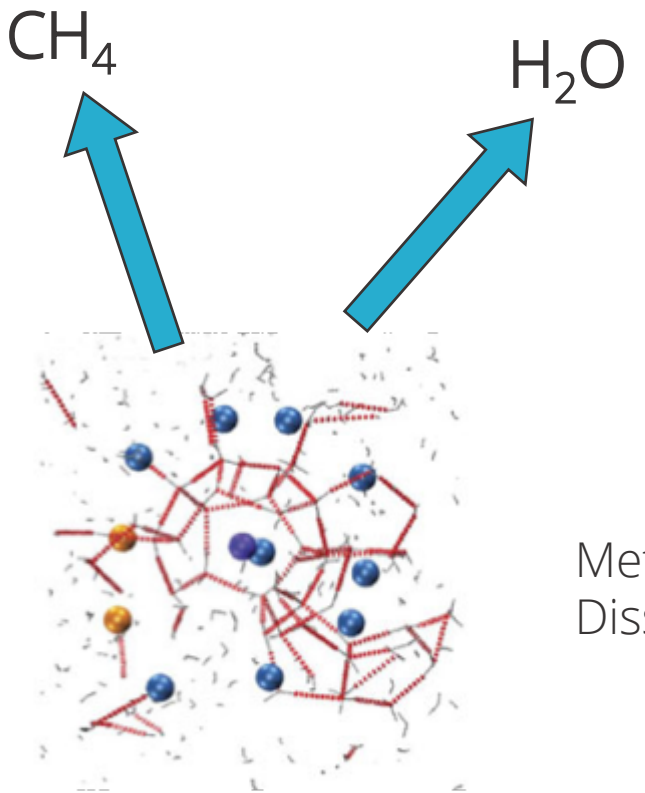


C. D. Ruppel and J. D. Kessler, *Rev. Geophys.*, 2017, **55**, 126–168

Thawing Permafrost, Dissociating Methane Gas Hydrate

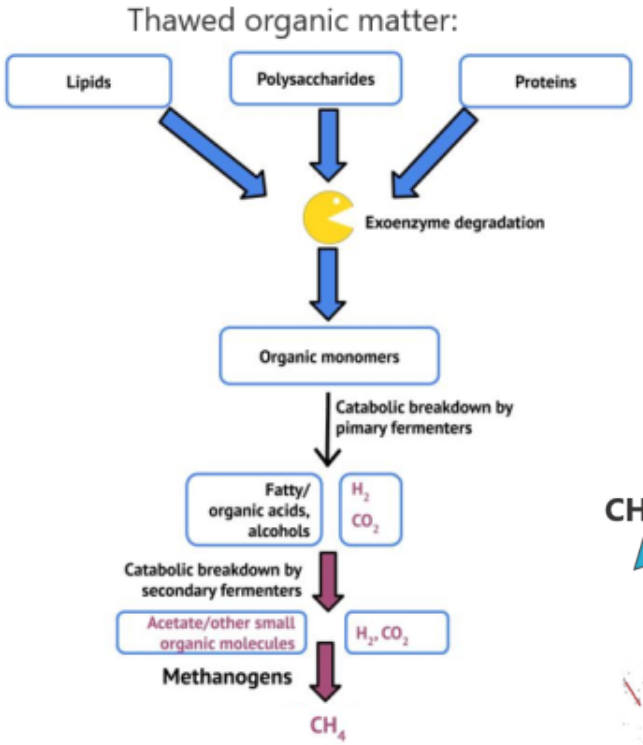
Thawed organic matter:

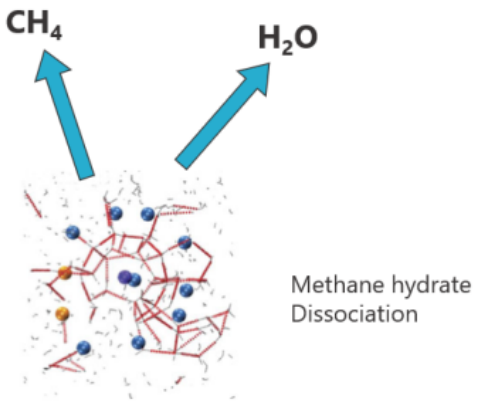




Methane hydrate
Dissociation

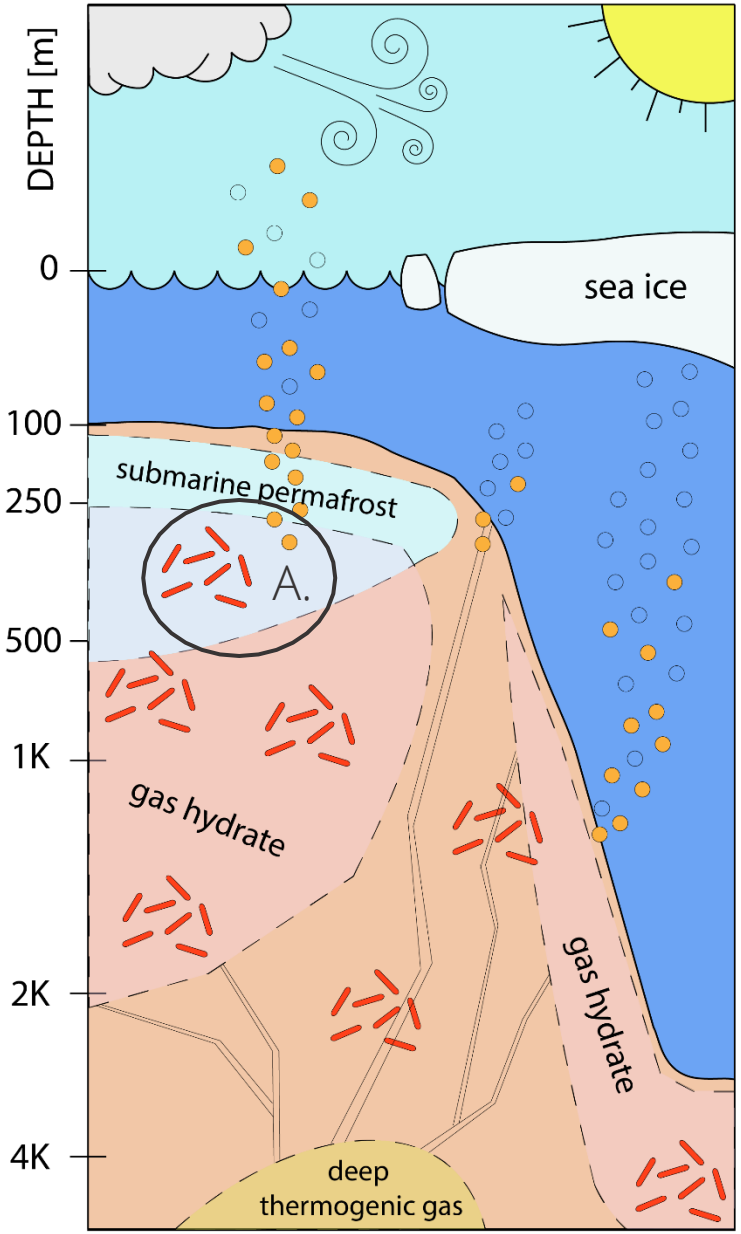
As the Arctic Warms, How Much Gas Will Be Released?





Methane hydrate Dissociation

The Fate of Methane Produced in the Marine Environment



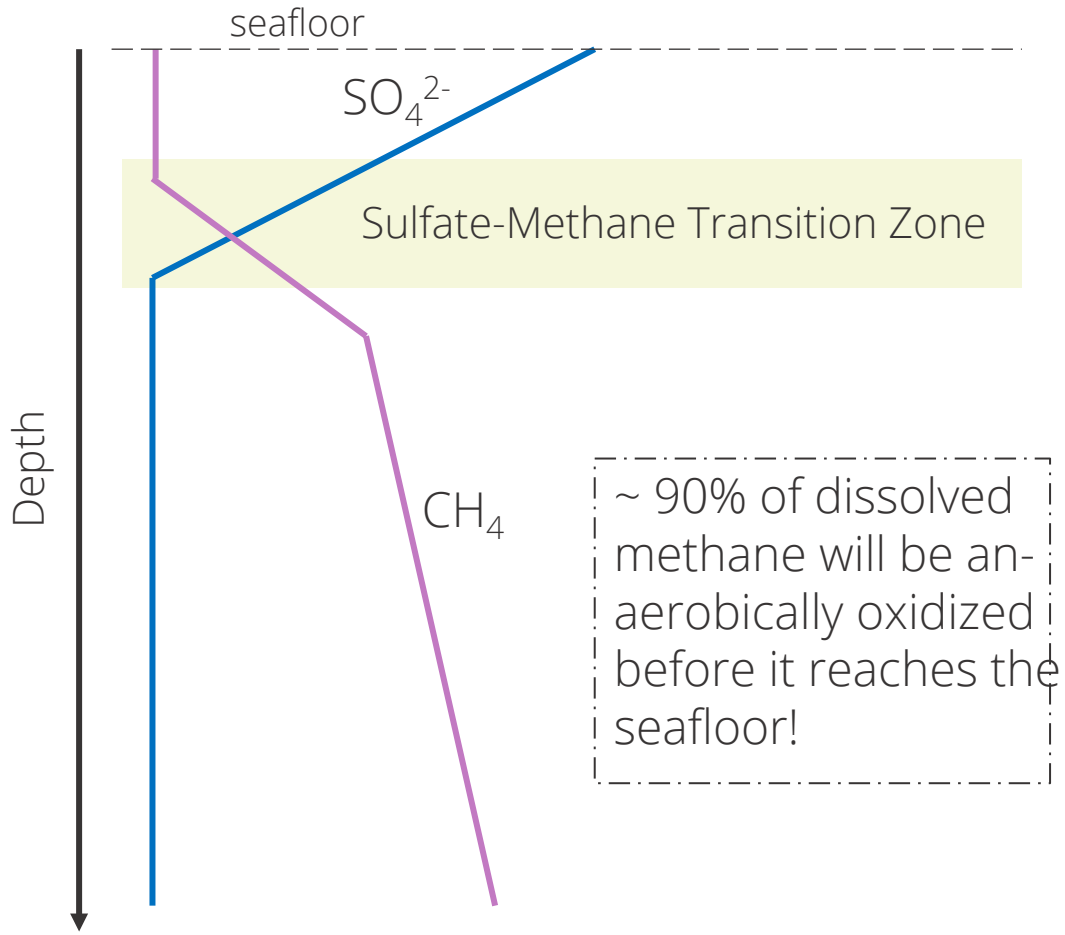
Original figure by J. M. Frederick.

A. Sources of methane

Organic matter in the sediments is consumed by methanotrophs, producing methane that is sequestered in gas hydrate. Deep thermogenic gas can also feed hydrate reservoirs.

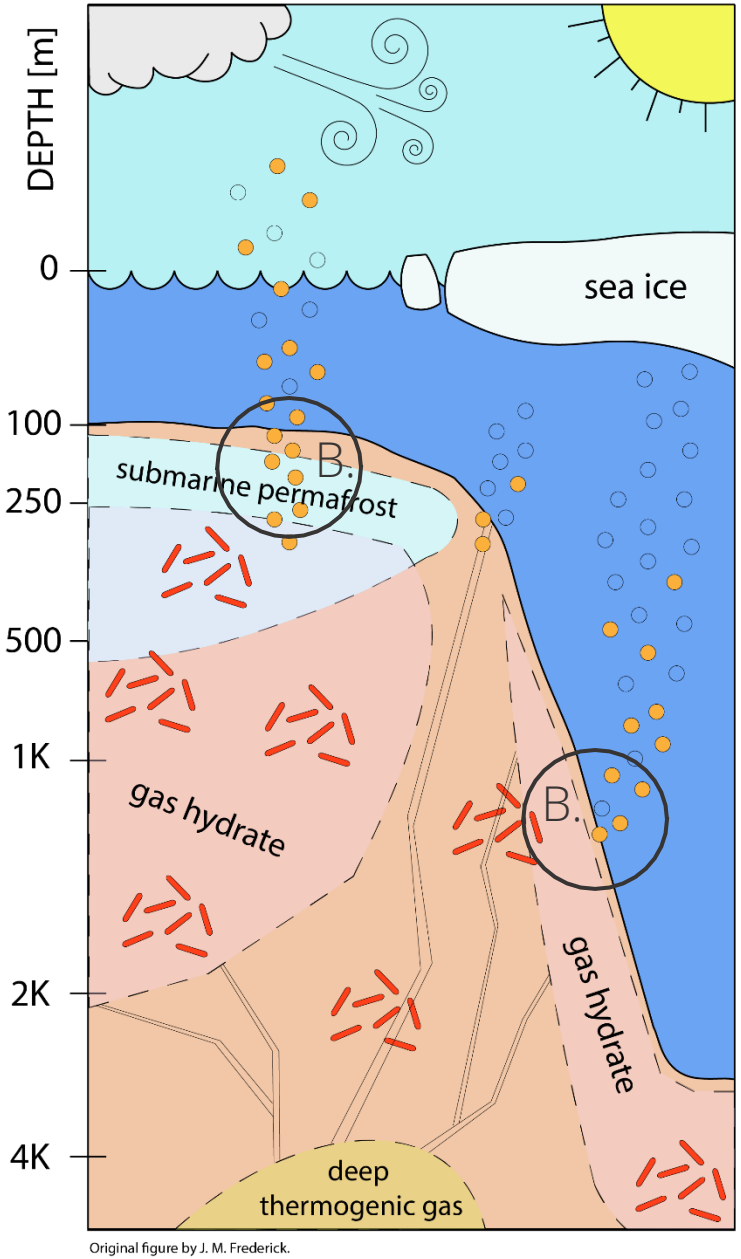
As the Arctic Warms, How Much Gas Will Be Released?

B.



~ 90% of dissolved methane will be anaerobically oxidized before it reaches the seafloor!

The Fate of Methane Produced in the Marine Environment



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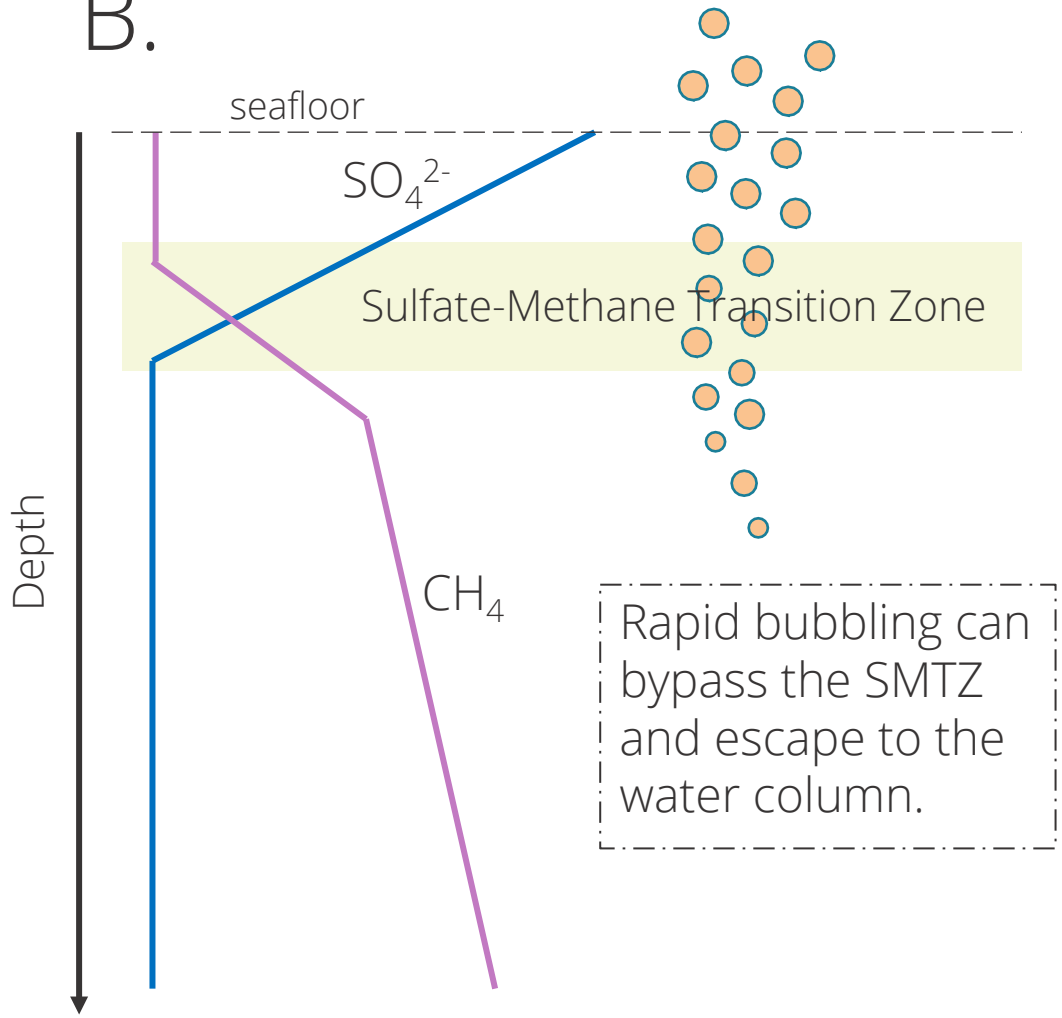
$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$

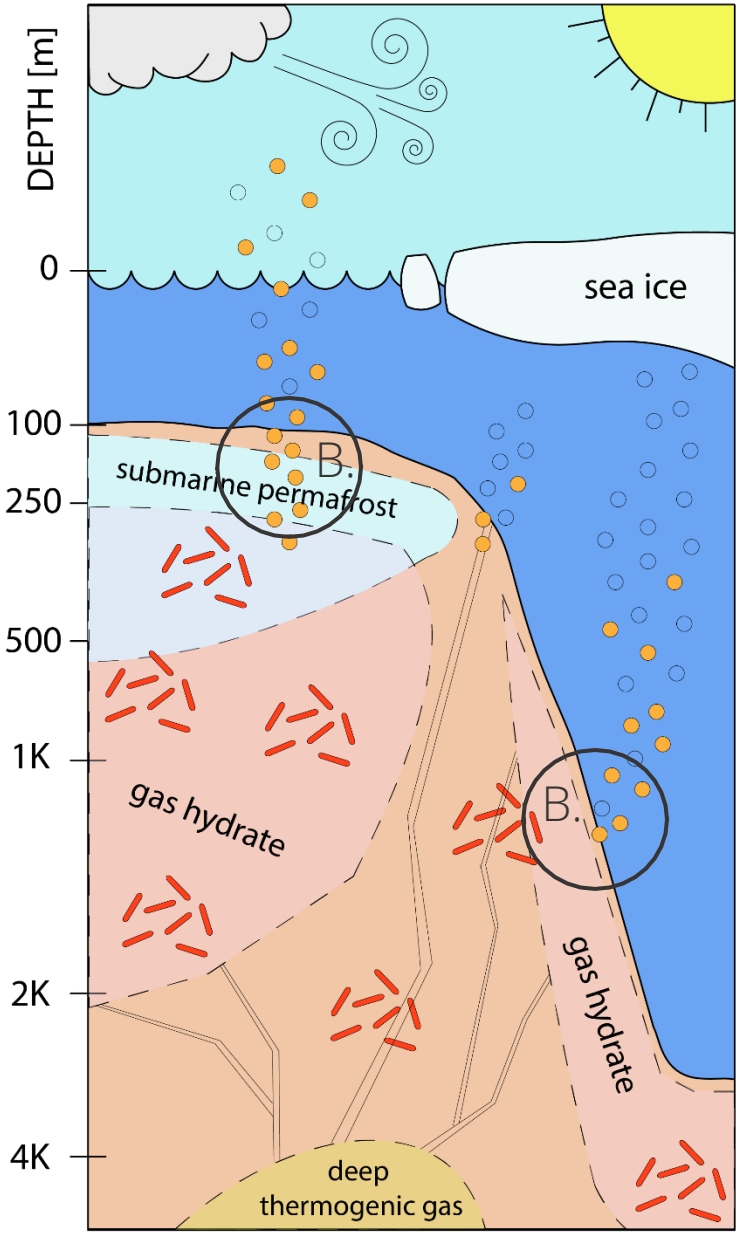
About 90% of dissolved methane flux is taken up by AOM, an effective biofilter. However, rapid advection as bubbles can bypass this filter.

As the Arctic Warms, How Much Gas Will Be Released?



Rapid bubbling can bypass the SMTZ and escape to the water column.

The Fate of Methane Produced in the Marine Environment



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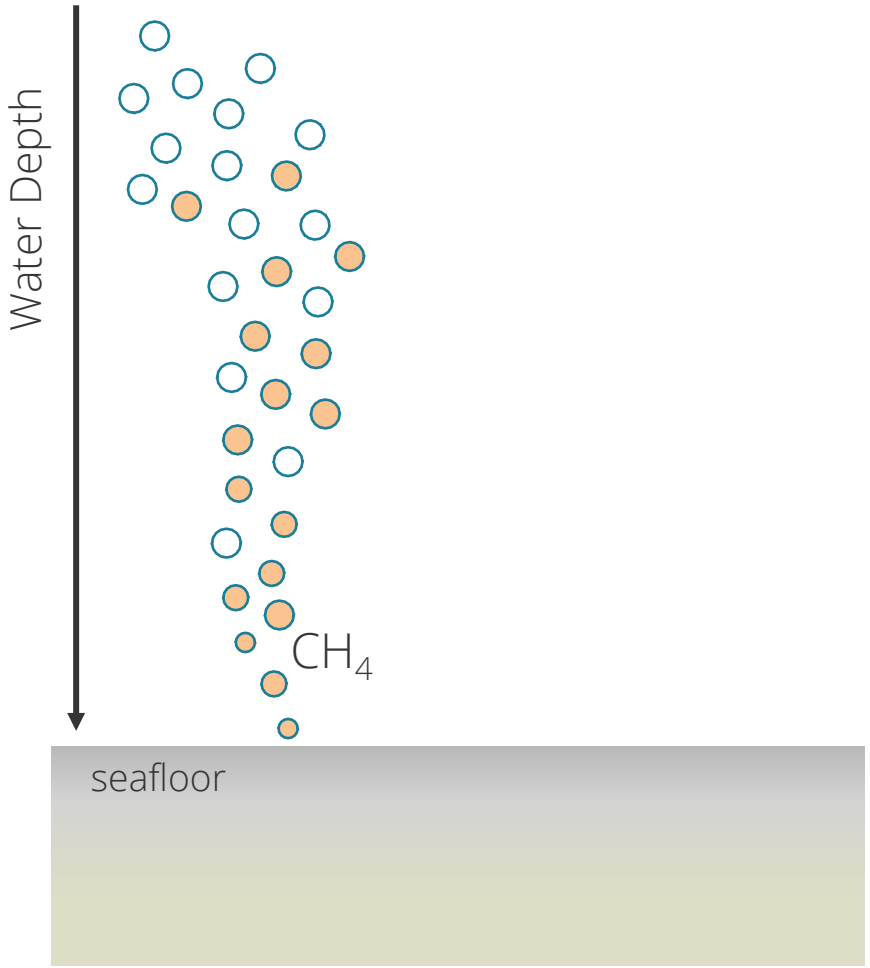

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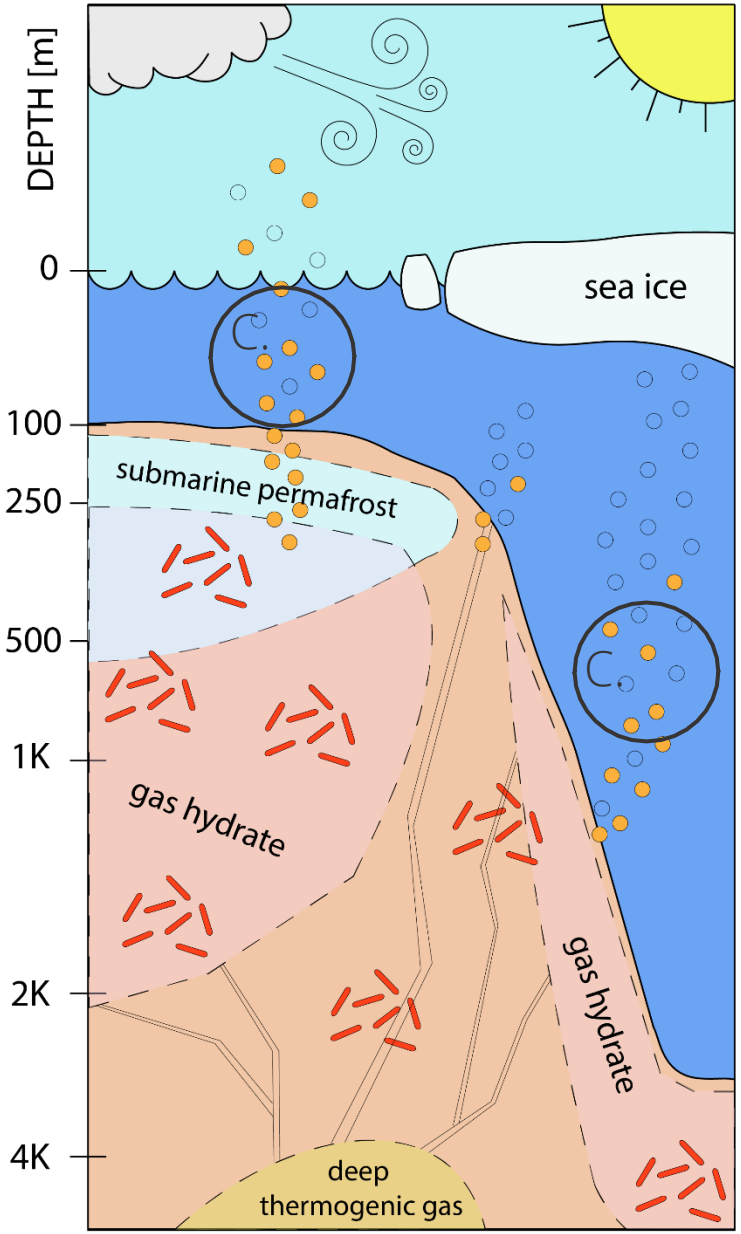

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C. Aerobic oxidation of methane in water column

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

As bubbles rise in the water column, methane is lost as it dissolves into the water and undergoes oxidation.

As the Arctic Warms, How Much Gas Will Be Released?

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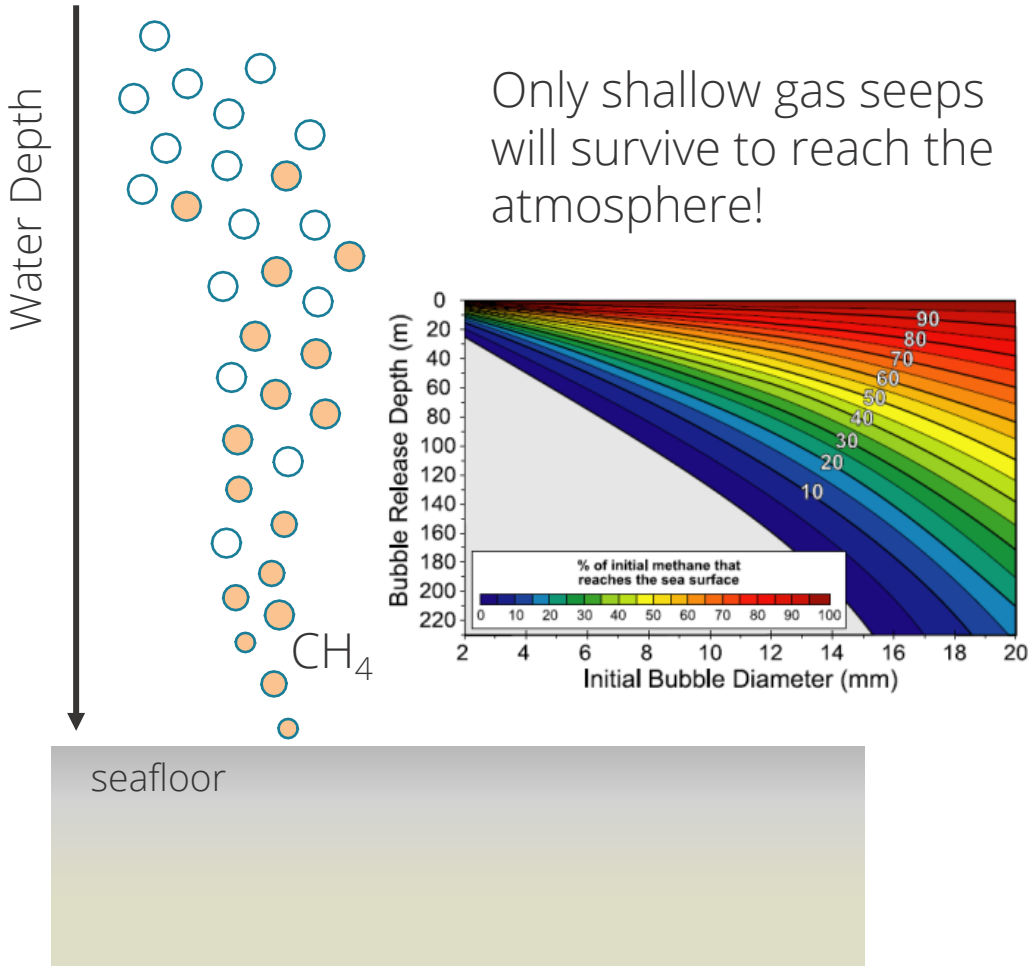
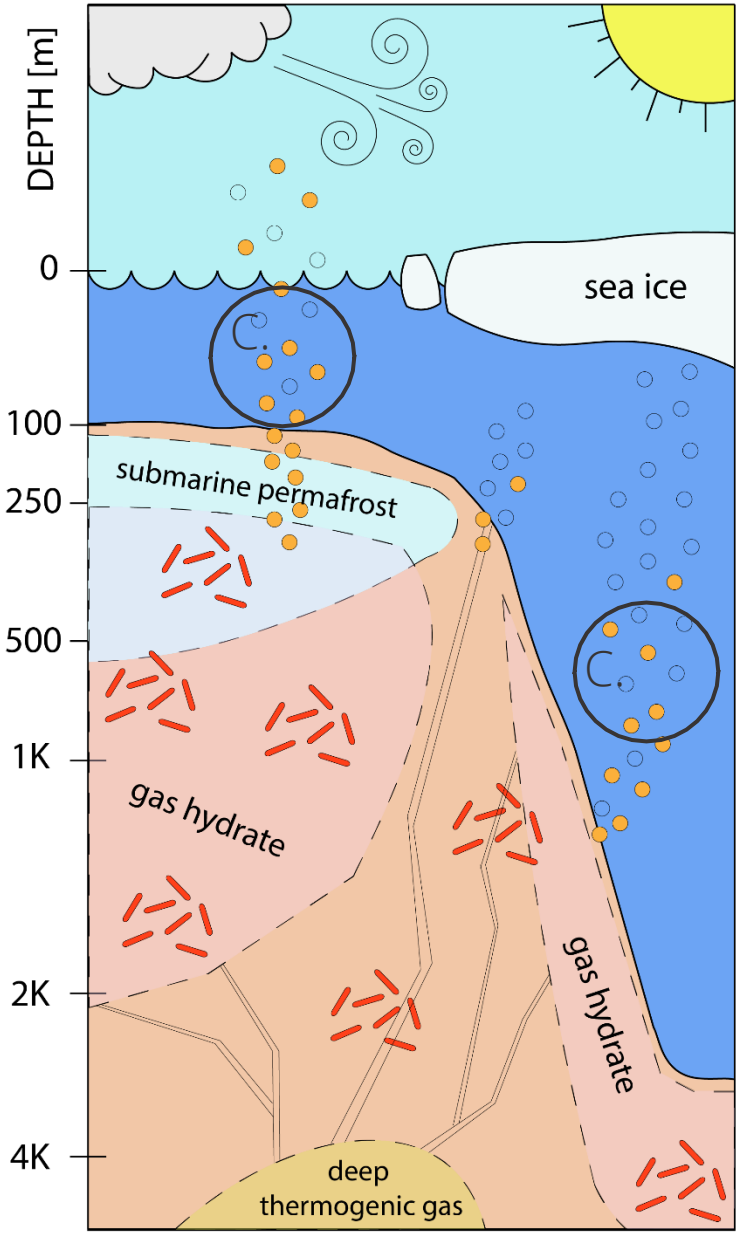


Only shallow gas seeps will survive to reach the atmosphere!

The Fate of Methane Produced in the Marine Environment



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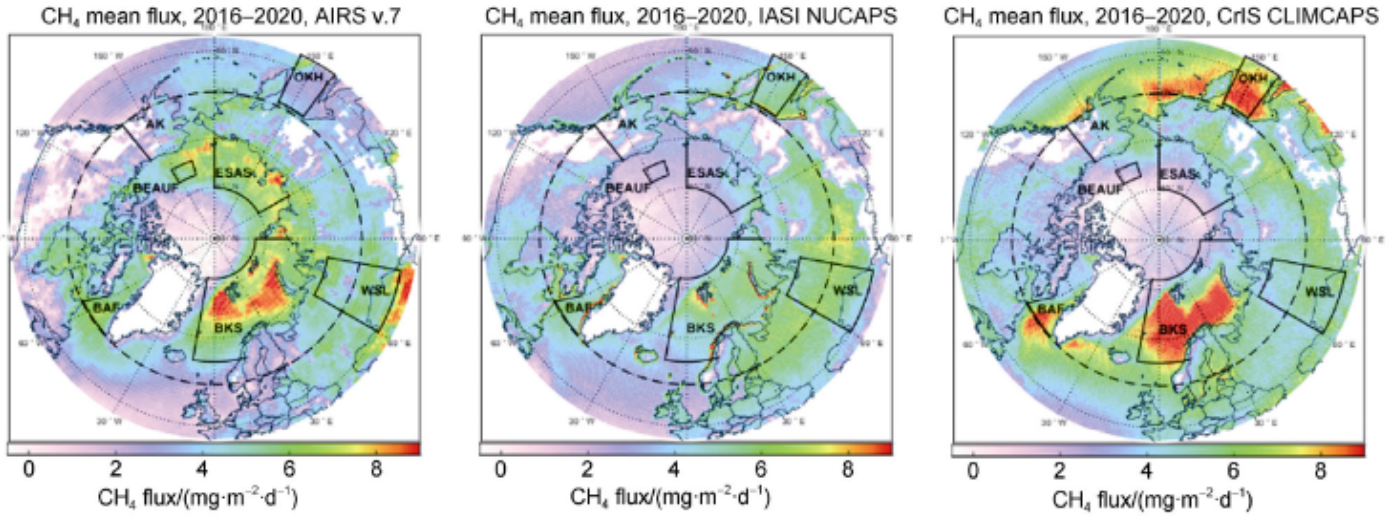
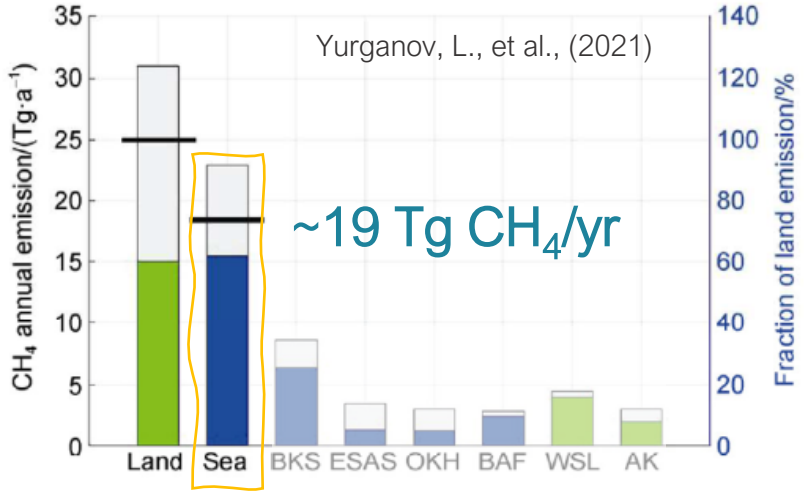
Estimating Modern Day Methane Emissions

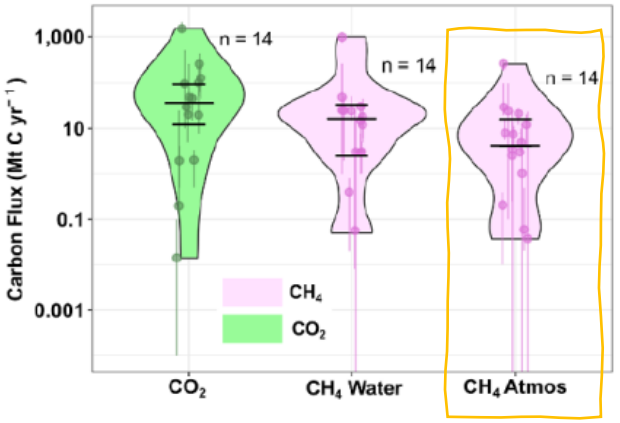
Yurganov, L., et al., (2021)





Averaged annual methane flux to atmosphere (excess over background) from three satellite instruments.

Modern annual methane flux from the sediments to the water column and atmosphere, based on expert assessment.



~3-16 Tg CH_4/yr

Sayedi, S. S., et al., (2020)

Modeling Modern Day Methane Emissions

Our Approach:

- Divide Arctic domain into 'pixels'
- Obtain physical characteristics (with uncertainty) for each pixel
  - GPSM - Geospatial machine learning maps
- Use statistical sampling software to create numerous realizations of each pixel
  - Dakota
- Run ensemble simulations using a thermodynamic numerical model for submarine permafrost and methane gas emissions
  - PFLOTRAN

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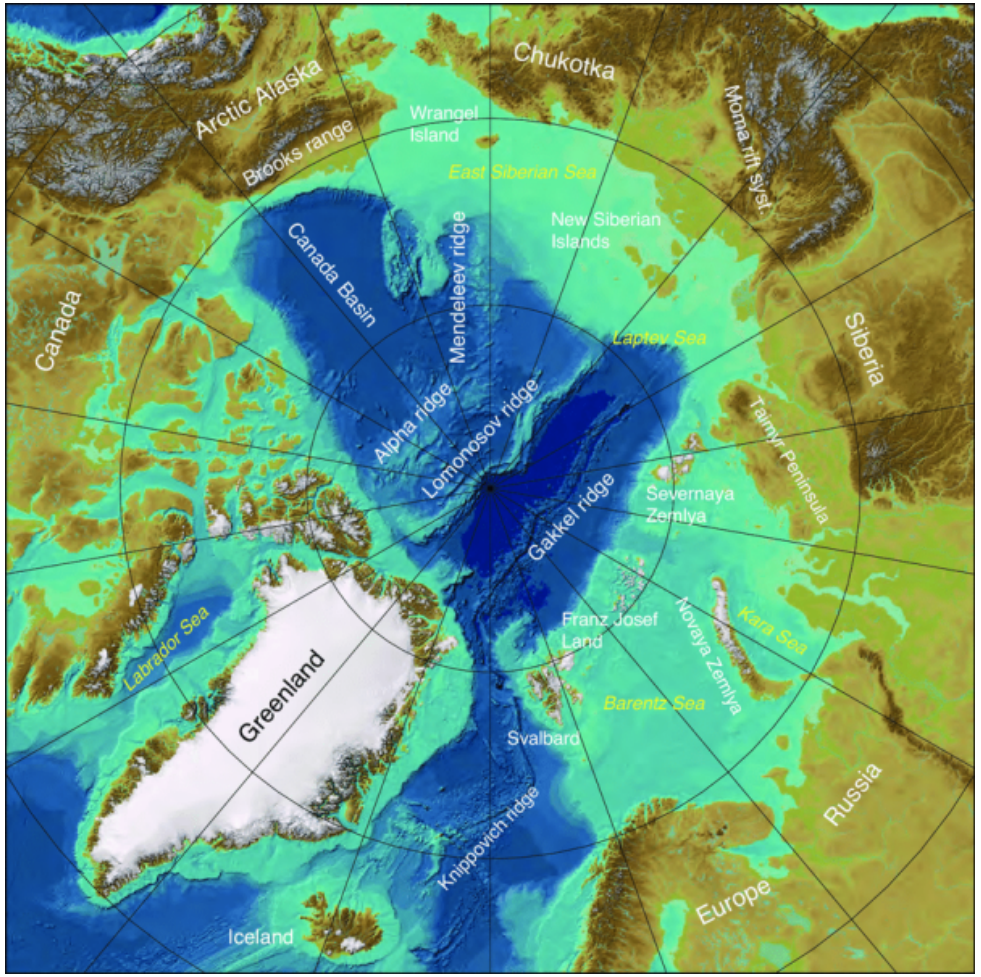
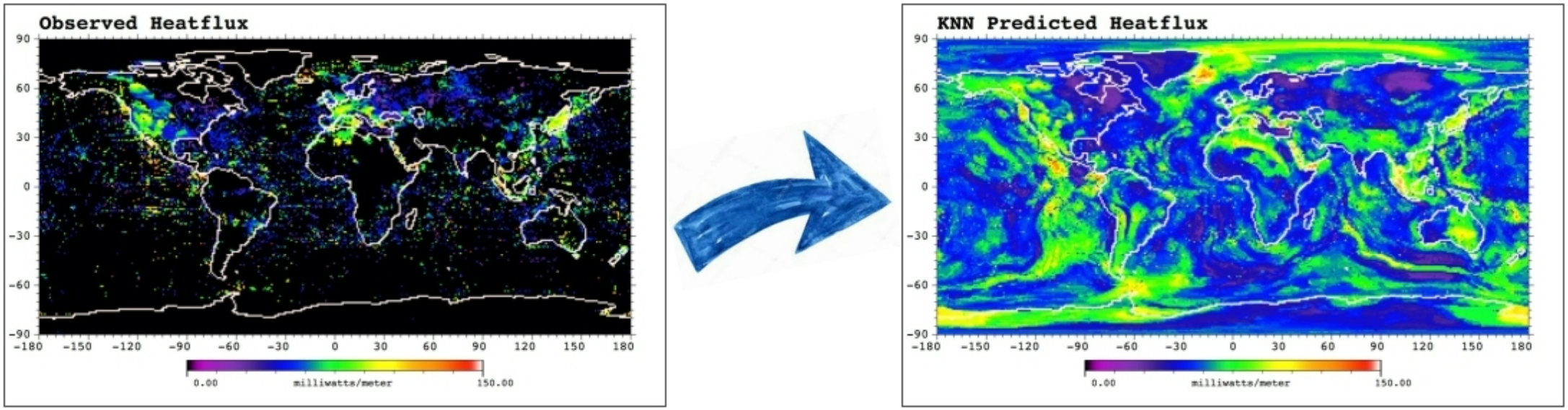


Modern Day Bathymetry

Global Predictive Seabed Model

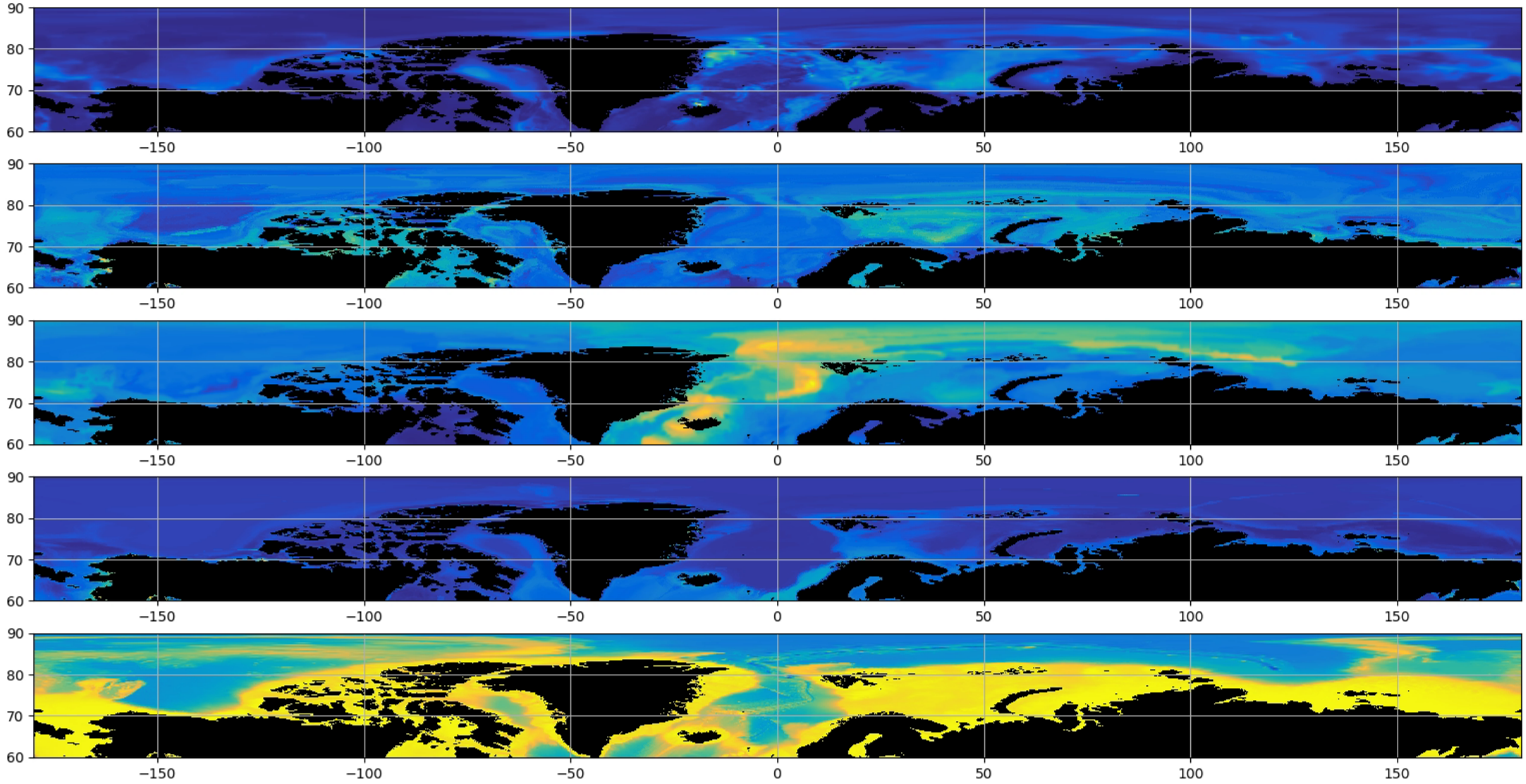
U.S. NAVAL RESEARCH LABORATORY



The Naval Research Laboratory's Global Predictive Seabed Model (GPSM) is a practical implementation of geospatial machine learning designed to provide near real-time estimates of Navy-relevant quantities from continuous seafloor property fields generated by machine learning algorithms (K-Nearest Neighbor, Random Forests, etc.) given often sparse measurements or direct observations compiled from widely available sources.
(Lee et al. 2019)

Global Predictive Seabed Model

U.S. NAVAL RESEARCH LABORATORY



Sedimentation Rate

Total Organic Carbon

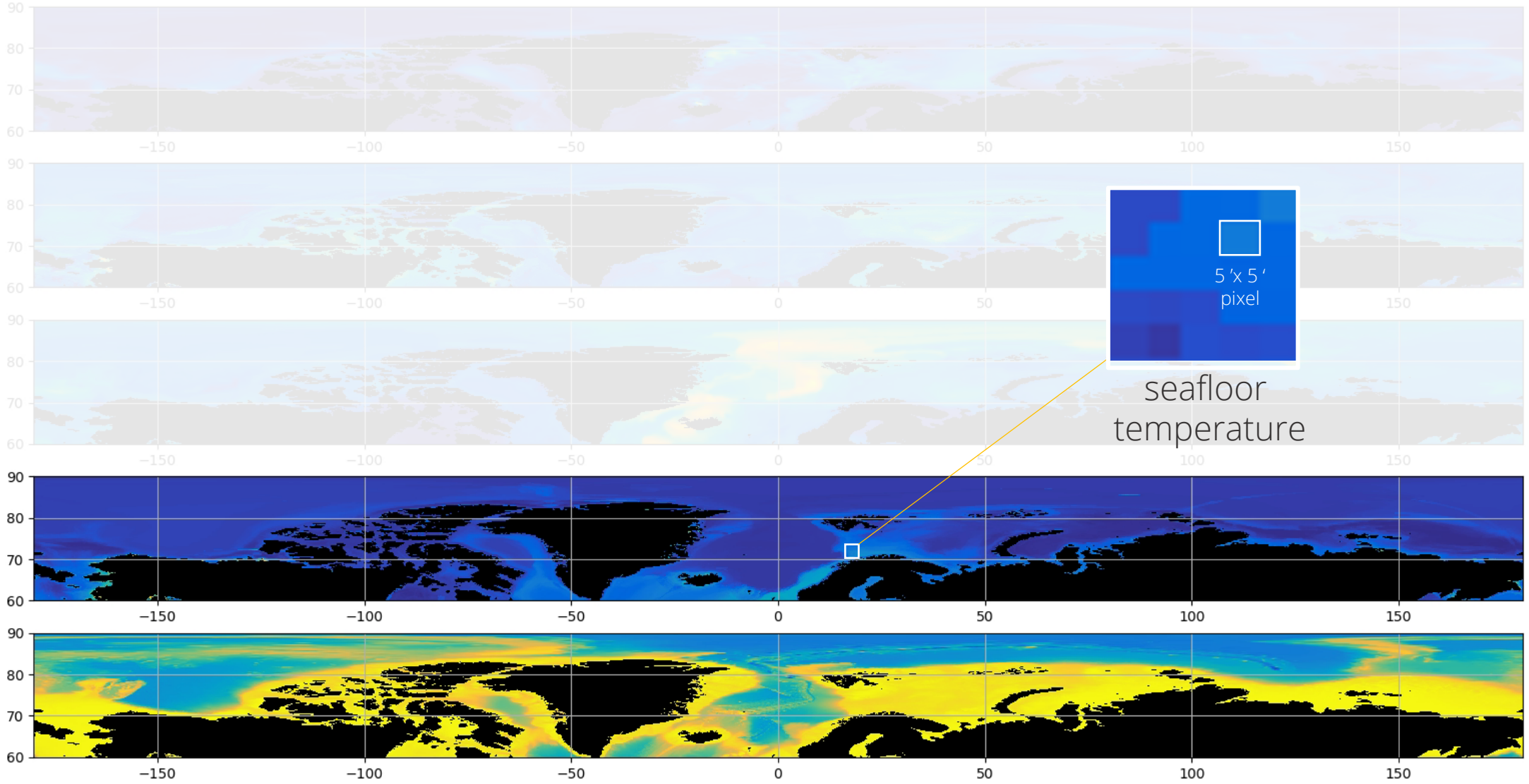
Heat Flux

Temperature

Depth (Pressure)

Global Predictive Seabed Model

U.S. NAVAL RESEARCH LABORATORY



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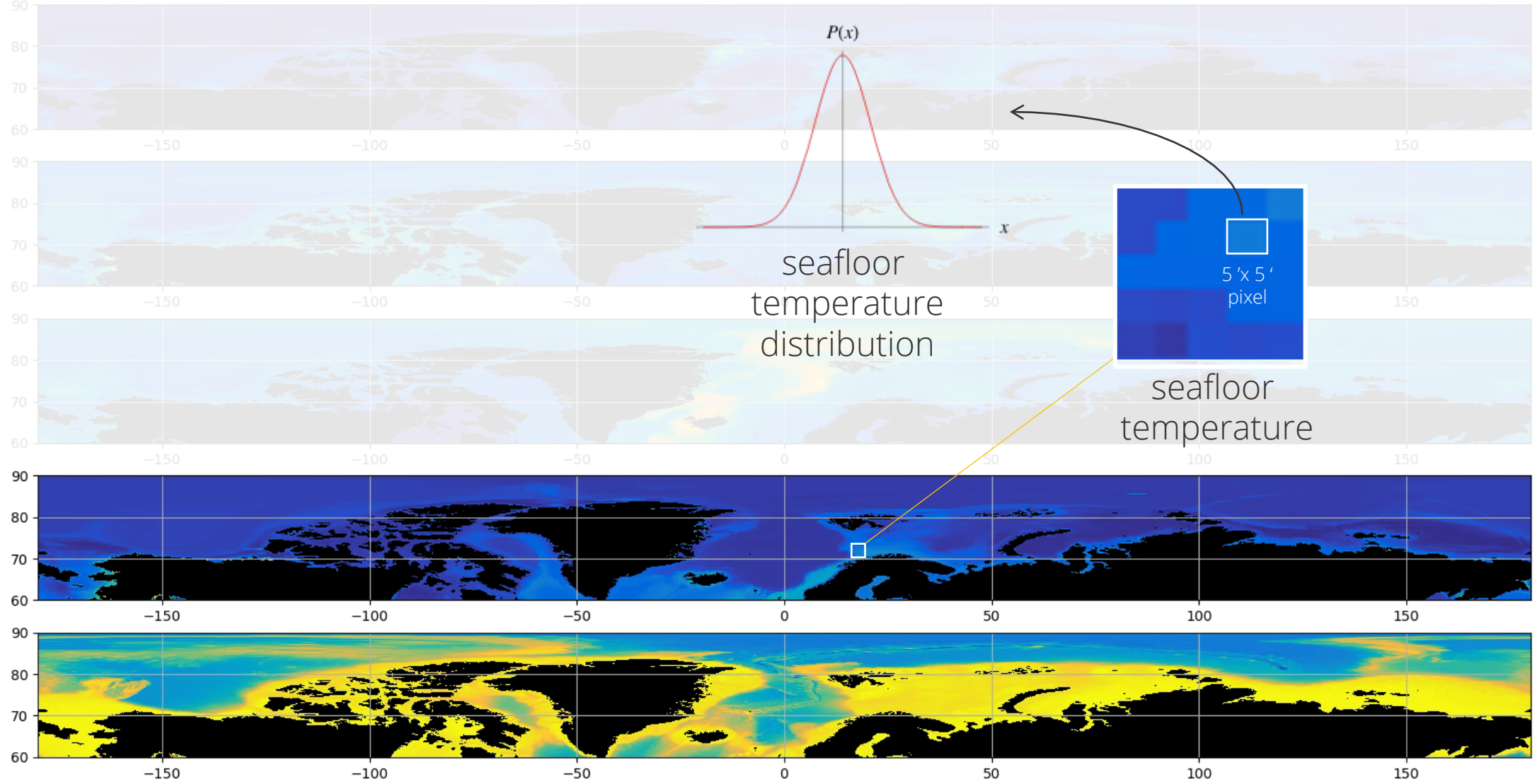

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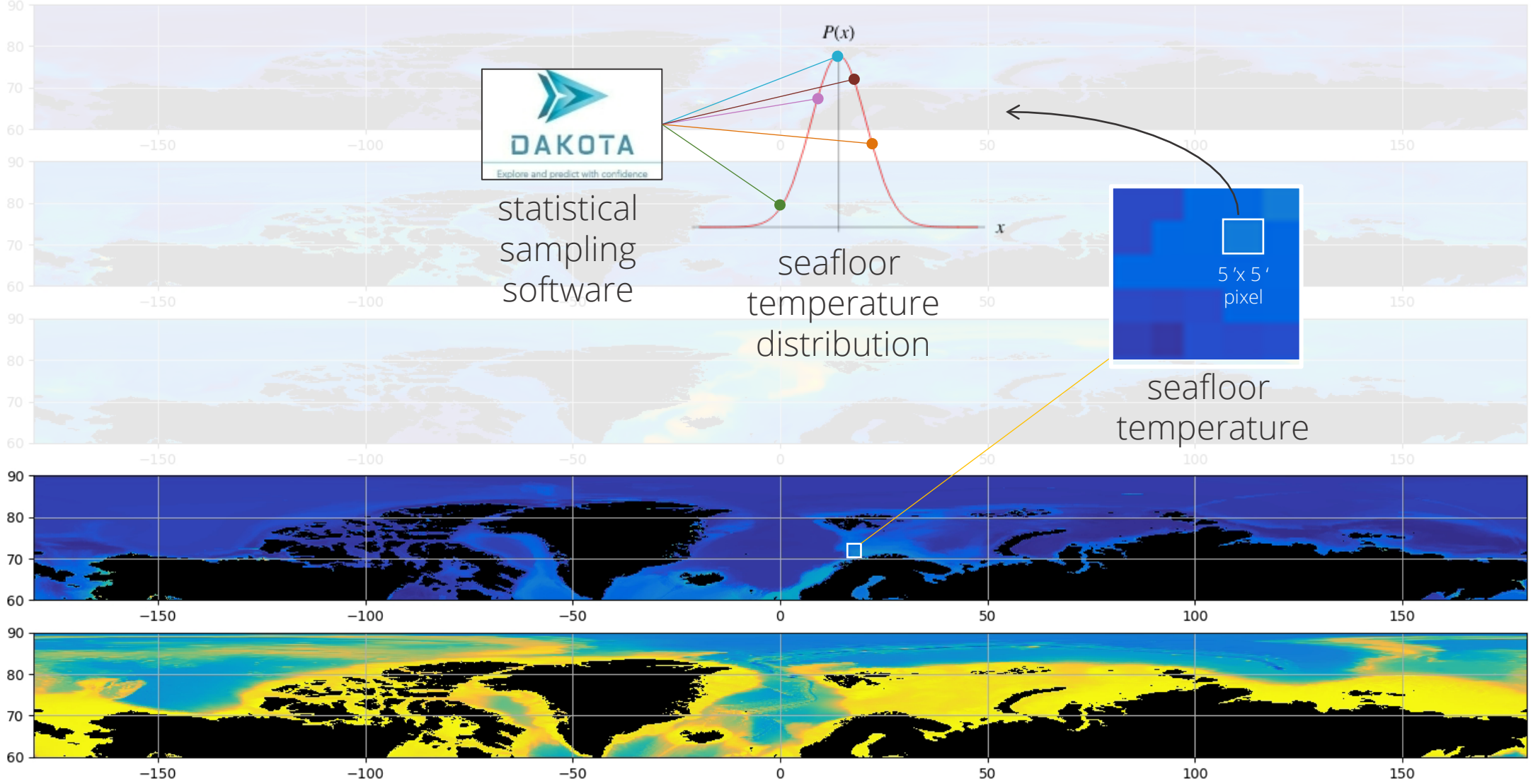

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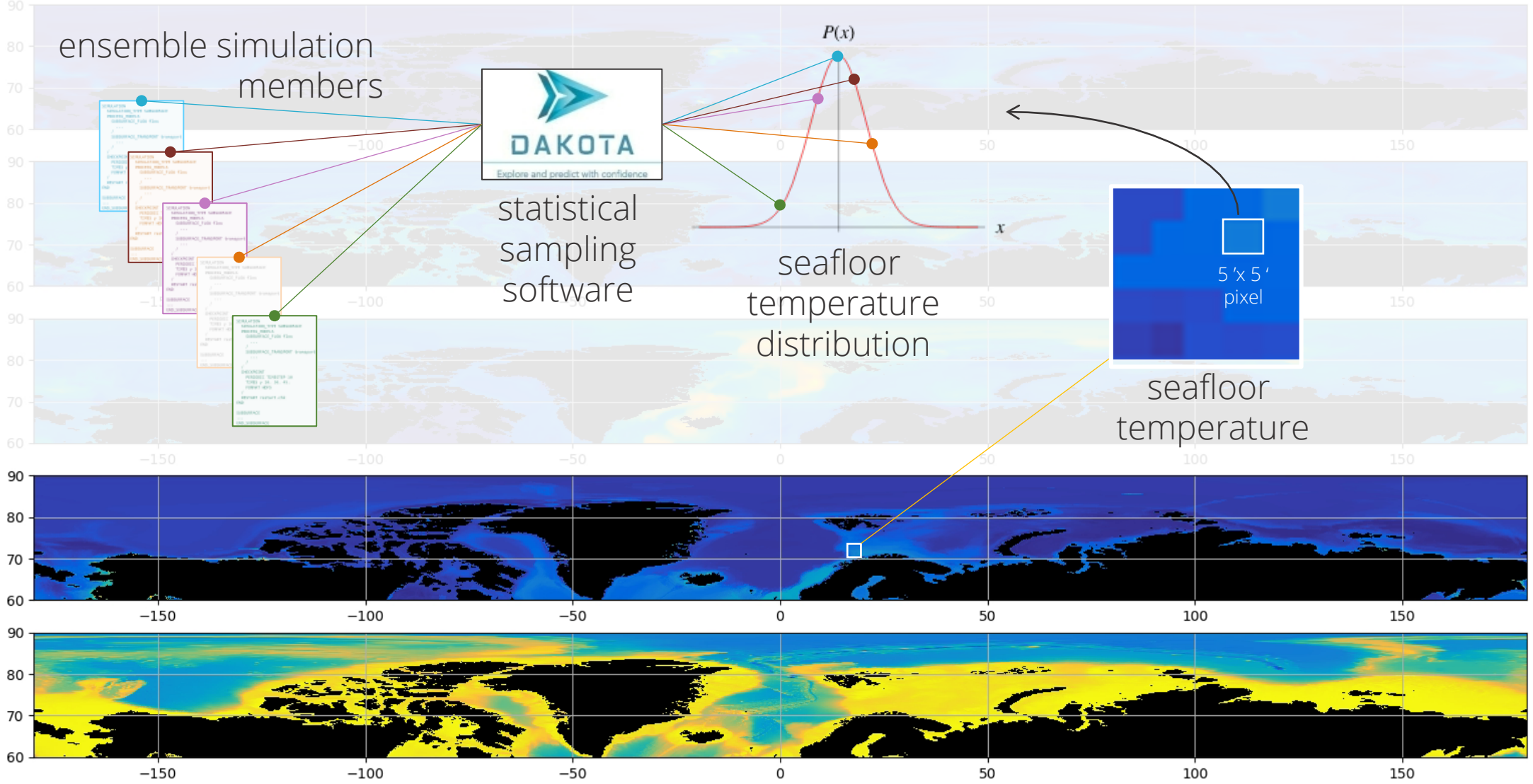

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Depth (Pressure)

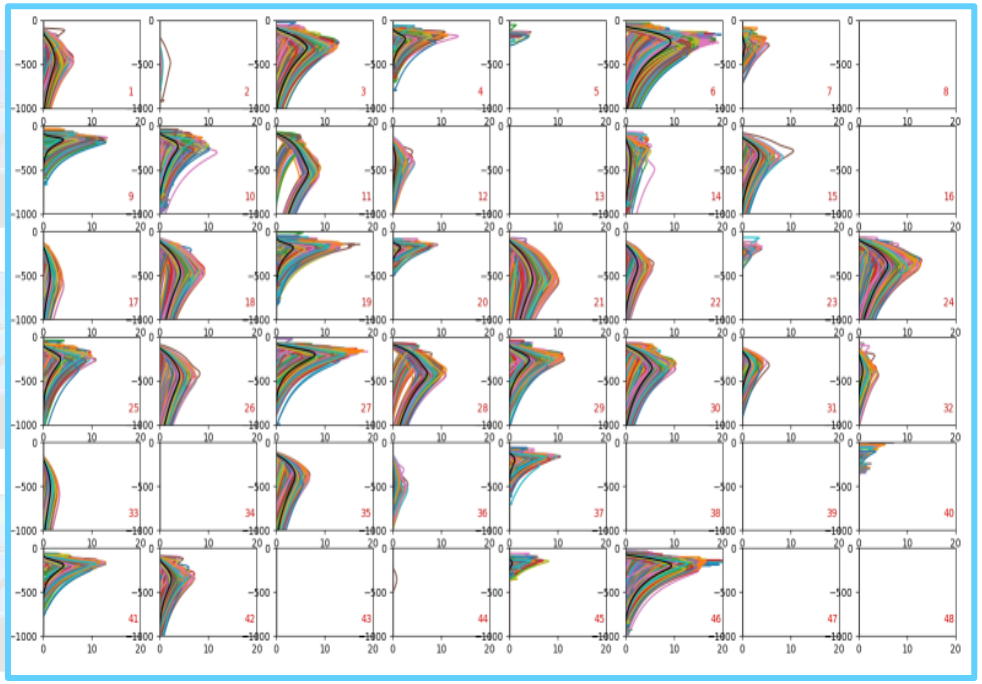
Global Predictive Seabed Model

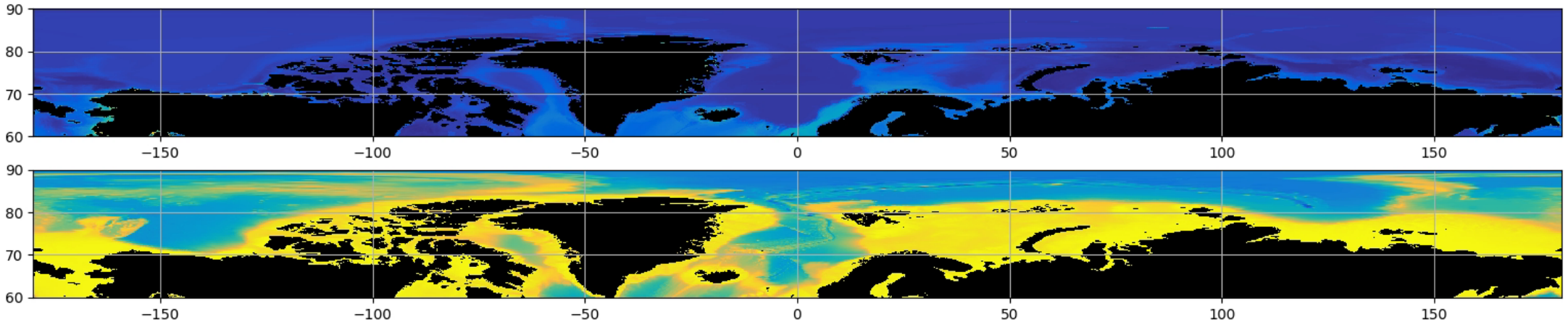
ensemble simulation members

PFLOTRAN

thermodynamic seabed model

ensemble model results





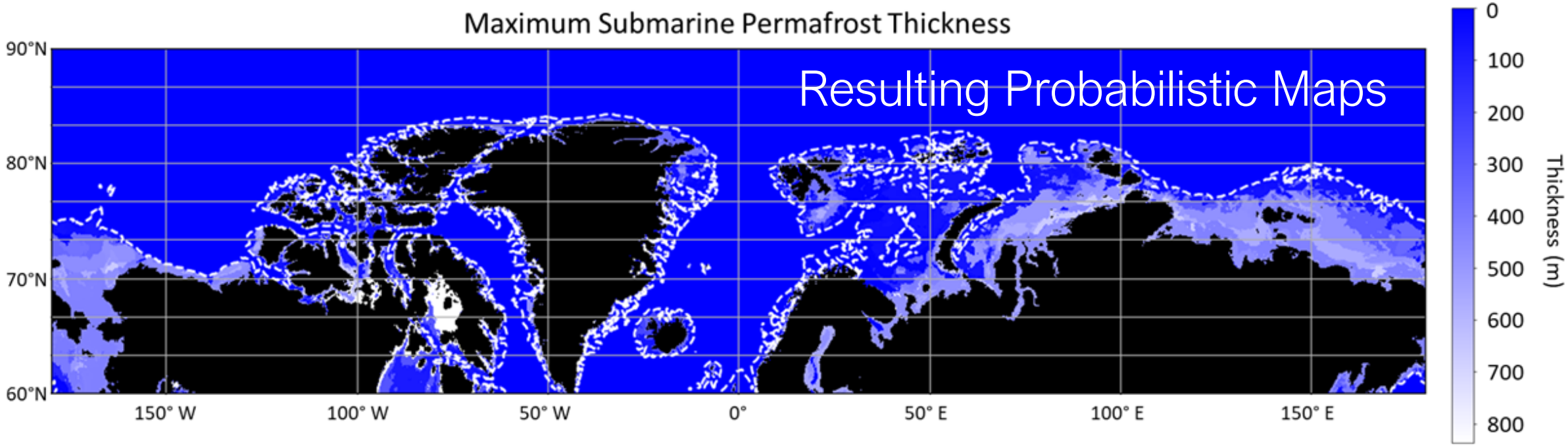
Temperature

Depth (Pressure)

Ensemble Model Results for Submarine Permafrost Distribution

Modeling PHASE I:

Obtain the submarine permafrost distribution (thickness and saturation) at the Last Glacial Maximum (~18,000 kyrs ago):



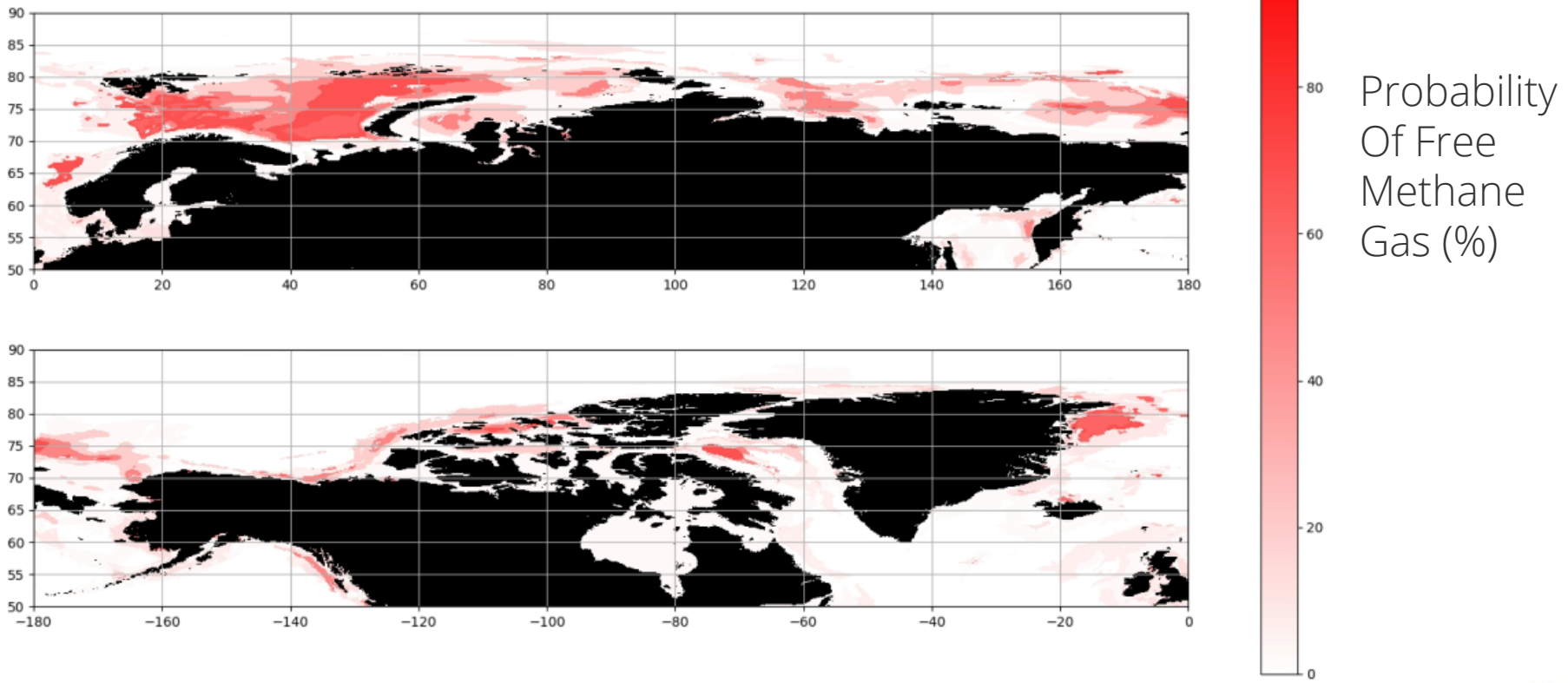
*dotted line shows the 150m isobath

Ensemble Model Results for Free Gas Distribution

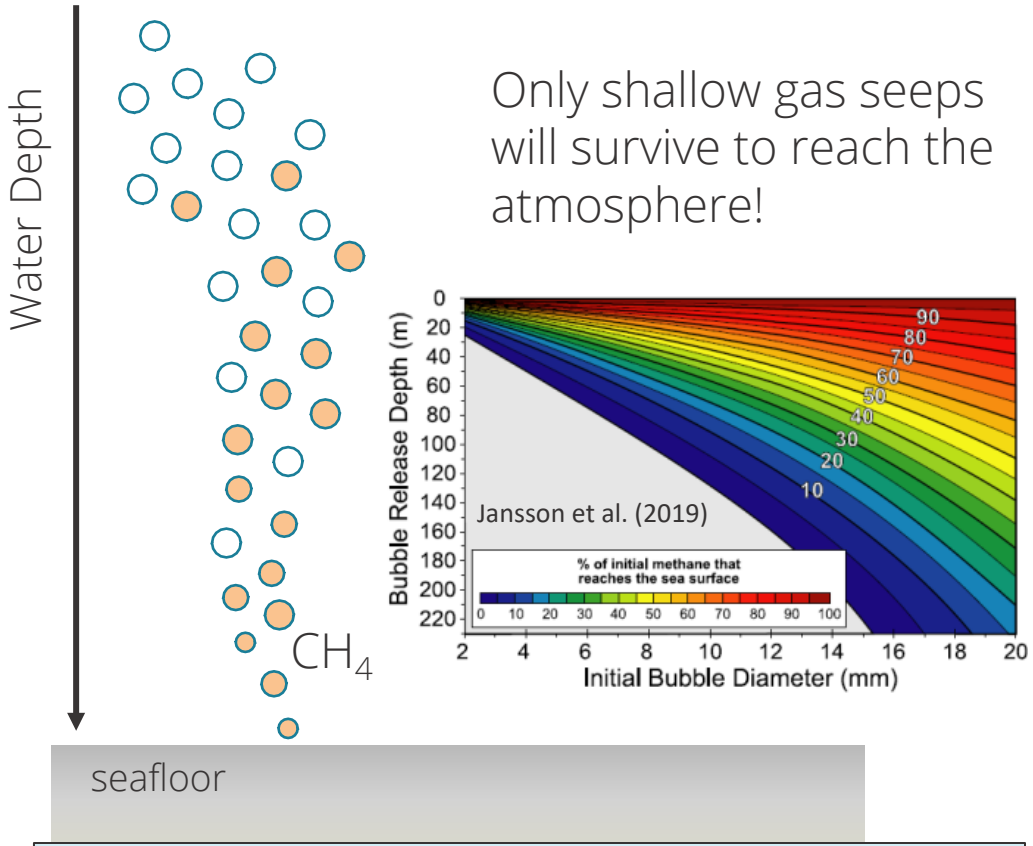
Modeling PHASE II:

Model submarine permafrost and gas hydrate degradation in response to warming and predict the amount of mobile gas in the marine sediments:

Initial modeling results show the probability that marine sediment host free gas.



Ensemble Model Results for Gas Emission to Atmosphere

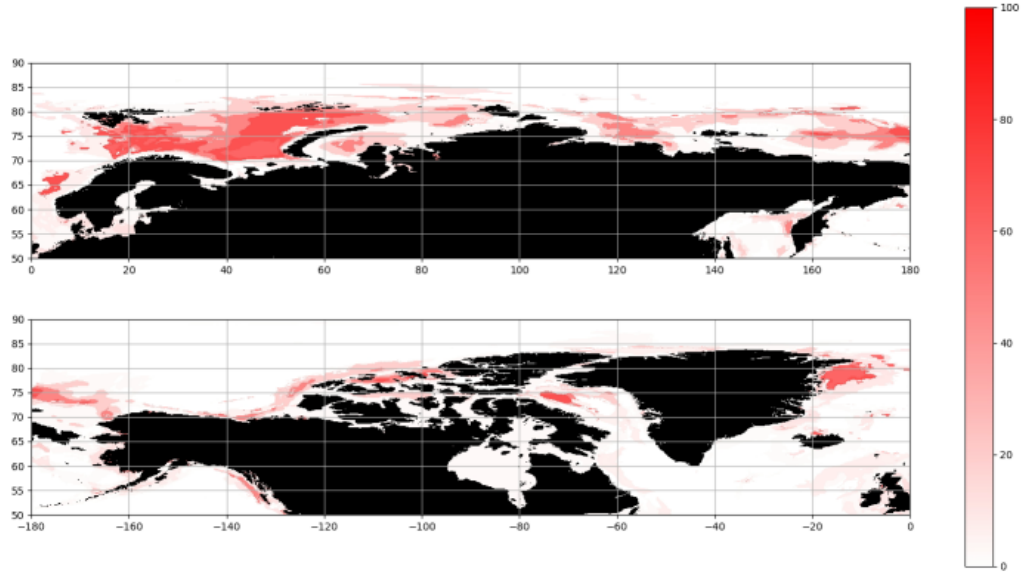


Only shallow gas seeps will survive to reach the atmosphere!

We will implement and couple this water column gas transport model to predict methane transport.

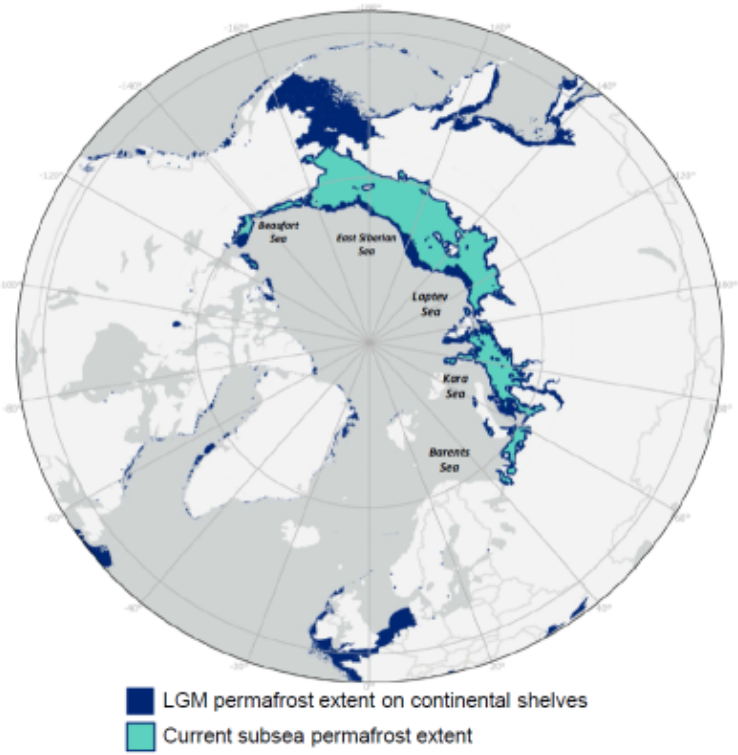
Modeling PHASE III: FUTURE WORK

- Quantify the amount of gas flux out of the sediment surface.
- Apply a bubble model to estimate how much survives to reach the atmosphere.



Submarine Permafrost Carbon Stocks & Methane Emissions

Key Points:



- Substantial carbon stocks are locked up in submarine permafrost (560 billion tons of carbon in organic matter and 45 billion tons in CH_4.)
- Warming since the last glacial maximum has resulted in submarine permafrost degradation and methane hydrate dissociation.
- ~90% of dissolved methane flux is taken up by sediment biofilter (AOM).
- ~75% of methane is oxidized in the water column before reaching the atmosphere.
- Observations and expert assessments indicate current Arctic marine methane flux to the atmosphere is 1.3 – 4.3 Tg/yr.
- As climate warms, marine sources will increase!
- This source has not yet been considered in global climate modeling nor policy discussions.
- Ongoing work at Sandia National Laboratories for methane emissions estimates.