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Pan-Arctic Methane:

Current Monitoring Capabilities, Approaches for Improvement, and Implications for Global Mitigation Targets

AUTHORS:

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Abstract

Arctic carbon emissions from thawing permafrost will accelerate the pace of global climate disruption and reduce the remaining headroom for direct human emissions before agreed global temperature targets are exceeded—the so-called "carbon budgets" for staying below, e.g., 1.5°C or 2.0°C above the pre-industrial global average surface temperature.[1] The key questions are how much and how fast. The proportion of future Arctic carbon emissions that will be methane (CH_4) rather than carbon dioxide (CO_2) is of particular importance in determining the answers because of CH_4's much higher impact, per molecule, on global temperature over the next several decades.

Better monitoring of ongoing CH_4 emissions across the Arctic is the necessary foundation for improving scientific understanding of the influence of climate change on these emissions and reducing the large current uncertainties around their expected magnitude during the remainder of this century. But the challenges to achieving monitoring adequate for this purpose are large: they include the high levels of spatial and temporal variability across the vast Arctic region, the difficulties of conducting year-round operations in the Arctic environment, and the need for a degree of coordination and data sharing among Arctic nations that is not currently feasible in the case of Russia (which has more permafrost than the other Arctic nations combined).

There are many notable research efforts related to Arctic carbon emissions. This paper does not attempt a comprehensive survey of all recent and ongoing studies, but rather summarizes major international emissions monitoring initiatives. It highlights two examples: the efforts of the Permafrost Pathways Project and Sandia National Laboratories to demonstrate technical approaches to Arctic CH_4 monitoring. It discusses associated opportunities for targeted policy intervention and heightened international collaboration.

The Permafrost Pathways project at Woodwell Climate Research Center is a partnership with the Arctic Initiative at the Harvard Kennedy School and the Alaska Institute for Justice, which builds upon the work of researchers who have been measuring CH_4 and CO_2 fluxes from Arctic lands and waters for decades (including Drs. Zona, Oechel, Schuur, Euskirchen, Goeckede, and Walter-Anthony). Permafrost Pathways seeks a comprehensive and equitable approach towards permafrost thaw monitoring and modeling, impact assessment, community adaptation, and policy analysis and development at the local, national, and international levels. Sandia National Laboratories is a federally funded research and development center at the cutting edge of scientific and technological innovation, with a long history of conducting atmospheric measurements and other research activities in the Arctic.

The Significance of Arctic Permafrost in Global Climate Change

The Arctic has been warming three to four times faster than the global average for several decades.[2] With this rapid warming, Arctic regions are experiencing a wide range of impacts at multiple scales, entailing not only damages to ecosystems and human wellbeing within the region—such as the local impacts from permafrost thaw and sea-ice retreat, altered abundance of economically and culturally important species, and wildfires increasing in coverage and intensity—but also far-reaching disruptions, including impacts of the altered North-South temperature gradient and Arctic Ocean freshening on Northern Hemisphere climate patterns, the contributions to global sea-level rise from shrinkage of Arctic glaciers and the Greenland Ice Sheet, and toxic smoke from Arctic wildfires propagating into the mid-latitudes.

As the Arctic region changes, moreover, ecosystems that have historically served as carbon sinks, such as wetlands and forests, may emerge as sources of carbon emissions.[3] Indeed, it is quite possible that the most important global impact of rapid Arctic warming over the next few decades will come from the emissions of the globally mixed greenhouse gases (GHGs), carbon dioxide (CO_2) and methane (CH_4), from thawing permafrost.[4] The amount of carbon in Arctic soils is about twice the amount currently in the atmosphere,[5] and most of that carbon is in organic matter frozen in permafrost.

Additional carbon is present in subsea permafrost, which was formerly a terrestrial permafrost environment when sea levels were lower during the last glacial maximum.[6],[7] Together, terrestrial and subsea permafrost contain an order of magnitude more organic carbon than contained in plant biomass (including woody debris and plant litter) in the same region[8], which suggests that carbon release from permafrost has the potential to significantly outweigh regional plants' potential for increased carbon storage.[9]

> "The amount of carbon in Arctic soils is about twice the amount currently in the atmosphere, and most of that carbon is in organic matter frozen in permafrost."

Emissions of carbon from permafrost result primarily from the activity of microbial communities, the organisms that produce CO_2 and CH_4 as part of their natural metabolism.[10] The aerobic decomposition of permafrost by microbial activity in an oxygen-rich environment produces CO_2, while anaerobic decomposition in an oxygen-poor (typically wetter) environment releases CH_4. As permafrost soils thaw, the existing cold-adapted microbial community (containing bacteria, archaea, viruses, and micro-eukaryotes such as fungi) is strongly affected by warmer temperatures, higher soil water content from melted ground ice, and increased nutrient availability from deeper rooting vegetation.[11],[12] These environmental changes alter the ecological conditions of the soil microbiome, increasing metabolic rates and thereby accelerating the decomposition of diverse organic carbon compounds into CO_2 and CH_4.[13]

Ecological and geomorphological processes are highly sensitive to the phase change between ice and water and are currently poorly understood.[15] Phase change sensitivity makes the structure and function of permafrost ecosystems unique and uniquely vulnerable to the changes arising from a warming climate. As research leads to improved knowledge of the identities and proportions of the relevant microorganisms in the ecosystem and how that relates to regional-scale emission rates, the projections (by carbon-cycle models) of future emissions in this critically important context will likewise improve.[16]

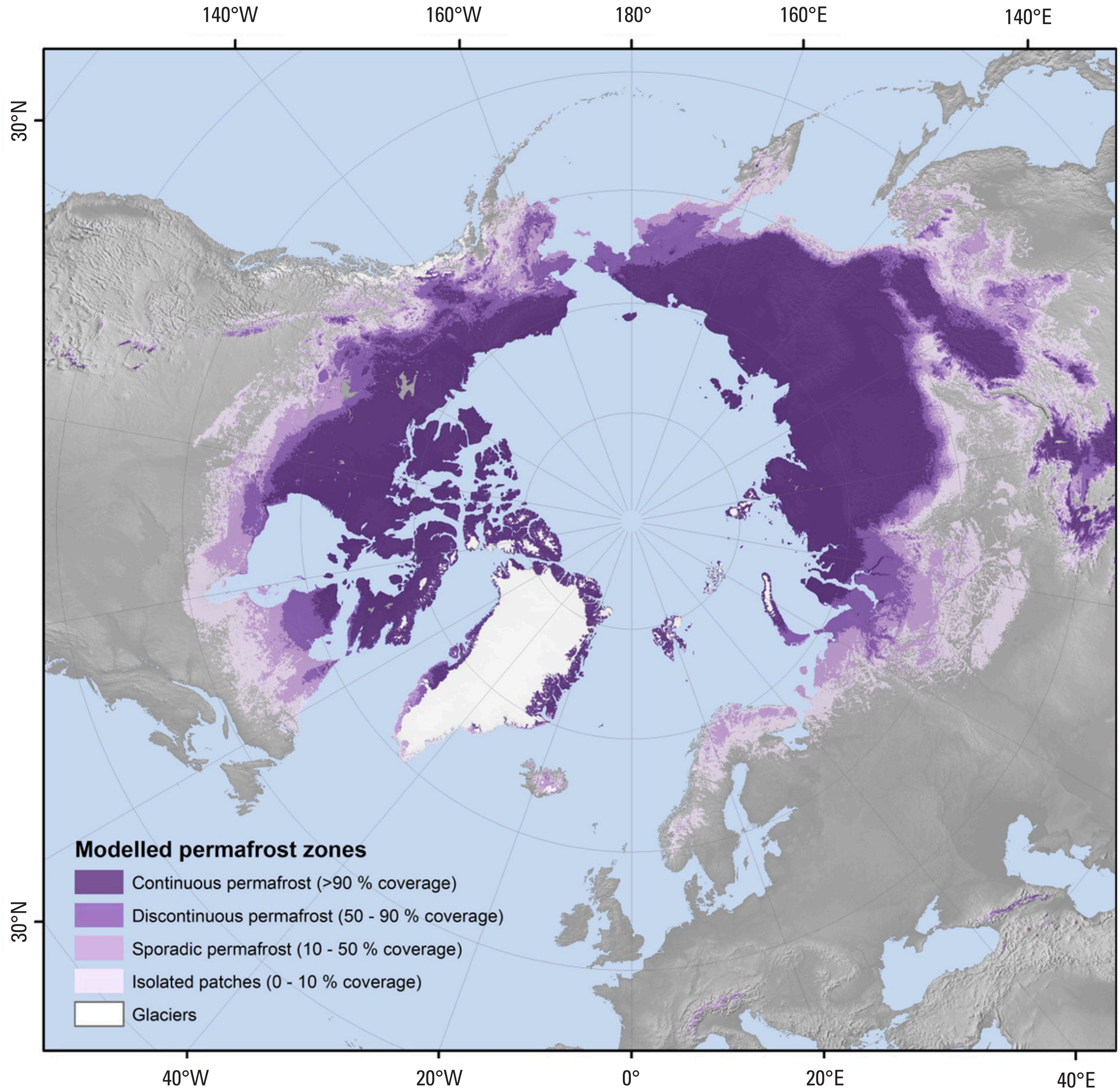


Image from Obu, et al. (2019)[14]

The effect that changes in Arctic permafrost soils will ultimately have on the global climate depends on several factors. These include not only the speed of permafrost thaw (itself a complex function of the pace of warming in interaction with multiple mechanisms by which permafrost is exposed to it), but also other processes: the other environmental factors that affect the speed of microbial action; how much of the mobilized carbon is released to the atmosphere as trace gases as opposed to stored as dissolved aquatic carbon; the proportion of the release that is CH_4 versus CO_2; and how much of this release is offset by increased plant biomass and new inputs to the soil carbon pool in a "greening Arctic."[17]

As result of this complexity and variations in how different studies have approached predictions in the face of inadequacies in both models and data, the scientific literature contains a wide range of estimates of the magnitude of emissions to be expected as a function of time for given trajectories of global and Arctic warming. Perhaps the most rigorous and comprehensive recent effort to sort through the estimates and arguments[18] found that:

"This under-representation of potential permafrost-thaw contributions in the models being used to inform deliberations about national and global climate policies compromises the ability to effectively achieve goals."

On a **low-warming global trajectory** (low emissions scenario RCP 2.6 in the IPCC Sixth Assessment Report):

- emissions from terrestrial permafrost over the current century in a representative scenario reached 37 billion tons of carbon in CO_2 and 1.1 billion tons of carbon in CH_4.
- Converting the carbon in CH_4 to its equivalent in carbon in CO_2 using the "sustainable global warming potential" multiplier of 16.45 recommended by Schuur et al. (2022)[ix] shows this CH_4 release to be equivalent to 18 billion tons of carbon in CO_2, giving 55 billion tons of carbon in CO_2-equivalent as the combined total for the two gases.
- A median estimate of society's carbon budget for a two-thirds chance of holding the global-average surface temperature increase to 2ºC is 315 billion tons of C in CO_2 after 2020.[19] The indicated permafrost emissions would eat up 17.5% of this figure.[20,21]

On a **high-warming global trajectory** (high emissions scenario RCP 8.5 in the IPCC Sixth Assessment Report):

- global-average surface temperature would careen past the 2ºC target and arrive at 3.5-4ºC above pre-industrial in 2100 (with Arctic-average surface temperature likely reaching 10-15ºC).
- On this trajectory, CO_2 and CH_4 emissions from gradually top-down thawing permafrost could release 5-15% of the permafrost carbon pool in the next decades and centuries,[22] but abrupt thaw (e.g., rapid thawing resulting in relatively sudden ground collapse) would degrade permafrost significantly faster than gradual top-down warming alone. About 20% of the northern permafrost region, containing at least 50% of the shallow permafrost carbon pool[23], has high ground ice content and is susceptible to abrupt thaw with warming. A higher fraction of CH_4 is emitted during abrupt thaw events compared to gradual thaw.[24]
- The scenarios developed in Schurr et al. for this high-emissions trajectory entail cumulative emissions over the current century of 75-150 billion tons of C in CO_2 and 2.5-5 billion tons of C in CH_4, the latter equivalent, with the Schurr et al. multiplier of 16.45, to another 40-80 billion tons of C in CO_2. The higher total of 230 billion tons of C in CO_2-equivalent is about 15% of the 21st century emissions of C in CO_2 under the IPCC's SSP3-7.0 trajectory.

Notwithstanding the evident potential importance of emissions from permafrost to the global climate future, the influence of permafrost thaw is largely absent from global earth system models. When included at all, only linear (gradual, top-down) thaw has been represented. Rapid thaw caused by thermokarst, hill slope collapse, wildfires, and other nonlinear phenomena, which are occurring with increasing frequency, are not modeled. This under-representation of potential permafrost-thaw contributions in the models being used to inform deliberations about national and global climate policies compromises the ability to effectively achieve goals.

Why Focus on Methane (CH_4)?

With an average lifespan of 10-12 years, CH_4 is significantly shorter-lived than CO_2, a substantial fraction of which will still be in the atmosphere after hundreds of years. The global warming potential of a kilogram of CH_4 over the first hundred years after its emission, however, is about 30 times greater than that of a kilogram of CO_2.[25] Over a twenty-year period, CH_4 has 84-87 times greater global warming potential than CO_2.[26] And CH_4 concentrations in the atmosphere have been growing even faster than the concentrations of CO_2.[27]

CH_4's high impact on global climate over the next few decades is reflected in the estimates cited above assigning about a third of the projected global climate impact in the current century from thawing permafrost to CH_4. That projection motivates a closer look at the state of scientific understanding of CH_4's contribution, which historically has received less attention than that of CO_2. But a further motivation is that the *uncertainties* surrounding the potential emissions of CH_4 from Arctic ecosystems are even larger than the uncertainties around CO_2 emissions. That's true in part because of poorly documented soil conditions—including depth of ground thaw, ground saturation, and carbon and nutrient content—which drive CH_4 production, consumption, and, thus, net emissions.

Also contributing to large uncertainty about future CH_4 emissions from permafrost are the rates and patterns of emissions from freshwater ecosystems, which are thought to account for approximately half of current global CH_4 emissions. These processes are largely undocumented in the Arctic.[28] Recent research has found that the amount of CH_4 emitted from rivers and streams is controlled primarily by their surrounding habitat rather than by temperature, which was initially believed to be the primary driver.[29] In high latitude environments, river and stream biogeochemistry is intertwined with carbon dynamics within peatlands and wetlands. Crucially, researchers have found that human modifications of these ecosystems, such as draining peatlands for agriculture, is a significant factor in subsequent CH_4 emissions.[30] Finally, the uncertainties around CH_4 emissions in marine environments—that is, from subsea permafrost and shallow methane clathrates—are even larger than the uncertainties on the terrestrial side.[31]

"a more rigorous understanding of methane release mechanisms and lifecycle, permafrost distributions, and changes in thaw rates must be a high priority for better understanding global climate change"

Clearly, then, a more rigorous understanding of CH_4 release mechanisms and lifecycle, permafrost distributions, and changes in thaw rates must be a high priority for better understanding global climate change. Gaining that understanding will require both more accurate estimates of current emissions from the Arctic and more realistic Earth System Models (ESMs).

Large permafrost bluff near Drew Point Alaska. Photo courtesy of Jennifer Frederick.

Geopolitical Complexity

International scientific research cooperation and data sharing are critical to understanding Arctic CH_4 emissions and managing the risks associated with pan-Arctic permafrost thaw. Russia's invasion of Ukraine in February 2022 led to policies largely halting and stripping financing from scientific cooperation with Russian scientists, including loss of access to Russian territory and field sites. The Russian government banned Russian scientists from sharing certain types of data outside of the country, and embargoes against Russia have made scientific exchanges more challenging. These constraints greatly complicate the task of addressing Arctic CH_4-monitoring gaps: Russian territory covers over 50% of Arctic landmass, and regions with the most significant scientific uncertainty are largely within Russian territory. It has been estimated that the loss of *in situ* data from Russia "will reduce the regions with good data coverage from 55% to 36%."[32]

The Arctic Council has been the premier intergovernmental forum for regional cooperation in areas of mutual interest among the eight Arctic states since the body became operational in 1998.[33] Its exclusion of military security and focus on scientific research and sustainable economic development have allowed it to remain functional during times of geopolitical tension, though the 2022 full scale invasion of Ukraine by Russia has hindered the body's functionality, including efforts to monitor permafrost and to address anthropogenic CH_4 emissions. While reviving full Arctic Council cooperative mechanisms is possible long-term, paths to building pan-Arctic permafrost CH_4 assessment must be pursued through other avenues, emphasizing scientific collaboration across the seven likeminded Arctic nations.

Given the vastness of the Arctic, there are constraints on ground and aerial measurements that necessitate better leveraging of space-based systems and sensors, including to fill some of the data gaps resulting from disrupted scientific cooperation with Russia. Significant challenges remain, however, because CH_4 mixes in the lower atmosphere with other gases, making it difficult to determine the origins of concentrations detected from space. Further, most satellite instruments are passive, which means that they rely on sunlight[34] to measure greenhouse gas concentrations (which are used to estimate CH_4 fluxes quantitatively), thereby limiting observations to a little over half the year due to polar winters. To improve the estimate of CH4 fluxes, it is imperative to accelerate the development of internationally coordinated effective pan-Arctic satellite monitoring capabilities that incorporate active sensors[35] and use optimal orbits to maximize view durations in the Arctic.

Arctic Relevance of Current International Methane-Monitoring Initiatives

At present, there are no satellites with dedicated permafrost monitoring missions, nor are there satellites that dwell over the Arctic (i.e., in highly elliptical orbit). While notable CH_4 monitoring initiatives with an Arctic component provide only limited CH_4 monitoring data, the data are nonetheless sufficient to support early-stage collaborative frameworks, as well as providing insight into current limitations of Arctic CH_4 monitoring capabilities and system-level data integration.[36] The initiatives highlighted below demonstrate the importance of international collaboration in global methane monitoring. Two complementary initiatives discussed below, Carbon Mapper and MethaneSAT, highlight the critical role of public-private partnerships for monitoring at scale.

The Arctic Methane and Permafrost Challenge (AMPAC)

Collaboration among scientists through AMPAC— a transatlantic initiative of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA)— facilitates transboundary scientific cooperation between North America and Europe. One AMPAC workshop found a "lack of in-situ observations in general and those suitable for atmospheric retrievals in particular"[37] in the Arctic. Satellite instrument performance for GHG retrievals has been identified as an area of concern, especially in winter. The TROPOspheric Monitoring Instrument (TROPOMI)— the satellite instrument on board the Copernicus Sentinel-5 Precursor satellite— provides some measurements, but retrievals are challenging when sun-angles are low in the shoulder in the winter, as well as over snow or ice-covered surfaces that absorb infrared radiation.[38] The AMPAC collaboration has revealed that retrieval issues, also linked to spatial resolution constraints, are a limiting factor for attaining reliable soil moisture estimates and time series in high latitudes.[39]

The National Oceanic and Atmospheric Administration (NOAA)'s CarbonTracker-CH4

NOAA's CarbonTracker-CH_4 provides a quasi-operational integration of measurements and modeling, aiming "to provide quantitative estimates of CH_4 emissions from microbial, fossil, and pyrogenic sources at a global scale." These data are used in various synthesis activities e.g., as part of the North American Carbon Program.[40] Atmospheric CH_4 data are collected from the NOAA Cooperative Global Air Sampling Network and collaborators such as Environment Canada. There are roughly 100 sampling sites worldwide that contribute to the World Meteorological Organization's Global Atmospheric Watch, including a limited number of sites in the Arctic, which provide calibration for CarbonTracker-CH_4.[41,42,43]

The CarbonTracker-CH_4 modeling system merges long-term observations with bottom-up emission estimates and atmospheric transport models, which helps understanding, tracking, and prediction of emissions.[44] Work is also being carried out by NOAA to integrate stable and radio-isotope measurements of CH_4 from existing networks to better characterize the age and depth of carbon being mobilized for respiration and methanogenesis. These data can be used as tracers within biogeochemical wetland models[45] to help constrain uncertainties and to translate local CH_4 and CO_2 emissions to regional estimates through upscaling.

National Aeronautics and Space Administration (NASA)'s Carbon Mapper

As part of a multi-partner coalition, NASA developed a state-of-the-art imaging spectrometer, which the non-profit Carbon Mapper will use to pinpoint and measure CH_4 and CO_2 sources from space.[46] In fall 2023, the instrument was integrated into Planet's Tanager-1 hyperspectral satellite, which is expected to launch in the second half of 2024.[47] The Tanager-1 satellite will have a sun-synchronous, low Earth orbit, allowing it to revisit the same places at the same local time every few days— including the Polar Regions— which is beneficial for comparison over time.[48] However, it is important to note that its usefulness for detailed characterization of Arctic emissions is limited due to commercial data constraints, very low revisit time, and targeting of oil and gas infrastructure. The design also lacks the low parts-per-billion detection capability necessary for monitoring CH_4 from wetlands. The data from this instrument, and Carbon Mapper in general, are or will be publicly available to maximize transparency and impact.[49]

MethaneSAT

MethaneSAT is an imaging satellite operated by MethaneSAT LLC (a wholly owned subsidiary of the Environmental Defense Fund and the New Zealand Space Agency). It was launched in March 2024 and aims to quantify medium and large point sources, dispersed area sources, and total emissions (column integrated concentrations). Its focus will be providing global, high-resolution coverage of CH4 emissions from oil and gas facilities, and other major sources of anthropogenic emissions. It will not contribute to monitoring of biological sources of CH_4 emissions, such as from permafrost thaw or wetlands.

Methane Alert and Response System (MARS)

The United Nations Environment Program unveiled the satellite-based Methane Alert and Response System (MARS) at COP27. This initiative focuses primarily on five anthropogenic- CH_4 sectors: oil and gas, coal, waste, rice, and livestock. Through a combination of scientific studies, industry partnerships, and robust measurement reporting, this initiative seeks to accelerate the progress of the Global Methane Pledge by transparently scaling up global efforts to detect and act on major CH_4 emissions sources.[50] The MARS Process consists of four components: 1) Detect and attribute, 2) Notify and engage, 3) Stakeholders take abatement action, and 4) Track, learn, collaborate, and improve.[51]

TROPOMI (as mentioned above) supports the detection and attribution component of the MARS Process by supporting the identification of methane plumes and hotspots. With a 2600-km wide swath, the satellite can image the entire planet daily. This swath includes daily surface coverage of radiance and reflectance measurements over both land and cloud-free areas for latitudes $> 7°$ and $< -7°$, and better than 95% coverage for latitudes in the interval [-7°, 7°]. While the MARS initiative currently has no focus on permafrost CH_4, it does provide some Arctic coverage. Its integrated monitoring and data analysis complements mitigation efforts by increasing emission reduction verification capability.

WMO Global Greenhouse Gas Watch (G3W)

Global Greenhouse Gas Watch (*G3W*)— an internationally coordinated, sustained, top-down GHG flux-estimation effort— was endorsed by the World Meteorological Organization (WMO) in May 2023. Key elements of the initiative include, 1) an integrated global greenhouse gas observing system of surface and space-based assets, 2) 24/7 operational GHG modeling/ assimilation of multiple systems, providing top-down flux estimates, and 3) routine internationally coordinated inter-comparison and verification of model output.[52] The initiative aims to provide primary outputs that are time-continuous global 3D fields of CO_2, CH_4, and eventually nitrous oxide (N_2O) fluxes in consolidated, top-down, monthly estimates at a global 100km by 100km resolution (with a goal of attaining 1km by 1km resolution eventually).[53] WMO envisions these outputs being used for numerous initiatives, including by parties to the Paris Agreement for the Global Stocktake in support of national reporting, to strengthen carbon markets through enhanced verification of offsets, and supporting IPCC work on emission pathways and future scenarios. Thus far, 192 countries have "committed to developing coordinated top-down GHG flux estimation with open access to inputs and output data."[54]

With its global-scale focus, the G3W initiative does not currently provide Arctic-specific data and analysis, but the Arctic was explicitly called out as a priority in the organization's draft plan. For instance, WMO argues that G3W could leverage World Weather Watch's Global Observing System infrastructure to monitor emissions (CO_2, CH_4, and N_2O) and increase international collaboration.[55]

Permafrost Emissions Processes, Monitoring, and Analysis— Capabilities and Gaps

As noted above, characterizing permafrost CH_4 release across variable terrains and conditions is a complex challenge. Although global initiatives and CH_4-sensing satellites can help bound CH_4 emissions from the Arctic, there are large gaps related to winter and wetland emissions, specific ecosystem responses, and future changes. Significant research is underway to differentiate the numerous permafrost CH_4 emissions processes. As noted above, CH_4 flux monitoring capabilities in multiple categories (ground, airborne, and satellite) are being developed and actively tested to identify sources of emissions more accurately, including from the Arctic. Translating the data to pan-Arctic regional scales requires upscaling, data integration, and various modeling approaches. The following summary of capabilities and gaps across this dynamic range of challenges has been developed through dialogue with researchers at the Woodwell Climate Research Center Permafrost Pathways Project (hereafter Permafrost Pathways), NASA Jet Propulsion Laboratory (Arctic Methane Research Program), NASA Goddard Space Flight Center, and Sandia National Laboratories (Climate Change Security Center).

Permafrost Methane Emissions Processes

Permafrost emission processes vary with ecosystem type, leading to large heterogeneity in Arctic CH_4 emissions and uncertainty in current CH_4 budgets and future CH_4 emission projections. An effort to address this gap is discussed in the modeling section below. Another challenge in understanding and predicting permafrost emissions is predicting ecosystem transition and associated greenhouse gas fluxes under different climate forcing and extreme weather scenarios. Quantifying uncertainty in the analysis is a further substantial challenge. To help address this challenge, research at Sandia is working to develop hydrologic models that couple thermal change models with models of the biological and chemical processes that occur in the earth.[56]

Research to understand changes in the underground environment that control the type and amount of carbon emissions is important. It has been shown that volatile organic compounds (VOCs) can be measured more easily than other carbon compounds and thus can be used as proxies to understand what is happening underground. Some VOCs have potential to indicate when a release tipping point is being reached. Metagenomic sequencing will likely reveal previously unidentified microbe species in permafrost and will hence improve understanding of the underground environment and relevant changes in it.

Methane Flux Monitoring—Ground & Aerial Based

Ground-level CH_4 flux measurements in the Arctic are critical for monitoring and process-level understanding, but present technical and logistical challenges given the large size, harsh winter climate, and relative inaccessibility of much of the Arctic. The Permafrost Pathways project is addressing this challenge by supporting and installing eddy covariance towers in areas of the permafrost region that are critically under-sampled in terms of CH_4 (and CO_2) fluxes. This effort is guided by an international steering team of flux scientists with deep knowledge of network gaps. The Permafrost Pathways team is also synthesizing all available historical and current flux data across the Arctic into the Arctic-Boreal Carbon Flux database version 2, which will be used for more accurate statistical upscaling of fluxes as well as improved ecosystem model parameterization and accuracy.

The initial plan included the installation of eddy covariance towers in areas of Russia that would significantly reduce uncertainties in ground-based monitoring. However, after Russia's invasion of Ukraine in 2022 and the resulting restrictions on travel, funding, and access to territory, this project has been modified to install flux towers in Canada instead. In 2022, towers were installed in Churchill, Manitoba, Scotty Creek, and Iqaluit. Community outreach was the focus in 2023, and tower installation will resume in 2024.

Extrapolating ground-based CH_4 measurements vertically into the atmosphere requires collaborative research to couple ground-based and aerial measurements. Through the previously noted NASA/European Space Agency AMPAC initiative, field studies from NASA's Arctic-Boreal Vulnerability Experiment field program (ABoVE) have been connected with with the German Aerospace Center CoMet 2.0 Arctic mission. In 2022, this collaboration used the German research aircraft HALO, equipped with remote sensors, to measure the CO_2 and CH_4 columns between the aircraft and ground and combine this with *in-situ* instruments collecting air samples at flight level. These aerial data were analyzed and correlated with ground-based measurements to better understand ground-based carbon flux and associated atmospheric transport.

Methane Flux Monitoring—Satellite Based

Satellite-based monitoring of Arctic CH_4 release includes both monitoring changes in Arctic permafrost landscapes, which is necessary for modeling CH_4 emissions, and direct sensing of CH_4 concentrations.

While providing valuable data, satellite-based CH_4 monitoring in the Arctic region has multiple challenges and significant limitations due to geometry, geography, and orbital dynamics. Different types of satellite-based CH_4 detection technologies each have benefits and limitations that must be considered (note these technologies are also used for airborne monitoring):

- SRS (Solar Reflectance Spectroscopy) is top-down and uses solar backscatter. This technology can detect total CH4 columns and plumes but requires direct sunlight, and it is not effective over water.
- DIAL (Differential Absorption LiDAR) is a top-down technology that can be used both day and night to detect CH4 and is potentially useful at steeper sensing angles over land and water. Clouds and turbid air limit sensitivity of this technology.
- TIR (Thermal Infrared) is useful both day and night for detecting CH4 and it can be effective over land and water. However, this technology is limited by clouds and cannot sense the lower atmosphere without a temperature differential.

Current and near-future satellite systems mostly rely on SRS for sensing, with a few using TIR and one using LiDAR (Light Detection and Ranging remote sensing). Most systems are in low earth orbit, but a few are in geosynchronous orbit. These systems offer a combination of point source imagers and area flux mappers. Particularly important for Arctic CH_4 monitoring, there are no satellites with dedicated permafrost CH_4 monitoring missions. Although a number of GHG monitoring satellites do fly over the Arctic, their orbits and sensing systems are not optimized for the unique challenges of monitoring in this region, and thus, produce less science quality data than could be achieved with dedicated arctic monitoring missions. Recent work has linked CH_4 emission patterns from permafrost in the Arctic to geomorphology, and changes in late-season subsidence measured by satellite InSAR may enable mapping of changes in ice-rich permafrost from space.[57] ,[58]

Verifying international agreements and treaties require effectively continuous monitoring with sufficient spatial resolution to quantify global greenhouse gas inventories. However, current global CH_4 sensing is from a collection of sensors, not a system with an integrated or even defined architecture. These systems include a wide range of technologies: towers, absorption chambers, solar heterodyne radiometers, Differential Absorption LiDAR (multi color and optical frequency comb), closed path absorption sensors, satellites and aircraft sensing reflected solar illumination, and satellites and aircraft sensing thermal infrared radiation. All of these systems have different sensing characteristics, noise floors, and calibration parameters. In practice there is no optimized or coherent global CH_4 monitoring architecture.

> "A key capability that will significantly improve CH_4 (and CO_2) monitoring data quality, as well as the means to integrate data for regional scale analysis, will be the ability to cross-calibrate data products from different types of CH_4 sensors."

A key capability that will significantly improve CH_4 (and CO_2) monitoring data quality, as well as the means to integrate data for regional scale analysis, will be the ability to cross-calibrate data products from different types of CH_4 sensors. Cross-calibration will enable significantly more accurate comparison of CH_4 data across a wide range of satellite and airborne sensors, which in turn will greatly strengthen data fusion and integration of CH_4 release at basin and regional scales.

In an effort to begin addressing this gap, Sandia has developed the "Rosetta Stone" concept to address the critical need for cross-calibration across a wide range of sensing systems. The concept relies on a ground-based, two-color LiDAR[59] for active collection day or night. This single, simple, CH_4 sensing instrument would enable traceable calibration that could be deployed on ground, air, and space systems.[60] The ground-based sensor would be placed (ideally) along the ground path of a passing overhead satellite, thereby enabling simultaneous top-down and bottom-up measurements. Analyses of these simultaneous measurements would enable much more accurate and novel cross-comparisons of results from different satellites. This capability would enable accurate collection and integration of both global and Arctic-focused CH_4 releases. Development of a Rosetta Stone prototype may be relatively inexpensive given the existence of required technologies and the precedent set by previous development of a similar system for astronomic observation at the University of New Mexico.

The ability to collect vertical CH_4 profiles in the atmosphere would add significant knowledge critical to the ability to model the impacts of distributed surface emissions coupled with atmospheric mixing and contributions from anthropogenic point sources. LiDAR systems are uniquely capable of providing such vertical profile measurements.[61] The underlying technology for all of these approaches exists—what is required is a dedicated effort to engineer these technologies into field-transportable collection systems and to start collecting data.

Modeling, Upscaling, and Systems-Level Data Integration

Strengthening greenhouse gas simulation capabilities is an important objective for multiple earth systems models. This includes development of representative emission inventories/source characteristics for both biological[62] and anthropogenic sources, improved characterization of atmospheric chemistry, processes and transport, and ultimately sinks of CH_4 to account for the complete budget. The emission source characteristics for earth system models should be informed through measurements of CH_4 fluxes across ecosystem types, as discussed earlier.

Permafrost Pathways is addressing this knowledge gap by developing robust CH_4 emission and uptake processes within the DVM-DOS-TEM ecosystem model and running it at 4 km resolution across the Arctic-boreal zone. DVM-DOS-TEM categorizes land cover into a variety of Arctic community types that contain assemblages of different plant functional types. This enables the model to capture vegetation- and ecosystem-specific characteristics that influence soil hydrology and CH_4 dynamics. The Permafrost Pathways team is conducting parameter sensitivity analyses and deploying a semi-automated parameter optimization routine at CH_4 flux observation sites across the circumpolar zone to better leverage existing data and constrain model behavior.

The Permafrost Pathways team is coupling their on-the-ground monitoring network with high-resolution satellite observations to track changing landscapes. This research includes mapping wildfires and retrogressive thaw slumps (a type of thermokarst resulting in landscape collapse) using deep learning (i.e., convolutional neural networks, which look at the surrounding context and have pattern recognition) and satellite imagery from Landsat, Sentinel, Planetscope, and Maxar. In collaboration with the Permafrost Discovery Gateway[63], the researchers are working towards annual circumpolar maps that can be easily visualized and accessed. The team is also exploring ways to map small water bodies across the Arctic, which is key to estimating seasonal CH_4 production and emissions.

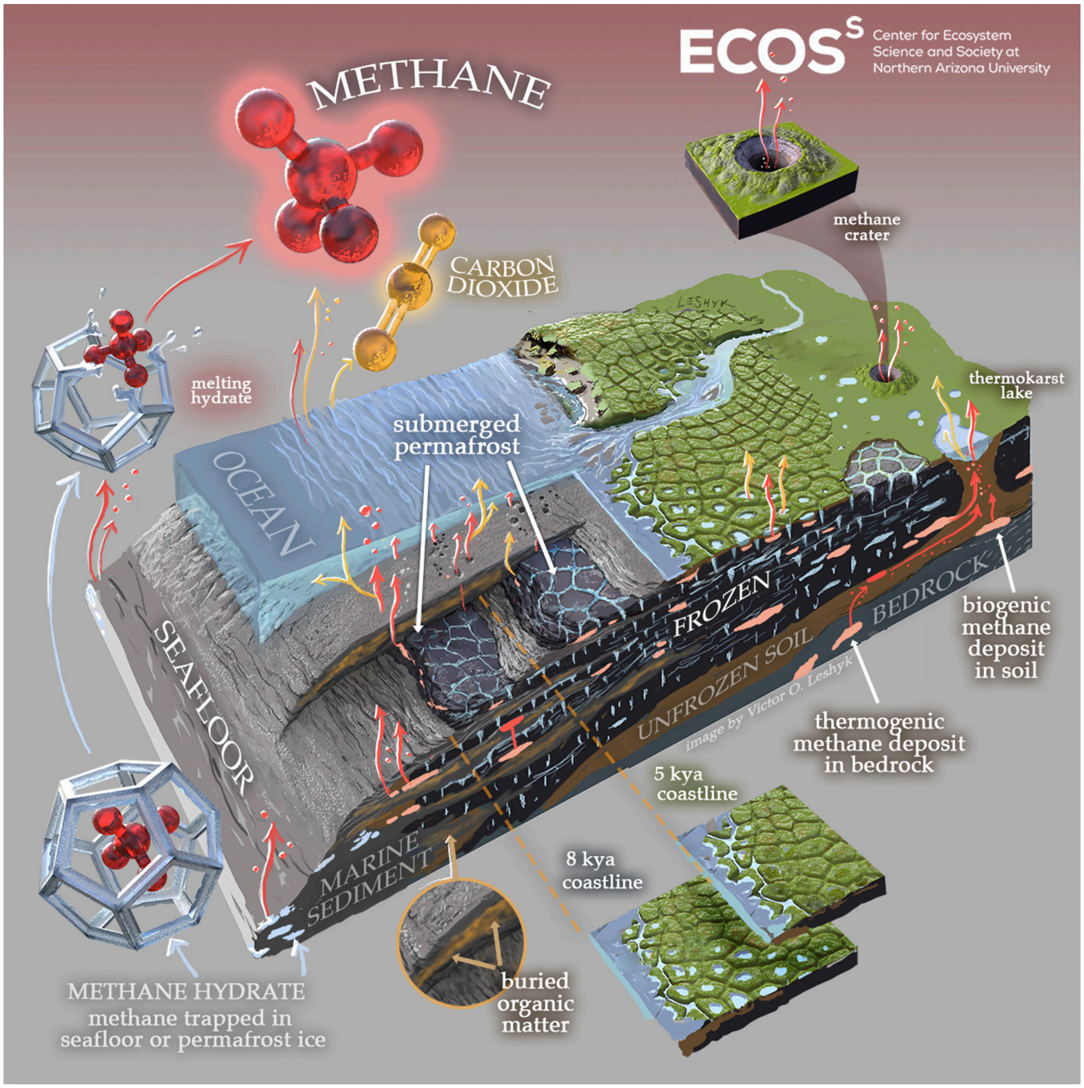
In addition to the deep learning capabilities of Permafrost Pathways, significant additional work is needed to strengthen systems-level upscaling and integration of CH_4 (and other GHG) data across widely varying satellite, ground, and aerial systems. The Permafrost Pathways project is using machine learning to more accurately upscale and model large pulses of CH_4 release as wetlands thaw in the spring. An upscaling model has been developed to provide daily, 10-km CH_4 fluxes for the Arctic, using data from 28 flux towers in combination with satellite variables. The model predicts spatial and temporal dynamics of arctic CH_4 emissions and evaluates uncertainties from underlying wetland area distribution data.[64] At a larger scale, the previously noted NASA/ESA AMPAC project has recently launched an initiative to create a data management and integration roadmap for the next generation of the Arctic Coastal Dynamics database. The focus is on coupling *in situ* records with satellite data across the Arctic.

One of the significant gaps in both field measurements and model representation of the ecosystem processes is in quantification and modeling of CH_4 emissions from abrupt thaw events. It is estimated that thermokarst covers over 1 million square kilometers across the Arctic, with that number rapidly growing.[65] Recent research at Sandia on designing an integrated monitoring framework for anthropogenic emissions of CH_4 in the Permian Basin can be leveraged to address similar concepts for the natural emissions in the Arctic. A combined three-tier approach to addressing measurement challenges over varying spatial and temporal scales throughout the atmosphere is strengthened with inverse Bayesian modeling to identify CH_4 emissions and plumes of varying intensity. Sandia is building a modeling framework, verifying it with satellite data, and using computational optimization to design the efficient placement and spacing of a sensor array for a specified cost. This will ultimately include the ability to sense and distinguish background concentrations of CH_4 and any anthropogenic sources. Part of the vision is to eventually combine techniques developed for point-source measurements in the Permian with methods to measure ecosystem-scale fluxes in the Arctic into a system architecture that will enable monitoring that can discriminate between biological and anthropogenic sources of CH_4 globally.

In addition to the quantification of source emissions, the atmospheric processing and transport of methane must be considered. Modeling capabilities for atmospheric CH_4 transport in current earth systems models have multiple limitations and are not always coupled with the terrestrial and marine systems. Modeling of the transport and atmospheric processing of CH_4 would benefit from use of the tracer transport and photochemical algorithms in the Department of Energy (DOE)'s Energy Exascale Earth System Model (E3SM), which have recently been rewritten to include more accurate transport physics and dramatically improve efficiency.

Looking to the future, two other important limitations of current earth systems modeling are computational speed and grid resolution. For instance, the most recent version of the DOE E3SM earth system model has been written and tested for portability to emerging exascale computers. The new atmosphere model for E3SM has been targeted for a 3.25-km uniform global grid, with local grid refinement to 1 km. A prototype version of this model, called SCREAM, runs at scale on exascale-class supercomputers and has demonstrated the ability to simulate more than one year of global climate at the 3.25-km resolution in one day of computational simulation time.

As discussed above, there is also significant potential for carbon locked up in submarine permafrost to be released as the atmosphere and Arctic Ocean increase in temperature. A recent study quantifies the stock of combined organic matter and CH_4 in subsea permafrost at approximately 600 gigatons of carbon. Current fluxes of CO_2 and CH_4 to the water column are on the order of 38 and 18 megatons of carbon per year respectively. However, both the exact quantity of carbon and the rate of release have significant uncertainty ranges, indicating that more research is needed in this area. The results of our current review also show that there is currently a slow but substantial climate forcing associated with carbon released from subsea permafrost that is on the order of 10–40% of emissions associated with the terrestrial domain, which is five times larger than the submarine domain.[66] Additional considerations include submarine CO_2 flux that could already be offsetting terrestrial permafrost carbon sinks. Our current review has established that the primary uncertainty in the analysis of submarine permafrost is insufficient field measurements, which lead to a reduction in reliability of estimates of carbon pools and fluxes in addition to the thermal and hydrological conditions of submarine permafrost. The quantification of methane release rates from submarine permafrost provides a unique and difficult challenge that warrants further research.



(Artwork by Victor O. Leshyk, Center for Ecosystem Science and Society, Northern Arizona University)

Engaging Arctic Indigenous Communities

In recent years, there has been increasing effort to integrate Indigenous knowledge and Western science approaches to understand rapid environmental changes across Arctic lands and waters. Given the complexity of climate impacts in the North, this knowledge integration is critical for better understanding and for guiding responses to rapid climate changes. Northern communities have been dealing with multiple climate hazards associated with permafrost thaw, flooding, erosion, loss of sea ice, and changing availability of food sources for decades. To fail to incorporate this largely Indigenous knowledge into the ongoing efforts of Western science to understand these processes would be a terrible oversight.

The Permafrost Pathways initiative includes partnerships between Indigenous knowledge holders and Western scientists to guide environmental monitoring, including of CH_4 fluxes. These partnerships can contribute substantially to adaptation decision making in response to permafrost thaw and other climate changes in the Arctic. Emerging initiatives, such as PermafrostNet, convene researchers, Indigenous communities, scholars, and government agencies to expand research to importantly address the "so what" of permafrost thaw, its impacts on communities, and contribute to adaptation efforts.[67] Indigenous community engagement is also a fundamental component of permafrost research collaborative networks, including the Canadian NSERC Permafrost Partnership Network, the Permafrost Community Practice of the US Interagency Arctic Research Policy Committee, and the Sustainable Development Working Group of the Arctic Council.

Summary and Conclusions

Given the combination of large quantities of organic carbon currently frozen in Arctic permafrost with its susceptibility to being emitted as CO_2 or CH_4 by microbial decomposition as the permafrost thaws, there is a danger that GHG emissions from permafrost will add significantly to the pace of global warming in this century, magnifying adaptation challenges and substantially reducing the chance of holding the increase in global-average surface temperature to 2°C above the pre-industrial level.

That potential is underscored by an estimate, in a recent comprehensive analysis, that cumulative releases of CO_2 and CH_4 from permafrost in this century, under a global emissions trajectory consistent with meeting the 2°C target, could be equivalent to 55 billion tons of carbon in CO_2, about a third of it coming from CH_4. That would consume 18% of society's "carbon budget" for that target—the direct CO_2 emissions allowable from human activities consistent with a two-thirds chance of not exceeding the 2°C target increase.

Significant uncertainties currently surround such estimates, resulting from shortfalls in monitoring permafrost thaw and its emissions across the Arctic, as well as from inadequacies in current understanding of the complex processes involved. For a number of reasons, these uncertainties are even larger for future contributions from CH_4 than for those from CO_2.

Achieving a more rigorous understanding of permafrost distributions, permafrost thaw mechanics under warming, and the processes governing CO_2 and CH_4 emissions by microbial decomposition under the variable soil conditions across the Arctic will be essential for clarifying the implications of permafrost emissions of greenhouse gases—and above all CH_4—for global climate policy. This will require more comprehensive monitoring, better incorporation of Indigenous knowledge, increased efforts at integrated data management, expanded research on the processes governing emissions from permafrost, and based on all of that, improved models for forecasting the future of permafrost emissions under plausible trajectories of Arctic warming.

Multiple monitoring regimes are important, including *in-situ* and remote sensing from near-surface, aerial, and satellite platforms needed to capture regional and global CH_4 lifecycles from emission to sink. Expanding spatial coverage and refining analysis capabilities of near-surface monitoring sites across various Arctic terrain types is an important priority for bottom-up monitoring. For top-down monitoring, satellites have the potential to provide important pan-Arctic scaling of regional permafrost CH_4 release. Current satellite coverage is limited by spatial/temporal continuity and the ability of sensors to detect and quantify permafrost CH_4 release, particularly under Arctic conditions of polar night and snow coverage. Cross-calibration between top-down and bottom-up measurements will require further advanced technical development and deployment. Additionally, understanding the contribution of CH_4 to the atmosphere from the water column due to submarine emissions is a critical path to reducing the uncertainty in the sources of CH_4. The largest uncertainty in characterizing submarine emissions is due to a lack of in-situ observations of the processes occurring at the seabed/water interface.

International scientific cooperation is imperative given the importance of pan-Arctic assessment of CH_4 release from permafrost thaw. Russia's invasion of Ukraine in February 2022 largely halted scientific cooperation with Russia, including ending multiple cooperative studies via the Arctic Council. While revival of full Arctic Council cooperative mechanisms may be possible in the long term, the science could likely be substantially advanced through developing alternative paths to building pan-Arctic permafrost CH_4 assessment. These could, for example, use a combination of scientific collaborations among the seven like-minded Arctic nations and accelerated development of effective pan-Arctic satellite monitoring capabilities.

The UNFCCC COP28 meetings made progress in recognizing CH_4's major global warming impact, but it was primarily within the context of anthropogenic CH_4. The role of biological CH_4 emission sources has not yet been widely recognized, with the scale of potential release almost completely missing from global carbon stock takes. This paper has focused on such emissions from the Arctic, but there are significant sources from other regions as well, such as unmanaged mid-latitude and tropical wetlands. All of these growing sources of CH_4 emissions are in need of better incorporation into global policy discussions. There is a clear need for policy leadership to bring these growing sources of "indirect" emissions more fully into the global climate dialogue.

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Endnotes

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