frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 15 October 2024
DOI 10.3389/fenvs.2024.1460155

Check for updates

OPEN ACCESS

EDITED BY
Tomas Halenka,
Charles University, Czechia

REVIEWED BY
Ewa Burwicz-Galerne,
University of Bremen, Germany
Wei Shan,
Northeast Forestry University, China

*CORRESPONDENCE
Frans-Jan W. Parmentier,
frans-jan@thissideofthearctic.org

RECEIVED 05 July 2024
ACCEPTED 23 September 2024
PUBLISHED 15 October 2024

CITATION
Parmentier F-JW, Thornton BF, Silyakova A and Christensen TR (2024) Vulnerability of Arctic-Boreal methane emissions to climate change. *Front. Environ. Sci.* 12:1460155.
doi: 10.3389/fenvs.2024.1460155

Vulnerability of Arctic-Boreal methane emissions to climate change

Frans-Jan W. Parmentier[1]*, Brett F. Thornton[2], Anna Silyakova[3] and Torben R. Christensen[4,5]

[1]Department of Geosciences, Centre for Biogeochemistry of the Anthropocene, University of Oslo, Oslo, Norway, [2]Department of Geological Sciences and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, [3]HUB Ocean, Oslo, Norway, [4]Arctic Research Centre, Department of Ecoscience, Aarhus University, Roskilde, Denmark, [5]Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland

The rapid warming of the Arctic-Boreal region has led to the concern that large amounts of methane may be released to the atmosphere from its carbon-rich soils, as well as subsea permafrost, amplifying climate change. In this review, we assess the various sources and sinks of methane from northern high latitudes, in particular those that may be enhanced by permafrost thaw. The largest terrestrial sources of the Arctic-Boreal region are its numerous wetlands, lakes, rivers and streams. However, fires, geological seeps and glacial margins can be locally strong emitters. In addition, dry upland soils are an important sink of atmospheric methane. We estimate that the net emission of all these landforms and point sources may be as much as 48.7 [13.3–86.9] Tg CH_4 yr^{-1}. The Arctic Ocean is also a net source of methane to the atmosphere, in particular its shallow shelves, but we assess that the marine environment emits a fraction of what is released from the terrestrial domain: 4.9 [0.4–19.4] Tg CH_4 yr^{-1}. While it appears unlikely that emissions from the ocean surface to the atmosphere are increasing, now or in the foreseeable future, evidence points towards a modest increase from terrestrial sources over the past decades, in particular wetlands and possibly lakes. The influence of permafrost thaw on future methane emissions may be strongest through associated changes in the hydrology of the landscape rather than the availability of previously frozen carbon. Although high latitude methane sources are not yet acting as a strong climate feedback, they might play an increasingly important role in the net greenhouse gas balance of the Arctic-Boreal region with continued climate change.

KEYWORDS

methane, permafrost, wetlands, lakes, gas hydrates, arctic ocean, Arctic-Boreal region

1 Introduction

The sweeping landscapes of the Arctic-Boreal region harbor a wide diversity of environments that are sources of methane to the atmosphere, including numerous wetlands and lakes, as well as ocean sediments. These sources are influenced by the presence of permafrost, and as the climate warms this perennially frozen ground may thaw. The soils of the permafrost region contain more than twice the amount of carbon present in the atmosphere, and if only a fraction of this is released as methane it could act as a significant feedback on the global climate (Schuur et al., 2022). Permafrost thaw may also impact surface wetness, altering the environmental conditions for methane formation (Nauta et al., 2014), or it might alter transport pathways up to the surface when the

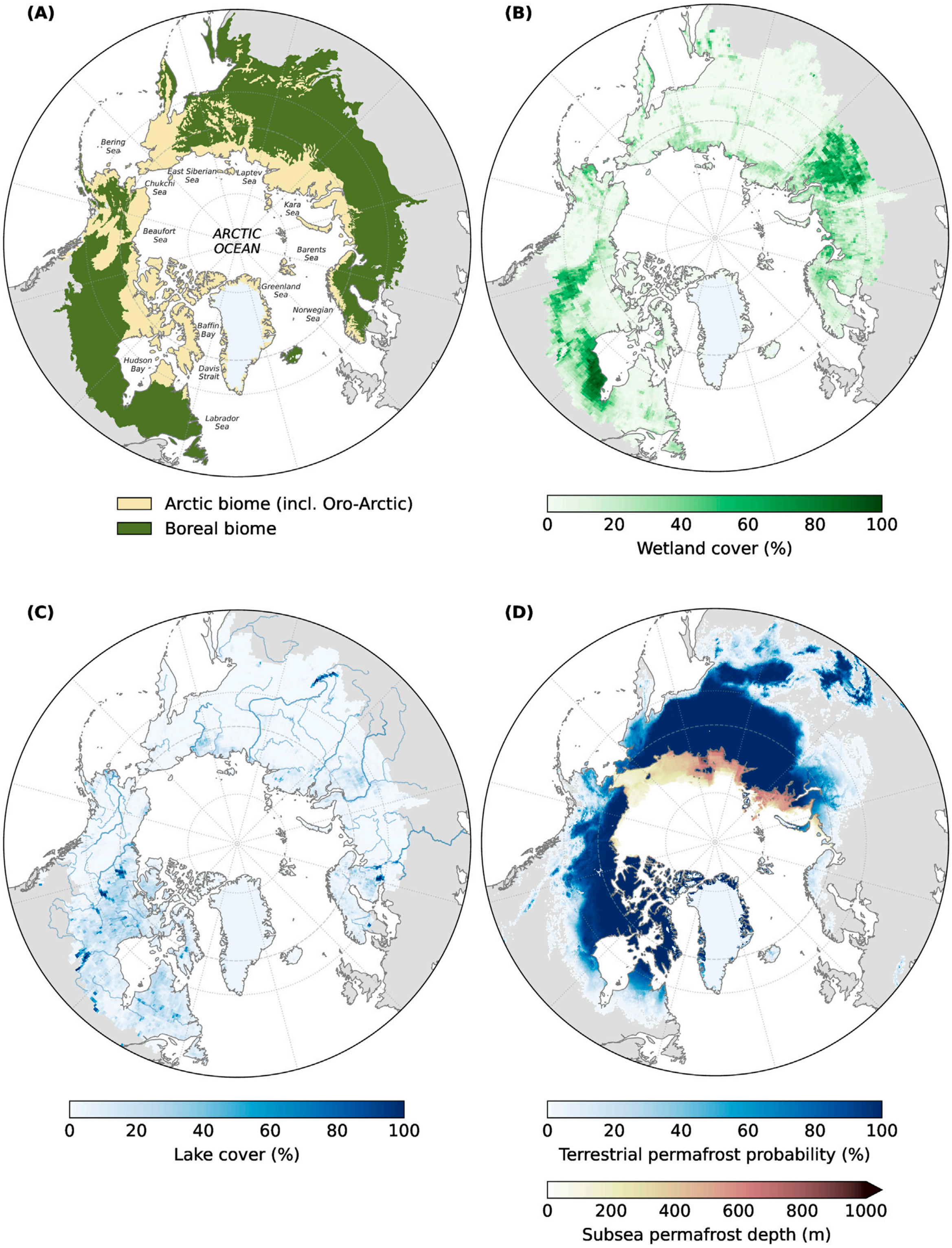

FIGURE 1
Ecoregions, wetlands, lakes and permafrost extent of the Arctic-Boreal region. **(A)** Spatial extent of the Arctic-Boreal region, showing the (Oro-) Arctic (yellow) and Boreal (green) terrestrial biomes, as well as the Arctic Ocean and its marginal seas. The Arctic Circle is depicted as a dashed line. **(B)** Wetland cover in the Arctic-Boreal region **(C)** lake cover and major rivers in the Arctic-Boreal region. **(D)** Extent of terrestrial permafrost (blue) and subsea permafrost (orange). The Arctic and Boreal biome extents are from Dinerstein et al. (2017). Wetland and lake cover are from the BAWLD dataset (Olefeldt et al., 2021). Terrestrial and subsea permafrost data are from Obu et al. (2019) and Overduin et al. (2019), respectively.

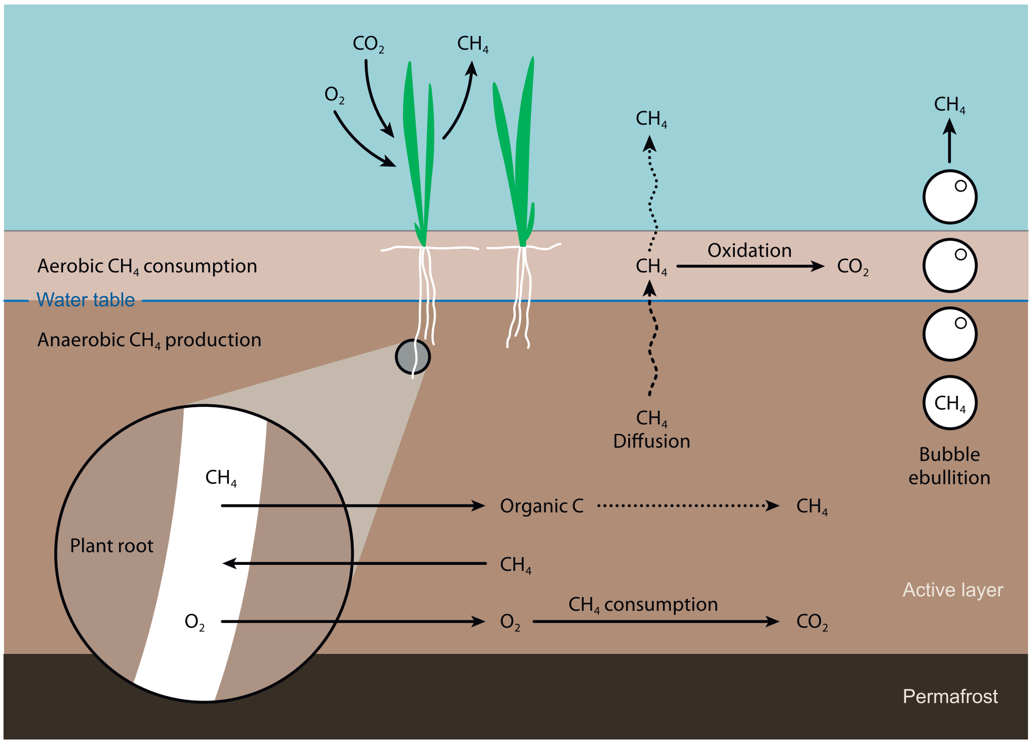

FIGURE 2
Pathways of methane emissions in wetland soils, and the role of vascular plants. Permafrost is shown for illustrative purposes. When it thaws, and the active layer deepens, it may act as an additional carbon source or alter surface hydrology. Episodic bursts of methane may also occur when the active layer refreezes in winter. Otherwise, the mechanisms shown here are similar in non-permafrost wetlands. Adapted from Joabsson et al. (1999) and AMAP (2015).

permafrost no longer acts as an impervious barrier (Walter Anthony et al., 2012). Most high latitude methane sources are microbial in origin, and global warming will increase this metabolic activity (Yvon-Durocher et al., 2014). Since methane is a potent greenhouse gas (AMAP, 2022), subsequent increases in emissions may pose a significant challenge to society (Hope and Schaefer, 2015).

These concerns have motivated extensive research efforts over the past decades to understand the processes underlying terrestrial and marine methane emissions from the high latitudes, and how they are associated with permafrost thaw. However, whether high-latitude methane emissions will increase in the future, and with what magnitude, remains highly uncertain. Many of these uncertainties arise from temporal and spatial omissions in current monitoring efforts (Peltola et al., 2019; Pallandt et al., 2022). Arctic landscapes are highly heterogeneous, complicating accurate monitoring, upscaling efforts and process modeling. In addition, the consumption of atmospheric methane by dry soils is also temperature-dependent (Voigt et al., 2023), which may counteract increased emissions elsewhere (Watts et al., 2014).

While acknowledging that CO_2 emissions are also an important part of the permafrost carbon feedback (Treat et al., 2024), this review restricts itself to methane by providing a broad overview of the current state of knowledge on sources, as well as sinks, in the Arctic-Boreal region. In this paper, we follow the terrestrial biome definitions from Dinerstein et al. (2017), which means that the terrestrial Arctic includes the treeless tundra of northern highlands (i.e., the oro-Arctic; Virtanen et al., 2015), while the boreal region is defined by areas predominantly covered by boreal forest or taiga (Figure 1A). In addition, we consider the Arctic Ocean and its marginal seas. A unique aspect of this paper is that it assesses sources in both the terrestrial and marine domain, including wetlands, lakes, gas hydrates and subsea permafrost, since all may potentially contribute to a rise in methane emissions from the high latitudes. We focus on how our understanding of these sources has evolved over the last decades, in the context of two assessments by the Arctic Monitoring and Assessment Programme (AMAP, 2015; 2022), to act as a guidance on this complex topic.

2 Natural sources and sinks of methane in the Arctic-Boreal region

2.1 Terrestrial environment

2.1.1 Wetlands

Early global atmospheric studies identified wetlands as a major natural source of methane to the atmosphere (Ehhalt, 1974). The early overall emission numbers (140–280 Tg CH_4 yr^{-1}) are still within the uncertainty range for the overall estimates of wetland-emitted methane in the most recent budgets (Christensen, 2014; Saunois et al., 2020). Although these global emissions are dominated by tropical wetlands, with a share of about 65% (Saunois et al., 2020), they hold a substantial contribution from northern wetlands including wet tundra and surrounding environments. The overarching background for these substantial emissions is the waterlogged nature of organic soils in the Arctic, which host stable anaerobic environments with optimal conditions for methanogenic activity (Figures 1B, 2).

These anaerobic conditions are found below the water table, where methane is produced from soil organic matter by methanogens that exclusively belong to the archaea domain (Ferry, 1999). Methane production is the final step in the degradation of organic matter, which methanogens most commonly do by reducing CO_2 with H_2 or by reducing the methyl group of acetate into methane (Thauer et al., 2008). If a water table drops below the surface, the top part of the soil becomes aerated and methane may be oxidized by a diverse group of bacteria – aerobic methanotrophs – when it diffuses upwards (Dean et al., 2018), as illustrated in Figure 2. However, oxidation can be avoided if this zone is bypassed through plant roots or by ebullition (Christensen et al., 2003; Ström et al., 2003). Ebullition, the fast upward movement of bubbles, happens too quickly for significant oxidation to occur in the top part of the soil, which is why it can be an important fraction of total emissions (Strack et al., 2005).

The role of plants in the production and transport of methane is more complex: many wet-tolerant plant species, such as sedges and rushes, contain a spongy tissue called aerenchyma which facilitates the transport of ambient air between the shoots and the roots (Figure 2). While this allows for the downward transfer of oxygen, it also provides a fast conduit for methane to travel upwards, while root exudates can act as additional substrate for methanogenesis (Ström et al., 2005).

Both of the microbial processes that produce and consume methane – methanogenesis and methanotrophy – are temperature dependent, and the position of the water table determines their relative importance (Olefeldt et al., 2013). Lower water tables increase the amount of oxygen in the soil, providing a larger habitat for methanotrophs, which is why this reduces net emissions – even if higher temperatures stimulate the activity of both methanogens and methanotrophs (White et al., 2023). Compared to tropical wetlands, influenced heavily by seasonality of flooding, wet northern source areas tend to be more stable in their extent (Yuan et al., 2024). Many factors, such as nutrients, plant species composition, soil carbon content, topography and hydrology, will modulate the size of the emissions, but a stable non-tidal natural wetland will under normal circumstances always be a source of atmospheric methane. In contrast, dry tundra is typically a sink for atmospheric methane (Voigt et al., 2023).

2.1.2 Point sources and disturbances

In a landscape perspective, the constantly emitting wet soil environments are surrounded by and intermixed with uplands, glaciers, lakes and rivers – all with their distinct and in some cases very different methane flux characteristics. Consequently, large temporal and spatial uncertainties exist in overall composite landscape emission estimates and new observations of unexpected fluxes remain possible. Recently, glacial outflow of methane has been identified as a hitherto unknown source of atmospheric methane in the terrestrial domain (Christiansen and Jørgensen, 2018; Lamarche-Gagnon et al., 2019). This emission source may be quite common for glaciers (Sapper et al., 2023), although its relative contribution to the Arctic-Boreal methane budget appears minor since it is restricted to the marginal areas of glaciers and ice sheets.

Another interesting phenomenon is the discovery of new crater-like formations, tens of meters wide and deep, in Siberian Russia – notably on the Yamal Peninsula (Bogoyavlensky et al., 2020). These features have been suggested to be the result of explosive degassing events, or cryovolcanism, although the exact mechanism remains under debate (Buldovicz et al., 2018; Bogoyavlensky et al., 2020; Hellevang et al., 2023). Due to the high methane concentrations measured in these craters, combined with their dramatic and sudden appearance in the landscape, they have attracted much media attention. Currently, however, these do not seem to be a significant new source of methane to the atmosphere, given their thus far limited extent, combined with the observation that they may revert to somewhat ordinary lakes a few years after formation (Chuvilin et al., 2020). Still, significant amounts of methane trapped within and beneath permafrost – e.g., from subsurface fossil hydrocarbon reservoirs – can be released to the atmosphere through geological seeps that form along faults, joints, fractures or open system pingos (Walter Anthony et al., 2012; Hodson et al., 2019).

Disturbances such as wildfires, thermokarst and animal activity may also impact the methane budget of the Arctic-Boreal region. Smoldering combustion of biomass increases the amount of methane emitted by fire relative to CO_2, when compared to flaming combustion. This slow burning process is common in boreal forests with carbon-rich organic soils (Wiggins et al., 2021), and they can persist throughout the winter, flaring up again in spring (Scholten et al., 2021). Boreal fires have been increasing in the past decades due to more frequent lightning and longer fire seasons (Veraverbeke et al., 2017), while projections show that fires may become more common in arctic tundra as well (Chen et al., 2021). These fires have a direct impact on permafrost thaw, through increases in soil temperatures and active layer depth, while climate change is expected to alter post-fire recovery (Holloway et al., 2020). While dwarfed by carbon losses in the form of CO_2, postfire impacts on methane emissions may be negligible to a slight increase in uptake, if soil temperatures increase and soil moisture declines (Ribeiro-Kumara et al., 2020).

Disturbances other than fire primarily alter methane emissions by transforming the hydrology of the landscape, such as surface subsidence from abrupt permafrost thaw (Christensen et al., 2004; Turetsky et al., 2020). Animal activity may also influence methane emissions, in particular the migration of beavers into the Arctic which construct dams that increase the number and size of beaver ponds (Tape et al., 2022), turning terrestrial environments into aquatic methane sources (Whitfield et al., 2015).

2.2 Freshwater systems

Freshwater systems (lakes, ponds, rivers, and streams) are abundant in the Arctic (Figure 1C), and subject to strong seasonal

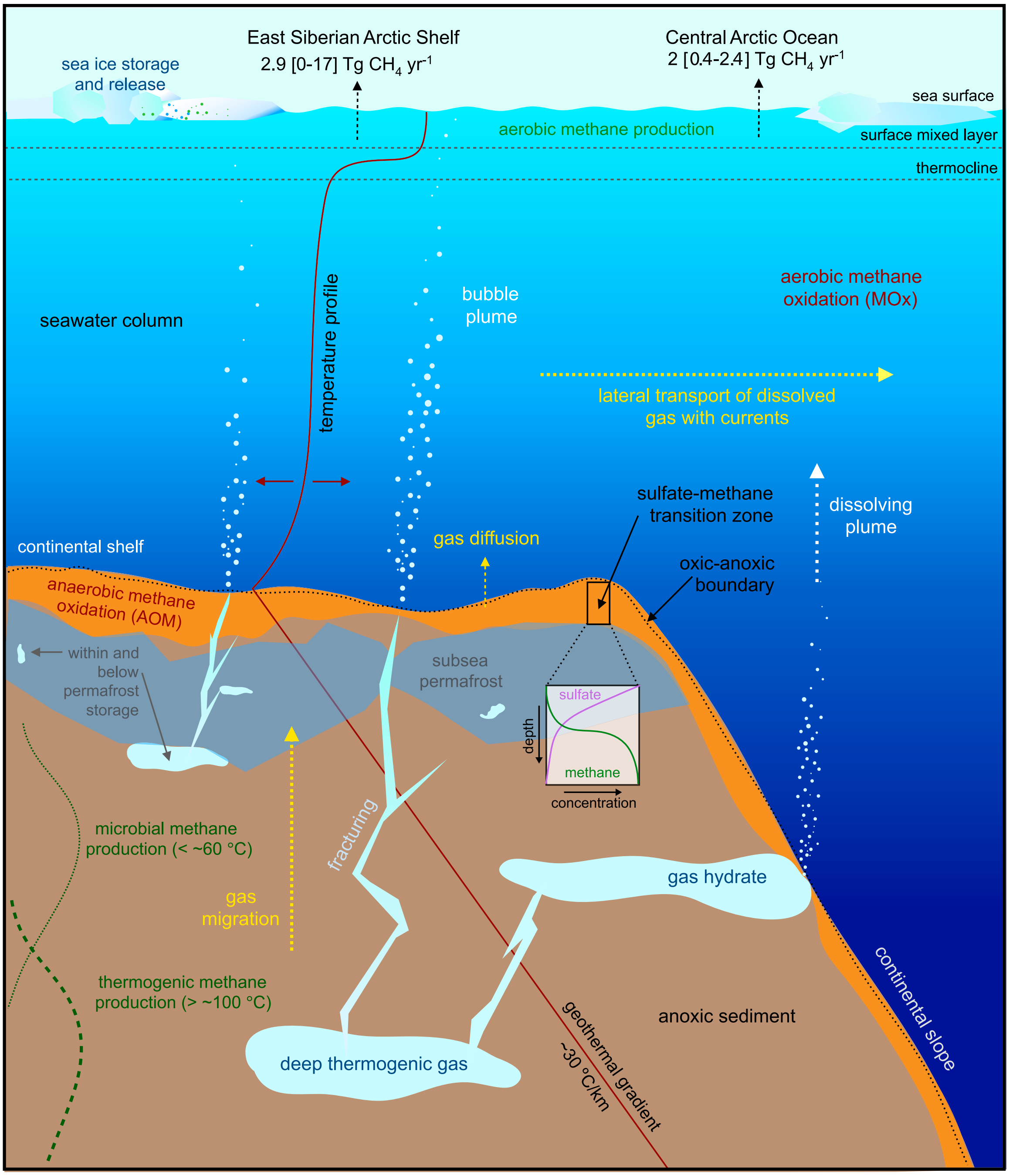

FIGURE 3
Typical areas of methane production, oxidation and migration within the ocean and its sediments. Emission estimates for the East Siberian Arctic Shelf (ESAS) and the Central Arctic Ocean are from Table 1. Figure is not drawn to scale.

variability in their methane emissions due to freeze-thaw cycles. The microbial production of methane in lakes and ponds is similar to that in wetlands, and follows the same upward pathways, but there's a larger relative contribution of ebullition to the emission to the atmosphere since diffusive methane fluxes can be anaerobically oxidized in surface waters and lake sediments (Walter et al., 2008a; Martinez-Cruz et al., 2018). Besides ebullition and turbulent dispersion, substantial emissions can also occur via transport through vascular plants in very shallow lakes (Bastviken et al., 2023).

Since harsh winter weather makes fieldwork demanding, there are few observations during winter, a similar gap in observational coverage as for wetlands (Kuhn et al., 2021). Although formerly thought to be mostly inert during the ice-covered or winter season, it is now well-known that methane is actively produced and destroyed in under-ice conditions, with rapid release of stored methane at spring thaw/ice-melt (Jammet et al., 2015). The dynamic nature of these systems, combined with the fact that current freshwater studies are taking place in a dynamic Arctic already experiencing the effects of climate change (Bruhwiler et al., 2021), complicates interpretation of observations when extrapolating to the Arctic as a whole.

2.3 Marine environment

2.3.1 Gas hydrates and subsea permafrost

Not so long ago, marine emissions of methane to the atmosphere were thought to be globally almost negligible and irrelevant to recent atmospheric methane increases (Reeburgh, 2007). This point of view was reasonable, as sulfate-rich seawater in sediments – in addition to ocean water itself – are hostile to methane, rapidly dissolving any methane in small bubbles, and then readily oxidizing it once dissolved (AMAP, 2015). Seafloor vents of methane and widespread production in the oxic surface layer of the ocean, while scientifically interesting, were not seen as systems changing with a warming climate. In the Arctic seas, early measurements supported this view (Kvenvolden et al., 1993), although it was unknown how these deposits would respond to present-day climate change (Kvenvolden, 1993). The tremendous amount of methane thought to be stored in ocean sediments in the form of hydrates (Hester and Brewer, 2009; Ruppel and Kessler, 2017) signifies the vast potential of the marine environment to emit large amounts of this greenhouse gas.

The production, consumption and transport of methane differs significantly between the terrestrial and marine environment (compare Figures 2, 3). Some similarity exists on the production side, since methanogens can also produce methane in ocean sediments (Garcia et al., 2000), but the environmental conditions are different: depending on the local geothermal gradient, microbial methane production occurs in the top ocean sediment, down to a depth of 1 to 2 km, at an optimum of 35°C–40°C and with an ultimate limit of 60°C (Judd, 2004). Thermogenic processes may occur deeper down in the ocean sediment, when temperatures exceed 110°C (Milkov, 2005). This may be as far down as 4 to 5 km, and depends on the presence of organic matter deposits such as coal beds (Judd, 2004). In addition, abiogenic methane formation can occur through metamorphic processes such as serpentinization, which is commonly associated with hydrothermal vents and faults in the oceanic crust, degassing of mafic magmas and cooling of mafic igneous rocks (Etiope and Sherwood Lollar, 2013).

When methane of any source origin migrates up towards the sea floor, it can be captured in gas hydrates – crystalline compounds that are stable under the high pressure from the overlying water and sediment column, and at low temperatures (Buffett, 2000). The range of depths with sufficiently high pressure and low temperatures are referred to as the gas hydrate stability zone (GHSZ). Globally, the GHSZ starts at ocean depths of 300–500 m, with the shallowest depths found in colder waters such as those of the Arctic (Kvenvolden, 1988). Commonly, such regions include the outer continental margins, slopes and rises (Kvenvolden, 1993), but also areas of permafrost, both onshore and offshore (Kvenvolden, 1988), where depths may be as shallow as 200 m, although the total amount of gas hydrates remains highly uncertain (Ruppel, 2015). Isotopic analyses indicate that the majority of the hydrate deposits on Earth contain biogenic methane (Archer, 2007), but hydrate formation may theoretically sequester methane from various origins (Rajan et al., 2013).

Besides hydrates, the shallow ocean shelves of the Arctic Ocean have known large petroleum systems (Cramer and Franke, 2005), and subsea permafrost that contains large amounts of frozen organic material laid down when sea level was lower in previous ice ages, leaving the land exposed (Romanovskii et al., 2000). The majority of subsea permafrost is found on the East Siberian Arctic Shelf (ESAS; consisting of the Laptev, East Siberian, and in most definitions, the Chukchi Sea), as shown in Figure 1D. The potential of methane originating from marine sediments to reach the atmosphere in these areas has somewhat shifted views on the marine environment within the global methane budget over the past two decades.

Still, the ultimate source of emissions from the shallow ocean shelves has been controversial. Methane could conceivably be sourced from eroded organics from thawing permafrost onshore, thawing submerged permafrost, surface seawater methane sources, sub-seafloor transport of methane-rich terrestrial freshwater (Charkin et al., 2017), or deep thermogenic (petroleum-associated) sources. The existence of extensive petroleum sources in the ESAS (Cramer and Franke, 2005), however, is not enough to imply an emission of methane to the atmosphere. For instance, while old thermogenic methane is present at depth on the petroleum-rich Beaufort Shelf, this does not reach the surface and atmosphere in substantial quantities even at depths as shallow as 30 m (Sparrow et al., 2018). A study of $\delta^{14}C$ in methane and stable methane isotopologues from water samples collected near a large gas seep in the outer Laptev Sea has also pointed to a deep thermogenic source (Steinbach et al., 2021).

Despite large potential sources, loss processes in the sediment – including anaerobic oxidation – limit present-day methane releases to the ocean water (Overduin et al., 2015; Stranne et al., 2019), and ultimately the atmosphere. Sulfate-dependent anaerobic oxidation of methane can occur near the ocean floor by anaerobic methanotrophic archaea, commonly referred to as the sulfate-methane transition zone (Knittel and Boetius, 2009). In areas with high production or hydrate dissociation, this transition zone may be bypassed, and methane bubbles can escape the seafloor through gas seeps, entering the water column. Some work has suggested that at high seafloor warming rates (>0.01°C yr^{-1}) – well within the range of some projections for the coming century – the efficiency of these biological methane "filters" cannot keep pace with overpressure-induced hydraulic fracturing of the sediment as methane hydrates decompose, and substantial methane is released to the water column (Stranne et al., 2022).

2.3.2 Water column and ocean surface

It is clear that some methane from seafloor gas seeps reaches the atmosphere via bubble transport (Leifer and Patro, 2002), although the total amount escaping via this pathway is controversial. Whether methane emitted from the sea floor reaches the atmosphere depends on the rate of dissolution of methane from these bubbles into the ocean water (Rehder et al., 2009), and the amount of aerobic methane oxidation (Steinle et al., 2015). The importance of these processes depend on water depth since the probability for methane dissolving into and microbially oxidizing in the ocean water (Valentine et al., 2001), before reaching the atmosphere, has greater probability with increasing depth. For example, despite widespread venting along the continental margin near Svalbard

(Sahling et al., 2014), a very minor fraction (0.07%) was estimated to reach the atmosphere (Mau et al., 2017), since 70% of observed bubble emissions occurred at depths of 120 m or greater. However, in shallow seas the water column depth is more amenable to mixing dissolved or bubble methane out of the water and into the atmosphere (McGinnis et al., 2006), and the Arctic Ocean has extensive shelf seas that are relatively shallow (Jakobsson, 2002).

In the central Arctic Ocean, deep water prevents seafloor sources from reaching the atmosphere. Under-ice methane production, and its connection with the more general "marine methane paradox" of methane production in oxygenated surface waters remains somewhat unclear, although Damm et al. (2010) proposed a model wherein phosphate-poor Pacific-origin seawater led to more near-surface methane production than in Atlantic-derived, phosphate-rich seawater. Methane production in oxic surface waters may be more prevalent than previously believed (Bižić et al., 2020) and this provides a likely additional source of methane from the marine environment in the Arctic. The scale of this process in the Arctic marine environment, and how much it contributes to the atmosphere, remains to be quantified.

Sea ice has been proposed as a modulator of the emission of methane from surface sources (Kvenvolden et al., 1993; Damm et al., 2015), and polynya openings may be a source of methane emissions even during winter (Damm et al., 2007). Aircraft and in-situ measurements demonstrated methane emissions from ice leads in the deep Arctic Ocean (Kort et al., 2012; Silyakova et al., 2022), areas which should not be easily influenced by seafloor methane sources – although the Transpolar Drift seems to move some dissolved methane from shallow shelf seas to the central Arctic Ocean (Damm et al., 2018). The discovery of methane supersaturations under sea ice in the ESAS (Shakhova et al., 2010) and in the Canadian Arctic (Kitidis et al., 2010) support the idea of wintertime accumulation and later release of methane.

3 Methane budget of the northern high latitudes

3.1 Challenges in upscaling fluxes

The upscaling of methane fluxes from plot level measurements to the entire Arctic-Boreal region is a challenging task. Periglacial landscapes exhibit a high degree of microtopography, which results in a surface where dry and wet ecosystems are alternating. Subsequently, methane emissions vary strongly across short distances (see e.g., Parmentier et al., 2011). Assessing the areal extent of wetlands is key to upscaling terrestrial methane emissions, but these ecosystems remain poorly mapped, leading to significant uncertainty in upscaled fluxes (Petrescu et al., 2010; Peltola et al., 2019). The need for spatial detail to achieve landscape emission estimates is further emphasized by the fact that the aerial extent of small lakes and ponds is poorly-constrained, which may lead to a double-counting of emissions that inflates budget estimates (Thornton et al., 2016b). Marine methane emissions can also be highly localized, leading to budget estimates that may vary up to an order of magnitude (Shakhova et al., 2014; Berchet et al., 2016; Thornton et al., 2020). In the following, we give an overview of the various methane budget estimates that have been made across the Arctic-Boreal region, using bottom-up methods such as extrapolations from site-data and process models, as well as the top-down method of inverse modeling constrained by atmospheric data (see e.g., Saunois et al., 2020).

3.2 Terrestrial methane emissions

3.2.1 A short history of upscaling techniques

From a ground-based measurement perspective, extrapolated northern wetland emission estimates have for a long time been lying between 20 and 100 Tg CH_4 yr^{-1}. Sebacher et al. (1986) estimated 45–106 Tg CH_4 yr^{-1} for Arctic and Boreal wetlands, Crill et al. (1988) estimated 72 Tg CH_4 yr^{-1} for undrained peatlands north of 40° N, Whalen et al., 1992 estimated 42 ± 26 Tg CH_4 yr^{-1} for wet meadow and tussock shrub tundra based on measurements, and Christensen (1993) estimated 18–30 Tg CH_4 yr^{-1} for global tundra based on measurements from comparable habitats on the North Slope of Alaska. Reviewing the literature available at the time, Bartlett and Harriss (1993) estimated a mean emission from wetlands north of 45° N of 38 Tg CH_4 yr^{-1} – a value not far from the early estimates of 42–45 Tg CH_4 yr^{-1} using inverse modeling for the northern hemisphere to derive a total emission estimate (Chen and Prinn, 2006).

These early, mostly ground-based, extrapolation-based estimates have been found to be mostly at the higher end of the ranges that emerged once dynamic process models capable of simulating methane emissions became available. Historically, these models focused on wetlands, since they represent the largest source of methane in the Arctic-Boreal region, but also because models can draw on a longer and more extensive record of observations for testing and validation. One of the earliest modeling attempts to establish a budget for northern wetlands modified a vegetation model by allocating a fixed fraction of heterotrophic respiration to methane production (Christensen et al., 1996). This built upon the assumptions that methane production generally scales with NPP and that forested and open wetlands each showed a narrow range of CH_4/CO_2 ratios. This study estimated that wetlands north of 50° N emitted 20 ± 13 Tg CH_4 yr^{-1}. Surprisingly, this was comparable to the 21.8 Tg CH_4 yr^{-1} estimated by a more process-based study released in the same year, that modeled methane production in relation to soil and vegetation carbon pools, temperature and the position of the water table (Cao et al., 1996). Nonetheless, both of these estimates were lower than the ~35 Tg CH_4 yr^{-1} that atmospheric inversions and extrapolations from flux measurements indicated at the time (Christensen et al., 1996).

The representation of methane production and consumption in these early model implementations was relatively basic, which reduced their usefulness to predict changing methane emissions under a future climate (Bruhwiler et al., 2021). Since then, models have been introduced that simulate both the production and consumption of methane as temperature sensitive processes, while accounting for diffusion, and bypassing of the oxic layer through aerenchyma and ebullition (Walter and Heimann, 2000). This class of models continues to be expanded by including numerous processes, with some recent advances focusing on the consumption of atmospheric methane in soils (Oh et al., 2020),

TABLE 1 Recent budget estimates of terrestrial, freshwater, and marine methane emissions to the atmosphere in the Arctic-Boreal region. Estimates are given with either confidence intervals (in brackets) or standard deviations as in the original studies. Where necessary, values were converted from Tg CH_4-C yr^{-1} to Tg CH_4 yr^{-1}. The estimates from Saunois et al. (2020) were extracted by Bruhwiler et al. (2021) and Yuan et al. (2024) for top-down and bottom-up methods respectively. We also extracted wetland emissions for the Arctic-Boreal region from the raw data presented in Peltola et al. (2019) and the lake emissions in Liu and Zhuang (2023). The 2 Tg yr^{-1} for Kort et al. (2012) is estimated by extending emissions for a year and scaling them to the area they surveyed.

Source	Method	Tg CH_4 yr^{-1}	Study
Wetlands			
Wetlands >50° N	Process model (1)	38.82 ± 3.03	Oh et al. (2020)
Wetlands >50° N	Atmospheric inversions (11)	33.6	Saunois et al. (2020), Bruhwiler et al. (2021)
Arctic-Boreal region	Upscaled flux measurements	26 [25.2–27]	Peltola et al. (2019), This study
Arctic-Boreal region	Process models (13)	16.4 ± 0.7	Saunois et al. (2020), Yuan et al. (2024)
Arctic-Boreal region	Process model	35	Watts et al. (2023)
Arctic-Boreal Region	Upscaled flux measurements	20.3 ± 0.94	Yuan et al. (2024)
Arctic-Boreal permafrost region	Upscaled flux measurements	34.1 [19.6–48.5]	Ramage et al. (2024)
Lentic systems (lakes and ponds)			
Lakes and ponds >50° N	Upscaled flux measurements	16.5 ± 9.2	Wik et al. (2016b)
Lakes and ponds >50° N	Upscaled flux measurements	13.8–17.7	Matthews et al. (2020)
Lakes and ponds >54° N	Upscaled flux measurements	13.4	Bastviken et al. (2011)
Arctic-Boreal region	Process model	8.0 ± 1.2	Liu and Zhuang (2023), This study
Arctic-Boreal permafrost region	Upscaled flux measurements	9.5 [3.9–13.6]	Ramage et al. (2024)
Lotic systems (rivers and streams)			
Rivers and streams >50° N	Upscaled flux measurements	2.4	Rocher-Ros et al. (2023)
Rivers and streams >54° N	Upscaled flux measurements	7.5	Stanley et al. (2016)
Rivers and streams >54° N	Upscaled flux measurements	0.3	Bastviken et al. (2011)
Arctic-Boreal permafrost region	Upscaled flux measurements	3.1 [2.1–3.9]	Ramage et al. (2024)
Upland soils			
Mineral soils >50° N	Process model (1)	−9.52 ± 0.59	Oh et al. (2020)
Boreal forest soils	Upscaled flux measurements	−1.5 [-2.9–0]	Ramage et al. (2024)
Other terrestrial sources			
Fires (Boreal and Tundra)	Satellite-derived upscaling	2.4 [1.9–2.8]	Ramage et al. (2024)
Geological emissions	Observation-based upscaling	2 [1.6–2.4]	Ramage et al. (2024)
Subsea permafrost			
ESAS	Upscaled diffusive fluxes and ebullition measurements	17	Shakhova et al. (2014)
ESAS	Upscaled diffusive fluxes	2.9	Thornton et al. (2016b)
ESAS	Upscaled eddy covariance flux measurements	3.02	Thornton et al. (2020)
ESAS	Regional atmospheric inversion	0–4.5	Berchet et al. (2016)
ESAS	Regional atmospheric inversion	0.58 ± 0.47	Tohjima et al. (2020)
Central Arctic Ocean			
Arctic Ocean + Beaufort and Chukchi Seas (<82° N)	Upscaled airborne flux measurements	2	Kort et al. (2012)
Arctic Ocean (excluding shelf regions)	Upscaled diffusive flux measurements	0.95 [0.36–2.35]	Lorenson et al. (2016)
Arctic Ocean (seas >60° N, ESAS excluded)	Regional atmospheric inversion	2 [1.7–2.2]	Tohjima et al. (2020)

microbial dynamics to improve temperature sensitivity and observed hysteresis (Chadburn et al., 2020) and coupled iron-redox cycling (Sulman et al., 2022).

Despite the large focus on adding process detail, it remains challenging to accurately parameterize these processes in models due to a lack of data across most of the Arctic-Boreal region, in particular across Siberia (Kuhn et al., 2021) – combined with the high spatial and temporal variability of observations as opposed to the coarse resolutions used by models (Treat et al., 2018b). Recent advances in machine learning help to disentangle this complexity, and by combining numerous data sources, from satellites, reanalysis products and land cover classes, Peltola et al. (2019) used a random forest technique to upscale site level observations to all wetlands north of 45° N. Estimates for that area ranged from 31 to 38 Tg CH_4 yr^{-1}, depending on the prescribed wetland map, with an average of 26 [25.2–27] Tg CH_4 yr^{-1} for the Arctic-Boreal region alone (Table 1).

3.2.2 Uncertainties related to wetland extent

A lack of knowledge on the total surface area of wetlands, and where they are located, have been a major obstacle to achieving accurate budgets for the entire terrestrial Arctic-Boreal region. It is telling, despite valuable attempts, that the global wetland map presented in the seminal paper by Matthews and Fung (1987) was still in use several decades later (see e.g., McGuire et al., 2012). This was mostly due to a lack of alternatives that were proven to perform substantially better in the Arctic (Petrescu et al., 2010). However, static wetland maps are potentially problematic to assess temporal trends in methane emissions since there is no guarantee that wetland extent will remain the same in a changing climate. Poulter et al. (2017), therefore, leveraged remote sensing data of surface inundation to vary the extent of wetlands depending on the presence of surface water, which resulted in the Wetland Area and Dynamics for Methane Modeling (WAD2M) wetland area dataset (Zhang et al., 2021).

WAD2M is a significant advance to represent seasonally varying wetlands in e.g., the tropics, but this approach may be less applicable to the Arctic where wetland area is less dynamic, while methane emissions can continue when water levels are well below the surface (Olefeldt et al., 2013). In addition, these remote-sensing based products effectively switch off in winter, even though cold season emissions can be up to half of the yearly budget (Treat et al., 2018a). This may explain why an ensemble of models by the Global Carbon Project that used WAD2M led to the relatively low estimate of 9 (2–18) Tg CH_4 yr^{-1} north of 60° N (Saunois et al., 2020), with a median of 16.7 Tg CH_4 yr^{-1} across the whole Arctic-Boreal region (Yuan et al., 2024). By upscaling flux measurements across the same region with machine learning, Yuan et al. (2024) estimated a slightly higher emission of 20.3 ± 0.9 Tg CH_4 yr^{-1} while using WAD2M. In contrast, a previous estimate by the Global Carbon Project, with many of the same models used by Saunois et al. (2020), came to a much higher central estimate of 35 (21–47) Tg CH_4 yr^{-1} across the smaller area of Arctic tundra alone (McGuire et al., 2012). Then again, this estimate is probably too high compared to observations since the same study also estimated a budget of 15 (0–29) Tg CH_4 yr^{-1} based on an upscaling of flux measurements alone.

An additional reason for the low estimates by studies that use WAD2M is that the areal extent of lakes and ponds was subtracted from the wetland extent to avoid the double counting of emissions from wetlands and aquatic systems (Thornton et al., 2016b). While it is important to address this bias, the areal extent of wetlands and open water was determined independently, leaving the total extent of methane emitting landforms poorly constrained. To resolve these issues, Olefeldt et al. (2021) developed The Boreal–Arctic Wetland and Lake Dataset (BAWLD) that accounts for the distribution and abundance of wetland, lake, and river classes within the same framework (Figures 1B, C). Each land class in the dataset has distinct methane emissions (Kuhn et al., 2021), including different types of wetlands (i.e., bogs, fens, marshes and wet tundra), but also dry ecosystems (e.g., dry tundra, bare rock). By defining them simultaneously, as a fraction of the total surface area of each grid cell, biases from overlaps between classes – i.e., double counting – are avoided.

While still a static mapping product, this approach may be more relevant for determining high-latitude methane budgets, since it accounts better for unique high-latitude ecosystems, such as permafrost bogs and tundra wetlands, while being specifically designed to estimate methane emissions. Moreover, WAD2M exhibits no trend in Arctic-Boreal wetland extent from 2002 to 2021 (Yuan et al., 2024), which shows that a static map remains suitable to estimate historical Arctic-Boreal methane budgets. Using the BAWLD dataset to categorize and upscale flux observations, Ramage et al. (2024) estimated that all natural sources of the Arctic-Boreal permafrost region combined are emitting 51.1 (29.1–71.2) Tg CH_4 yr^{-1}, of which about two-thirds was emitted by terrestrial ecosystems (35.6 Tg CH_4 yr^{-1}), a quarter by inland waters (12.5 Tg CH_4 yr^{-1}), and the remainder by fires (2.4 Tg CH_4 yr^{-1}) and geological sources (2 Tg CH_4 yr^{-1}).

3.2.3 Gaps in temporal and spatial coverage

Apart from the challenge of accurately assessing the spatial extents of methane-emitting landscapes, dry upland soils can take up atmospheric methane, where it is oxidized by methanotrophs (Whalen et al., 1992). This may lower regional estimates (>50° N) of net methane emissions by as much as −9.5 Tg CH_4 yr^{-1} when included in models (Oh et al., 2020) – although observation-based upscaling suggests that this sink may be as little as −1.5 Tg (−2.9–0) CH_4 yr^{-1} (Ramage et al., 2024). Still, these areas are often overlooked in observational studies (Jørgensen et al., 2014), despite the fact that this methane sink will also increase with rising temperatures (Voigt et al., 2023), compensating for emissions elsewhere. Recently, it was also proposed that microbially mediated drawdown of methane on and in trees may reduce boreal emissions slightly, by −0.055 Tg CH_4 yr^{-1} (Gauci et al., 2024).

Apart from these oversights in the uptake of methane, the winter period is under-sampled, even though the cold season may account for up to half of annual emissions (Treat et al., 2018a). Short-lived pulses caused by freeze-thaw actions can contribute significantly to cold season emissions, but observations remain sparse (Mastepanov et al., 2013; Pirk et al., 2015; Raz-Yaseef et al., 2017). Improved mapping of Arctic-Boreal landscapes and year-round monitoring remain necessary to better constrain budget estimates.

3.2.4 Atmospheric constraints

In addition to above-mentioned bottom-up methods, atmospheric inversion models are useful tools to determine top-down budget estimates across large regions (Bruhwiler et al., 2021). The 11 inversions included in a comparison by the Global Carbon Project estimated a mean emission from wetlands north of 50° N of 33.6 Tg CH_4 yr^{-1} (Saunois et al., 2020; Bruhwiler et al., 2021). These atmospheric flux inversions use statistical optimization and atmospheric transport models to estimate fluxes that are in optimal agreement with both a prior estimate (initial guess) and observations of atmospheric methane concentrations. The prior is typically a bottom-up method, such as a process model or statistically upscaled fluxes of wetland emissions, as well as inventories of anthropogenic emissions from fossil fuels and agriculture. In regions with little data coverage, atmospheric transport can become a large source of uncertainty, which may lead to model-data mismatch errors (Bruhwiler et al., 2021). Moreover, inversions rely on their prior, which means that uncertainties in bottom-up methods, e.g., the wetland extent or poor cold season data coverage, also affect budget estimates from inversions.

Atmospheric inversions are highly useful to determine the total methane budget, since they are constrained by atmospheric concentrations, but a caveat is that they struggle to distinguish between anthropogenic sources, wetlands and lakes unless their priors are strongly separated spatially (Bruhwiler et al., 2014). Inversions provide an overview of the size and trends of all emissions, but they are limited in the amount of information they can provide on individual sources, even though they are an important constraint on the combined amount of these individual sources.

3.3 Freshwater methane emissions

3.3.1 Observation-based and modeled lake emissions

Lakes have long been recognized to be a substantial source of methane to the atmosphere, but estimates are typically below those of wetlands. Bastviken et al. (2011) estimated a total emission north of 54° N of 13.4 Tg CH_4 yr^{-1}, with just 6.8 Tg CH_4 yr^{-1} north of 66° N. Wik et al. (2016b) boosted the prominence of lakes in the Arctic, deriving a pan-Arctic estimate of 16.5 ± 9.2 Tg CH_4 yr^{-1} of methane from lakes and ponds. However, the aforementioned problems of overlapping and conflation of small, shallow lakes and ponds with wetlands, and lake-wetland interface zones, continued to be a challenge (Thornton et al., 2016b). In addition, ebullition from lakes is the most difficult to quantify, due to its episodic and often stochastic nature. Approaches have included ice-bubble surveys on frozen lakes (Walter Anthony et al., 2010; Wik et al., 2011), bubble traps (e.g., Wik et al., 2013), and synthetic aperture radar surveys of frozen lake surfaces (Walter et al., 2008b; Engram et al., 2020). The high temporal variability of ebullition, combined with the difficulty and expense of long-term lake ebullition sampling in the Arctic, has likely led to many studies underestimating lake methane emissions (Wik et al., 2016a).

While the estimate by Wik et al. (2016b) put Arctic lakes' methane emissions at a similar magnitude to that of wetlands, recent estimates using newly available databases are again lower. Matthews et al. (2020) estimate 13.8–17.7 Tg CH_4 yr^{-1} for lakes <5000 km^2 north of 50° N, while Ramage et al. (2024) estimated just 9.5 (3.9–13.6) Tg CH_4 yr^{-1} for lakes in the Arctic-Boreal permafrost region. Meanwhile, model implementations of lake methane emissions are dwarfed by the work on wetlands, but a recent attempt by Tan and Zhuang (2015) estimated a budget of 11.9 (7.1–17.3) Tg CH_4 yr^{-1} for lakes north of 60° N, not too dissimilar from the observation-based upscaling. An updated version of the same model estimated an emission of 14.76 ± 0.44 Tg CH_4 yr^{-1} for all lakes north of 45° N (Liu and Zhuang, 2023), of which 8.0 ± 1.2 Tg CH_4 yr^{-1} originated from lakes in the Arctic-Boreal region.

3.3.2 Gaps in temporal and spatial coverage

As with wetlands, local hydrology is a key regulator of carbon cycling and methane emissions in lake landscapes. Terrestrially produced methane can be transported from wetlands' active layer into lakes via groundwater flow (Paytan et al., 2015). Large numbers of Arctic lakes are in thermokarst environments, and are often quite shallow, making them more vulnerable to heating and increased permafrost thaw, below and around the lakes, under climate warming (Walter et al., 2006). The net contribution of small lakes and thaw ponds has proven difficult to determine; such lakes are numerous and rich in dissolved organic carbon (DOC) and methane (Langer et al., 2015). High-resolution airborne hyperspectral mapping of water bodies also confirmed a strong relation between methane emissions and the distance to standing water (Elder et al., 2020). However, a study of lakes in the West Siberian Lowlands (a well-known major terrestrial wetland methane source) found only a minimal contribution to total methane from the small thaw lakes within this landscape (Polishchuk et al., 2018). On the other hand, lakes in carbon-rich Yedoma sediments have been found to be highly productive, and methane can be produced year-round if a thaw bulb has been established in lake sediments, despite low mean annual air temperatures (Walter et al., 2007).

Similar to wetlands, it has become more recognized in recent years that the so-called edge seasons – spring and autumn – are major, and variable, contributors to total annual methane emissions depending on lake ice-out and freeze-up conditions. Additionally, these edge seasons are expected to experience the most dramatic warming changes in the future, as ice-free seasons of lakes are extended. Year-round eddy covariance observations have demonstrated that lake spring methane efflux is variable between years (Jammet et al., 2017), and is lower in years with less snowmelt (Jansen et al., 2019). Spring contributions to annual emissions vary hugely interannually, 4%–74% of total annual emissions (Denfeld et al., 2018), and are driven by sub-ice and in-ice methane buildup overwinter (Juutinen et al., 2009; Wik et al., 2011; Walter Anthony and Anthony, 2013). Although the spring emission was once thought to be a single large burst or pulse at ice-out and lake overturn (mixing of the entire water column), recent measurements have shown more variability (Denfeld et al., 2015).

3.3.3 Rivers and streams

Compared to wetlands and lakes, little data exists on methane emissions from rivers and streams in the Arctic-Boreal region. A compilation of measurements from freshwater fluvial systems suggests an emission of 7.5 Tg CH_4 yr^{-1} from these systems alone, north of 66° N (Stanley et al., 2016; Thornton et al., 2016b) – 25x higher than an earlier estimate of 0.3 Tg CH_4 yr^{-1} (Bastviken et al., 2011). A recent global estimate of riverine methane emissions falls in between these two estimates, at 2.4 Tg CH_4 yr^{-1} for the area North of 50° N (Rocher-Ros et al., 2023). This is about the same fraction of global emissions from fluvial systems (17% vs. 15%)

as temperate and subtropical regions (30°–50° N), despite being ice covered for a large part of the year. A rather similar estimate of 3.1 (2.1–3.9) Tg CH_4 yr^{-1} was derived by Ramage et al. (2024) for the rivers of the Arctic-Boreal permafrost region. Although there remains a high uncertainty to these numbers, the influence of large freshwater fluvial systems on coastal marine methane cannot be understated, as large increases in dissolved methane in surface waters are frequently observed near major river outlets (Shakhova et al., 2010; Bussmann, 2013; Kohnert et al., 2017).

3.4 Marine methane emissions

The past decade has seen a wide variety of estimates of present-day methane emissions from the Arctic Ocean, and considerable uncertainty remains about the net emissions from the surface waters from the Arctic Ocean proper, and how that may change in the future. Interest has continued to be focused on shallow shelf areas of the Arctic Seas, especially the ESAS. Emissions are, in some areas, enhanced by direct bubble transport from the sediment to the atmosphere, and resupply to surface waters by dissolving bubbles.

Early studies from the ESAS estimated fluxes as high as 8 to 17 Tg CH_4 yr^{-1} (Shakhova et al., 2010; Shakhova et al., 2014). A global modelling study by Warwick et al. (2016), indicated that Arctic wetland emissions would have to be overestimated to accommodate such large emissions from the ocean. Atmospheric measurements of methane concentrations and isotopic signatures also show that Arctic methane emissions are dominated by wetlands and not the ocean (Fisher et al., 2011; Thonat et al., 2017). Several follow-up studies show that ESAS emissions had been overestimated in the early studies. Berchet et al. (2016) used a regional inverse model and suggested a range of 0–4.5 Tg CH_4 yr^{-1}. Thornton et al. (2016a) used surface water and atmospheric measurements in the central ESAS to suggest 2.9 Tg yr^{-1} from the ESAS region, drastically lower than the earlier estimate of 17 Tg yr^{-1} (Shakhova et al., 2014). An eddy-covariance based study (Thornton et al., 2020), estimated 3.02 Tg yr^{-1} for the ESAS, even though emission "hotspots" above seafloor gas seeps reached emission rates of >600 mg m^{-2} d^{-1} – roughly an order of magnitude higher than onshore sources. The apparent spatial rarity of these large emissions seems to limit their regional-scale influence.

Measurements in other regions of the Arctic have to date revealed much smaller methane emissions to the atmosphere than in the ESAS. Notably, emissions from the North American Arctic have been estimated to be as low as 0.009 [0.002–0.023] Tg CH_4 yr^{-1} (Fenwick et al., 2017; Manning et al., 2022; Vogt et al., 2023). Rivers appear to be a significant contributor to marine methane in the nearshore Canadian Arctic, in particular during spring ice melt (Manning et al., 2020). In the waters near Svalbard, where extensive seepage from gas hydrates has been documented (Westbrook et al., 2009; Sahling et al., 2014), it appears that very little enters the atmosphere, with budget estimates ranging from 0.0015 to 0.06 Tg CH_4 yr^{-1} (Graves et al., 2015; Lund Myhre et al., 2016; Mau et al., 2017). In this area, it was demonstrated that carbon dioxide uptake from the atmosphere above active seafloor methane seeps resulted in a net negative radiative forcing despite some methane reaching the atmosphere (Pohlman et al., 2017). For the Central Arctic Ocean, methane emissions are relatively small compared to terrestrial sources (Lorenson et al., 2016; Silyakova et al., 2022; Prytherch et al., 2024), and budget estimates range from 0.36 to 2.35 Tg CH_4 yr^{-1} (Kort et al., 2012; Lorenson et al., 2016; Tohjima et al., 2020).

4 Discussion

4.1 Future trajectories under continued climate change and permafrost thaw

4.1.1 Terrestrial emission trends

Whether northern wetlands will become a significantly larger source of methane to the atmosphere remains highly uncertain, and this will depend on the relative change in temperature and surface hydrology. From a temperature perspective, it would be expected that methane emissions will increase with continued climate change, since this will raise the activity of methanogens (Yvon-Durocher et al., 2014). In principle, this will also raise the activity of methanotrophs (Voigt et al., 2023), but model simulations show that this increasing sink capacity can compensate for, but will not outpace, increases in methane production (Oh et al., 2016). However, if the permafrost region becomes drier, and the total extent of wetlands decreases, methane emissions could stay the same or even decline. The direction in which the hydrology of the permafrost region will develop with climate change remains the largest wildcard in the Arctic-Boreal methane budget.

The recent past may provide some hints about the trajectory that high latitude methane emissions are on. The longest eddy covariance record of methane emissions, from the Samoylov research station in the Lena delta, showed that June-July emissions had increased by 1.9% ± 0.7% yr^{-1} since 2004 due to earlier snowmelt and higher temperatures (Rößger et al., 2022). However, emissions were not statistically different in August and September. This may be related to drier conditions in late summer when active layer depths are deeper, making surface drainage more effective, suggesting that methane emissions can be sensitive to the seasonality in warming trends – as was previously shown for CO_2 (Helbig et al., 2022). Similarly, Yuan et al. (2024) showed in their upscaling of fluxes across the Arctic-Boreal region that the strongest increases in emissions occurred in June and July, but not late summer, and that the annual total had increased by ~9% (~1.7 Tg CH_4 yr^{-1}) from 2002 to 2021.

Model ensembles have generally struggled to show similar increases in annual emissions (McGuire et al., 2012; Saunois et al., 2017), but this may be related to a high variability in simulated flux magnitude among models, as well as a high interannual variability (Ito et al., 2023). Despite generally underestimating emissions, the models of the Global Carbon Project appear to show a slight increase in cold season emissions (Ito et al., 2023). It is also possible that such increases are restricted to smaller regions. Parmentier et al. (2015) combined three process models to show that warming along the Arctic Ocean, related to the sea ice albedo effect, can lead to an amplification of methane emissions from near-coastal wetlands in autumn and early winter. This may be one of the reasons why atmospheric inversion models show an average increase of ~3 Tg CH_4 yr^{-1} from 2000 to 2018 in high latitude emissions (>60° N) while emissions remained unchanged further south (50°–60° N) despite significant year-to-year variation (Bruhwiler et al., 2021).

While recent studies point to a modest increase in methane emissions, the question is whether this is due to microbes processing ancient permafrost carbon that has recently thawed, or whether this is due to a general intensification of the carbon cycle. The latter would provide larger amounts of fresh substrate, e.g., in the form of root exudates, that can be readily transformed to methane. A study from thawing permafrost peatlands in northern Canada suggested that the former is likely, with less than 10% of methane fluxes being derived from previously frozen carbon (Cooper et al., 2017).

Furthermore, a meta-analysis of methane fluxes across the Arctic-Boreal region has shown that thermokarst sites had higher emissions than adjacent intact permafrost sites, which was attributed to differences in temperature (Olefeldt et al., 2013). Given comparable environmental conditions, however, there was no statistical difference between thermokarst sites and permafrost-free sites. This suggests that changes in methane emissions are more closely related to changes in hydrology, vegetation composition and temperature following permafrost thaw rather than the availability of ancient permafrost carbon (Olefeldt et al., 2013; Cooper et al., 2017). Still, thermokarst significantly changes the hydrology of the landscape, and it has been suggested that abrupt thaw may be responsible for as much as 30.9 (19.7–41.9) Tg CH_4 yr^{-1} of terrestrial methane emissions (Ramage et al., 2024) – although this estimate may be inflated by double counting.

4.1.2 Freshwater emission trends

A growing body of evidence points towards an increase of lake methane emissions with climate change. Ever larger lake site-specific datasets have allowed detailed analyses of how different regulators, such as wind shear and temperature, control methane emissions over short and long timescales (e.g., Jansen et al., 2019). In addition, it has been proposed that ebullition is controlled by the energy input to lakes (Wik et al., 2014) as well as temperature and lake productivity (DelSontro et al., 2016). Shallow lakes in permafrost regions appear more vulnerable to warming (Arp et al., 2016) and longer ice-free seasons increase the solar energy input to all lakes (Wik et al., 2014; Thornton et al., 2015). Overall, longer and warmer ice-free seasons raise microbial methane production, which seems to prime lakes to be a sustained methane source under warming (Wik et al., 2018) – a prediction not confined to the Arctic (see e.g., Guo et al., 2020; Zhu et al., 2020).

Increased production of methane can originate from both ancient permafrost carbon and modern carbon pools. Dean et al. (2020) showed through an analysis of carbon isotope compositions that emissions from inland waters in the East Siberian Arctic were primarily (>80%) driven by the decomposition of contemporary carbon, although sites with active permafrost thaw saw contributions of ancient carbon above 50%. Since both old and recent carbon inputs can act as a source of methane, and given the general rise in temperature, it is likely that the per-unit area emissions of freshwater systems will go up with climate change.

Even though the direction appears clear, the magnitude of this change remains poorly quantified. Tan and Zhuang (2015) used a process-based model to estimate that methane emissions from lakes north of 60° N will increase by 10.3 and 16.2 Tg CH_4 yr^{-1} by the end of the 21st century under a low or high warming scenario, respectively (Representative Concentration Pathways 2.6 and 8.5). However, as with wetlands, local hydrology will play an important role in these trajectories. Arctic lakes can be highly dynamic, and both increases and decreases in lake size have been observed with remote sensing in the past (Smith et al., 2005; Carroll et al., 2011). If lake drainage reduces the number and total extent of lakes, this can ultimately limit the amount of methane emitted from lakes and ponds (van Huissteden et al., 2011). Finally, whether emissions from fluvial systems will go up depends much on the quantity and lability of the inflow of carbon from terrestrial environments, and lakes and ponds (Vonk et al., 2015).

4.1.3 Marine emission trends

For decades, the concept of large-scale release of methane from subsea methane hydrate (also known as clathrate) sources, directly to the atmosphere in rapid cataclysmic events, has been seen as a potential climate tipping point (e.g., Nisbet, 1990; Dickens, 2003; 2011). Hydrates are present beneath the Arctic continental shelves, and can be exposed on some Arctic continental slopes (Westbrook et al., 2009). However, due to the aforementioned processes that destroy methane in the ocean water, the scale of hydrate emissions reaching the atmosphere appears to be relatively insignificant (James et al., 2016; Mau et al., 2017). Also, previous modelling work suggested that methane releases from hydrates under a warmer climate will most likely be a slow process, over timescales of centuries or millennia (Archer, 2015; Kretschmer et al., 2015).

Nonetheless, uncertainties remain with respect to hydrate stabilities and rapid transport through sediments under certain circumstances (Stranne et al., 2016; 2017). The storage of hydrates has been modulated over glacial-interglacial cycles by the presence of massive ice sheets in the Arctic, and associated glacial rebound, which alter the location of the hydrate stability zone (Portnov et al., 2016; Wallmann et al., 2018). Internal cyclical behavior of gas hydrates may make them more vulnerable to climate perturbations, triggering mechanical sediment failures such as the formation of pipes, chimneys or pockmarks (Gupta et al., 2023). Also, long-distance migration of methane through permeable sediments may be the cause of methane venting at shallower depths, beyond the marine limit of gas hydrates (Davies et al., 2024). This highlights that significant uncertainty still exists regarding the dynamics of methane release from gas hydrates to ocean waters.

Changes are occurring more quickly on the shallow shelves of the Arctic Ocean, where thaw rates of 1–15 cm yr^{-1} have been observed near the coast of the Laptev and East Siberian Seas (Overduin et al., 2007). While this thawing of previously frozen permafrost can lead to methane release, this gas still has to traverse the top sediment before entering the water column. Overduin et al. (2015) showed that methane concentrations in the top ~25 m of overlying unfrozen sediment were much lower than in the ice-bonded permafrost below, which was due to rapid anaerobic oxidation of methane long before reaching the seabed. Observed methane emissions in this region are not derived from degrading permafrost, but they must originate from deeper sources (e.g., thermogenic or gas hydrates), possibly released along fault lines (Nicolsky et al., 2012). These deeper sources are unlikely to be influenced by contemporary climate change since the warming

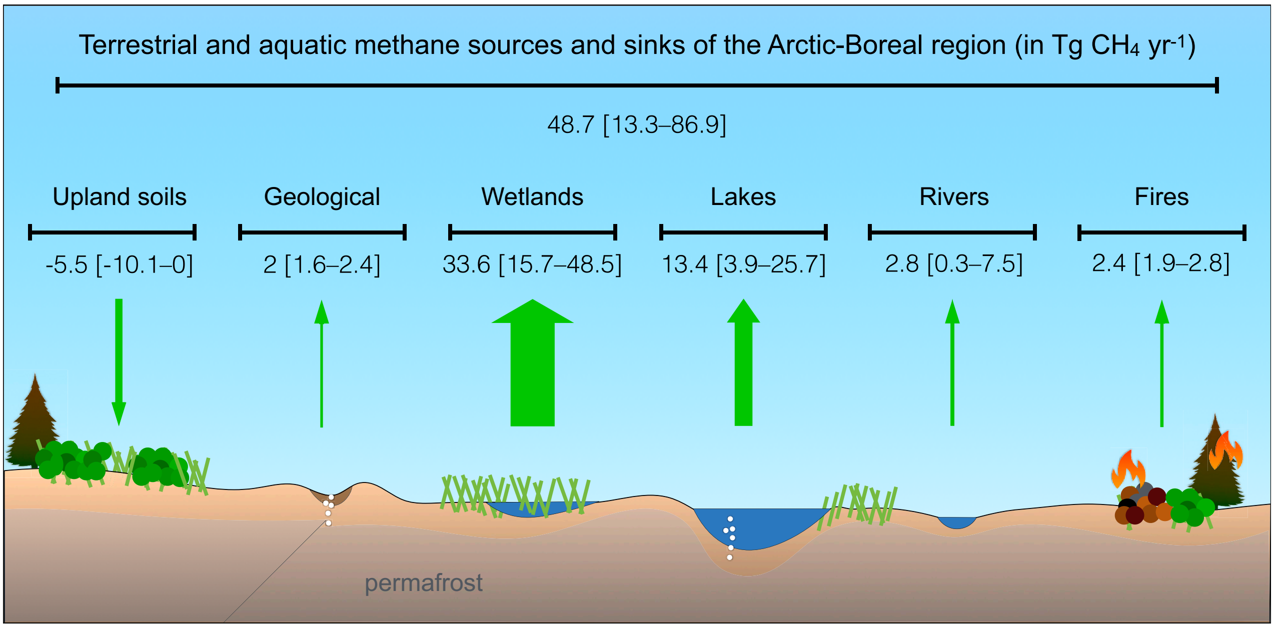

FIGURE 4
Terrestrial and freshwater methane sources and sinks, and their estimated sizes in Tg CH_4 yr^{-1}. Confidence intervals are given in brackets. Green arrows indicate the direction and relative size of each flux. See Table 1 for individual source estimates.

signal takes up to a millennium to reach the depths of the gas hydrate stability zone in subsea permafrost (Dmitrenko et al., 2011).

This indicates that marine methane emissions to the atmosphere are unlikely to significantly increase in magnitude in the near future despite a recent estimate that subsea permafrost contains about double the amount of carbon stored in terrestrial permafrost (Miesner et al., 2023). However, the same study also showed that the large permafrost shelf carbon pool is largely insensitive to thaw, strongly limiting the availability of permafrost carbon and the potential for it to be released to the atmosphere as methane. Still, environmental changes in the Arctic Ocean do matter for the regional methane budget since reductions in sea-ice coverage will increase atmospheric warming due to the sea ice-albedo effect (Screen et al., 2012). This warming extends to the land, which will likely raise terrestrial methane emissions and also affect the CO_2 balance (Parmentier et al., 2013).

4.2 Methane vs. CO_2 emissions

While this study focuses on methane, it is important to note that changes in the surface hydrology of the high latitudes will also have serious consequences for the exchange of CO_2. The decomposition of soil organic matter in wetlands is generally slowed down due to high water tables and low oxygen content. This means that wetlands are typically a source of methane but a sink of CO_2, while dry ecosystems are typically a sink of methane but do not build up equally large soil carbon pools (Treat et al., 2024). If, however, wet ecosystems become drier and soil organic matter is exposed to oxygen, this would lead to a release of CO_2 emissions instead of methane (Schuur et al., 2022). Alternatively, thermokarst can lead to a transformation from dry to wet tundra, leading to a large increase in landscape scale methane emissions, while releasing soil carbon into the aquatic domain in the process (Christensen et al., 2004). These strong links with hydrology emphasize that the exchanges of methane and CO_2 do not happen in isolation, but rather that they are two sides of the same coin.

Combined, the terrestrial ecosystems of the Arctic-Boreal region are most likely a sink of CO_2 (Bruhwiler et al., 2021; Virkkala et al., 2021), but this may be largely offset by CO_2 emissions from inland waters and fires. By accounting for this, Ramage et al. (2024) concluded that it is possible that the combined terrestrial and freshwater systems of the Arctic-Boreal permafrost region are near carbon neutral, emitting 12 (−606.4–661.4) Tg C yr^{-1} on a CO_2 basis alone (Ramage et al., 2024). Still, this estimate comes with a very high uncertainty, and excludes the Arctic Ocean, which is a strong sink of CO_2 (Parmentier et al., 2017), while emitting much less methane to the atmosphere than the land due to efficient oxidation in ocean waters. Nonetheless, if methane is released in large enough amounts from the sea floor, this will enhance ocean acidification, impact marine biogeochemistry and negatively affect calcifying organisms (Biastoch et al., 2011; Boudreau et al., 2015). In the terrestrial domain, the future direction of the CO_2 balance will strongly depend on whether enhanced vegetation growth can or cannot compensate for enhanced soil carbon loss from respiration and increases in disturbances such as fires, thermokarst and extreme weather events (Treat et al., 2024).

5 Conclusion

Over the past decade, longer observational records, more detailed process models, better mapping of wetlands and lakes, and novel upscaling techniques with machine learning have all been tremendously important to improve budget estimates of high latitude methane sources. Table 1; Figure 4 summarize recent budget estimates that predominantly cover the Arctic-Boreal region. Surveyed regions were broadly similar but varied from a simple latitudinal cutoff to the whole Arctic-Boreal region. We extracted data for the Arctic-Boreal region where possible and based our central estimates on medians to minimize biases due to outliers.

Collectively, these studies indicate that the wetlands of the Arctic-Boreal region are emitting 33.6 [15.7–48.5] Tg CH_4 yr^{-1}, followed by lakes and ponds emitting 13.4 [3.9–25.7] Tg CH_4 yr^{-1}. Of the smaller sources, rivers and streams emit 2.8 [0.3–7.5] Tg CH_4 yr^{-1}, fires may add 2.4 [1.9–2.8] Tg CH_4 yr^{-1} and geological emissions about 2 [1.6–2.4] Tg CH_4 yr^{-1}. However, upland soils may compensate somewhat for these emissions by taking up as much as −5.5 [−10.1–0] Tg CH_4 yr^{-1}. Together, this sums up to a total methane budget for the terrestrial Arctic-Boreal region of 48.7 [13.3–86.9] Tg CH_4 yr^{-1}, which is roughly a quarter of all global natural emissions as estimated by inversions (Saunois et al., 2020). In addition, the East Siberian Arctic Shelf may release 2.9 [0–17] Tg CH_4 yr^{-1} while the rest of the Arctic Ocean is estimated to emit 2 [0.4–2.4] Tg CH_4 yr^{-1}, adding up to a total of 4.9 [0.4–19.4] Tg CH_4 yr^{-1} for the whole Arctic marine environment.

Arctic-Boreal methane sources are diverse and dynamic in nature, with a high interannual variability. For a long time, this has made it difficult to separate the signal from the noise when identifying trends. However, recent studies constrained by observations indicate that high latitude methane sources from wetlands have slightly increased over the first two decades of this century by about 1.7–3 Tg CH_4 yr^{-1} (Bruhwiler et al., 2021; Yuan et al., 2024). This increase appears to be due to higher temperatures in early summer, leading to earlier snowmelt and a general higher activity of methanogens. At the moment, however, the observational record remains too sparse to quantify how sources other than wetlands have responded to climate warming.

In a global context, this increase is modest, representing roughly 5%–10% of the recent growth in methane emissions attributed to natural sources worldwide (Nisbet et al., 2023) – albeit with high uncertainty. Natural contributions to the recent rise in atmospheric methane are strongly influenced by tropical wetlands, with the permafrost region contributing to, but not clearly dominating, these changes. Moreover, anthropogenic reductions in methane emissions have the potential to compensate for such natural increases (Christensen et al., 2019), although natural feedbacks will make it more difficult to achieve the goals set out by the Paris agreement (Schuur et al., 2022).

Going forward, a large release of methane from the Arctic-Boreal region remains probable, despite relatively minor emission changes in the recent past. Future trajectories remain highly uncertain and difficult to predict, while the Arctic-Boreal region continues to warm more rapidly than the rest of the world. Wetland methane emissions are highly sensitive to the local hydrology, which means that shifts in the extent of wetlands and inland waters will strongly impact future methane emissions – on top of what can be expected from increased microbial activity following warming. There remains a distinct likelihood that methane emissions from the Arctic-Boreal region will show substantial growth – becoming a more dominant component of the global methane budget.

The evidence presented here appears to point towards a modest rise in methane emissions from the Arctic-Boreal region since the start of the century. At the same time, it is uncertain whether the region as a whole is a net sink or source of CO_2 – when accounting for lateral flows and disturbances. Given the stronger global warming potential of methane compared to CO_2, a change in methane emissions can be an important factor in whether permafrost thaw will lead to a strong positive climate feedback. A continued focus on expansion of monitoring, improvement in process understanding, and added detail in the modeling of vegetation dynamics, microbial processes, geomorphology, and hydrology of high-latitude landscapes will be crucial to determine how climate change will continue to alter methane emissions from the Arctic-Boreal region in the future.

Author contributions

F-JP: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. BT: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review and editing. AS: Writing–original draft, Writing–review and editing. TC: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Research Council of Norway (Grant #323945) as part of the BioGov project. TC was supported by the Danish Energy Agency.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

AMAP (2015). *AMAP assessment 2015: methane as an arctic climate forcer*. Oslo, Norway: Arctic monitoring and assessment programme.

AMAP (2022). *AMAP assessment 2021: impacts of short-lived climate forcers on arctic climate, air quality, and human health*. Tromsø, Norway. Arctic monitoring and assessment programme.

Archer, D. (2007). Methane hydrate stability and anthropogenic climate change. *Biogeosciences* 4, 521–544. doi:10.5194/bg-4-521-2007

Archer, D. (2015). A model of the methane cycle, permafrost, and hydrology of the Siberian continental margin. *Biogeosciences* 12, 2953–2974. doi:10.5194/bg-12-2953-2015

Arp, C. D., Jones, B. M., Grosse, G., Bondurant, A. C., Romanovsky, V. E., Hinkel, K. M., et al. (2016). Threshold sensitivity of shallow Arctic lakes and sublake permafrost to changing winter climate. *Geophys. Res. Lett.* 43, 6358–6365. doi:10.1002/2016GL068506

Bartlett, K. B., and Harriss, R. C. (1993). Review and assessment of methane emissions from wetlands. *Chemosphere* 26, 261–320. doi:10.1016/0045-6535(93)90427-7

Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M., and Enrich-Prast, A. (2011). Freshwater methane emissions offset the continental carbon sink. *Science* 331, 50. doi:10.1126/science.1196808

Bastviken, D., Treat, C. C., Pangala, S. R., Gauci, V., Enrich-Prast, A., Karlson, M., et al. (2023). The importance of plants for methane emission at the ecosystem scale. *Aquat. Bot.* 184, 103596. doi:10.1016/j.aquabot.2022.103596

Berchet, A., Bousquet, P., Pison, I., Locatelli, R., Chevallier, F., Paris, J.-D., et al. (2016). Atmospheric constraints on the methane emissions from the East Siberian shelf. *Atmos. Chem. Phys.* 16, 4147–4157. doi:10.5194/acp-16-4147-2016

Biastoch, A., Treude, T., Rüpke, L. H., Riebesell, U., Roth, C., Burwicz, E. B., et al. (2011). Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. *Geophys. Res. Lett.* 38, L08602. doi:10.1029/2011GL047222

Bižić, M., Klintzsch, T., Ionescu, D., Hindiyeh, M. Y., Günthel, M., Muro-Pastor, A. M., et al. (2020). Aquatic and terrestrial cyanobacteria produce methane. *Sci. Adv.* 6, eaax5343. doi:10.1126/sciadv.aax5343

Bogoyavlensky, V., Bogoyavlensky, I., Nikonov, R., and Kishankov, A. (2020). Complex of geophysical studies of the seyakha catastrophic gas blowout crater on the yamal Peninsula, Russian arctic. *Geosciences* 10, 215. doi:10.3390/geosciences10060215

Boudreau, B. P., Luo, Y., Meysman, F. J. R., Middelburg, J. J., and Dickens, G. R. (2015). Gas hydrate dissociation prolongs acidification of the Anthropocene oceans. *Geophys. Res. Lett.* 42, 9337–9344A. doi:10.1002/2015GL065779

Bruhwiler, L., Dlugokencky, E., Masarie, K., Ishizawa, M., Andrews, A., Miller, J., et al. (2014). CarbonTracker-CH_4: an assimilation system for estimating emissions of atmospheric methane. *Atmos. Chem. Phys.* 14, 8269–8293. doi:10.5194/acp-14-8269-2014

Bruhwiler, L., Parmentier, F.-J. W., Crill, P., Leonard, M., and Palmer, P. I. (2021). The arctic carbon cycle and its response to changing climate. *Curr. Clim. Change Rep.* 7, 14–34. doi:10.1007/s40641-020-00169-5

Buffett, B. A. (2000). Clathrate hydrates. *Annu. Rev. Earth Planet. Sci.* 28, 477–507. doi:10.1146/annurev.earth.28.1.477

Buldovicz, S. N., Khilimonyuk, V. Z., Bychkov, A. Y., Ospennikov, E. N., Vorobyev, S. A., Gunar, A. Y., et al. (2018). Cryovolcanism on the Earth: origin of a spectacular crater in the yamal Peninsula (Russia). *Sci. Rep.* 8, 13534. doi:10.1038/s41598-018-31858-9

Bussmann, I. (2013). Distribution of methane in the Lena delta and buor-khaya bay, Russia. *Biogeosciences* 10, 4641–4652. doi:10.5194/bg-10-4641-2013

Cao, M. K., Marshall, S., and Gregson, K. (1996). Global carbon exchange and methane emissions from natural wetlands: application of a process-based model. *J. Geophys. Res. Atmos.* 101, 14399–14414. doi:10.1029/96JD00219

Carroll, M. L., Townshend, J. R. G., DiMiceli, C. M., Loboda, T., and Sohlberg, R. A. (2011). Shrinking lakes of the Arctic: spatial relationships and trajectory of change. *Geophys. Res. Lett.* 38. doi:10.1029/2011GL049427

Chadburn, S. E., Aalto, T., Aurela, M., Baldocchi, D., Biasi, C., Boike, J., et al. (2020). Modeled microbial dynamics explain the apparent temperature-sensitivity of wetland methane emissions. *Glob. Biogeochem. Cycles* 34, e2020GB006678. doi:10.1029/2020GB006678

Charkin, A. N., Rutgers van der Loeff, M., Shakhova, N. E., Gustafsson, Ö., Dudarev, O. V., Cherepnev, M. S., et al. (2017). Discovery and characterization of submarine groundwater discharge in the Siberian Arctic seas: a case study in the Buor-Khaya Gulf, Laptev Sea. *Cryosphere* 11, 2305–2327. doi:10.5194/tc-11-2305-2017

Chen, Y., Romps, D. M., Seeley, J. T., Veraverbeke, S., Riley, W. J., Mekonnen, Z. A., et al. (2021). Future increases in Arctic lightning and fire risk for permafrost carbon. *Nat. Clim. Chang.* 11, 404–410. doi:10.1038/s41558-021-01011-y

Chen, Y.-H., and Prinn, R. G. (2006). Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. *J. Geophys. Res. Atmos.* 111. doi:10.1029/2005JD006058

Christensen, T. R. (1993). Methane emission from Arctic tundra. *Biogeochemistry* 21, 117–139. doi:10.1007/BF00000874

Christensen, T. R. (2014). Climate science: understand Arctic methane variability. *Nature* 509, 279–281. doi:10.1038/509279a

Christensen, T. R., Arora, V. K., Gauss, M., Höglund-Isaksson, L., and Parmentier, F.-J. W. (2019). Tracing the climate signal: mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. *Sci. Rep.* 9, 1146. doi:10.1038/s41598-018-37719-9

Christensen, T. R., Johansson, T. R., Akerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., et al. (2004). Thawing sub-arctic permafrost: effects on vegetation and methane emissions. *Geophys. Res. Lett.* 31, L04501. doi:10.1029/2003GL018680

Christensen, T. R., Panikov, N. S., Mastepanov, M., Joabsson, A., Stewart, A., Oquist, M., et al. (2003). Biotic controls on CO_2 and CH_4 exchange in wetlands - a closed environment study. *Biogeochemistry* 64, 337–354. doi:10.1023/A:1024913730848

Christensen, T. R., Prentice, I. C., Kaplan, J., Haxeltine, A., and Sitch, S. (1996). Methane flux from northern wetlands and tundra. *Tellus B Chem. Phys. Meteorology* 48, 652–661. doi:10.3402/tellusb.v48i5.15938

Christiansen, J. R., and Jørgensen, C. J. (2018). First observation of direct methane emission to the atmosphere from the subglacial domain of the Greenland Ice Sheet. *Sci. Rep.* 8, 16623. doi:10.1038/s41598-018-35054-7

Chuvilin, E., Stanilovskaya, J., Titovsky, A., Sinitsky, A., Sokolova, N., Bukhanov, B., et al. (2020). A gas-emission crater in the erkuta river valley, yamal Peninsula: characteristics and potential formation model. *Geosciences* 10, 170. doi:10.3390/geosciences10050170

Cooper, M. D. A., Estop Aragonés, C., Fisher, J. P., Thierry, A., Garnett, M. H., Charman, D. J., et al. (2017). Limited contribution of permafrost carbon to methane release from thawing peatlands. *Nat. Clim. Change* 7, 507–511. doi:10.1038/nclimate3328

Cramer, B., and Franke, D. (2005). Indications for an active petroleum system in the Laptev Sea, Ne Siberia. *J. Petroleum Geol.* 28, 369–384. doi:10.1111/j.1747-5457.2005.tb00088.x

Crill, P. M., Bartlett, K. B., Harriss, R. C., Gorham, E., Verry, E. S., Sebacher, D. I., et al. (1988). Methane flux from Minnesota peatlands. *Glob. Biogeochem. Cycles* 2, 371–384. doi:10.1029/GB002i004p00371

Damm, E., Bauch, D., Krumpen, T., Rabe, B., Korhonen, M., Vinogradova, E., et al. (2018). The transpolar Drift conveys methane from the siberian shelf to the central Arctic Ocean. *Sci. Rep.* 8, 4515. doi:10.1038/s41598-018-22801-z

Damm, E., Helmke, E., Thoms, S., Schauer, U., Noethig, E., Bakker, K., et al. (2010). Methane production in aerobic oligotrophic surface water in the central Arctic Ocean. *Biogeosciences* 7, 1099–1108. doi:10.5194/bg-7-1099-2010

Damm, E., Rudels, B., Schauer, U., Mau, S., and Dieckmann, G. (2015). Methane excess in Arctic surface water-triggered by sea ice formation and melting. *Sci. Rep.* 5, 16179. doi:10.1038/srep16179

Damm, E., Schauer, U., Rudels, B., and Haas, C. (2007). Excess of bottom-released methane in an Arctic shelf sea polynya in winter. *Cont. Shelf Res.* 27, 1692–1701. doi:10.1016/j.csr.2007.02.003

Davies, R. J., Yang, J., Ireland, M. T., Berndt, C., Maqueda, M. Á. M., and Huuse, M. (2024). Long-distance migration and venting of methane from the base of the hydrate stability zone. *Nat. Geosci.* 17, 32–37. doi:10.1038/s41561-023-01333-w

Dean, J. F., Meisel, O. H., Rosco, M. M., Marchesini, L. B., Garnett, M. H., Lenderink, H., et al. (2020). East Siberian Arctic inland waters emit mostly contemporary carbon. *Nat. Commun.* 11, 1627. doi:10.1038/s41467-020-15511-6

Dean, J. F., Middelburg, J. J., Röckmann, T., Aerts, R., Blauw, L. G., Egger, M., et al. (2018). Methane feedbacks to the global climate system in a warmer world. *Rev. Geophys.* 56, 207–250. doi:10.1002/2017RG000559

DelSontro, T., Boutet, L., St-Pierre, A., Giorgio, P. A. del, and Prairie, Y. T. (2016). Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity. *Limnol. Oceanogr.* 61, S62–S77. doi:10.1002/lno.10335

Denfeld, B. A., Baulch, H. M., Giorgio, P. A. del, Hampton, S. E., and Karlsson, J. (2018). A synthesis of carbon dioxide and methane dynamics during the ice-covered period of northern lakes. *Limnol. Oceanogr. Lett.* 3, 117–131. doi:10.1002/lol2.10079

Denfeld, B. A., Wallin, M. B., Sahlée, E., Sobek, S., Kokic, J., Chmiel, H. E., et al. (2015). Temporal and spatial carbon dioxide concentration patterns in a small boreal lake in relation to ice-cover dynamics. *Boreal Environ. Res.* 20, 679–692.

Dickens, G. R. (2003). A methane trigger for rapid warming? *Science* 299, 1017. doi:10.1126/science.1080789

Dickens, G. R. (2011). Down the Rabbit Hole: toward appropriate discussion of methane release from gas hydrate systems during the Paleocene-Eocene thermal maximum and other past hyperthermal events. *Clim. Past* 7, 831–846. doi:10.5194/cp-7-831-2011

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N. D., Wikramanayake, E., et al. (2017). An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* 67, 534–545. doi:10.1093/biosci/bix014

Dmitrenko, I. A., Kirillov, S. A., Tremblay, L. B., Kassens, H., Anisimov, O. A., Lavrov, S. A., et al. (2011). Recent changes in shelf hydrography in the Siberian Arctic: potential for subsea permafrost instability. *J. Geophys. Res. Oceans* 116, C10027. doi:10.1029/2011JC007218

Ehhalt, D. H. (1974). The atmospheric cycle of methane. *Tellus* 26, 58–70. doi:10.1111/j.2153-3490.1974.tb01952.x

Elder, C. D., Thompson, D. R., Thorpe, A. K., Hanke, P., Anthony, K. M. W., and Miller, C. E. (2020). Airborne mapping reveals emergent power law of arctic methane emissions. *Geophys Res. Lett.* 47, e2019GL085707. doi:10.1029/2019gl085707

Engram, M., Anthony, K. M. W., Sachs, T., Kohnert, K., Serafimovich, A., Grosse, G., et al. (2020). Erratum: publisher Correction: current and future global climate impacts resulting from COVID-19. *Nat. Clim. Chang.*, 1–7. doi:10.1038/s41558-020-0904-z

Etiope, G., and Sherwood Lollar, B. (2013). Abiotic methane on Earth. *Rev. Geophys.* 51, 276–299. doi:10.1002/rog.20011

Fenwick, L., Capelle, D., Damm, E., Zimmermann, S., Williams, W. J., Vagle, S., et al. (2017). Methane and nitrous oxide distributions across the North American Arctic Ocean during summer, 2015. *J. Geophys. Res. Oceans* 122, 390–412. doi:10.1002/2016JC012493

Ferry, J. G. (1999). Enzymology of one-carbon metabolism in methanogenic pathways. *FEMS Microbiol. Rev.* 23, 13–38. doi:10.1111/j.1574-6976.1999.tb00390.x

Fisher, R. E., Sriskantharajah, S., Lowry, D., Lanoisellé, M., Fowler, C. M. R., James, R. H., et al. (2011). Arctic methane sources: isotopic evidence for atmospheric inputs. *Geophys. Res. Lett.* 38, L21803. doi:10.1029/2011GL049319

Garcia, J.-L., Patel, B. K. C., and Ollivier, B. (2000). Taxonomic, phylogenetic, and ecological diversity of methanogenic archaea. *Anaerobe* 6, 205–226. doi:10.1006/anae.2000.0345

Gauci, V., Pangala, S. R., Shenkin, A., Barba, J., Bastviken, D., Figueiredo, V., et al. (2024). Global atmospheric methane uptake by upland tree woody surfaces. *Nature* 631, 796–800. doi:10.1038/s41586-024-07592-w

Graves, C. A., Steinle, L., Rehder, G., Niemann, H., Connelly, D. P., Lowry, D., et al. (2015). Fluxes and fate of dissolved methane released at the seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard. *J. Geophys. Res. Oceans* 120, 6185–6201. doi:10.1002/2015JC011084

Guo, M., Zhuang, Q., Tan, Z., Shurpali, N., Juutinen, S., Kortelainen, P., et al. (2020). Rising methane emissions from boreal lakes due to increasing ice-free days. *Environ. Res. Lett.* 15, 064008. doi:10.1088/1748-9326/ab8254

Gupta, S., Burwicz-Galerne, E., Schmidt, C., and Rüpke, L. (2023). Periodic states and their implications in gas hydrate systems. *Earth Planet. Sci. Lett.* 624, 118445. doi:10.1016/j.epsl.2023.118445

Helbig, M., Živković, T., Alekseychik, P., Aurela, M., El-Madany, T. S., Euskirchen, E. S., et al. (2022). Warming response of peatland CO2 sink is sensitive to seasonality in warming trends. *Nat. Clim. Chang.* 12, 743–749. doi:10.1038/s41558-022-01428-z

Hellevang, H., Ippach, M. R., Westermann, S., and Nooraiepour, M. (2023). *Formation of giant Siberian gas emission craters (GECs)*. Available at: https://eartharxiv.org/repository/view/6351/ (Accessed March 26, 2024).

Hester, K. C., and Brewer, P. G. (2009). Clathrate hydrates in nature. *Annu. Rev. Mar. Sci.* 1, 303–327. doi:10.1146/annurev.marine.010908.163824

Hodson, A. J., Nowak, A., Redeker, K. R., Holmlund, E. S., Christiansen, H. H., and Turchyn, A. V. (2019). Seasonal dynamics of methane and carbon dioxide evasion from an open system pingo: lagoon pingo, svalbard. *Front. Earth Sci.* 7. doi:10.3389/feart.2019.00030

Holloway, J. E., Lewkowicz, A. G., Douglas, T. A., Li, X., Turetsky, M. R., Baltzer, J. L., et al. (2020). Impact of wildfire on permafrost landscapes: a review of recent advances and future prospects. *Permafr. Periglac. Process.* 31, 371–382. doi:10.1002/ppp.2048

Hope, C., and Schaefer, K. (2015). Economic impacts of carbon dioxide and methane released from thawing permafrost. *Nat. Clim. Change* 6, 56–59. doi:10.1038/nclimate2807

Ito, A., Li, T., Qin, Z., Melton, J. R., Tian, H., Kleinen, T., et al. (2023). Cold-season methane fluxes simulated by GCP-CH4 models. *Geophys. Res. Lett.* 50, e2023GL103037. doi:10.1029/2023GL103037

Jakobsson, M. (2002). Hypsometry and volume of the Arctic Ocean and its constituent seas. *Geochem. Geophys. Geosystems* 3, 1–18. doi:10.1029/2001GC000302

James, R. H., Bousquet, P., Bussmann, I., Haeckel, M., Kipfer, R., Leifer, I., et al. (2016). Effects of climate change on methane emissions from seafloor sediments in the Arctic Ocean: a review. *Limnol. Oceanogr.* 61, S283–S299. doi:10.1002/lno.10307

Jammet, M., Crill, P., Dengel, S., and Friborg, T. (2015). Large methane emissions from a subarctic lake during spring thaw: mechanisms and landscape significance. *J. Geophys. Res. Biogeosciences* 120, 2289–2305. doi:10.1002/2015JG003137

Jammet, M., Dengel, S., Kettner, E., Parmentier, F. J. W., Wik, M., Crill, P., et al. (2017). Year-round CH_4 and CO_2 flux dynamics in two contrasting freshwater ecosystems of the subarctic. *Biogeosciences* 14, 5189–5216. doi:10.5194/bg-14-5189-2017

Jansen, J., Thornton, B. F., Jammet, M. M., Wik, M., Cortés, A., Friborg, T., et al. (2019). Climate-sensitive controls on large spring emissions of CH4 and CO2 from northern lakes. *J. Geophys. Res. Biogeosciences* 124, 2379–2399. doi:10.1029/2019JG005094

Joabsson, A., Christensen, T. R., and Wallen, B. (1999). Vascular plant controls on methane emissions from northern peatforming wetlands. *Trends Ecol. & Evol.* 14, 385–388. doi:10.1016/S0169-5347(99)01649-3

Jørgensen, C. J., Lund Johansen, K. M., Westergaard-Nielsen, A., and Elberling, B. (2014). Net regional methane sink in High Arctic soils of northeast Greenland. *Nat. Geosci.* 8, 20–23. doi:10.1038/ngeo2305

Judd, A. G. (2004). Natural seabed gas seeps as sources of atmospheric methane. *Environ. Geol.* 46, 988–996. doi:10.1007/s00254-004-1083-3

Juutinen, S., Rantakari, M., Kortelainen, P., Huttunen, J. T., Larmola, T., Alm, J., et al. (2009). Methane dynamics in different boreal lake types. *Biogeosciences* 6, 209–223. doi:10.5194/bg-6-209-2009

Kitidis, V., Upstill-Goddard, R. C., and Anderson, L. G. (2010). Methane and nitrous oxide in surface water along the North-west passage, Arctic Ocean. *Mar. Chem.* 121, 80–86. doi:10.1016/j.marchem.2010.03.006

Knittel, K., and Boetius, A. (2009). Anaerobic oxidation of methane: progress with an unknown process. *Annu. Rev. Microbiol.* 63, 311–334. doi:10.1146/annurev.micro.61.080706.093130

Kohnert, K., Serafimovich, A., Metzger, S., Hartmann, J., and Sachs, T. (2017). Strong geologic methane emissions from discontinuous terrestrial permafrost in the Mackenzie Delta, Canada. *Sci. Rep.* 7, 5828. doi:10.1038/s41598-017-05783-2

Kort, E. A., Wofsy, S. C., Daube, B. C., Diao, M., Elkins, J. W., Gao, R. S., et al. (2012). Atmospheric observations of Arctic Ocean methane emissions up to 82° north. *Nat. Geosci.* 5, 318–321. doi:10.1038/NGEO1452

Kretschmer, K., Biastoch, A., Rüpke, L., and Burwicz, E. (2015). Modeling the fate of methane hydrates under global warming. *Glob. Biogeochem. Cycles* 29, 610–625. doi:10.1002/2014GB005011

Kuhn, M. A., Varner, R. K., Bastviken, D., Crill, P., MacIntyre, S., Turetsky, M., et al. (2021). BAWLD-CH_4: a comprehensive dataset of methane fluxes from boreal and arctic ecosystems. *Earth Syst. Sci. Data* 13, 5151–5189. doi:10.5194/essd-13-5151-2021

Kvenvolden, K. A. (1988). Methane hydrate — a major reservoir of carbon in the shallow geosphere? *Chem. Geol.* 71, 41–51. doi:10.1016/0009-2541(88)90104-0

Kvenvolden, K. A. (1993). Gas hydrates—geological perspective and global change. *Rev. Geophys.* 31, 173–187. doi:10.1029/93RG00268

Kvenvolden, K. A., Lilley, M. D., Lorenson, T. D., Barnes, P. W., and McLaughlin, E. (1993). The Beaufort Sea continental shelf as a seasonal source of atmospheric methane. *Geophys. Res. Lett.* 20, 2459–2462. doi:10.1029/93GL02727

Lamarche-Gagnon, G., Wadham, J. L., Sherwood Lollar, B., Arndt, S., Fietzek, P., Beaton, A. D., et al. (2019). Greenland melt drives continuous export of methane from the ice-sheet bed. *Nature* 565, 73–77. doi:10.1038/s41586-018-0800-0

Langer, M., Westermann, S., Walter Anthony, K., Wischnewski, K., and Boike, J. (2015). Frozen ponds: production and storage of methane during the Arctic winter in a lowland tundra landscape in northern Siberia, Lena River delta. *Biogeosciences* 12, 977–990. doi:10.5194/bg-12-977-2015

Leifer, I., and Patro, R. K. (2002). The bubble mechanism for methane transport from the shallow sea bed to the surface: a review and sensitivity study. *Cont. Shelf Res.* 22, 2409–2428. doi:10.1016/S0278-4343(02)00065-1

Liu, X., and Zhuang, Q. (2023). Methane emissions from Arctic landscapes during 2000–2015: an analysis with land and lake biogeochemistry models. *Biogeosciences* 20, 1181–1193. doi:10.5194/bg-20-1181-2023

Lorenson, T. D., Greinert, J., and Coffin, R. B. (2016). Dissolved methane in the Beaufort sea and the Arctic Ocean, 1992–2009; sources and atmospheric flux. *Limnol. Oceanogr.* 61, S300–S323. doi:10.1002/lno.10457

Lund Myhre, C., Ferré, B., Platt, S. M., Silyakova, A., Hermansen, O., Allen, G., et al. (2016). Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere. *Geophys. Res. Lett.* 43, 4624–4631. doi:10.1002/2016GL068999

Manning, C. C., Preston, V. L., Jones, S. F., Michel, A. P. M., Nicholson, D. P., Duke, P. J., et al. (2020). River inflow dominates methane emissions in an arctic coastal system. *Geophys. Res. Lett.* 47, e2020GL087669. doi:10.1029/2020GL087669

Manning, C. C. M., Zheng, Z., Fenwick, L., McCulloch, R. D., Damm, E., Izett, R. W., et al. (2022). Interannual variability in methane and nitrous oxide concentrations and sea-air fluxes across the North American Arctic Ocean (2015–2019). *Glob. Biogeochem. Cycles* 36, e2021GB007185. doi:10.1029/2021GB007185

Martinez-Cruz, K., Sepulveda-Jauregui, A., Casper, P., Anthony, K. W., Smemo, K. A., and Thalasso, F. (2018). Ubiquitous and significant anaerobic oxidation of methane in freshwater lake sediments. *Water Res.* 144, 332–340. doi:10.1016/j.watres.2018.07.053

Mastepanov, M., Sigsgaard, C., Tagesson, T., Strom, L., Tamstorf, M. P., Lund, M., et al. (2013). Revisiting factors controlling methane emissions from high-Arctic tundra. *Biogeosciences* 10, 5139–5158. doi:10.5194/bg-10-5139-2013

Matthews, E., and Fung, I. (1987). Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. *Glob. Biogeochem. Cycles* 1, 61–86. doi:10.1029/GB001i001p00061

Matthews, E., Johnson, M. S., Genovese, V., Du, J., and Bastviken, D. (2020). Methane emission from high latitude lakes: methane-centric lake classification and satellite-driven annual cycle of emissions. *Sci. Rep.* 10, 12465. doi:10.1038/s41598-020-68246-1

Mau, S., Römer, M., Torres, M. E., Bussmann, I., Pape, T., Damm, E., et al. (2017). Widespread methane seepage along the continental margin off Svalbard - from Bjørnøya to Kongsfjorden. *Sci. Rep.* 7, 42997. doi:10.1038/srep42997

McGinnis, D. F., Greinert, J., Artemov, Y., Beaubien, S. E., and Wüest, A. (2006). Fate of rising methane bubbles in stratified waters: how much methane reaches the atmosphere? *J. Geophys. Res. Oceans* 111, C09007. doi:10.1029/2005JC003183

McGuire, A. D., Christensen, T. R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J. S., et al. (2012). An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences* 9, 3185–3204. doi:10.5194/bg-9-3185-2012

Miesner, F., Overduin, P. P., Grosse, G., Strauss, J., Langer, M., Westermann, S., et al. (2023). Subsea permafrost organic carbon stocks are large and of dominantly low reactivity. *Sci. Rep.* 13, 9425. doi:10.1038/s41598-023-36471-z

Milkov, A. V. (2005). Molecular and stable isotope compositions of natural gas hydrates: a revised global dataset and basic interpretations in the context of geological settings. *Org. Geochem.* 36, 681–702. doi:10.1016/j.orggeochem.2005.01.010

Nauta, A. L., Heijmans, M. M. P. D., Blok, D., Limpens, J., Elberling, B., Gallagher, A., et al. (2014). Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. *Nat. Clim. Change* 5, 67–70. doi:10.1038/nclimate2446

Nicolsky, D. J., Romanovsky, V. E., Romanovskii, N. N., Kholodov, A. L., Shakhova, N. E., and Semiletov, I. P. (2012). Modeling sub-sea permafrost in the East Siberian arctic shelf: the Laptev Sea region. *J. Geophys. Res. Earth Surf.* 117, F03028. doi:10.1029/2012JF002358

Nisbet, E. G. (1990). The end of the ice age. *Can. J. Earth Sci.* 27, 148–157. doi:10.1139/e90-012

Nisbet, E. G., Manning, M. R., Dlugokencky, E. J., Michel, S. E., Lan, X., Röckmann, T., et al. (2023). Atmospheric methane: comparison between methane's record in 2006–2022 and during glacial terminations. *Glob. Biogeochem. Cycles* 37, e2023GB007875. doi:10.1029/2023GB007875

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., et al. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale. *Earth-Science Rev.* 193, 299–316. doi:10.1016/j.earscirev.2019.04.023

Oh, Y., Stackhouse, B., Lau, M. C. Y., Xu, X., Trugman, A. T., Moch, J., et al. (2016). A scalable model for methane consumption in arctic mineral soils. *Geophys Res. Lett.* 43, 5143–5150. doi:10.1002/2016gl069049

Oh, Y., Zhuang, Q., Liu, L., Welp, L. R., Lau, M. C. Y., Onstott, T. C., et al. (2020). Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic. *Nat. Clim. Change* 10, 317–321. doi:10.1038/s41558-020-0734-z

Olefeldt, D., Hovemyr, M., Kuhn, M. A., Bastviken, D., Bohn, T. J., Connolly, J., et al. (2021). The boreal–arctic wetland and Lake dataset (BAWLD). *Earth Syst. Sci. Data* 13, 5127–5149. doi:10.5194/essd-13-5127-2021

Olefeldt, D., Turetsky, M. R., Crill, P. M., and McGuire, A. D. (2013). Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. *Glob. Change Biol.* 19, 589–603. doi:10.1111/gcb.12071

Overduin, P. P., Hubberten, H.-W., Rachold, V., Romanovskii, N., Grigoriev, M., and Kasymskaya, M. (2007). "The evolution and degradation of coastal and offshore permafrost in the Laptev and East Siberian Seas during the last climatic cycle," in *Coastline changes: interrelation of climate and geological processes*. Editors J. Harff, W. W. Hay, D. M. Tetzlaff Boulder, and Colo (Boulder, CO: The Geological Society of America special paper), 426. doi:10.1130/2007.2426(07)

Overduin, P. P., Liebner, S., Knoblauch, C., Günther, F., Wetterich, S., Schirrmeister, L., et al. (2015). Methane oxidation following submarine permafrost degradation: measurements from a central Laptev Sea shelf borehole. *J. Geophys. Res. Biogeosciences* 120, 965–978. doi:10.1002/2014JG002862

Overduin, P. P., Schneider von Deimling, T., Miesner, F., Grigoriev, M. N., Ruppel, C., Vasiliev, A., et al. (2019). Submarine permafrost map in the arctic modeled using 1-D transient heat flux (SuPerMAP). *J. Geophys. Res. Oceans* 124, 3490–3507. doi:10.1029/2018JC014675

Pallandt, M. M. T. A., Kumar, J., Mauritz, M., Schuur, E. A. G., Virkkala, A.-M., Celis, G., et al. (2022). Representativeness assessment of the pan-Arctic eddy covariance site network and optimized future enhancements. *Biogeosciences* 19, 559–583. doi:10.5194/bg-19-559-2022

Parmentier, F.-J. W., Christensen, T. R., Rysgaard, S., Bendtsen, J., Glud, R. N., Else, B., et al. (2017). A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere. *Ambio* 46, 53–69. doi:10.1007/s13280-016-0872-8

Parmentier, F.-J. W., Christensen, T. R., Sørensen, L. L., Rysgaard, S., McGuire, A. D., Miller, P. A., et al. (2013). The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. *Nat. Clim. Change* 3, 195–202. doi:10.1038/nclimate1784

Parmentier, F.-J. W., van Huissteden, J., van der Molen, M. K., Schaepman-Strub, G., Karsanaev, S. A., Maximov, T. C., et al. (2011). Spatial and temporal dynamics in eddy covariance observations of methane fluxes at a tundra site in northeastern Siberia. *J. Geophys. Res. Biogeosci.* 116, G03016. doi:10.1029/2010JG001637

Parmentier, F.-J. W., Zhang, W., Mi, Y., Zhu, X., Huissteden, J., Hayes, D. J., et al. (2015). Rising methane emissions from northern wetlands associated with sea ice decline. *Geophys. Res. Lett.* 42, 7214–7222. doi:10.1002/2015GL065013

Paytan, A., Lecher, A. L., Dimova, N., Sparrow, K. J., Kodovska, F. G.-T., Murray, J., et al. (2015). Methane transport from the active layer to lakes in the Arctic using Toolik Lake, Alaska, as a case study. *Proc. Natl. Acad. Sci.* 112, 3636–3640. doi:10.1073/pnas.1417392112

Peltola, O., Vesala, T., Gao, Y., Räty, O., Alekseychik, P., Aurela, M., et al. (2019). Monthly gridded data product of northern wetland methane emissions based on upscaling eddy covariance observations. *Earth Syst. Sci. Data* 11, 1263–1289. doi:10.5194/essd-11-1263-2019

Petrescu, A. M. R., van Beek, L. P. H., van Huissteden, J., Prigent, C., Sachs, T., Corradi, C. A. R., et al. (2010). Modeling regional to global CH_4 emissions of boreal and arctic wetlands. *Glob. Biogeochem. Cycles* 24, GB4009. doi:10.1029/2009GB003610

Pirk, N., Santos, T., Gustafson, C., Johansson, A. J., Tufvesson, F., Parmentier, F.-J. W., et al. (2015). Methane emission bursts from permafrost environments during autumn freeze-in: new insights from ground penetrating radar. *Geophys. Res. Lett.* 42, 6732–6738. doi:10.1002/2015GL065034

Pohlman, J. W., Greinert, J., Ruppel, C., Silyakova, A., Vielstädte, L., Casso, M., et al. (2017). Enhanced CO_2 uptake at a shallow Arctic Ocean seep field overwhelms the positive warming potential of emitted methane. *Proc. Natl. Acad. Sci.* 114, 5355–5360. doi:10.1073/pnas.1618926114

Polishchuk, Y. M., Bogdanov, A. N., Muratov, I. N., Polishchuk, V. Y., Lim, A., Manasypov, R. M., et al. (2018). Minor contribution of small thaw ponds to the pools of carbon and methane in the inland waters of the permafrost-affected part of the Western Siberian Lowland. *Environ. Res. Lett.* 13, 045002. doi:10.1088/1748-9326/aab046

Portnov, A., Vadakkepuliyambatta, S., Mienert, J., and Hubbard, A. (2016). Ice-sheet-driven methane storage and release in the Arctic. *Nat. Commun.* 7, 10314. doi:10.1038/ncomms10314

Poulter, B., Bousquet, P., Canadell, J. G., Ciais, P., Peregon, A., Saunois, M., et al. (2017). Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics. *Environ. Res. Lett.* 12, 094013. doi:10.1088/1748-9326/aa8391

Prytherch, J., Murto, S., Brown, I., Ulfsbo, A., Thornton, B. F., Brüchert, V., et al. (2024). Central Arctic Ocean surface–atmosphere exchange of CO_2 and CH_4 constrained by direct measurements. *Biogeosciences* 21, 671–688. doi:10.5194/bg-21-671-2024

Rajan, A., Bünz, S., Mienert, J., and Smith, A. J. (2013). Gas hydrate systems in petroleum provinces of the SW-Barents Sea. *Mar. Petroleum Geol.* 46, 92–106. doi:10.1016/j.marpetgeo.2013.06.009

Ramage, J., Kuhn, M., Virkkala, A.-M., Voigt, C., Marushchak, M. E., Bastos, A., et al. (2024). The net GHG balance and budget of the permafrost region (2000–2020) from ecosystem flux upscaling. *Glob. Biogeochem. Cycles* 38, e2023GB007953. doi:10.1029/2023GB007953

Raz-Yaseef, N., Torn, M. S., Wu, Y., Billesbach, D. P., Liljedahl, A. K., Kneafsey, T. J., et al. (2017). Large CO_2 and CH_4 emissions from polygonal tundra during spring thaw in northern Alaska. *Geophys. Res. Lett.* 44, 504–513. doi:10.1002/2016GL071220

Reeburgh, W. S. (2007). "Global methane biogeochemistry," in *Treatise on geochemistry* (Elsevier), 71–94.

Rehder, G., Leifer, I., Brewer, P. G., Friederich, G., and Peltzer, E. T. (2009). Controls on methane bubble dissolution inside and outside the hydrate stability field from open ocean field experiments and numerical modeling. *Mar. Chem.* 114, 19–30. doi:10.1016/j.marchem.2009.03.004

Ribeiro-Kumara, C., Köster, E., Aaltonen, H., and Köster, K. (2020). How do forest fires affect soil greenhouse gas emissions in upland boreal forests? A review. *Environ. Res.* 184, 109328. doi:10.1016/j.envres.2020.109328

Rocher-Ros, G., Stanley, E. H., Loken, L. C., Casson, N. J., Raymond, P. A., Liu, S., et al. (2023). Global methane emissions from rivers and streams. *Nature* 621, 530–535. doi:10.1038/s41586-023-06344-6

Romanovskii, N. N., Gavrilov, A. V., Tumskoy, V. E., Kholodov, A. L., Siegert, C., Hubberten, H.-W., et al. (2000). Environmental evolution in the Laptev Sea region during late pleistocene and holocene. *Polarforschung* 68, 237–245. doi:10.1002/1099-1530(200004/06

Rößger, N., Sachs, T., Wille, C., Boike, J., and Kutzbach, L. (2022). Seasonal increase of methane emissions linked to warming in Siberian tundra. *Nat. Clim. Chang.* 12, 1031–1036. doi:10.1038/s41558-022-01512-4

Ruppel, C. (2015). Permafrost-associated gas hydrate: is it really approximately 1 % of the global system? *J. Chem. & Eng. Data* 60, 429–436. doi:10.1021/je500770m

Ruppel, C. D., and Kessler, J. D. (2017). The interaction of climate change and methane hydrates. *Rev. Geophys.* 55, 126–168. doi:10.1002/2016RG000534

Sahling, H., Römer, M., Pape, T., Bergès, B., dos Santos Fereirra, C., Boelmann, J., et al. (2014). Gas emissions at the continental margin west of Svalbard: mapping, sampling, and quantification. *Biogeosciences* 11, 6029–6046. doi:10.5194/bg-11-6029-2014

Sapper, S. E., Jørgensen, C. J., Schroll, M., Keppler, F., and Christiansen, J. R. (2023). Methane emissions from subglacial meltwater of three alpine glaciers in Yukon, Canada. *Arct. Antarct. Alp. Res.* 55, 2284456. doi:10.1080/15230430.2023.2284456

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., et al. (2017). Variability and quasi-decadal changes in the methane budget over the period 2000–2012. *Atmos. Chem. Phys.* 17, 11135–11161. doi:10.5194/acp-17-11135-2017

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., et al. (2020). The global methane budget 2000–2017. *Earth Syst. Sci. Data* 12, 1561–1623. doi:10.5194/essd-12-1561-2020

Scholten, R. C., Jandt, R., Miller, E. A., Rogers, B. M., and Veraverbeke, S. (2021). Overwintering fires in boreal forests. *Nature* 593, 399–404. doi:10.1038/s41586-021-03437-y

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., et al. (2022). Permafrost and climate change: carbon cycle feedbacks from the warming arctic. *Annu. Rev. Environ. Resour.* 47, 343–371. doi:10.1146/annurev-environ-012220-011847

Screen, J. A., Deser, C., and Simmonds, I. (2012). Local and remote controls on observed Arctic warming. *Geophys. Res. Lett.* 39, L10709. doi:10.1029/2012GL051598

Sebacher, D. I., Harriss, R. C., Bartlett, K. B., Sebacher, S. M., and Grice, S. S. (1986). Atmospheric methane sources: alaskan tundra bogs, an alpine fen, and a subarctic boreal marsh. *Tellus. Ser. B* 38B, 1–10. doi:10.1111/j.1600-0889.1986.tb00083.x

Shakhova, N., Semiletov, I., Leifer, I., Sergienko, V., Salyuk, A., Kosmach, D., et al. (2014). Ebullition and storm-induced methane release from the East Siberian arctic shelf. *Nat. Geosci.* 7, 64–70. doi:10.1038/ngeo2007

Shakhova, N., Semiletov, I., Salyuk, A., Yusupov, V., Kosmach, D., and Gustafsson, Ö. (2010). Extensive methane venting to the atmosphere from sediments of the East Siberian arctic shelf. *Science* 327, 1246–1250. doi:10.1126/science.1182221

Silyakova, A., Nomura, D., Kotovitch, M., Fransson, A., Delille, B., Chierici, M., et al. (2022). Methane release from open leads and new ice following an Arctic winter storm event. *Polar Sci.* 33, 100874. doi:10.1016/j.polar.2022.100874

Smith, L. C., Sheng, Y., MacDonald, G. M., and Hinzman, L. D. (2005). Disappearing arctic lakes. *Science* 308, 1429. doi:10.1126/science.1108142

Sparrow, K. J., Kessler, J. D., Southon, J. R., Garcia-Tigreros, F., Schreiner, K. M., Ruppel, C. D., et al. (2018). Limited contribution of ancient methane to surface waters of the U.S. Beaufort Sea shelf. *Sci. Adv.* 4, eaao4842. doi:10.1126/sciadv.aao4842

Stanley, E. H., Casson, N. J., Christel, S. T., Crawford, J. T., Loken, L. C., and Oliver, S. K. (2016). The ecology of methane in streams and rivers: patterns, controls, and global significance. *Ecol. Monogr.* 86, 146–171. doi:10.1890/15-1027

Steinbach, J., Holmstrand, H., Shcherbakova, K., Kosmach, D., Brüchert, V., Shakhova, N., et al. (2021). Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf. *PNAS* 118, e2019672118. doi:10.1073/pnas.2019672118

Steinle, L., Graves, C. A., Treude, T., Ferré, B., Biastoch, A., Bussmann, I., et al. (2015). Water column methanotrophy controlled by a rapid oceanographic switch. *Nat. Geosci.* 8, 378–382. doi:10.1038/ngeo2420

Strack, M., Kellner, E., and Waddington, J. M. (2005). Dynamics of biogenic gas bubbles in peat and their effects on peatland biogeochemistry. *Glob. Biogeochem. Cycles* 19. doi:10.1029/2004GB002330

Stranne, C., O'Regan, M., Dickens, G. R., Crill, P., Miller, C., Preto, P., et al. (2016). Dynamic simulations of potential methane release from East Siberian continental slope sediments. *Geochem. Geophys. Geosystems* 17, 872–886. doi:10.1002/2015GC006119

Stranne, C., O'Regan, M., Hong, W.-L., Brüchert, V., Ketzer, M., Thornton, B. F., et al. (2022). Anaerobic oxidation has a minor effect on mitigating seafloor methane emissions from gas hydrate dissociation. *Commun. Earth Environ.* 3. doi:10.1038/s43247-022-00490-x

Stranne, C., O'Regan, M., and Jakobsson, M. (2017). Modeling fracture propagation and seafloor gas release during seafloor warming-induced hydrate dissociation. *Geophys. Res. Lett.* 44, 8510–8519. doi:10.1002/2017GL074349

Stranne, C., O'Regan, M., Jakobsson, M., Brüchert, V., and Ketzer, M. (2019). Can anaerobic oxidation of methane prevent seafloor gas escape in a warming climate? *Solid earth.* 10, 1541–1554. doi:10.5194/se-10-1541-2019

Ström, L., Ekberg, A., Mastepanov, M., and Christensen, T. R. (2003). The effect of vascular plants on carbon turnover and methane emissions from a tundra wetland. *Glob. Change Biol.* 9, 1185–1192. doi:10.1046/j.1365-2486.2003.00655.x

Ström, L., Mastepanov, M., and Christensen, T. R. (2005). Species-specific effects of vascular plants on carbon turnover and methane emissions from wetlands. *Biogeochemistry* 75, 65–82. doi:10.1007/s10533-004-6124-1

Sulman, B. N., Yuan, F., O'Meara, T., Gu, B., Herndon, E. M., Zheng, J., et al. (2022). Simulated hydrological dynamics and coupled iron redox cycling impact methane production in an arctic soil. *J. Geophys. Res. Biogeosciences* 127, e2021JG006662. doi:10.1029/2021JG006662

Tan, Z., and Zhuang, Q. (2015). Arctic lakes are continuous methane sources to the atmosphere under warming conditions. *Environ. Res. Lett.* 10, 054016. doi:10.1088/1748-9326/10/5/054016

Tape, K. D., Clark, J. A., Jones, B. M., Kantner, S., Gaglioti, B. V., Grosse, G., et al. (2022). Expanding beaver pond distribution in Arctic Alaska, 1949 to 2019. *Sci. Rep.* 12, 7123. doi:10.1038/s41598-022-09330-6

Thauer, R. K., Kaster, A.-K., Seedorf, H., Buckel, W., and Hedderich, R. (2008). Methanogenic archaea: ecologically relevant differences in energy conservation. *Nat. Rev. Microbiol.* 6, 579–591. doi:10.1038/nrmicro1931

Thonat, T., Saunois, M., Bousquet, P., Pison, I., Tan, Z., Zhuang, Q., et al. (2017). Detectability of Arctic methane sources at six sites performing continuous atmospheric measurements. *Atmos. Chem. Phys.* 17, 8371–8394. doi:10.5194/acp-17-8371-2017

Thornton, B. F., Geibel, M. C., Crill, P. M., Humborg, C., and Morth, C.-M. (2016a). Methane fluxes from the sea to the atmosphere across the Siberian shelf seas. *Geophys. Res. Lett.* 43, 5869–5877. doi:10.1002/2016GL068977

Thornton, B. F., Prytherch, J., Andersson, K., Brooks, I. M., Salisbury, D., Tjernström, M., et al. (2020). Shipborne eddy covariance observations of methane fluxes constrain Arctic sea emissions. *Sci. Adv.* 6, eaay7934. doi:10.1126/sciadv.aay7934

Thornton, B. F., Wik, M., and Crill, P. M. (2015). Climate-forced changes in available energy and methane bubbling from subarctic lakes. *Geophys. Res. Lett.* 42, 1936–1942. doi:10.1002/2015GL063189

Thornton, B. F., Wik, M., and Crill, P. M. (2016b). Double counting challenges the accuracy of high latitude methane inventories. *Geophys. Res. Lett.* 43 (12), 569–12577. doi:10.1002/2016GL071772

Tohjima, Y., Zeng, J., Shirai, T., Niwa, Y., Ishidoya, S., Taketani, F., et al. (2020). Estimation of CH4 emissions from the East Siberian Arctic Shelf based on atmospheric observations aboard the R/V Mirai during fall cruises from 2012 to 2017. *Polar Sci.* 100571, 100571. doi:10.1016/j.polar.2020.100571

Treat, C. C., Bloom, A. A., and Marushchak, M. E. (2018a). Nongrowing season methane emissions–a significant component of annual emissions across northern ecosystems. *Glob. Chang. Biol.* 44, 3331–3343. doi:10.1111/gcb.14137

Treat, C. C., Marushchak, M. E., Voigt, C., Zhang, Y., Tan, Z., Zhuang, Q., et al. (2018b). Tundra landscape heterogeneity, not interannual variability, controls the decadal regional carbon balance in the Western Russian Arctic. *Glob. Chang. Biol.* 24, 5188–5204. doi:10.1111/gcb.14421

Treat, C. C., Virkkala, A.-M., Burke, E., Bruhwiler, L., Chatterjee, A., Fisher, J. B., et al. (2024). Permafrost carbon: progress on understanding stocks and fluxes across northern terrestrial ecosystems. *J. Geophys. Res. Biogeosciences* 129, e2023JG007638. doi:10.1029/2023JG007638

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., et al. (2020). Carbon release through abrupt permafrost thaw. *Nat. Geosci.* 13, 138–143. doi:10.1038/s41561-019-0526-0

Valentine, D. L., Blanton, D. C., Reeburgh, W. S., and Kastner, M. (2001). Water column methane oxidation adjacent to an area of active hydrate dissociation, Eel river Basin. *Geochimica Cosmochimica Acta* 65, 2633–2640. doi:10.1016/S0016-7037(01)00625-1

van Huissteden, J., Berrittella, C., Parmentier, F. J. W., Mi, Y., Maximov, T. C., and Dolman, A. J. (2011). Methane emissions from permafrost thaw lakes limited by lake drainage. *Nat. Clim. Change* 1, 119–123. doi:10.1038/nclimate1101

Veraverbeke, S., Rogers, B. M., Goulden, M. L., Jandt, R. R., Miller, C. E., Wiggins, E. B., et al. (2017). Lightning as a major driver of recent large fire years in North American boreal forests. *Nat. Clim. Change* 7, 529–534. doi:10.1038/nclimate3329

Virkkala, A.-M., Aalto, J., Rogers, B. M., Tagesson, T., Treat, C. C., Natali, S. M., et al. (2021). Statistical upscaling of ecosystem CO2 fluxes across the terrestrial tundra and boreal domain: regional patterns and uncertainties. *Glob. Change Biol.* 27, 4040–4059. doi:10.1111/gcb.15659

Virtanen, R., Oksanen, L., Oksanen, T., Cohen, J., Forbes, B. C., Johansen, B., et al. (2015). Where do the treeless tundra areas of northern highlands fit in the global biome system: toward an ecologically natural subdivision of the tundra biome. *Ecol. Evol.* 6, 143–158. doi:10.1002/ece3.1837

Vogt, J., Risk, D., Bourlon, E., Azetsu-Scott, K., Edinger, E. N., and Sherwood, O. A. (2023). Sea–air methane flux estimates derived from marine surface observations and instantaneous atmospheric measurements in the northern Labrador Sea and Baffin Bay. *Biogeosciences* 20, 1773–1787. doi:10.5194/bg-20-1773-2023

Voigt, C., Virkkala, A.-M., Hould Gosselin, G., Bennett, K. A., Black, T. A., Detto, M., et al. (2023). Arctic soil methane sink increases with drier conditions and higher ecosystem respiration. *Nat. Clim. Chang.* 13, 1095–1104. doi:10.1038/s41558-023-01785-3

Vonk, J. E., Tank, S. E., Bowden, W. B., Laurion, I., Vincent, W. F., Alekseychik, P., et al. (2015). Reviews and syntheses: effects of permafrost thaw on Arctic aquatic ecosystems. *Biogeosciences* 12, 7129–7167. doi:10.5194/bg-12-7129-2015

Wallmann, K., Riedel, M., Hong, W. L., Patton, H., Hubbard, A., Pape, T., et al. (2018). Gas hydrate dissociation off Svalbard induced by isostatic rebound rather than global warming. *Nat. Commun.* 9, 83. doi:10.1038/s41467-017-02550-9

Walter, B. P., and Heimann, M. (2000). A process-based, climate-sensitive model to derive methane emissions from natural wetlands: application to five wetland sites, sensitivity to model parameters, and climate. *Glob. Biogeochem. Cycles* 14, 745–765. doi:10.1029/1999GB001204

Walter, K. M., Chanton, J. P., Chapin III, F. S., Schuur, E. A. G., and Zimov, S. A. (2008a). Methane production and bubble emissions from arctic lakes: isotopic implications for source pathways and ages. *J. Geophys. Res. Biogeosciences* 113, G00A08. doi:10.1029/2007JG000569

Walter, K. M., Engram, M., Duguay, C. R., Jeffries, M. O., and Chapin, F. S. (2008b). The potential use of synthetic aperture radar for estimating methane ebullition from arctic lakes. *JAWRA* 44, 305–315. doi:10.1111/j.1752-1688.2007.00163.x

Walter, K. M., Smith, L. C., and Chapin III, F. S. (2007). Methane bubbling from northern lakes: present and future contributions to the global methane budget. *Philosophical Trans. Ser. A, Math. Phys. Eng. Sci.* 365, 1657–1676. doi:10.1098/rsta.2007.2036

Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D., and Chapin III, F. S. (2006). Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443, 71–75. doi:10.1038/nature05040

Walter Anthony, K. M., and Anthony, P. (2013). Constraining spatial variability of methane ebullition seeps in thermokarst lakes using point process models. *J. Geophys. Res. Biogeosciences* 118, 1015–1034. doi:10.1002/jgrg.20087

Walter Anthony, K. M., Anthony, P., Grosse, G., and Chanton, J. (2012). Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers. *Nat. Geosci.* 5, 419–426. doi:10.1038/ngeo1480

Walter Anthony, K. M., Vas, D. A., Brosius, L., Chapin, F. S., Zimov, S. A., and Zhuang, Q. (2010). Estimating methane emissions from northern lakes using ice-bubble surveys. *Limnol. Oceanogr. Methods* 8, 592–609. doi:10.4319/lom.2010.8.0592

Warwick, N. J., Cain, M. L., Fisher, R., France, J. L., Lowry, D., Michel, S. E., et al. (2016). Using \emph$^{13\$}$C-$CH_4$ and \emphδD-CH_4 to constrain Arctic methane emissions. *Atmos. Chem. Phys.* 16, 14891–14908. doi:10.5194/acp-16-14891-2016

Watts, J. D., Farina, M., Kimball, J. S., Schiferl, L. D., Liu, Z., Arndt, K. A., et al. (2023). Carbon uptake in Eurasian boreal forests dominates the high-latitude net ecosystem carbon budget. *Glob. Change Biol.* 29, 1870–1889. doi:10.1111/gcb.16553

Watts, J. D., Kimball, J. S., Bartsch, A., and McDonald, K. C. (2014). Surface water inundation in the boreal-Arctic: potential impacts on regional methane emissions. *Environ. Res. Lett.* 9, 075001. doi:10.1088/1748-9326/9/7/075001

Westbrook, G. K., Thatcher, K. E., Rohling, E. J., Piotrowski, A. M., Palike, H., Osborne, A. H., et al. (2009). Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophys. Res. Lett.* 36, L15608. doi:10.1029/2009gl039191

Whalen, S. C., Reeburgh, W. S., and Barber, V. A. (1992). Oxidation of methane in boreal forest soils: a comparison of seven measures. *Biogeochemistry* 16, 181–211. doi:10.1007/bf00002818

White, J. D., Ahrén, D., Ström, L., Kelly, J., Klemedtsson, L., Keane, B., et al. (2023). Methane producing and oxidizing microorganisms display a high resilience to drought in a Swedish hemi-boreal mire. *J. Geophys. Res. Biogeosciences* 128, e2022JG007362. doi:10.1029/2022JG007362

Whitfield, C. J., Baulch, H. M., Chun, K. P., and Westbrook, C. J. (2015). Beaver-mediated methane emission: the effects of population growth in Eurasia and the Americas. *AMBIO* 44, 7–15. doi:10.1007/s13280-014-0575-y

Wiggins, E. B., Andrews, A., Sweeney, C., Miller, J. B., Miller, C. E., Veraverbeke, S., et al. (2021). Boreal forest fire CO and CH_4 emission factors derived from tower observations in Alaska during the extreme fire season of 2015. *Atmos. Chem. Phys.* 21, 8557–8574. doi:10.5194/acp-21-8557-2021

Wik, M., Crill, P. M., Bastviken, D., Danielsson, A., and Norback, E. (2011). Bubbles trapped in arctic lake ice: potential implications for methane emissions. *J. Geophys. Res. Biogeosciences* 116, G03044. doi:10.1029/2011JG001761

Wik, M., Crill, P. M., Varner, R. K., and Bastviken, D. (2013). Multiyear measurements of ebullitive methane flux from three subarctic lakes. *J. Geophys. Res. Biogeosciences* 118, 1307–1321. doi:10.1002/jgrg.20103

Wik, M., Johnson, J. E., Crill, P. M., DeStasio, J. P., Erickson, L., Halloran, M. J., et al. (2018). Sediment characteristics and methane ebullition in three subarctic lakes. *J. Geophys. Res. Biogeosciences* 123, 2399–2411. doi:10.1029/2017JG004298

Wik, M., Thornton, B. F., Bastviken, D., MacIntyre, S., Varner, R. K., and Crill, P. M. (2014). Energy input is primary controller of methane bubbling in subarctic lakes. *Geophys. Res. Lett.* 41, 555–560. doi:10.1002/2013GL058510

Wik, M., Thornton, B. F., Bastviken, D., Uhlbäck, J., and Crill, P. M. (2016a). Biased sampling of methane release from northern lakes: a problem for extrapolation. *Geophys. Res. Lett.* 43, 1256–1262. doi:10.1002/2015GL066501

Wik, M., Varner, R. K., Anthony, K. W., MacIntyre, S., and Bastviken, D. (2016b). Climate-sensitive northern lakes and ponds are critical components of methane release. *Nat. Geosci.* 9, 99–105. doi:10.1038/ngeo2578

Yuan, K., Li, F., McNicol, G., Chen, M., Hoyt, A., Knox, S., et al. (2024). Boreal–Arctic wetland methane emissions modulated by warming and vegetation activity. *Nat. Clim. Chang.* 14, 282–288. doi:10.1038/s41558-024-01933-3

Yvon-Durocher, G., Allen, A. P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., et al. (2014). Methane fluxes show consistent temperature dependence across microbial to ecosystem scales. *Nature* 507, 488–491. doi:10.1038/nature13164

Zhang, Z., Fluet-Chouinard, E., Jensen, K., McDonald, K., Hugelius, G., Gumbricht, T., et al. (2021). Development of the global dataset of wetland area and dynamics for methane modeling (WAD2M). *Earth Syst. Sci. Data* 13, 2001–2023. doi:10.5194/essd-13-2001-2021

Zhu, Y., Purdy, K. J., Eyice, Ö., Shen, L., Harpenslager, S. F., Yvon-Durocher, G., et al. (2020). Disproportionate increase in freshwater methane emissions induced by experimental warming. *Nat. Clim. Change* 10, 685–690. doi:10.1038/s41558-020-0824-y