

RESEARCH ARTICLE

The imprint of physical mixing on surface water N₂O and CH₄ concentrations in the eastern Canadian Arctic Ocean

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Abstract

We present high-frequency surface water measurements and discrete depth profiles of nitrous oxide (N₂O) and methane (CH₄) across the eastern Canadian Arctic Ocean, during early autumn 2023. Over the entire study region, surface water N₂O concentrations were close to atmospheric saturation (96–111%), while surface water CH₄ was generally supersaturated (between 197 and 445%). The highest surface water saturation of both gases was observed in northern Foxe Basin, a region of intense mixing over a shallow continental shelf. To examine the influence of vertical mixing on N₂O and CH₄ distributions, we coupled our field observations with output from a numerical model of the Arctic Ocean. This analysis revealed that gas supersaturation was associated with regions of enhanced vertical mixing, as indicated by elevated vertical eddy diffusivity (K_z) and weakly stratified seawater density profiles. Our results also suggest a significant imprint of lateral advection on the surface water distribution of N₂O and CH₄. Air–sea fluxes of N₂O and CH₄ during our early autumn sampling period exceeded previous summertime estimates from the eastern Canadian Arctic by up to an order of magnitude. On the basis of this observation, and an analysis of seasonal variability in model-derived mixing intensity, we argue that summertime studies may not adequately resolve high air–sea fluxes during early autumn associated with reduced stratification, low sea-ice cover, elevated mixing and wind-driven gas exchange. Our work highlights potential variability in surface gas concentrations associated with enhanced water column stratification under warming conditions across the Arctic Ocean and prompts the need for further measurements over a greater part of the seasonal cycle.

Keywords

Climate change; greenhouse gases; polynyas

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Abbreviations

AOU: apparent oxygen utilization
CAA: Canadian Arctic Archipelago
CH₄: methane
CTD: conductivity–temperature–depth instrument
IPCC: Intergovernmental Panel on Climate Change
MLD: mixed layer depth
N₂O: nitrous oxide
RMSE: root mean square error

To access the supplementary material, please visit the article landing page

Introduction

N₂O and CH₄ are the two most abundant greenhouse gases in the atmosphere after carbon dioxide (IPCC 2023). The release of these and other greenhouse gases has particularly strong impacts on sensitive polar regions of the globe, most notably in the Arctic, which has been warming at a faster rate than other regions (e.g., Hoegh-Guldberg & Bruno 2010; Rantanen et al. 2022). Global warming accelerates existing climate feedbacks in the Arctic and has reduced sea-ice cover in recent years (e.g., Kim et al. 2023; Johannessen & Olaussen 2025). As localized regions of the Arctic Ocean are supersaturated in

both N₂O and CH₄ (e.g., Kitidis et al. 2010; James et al. 2016; Rees et al. 2022), changes in warming and ice cover may amplify the flux of N₂O and CH₄ to the atmosphere, resulting in a positive climate feedback.

Understanding the future trajectory of Arctic Ocean N₂O and CH₄ fluxes is limited by current knowledge of the distribution of these gases throughout Arctic waters. Existing studies point to large spatial and temporal variability in N₂O and CH₄ concentrations and air–sea fluxes in the Arctic Ocean (e.g., Shakhova & Semiletov 2007; Kitidis et al. 2010; Fenwick et al. 2017; Shakirov et al. 2020; Manning et al. 2022), but the underlying processes driving this variability are not fully understood and large

parts of the region remain understudied. As in other ocean regions, N_2O is produced through nitrification and, under suboxic conditions, partial denitrification (Kitidis et al. 2010; Verdugo et al. 2016; Fenwick et al. 2017). Air–sea flux from surface waters and denitrification under anoxic conditions are the primary known sinks of N_2O in ocean environments, but other potential sink terms in the marine N_2O budget are not well constrained (Verdugo et al. 2016; Rees et al. 2021). Sources of CH_4 in the Arctic Ocean include riverine input, release from hydrocarbon seeps, hydrate deposits, permafrost and sediments, and water column methanogenesis, which occurs through a variety of pathways (Reeburgh 2007; Damm et al. 2008; Bogard et al. 2014; Manning et al. 2020). Biological oxidation is the main sink of CH_4 , with an additional loss term associated with air–sea flux (Reeburgh 2007). Superimposed on these sources and sink terms for N_2O and CH_4 , physical processes, such as vertical mixing, shape the observed distributions in the water column, potentially amplifying or diminishing the fluxes of these gases to the atmosphere (Malakhova & Golubeva 2022; Schuler & Tortell 2023; Zhao et al. 2025).

Previous studies of N_2O and CH_4 emissions from the Arctic Ocean have focused on the Siberian Shelf, as this region is a particularly important area for examining melting sub-sea permafrost and hydrates in a warming climate (e.g., Shakhova & Semiletov 2007; Shakhova et al. 2015; Shakhov et al. 2020). However, many Arctic Ocean regions remain understudied. Work in the North American Arctic has largely focused outside of the CAA, in the Beaufort Sea (e.g., Kvenvolden et al. 1993; Kitidis et al. 2010; Fenwick et al. 2017; Manning et al. 2022), Chukchi Sea (e.g., Hirota et al. 2009; Li et al. 2017; Manning et al. 2022) and Baffin Bay (e.g., Kitidis et al. 2010; Punshon et al. 2014; Schuler & Tortell 2023). Fieldwork in the CAA is subject to significant logistical complexity, including poorly mapped ocean bathymetry and significant ice cover, which create challenges for oceanographic vessel access. However, the CAA may be an important site of N_2O and CH_4 cycling, as this region overlies a shallow continental shelf, where vertical and tidal mixing can enhance N_2O and CH_4 transport from marine sediments to the overlying atmosphere (Kitidis et al. 2010; Fenwick et al. 2017). Observations from Baffin Bay, adjacent to the CAA, have found water column N_2O and CH_4 to be sourced from the sediments (Kitidis et al. 2010; Punshon et al. 2014; Schuler & Tortell 2023), but observations in many parts of the CAA remain scarce, leaving a gap in current understanding of the distributions and air–sea fluxes of N_2O and CH_4 in this region.

Among the various regions of the CAA, Foxe Basin is of particular interest as it sits over a broad and shallow portion of the continental shelf, with surface waters

containing elevated sediment loads due to resuspension of bottom sediments (Prinsenberg 1986). The presence of polynyas in Foxe Basin has been identified in surveys by the Canadian Government, which has classified this region as a biological hotspot in the CAA (Paulic et al. 2014). The region is also characterized by localized, tidally driven vertical mixing, which could transport N_2O and CH_4 -rich sub-surface waters into the mixed layer, enhancing air–sea fluxes (Prinsenberg 1986). Previous studies have pointed to polynyas as Arctic Ocean hotspots of CH_4 production on account of the high organic carbon accumulation at the sediment interface (Damm et al. 2007). The combination of polynyas and strong vertical mixing in Foxe Basin likely influences N_2O and CH_4 dynamics in this region. As the Foxe Basin region is understudied, the role of melting permafrost and hydrates on CH_4 distributions is unknown. If present, such features could create additional variability in CH_4 concentrations throughout the basin.

This study aims to better understand the dominant controls on N_2O and CH_4 distributions and air–sea fluxes in Foxe Basin and adjacent regions of the CAA during the early autumn season. To accomplish this, we used a combination of high-frequency surface water measurements, discrete water column sampling and numerical model analysis. High-resolution surface measurements capture both small-scale features and broad-scale distributions within surface waters, while discrete depth profile sampling can be used to explore vertical structure across the water column. Model output can supplement observational data, providing additional oceanographic context to interpret N_2O and CH_4 variability. Our results demonstrate how integrated field measurements and numerical model analysis can be used to examine the impact of vertical mixing on N_2O and CH_4 distributions and air–sea fluxes in Foxe Basin, enhancing our understanding of the processes controlling the release of these two greenhouse gases from a poorly studied Arctic Ocean region during an important part of the seasonal cycle.

Methods

Study area and hydrographic setting

Sampling occurred during Leg 4 of the CCGS *Amundsen* 2023 Expedition, 5–26 October 2023 (Fig. 1). The cruise began in the Gulf of Boothia and then transited through Fury and Hecla Strait, Foxe Basin and Hudson Strait. Nearly the entire region was ice-free during the sampling period. Foxe Basin is a region of interest because of its relatively shallow water column as well as intense

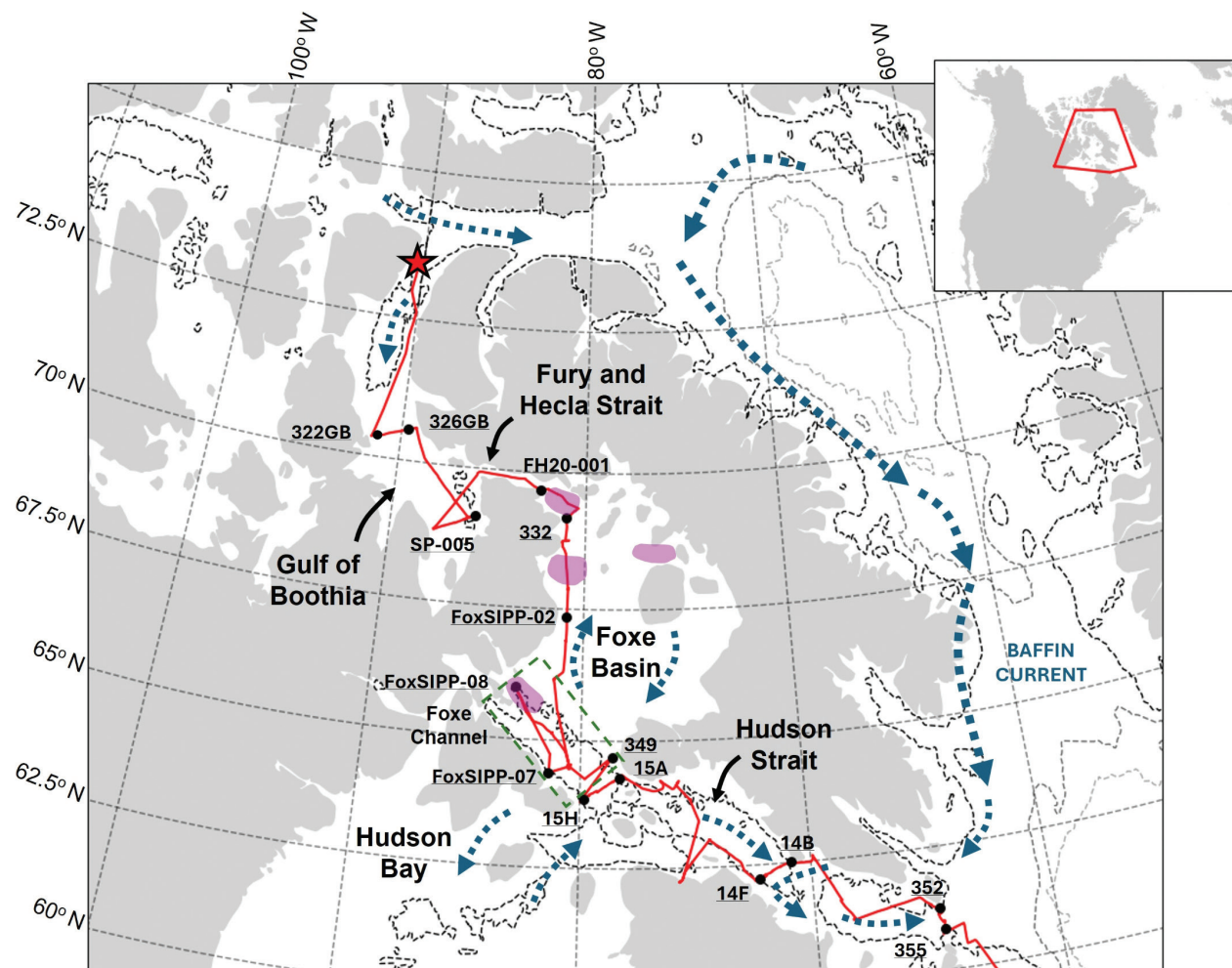


Fig. 1 Map of the study region. The red line is the cruise track (starting at the location of the red star), black dots are (labelled) stations where discrete samples were taken for N_2O and CH_4 analysis, pink patches are regions of reoccurring polynyas (Defossez et al. 2012; Paulic et al. 2014) and blue arrows represent the dominant surface currents in the region (derived from AMAP 1998). Foxe Channel is highlighted by a green box within Foxe Basin. The bathymetric lines represent the 200 m (black), 1000 m (grey) and 2000 m (light grey) depth contours.

localized mixing (Tan & Strain 1996; Defossez et al. 2008). Previous research in this region has focused on sea-ice formation patterns (Campbell & Collin 1958; Prinsenberg 1986; Saucier et al. 2004) and regional circulation (Tan & Strain 1996; Defossez et al. 2008). Water enters the Gulf of Boothia (Fig. 1) and flows through Fury and Hecla Strait before entering Foxe Basin from the north. Water then circulates throughout Foxe Basin and, in the south, exchanges between Foxe Basin, Hudson Bay and Hudson Strait, with Hudson Strait water sourced from the Baffin current (AMAP 1998). Foxe Basin and Hudson Strait are both known to experience intense mixing, and the larger Foxe Basin region is typically ice-free in autumn. Mixed layer stratification due to summer ice melt may be minimal at this time, resulting in a well-mixed water column in localized areas (Prinsenberg 1986; Tan & Strain 1996;

Saucier et al. 2004). Some studies have reported increased air–sea fluxes during autumn in Arctic regions, coinciding with the breakdown of the pycnocline as wind speeds increase and surface waters cool (Yurganov et al. 2021). However, much of the work done in the CAA has been conducted during the summer, with only limited observations in autumn (Kitidis et al. 2010; Fenwick et al. 2017; Manning et al. 2022).

The deep water in Foxe Basin experiences a renewal event each year, when dense water is formed in polynyas as a result of brine rejection and surface cooling in the northern part of the basin (Tan & Strain 1996; Defossez et al. 2008). This dense water sinks down through the water column in the spring and moves south into Hudson Bay where it becomes Hudson Bay Bottom Water. Another portion of this surface-derived water mass

circulates at depth throughout Foxe Basin (Saucier et al. 2004; Defossez et al. 2008). As the seasons progress, the deep water pulse warms and freshens, dissipating approximately three months after it is first observed (Defossez et al. 2008). In the summer months, when other Arctic regions experience strong stratification due to sea-ice melt, a large portion of the eastern side of Foxe Basin remains well mixed, and the more central and western side of the basin can exhibit a transitional state between mixed and stratified conditions (Griffiths et al. 1981). Intense vertical mixing occurs throughout Foxe Basin, driven by the shallow nature of the basin and large tidal amplitudes of up to 4.5 m. These processes create deep MLDs and sediment resuspension within the water column, which can sometimes result in a red tint in first-year sea ice (Prinsenberg 1986). Hudson Strait also experiences intense tidal mixing that can influence gas distributions throughout the water column (Ridenour et al. 2021; Izett et al. 2022). The physical processes occurring in Foxe Basin and the adjacent regions make these areas of particular interest for studying the biogeochemical cycling of N₂O and CH₄.

Sampling and data analysis

We used both continuous and discrete sample analysis to examine the spatial distribution of N₂O and CH₄ along the cruise track. Continuous measurements of N₂O and CH₄ were collected using an off-axis integrated cavity output spectroscopy gas analyser (Los Gatos Research, N₂O/CH₄ Analyzer, model number 913-0055). The analyser was connected to a gas extraction module (Schuler & Tortell 2023), which was adapted to use a smaller membrane (model MM 1X5.5 Series Membrane Contractor G543), reducing the extraction efficiency for both gases. The reduction in extraction efficiency, resulting from the smaller surface area of the membrane, decreases the amount of gas delivered to the detector, but does not influence sampling resolution. Data points were collected approximately every 10 s and averaged into one-minute bins. Water from the ship's seawater line (nominal sampling depth of 7 m) was passed through the gas extraction module, where sample gas was continuously extracted for real-time analysis on the spectrometer. Calibration samples for seawater analysis were periodically taken from a sampling tube connected upstream of the gas extraction module. These samples were used to calculate the system's extraction efficiency, which was 49.1% ($R^2 = 0.99$) for N₂O and 4.0% ($R^2 = 0.72$) for CH₄. The higher extraction efficiency for N₂O is consistent with previous results (Schuler & Tortell 2023), and expected based on the higher solubility of this gas relative to CH₄ and lower theoretical equilibrium time (Nicholson et al. 2018).

Additional discrete calibration samples were taken from the rosette at 7 m depth to ensure that the gas extraction module was not introducing any measurement artifacts. Notably, surface water and 7 m samples gave similar results for both N₂O and CH₄ within the standard error of triplicate measurements, indicating that the 7 m sampling depth was representative of surface waters. No other calibration was conducted during the expedition and there was no noticeable drift in the instrument. Gas and water flow rates across the gas extraction module were kept constant throughout the cruise to reduce changes in extraction efficiency.

In addition to high-resolution surface sampling, discrete depth profile samples were taken from 15 stations to characterize the water column structure of N₂O and CH₄ across the region (Fig. 1). Samples were collected at varying depths using 12L Niskin bottles mounted to a rosette, which was equipped with a Sea-Bird Scientific SBE 911plus CTD containing oxygen, beam transmissivity, salinity and temperature sensors. Calibration and depth profile samples for N₂O and CH₄ analysis were collected in 80 mL glass serum vials, allowing three volumes of overflow before the sample was collected, spiked with 100 mL of saturated HgCl₂ solution, capped with butyl rubber stoppers and sealed with aluminum crimp seals. Samples were stored at 4°C and transported to our university laboratory for analysis. Sample analysis was conducted using an automated purge and trap system (Capelle et al. 2015) connected to a gas chromatograph-mass spectrometer. The instrument was calibrated prior to each batch and air equilibrated water samples were analysed during batch processing of samples to correct for any instrument drift.

Biogeochemical and air-sea flux calculations

AOU was calculated as the difference between the atmospheric equilibrium and observed concentration of oxygen in a water sample, following the method of Weiss (1970), using temperature, salinity and oxygen measurements obtained from the CTD. Using our continuous measurements of the mixing ratios of N₂O and CH₄, dissolved gas concentrations in moles per litre were calculated assuming an atmospheric pressure of 1 atm, and using temperature and salinity measurements from the ship's thermosalinograph, following the methods of Weiss & Price (1980) and Wiesenburg & Guinasso (1979). Dissolved gas concentrations were then used to calculate instantaneous air-sea fluxes (F , $\mu\text{mol m}^{-2} \text{d}^{-1}$) using the following equations.

$$F = k_w \Delta C \quad \text{Eqn. 1}$$

$$\Delta C = (C_{\text{measured}} - C_{\text{equilibrium}}) \quad \text{Eqn. 2}$$

$$k_w = 0.251 * U^2 \left(\frac{Sc}{660} \right)^{-0.5} \quad \text{Eqn. 3}$$

Here ΔC (nmol L⁻¹) is the disequilibrium value of N₂O and CH₄, C_{measured} is the measured concentration, and $C_{\text{equilibrium}}$ is the dissolved gas value at atmospheric equilibrium. Daily air sample measurements by the analyser averaged 330.9 ± 0.5 ppb for N₂O and 1.99 ± 0.01 ppm for CH₄. Our atmospheric CH₄ measurements agree with data obtained from the nearest atmospheric station in the same zonal band, which is the ICE station in Iceland (2.01 ± 0.01 ppm; Global Monitoring Laboratory n.d.), while our N₂O atmospheric measurements are within 2% of the values recorded at ICE (336.9 ± 0.1 ppm). The small discrepancy in our atmospheric N₂O measurements may reflect the location of the ICE measuring station in Iceland, far from our study site. We note that the difference in these atmospheric values is negligible compared to the error associated with other variables, such as the gas exchange coefficient. The gas exchange coefficient, k_w (m d⁻¹), was calculated following Wanninkhof (2014) for intermediate wind speeds between 3 and 15 m s⁻¹. This calculation provides an estimate of k_w based on wind speed observations and calculated Schmidt numbers (Sc) derived from sea-surface temperature data (Wanninkhof 2014). Wind-speed data (U; m s⁻¹) were obtained from the ship's weather station, with measurements averaged into one-minute bins and adjusted to a reference height of 10 m asl (Johnson 1999).

Model implementation

To examine vertical mixing across our study region, the vertical eddy diffusivity parameter (K_z , m² s⁻¹) was obtained from an ocean model simulation of the Arctic Ocean using output from September to October 2023. This model-derived quantity describes the rate at which properties of seawater, including dissolved gases, are mixed throughout the water column as a result of turbulence. We employed a 1/4° Arctic Northern Hemisphere Atlantic configuration (ANHA4) of the Nucleus for European Modeling of the Ocean framework (Madec et al. 2023), utilizing a baroclinic timestep of 1080 s on a grid with a horizontal resolution of 0.25° and 50 depth levels, from 1 m at the surface to greater than 100 m depth, with non-linear spacing. Further description of the simulations are provided by Garcia-Quintana et al. (2019) and Myers et al. (2024). A subset of the model

output, consisting of five-day averages of physical and hydrographic fields, was extracted for a sub-region spanning from 60 to 75°N and 60 to 100°W, and values were averaged over the 15 days prior to the time of our sampling at each location along the cruise track. The methodology for determining K_z at each station and evaluating the model output followed the approach outlined by Izett et al. (2022). Model grid cells were matched spatially with station locations and values from multiple stations within a single grid cell were averaged. Following the method of Izett et al. (2022), the value of K_z was calculated as the average of model output between the derived MLD and the pycnocline depth plus 10 m. Grid points where K_z was greater than 10⁻² m² s⁻¹ were excluded, as these values represent the upper threshold for this parameter. These high values may indicate numerical instability, or the initiation of model convection parameterization to remove a static instability, which obscures the actual K_z value (Madec et al. 2023). Izett et al. (2022) eliminated stations with depths less than 100 m or where model grid cells overlapped with landmasses because of poor model performance in these areas. In contrast, we chose to keep these locations in our analysis, given our interest in the relatively shallow Foxe Basin. In this study, model evaluation (see below) demonstrated similar performance for grid cells with bottom depths less than 100 m and adjacent to land, as compared to grid cells in deeper waters.

Model evaluation

To evaluate the model results, physical parameters including MLD, pycnocline depth and density profiles produced by the model were compared with CTD measurements at stations along the cruise track (Fig. 2, Supplementary Figs. S1 and S2). For this comparison, the locations of CTD casts were matched spatially to model grid cells and model output was then averaged for the 15 days prior to the sampling date. This time period was chosen to capture the typical conditions in the region at this time of year. The quality of fit between the model and observations was determined based on an evaluation of the RMSE.

We note that our model evaluation is subject to several caveats. Firstly, the model produces five-day averages, whereas physical parameters, such as K_z can be highly localized and dynamic, leading to a temporal mismatch between the model output and observed values. In addition, we lack observational K_z measurements and are therefore unable to directly evaluate model K_z against observations. Nonetheless, as discussed below, we believe that the model remains a useful tool for evaluating regional-scale patterns in vertical mixing intensity.

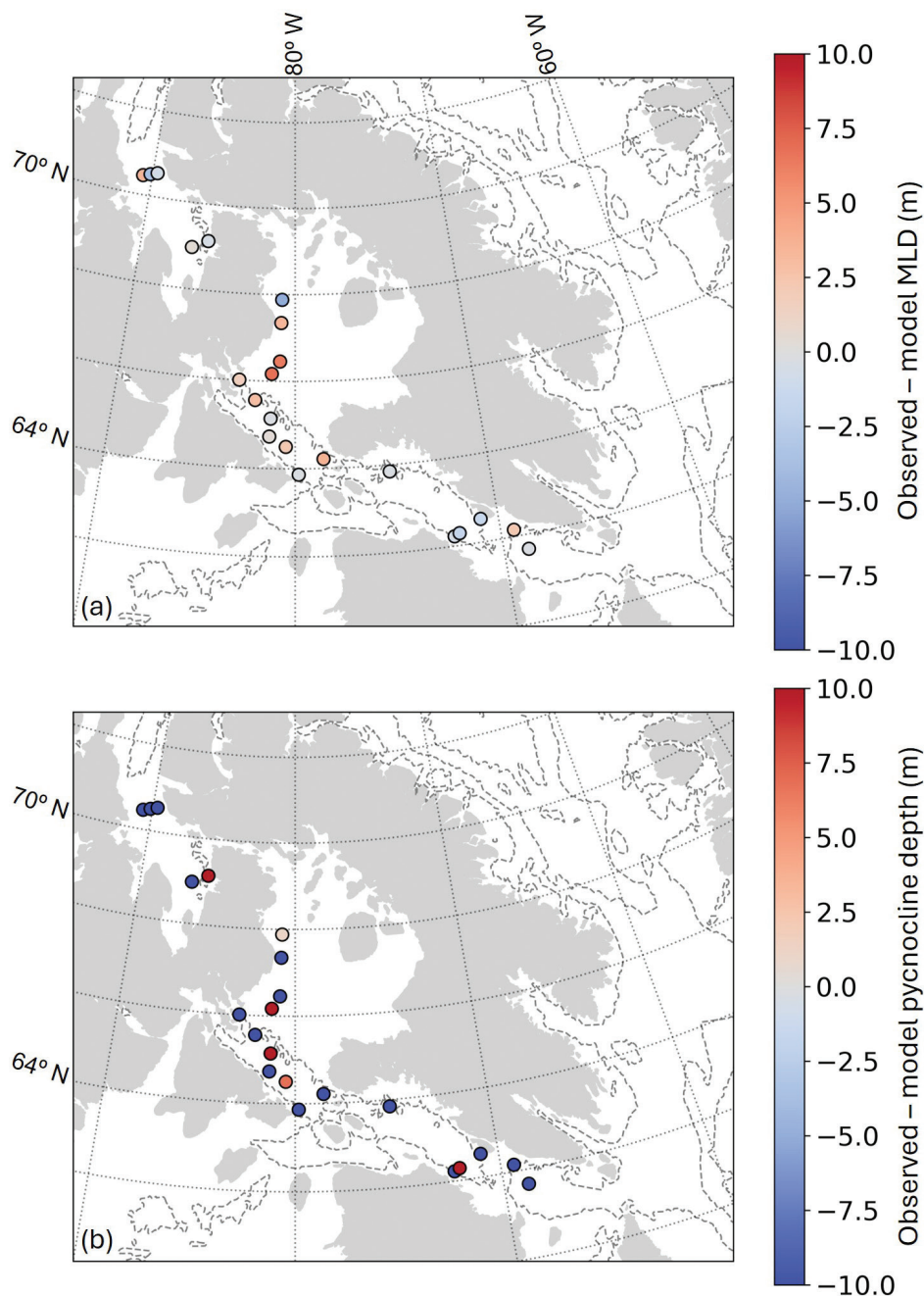


Fig. 2 Maps showing the differences in observed and modelled (a) MLD and (b) pycnocline depths at stations. Blue values indicate model overestimation of densities, while red values indicate model underestimates. Note that the distribution of stations shown here (and in Fig. 3) differs from that in Fig. 1, as all stations with CTD data are shown here, whereas only those with N_2O and CH_4 sampling are shown in Fig. 1.

Results

Model performance

Comparisons between model-derived and observed density, MLD and pycnocline depth revealed that the model

performed generally well in some regions, with lower performance in other parts of the study area. To facilitate regional comparison, the study area was divided into three sub-regions, the Gulf of Boothia and Fury and Hecla Strait, Foxe Basin and Hudson Strait (Supplementary Figs. S1 and S2). Further details describing the differences between

the modelled and observed values across the sub-regions can be found in the Supplementary material.

Figure 3 shows the water column averaged model-derived K_z values at stations where CTD casts were made across the cruise track (note the logarithmic scaling on the colour bar). The largest derived K_z values occurred in Hudson Strait, where tidal mixing is known to be particularly intense, while the lowest derived K_z occurred in the Gulf of Boothia, a region that exhibited strong stratification compared to Foxe Basin and Hudson Strait. The higher apparent K_z values in Foxe Basin and Hudson Strait indicate elevated vertical mixing within the water column in these regions, which is consistent with previous hydrographic observations (Prinsenberg 1986; Ridenour et al. 2021; Izett et al. 2022).

Surface distribution of N_2O

N_2O saturations in surface waters were generally near atmospheric equilibrium across the entire cruise track, with a median saturation of 104% (Fig. 4). An exception was observed at the junction of Foxe Basin and Fury and Hecla Strait, where we observed the highest N_2O saturation in the study region (111%; Fig. 4). In contrast, the rest of Foxe Basin exhibited only moderate N_2O supersaturation, while the Gulf of Boothia and Fury and Hecla Strait experienced slight N_2O supersaturation, with some areas at atmospheric equilibrium. The majority of Hudson

Strait was near atmospheric equilibrium for N_2O , except for one portion of the cruise track where N_2O undersaturation (96% saturation) was measured (Fig. 4).

N_2O depth profiles

Across all stations where discrete sampling took place, N_2O saturation ranged from 95% in surface waters to 122% near the sediment interface. In some discrete samples, reproducibility among replicates was poorer than anticipated (Capelle et al. 2015), potentially because of atmospheric contamination during bottle sampling. On average, surface water N_2O saturations in northern Foxe Basin were lower than values near the sediment. In contrast, Foxe Channel showed the opposite trend, with higher surface saturations compared to bottom water samples (Fig. 5). In Hudson Strait, N_2O saturation was more variable throughout the water column, with surface saturations tending to be smaller, on average, than those near the sediments (Fig. 5). The Gulf of Boothia and Fury and Hecla Strait tended to have lower N_2O saturations in surface waters, as compared to values in the denser sub-surface water masses (Fig. 5).

The relationship between the disequilibrium value of N_2O (ΔN_2O) and AOU has previously been used to determine the source of N_2O within the water column (e.g., Cohen & Gordon 1978; Elkins et al. 1978; Walter et al. 2006). In this study, a positive relationship was observed

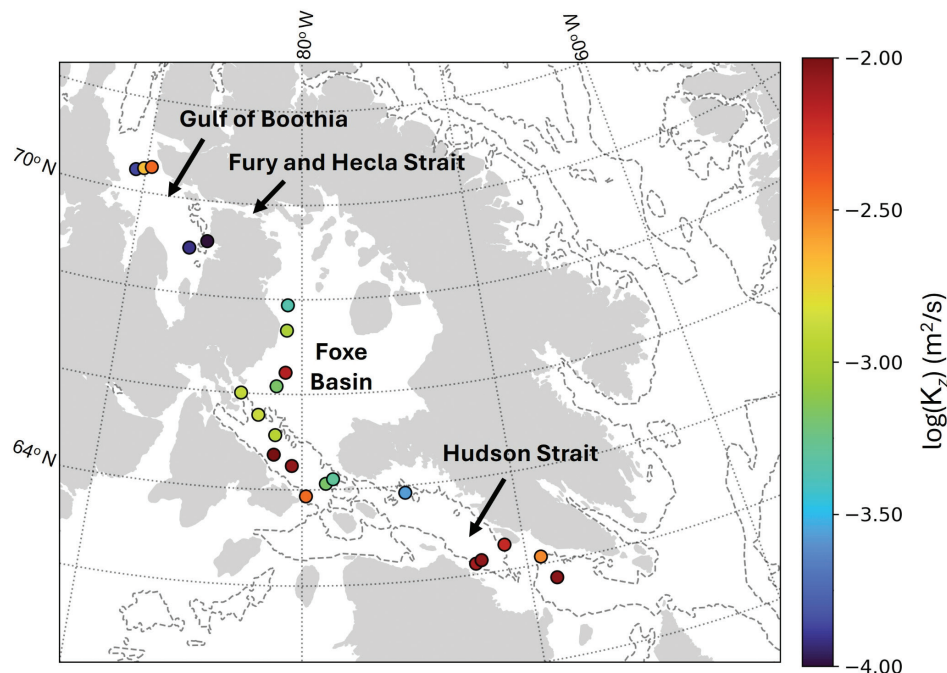


Fig. 3 Distribution of the average model-derived $\log(K_z)$ values at stations across the cruise track.

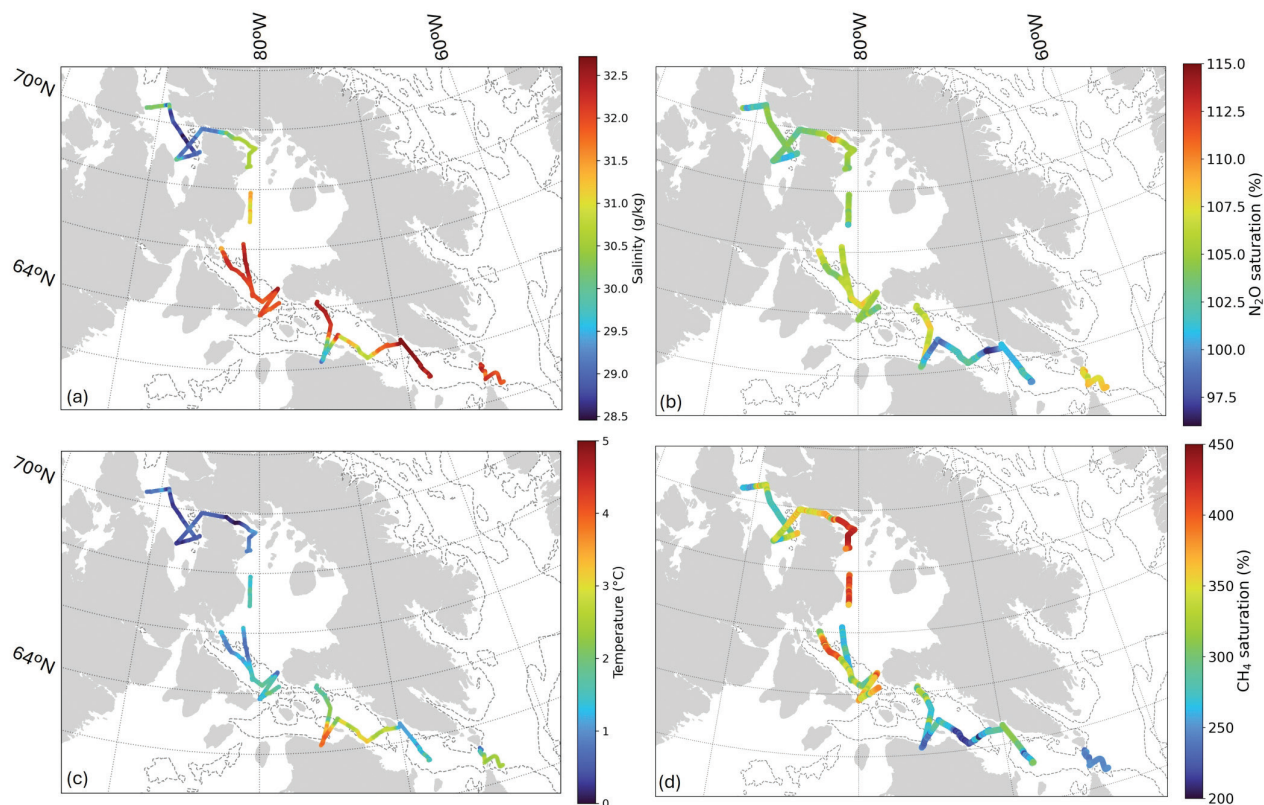


Fig. 4 Spatial distribution of (a) surface water salinity, (b) N₂O saturation, (c) temperature and (d) CH₄ saturation across the study region.

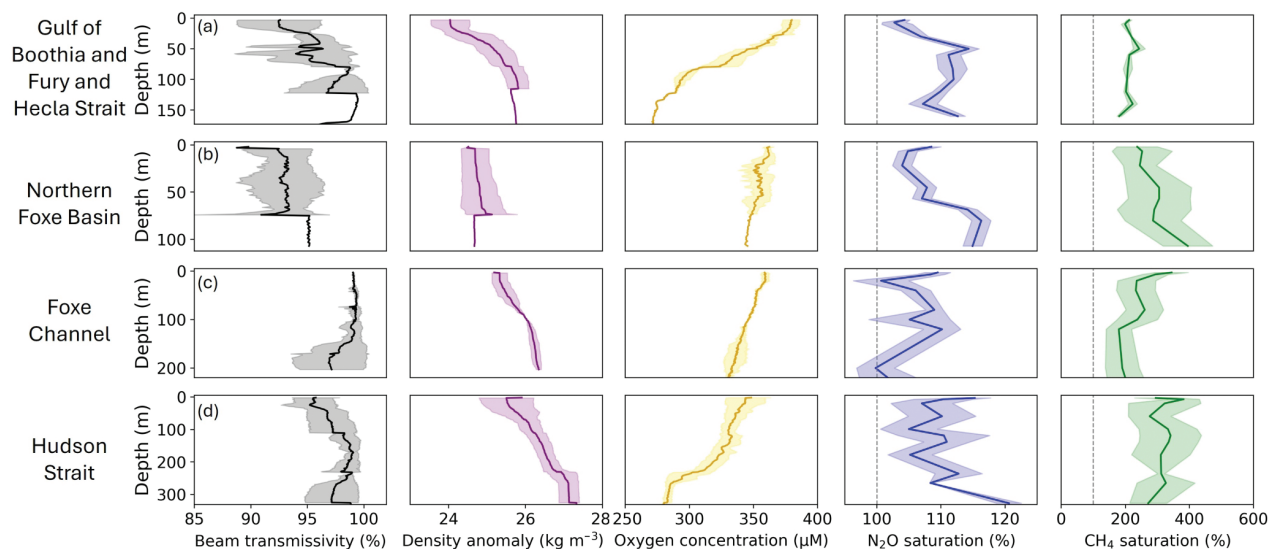


Fig. 5 Depth profiles of average beam transmissivity, seawater density, oxygen concentration, N₂O saturation and CH₄ saturation in (a) the Gulf of Boothia and Fury and Hecla Strait, (b) northern Foxe Basin, (c) Foxe Channel and (d) Hudson Strait. The plotted line represents the average value derived from all depth profiles, while the shaded areas are the standard deviation for beam transmissivity, density and oxygen concentration and the standard error for N₂O and CH₄ measurements. Where no shaded area is present, only one CTD profile was collected. The grey dashed lines in the gas saturation panels represent 100% saturation.

between $\Delta\text{N}_2\text{O}$ and AOU in the Gulf of Boothia and Fury and Hecla Strait ($R^2 = 0.63$, $p < 0.001$). However, no significant relationship was found in the sub-regions of Foxe Basin or Hudson Strait (Fig. 6).

Surface distributions of CH_4

In contrast to N_2O , CH_4 exhibited large and highly variable supersaturation in surface waters along the entire cruise track, with a median saturation of 285% (Fig. 4). The maximum CH_4 supersaturation along the cruise track (445%) was observed in northern Foxe Basin, in an area of reoccurring polynyas. As compared to the northern region, Foxe Channel exhibited elevated, but more variable, CH_4 saturation (Fig. 4), with values ranging from 250 to 424%. The Gulf of Boothia and Fury and Hecla Strait showed CH_4 saturation similar to that observed in Foxe Channel, while the lowest saturation of 199% was measured in Hudson Strait (Fig. 4).

Discrete CH_4 samples and depth profiles

Across the study region, CH_4 saturation measured in discrete depth profile samples ranged from 207% in the surface waters to 389% at the sediment interface. In northern Foxe Basin, CH_4 saturation was higher, on average, near the sediments than in the surface waters. Conversely, in Foxe Channel, where strong stratification was observed, higher CH_4 saturations were observed in surface waters, as compared to deeper waters. Unfortunately, samples were not taken in the middle of Foxe Channel, where depths exceeded 400 m. This limits our understanding of the gas cycling in the deep water masses of that region. The Gulf of Boothia and Fury and Hecla Strait and Hudson Strait showed greater variability in the distribution of CH_4 throughout the water column, with less evident vertical structure in depth profiles (Fig. 5).

Air-sea fluxes

Instantaneous air-sea fluxes were calculated for both N_2O and CH_4 (Fig. 7). On average, air-sea N_2O fluxes were small, but positive, with a mean value of $0.52 \text{ mmol m}^{-2} \text{ d}^{-1}$, (positive values indicate oceanic emission of N_2O to the atmosphere). The largest flux of N_2O , $4.3 \text{ mmol m}^{-2} \text{ d}^{-1}$, was observed in southern Foxe Basin, where large wind speeds and elevated N_2O saturations were observed. Elsewhere in Foxe Basin, N_2O air-sea fluxes were only slightly above zero. In the Gulf of Boothia and Fury and Hecla Strait, air-sea N_2O fluxes were similar to those observed in Foxe Channel, while fluxes in Hudson Strait were generally low. The fluxes in this region were even negative at times, with a minimum value of $-1.5 \text{ mmol m}^{-2} \text{ d}^{-1}$. At the boundary of Hudson Strait and the Labrador Sea, a positive air-sea flux of N_2O was observed.

Relative to N_2O , air-sea CH_4 fluxes showed more variability across the study region and larger absolute values. The largest flux ($23.5 \text{ mmol m}^{-2} \text{ d}^{-1}$) was observed in southern Foxe Basin, where the highest N_2O fluxes were observed as well. Large CH_4 fluxes were also seen throughout the Gulf of Boothia and Fury and Hecla Strait. Air-sea CH_4 fluxes decreased through Hudson Strait, reaching a minimum of $0.002 \text{ mmol m}^{-2} \text{ d}^{-1}$. Elevated fluxes were observed in the eastern part of the Strait, corresponding with regions of higher CH_4 saturation and elevated wind speeds. Across our entire study region, the average air-sea flux of CH_4 was $8.1 \text{ mmol m}^{-2} \text{ d}^{-1}$.

Discussion

Across our cruise track, we observed a number of notable spatial patterns in the surface water distribution of N_2O and CH_4 . In particular, regions characterized by seasonal polynyas (Tan & Strain 1996; Defossez et al. 2008) and intense vertical and tidal mixing (Prinsenbergh 1986; Tan

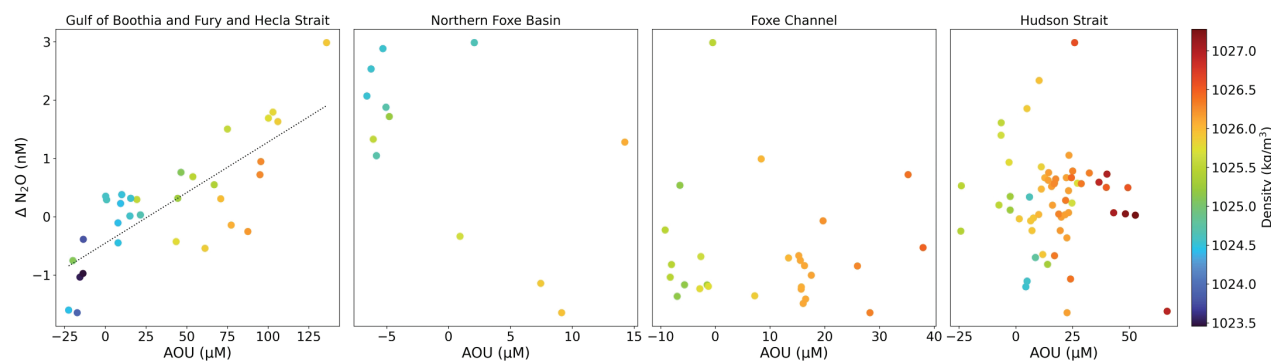


Fig. 6 Comparison of $\Delta\text{N}_2\text{O}$ –AOU relationships coloured by density (kg m^{-3}) across various regions of the cruise track. The R^2 value for the Gulf of Boothia and Fury and Hecla Strait is 0.63 ($p < 0.001$).

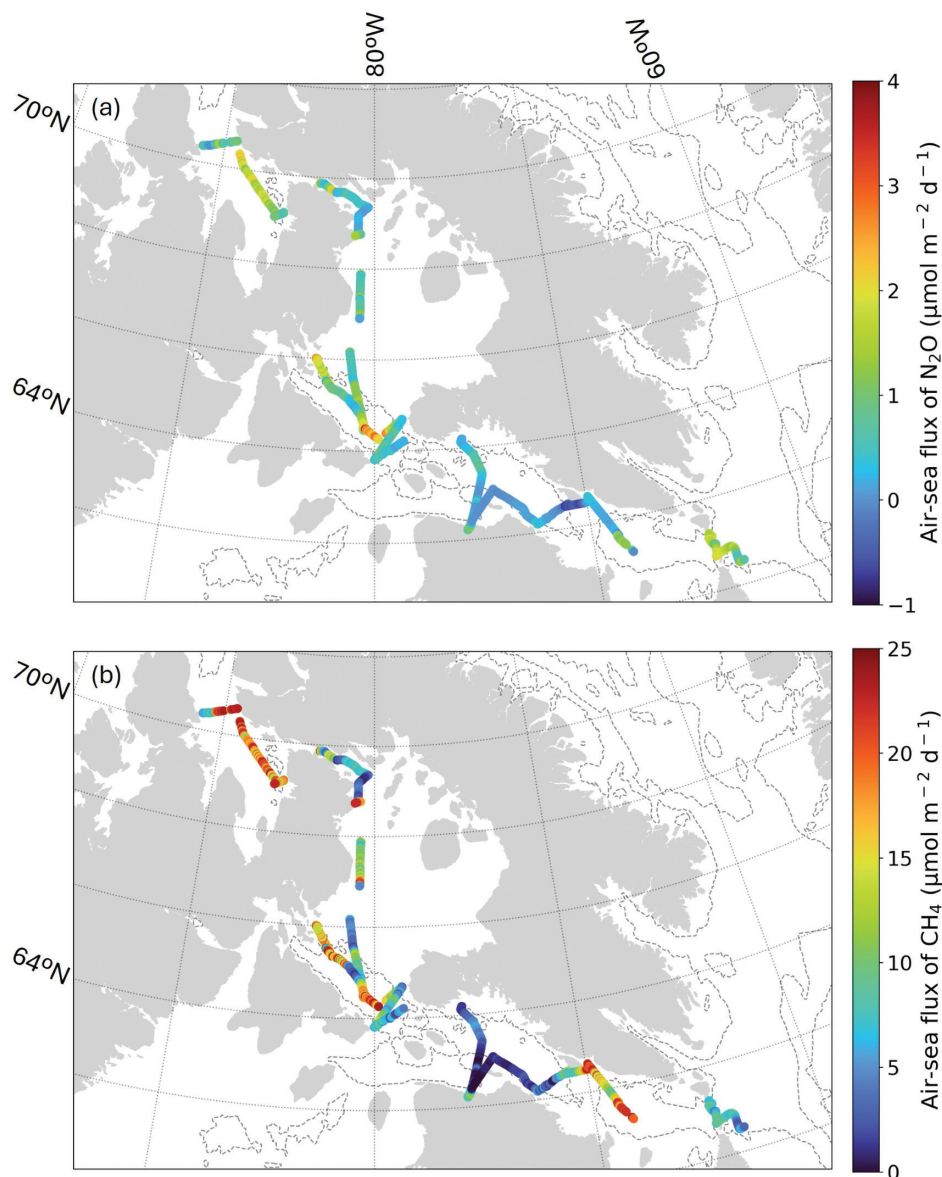


Fig. 7 Plot of instantaneous air-sea flux of (a) N_2O and (b) CH_4 along the cruise track.

& Strain 1996; Saucier et al. 2004) exhibited high saturation of both N_2O and CH_4 in surface waters. Polynyas, with their elevated primary productivity and organic carbon export (Klein et al. 2002; Tremblay et al. 2002; Tremblay & Smith 2007), potentially create conditions for enhanced sedimentary N_2O and CH_4 production (Damm et al. 2007). Vertical mixing can facilitate gas transport from sub-surface to surface waters, while lateral advection can transport water masses rich in these gases throughout basins. Mixing is expected to be elevated during the early autumn period we sampled, as surface waters begin to cool and re-freeze, leading to a breakdown in seasonal stratification. As discussed next, this

enhanced seasonal mixing may help to explain the elevated surface saturation and air-sea fluxes of N_2O and CH_4 we observed relative to previous measurements from the same region earlier in the summer season.

To better understand the physical dynamics operating across our study region, we used numerical model output to identify regions of enhanced vertical mixing. At broad scales, model output can provide additional oceanographic context to help interpret our observations, especially in Arctic regions where observational data are sparse. We note, however, that the robustness of the model varies across sub-regions, as demonstrated in Fig. 2 and Supplementary Figs. S1 and S2. Nonetheless,

we believe that the model can help identify contrasting mixing regimes across our study area, and we use the model-derived K_z values in a qualitative manner, alongside CTD observations of beam transmissivity, oxygen and density profiles, to identify regions of more intense mixing across our study region.

Surface saturation and air–sea fluxes of N_2O and CH_4

During the time of our sampling, CH_4 was consistently supersaturated along the entire cruise track, exceeding previously reported levels for the CAA (Fenwick et al. 2017; Manning et al. 2022). In contrast, the N_2O saturation we measured was comparable to earlier observations in the region. Previous studies have reported N_2O and CH_4 saturation near 100% within the CAA, with localized deviations from air-equilibrium values (Fenwick et al. 2017; Manning et al. 2022). Notably, these previous measurements have all been based on discrete sampling, resulting in relatively sparse data coverage, which does not resolve fine-scale variability. Prior studies have also been derived mostly from measurements conducted earlier in the summer months.

Figure 8 compares the data obtained in this study with previous discrete measurements from the Foxe Basin region compiled by Manning et al. (2022), analysed with the same methodology used here. Supplementary Fig. S3 presents a full comparison of the two data sets, featuring all samples from Manning et al. (2022) across the larger North American Arctic Ocean. Comparison between the two data sets from the Foxe Basin region reveals slightly higher N_2O saturations in this study as compared with values previously reported for the CAA, although we note that Manning et al. observed elevated N_2O saturation in Foxe Basin and elevated saturations elsewhere in the North American Arctic. In contrast to N_2O , the CH_4 saturation measured in this study was notably higher than prior observations in the CAA, with some regions showing four-fold greater saturation, on average, during our study and air–sea fluxes more than six-fold larger, on average, than previous measurements conducted earlier in the season (Fenwick et al. 2017; Manning et al. 2022). We note, however, that previous work has documented much higher CH_4 concentrations across the Siberian Shelf during a similar time of year (Shakhova & Semiletov 2007).

The difference between the observed surface saturations in this study and those reported by Manning et al. (2022) in Foxe Basin could result from a variety of factors, including the different seasonal timing of our sampling campaigns. Our sampling was conducted during October, while Manning et al. collected samples

throughout the CAA largely in the summer months (July–Sept), with only about 10% of stations sampled in October and all Foxe Basin samples collected during August. Hydrographic conditions are expected to differ between August and October, and an analysis of both CTD observations and model output support this. More saline surface waters were observed in this study compared to the samples collected by Manning et al., and model output shows higher derived K_z throughout the water column in October compared to August (Supplementary Fig. S4). During the summer months in the Arctic Ocean, surface waters are impacted by sea-ice melt, which creates strong salinity stratification in the upper water column. In contrast, at the time of our sampling in October, the water column was well mixed over much of our sampling region, with an average MLD from CTD casts of 26.5 m (using 5 m reference depth and $D_s = 0.125$), and evidence that the entire water column was mixed to depths of about 100 m in northern Foxe Basin. By comparison, Manning et al. (2022) reported an average MLD of 18.9 m for the North American Arctic during summer. The shallow waters of northern Foxe Basin could have enhanced the transport of sediment-derived CH_4 to surface waters, particularly in autumn, when storm-driven convection increases and water column stratification decreases. Previous observations (Damm et al. 2015; Yurganov et al. 2021) have demonstrated increased air–sea flux from Arctic waters associated with higher autumn wind speeds and enhanced winter convection in ice-free regions. In addition, previous results from a modelling study in the Arctic have predicted an increase in surface water CH_4 fluxes in October, coincident with increased convection (Malakhova & Golubeva 2022). Similar results were found in a modelling study of the Indian Ocean, where enhanced convection in the winter was associated with elevated surface N_2O concentrations (Zhao et al. 2025).

Notably, our measured discrete surface water CH_4 saturations in northern Foxe Basin showed saturation values approximately two-fold greater than that of the deep-water CH_4 signatures reported by Manning et al. (2022) for this region. This difference may be attributed to increased mixing enhancing the input of sedimentary sources to the water column during autumn, as discussed above, or to a difference in sea-ice conditions between our study and that of Manning et al. During the August sampling of Manning et al., there was sea ice in Foxe Basin and Fury and Hecla Strait and melting ice may have acted to dilute CH_4 concentrations, as seen in previous studies (Damm et al. 2015). In contrast, there was no ice during our sampling period and we observed higher surface water salinity than those sampled by Manning et al. Without additional data, we are unable to draw firm conclusions on the

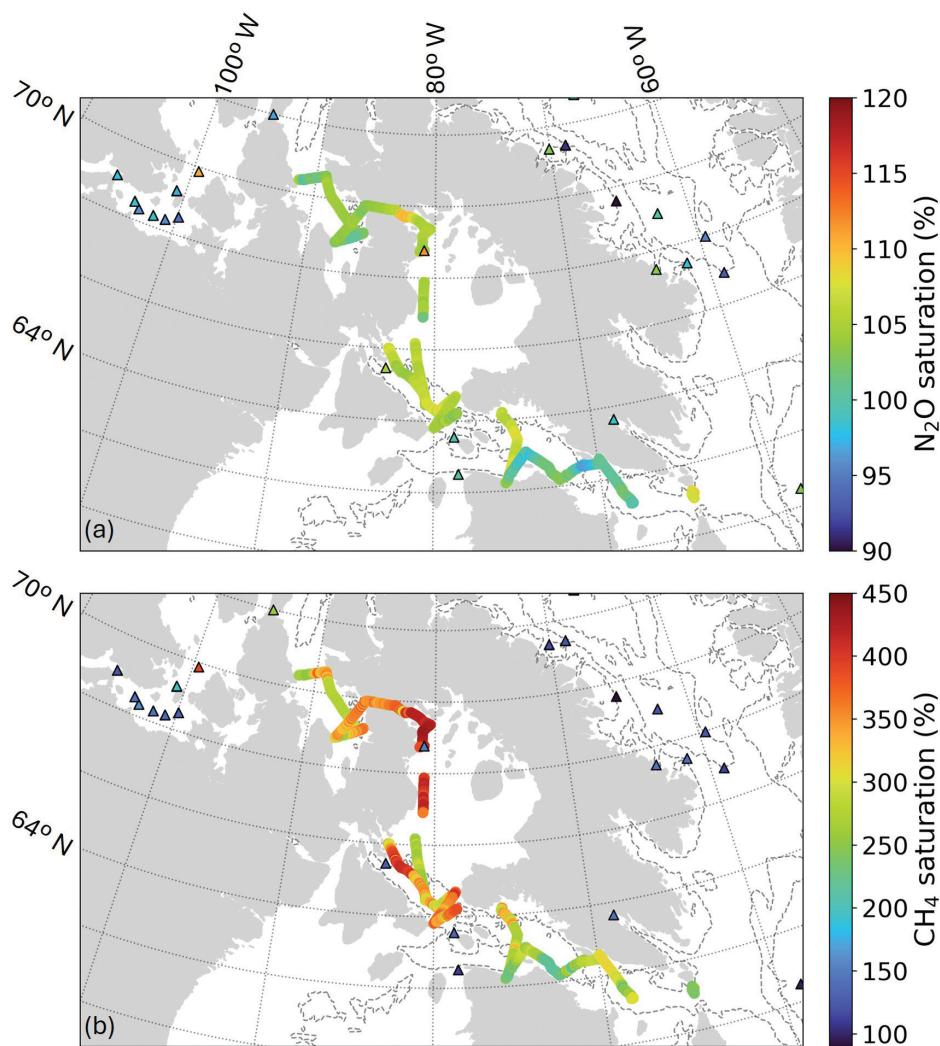


Fig. 8 Comparison of surface water (a) N_2O and (b) CH_4 saturation from this study (dots) and Manning et al. (2022) (triangles) in the Foxe Basin region.

factors causing the difference between our measurements and those of Manning et al. Nonetheless, the available evidence suggests that the elevated CH_4 observed during our cruise reflects a relatively short period when the water column is weakly stratified prior to winter freeze-up. This seasonal period may be disproportionately important in determining annual air-sea CH_4 fluxes from the CAA, prompting the need for further studies at this transitional time of year.

Sources of N_2O to the water column

Both sedimentary and water column processes appear to influence observed N_2O distributions within our study region. In the well-mixed water column of northern Foxe Basin, N_2O was supersaturated in bottom samples (ca. 100 m; Fig. 5). Weak vertical stratification of the

water column in this region, evident through near-constant vertical density, oxygen and beam transmissivity profiles (Fig. 5), would have allowed N_2O sourced from sedimentary processes to be supplied to the surface waters via vertical mixing. Notably, bottom water N_2O saturation here was greater than in surface waters, potentially because sedimentary production outpaced vertical mixing. Beam transmissivity can be used as a proxy for sediment resuspension, and homogenous vertical profiles of this variable suggest that sediments were being resuspended throughout the water column in northern Foxe Basin. Unfortunately, the K_z values for several stations in northern Foxe Basin were excluded from analysis, as they exceeded our upper cut-off limit. Nonetheless, the high K_z at other Foxe Basin stations provide evidence for enhanced vertical mixing in the northern part of this region. Elevated K_z values were

also apparent in Hudson Strait, likely associated with strong tidal currents in this region. At the same time, stronger water column stratification would act to limit sedimentary N_2O sources in this region, helping to explain the higher mixed layer beam transmissivity values observed in Hudson Strait, relative to Northern Foxe Basin (Fig. 5). Given the similar density layers found in Foxe Basin surface waters and much of Hudson Strait (Fig. 9) and the known circulation patterns in the region (AMAP 1998), it is likely that lateral advection and mixing of surface waters from Foxe Basin and Hudson Bay is partially responsible for the elevated N_2O saturation in the western side of Hudson Strait.

Throughout the water column, nitrification likely contributed to observed N_2O distributions, particularly in Foxe Channel and other regions where water column stratification was more intense (Fig. 5). Previous work has identified sedimentary and water column nitrification as N_2O sources to the water column in the Arctic Ocean (Kitidis et al. 2010; Zhang et al. 2015; Fenwick et al. 2017; Schuler & Tortell 2023), and the N_2O distributions we observed are at least partially consistent with these observations. A positive relationship between $\Delta\text{N}_2\text{O}$ and AOU has been used to indicate a nitrification source for water column N_2O (e.g., Cohen & Gordon 1978; Elkins et al. 1978; Walter et al. 2006). We observed such a relationship in the Gulf of Boothia and Fury and Hecla Strait, but not in the sub-regions of Foxe Basin and Hudson Strait (Fig. 6), suggesting that other processes in the water column could be obscuring the $\Delta\text{N}_2\text{O}$ and AOU relationship in these regions. Water column ventilation, which would be enhanced by intense mixing, has previously been shown to affect the nitrification signature on O_2 and N_2O distributions (Reeve et al. 2019). Consistent with this observation, both northern Foxe Basin and Hudson Strait, which were characterized by strong vertical and tidal mixing, showed no significant $\Delta\text{N}_2\text{O}$ – AOU relationship (Fig. 6). In contrast, a significant positive $\Delta\text{N}_2\text{O}$ –AOU relationship (Fig. 6) was observed in the stratified waters of the Gulf of Boothia and Fury and Hecla Strait (Figs. 3 and 5). The slope of the line of best fit in this region is similar to that found previously in the Canadian Arctic (Fenwick et al. 2017), where water column nitrification was only a small source (<10%) of N_2O to the water column. Without additional data, we cannot unambiguously identify the processes driving the observed N_2O saturation in the area. Nonetheless, our observations suggest a combined role for sedimentary sources and water column nitrification in controlling N_2O distributions across the study region, with an overprint of physical circulation driving additional spatial variability. Our work highlights how interacting processes can be resolved through

a combination of high-resolution surface measurements, depth profile analysis and numerical model output.

Sources of CH_4 to the water column

Previous work has identified relationships between CH_4 saturation, salinity and chlorophyll fluorescence (e.g., Damm et al. 2008; Fenwick et al. 2017; Manning et al. 2020). In contrast, we did not observe any such relationships across our study region. A negative relationship between surface water salinity and CH_4 has been used to suggest riverine input or glacial melt as CH_4 sources, but such freshwater sources are unlikely during October, long after peak melt season (Manning et al. 2020). A relationship with fluorescence has been previously used as evidence of a possible CH_4 source associated with CH_4 release during phytoplankton metabolism of dimethylsulfoniopropionate (Damm et al. 2008; Fenwick et al. 2017), while water column methanogenesis (potentially within anoxic microzones of suspended particles) could have been an additional CH_4 sources to the water column. The magnitude of these potential sources is difficult to constrain without isotopic or molecular data.

High CH_4 surface saturation was observed in northern Foxe Basin, a region characterized by the presence of seasonal polynyas (Paulic et al. 2014). Polynyas exhibit heightened biological activity and vertical carbon export, generating organic-rich sediments that can stimulate sedimentary CH_4 production (Damm et al. 2007). Although no active polynyas were observed during our sampling period, sediments in northern Foxe Basin would nonetheless be expected to retain high organic carbon content, creating favourable conditions for CH_4 accumulation. Consistent with this expectation, we observed elevated CH_4 concentrations in near-bottom waters of northern Foxe Basin relative to surface waters (Fig. 5). Model results (apparent K_z values), indicated enhanced vertical mixing in this region (Fig. 3), suggesting significant potential for the transport of CH_4 -rich bottom waters into the mixed layer. This mixing would be expected to homogenize vertical profiles of seawater properties, as was observed for a number of oceanographic variables (Fig. 5). In contrast, CH_4 concentrations remained strongly depth-dependent, with significantly higher saturation in bottom waters. As proposed for N_2O , high rates of sedimentary CH_4 production may have outpaced water column mixing in this region, leading to deep water CH_4 accumulation despite vigorous water column exchange. Together, strong vertical mixing and sedimentary CH_4 production could help explain the elevated surface water CH_4 saturations observed in northern Foxe Basin.

Like Foxe Basin, Foxe Channel is also characterized by reoccurring polynyas. However, the water column in this

region is much more stratified (Fig. 5). Model output provided evidence of some vertical mixing in Foxe Channel, but the relatively stronger stratification would have acted to isolate sedimentary CH_4 sources from the mixed layer. Indeed, surface CH_4 saturation in Foxe Channel was significantly higher than that observed in bottom waters, providing evidence against a sedimentary source. Rather, the high CH_4 saturation observed in this region may reflect the lateral coastal transport of surface waters from northern Foxe Basin, as previously observed (Defossez et

al. 2012). In support of this idea, hydrographic analysis revealed that the surface water masses in northern Foxe Basin and Foxe Channel exhibited similar T–S characteristics (Fig. 9). We therefore suggest that the CH_4 signature of Foxe Channel reflects lateral advection of south-flowing, high- CH_4 surface waters from northern Foxe Basin, rather than local production.

Lateral advection also likely transported waters from Foxe Channel into Hudson Strait, leading to the elevated CH_4 (and N_2O) saturation in Hudson Strait surface waters.

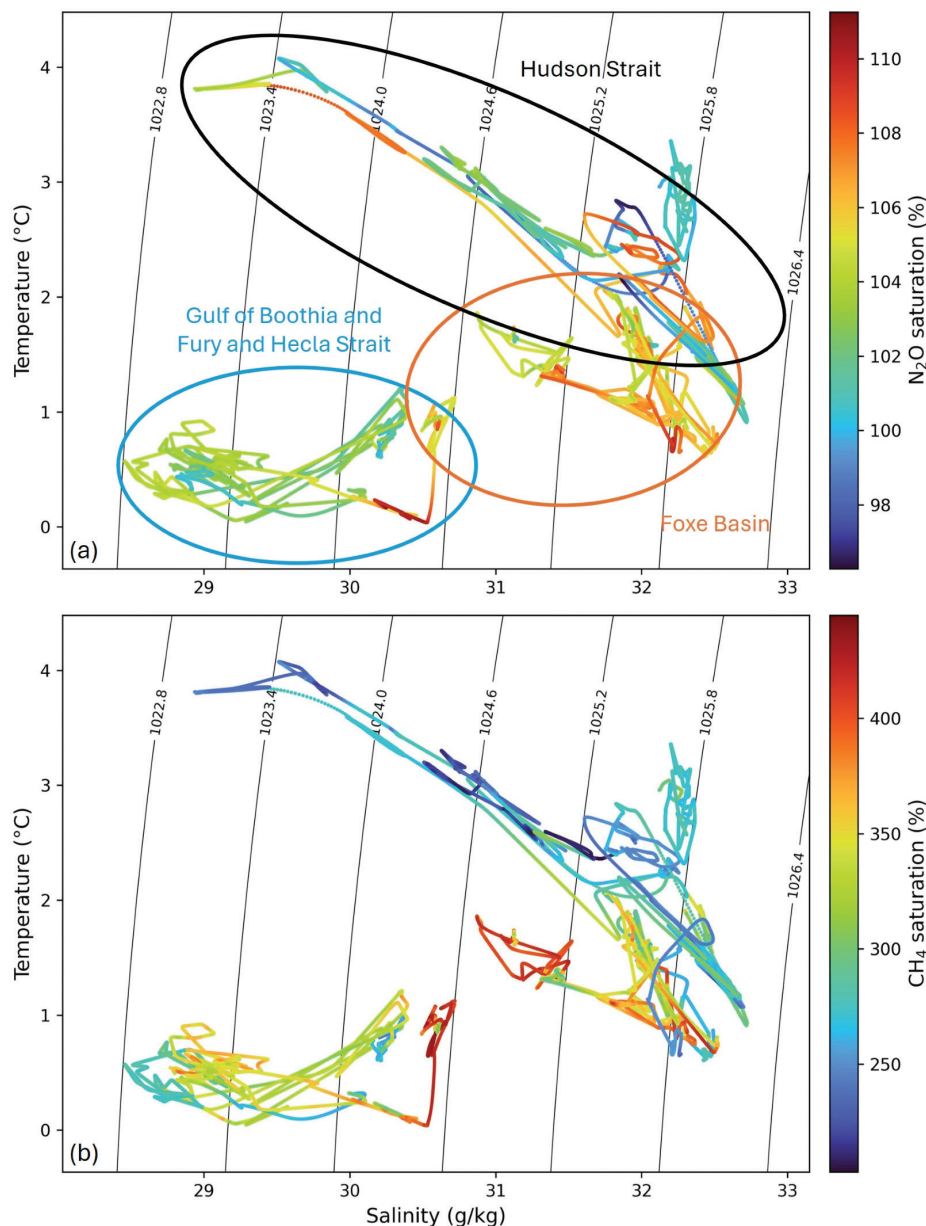


Fig. 9 Temperature–salinity plot of the surface waters along the cruise track. Regions of interest are circled and labelled in (a) and the scatter dots are coloured by the percent saturation of (a) N_2O or (b) CH_4 . Lines of constant seawater density (kg m^{-3}) are also shown on the figure.

Despite similar temperature and salinity characteristics (Fig. 9), surface waters in Hudson Strait showed lower CH₄ supersaturation than northern Foxe Basin, potentially reflecting loss to the atmosphere as waters travelled through the basin. Additional data are needed to fully characterize CH₄ sources across our study region, but our results highlight the contrasting roles of vertical mixing, sedimentary input and lateral transport in the Foxe Basin region.

Conclusion

Given the impacts of rapid climate change on the Arctic Ocean (e.g., Hoegh-Guldberg & Bruno 2010; Rantanen et al. 2022), monitoring the release of N₂O and CH₄ from Arctic Ocean surface waters is paramount to understanding potential biogeochemical feedbacks on greenhouse gases. Our findings underscore the importance of the autumn season for greenhouse gas fluxes in the Arctic Ocean due to a decrease in water column stratification. However, without increased monitoring and a deeper understanding of the cycling of N₂O and CH₄ in the Arctic, it will be difficult to assess how warming will impact biogeochemistry in these regions across the seasonal cycle. Increased ice melt may lead to greater stratification, potentially reducing vertical mixing and the associated transport of N₂O and CH₄ from the sediments to the surface waters. Conversely, CH₄ released from glacial meltwater could enhance fluxes to the atmosphere (Damm et al. 2015). Future research should utilize high-resolution sampling to capture localized hotspot regions, while isotopic data can help constrain the sources and sinks of greenhouse gases in the region. Sampling should also be carried out across a larger portion of the annual cycle to better resolve seasonal variability in surface gas distributions and cycling. Our results demonstrate the utility of combining model output with observations to derive insight into the drivers of gas distributions. Though many current models, including the one used in this work, do not explicitly parametrize N₂O or CH₄ dynamics, they can provide information about potential changes in seawater stratification and mixing regimes, which will likely have a first-order impact on surface water saturations and air-sea fluxes of these gases. The continued joint use of models and observations is particularly critical in the Arctic Ocean, where measurements are often sparse and fieldwork is logistically challenging.

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Disclosure statement

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References

- AMAP 1998. *AMAP assessment report: Arctic pollution issues*. Oslo: Arctic Monitoring and Assessment Programme.
- Bogard M.J., Del Giorgio P.A., Boutet L., Chaves M.C.G., Prairie Y.T., Merante A. & Derry A.M. 2014. Oxidic water column methanogenesis as a major component of aquatic CH₄ fluxes. *Nature Communications* 5, article no. 5350, doi: 10.1038/ncomms6350.
- Campbell N.J. & Collin A.E. 1958. The discoloration of Foxe Basin ice. *Journal of the Fisheries Research Board of Canada* 15, 1175–1188, doi: 10.1139/f58-062.
- Capelle D.W., Dacey J.W. & Tortell P.D. 2015. An automated, high through-put method for accurate and precise measurements of dissolved nitrous-oxide and methane concentrations in natural waters. *Limnology and Oceanography: Methods* 13, 345–355, doi: 10.1002/lom3.10029.
- Cohen Y. & Gordon L.I. 1978. Nitrous oxide in the oxygen minimum of the eastern tropical North Pacific: evidence for its consumption during denitrification and possible mechanisms for its production. *Deep Sea Research* 25, 509–524, doi: 10.1016/0146-6291(78)90640-9.
- Damm E., Kiene R.P., Schwarz J., Falck E. & Dieckmann G. 2008. Methane cycling in Arctic shelf water and its relationship with phytoplankton biomass and DMSP. *Marine Chemistry* 109, 45–59, doi: 10.1016/j.marchem.2007.12.003.
- Damm E., Rudels B., Schauer U., Mau S. & Dieckmann G. 2015. Methane excess in Arctic surface water-triggered by sea ice formation and melting. *Scientific Reports* 5, article no. 16179, doi: 10.1038/srep16179.

- Damm E., Schauer U., Rudels B. & Haas C. 2007. Excess of bottom-released methane in an Arctic shelf sea polynya in winter. *Continental Shelf Research* 27, 1692–1701, doi: 10.1016/j.csr.2007.02.003.
- Defossez M., Saucier F.J., Myers P.G., Caya D. & Dumais J.-F. 2008. Multi-year observations of deep water renewal in Foxe Basin, Canada. *Atmosphere–Ocean* 46, 377–390, doi: 10.3137/ao.460306.
- Defossez M., Saucier F.J., Myers P.G., Caya D. & Dumais J.-F. 2012. Comparing winter and summer simulated estuarine circulations in Foxe Basin, Canada. *Atmosphere–Ocean* 50, 386–401, doi: 10.1080/07055900.2012.693256.
- Elkins J.W., Wofsy S.C., McElroy M.B., Kolb C.E. & Kaplan W.A. 1978. Aquatic sources and sinks for nitrous oxide. *Nature* 275, 602–606, doi: 10.1038/275602a0.
- Fenwick L., Capelle D., Damm E., Zimmermann S., Williams W.J., Vagle S. & Tortell P.D. 2017. Methane and nitrous oxide distributions across the North American Arctic Ocean during summer, 2015. *Journal of Geophysical Research—Oceans* 122, 390–412, doi: 10.1002/2016JC012493.
- Garcia-Quintana Y., Courtois P., Hu X., Pennelly C., Kieke D. & Myers P.G. 2019. Sensitivity of Labrador Sea water formation to changes in model resolution, atmospheric forcing, and freshwater input. *Journal of Geophysical Research—Oceans* 124, 2126–2152, doi: 10.1029/2018JC014459.
- Global Monitoring Laboratory n.d. Observation sites. Vestmannaeyjar: Stórhöfði. Accessed on the internet at <https://gml.noaa.gov/dv/site/ICE.html> on 2 February 2026.
- Griffiths D.K., Pingree R.D. & Sinclair M. 1981. Summer tidal fronts in the near-Arctic regions of Foxe Basin and Hudson Bay. *Deep-Sea Research Part I* 28, 865–873, doi: 10.1016/S0198-0149(81)80006-4.
- Hirota A., Ijiri A., Komatsu D.D., Ohkubo S.B., Nakagawa F. & Tsunogai U. 2009. Enrichment of nitrous oxide in the water columns in the area of the Bering and Chukchi seas. *Marine Chemistry* 116, 47–53, doi: 10.1016/j.marchem.2009.09.001.
- Hoegh-Guldberg O. & Bruno J.F. 2010. The impact of climate change on the world's marine ecosystems. *Science* 328, 1523–1528, doi: 10.1126/science.1189930.
- IPCC 2023. *Climate change 2022. Mitigation of climate change. Working Group III contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- Izett R.W., Castro De La Guardia L., Chanona M., Myers P.G., Waterman S. & Tortell P.D. 2022. Impact of vertical mixing on summertime net community production in Canadian Arctic and Subarctic waters: insights from in situ measurements and numerical simulations. *Journal of Geophysical Research—Oceans* 127, e2021JC018215, doi: 10.1029/2021JC018215.
- James R.H., Bousquet P., Bussmann I., Haeckel M., Kipfer R., Leifer I., Niemann H., Ostrovsky I., Piskozub J., Rehder G., Treude T., Vörländer L. & Greinert J. 2016. Effects of climate change on methane emissions from seafloor sediments in the Arctic Ocean: a review. *Limnology and Oceanography* 61, S283–S299, doi: 10.1002/lno.10307.
- Johannessen O.M. & Olaussen T.I. 2025. Arctic sea-ice extent: no record minimum in 2023 or recent years. *Atmospheric and Oceanic Science Letters* 18, article no. 100499, doi: 10.1016/j.aosl.2024.100499.
- Johnson H.K. 1999. Simple expressions for correcting wind speed data for elevation. *Coastal Engineering* 36, 263–269, doi: 10.1016/S0378-3839(99)00016-2.
- Kim Y.-H., Min S.-K., Gillett N.P., Notz D. & Malinina E. 2023. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. *Nature Communications* 14, article no. 3139, doi: 10.1038/s41467-023-38511-8.
- Kitidis V., Upstill-Goddard R.C. & Anderson L.G. 2010. Methane and nitrous oxide in surface water along the North-West Passage, Arctic Ocean. *Marine Chemistry* 121, 80–86, doi: 10.1016/j.marchem.2010.03.006.
- Klein B., LeBlanc B., Mei Z.-P., Beret R., Michaud J., Mundy C.-J., Von Quillfeldt C.H., Garneau M.-È., Roy S., Gratton Y., Cochran J.K., Bélanger S., Larouche P., Pakulski J.D., Rivkin R.B. & Legendre L. 2002. Phytoplankton biomass, production and potential export in the North Water. *Deep-Sea Research Part II* 49, 4983–5002, doi: 10.1016/S0967-0645(02)00174-1.
- Kvenvolden K.A., Lilley M.D., Lorenson T.D., Barnes P.W. & McLaughlin E. 1993. The Beaufort Sea continental shelf as a seasonal source of atmospheric methane. *Geophysical Research Letters* 20, 2459–2462, doi: 10.1029/93GL02727.
- Li Y., Zhan L., Zhang J., Chen L., Chen J. & Zhuang Y. 2017. A significant methane source over the Chukchi Sea shelf and its sources. *Continental Shelf Research* 148, 150–158, doi: 10.1016/j.csr.2017.08.019.
- Madec G., Bell M., Blaker A., Bricaud C., Bruciaferri D., Castrillo M., Calvert D., Chanut J., Clementi E., Coward A., Epicoco I., Éthé C., Ganderton J., Harle J., Hutchinson K., Iovino D., Lea D., Lovato T., Martin M., Martin N., Mele F., Martins D., Masson S., Mathiot P., Mocavero S., Müller S., Nurser A.J.G., Paronuzzi S., Peltier M., Person R., Rousset C., Rynders S., Samson G., Téchené S., Vancoppenolle M. & Wilson C. 2023. *NEMO Ocean Engine*. Version 4.2.1 – July, 2023, doi: 10.5281/ZENODO.8167700. Accessed on the internet at <https://zenodo.org/records/8167700> on 13 August 2026.
- Malakhova V. & Golubeva E. 2022. Model study of the effects of climate change on the methane emissions on the Arctic shelves. *Atmosphere* 13, 274, doi: 10.3390/atmos13020274.
- Manning C.C., Preston V.L., Jones S.F., Michel A.P.M., Nicholson D.P., Duke P.J., Ahmed M.M.M., Manganini K., Else B.G.T. & Tortell P.D. 2020. River inflow dominates methane emissions in an Arctic coastal system. *Geophysical Research Letters* 47, e2020GL087669, doi: 10.1029/2020GL087669.
- Manning C.C.M., Zheng Z., Fenwick L., McCulloch R.D., Damm E., Izett R.W., Williams W.J., Zimmermann S., Vagle S. & Tortell P.D. 2022. Interannual variability in methane and nitrous oxide concentrations and sea–air fluxes across the North American Arctic Ocean (2015–2019). *Global Biogeochemical Cycles* 36, e2021GB007185, doi: 10.1029/2021GB007185.
- Myers P.G., Barber D., Braun M., Burchart L., De La Guardia L.C., Deschepper I., Dupont F., Ehn J., Garcia-Quintana Y., Gillard L.C., Grivault N., Hu X., Kirillov S.A., Jafarikhasragh S., Lukovich J., Maps F., Marson J.M., Papakyriakou T., Pennelly C., Ridenour N., Stadnyk T.A., Sydor K., Tao R., Tefs A., Tremblay J.-É. & Xu Y. 2024. An

- overview of the NEMO modelling for the BaySys project. *Elementa Science of the Anthropocene* 12, article no. 00111, doi: 10.1525/elementa.2022.00111.
- Nicholson D.P., Michel A.P.M., Wankel S.D., Manganini K., Sugrue R.A., Sandwith Z.O. & Monk S.A. 2018. Rapid mapping of dissolved methane and carbon dioxide in coastal ecosystems using the ChemYak autonomous surface vehicle. *Environmental Science & Technology* 52, 13314–13324, doi: 10.1021/acs.est.8b04190.
- Paulic J.E., Cleator H. & Martin K.A. 2014. *Ecologically and Biologically Significant Areas (EBSA) in northern Foxe Basin, Nunavut*. DFO Canadian Science Advisory Secretariat Research Document 2014/042. Ottawa: Fisheries and Oceans Canada.
- Prinsenberg S.J. 1986. On the physical oceanography of Foxe Basin. In I.P. Martini (ed.): *Canadian inland seas*. Pp. 217–236. Amsterdam: Elsevier.
- Punshon S., Azetsu-Scott K. & Lee C.M. 2014. On the distribution of dissolved methane in Davis Strait, North Atlantic Ocean. *Marine Chemistry* 161, 20–25, doi: 10.1016/j.marchem.2014.02.004.
- Rantanen M., Karpechko A.Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment* 3, article no. 168, doi: 10.1038/s43247-022-00498-3.
- Reeburgh W.S. 2007. Oceanic methane biogeochemistry. *Chemical Reviews* 107, 486–513, doi: 10.1021/cr050362v.
- Rees A.P., Bange H.W., Arévalo-Martínez D.L., Artioli Y., Ashby D.M., Brown I., Campen H.I., Clark D.R., Kitidis V., Lessin G., Tarran G.A. & Turley C. 2022. Nitrous oxide and methane in a changing Arctic Ocean. *Ambio* 51, 398–410, doi: 10.1007/s13280-021-01633-8.
- Rees A.P., Brown I.J., Jayakumar A., Lessin G., Somerfield P.J. & Ward B.B. 2021. Biological nitrous oxide consumption in oxygenated waters of the high latitude Atlantic Ocean. *Communications Earth & Environment* 2, article no. 36, doi: 10.1038/s43247-021-00104-y.
- Reeve J.L., Hamme R.C. & Williams W.J. 2019. Tracing denitrification in the Canada Basin: N₂ loss to the atmosphere on the Chukchi Shelf and benthic inputs in deep waters. *Deep-Sea Research Part I* 143, 127–138, doi: 10.1016/j.dsr.2018.11.003.
- Ridenour N.A., Straneo F., Holte J., Gratton Y., Myers P.G. & Barber D.G. 2021. Hudson Strait inflow: structure and variability. *Journal of Geophysical Research—Oceans* 126, e2020JC017089, doi: 10.1029/2020JC017089.
- Saucier F.J., Senneville S., Prinsenberg S., Roy F., Smith G., Gachon P., Caya D. & Laprise R. 2004. Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada. *Climate Dynamics* 23, 303–326, doi: 10.1007/s00382-004-0445-6.
- Schuler K.H. & Tortell P.D. 2023. Impacts of vertical mixing and ice-melt on N₂O and CH₄ concentrations in the Canadian Arctic Ocean. *Continental Shelf Research* 269, article no. 105124, doi: 10.1016/j.csr.2023.105124.
- Shakhova N. & Semiletov I. 2007. Methane release and coastal environment in the East Siberian Arctic shelf. *Journal of Marine Systems* 66, 227–243, doi: 10.1016/j.jmarsys.2006.06.006.
- Shakhova N., Semiletov I., Sergienko V., Lobkovsky L., Yusupov V., Salyuk A., Salomatin A., Chernykh D., Kosmach D., Panteleev G., Nicolsky D., Samarkin V., Joye S., Charkin A., Dudarev O., Meluzov A. & Gustafsson O. 2015. The East Siberian Arctic Shelf: towards further assessment of permafrost-related methane fluxes and role of sea ice. *Philosophical Transactions of the Royal Society A* 373, article no. 20140451, doi: 10.1098/rsta.2014.0451.
- Shakirov R.B., Mau S., Mishukova G.I., Obzhairov A.I., Shakirova M.V. & Mishukova O.V. 2020. The features of methane fluxes in the western and eastern Arctic: a review. Part I. *Geosystems of Transition Zones* 4, 4–25, doi: 10.30730/2541-8912.2020.4.1.004-025.
- Tan F.C. & Strain P.M. 1996. Sea ice and oxygen isotopes in Foxe Basin, Hudson Bay, and Hudson Strait, Canada. *Journal of Geophysical Research—Oceans* 101, 20869–20876, doi: 10.1029/96JC01557.
- Tremblay J.-E., Gratton Y., Fauchot J. & Price N.M. 2002. Climatic and oceanic forcing of new, net, and diatom production in the North Water. *Deep-Sea Research Part II* 49, 4927–4946, doi: 10.1016/S0967-0645(02)00171-6.
- Tremblay J.-E. & Smith W.O. 2007. Primary production and nutrient dynamics in polynyas. In W.O. Smith & D.G. Barber (eds.): *Polynyas: windows to the world*. Pp. 239–269. Amsterdam: Elsevier.
- Verdugo J., Damm E., Snoeijis P., Díez B. & Farías L. 2016. Climate relevant trace gases (N₂O and CH₄) in the Eurasian Basin (Arctic Ocean). *Deep-Sea Research Part I* 117, 84–94, doi: 10.1016/j.dsr.2016.08.016.
- Walter S., Bange H.W., Breitenbach U. & Wallace D.W.R. 2006. Nitrous oxide in the North Atlantic Ocean. *Biogeosciences* 3, 607–619, doi: 10.5194/bg-3-607-2006.
- Wanninkhof R. 2014. Relationship between wind speed and gas exchange over the ocean revisited. *Limnology and Oceanography: Methods* 12, 351–362, doi: 10.4319/lom.2014.12.351.
- Weiss R.F. 1970. The solubility of nitrogen, oxygen and argon in water and seawater. *Deep Sea Research and Oceanographic Abstracts* 17, 721–735, doi: 10.1016/0011-7471(70)90037-9.
- Weiss R.F. & Price B.A. 1980. Nitrous oxide solubility in water and seawater. *Marine Chemistry* 8, 347–359, doi: 10.1016/0304-4203(80)90024-9.
- Wiesenburg D.A. & Guinasso N.L. 1979. Equilibrium solubilities of methane, carbon monoxide, and hydrogen in water and sea water. *Journal of Chemical & Engineering Data* 24, 356–360, doi: 10.1021/jc60083a006.
- Yurganov L., Carroll D., Pnyushkov A., Polyakov I. & Zhang H. 2021. Ocean stratification and sea-ice cover in Barents and Kara seas modulate sea–air methane flux: satellite data. *Advances in Polar Science* 32, 118–138, doi: 10.13679/j.advps.2021.0006.
- Zhang J., Zhan L., Chen L., Li Y. & Chen J. 2015. Coexistence of nitrous oxide undersaturation and oversaturation in the surface and subsurface of the western Arctic Ocean. *Journal of Geophysical Research—Oceans* 120, 8392–8401, doi: 10.1002/2015JC011245.
- Zhao Y., Resplandy L., Wan X.S., Yang F., Liao E. & Ward B. 2025. Decoupling of N₂O production and emissions in the northern Indian Ocean. *Global Biogeochemical Cycles* 39, e2024GB008481, doi: 10.1029/2024GB008481.