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Baseline

Fossil mosses are emitting methane after maritime Antarctic glacier retreat

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ABSTRACT

In the extraordinary weather conditions of the austral summer of 2023, fossil mosses thawed out from under the Bellingshausen Ice Dome, King George Island, Southern Shetland Archipelago of maritime Antarctica. At the end of the austral summer, we directly measured greenhouse gas fluxes (CH_4 and CO_2) from the surface of fossil mosses. We showed that fossil mosses were strong emitters of CH_4 and weak emitters of CO_2. The real-time measured CH_4 emissions reached 0.173 μmol m^{-2} s^{-1}, which is comparable to CH_4 efflux in water bodies or wet tundra in the Arctic.

1. Introduction

Bellingshausen Ice Dome (Fildes Peninsula, King George Island, Southern Shetland Archipelago, maritime Antarctica) is unique because it is located in a fairly temperate climate compared to the rest of Antarctica. In addition, the temperature of the dome's ice is not very cold and continues to rise, which makes this dome a unique research site where fossil remains of organic life can be found, which is problematic for the rest of Antarctica. Because the ice sheet is quite thick throughout the rest of Antarctica, it will take a long time for it to melt and allow fossil organic life to appear on the surface to conduct research on greenhouse gas (GHG) fluxes. And, because of the current environmental conditions, we had a unique opportunity to assess what will happen when the ice melts and fossil remains appear in the context of global warming and GHG emissions at the Bellingshausen Ice Dome.

During the Antarctic summer of 2023, the unprecedented lowest extent of sea ice around Antarctica has been observed along with high air temperatures (https://earthobservatory.nasa.gov/images/151093/antarctic-sea-ice-reaches-another-record-low). According to satellite records, it is the lowest sea ice extent since 1979, when the satellite observations started (Cai et al., 2023).

Local warming was also registered at King George Island (Southern Shetland Archipelago, maritime Antarctica) during the austral summer of 2023, where, owing to satellite observations, a retreat of the glacier boundary of Bellingshausen Ice Dome has been observed (Fig. 1). According to the Bellingshausen weather station data, an increase in mean summer air temperature and annual air temperature, annual precipitation, and a decrease in the sum of snow days during a year have been observed at the Fildes Peninsula during recent years (Fig. 2A-D). Moreover, long-term monitoring data of active layer thickness (ALT) at the Fildes Peninsula demonstrate a strong rising trend for 2010–2023 (see 'Active layer thickness observations' in Methods) (Fig. 2E). Under current conditions, a thawing out of fossil mosses occurs from under the edge of the Bellingshausen Ice Dome. Besides, it is worth noting that according to satellite data, the thawing out of fossil mosses from under the glacier occurs periodically (Fig. 1) due to the glacial retreat and glacial readvance of Bellingshausen Ice Dome (Heredia Barión et al., 2023). The Bellingshausen Ice Dome has been monitored in response to climate change for a long time (Zamoruev, 1972; Jiahong et al., 1998; Hall, 2007; Rückamp et al., 2011; Boy et al., 2016). The question of the age of the moss remains debatable. The age of the discovered terrestrial mosses, which appeared from under the glacier, varies in a wide range,

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which corresponds to the Holocene Little Ice Age (Hall, 2007; Simms et al., 2012; Cofaigh et al., 2014; Heredia Barión et al., 2023). Immediately, these fossil mosses became available for microorganisms as a substrate. Polar ecosystems are considered highly vulnerable to climate change due to the organic matter from degraded permafrost becoming a source of greenhouse gas (GHG) fluxes (e.g., CH_4 and CO_2) (IPCC, 2022). Subject to the aforementioned, fossil mosses can be interesting objects for GHG flux research in Antarctica, where soil organic matter is scarce.

On the other hand, fossil mosses, which have lain for several thousand years beneath the glacier dome, represent dead organic matter that has not decomposed yet and is thus easily accessible to microbes. Furthermore, fossil microbes may remain, or microbes living in the ice will colonize dead organic matter. Therefore, these melted-out mosses in the context of GHG fluxes and climate change serve as an example of what will happen when the Antarctic ice thaws, and our research can simply be expanded further into the territory. Thus, the aim of the study was to estimate the GHG fluxes from the surface of fossil mosses and to understand how quickly the organic matter of mosses becomes susceptible to microbial decomposition.

2. Materials and methods

2.1. Study area

Bellingshausen Ice Dome (formerly Small Dome, Dome A, Collins Ice Cap, Collins Glacier) is a small ice cap that is located on the NE side of Fildes Peninsula, and on the NE side, it is connected with other ice caps on King George Island (Waterloo), Southern Shetland Archipelago, Antarctica (Fig. 1). The ice cap has dimensions of 3.5 × 4.5 km, an elevation of up to 250 m a.s.l., and an area of clean ice of about 9 km^2. The edge of the dome ends on land at altitudes ranging from 0 to 50 m a.s.l. In the northeastern part, the Bellingshausen Ice Dome is adjacent to the larger Arctovsky Ice Dome (Verkulich et al., 2012). Most of the ice cap perimeter is rounded by an ice-core moraine, and only in the area of our investigation, the moraine is absent. Almost everywhere, the edge of the ice dome borders the land. The study place is located in the western part of the Bellingshausen Ice Dome, where the moraine is covered by glacial ice. This research is a case study where we just started to explore the GHG fluxes in the area after the Antarctic glacier retreat. For that, we made a transect that started from the plot where we detected the presence of moss that had melted from under the ice (consisting of 10 fossil moss plots of size 50 × 50 cm) and which had not yet been disturbed

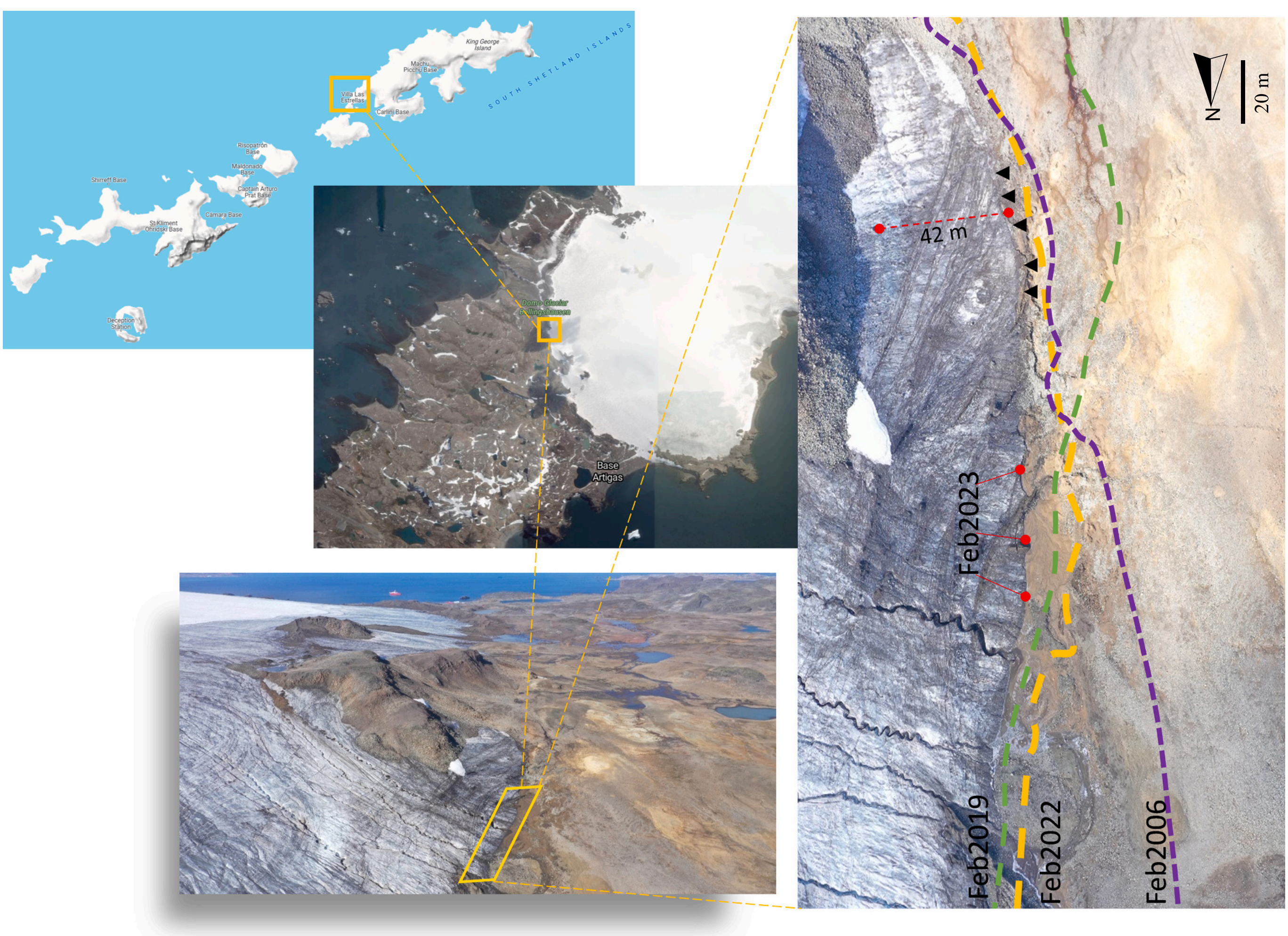

Fig. 1. Layout of studies of CH_4 and CO_2 fluxes from fossil mosses that appeared after the retreated edge of the Bellingshausen Ice Dome (King George Island, Southern Shetlands Archipelago). A right photograph taken by the UAV in February 2023 represents the glacier boundary in February 2023. The orange-dotted line represents the glacier boundary for February 2022. The green dotted line represents the glacier boundary for February 2019. The violet dotted line represents the glacier boundary for February 2006. The red dotted line represents the 42-m transect (eight measurement points in every 6 m), and the black triangles are plots for CH_4 and CO_2 flux measurements from the surface of fossil mosses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

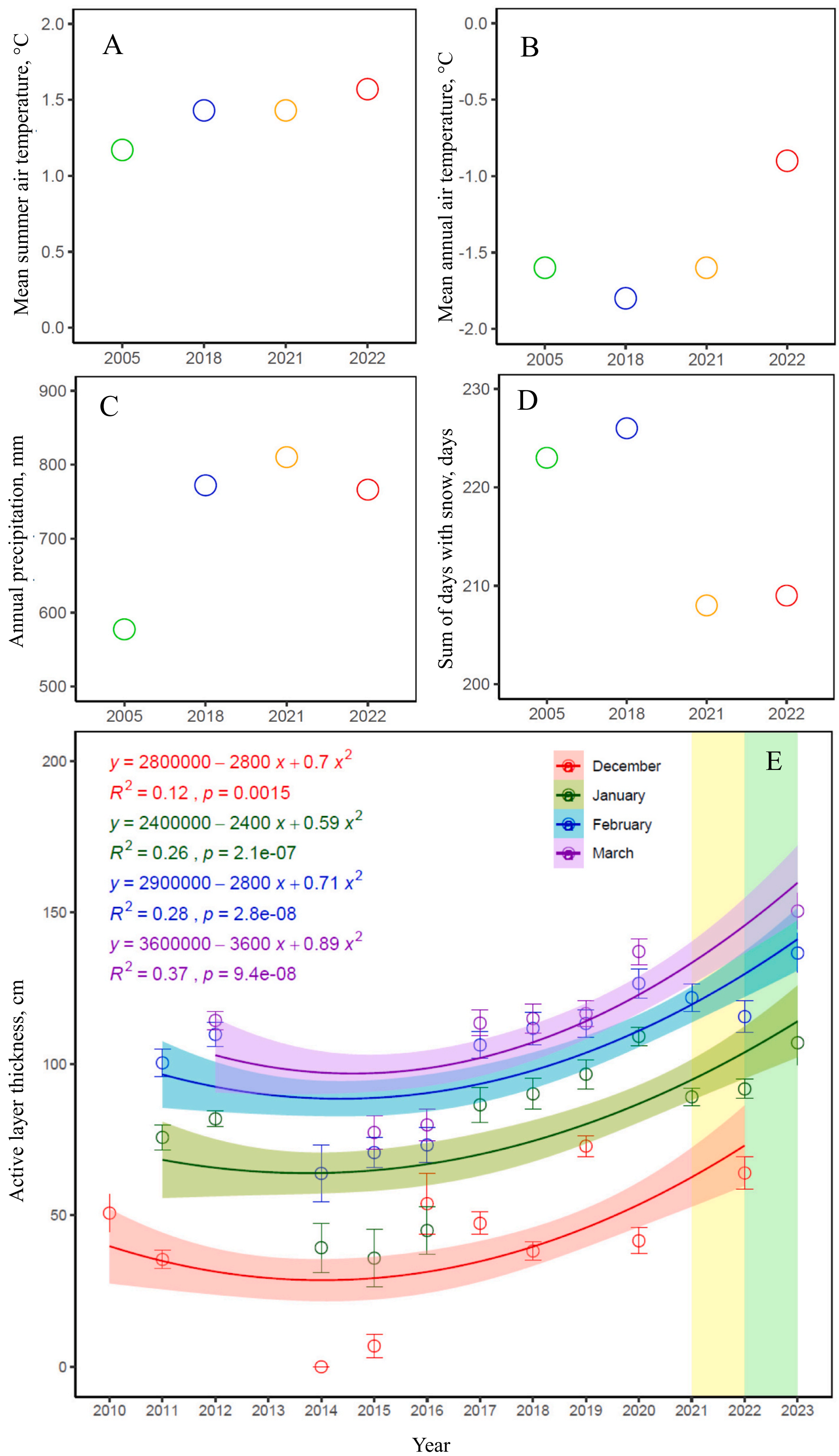

Fig. 2. Mean summer air temperature (A), mean annual temperature (B), annual precipitation (C), and a sum of days with snow per year (D) assessed for years that preceded the years of monitoring the glacier boundary (e.g., 2006, 2019, 2022, 2023 at Fig. 1). Active layer thickness (E) for the period of 2010–2023. The summer of 2022 is filled with yellow, and the summer of 2023 is filled with green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1). This transect, starting from the thawed areas, was prolonged on the ice of the glacier towards the center of the glacier. The 42-m ice transect consisted of eight measuring points located every 6 m ("ice8"-"ice1", where the point "ice8" is close to fossil moss sites). The homogeneous structure and small areas of melted-out mosses did not allow us to expand our research more; however, we expect that the process of glacier melting will continue and more areas covered by the fossil mosses will appear.

2.2. Glacier boundary observations

Glacier boundaries for the different years are taken from freely accessible resources (Bing Maps, Google Earth) and from a UAV survey (Fig. 2).

2.3. Active layer thickness observations

The active layer thickness was measured on a weekly basis during the summer of 2010–2023 using a metal probe at 8 plots located at Fildes Peninsula on a sub-latitudinal profile.

2.4. GHG (CH_4 and CO_2) flux measurements

GHG fluxes (CH_4 and CO_2) were directly measured from the surface of fossil mosses (10 points near the ice boundary of the glacier) at the end of the austral summer (April 8, 2023) near the Bellingshausen Ice Dome (−62.167 N, −58.920 E, King George Island, Southern Shetland Archipelago, Antarctica; Fig. 2). Ten replicated GHG flux on-site measurements from the fossil moss surface have been conducted using the Cavity Ringdown Spectrometer Picarro G4301 (Picarro Inc., USA) equipped with the soil chamber (The Mobile Soil Flux System, A0947). Cavity Ringdown Spectroscopy (CRDS) is an optical method that allows measuring GHG concentrations (CH_4 and CO_2, as in the case of Picarro G4301) and then recalculating them to the fluxes (Yakir and Sternberg, 2000; Dickinson et al., 2017). Unlike gas chromatography, which is limited to only discrete measurements (Rapson and Dacres, 2014), optical gas analyzers can make continuous measurements at high frequencies (Davidson et al., 2002). The raw precision of measurements is 0.15 ppm for CO_2 and 0.8 ppb for CH_4. Besides, the GHG fluxes were measured from the ice surface of the glacier. For that, we set the 42-meter transect on the glacier close to where the mosses are measured. The ice transect consisted of eight measuring points located every 6 m. Soil/ice temperature was measured using a temperature soil probe (Hanna Instruments) during GHG flux measurements. Gas flux units were $\mu mol\ m^{-2}\ s^{-1}$.

2.5. Ice core sampling along the ice transect

Ice cores were taken along the transect for subsequent isotope analysis using ice corer.

2.6. Ice core isotope analysis

Determination of the isotopic composition of samples of the surface layer of ice along the ice transect (points "ice8"-"ice1") was carried out at the Laboratory of Climate Change and Environment of the AARI using Picarro L2130-i and Picarro L2140-i gas analyzers. The standard was taken as distilled tap water from St. Petersburg (SPB-2) with the following characteristics relative to "V-SMOW2": −9.79 ‰ for $\delta^{18}O$ and −75.47 ‰ for δ^2H relative to the IAEA standard "V-SMOW2". The measurement accuracy is 0.02 ‰ for $\delta^{18}O$ and 0.3 ‰ for δ^2H (Ekaikin, 2016).

2.7. Data analysis

All calculations and statistical analyses were conducted using R statistical software (version 4.2.3 (2023-03-15) - "Shortstop Beagle") in RStudio (version 2023.03.0 Build 386 "Cherry Blossom" release (3c53477a, 2023-03-09) for Windows).

3. Results

Here we show that the fossil mosses that appeared from the retreated glacier Bellingshausen Ice Dome are the sources of CH_4 and CO_2 in the atmosphere (Fig. 3). For that, we measured GHG fluxes (CH_4 and CO_2) from the surface of fossil mosses near the glacier boundary at the end of the austral summer (April 8, 2023) near the edge of the Bellingshausen Ice Dome (see 'GHG (CH_4 and CO_2) flux measurements' in Methods) (−62.167 N, −58.920 E, King George Island, Southern Shetland Archipelago, Antarctica; Fig. 1). After measuring GHG fluxes from the fossil moss surface, we measured real-time GHG fluxes from the ice surface at the ice transect (from the "ice8" point to the "ice1") that was established directly above the place where fossil mosses thawed out (Fig. 3). The maximum CH_4 flux that we registered from the surface of mosses was 0.173 $\mu mol\ m^{-2}\ s^{-1}$. The CH_4 fluxes from mosses were significantly different from the CH_4 fluxes from the ice surface along the ice transect (Fig. 3). At the lower part of the ice transect (points from "ice8" to "ice4"), there was registered CH_4 uptake by the ice, whereas at the upper part of the ice transect (points from "ice3" to "ice1"), there was CH_4 emission from the ice surface. The CO_2 fluxes showed patterns similar to CH_4 fluxes along the moss-ice transect (Fig. 3). Mosses emitted CO_2 at rather slow rates, ca. 0.0915 $\mu mol\ m^{-2}\ s^{-1}$. Though at the lower part of the ice transect we registered CO_2 uptake by the ice, and at the upper part of the ice transect there were CO_2 emissions observed from the ice surface (Fig. 3).

Thus, we found weak uptake of CH_4 and CO_2 from the ice surface in the ice boundary area close to the location of the mosses, and only at a 25–40-m distance from the glacier boundary there were emissions of CH_4 and CO_2 observed.

In addition, in our study, we assessed the ice isotopic composition along the ice transect, where we measured GHG fluxes from the ice surface and compared them with the values for atmospheric precipitation samples. We found the isotopic composition of ice samples corresponds to layers formed from snow during both cold and warm periods, which is explained by the high dynamics of the glacier's margin and the mixing of ice and freshly fallen snow. The values of the isotopes studied ranged from −11.8 ‰ to −8.54 ‰ (on average − 9.66 ‰) for $\delta^{18}O$ and from −90.61 ‰ to −65.12 ‰ for δ^2H (on average − 74.14 ‰). The values for atmospheric precipitation samples varied from −6.09 ‰ to −14.88 ‰ for $\delta^{18}O$ and from −49.34 to −117.24 for δ^2H. However, the data analysis showed no tendency to alter the isotopic composition when heading from fossil moss sites to the glacier's center. A local line of meteoric waters was determined using surface ice samples, which represent the accumulated precipitation. This line followed the equation $\delta^2H = 7.69\ \delta^{18}O + 0.12$ (Fig. 4).

4. Discussion

The maximum CH_4 flux that we registered from the surface of mosses was 0.173 $\mu mol\ m^{-2}\ s^{-1}$; that was significantly higher than the CH_4 fluxes observed in tundra wetlands in Eastern Antarctica (Zhu et al., 2007). Mosses became the source of CH_4 because the Fildes Peninsula is known to have a methanogenic microbiota that equally uses both hydrogenotrophic and acetoclastic pathways (Aguilar-Muñoz et al., 2022) and possibly can do it in microaerophilic conditions. We also found the heterotrophic CO_2 emitted by mosses to be weak, possibly due to the emitted CO_2 being used by hydrogenotrophic methanogens as a substrate. That can also be indicated by the CH_4/CO_2 production ratio, which is 0.53 ± 0.21 in our study, which points to the presence of CH_4 metabolic pathways that characterize thawing permafrost ecosystems (McCalley et al., 2014).

Though the studies exploring the GHG fluxes from the fossil mosses

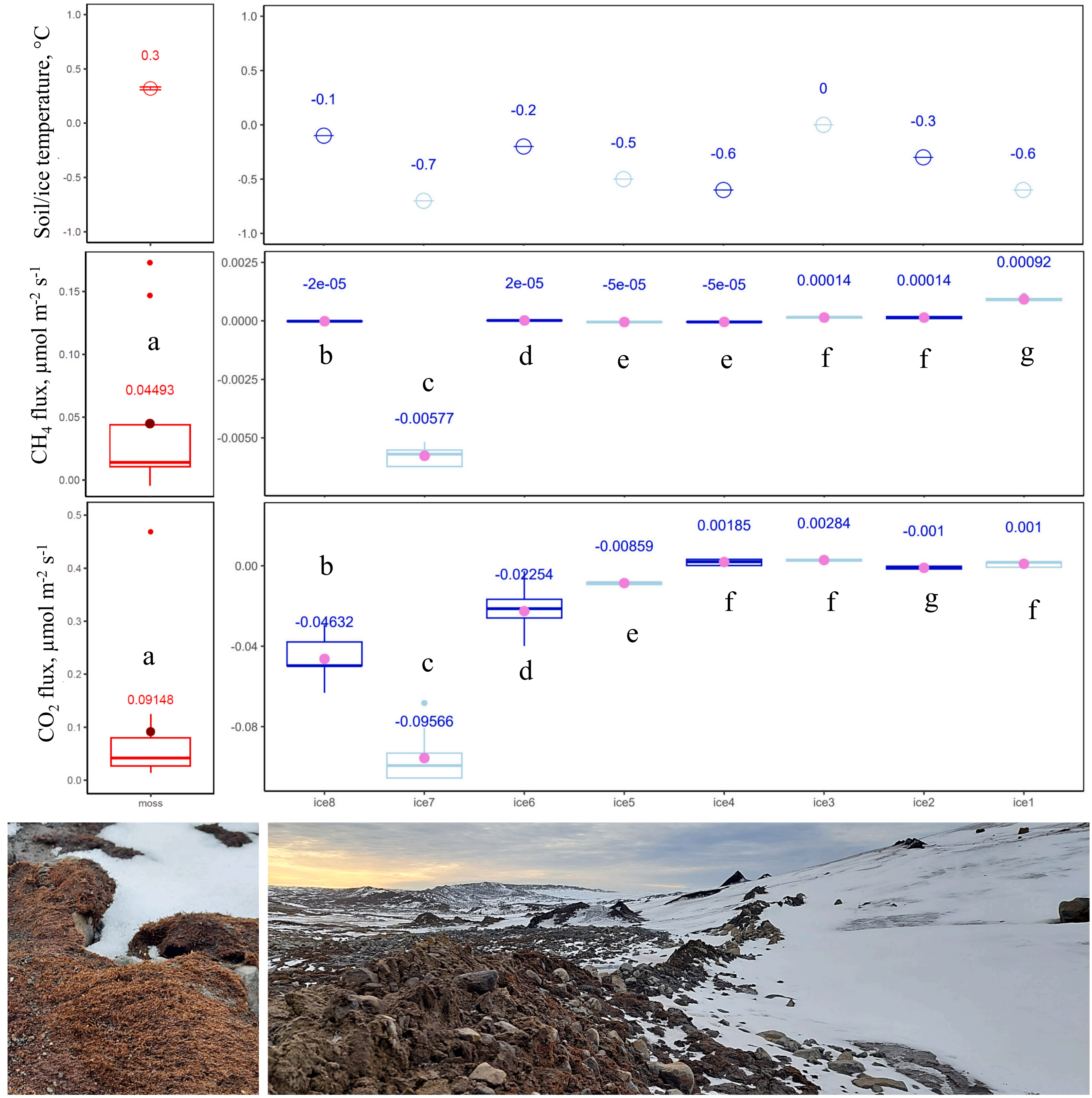

Fig. 3. CH_4 and CO_2 fluxes measured from the surface of fossil mosses exposed from the retreated glacier (Bellingshausen Ice Dome) and the ice surface of the ice transect (42 m, 8 points every 6 m ("ice8"-"ice1"), where "ice8" is close to fossil moss sites) plotted as boxplots with median, 25th- and 75th-percentile boundaries, whiskers as highest and lowest values, and dots as outliers. Violet and red dots are mean values in boxplots, and the values are the means of the boxplot. Positive fluxes mean GHG emissions, and negative fluxes reflect GHG consumption. The letters indicate significant ($p < 0.05$) differences in the GHG fluxes between the transect points as found by pairwise comparisons using the Wilcoxon rank sum exact test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thawed out of the retreating glacier Bellingshausen Ice Dome are scarce, there are some studies on the soil GHG fluxes of the same location. For example, Thalasso et al. (2022) showed that soils surrounding lakes mainly act as CH_4 sinks (CH_4 fluxes varied from −0.00039 to +0.000087 μmol m^{-2} s^{-1} or −19.50 to 5.02 μg m^{-2} h^{-1}). The CO_2 fluxes from the soils surrounding lakes ranged from −0.09 to +0.22 μmol m^{-2} s^{-1} (or −14.36 to 35.48 mg m^{-2} h^{-1}; Thalasso et al., 2022). The average CH_4 emissions from the fossil mosses thawed out after the retreat of the glacier observed in our study are much higher compared to the CH_4 fluxes in soils surrounding lakes on King George Island evaluated by Thalasso et al. (2022). Though the average CO_2 emissions from fossil mosses are lower (ca. 0.091 μmol m^{-2} s^{-1}) than those observed from the soils surrounding lakes in the study of Thalasso et al. (2022). In another study (Bao et al., 2018), tundra N_2O and CH_4 fluxes were measured under a simulated reduction of UV radiation in maritime Antarctica. The maximal CH4 emissions under the maximal (50 %) simulated reduction of UV radiation in maritime tundra were ca. 0.002 μmol m^{-2} s^{-1} (or 128 μg CH_4 m^{-2} h^{-1}; Bao et al., 2018), which is lower than CH_4 emission

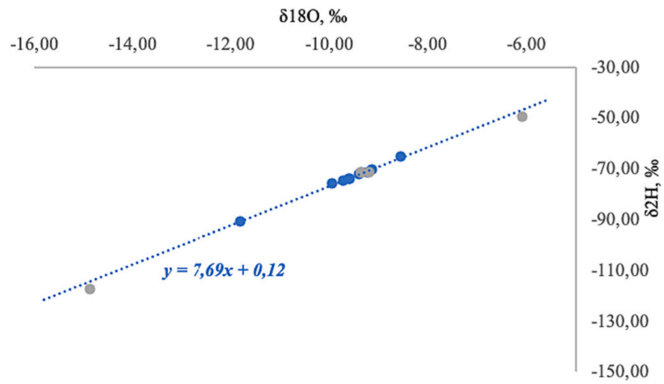

Fig. 4. The local line of meteoric water isotopic composition measured in the ice samples collected along the studied ice transect on the Antarctic glacier (blue dots) and collected precipitation waters (gray dots) in the vicinity of the glacier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

levels observed from the surface of fossil mosses in our study.

There are some studies conducted in maritime Antarctica regarding the potential GHG fluxes from the surface of various types of vegetation cover near the Polish Henry Arctowski Station conducted during the incubation studies (Ferrari et al., 2022). For example, moss cover had the highest CH_4 emissions while producing the least CO_2. Fruticose lichen cover exhibited the highest CO_2 values and a CH_4 sink effect (Ferrari et al., 2022). Another incubation study (Zhu et al., 2009) showed the potential for GHG emissions in Antarctic penguin guano, ornithogenic soils, and seal colony soils through a laboratory incubation experiment. One more study assessed CH_4 oxidation potential in the sediment samples collected in several lakes and ponds on the Fildes Peninsula of King George Island as similar across all studied lakes (Roldán et al., 2022). Unfortunately, we cannot compare these data to our study since the fluxes in the incubation studies are calculated per g of the moss, lichen, penguin guano, ornithogenic soils, etc.

As the mosses thawed out from under the ice of the glacier, we measured GHG fluxes from the ice surface of the glacier, i.e., at the 42-meter ice transect on the glacier in the vicinity of the place where the mosses were measured. It is usually assumed that ice and snow cover shows CH_4 consumption capacity (Zhu and Sun, 2005), except for those cases when geothermal activity creates sub-oxic conditions suited to CH_4 production and release to the atmosphere, such as in the glacier Sólheimajökull (Iceland) (Burns et al., 2018). Therefore, we measured real-time GHG fluxes from the ice surface at an ice transect that was established directly above the place where fossil mosses thawed out (Fig. 3). We found weak uptake of CH_4 and CO_2 from the ice surface in the boundary area (ca. 0–25 m) close to the location of the mosses, and only at a 25–40-m distance from the glacier boundary there were registered emissions of CH_4 and CO_2.

The studied isotopic composition of the ice samples along the ice transect, where we measured GHG fluxes from the ice surface, did not show a tendency to alter the isotopic composition when heading from fossil moss sites to the glacier's center. Our data showed a mixture of ice and freshly fallen snow due to dynamic changes in the area of the glacier's margin.

Our study has limitations in the data proving the microbial pathways of CH_4 emission at fossil moss decomposition, which could be obtained during incubation experiments or using direct gas sampling on stable isotope analysis. This question remains open and requires further investigation. Another limitation is related to the exact age of the mosses. It is known that readvance of glaciers occurred on King George Island during Neoglacial cold events, for example, between 0.45 and 0.25 cal ka BP (Simms et al., 2012; Cofaigh et al., 2014). But there is no information on how long the mosses were growing in this area before these Neoglacial cold events.

5. Conclusion

In summary, our results provide empirical evidence that thawed-out fossil mosses became the source of CH_4 after the Antarctic glacier retreat. The real-time measured CH_4 emissions reach ca. 0.173 μmol m^{-2} s^{-1} (with mean value ca. 0.045 μmol m^{-2} s^{-1}) which is comparable to CH_4 efflux in water bodies or wet tundra in the Arctic. Our study shows that the glacier ice of the studied Bellingshausen Ice Dome demonstrates a CH_4 and CO_2 consumption ability in the narrow (ca. 0–25 m) boundary zone. In contrast, if forwarding to the upper parts of the glacier, the ice is a weak emitter of CH_4 and CO_2. These findings have important implications for predicting GHG fluxes in the area of retreating glaciers in the Polar Regions in response to climate change.

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CRediT authorship contribution statement

Svetlana Y. Evgrafova: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Bulat R. Mavlyudov:** Investigation, Writing – review & editing. **Pavel V. Chukmasov:** Investigation, Resources, Writing – review & editing. **Antonina A. Chetverova:** Investigation, Writing – review & editing. **Oxana V. Masyagina:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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