The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-208-AC2, 2021


The Cryosphere Discussions

# *Interactive comment on* "Methane cycling within sea ice; results from drifting ice during late spring, north of Svalbard" *by* Josefa Verdugo et al.

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Received and published: 3 January 2021

Dear Reviewer 1,

Thank you very much for your feedback. We greatly appreciate your helpful comments and suggestions to improve our manuscript.

With respect to your major comments made

- Results: Most of the results are direct descriptions of the figures without any further take or analysis. It is very repetitive and sometimes hard to link to the further steps you take in the Discussions. It might be useful to move some of the discussion results in the Result section.



The ice conditions of our floe were very heterogeneous, e.g., different snow thickness, ice thickness, ice types/structures, hence we are convinced that a detailed description of all ice cores will be very helpful. Especially for readers interested in comparison of ice cores from later studies with the ice cores presented in our study.

But to improve the overview, we will include the following text in section 3.1.

"The ice floe was formed by FYI and ridged/rafted ice. The ice thickness at the sampled stations varied between 90 and 280 cm, while snow thickness on top of the ice varied from 0 to 90 cm (Table 1). Of the nine ice cores sampled on the ice floe, eight were taken in the ridged/rafted site along a 1.2 km transect (Fig. 1d). Ridged and rafted ice can be especially relevant for the methane cycling, due to the fact that they remain more consolidated even in the summer season (in comparison to FYI) and thus allow us to investigate methane-related processes in certain layers of these ice structures. Vertical profiles of temperature, salinity, BVF, NO3-, CH4 concentration and the ïĄď13C-CH4 for all ice cores are shown in Fig. 2 with additional information in Table 1. Following Golden et al. (1998), permeable ice for gas migration was classified for a BVF above 5 % (see methods). To highlight the spatial variability of the sea ice's physical and biogeochemical properties, we present detailed descriptions of each ice core. To highlight the spatial variability of the sea ice's physical and biogeochemical properties, we present detailed descriptions of each ice core".

- Discussion and conclusions: what are your main findings or take-home message? At the moment it is not obvious. For example, in the abstract the last sentence states 'We point to sea ice as a potential source of methane'. This sounds very speculative with 'we point' rather than 'we find'; and with 'a potential'. Either be more assertive about what you have found, or if you must stay speculative, then suggest more alternative theories that explain your observations.

In the abstract the following sentence: We point to sea ice as a potential source of methane" it will be changed to: "We suggest sea ice loaded with methane as a source

of methane for Polar Surface waters during early spring".

We will include the following take-home messages:

- Our study provides evidence that ridged/rafted sea ice structures create environments where methane oxidation occurs during the Transpolar Drift Stream, eventually acting as a sink for methane. - We propose methane release from sea ice into the meltwater layer as a pathway, mainly in early spring when basal melt is occurring and the top of sea ice loaded with methane is still impermeable. - The ongoing ice melt triggers the methane excess formed in PSW, both temporally and spatially. - The relative velocities of the ice and water and the impacts of stratification on methane signal retention in the surface waters are important factors for the detection of sea ice-induced methane excess in seawater underneath the ice.

-For example, you never mention the potential of the local sediments as sources of methane in the water column, for example nearby or on the Yermak Plateau? Why could this not be the case? Please try to better highlight your key findings throughout the manuscript (abstract, discussion and conclusions).

In section 4.2 "Dissolved methane in Polar Surface Water (PSW)" we will include an explanation why we ruled out the sediment sources for the methane excess in PSW as followed:

"Irrespective of the mixing mechanisms at play during our study, all CTD profiles during the drift showed that the upper 100 m were consistently characterized as PSW. This means that our samples were taken above the depths with substantial stratification and above waters that were influenced by Atlantic-origin. In addition, methane released from sediments in the region West of Svalbard (Sahling et al., 2014; Smith et al., 2014; Westbrook et al., 2009) are laterally transported in the deep ocean and do not reach the surface waters (Damm et al., 2005; Graves et al., 2015; Silyakova et al., 2020). Hence, the PSW in our study area remains unaffected by methane released from seafloor sources further south. Based on our data and the regional oceanographic conditions,



we suggest that methane release from sea ice is the source of the observed excess in PSW".

With respect to your minor comments made

- Some English grammatical and formulation issues, as well as missing words and typos. Please read and check carefully before re-submission.

We agree, we will check the English grammar and formulation in the revised version of the manuscript.

With respect to your individual comments made

1.Introduction:

- L25-27: Add somewhere that you are talking about enhanced methane emissions from the ocean to the atmosphere.

It will be changed to: "In particular, sea ice retreat may quickly induce enhanced methane (CH4) emissions from the surface ocean into the atmosphere due to the loss of its barrier function for sea-air gas exchange (Wahlstrom and Meier, 2014)".

- L27: 'Because the Arctic holds large natural sources of this highly potent...' again ,do you mean the 'Arctic Ocean'?? or sea floor or sediments?

We will include the following sentence in the introduction section: "Accordingly, the methane reservoir estimate in the East Siberian and Laptev Seas, ranges from 1.6 and 5.7 Gg CH4 in the seawater, varying with season and depending on the ice cover (Shakhova et al., 2005; McGuire et al., 2009)".

And the following sentence will be removed "Because the Arctic holds large natural sources of this highly potent...' again ,do you mean the 'Arctic Ocean".

- L37: 'sea ice charged with methane' Consider using 'sea ice loaded with' or another term?

It will be changed to: “sea ice loaded with methane”

- L39: ‘during the last years’ please add if you can a time period here to better indicate what you mean by ‘the last years’.

It will be changed to: "Recent trends in sea ice transported by the TDS, show that sea ice structure has undergone substantial changes since the early 1980s, shifting from thicker multi-year ice (MYI) to thinner and more fragile first-year ice (FYI; Zamani et al., 2019; Hansen et al., 2013; Maslanik et al., 2011, 2007)".

3.Result:

- Table 1: For clarity, could you add ‘-’ when you don’t have values for the isotopic composition? I expect that for station C9, the 3 values of isotopic composition is 3 different estimates? Can you add that information in the Table caption?

The following sentence will be added to the table caption: “In station C9, three samples were taken, while in C8, C10 and C11, one sample. The rest ice cores stations, no brine samples were taken”.

- L122: ‘has an age of 1 to 3 years, respectively’ What do you mean by respectively there?

It will be changed to: "Backward drift trajectories suggest that our floe originated in the Siberian Sea, while the age of the sea ice was estimated to be between 1 and 3 years (Wollenburg et al., 2020)".

- Section 3.11 and 3.12: These 2 sections are rather tedious reading; they very carefully describe each panel of Fig2 one by one. There might be a way to pull the numbers together in a way that builds on from Fig2.

Answer is given in the beginning of our reply to major comments.

- Line 196: ‘at 90-100 m depth (Fig. 6a and 7a).’ You refer to Fig 6 and 7 after Fig2, without having mentioned Fig 3-5. You will have to reorder the figures to match the



order you refer to them.

Figures will be re-ordered in the revised manuscript

- Figure 7: There are 6 subplots but you only label 5 of them (a-e). The odd one out is the 3rd from the top, which I think is the ice melt estimates? Please add a subplot letter and clarify the figure caption.

The subplot letter will be added, and in the caption the following sentence will bee included:

"(c) the bars on the panel show the degree of ice melt at each station estimated from the T/S profiles following Peralta-Ferriz and Woodgate (2015). Their length scale has been omitted to emphasize that this is only used as a qualitatively guidance of the early melt season (melted ice $\sim$ 0-10 cm)".

4. Discussion:

- Fig.3: Very nice figure. We can guess most of the media but they should still be annotated: Atmosphere, ocean, sea ice, snow? In (IIa), what’s the white section with blue dots? Why the gradual change in color of the blue ocean? And do all the CH4 annotation in the ocean indicate concentrations? If so, make it more obvious. Also adda definition of the black arrows in the caption.

“Atmosphere, ocean, sea ice, snow”, will be added in the cartoon.

The caption will be changed to:

"Figure 6: Potential pathways of methane in sea ice with varying impermeable (indicated in grey) and permeable sections (in white with blue dots), i.e. winter (I) and spring (II) conditions. I (a) Relicts of the initial methane signal (source) entrapped in impermeable ice. Impermeable intermediate sea ice layers, act as a barrier for the upward/downward transport of methane (black arrow overlaid by a blue cross). (b) Residual methane signal after methane oxidation occurred in permeable sea ice (“wa-

ter pocket"), enclosed by impermeable ice layers (see Fig. 7). II (a) When basal melt starts and impermeable layers still on top with snow cover (white layer on top of the ice), downward brine transport initiates release of dissolved methane. Flushing events trigger methane released into the ocean. (see chapter 4.1.3). (b) Un-restricted migration of methane in permeable sea ice (black dotted arrow). Ongoing sea ice melt, freshwater from melted sea ice is released into the water underneath, resulting on a "meltwater layer", where methane remains sustained during early spring. Methane (CH4) annotation indicates concentration. Blue gradient in the ocean, reflects the increasing stratification during the seasonal evolution of the upper part of the WML into a fresh meltwater layer".

- L278-279: 'With changes in sea ice dynamics, more of this complex ice structures may be formed, which in turn may promote changes on the methane cycling within sea ice.': here you mean to discuss implications for the future Arctic but its not obvious. Please rephrase.

It will be changed to: "In response to Arctic amplification of global warming, thinner sea ice is expected to occur. Thus, an increased number of permeable pockets formed during ice ridging may lead to favored methane oxidation therein. Under these circumstances, we suggest that the methane pathways can be modified, i.e., sea ice may be considered as a sink for methane".

- L343-344: 'In summary, the excess of methane in the surface water clearly point to sea-ice-sourced and early melt events as most important factors for methane release.'. This seems like too strong a statement considering the evidence you have presented.

It will be changed to: "In summary, the methane excess in PSW, at this time of the year, is likely to be sea ice-sourced and the ongoing ice melt process influences this excess".

- Section 4.2.2: some attention needs to be given to the English in this section, with many language choices that are not English based. Eg: 'the more joint journey is



made...', 'According the drift direction, one would'

The English grammar will be checked for the revised manuscript

5. Outlook/conclusion

- L379: 'We suggest that sea ice methane-released into the ocean, and in this case into the PSW, is the favored pathway in early spring.' Do you mean anywhere? In the whole Arctic? In this region only? Please add details.'

It will be changed to:

"We propose methane release from sea ice into the meltwater layer as a pathway, mainly in early spring when basal melt is occurring and the top of sea ice loaded with methane is still impermeable. Studies are needed to estimate the amount of methane released into the atmosphere by the sea ice-to-air flux compared to the amount released by brine rejection into the marine environment".

- L385: 'The final fate of the methane (excess) thereafter depends on to which extent it is diluted by additional meltwater.' What about the dilution by ocean mixing, currents, tides etc..? You don't mention the role of stratification here.

It will be changed to:

"Our study suggests that the excess of methane in PSW during early spring, is sea ice-sourced. The degree of ice melt affects both the actual freshwater content and the stratification. Hence, the latter affects the potential for the sea-ice released methane to be retained in the meltwater layer. The sea to air flux is inhibited by the formation of the meltwater layer and increasingly so during its seasonal development (i.e. freshening and warming) and its deepening through wind-induced mixing. The methane excess trapped within this layer is subject to this freshwater discharge and diluted, in a later stage of melt. That is to say, the ongoing ice melt triggers the methane excess formed in PSW, both temporally and spatially. Further work is required to investigate the relevance of more ice-free waters in summer to methane pathways during the melt

season".

- L390-393: You mention warmer waters and Atlantification, Atlantification also changes the vertical ocean stratification in the region. If stratification was to increase, then methane released in surface waters could be trapped close to the surface during summer, leading to potentially increased exchanges with the atmosphere (and transfers into the atmosphere). If stratification was to decrease, methane could spread deeper into the ocean.

It will be changed to:

"For potential long-term consequences, we consider the effects of an increased ocean heat content leading to enhanced ice melt and, hence, more freshwater discharged into the surface layer in the region of the Yermak Plateau. A fresher (and perhaps thicker) surface layer 'cap' than today would cause stronger stratification, inhibiting the exchange between the atmosphere and the subsurface ocean layers. Thus, any methane excess in the waters below this 'cap' would be disconnected from the atmosphere and remains preserved. Within the surface layer itself, however, a larger amount of freshwater could potentially lead to an increased dilution effect. Although the Yermak Plateau area is, in general, identified as a region of large tidal variability and enhanced mixing rates (Fer et al., 2015; Meyer et al., 2017b), these tidal mixing mechanisms are mainly manifested at deeper levels due to the interference between the tidal flow and the highly variable bottom topography. Since our study focuses on the upper 100 m, the effect of tidal mixing is minor. Under the scenario of warmer AW inflow waters, the sink capacity of the surface waters for sea ice released methane may be enhanced, either by dilution in the PSW or by mixing into the deeper ocean. Atlantification may finally contribute to disconnect the meltwater layer and a potential methane excess therein from the atmosphere. Furthermore, enhanced deep winter convection may lead to a weakened stratification, and downwards transport of methane formerly preserved in meltwater layers into the entire PSW. Especially vulnerable for such changes are the areas beyond the current inflow area in the Eurasian basin, where the effect of the



"Atlantification" is expected to be enhanced (Polyakov et al., 2017)".

- L394-398: The overall transfer of methane from sea ice to the ocean stays the same, whether the ice and ocean 'travel' together or not. But changes in how far from the source, the methane is released into the ocean and atmosphere. This you don't mention here.

It will be changed to:

"Finally, the relative velocities of the ice and water and the impacts of stratification on methane signal retention in the surface waters are important factors for the detection of sea ice-induced methane excess in seawater underneath the ice. Tracing the overall transfer of methane from sea ice into the ocean is important for understanding and quantifying the dynamic contribution of sea ice for the methane source-sink balance. It is not yet clear which process contributes the largest amount of methane release from sea ice: the brine release during freeze-up in winter or during melting in spring. Both processes need to be considered and the amount of methane needs to be quantified. Extended analyses and robust numerical modelling of these processes within the entire sea ice-ocean (and atmosphere) system are needed to improve our ability to predict the consequences of the methane source-sink balance modifications in the Arctic Ocean".

-There is also the acceleration of sea ice drift in the Arctic which means that sea ice rich in methane that formed on the Siberian shelves, is now potentially drifting further out with the TPD towards Fram Strait before melting and changing and therefore before releasing its methane.

The following paragraph will be included:

"The type and structure of Arctic sea ice affects the capacity for methane storage (Fig. 9). Our study provides evidence that ridged/rafted sea ice structures create environments where methane oxidation occurs during the Transpolar Drift Stream (TDS), eventually acting as a sink for methane. A faster sea ice drift (Spreen et al., 2011) resulting

from a thinning ice cover may reduce the time for methane to be oxidized within the ice, leading to changes in the methane pathways. Further research should consider rate measurements of methane oxidation mainly in ridged/rafted ice structures to determine the impact of this process in the long-term. On the other hand, with an accelerated sea ice transport, methane up-taken in sea ice will be transported to remote areas, and released in surface waters of regions not yet affected by methane excess. We suggest that future studies should be focused on sea ice formation on different Arctic shelves to validate the importance of methane uptake during ice formation".

-Figure 1: Make it clearer which part of the drift is in Region 1 and which part in Region2.

It will be changed to: "drifting days of region 1 in red and of region 2 in black color."

-Figure 9: Add 'Within ridges / rafted sea ice' for FYI and 'Under ridged / rafted sea ice' for PSW on the figure. The arrow for the atmospheric background signature is not great. Could you not instead have a dot, or create another color rectangle to represent standard local atmospheric ranges?

"The arrow will be changed for a rectangle and within ridges / rafted sea ice' for FYI and 'Under ridged / rafted sea ice' for PSW on the figure will be included".

Once again, thank you very much for the careful revision of the manuscript and valuable feedback. Sincerely on behalf of all co-author. Josefa Verdugo

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