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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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Dear Editor, We send answers to comments made by Reviewer#1 as suggested, which show that we are able to sufficiently improve our manuscript. Sincerely, Josefa Verdugo

Answers to comments made by Reviewer#1

Why methane released from e.g., sediments nearby or on the Yermak Plauteu is unlikely to be a source for supersaturations in surface waters?

Answer:

We will add this information to discussion: 4.2. Methane excess in Polar Surface Water (PSW) by release from sea ice when melt starts.

Significant methane released from sediments is reported to occur in areas of West of Svalbard (Sahling et al., 2014; Smith et al., 2014; Westbrook et al., 2009). In addition, methane bubble release was also documented at the deep sea Haakon Mosby Mud Volcano, on the SW Barents Sea slope (Sauter et al., 2006). However, most of this methane released by sediments are laterally transported within the deeper ocean and does not reach the surface waters (Damm et al., 2005; Damm and Budéus, 2003; Graves et al., 2015). In addition, while transported by ocean currents, dissolved methane is partly oxidized by microbes and partly diluted by mixing with background methane transported by ocean currents (Mau et al., 2017). Additionally, the sea ice drifted from East to West, while the sediment sources are west of Svalbard, i.e., the source area is localized in South-West direction of our study area. Hence, sea ice formation and methane uptake occurred in a region far away from these known sources.

- 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.

Answer:

Will be changed to:

In response to Arctic amplification of global warming, thinner sea ice is expected to occur and, more of these micro-niches formed during ice ridging may lead to favored methane oxidation therein. Under these circumstances, the methane pathways can be modified, i.e., sea ice may be considered as a sink for methane. In addition, 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 up to now not affected by methane excess.

- 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.'

Answer:

This information will be included in outlook/discussion

We suggest methane release from sea ice into the meltwater layer as yet unconsidered pathway mainly in early spring when the top of sea ice is still impermeably, but basal melt started. Further investigations are needed to estimate the amount of methane released into the atmosphere by sea ice to air flux, compared to the amount released by brine rejection into the marine environment. All methane pathways should be considered for the parameterization of process modelling studies. However, detailed process studies of sea ice formation on different Arctic shelves are crucial to validate the importance of methane uptake during ice formation.

- 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.

Answer:

This information will be included in outlook/conclusion

Our study suggests that the excess of methane in PSW, at this time of the year, is sea ice-sourced and that the ongoing ice melt process influences this excess, both temporally and spatially. The degree of ice melt impacts both the actual freshwater content and the stratification and, hence, 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 subjected to this freshwater discharge and diluted, in a latest stage of melt. Mixing may also be inferred by ocean currents, and their interplay with the drifting ice. At occasions of strong winds the shear (i.e., the velocity difference

between the two media) will be particularly large and give rise to enhanced turbulence in the upper water layers affected by the motion (and speed) of the ice. 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., 2017). These tidal mixing mechanisms are mainly manifested at deeper levels due to the interference between the tidal flow and the very variable bottom topography. Since our study focuses on the upper 100 m, the effect of tidal mixing should be minor. Whichever mixing mechanisms were at play during our study, all CTD profiles during the drift showed that the upper 100 m consistently where characterized as PSW, meaning our samples were taken above the depths with substantial stratification (i.e., the main pycnocline, between surface waters and AW-influenced waters) and above the depths were waters showed an increasing influence of Atlantic-origin waters.

- 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.

Answer:

It will be included in outlook/conclusion

For the potential long-term effect, we relate to the effect of an increased ocean heat content leading to enhanced ice melt and, hence, more freshwater discharged into the surface layer. A fresher (and perhaps thicker) surface layer 'cap' than today would imply stronger stratification efficiently inhibiting the exchange between the atmosphere and the subsurface ocean layers. Any methane excess in the waters below this 'cap' would thus be disconnected from the atmosphere and remain preserved. Within the surface layer itself, however, a larger amount of freshwater would potentially lead to an increased dilution effect. Hence, Atlantification finally contribute to disconnect the meltwater layer and a potential methane excess therein from the atmosphere. Further, an enhanced deep winter convection may lead to a weakened stratification, and downwards transport of methane formerly preserved in meltwater layers into the entire PSW. Hence, we suggest that Atlantification most likely will enhance the sink capacity of the PSW for methane, either by dilution in the PSW itself or by mixing into the deeper ocean.

- 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. 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.

Answer:

It will be included in outlook/conclusion

The overall transfer stays the same, but there is a difference in terms of the source-sink balance if methane is transported within sea ice or in seawater underneath when released. It is not yet clear which process contributes to a larger amount to the release of methane from sea ice, either the brine release during freezing in winter or during melting in spring. Both processes have to be considered and the amount of methane has to be quantified, before we are able to discuss the potential effect of the acceleration of the sea ice drift. One of the main results of our study is that we show for the first time that methane oxidation occurs in certain layers of complex sea ice structures. Under this circumstance, sea ice might act as a sink for methane. A faster sea ice drift (Spreen et al., 2011) resulting from a thinning ice cover on one side may reduce the time for methane to be oxidized within the ice, leading to changes in the methane

pathways. On the other hand thinner ice breaks up more easily by winds and waves resulting in the formation of more leads (open waters). This, in turn, may enhance the exchange of methane between the ocean and atmosphere (Kort et al., 2012).

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