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Interactive comment on “Observations of brine plumes below Arctic sea ice” *by* Algot K. Peterson

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The author thanks the reviewers for their good and constructive comments. The comments are reproduced below, followed by the authors response and any changes to the manuscript. Author responses are indented and typed bold fonts. The response to the first reviewer also contains a track-changes pdf of the manuscript.

Overall, this is a nice dataset that has been carefully analyzed, but the presentation and arguments could use some improvement. The ability to compare salinity changes in the ice, due to melting of the ice or changes in storage / drainage, and the turbulent salt fluxes in the ocean is novel, and a revised version should be published in the literature. My suggestions below are primarily asking for clarification and expansion of some of the points made in the paper, and I recommend it be published after major revisions.

Major comments: Anti-correlated fluxes: As presented, I am left wondering about other processes besides brine from the ice that would result in correlated fluxes. The results section should begin with an overview of the salinity changes to the ice. Otherwise, the assertion (page 4 paragraph at line 19) that salinity fluxes are due to brine drainage is simply an assertion. There is a consistent story here, but it is somewhat confusing as presented.

The overview of salinity changes in the sea ice has been moved to the end of Section 3 (environmental setting), and now comes right before the results section.

In addition, the following two points may warrant a brief mention:
- Anti-correlation of heat and salt fluxes could also result from entraining water from beneath the mixed layer base during the June 13 storm. But if the water beneath the mixed layer is warm (shown in Fig 3) and salty (?), it would not explain the negative salt fluxes. This should be explicitly stated (that entrainment from below cannot explain the correlated fluxes), and Figure 3 should be altered to show salinity profiles/transects.

A panel showing profiles of salinity has been added to Figure 3. The second paragraph of Section 4 now starts with reference to the T/S profiles in Figure 3: “At the surface we generally find cooler, fresher water than below (Figure 3), consistent with observed melting at the surface. The negative salt flux can thus not be caused by entrainment of saline water from below.”

- Anti-correlation could also result from a mixed layer at the freezing temperature, for which salty water is cold. If a parcel of salty water at the freezing temperature moves downwards, then it will have negative salt fluxes and positive heat fluxes (e.g., Cole et al., 2014; Randelhoff et al. 2014). Figure 5a shows that maximum heat fluxes are associated with water very close to the freezing temperature for the plumes, is this also true for the 15-min or 3-hour timescale? A correlation between T and S is a simple explanation for the correlated fluxes.

The answer to this comment is found in Section 3, quoted below. Figure 5 shows the maximum/minimum values within each plume, and represents the 0.5 s measurement time scale. For longer time-scales, temperatures are well above freezing.
"Temperature at 1m below the ice averaged to ΔT= $0.6°$C above freezing, lowest on June 11 ΔT= $0.1°$C) and highest (1.6C) during the storm on June 13. Atlantic water flows along the topographic slope (Meyer2017b), and is often found at depths shallower than 30m (T>0C, Figure 3). Toward the end of the drift a warm intrusion is also observed at 5 to 10m depth."

Cole ST, Timmermans M-L, Toole JM, Krishfield RA, Thwaites FT, 2014: Ekman veering, internal waves, and turbulence observed under Arctic Sea Ice, J. Phys. Oceanogr., 44, 1306-1328. Randelhoff A, Sundfjord A, Renner AHH, 2014: Effects of a shallow pycnocline and surface meltwater on sea ice-ocean drag and turbulent heat flux, J. Phys. Oceanogr., 44, 2176-2190.

The uppermost meter of the ice: The assertion seems to be that the uppermost meter of the ocean is stratified with fresh meltwater remaining shallow while the brine plumes are able to penetrate through this fresh layer (Page 13, line 17-18 'Such plumes...'). Is this correct? And how is the uppermost meter of water not a) fresh, and b) well mixed due to the turbulence and large ice speeds?

Yes, this must be the case. Over time, freshwater is indeed mixed downwards, but on a time-scale longer than the 15-minute turbulent time-scale used here. A possible way this can be facilitated is if the roughness elements in the ice-ocean boundary layer are sufficiently large, the turbulent eddies do not reach the interface to mix down the layer closest to the surface. Still, even for quite large roughness elements this layer is on the order of a few centimeters. See the paragraph quoted from the discussion section in my reply to the next comment.

Brine salinity: More careful treatment of the bulk salinity of the ice (5, fresh to the

ocean), versus the salinity of the brine (presumably of higher salinity than the ocean) is needed. Overall, how does drainage of water with a salinity of 5 (ice+brine on average?) cause a negative salt flux? The ocean should 'see' it as fresh water flowing downwards, which is a positive salt flux. Are the plumes 'visible' to the ocean only when there is no active melting during those 10 second bursts?

This is a paradox, and I have tried to clarify my thoughts on this by adding the following paragraph quoted below to the discussion section. In addition, there is also a mention of separation in time-scales in Section 6, which should remind us that what the ocean 'sees' is not necessarily the same as what our instrumentation sees.

"When sea ice melts, it contributes to a net freshening of the upper ocean, since the bulk salinity is about 5 (Figure 4). Over the course of the drift, a freshening of the surface layer is observed, while the turbulence measurements at 1 m show negative salt flux. This paradox warrants some consideration of the structure of sea ice. Sea ice consists of freshwater ice surrounding pockets of liquid high-salinity brine. When the sea ice melts, the brine sinks through the surface layer due to its high density, while the fresh meltwater stays at the surface. The fresh surface water is gradually entrained into the mixed layer, but since the salt flux is nearly always negative, this freshwater flux likely occurs on timescales longer than the 15-minute segments used here. Why freshwater at the surface is not immediately mixed down, even during quite strong mixing events, is not entirely clear. The ice floe consists of first-year ice (Granskog, 2017), but the floe was deformed through several storms. This is evident e.g. from the hot wire measurements, which were made in an area of deformed ice. A rough under-surface of the sea ice leads to a thicker layer where molecular viscosity and diffusivity is important. This "transitional sublayer" is usually taken as 1/30 of the scale of the roughness elements, and is on the scale of a few centimeters (McPhee, 2017)."

The link between the turbulent scale processes and larger-scale picture is not complete: - What does averaging Figure 4 in a distance framework look like? What is the characteristic horizontal scale of the plumes? Roughly, 10 s x 0.23 cm/s = 2 cm width. There is a missing link between some of the arguments about turbulent features at these small scales (2 cm) and the larger scale arguments regarding salty water dragging over fresher water in a marginal ice zone. The later would suggest a much larger-scale instability.

There is a comment to the first reviewer concerning plume width as a function of velocity. I do not know where you get the 0.23 cm s^{-1} to calculate a plume width. I would rather use the $= U_{drift} - U_{measured}$ of about 10 cm s^{-1} to infer 'plume width', which leads to scales up to 100 cm. I do not think a discussion of this is necessary, as this mechanism is already ruled out as explanation for the negative salt fluxes.

- Salty plumes are observed for a wide range of 15-min or 3 hour salt flux values. Are plumes of salty water traveling upwards observed? What about freshwater traveling downwards? To what extend are these 10 s plumes dominating the 15 minute or 3 hour average?

Remarkably few 15-minute segments show positive salt fluxes (freshwater traveling downwards). The plume algorithm does not look for salty water traveling upward, but from the overall time-series, such features are dwarfed by the large negative fluxes. The plumes account for 9% of the total salt fluxes, and are thus dominating the 15-minute averages where they appear in.

Additional comments: - Consider a more descriptive title, e.g., Observations of sea ice desalination and turbulent brine plumes beneath melting Arctic sea ice.

Title changed to "Observations of brine plumes below melting Arctic sea ice".

- Why aren't the other TIC measurements discussed here? Is there something unique

about this ice floe (floe 4) that leads to brine plumes, or was it simply more heavily instrumented / sampled?

Anti-correlated heat and salt fluxes were only observed on floe 4, which is why it is the only one discussed in this paper. The reason why we do not observe this in the preceding floes is because little or no melt is taking place, and the ice is cold.

- page 2, line 12: is this really the first observation? What makes it so?

Observing plumes requires relatively detailed measurements in the ice-ocean boundary layer. Direct measurements of salt flux are not very common, which reduces the chance to observe the plumes, at least in this manner. I do mention the closest previous observations in the manuscript. The study by Sirevaag (2009) in Whaler's Bay did not find anti-correlated fluxes, even though it is close in both season and location to the present study. I added a paragraph about differences to this study at the end of the discussion section: "The observations of brine plumes raise interesting questions concerning the conditions in which they occur, and importantly, why they have not been observed before. Few studies have reported measurements of turbulent salt fluxes in the Arctic Ocean, and the season of the observations may be of the essence. In the preceding ice camp (Floe 3) in the N-ICE campaign, the salt fluxes were below the sensor accuracy level, and could not be analyzed for correlation with heat flux. The study by Sirevaag (2009) is relevant for comparison, because it was set in roughly the same place, Whaler's Bay, in April 2003. The differences between this study and Sirevaag may give some clues to the matter. They deployed the TIC in a refrozen lead, surrounded by ridged multiyear sea ice. An ice core revealed a linear temperature gradient of -21.7 K m^{-1}, meaning that the ice was not above the critical 5% threshold for gravity drainage. The cold ice column may explain why brine was prevented from leaving the sea ice in plumes, despite rapid melt. When brine is released slowly as melt progresses, it is more likely to be mixed in with

meltwater, than to descend in plumes.”

Sirevaag, A. (2009). Turbulent exchange coefficients for the ice/ocean interface in case of rapid melting. Geophysical Research Letters, 36(4), L04606. https://doi.org/10.1029/2008GL036587

- page 3, lines 7-12: a reference to Section 6, which has some additional details on processing would be useful.

The following has been added to the paragraph:
“For the data presented here, 85 out of 612 segments (14%) were rejected in quality control. Additional details on processing and data considerations are discussed in Section 6.”

- Page 9, line 19: is the net change in salt content (2.8 kg/mËĘ2) a decrease?

Yes. I changed the word ‘change’ to ‘decrease’.

- Page 9, line 18 to page 11 line 7: reading this paragraph, it would be useful to refer to Figure 2, and to have Figure 2 show the two estimates of salinity loss (ice cores and salt fluxes).

Salt content of the two ice cores is added to Figure 2b. Caption is updated accordingly. There is reference to Figure 2b in the updated paragraph discussing this (which was restructured in response to a previous comment to introduce ice cores/salt loss before the results section).

- Page 14 line 4-10: how much data was excluded from analysis due to the various processing procedures? Some detail here is warranted even if it is described elsewhere.

The section concerning quality control has been extended to include: “For the data presented here, 85 out of 612 segments (14%) were rejected in quality control.”

- Page 15 line 25-26 (‘In the interior...’): Why? There is still seasonal melting in the interior that melts ice. Isn’t the brine release related to the volume of ice melted? I am missing the connection to processes that happen in the marginal ice zone.

The brine release depends both on the heat reaching/melting the ice, and the salinity of the sea ice. This is now clarified in the manuscript (concluding remarks) as follows: “Triggering by ocean heat flux is less likely, both because there is typically less heat available to be mixed up (e.g. less open water to be warmed by insolation), and less mixing due to internal forces in the pack ice. In the interior Arctic Ocean, sea ice is typically second- or multi-year ice, which is thicker and less saline than first-year ice. Brine release in the quantities. . .”

- Section 7: What are the specific conclusions of this work? I find it difficult to state this explicitly, and would like to see the final section expanded with such a statement.

The following is added to the beginning of section 7:
“This study reports observations of inversely correlated heat and salt fluxes below melting sea ice north of Svalbard. The evidence suggests that the fluxes are caused by brine release from the sea ice as it melts, and a significant fraction of the salt fluxes are seen descending past the measurement volume in plumes.”

- Figure 1: Please indicate the start location for the drift. Consider also just showing the floe 4 drift track.

Figure 1 has been changed to only show the Floe 4 drift studied here, with references to Van Mijenfjorden and Whaler’s Bay experiments. Start point of the drift is now indicated by a black cross, and the figure caption is adjusted accordingly.

- Figure 3: Yellow lines are difficult to see. Add in something that indicates mixed layer depth (panel a and/or b), and a salinity section or salinity profiles.

Yellow lines are chosen so to not be very distracting, and depth is not the most important part of this figure. However, I did add labels to the depth contours (1000m, 2000m) which had been left out by accident in the original submission.

Salinity profiles are added as a panel c). Mixed layer depth is easily enough to see from the salinity profiles, as well as described in the text, so I prefer not to add further details to the figure.

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