Biogeosciences Discuss., 12, C7561–C7580, 2015
www.biogeosciences-discuss.net/12/C7561/2015/

Biogeosciences
Discussions
Open Access

Interactive comment on "Identification and analysis of low molecular weight dissolved organic carbon in subglacial basal ice ecosystems by ion chromatography" *by* E. C. Lawson et al.

E. C. Lawson et al.

emily.lawson@nottingham.ac.uk

Received and published: 10 November 2015

We thank Jacob for his thorough review and constructive comments which have improved the content of this manuscript. In the following, we reply to all referee comments (in italics) point by point.

The authors have indeed conducted an interesting and novel study of low molecular weight dissolved organic carbon (LMW-DOC) in basal ice. The text is well written and suitable for Biogeosciences. The authors have good control on the biological and biogeochemical aspects of the study. Therefore, I have focused my review mainly on the glaciological and sedimentological aspects.

1. My main concern is the lack of information about the sampling sites and character of the basal ice (i.e. the basal ice facies). This makes it difficult to know how the basal ice was formed (regelation, adfreezing, thrusting) and to assess whether the authors make appropriate comparisons, interpretations and conclusions. I will like to see a better description of the basal ice at each sampling site, including a figure showing close-up photos of the basal ice.

We did not conduct an extensive investigation into how the basal ice was formed as we did not possess the necessary information and analytical data to be able to provide a thorough account of the basal ice formation processes at each site. For instance, we lacked data on ice crystallography, sediment grain-size distribution, clast-shape and form analyses, co-isotope analyses (ïĄď18O and ïĄďD), and gas composition of CO_2, CH_4 and O_2 in bubbles in the ice, which are typically used to describe and differentiate the basal ice facies. We also did not have detailed accounts of the thickness of individual debris layers or structural measurements of basal ice facies. Instead, we were relying on visual description of the basal ice, sediment concentration (by mass) and published literature to infer how the basal ice formed. This lack of detailed data made us cautious when inferring basal ice formation processes as these are often controversial and basal ice formed by different mechanisms may be indistinguishable (Sleewaegen et al., 2003) and flow related to post- or syn-deformational processes may alter the primary character of the basal ice (Waller et al., 2000).

Nonetheless, we agree with the Reviewer that more information is needed on the location and character of the sampling sites and basal ice facies, which we provide in Section 2.5 (Sample collection). We refer the Reviewer to points 17-25 where we address particular comments on the sample collection and basal ice description in more detail.

2. I am also concerned about the coupling between LMW-DOC and debris concentration in basal ice because debris concentration is a poor proxy for the surface area of the debris within a sample. I would have liked to see some data on particle size

distributions. Again, this makes me skeptical to some of the interpretations and conclusions.

We have revised some of our interpretations and conclusions based on the Reviewer's valid comment that debris concentration is a poor proxy for the surface area of the debris (which would be the controlling variable to test whether DOC was leached from the basal debris). Unfortunately, we do not have data on particle size distribution <2mm or the debris concentration for particle sizes <2mm, and are restricted to presenting only debris concentration (by mass). We have however, removed our hypothesis and revised sections of the results and discussion, while noting the limitations of our dataset when discussing the potential for DOC to leach from sediments (e.g. Section 5.2). We refer the Reviewer to points 28 and 30 where we address the specific comments in more detail.

Overall, this study is a step forward in the understanding subglacial biogeochemistry and I look forward to read the revised paper.

3. Abstract 14141, L2-4: It seems awkward to start the Abstract by talking about glacial runoff, when the focus of this paper is on basal ice and the subglacial environment. I suggest that you delete the first 2-3 sentences and direct the reader's attention towards the lack of knowledge about DOC in basal ice.

We take on board the Reviewer's point that the paper is focussed on basal ice and process in the subglacial environment rather than on glacial runoff. Initially, we began the Abstract by mentioning glacial runoff to outline the wider significance of glacial melt and how the export of organic compounds could impact on downstream ecosystems, which is dependent on the composition of the organic material that is released. Basal ice melt is one of the contributors to glacial melt, and so the compounds released in basal ice melt will contribute to net glacial export. This rationale has been used in other published research (Barker et al., 2010; Pautler et al., 2012; Pautler et al., 2011) and hence we followed their reasoning. We have now revised the start of the Abstract to

focus more on the lack of knowledge about DOC in basal ice and then related this to the wider context of glacial meltwater export.

4. 14141, L7-8: I certainly don't like this definition of basal ice. Several other processes than basal adfreezing may form basal ice, and basal ice may contain incorporated segregation ice or intermixed glacier ice. Here in the Abstract there is no need to define basal ice, but you must present a proper definition of basal ice in the Introduction section.

Following the advice of the Reviewer, we have removed this definition of basal ice from the Abstract. We have also expanded on our definition of basal ice in the Introduction section (see point 7).

5. 14141, L11: It is unclear what is meant by "basal debris type".

What we mean is 'different type of overridden material'. We have amended this in the text.

6. 14141, L13: Make it clear to the wide readership of Biogeosciences that FAA refers free amino acids.

This has been edited in the text (FAA = free amino acids).

7. Introduction 14142, L2-21: In my opinion, the Introduction section needs to be rewritten. You use 20 lines to talk about glacial runoff, and a single sentence to give a wrong definition of basal ice, which is the environment that you are actually examining. I cannot follow the leap from "Thus, further knowledge is needed to accurately assess the source of LMW-DOC in glacial runoff. . ." to "... and determine the abundance and composition of potentially bioavailable LMW-DOC in basal ice at the base of glaciers and ice sheets". This paper does not accurately assess the source of LMW-DOC in glacial runoff. What is the link between subglacial meltwater runoff and basal ice? At three of the four glaciers that you are studying I will assume that the basal ice is primarily formed at cold-based conditions; at temperate Engabreen, I will assume that

the basal ice consists of glacier ice and ice formed by regelation.

I recommend that you focus the first paragraph on basal ice. For example, use the definition of basal ice by Hubbard et al. (2009) and inform the readers about metamorphose of glacier ice into basal ice (Sharp et al., 1994) and post-formational tectonic deformation of basal ice causing intermixing of glacier ice and basal ice (Waller et al., 2000), in addition to basal ice formation by adfreezing and regelation. Then, you may continue by describing subglacial entrainment of LMW-DOC into basal ice.

On the advice of the Reviewer, we have revised the Introduction section and focus the first paragraph on defining basal ice, and have included the references that the Reviewer has helpfully supplied above. We have focussed less on glacial runoff and only briefly mention that basal ice melt is one of the contributors to glacial melt, and so the compounds released in basal ice melt will contribute to net glacial export. This is our rationale for linking basal ice and subglacial meltwater runoff – basal ice melt may contribute to the subglacial runoff exported from glaciers with outflow channels. However, we recognise that this is a small component when compared with the large volume of supraglacial meltwater that travels through the subglacial systems within temperate and polythermal glaciers. Nonetheless, the export of subglacially stored meltwater, or basal waters with distinct chemical; signatures, which may contain basal ice melt, can be detected in glacial runoff (Bhatia et al., 2013; Hawkings et al., 2015) and thus cannot be excluded from glacial chemical export budgets. We do not overplay this link as the Review is correct in that we did not quantitatively assess the source of LMW-DOC in glacial runoff.

As Russell Glacier and Finsterwalderbreen are classified as polythermal-based, it is possible that the basal ice that we sampled at the margin was formed by regelation in addition to cold-based processes. This has been included in the description of basal ice sampled at each site (Section 2.5).

8. 14142, L22-25: The subglacial environment and the basal ice environment are not

synonymous. The basal ice environment is a part of the subglacial environment. Here, it is unclear to me whether you make this distinction.

We have edited our definition of basal ice in the introduction to make this distinction more clear. The references that we have used on pg 14142 L22-25 all refer to sampled basal ice (and subglacial sediment in (Foght et al., 2004)).

9. 14143, L1: Introduce the abbreviation of free amino acids here.

This has been added to the text as suggested.

10. 14144, L1-3: You mention that the four glaciers have distinct temperature regimes, but you only list the four glaciers with their assumed substrates. It will be informative to include the temperature regimes in the list.

The temperature regimes are listed in Section 2.1-2.4 when each of the sample sites is described. On the advice of the Reviewer, we have included these temperature regimes when we introduce the four sample sites towards the end of the Introduction.

11. Sample sites and basal ice sample collection 14144, L9: What does the reference refer to? It seems superfluous.

We have rechecked this reference and agree with the Reviewer that it is not necessary and have removed it from the text.

12. 14144, L17: I would say west margin rather than southwest margin.

We have edited the text and now refer to Russell Glacier as situated on the west margin of the GrIS.

13. 14144, L21: I think that you mean Archaean, not Achaean.

This has been edited in the text.

14. 14144, L21-22: A more correct reference to the local geology will be Escher and Watt (1976).

The reference in the text has been changed to Escher and Watt (1976).

15. 14145, L2-8: It is relevant to mention that Finsterwalderbreen last surged between 1898 and 1910 (Liestøl, 1969) because the formation of the basal ice is very likely linked to the surge event, as it has been shown at Variegated Glacier (Sharp et al., 1994) and Kuannersuit Glacier.

We have edited the text to mention the surging of Finsterwalderbreen between 1898 and 1910 (Liestøl, 1969) and how this may have influenced the formation of basal ice.

16. 14145, L10: Better use the term temperate than warm-based.

This has been amended in the text.

17. 14145, L16-14146, L2: The description of the sampling sites is very cursory. It will be difficult for others to find the sampling sites in the field based on these few sentences, and even if they manage to find the sampling sites they will not know which basal ice facies they should sample to replicate your sampling. It is important with a more detailed site description and a characterization of the basal ice in order to get an idea of the differences in the formational processes of the basal ice, as these processes may influence the abundance and composition of LMW-DOC (the aim of this paper). A figure showing photos of the basal ice at each sampling site (both the BI and PR for Finsterwalderbreen) will give an impression of the character of the basal ice. This may also be helpful to readers of Biogeochemistry, who are not familiar with basal ice.

Following the advice of the Reviewer, we have revised the description of the sampling sites to include greater detail on how, and where, the basal ice samples were collected. We did not include detailed maps highlighting where the samples were collected, as the Reviewer did in their 2010 basal ice paper (Yde et al., 2010), as we felt that this would make the introduction to the research too long (as we would need to describe four glacial sampling sites) and detract focus from the analytical results and interpretation. We followed the approach of published research that sampled basal ice from multiple

locations and restricted the description of the samples to text, e.g. (Pautler et al., 2011; 2012; Sharp et al., 1999; Stibal et al., 2012), and hence, we did not include photographs of the basal ice at each sampling point. While this would help given an impression of the character of the basal ice, unfortunately, we don't have an up-close photograph of the Joyce Glacier or Finsterwalderbreen 'pressure ridge' basal ice samples, and there is not adequate sample remaining to take a new photograph. We believe that it would look odd if there were photographs of four out of the five sample types and opt not to include photographs.

Our research is intended to be an exploratory investigation that aims to; a) test whether ion chromatography is a valid analytical approach for the assessment of trace level LMW-DOC compounds in glacial samples, and b) investigate whether basal ice from different sample locations with different overridden material types had distinct LMW-DOC signatures. The next phase of research would be to consider how LMW-DOC varied within basal ice facies at each sampling location as we acknowledge that the different formation processes may influence the abundance and composition of LMW-DOC. However, this was beyond the scope of our research and would have required analytical equipment that we did not have access to when we were analysing the samples. For instance, it would have been interesting to describe and differentiate the basal ice facies using ice crystallography, co-isotope analysis of ïĄď18O and ïĄďD, and gas composition of CO2, CH4 and O2 in bubbles in the ice; however, this was not possible during the analysis period. Due to limited sample volume, we are unable to run any further experiments on the basal ice samples that we have analysed in this paper. Nonetheless, we now present a more detailed site description and characterisation of the basal ice using available data and literature (Section 2.5).

18. 14145, L16-17: Is this actually basal ice or is it in fact subglacial frozen lacustrine sediment? If it is basal ice, it must have distinct physical or chemical characteristics different from frozen lacustrine sediments (see definition of basal ice by Hubbard et al., 2009). From this single sentence I am unable to assess whether you have actually

sampled frozen lacustrine sediment.

We agree that the phrasing in this sentence is poor and does not adequately explain what we sampled. We sampled basal ice where the facies were composed of frozen debris and only weakly exhibited layers that were >1 mm thick but < 1m thick. According to the classification in (Hubbard et al., 2009), we sampled solid banded basal ice. This has been included in the basal ice description (Section 2.5).

19. 14145, L16-19: A characterization of the sampled basal ice beneath Engabreen will be useful (see Jansson et al., 1996), as the formation of basal ice at Engabreen may differ from the other three glaciers because of its temperate basal regime.

We have described the character of the ice sampled beneath Engabreen in more detail and thank the Reviewer for recommending (Jansson et al., 1996) which we now cite.

20. 14145, L20: It sounds a bit dangerous to collect basal ice samples at the calving terminus of Russell Glacier. If you collected the samples at the northern corner of the terminus, you have to be aware that before the 1990s there were some small lakes here, dammed between the moraine and the glacier. When the glacier advanced during the 1990s the lakes were overridden and the glaciolacustrine sediment may have been incorporated into the basal ice. At the southern corner, the glacier advanced into a dune. Detailed information about the location and character of the sampling site is therefore very important, as it may have significant impact on LMW-DOC.

Our Russell Glacier samples were collected towards the southern corner where the glacier has previously advanced into a dune and hence, we are confident that our basal ice samples did not contain any glaciolacustrine sediment. Our basal ice samples were taken from the same location as those analysed in (Stibal et al. 2012), where biomarker analyses found OC characterised by n-alkanoic acids steroids and other functionalized compounds consistent with a higher plant, and thus, soil organic matter source. We now describe the location and character of the Russell Glacier sampling site in greater detail (Section 2.5) and use this information when interpreting the basal ice LMW-DOC

signature in the Discussion (throughout Section 5).

21. 14145, L20: Also, it is relevant to mention whether you sampled the solid or banded basal ice facies at Russell Glacier. You make a distinction between two ice facies at Finsterwalderbreen, but the same argument can be used for Russell Glacier. It is okay that you just sampled one ice facies at Russell Glacier, but the readers need to know which one. I will encourage you to do a follow-up study on the horizontal distribution of LMW-DOC in basal ice to examine potential links between genetic basal ice facies and the abundance and character of LMW-DOC.

We recognise that the descriptions we have given regarding the location and type of basal ice sampled are lacking in detail. As mentioned in point 17, we have revised Section 2.5 (Sample collection). This includes the Reviewer's suggestion that we state which ice facies we sampled at Russell Glacier. We sampled banded basal ice where the debris was generally restricted to narrow sediment layers and large vein networks were clearly evident.

It would be very interesting to do a follow up study on the horizontal distribution of LMW-DOC in basal ice to examine potential links between genetic basal ice facies and the abundance and character of LMW-DOC.

22. 14145, L21-22: Again, it will be nice with information about which basal ice facies was sampled.

Information on the type of basal ice facies that were sampled has now been added to the text as part of the general revision of Section 2.5.

23. 14145, L22: Insert the word glacier in front of surface, and delete the word frozen unless you actually mean that the subglacial material was frozen when it was entrained into the shear planes.

We are referring to outcrops of frozen subglacial material that have been upthrust from the glacier bed and are now evident on the glacier surface. We believe that the original sentence describes the ice that we sampled.

24. 14145, L23-24: To me the term Pressure Ridge is related to sea ice, making this sentence rather confusing. A more appropriate term could be debris layer, thrust band or shear plane (I am guessing a bit here, as it is unclear to me what you sampled). No matter what you sampled I am pretty sure that the thrusting did not happen "during cycles of (glacier) advance and retreat". As Finsterwalderbreen is a polythermal surgetype glacier, my guess is that primary thrusting occurred during the early surge phase in the subglacial zone between temperate ice and cold ice, and secondary trusting may have occurred during surge termination due to ice flow compression. This is at least how it is envisaged at the polythermal surge-type Kuannersuit Glacier (Larsen et al., 2010). All this is relevant because it may indicate that the PR debris derives from further upglacier than the BI debris, and that the PR debris may have been glacier-covered for a much longer period than the BI debris.

We take on board the comments of the Reviewer and have revised the terminology that we use to describe the two types of basal ice that were sampled at Finsterwalderbreen. Instead of using the term 'Finsterwalderbreen basal ice (BI)', we refer to 'Finsterwalderbreen DB (dispersed banded) basal ice'. Instead of 'pressure ridge' ice, we refer to 'Finsterwalderbreen SB (solid banded) basal ice', which denotes the fact that these samples were taken from surface outcrops of frozen subglacial material, or thrust bands, with distinct debris layers.

We agree with the Reviewer's reasoning that the thrusting could have occurred in two phases: primary thrusting during the early surge phase in the subglacial zone and secondary thrusting during the surge termination due to ice flow compression. This has been incorporated into the description of the sampling site at Finsterwalderbreen (Section 2.5). We also make note in the Discussion that this could indicate that the 'PR debris' (now referred to as 'SB debris') derives from further upglacier than the 'BI debris' (now referred to as 'DB debris'). However, we are cautious when describing the basal ice formation processes as we are limited in the data that we have to be able to

interpret these processes, as discussed in points 1 and 17.

25. 14145, L23-24: It is also unclear to me whether the debris-rich ice in the pressure ridges is in fact basal ice. Maybe it is glacier ice with discrete debris layers (although the debris may derive from the glacier bed).

We now refer to the 'pressure ridge ice' as 'Finsterwalderbreen SB (solid banded) basal ice', which we believe is basal ice rather than glacier ice with distinct debris layers, based on its composition according to the classification in (Hubbard et al., 2009). The area where we sampled the ice consisted primarily of solid banded ice in thrust bands and there was a lack of clean (glacier) ice.

26. 14146, L1 and elsewhere: It is more scientifically correct to write (by mass) rather than (by weight).

This has been amended in the text.

27. 14146, L6-7: Maybe debris-rich basal ice is a better term than "dirty basal ice". This sentence is awkward because your Finsterwalderbreen BI samples had a debris concentration of 20 +/- 27% and thereby not meet the criteria of having a debris concentration >20%. I suggest that you delete the sentence.

We have changed this sentence to "We focus this study on debris-rich basal ice" to make it clear that we did not include any 'clean, debris-poor' ice in the analyses.

28. 14147, L22-28: Basal ice debris concentrations are not very useful, as basal ice often contains boulders, stones and sorted gravel lamina. Therefore, the basal ice debris concentration depends on whether you choose to collect you samples in places without large boulders or stones. It will be meaningful to present the basal ice debris concentration for particle sizes <2mm and preferably in combination with data on particle size distribution <2mm.

We accept the Reviewer's point. When we refer to 'basal ice debris' we are referring to sediment particles predominantly <2mm (plus some small gravel in the Finsterwalderbreen ‘pressure ridge/solid banded’ samples). However, we do not have data on particle size distribution <2mm or the debris concentration for particle sizes <2mm. While we agree that information on particle size distribution would have been very useful in describing the basal ice facies, this was not the scope of the paper as we were primarily focussed on analysing the LMW-DOC compounds in the basal ice. We accept that the particle size distribution would have aided our interpretations of the potential origins of the LMW-DOC compounds and degree of interaction between the sediment particles and water films within the basal ice matrix. However, we included the basal ice debris concentrations to demonstrate that the basal ice samples from the different glaciers differed in terms of debris:ice ratios, particularly ‘FPR’ samples (86.5% debris, compared with 20-55% in the other basal ice samples).

29. 14151, L17 and L21: Here, you use the abbreviations FPR and FBI rather than PR and BI.

Yes, we used FPR and FBI as abbreviations for Finsterwalderbreen pressure ridge and Finsterwalderbreen basal ice to make it clear which Finsterwalderbreen samples we are referring to. We also used these abbreviations in the Tables and Figures and believe that they are necessary to avoid confusion between the different ice samples. We have now revised the terminology that we use to describe the two Finsterwalderbreen basal ice types (see point 24) and used the abbreviations FSB (Finsterwalderbreen solid banded) and FDB (Finsterwalderbreen dispersed banded) instead.

30. 14153, L16-23 (and section 5.2): I am not sure how robust this hypothesis between DOC (and LMW-DOC) and debris concentrations really is, as long as you do not present any data on particle size distributions <2 mm. Assuming that DOC is leached from sediments, the controlling variable will be the surface area of the debris rather than debris concentration. I think that you need to rethink this part of the paper. It is important to present information about debris concentration in the basal ice because it tells something about the material, but it is probably not appropriate to test a hypothesis between DOC and debris content unless you have the appropriate data to do it. As

I am skeptical to your hypothesis, I am also skeptical to your use of this hypothesis in the Discussion section.

We take into consideration the Reviewer’s point that while it is important to present information on debris concentration, the fact that we do not have data on particle size distribution < 2mm means that our hypothesis may not be robust enough to test with our existing data. We have therefore removed this hypothesis from the text and incorporated parts of Section 4.3 (Debris concentrations) into Section 4.1 (Basal sediment characteristics). In this revised section, we state that we investigate possible correlations between DOC (and LMW-DOC) and the debris content of the basal ice, which may provide information on DOC provenance and the potential for DOC to leach from sediments into the basal ice. We acknowledge that if DOC is leached from sediment, the controlling variable will be the surface area of the debris, rather than the debris concentration. However, as a detailed investigation into the particle size distribution was beyond the scope of this study, we use debris concentrations for a preliminary analysis to see if the relationship with debris concentration was different for DOC and LMW-DOC. One of the key observations from Figures 4a and 4b (now relabelled as Figure 1a and 1b) is that no significant associations between LMW-DOC and debris concentrations were observed, which suggests that LMW-DOC in basal ice is not simply leached from the debris, and that there are other sources (potentially microbial) and/or processes (e.g. LMW-DOC cycling) that influences the abundance in basal ice. We have therefore played down our discussion of the potential for DOC to leach from sediments (Section 5.2).

31. 14153, L23: Where is the presentation of the major ion concentrations in basal ice that you mention in the Methodology section? If you have these data, please show them.

We did not intend to mention major ion concentrations and have removed this reference (when discussing blank corrections in Section 3.3.4).

32. 14154, L5: To my knowledge this is the first study to quantify LMW-DOC in basal ice. It not, insert references to other studies.

To our knowledge, this is the first study to quantify LMW-DOC in basal ice. This has been made clear in the text (Section 5).

33. 14154, L15: Specify what you mean by "type of overridden material"? Do you mean differences in lithology or unconsolidated vs. consolidated substrata or differences between pre-entrainment sedimentary types (till, glaciofluvial, lacustrine, soil)?

By 'type of overridden material' we specifically mean pre-entrainment sedimentary type according to our previous classification of the overridden material at each sampling site, e.g. lacustrine material - Joyce Glacier, paleosols – Russell Glacier. We have made this more specific in the text (Section 5.1).

34. 14154, L17: This is slightly confusing, as one will expect the values in brackets to be the mean values, not maximum limits.

We agree that this could be confusing and we have removed these values in brackets and instead refer the reader to Tables 1 and 2 where the mean concentrations are presented. This is clearer than presenting all of the mean concentrations in the text.

35. 14154, L18: Not sure what you mean by comparable. Most things are comparable. Rephrase this sentence.

We have amended this sentence to read "the mean basal ice DOC concentrations and mean sediment OC content were relatively similar in all basal ice samples despite the differences in the types of overridden material."

36. 14155, L25-26: I am not convinced that the GrIS debris in basal ice derives from a soil origin. It all depends on where you collected you samples along the margin of Russell Glacier. It could be of glaciofluvial, glaciolacustrine or aeolian origin, or derive from subglacial erosion.

We understand the Reviewer's concern that we are generalising the basal debris type for the entire GrIS based on our samples collected at Russell Glacier. As previous studies have shown, the debris type beneath the GrIS could also contain sediment of glaciofluvial, glaciolacustrine or aeolian origin. We have amended this statement to refer to Russell Glacier only, rather than the GrIS. We also refer the Reviewer to point 20 where we describe where we collected our Russell Glacier samples (towards the southern corner where the glacier has previously advanced into a dune). We are relatively confident that the GrIS debris (in this location) derives from a soil origin and we base this assertion on published literature, e.g. (Stibal et al., 2012).

37. 14155, L29 and Table 2: These ages are only relevant if you have collected the samples at the exact same site as Stibal et al. (2012). If you did so, mention it in the text.

The samples were collected at the same site as Stibal et al. (2012). This has been clarified further in the text (Section 2.5).

38. 14156, L4: No reason to mention again that the Russell Glacier samples were collected from the GrIS margin.

This has been removed from the text.

39. 14156, L17-20: Could the lack of organic biomarkers at Engabreen be due to debris entrainment by regelation rather than adfreezing?

Yes, it is possible that the lack of organic biomarkers in Engabreen basal ice could be due to debris entrainment by regelation, particularly as the glacier is temperate. This has been included in the text as an alternative explanation.

40. 14156, L21: It seems relevant to distinguish between glacial (ice-contact) lakes and other lake types. Again, I miss information about the chemistry of your basal ice.

We take on board the Reviewer's comment and have amended this sentence to refer to lacustrine sediments, rather than lakes. We have looked again at the literature which proposes that the recent advance of Joyce Glacier is thought to have resulted in the upthrust and exposure of lacustrine sediments (Hendy, 2000; Stuiver et al., 1981). However, we are unable to find a more detailed description of what specific type of lake was overridden. We know that the Garwood Valley was completely occupied by two large lakes but we do not know if the lakes were bordered by a calving glacier (ice-contact lake) or were located some distance downstream of Joyce Glacier (non-contact glacier fed lake) (Einsele, 2000).

41. 14157, L9-10: These are not the only sources of parent water. Refreezing of water from pressure melting during the regelation process is important.

We have revised this sentence to include some of the other sources of parent water as suggested by the Reviewer.

42. 14157, L20: But you do not have age data from Joyce Glacier and Engabreen, so how do you know that age is a controlling parameter? How can you exclude that other parameters at Russell Glacier are less important?

The Reviewer makes a valid point that we cannot support the assertion that age is a controlling parameter on DOC acquisition as we do not have age data from all four glaciers. We were originally making the case that, for the two samples that we do have age data for (Finsterwalderbreen and Russell Glacier), where the sediment is relatively young (1830 $\pm$ 50 14C yrs BP beneath Russell Glacier) there is a stronger relationship between DOC and debris concentration, compared with the older sediment in Finsterwalderbreen basal ice (3750 $\pm$ 150 14C yrs BP). Nonetheless, we have removed all mention of age as a controlling parameter as we do not have age data for all samples.

43. L14159, L19-21: In a warming climate the tendency is that temperate/polythermal glaciers become cold-based as the ice thickness decreases, not the other way around.

We have removed our reference to a warming climate and changing thermal regimes. Instead, we discuss how DOC may be released from cold-based (and warm-based,

polythermal) glaciers during the current climate (see point 44).

44. L14159, L19-21: Why is a change in basal thermal regime needed? Cold-based glaciers may have discrete subglacial channels where water is in contact with the substrate (e.g, at Longyearbreen).

We agree with the Reviewer that a change in basal thermal regime may not necessarily be needed to release DOC in basal ice to downstream ecosystems. We have amended this sentence to take into consideration the possibility of discrete subglacial channels beneath cold-based glaciers such as Longyearbreen (Yde et al., 2008) which may be in contact with the substrate and hence may represent a mechanism for DOC release to downstream ecosystems.

References

Barker, J., Klassen, J., Sharp, M., Fitzsimons, S., Turner, R., 2010. Detecting biogeochemical activity in basal ice using fluorescence spectroscopy. Annals of Glaciology 51, 47-55.

Bhatia, M.P., Das, S.B., Xu, L., Charette, M.A., Wadham, J.L., Kujawinski, E.B., 2013. Organic carbon export from the Greenland ice sheet. Geochimica et Cosmochimica Acta 109, 329–344.

Einsele, G., 2000. Sedimentary basins: evolution, facies, and sediment budget. Springer Science & Business Media.

Foght, J., Aislabie, J., Turner, S., Brown, C.E., Ryburn, J., Saul, D.J., Lawson, W., 2004. Culturable bacteria in subglacial sediments and ice from two Southern Hemisphere glaciers. Microbial Ecology 47, 329-340.

Hawkings, J., Wadham, J., Tranter, M., Lawson, E., Sole, A., Cowton, T., Tedstone, A., Bartholomew, I., Nienow, P., Chandler, D., 2015. The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet.

Hendy, C.H., 2000. Late Quaternary lakes in the McMurdo Sound region of Antarctica. Geografiska Annaler: Series A, Physical Geography 82, 411-432.

Hubbard, B., Cook, S., Coulson, H., 2009. Basal ice facies: a review and unifying approach. Quaternary Science Reviews 28, 1956-1969.

Jansson, P., Kohler, J., Pohjola, V.A., 1996. Characteristics of basal ice at Engabreen, northern Norway. Annals of Glaciology 22, 114-120.

Liestøl, O., 1969. Glacier surges in west Spitsbergen. Canadian Journal of Earth Sciences 6, 895-897.

Pautler, B., Woods, G.C., Dubnick, A., Simpson, A.J., Sharp, M.J., Fitzsimons, S., Simpson, M.J., 2012. Molecular characterization of dissolved organic matter in glacial ice: Coupling natural abundance 1H NMR and fluorescence spectroscopy. Environmental Science & Technology.

Pautler, B.G., Simpson, A.J., Simpson, M.J., Tseng, L.H., Spraul, M., Dubnick, A., Sharp, M.J., Fitzsimons, S.J., 2011. Detection and Structural Identification of Dissolved Organic Matter in Antarctic Glacial Ice at Natural Abundance by SPR-W5-WATERGATE 1H NMR Spectroscopy. Environmental Science & Technology.

Sharp, M., Parkes, J., Cragg, B., Fairchild, I.J., Lamb, H., Tranter, M., 1999. Widespread bacterial populations at glacier beds and their relationship to rock weathering and carbon cycling. Geology 27, 107-110.

Sleewaegen, S., Samyn, D., Fitzsimons, S.J., Lorrain, R.D., 2003. Equifinality of basal ice facies from an Antarctic cold-based glacier. Annals of glaciology 37, 257-262.

Stibal, M., Wadham, J.L., Lis, G.P., Telling, J., Pancost, R.D., Dubnick, A., Sharp, M.J., Lawson, E.C., Butler, C.E.H., Hasan, F., 2012. Methanogenic potential of Arctic and Antarctic subglacial environments with contrasting organic carbon sources. Global Change Biology 18, 3332–3345.

Stuiver, M., Denton, G.H., Hughes, T.J., Fastook, J.L., 1981. History of the marine ice sheet in West Antarctica during the last glaciation: a working hypothesis. The last great ice sheets, 319-436.

Waller, R., Hart, J., Knight, P., 2000. The influence of tectonic deformation on facies variability in stratified debris-rich basal ice. Quaternary Science Reviews 19, 775-786.

Yde, J., Riger-Kusk, M., Christiansen, H., Knudsen, N., Humlum, O., 2008. Hydrochemical characteristics of bulk meltwater from an entire ablation season, Longyearbreen, Svalbard. Journal of Glaciology 54, 259-272.

Yde, J.C., Finster, K.W., Raiswell, R., Steffensen, J.P., Heinemeier, J., Olsen, J., Gunnlaugsson, H.P., Nielsen, O.B., 2010. Basal ice microbiology at the margin of the Greenland ice sheet. Annals of Glaciology 51, 71-79.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/12/C7561/2015/bgd-12-C7561-2015-supplement.pdf

---

Interactive comment on Biogeosciences Discuss., 12, 14139, 2015.