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Interactive comment on "Pervasive diffusion of climate signals recorded in ice-vein ionic impurities" *by* Felix S. L. Ng

Anonymous Referee #1

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Overall assessment

The paper by Ng tackles an issue from a theoretical point of view that bothered ice core science for nearly two decades, i.e., the potential signal migration of bulk chemical signals through the vein network in the presence of an in situ temperature gradient. This hypothesis was put forward by A. Rempel in 2001, but while no unambiguous ice core evidence for this hypothesis was provided in the meantime it could also not be refuted as the theory of migration through the vein network is physically not disputed. However it is still unknown how much of the impurities are located in veins and, thus, really subject to this transport.

The results by Ng provide a convincing argument why no evidence for a migrated signal CAN be found, i.e., because any migration signal would also be subject to intense

diffusional smoothing. Ng expands on the theory by Rempel by taking into account the curvature effect on vein volume that had been intentionally neglected by Rempel. Ng is able to convincingly show that taking this additional term into account, does not stop any migration but leads to strong diffusion of such a migrating signal and, thus, to the disappearance of the displaced signal in the ice. This has two very important implications for ice core science: Firstly, any short-lived peaks in the ice core record that are imprinted in the veins cannot survive the migration process. Vice versa, if there is a peak found in the ice core record it cannot be shifted relative to its initial bulk position. Secondly, the presence of distinct peaks in many deep ice core records suggests that vein migration and diffusion cannot be a dominant process as otherwise any peaks would have disappeared. This implies, as explicitly outlined in the paper by Ng, that either the part of impurities located in veins is only small or that vein transport is increasingly suppressed by a fragmenting vein network as already suggested by other authors.

The paper is well written and excels by its stringent, mathematical approach, while at the same time performing model experiments that are very instructive and, therefore, of great value for the ice core practitioners. It is therefore of high relevance and well suited for publication in The Cryosphere. The mathematical approach (although well laid out) and some for the outsider unintuitive formulations make the access to the paper a little more difficult than necessary. Below I make some suggestions for minor revisions that may help to remedy that. In summary, I highly recommend the paper for publication in The Cryosphere after taking care of these minor revisions.

General comments

The paper is a little "dry" as there are no ice core examples provided. Thus, for those readers who are not specialists in ice core chemistry, it is hard to imagine how those signal that Ng talks about, look like. Here, it would be helpful to see (in the Introduction or the Discussion) a figure that shows examples for high peaks in deep ice on the one hand (for example for in the Ca2+ or SO42- record) and examples of a general reduction of variability as seen on others (for example in the Na^+ and NO_3^- record). Examples can be found in the papers by (Traversi et al., ES&T 2009, Röthlisberger et al., CP 2008, Schüpbach et al., Nature Communications 2018, Barnes et al., JGR 2003, and others).

In addition to Table 1, which provides the values of the constants used, I would suggest to provide a table 2 where all variables used are listed with a short explanation and their units.

The information on the age span is provided in figures 6 and 7, however the discussion of this parameter, despite its great importance for ice core science in particular for very old ice, is rather limited. Looking at the EPICA Dome C results it appears that the age span in Fig. 7 approaches several thousand years or even the precession age scale when reaching an age of 700-800 kyr (unfortunately the current scale of the x-axis does not allow to quantify this for the control run). On the other hand, the EPICA Dome C ice core record provides some information about the time scale of variability that can still be resolved, thus, would constrain the degree of vein transport smoothing empirically. I would recommend to extend the discussion on this point, as it is of great relevance for ice core sciences.

Specific comments:

Introduction 1st paragraph. You could also mention here already the loss of species such as NO_3^- or Cl^- at the surface (Röthlisberger et al., Ann Glac 2002, Weller et al., JGR 2004) migration processes (for example for methanesulphonate) that occur already at the surface (Osman et al., 2017) or the aggregation of dust particles in the deepest ice (Tison et al., 2015)

p2 l33: "...migrate relative to the ice..."

p2 l35: "... could decouple..."

p2 l41: "... signal migration in deep ice may..."

p2 l51: this is one of the examples where the author refers to the ice core evidence without showing it

p2 l62: One intrinsic assumption made in the Rempel theory and also in the work by Ng is that c_B=c*Phi. However, if impurities are located in microinclusions or grain boundaries, hence not in contact with the veins, then the vein transport is not representative of changes in bulk concentrations. In fact, this is discussed later, but I would recommend that this assumption is explicitly mentioned when c_B=c*Phi is introduced.

p3 l63: when I first read the word "ice porosity" I got confused. I would suggest to write: " is mirrored by variations in the liquid filled vein volume relative to the total ice volume, in the following called ice porosity Phi"

p3 line 68: please change the unclear wording "Thus the c_B peak translates"

p4 l96: replace "we" by "I" throughout the manuscript

p4 l111: "The three terms on its right-hand side describe the temperature depressions due to (i) solute, (ii) interfacial curvature (the Gibbs-Thomson effect) and (iii) pressure, respectively;"

p4 l 113: what does the constant gamma represent?

p6 l147: "... where the melt rate m (in units?) at the interfacial boundaries of the vein accounts..."

p6 line 155: why not explain the last term here?

p7 equations 17 and 18: You neglect dw/dz. Say explicitly why.

p11 l256: "while anomalous (Rempel) diffusion"

p11 l273-274: use a different variable for the basal melt rate (for example m_bas) to distinguish it from the interfacial melt rate m used above

p12 l298: Likely a topic to be looked at in a separate paper, but the theory by Ng should be also able to predict how much vein diffusional smoothing occurs for the water isotopes.

p13 l318: " to become so large to be ..."

p13 l321. The data provided in the Mayewski papers are not of really high resolution. You may also want to cite Schüpbach et al, Nature Communications 2018, Bigler et al., Quaternary Science Reviews 2010, Röthlisberger et al, CP 2008)

p13 l332: "we observe an interesting"

p13 l335-337: expand the discussion of the age span and the potential resolution loss

p15 3rd paragraph: The movies provided are very helpful! In Movie S3 and Figure 9 one of the two peaks in the GRIP ice core moves relatively upward. This deserves some discussion in the main text. Also the y-axis for the temperature profile in the movies could be scaled equally for all time steps.

p16 l403-404. I am not sure I understand this correctly, please clarify. Again, a discussion of the time-scale that could be resolved and those found in ice core records would be helpful.

p17 scenario 2: here you mention the issue of micro-inclusions which would contradict the assumption that c_B=c*Phi. As mentioned before, this assumption should be qualified as such earlier in the manuscript.

p17 l455: "vein c_B" is the wording correct???

p17 l458-459. The sentence "In any case... from SO42-" is way too general and should be specified. Fr example to which depth could we see volcanic peaks at GRIP and EPICA Dome C. Which longer-term variations could be still resolved (discussion of age span)

p18 l2: "of any vein impurities"

p18 line 476-478. expand the discussion on longer variations

p19 l498-500: This comes unexpected and justifies a little bit more discussion.

Figure 1: I know these are only illustrative figures, but the scale of the anomaly (centimeters) and the approximate location within the ice sheet of the sketch (lower third, where temperature gradients exist both in Greenland and Antarctica) should be indicated either in the figure itself or at least in the caption.

Figure 2: clarify what you mean by "that measures distance from ice at age t"

Figure 7: rescale panel f to show the age span for ice with an age of 800 kyr.

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