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

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The manuscript by Felix Ng revisits the question of what happens to soluble impurities in glacial ice over the long time periods represented by ice-core climate records. Assuming that these impurities are primarily contained within a connected liquid-filled vein-node network along three- and four-grain contacts (e.g. Nye and Frank, 1973), an earlier model predicted that the control of impurity loading on liquid content should produce spatial variations in the effective compositional diffusivity that would help to explain the long-term preservation of short wavelength (e.g. representing seasonal to decadal time periods) bulk compositional signals, while also leading to their translation relative to the surrounding ice (Rempel et al., 2001). This so-called "anomalous diffusion" phenomenon has proved very difficult to test, since the predicted rate of signal

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migration is very low (largely controlled by the shallow temperature gradients in polar ice) and firm constraints are rarely, if ever, available on the relative timing of compositional and ice-borne (e.g. oxygen isotopes) proxy deposition in the distant past. If the compositional signals themselves aren't altered in form, but only displaced a small distance relative to the ice with which they were originally deposited, what evidence is there to unequivocally demonstrate such subtle effects?

Ng's analysis predicts qualitatively different behavior in a slightly modified system, by focussing on the role of vein surface energy embodied in the Gibbs-Thomson effect, while assuming that the ice is characterized by locally uniform (but slowly growing) grain sizes. The models of anomalous diffusion that had been presented earlier had differed by employing a different assumption concerning the relationship between ice grain size and impurity loading. Measurements show that average grain size and impurity content are negatively correlated in ice cores (e.g., Gow and Williamson, 1976; Gow et al., 1997; Lipenkov et al., 1989; Azuma et al., 1999, 2000; Thorsteinsson et al., 1995; Durand et al., 2009). Rempel et al. (2001) highlighted this anticorrelation as consistent with the assumption that "the surface energy of curved interfaces acts to make vein radii uniform (Nye, 1989; Mader, 1992)", reasoning that "variations in [bulk impurity loading] must correlate with changes in the total length of veins per unit sample volume". Effectively, the idea was that by responding to impurity loading, grain sizes could adjust and prevent differences in vein radii from occuring. By contrast, Ng treats the grain size and impurity loading as unrelated, implying that vein radii are initially in disequilibium when changes in deposition produce changes in impurity loading, so that the vein radii subsequently evolve towards uniformity. This equilibration of vein radii drives additional computational transport that adjusts the impurity loading, thereby modifying the form of the compositional signals and preventing their displacement relative to the ice.

The analysis by Ng is elegant and clearly presented, and represents a welcome addition to the literature that describes post depositional processes with potential to be

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relevant to ice core records. To better convey the departure from the earlier efforts to address this particular problem, it would be helpful to clarify the discussion surrounding the different assumptions regarding ice grain size. At present, the reason given by Ng for neglect of the Gibbs-Thomson effect in the Rempel et al. (2001) model is the scaling in the liquidus relation (line 122). However, the original reasoning provided by Rempel et al. (2001, p. 370) emerges from the assumption that an anti-correlation between grain size and impurity loading makes vein radii uniform, as predicted if grain size scales inversely with the square of bulk impurity loading in equation (7) of the current work, thereby rendering the second term in equation (8) spatially uniform as well. Unfortunately, as noted by Ng around line 239, “reliable grain-size modelling remains out of reach”, though impressive improvements have been made in recent years (e.g. Faria et al., 2014; Ng and Jacka, 2014). Nevertheless, no convincing treatment has yet been provided that is quantitatively successful at representing the causal mechanisms that produce the observed anti-correlation between grain size and impurity loading. The current work highlights yet another reason, in addition to more commonly evoked considerations of the effects of grain growth on rheology and fabric development, for the importance of addressing this challenge.

Under the impurity-independent grain size assumption, Ng demonstrates convincingly that short-wavelength compositional variations (with impurities confined entirely to the vein-node network) should not persist over multi-millennial time scales under typical ice core conditions. Clearly, the apparent preservation of such signals deep in the ice requires further explanation, and Ng provides considerable insight into various potential mechanisms that might resolve this conundrum. Ultimately, two scenarios are championed, with the first involving some mechanism for blocking vein transport, for example with dust particles (e.g. Raymond and Harrison, 1975), and the second relying on impurities being largely confined to the ice matrix or two-grain boundaries (e.g. Eichler et al., 2017). The model of Rempel et al. (2001) shows that a strong coupling between bulk impurity content and grain growth could provide a third mechanism by reducing or eliminating spatial variations in vein radius and greatly damping the influence of the Gibbs-Thomson effect on impurity transport. Likely some elements of all three scenarios contribute, and efforts to quantify post-depositional changes would benefit from further efforts aimed at unravelling their relative importance. Ng's manuscript represents a valuable, detailed exploration of the end member case in which grain size is independent of bulk impurity content. This clear and cogent analysis has important implications, and it is to be hoped that it will motivate efforts that provide even further constraints on how exactly post depositional compositional migration occurs in nature.

I note that Reviewer 1 has already provided detailed suggestions for minor wording changes and I have nothing significant to add.

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