Reply to comments provided by **D. Etheridge** on "*Local artifacts in ice core methane records caused by layered bubble trapping and in-situ production*" by R.H. Rhodes et al.

We thank David Etheridge for his positive assessment of our detailed study into gas trapping artifacts.

The major comments are addressed individually below:

- *Is it possible that some CH_4 artefact could have been produced by production during the melt extraction process for the ice core gases?*
  A process that could produce CH_4 by melting ice containing trace levels of impurities would be very interesting but our observations suggest it does not occur. We are confident that the signals we observe are present in the ice because 6 cm resolution discrete CH_4 measurements display similar fluctuations (Fig. 3). Additionally, repeated analyses of parallel ice sticks have revealed consistent signals (Fig. 6, (Rhodes et al., 2013) EPSL). Moreover, during conventional melt extraction of discrete ice samples, the gas phase is in contact with the liquid phase for a much longer period of time without any apparent CH_4 production.
- *Would [post-coring bubble closure] help explain the variability measured in the [lock in zone] region of the cores?*
  Yes, it seems likely that this occurs and contributes to some of the additional variability in the lock in zone region of all the cores analysed (Fig. S4). The likelihood of post-coring bubble closure contamination is considered in section 3.3, Pg. 12. We can not quantify the contribution from post-coring bubble closure as Mitchell et al. (2015) were able to for WAIS-Divide but they suggested ~10% of the air was affected by it.
- *How the processes of bubble closure and firn diffusion might interact...early bubble closure might impede diffusion to lower layers...How could this effect be observed or quantified...?*
  The majority of coring sites contain at least a few melt layers within the firn column, but to our knowledge there is only one documented case (an exceptionally thick melt layer at DE08-2) where such a layer actually impeded vertical diffusion (Trudinger et al. 1997). Therefore, it seems unlikely that regular firn layering, which is much less extreme than melt layering, would significantly reduce vertical mixing. From the data we have, we conclude that the regularity of the CH_4 oscillations argues for a maintenance of vertical diffusion in the firn column (until the lock-in depth is reached). This allows the [less dense] summer layers, located deeper than the winter layers that begin to close off early, to obtain higher CH_4 concentrations.
  The ice layers in the NEEM core (2 and 0.6 cm thick) were found to have some permeability (Keegan et al., 2014) and not exert a profound impact on the composition of the open porosity. In contrast the melt layer in DE08-2 appeared reduce molecular diffusion by about 80% (Trudinger et al., 1997). If a firn column did have a true sealing layer of sufficient horizontal extent to drastically limit vertical diffusion, the CH_4 trapping signal amplitude at deeper depth would be damped and an abrupt increase in the CH_4 trapping signal amplitude would occur across the depth of the sealing layer. This might be recognisable by a deviation from the linear atmospheric growth rate – trapping signal amplitude relationship (Fig. 5).

- *Sealing layers...have been observed...but not in sites in the present study. How would such layers, if they existed show up in the observation presented here?*
  The possibility of sealing layers existing in the firn column above the lock-in zone is discussed above. Sealing layers must exist in the lock-in zone (because firn air studies show that vertical diffusion ceases) and our data provide strong support for the sealing layers at the lock-in depth being dense winter layers, as Martinerie et al. (Martinerie et al., 1992). The CH_4 data through the lock-in zones of three cores presented on Fig. S4 show contrasting CH_4 concentration between layers, and for the high accumulation D4 site these oscillations are definitely annual. These data record the change between sealed-off, dense winter layers with low CH_4 values and less dense, highly permeable summer layers with high CH_4 values (resulting at least in part from contamination).
- *Is it possible, although I understand it's probably beyond the scope of this work, that vertical movement through cracks or channels...could induce non-diffusive mixing with implications for isotopic fractionation as well as age spread?*
  This is certainly a conceivable scenario. It has been shown at the NEEM site that non-diffusive mixing occurs within the lock-in zone (Buizert et al., 2012). The most likely explanation for this effect is dispersive mixing driven by surface pressure variations (so-called barometric pumping). The presence of channels or vertical cracks could greatly enhance dispersive mixing.

Most of the minor comments listed can be addressed with minor changes to the manuscript text or figures. Answers to specific queries are below:

- *Pg. 7 lines 21-26. Where these measurements made on horizontally-adjacent ice?*
  Yes, the text will be updated.
- Pg. 8 line 22. *The differences may also be due to the other chemical-physical processes presented in this work?*
  The differences in multi-decadal signal amplitude between ice core sites are primarily the result of diffusive mixing and gradual bubble occlusion which occur in the firn pack. So yes, the gas trapping artifacts we investigate are associated with these same processes.
- *Did the forest fire cause high CO in the laboratory air? Wouldn't this help to detect ingress of ambient air?*
  Yes, the forest fires caused high CO values in the ambient air. In a previous study (Rhodes et al., 2013) we were able to use the *absence* of elevated CO as indicative of ambient air and the *presence* of high CO, in conjunction with high CH_4, as indicative of an anomalous in-situ CH_4 signal. The high lab air CO prevented us from making this distinction in this study.
- *How does microbial activity enhance CH_4 in the vicinity of melt?*
  This remains unknown. Page 9 line 24 has been reworded in the revised manuscript to: "Anomalously high CH_4 values in ice cores have been linked to melt layers because a) the solubility of CH_4 in water is greater than that of bulk air, and/or b) previous studies suggest a potential for CH_4 production by microbial activity, via reaction pathways that are currently unknown (Campen et al., 2003; NEEM community members, 2013)."
- *Isn't the dissolved CH_4 released during refreezing of the layer?*

This probably happens to some extent but we don't consider it because we want to calculate the maximum possible CH_4 concentration that could be produced by the preferential dissolution of CH_4 relative to N_2 in the meltwater.

Buizert, C., Martinerie, P., Petrenko, V.V., Severinghaus, J.P., Trudinger, C.M., Witrant, E., Rosen, J.L., Orsi, A.J., Rubino, M., Etheridge, D.M., Steele, L.P., Hogan, C., Laube, J.C., Sturges, W.T., Levchenko, V.A., Smith, A.M., Levin, I., Conway, T.J., Dlugokencky, E.J., Lang, P.M., Kawamura, K., Jenk, T.M., White, J.W.C., Sowers, T., Schwander, J., Blunier, T., 2012. Gas transport in firn: multiple-tracer characterisation and model intercomparison for NEEM, Northern Greenland. Atmospheric Chem. Phys. 12, 4259–4277. doi:10.5194/acp-12-4259-2012

Campen, R.K., Sowers, T., Alley, R.B., 2003. Evidence of microbial consortia metabolizing within a low-latitude mountain glacier. Geology 31, 231–234. doi:10.1130/0091-7613

Keegan, K., Albert, M.R., Baker, I., 2014. The impact of ice layers on gas transport through firn at the North Greenland Eemian Ice Drilling (NEEM) site, Greenland. The Cryosphere 8, 1801–1806. doi:10.5194/tc-8-1801-2014

Martinerie, P., Raynaud, D., Etheridge, D.M., Barnola, J.-M., Mazaudier, D., 1992. Physical and climatic parameters which influence the air content in polar ice. Earth Planet. Sci. Lett. 112, 1–13. doi:10.1016/0012-821X(92)90002-D

Mitchell, L.E., Buizert, C., Brook, E.J., Breton, D.J., Fegyveresi, J., Baggenstos, D., Orsi, A., Severinghaus, J., Alley, R.B., Albert, M., Rhodes, R.H., McConnell, J.R., Sigl, M., Maselli, O., Gregory, S., Ahn, J., 2015. Observing and modeling the influence of layering on bubble trapping in polar firn. J. Geophys. Res. Atmospheres 120, 2558–2574. doi:10.1002/2014JD022766

NEEM community members, 2013. Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493, 489–494.

Rhodes, R.H., Faïn, X., Stowasser, C., Blunier, T., Chappellaz, J., McConnell, J.R., Romanini, D., Mitchell, L.E., Brook, E.J., 2013. Continuous methane measurements from a late Holocene Greenland ice core: Atmospheric and in-situ signals. Earth Planet. Sci. Lett. 368, 9–19. doi:10.1016/j.epsl.2013.02.034

Trudinger, C.M., Enting, I.G., Etheridge, D.M., Francey, R.J., Levchenko, V.A., Steele, L.P., Raynaud, D., Arnaud, L., 1997. Modeling air movement and bubble trapping in firn. J. Geophys. Res. Atmospheres 102, 6747–6763. doi:10.1029/96JD03382