

Reply to referee's comments

Referee 1: Mauro Rubino

General comments

The manuscript by Jang et al. describes a study performed on the firn, the upper part made of partially compacted snow/ice, of Styx Glacier (near the coast of East Antarctica). The authors report older than usual firn air for a coastal site in Antarctica, where snow accumulation rate and temperature are relatively high. They suggest that firn layering, possibly produced by blizzards, creates a thick lock-in zone, which, in turn, causes the age of firn air to grow quickly before close-off.

Interactive comment

The paper is decently well written and clear enough (though I suggest some changes to improve clarity in the attached document). The methodology is adequate and the results are discussed in a balanced way. However, the conclusions are somewhat overstated because the authors generalise their findings without showing that the correlation between lock-in zone thickness and firn air age holds for all sites in Antarctica.

- ⇒ The high resolution (cm-scale) density measurements needed to generalize our analysis to all Antarctic firn sites are not available, unfortunately. Firn air data show very clearly that within the lock-in zone air ages much faster (in units of years/m). Therefore it is clear that all else being equal, a thicker lock-in zone will always lead to older air.
- ⇒ To address this comment we reworded the last sentence in the abstracts as follows:
"Our study demonstrates that all else being equal, sites where weather conditions are favourable for the formation of large density variations at the lock-in zone preserve older air within their open porosity, making them ideal places for firn air sampling."

The results seem to be relevant to the journal's readers and, more in general, to the scientific community working on ice core science. However, the major novelty is the finding of the relatively old firn air for a coastal site. There is no major advancement in understanding the mechanisms of firn formation and air bubble sealing. I believe the article can be published in a technical, specialist journal (after some revisions as suggested in the attached document), but I leave it to the Editor to decide whether the manuscript is suitable for The Cryosphere.

- ⇒ The Cryosphere has a long history of publishing articles on firn air, gas diffusion, and snow layering. We clearly demonstrate a link between strong density layering and a thicker lock-in zone, which provides new insights into the nature of the lock-in zone (which is not completely understood). We now also discuss age distributions at various sites with old firn air, showing that the Styx age distribution is very narrow, allowing for higher resolution atmospheric reconstructions. We believe all these contributions make the article suitable for The Cryosphere.

Specific comments and technical corrections See notes in the attached document.

- ⇒ We appreciate the reviewer's comments. We have responded to each comment below.

Specific comments from Referee #1

Line 27: Maybe better "more rapidly than in the diffusive zone"

- ⇒ We reworded the sentence as follows:
"We hypothesize that the large density variations in the firn increase the thickness of the lock-in zone and, consequently, increase the firn air ages because the age of firn air increases more rapidly with depth in the lock-in zone than in the diffusive zone."

Line 35: What do you mean by "those"? Which ones? I would delete "those"

- ⇒ Deleted.

Line 37: It is not clear why you have decided to cite Etheridge et al. (1996 and 1998) to support your statements about obtaining records of atmospheric history from firn air. I understand Etheridge et al. have been among the first to show overlap of ice core, firn and atmospheric gas measurements, but, here I would rather cite the early articles on firn air from Schwander et al. (1989 and 1993)

- ⇒ Etheridge et al. (1996, 1998) was replaced with Schwander et al. (1989 and 1993)

Line 39: "trace" => and ultra-trace

- ⇒ "trace" is a more general term and may help readers understand better. Therefore, we decided to retain the word "trace"

Line 42: You need to cite the relevant articles for South Pole and McMurdo here

- ⇒ We added Battle et al. (1996) and Severinghaus et al. (2010)

Line 46: "The firn air" => Delete "the"

- ⇒ Deleted.

Line 52: "diffusive and lock-in zones" => Delete "zones"

⇒ Deleted.

Line 55: "d15N of N2" => Why do you mention d15N of N2 only and not other species? Given that you mention it again below, for non-experts, it could be worth explaining here why d15N of N2 is a powerful tracer of firm processes.

=> We added the following line to help the non-expert readers:

"The gravitational enrichment in $\delta^{15}\text{N}$ of N_2 is traditionally used to define the boundaries between these zones."

Line 59: "stagnant" => I would remove "stagnant"

⇒ Deleted.

Line 64: "mature" => Maybe "sealed" is a better word than "mature"?

⇒ "mature" was replaced with "sealed."

Line 65: "occurs the density" => Add "when": "... occurs when the density..."

⇒ "when" was added.

Line 77: "-" => Delete dash; "The firm air models..." => Delete "the"

⇒ Deleted.

Line 78: "the layering" => Delete "the"

⇒ Deleted.

Line 79: "movement the firm air" => Delete "the"

⇒ Deleted.

Line 101: Replace "that was" with a comma

⇒ Replaced.

Line 103: Replace "two-year" with "two years"

⇒ Replaced.

Line 115: Delete "being inflated in", and maybe add something like "providing no risk of sample contamination" at the end of the sentence

⇒ Corrected.

Line 125: "4 types of..." => Is this the model version containing the parametrization of bubble

trapping described in Mitchell et al. (2015)? Please, specify.

⇒ Yes, it is. We added:

"The model uses the stochastic bubble trapping formulation described by Mitchell et al. (2015)."

Line 127: Replace "A velocity of the air" with "Air velocity". Also, it is not very clear to me why you have decided to show this equation here. Is the mathematical formulation of air velocity important for your interpretation? Please, explain your choice.

⇒ We deleted the equation as the reviewer suggested. We also deleted "A velocity of the air" because the words are used to introduce the equation.

Line 129: Should "Wair" actually be "Wair(z)"?

⇒ Yes. We replaced "Wair" with "Wair(z)."

Line 134: "total air content measurements" => I do not see any description of the measurements of total air content in this section

⇒ We newly added a few sentences to describe the methods.

Line 139: Please explain why removing surface ice is needed.

⇒ "to remove the surface ice" was changed to "to remove contaminants on the surface ice."

Line 140: "in the cooled" => Replace "the" with "a"

⇒ Replaced.

Line 142: "air in the bubbles were extracted" => Replace "were" with "was"

⇒ Corrected.

Line 149: "After the measurement" => After completing the measurements of...

⇒ Corrected.

Line 152: "Wrap text for the equations, as done for equation 1"

⇒ Done.

Line 171: (Fig 2a) => It is not clear to me why in the figure caption you state that the pit is 220 cm deep, but you only show 180 cm in figure 2b. I would make them the same for consistency.

⇒ We measured only the top 180 cm because that is sufficient for the purpose of the research.

Line 172: "hoarse" => I have never heard this term (hoarse) used in this way. Could you explain what that means?

⇒ We revised the word “hoarse” to “depth hoar”

Line 173: (Fig. 2b) => I cannot really see the difference between low-density and high-density layers from the red line and the blue layers in figure 2b. First of all, you should explain what the blue and light-blue layers represent. Most importantly, what is the relationship between changes in density (as shown by the red line) and changes in the blue/light-blue layering?

⇒ We added a few words in the figure caption as follows:

“(b) Illustration of qualitatively defined hard (high-density, dark blue) and soft (low-density, pale blue) layers observed in the top 180-cm-depth interval. Progressive blue color changes indicate a gradual density decreases with depth. The red line is a 10-cm-resolution density profile.”

Line 177: Fig. 2b-d => It would be good to explain how you have obtained the pictures in figures 2c-d in the Method section.

⇒ 2b. Method for obtaining the 10-cm-resolution density measurements is described in Section 3.1.

⇒ 2c-d photographs. We added scale bars in the figures and words in the figure caption, so that the readers can better understand how the figure was obtained.

Line 182: “Etheridge et al. (1996, 1998)” => Are you saying that you have used Law Dome firn air for calibration? If so, please specify it. Also, Etheridge et al. might not be the best references to cite here. There are two articles with Law Dome firn air records published more recently: MacFarling Meure et al. (2006) and Rubino et al. (2019)

⇒ We revised the references. The history was based on MacFarling Meure et al (2006)

Line 183: “The simulated mole fraction profiles match well with observations” => It would be good to comment on by how much and why the model seems to overestimate CO₂ and especially CH₄ at the bottom of the firn column.

⇒ We have updated the tuning of the diffusivity and dispersion using the automated method described in Buizert et al. (2012) and Buizert (2011). This has improved the fit to the deepest data, and the calculated gas ages are indeed older now, as suggested by the reviewer.

Line 191: “(MacFarling Meure et al., 2006)” => A new version of the Law Dome greenhouse gas records has just been published in Earth System Science Data: Rubino et al. (2019). Consider replacing MacFarling Meure et al. (2006) with Rubino et al. (2019)

⇒ We reworded this sentence as follows:

“The lowest CO₂ mole fraction of 305.18 ppm at depth of 64.8 m (304 ppm after correcting for gravitational enrichment) corresponds to the year of 1922 and an effective age of 93 years (relative to sampling year 2014) on the Law Dome ice core

record (MacFarling Meure et al., 2006; Rubino et al., 2019)."

Line 195: "(Severinghaus et al., 2001; Fig. 4)" => This is confusing: are you referring to figure 4 of your manuscript or figure 4 in Severinghaus et al. (2001)? If you refer to your figure 4, then it might be better to move "Fig. 4" before, maybe where the colon is.

⇒ We deleted "Fig. 4" to avoid the confusion.

Line 197: I wonder why you have not included Law Dome in Table 1, given that you have used Law Dome firn air records for calibration purposes (if I have understood) and you have cited the main publications of Law Dome records.

⇒ We added the Law Dome data in Table 1.

Line 197: "therefore the firn air" => Delete "the"

⇒ Deleted.

Line 204: Replace "and therefore" with "because"

⇒ Replaced.

Lines 207-208: CO₂ has increased as well during the last century. Why have you not used CO₂ too? Please explain

⇒ Only CH₄ is sufficient for qualitative data interpretation in this study. Additional measurements for other gas species would not change the main conclusions of the article. CH₄ is more easily measured in ice than CO₂ is, because a melt extraction can be used.

⇒ We slightly changed the words as follows:

"Because the mole fractions of atmospheric greenhouse gases (CO₂, CH₄, N₂O) have increased during the last century, we may obtain information on the timing of the closure of the bubbles from the greenhouse gas mole fractions of the air trapped in closed bubbles. In this study, we used the CH₄ concentration in closed bubbles ([CH₄]_{cl}) and the total air content of the firn ice as indicators of the close-off process."

Line 210: "density and [CH₄]_{cl} show an anti-correlation (Fig. 5)" => Please, specify that you have measured it near the COD. Also, it is not clear to me what shows the anticorrelation you mention. Could you include an inset showing the density vs CH₄cl anticorrelation in a scatter plot?

⇒ As the 2nd reviewer suggested, we expanded the depth axis in Fig. 5a-5d such that the anti-correlation may be easily seen.

Line 211: "low-density layers do" => Delete "do"

⇒ Deleted.

Line 213: Delete "Meanwhile"

⇒ Deleted.

Line 214: Cite Aydin et al. (2010), "Post-coring entrapment of modern air in some shallow ice cores collected near the firn-ice transition: evidence from CFC-12 measurements in Antarctic firn air and ice cores", Atmos. Chem. Phys., 10, 5135-5144

⇒ Citation was added.

Line 218: Maybe better something like: "cm-scale variability becomes lower with depth", if this is what you mean by "variations are stabilized at deeper layer"

⇒ "the variations are stabilized at a deep layer" was changed to "the cm-scale variability is reduced in deep layers"

Line 222: "snow fit likewise showed..." => Keep on using present tense for consistency: replace "showed" with "shows"

⇒ Changed.

Line 227: "[www.clim-past...](#)" => I do not think this is needed

⇒ Deleted.

Line 237: "defined by the firn air d15N-N2" => I would say: "defined by the modelled d15N-N2 firn air profile".

⇒ Revised as suggested.

Line 237: Delete "Meanwhile"

⇒ We think that it would be better to retain this word.

Line 240: "thickness of LIZ from density data" => Worth specifying "(between the two orange lines in Fig. 6a)"

⇒ We added "(between the two orange lines in Fig. 6)".

Line 240: "comparable" => Please, provide numbers. How thick is the LIZ from density data and from firn air analysis?

⇒ We added "(15.6 vs. 12.4 m)"

Line 244: "in spite of the possibilities of error" => I suggest you delete this sentence, as there is always the possibilities of error

⇒ We deleted the words.

Line 244-246: "similarity in the LIZ thicknesses..." => This reasoning is not clear to me. Please rephrase

=> We added the following explanation of our procedure: "We test the idea that the lock-in zone corresponds to the depth range bounded by the first closed layer (porosity below 0.1) on the shallow side, and the last open layer (porosity above 0.1) on the deep side."

⇒ We reworded the sentence as follows:

⇒ "The similarity in the LIZ thicknesses from the two methods support the idea that..."

Line 246-247: "We demonstrate here that..." => I do not think you have demonstrated this. Rather, it is something known from past studies (Mitchell et al., 2015 and Horohold et al., 2011) that your study is just confirming at one more site (Stix Glacier). I suggest you replace "demonstrate" with "confirm". To generalise your results, you should show that they hold for all firn sites in Antarctica. For example, in the Introduction you mention Dome C as an exception of site with low accumulation and temperature, but relatively young firn air. Can the characteristic layering at Dome C explain why firn air does not get very old at that site? If you can show this, then your results are valid more in general.

⇒ We changed "demonstrated" to "confirm."

With regard to the generalization, unfortunately, the high-resolution density data are limited only a few ice cores. Our main goal is not to generalize, but rather report on the old firn air in the coastal site and discuss its causes.

Line 262: "Horhold et al. (2011) did (Table 2)" => "as Horhold et al. (2011) did for the other sites listed in Table 2."

⇒ Changed as suggested.

Line 267: Why have you not plotted the correlation between sigma density and LIZ thickness for all sites in table 2 (or even more, if data exist)?

⇒ High-resolution density data are required to calculate the sigma density, but they are not available for the other sites.

Line 273-281: All this section could go in section 3.1, whereas here you just comment on it.

⇒ We think the paragraph is better located here because the d18O data support the idea that non-seasonal events (e.g., blizzards) are the main control of snow layering.

Line 282-283: Are you suggesting that blizzards can be the main factor controlling snow density variability in firn? If so, you should write it clearly.

⇒ We added the following sentence at the end of the paragraph to clarify the possibility: "In summary, blizzard events may have played a major role in forming snow density layers."

Line 330: The surname of the third coauthor appears to be missing

⇒ Corrected.

Fig. 1b: What is the black object in fig 1b? A pen? What is its size? It would be good to provide some indications of the size of each element shown in fig 1b.

- ⇒ We added the following sentence in the figure caption:
"The length of the black sharp pencil in (b) is 14.3 cm."

Fig. 4: Eight (8) figures are definitely too many for such a short paper. This figure (fig 4), and also figure 8, could go in a Supplement.

- ⇒ We moved Fig. 4 and Fig. to *Supplement Materials*.

Fig. 5a: Please, include Total air content and CH₄cl in the legend. Also, explain in the figure caption what the "b" above the blue line represents.

- ⇒ As the 2nd referee suggested we extended the depth axes and separated the previous Fig. 5a into Fig. 5a-5d. We also made a box in Fig. 5d where the Fig. 5e is located (previous Fig 5b is now Fig 5e).