Clim. Past Discuss.,
https://doi.org/10.5194/cp-2017-158-AC2, 2018

Climate of the Past Discussions

Interactive comment on "High latitude Southern Hemisphere fire history during the Mid-Late Holocene (750–6000 yr BP)" *by* Dario Battistel et al.

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Received and published: 22 March 2018

Anonymous Referee #2

This manuscript describes the first long-term record of levoglucosan from Antarctica. Levoglucosan, a specific biomarker of biomass burning, was measured from 750-6000 yr BP. The levoglucosan record was compared to Kbb of the same ice core. The authors conclude that the Kbb record supports the Levoglucosan record and for the interpretation rely on the Levoglucosan record. The authors compare the levoglucosan record to charcoal records and demonstrate the greatest correlation to Patagonia charcoal. The authors propose that in general, the levoglucosan record demonstrate a linkage between climatic changes in Patagonia and biomass burning. Lastly the authors focus on

a peak in Levoglucosan centered at âĹij2,000 yr BP. In general, I found this manuscript interesting to read and the manuscript is well written. I appreciate that this the first long-term ice core record of levoglucosan from Antarctica.

I recommend the authors do not focus the manuscript on the individual spikes observed in their records as these spikes have not be replicated in other Antarctic ice cores and therefore the spikes may be driven by degradation/transport rather than changes at the source. I think the manuscript would benefit from removing repetitive sections in Section 3 while adding additional discussion in other parts of the manuscript. In addition, this manuscript would benefit from a clearer explanation of the climatic mechanisms driving the observed correlations.

Specific comments:

Introduction: It is worth noting on page three that while few Levoglucosan records exist in Antarctica, several studies on the monitoring of biomass burning byproducts (Hu et al., 2013 Scientific Reports; Pereira et al., 2006; Weller et al., 2013; Wolff and Cachier, 1998; Fiebig et al., 2009; Hara et al., 2010) have been conducted in Antarctica. In addition, other biomass burning proxy records have been published from Antarctic ice cores (ex. Pasteris et al., 2014; Bisiaux et al., 2012; Arienzo et al., 2017) and are also worth mentioning here.

Reply:Thank you for this suggestion. We included these references in the introduction section in the following sentences:

"However, Southern Hemisphere levoglucosan records still leave much to be explored. Antarctic levoglucosan records will likely differ from Arctic records due to the substantially smaller land masses surrounding near the ice sheet and the long distances required for atmospheric transport of biomass burning material. The southernmost tip of Patagonia, the closest continental landmass to Antarctica, only extends to $\sim$55°S, whereas the Arctic contains the largest land masses in the world. Although long-term levoglucosan records have never been reported for Antarctic ice cores, several stud-

ies determine other biomass burning by-products (i.e. secondary organic aerosol and black carbon) during the last few decades and centuries (Wolff and Cachier, 1998, Fiebig et al. 2009, Hara et al. 2010, Hu et al. 2013, Weller et al. 2013, Pasteris et al. 2014) as well as during the Holocene (Arienzo et al. 2017)."

Section 2.1: How was LoQ determined?

Reply: We added the following discussion to page 4 to better explain how we determined the LOQ:

"The instrumental limit of quantification (LoQ) for levoglucosan was 4 pg mL-1, determined following the analytical method reported in Gambaro et al. 2008. From an analytical point of view, a reliable procedural LoQ is difficult to determine in this case, due to the lack of a suitable aqueous matrix. The glacier water often contains lower concentrations of levoglucosan than the ultra-pure laboratory water, thereby complicating obtaining a true LoQ. However, this method only requires as a few pre-analytical procedures, where these steps are always performed in a dedicated clean room, we therefore use the instrumental values as the LoQ."

Section 2.2: What are the errors on the ages at this depth in the ice core? Since Kbb is introduced in this section, I would suggest moving equation 1 and the explanation here.

Reply:We now include a supplementary file with all of the raw data and associated age errors (rawdata.xls). We followed your suggestion to move equation 1 to section 2.2.

Figure 2: I found figure 2 very confusing in particular since the X-axis and Y-axis vary per plot. I would recommend plotting the fluxes on the same X axis and possibly changing the color of the lines to indicate the different data being plotted. I would also include accumulation rate in this plot to demonstrate that the levoglucosan and Kbb flux records are not dominated by variations in accumulation. Lastly, in both A and B a LOWES smoothing is shown with two varying SPAN parameters. I don't understand

why the red curve in panel A is lower frequency and the red curve in panel B is higher frequency (when compared to the black cure in each panel). I also noticed that in figure 3, a different SPAN is used and then in figure 4 a 250-year average window is shown. I would recommend choosing one smoothing parameter and showing the results using that smoothing in all figures. This allows the reader to easily compare between the various plots.

Reply: We completely revised Figure 2, following your suggestions. We now use a SPAN parameter of 0.2 in each figure. We also include a graph of the accumulation in Figure 2.

Section 3.1: In this section, the authors demonstrate at the end of page 5 to the second paragraph on Page 6 that there are significant uncertainties associated with interpreting the spikes observed in the Levoglucosan record. This provides the justification for removing the large spikes when discussing the overall trend of the Levoglucosan record. However, later in this section and in other parts of the manuscript the authors discuss the spikes as potential evidence of specific fires. I would caution the authors about interpreting the spikes observed in the record as changes in the source area, considering that there are very few that agree between the levoglucosan and Kbb records and that transport is potentially a large driver of the spikes.

Reply: We agree with the fact that spikes are not very informative by themselves and that they may lead to incorrect assumptions. In the original version, we tried to emphasize the fact that spikes must be considered carefully. In order to deemphasize the spikes, we reduced the discussion of spikes, and moved this discussion to the end of Section 3.1. This paragraph is now the following:

"The attribution of the levoglucosan spikes to individual large fire events is difficult to assess as atmospheric transport and stability may alter the signal, resulting in an amplification of modest fires. A similar situation occurs for individual peaks in charcoal records as these spikes can either be intense local fire events or can result from an

increase in short-term transport. For example, the high charcoal signals observed in Laguna Padre Laguna (Argentina) between ∼1500 and ∼2000 yr BP and at Laguna Zeta (Argentina) between ∼2000 and ∼2500 yr BP (Iglesias and Whitlock, 2014) are consistent with the spikes observed in the levoglucosan record, as well as intense fire episodes recorded between ∼2100 and ∼2300 yr BP in the Wingecarribee Swamp (Southern Australia (de Montford, (2008); ID site=857 in the GCD) and at 2160 yr BP in Eweburn Bog (New Zealand, (Ogden et al. 1998)); ID site=441 in the GCD). A possible correspondence with levoglucosan and these individual charcoal spikes is only speculative. Comparing trends in long-term fire activity, as identified by smoothed levoglucosan records and charcoal syntheses, is more indicative of changes in biomass burning as opposed to comparing individual, likely localized, events. We therefore only discuss biomass burning trends rather than individual spikes from this point forward."

Section 3.3: I suggest renaming this section "Biomass Burning Sources" I appreciate that the authors discuss the potential for other biomass burning sources in this section (lines 19-29, p. 9). However, I would encourage the authors to preface this with a discussion of the comparison between the Patagonia and the TALOS record as several differences and similarities exist. For example, at 4.5 kyr the TALOS Levoglucosan begins to increase, while the Patagonia record is decreasing at this time. This could then be followed by a discussion of other possible biomass burning sources. Lines 26 to 29 p. 9 would be more appropriate in section 3.4.

Reply: We changed the title of this section to "Biomass Burning Sources" and expanded the discussion of the similarities and differences in the records into the following paragraph. In addition, we combined Sections 3.2 and 3.3 (please see the following point) to better continue the discussion of possible fire sources.

"Talos Dome Levoglucosan and southern South America charcoal records (Fig.3) both depict an increasing long-term trend in biomass burning from 4000 to 750 yr BP, although these trends do not perfectly coincide. These records differ both before and after these ∼3000 years of similarity. The Talos Dome record begins its major and sus-

tained increase in fire activity around 4500 yr BP, while the southern South American record is decreasing during this time period. The southern South America and East Australian records substantially diverge after 750 yr BP, where the southern South American fires decrease and the East Australian and SH fires both markedly increase. The Talos Dome levoglucosan record does not extend to the present, and so comparisons with this major difference in regional fire sources is not possible."

Section 3.3 addresses the potential sources of biomass burning, not the impact of climate on the charcoal records. Lines 19-26 are relevant as they explain the heterogeneity of fire in Australia so maybe something like "Similar heterogeneities are not observed in Patagonia (Ref)" would be more appropriate instead.

Reply: We now concentrate the only the sources of biomass burning in this section, and have moved what was Section 3.3 to the end of Section 3.2. This paragraph is now the following:

"These results may suggest a higher contribution from southern South American fires rather than Australian biomass burning over centennial to millennial timescales between 4000 to 750 yr BP, although the contribution from East Australia cannot be completely neglected. However, it is also possible that this observation may be due to the higher regional variability in East Australian fire activity (Mooney et al., 2011). During the Mid-Holocene, sites in the far south of South-Eastern Australia showed higher fire activity due to a shift toward more moisture-stressed vegetation, while sites in the Southern Tablelands and east of the Great Dividing Range showed less fire activity with the region supporting relatively moisture-demanding vegetation (Pickett et al., 2004; Mooney et al., 2011). Thus, over a wider spatial scale, these contributions tend to cancel one another. As a result, although the South-Eastern Australia charcoal synthesis is characterized by higher values at about 6000 yr BP, during the Mid-Holocene, only small local increases at ∼4000 y BP and ∼2500 yr BP were observed. The southern South American fire synthesis is generally more homogenous, although some regional spatial variability between northern and southern Patagonia does exist (Mundo et al.

2017). The southern South American region defined in these charcoal syntheses extends Patagonia to the Argentinian Pampas, encompassing grassland, steppe, desert and forest vegetation."

Section 3.4: I would rename this section "Drivers of biomass burning" This section overlaps with section 3.6. I would consider merging the two sections to make one section that very clearly states what the proposed drivers of biomass burning and the mechanisms driving these changes are. Also reorganizing would allow the authors to discuss figure 4 in its entirety in one section.

Reply: We merged sections 3.4 and 3.6, and omitted section 3.5 in order to improve the flow of the paper.

Section 3.5: Given the uncertainties in the sources of levoglucosan and transport variations I would be cautious about attributing the spikes in the Levoglucosan record to specific fire events within charcoal records.

Reply: We omitted section 3.5, but did keep the following short discussion on individual spikes, which is now at the end of section 3.1. We kept the following paragraph in order to primarily address the fact that we will only examine long-term trends in the data:

"The attribution of the levoglucosan spikes to individual large fire events is difficult to assess as atmospheric transport and stability may alter the signal, resulting in an amplification of modest fires. A similar situation occurs for individual peaks in charcoal records as these spikes can either be intense local fire events or can result from an increase in short-term transport. For example, the high charcoal signals observed in Laguna Padre Laguna (Argentina) between $\sim$1500 and $\sim$2000 yr BP and at Laguna Zeta (Argentina) between $\sim$2000 and $\sim$2500 yr BP (Iglesias and Whitlock, 2014) are consistent with the spikes observed in the levoglucosan record, as well as intense fire episodes recorded between $\sim$2100 and $\sim$2300 yr BP in the Wingecarribee Swamp (Southern Australia (de Montford, (2008); ID site=857 in the GCD) and at 2160 yr BP in Eweburn Bog (New Zealand, (Ogden et al. 1998)); ID site=441 in the GCD). A pos-

sible correspondence with levoglucosan and these individual charcoal spikes is only speculative. Comparing trends in long-term fire activity, as identified by smoothed levoglucosan records and charcoal syntheses, is more indicative of changes in biomass burning as opposed to comparing individual, likely localized, events. We therefore only discuss biomass burning trends rather than individual spikes from this point forward."

Section 3.6: As stated above, the overall discussion of climate/fire linkages would be much stronger if this section was merged with section 3.4. For example, P.11 line 14 the authors state that "variable and generally wet conditions prevailed in South America after 4000 yr BP" which would very nicely flow with the discussion in section 3.4. While this section includes a very nice statistical comparison to various climatic indicators, the mechanistic linkages between the climate and biomass burning (and hence Levoglucosan) are unclear. For example, what climatic mechanism would link 30 degree solar radiation in December to Patagonia biomass burning/Levoglucosan? Additional discussion with references would strengthen this section of the article. In the discussion about ENSO, is there evidence in the modern for an impact of ENSO on burning in Patagonia? It might be worth noting, other proxy biomass burning records from Antarctica (ex Bisiaux et al., 2012, ACP) demonstrate a modern relationship to ENSO. In the discussion of the drivers of the peak Levoglucosan (P. 12 lines 1-7), I appreciate the discussion here.

Reply: We agree that merging sections 3.4 and 3.6 help with the flow of the paper. As stated in one of the previous replies, we merged these sections and omitted section 3.5. We also agree that using insolation for 30°S December was not the best choice and now use solar radiation at 45°S between October-February. (Please see the new Figure 4). We also expanded the discussion section in general.

Conclusions: The statement "Potassium was analyzed in order to provide a more complete biomass burning record through the comparison with another fire proxy" should be reworded. I would suggest instead "The comparison between levoglucosan and the multi-sourced Kbb suggests that Kbb is best used in conjunction with other biomass

burning markers."

Technical/minor comments:

Page 5, line 16: This would be appropriate in the background.

Reply: We moved this phrase to the background information on page 2.

While changes in the westerly wind belt would have changed climate in Patagonia, is it possible that changes in the regional scale winds would also have impacted transport of Levoglucosan to Antarctica?

Reply: We now include the following sentence in Section 3.3.: "This interpretation is consistent with the increase of more humid conditions in continental records ((Iglesias and Whitlock, 2014 and Iglesias et al. 2014) although it cannot be excluded that the changes in the westerly wind belt may have affected, at least in part, increased transport of aerosols to Antarctica."

Why is the levoglucosan record compared to Southern Hemisphere charcoal (page 10 line 27-28) when in section 3.3 the source was determined to be most likely Patagonia? P. 11 lines 10-12: this sentence is unclear.

Reply: The Southern Hemisphere compilation helps determine the relative contributions of both southern South America, we well as including the all location south of 45°S that do not include sufficient charcoal site to be individually discussed. We expanded this section, which we hope will show the use of the Southern Hemisphere compilation:

"Talos Dome Levoglucosan and southern South America charcoal records (Fig.3) both depict an increasing long-term trend in biomass burning from 4000 to 750 yr BP, although these trends do not perfectly coincide. These records differ both before and after these $\sim$3000 years of similarity. The Talos Dome record begins its major and sustained increase in fire activity around 4500 yr BP, while the southern South American record is decreasing during this time period. The southern South America and East

Australian records substantially diverge after 750 yr BP, where the southern South American fires decrease and the East Australian and SH fires both markedly increase. The Talos Dome levoglucosan record does not extend to the present, and so comparisons with this major difference in regional fire sources is not possible."

P.11 line 16: "This 1000-year peak in levoglucosan. . ." I would encourage the authors to define the age range of the peak referenced here. A reference is needed to support the statement "the cooling period coincides with a shift to drier conditions in South America (page 12 line 6-7)".

Reply: The sentence is now the following: "This 1000-year peak in levoglucosan (between 2450$\pm$100 and 1600$\pm$1000 yr BP) occurs at the same time as a local decrease in temperature between 1500 and 2500 yr BP."

Figure 2: The Y axis for plot 2B does not have a complete label. The caption in missing a parentheses.

Reply: We completely changed Figure 2, following both these suggestions as well as your earlier idea.

Figure 4: This plot would be clearer if the y-axes were labeled rather than having the labels floating within the plot. Does the 250 yr average window include the spikes? This is unclear since the spikes are plotted.

Reply: We changed Figure 4 to include axes that are easier to read. We also changed the plotted insolation We also agree that using from 30°S to 45°S between October-February.

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