Comment on "Synchronous records of $p\text{CO}_2$ and $\Delta^{14}\text{C}$ suggest rapid, ocean-derived $p\text{CO}_2$ fluctuations at the onset of Younger Dryas" by Steinthorsdottir et al.

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Steinthorsdottir et al. (2014) used a previously published stomata-based CO_2 record (Steinthorsdottir et al., 2013) to argue for a large, abrupt change in atmospheric carbon dioxide at the onset of the Younger Dryas (YD) cold interval. Their record implies a 50 ppm CO_2 rise followed by a decline by 100 ppm. They compare their results to a hypothetical and highly unlikely simulation scenario in which vertical mixing in the ocean is increased by a factor of 100 and wind strength by a factor of 7. They furthermore compare their stomata-based CO_2 record with the ice core CO_2 record derived from EPICA Dome C (EDC).

We here question their interpretation. In detail, we argue

- that the large scatter in their data and uncertainty in the reconstructed CO_2 concentration do not allow any conclusions about decadal to centennial CO_2 variations on the order of $10 - 100$ ppm. In particular their large CO_2 excursion at the Allerød/YD boundary is mainly based on a single data point with a 2σ uncertainty of more than 150 ppm;
- that the changes invoked in their climate runs to explain such large CO_2 shifts are highly unlikely in reality and therefore suggest a more straightforward argument that such large changes in CO_2 are also highly unlikely without invoking major, undocumented shifts in the climate system;
- that in the comparison with the ice core data a full consideration of the gas enclosure processes in the ice was not considered in context with the purported CO_2 data from the stomatal record;
- that the simulations of oceanic flushing events produce carbon isotope changes in the atmosphere well outside what has been measured.

Based on these observations we suggest that the authors should explore whether the stomatal index may be influenced not only by CO_2 concentrations but also by local to regional climate anomalies (such as changes in local temperature, relative humidity, etc.), which would explain the synchronicity of changes in the stomatal index and local climate in their records in a straightforward way.

We first scrutinize the stomata-based CO_2 data, which is characterized by substantial scatter. The stomatal index (SI) data presented in Steinthorsdottir et al. (2013), which were used in the paper by Steinthorsdottir et al. (2014), are based on a small number of leaf fragments in each stratigraphic level of the core (see Fig. 5 in Steinthorsdottir et al., 2013). Each level is characterized by a very large scatter in the SI of all the individual samples in one level, which is clearly larger than the temporal changes discussed in the record. This large scatter in each level, however, is not reflected in the uncertainty of the average SI of each level given in Steinthorsdottir et al. (2013). Unfortunately, the authors did not explain how the mean and its uncertainty for each time slice was calculated. This appears to be worrysome, as some depth intervals / time slices in Steinthorsdottir et al. (2013) are defined by only one leaf fragment and it remains unclear how the uncertainty is defined. Being unable to reconstruct how the raw data has been treated statistically in the original publication, we start out in our error analysis with the mean values and uncertainties as published in Table 3 of Steinthorsdottir et al. (2013). We also used their equation to calculate CO_2:

$$\mathrm{CO_2}(t) = \mathrm{CO_2}(\mathrm{eH}) \times \frac{\mathrm{SI(eH)}}{\mathrm{SI}(t)}, \tag{1}$$

with t for time, eH for "early Holocene", and SI for stomatal index.

Steinthorsdottir et al. (2013, 2014) cite a SI reconstruction by McElwain and Chaloner (1995, 1996) as basis of this functional dependency of atmospheric CO_2 on stomatal ratio. Clearly, finding the best transfer function to translate SI data into CO_2 is a formidable task for the specialists in plant science and we are not in the position to provide a better transfer function. Nevertheless, it should be pointed out that the CO_2 changes considered in the work by McElwain and Chaloner (1995, 1996) are a factor of 10 larger. Thus, the applicability of this relationship for relatively small CO_2 changes during the Late Quaternary and its statistical robustness could be questioned.

To stay as close as possible to the approach of Steinthorsdottir et al. (2013, 2014) we used the same functional dependency here. In Steinthorsdottir et al. (2013) CO_2 is calculated based on either 280 or 300 ppm for the early Holocene. For reasons of simplicity we follow only one of the choices (CO_2(eH) = 300 ppm), which would represent maximum values. If alternatively CO_2(eH) = 280 ppm is chosen, all calculated CO_2 values would then be 7% smaller. We apply Gaussian error propagation accounting for both the errors in each SI(t) value as well as in the uncertainty of the mean value for the early Holocene SI(eH), which is based on three data points only. We undertook this calculation as we were puzzled that in some cases the larger uncertainties in the SI values in Table 3 of Steinthorsdottir et al. (2013) were not reflected in larger errors in their derived CO_2 values. For example, the data point with highest CO_2 of more than 400 ppm (sample depth of 3.43 m) has the smallest error in CO_2, but one of the largest errors in the corresponding stomatal index.

The result of our error analysis is shown in Fig. 1, where the CO_2 and its 2σ error for each depth interval or calender age are plotted. This clearly shows that the uncertainties in the data are very large, particularly for the apparent peak during the Allerød/YD boundary, where no robust conclusions can be drawn from this peak.

Looking at the entire CO_2 data set of Steinthorsdottir et al. (2013), the variability in Fig. 1 does not allow a rejection of the null hypothesis that all data points reflect the same CO_2 value. In this case, the CO_2 maximum during the Allerød/YD boundary is in line with one or two out of 31 data points being expected outside of the 95% probability range covered by the 2σ error around the mean (black horizontal lines in Fig. 1A including the data point with CO_2 maximum).

Also, Steinthorsdottir et al. (2014) recognize that their record is subject to considerable noise and argue that a 3-to-5 points running mean (averaging ∼200 years) might be a good representation of the true atmospheric signal. Our analysis above shows that a much stronger smoothing is required to obtain statistically reliable values, more similar or even longer than the 9-pt average shown in the Appendix A of Steinthorsdottir et al. (2014), which unfortunately is not discussed in the main text.

Looking at the end of the Allerød and the beginning of the YD time intervals separately, the data in Fig. 1A show that the two intervals are not significantly different. If we took the difference in the mean CO_2 concentration of the two intervals at face value, this would indicate that in the stomata-based reconstruction the beginning of YD is characterized by lower CO_2 concentration than the end of the Allerød in clear contradiction to the ice core record, which provides a reliable picture of the atmosphere on this multi-centennial time scale (Fig. 1). Accordingly, we must conclude that the stomata-based CO_2 reconstruction is not sufficiently precise to draw any conclusions on centennial or even sub-centennial CO_2 variations.

In principle the discussion of the rapid CO_2 variation at the Allerød/YD boundary could stop at this point. Nevertheless, in a second step, we take the values derived by Steinthorsdottir et al. (2013) at face value to show that such rapid variations are not in line with the ice core record and highly unlikely in terms of carbon cycle changes.

Ice core gas records are known to show only a smoothed version of the true atmospheric signal, because prior to full enclosure of gas bubbles in the ice, the air in the firn can still exchange with the atmosphere and individual bubbles are enclosed slowly at different points in time (e.g. Spahni et al., 2003). This bubble enclosure process is faster (and thus the age distribution narrower) with higher snow accumulation. Accordingly, to obtain gas records with high temporal resolution, ice cores with high accumulation rates are required. Unfortunately, up until now the CO_2 record measured in highest precision and accuracy over the last deglaciation was obtained from the EDC ice core (Monnin et al., 2001; Lourantou et al., 2010; Schmitt et al., 2012), which is a site with low accumulation rate. In fact for Holocene conditions, sub-centennial variations, such as the apparent CO_2 excursion during the Allerød/YD boundary cannot be resolved in the EDC ice core. Steinthorsdottir et al. (2014) correctly points to the upcoming new CO_2 data from the WAIS Divide ice core (allowing multi-decadal resolution), which show a more dynamic behavior because of higher accumulation rate, and thus less averaging. But even in the WAIS Divide record (Marcott et al., 2014) the largest rise during the deglaciation is only about 15 ppm and occurred at the end of the YD, not the onset. In fact, at the onset of the YD there is no indication of a rapid rise in CO_2 in the highly resolved WAIS Divide record, instead the data show the start of a slow rise that continues through the YD and is well documented in the EDC record. Note that the CO_2 measurements in the WAIS Divide core are sampled at $10 - 20$ year resolution, so aliasing of the true atmospheric signal is unlikely at the decadal scale. Furthermore, CO_2 time series from the ice cores at Taylor Dome, Siple Dome and Byrd (Neftel et al., 1988; Smith et al., 1999; Ahn et al., 2004; Pedro et al., 2012), which all have modern accumulation rates in-between those of EDC and the WAIS Divide ice core (Köhler et al., 2011), give all no indication on such rapid changes in CO_2 (Fig. 1).

Due to the slow bubble enclosure process, the gas records in the ice are a smoothed representation of the atmospheric history, especially during rapid climate transitions. In that respect a prominent event, which has been previously analyzed, is the warming into the Bølling around 14.6 kyr ago (Köhler et al., 2011). The measured rise in EDC CO_2 of 10 ppm in about 200 years was hypothesized to be connected with an amplitude in true atmospheric CO_2 of more than twice that size. In a previous analysis Köhler et al. (2011) used a log-normal transfer function, fitted to output of firn densification models, which describe the physics of the firn enclosure process, to derive a filtered signal, which might be recorded in the EDC ice core from a true atmospheric peak. Similarly, to compare the results by Steinthorsdottir et al. (2014) with EDC they also need to consider the smoothing due to gas enclosure. In Köhler et al. (2011), Fig. 3, the mean age (filter width E) for the onset of the YD in EDC was determined to be 400 years. If we now use this previously established log-normal function with a mean width $E = 400$ years on the 200 yr-running mean of the stomata-based CO_2, we end up with amplitudes in the CO_2 drop of 35 or 28 ppm now occuring between ∼13,000 and ∼12,750 years BP, depending in amplitude on the potential outlier (red lines in Fig. 1B). The maximum in CO_2 described by this single measurement is clearly responsible for the peak height in the 200 yr-running mean records (black lines in Fig. 1B). The overall amplitude of the CO_2 anomaly described by the whole stomata record from Haesseldala would be a positive peak in CO_2 of about 57 or 45 ppm in EDC (red lines in Fig. 1B), again depending on the potential outlier. These filtered amplitudes are still larger than what is seen in the ice cores, however, they are now properly treated so that a meaningful discussion of potential reasons leading to the ice core-stomata mismatch might begin.

Steinthorsdottir et al. (2014) also compared their stomata-based CO_2 record from Haesseldala with two other stomata-based records obtained in Scandinavia, and referred to another paper with two more stomata records from the Atlantic coast of Canada (McElwain et al., 2002). All other records also show an inferred prominent maximum in CO_2 of around 320 ppm before the onset of the YD, however, none claims values above 400 ppm. Steinthorsdottir et al. (2014), but also McElwain et al. (2002) argue, that their CO_2 records appear synchronous to local/regional temperature maxima, e.g. Haesseldala is compared to water isotopes obtained from Greenland ice cores. We therefore suggest, that these stomata-based CO_2 records, all derived from locations around the North Atlantic, might be influenced by local climate overprinting the CO_2-dependencies. A possible test for this hypothesis might be stomata-based CO_2 records across the YD from other regions that show a different temperature anomaly, e.g. from the southern hemisphere.

Finally, we discuss the outcome of the model runs performed in Steinthorsdottir et al. (2014) and contrast them to previous model studies (Köhler et al., 2010). The simulation scenarios performed in Steinthorsdottir et al. (2014) are in principle able to accommodate a fast increase in atmospheric CO_2 on the order of 50–100 ppm in 100 years, however, only by assuming virtually impossible changes in ocean ventilation or wind stress. Additionally, the model struggles to reduce the excess CO_2 in the atmosphere, after these strong changes are relaxed to normal conditions. Thus, the reduction of CO_2 by 100 ppm is not explained in their model runs. Moreover, their simulated changes in CO_2 also lead to corresponding changes in atmospheric $\delta^{13}CO_2$ with amplitudes of $-1.0‰$ and more in 100 years. Again, this carbon isotope imprint is not in line with the ice core record (Schmitt et al., 2012). Köhler et al. (2010) have shown that the gas enclosure in the ice cores leads to a damping of a $\delta^{13}CO_2$ peak stored in the EDC ice core from 42% to 21% of its atmospheric size, when filtering with a mean filter width of $E = 213$ or 590 years for typical Holocene and Last Glacial Maximum (LGM) conditions, respectively. YD climate conditions and, thus, filter width are somewhere in-between those of the Holocene and the LGM. Accordingly, a $-1.0‰$ peak in the atmosphere at the Allerød/YD boundary, which has similar temporal features as the peak tested in Köhler et al. (2010), should be imprinted in the ice core record by a negative anomaly of $0.2 - 0.4‰$. A negative anomaly in $\delta^{13}CO_2$ measured in EDC on the order of 0.2‰ has been initially observed for the onset of the YD based on one method (Lourantou et al., 2010), but has not been confirmed by two other (more precise) methods using samples from the same ice core (Schmitt et al., 2012). The data-based evidences on atmospheric $\delta^{13}CO_2$ are therefore in disagreement with results from the chosen simulation scenario.

Changes in atmospheric CO_2 based on stomatal index reconstructions being more dynamic than CO_2 data obtained from ice cores was already proposed for a time period around 11,300 years ago at the onset of the Holocene (Wagner et al., 1999a). This paper also received some technical comments challenging their findings of rapid and large changes in atmospheric CO_2 which are in disagreement with ice core CO_2 and other records (Indermühle et al., 1999; Birks et al., 1999; Wagner et al., 1999b). Furthermore, for the abrupt cooling event around 8,200 years ago a similar dispute was also published with stomata-based CO_2 suggesting a CO_2 decline on the order of 25 ppm (Wagner et al., 2002), that is in conflict with high resolution findings from ice core CO_2 (Ahn et al., 2014).

To conclude, we believe that comparing stomata-based and ice core-based CO_2 data is an important exercise that could lead to better understanding of both types of records. However, such a comparison needs to be performed with care to really include the existing knowledge on these proxies. Such a comparison has to reliably assess the stochastic and systematic uncertainties in the records and all the knowledge of potential processes affecting the records. Since ice cores directly sample the ancient atmosphere, albeit in a low-pass filtered way, any rapid changes in true atmospheric CO_2 are only contained in a low-pass filtered form. For an objective comparison with ice core CO_2 an appropriate gas enclosure transfer function needs to be applied to all suggested atmospheric CO_2 records. If such an application leads to a smoothed CO_2 record that disagrees with the ice core CO_2, the most likely explanation is, that the suggested atmospheric CO_2 is biased, suggesting that a revision of the underlying methods, e.g. recalibration of proxy-based approaches, may be needed.

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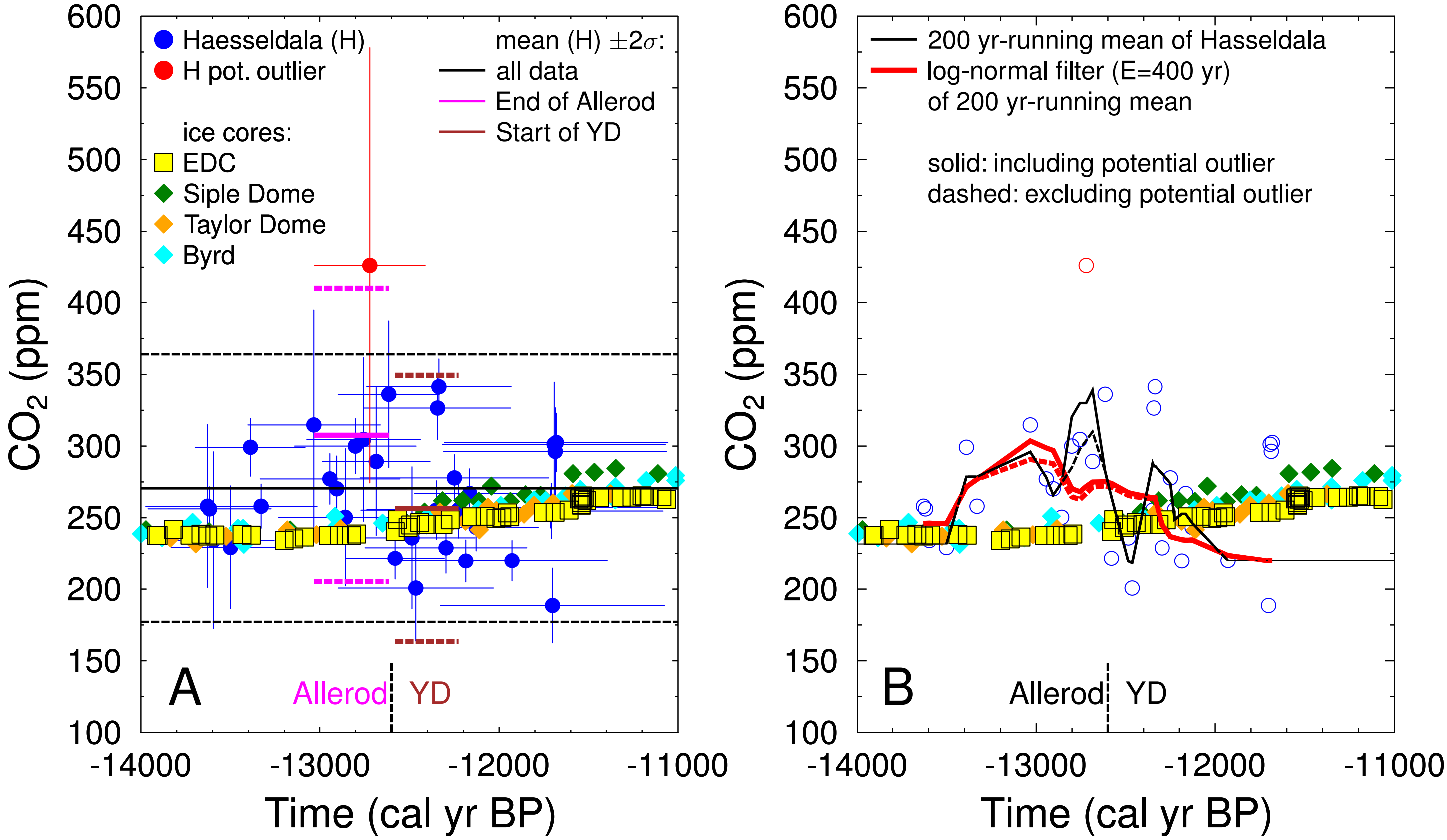
Figure captions

Figure 1: Stomata-based CO_2 versus CO_2 from the ice cores. Haesseldala data based on Steinthorsdottir et al. (2013) using an early Holocene CO_2 reference value of 300 ppm. Error bars show 2σ uncertainties in CO_2 (own calculations, see text) and the given 95% range of the calender age derived from ^{14}C measurements (Table 2 in Steinthorsdottir et al., 2013). Ice core data from EDC (Monnin et al., 2001; Lourantou et al., 2010; Schmitt et al., 2012) plotted on AICC2012 age scale (Veres et al., 2013), Taylor Dome on revised age model (Smith et al., 1999; Ahn et al., 2004), Siple Dome and Byrd (Ahn et al., 2004; Neftel et al., 1988) synchronized to Greenland annual layer-counted age model GICC05 as published in Pedro et al. (2012). A: Haesseldala data including uncertainties against ice core data. Vertical lines represent the mean (solid) and 2σ environment (broken) over all Haesseldala data (black), the end of the Allerød (magenta), the beginning of the YD (brown) with the boundary between both intervals around 12600 years BP, as dervied in Fig. 1 of Steinthorsdottir et al. (2014). B: Running means of the Haesseldala data against ice core data. Original Hasseldala data sketched by open circles without uncertainties. The 200 yr-running mean (black) is suggested to represent atmospheric CO_2 in Steinthorsdottir et al. (2014) and that 200 yr-running mean is transferred with a log-normal filter into a signal potentially recorded in EDC (red). The potential outlier is either included (solid) or excluded (dashed) in the underlying data of the running means. The log-normal filter function (Köhler et al., 2011) $f(x) = \frac{1}{x \cdot \sigma \cdot \sqrt{2\pi}} \cdot e^{-0.5\left(\frac{\ln(x)-\mu}{\sigma}\right)^2}$, with x (yr) as the time elapsed since the last exchange with the atmosphere, has two free parameters μ and σ. We chose for simplicity σ=1, which leads to $E = e^{\mu+0.5}$. The mean time since exchange with the atmosphere E was calculated with firn densification models to 400 years around the Allerød/YD transition (Köhler et al., 2011). The shape of the PDF is in reasonable agreement for output from those firn densification models. Due to the shortness of the CO_2 time series we truncate the long tail of the log-normal filter function at $2 \times E = 800$ years and normalize accordingly to avoid loss of data. Filtering reduces the length of a time series by half of the width of the filter at both ends. To be able to apply the log-normal filter over the whole CO_2 anomaly the 200 yr-running mean is extended by constant values (black thin horizontal lines).



Haesseldala (H)
H pot. outlier
ice cores:
EDC
Siple Dome
Taylor Dome
Byrd
mean (H) ±2σ:
all data
End of Allerod
Start of YD
A
Allerod
YD
CO_2 (ppm)
Time (cal yr BP)
200 yr-running mean of Hasseldala
log-normal filter (E=400 yr)
of 200 yr-running mean
solid: including potential outlier
dashed: excluding potential outlier
B
Allerod
YD

Figure 1: