Dear reviewers,

We thank two reviewers for their careful review of our paper, and their suggestions. We appreciate their useful comments and believe their input has improved the paper. Below, we address the comments in blue and the revised texts in the manuscript in green.

All the best, on behalf of all co-authors,
Jinhwa Shin

Review of Millennial variations of atmospheric CO_2 during the early Holocene (11.7-7.4 ka)

by J. Shin et al.

The authors present a new high-resolution CO_2 record, measured on samples from the Siple Dome ice core, from 11.7 to 9 ka and complement an earlier data set from 9 to 7.4 ka from the same core. This results in a high-resolution CO_2 record covering the beginning of the Holocene. Interpreting the combined data set they identify small millennial-scale variations of a few ppm and correlate them to various paleoclimate records. The authors speculate that solar irradiation may be responsible for the CO_2 variations. The new data, although covering only 2,700 years and thus very short, are important as they close the gap of the early Holocene in the CO_2 data of this ice core.

In the present version the authors do not make a sufficiently convincing case for their hypothesis of an influence of solar fluctuations in causing CO_2 changes. This is due to (i) questionable data processing that results in very small sigma uncertainties, (ii) essentially correlation-based arguments, (iii) a relatively short discussion of mechanisms, (iv) a nearly inexistent critical reflection on leads and lags that are identified in the data, and (v) a missing credible causal chain from solar fluctuations to purported CO_2 variations. Overall, this manuscript requires substantial revisions to reach the maturity of a CP article.

Comments:

1) The interpretation rests on the relatively small CO2 fluctuations that are visible in the filtered data presented in Fig 1. The authors report 2 sigma uncertainties based on Monte Carlo simulations. 2 sigma uncertainties typically contain more than 95% of the data points based on the assumption of normal distribution. The dashed lines in Fig 1, however, are extremely close to the running mean. How can this be? I would have expected a much wider uncertainty band based on the scatter of the data points. Such a wider band would put serious question marks on the significance and robustness of the small fluctuations (few ppm) that are reported in this paper and that are the basis for the claimed sun-CO2 relationship. The authors need to critically revisit the determination and depiction of this 2 sigma uncertainty.

Small variations of atmospheric CO_2 are usually smoothed by the gas trapping process in the firn. However, when CO_2 data is reconstructed, high-frequency variability of reconstructed CO_2 is detected, which might be related to proxy-related noise. Thus, we tried to remove this variability by using a 250-running mean. Due to a 250-running mean, those small variations were removed, thus, the uncertainty band becomes narrow.

The main reason of the small uncertainty is attributed to the removal of the high frequency signal by a 250-running mean as we discussed earlier. When the Monte Carlo simulation was conducted, we considered that each data follows a normal distribution. The width of the error band is affected by neighbouring data points. If the data points are close together, the error of neighbouring data points in the opposite direction can be cancel out, resulting in a narrow uncertainty band.

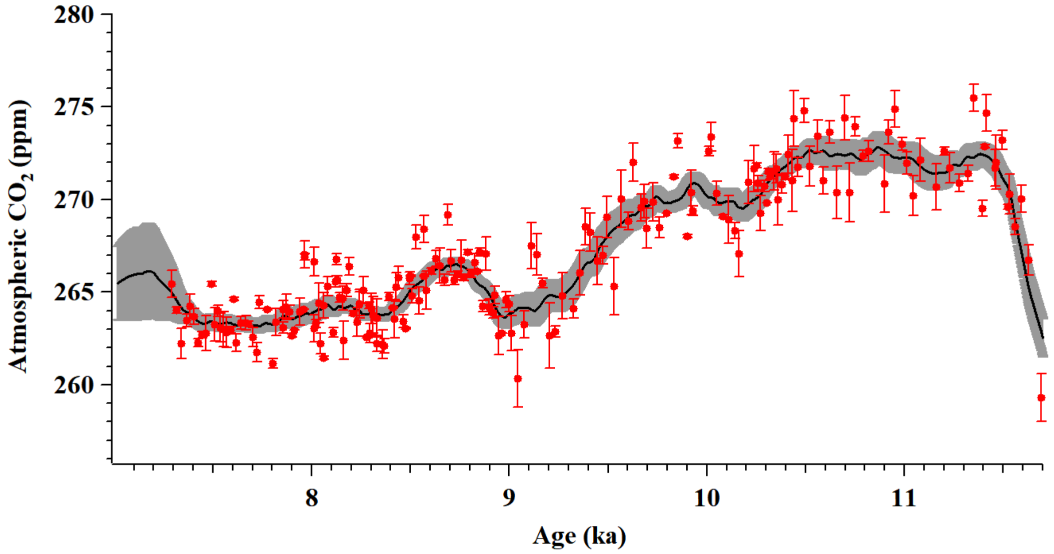

Figure 1. Red circles are Siple Dome ice core records during the early Holocene (11.7-7.4 ka). The black line indicates the average of 1,0000 times modified akima simulations showing an error-weighted average of the CO_2 record. The dark shaded indicates 2σ uncertainties calculated from modified akima simulations.

To assess variability on the millennial time scale, we evaluated 250-year running means and their uncertainties by using a new Monte Carlo approach. Random sampling was made from a probability distribution for each measured value and its standard deviation. If a standard deviation was smaller than the average reproducibility of the measurement ($1\sigma = 0.87$ ppm), we used 0.87 ppm as the uncertainty of a measured value. Then, interpolation and resampling (1 yr) were applied to generate an evenly-spaced time series and to calculate the 250-year running means. We repeated this series of simulations 10,000 times and evaluated the mean of 250-year running means and its uncertainty (shown as 2σ in Figure 1). We used a modified Akima method using the built-in makima function in Matlab for the interpolation. The different types of interpolation and smoothing methods resulted in insignificant differences in the 250-year running means.

2) The authors use a data processing that is not sufficiently explained. They mention a 1-yr interpolation (line 193) and a 250-yr smoothing, followed by a high-pass filtering at 1/1800 yr-1 and a resampling every 10 years. This sounds like very heavy machinery, and I wonder how robust the results are in light of these interventions. In particular, the 1-year interpolation may add some information to the time series that is simply not inferable from the limited resolution of the measurements and their individual uncertainties. I am very sceptical of this statistical treatment of the data.

250-year running means were made to eliminate high-frequency variability. It is likely that high-frequency variabilities of atmospheric CO_2 record (decadal-scale variations and centennial-scale variations) is high frequency noise of atmospheric CO_2 record. Thus, we smoothed data sets to eliminate high-frequency variability. Before making a 250-year running mean, we made a 1-year interpolation, because sample spacing between data points covering the early Holocene is not constant. Then, to eliminate this long-term drift of CO_2 record, the data was high pass filtered at 1/1800 yr, following previous studies by Bond et al. (2001) and Marchitto et al., (2010). The proxy records were also processed in the same way as the CO_2 record to remove high-frequency variability and long-term draft.

It is unlikely that the 1-year interpolation makes any change in our discussion on millennila varitions of CO_2 because our original data has a sampling resolution of ~30 years for 11.7–9.0 ka and ~15 years for 9.0–7.3 ka.

Furthermore, all other paleoclimate data are treated with the same method, and without showing the original data points of these records the authors do not make a convincing case for the significance of such small variations. In short, the data treatment is insufficiently described, and a robustness analysis is missing.

We modified figure 2 so that we may present all the original records as well as 250-year running means (figure 2). The smoothing by a 250-year running is necessary to clearly show the millennial variations. To detrend the long-term change and focus on millennial variations, we can apply the high-pass filtering at 1/1800 year^{-1}. Regardless of the high-pass filtering, the 250-year running means show similar millennial variations among the multiple proxy records.

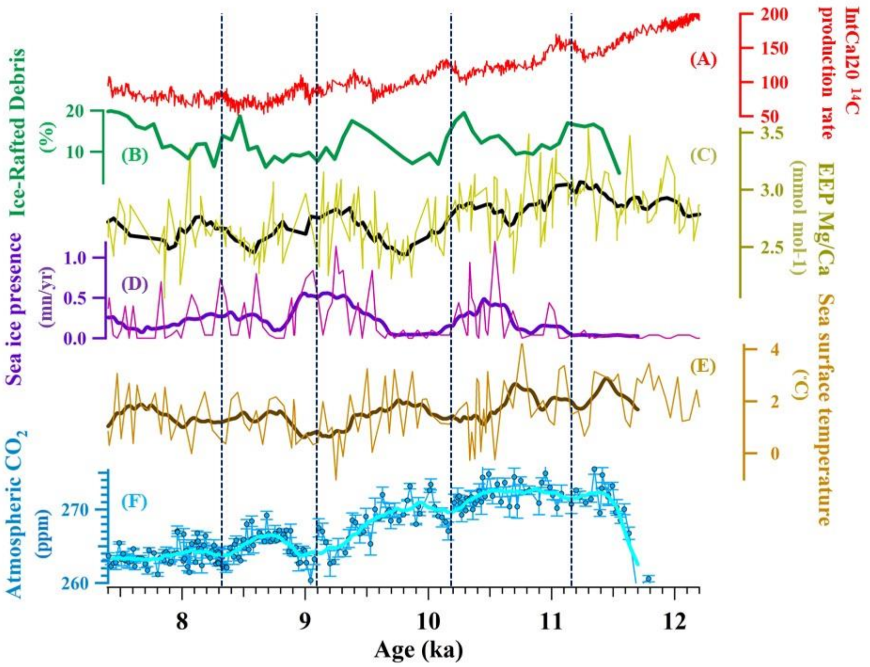

Figure 2. Comparison of atmospheric CO_2 with climatic proxy records over the early Holocene. Lines represent 250–yr running means. (A) IntCal20 ^{14}C production rate (Reimer et al., 2020). (B) Ice rafted debris stacked records from the North Atlantic regions on untuned calibrated ^{14}C age model (Bond et al., 2001; Marchitto et al., 2010). (C) Sea surface temperature from the eastern equatorial Pacific indicating El Niño–like or La Niña–like conditions (Marchittoet al., 2010). (D) Sea ice presence from the Polar Front of the Southern Ocean on the chronology of Mortyn et al. (2003) (Nielsen et al., 2004). (E) Sea surface temperature from the Polar Front of the Southern Ocean on the chronology of Mortyn et al. (2003) (Nielsen et al., 2004). (F) Atmospheric CO_2 record from Siple Dome (in this study).

3) Panel B of Fig 1 shows the high-pass filtered signal. Peak-to-peak amplitudes are max 4 ppm with some fluctuations of less than 1 ppm relative to the mean. So far, such small variations in CO2 measured from ice core samples, have not been interpretable, given the typical measurement uncertainties that are known from the literature. The authors have the burden of making a convincing case that such fluctuations here can indeed be interpreted as variations in atmospheric CO2 concentrations.

Previous paleoclimate studies showed climate fluctuations on millennial time scales with the local minima at around ~11.1, 10.3, 9.4, 8.1 ka covering the early Holocene (Bond et al., 2001; Marchitto et al., 2010; Nielsen et al., 2004; Reimer et al., 2004; Vonmoos et al., 2006). In this study, we wished to focus on how this millennial climate fluctuations affect atmospheric CO_2. The data interpretation was mainly about the millennial-scale variation of atmospheric CO_2 with the amplitude of ~4 ppm. These variations are relatively small compared to CO_2 variations during other periods such as glacial periods. However, the amplitude was calculated using a smoothing curve, which implies that artificial noise made by the gas trapping process in the firn was deleted. In addition, as we discussed earlier, the types of interpolation and smoothing methods do not resulted in significant differences in the 250-year running means. Thus, these variations by ~4 ppm cannot be ignored.

4) Comments 1 to 3 also apply to Fig. 2. For the CO2 data from EDC (Monnin et al) and WAIS (Marcott et al), the curves are misleading. Inspecting the original data in these papers, I am not convinced that the fluctuations that are shown in the processed data exhibit a robust signal that would represent atmospheric variations. Here a much more careful analysis and statistical assessment (see comment 2) would have to be carried out to see whether such small CO2 fluctuations can be identified in all three ice cores. It appears on the basis of the presented information that the authors go too far in their interpretation for this relatively short record.

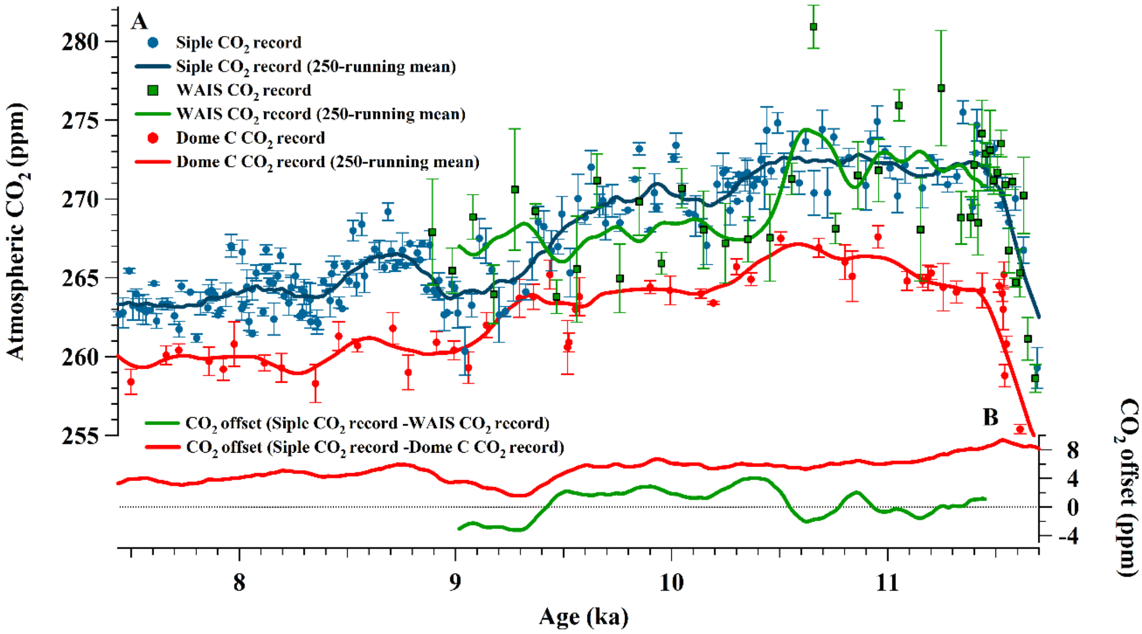

Figure 3. A: Atmospheric CO_2 records. Red dots: Atmospheric CO_2 record from Dome C ice core. Red line**:** 250-running mean of atmospheric CO_2 record from Dome C ice core. Blue dots: Atmospheric CO_2 record from Siple Dome ice core. Blue line**:** 250-running mean of atmospheric CO_2 record from Siple Dome ice core. Green dots: Atmospheric CO_2 record from WAIS Divide ice core. Green line**:** 250-running mean of atmospheric CO_2 record from WAIS Divide ice core. B: CO_2 offset between Siple Dome CO_2 record and other published CO_2 records. Red line: CO_2 offset between Siple Dome CO_2 record and Dome C CO_2 record. Green line: CO_2 offset between Siple Dome CO_2 record and WAIS divide CO_2 record.

To verify the levels of agreement, we calculate the Pearson correlation coefficient between Siple Dome CO_2 and existing CO_2 records (Figure 3). The offsets between existing CO_2 records and our data are also calculated (Figure 3). Before calculating the correlation coefficient between Siple Dome CO_2 record and other CO_2 records, all CO_2 records were smoothed by 250-running means to eliminate high frequency noise.

We observe that CO_2 data sets from Siple dome and Dome C share similar trends in CO_2 variations despite the CO_2 offset in longer term means of 3~8 ppm. The CO_2 record from the Siple dome is highly correlated with the CO_2 record from Dome C (r= 0.89). The CO_2 offset between Dome C record and Siple Dome record decreases continuously from 11.7 ka to 7 ka with small variations at around 9.3 and 8.3 ka (Figure 3B). The small variations of Dome C CO_2 record might be caused by the low sampling resolution and a stronger damping effect on CO_2 concentration change due to the slower gas trapping process at the Dome C site (Spahni et al., 2003).
The Correlation coefficient between Siple Dome CO_2 and WAIS divide CO_2 is 0.7. However, the CO_2 offset between Dome C record and Siple Dome record is quite random (Figure 3B) because of scattering in the WAIS Divide CO_2 record during the early Holocene period.

The WAIS Divide CO_2 data was reconstructed from the ice just below the bubble clathrate transition zone (BTCZ). Previous studies raised an issue about the possibility of high frequency noise of atmospheric CO_2 record in the ice just below the bubble clathrate transition zone (Lüthi et al., 2010; Shackleton et al, 2019). This phenomenon might be related to gas fractionation effect because of clathrate layering during bubble-clathrate transformation. Gas content starts to be fractionated in the BCTZ because of the differential permeation of gas species when bubbles have transformed to clathrates. CO_2 concentration in the first layer of clathrates is more enriched with higher bubble-to-clathrate permeation rates. Below the BCTZ, gas content slowly homogenizes again through molecular diffusion (Bereiter et al., 2009), which can cause high frequency noise to the ice below the BCTZ. Thus, the WAIS Divide CO_2 data is not sufficient to discuss millennial variabilities of the early Holocene.

In short, our comparison with the Dome C and WAIS Divide records supports our Siple Dome record although the comparison is limited due to relatively large offsets and low data resolution of the existing records. We will add words in the text to clarify the limits of the assessment.

Fig 3 suggests evident leads and lags, but they are not discussed and explained in the text. If it turns out that the fluctuations are robust, then these leads and lags need to be considered and discussed in the context of mechanisms. They may be helpful in constraining the causal chain, if such does indeed exist, from solar variations to the CO2 fluctuations. The authors end their discussion at a correlation analysis among the different paleoclimatic records of Fig 3. Correlation is not causation, and thus the arguments for a solar connection to CO2 fluctuations is rather weak, if it is active at all.

Figure 3 shows a possible link between solar activity/climate variations and atmospheric CO_2 during the early Holocene. Unfortunately, each data has their own age scale, thus with this figure, it is difficult to discuss a link between solar activity and atmospheric CO_2.

We found maximum correlation coefficients between CO_2 and climate proxies with CO_2 time lags of ~90 years (Table 2). Thus, we assumed that atmospheric CO_2 might be affected by solar activities via climate (Figure 4 and Table 2). Changes of solar activities may impact on stratospheric ozone concentrations, which can change stratospheric and tropospheric circulation patterns (Meehl et al., 2009). Higher solar activity enhanced precipitation in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) (Meehl et al.,2009; van Loon et al., 2007). The intensified moisture at those areas increased trade wind strength and upwelling in the East Equatorial Pacific region. These conditions lead to Na Niña like climate states on millennial time scale (Marchitto et al.,2010). This ocean condition change in the East Equatorial Pacific has affected the North Atlantic (Darby et al., 2012).

5) Further to Fig 3, age scale uncertainties between the different records seem to be ignored. These would represent an additional significant uncertainty regarding leads and lags. It is evidently difficult to come up with a common age scale, but the minimum expected would be an assessment the consequences for the conclusions.

Each record has their own age scales. Thus, as the reviewer mentioned, we may miss the relationship between CO_2 and proxies due to the age uncertainties of proxies and CO_2 records. This would be the case for centennial variations. As we focus on millennial variations, we check the leads and lags which are mostly smaller than 200 years. Even we consider the age uncertainties, we found similar variations of proxies and CO_2 on millennial time scales during the early Holocene. Figure 3. Figure 4 and Table 2 show the relationship between CO_2 and proxies by considering age uncertainties.

6) ENSO is offered as one of the possible mechanisms for CO2 fluctuations (lines 227ff). The discussion is rather superficial and incomplete. While Feely et al (1999) identify a decrease of CO2 during the 1991-94 El Nino, Chatterjee et al (2017) provide a more detailed, satellite-based analysis of the effects of the 2015-16 El Nino. After an initial decrease, consistent with Feely et al, they observe a stronger increase in the later stages of this El Nino, with the overall result of a CO2 increase. The two El Nino episodes are quite different with the former persisting for 3 years, while the later lasts for only one year but is stronger. Therefore, it seems not robust to assign a clear correlation between small OC2 fluctuations and ENSO.

Thank you for your suggestion. As you suggested, we considered adding this information about two oppositional observations in the manuscript. However, the time scale is one of the important factors to interpret CO_2 records. Because depending on the time scale, the role of the ocean also can vary (Gottschalk et al., 2019). Two papers are about the relationship between CO_2 and ENSO on the annual time scale. Thus, it is not necessary to apply the annual observations to the relationship between CO_2 and ENSO on the millennial time scale.

7) Lines 256ff on a possible role of the AO are speculative and do not add substance to the paper. Either this connection should be explored more in depth or deleted.

Deleted.

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