Supplementary information

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Supplementary Information (SI)

Details of the stochastic simulation

A schematic of how residuals between the change point representation and the time series are calculated is included in Figure 1.

In order to eliminate the need to specify an initial fit to estimate the autocorrelation matrix, we perform two subsequent optimizations. During the initialization, we use very rough estimates of the autocorrelation matrix of the residuals and the modeling uncertainty: identity and the standard deviation of the observations, respectively. An automated first guess is proposed by randomly generating the n x_i values and interpolating the y_i values from the observations. This quickly orients the optimization toward the correct region. The optimization is then allowed to run for an initialization period of 25,000 iterations, with 50 individual walkers.

The best fit encountered in the initialization is used to start the true optimization (250,000 iterations with 50 walkers): modeling uncertainty is reestimated as the mean of the absolute residuals on the best fit; and the autocorrelation matrix is reestimated by taking the autocorrelation of the residuals of the best fit. A histogram of the proposals accepted by the second optimization is taken as the final result.

The constant a in equation 3 is set to 2, following Goodman and Weare (2010).

Phasing at the Holocene onset

It is possible that the multiple modes of CO_2 at the Holocene onset are artifacts caused by sampling noise, as the series loses resolution after 11.5 ka. In figure 2 we show two calculations of phasing at the Holocene onset, one between 11 ka and 12.5 ka as in the main text, and one between 11.5 and 12.5 ka, to eliminate potential sampling noise. The ATS lead is reduced to 195 $\pm$ 62 years; but the conclusion of a multicentennial lead still holds. This ambiguity is discussed in the main text.

Testing the common air chronology

We plot continuous atmospheric CH_4 measurements from the Wais Divide (WD) ice core (Rhodes et al., 2015), and discrete measurements of CH4 from EPICA Dome C (EDC) (Loulergue et al., 2008), with a resolution of several meters, on the WD2014 age scale (SI). The overall agreement between the two series indicates that it is appropriate to compare our results with those of Parrenin et al. (2013). It also supports the zero-convective zone hypothesis used by Parrenin et al. (2013) to

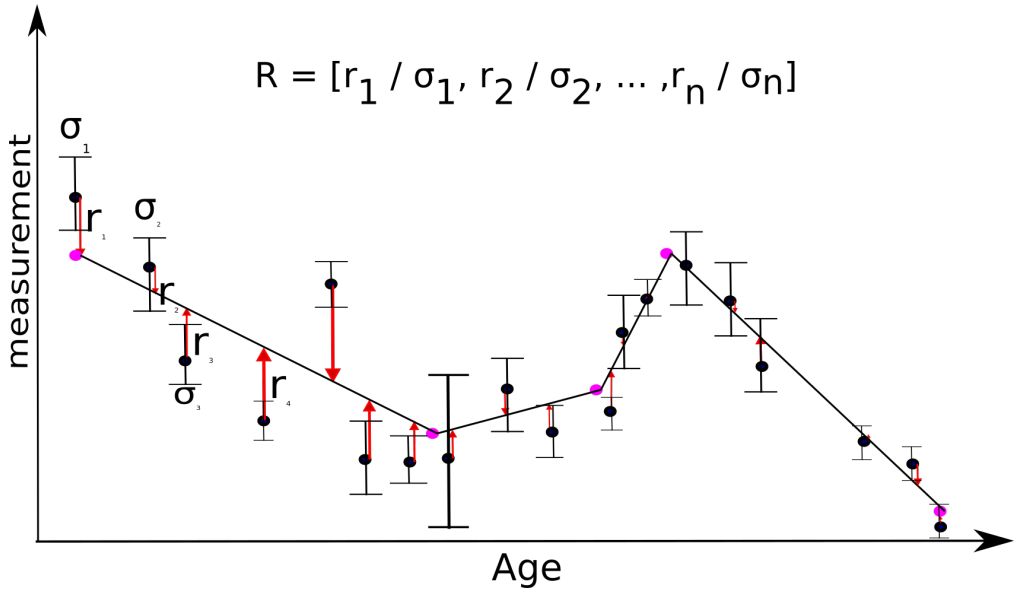

Figure 1. Schematic of the calculation of residuals between a data series and its change point representation. Here, the data series is shown as black points, with 1σ error bars. Change points are shown in pink, and the interpolations between them as black lines. The differences between the data points and the interpolations are shown as red arrows; the residual vector is composed of this distance divided by the uncertainty σ at each point.

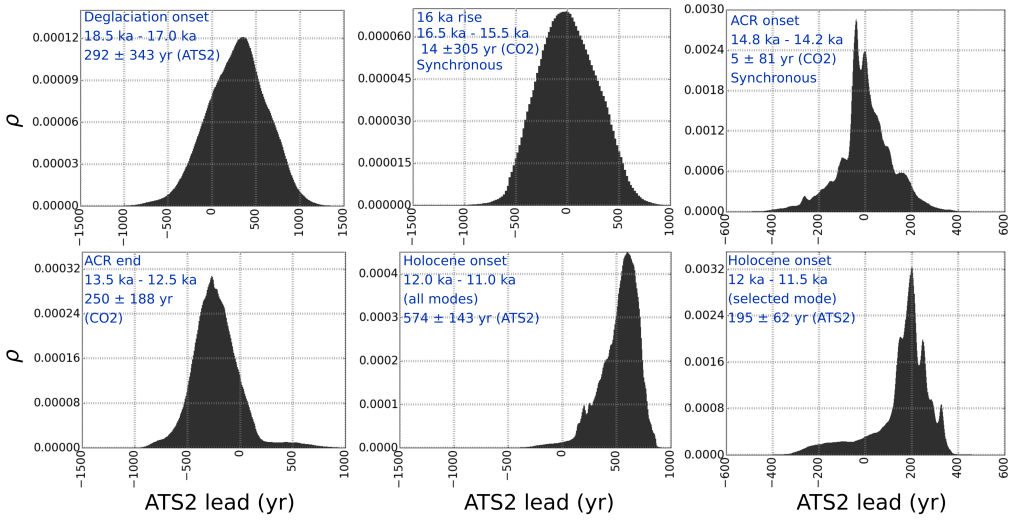

Figure 2. Probability density ρ (y-axis, normalized) of an ATS lead (x-axes, in years) at each of the selected change point intervals (noted on subfigures). Negative x-axis values indicate a CO_2 lead. In the text in each box, the name of the period, the time period in which the lead is calculated, the gaussian lead estimate (μ and 1σ), and the leading variable are given.

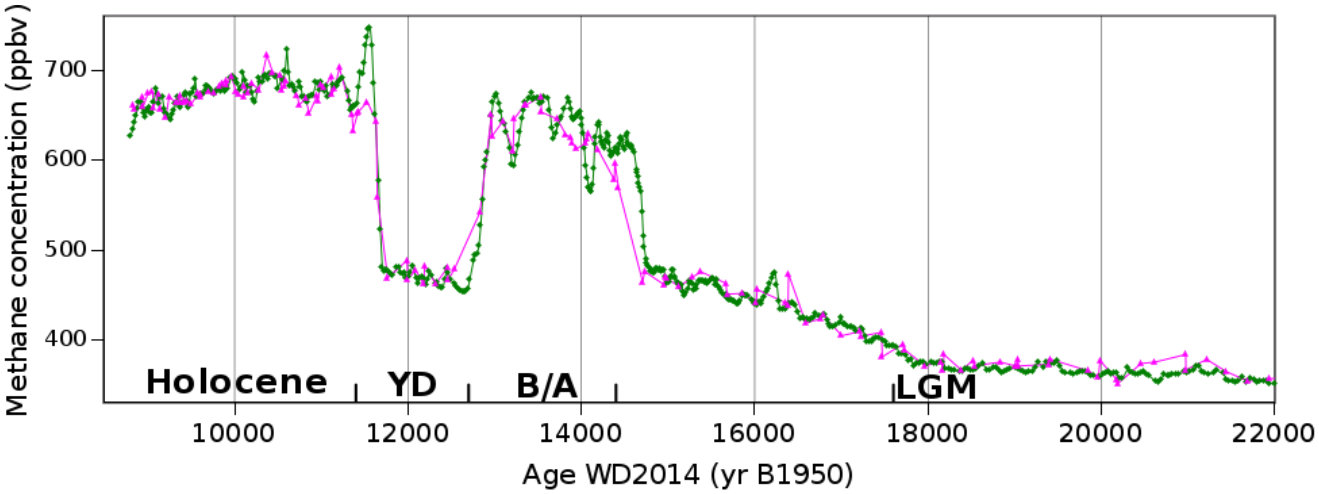

Figure 3. Methane records at WD and EDC on the WD2014 agescale (the WD data were shifted downward by 10 ppbv for a better visual agreement). Δage at WD (Buizert et al., 2015) is an order of magnitude smaller than at EDC (Parrenin et al., 2013). The agreement between both chronologies at times of fast methane transitions confirms that our results can be compared with Parrenin et al. (2013). This result also supports the validity of the chronological approach taken by Parrenin et al. (2013) particularly the assumption of a zero convective zone and the use of nitrogen-15 isotopes to estimate the height of the diffusive zone.

calculate Δdepth during T1. A varying convective zone is thus not necessary to explain the nitrogen-15 record at EDC (Dreyfus et al., 2010). Differences between the two chronologies can help explain differences in phasings between the two studies.

Change point sensitivity tests

We run tests to test the sensitivity of our results to the use of 7 change points rather than 8 (Figure 4.) The results of runs with 8 and 7 points do not show major differences in the directionality of phasing, and differences in the magnitude of phasing are minor. However, readers will note that the older mode (at 18.1 ka for ATS2, and at 17.8 ka for CO_2) is deemed much more probable in the 7 point simulation than in the 8 point simulation. This further supports our conclusion that additional forcings may have preceded the Mt. Takahe eruption during this acceleration.

A further note on Gaussian Estimates

Readers will note that we avoid providing estimates of change point timings in Gaussian form, i.e. as a mean $\pm$ a standard deviation. This is because the change point histograms we calculate are often jagged and multimodal: there are often multiple, separate probability peaks in a given time period where change is likely. These peaks can be due to sub-millenial scale variations at these points the two series.

Importantly, the leads and lags themselves, calculated using the cross-correlation and convolution operators, are often near-gaussian, as such we give Gaussian estimates of phasing.

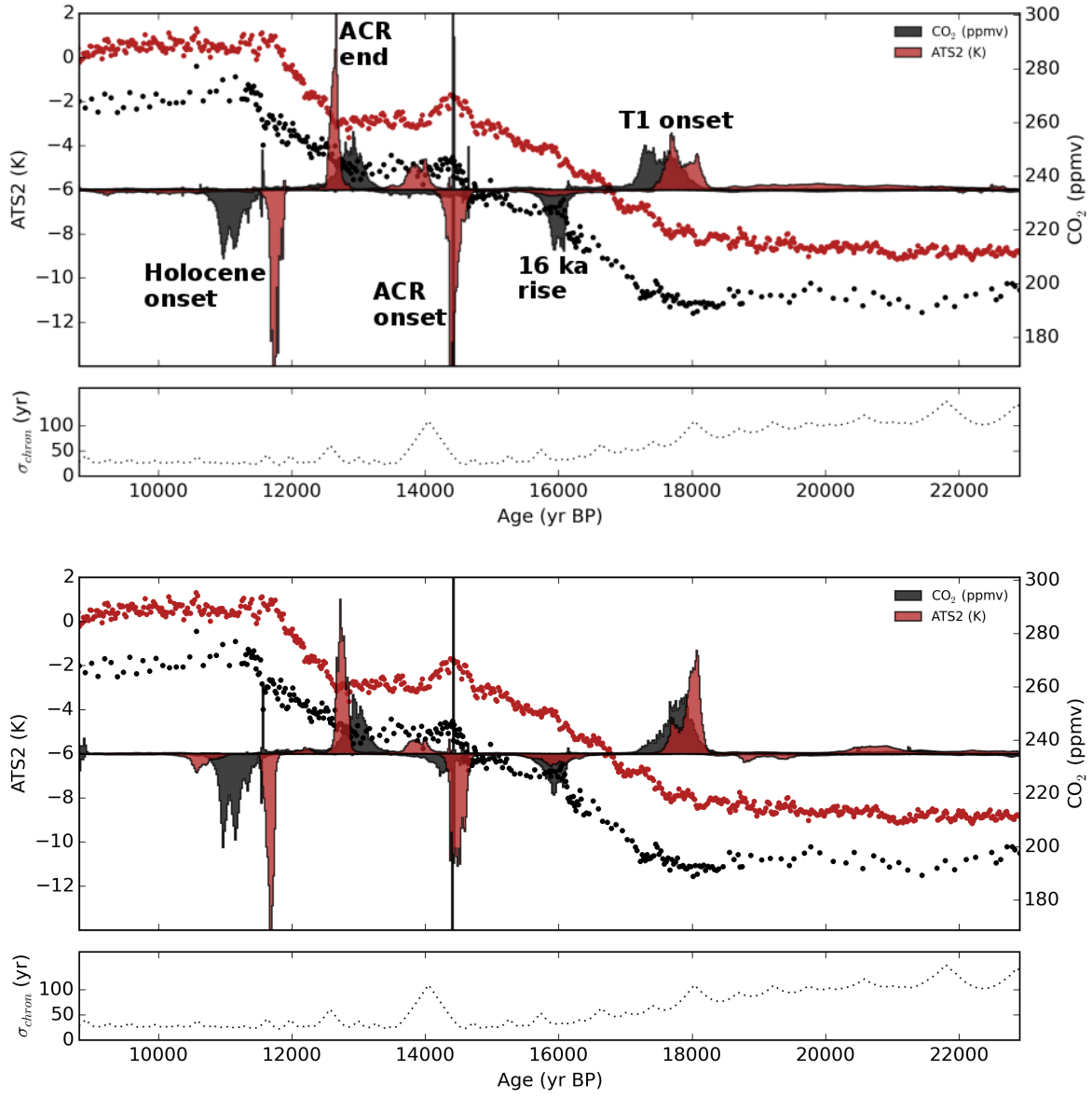

Figure 4. Top: Atmospheric CO_2 (black) and ATS2 including WD (red) placed on a common time scale, with the normalized histograms of probable change points from the 8-point run of LinearFit. Bottom: Same as above, but run with 7 points rather than 8.

References

Dreyfus, G. B., Jouzel, J., Bender, M. L., Landais, A., Masson-Delmotte, V., and Leuenberger, M.: Firn processes and δ 15 N: potential for a gas-phase climate proxy, Quaternary Science Reviews, 29, 28–42, 2010.

Goodman, J. and Weare, J.: Ensemble samplers with affine invariance, Comm app math comp sci, 5, 65–80, 2010.

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.-M., Raynaud, D., Stocker, T. F., and Chappellaz, J.: Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years, Nature, 453, 383–386, 2008.

Parrenin, F., Masson-Delmotte, V., Köhler, P., Raynaud, D., Paillard, D., Schwander, J., Barbante, C., Landais, A., Wegner, A., and Jouzel, J.: Synchronous change of atmospheric CO_2 and Antarctic temperature during the last deglacial warming, Science, 339, 1060–1063, 2013.

Rhodes, R. H., Brook, E. J., Chiang, J. C., Blunier, T., Maselli, O. J., McConnell, J. R., Romanini, D., and Severinghaus, J. P.: Enhanced tropical methane production in response to iceberg discharge in the North Atlantic, Science, 348, 1016–1019, 2015.