Clim. Past Discuss., 8, C227–C234, 2012
www.clim-past-discuss.net/8/C227/2012/

Climate of the Past Discussions

Interactive comment on "Climate bifurcation during the last deglaciation" *by* T. M. Lenton et al.

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Received and published: 5 April 2012

We thank the referee for their supportive remarks regarding the readability of the paper, and we acknowledge their main concerns, all of which have concerned us at different times whilst gestating the paper. Preliminary consideration of the issues raised suggests that the message of our paper will change significantly in the revision phase. Addressing each concern in turn:

1. We acknowledge that the signals of critical slowing down do not prove a bifurcation exists. It is conceivable that autocorrelation and variance can increase together for other reasons. We certainly did not intend to give the impression that the results we have somehow prove the hypothesis of a bifurcation. We are well aware from studying the philosophy of science that hypotheses can only be falsified (following Hume and Popper). We will change the tone of the discussion and conclusions accordingly.

2. The whole burgeoning field of 'critical transitions in complex systems' would be benefitted by a shift towards constructing null models and testing the statistical significance of results against a null hypothesis. In Dakos et al. (2008) a method of doing null model hypothesis testing is developed. We have two ideas for potential null models in this case:

a. The simplest null model would probably be a red noise process. We have done some work on this separately and found that multiple realisations with e.g. a window length of half the series produces a distribution of expected values of the Kendall tau coefficient for the AR(1) coefficient that is actually bimodal, with most likely values of +0.5 and -0.5 (for shorter window lengths the distribution becomes centred on zero). However, it remains a subjective choice which Kendall tau value from the original analysis to compare to such a distribution.

b. A more interesting null model would be to consider a static two-well potential with warm and cold states and noise-induced transitions between them (Ditlevsen and Johnsen 2010). This should not produce any consistent trend in the indicators (i.e. Kendall tau distribution centred on zero), except due to random effects or insufficient detrending. We think it the most pertinent null model to test against for our case study. In revising we will try to establish how likely or unlikely our results are relative to null model (b) to see if we can reject the null hypotheses (that all the transitions during the deglaciation are noise-induced and there is no change in the underlying potential) and if so at what level of statistical significance.

3. The referee raises two issues that could influence the results we report without being related to critical slowing down:

a. We are well aware that inadequate detrending of the transitions into or out of the Bølling-Allerød can create positive trends in the indicators, but this non-stationarity has nothing to do with slowing down. Imperfect detrending of the abrupt transition into the Bølling-Allerød does influence some of our results (as mentioned in the paper) but it is not the sole cause of the trends in the indicators. For example, there are visible low-frequency fluctuations during the Bølling-Allerød that were not present beforehand and clearly show a more sluggish system. There is a difficult trade-off here in that reducing the bandwidth to the point that detrending removes the very abrupt transition into the Bølling-Allerød also removes many of the smaller fluctuations that we want to study to be able to detect (or not) the signal of critical slowing down. With a bandwidth of 10 we still get an overall rise in AR(1) coefficient across all 6 datasets (as is clear from the contour plots in Figures 2-3 of the original paper). When we go to a bandwidth of 5, the rise in AR(1) coefficient is still there in all three ln(Ca) datasets, and in GISP2 d18O (Fig. 1), but it is no longer present in GRIP d18O (Fig. 2) or NGRIP d18O (analysis looks similar to GRIP d18O). Currently we are experimenting with ways of manually detrending the abrupt transitions themselves before applying the more sophisticated Gaussian filtering with a larger bandwidth.

b. The referee's deeper criticism is that we are mixing different states by including the Bølling-Allerød and the states before and after it in the same time-series for analysis. The idea that these are different climate states is already implicit in our conceptual model (Figure 7 of the original paper). We acknowledge that the dynamics of the different states could be quite different, including the decay rate of fluctuations. To address this we have constructed revised time-series by taking out the Bølling-Allerød and splicing together the intervals before and after it (joining the Last Glacial Maximum to the Younger Drays). This does not create a serious discontinuity in any of the data series, which now represent the behaviour of the cold climate state, alone. We have done some preliminary analyses of these datasets and the results are changed considerably. We find that in all three ln(Ca) datasets there is a pronounced signal of rising variance, especially at the end of the Younger Dryas, and at GRIP (Fig. 3) and NGRIP (Fig. 4) the ACF and DFA indicators are also rising. In contrast, in the d18O datasets there are mixed trends in the indicators, which do not support the hypothesis of the cold climate state approaching a bifurcation. The ln(Ca) results could be consistent with critical slowing down, if one takes the view (Ditlevsen and Johnsen 2010)

that rising variance should present an earlier and stronger signal than rising AR(1) coefficient. However, one might equally argue that the re-advance of ice sheets in the Younger Dryas increased climate variability, which in turn increased the likelihood of a noise-induced transition into the Holocene.

We need to redo the new analyses more carefully, but the preliminary results from 3b suggest a key change to the thrust of the paper. We propose to reframe the paper in terms of testing the hypothesis of a bifurcation during the deglaciation, with the distinct possibility that it is rejected in favour of the null model of noise-induced transitions. Still we feel the analysis and results are worthwhile.

References

Dakos, V., et al. (2008), Slowing down as an early warning signal for abrupt climate change, Proceedings of the National Academy of Sciences USA, 105(38), 14308-14312.

Ditlevsen, P. D., and S. J. Johnsen (2010), Tipping points: Early warning and wishful thinking, Geophysical Research Letters, 37, L19703.

Interactive comment on Clim. Past Discuss., 8, 321, 2012.

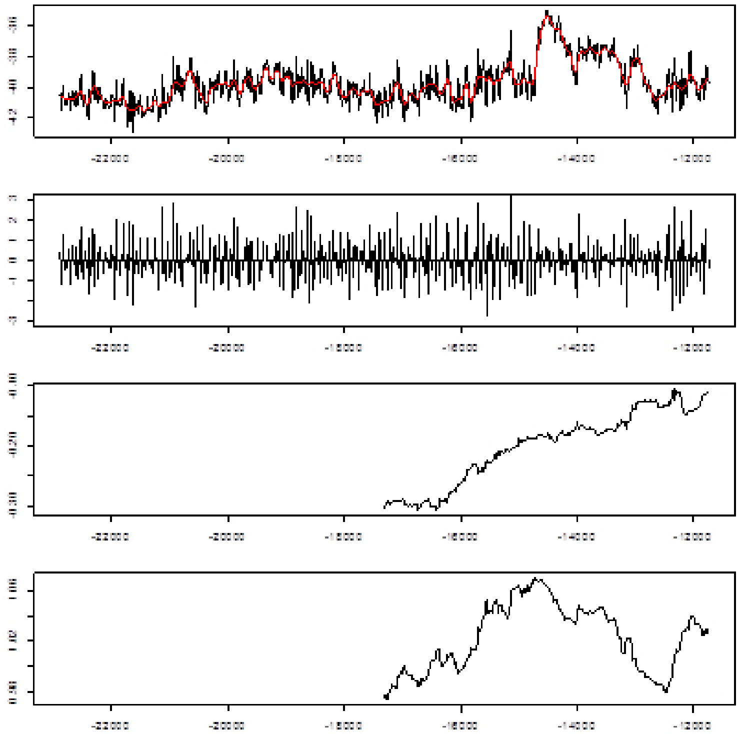

Fig. 1. Analysis of (top row) GISP2 d18O 22.9-11.7 ka, detrending (red line) with a filtering bandwidth of 5, (second row) detrended data, (third row) ACF-indicator, (bottom row) variance.

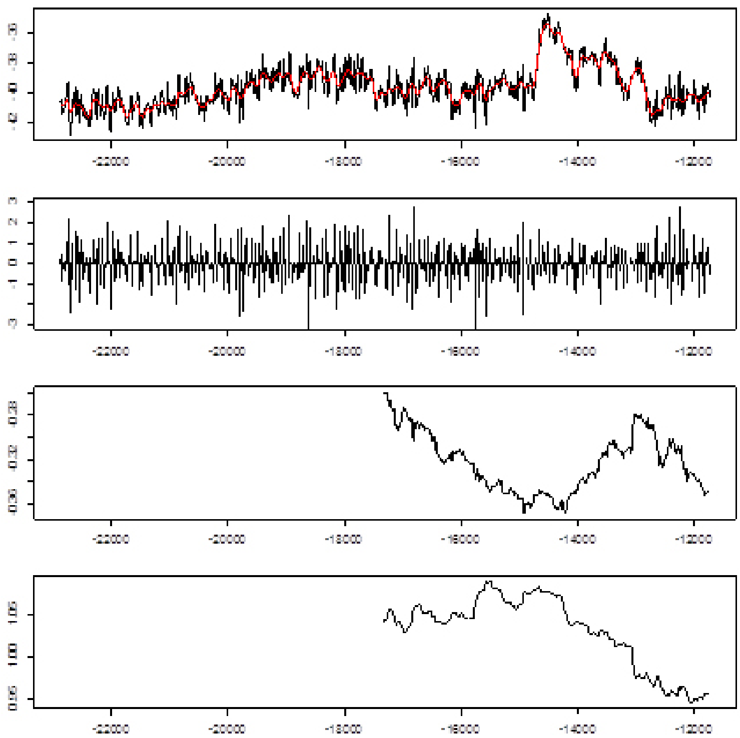

Fig. 2. Analysis of (top row) GRIP d18O 22.9-11.7 ka, detrending (red line) with a filtering bandwidth of 5, (second row) detrended data, (third row) ACF-indicator, (bottom row) variance.

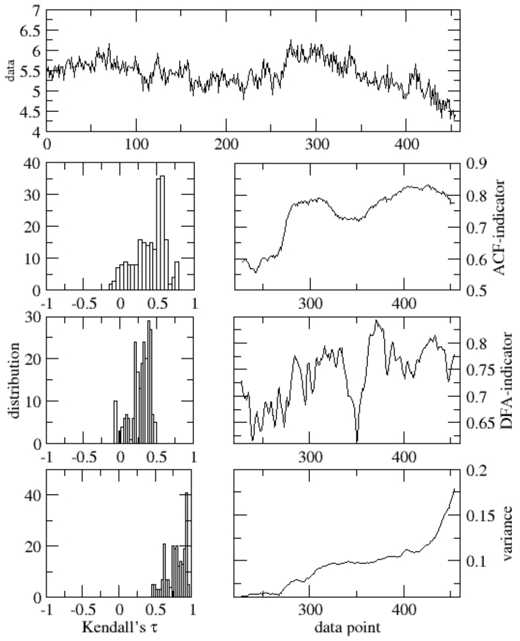

Fig. 3. Analysis of (top row) GRIP spliced record of ln(Ca) removing the Bølling-Allerød, (left panels) sensitivity analysis for trends in indicators, (right panels) example indicators.

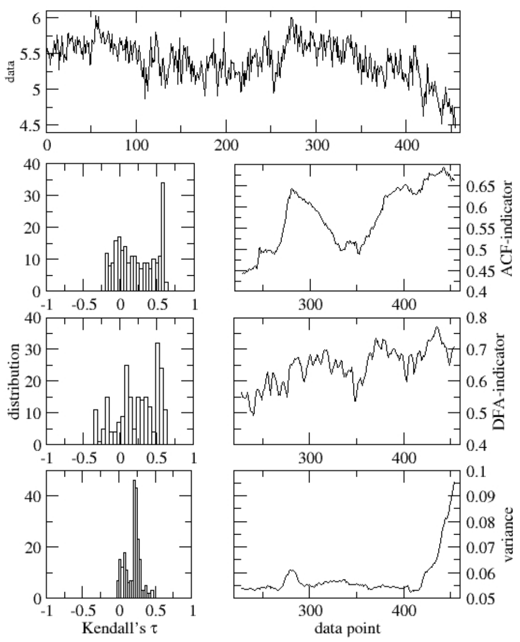

Fig. 4. Analysis of (top panel) NGRIP spliced record of ln(Ca) removing the Bølling-Allerød, (left panels) sensitivity analysis for trends in indicators, (right panels) example indicators.