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Climate of the Past Discussions

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

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We thank Michel Crucifix for his thoughtful review. Here we focus on the two main issues raised. (As a point of information, the ln(Ca) data used for most of the analysis has the same 20-year resolution as the d18O data, it is just in Figure 6 that we analyse annual resolution ln(Ca) data.)

Dynamical systems framework

The analysis was carried out with the possibility of some form of climate bifurcation in mind, but not necessarily a saddle-node. When it came to drawing a sketch of our interpretation this seemed the easiest way to try and visualise it, inspired in part by the frequent use of such diagrams for the stability regimes of the Atlantic meridional overturning circulation. On reflection however, Michel is correct that what we drew (or how we labelled it) is too simplistic for describing the deglaciation.

The suggestion to reinterpret in terms of a 'slow-fast' system is an excellent one. There is indeed interplay between changes in ocean circulation and slower components of the Earth system, in this case freshwater input to the North Atlantic, or at least the contribution to it from slow changes in Northern Hemisphere ice volume. We discuss this a little in the paper; there being some paleo-data support for the idea that the warm Bølling-Allerød interval encouraged ice melt and pulses of freshwater to the ocean that in turn weakened the Atlantic overturning circulation. The hypothesis that the Younger Dryas was triggered by a large freshwater pulse that had accumulated in the warm conditions of the Bølling-Allerød is also broadly consistent with this view. So, we agree that Figure 7 of the original paper was really an attempt to capture the dynamics of the fast system (in this case the Atlantic meridional overturning circulation). We propose to reframe the discussion in terms of a slow-fast system and redraw the figure along the lines of Fig. 1.

In Fig. 1 we suggest that the isocline of the slow variable is only modestly sloped (i.e. a small effect of Atlantic MOC state on freshwater input to the N. Atlantic), such that the Bølling-Allerød is an alternative stable state but close to being degenerate. Sloping the isoclines further could of course make it a quasi-stable transient state. We further suggest that the slow isocline is moving to the left with time, associated with the overall rise in CO_2 and deglaciation of the planet. This is of course a simplified picture as in reality only the orbital forcing is truly external to the Earth system. Furthermore, we have not drawn the movement of the isocline between the start and end of the Bølling-Allerød, which would work against the movement to the right on the upper branch of the slow manifold. Instead we show the closed loop of a DO cycle if there were no movement of the isocline. To make things clearer we would probably need three figures, one for the situation at each transition. Furthermore, we think that to fully explore the 'slow-fast' system interpretation of the Dansgaard-Oeschger events would be a further paper in itself.

We greatly enjoyed the review by Crucifix (2012) and were aware of alternative dynamical system models for the Dansgaard-Oeschger events, based around oscillators, but not with the same depth and clarity as described there. In revising, we propose to discuss the alternatives, and to make it clear that the revised Figure above does not cover them (although we prefer not to add further figures to our paper). Some initial thoughts follow:

First a point of clarification; we note that in the deglaciation, the transition is from what could be an oscillating regime to a final state that has deep convection (the Holocene) rather than a 'diffusive haline' regime (without deep convection), which is what is seen in the models with a homoclinic bifurcation. Therefore, we do not think a homoclinic bifurcation is the appropriate model for entry into the Holocene, at least not based on current theory. Instead, Timmermann et al. (2003) (their Figure 10) suggest a model for the transition from an oscillating to a convective regime, which is a reversal through a Hopf bifurcation (from cyclic to fixed point attractor). If there were a Hopf bifurcation then the signal of critical slowing down is expected. So, this scenario at least would be compatible with the data for the indices presented.

Interestingly, in the theory of Timmermann et al. (2003) entry into a Heinrich event is through a saddle-node (fold) bifurcation, which should also show a slowing down signal. We note that in our analysis of ln(Ca) data in the run up to the Bølling warming (Figure 5 of the original paper), there is the signal of slowing down accompanied by increased variance in the run up to Heinrich Event 1 around 16.8 ka BP.

If there were a homoclinic bifurcation or an infinite period bifurcation involved in the deglaciation, then in the case of a homoclinic connection where a cycle connects to a saddle (called a 'saddle connection' by Thompson and Sieber 2011) then this should be characterised by the period of the cycle tending to infinity. From an early warning point of view, considering the case of deglaciation, this is not particularly helpful as if there is cyclic behaviour there is only one instance of the cycle in going from the Last Glacial Maximum to the Holocene, so no way to say if the cycle is getting longer. This type of interpretation is more fruitful if one reverses time and looks in the other direction

(back toward the Eemian); it is clear that as ice volume on the planet decreases, the duration of the warm intervals get longer and with this the overall DO cycle gets longer (although there are exceptions to the rule). We think a more detailed discussion of this would be appropriate for a paper exploring the phenomenon of DO events as a whole, rather than our paper focused on the deglaciation.

Visualisation of the results

We have thought again about how to rationalise the number of figures or sub-panels. We propose to replace Figures 4 and 5 (analysis of the run-up to the Bølling warming) with new results in response to referee #1, which analyse composite time-series that remove the Bølling-Allerød and splice the Younger Dryas to the run up to the Bølling-Allerød. This at least would not add to the figures. To reduce the number of figures we propose to move Figure 6 (analysis of the annual resolution Ca data) to an Appendix or to remove it altogether.

References

Crucifix, M. (2012), Oscillators and relaxation phenomena in Pleistocene climate theory, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1962), 1140-1165.

Thompson, J. M. T., and J. Sieber (2011), Predicting climate tipping as a noisy bifurcation: a review, International Journal of Bifurcation and Chaos, 21(2), 399-423.

Timmermann, A., et al. (2003), Coherent Resonant Millennial-Scale Climate Oscillations Triggered by Massive Meltwater Pulses, Journal of Climate, 16(15), 2569-2585.

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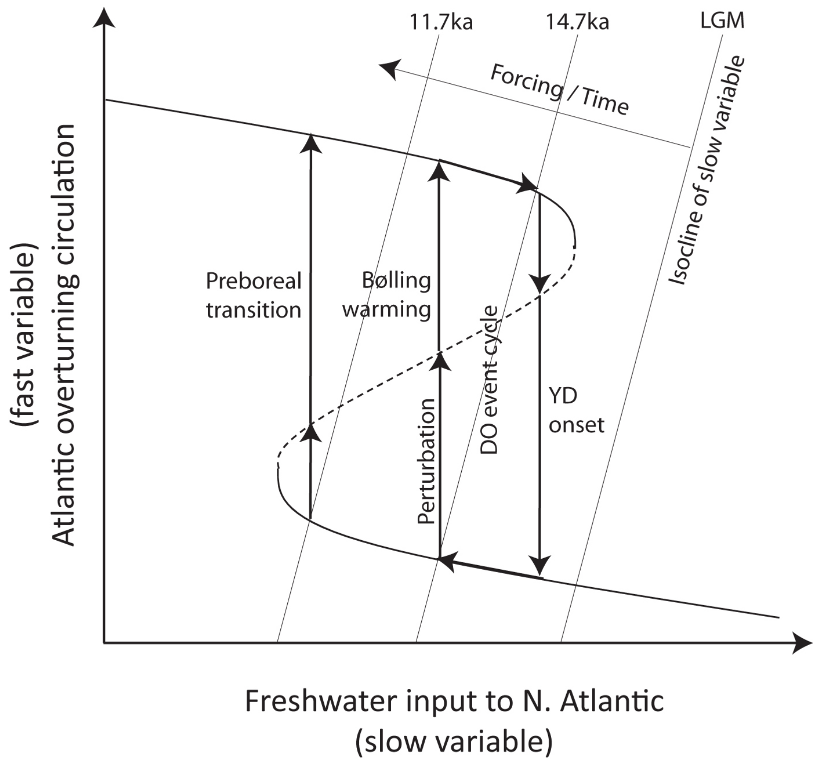

Fig. 1. Revised conceptual model of the deglaciation in terms of a slow-fast system.