Earth Syst. Dynam. Discuss.,
https://doi.org/10.5194/esd-2018-26-RC1, 2018

Earth System Dynamics Discussions

Interactive comment on "Cascading transitions in the climate system" *by* Mark M. Dekker et al.

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Received and published: 2 June 2018

The authors set up a mathematical framework for the study of cascading tipping points based on the extension of bifurcation theory and normal forms to coupled critical systems. After a numerical study of the potential early-warning indicators for cascading transition, the authors apply this framework to the interaction of the AMOC collapse and ENSO strengthening observed in a hosing experiment with a large ensemble of simulations from a General Circulation Model (GCM). For that purpose, they use a minimal coupled model for which the bifurcation diagrams can be calculated. The aim of this study is not to set up a complete mathematical theory for the study of cascading bifurcations, but rather to bring theoretical support to study successive abrupt climate changes, such as observed in paleoclimatological records during the Eocine-Oligocene transition. Application to climate variability is particularly relevant, since abrupt climate changes have happened in the past. Moreover, abrupt changes are found in a hi-

erarchy of climate models, although it is not yet clear whether GCMs used for the Intergovernmental Panel on Climate Change assessment reports are able to resolve them properly. The application to the AMOC collapse and ENSO is particularly relevant, since the melting of Greenland as a result of global warming is expected to lead to the collapse, or at least a weakening of the AMOC. In addition, the article is clear, well written and fit well the scope of Earth System Dynamics. I therefore recommend it for publication after minor revisions.

Specific comments:

Section 2:

- The authors first describe possible scenarios of cascading tipping by combining the normal forms most relevant for applications and involving only one or a pair of stability exponents crossing the imaginary axis. As such, the framework is suited for coupled systems for which both the leading and the following systems are close to a saddle and/or a Hopf bifurcation, a situation relevant for the applications considered here. However, the climate system is a high-dimensional system with a large number of positive Lyapunov exponents, whereas the bifurcations considered here involve only one or two-dimensional attractors rather that chaotic sets. As such, while the mathematical framework considered here appears to be an important direction to explore for climate applications, I would consider it only as a first important step towards understanding more complex abrupt climate changes, such as the one studied in section 4. This point could be discussed more by the authors.

- In bifurcations involving meta-stable states, such as the double saddle node bifurcation, or bifurcations involving strange attractors (e.g. (Tantet, Lucarini, Lunkeit, & Dijkstra, 2018)âĄă), a critical transition occurs through a saddle point, or a strange saddle. In this case, although the saddle set is globally unstable, its stable manifold may be responsible for a slowing down at the vicinity of the saddle, resulting in what also looks like a two step transition. Could you discuss why the cascading bifurcations may or may not be a better candidate to explain the two-steps transitions such as observed during the Eocene-Olegocene transition?

Section 4:

- In Fig. 7, there is indeed a strong correlation between the temperature gradient and the wind stress. However, as the author remark, there is also a strong spread, which should result in a strong variance in the estimate of the coefficients in Eq. 21. Could you use an ensemble method such as bootstrapping or a Bayesian model to test the probability that such a cascading tipping indeed occurs when sampling the different values of the coefficients of Eq. 21? This would allow to discuss the robustness of the results to the dependence of the wind stress on the temperature gradient.

- You explain well how the parameters of the wind stress equation are estimated from the model runs. However, it is not clear to me how the parameters of the Stommel and of the Timmermann are chosen. Are the parameter values used the same as in the references? Are they chosen so as to be as close as possible to historical data? So has to reproduce the mean state and variability found in observations? Or so as to favor the occurrence of the cascading tipping? In any case, I understand that estimating the parameter values of minimal models from observations or complex models is a difficult and not always relevant task. However, the sensitivity of the occurrence of the cascading tipping on the parameters of the coupled Stommel-Timmermann model should be discussed to better assess the likelihood of such tipping to occur.

Discussion:

- Salinity biases, such as found in the GCM used in this study, have shown to have a strong impact on the bi-stability of the AMOC (Mecking, Drijfhout, Jackson, & Andrews, 2017). Considering that the strengthening of ENSO also occurs in the control run, could you discuss whether this is/is not an important factor to take into account when asking whether or not such a cascading tipping of the AMOC+ENSO system could occur in the future.

References:

Mecking, J. V., Drijfhout, S. S., Jackson, L. C., & Andrews, M. B. (2017). The effect of model bias on Atlantic freshwater transport and implications for AMOC bi-stability. Tellus, Series A: Dynamic Meteorology and Oceanography, 69(1), 1–15. http://doi.org/10.1080/16000870.2017.1299910 Tantet, A., Lucarini, V., Lunkeit, F., & Dijkstra, H. A. (2018). Crisis of the Chaotic Attractor of a Climate Model: A Transfer Operator Approach. Nonlinearity, 31(5), 2221. http://doi.org/https://doi.org/10.1088/1361-6544/aaaf42 âĄă

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