

Interactive comment on “Detecting causality signal in instrumental measurements and climate model simulations: global warming case study” by Mikhail Y. Verbitsky et al.

Mikhail Y. Verbitsky et al.

verbitskys@gmail.com

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Comment: This paper presents a method to detect causality in climate time series. This method is based on principles of recurrences in dynamical systems. While interesting a priori, many points need to be improved and/or discussed.

Answer: Dear Anonymous Referee #1, Thank you for your insightful review. We appreciate that you consider our approach to be interesting. The following is our response to your comments:

Major points

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Comment: The literature review does not seem complete and misses crucial contributions. The paper is about attribution (of climate change), through the identification of causal links. There is an ample published literature on the subject, including in climate sciences. For instance, google scholar shows: Hannart, A., Pearl, J., Otto, F. E. L., Naveau, P., & Ghil, M. (2016). Causal counterfactual theory for the attribution of weather and climate-related events. *Bulletin of the American Meteorological Society*, 97(1), 99-110. (J. Pearl, who made the theory of causality, is a co-author of that paper); Runge, J., Petoukhov, V., Donges, J. F., Hlinka, J., Jajcay, N., Vejmelka, M., ... & Kurths, J. (2015). Identifying causal gateways and mediators in complex spatio-temporal systems. *Nature communications*, 6, 8502; A report of the US Academies of Science (National Academies of Sciences Engineering and Medicine 2016) also mention causality.

Answer: Though we have never aspired that our contribution may serve our readers as a review paper, we concede that you are correct and the reference list must be extended.

Action: In addition to a few items you advised us about, we will discuss and reference additional sources such as,

Abarbanel, H. D., Brown, R., Sidorowich, J. J., and Tsimring, L. S.: The analysis of observed chaotic data in physical systems. *Reviews of modern physics*, 65(4), 1331, 1993;

Attanasio, A., Pasini, A., and Triacca, U.: A contribution to attribution of recent global warming by out of sample Granger causality analysis. *Atmospheric Science Letters*, 13(1), 67-72, 2012;

Egorova, T., Schmutz, W., Rozanov, E., Shapiro, A.I., Usoskin, I., Beer, J., Tagirov, R., and Peter, T.: Revised historical solar irradiance forcing, *Astron. Astrophys.*, 615, id A85. doi 10.1051/0004-6361/201731199, 2018;

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McCracken, J. M.: Exploratory Causal Analysis with Time Series Data. Synthesis Lectures on Data Mining and Knowledge Discovery, 8(1), 1-147, 2016;

Meehl, G. A., Arblaster, J. M., Matthes, K., Sassi, F., and van Loon, H.: Amplifying the Pacific climate system response to a small 11-year solar cycle forcing. Science, 325(5944), 1114-1118, 2009;

O'Brien, J. P., O'Brien, T. A., Patricola, C. M., and Wang, S. Y. S.: Metrics for understanding large-scale controls of multivariate temperature and precipitation variability. Climate Dynamics, 1-19, 2019;

Sauer, T., Yorke, J. A., and Casdagli, M.: Embedology. Journal of statistical Physics, 65(3-4), 579-616, 1991;

Vejmelka, M. et al.: Non-random correlation structures and dimensionality reduction in multivariate climate data. Climate Dyn. 44, 2663–2682, 2015;

Comment: Although I do like dynamical systems, the transition from a 2-D discrete Hénon attractor to a “real world” problem sounds like a leap of faith. There are many numerical problems with the application of embedding methods (“à la” Takens). The main one is that there is no bound to the necessary embedding dimension, so that the low dimensional example that is treated is not sufficient to be convincing. The authors never mention questions linked to the so called “curse of dimensionality” to treat causality. When they treat the Hénon attractor, they use variables of the dynamical system, and do not need to evaluate embedding to make reconstructions. The climate application uses observables of the climate system (northern hemisphere temperature and CO₂), which might not give a straightforward connection to variables of the underlying system. Therefore all interpretations might be misleading.

Answer: We use Hénon attractor just as an illustration of the MCD concept because we want our readers to be well equipped before they review and interpret the sigma(epsilon) curves that are presented in the following chapters. Nevertheless, your

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concern regarding the “curse of dimensionality” is legitimate. Yes, we treat the climate variables the same way as Hénon attractor variables (with evaluation “à la” Takens embedding, dimension 7). Fortunately, though, as it has been shown by Čenys et al. (1991), the MCD method is not very sensitive to the embedding dimension and the slope of $\sigma(\epsilon)$ curves increases only slightly with the increase of the dimension. Indeed, despite the fact that numerous methods have been developed to better determine an embedding dimension (e.g., Abarbanel et al. 1993), it is still a challenge to determine embedding from a measured variable (such as temperature) because time series always have limited length and are corrupted with the noise which can be misinterpreted as a higher dimension. We use a hypothesis that NH temperature is an observable of the global climate system and CO₂ concentration is an observable of the system of external forcing. An observable may not necessary have straightforward connection to (“hidden”) physical variables of the underlying system. The embedding theorem (e.g. Sauer et al., 1991) states that reconstructed space is topologically equivalent to the underlying system in a sense that there exists a continuous differentiable transform from a reconstructed to the hidden space.

Action: We will add this discussion to the appropriate parts of the paper.

Comment: In Eqs (1-5), the systems have dimensionless variables, so that the choice of the range for ϵ is easy. The normalization of CO₂ and temperature for figure 2, to compute Eq. (1) is not explained. The authors do not explain how they embed the climate time series. Their results are not reproducible from the text and figures.

Answer: CO₂ and temperature time series have been normalized by subtracting their mean values and by dividing over standard deviation.

Action: This will be added to the text

Comment: I do not quite agree with the interpretation of Fig. 2b. The slopes of $\sigma(\epsilon)$ are significantly positive for both ways (T and CO₂). Therefore both observable interact with each other, in rather well physically understood way. The dis-

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discussion on the slope to define the strength of the unidirectional interaction is irrelevant because it depends on the units of the variables and the shape of their probability distribution (from eye-balling Eq. (1)). The authors should compare how curves depart from a horizontal line when dealing with heterogeneous variables. If this type of analysis was done between a proxy for solar activity and temperature, I would expect a horizontal line. Is it the case?

Answer: It is not the case. We have relatively short time series with a strong linear trend. We show in Fig. 5 that the $\sigma(\epsilon)$ slope can deviate significantly from the horizontal line because of linear correlation introduced by a trend, even in the case of completely independent time series. Solar activity does have a trend and the corresponding $\sigma(\epsilon)$ curve will deviate from the horizontal line. Therefore, in our paper, we are focusing not on the slope by itself but on the difference between two slopes, both in instrumental measurements and in model simulations.

Action: We will articulate this notion more clearly in the text.

Comment: What is the added value of the MCD analysis over the CMIP5 simulations and all the literature on attribution? The trend in observations cannot be obtained with control simulations and simulations with natural forcings. Only simulations with increasing CO₂ can reproduce the recent trend. The analysis of this manuscript “just” reflects this known result. Such diagnostics (either visual, as reported by the IPCC or statistical in this manuscript) are relevant to measure causality. They do not state by which mechanism this causality operates: only first principles of physics can do that!

Answer: We can't agree more that only laws of physics may identify the mechanism of causality. In this sense the causality is encoded in the differential equations of the mathematical models. With our calculations, we are not challenging the consensus whether CO₂ is the cause of the temperature increase, but rather calibrate MCD against existing measurements and simulations. Unfortunately, despite the fact that multiple methods exist to detect causality in the data, none is perfect for analysis of complex systems

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such as the Earth climate (McCracken, 2016). High uncertainty in natural forcing (e.g., Egorova et al., 2018) may be amplified by model uncertainties (e.g. Meehl et al., 2009). Therefore, a properly calibrated causality detection method like MCD may help to reduce these uncertainties in quantifying the climate response to different forcings by providing new data driven constraints. As long as MCD is recognized as a trusted approach, it can be used for express testing of new models and, may be more importantly, can serve as a first test for any new candidate external forcing that may be considered as an alternative or supplement to CO₂.

Action: We will add this discussion to the test.

Comment: Specific points Fig. 1 caption: $\alpha=0$ and $\beta=0.3$ is when x is the cause of u . The legend says the opposite (x depends on u). Please clarify or correct.

Answer: We agree that it may be confusing

Action: We will make a more clear legend.

Interactive comment on Geosci. Model Dev. Discuss., <https://doi.org/10.5194/gmd-2019-25>, 2019.

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