EGU24-2554, updated on 03 Nov 2024
https://doi.org/10.5194/egusphere-egu24-2554
EGU General Assembly 2024

Koopman operator theory for enhanced Pacific SST forecasting

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El Niño-Southern Oscillation (ENSO) is a complex climatic phenomenon with significant impacts on global weather patterns and ecosystems. Improving ENSO predictability is therefore an issue of high societal value. However, Global Circulation Models present severe biases when predicting ENSO, and their skill remains comparable to that of vastly simpler empirical models such as Linear Inverse Models (LIMs). LIMs, however, rely on linear dynamics, and they have inherent limitations in capturing the behavior of non-linear phenomena. In this context, Koopman operator theory has emerged as a powerful mathematical framework, offering a novel perspective for analyzing complex non-linear systems, such as ENSO. In this study, we investigate the potential of Koopman operator theory to enhance ENSO forecasting accuracy. Leveraging 2000 years of tropical SST pre-industrial CESM data, we have assessed the skill of the Niño 3.4 index forecasts using the Koopman framework, and compared it to the benchmark set by LIMs. Our analysis includes sensitivity testing of both methods across various parameters, such as retained variability and data length used for operator computations. Our findings reveal nuances in the robustness of Koopman Operator estimates, particularly evident when using shorter training periods, contrasting with more stable LIM counterparts. However, a notable breakthrough emerges as we demonstrate the higher skill of Koopman multimodel ensembles, showcasing consistent improvements over linear models. The comparative analysis highlights the potential of Koopman operator theory in advancing ENSO forecasting beyond linear models. The utilization of Koopman multimodel ensembles emerges as a promising strategy, demonstrating enhanced forecasting capabilities. Yet, challenges in robustness persist, particularly in shorter data spans, signaling avenues for further refinement. Overall, these findings underscore the significance of the Koopman framework and lay the groundwork for future research aimed at refining methodologies for more accurate predictions in complex climatic systems.