Predicting ENSO dynamics with climate network and complexity analyses

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The El Niño–Southern Oscillation (ENSO) is a quasi-periodic oscillation of the Pacific ocean-atmosphere system that alternates between warm (El Niño), cold (La Niña) and neutral phases. ENSO is the primary driver of interannual global climate variability and can lead to extreme weather events like droughts and flooding. However, current operational forecasts are hampered by the so-called spring predictability barrier (SPB), which shortens their reliable warning time to around 6 months.

To overcome this prediction barrier, we developed a dynamical climate network approach [1,2] that can forecast El Niño onsets well before the SPB. In this network, nodes are reanalysis grid points in the Pacific, and link strengths are derived from the cross-correlations of atmospheric surface temperatures at the grid points. In the year preceding an El Niño, links between the eastern equatorial Pacific and the rest of the tropical Pacific typically strengthen and the average link strength exceeds a certain threshold. Predictions based on this feature for the presence or absence of an El Niño onset are correct with 75% and 90% probability, respectively. Compared to random guessing based on the climatological average, the p-value of the hindcasting and forecasting phase (1981–2025) prediction skill is 1.9×10^{-5}.

We complement the climate network approach with additional forecasting methods that can also overcome the spring barrier. First, information entropy in the Niño3.4 region of the central Pacific strongly correlates with the magnitude of an El Niño starting in the following year [3]. Second, the temperature gradient between the western and central Pacific provides an early predictor for the type of an El Niño event (Eastern Pacific or Central Pacific) [4]. Finally, the interannual relationship of the Oceanic Niño Index is an early indicator of La Niña or neutral events [5]. Combining these four approaches enables probabilistic forecasting of all three ENSO phases. Additionally, concordant predictions among methods increase overall forecast confidence. For instance, in December 2024, we correctly forecasted the absence of an El Niño in 2025 with 91.4% probability and identified a neutral event as the most probable outcome with 69.6% probability. Collectively, these methods approximately double the pre-warning time before ENSO events, enabling earlier and more targeted mitigation measures.

References:
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