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Ocean response to wind variations, the equatorial warm water volume, and simple models of ENSO in the low-frequency approximation

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Physical processes that control ENSO dynamics are relatively fast. For example, it takes several months for an equatorial Kelvin wave to cross the Pacific basin (T_k = 2 months), while Rossby waves travel the same distance in about half a year. Compared to such short timescales the typical periodicity of El Nino is much longer (T = 3-6 years). Thus, ENSO is fundamentally a low-frequency phenomenon in the context of these faster processes. Here, we take advantage of this fact and use the smallness of the ratio $\varepsilon_k = T_k/T$ to expand solutions of the ocean shallow-water equations into power series (the actual parameter of expansion ε is related to ε_k but further modified by the oceanic damping rate). Using this expansion, here referred to as the low-frequency approximation, we obtain simplified formulations of ENSO dynamics and show how the meridional structure of wind stress anomalies and oceanic damping rates affect the amplitude and periodicity of El Nino, as well as the phase lag between variations in the mean thermocline depth (related to the equatorial warm water volume) and temperature in the eastern equatorial Pacific. This phase lag is a key feature of the recharge/discharge physics of ENSO. A simple analytical expression is derived for the lag as a function of the oscillation frequency, the oceanic damping rate, and the curl of wind stress anomalies.