Can meridional flow variations explain the observed rising/declining phase asymmetry in the solar cycle?

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Accurately forecasting the 11-year solar cycle remains one of the central challenges in solar physics, with important implications for space weather prediction. A striking feature of the cycle is its intrinsic asymmetry between the rising and declining phases, with the decay phase typically lasting much longer than the rise. Understanding the physical origin of this asymmetry requires examining the role of various processes within the solar dynamo. For instance, the temporal variability of the Sun's meridional circulation and its interaction with the Babcock–Leighton mechanism of poloidal field generation is a plausible solution to consider and analyze further.

In this work, we performed a series of kinematic flux-transport dynamo simulations to assess how variations in meridional flow influence the rise–decay asymmetry of the solar cycle. We considered three main scenarios: (1) both the meridional flow and the Babcock–Leighton mechanism treated as stochastic, (2) a physically motivated deterministic meridional flow profile combined with stochastic Babcock–Leighton fluctuations, and (3) a hybrid meridional flow containing both deterministic and stochastic components together with stochastic Babcock–Leighton fluctuations. To quantify solar cycle asymmetry, we evaluated four key diagnostics: (1) the ratio of rise to decay times, (2) the correlation between cycle amplitude and rise time, (3) the correlation between cycle amplitude and rise rate, and (4) the correlation between cycle amplitude and the decay rate near the preceding cycle minimum. These diagnostics allow us to systematically compare the influence of different meridional flow profiles on the observed asymmetry between rising and declining phases of the solar cycle.

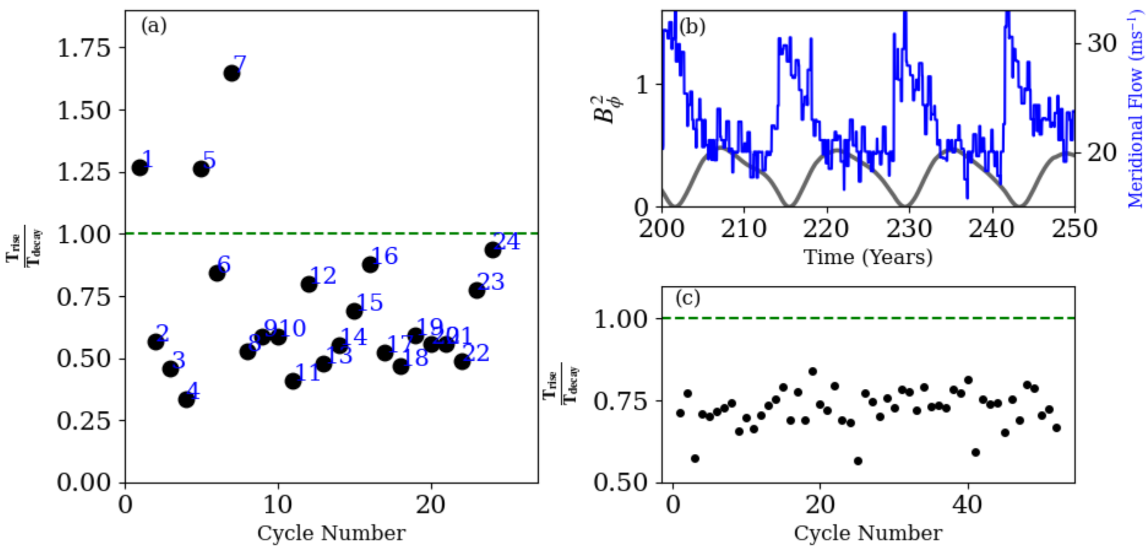

Figure 1: **Figure (a):** Variation of $\frac{T_{rise}}{T_{decay}}$ with the cycle number obtained from the observed sunspot number data. **Figure (b), right panel:** Simulation results where the meridional flow is modulated by the active region eruption belt using the term $\delta v \sin^2(2\theta_{\max})$, with $\theta_{\max}$ denoting the latitude of peak toroidal field strength. A random component with a coherence time of three months is superimposed on this modulation to account for convective turbulence, resulting in a hybrid meridional flow profile. The black curve (right y-axis) shows the evolution of magnetic energy density, while the blue curve (left y-axis) shows the variation in the amplitude of the meridional flow. Figure (c), right panel: Variation of $\frac{T_{rise}}{T_{decay}}$ with the cycle number obtained from simulation.

Our simulations show that the rise–decay asymmetry is highly sensitive to the temporal structure of the meridional circulation. In deterministic scenarios with a deliberately chosen flow profile, faster during the rising phase and slower during the declining phase, the model produces pronounced asymmetry—shorter rise times and longer decay times—that qualitatively matches observations. However, these early profiles are largely ad hoc and not physically motivated. When both the meridional flow and the Babcock–Leighton mechanism are treated as stochastic, the model fails to consistently produce cycles with decay times exceeding rise times. Similarly, stochastic fluctuations in the Babcock–Leighton mechanism alone cannot explain the observed rise–decay asymmetry. In contrast, physically motivated, well-chosen deterministic variations of the meridional flow, inspired by Lorentz-force feedback, successfully reproduce the observed asymmetry when combined with stochastic Babcock–Leighton fluctuations. For example, when the flow varies as $\delta v \sin^2(2\theta_{\max})$, where δv is the amplitude of the modulation and $\theta_{\max}$ is the latitude of the toroidal field maximum, the flow is weaker near the cycle maximum, remains weak for some time after the maximum, and then increases again. This configuration captures the essential effect of Lorentz-force feedback.

Hybrid scenarios, in which the meridional flow includes both deterministic and stochastic components along with stochastic Babcock–Leighton fluctuations, produce the most realistic observed rise–decay asymmetry (see Figure 1). However, we note that the degree of agreement depends on parameters such as the α-coefficient and the specific deterministic flow profile, highlighting the sensitivity of results to physical and numerical choices. These simulations demonstrate that the interplay between systematic magnetic feedback and convective randomness provides a plausible explanation for the observed asymmetry. Importantly, the hybrid approach consistently produces a strong, statistically significant positive correlation between cycle amplitude and rise rate, confirming that stronger cycles rise more rapidly. In contrast, correlations involving the decay rate near the preceding minimum remain weak, though occasionally statistically significant. These findings underscore the critical role of meridional circulation variability in shaping solar cycle asymmetry. Incorporating such variability into forecasting frameworks—such as the Solar Predict tool—can significantly enhance the physical realism and predictive skill of solar cycle predictions.