Three-Dimensional Empirical Orthogonal Function (3D-EOF) Analysis of Venusian Atmosphere Dynamics

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The super rotation and wave dynamics of the Venusian atmosphere have traditionally been characterized using Fourier decomposition analysis applied layer by layer. Despite being effective for periodic signals, these methods often require subjective prior assumptions about the wave structure and obscure the anharmonic wave structures common in higher-dimensional planetary atmospheric flows. As illustrated by Sanchez-Lavega et al. (2017), a primary challenge in explaining the maintenance of Venusian super rotation is our limited understanding of how angular momentum is transported vertically between the deep atmosphere and the cloud layer. Addressing these gaps, we introduce a Three-Dimensional Empirical Orthogonal Function (3D-EOF) methodology to analyze the zonal wind field (u) derived from three Earth years of AFES-Venus GCM (Sugimoto et al., 2014), offering Venusian community a relatively new, objective, and purely data-driven perspective on the Venusian atmospheric dynamics. To ensure physical fidelity, we employ a vertically mass-weighted and meridionally area-weighted covariance matrix that rigorously accounts for variable pressure layer depths and spherical geometry. Because $\mathbf{E}_n$ is derived directly from the mass-weighted covariance matrix rather than a predetermined mathematical form, the reconstructed signal naturally retains asymmetric vertical tilts and localized wave packets that Fourier methods would otherwise fragment across multiple harmonics. Our result reveals dominant patterns that not only align with previously identified planetary-scale waves (e.g., the Thermal tide) but also explicitly resolve their vertical coupling. Notably, our method demonstrates that the Venusian zonal wind variability are dominated by the first four modes, which collectively capture 73.1% of the variance, a level of characterization unprecedented to date. This shift from 2D to 3D and from subjective to data-driven analysis provides a robust framework for quantifying vertical angular momentum transport, demonstrating that 3D-EOF is a powerful tool for isolating the dynamics that maintain Venus super-rotation.

Keywords: Venus, Super-rotation, Zonal wind, 3D-EOF

qt_sim_3D Structure of u Mode 1 (28.5% Variance)