Critical wave speed governs heat transfer in buoyancy-driven turbulence under hybrid spatiotemporal modulation

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Abstract

Thermal forcing within natural systems, like Earth's surface, displays intricate spatiotemporal variability driven by diurnal and seasonal cycles. Inspired by this complexity, we examine Rayleigh–Bénard convection under hybrid spatiotemporal modulation at the thermal boundary, implemented by imposing a traveling thermal wave of wavenumber k and frequency f at the bottom plate. At low frequencies, spatial modulation becomes dominant, giving rise to coherent thermal plumes. Conversely, at high frequencies, rapidly propagating thermal wave effectively smoothens plume structures and diminishing convective efficiency. We show that the onset of this smoothing behavior is dictated by the ratio of the thermal wave speed c=f/k to a scale-dependent pseudo-speed of thermal diffusion, which quantifies thermal damping. Based on this comparison, we distinguish two dynamical regimes: (I) a spatial-modulation-dominated regime, where the boundary thermal wave moves slowly enough for thermal plumes to remain coherent in space and time; and (II) a traveling-wave-dominated regime, in which a rapidly propagating thermal wave disrupts the spatial coherence of thermal structures within the boundary layer. These findings establish a new framework for understanding the interplay of spatial and temporal modulation, advancing our knowledge of heat transfer in systems with complex boundary conditions.

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