On Sunspot Penumbra and Evershed Flow III: Deep Convective Origin of Small-Scale Upflows

○堀田 英之[1] Rempel Matthias[2] (1.Nagoya University 2.HAO/NSF NCAR)

Recent high-resolution radiative MHD simulations have reproduced sunspot penumbrae and Evershed flows without imposing strongly inclined magnetic fields at the upper boundary. Our previous analysis showed that small-scale elongated upflows in the penumbra play a crucial role in supplying mass to the Evershed flow. In this work, we investigate the deep origin of these upflows. By tracing the flow structure into deeper layers, we find that the small-scale penumbral upflows are connected to localized regions of large entropy beneath the penumbra. Regions without upflows do not show a comparable entropy excess. This indicates that the resolved upflows are buoyantly driven thermal convection occurring in the strongly magnetized penumbral environment. To understand why these upflows emerge only in high-resolution simulations, we compare simulations with different spatial resolutions. We find that the deep layers exhibit similar entropy distributions in both cases, and that the high-resolution simulation contains no significantly greater amount of high-entropy material. The key difference is therefore not the thermodynamic structure of the deep convection zone. Instead, the higher resolution resolves small-scale turbulent motions that locally perturb the magnetic field and allow buoyant fluid to locally overcome magnetic suppression. These results suggest that small-scale turbulence is essential for triggering penumbral convective upflows and therefore plays a fundamental role in the formation of the penumbra and the Evershed flow.