# Boundary Layer Structure in Stratified Convection

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**1. Introduction.** The solar photosphere serves as an important boundary layer for the highly stratified solar convection zone, and surface convection is largely driven by this layer. The interactions between the plumes driven at the surface and the deep flows of the solar interior may be essential to understanding the solar convection conundrum in which observed large-scale velocities are lower than predicted by numerical simulations and mixing length theory [1,2,3]. Here we use the Dedalus pseudospectral framework [4] to study 2-D fully compressible convection in high resolution (e.g. 1536x6144 in Fig. 1b), stratified, solar-like atmospheres and the boundary layers which naturally evolve in such systems.

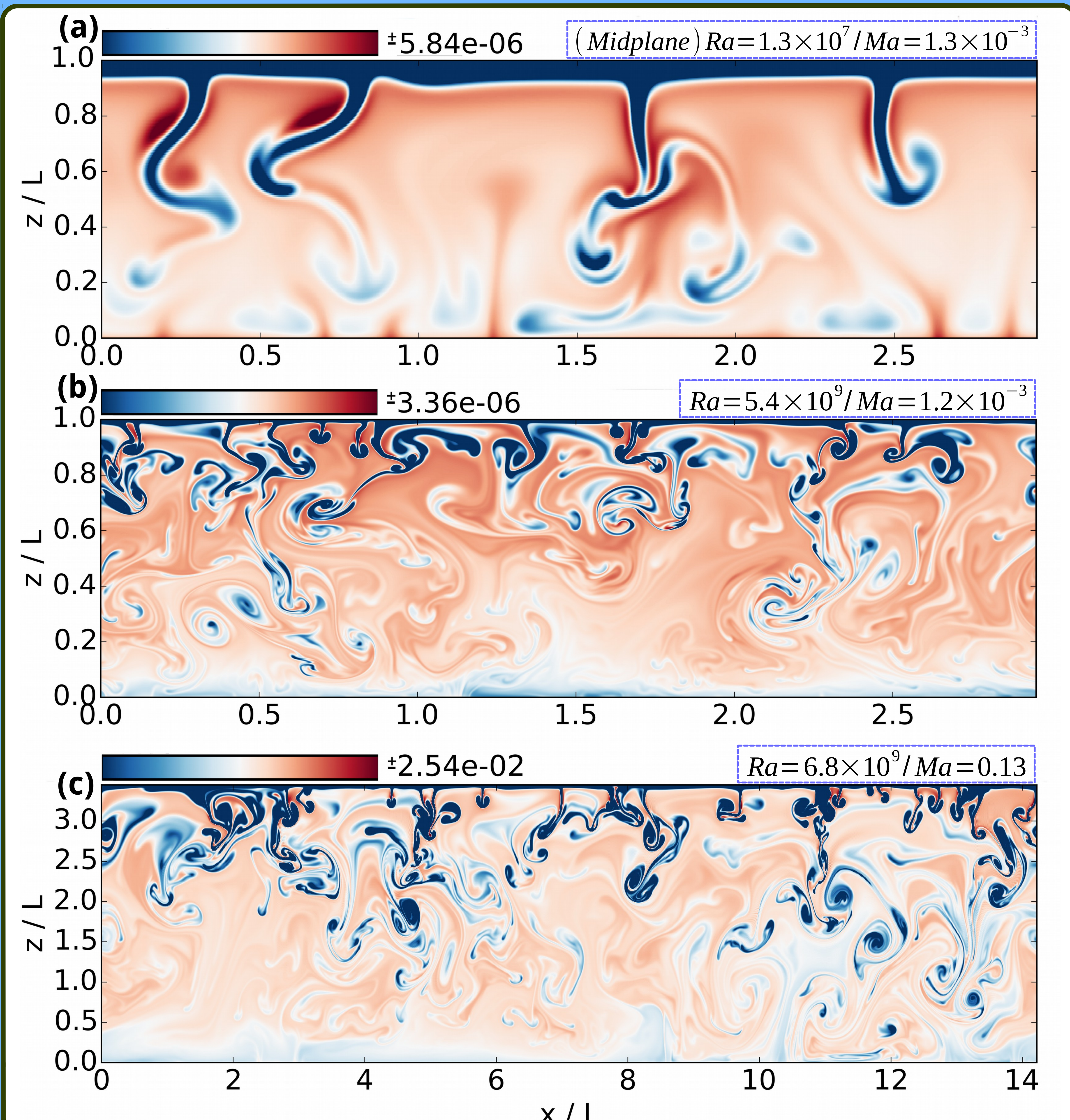


**Figure 1.** Low (a, b) and moderate (c) Mach number (Ma) convection in a polytropically stratified atmosphere spanning 3.5 density scale heights. We specify a Rayleigh number (Ra) at the top of the domain (a, $10^6$; b&c $4\times10^8$), which increases by roughly an order of magnitude at the midplane. Shown are entropy fluctuations relative to the adiabatic atmosphere. Increasing Ra leads to thinner entropy boundary layers and smaller convective structures. Increasing Ma results in structures which persist through the domain and splash off of the bottom boundary (e.g. bottom right of c).

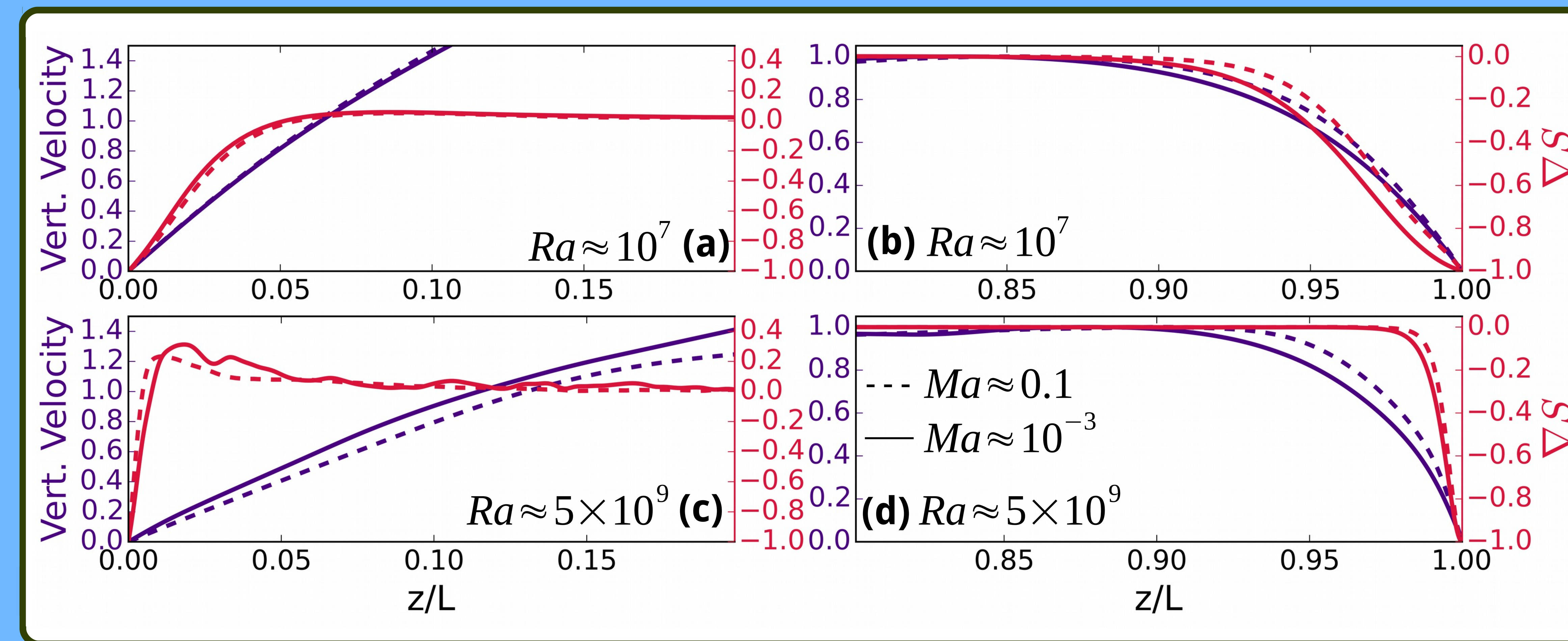


**Figure 2.** Boundary layer profiles for vertical velocity and the entropy gradient are shown at the lower (a, c) and upper (b, d) boundaries. All profiles are normalized along both axes. At low Rayleigh number (Ra; a, b) the two boundary layers are strongly coupled, but they separate at moderate Ra (c, d). Higher Mach number (Ma) generally shows thinner boundary layers.

**2. Results.** Increasing the Rayleigh number (Ra), the ratio of buoyant driving to diffusivity, decreases the average size of thermodynamic structures. Increasing the Mach number (Ma) has a similar effect (Fig. 1). The size of the entropy boundary layer shrinks with increasing Ra (Fig. 2), and the velocity boundary layer decouples from the entropy boundary layer at moderate Ra (~ $5\times10^9$). When normalized by the boundary layer thickness (Fig. 3), the profiles within the boundary collapse across Ra and Ma, showing that the change in parameters does not affect the overall structure of the boundary layer. It is also clear (Fig. 3) that higher Ra corresponds to thicker velocity and thinner entropy boundary layers.

**3. Future Work.** Most global models of solar convection exist within the low Ra regime (Fig. 1a); we aim to push these studies past the moderate Ra regime (Fig. 1b) to higher Ra (~$10^{11}$) which better resemble solar convection. We will also compare these 2-D results to future 3-D simulations in developing our boundary layer theory. Finally, we aim to examine similar parameters and atmospheres under the commonly-used anelastic approximation to determine whether or not these boundary effects are consistent across equation sets.

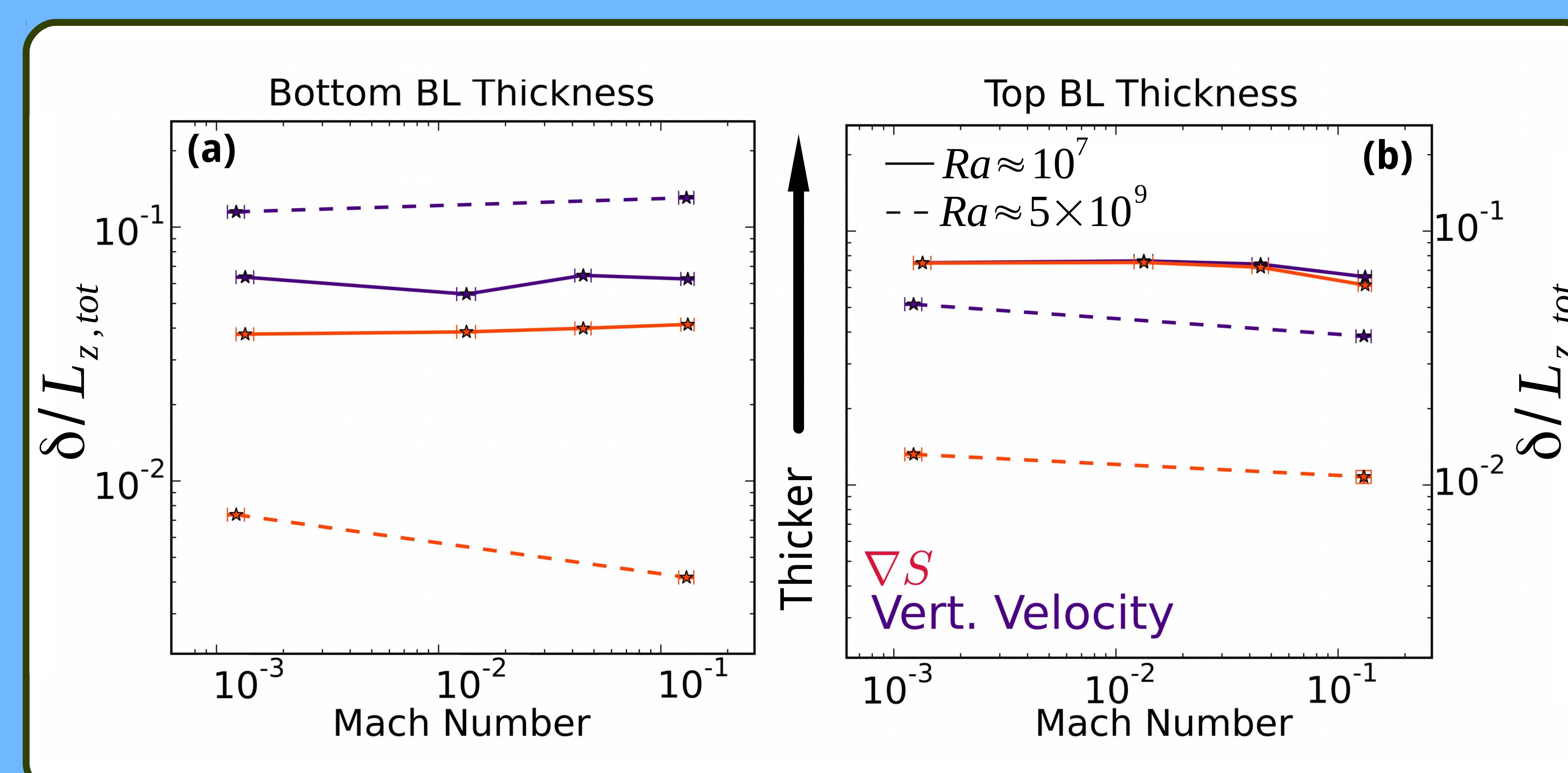


**Figure 3.** Measured boundary layer profiles (δ) at low (solid) and moderate (dashed) Rayleigh Number (Ra) for the bottom (left) and top (right) boundary layers. At high Rayleigh number, the velocity boundary layer is substantially thicker than the entropy boundary layer. Boundary thickness shows weak dependence on Mach number.

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**4. References.** [1] Hanasoge et al. 2012, PNAS, 109; [2] Greer et al. 2015, ApJ, 803; [3] Lord et al. 2014, ApJ, 793; [4] http://dedalus-project.org/