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On the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties

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We examined in an analytical manner the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties, in order to obtain the fundamental insights into the convective motion in the mantles of "super-Earths". We consider a stability in a horizontal layer of a highly compressible fluid which is in a hydrostatic (motionless) state under a uniform gravitational field. As a model of pressure-dependence in material properties, for simplicity, we employed an exponential decrease in thermal expansivity and exponential increase in thermal conductivity with depth. By using the "parcel method" as in meteorological studies, we investigated the change in the stability of thermal stratification depending on the changes in the depth-dependence of thermal expansivity and conductivity and/or those in the compressibility of fluids, with a special emphasis on the changes in the depth ranges (or the vertical extent) of unstable thermal stratifications.

Our analysis demonstrated that, for given magnitudes of compressibility and depth-dependence in thermal conductivity, the decrease in thermal expansivity enhances the instability within the entire layer. This is because the smaller thermal expansion at depth reduces the adiabatic temperature gradient there despite a high temperature, which further results in a smaller loss of thermal buoyancy associated with the vertical motion of the parcel. We also found that, under the conditions relevant to super-Earths whose mass is 10 times larger than the Earth's mass, the stability of the thermal stratification is strongly affected depending on the combinations of various parameters of the fluid layer. For example, the fluid becomes unstable in the entire layer only for the cases with a significant decrease in thermal expansion with depth and/or a sufficiently low temperature at the top surface. In particular, when the above conditions are not met, the layer of compressible fluids can be split into sublayers as in the atmosphere, i.e., a "troposphere" with an unstable thermal stratification and a "stratosphere" with a stable stratification. Since the present results are in a stark contrast with those for the cases without the compressibility of fluids, our study strongly suggests the crucial importance of the effects of adiabatic (de)compression in the understanding of the dynamics and/or the evolution of the mantles of massive super-Earths.

We also found that, under some extreme conditions with very high temperatures at the top surface, the thermal stratification can be stable in the entire depth of the fluid layer. This result may imply the possibility of super-Earths orbiting their parent stars very closely whose mantle never convects.

Keywords: super-Earths, mantle convection, compressibility, thermal stratification