Progress report for: "Fundamental studies into the solar convective conundrum: Do giant cells exist?"

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1 Work accomplished Fall 2018 - Feb 2019:

My work in Fall 2018-Spring 2019 was instructed by both an unanticipated opportunity which arose over the summer of 2018 and an unusual development (which has led to another unanticipated opportunity) in the original research plan. I will describe both of these below, including how they are informing the work of spring and summer 2019.

1.1 Unanticipated opportunity: Predicting the Rossby number in rotating systems

Preliminary work into rotating convection in our research group revealed some interesting results during the summer of 2018, and I chose to gain a greater understanding of these results and publish them during fall 2018. This work was recenly published in The Astrophysical Journal (Anders et al., 2019).

Recent work by e.g., Featherstone & Hindman (2016) suggests that rotational effects could be one possible solution or explanation to the "Solar Convective Conundrum," the apparent absence of large-scale motions at the solar photosphere and the focus of my NESSF proposal. More specifically, if flows in the deep solar convective interior are heavily influenced by the rotation of the Sun, they may not manifest themselves in the way that traditional mixing length theory or simulations predict. If rotation is the dominant force on these deep convective flows, they are at very low *Rossby number* (Ro). Unfortunately, Ro is an *output* parameter in convective simulations and it is difficult to specify its value *a priori*. In our recently published work, Anders et al. (2019), we demonstrated a manner of specifying the Rossby number of simulations in the initial conditions, as we demonstrate in Fig. 1, which is Figure 1 of Anders et al. (2019).

This recently published work has lead to fruitful discussions with multiple scientists across campus at CU Boulder, including those who are experts in rotating convection (Drs. Keith Julien and Ian Grooms) and also experts in solar convection simulations (Dr. Nick Featherstone). These discussions have led to potential collaborations which further explore the results of Anders et al. (2019), and I will describe these possibilities more fully in section 2.2.

1.2 Convection with Kramer's opacity and thermals

During the fall of 2018, I additionally worked on "project 1" in our original NESSF proposal, as quoted here:

> "Conduct literature review on convection with Kramers' opacity early fall 2018. Understand past work done, and implement fully compressible equations with Kramers' opacity in simple atmospheres. Understand how to control the Mach

number in these atmospheres by end of year 2018. Run simulations, analyze data, and submit a paper to The Astrophysical Journal on the nature of convection with Kramers' opacity at both low and high Mach number by end of spring 2019."

Through this preliminary work, I have realized that the fundamental process that I proposed to study is that of *entrainment*, and that the initially proposed project is too complex of a starting point for a detailed study of this phenomenon. Recently, Dr. Daniel Lecoanet (Princeton) has performed an in-depth study of entrainment in Boussinesq thermals (Lecoanet & Jeevanjee, 2018, in review). A thermal is a region of cold (or hot) fluid that evolves from rest according to buoyant forces, and they were able to easily study entrainment in these thermals in both the laminar and turbulent regime. I have formed a collaboration with Dr. Lecoanet in order to extend his work to study entrainment of thermals in stratified domains under the fully compressible equations. These simulations are, in some way, a simple model of the "entropy rain" proposed by Brandenburg (2016), and understanding how the complexities of the fully compressible equations and highly stratified domains will be important to understanding whether or not the entropy rain hypothesis is vald.

I have been studying stratified thermals since late fall 2018, and currently have a fully functioning code for simulating and analyzing thermals, as in Fig. 2. We aim to come up with a robust theory of the behavior of laminar thermals (Reynolds number [Re] $\sim$ 600, Fig. 2) which describes the downwards propagation and entrainment of these fluid regions

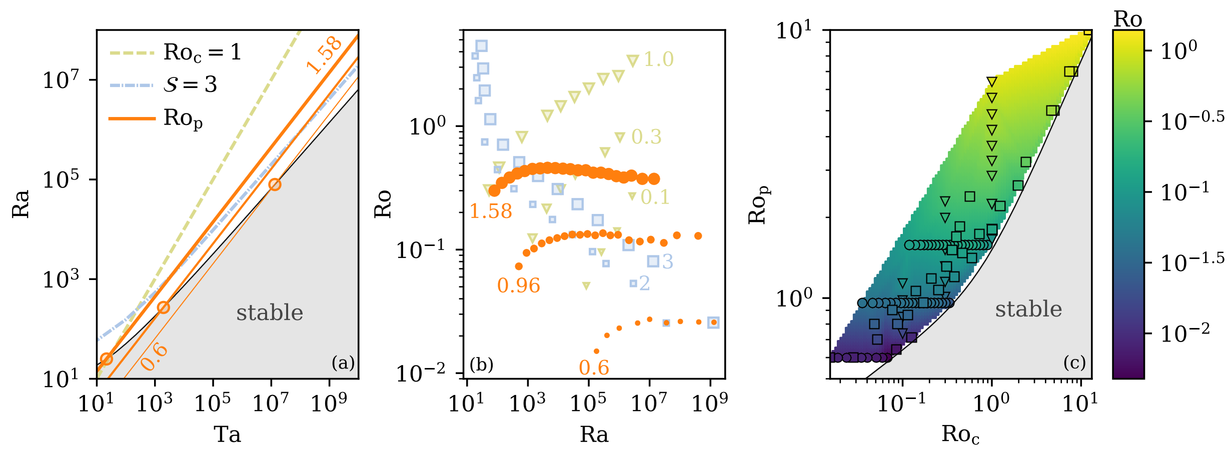

Figure 1: Figure 1 of Anders et al. (2019) is shown. In (a), we show the parameter space of rotating convection, with Rayleigh number (Ra, ratio of buoyant driving to diffusive damping) on the y-axis and the Taylor number (Ta, strength of rotation compared to diffusive damping) on the x-axis. We also show three types of "paths" through this space that simulations can walk in blue (constant supercriticality, $\mathcal{S}$), green (constant "convective Rossby number," $\mathrm{Ro_c}$), and orange (constant "predictive Rossby number," $\mathrm{Ro_p}$). In (b), we show that along the orange paths, at constant $\mathrm{Ro_p}$, the evolved Rossby number (Ro) of simulations is roughly constant across orders of magnitude of Ra, while the other two paths show increasing or decreasing Ro. In (c), we show that the evolved Rossby number is roughly a function of the predictive Rossby number alone, and not significantly a function of the commonly-used $\mathrm{Ro_c}$. These results imply that by choosing the value of $\mathrm{Ro_p}$ and walking along these paths in parameter space, the degree of rotational constraint of simulations can be chosen by construction.

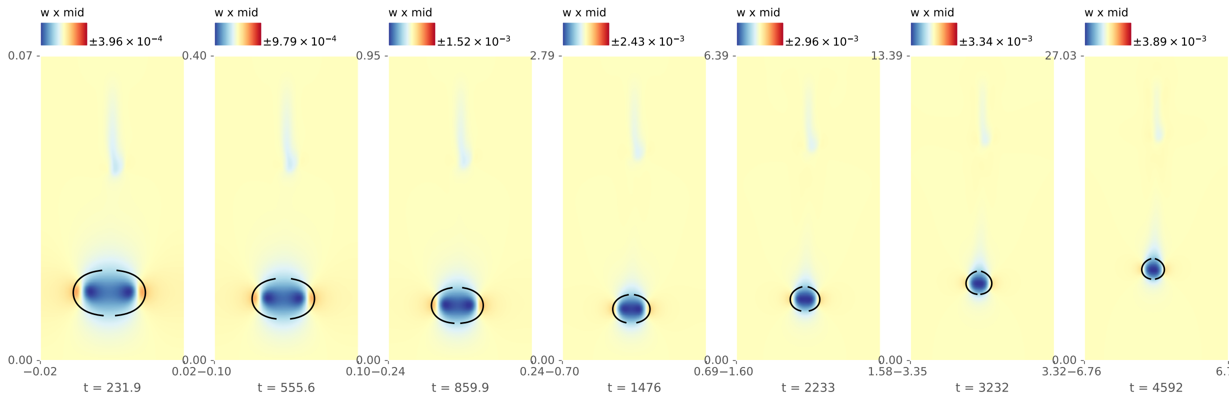

Figure 2: Snapshots of the vertical velocity fields late in the evolution of thermals with characteristic Reynolds numbers of 600 are shown. From left to right, the atmosphere through which the thermal is falling is stratified by $n_\rho = [0.1, 0.5, 1, 2, 3, 4, 5]$ density scale heights, so the simulation on the left is essentially in the Boussinesq limit of Lecoanet & Jeevanjee (2018) and the simulation on the right is highly stratified. The thermal tracking algorithm of Lecoanet & Jeevanjee (2018) has been extended to work robustly in stratified domains, and the black outlines show the boundaries of the thermal obtained by this algorithm. These are 3D simulations, and these are cuts of the $y - z$ at $x = 0$.

regardless at both small and large stratification. Once we fully understand this theory, we will study whether this linear theory describes the evolution of turbulent thermals (Re $\sim$ 6000), whose evolution more accurately reflects that of the solar context. This work should be submitted for publication by the end of spring 2019.

2 Future plans for 2019-2020

Forthcoming work according to the original proposal is as follows:

Year 1 (Summer 2019):

- Conduct literature review on past work done on ionizing convection and moist convection. Construct appropriate atmospheres for studying ionizing convection, and learn what properties of these atmospheres control different aspects of the evolved solutions.

Year 2 (Fall 2019 - Spring/Summer 2020):

- Run simulations of ionizing convection, analyze data, and submit a paper to The Astrophysical Journal by the end of year 2019.
- *Academic progression:* Combine work from five published (or submitted) papers into a thesis, to be defended at the end of Spring 2020.

This general outline still holds true to my plans for the upcoming academic year: I will do research this summer and next fall, then graduate in the spring or early summer and move on to a postdoctoral position at a new university.

Currently, my plan is to work on the originally proposed research (modern, parameterized simulations of ionizing convection) in an effort to gain an understanding of the size of convective elements driven at the surface. However, due to the unexpected turns which arose over the past year, there are a few other projects that I may also investigate coincidentally with these ionizing simulations. While it would be impossible to study all three of the following projects coincidentally with ionizing convection, it should be feasible to work on the initially proposed work as well as one of the following opportunities that has arisen in discussions with colleagues and collaborators over the past year:

2.1 Possible mini-project 1: Kramer's opacity thermals

In the study of thermals that I am currently conducting to learn about entrainment in the solar convective envelope (see section 1.2), I am using a simple, constant-thermal-conductivity specification in order to study the simple underlying physics. Adding in a nonlinear, Kramer's-like opacity to these thermal simulations is trivial, and with the tools I have already developed it would be very easy to see if such a nonlinear opacity affects the magnitude of entrainment in these experiments measurably. Such a complication is beyond the scope of the current paper on stratified thermals, but this small, letter-length project would probe the same scientific answer as my originally proposed project 1: *does a nonlinear, solar-like opacity reduce entrainment in cold downflows?*

2.2 Possible mini-project 2: Continuing rotation work

As I mentioned earlier, the work published in Anders et al. (2019) has potentially launched launched future collaborations with, e.g., Drs. Julien, Grooms, and/or Featherstone. Working alongside these experts, I could further study the results published in Anders et al. (2019) with the goal of determining what physical mechanism is responsible for setting the Rossby number. Put differently, in our recent work we showed that, empirically, the Rossby number is fairly constant if you hold the "predictive Rossby number" constant. A follow-up project would aim to understand the physical mechanism in the Navier-Stokes equations that leads to this result, and understand if the Rossby number can be predicted in the solar regime.

2.3 Possible mini-project 3: Accelerated evolution of stratified, overshooting convection

In my second paper (Anders et al., 2018), I studied a method of fast-forwarding through the long relaxation of the atmosphere's thermal structure in a simple, boussinesq convective system. A fellow graduate student in our research group and I have some promising first results of an extension of this method to stratified, compressible simulations, and I could follow up on these results without too much time investment. This method shows promise for saving millions of cpu-hours in future work by allowing computer time to be used on studying "useful" parts of simulations (in which the thermal structure is relaxed and the convective flows are no longer rearranging it) rather than transient phases.

References

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