Modeling Double–Diffusive Processes in Ocean and Stars

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1 Introduction

On the whole, the ocean is stably stratified with lighter water overlying denser water. Because the ocean's density is determined by both temperature and salinity, double diffusive processes can, in certain situations, erode the statically stable stratification. Double diffusion occurs when two different active scalars exist, eg. T and μ, which have very different kinematic diffusivities, where μ is molecular weight. There are two main types of double–diffusive processes in the ocean:

1. Saltfingering: warm and salty water lies over cold and less salty water, the vertical salinity gradient destabilizes and the temperature gradient stabilizes the water column (e.g. in Tyrrhenian Sea, Caribbean Sea)
2. Semiconvection: cold and less salty water lies over warm and salty water, the vertical salinity gradient stabilizes and the temperature gradient destabilizes the water column (e.g. Arctic, underneath melting sea ice).

Thus, double–diffusive processes can increase the vertical transport of material by turbulences but the mean vertical velocity will be zero.
Double–diffusion may have an observable effect on large scale circulation patterns in the ocean [1], [2].
In stars the regime is similar where salinity is replaced by He and semiconvection is the field of interest under the assumption, that the temperature gradient destabilizes and the molecular weight gradient stabilizes a certain region.

Semiconvection plays a fundamental role in understanding the evolution of massive stars. It may lead to structural modifications outside the convective core that have significant effects on later phases of stellar evolution. Cold He-poor plasma is stratified above hot He-rich material, which yields the existence of a destabilizing temperature gradient ∇T and a stabilizing molecular weigth gradient $\nabla\mu$.

Main goals:

1. Calibration of models of this physical process for stellar structure and evolution models.
2. Validation of the appropriate physical scenario of semiconvection.

2 Astrophysics / Oceanography - The connection

Flows in astrophysics and in oceanography are usually described with the Navier-Stokes equations. Due to the fact that salt or helium enriched matter leads to a additional mass or concentration equation, further diffusivities have to be taken into account. These diffusivities (thermal diffusivity and salt/helium diffusivity) are commonly expressed in terms of the Prandtl number and the Lewis number. The Prandtl number is the ratio of the viscous diffusion rate and the thermal diffusivity, while the Lewis number is the ratio of the helium/salt diffusivity and the thermal diffusivity. In both, oceanography and astrophysics, the ratio Pr/Le is in order of magnitude about 100, which means, that the viscous diffusion rate is 100 times larger, than the salt/helium diffusivity. This leads to comparable regimes, although both fluids (water / plasma) are dominated by completely different microphysics.

Double–Diffusion in the Ocean

3 Different simulations of saltfingers with "DNS"

Double-diffusive processes are modelled by using the finite-volume ocean model MITgcm [3].
Several **D**irect **N**umerical **S**imulations of 2.5D and 3D problems to provide estimates of turbulent fluxes of heat and salinity. In 3D we used 50^3 gridpoints and Lewis Number $\tau = 0.1$, while in 2.5D the simulations is done with $512 \times 8 \times 512$ gridpoints and $\tau = 0.01$ and $\tau = 0.1$. There is a contrast in the structure of Saltfingers by using different Lewis numbers (Figure 1).
Figure 1 shows salinity snapshots of 2.5D saltfinger simulations with Lewis Numbers $\tau = 0.01$ (left side) and $\tau = 0.1$ (right side) after 400sec. The only difference in initial conditions of these two simulations is the τ.

Figure 1

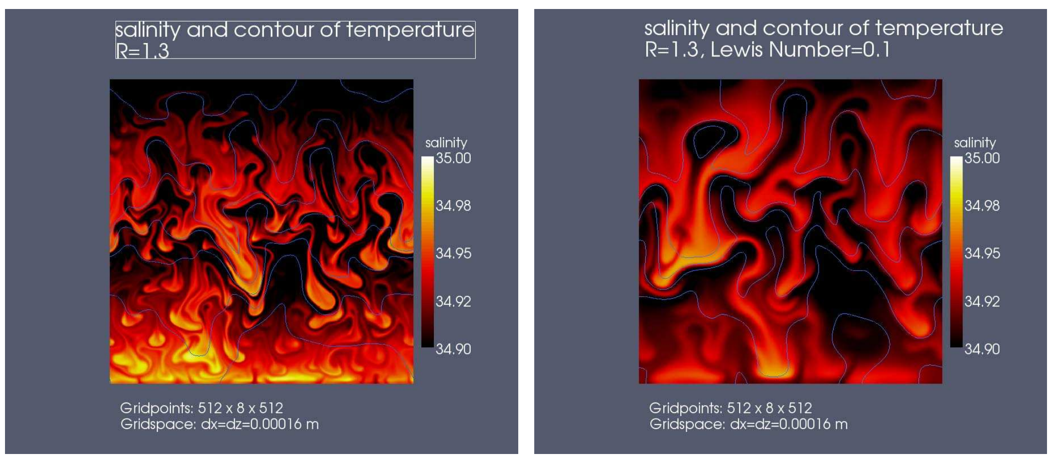
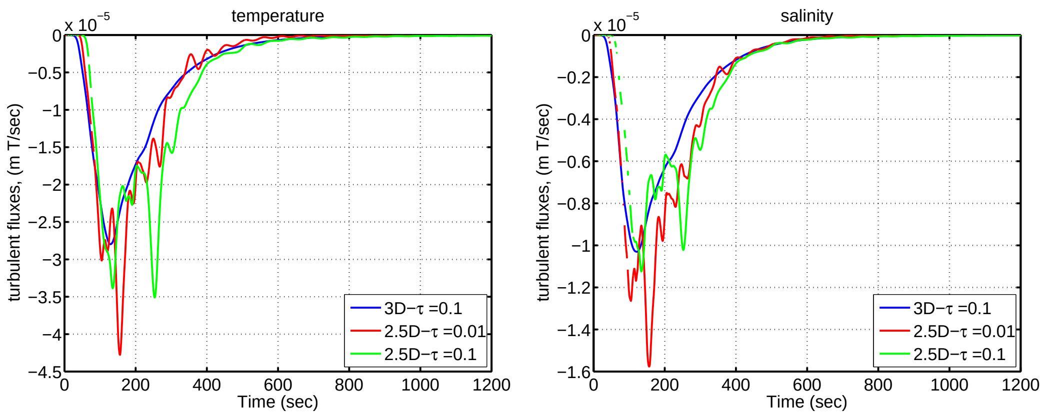


Figure 2 shows the mean turbulent fluxes of 3D (blue line) and 2.5D (red and green lines) simulations. The turbulent fluxes depends only weakly on the Lewis Number

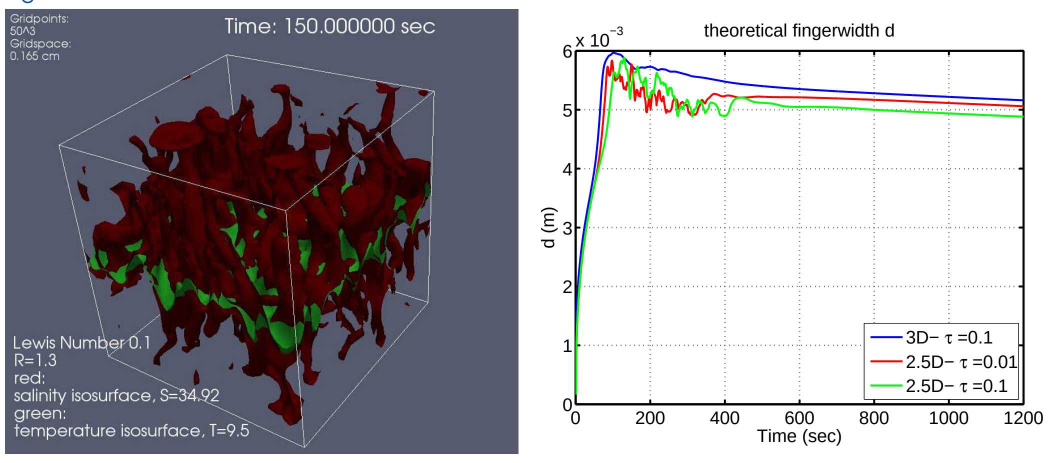
Figure 2



4 3D–Simulation of Saltfingers

Figure 3 shows the evolution of 3D saltfingers with $\tau = 0.1$ after 150sec (left). On the right hand side we find the fingerwidth $d = \left(\frac{\nu\kappa_T}{\alpha g \partial_z \overline{T}}\right)^{1/4}$ of all three simulations.

Figure 3



5 Observations/Conclusions

The simulations begins with diffusive processes, after the first 20 seconds we observe a transition to a turbulent regime for temperature **and** salinity, where temperature and salinity are efficiently transported through the domain. $400 - 500$sec later there is a transition back to a diffusive regime, but only for temperature. The diffusive flux of salinity is smaller than the turbulent flux by $2 - 3$ orders of magnitude and more.
The observed fingerwidth agrees to the theoretical and is resolved by 10 gridpoints in each simulation except for 3D case, where the resolution is coarse.
Our Experiments suggests that 2.5D simulations are sufficient for estimating the effective transport of temperature and salinity. Nevertheless, to study the physics of the plumes of saltfingers $3D$ simulations are neccesary

6 Aims and Outlook

- Simulations by more than 1024^3 grid points are required but still very expensive
- model vertically bigger domains to study lamination
- use parameterisations obtained from the **"DNS"** part to run **LES** and check existing parametrisations
- compare to stellar conditions in low Prandtl Number regime for spatial and temporal much larger scales, also simulations to semiconvection are of interest

Double–Diffusion in stars

7 Simulations

Figure 4

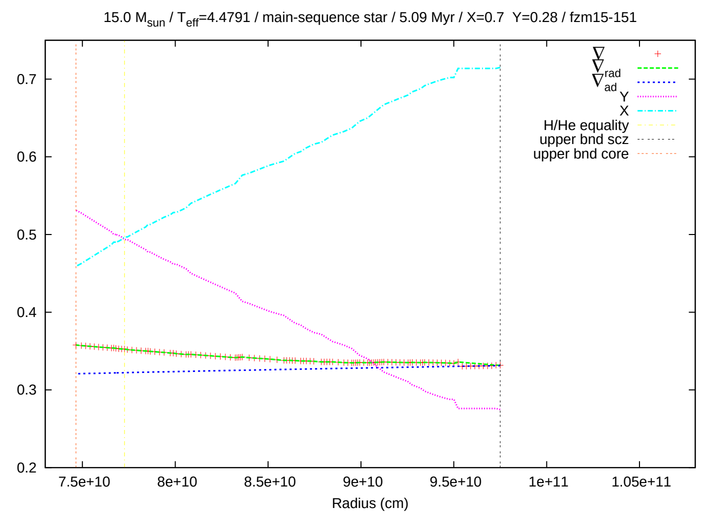


Figure 4 Typical semi-convection zone of a 15 solar mass star. The height of the SCZ is about 200 Mm or 5% of the radius of the star. The plot shows the gradients (real temperature gradient, radiative gradient, adiabatic gradient) and the mass-fractions of hydrogen (X) and helium (Y). These values, especially the gradients, will be used for upcoming more realistic simulations.

8 The ANTARES code

ANTARES (Advanced Numerical Tool for Astrophysical RESearch): The Navier-Stokes equations are solved explicitly with an additional Helium concentration equation for semi-convection simulations. A weighted essentially non-oscillatory method in fifth order is used to resolve upcoming steep gradients. Idealized microphysics (fully ionized, ideal gas with radiation pressure, OPAL opacities) gain a realistic simulation environment. The ANTARES code is written for 1D-3D simulations and is parallelized hybrid in MPI and OpenMP, which scales up to 1024 CPUs on a wide range of different platforms.

9 Simulations in 2D

Simulating the entire star is not feasible, so a "box-in-the-star" model is choosen. Semi-convection zones of our interest occur in so called massive main sequence stars, where the nuclear reactions are dominated by the proton-proton chain (hydrogen fuses to helium, mainly through the CNO cycle). Typical semi-convective zones are in the order of $200 - 400Mm$, which is about 10 percent of the radius of the star. The main goal is to understand the nature of semiconvection by simulating its behavior numerically. This is done in boxes with heights of about $2 - 20Mm$, to resolve diffusive mixing mixing processes with high resolution.

Following figures show a stellar interior region of about 50Mm (50.000 km) which is about 25% of the semiconvection zone. Prandtl and Lewis numbers are choosen very high (both 0.05). The resolution is 200 x 200 points. On the left side the helium density in absolute values of about 0.6 g/cm^2 is plotted, on the right side the corresponding temperature field with values of about 22 Mio. K. These simulations are first results and show the correctness of the used physics and numeric. Further 2D results are expected in the next month.

Figure 5

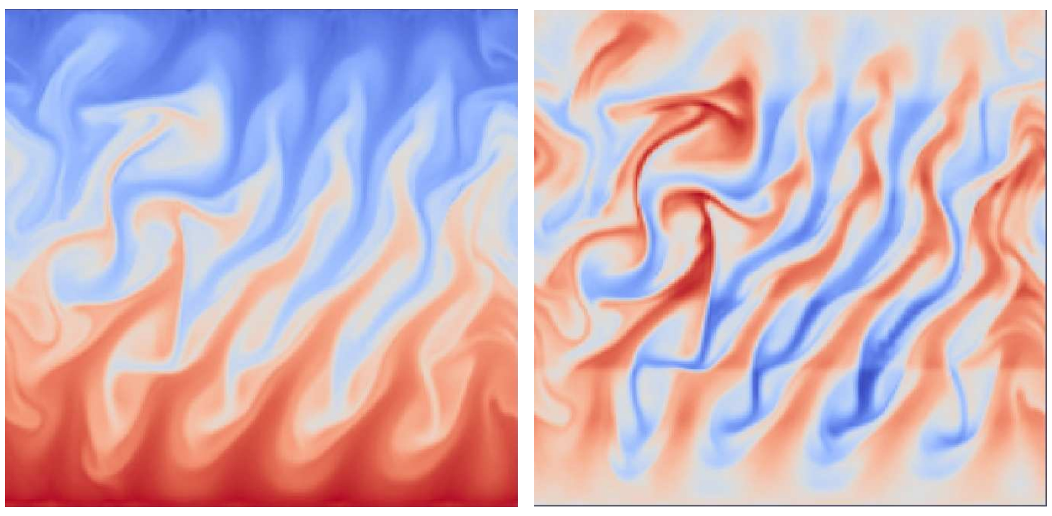


Figure 5 shows density of helium and temperature of a 2D simulation.

10 Collaborations

1. Universität Wien (ACORE group): H. Muthsam

References

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