Shear mediates downward heat fluxes in unstably stratified environments

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Introduction

The role of winter time dynamics in ice covered lakes has gained considerable prominence over the past few years. It is thus important to determine how the energy from incident solar radiation modifies an under-ice flow. For cold freshwater settings ($T < T_{md}$), the incident solar radiation results in an increase in fluid density near the surface, inducing convection and mixing. Often subsurface currents (e.g. an under ice river plume) that can carry momentum and heat are also present. Is mixing more vigorous under these conditions? Can this process be parameterized?

Methods

We solve the 3D Incompressible Navier-Stokes Equations to simulate a system with a simple penetrative short wave radiation model in cold water (below four degrees C) in the presence of a shear flow. The domain is a rectangular box of dimensions 1m x 1m x 2m with periodic horizontal boundaries.

Theory

Shortwave radiation adds energy to the water column, and in cold water settings, an unstable stratification is created, leading to mixing. However, in the presence of a subsurface current, previous studies have shown that the instability growth is spatially limited, becoming quasi-2D. At some point, this system becomes fully 3D and turbulent, and the transition to the turbulent state is typically associated with rapid kinetic energy generation and dissipation (friction as fluid parcels rub against each other). How does the sub-surface current affect this process?

References

Benilov, E. S., Naulin, V., & Rasmussen, J. J. (2002). Does a sheared flow stabilize inversely stratified fluid?. *Physics of Fluids*, *14*(5), 1674-1680.
Kundu, P. K., Cohen, I. M., & Dowling, D. W. (2008). Fluid Mechanics 4th.
Subich, C. J., Lamb, K. G., & Stastna, M. (2013). Simulation of the Navier–Stokes equations in three dimensions with a spectral collocation method. *International Journal for Numerical Methods in Fluids*, *73*(2), 103-129.
Mikhailenko, V. S., Scime, E. E., & Mikhailenko, V. V. (2005). Stability of stratified flow with inhomogeneous shear. *Physical Review E*, *71*(2), 026306.

Experiments

Three cases are considered, "Fast" (1 cm/s current), "Slow" (1mm/s current) and "Base" (no current). The incident radiation is 30 W/m² and the initial temperature is 1°C. The solar radiation model is a single band model. Figure 1 shows the model setup, Figure 2 shows the 3D temperature field at various times, Figure 3 shows horizontally averaged kinetic energy, and Figure 4 shows time series of the mean dissipation.

Setup

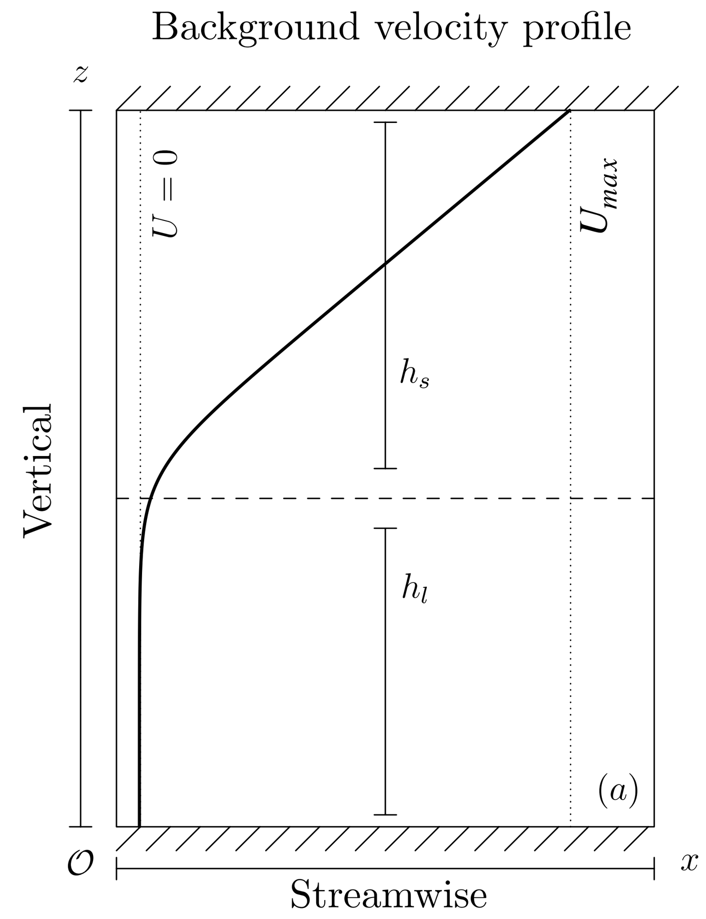

Figure 1: schematic of model setup. Spanwise direction is out of the page here.

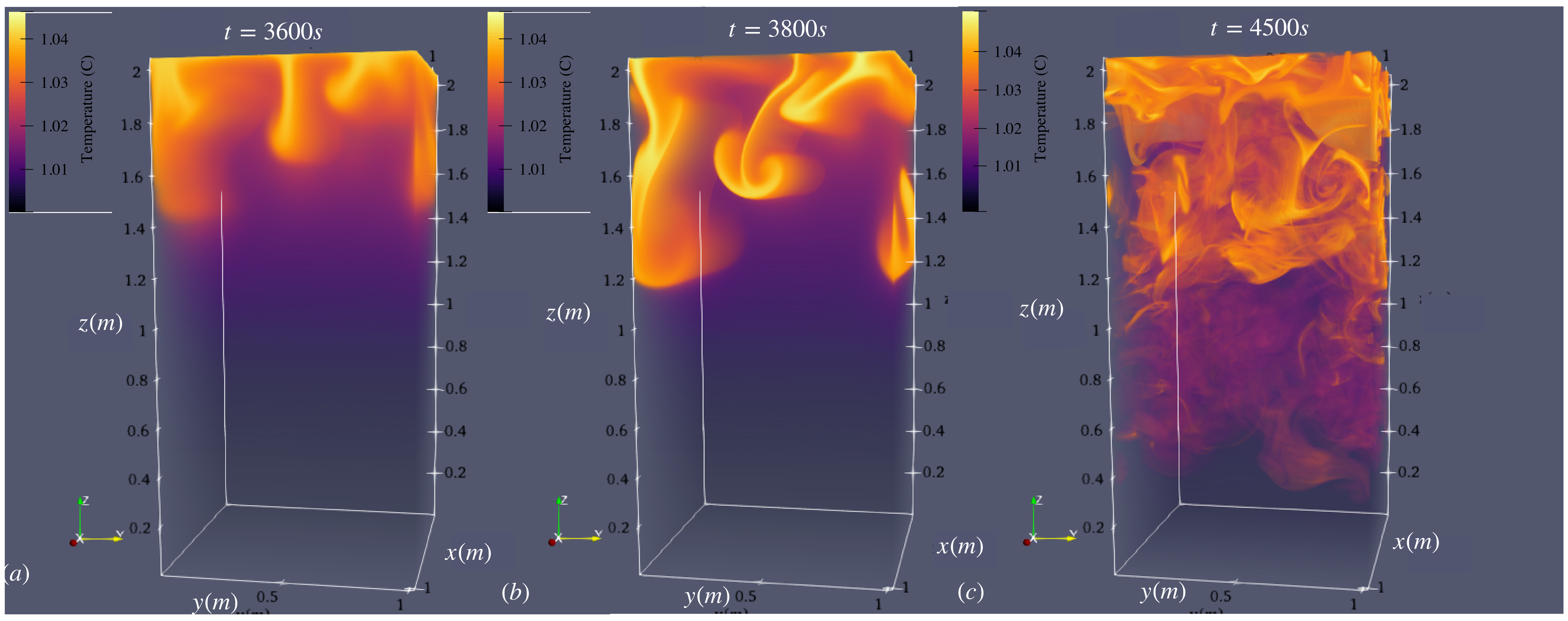

Figure 2: 3D temperature fields at three times for the Fast case. Panels (a) and (b) are at various stages of the quasi-2D instability development, and (c) shows the full 3D state when the instabilities have collapsed. The background current is directed out of the page in this figure. Opacity on the plot correlates with temperature (higher temperatures mean higher opacity).

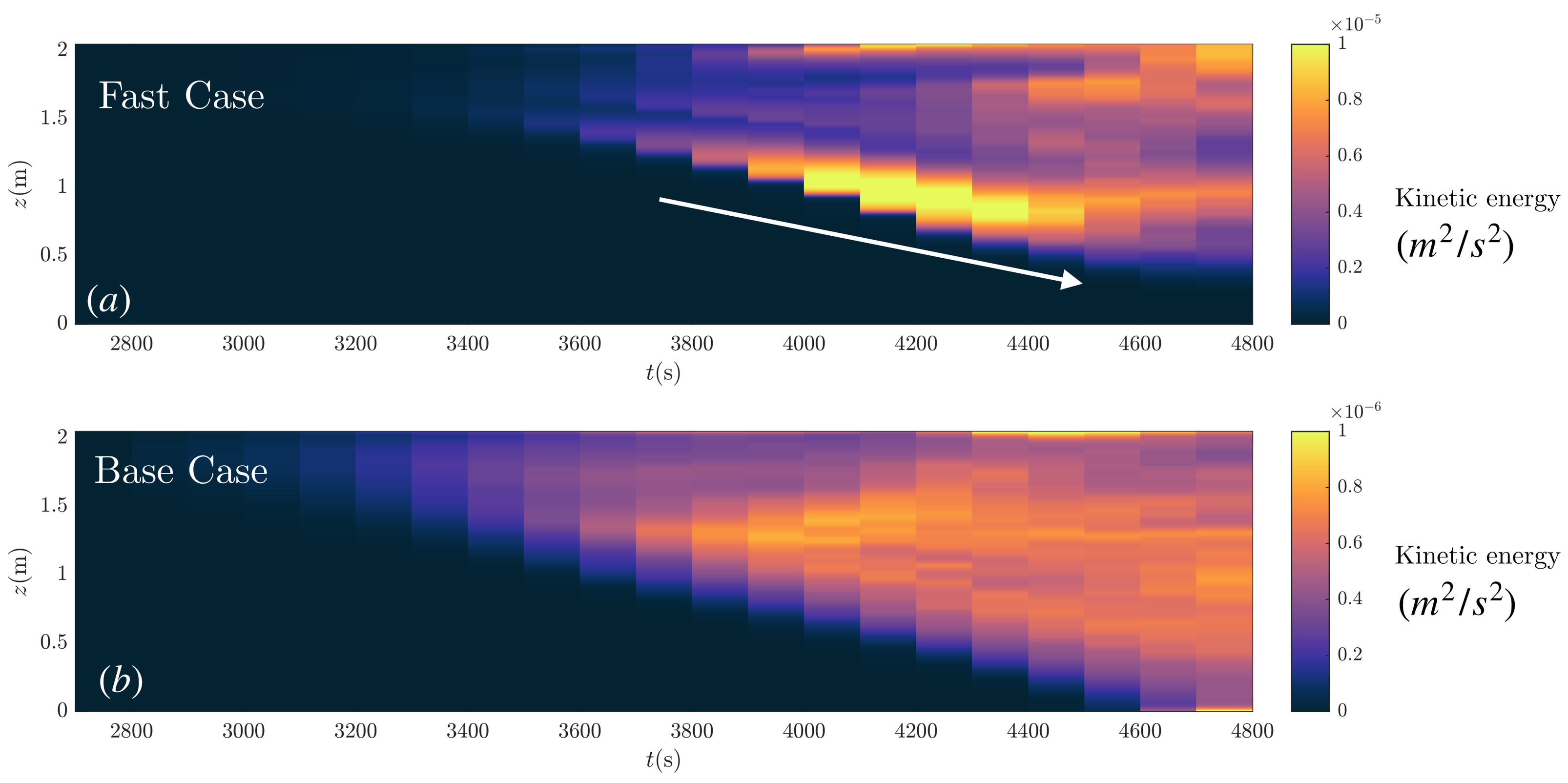

Figure 3: Time series of perturbation kinetic energy profiles for the Fast case (panel (a)) and Base case (panel (b)), prior to and during three-dimensionalization. Note the burst of kinetic energy as the instability propagates downward, indicated by the white arrow. Also note the scale difference between panels (a) and (b).

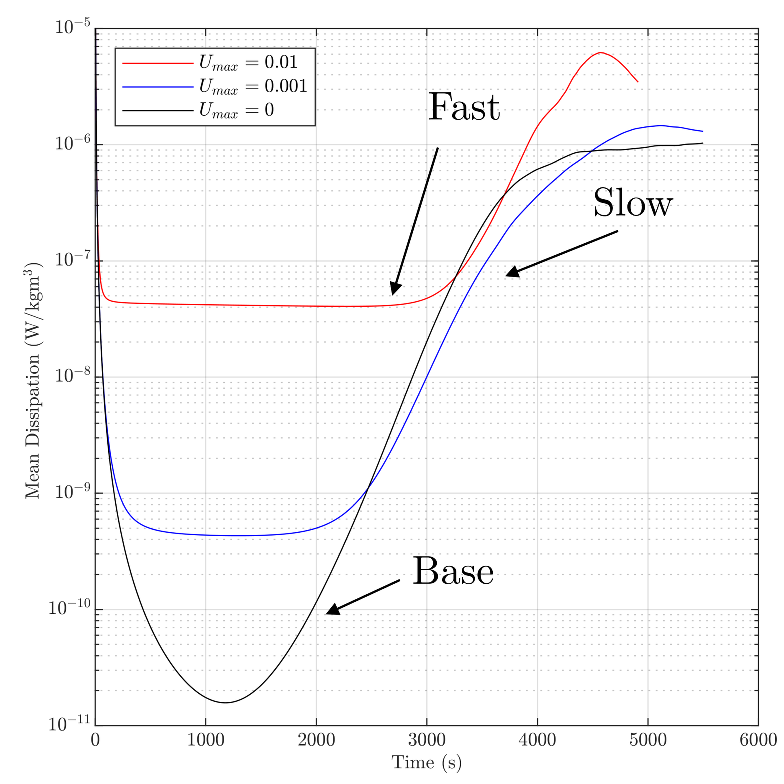

Figure 4: Mean kinetic energy dissipation in three cases with varying strengths of background currents. Red is the Fast case, blue is the Slow case, and black is the Base case. Note the difference in the order of magnitude in the peaks of each curve.

Discussion

The solar radiation generates convective instabilities (the tendrils in figure 2 (a) and (b)), but the shear flow spatially limits their growth. As the instabilities mature, they undergo strong complicated nonlinear interactions that lead to a chaotic and turbulent flow (figure 2 (c)). The vortical interactions are strongest in the fast case and cause a burst of kinetic energy (figure (3)) leading to increased levels of dissipation (figure (4)). Properly accounting for the dissipation is a key step to include this process in larger scale models.

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