Interaction of an axisymmetric turbulent jet with a thermocline

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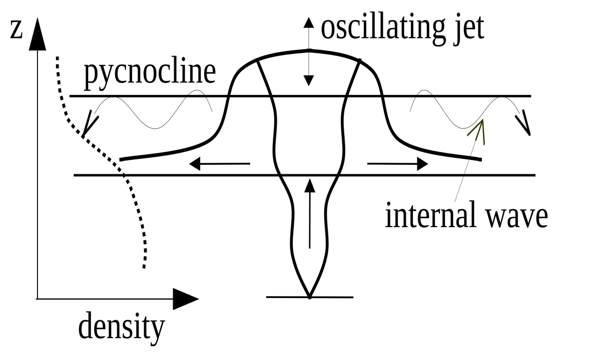
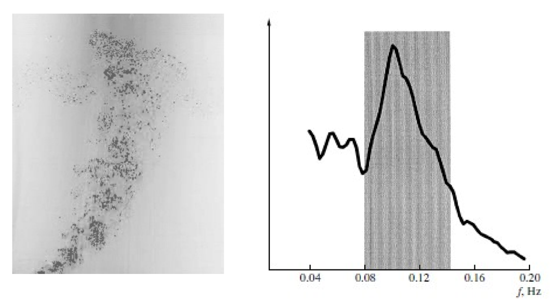
Introduction

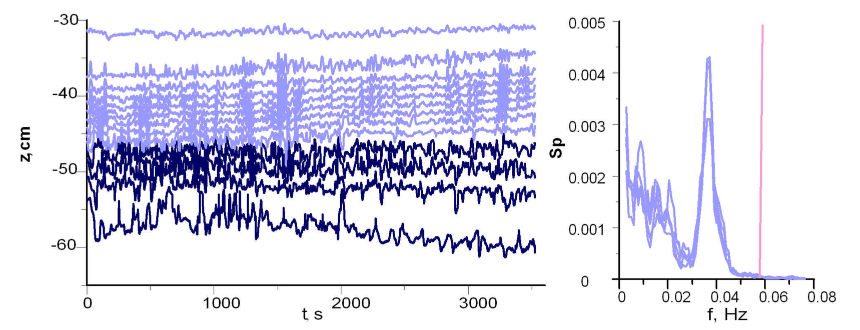
Self-sustained oscillations of the jets in the pycnocline can effectively generate internal waves [1].



Jet in a stratified fluid



Spectrum of jet oscillations: experiment and theory (shaded)



Experiments of Internal waves generated by a jet

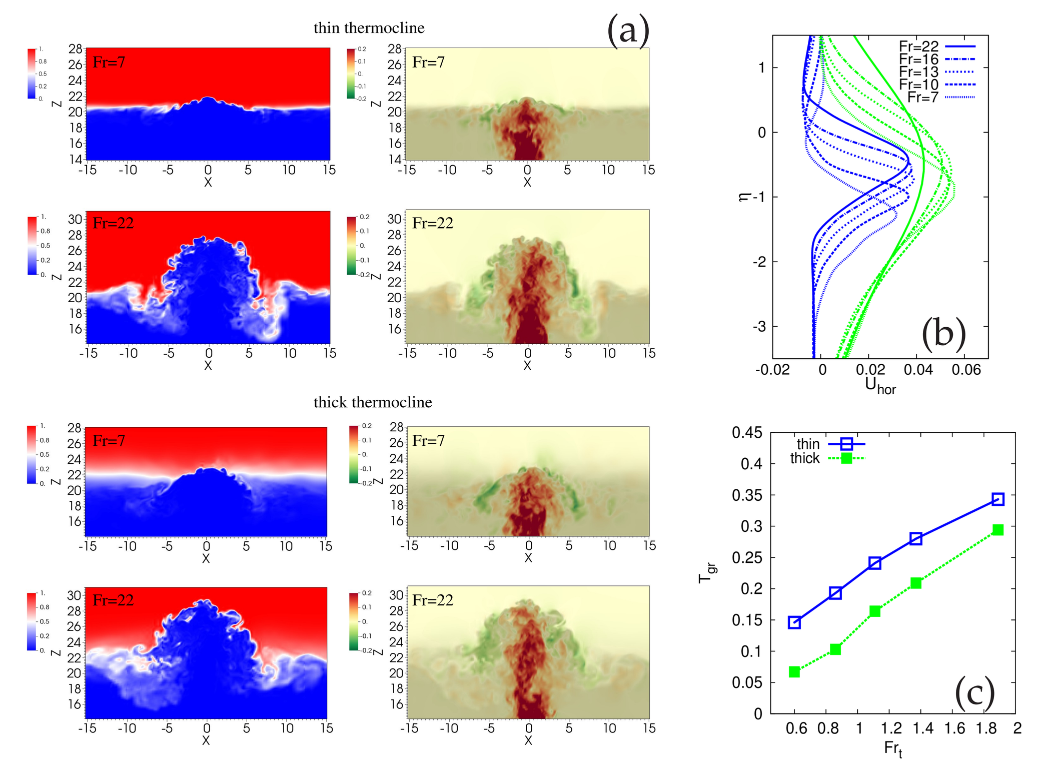
How stratification influences self-sustained regime?

Objectives

We investigate the interaction of a turbulent jet with a thermocline by means of LES.

1. Validation of a LES model (dynamic Smagorinsky) in Nek5000 [2] for a turbulent jet in homogeneous and stratified fluid.
2. Investigation of jet dynamics in a stratified fluid: mean penetration height through the thermocline.
3. Turbulent stratified entrainment.
4. Generation of internal waves: jet oscillations and internal waves spectra, comparison with the experiment.

Turbulent stratified entrainment

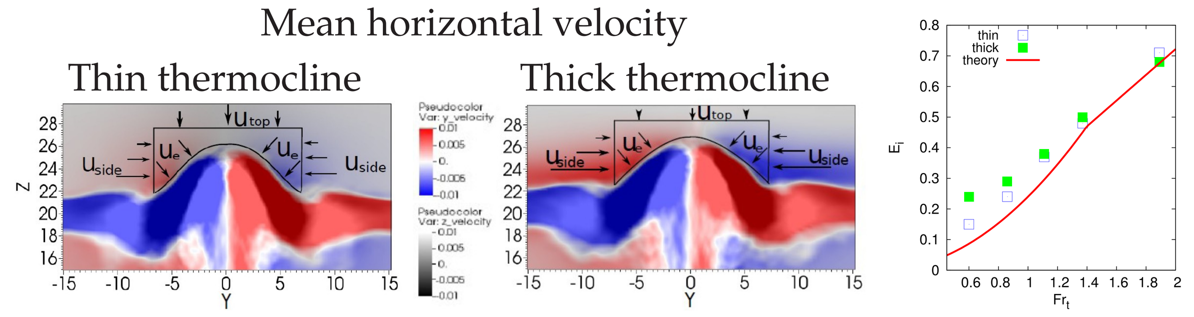


(a) Snapshots of temperature and vertical velocity.
(b) Profiles of mean horizontal velocity at r=20.
(c) Temperature of a gravity current $T_{gr} = \int TU_{hor}dz / \int U_{hor}dz$

At large Fr: ∼ same penetration, but different temperature -> entrainment of a colder fluid from the thick thermocline Formation of a horizontal flow towards the jet

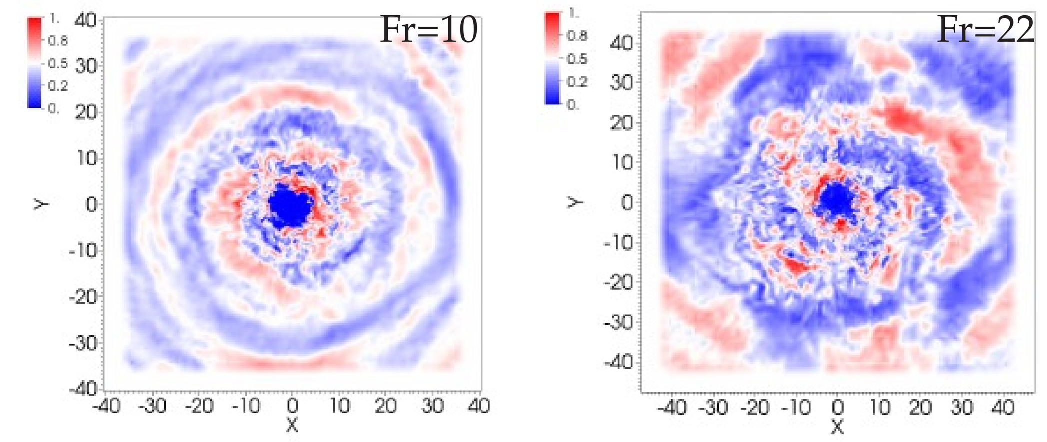
Mean horizontal velocity

Thin thermocline | Thick thermocline

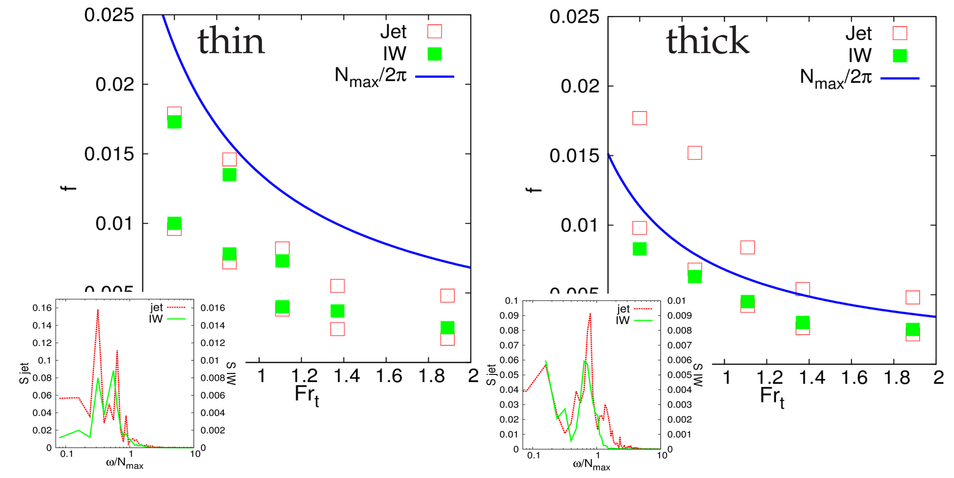


Entrainment coefficient $E_i = Q_e/Q_i$ (entrained-to-inflow ratio) in the thin thermocline is in agreement with the theory for a two-layer stratified fluid [3]

Internal waves

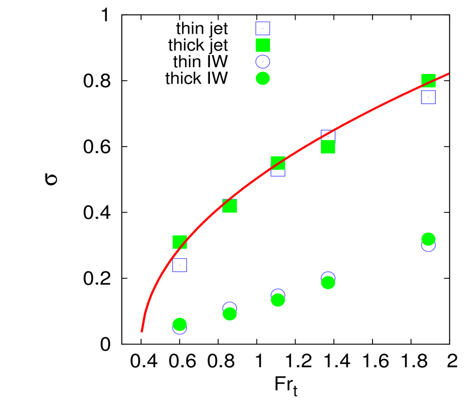


Instantaneous temperature fields in the horizontal plane at the centre of the thin thermocline - **generation of internal waves.**



Frequencies of jet oscillations and internal waves.

Jet-oscillation spectra with two frequencies - only peak at frequency lower than the maximal buoyancy frequency found for internal waves in the thick thermocline (in agreement with experiments)



Amplitudes of jet oscillations and internal waves versus Fr_t. Red curve is the stationary solution of Landau equation.

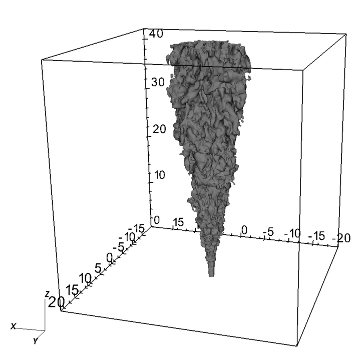
Self-sustained regime of jet oscillations confirmed.

1 Jet in a homogeneous fluid

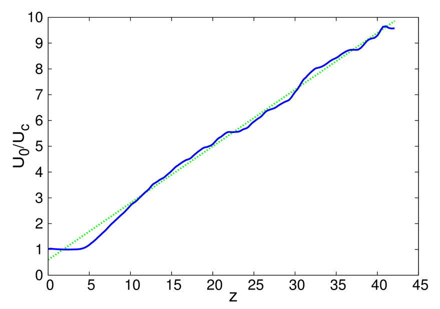
Navier-Stokes equations with subgrid-scale model.

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j^2} - \frac{1}{Re}\frac{\partial \tau_{ij}}{\partial x_j}, \quad \frac{\partial u_i}{\partial x_i} = 0.$$

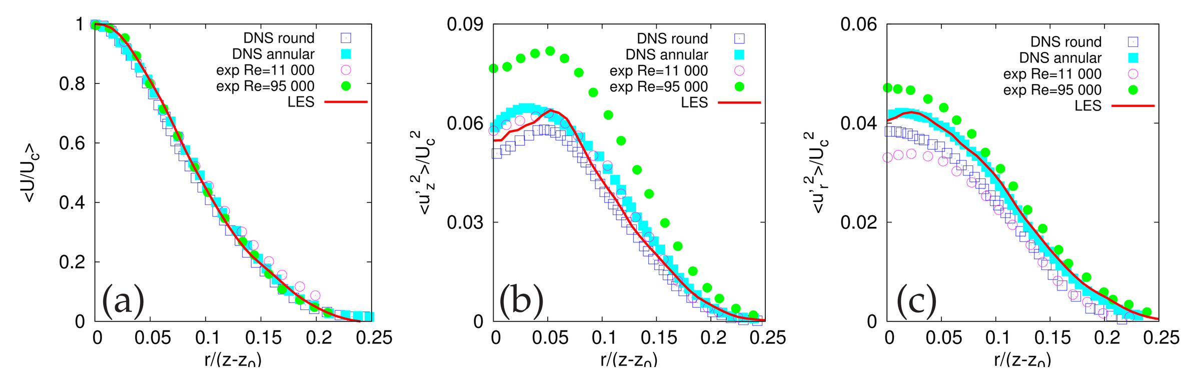
- Inflow: $U = U_0(-0.5\tanh((r-0.4)/0.05)+0.5)$.



Jet illustration



Inverse centerline velocity along z



Mean velocity profile (a) and turbulent stresses (b),(c)

Validation against experiments and DNS

Developed turbulent jet after z=14 -> Thermocline at z=20

2 Jet in a stratified fluid

Navier-Stokes equations with Boussinesq approximation

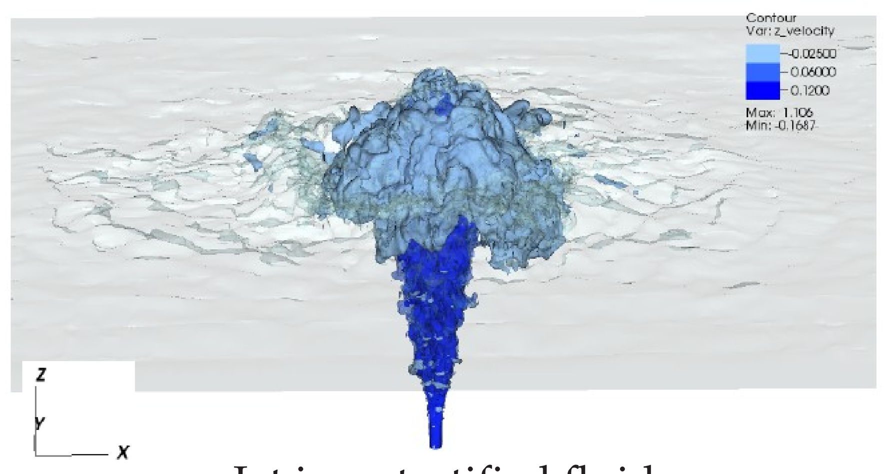
$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j^2} + \frac{(T-T_s')\delta_{iz}}{Fr^2} - \frac{1}{Re}\frac{\partial \tau_{ij}}{\partial x_j},$$

$$\frac{\partial T}{\partial t} + u_j\frac{\partial T}{\partial x_j} = \frac{1}{RePr}\frac{\partial^2 T}{\partial x_j^2} - \frac{1}{Re}\frac{\partial \Theta_j}{\partial x_j}, \quad \frac{\partial u_i}{\partial x_i} = 0.$$

- Profile of stratification: $T_s' = \frac{1}{2}(1+\tanh(\gamma(z-z_0)))$
- Jet temperature at the inflow is equal to ambient
- Side: Open boundary conditions + sponge on the lateral sides
- Top: Open boundary condition

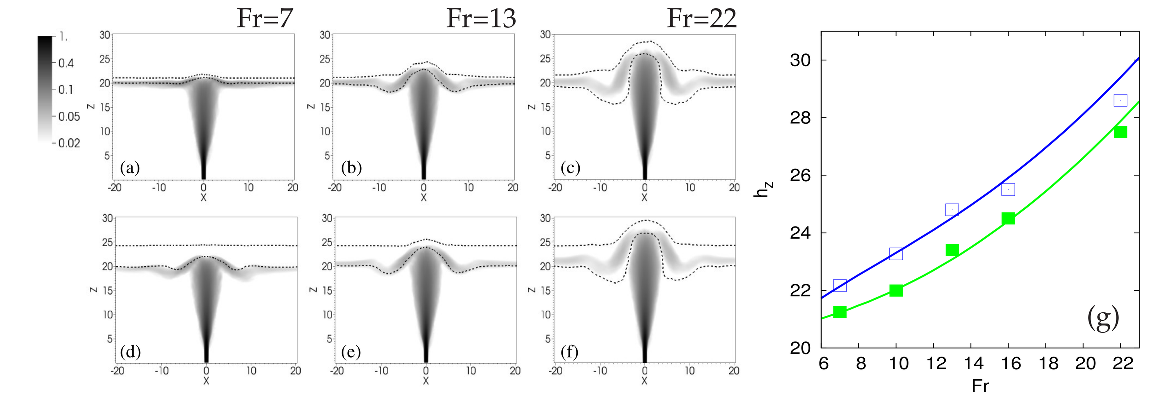
Range of parameters:

1. **Froude number:** $7 < Fr = U_0/\sqrt{g' D_0} < 22$ (at the thermocline entrance $0.6 < Fr_t < 1.9$)
2. **Thermocline thickness versus jet diameter in the thermocline:** **thin** thermocline: jet diameter is ∼4 times larger (γ =2, z_0=20.5), **thick** thermocline: of the same order ($\gamma = D_0/H$ =0.5, z_0=22).



Jet in a stratified fluid

Mean penetration height



(a-f) Mean velocity magnitude (top - thin thermocline, bottom - thick)
(g) Mean jet penetration: LES results versus theory

Theory: from the conservation of source energy at the thermocline :

$$\frac{u_m^2}{2} \sim \int_0^{h_z^*} g a_T (T - T_s)dz, \quad (\frac{\lambda u_m}{U_0})^2\frac{Fr^2}{2} = \int_0^{h_z} T_s' dz$$

$\lambda = 0.8$ from the best fit of the LES data.

Good correspondence between LES and theory

Conclusion

- We performed LES of a turbulent jet in a stratified fluid with thermocline of different thicknesses.
- The mean penetration height follows from the conservation of the source energy at the thermocline.
- Jet penetrating through the thick thermocline entrains colder fluid from the sides, not from the upper stratification layer.
- The frequencies of the jet oscillations are the same at fixed Froude number while the frequencies of internal waves are different.

References

[1] Yu. I. Troitskaya, D. A. Sergeev, E. V. Ezhova, et al. *Doklady Earth Sci.*, 419:506–510, 2008.

[2] P. F. Fischer et al., 2008. http://nek5000.mcs.anl.gov.

[3] A.B. Shrinivas and G.R. Hunt. *J. Fluid Mech.*, 757:573–598, 2014.

Future Research

We perform LES of turbulent buoyant plumes in real winter and summer stratifications in a typical Greenland fjord modelling subglacial discharge.

We focus on the dynamics of plumes, investigate turbulent entrainment and internal waves for various discharge distribution.

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