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Dispersion of a vertical jet of buoyant particles in a stably stratified wind-driven Ekman layer

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Abstract

Dispersion of a buoyant jet of particles (i.e. fresh water) in a salt water thermally stratified environment is investigated. The carrying flow field is a wind-driven mid-latitude Ekman layer. The investigation is carried out using Large Eddy Simulation. The dispersed phase is simulated in a Lagrangian way, solving a modified form of the Maxey and Riley equation for each particle of the jet. In order to simulate a large Reynolds number flow, the thin wall layer is not directly resolved and the wall stress and the wall heat flux are directly imposed at the free surface. Results of the simulations show that the presence of incoming heat flux produces a thin region of large density gradients below the free surface and inhibits turbulent transport. In particular, the turbulent penetration depth is strongly reduced by stratification as well as the level of the turbulent fluctuations. In order to consider the effect of the actual density field on the particle dynamics, an improved version of the particle-motion equation is here proposed. The results of our simulations show that the dispersion of the buoyant plume of particles is dramatically modified by stratification. In the neutral case, the plume is spread over the horizontal direction in the free surface region and is driven by the mean Ekman current. In the stratified case, the particles remain entrapped in wavy motion present in the region of large mean density gradients. The horizontal transport is strongly reduced for two reasons: first in the region where large density gradients develop the mean velocity is small compared with the value reached at the free surface; second, the turbulent transport is very small due to the suppression of velocity fluctuations. Finally, our results show that very inaccurate predictions are obtained if the variation of density due to the vertical stratification is not taken into account in the particle motion equation.

Keywords: LES; Ekman layer; Stable stratification; Particle dispersion

1. Introduction

An environmental problem that is becoming increasingly relevant nowadays is the prediction of dispersion of polluting particulate in a marine environment. Particles of buoyant fluid in a marine environment may be released for example when leakage occurs in submarine pipelines or other devices (oil spilling problems). In this kind of applications it is of significant interest the evaluation of the concentration of the released substance as well as the evaluation of the amount of particulate that reaches the free surface of the sea. In literature (see for example Rubin and Atkinson (2001) for a general discussion) Eulerian models are commonly used, in which the plume of particles is described in an Eulerian way as a space-time distribution of their concentration. Although this approach is computationally inexpensive, it suffers from empiricism in particular when the concentration of the dispersed phase is small and it is mainly composed of an ensemble of separate particles traveling in the carrying fluid. In the present paper we study the dispersion of a buoyant jet of particles released into a salty water basin. Note that since the time scale of diffusion of salinity is usually much larger than the buoyancy time scale, this analysis can also be applied to upwelling of fresh water particles in a salty water ambient.

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In particular, we study an archetypal problem, representative of the upper part of the ocean forced by a constant wind stress and the release of the buoyant particles in a region below the free surface where turbulent mixing is negligible.

From a fundamental point of view, the top region of the sea can be treated as a wind-driven Ekman layer, namely the boundary layer created by the tangential stress supplied by the action of the wind in a rotating environment. The Coriolis force causes a rotation of the velocity profiles and thus generates a component in the spanwise direction. In laminar conditions the penetration depth of the Ekman layer (the thickness on the boundary layer) is proportional to $\sqrt{2\nu/f_z}$ (the z-direction is vertical upward) where ν is the fluid viscosity and f_z is the Coriolis parameter. In the turbulent regime the penetration depth is found to be proportional to u_τ/f_z where $u_\tau = \sqrt{\tau_w/\rho_0}$ is the friction velocity associated to the free surface wind stress τ_w, and ρ_0 is the reference density of the water. A detailed discussion on the Ekman layer and its relevance in environmental fluid mechanics is in Price and Sundermeyer (1999). The main scope the present work is to understand how a cloud of buoyant particles released in the water column is dispersed in the wind-driven Ekman layer subject to different conditions of thermal stratification. To this aim an extension of the Maxey and Riley equation (Maxey and Riley, 1983) for the particle motion is proposed, which takes into account the actual fluid density during the space-time evolution of the particle swarm. The study is performed numerically using a Lagrangian–Eulerian approach, which consists of moving Lagrangian particles in an Eulerian carrier phase. The paper is organized as follows: Section 2 contains a description of the problem investigated together with the mathematical formulation. Specifically the new form of the particle-motion equation is presented and discussed. In Section 3 the results of the simulations are discussed and concluding remarks are given in Section 4.

2. The problem formulation

We use a Lagrangian–Eulerian approach, in which the dispersed phase is treated as an ensemble of Lagrangian particles moving in an Eulerian flow field. In order to evaluate the force field acting over the Lagrangian particles an interpolation of the Eulerian flow field onto the particle position is carried out. A detailed description of the mathematical method is here supplied.

2.1. The Eulerian field

We consider a mid-latitude, wind-driven Ekman layer, thus including both the vertical and the horizontal components of the rotation vector in the governing equations (see Coleman et al. (1990) and Salon et al. (2005)). The relevant scales of the problem are: the already defined friction velocity u_τ, the time scale $T = 1/f_z$ associated to the Coriolis parameter and the penetration length $\delta = u_\tau/f_z$ which gives an estimation of the depth of the turbulent boundary layer. The stratification is considered as a variation of the density field with respect to a reference value ρ_0. Specifically the density field is $\rho_{\mathrm{tot,d}}(x,y,z,t) = \rho_0 + \rho_{\mathrm{d}}(x,y,z,t)$ with $\rho_{\mathrm{d}} \ll \rho_0$ (hereafter the index d denotes dimensional quantities). In our numerical experiment the stratification comes from the imposition of a heat flux at the free surface, as in Taylor et al. (2005); physically this corresponds to heating a fluid column by an incoming heat flux. Here we discuss two cases, respectively the case of neutral flow $Ri \to 0$ and the case of strongly stratified flow $Ri = 40$ where the Richardson number is $Ri = g/\rho_0 |\mathrm{d}\rho/\mathrm{d}z|_{fs}| \delta^2/u_\tau^2$. In the present case, the Richardson number is defined using a density scale $|\mathrm{d}\rho/\mathrm{d}z|_{fs}|\delta$ which is related to the free surface heat flux as follows $\mathrm{d}\rho/\mathrm{d}z|_{fs} = -\rho_0 \alpha \mathrm{d}T/\mathrm{d}z|_{fs}$, with α the thermal expansion coefficient. The wind stress acts in the direction south-north (x axis), the y-axis is directed from east to west and the z-axis is vertical upward. A mid-latitude case ($\theta = 45^\circ$ where θ is the latitude) is here considered: with the frame of reference herein used, the components of the rotation vector are the vertical one $f_z = 2\Omega_H \sin\theta$ and the horizontal one $f_x = 2\Omega_H \cos\theta$ where Ω_H is the earth rotation frequency. A typical full-scale value of $Re = u_\tau\delta/\nu$ is of the order of 7×10^5 considering the data of wind stress given in Price and Sundermeyer (1999). Although the approach we use, equivalent to that employed in the $Re \to \infty$ simulation of Zikanov et al. (2003), can deal with applicative values of the Reynolds number, here we consider a moderate value of Reynolds number $Re = 10{,}000$ (see Section 2.3). This value of Re is such to minimize Reynolds number effects on the dynamics of the flow field.

The equations of the Eulerian flow are solved using Large Eddy Simulation (LES). We use the Boussinesq approximation which holds in cases where the density variations in the flow field are small compared to a reference density ρ_0. This approximation is commonly used in the analysis of thermally stratified water. In the present paper directions 1, 2, 3, respectively correspond to x, y, z. The non-dimensional filtered equations are:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \epsilon_{ijk}\frac{f_j}{|f_3|}\bar{u}_k - Ri\bar{\rho}\delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{u}_j \bar{\rho}}{\partial x_j} = \frac{1}{RePr}\frac{\partial^2 \bar{\rho}}{\partial x_j \partial x_j} - \frac{\partial \lambda_i}{\partial x_i} \tag{3}$$

where the symbol $\bar{\cdot}$ denotes a filtering operation. In Eqs. (1) and (2) t is time made non-dimensional with $1/f_z$, u_i is the velocity component in the i-direction made non-dimensional with u_τ, x_i is the i-coordinate made non-dimensional with δ, p is the pressure made non dimensional with $\rho_0 u_\tau^2 = \tau_w$, and ρ is the density made non-dimensional with the density scale $\delta|\mathrm{d}\rho/\mathrm{d}z|_{fs}|$. The non-dimensional groups