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DOWNSLOPE FLOWS INTO A STRATIFIED ENVIRONMENT

Peter G. BAINES

CSIRO Atmospheric Research
PMB No. 1, Aspendale 3195, Victoria, AUSTRALIA

INTRODUCTION

Many fluid flows in nature are driven by the buoyancy of dense fluids. Such flows are commonly termed "gravity currents", and sea breezes are a common example. When gravity currents occur on sloping terrain, the buoyancy effects are stronger and invoke substantial balancing drag forces acting above and below the current. Studies of such downslope flows have so far mostly been with homogeneous environments, whereas flow down slopes in the atmosphere and ocean generally occurs in density stratified environments and this stratification is important. Examples are downslope flows at high latitudes in the North Atlantic and around Antarctica, driven by surface cooling and brine rejection due to freezing of sea water, and nocturnal flows in the atmosphere driven by radiative surface cooling on slopes.

This paper presents a description of laboratory experiments on downslope flows with stratified environmental fluid, with a dynamical interpretation of the observations, and with measurements of the relevant quantities to enable application of these results to larger scale models. Ellison & Turner (1959) showed that, with a homogeneous environment, an essential ingredient of the dynamics was the process of turbulent *entrainment*, in which fluid was added to the downflow with an inflow velocity equal to EU, where U is the mean velocity of the downflow, and the entrainment coefficient E is a function of the Richardson number $R_i = g'd/U^2$, where d is the thickness of the dense layer and $g' = g\Delta\rho/\rho$, where ρ is the mean density and $\Delta\rho$ the initial density difference between the dense fluid and the environment. The presence of external stratification modifies this behaviour, and introduces a new process of turbulent *detrainment*, whereby fluid leaves the downflow.

EXPERIMENTS

The experiments were carried out in a glass-sided tank 80 cm high and 299 cm long, in which two-dimensional downslope flows of width 23 cm were generated. The tank was uniformly stratified with a combination of fresh and salty water, using the familiar two-tank mixing method. For each run, a continuous two-dimensional source of dense salty water was introduced at the top of a sloping bottom, for a finite time that depended on the strength of the source, and was typically of several minutes duration. The dense fluid was dyed with fluorescene, two-dimensional sections of the flow were illuminated by light from an oscillating laser beam, and the flow was recorded visually by video camera. Density profiles were taken before the downflow, and sometime after, when all residual motion had ceased. Taking the difference between these before and after profiles revealed the final disposition of the introduced fluid, and consequent additional redistribution of the ambient stratification. It also gave quantitative information on the nett downflow as a function of distance downslope, and the distribution of nett inflow and outflow from the current. A range of experimental parameters (nett flux, stratification and initial density) was covered for each of the bottom slopes of 3°, 6°, 12° and 30°. The principal parameters characterising the overall flow were found to be the Reynolds number and the parameter M_0, given by

$$M_0 = \frac{Q_0}{(g_0' D)^{1/2}} = \frac{Q_0 N^3}{g_0'^2} , \quad R_e = Q_0 / \nu ,$$

where Q_0 is the volume flux and g_0' the value of g' at the top of the slope, N is the buoyancy frequency of the ambient stratification, and ν is the kinematic viscosity. A local value of M may also be defined, dependent on the local values of Q and g'.

RESULTS

Four regions can be identified in such downslope flows: an initial region (I) where the flow adjusts to a state of uniform thickness of the current; a "central" region (II) of constant current thickness; a region (III) in which the remaining main current leaves the vicinity of the slope and finds its neutral level; and (IV) an "overshoot" region, to which the current may penetrate, but then returns under buoyancy to region III. The main region of the current is region II, where entrainment of ambient fluid into the main downflow occurs, but there is also detrainment of fluid from the downflow into the environment. Thus there is a two-way exchange of fluid as a result of the turbulent processes at the upper boundary of the downflow. In these experiments, region IV only occurs for 30° slopes, and region III may also be absent if the detrainment in region II is sufficiently large. In region II entrainment and detrainment may be represented by respective coefficients E_e and E_d, of which E_d is the larger and is an increasing function of the local value of M, which generally increases with distance downslope . Quantifying this functional relationship for parametrisation of these effects in large scale models of the ocean constitutes a major part of these results.

A number of different features in the vertical profile of the outflow from the current are observed, depending on the values of M_o, bottom slope and R_e. These include: the apearance of a second, upper tongue of outflow (like a smaller version of region III); for M_0 small, fixed vertical periodic variations in outflow may occur in region II, and independently, rising motion outside the downflow in region I may occur for steep slopes due to downslope dragging; and the overshoot region. All of these results present a very different and more complex picture of downslope flows in stratified fluids, compared with that of Ellison & Turner (1959) for homogeneous fluids.

REFERENCES

ELLISON, T. and TURNER, J.S. "Turbulent entrainment in stratified flows", *J. Fluid Mech.* **6**, 423-448, 1959.