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LABORATARY EXPERIMENTS ON STABILITY AND ENTRAINMENT OF OCEANIC STRATOCUMULUS -- Part I: Instability Experiment

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1. INTRODUCTION

The existence and persistence of marine stratocumulus play a significant role in the overall energy budget of the earth. Their stability and entrainment process are important in global climate studies, as well as for local weather forcasting.

Lilly(1968) and Randall(1980) recognized that the evaporative cooling of unsaturated air which had been entrained into a cloud can under some conditions cause the entrained air to sink unstably as a convective downdraft. They called it conditional instability of the first kind upside-down (CIFKU). It was suggested (Randall, 1980; Deardorff, 1980) that the CIFKU was responsible for the breakup of subtropical stratocumulus layers as long as such nonlinear buoyancy reversal occurred. Contrary to the expectations of Randall and Deardorff, Turner and Yang (1963) in their laboratory simulation on entrainment at the top of stratocumulus clouds suggested that the entrainment was slightly reduced by nonlinearity and the change would be negligible in practice. Caughey et al. (1985) and Nicholls and Turton (1986) suggested that evaporative cooling enhances entrainment over that expected in the linearly mixing case from observations in stratocumulus. However, Hanson (1984) and Albrecht et al. (1985) observed that clouds do not necessarily thin or breakup due to evaporative cooling, as had been suggestd by Randall and Deardorff.

These apparent contradictions may arise from three reasons; namely, (1) the Richardson number effect, (2) the mixing model, or (3) the Reynolds number effect. First, cloud top entrainment instability (CTEI) is an interfacial instability. It requires that the dry unsaturated air entrains into the cloud and then the two fluids mix together to release additional kinetic energy from mixing-induced buoyancy reversal, thereafter leading to a runaway entrainment. The questions then arise: What is the entrainment mechanism in order that the two fluids can be mixed together across an inversion? What are the key parameters that dominate the process of entrainment? What is the physical mechanism that determines instability? As Miles (1986) noted, the Richardson number is seminal for our understanding of atmospheric dynamics and is the dominant parameter in any rational discussion of stratified flow. It indicates the response of the interface to the turbulence. Neither the experimental approaches nor the numerical simulations have investigated the effect of the Richardson number on the buoyancy reversal case. Therefore, that may explain why so little is known about the impact of buoyancy reversal on entrainment rate. The physics of the breakup process remains poorly understood and unsolved. Second, in many numerical simulations of cloudtop turbulent entrainment and instabilities the equations of motion are two dimensional and laminar, neglecting the density perturbation everywhere except in the gravitational term (Boussinsq approximation) with the consequence that the convective motions due to perturbation from buoyancy reversal may be sustained much longer than it should be. The highly dissipative behavior which necessarily accompanies the turbulent mixing is missing in the simplified equations. Third, neither the experiments nor the numerical simulations have studied turbulent flows at large Reynolds number. The Reynolds number based on the eddy's characteristic length scale at the interface estimated from Turner and Yang (1963) and Townsend (1964) papers to be below 50. It follows that their results may not correspond to fully turbulent mixing flow.

The purposes of our experimental simulations are to study this process and to address these paradox. In this paper we investigate the effects of buoyancy reversal, followed by two types of experiments. (1) An instability experiment involves the behavior of a fully turbulent wake near the inversion generated by a sliding plate. Due to buoyancy reversal, the heavy, mixed fluid starts to sink, turning the potential energy created by the mixing process into kinetic energy, thereby increasing the entrainment rate. (2) An entrainment experiment, using a vertically oscillating grid driven by a controllable speed motor, produces many eddy-induced entrainment at a surface region on scales much less than the depth of the layer.

2. EXPERIMENTAL METHODS

2-1 *Density as a Function of Mixture Ratio*

Evaporative cooling in atmospheric clouds produces mixtures whose density can be greater than either parent parcel. In clouds, the density relationship is composed of two essentially straight lines (Fig.1a). In the laboratory, an imperfect approximation to this has been realized. Density is plotted as a function of the mixture fraction of the upper fluid for water-alcohol mixtures in figure 1b, using the same fluid system as Turner (1966).

Glycol is added to the alcohol in order to raise the density nearer to that of water. The density is a maximum at a mixture fraction $p=p^*$. For these experiments, p^* is in the range of about 0.3 to 0.7. The range can be extended from 0.1 to 0.7 by adding appropriate amounts of potassium iodide and glycerine into the two fluids. A dimensionless buyancy reversal parameter is defined as follows:

$$D \equiv \frac{\rho(p^*) - \rho(p)}{\rho(p) - \rho(0)} \quad \text{for } p < p^*,$$

which indicates the ratio of the maximum density change at p^* to the density difference between two layers fluid. $\rho(p)$ is the density of mixed fluid consisting of p parts of pure fluid and (1-p) parts of pure lower fluid; $\rho(1)$ is the density of pure upper fluid (the simulated dry, unsaturated layer). $\rho(0)$ is the density of pure lower fluid (the simulated cloud). Before a run (p=0), the initial value of D, D_i, was selected from avalue between 0 to 15 for these experiments.

2-2 *The Apparatus*

The apparatus is sketched in figure 2. Two lucite mixing boxes with different geometries were used, a vertical circular cylinder of 15 cm inside diameter and 30 cm height which we call 'small box' and one 28x28x60 cm height, the 'large box'. Both boxes were separated into two compartments by a thin, horizontal sliding stainless steel plate of 0.07 cm thickness. Before a run, the compartment below the plate was filled with water and that above the plate with a mixture of alcohol and glycol.

2-3 *Flow Visulization Technique*

By adding a pH indicator, phenolphthalein in one fluid and appropriate base in the two-layer fluids, the initially colorless fluids became dark red when they mixed. The volume mixing ratio of lower to upper fluid at which this occurs is the equivalence ratio ϕ, which can be chosen to be about 20. This means that 100 c.c. of pure lower fluid needs only to mix with 5 c.c. of pure upper fluid to turn red. The chemistry is fast.

3. RESULTS FOR INSTABILITY EXPERIMENT

3.1 *Large Disturbance*

It is important that the initial perturbation be sufficiently large at the interface to insure that the flow is above the mixing transition (Breidenthal, 1981) so that the results correspond to the high Reynolds number atmosphere case. The plate was withdrawn quickly enough to create a fully turbulent wake at the interface, where the Richardson number ($Ri=\Delta\rho g\delta/\rho\omega^2$) based on the thickness (δ) of the wake, its maximum density difference ($\Delta\rho$) with the underlying fluid, and the average speed of the withdrawing plate (ω) was small (Ri<6). Then the behavior of the interface depended on the initial $D=D_i$.

(A) Flow Structure

The results of several runs are described for several values of the initial buoyancy reversal parameter Di.

(1) Linear case, $D_i=0$

The initial disturbance decayed quickly. The mixture was intermediate in density between that of the two initial fluids, and therefore it accumulated at the inversion. The evolution of the experiment at different stages is shown in figure 3a.

(2) Nonlinear case, $D_i>0$

a) $0 < D_i < 1.0$ Figure 3b shows the evolution of the system at different times for relatively weak nonlinearity ($D_i=0.2$). For $D_i<1$, the interface tilted gently and then promptly returned back to horizontal after the heavy mixed parcel descended. Note that the interface remained almost flat. After the turbulence decayed, samples of the fluid at the bottom of each tank and just below the interface were taken to determine their composition and the current value of D. These measurements were repeated at five and ten minutes. Neither the composition of the bottom fluid nor D changed significantly during this time.

b) $D_i > 1.0$ Figure 3c shows the evolution of the flow at different times for a case of stronger buoyancy reversal ($D_i=2.0$). For $D_i>1$, again the heavy, mixed fluid produced by the initial perturbation descended into the lower layer. However, a distinct difference was observed in the interface for this case: It became strongly tilted. The heavy, descending parcel formed a vortex structure which tilted the interface, which in turn fed the structure fresh fluid from above, thereby maintaining the structure as it grew. An 'entrained tongue' of upper fluid was pulled into the lower fluid. Sustained vigorous entrainment and mixing occurred. Soon, however, the walls constrained the flow as the structure filled the lower region and consumed all the lower fluid. Then the effective value of D across the inversion was reduced, and the Richardson number was increased. The system became stable again. Figure 3d shows the evolution of the flows at four times for D_i=5.0. The interface tilt is even more pronounced. The system was unstable in the sense that an 'entrained tongue' was formed, leading to a plume like runaway entrainment.

(B) Instability Condition for Large Disturbance

The results for the large box are qualitatively the same as those for the small box, except for a time lag. Figure 4 shows D at 40 sec in the small box and at 100 sec in the large box as a function of its initial value. We saw above that for D_i greater than 1.3, the interface became strongly tilted to form a tongue of upper fluid which descended below the level of the undisturbed inversion. This tongue was engulfed into the descending parcel. Runaway entrainment proceeded until a large enough fraction of upper fluid was mixed into the lower fluid to change the composition to where D was reduced to be about 1.

3.2 *Small Disturbance*

If the plate was pulled out slowly such that the Richardson number was large (R_i >> 6) and Reynolds number based on the thickness of the wake at the interface was small (R_e < 100), the sustained vigorous mixing was absent for even D_i up to 10. The mixtures due to this small diturbance started to descend and result in slowly convective motion in the lower layer fluid especially near the interface that slowly drained the layer fluid above. The observation showed that many convective cells on the inversion trapped and produced the mixtures which sank and dripped many streamers from the interface, and thus generated further agitation and mixing, but at a relatively slow rate as long as D > 0. This slowly convective motion continued until D went to zero, in which the mixtures were no longer heavier than the lower fluid (enviroment saturated). Although this phenomenon may be important in nature, the present experiments are to study the case where the disturbances are driven from some turbulent source other than a laminar molecular diffusion process.

4. DISCUSSION AND MODEL

The central surprise of these results is that the system is stalbe to strong perturbation unless the buyancy reversal parameter D is greater than 1. The original concept of the instability predicts a critical value of D near zero, so that any heavy, mixed parcels produced would, upon falling, energize the turbulence in the lower fluid enough to precipitate enough additional mixing to generate runaway entrainment. Apparently, the mere production of heavy mixed fluid is neither a sufficient condition nor a necessary condition for instability.

Here we present a simple physical model based on the experimental observations. Consider a sizable vortex δ of large enough circulation Γ in which the vortex has an excess of kinetic energy (small R_i), it engulfs fluid from above and below the inversion, mixing them together to form a heavy vortex core of density ρ^* as sketched in figure 5a. The experimental data indicate that $R_i=g'\delta/\omega^2 < 6$ for the occurrence of such phenomenon (Shy, 1989), where the velocity of the vortex ω is proportional to Γ/δ and $g'=(\rho^*-\rho_o)g/\rho_o$. At point A in the figure, the heavy vortex induces an overturning force per unit volume $Fo=(\rho^*-\rho_o)g$. At the same time, baroclinic torques generate vorticity at the tilted interface (tongue) near A which tends to restore the interface to horizontal. In other words, the rebounding vorticity at the interface corresponds to a restoring force per unit volume $Fr=(\rho_o-\rho_1)g$ at A. Stability depends on the ratio Fo/Fr. Therefore,

$$\frac{\text{Overturning Force}}{\text{Restoring Force}} = \frac{\rho^* - \rho_o}{\rho_o - \rho_1} = D_i.$$

It is important to note that the initial perturbation be sufficiently large at the interface (Ri ~ 1) to ensure that the vortex reaches approximately its maximum density of ρ^*, followed that the instability may depend on the initial value of D, D_i. The interface is stable to strong perturbation if Fo<Fr (D_i<1), the mixing is largely confined to that of the initial heavy vortex without much additional engulfment of upper fluid (dry dir). The votex can not pull down the tongue due to its relatively weak buoyancy reversal. Indeed, the tilted interface (tongue) will recoil back to hrizontal because of its lighter density (ρ_1). This mixing structure is termed 'thermal-like mode' as shown in figure 5b, implying that the heavy parcel would sink like a downward movement of thermal convection due to gravitation, thereafter detaching from the interface and re-distributing itself into the lower layer fluid (clouds). For Fo>Fr (D_i>1), the votex bas strong buoyancy reversal to pull the tongue down further to trigger sufficiently additional entrainment from above. The interface is unstable and the vortex will continue to engulf fluid. Such a structure is then termed 'plume-like mode' as shown on figure 5c, suggesting that the heavy, descending parcel could tilt the interface to form an entrained tongue, leading to a plume-like runaway entrainment or penetrative downdraft. The transition from stable to unstable behavior is sharp because the criterion for instability depends on the amount of mixing due to the depressed tongue. Until the tongue can be drawn down further by strong buoyancy reversal (D_i>1), the amount of mixing is modest. Indeed, other experimental results, to be reported in Part II, indicate that the entrainment rate under continual forcing is a weak function of D below the instability transition.

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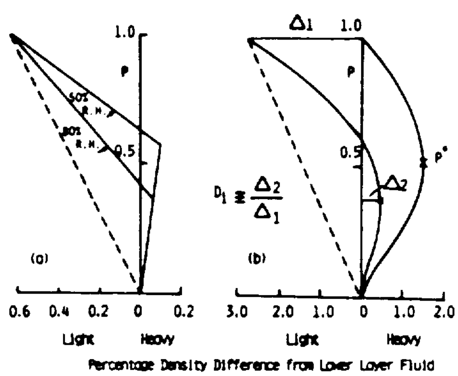

Figure 1: Mixing density as a function of mixture fraction p of upper fluid. (a) Cloud at 2^0c and 700 mb, containing 1g/kg of liquid water mixing with an environment 2^0c cooler having various relative humidities (R.H.) (Turner, 1966) (b) The experimental two-layer fluids, consisting of alcohol and glycol mixtures in various proportions, mixing with water, using the same fluid system as Turner (1966). The dash line represents the linearly mixing case (enviroment saturated).

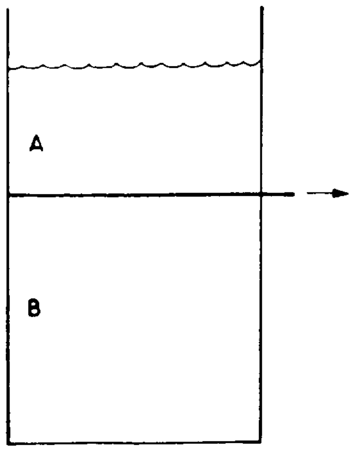

Figure 2: Sketch of the apparatus. A - mixtures of alcohol and glycol. B - water.

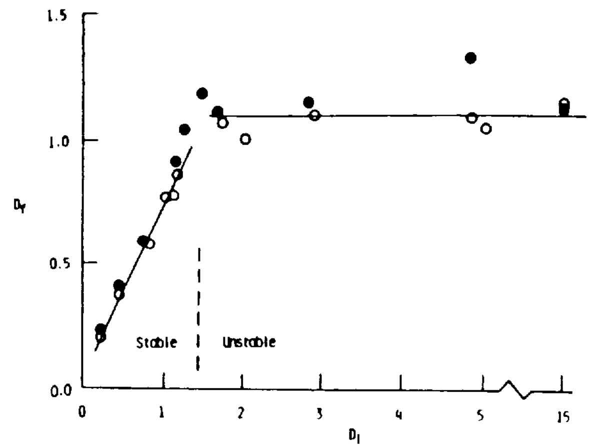

Figure 4: The final value of D, as a funtion of its initial value Di. White circles, large box; Dark circles, small box. For Di<1.0, the system is stable; for Di>1.3, the system is unstable, under strong perturbation.

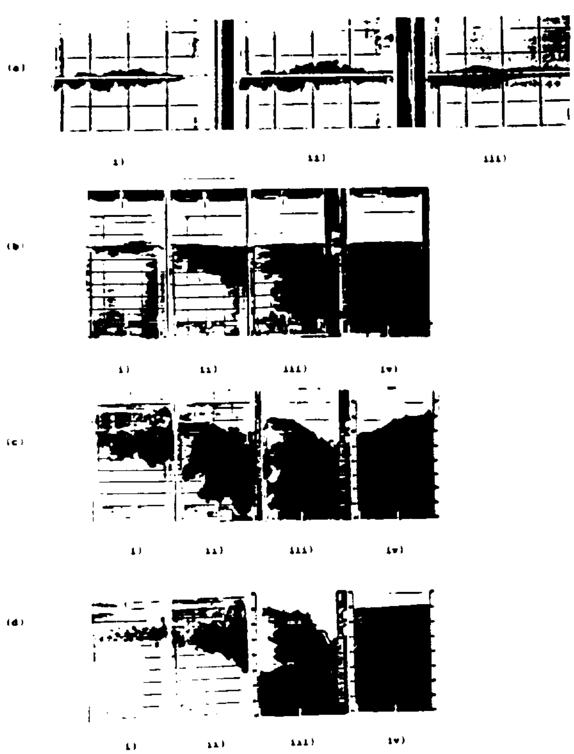

Figure 3: The evolution of the flows.
(a)Di=0.0 i)1.0sec ii)2.5sec iii)45.4sec.
(b)Di=0.2 i)0.9sec ii)5.7sec iii)13.8sec iv)44.7sec.
(c)Di=2.0 i)3.7sec ii)7.4sec iii) 9.9sec iv)27.4sec.
(d)Di=5.0 i)1.0sec ii)3.5sec iii) 9.9sec iv)97.2sec.

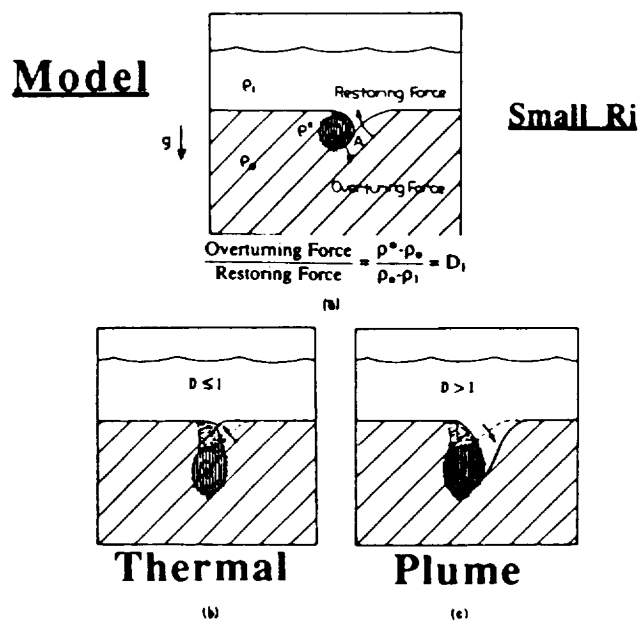

Figure 5: Model of the entrainment process and the instability.

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