Progress Report
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FLUID DYNAMICS OF DOUBLE DIFFUSIVE SYSTEMS

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PRINCIPAL INVESTIGATOR

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PROJECT SUMMARY

A study of mixing processes in doubly diffusive systems is being conducted. Continuous gradients of two diffusing components (heat and salinity in our case) are being used as initial conditions, and forcing is introduced by lateral heating and surface shear. The goals of the proposed work include: (1) quantification of the effects of finite amplitude disturbances on stable, double diffusive systems, particularly with respect to lateral heating, (2) development of an improved understanding of the physical phenomena present in wind-driven shear flows in double diffusive stratified environments, (3) increasing our knowledge-base on turbulent flow in stratified environments and how to represent it, and (4) formulation of a numerical code for such flows. The work is being carried out in an experimental facility which is located in the Stanford Environmental Fluid Mechanics Laboratory, and on laboratory minicomputers and CRAY computers.

In particular we are focusing on the following key issues:

- (i) The formation and propagation of double diffusive intrusions away from a heated wall and the effects of lateral heating on the double diffusive system;
- (ii) The interaction between the double diffusively influenced fluxes and the turbulence induced fluxes;
- (iii) The measurement of heat and mass fluxes; and
- (iv) The influence of double diffusive gradients on mixed layer deepening.

PROJECT GOALS FOR THE SECOND YEAR

The goals of the project for the second year (Aug. 1 1988 to Jul. 31 1989) were as follows:

a. Physical experiments

- (i) To begin a systematic set of physical experiments
- (ii) To perform rheoscopic and liquid crystal visualization experiments
- (iii) To measure temperature and salinity fields

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(iv) To develop first systematic interpretation of the data.

b. Numerical experiments

- (i) To continue with the development of the numerical code
- (ii) To focus on refinement of a closure method for treatment of turbulent fields.

PROGRESS TO APRIL 1 1989

A great deal of progress has been made in the past 7 months in all the experimental aspects of the project outlined above. We have, however, altered our strategy with respect to the numerical aspects of the project. The details of our progress are outlined next.

Experimental Program

In the last 12 months considerable progress has been made towards attaining a set of baseline data for the stability and dynamics of a two component linearly stratified system subject to lateral heating (see Fig. 3a for typical initial salinity and temperature stratifications). Using two dimensionless ratios to characterize stability,

$$R_l = \alpha(q/k)/(\alpha\partial T/\partial z + \beta\partial S/\partial z), \text{ and}$$

$$R_p = (\beta\partial S/\partial z)/(\alpha\partial T/\partial z),$$

we have defined a wide range of lateral forcing and vertical stability conditions.

Figure 1: Experiments completed and to be completed for various values of Lateral Ratio and Rayleigh Ratio.

Generally, a large value of R_l indicates strong lateral forcing while a large value of R_p indicates weak double diffusive effects. The applied heat flux produces lateral temperature and salinity gradients at the end-wall, where convective intrusions form and propagate into the interior of the fluid. By initially conducting experiments over a wide range of R_l and R_p values we are aiming to characterize the nature of the intrusions that result. Figure 1 displays the extent of our work to date. We have concentrated on low values of R_p and a generally wide range of R_l . In the coming months we intend to obtain data for the intermediate R_p values.

Results to date suggest that there is a definite change in the nature of the intrusions as we move through the R_p - R_l plane. Initially small roll cells develop along the heated wall, but these quickly merge to form a series of well-mixed layers separated by sharp density interfaces. Within each layer, strong shear is created along each interface by flow moving away from the wall in the upper region and back towards the wall in the lower region. The specific flow behavior and structure of the intrusions vary significantly, depending on the stability of the system. To date we have distinguished three regimes of intrusions, based upon the initial values of R_p and R_l in each experiment.

Regime I (see Figs. 2a and 3b) is characterized by quiescent flows which form under conditions of relatively high gravitational and lateral stability. The resulting convection cells develop into intrusions 5-10 mm in depth which propagate slowly (~ 3 -5 cm/hr) during the period of applied heat flux, but quickly diffuse away when the applied heat flux is removed. The intrusions are well mixed with respect to salinity, however, a stable temperature stratification develops due to the flow of colder "interior" fluid towards the end-wall in the lower region and warmer fluid away from the end-wall in the upper region of each layer.

Motions in Regime II (see Figs. 2b and 3c) are seemingly more dynamic than those in Regime I. The intrusions propagate at a moderate speed (~ 5 -7 cm/hr) away from the heated end-wall, and develop into 10-20 mm layers. As in Regime I, the intrusions stop propagating when the applied heat flux is removed, and the layered structure eventually diffuses back to a continuous stratification. Overall, much more active convection is observed visually in this regime due to the lower stability and stronger shear. A stable temperature stratification still develops within each layer.

Flows in Regime III (see Figs. 2c and 3d) are observed under conditions of relatively low gravitational and lateral stability. The intrusions propagate relatively quickly (> 8 cm/hr), and are self-perpetuating in that they continue to propagate away from the end-wall after removal of the applied heat flux. The convective cells develop into 20-40 mm layers, which, unlike Regimes I and II, are well mixed with respect to both salinity and temperature. The flow structure is very similar to that of Regime II, but appears to be more dynamic with stronger interfacial shear and more interaction between the layers.

In summary, experiments to date indicate that the presence of the destabilizing component (temperature) in the vertical density gradient contributes to some interesting behavior not observed before in similar experiments performed with only single component stratifications. The results suggest that the destabilizing component does not always provide sufficient energy to drive continued propagation of the intrusions following removal of the applied lateral heat flux.

Development of Techniques

Double Diffusive Stratification: Following extensive experimentation we have now reached a high level of competency and repeatability with respect to constructing continuous, linear gradients of salinity and temperature in the test facility. We are concurrently seeding the stratification with various reflective media to assist in our flow visualization and image processing work.

Image Processing: A sheet of laser light is used to illuminate a plane at right angles to the end wall of the experimental facility. The experiment is recorded on videotape using a high resolution Pulnix CCD camera. If a picture of overall flow patterns is desired, fluorescent dye is injected into the light sheet and acts as a tracer of the motions and the mixing in the intrusions. The recorded images are later processed on an Imaging Technologies Series 200 image processor to enhance the contrast between dyed and undyed regions of the flow. We are currently experimenting with the production of instantaneous velocity fields using the images of seed particles that have been deliberately incorporated into the stratification. By integrating their positions over time, a series of pathline images can be attained. By differentiating them, velocity fields are produced. The major difficulties associated with this latter task is the automated identification of what constitutes a valid path of an individual particle. Particle paths crossing (due to inherent unsteadiness of the flow and too great a seeding density) and particles moving in and out of the plane of view are problems we are presently trying to resolve. Our results to date, however, have been very encouraging.

High Resolution Profiling: Our system of taking rapid profiles of conductivity and temperature with approximately 1mm spatial resolution is working well. We have improved the traversing system, to the point where we can currently obtain profiles at any position along the tank rather than at a few discrete stations. Data from our experimental program to date is currently being analyzed. Mac II workstations are used to control the instruments, to acquire the data and to process it. This system is proving very satisfactory.

Vortex Shedding Anemometer: As a precursor to commencing experiments with wind forcing we have had to develop a means of accurately measuring velocity profiles in our low flow wind tunnel. To this end we have been working towards the design and construction of a vortex shedding anemometer. A cylindrical obstruction of known diameter is placed in the flow. It causes vortices to be shed downstream which may be detected by periodic fluctuations in the voltage across a hot wire anemometer. For a narrow range of Reynolds numbers there is a known and quite precise relationship between Reynolds and Strouhal numbers. By suitably matching the flow with the obstruction diameter the frequency of vortex shedding can be simply detected by zero crossings of the hot wire output, thus avoiding the extreme difficulty of constantly recalibrating the hot wire itself. Testing of the concept has been carried out to our satisfaction in water, and we are about to commence construction of the instrument.

Numerical Simulations

Simulations of the better studied bottom heated salt stratification have been conducted, in order to test the performance of our code and to assist in its development. The results have been satisfactory; however, the simulations have not been very extensive as the dynamics of this configuration make the computations extremely resource intensive. In a separate project, development of an adaptive gridding algorithm for use with our basic flow solver has made considerable progress. This approach will

ultimately be incorporated in our numerical simulations. We are, however, commencing on the direct simulation of the laterally heated, double diffusively stratified case.

PLANNED PROGRESS TO AUGUST 1, 1989

Our plans for the rest of the funding period can be sub-divided into three categories: (i) continued analysis and interpretation of data from completed experiments, (ii) additional physical experiments, and (iii) development of new experimental techniques and instrumentation. As outlined above we have begun a more detailed analysis of our experiments with the specific goal of classifying the dynamics of the convective intrusions using the classification scheme shown in Figure 1. We plan to complete the initial part of this analysis in the next few months and submit our results for archival publication. In category (ii) we are planning to perform experiments in the Rayleigh ratio-Lateral Ratio region shown in Figure 1. Once the analysis of these experiments is complete we will have a more complete picture of the behavior of the convective intrusions using this classification scheme. Finally, under category (iii), we are working on improving our fluorescence-visualization and particle-imaging-velocimetry techniques by using a more intense light source. In addition, we are building a vortex-shedding velocity probe for measuring the relatively low (0-2m/s) velocities in our wind tunnel.

PLANS FOR THE THIRD YEAR

In general we plan to follow the research program outlined in our original proposal. We shall, however, focus more closely on the following issues.

1. Preliminary investigations indicate that the stability is a function of R_p and R_l . Three regimes of stability have been identified but additional experiments are necessary to further substantiate this hypothesis and to define the distinguishing characteristics of each regime more precisely.
2. The processes controlling mixing in double diffusive systems are not yet well understood and, therefore, identification of the dominant mixing mechanisms over the full range of stabilities is a primary goal of the research. We will focus primarily on the influence of turbulence, as well as other mixing mechanisms, on the vertical and horizontal fluxes of heat and salt.
3. Investigation of the stability properties and mixing behavior sets the groundwork for development of relationships between heat and salt fluxes and the stability of the system. We will focus primarily on developing a relationship between the heat and salt fluxes and the stability parameters, R_p and R_l , and on comparing this relationship with that obtained for systems composed of two homogeneous layers with sharp property gradients between them.
4. A qualitative investigation of the influence of double diffusive gradients on mixed layer deepening will be performed using wind-shear as the destabilizing mechanism.

BUDGET MODIFICATIONS

A budget for the third year of the project is attached. Because we asked for an additional \$50,691 to cover the salary of Dr. Geoffrey Schladow for the present budget period we have modified the budget for the third year substantially. The total amount requested over the three year period is still the same.

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