

SIMULATION OF OCEANOGRAPHIC PROCESSES IN THE HYDRODYNAMICS RESEARCH LABORATORY

The Hydrodynamics Research Laboratory at APL is a comprehensive, flexible facility for performing research on oceanographic stratified-flow phenomena. This article presents a description of the laboratory and describes a recently completed experiment on the propagation of internal waves through a double-diffusive stratified region.

OVERVIEW OF THE HYDRODYNAMICS RESEARCH LABORATORY

The laboratory houses experimental tanks that can be stratified by varying the salinity as a function of depth to simulate the density stratification in the ocean. The major attributes and unique capabilities of these facilities are summarized in Table 1 and described below, together with examples of experiments performed.

Main Towing Tank

Figure 1 is a photograph of the main towing tank, which is 9.14 meters long, 0.91 meter wide, and 0.58 meter deep, with an expanded test section 1.83 meters square. Density stratification of the main towing tank is accomplished by filling the tank from the bottom with successive layers of saline solution, each layer having a slightly greater density than the preceding one. After several hours, molecular diffusion smooths out the sharp steps between layers, resulting in a smooth density profile with the desired vertical distribution. Salinity and density are obtained using the known relationships between state variables, together with probe measurements of electrical conductivity and temperature. The vertical distributions of salinity, density, and Brunt-Väisälä frequency associated with a representative stratification profile are shown in Fig. 2. (The Brunt-Väisälä frequency is the natural oscillation resulting from vertical displacement of a neutrally buoyant body.)

The stratification of the tank can be regarded as a model of the density stratification that occurs naturally in the ocean. However, the vertical density gradient in the ocean is much smaller than the minimum gradient that can be used for laboratory experiments. A measure of the density gradient is the Brunt-Väisälä frequency, N , which is defined as:

$$N \equiv \left(-\frac{g}{\rho} \frac{d\rho}{dz} \right)^{1/2}, \quad (1)$$

where ρ is the density at depth z and g is gravitational acceleration. A high value of N indicates a large density gradient and a strong stratification. For a ho-

Table 1
EXPERIMENTAL FACILITIES
IN THE HYDRODYNAMICS RESEARCH LABORATORY

Main Towing Tank

- 9.14 × 0.91 × 0.61 meters deep (30 × 3 × 2 feet) with a 1.83 × 1.83 meter (6 × 6 foot) test section
- Arbitrary stratification by control of salinity
- Self-propelled axisymmetric model
- High-speed cross-track instrument carriage
- Two-interface selective withdrawal system

Wave Interaction Tank

- 6.71 × 0.46 × 0.61 meter (22 × 1.5 × 2 feet)
- Arbitrary stratification by control of salinity
- Two-interface selective withdrawal system
- Surface and interfacial wave generators
- Can use Freon-kerosene mixtures for immiscible fluid experiments

Double-Diffusive Tank

- 1.22 × 0.15 × 0.46 meters deep (4 × 0.5 × 1.5 feet)
- Stratification by control of temperature and salinity
- Wave generating and selective withdrawal capabilities

Counter-Flow/Co-Flow Stratified Shear Tunnel

- 7.62 × 20.3 centimeters cross section × 6.1 meters long (0.25 × 0.67 × 20 feet)
- Two-layer stratification with variable shear-layer thickness
- Variable tunnel length
- Wave generators

mogeneous fluid, N equals zero. Positive values of $d\rho/dz$ (z measured positive upward), and resulting imaginary values of N , imply an unstable stratification. For a typical ocean stratification (primarily due to temperature), $N \approx 5$ cycles per hour $\approx 1.4 \times 10^{-3}$ hertz. In the laboratory, a typical value of N achieved by variations in salinity is 0.16 hertz.

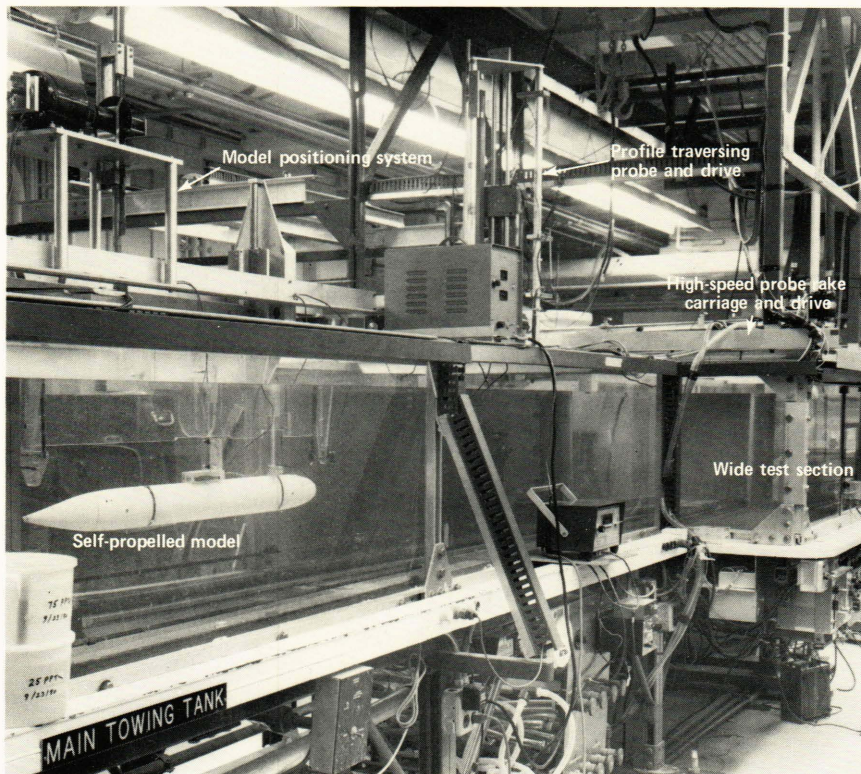


Figure 1 — Stratified towing tank 9.14 meters long with 1.83-meter-wide test section. An axisymmetric self-propelled model is shown below the positioning mechanism.

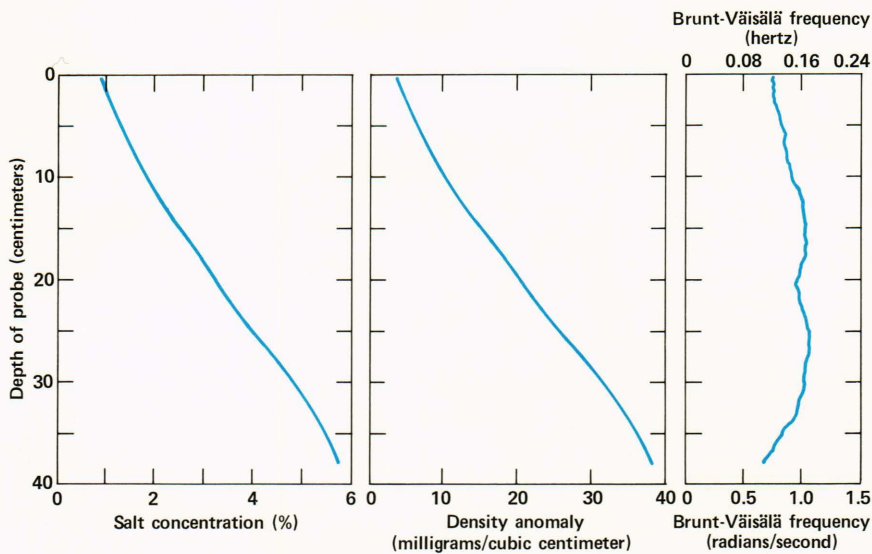


Figure 2 — Vertical profiles in main towing tank for nearly linear stratification, constant N . Stratification is achieved by varying the salt concentration with depth. The Brunt-Väisälä frequency profile, $N(z)$, shows small-scale variability in density gradient. Elevation is referenced to water surface.

The main towing tank is equipped with an axisymmetric, powered model as shown in Fig. 1. The model's propeller is driven by an internal motor with a remotely programmable speed control system. The rate of revolution of the propeller can be matched to the towing speed so that the body is effectively self-propelled and, therefore, has a momentumless wake. The model is 0.91 meter long and 0.076 meter in diameter, is guided by thin (0.1 millimeter) lateral wires, and can be towed at speeds ranging from 0.30 to 1.83 meters per second in the self-propelled mode. Dye is dispensed from the nose of the body for wake flow visualization.

The instrumentation routinely used with this facility includes a vertically traversing temperature/conductivity measurement probe for fluid vertical profile data such as shown in Fig. 2. A fast traversing conductivity probe array is used for making, at a selectable distance behind the test vehicle, a "snapshot" of the cross-track variation in electrical conductivity caused by fluid displacement. Dye and shadowgraph photography are routinely used for flow visualization.

An experiment performed in the main towing tank in 1974 examined the effects of stratification on the flow into an Ocean Thermal Energy Conversion

(OTEC) warm-water inlet (shown in Fig. 3). The OTEC-related experiments demonstrated that the ocean thermocline would provide a natural, effective separation of the warm surface water from the colder deep water, a separation necessary for efficient operation of the warm inlet pipe that was proposed in the APL OTEC plant design.¹

Wave Interaction Tank

The wave interaction tank (Fig. 4) is a multipurpose facility used for the study of wave generation and propagation. It is 6.71 meters long, 0.46 meter wide, and 0.61 meter deep. Like the main towing tank, it can be density stratified by varying the salini-

ty of the fluid layers introduced into the tank. It is equipped with a selective fluid-withdrawal system for simulating the characteristics of sheet-and-layer density structures that commonly occur in the ocean and is also equipped with devices for generating either surface waves or internal interfacial waves. It can also handle Freon-kerosene mixtures used for studies of waves on an immiscible interface. A vertically traversing temperature/conductivity probe (for measuring the temperature and electrical conductivity profiles) and arrays of conductivity probes are available. The latter probes can be fixed at selected positions along the tank for detection and measurement of fluid displacement caused by internal wave propagation. Capacitance probes are employed for wave de-



Figure 3 — Dye streak deformation patterns indicative of flow into the OTEC warm-water inlet. Dye streaks were initially vertical. Patterns indicate that the inlet will not capture water from the lower, colder layer, simulated by a dense, dark layer below the inlet.

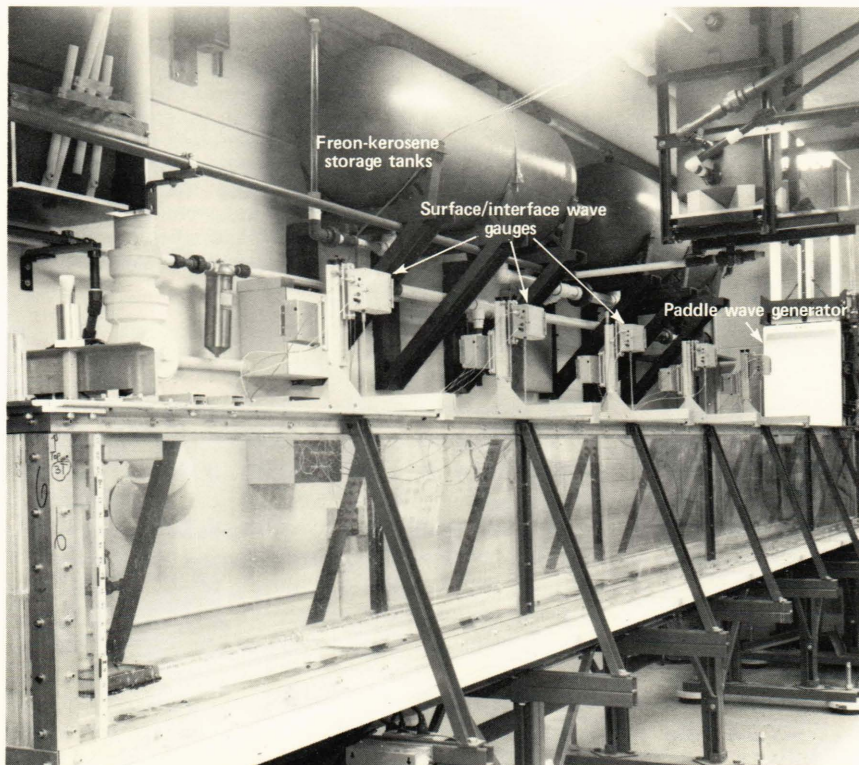


Figure 4 — Wave interaction tank, 6.71 meters long, configured for surface wave/internal wave experiment.

tection and measurement at the free surface or at an immiscible interface.

Experiments in the wave interaction tank have demonstrated the periodic nature of energy transfer between surface waves and internal waves and have provided the first experimental check of a wave interaction theory based on a resonance condition among two surface waves and an internal wave.² Figure 5 shows the internal wave generated at a stratified interface as a result of the resonant coupling between two periodic surface waves. This mechanism is thought to be one of the principal means by which internal waves are generated in the open ocean, far from land boundaries.

Double-Diffusive Tank

Figure 6 shows the principle of operation and an overall view of the double-diffusive tank. It is 1.22

meters long, 0.15 meter wide, and 0.46 meter deep. The double-diffusive tank was designed for a specific investigation of wave propagation in the presence of thermohaline convection. The experiments will be described in more detail in this article. The double-diffusive, salt-finger, convective process is illustrated in Fig. 7. This facility is suitable for other stratified-flow experiments where temperature and salinity must be carefully controlled so as to simulate ocean microstructure. The tank has heavily insulated side boundaries; the temperature of its lid and bottom can be controlled to selected levels. It is equipped with wave generators and with a selective withdrawal system that can be used to control the thickness of a single interface located at mid-depth between two saltwater layers of different densities. Temperature/conductivity probes are used for profile measurement and for measurement of fluid displacements due to internal wave propagation.

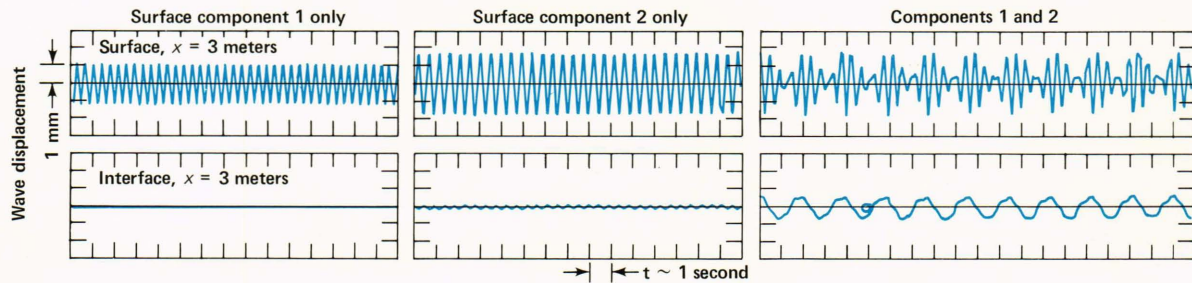


Figure 5 — Interfacial internal wave generation at near-resonance condition. The top three traces show surface wave signatures, generated by the paddle wave generator. Lower traces show the induced internal wave, where a significant amplitude is apparent near the triad resonance condition. Measurements were made in the wave interaction tank, 3 meters downstream of the wave generator.

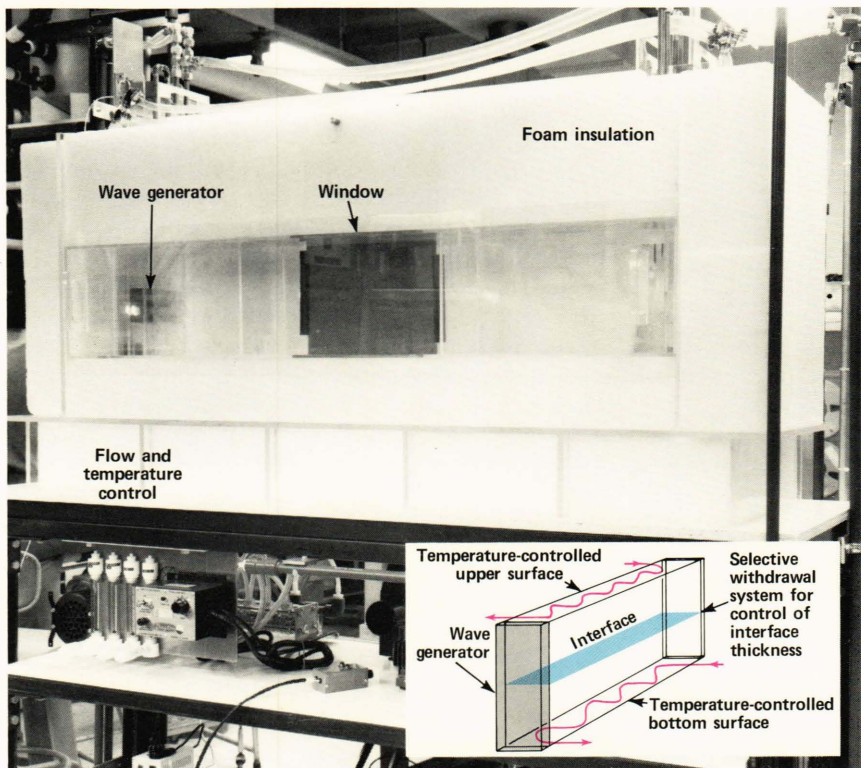


Figure 6 — Double-diffusive interaction facility. The principle of operation using temperature and salinity control to create a double-diffusive interface is shown in the inset. Insulation surrounding all but the test window is required to maintain adequate temperature control.

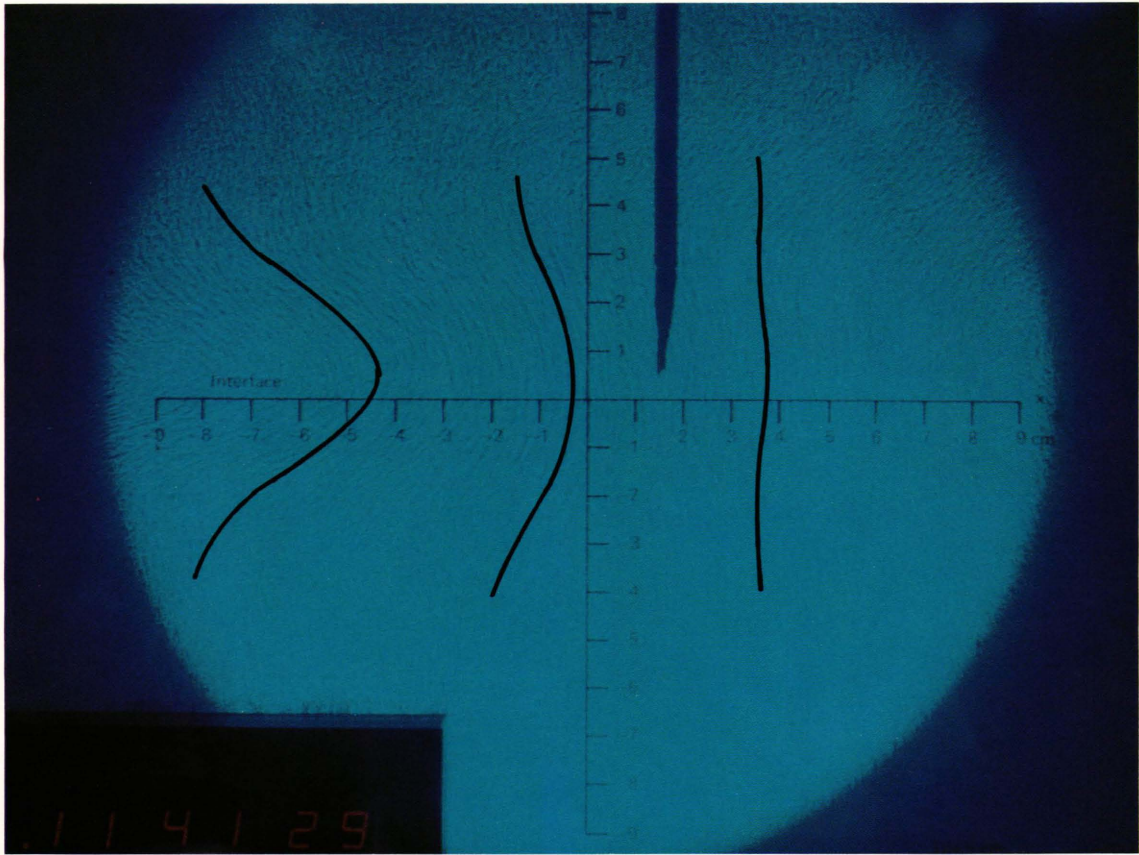


Figure 7 — Straining of salt fingers by a left-to-right propagating internal wave. The photograph is a shadowgraph obtained in the double-diffusive facility. Diffusive salt fingers are the small-scale, 1-millimeter-wide, curved striations, which were originally vertical.

Stratified Shear Tunnel

A facility has also been developed for the purpose of studying internal wave propagation along a stratified interface in the presence of a velocity gradient (i.e., shear). It is designed to operate in either the counterflow or co-flow mode as a stratified, two-fluid, nonrecirculating system. The tunnel cross section is 0.08 meter wide by 0.20 meter deep. Its length can be varied up to 6.10 meters. In a stratified shear flow, the critical fluid dynamic parameter is the Richardson number,

$$Ri \equiv \frac{N^2}{(du/dz)^2}, \quad (2)$$

where N is the Brunt-Väisälä frequency and du/dz is the vertical gradient of the horizontal velocity. The Richardson number represents the ratio between the buoyancy and dynamic inertial (shear) forces. At sufficiently low values of Ri , stratified flows become unstable and energy can be transferred between larger-scale internal wave motions and smaller scale turbulence. Richardson numbers less than 10 are achievable in this tunnel. (Low Ri values are not readily achievable in most laboratory facilities that are capable of creating shear in a stratified fluid, but low values are quite common in the ocean.) In a ser-

ies of experiments performed in this tunnel, it was found that the presence of shear resulted in the dissipation of an otherwise long-lived interfacial wave of a type called “solitary waves.”

Data Acquisition and Reduction System

The laboratory is equipped with a dedicated PDP-11/34A minicomputer. It has 32 analog-to-digital channels for data acquisition. Files of raw data acquired during a test are temporarily stored on disk until they have been reduced. Archival storage of the files of both raw and reduced data is on magnetic tape. The laboratory staff has developed a substantial library of software for the reduction and analysis of laboratory data. This library includes programs for calculating salinity, temperature, and density profiles (Fig. 2), wave displacements, wave-field potential energy distributions, and wave amplitude spectra. Some of this software requires user interaction with the computer in selecting points or segments of plotted data. Two graphics display terminals are available for that purpose.

INTERACTION OF INTERNAL WAVES WITH DOUBLE-DIFFUSIVE CONVECTION

An exploratory investigation was performed on the dynamic interactions between an interfacial internal

wave and a region of active double-diffusive convection. Although theoretically possible, no precipitous overturning within the interaction region was observed; however, the internal wave propagation was clearly affected by the double-diffusive environment.

Double-Diffusive Convection

Convective motion in a container of pure water heated from below occurs because the added heat produces an unstable density gradient. When a solute such as salt is present, with a vertical distribution that makes a contribution to a stable density profile opposite to the contribution of temperature, convective effects can still occur. In this case, the nature of the motion is quite different from ordinary thermal convection. Such double-diffusive phenomena depend on the presence of two diffusive “components” having significantly different molecular diffusivities. In the case of heat and salt, where the diffusivity ratio is 100:1, the phenomenon is generally called “thermohaline convection,” which is an intruding front of warm salty water. Thermohaline convection is a common oceanographic phenomenon, especially in outflow/frontal regions such as the Mediterranean outflow. A general description of double-diffusive phenomena is presented by Turner.³

One case of thermohaline convection is that in which warm saline water overflows colder, less salty water, as illustrated in Fig. 8. In this case, the salinity distribution represents an unstable component that is more than balanced by the temperature gradient. However, the response of this system to a vertical perturbation is to produce small-scale vertical motions over an ever-widening interfacial region that appear as small salt fingers. These fingers result directly from the differences in diffusivity of salt and temperature. Figure 7 is a prototype of laboratory-generated salt fingers, albeit distorted by an internal wave, as described below.

Internal Wave Interactions

While the double-diffusive phenomenon is relatively well understood, the many effects of internal waves on this process are not. Such interactions are certainly typical in any region of the ocean where double-diffusive convection is present; they may play an important role in the oceanic mixing process.

The double-diffusive facility (Fig. 6) was constructed to study internal wave double-diffusive interactions. Of specific interest was the overall extent of that phenomenon, i.e., whether a precipitous overturning would occur with an attendant release of the potential energy stored in the unstable diffusive component.

To study that problem, a two-layer salt-temperature stratification was established in the tank and allowed to evolve into an interfacial salt-finger region, as shown in Fig. 8. When the salt-finger diffusion process was established, an interfacial solitary wave was generated by ejecting a small amount of fluid into the interface at one end of the tank. That wave

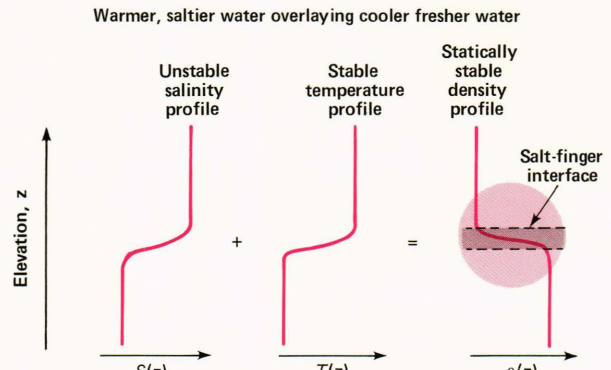


Figure 8 — Temperature, salinity, and density configuration for a salt-finger interface. Vertical salt fingers are developed by diffusion in the interfacial region.

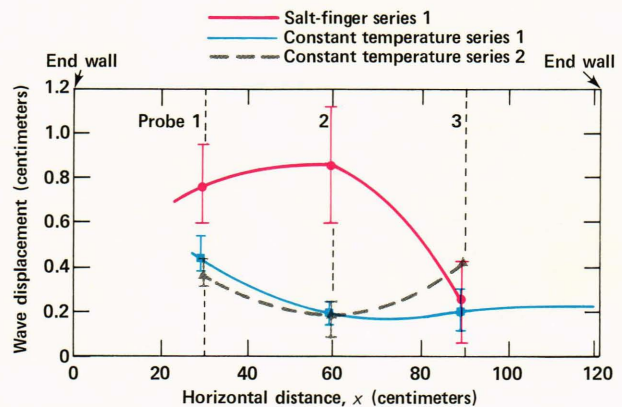


Figure 9 — Ensemble-averages of maximum internal wave displacements in double-diffusive, salt-finger experiments. Initial amplification of internal waves resulting from interaction with salt fingers is evident.

propagated along the interface and thereby interacted with the salt fingers.

In the experiments performed, that interaction did not result in a precipitous overturning of the unstable region but did, as shown in Fig. 7, significantly distort the vertical salt-finger motion.

Quantitative measurements were also made with conductivity probes placed in the salt-finger region (one is shown in Fig. 7). The results of the measurements are shown in Fig. 9, where the wave amplitudes measured in the presence of salt fingers are compared with amplitudes from two baseline test series. In the baseline tests, a density interface was created by salinity variations alone (constant temperature) so that no unstable component was present. The measurements confirmed the qualitative observations that no precipitous overturning occurred. They also indicated that, in the presence of salt fingers, the internal wave displacement undergoes an initial amplification that is quickly damped, bringing it back to the baseline level. The dynamics of these interactions are quite complex and interesting but are not fully understood.

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