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FLUID DYNAMICS, INTRODUCTION AND LABORATORY EXPERIMENTS

S. A. Thorpe, Southampton Oceanography Centre, Southampton, UK

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Introduction

Laboratory experiments have provided considerable insight and quantitative information about many of the physical processes which affect the fluid ocean. Although often made with the purpose of investigating some fundamental process in fluid dynamics, motivation for making laboratory experiments frequently comes directly from a need to improve understanding of processes in the oceans, or in some other geophysical fluid such as the fluid interior or atmosphere of the Earth and other planets, and such studies consequently belong to the broad field of geophysical fluid dynamics. Laboratory experiments are particularly valuable in testing theory and in providing quantitative, if empirical, estimates of, for example, constants of proportionality which cannot presently be determined by theory or numerical computations. They are therefore an essential component of geophysical fluid dynamics in relating theory to reliable application.

Laboratory experiments as a means of illuminating oceanographic processes have a long history which can be traced back at least as far as the experiment by Marsigli, reported in 1681, which demonstrated the way in which density differences drive exchange flows in the Bosphorus between the Mediterranean and the less dense Black Sea. The purpose of making laboratory experiments is rarely, however, to reproduce some aspect of ocean circulation. More often it is to study a particular process in isolation from others which occur in the natural environment. In addition to density differences or stratification, laboratory studies have been made of processes which result, for example, as a consequence of the Earth's rotation (including the β effect) and from the effect of free or fixed boundaries (e.g., promotion of turbulence or waves).

Several general objectives in making laboratory experiments may be identified and some are briefly described in the following sections. The particular experiments mentioned as examples are perhaps not always the best which might be chosen, but they are ones (among many) which demonstrate some particular value of making laboratory studies.

Testing Predictions

A beautiful example is the study made by Mowbray and Rarity of internal gravity wave propagation in a tank filled with salt-stratified water. Waves were generated by the slow oscillation of a horizontal cylinder and made visible using an optical Schlieren system. The experiments demonstrated beautifully the theoretical prediction that internal waves propagate away from the cylinder in a vertical plane at an angle to the horizontal given by $\sin^{-1}(\sigma/N)$, where σ is the frequency of the cylinder and N the buoyancy frequency in the stratified fluid (*see* **Internal Waves**).

Providing Measures of Unknown Coefficients or Values

An example is provided by the studies of Britter and Linden on the flow of a dense gravity current (*see* **Non-rotating Gravity Currents**) down a sloping boundary. They released dense salty fluid at a constant rate from the top of a uniform slope in a tank filled with fresh water, and measured the speed of advance of the 'head' of the gravity current formed by the salty water as it descended the slope. It may be deduced on dimensional grounds that the speed will be proportional to the buoyancy flux, B, to the one-third power, and to some function of the angle of inclination of the slope to the horizontal, α. The flux, B, is a product of the measured flow rate of salty water into the tank and its reduced gravity (the acceleration due to gravity times the fractional density difference between the ambient water and the dense water). The experiment shows that the speed is uniform and equal to $(1.5 \pm 0.2)B^{1/3}$, independent of α provided it is greater than about 5°. The experiment nicely supplements the dimensional arguments and provides a value of the coefficient of proportionality (and its uncertainty) which are of use in predicting the descent of dense water down slopes in the ocean provided that the conditions of the laboratory experiment are met, one being that the stratification of the ambient water is negligible.

Provision of Information Beyond the Range of Existing Theory or Numerical Calculation

The classic example in this category is the experiment by Osborne Reynolds on the transition from laminar to turbulent flow in a pipe. It was not made with oceanographic applications in mind but is fundamental, not only demonstrating the nature of flow that will occur in the ocean but providing a measure of the conditions under which a laminar flow becomes turbulent. This 'measure' is what is now called the Reynolds number. As a direct consequence of these studies, turbulent transfer and what are now known as Reynolds stresses, are now understood to be active in the processes of flux of momentum, heat, solutes, and suspensions, particularly (but not only) in the boundary layers at the sea surface and the ocean floor. Reynolds was also the first to investigate the onset of mixing in stratified shear flows, now generally called Kelvin–Helmholtz instability (KHI), well before others had advanced the theory sufficiently to identify a critical parameter, the Richardson number, below which instability may occur.

An experiment which has had profound influence on the development of analytical and numerical models is that of Morton, Taylor and Turner on the rise of buoyant thermals, mainly because of their successful demonstration of the validity of a hypothesis attributed to Sir G. I. Taylor, that the rate of flux of fluid into a turbulent plume (the entrainment rate) is proportional to the mean excess speed of the turbulent fluid through the ambient, and their determination of the proportionality factor. The small-scale laboratory experiment proves useful in providing estimates valid at far greater scale in the atmosphere and the ocean (*see* **Deep Convection**) because it is able to identify and quantify the parameters of importance in the process of convection and entrainment.

In the experiments of Rapp and Melville (*see* **Breaking Waves and Near-surface Turbulence**) a train of waves is produced by an oscillating wavemaker with its frequency controlled so that the lower frequency, faster-moving waves catch up with the higher-frequency waves produced early in the experiment, all combining to create a breaking wave at a predetermined location in the wave channel. The energy lost from the wave in breaking and the rate of dissipation of energy within the water are carefully measured. These experiments typify an important aspect of laboratory studies which is unattainable in the natural environment: Conditions are controlled and reproducible, and given processes may be carefully measured in the absence of extraneous factors (e.g., wind forcing of waves). The experiment goes beyond what is presently possible in numerical studies in that it provides measures of the evolution and decay of turbulence and the generation of circulation within the water column.

Unexpected Advances

Discoveries are sometimes made by chance through making laboratory experiments. The experiments now associated with the discovery of Benjamin–Feir instability were originally performed with the intension of examining wave reflection phenomena at a sloping beach. Very regular waves were required, and considerable care was therefore taken over the design of an oscillating-paddle wavemaker. Quite unexpectedly the regular wave train it produced broke up into short groups. This prompted theoretical advances proving that the classical Stokes waves can be unstable and initiated substantial revision of the understanding of oceanographic wave phenomena (*see* **Surface, Gravity and Capillary Waves**).

Influences on Ocean Observation

Double-diffusive convection (*see* **Double-diffusive Convection**) has been intensively studied in the laboratory and, perhaps more so than for any other process, the experiments have been very influential in establishing the importance of double-diffusive convection in the ocean, in interpreting the observations of the associated 'steps and layers' in the temperature and salinity structure of the ocean, and in providing guidance for further measurement. Although the dynamical transfers in the relatively high vertical-gradient 'steps' containing salt fingers can be described by theory and numerical simulation, insufficient can be yet predicted of the formation and properties of the intermediate thick turbulent layers.

Laboratory studies often go far beyond a (perhaps) preconceived and limited objective of testing theory, for example by revealing information about the stages involved in the transition from a laminar to a turbulent flow in stratified or rotating flows. Transitional phenomena are of particular relevance in the ocean where, except near boundaries, turbulence is rarely well developed or continuously sustained and where mixing processes are consequently transient and less-than-perfectly efficient or effective in homogenizing the water column (*see* **Fossil Turbulence**). Studies of processes in turbulent boundary layers (*see* **Turbulence in the Benthic Boundary Layer**), such as 'bursting' and 'ejection' events with relatively rapid transfer of slow-moving fluid from near a rigid boundary, have had significant impact on measurement strategies and observational requirements needed to provide accurate estimates of quantities like turbulent dissipation rates, which are log-normally distributed and whose mean magnitude is determined by highly intermittent events.

Conclusion

Laboratory experiments provide cost-effective means of quantifying processes and of examining the bounds of validity of theory, especially when nonlinearity is important and approximations are required to make progress in developing theoretical analysis. They often reveal unexpected or previously unknown features, processes or phenomena which, without the insight provided by the experiments, might not have been recognized or discovered by other means. They are consequently an important component of geophysical fluid dynamics. Laboratory experiments may suggest measurements which should be made in the ocean to test theories and ways of designing sea-going experiments so that the data collected are the most appropriate and useful.

See also

Breaking Waves and Near-surface Turbulence. Deep Convection. Double-diffusive Convection. Fossil Turbulence. Internal Waves. Non-rotating Gravity Currents. Overflows and Cascades. Rotating Gravity Currents. Turbulence in the Benthic Boundary Layer.

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