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PYCNOCLINES CREATED BY MIXING IN AN AQUARIUM TANK

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FOREWORD

The experiments described in this paper were carried out by the author before his death in an airplane crash near Guadalajara, Mexico, 2 June 1958. We had planned to collaborate in studying the results from the standpoint of possible model similarity between events in the experimental tank and in the ocean, possibly repeating some of the experiments or devising new ones. But I was unable to find many of the pertinent numerical data in Mr. Cromwell's files.

It was the general opinion of our colleagues that Mr. Cromwell's interesting experiments had shed considerable light on the problem of thermocline formation and that a qualitative description would be of value even without a detailed discussion of the results. Fortunately, Mr. Cromwell had finished writing a preliminary draft and had prepared several figures. The present article consists entirely of that draft, with few minor changes by myself.

Considering the possibility of performing further experiments on pycnocline formation, Mr. Cromwell and I agreed that the initial linear density gradient herein used was probably an unnecessary complication; the fluid above the pycnocline was shown to be sensibly homogeneous, and apparently only a thin layer of fluid immediately below participates in the process at any given time. Rouse and Dodu (1955), using the simpler initial state of two homogeneous layers, kept the pycnocline in the same relative position by allowing water to flow into the lower layer and out of the upper. It would be even simpler to eliminate the flow and allow the pycnocline to descend during the experiment. Then a thorough investigation of the effects of all parameters influencing the experiment, including mesh size, agitation frequency and amplitude, distance from mesh to pycnocline, etc., would be enlightening. Or, it might be possible to devise parameters that come closer to de-
scribing the turbulence introduced than those mentioned, thus facilitating comparison with an ocean where there is no oscillating mesh.

The loss of Townsend Cromwell was a great loss to the science of the oceans. It is hoped that others may be inspired to undertake model studies of thermocline behaviour, in which he had such an enthusiastic interest.

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ABSTRACT

Experiments here reported show that a vertical density gradient can be concentrated in a small aquarium tank by simple agitation immediately below the fluid surface with a mesh. A pycnocline, which is immediately formed, descends rapidly at first and then more and more slowly as its distance from the source of turbulence increases. An explanation for pycnocline descent is suggested. Fluid particles which move upward from the region of the pycnocline are rapidly deformed and mixed throughout the upper layer whereas fluid particles which move downward into the quiet layer below are buoyed upward intact. Thus the upper layer increases in thickness at the expense of the lower layer, i.e., mixing across the pycnocline is one-way.

The sequence of events in the tank agrees with the hypothesis that pycnoclines in the ocean can be formed as a result of turbulence produced at the sea surface by wind. However, since these experiments were not properly scaled and since the turbulence spectrum in the ocean is undoubtedly dissimilar from that in the aquarium tank, our results are only suggestive and do not incontestably verify this hypothesis.

Introduction. Thermoclines are among the most striking features of the ocean’s thermal structure. Since the effect of salt on density in the open ocean is generally small, the thermocline is a layer through which the vertical density gradient is large relative to overlying and underlying gradients; i.e., the thermocline is also a “pycnocline”.

Knowledge of pycnocline formation and maintenance is summarized in a report of the Chesapeake Bay Institute of the Johns Hopkins University (Pollak, 1954). Qualitative explanations of the phenomenon appear in a number of publications (Sverdrup, et al., 1942; Schule, et al., 1952; Anonymous, 1946). Presumably wind stress on the sea surface produces stirring and mixing downward
to a limited depth. The layer affected is rendered nearly homoge-
neous, but below the region of effective mixing the vertical density
gradient remains essentially unaffected. In between is a thin layer
of sharp transition. In this way an initial vertical gradient, perhaps
established by warming near the sea surface, is modified only by
redistribution of mass in a vertical column, thereby "creating" a
pycnocline.

**Purposes of Experiment.** Experiments were performed in a small
tank to ascertain whether or not a pycnocline could be formed by
introducing turbulent energy near the surface and possibly to gain
insight into the mechanism of pycnocline formation and maintenance.
Although the results were affirmative, it will be pointed out below
that there are objections to drawing an analogy to events as they
occur in the ocean.

**Equipment and Experimental Procedure.** A small rectangular
aquarium tank, $27 \times 17$ cm and 19 cm deep, was used. A rectangular
one-quarter inch galvanized iron mesh (hardware cloth) was cut to
fit snugly into the tank. The mesh, with appropriate linkages to an
electric motor, was driven up and down in regular oscillatory motion
near the surface. This equipment is illustrated in Fig. 1.

The density structure desired initially was a linear increase with
depth from top to bottom of tank. A clear mixture of roughly half
sea water and half distilled water was diluted with dyed sea water
in four proportions. It was found most practical to introduce the
lightest (least colored) mixture into the tank first. Successively
denser (more deeply colored) mixtures were then introduced near
the bottom through a siphon. Sharp interfaces, visible because of
the dye and because of refraction of light from a source behind the
tank, tended to develop between successive mixtures. However,
sharp gradients could be smoothed out by waving the nozzle up
and down across the interfaces during siphoning. It was impossible
to avoid all sharp vertical density gradients, but those which re-
mained after siphoning could be "mixed away" by means of a small
piece of hardware cloth on the end of a pencil. Establishing the
initial gradient in the tank was the most difficult part of the whole
experimental procedure, but by these crude methods a gradual
increase in density with depth could be obtained (Fig. 2, curve A;  
Fig. 4).
The experimental procedure was to agitate the fluid near its surface, the mesh describing simple harmonic motion over a 2.5 cm range of depth. From time to time the motor was stopped and, after all visible movement of the fluid had ceased, samples were drawn with a volumetric syringe and titrated. Titration and temperature measurements in the tank were to an accuracy allowing the determination of density to 0.1 in $\sigma_t$.

Sampling depth was read from a scale pasted to the tank and zeroed at the water surface before any samples were drawn. "Adjusted
"depth" enters because withdrawal of the samples lowered the fluid surface appreciably during the experiments. Adjustments were made according to the formula, 
\[ z_a = [z - (h_i - h_n)] \frac{h_i}{h_n}, \]
where \( z_a \) is "adjusted depth", \( h_i \) is water depth at start of the experiment, \( h_n \) is water depth at start of sampling run, and \( z \) is reading from depth scale.

During agitation by the mesh, the tank was checked visually to see that no "large scale" circulation was set up, i.e., that there were no circulation cells which seemed to be bounded by the walls of the tank. When this happened, as it sometimes did, the fluid to a considerable depth would overturn, producing a homogeneous layer very quickly. However, when a mesh was obtained that was manufactured with reasonable precision, when it filled the tank snugly, and when it was nearly level, the motion appeared to result only from the irregular "turbulent" elements produced by the mesh grid, free of the influence of lateral boundaries.

**Results.** Results of a typical experiment appear in Fig. 2. A homogeneous surface layer is created by the stirring and mixing produced by the mesh. Immediately below, a sharp pycnocline appears. The vertical gradient in this pycnocline is greater than that which existed anywhere in the tank before agitation was begun. With the passage of time the pycnocline descends, rapidly at first but then more and more slowly as the distance from the mesh increases.

There are some further qualitative observations of tank experiments that can be mentioned. If the mesh is oscillated close to the bottom of the tank, a pycnocline forms above the mesh and gradually ascends. If the mesh is oscillated through an intermediate depth, pycnoclines form both above and below, rising and descending respectively. Thus, the position at which turbulent energy is introduced is important in determining the modification of the density structure that will occur.

Pycnoclines can be destroyed, or at least diminished in intensity, as well as created by the mixing. If, during an experiment, the frequency of mesh oscillation is increased suddenly, then turbulent elements penetrate into the lower stratum. As a result the gradient in the pycnocline becomes diminished. If the mesh is allowed to continue oscillating at this new, higher frequency, a new sharp pycnocline will form at some greater depth in the tank.
Figure 2. Successive density profiles in tank during an experiment; Curve A represents initial profile, curves B, C, and D occurring at later times.

Pycnocline Formation. Turbulence over the range of the mesh is so extreme that a mixed layer, bounded below by an interface, is formed with the first thrust. This occurrence defies any useful interpretation. At the same time, however, fluid elements are impelled downward by the mesh, interspersed by upward elements (Fig. 3a). Their spacing is uniform and equal to the grid size of the agitating mesh. Across the interfaces separating these elements of differing density, molecular diffusion is favored. Those down-
ward elements which penetrate most deeply into the undisturbed fluid below are buoyed upward, intact, before any appreciable mixing takes place. At an intermediate level, somewhat above the level to which extreme downward elements penetrate, an interface gradually appears. The quantitative aspects of these events, e.g., the depth and rapidity of pycnocline formation, depend on the original density structure, on the fundamental dimensions of the mesh, and on the frequency; but qualitatively it seems that the development of a mixed surface layer and a subjacent stable layer may occur when stirring is induced by any means whatever. For example, when the surface of the tank is cooled by suspending a sheet of dry ice just above it, roughly the same series of events takes place. But in this case other factors determine the size and spacing of the fluid filaments.

Once formed, the pycnocline maintains its identity and progresses downward. The interface is in irregular wave-like motion, and it separates the turbulent surface layer from the stable fluid below, which is quiet (Fig. 3b). This abrupt change in the state of motion across the interface can be seen during the experiment by sprinkling ashes from above, which, as they sink, describe irregular and varied paths downward until they pass the interface. Thereafter the particles sink slowly, straight downward. The predominant wave length of the wavy interface is now greater than it was just after the first few thrusts of the mesh, and apparently it is unrelated to the grid

Figure 3a. Initial appearance of interface after first thrust of mesh.
Figure 3b. Subsequent appearance of interface.

size. Segments of typical paths are illustrated in Fig. 3b by dashed arrows.

The explanation for descent of the pycnocline is as follows: Downward directed fluid elements at the interface (e.g., at D) enter a quiet environment and are buoyed upward, intact. Upward directed elements (e.g., at U) enter a turbulent environment where they are deformed and mixed quickly throughout the surface layer. Thus the mixing, or entrainment, is one way, and the surface layer thickens at the expense of the lower layer, so that the pycnocline must gradually descend. Fig. 4 illustrates the varying rate of descent of the pycnocline.

Rouse and Dodu (1955) performed experiments with equipment basically similar to that described here. They began their experiments with a two-layered system of fresh and saline waters. They found that turbulence induced in the upper layer by a mesh was restricted to the upper layer, with entrainment from the layer below, an occurrence which our experiments have duplicated.

Analogy to Events in the Ocean. There is a striking similarity between events in the tank and those occurring in the ocean during increased winds. Francis and Stommel (1953), using data from weather ships, have shown that the oceanic thermocline descends during a gale. The author analyzed these same data in greater detail and found that (1) the surface layer becomes more nearly
isothermal (as measured by the BT), (2) the temperature gradient in the upper part of the thermocline becomes more intense, and (3) the separation between surface layer and thermal layer becomes sharper. An example of this series of events has been shown by Cromwell and Reid (1956: Fig. 6). This series of events can also be seen here in Fig. 2.

It has been suggested (by Carl Eckart) that the turbulence spectra in the tank and in the ocean are dissimilar and that this dissimilarity may be critical. The turbulent energy introduced into the tank by the mesh lies within the dissipative range of the spectrum, whereas
in the ocean there may be relatively little turbulent energy concentrated at such small scale. Thus, even when properly scaled model experiments are performed, results cannot be applied to the ocean with certainty until more is known of the spectrum of ocean turbulence.

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