A one-dimensional model of the seasonal thermocline

I. *A laboratory experiment and its interpretation*

By J. S. TURNER and E. B. KRAUS, *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts*

((Manuscript received October 11, 1965)

ABSTRACT

A simple model of the seasonal thermocline is examined theoretically and with the aid of a laboratory experiment. It is argued that all the heat and mechanical energy which affect the water column can be put in near the surface and propagated downwards, without being influenced significantly by horizontal velocities, advection or rotation. If all the kinetic energy of stirring is used to change the potential energy of the system, one can calculate the temperature and depth of the well-mixed surface layer as a function of time, given the heat input. This has been done explicitly for a saw-tooth seasonal heating function and constant stirring rate. A step-by-step heating process has been simulated by an intermittent input of buoyant fluid at the surface, both theoretically and experimentally.

Many features observed in the ocean are reproduced by both the theory and the experiments. The depth and temperature dependence of the upper mixed layer as functions of time, and the relation to the heating and cooling cycle, are in good qualitative agreement. Most important, this model shows clearly that surface mixing affects only the properties down to the topmost density interface, and that deeper features laid down early in the heating season can persist until the well-mixed layer reaches them again late in the winter.

1. Introduction

Many theoretical models have been proposed to explain the structure of the surface layers of the ocean and their variations over short and long periods of time. Several rather different physical processes have been invoked, and indeed all of these are probably important at different times or in different geographical regions. MUNK & ANDERSON (1948) extended the Ekman spiral calculations by taking into account the dependence of vertical eddy viscosity and conductivity on the shear and density gradients, and thereby determined steady state distributions which have many of the observed features. STOMMEL & WOODCOCK (1951) considered the effects of surface heat flux and wind stirring on the eddy transport coefficients, and KITAIGORODSKY (1960) used a dimensional argument to relate the depth of the upper mixed layer to the surface stress and heat flux. KRAUS & ROOTH (1961) showed how a well-mixed layer is formed by convection produced by the absorption of heat in depth and a loss at the surface. In contrast to these "local" treatments, theories of the deep (permanent) thermocline have involved advection effects, either without vertical mixing (WELANDER, 1959) or with this included (ROBINSON & STOMMEL, 1959; ROBINSON & WELANDER 1963). For these large scale models the earth's rotation always enters in an important way. The relative influence of all these processes in various regions has recently been reviewed by TULLY (1964).

Most of these, and other studies not cited, suffer from two disadvantages. They often contain more than one physical process in a way which makes it difficult to disentangle them, and they are nearly all steady state calculations. In the present paper the aim has been to return to one of the simplest possible single processes which can account for the *time dependent* behaviour of the upper mixed layer. This will be studied theoretically and using laboratory experiments. It is assumed that the formation of the mixed layer can be regarded as one-dimensional, i.e., generated locally and propagated vertically, and that the mechanism of mixing is through surface stirring associated with waves or a mechanical mixing process; the earth's rotation will be ignored. The rate of heat input affects the model through its influence on the density structure, since stable density gradients can inhibit vertical mixing. A more general theory of the same physical process will be presented in the following paper (KRAUS & TURNER, 1966), which will be referred to as II.

2. An example of the phenomena to be modelled

Before the details of the model are described it will be helpful to summarize some observational data which seem to typify the phenomenon which we aim to understand. TABATA & GIOVANDO (1963) have reported a long series of measurements of temperature profiles at Ocean Weather Station P in the North Pacific from which they deduce a typical cycle of growth and decay of the seasonal thermocline. As pointed out by TULLY (1964), this is a region where there is a net heat transfer to the sea when the sun is north of the equator and a loss to the air when it is south, with very nearly a balance over the year (see Fig. 1). The development of the warm layer at the surface in this area and also near Bermuda (in the North Atlantic) is shown in Fig. 2. The figures reveal the characteristic well-mixed upper layer, whose depth decreases as the heating increases, and then increases again during the cooling season. Tabata and Giovando also discuss the formation of daily temperature structures by a combination of heating and surface evaporation together with wind mixing, and in a more recent paper (TABATA *et al.*, 1965) the effect of strong winds on the descent of the interface is examined.

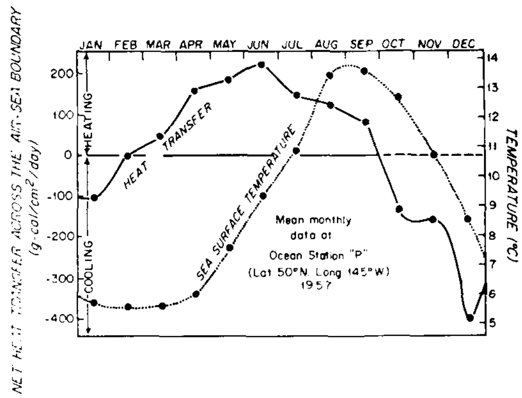

FIG. 1. The heat budget and surface temperature deduced from observations in the North Pacific (after TABATA & GIOVANDO, 1963).

Many features of these observations have been reproduced in our model and will be discussed in detail later, but some points emphasized by TULLY (1964) might be mentioned now. First, the seasonal warming of the sea is an intermittent process (on several time scales), not a continuous one, and the effect of this on the final structure should be examined carefully. Secondly, and probably more important, it is discontinuous in depth. A heat input at the surface contributes to the warming of the water above the uppermost thermocline, and associated properties are transferred downwards at a substantial rate only when this interface is moved downwards by stirring from the surface. The small effect of internal mixing, at least in this region, is made clear by the persistence of small features of the deeper layers, so that "the structure provides a historical record of the processes that created it."

There are, of course, other observations of a less extensive kind which support this same general picture. FRANCIS & STOMMEL (1953) had used earlier ocean station records to show that a single gale may deepen the mixed surface layer by 20 to 30 ft, and CROMWELL & REID (1956) pointed out that the gradient at the bottom of the mixed layer is intensified by the turbulent processes which make this upper layer uniform.

3. Past and present experimental models

Several laboratory experiments have been reported in the past which bear on the present problem. A basic study of the mixing processes at a stable interface stirred on one side was carried out by ROUSE & DODU (1955). They expected that such stirring would smear out the interfacial gradients, but discovered to their surprise that the interface in fact became sharper, with a transfer of material always from the nonturbulent into the turbulent fluid, where it quickly became well mixed. This phenomenon of *entrainment*, with a sharp boundary between turbulent fluid and fluid at rest, has become familiar in other contexts even in uniform

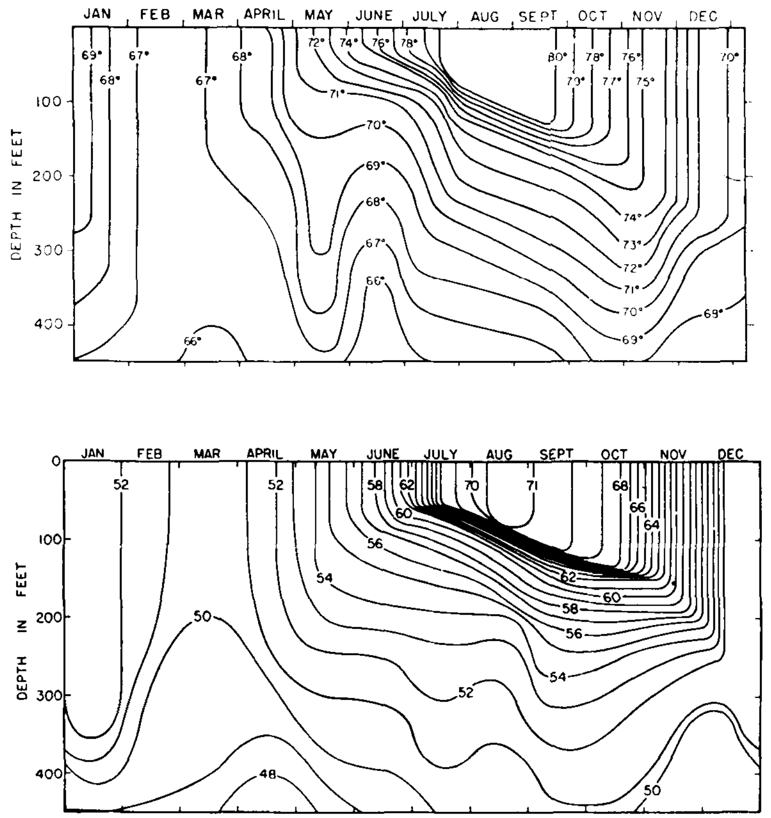

Fig. 2. The seasonal temperature cycle (°F) in (*a*) the Bermuda area, (*b*) the North Pacific. (From Summary Technical Report of Division 6, N.D.R.C., Washington, 1946.)

fluids (e.g. the spread of a wake or jet), but it is even more striking with a density interface which rapidly damps out turbulent fluctuations near it.

The conditions of Rouse & Dodu's experiment, though excellent for their original purpose, were not the most appropriate ones for the present study. They started with two layers of different constant densities (which we will also do here) but kept the *geometry* constant throughout. That is, the layers were maintained at the same depth and the stirrer at the same position relative to the interface, by continuously drawing off fluid from one layer and replacing it in the other at a rate which at any time just compensated for the advance due to entrainment. Thus the density of the stirred layer was changing with time (until eventually it became equal to the density of the other, and the whole system mixed) but the effect of changing the distance from the source of turbulent energy to the interface was not studied explicitly.

Another experiment, which was carried out with the ocean thermocline (or pycnocline) particularly in mind, was that of Cromwell (1960). He used a finer stirring grid than Rouse & Dodu, but came to essentially the same qualitative conclusions about the sharpening of the interface. The original density distribution of the unstirred layer, however, was linear rather than uniform: this was chosen with the deep thermocline in mind. For the present purpose it seems preferable to return to the uniform initial distribution, since this is both easier to study experimentally and more appropriate for the kind of upper mixed layer we wish to investigate.

In our model, we have initially a deep tank filled with a liquid of uniform density. Just below the surface of the liquid is a stirring grid to introduce turbulence mechanically at a fixed level. Increases of heating rate with time are represented by adding increasing volumes of lighter fluid at the surface. Since the scale of the laboratory experiment is small, molecular heat diffusion could be important; differences in salt concentration have therefore been used instead of temperature differences to produce the changes in density. In the oceanic phenomena of interest nearly all the density differences may be caused by temperature variations, or there could be contributions from salinity variations due to rain or evaporation, but it is only the density structure which is relevant in all cases, when turbulent processes are dominant. Correspondingly, cooling periods will be represented by adding salt solution denser than that in the original tank. Each addition will be made at fixed intervals of time with the stirring going on continuously, though there is little difference in the results if stirring is stopped during the "heating" periods. The main question we set out to answer here is: how much of the observed time dependence of the mixed layer depth and the surface temperature can be explained by this one-dimensional model, with a *fixed* stirring rate and a correct modelling of the surface heat input alone? Large variations are clearly possible if the stirring rate is changed too, but first let us see if the mean behaviour can be properly represented in this way.

In order to understand the behaviour of this system, it is also important to study in more detail the simpler problem of the advance of a *single* interface away from the stirring grid. Qualitatively, it is to be expected that as the interface descends the turbulence level near it will be decreasing due to damping by viscosity: on the other hand, the density difference across it must decrease as the surface layer deepens and this will make the entrainment easier. The net effect will be the result of a balance between these two opposing tendencies.

4. Experimental procedure and results

The vessel used was a plexiglass tank 25.5 × 23 cm in cross section and 44 cm deep. The stirrer consisted of a grid of 1 cm wide plexiglass strips 1.5 mm thick, cemented together in a square array with 4.5 cm between centers, and set horizontally near the top of the tank, covering its whole area. It was driven by a variable speed electric motor through an eccentric which provided an approximately simple harmonic motion of fixed amplitude (about 1 cm). Experiments were begun with saline water of known density filling the tank to about 1 cm above the stirrer, and a measured quantity of dyed fresh water was carefully floated on top. Some experiments were conducted with a wire mesh lid at the level of the mean water surface, but for most of them the surface was left free. The depth of the interface at any time could be measured by means of a scale attached to the tank.

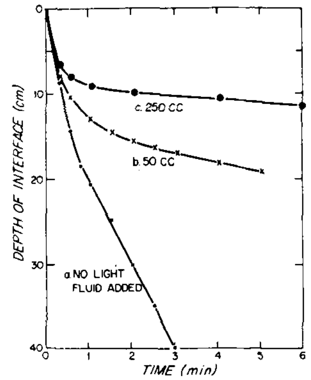

Fig. 3. The behaviour of individual stable interfaces descending due to stirring near the surface. Volumes of light fluid, giving a measure of the total buoyancy of the upper layer, are marked on the curves.

In the first runs, stirring was stopped each time a reading was required, but this was found not to give exactly the same results as with continuous stirring: during the pause, the upper layer was made very uniform by the residual motion, and when stirring was resumed the interface started to move downwards more quickly than it should initially while a salinity gradient near the interface was building up. In all the runs reported here, depth readings were made with the stirrer running, in spite of the inaccuracies introduced by the fluctuations of the interface.

First, let us consider the behaviour of a single interface as it develops in time. The results of three such experiments, conducted with a fixed stirring rate and density of tank fluid but various initial volumes of buoyant fluid, are shown in Fig. 3. Curve *a* shows the behaviour with *no* buoyant fluid added (but just a small amount of dye to trace the motion). The veloc-

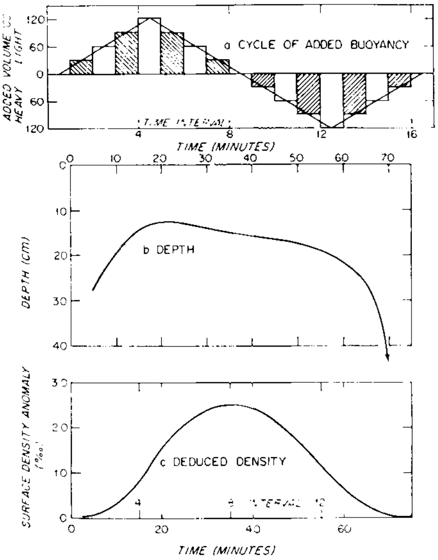

FIG. 4. The experimental results for a time-dependent surface layer, produced by stirring at a constant rate with a variable density input. (*a*) The saw-tooth "heating" function, and its approximation by the addition of discrete volumes of buoyant fluid at 5 minute intervals. (*b*) Depth of the well-mixed surface layer at the end of each stirring interval. (*c*) The surface density anomaly deduced from (*a*) and (*b*).

ity of advance at first decreased rapidly, but then stayed substantially constant over a range of depths until the stirred layer reached the bottom of the tank. With increasing amounts of buoyant fluid, the initial rate of advance was again very rapid, but the density differences soon became important and the velocity of the interface depended strongly on the stability. Over a considerable interval of time (say 3–6 minutes in these experiments) this velocity was changing only slowly, but at much longer times (not shown here) it becomes very small if the density differences are large.

To illustrate the second type of experiment, that with a variable density input, we have taken a run with the identical tank fluid (density 1.051) and stirring rate (6.5 cycles/sec) as in those just discussed, but with extra density increments added at 5 minute intervals. The first sample of 30 cc of fresh water was added as the stirring was begun. At the end of 5 minutes the depth was read and 60 cc of fresh water poured carefully in the top, and this process was repeated every 5 minutes thereafter, with the volume of sample adjusted to follow the "sawtooth" heating cycle shown in Fig. 4. Stirring was carried on continuously, but as each new sample was added, a new interface formed near the surface and propagated downwards; the turbulence below this top interface very quickly died away. From the successive positions of the interface and the known volumes of fluid added, one can easily deduce the density structure as a function of depth at any time. The total buoyancy is conserved, so the area under the depth $-\Delta\varrho$ curve must just be equal to the net buoyancy input; the results so obtained are plotted in Fig. 5. The "cooling" cycle was continued in this way, adding in the same sequence volumes of *heavy* fluid (density 1.100). This of course has the same density difference from the original tank fluid as the fresh water, but in the opposite sense, so that when the cycle was complete the density of the tank remained unchanged. During the whole experiment the surface was kept at the same level by withdrawing a compensating amount of fluid from the bottom of the tank, and the measured positions of the interface were corrected to allow for this. Fig. 4 shows the depth of the well-mixed layer and the deduced surface density as a function of time in this experiment.

5. Theories of the mixing process

(a) *A single interface*

Using the experimental results as a guide, we can now attempt a physical interpretation of the surface mixing processes, starting with the basic problem of a single density interface. PHILLIPS (1966) has discussed two extreme cases of the advance of a turbulent layer into one at rest, which he calls "fully turbulent" and "quasi-laminar" entrainment. For both of these, the turbulence is produced by imposing a stress on the upper surface, so that a mean velocity is produced and the scale of the turbulence can adjust itself to the depth of the upper layer. They may therefore be more closely applicable to the ocean than to the turbulence generated by a grid, but a comparison with our results will still be of interest.

In the first, "turbulent" case, density differences are supposed to be negligible, so this is equivalent to a front of turbulence advancing into a uniform fluid at rest. Dimensional arguments suggest that in this case the only relevant velocity scale is $u_* = (\tau/\varrho)^{\frac{1}{2}}$, the friction velocity associated with the surface stress τ, and that the velocity of advance of the front v is just proportional to u_*. For "quasi-laminar" entrainment, on the other hand, the reduced gravitational accelerations are much larger than those characteristic of the turbulence itself, i.e.

$$\frac{g\delta\varrho}{\varrho} \gg \varepsilon^{\frac{3}{4}} \nu^{-\frac{1}{4}} \tag{1}$$

(where g is the acceleration due to gravity, ε is the rate of energy dissipation per unit mass and ν is the kinematic viscosity), and a very stable interface is being considered. Small scale turbulence is damped out entirely, and transfer is effected by the large eddies sweeping away the viscous boundary layer at the interface. The volume transport found in this way is again constant, but much slower than the "turbulent" rate. No direct effects of the density difference appear in this limiting case.

The density difference can be taken into account explicitly using the following energy argument. The potential energy of a system consisting of a well-stirred upper layer of depth h, and a lower layer of depth $(d-h)$ with a density difference $\Delta\varrho$ between them is, with an arbitrary additive constant,

$$E = gh\Delta\varrho\left(\tfrac{1}{2}h - d\right). \tag{2}$$

As the interface descends due to mixing from the bottom into the top layer, the product $gh\Delta\varrho$ will remain constant (equal to $C\varrho$ say) because the total amount of buoyant fluid is conserved. Therefore the rate of change of potential energy is

$$\frac{dE}{dt} = \tfrac{1}{2}(gh\Delta\varrho)\frac{dh}{dt} = \tfrac{1}{2}Cv. \tag{3}$$

If we now assume that kinetic energy due to stirring is being put in at a constant rate, and is *all* being used to increase the potential energy of the system, then from (3) the interface should descend at a constant rate, which is inversely proportional to C or the "total buoyancy per unit area" of the top layer.

Three arguments have now been used to predict the behaviour of a single entraining interface. Each of these has led to a (different) constant rate of descent, but has included only one physical process at a time. Qualitatively the last seems to agree best with what we have learned from the observations, but the potential energy argument cannot be used at small values of C: at this limit we would expect that the rate of descent should approach a finite value, as in Phillips' "turbulent" case, rather than becoming infinite. These two cases can be combined if we suppose that the entrainment velocity depends not only on u_* but also on a stability parameter in the form of a Richardson number Ri defined by

$$\mathrm{Ri} = \frac{gh\Delta\varrho}{\varrho u_*^2} = \frac{C}{u_*^2}. \tag{4}$$

Thus by dimensional reasoning

$$\frac{dh}{dt} \sim u_* f(\mathrm{Ri}) \tag{5}$$

where the functional form $f(\mathrm{Ri})$ must be determined experimentally. This might be expected to fall rapidly from the "unstratified" value as Ri increases, much as it does for the case of a density current (ELLISON & TURNER, 1959). Thus again, for a constant stirring rate, the velocity of advance of the interface will be constant and a function of C alone (though a different function from the $1/C$ obtained by the potential energy calculation).

The above argument does not take into account explicitly the effect of viscous damping on the energy balance, and the important fact that energy is being put in at the surface (not throughout the top layer as in a shear flow), while it becomes effective for mixing only near the interface. One might expect, therefore, that the velocity of advance would decrease with time when there is only surface stirring, and this is indeed the case in our laboratory experiments. When viscous effects are important, then another non-dimensional number can enter the problem. This may for instance be defined in the form of a Reynolds number

$$\mathrm{Re} = \frac{u_* h}{\nu} \tag{6}$$

and the functional relationship replacing (5) becomes

$$\frac{dh}{dt} = u_* f_1(\mathrm{Ri}, \mathrm{Re}). \tag{7}$$

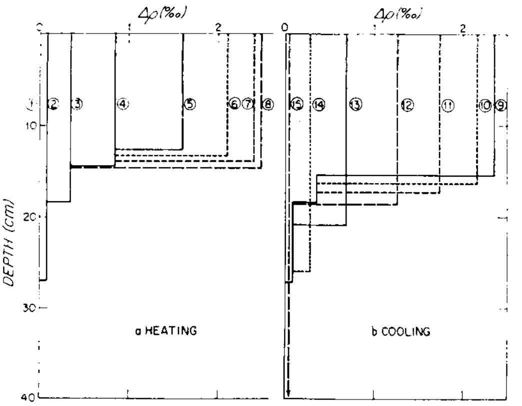

Fig. 5

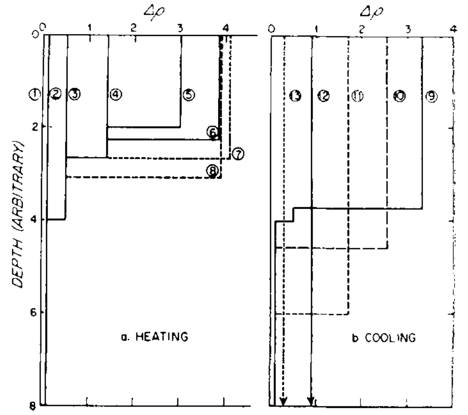

Fig. 6

FIG. 5. Successive layer structures in our experiments, with observed depths plotted against deduced density anomalies at the end of each stirring interval. The numbers refer to the time intervals marked on Fig. 4.

FIG. 6. The successive layer structures deduced theoretically, using a potential energy argument for the intermittent input of heat according to the cycle of Fig. 7. The numbers refer to the time intervals marked in Fig. 7.

In the ocean, however, there is still the possibility that arguments based on a stability parameter alone might give a good representation of the actual state of affairs. Firstly, the effect of the wind *is* transmitted to the water surface as a stress, and eddies of all scales up to the depth of the well-mixed layer are possible. Secondly, evaporation will produce convective motions on a large scale, and as BALL (1960) has shown for a similar case in the atmosphere it is then reasonable to balance the kinetic energy of the turbulence against the potential energy changes. For this reason it seems worth pursuing this simpler case further theoretically, and investigating the effect of a time dependent density input at the top. A comparison with the experimental results, which do include the effects of dissipation, may allow us to assess the influence of these on the phenomena we set out to study.

(b) *Multiple interfaces and varying heat inputs*

An extension of the potential energy argument can be used to explain the time dependent behaviour of a system driven by surface stirring, both in the case of the discrete interfaces present in our laboratory experiment or (in paper II) a continuously changing input. Consider first the discrete case. We have seen from (3) that when there is no dissipation of energy the velocity of advance of the interface separating the stirred fluid from that below it is proportional to $C^{-1} = (gh\Delta\varrho)^{-1}$. When a small amount of buoyant fluid is added at the top and stirred for a given time, the interface will descend a relatively large distance. When a second, larger volume of buoyant fluid is added, a new stable interface is formed which descends more slowly, so that in the same time interval it will never overtake the first (as we observed in the experiments). Thus during periods corresponding to *increasing* heating rates the temperature of the well-mixed layer is increasing while its thickness is decreasing, and the structure of the thermocline is established and left behind (see Fig. 5*a*).

Whenever the rate of heating is being reduced, however, or when there is cooling at the surface, we have the different situation illustrated by the later stages of 5*a* and by 5*b*. Then the mixing in successive intervals of time tends to cause penetration to greater and greater depths, and some of the previously laid down structure will be eroded away. A sharp step in density between the well-mixed layer and the water below it will be characteristic of this phase, for the continuous as well as the discrete heat inputs. A general theory of both stages of this process is given in paper II but it is instructive to carry through in detail here a simpler argument for the case which corresponds as closely as possible to the conditions of our laboratory experiment, with the sawtooth heating function and constant stirring.

The calculations for the "rising" phase are very simple, since each interface is independent of the ones before it, and after a fixed time interval is at a depth proportional to C^{-1}. This is shown in Fig. 6*a*, where the scale is arbitrary but of course the same for each step. The successive additional areas are just proportional to the added buoyancy or to C. In this way we build up the density structures labeled 1–5, corresponding to the ends of the corresponding time intervals marked on the saw-tooth heating function in Fig. 7.

The curves labeled 6, 7, 8 in Fig. 6*a* are those corresponding to calculations during the period when "heating" is being continued but at a *decreasing* rate. In this case the velocity of the top interface is greater than that in the preceding interval, so that during the fixed time interval it will overtake one (or perhaps several) of the previously formed interfaces. Each time this happens we must recalculate C and the velocity of advance, since the stability of the top layer relative to the fluid immediately below it will be changed. The same total time will again be available, but this will be split up into several intervals during which the velocity is different. The final density of the top layer may again be calculated by using the known total buoyancy input during the period. During this period the "temperature" of the surface is increasing further, while the well-mixed layer is deepening slightly.

Finally, when cooling (or the addition of heavy fluid) is begun, we get the behaviour shown in Fig. 6*b*. To obtain these curves we assumed that the added heavy fluid is first well mixed by convection through the upper layer in a time short compared with the period of mechanical stirring, and that during this process there is no net change in potential energy. This implies that there must also be some mixing of fluid from below, and that the buoyancy and depth of the upper layer are changed effectively instantaneously. The interface then descends due to mechanical stirring, at a rate determined by the net density difference (which is always stable), allowing for the sudden changes in this as earlier interfaces are eroded. During this final period the "temperature" of the upper mixed layer is decreasing, and its depth increasing rapidly, until finally the density contrasts disappear completely. The behaviour of the calculated surface density and the mixed layer depth as functions of time are shown in Fig. 7. Notice that the surface layer is typically deeper (for the same temperature) during the cooling season than when it is being heated: this and many other features are to be found in the observations shown in Fig. 2.

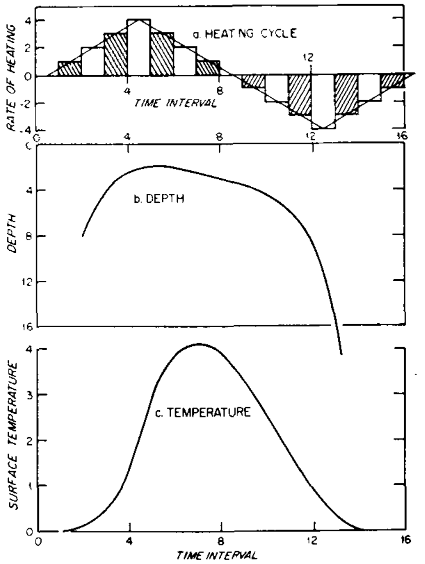

FIG. 7. Theoretical calculation of time-dependent surface layer behaviour, with constant sitrring and an intermittent heat input. (*a*) The assumed sawtooth heating function, and its approximation by steps. (*b*) Depth of the well-mixed surface layer at the end of each stirring interval. (*c*) The surface temperature at the end of each interval.

The deduced behaviour is not critically dependent on the assumptions made. Similar results are obtained if other forms are adopted for the dependence of mixing rate on stability: for example, if it is supposed that the entrainment velocity is some function $f(\mathrm{Ri})$ of the Richardson number, and we take a form like $f(\mathrm{Ri}) \propto e^{-C}$ which tends to a finite value in a uniform fluid and has roughly the same shape as the function determined for stratified shear flows, then the qualitative behaviour is almost unchanged. The laboratory results, though they certainly are influenced by viscosity, show these similarities too, and a fuller discussion of the comparison between all these cases can now be given.

6. Discussion

It is clear from Figs. 2, 4 and 7, showing the variations of layer depth and surface density for similar cycles of input and extraction of heat, that the qualitative behaviour in the three cases (ocean, laboratory experiment and theory) is very similar indeed. The features of the rising interface during the heating season, followed by first a slow and then an accelerating increase of the depth after the heating has reached its maximum, appear in all of them. The more nearly symmetrical rise and fall of surface temperature in spite of the asymmetrical variation in layer depth is also apparent. Moreover the same phase relations are preserved: the times of maximum heating and minimum depth occur close together, and the maximum surface density anomaly comes just before the time of zero heat input. All of them have the property that a density anomaly laid down during the heating season is preserved until later mixing from the surface incorporates them in the well-mixed layer: this is an essential difference from models which invoke turbulence due to the local shear, or a vertical mixing rate which depends on stability but is constant throughout the year.

The similarities between the curves obtained using our theoretical arguments and the laboratory and oceanic results suggest that dissipation of turbulent energy by processes other than working against gravity cannot be a dominant factor within the layer as it deepens. The theoretical argument was based completely on potential energy changes, with no dissipation, and the laboratory experiments presented here were chosen to have a set of conditions for which the velocity of entrainment was not changing rapidly with depth, i.e., also as close as possible to the predicted behaviour with no dissipation. Experiments conducted over a range of depths where the rate of advance of the interface *was* changing rapidly with depth in fact give a worse agreement with the observations in the ocean. Nevertheless, the understanding of the decay of turbulence with distance from the source of energy is an interesting problem in its own right, and further detailed laboratory work is being continued along these lines.

The most important conclusions to be drawn from these experiments are therefore qualitative in nature. There is little to be gained by trying at this stage to compare numerically the energy inputs produced by two such different mechanisms as grid stirring and wind stress. This unknown velocity scaling has not, however, entered into our qualitative comparisons of the seasonal behaviour in any critical way, since the stirring rate has been kept constant throughout. We have succeeded in demonstrating that a realistic mean thermocline behaviour can be obtained by taking into account variations of heat input alone, and that it is plausible to use a potential energy argument to calculate layer depths and surface temperatures. A comparison of numerical values with those observed in the ocean will be made in paper II after a more general theory has been presented.

Acknowledgments

This is Contribution No. 1716 of the Woods Hole Oceanographic Institution. We are grateful to Dr. Claes Rooth for many helpful discussions during the course of this work. The work was supported by the National Science Foundation with Grant GP 317, by the U.S. Army Electronics Research and Development Laboratory Project SC 90784, and by ONR Contract No. 2196.

REFERENCES

BALL, F. K., 1960, Control of inversion height by surface heating. *Q. J. R. Met. Soc.*, **86**, pp. 483–494.

CROMWELL, T., 1960, Pycnoclines created by mixing in an aquarium tank. *J. Mar. Res.*, **18**, pp. 73–82.

CROMWELL, T., and REID, J. L., 1956, A study of oceanic fronts. *Tellus*, **8**, pp. 94–101.

ELLISON, T. H., and TURNER, J. S., 1959, Entrainment in stratified flows. *J. Fluid Mech.*, **6**, pp. 423–448.

FRANCIS, J. R. D., and STOMMEL, H., 1953, How much does a gale mix the surface layers of the ocean? *Q. J. R. Met. Soc.*, **79**, pp. 534–536.

KITAIGORODSKY, S. A., 1960, On the computation of the thickness of the wind-mixing layer in the ocean. *Bull. Acad. Sci. USSR, Geophys. Ser.*, **3**, pp. 284–287.

KRAUS, E. B., and ROOTH, C., 1961, Temperature and steady state vertical heat flux in the ocean surface layers. *Tellus*, **13**, pp. 231–238.

Kraus, E. B., and Turner, J. S., 1966, A one-dimensional model of the seasonal thermocline. II. The general theory. *Tellus*.

Munk, W. H., and Anderson, E. R., 1948, Notes on a theory of the thermocline. *J. Mar. Res.*, 7, pp. 276–295.

Phillips, O. M., 1966, The dynamics of the Upper Ocean. Cambridge University Press.

Robinson, A. R., and Stommel, H., 1959, The oceanic thermocline and the associated thermohaline circulation. *Tellus*, 11, pp. 295–308.

Robinson, A. R., and Welander, P., 1963, Thermal circulation on a rotating sphere; with application to the oceanic thermocline. *J. Mar. Res.*, 21, pp. 25–38.

Rouse, H., and Dodu, J., 1955: Turbulent diffusion across a density discontinuity. *La Houille Blanche*, 10, No. 4, pp. 522–532.

Stommel, H., and Woodcock, A. H., 1951, Diurnal heating of the surface of the Gulf of Mexico. *Trans. Am. Geophys. Union*, 32, pp. 565–571.

Tabata, S., and Giovando, L. F., 1963, The seasonal thermocline at Ocean Weather Station "P" during 1956 through 1959. Fish. Res. Bd. of Canada, Manuscript Rep. Series No. 157.

Tabata, S., Boston, N. E. J., and Boyce, F. M., 1965, The relation between wind speed and summer isothermal surface layer of water at Ocean Station P. *J. Geophys. Res.* 70, pp. 3867–3878.

Tully, J. P., 1964, Oceanographic regions and processes in the seasonal zone of the North Pacific Ocean. *Studies on Oceanography*, ed. K. Yoshida, University of Washington Press.

Welander, P., 1959, An advective model of the ocean thermocline. *Tellus*, 11, pp. 309–318.

ОДНОМЕРНАЯ МОДЕЛЬ «СЕЗОННОЙ ТЕРМОКЛИНЫ»

I. *Лабораторные экспернненмы и их интерпретация*

Теоретически и эксперементально (лабораторные эксперементы) рассматривается простая модель верхнего слоя океана (сезонная термоклина). Обосновывается что тепло и механическая энергия, действующая на вертикальный столб жидкости, могут прилагаться около поверхности и распространяться вниз без существенного влияния на них горизонтальной скорости, адвекции или вращения. Если приток тепла задан, то можно вычислить температуру и глубину хорошо перемешенного поверхностного слоя, при условии, что вся кинетическая энергия перемешивания переходит в потенциальную энергию системы. Это было подробно сделано для постоянного коэффициента перемешивания и пикообразной функции сезонного нагрева. Теоретически и эксперементально процесс нагревания был моделирован шаг за шагом с помощью прерывистого притока тепла от плавающей на поверхности жидкости. Многие свойства наблюдаемые в океане воспроизводились в эксперементах и теоретически. Хорошо качественно согласуются между собой глубина верхнего перемешенного слоя, зависимость его температуры от времени и отношение между циклами нагревания и охлождения. Наиболее важно, что рассматриваемая модель описывает тот факт, что поверхностное перемешивание влияет только на свойства жидкости до главной поверхности раздела (разрыва) плотности. Поэтому более глубокие слои могут сохранять характеристики, установившиеся раньше во время теплого сезона, до тех пор пока слой с хорошим перемешиванием не достигнет их опять зимой.