J. Fluid Mech. (1968), *vol.* 34, *part* 3, *pp.* 443–448
Printed in Great Britain

Some observations of the occurrence of turbulence in and above the thermocline

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(Received 9 September 1967 and in revised form 28 June 1968)

A hot film flowmeter, a thin film resistance thermometer and several thermistors were mounted on a submarine and used to study turbulence and temperature microstructure in the open sea. The surface layer is found to be continuously turbulent and patches of turbulence have been found in and below the main ocean thermocline.

Introduction

The purpose of this paper is to describe some observations of small-scale velocity and temperature fluctuations in the upper layers of the ocean. The results are largely qualitative and the measurements were made in only one location at one time of the year so they are not adequate to provide the basis for a detailed heat and momentum transport model. They do, however, indicate the complexity of the mixing structure which may have to be taken into account in such a model.

Instrumentation

The instrumentation was mounted on a submarine which is a sufficiently steady platform for measurements of velocity fluctuations in the open sea. The arrangement is shown in figure 1. The hot film flowmeter had characteristics similar to the one described by Grant, Stewart & Moilliet (1962), but it was a more highly developed instrument using an a.c. feedback loop. The thin film resistance thermometer is described in Grant *et al.* (1968). The thermistors were very small glass-covered beads with a time constant of about 0·02 sec but they were connected to d.c. amplifiers which did not pass signals above about 1 Hz. The amplifier used with thermistor T_1 was particularly slow.

Observations

The observations to be described were made in November 1962 about 40 miles off the west coast of Vancouver Island, over the continental slope where the water depth was about 1000 m. The temperature, salinity and density structure is shown in figure 2.

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Figure 3 is a short sample of the record made at a depth of 90 m, which is deep in the thermocline. The record represents a total time of about 10 min during which the submarine travelled 600 m through the water.

The top trace is the velocity derived from the hot film flowmeter. There was a heavy swell running overhead with a wavelength of about 200 m. The instrument was half a wavelength down but still the wave motion provided by far the largest velocity fluctuation. The submarine was attempting to steer a course parallel

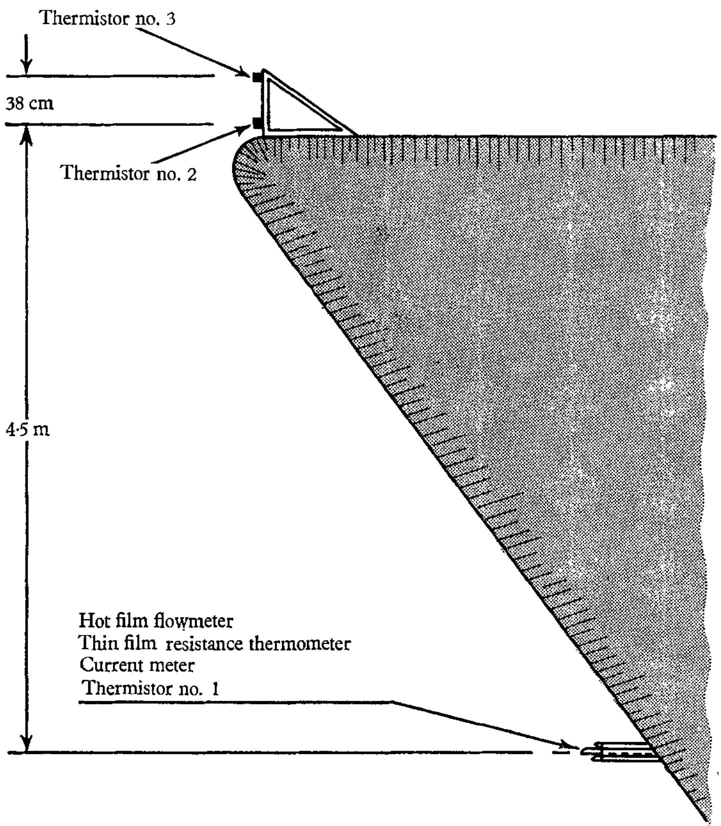

FIGURE 1. Arrangements of the instruments on the bow of the submarine.

to the wave crests, otherwise the amplitude of the wave signal would have been two or three times larger since the system is designed to see only the component of velocity in the direction in which the submarine is travelling. Fortunately the large waves occupy only a narrow frequency band and we can easily filter them out electrically.

The next trace shows the time derivative of the velocity trace and we assume Taylor's hypothesis in writing it as dV/dx. The differentiation emphasizes the high frequencies and in addition we have passed the signal through a high-pass filter with a cut-off at 10 Hz. This eliminates the wave signal and some vibrations in the probe mounting. The response of the paper recorder falls off rapidly at frequencies around 100 Hz so, in effect, activity on this trace indicates velocity structure with characteristic scales between 1 and 10 cm. This trace thus serves as an indication of the presence of turbulence and its amplitude can be shown to be an approximate measure of the rate of dissipation of kinetic energy. The most striking conclusions from this record are that there is turbulence in the thermocline and that it is in patches. On the left of this record is a very small region of turbulence followed by one which is almost continuously turbulent for 170 m. The next 170 m contain no turbulence above the noise level of the electronics and then we have 30 m of turbulence. This is typical of what we have found at this depth.

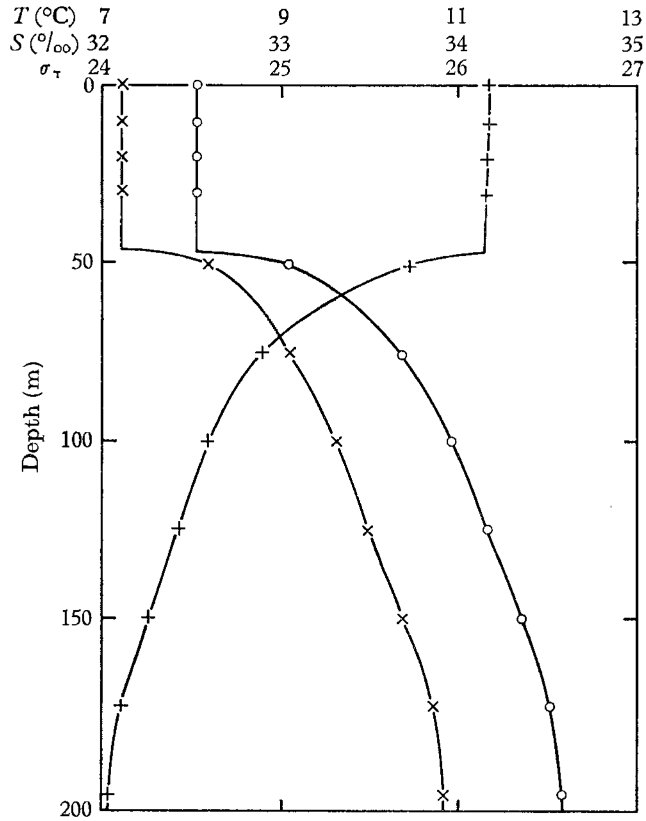

FIGURE 2. Typical variation of water properties with depth, November 1962. +, temperature; ×, salinity, in parts per thousand by weight; ⊙, density anomaly; $\sigma_T = 1000$ (density − 1) where density is in g/cm³ and is measured at atmospheric pressure.

The fourth record, labelled *T*, is the temperature derived from the thin film resistance thermometer. The maximum excursion of the trace is about 1·1 °C. The signal has been treated with a high-pass filter with a time constant of about 100 sec so that the record stays on scale without frequent zero adjustments. The signal dT/dx has been derived in the same way as dV/dx and it shows the small-scale components of the temperature structure. It will be noted that temperature microstructure exists only when turbulence is present. When the turbulence disappears, conduction effects erase the small-scale temperature structure.

The remaining records are signals from the three thermistors. The record labelled T_1 is obtained from a thermistor located 8 cm from the thin film resistance thermometer and at the same depth. It will be seen that the two records are almost identical except for the lack of high-frequency response and the lack of a long time-constant, high-pass filter in T_1. T_2 is 4·5 m above T_1 and very large differences are found between the two. There are several places where a feature, 30 m or more in length, shows on only one thermistor. T_3 is 40 cm above T_2 and even here the records are far from identical. Near the middle of the T_2 trace there is a cold spot with horizontal extent of nearly 40 m which does not appear 40 cm higher.

The trace $T_1 - T_2$ is the difference in temperature between two points with vertical separation of 4·5 m. The small horizontal line at the left end of the trace indicates the zero point and full-scale deflexion downward is approximately 0·1 °C. It will be noted that there is a mean difference over the length of the record, but that the fluctuations in the difference are of the same order as the difference itself. Sometimes the difference even appears to become negative, i.e. the bottom thermistor appears to be hotter than the top one. This observation need not be taken very seriously because we are not certain that there was no drift in the zero of the instrument. Even if the temperature gradient is inverted it does not necessarily indicate an unstable situation because we have no way of observing salinity at these small scales.

It will be seen in figure 3, plate 1, that there is a tendency for $T_1 - T_2$ to have low values when the lower thermistor is in a patch of turbulence. This has been confirmed by examination of a 2 h record made at this depth. When the bottom instrument is in a turbulent patch the average value of $T_1 - T_2$ is about 20 % of the average when the lower instrument is in quiet water.

Figure 4, plate 2, is a similar record made at a depth of approximately 15 m, which is well above the thermocline. There was a 40-knot wind and the height of the sea was about 4 m. Being much closer to the surface, the velocity trace shows smaller waves as well as the big swell. The recording gain is only one-fifth of that used in the deep record. It is almost continuously turbulent and the gain of dV/dx is one-half of that used in the deep record. All of the temperature gains are unchanged. dT/dx shows nearly continuous small-scale structure but the amplitude is generally smaller than in the bursts of microstructure at 90 m. All of the other temperature traces show fluctuations of smaller amplitude and there is much better correlation between the records from the vertically spaced thermistors, indicating a more isotropic structure.

Discussion

Our main purpose is to illustrate the complexity of the temperature structure in the thermocline. It is layered, but not completely so, and much more complicated than the bathythermograph would suggest. In some spots there is quite vigorous turbulent mixing. Runs were made with the submarine at several depths down to 90 m and the crosses on figure 5 indicate the proportion of the run during which turbulence was present. In November 1963 we made observations of temperature microstructure with equipment towed below a surface ship. No velocity observations were made but, taking small-scale temperature fluctuations as an indication of turbulence, the results are shown as dots on figure 5. The density structure was about the same in the two cases but the wind was approximately 20 knots in 1963. We do not know the reason for the increasing occurrence of turbulence in the neighbourhood of 300 m.

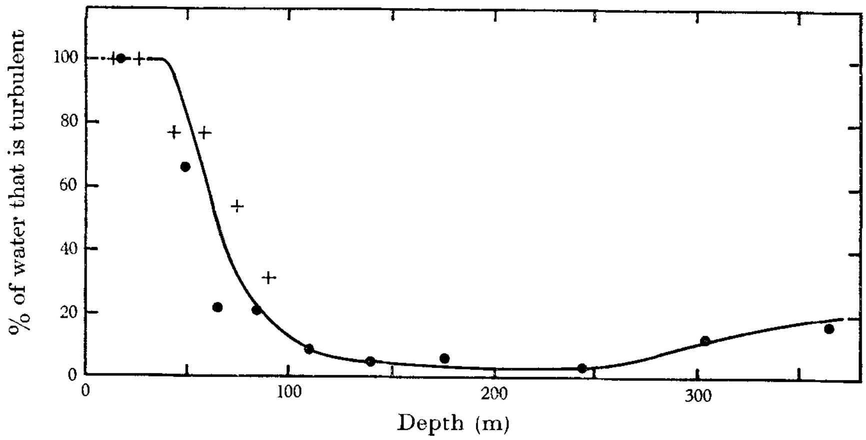

FIGURE 5. Distribution of turbulence in the water.

Typical rates of dissipation of energy (ϵ) within the turbulent patches under the prevailing conditions are given in table 1 as a function of depth. Dissipation rates are found from the energy spectrum of the turbulence by the methods described by Stewart & Grant (1962). Also shown are average values of ϵ obtained by multiplying the dissipation rate in the patches by the percentage of the area which is turbulent at this depth. 't' is the length of sample from which each spectrum was computed.

Depth (m)	t (sec)	ϵ (cm^2 sec^{-3})	Average ϵ (cm^2 sec^{-3})	χ (°C^2 sec^{-1})
15	468	$2 \cdot 5 \times 10^{-2}$	$2 \cdot 5 \times 10^{-2}$	$5 \cdot 6 \times 10^{-7}$
27	508	$5 \cdot 2 \times 10^{-3}$	$5 \cdot 2 \times 10^{-3}$	$5 \cdot 7 \times 10^{-7}$
43	150	$3 \cdot 0 \times 10^{-3}$	$2 \cdot 3 \times 10^{-3}$	$6 \cdot 7 \times 10^{-6}$
58	270	$4 \cdot 8 \times 10^{-3}$	$3 \cdot 7 \times 10^{-3}$	$4 \cdot 3 \times 10^{-6}$
73	184	$1 \cdot 9 \times 10^{-3}$	$1 \cdot 0 \times 10^{-3}$	$9 \cdot 6 \times 10^{-7}$
89	246	$1 \cdot 1 \times 10^{-3}$	$3 \cdot 4 \times 10^{-4}$	$1 \cdot 6 \times 10^{-7}$
90	190	$1 \cdot 0 \times 10^{-3}$	$3 \cdot 1 \times 10^{-4}$	$1 \cdot 3 \times 10^{-7}$
90	294	$4 \cdot 8 \times 10^{-4}$	$1 \cdot 5 \times 10^{-4}$	$7 \cdot 2 \times 10^{-8}$

TABLE 1

It would be very risky to attempt to determine the energy dissipation per unit surface area by integrating the average dissipation over all depths because of the very uncertain extrapolation that would have to be made at both the top and bottom of the observed range. In particular, we would not dare to guess the dissipation rate in the top few metres of the water where it could be extremely high. We can integrate from 15 to 90 m, and in this layer we find a dissipation of 3×10^{-2} watts/m^2. A crude estimate of the energy lost by the wind is 5 watts/m^2, so this is a likely source of the turbulent energy, but there could be a contribution associated with gradients in the mean current or the tidal current.

The final column in table 1 gives values of the rate of dissipation of temperature structure, χ. Most of these figures are taken from Grant *et al.* (1968) where the method of determining χ is described. The samples at 43 and 73 m depth were not included in that paper because the results of the temperature spectrum calculation contained internal inconsistencies which made them unsuitable for determining the constants of the temperature spectrum. They do contain sections which are proportional to $k^{-\frac{5}{3}}$ and therefore can be used to determine a value of χ with the constants given by Grant *et al.* (1968).

This limited group of samples suggests that χ varies much less with depth than ϵ and that the maximum may occur near the top of the thermocline.

The authors are pleased to record their indebtedness to the Commanding Officer, Officers and men of H.M.C.S. *Grilse*, who have helped them greatly in the work at sea.

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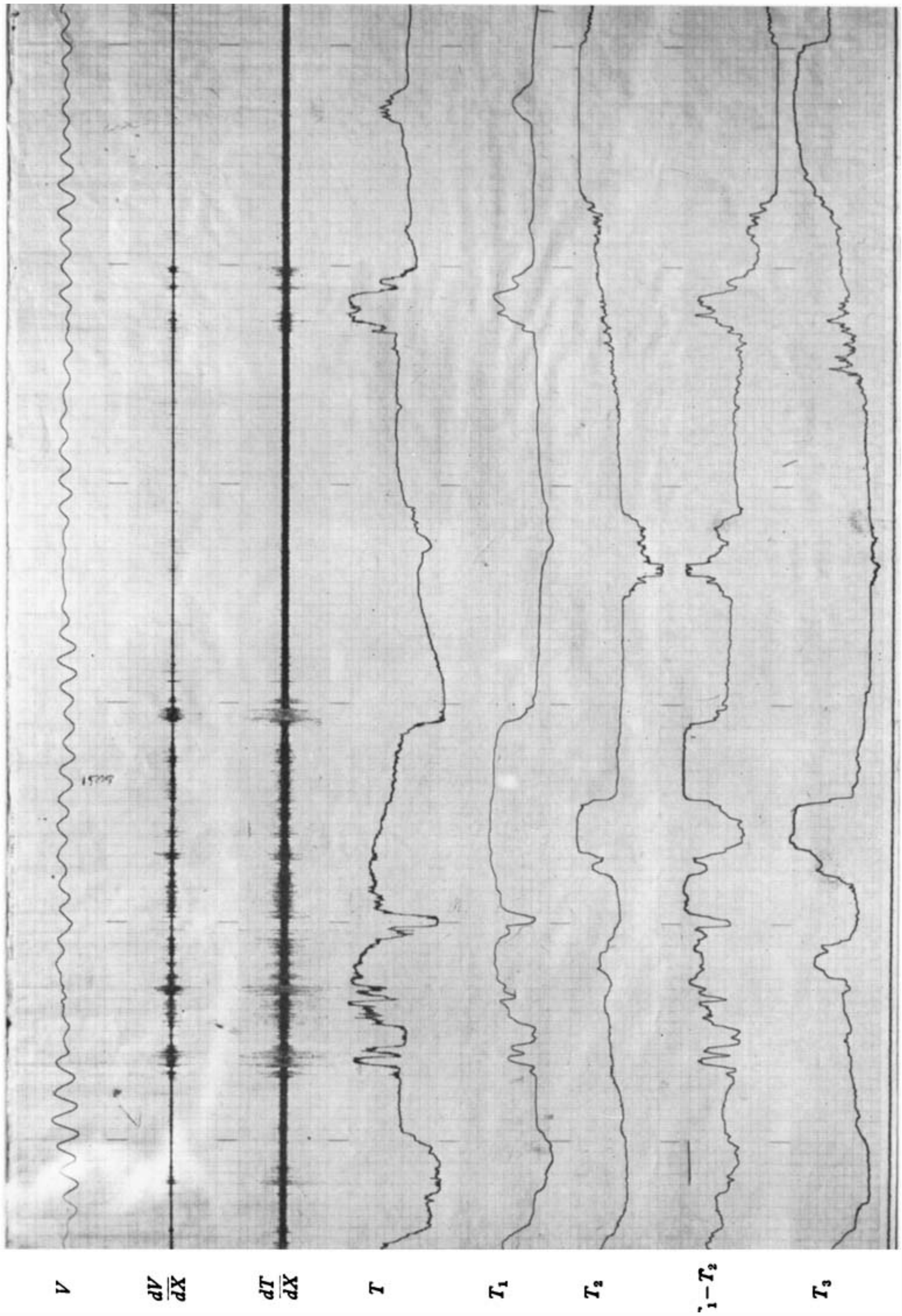

FIGURE 3. Velocity and temperature records from 15 m depth.

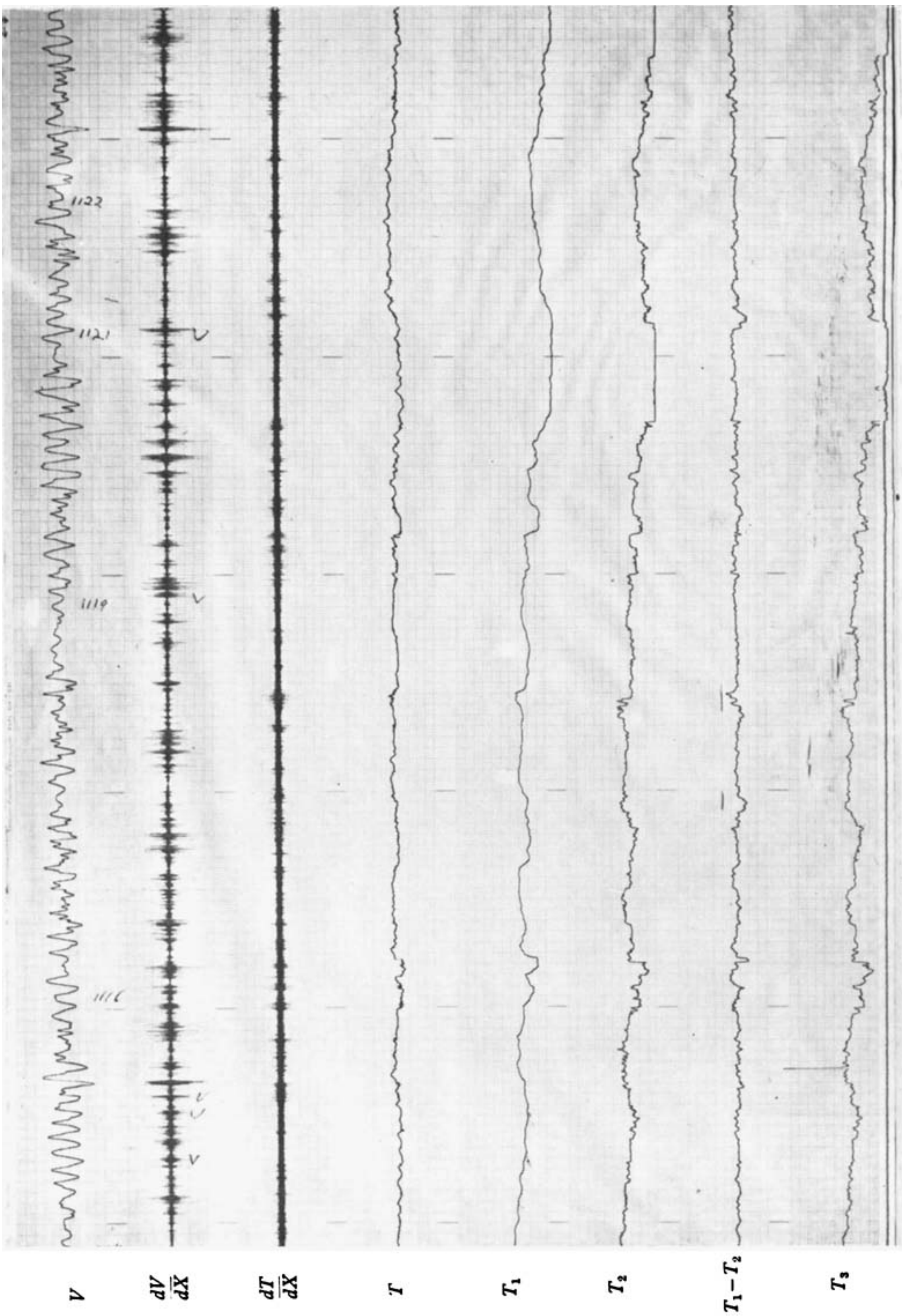

FIGURE 4. Velocity and temperature records from 90 m depth.