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# Observations of the thermal structure of a lake using a submarine

*Abstract*—This note describes how a submarine, the *F.A. Forel,* carrying a vertical array of high-resolution temperature sensors, was used along with conventional measurements from a lowered conductivity-temperature-depth probe (CTD) to make novel measurements of the temperature field in Lake Geneva during summertime conditions of stable stratification and during winter convection. The submarine speed was about 0.5 m $s^{-1}$. In addition to the temperatures, the pressure, orientation, and tilt were recorded at frequencies of at least 10 Hz. Observations were made on a vertical scale of 0.1 to 2.5 m and on a horizontal scale from 0.5 m to 1 km. Examples of the data are presented. During the summer, evidence was found of internal waves and of extensive layers of low vertical temperature gradient, with vertical and horizontal scales of 0.5 m and 0.5 km, respectively; within this gradient, the temperature changed monotonically in the horizontal. During periods favoring convection, in the winter, when air temperatures were about 7°C below the surface-water temperature, convectively unstable regions, typically of 5-m horizontal scale, were observed in the mixed layer. These appeared to be convective plumes. These winter measurements also included observations of a layer of cold water that was adjacent to the sloping boundary of the lake. This was identified as being a plume of dense cold water with thickness on the order of 10 m, which was driven by surface cooling, and consequent more rapid temperature decrease, in the shallow nearshore water. On meeting the thermocline at a depth of about 100 m, this plume spread horizontally and formed an intrusion some 30 m thick.

A few accounts describing the use of submarines in making physical measurements in the ocean have been published. These include that of Osborn and Lueck (1985), who made measurements of turbulence in the ocean from the *USS Dolphin* submarine, that of Osborn et al. (1992), who also made acoustic measurements of subsurface bubble clouds from the *USS Dolphin,* that of Gargett (1982), who measured turbulence from a Pisces submersible, and those of Wadhams (1978) and Wadhams et al. (1979), who made measurements from a submarine under ice. There are, so far as we know, no accounts of comparable observations made from manned submarines in lakes.

Here we describe measurements of the thermal structure of the upper layers of Lake Geneva made from a small submarine, *F.A. Forel*; these measurements illustrate the value of submarine observations in lakes. The objective of these submarine dives was to investigate fine-scale spatial distribution and variability of the temperature structure in the lake. During summer, measurements were made in the thermocline over the sloping sides of the lake as part of an investigation into the effect of internal waves in boundary mixing. During winter, we observed the structure of cold convective plumes that form in the near-surface layer and those that descend the sloping boundaries as gravity currents as a consequence of cooling in shallow water around the lake boundaries. Observations were made at 0.1 to 2.5 m on a vertical scale and at 0.05 m to 1.0 km on horizontal scales, these being the observations most readily made from the submarine. While the submarine does not provide a unique method of measuring the temperature structure described here, it is a fairly stable platform to use to make measurements that would be more difficult to make from the surface (e.g., by towed arrays). In addition, the submarine provides direct observations of the motions made visible by suspended sediment or passive organisms, and it is a useful facility to use to examine bottom-mounted or moored instruments in situ in order to ensure that they are properly and freely deployed.

*The lake, the submarine, and the sensors*—The observations described here were made in the vicinity of Ouchy (46°32′N, 6°13′E), on the northern shore of Lake Geneva, where the shoreline lies in a 110° direction. The lake here is about 15 km wide and, after a region some 100 m wide close to the shore (where the depth increases gradually to about 4 m), the sides slope down at some 10° to a maximum lake depth of 309 m (see Fig. 4a later). Depths of 100 m are reached at about 0.7 km from shore. The slopes are composed of soft, fine sediment and are irregular—incised by channels a few meters in depth that run mainly downslope—and are sometimes observed to have steep (>30°) sides.

The *F.A. Forel*, sketched in Fig. 1, is 2.2 m wide and 7.55 m in overall length and is 2.25 m high from the skids to the top of the bars protecting the upward-looking observation window. It has a displacement of 11 tonnes. It can accommodate three people, including the pilot. There is a second observation window in the bow that faces downward and forward. Visibility in the lake is typically about 2–3 m. The submarine carries exterior lights, TV, a mechanical arm for sampling, a pressure gauge, and a recording echosounder. There are 100 connections through the hull that are made up to suit users. Power is available at 24 v, and the normal electrical capacity available for scientific use is 24 Ahr. The submarine is connected by an underwater radio link to a 12-m mother vessel, *Black Prince,* which carries a global positioning system (GPS). The submarine tracks over the ground are recovered and plotted after dives, giving the submarine's horizontal position to within about 2 m and its speed over the ground, typically 0.5 ± 0.05 $m^{-1}$, to within 0.5 cm $s^{-1}$. It has a normal operational capacity of 8 h and can work to a depth of 500 m, although our observations were limited to the upper 90 m of the lake. Navigation just above the bottom, following isobaths along the sloping boundaries of the lake, is difficult because of the channels and poor visibility, and in this mode of operation, the submarine is prone to make occasional contact with the soft sediment, which is a hazard to sensors carried ahead of the submarine. The majority of our studies near the bottom were therefore restricted to measurements obtained during runs at constant depth, when we were either approaching or reced-

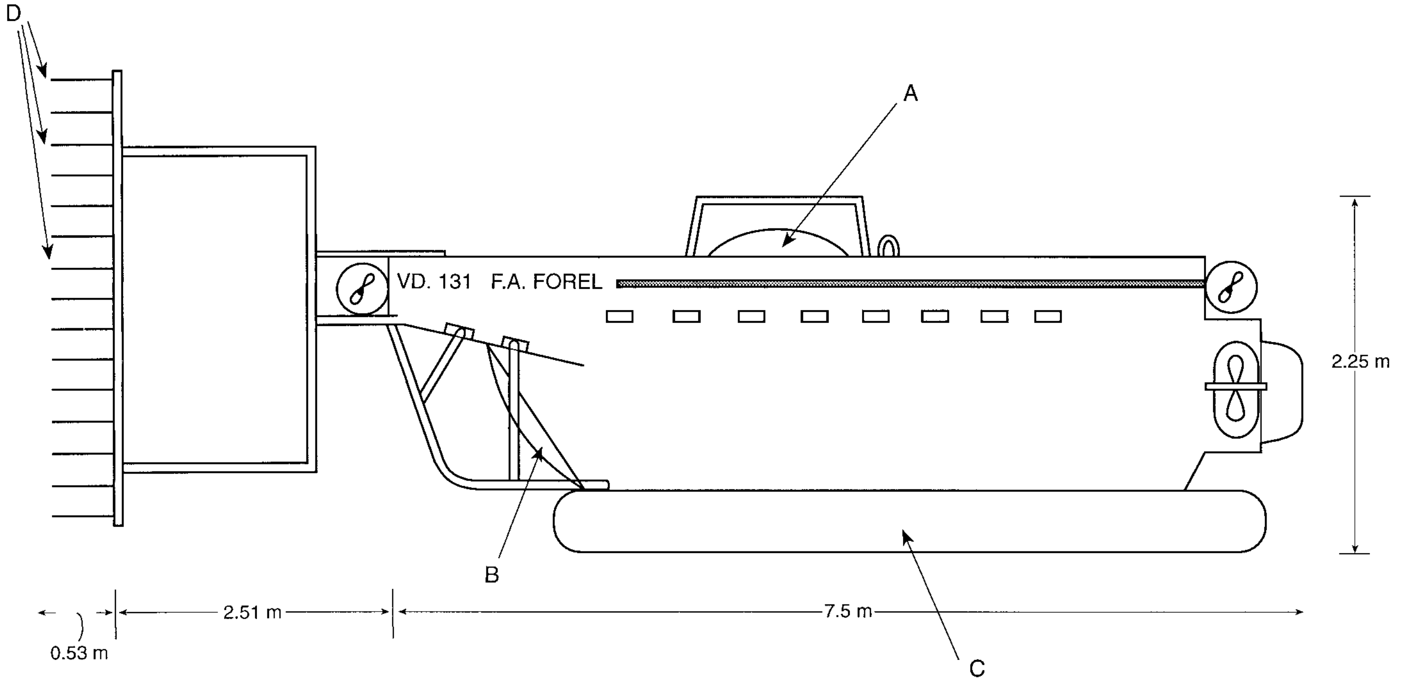


Fig. 1. Sketch, not to scale, of the submarine *F.A. Forel,* showing overall dimensions and the mounting used to support the temperature sensors ahead of the main body of the submarine. (A) Upper observation window. The window forms a hatch, providing for entry into the submarine; (B) forward observation window; (C) skids; and (D) temperature sensors.

ing from the slopes. Preliminary trials of the submarine in the thermocline and at 6-m depth in 8 m $s^{-1}$ winds in 1993 showed that the submarine can maintain constant depth to ±1 m, with typical standard deviation of 0.5 m. The present trials gave similar values, both in a winter convective mixed layer and in the summer thermocline. The preliminary trials found that pressure and pitch had broad spectral peaks, both of which were centered at about 30 s, which were ascribed to the pilot's adjustments to hold constant depth. Roll oscillations of the submarine are typically ±2°, with periodicity of 6–10 s and a spectral peak at 9 s, which was ascribed to a natural oscillation period of the submarine. The rms variations in heading (yaw) were under pilot control and were typically 5°. Root mean square sensor motions relative to the water induced by these angular oscillations were typically about 1 cm $s^{-1}$.

For the work described here, the submarine was equipped with a vertical array of 11 high-precision temperature sensors, which were supplied by Precision Measurement Engineering and which spanned a maximum vertical range of 2.5 m. The sensors had a time response of 0.02 s and were sampled sequentially and recorded to $1 \times 10^{-3}$ °C resolution at frequencies of 10 or 30 Hz. Pressure (to 0.1 m resolution) and two tilt and compass angles (to 1° resolution) were sampled at the same frequency. All data were recorded on a personal computer within the submarine that displayed data in real time. The temperature sensors were mounted on rods that protruded horizontally 0.53 m ahead of a vertical spar, which was supported on a frame and was carried 2.51 m ahead of the bow of the submarine (Fig. 1). The distance of the sensors from the bow was a compromise between two effects, that of the submarine's influence on the thermal structure ahead of it, which required a large distance, and that of the avoidance of lateral motions of the sensors (resulting from submarine oscillations such as pitch and roll), which required a small distance. The vertical cross-section of the submarine had a radius, R, of about 1.1 m, and the sensors were at a distance of 2.7R ahead of the bow. The Reynolds number based on speed (U) and R is on the order of $10^6$, and the Froude number, $Fr = (U/NR)^2$, is much greater than unity, even when the submarine is in the thermocline, where the buoyancy frequency, N, is about $2 \times 10^{-2}$ $s^{-1}$. These numbers suggested that upstream influence should be small. Further confirmation of this came from the present and preliminary trials; good general agreement is found (Figs. 2, 3) between the levels of temperature fluctuations at different vertical positions relative to the axis of the submarine. Care was taken to avoid reciprocal runs through the submarine's own wake.

The temperature sensors were calibrated in the laboratory prior to the dives. Small shifts in relative calibration, about 3 mK from the mean trend, were found, however, when the mean (typically taken over several minutes) output of individual sensors was compared with the submarine operating in well-mixed layers, and data were corrected accordingly. Submarine temperature observations were supplemented by conventional measurements from the surface using a lowered OTS 1500 CTD, built by Meerestechnik Electronic.

*Examples of the observed thermal structure: Summer*—The observations formed part of our program of research into the internal surf zone, the region where the internal

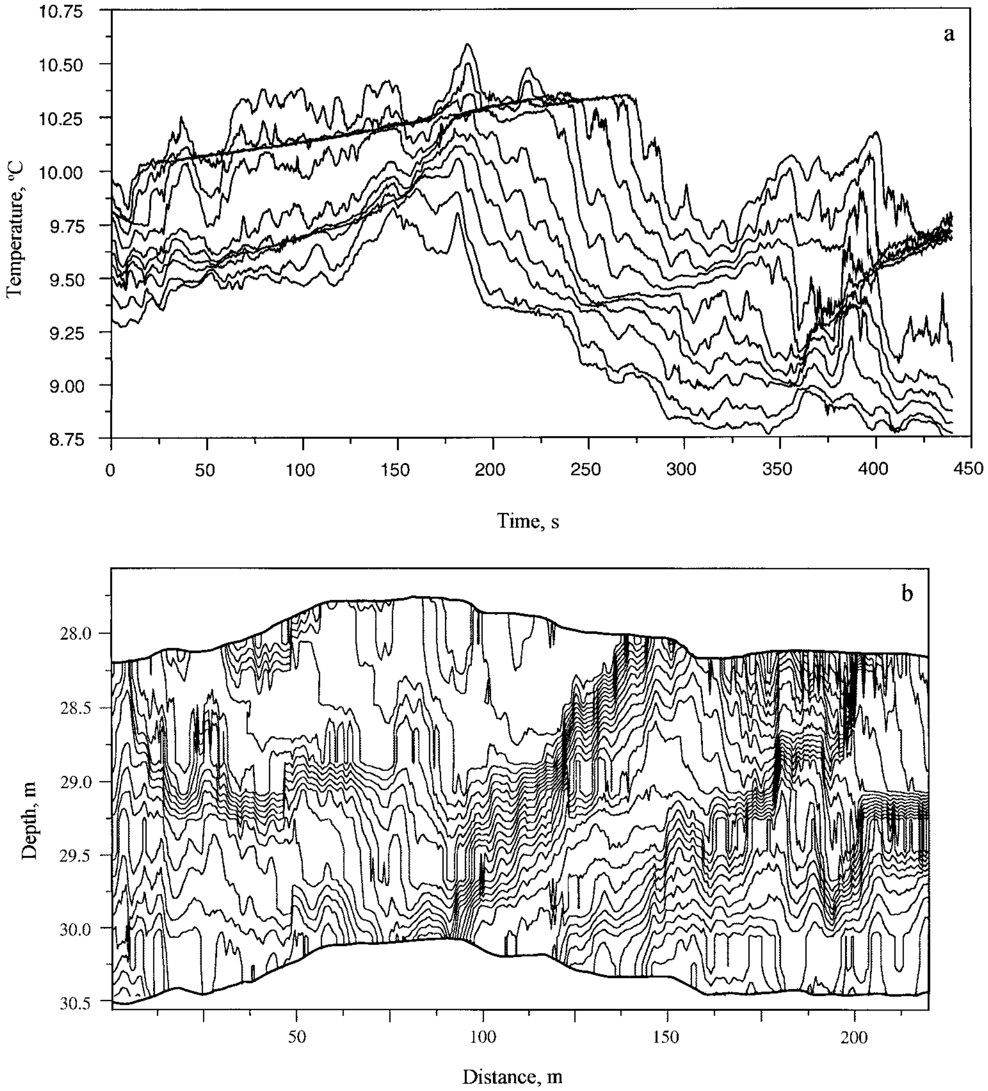


Fig. 2. (a) Temperature-versus-time plot obtained from the submarine operating in the summer thermocline, showing a periodic structure of layers in which the temperature is uniform in the vertical. The 11 sensors are at heights (above the lowest) of 0.0, 16.5, 49.5, 66.0, 82.5, 99.0, 132.0, 158.5, 181.5, 198.0, and 231.0 cm, respectively. Data, collected at 10 Hz, are smoothed with 0.5-s averages. (b) Isotherm contours, depth versus horizontal distance, derived from a. The contour interval is 0.05 °C. The heavy lines indicate the depth range sampled by the sensor array on the submarine. The contour interval is 0.05 °C.

waves in the thermocline encounter and interact with the sloping sides of the lake (Lemmin et al. 1998; Thorpe and Jiang 1998).

Figure 2a shows temperatures measured over a vertical span of 2.31 m as the submarine, at about 29 m in depth, travels well above the sloping bottom at uniform speed from water of 75 to 62 m in depth. The CTD casts showed that the mean temperature gradient at this depth was nearly uniform with buoyancy frequency $(5.2 \pm 0.5) \times 10^{-3}\ \mathrm{s}^{-1}$ below a thermocline at 5–15 m. The prominent feature in this and many of the other records in the summer thermocline was the bunching of temperatures near decreasing or, as indicated here, increasing values (e.g., the band running from 9.60°C, starting at 50 s, to 9.9°C, at 16 s). These bands mark regions in which the temperatures recorded at different sensor depths were the same but which contain horizontal temperature gradients, as shown in the isotherm contour plot (Fig. 2b). The horizontal scale was converted into distance using the mean submarine speed, and the vertical scale was depth. The heavy lines mark the depths of upper and lower limits of the water column spanned by the array of sensors. The series of layers of low temperature gradient, particularly noticeable in the latter part of the record (200 s onward), were about 0.7 to 1.0 m high and 40 m in horizontal extent. They were separated by relatively thin sheets of larger temperature gradient, where the isotherms cluster together, tilted at an angle

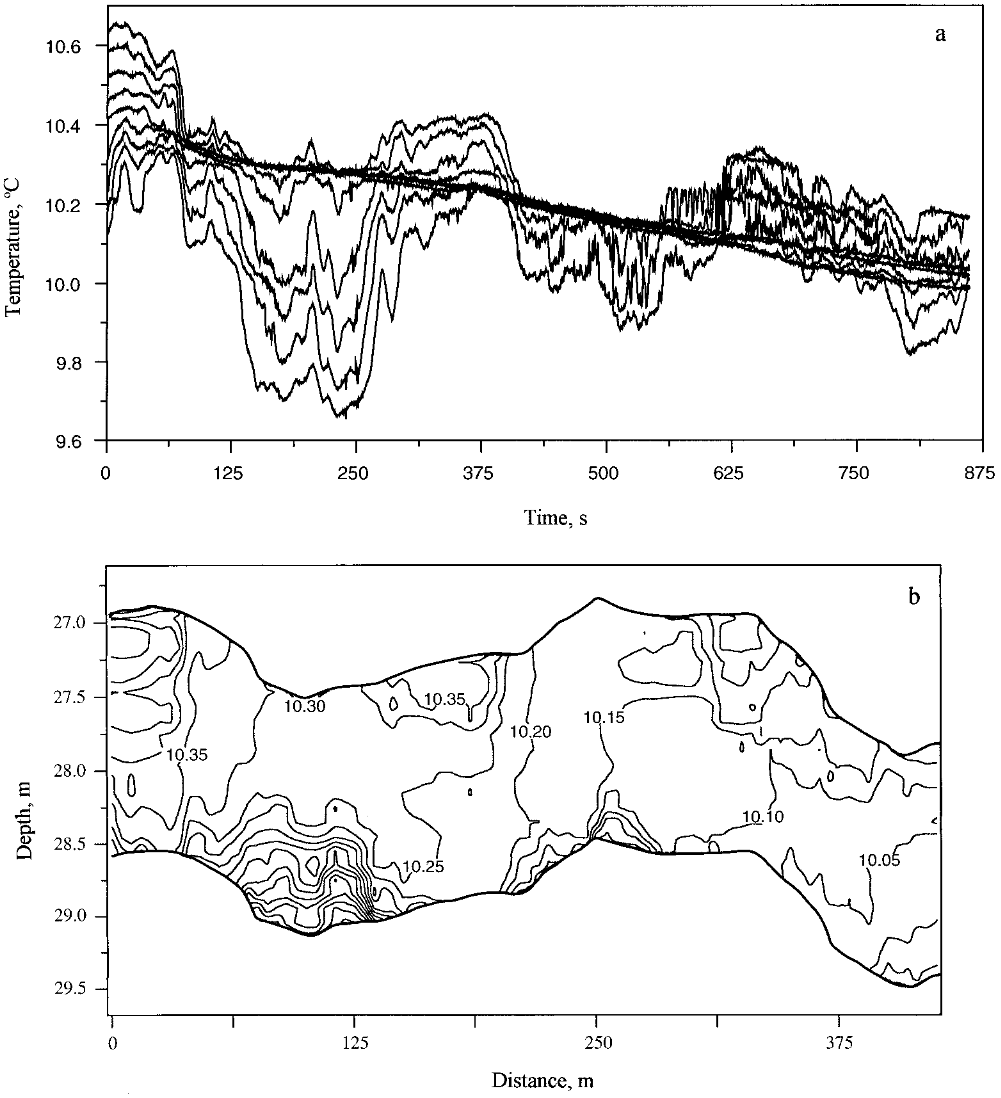


Fig. 3. (a) Temperature-versus-time plot, showing a layer of near-uniform temperature. The nine sensors are at relative heights (above the lowest) of 0.0, 16.5, 33.0, 49.5, 82.5, 99.0, 132.0, 148.5, and 181.5 cm, respectively. Data, collected at 10 Hz, are smoothed with 0.5-s averages. (b) Isotherms contours, depth versus horizontal distance, derived from a. The contour interval is 0.05 °C.

of $\tan^{-1}(0.015)$, or about 0.9° to the horizontal. The isotherms were almost vertical within the layers.

Figure 3 shows an example of a single, and more extensive, layer of this type, in which temperature decreases. This layer was 1.5 m high and 430 m in length. It appeared to be perturbed by an internal wave with a length of about 300 m and a height of 0.5 m.

*Examples of observed thermal structure: Winter*—Figure 4a shows the temperature distribution derived from CTD casts at the site on the morning of 22 January 1998. Cold water lies above the shallow regions with a depth of <20 m. The surface temperature was about 7.15°C, and the air temperature was close to 0°C. The sky was overcast, and the wind was almost directly offshore from the northeast at about 8 m $s^{-1}$. Cold water was present on the slope extending from the nearshore zone (<20 m depth) to an intrusive feature between the 7.0 and 7.1°C isotherms lying at the top of the stratified water below 100 m in depth. The intruding layer contained a bulge, perhaps a second-mode internal wave, which thickened the intrusion at a distance of 1,230 m from shore.

The temperature in the upper layer above the cold water on the slope was relatively uniform. Figure 4b shows temperatures in this layer measured by an array of six sensors that spanned 1.65 m in the vertical, with the submarine moving across wind at a speed over the ground of 0.47 m $s^{-1}$ and at a depth of about 10 m. The submarine track toward deeper water is shown by a line in Fig. 4a. The recorded temperatures from individual sensors were closely clustered, generally with variation about the mean of about $\pm 5 \times 10^{-3}$ °C, but occasionally over greater ranges, notably where the

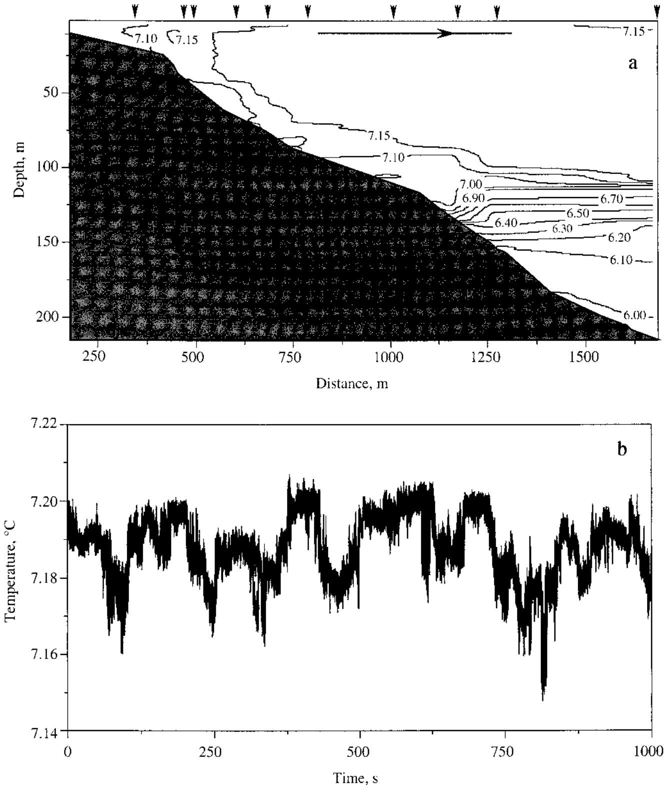


Fig. 4. (a) Isotherm contours derived from a CTD section made over the sloping side of the lake on the morning of 22 January 1998. Temperatures (in °C) are marked on isotherms. The horizontal scale is distance from shore, and the vertical scale is depth. The profile of the lake bed is derived from charts produced by the Swiss Topographical Service and, in general, agrees well with depths obtained by echosounder and GPS. The location of the CTD profiles is indicated by arrows. The figure shows cold water adjacent to the slope forming an intrusion along the top of the thermocline near 100 m in depth. The deeper water is strongly stratified, in contrast to the upper convective layer. (b) Temperatures measured by the vertical array of sensors on the submarine while it traversed the track at 10 m depth (marked by a horizontal line in part a) at a speed over the ground of 0.47 m $s^{-1}$, in a cross-wind direction and with sampling at 30 Hz.

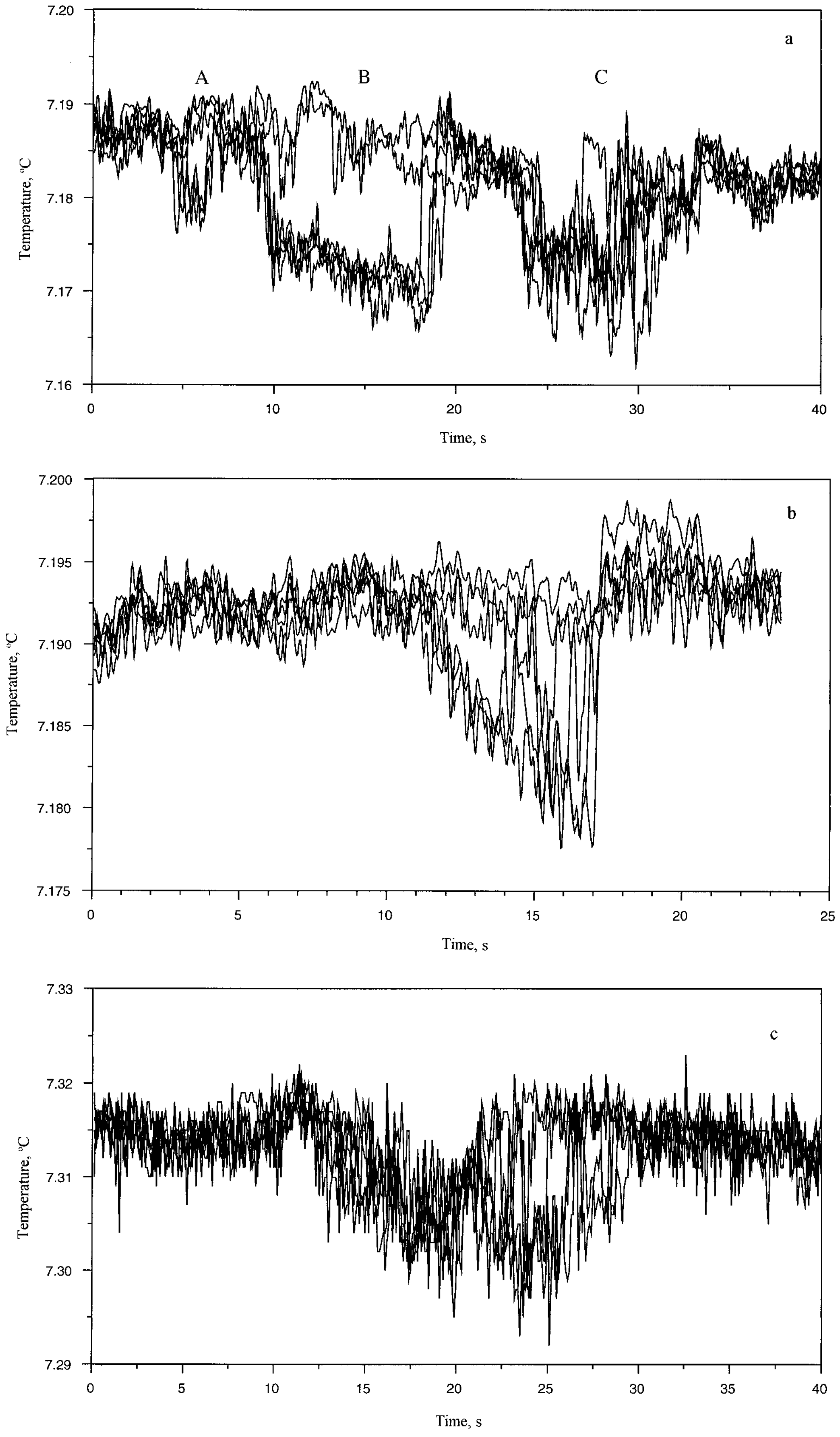
temperature falls to lower values (e.g., at about 100 and 800 s). This mean temperature varied by $2 \times 10^{-2}$ °C over horizontal scales of typically 30–60 m. Regions of anomalously low temperatures were usually found to be associated with temperature inversions—the temperature at the upper sensor fell below that of the lowest—which implied that the submarine was moving through convectively unstable water.

Three examples that typify the temperature variation in such regions are shown in Fig. 5. Figure 5a is an expanded section of the feature near 310 s in Fig. 4b. (Relative positions of the six sensors are given in the figure caption.) Three events, marked A, B, and C, in which temperatures fell below the mean trend were evident. In A, about 3.5 m long, the three upper traces (those of higher temperatures) were from the lowest sensors on the array; the upper three sensors recorded temperatures that were about $7 \times 10^{-3}$ °C lower. Event B was 5 m in length. Here, the temperatures recorded by the upper four sensors fell abruptly to about $1.3 \times 10^{-2}$ °C below those of the lower two and then decreased with time or distance along the submarine track before suddenly, and sequentially (the lower sensor first), rising back to ambient. In C, which was again about 5 m in extent, all sensors recorded lower temperatures. The structure of events A and B suggest that the submarine was crossing the lower boundary of cold convectively driven plumes, while at C, it passed directly through an established plume. Figure 5b shows a similar feature, which was measured when the submarine was traveling downwind on the same morning. There was a more gradual decrease in temperature (of about $1 \times 10^{-2}$ °C) in the upper four sensors but an abrupt but sequential (the upper sensor was the last to recover) eventual increase. The ‘‘event’’ was about 3.5 m in length. Figure 5c shows data obtained in the surface layer in calm conditions but when, as on 22 January 1998, the air temperature was close to the freezing point. This event is about 10 m in extent. In the early part of the event, temperatures at all sensors gradually and simultaneously fell about 10 mK lower than ambient. The temperatures at two lower sensors subsequently rose back to ambient before the upper sensors.

There is no significant difference between the frequency or structure of such ‘‘convective events,’’ either in windy (e.g., Fig. 5a,b) and calm conditions (e.g., Fig. 5c) or in directions acrosswind (Fig. 5a) and downwind (Fig. 5b) in windy conditions. Events with temperature differences between top and bottom sensors averaged over 1 m, with standard deviations that exceeded twice the standard deviation of the difference, occured at mean separations of about 17 m. The typical width of such features was 5 m.

Figure 6a shows the temperatures recorded by the CTD during the afternoon of 22 January 1998. These may be compared with the morning temperature distributions shown in Fig. 4a. The cold water near the slope was still present, but the temperature of the intrusion was about 0.05°C higher, again with a bulge 1,250 m from shore. Figure 6b and c indicates the temperatures measured by the submarine along the tracks toward the slope at 30 m and 85 m in depth, respectively, as marked in Fig. 6a. It shows the presence of the dense cold-water plume on the slope. The outer boundary of the plume at 30 m was marked by quite an abrupt drop in temperature. The horizontal extent of the plume here was 120 m. The water temperature fell rapidly by 0.1°C as the submarine entered the plume. Here, its height off the bottom (giving the plume thickness) was 12 m. The echosounder record on the submarine showed that before reaching the sloping bottom of the lake, the submarine crossed a low ridge and an 8-m deep channel beyond, which may account for the large plume width. The plume at 85 m was relatively narrow, about 25 m, and was marked by a rather gradual decrease in temperature.

*Discussion: Internal waves*—The temperature structure of Fig. 2b resembles that produced by internal waves. Figure 7 shows the analytical form of an internal wave with steepness, s, = 1 (where s is equal to the amplitude of isopycnal disturbances multiplied by the vertical wave number), propagating in water with constant mean buoyancy frequency, N. The wave distorts the temperature, or density field, produc-


a
A
B
C
Temperature, °C
7.20
7.19
7.18
7.17
7.16
0
10
20
30
40
Time, s
b
Temperature, °C
7.200
7.195
7.190
7.185
7.180
7.175
0
5
10
15
20
25
Time, s
c
Temperature, °C
7.33
7.32
7.31
7.30
7.29
0
5
10
15
20
25
30
35
40
Time, s

ing regions of high and low gradient. The steepness $s = 1$ is the limiting value preceding the onset of convective overturn when isopycnal surfaces become vertical (Thorpe 1994). The features shown, especially the tilted regions of enhanced and reduced vertical temperature gradients, are replicated in Fig. 2b. The wave frequency, $\sigma$, is given by $\sigma^2 = N^2\sin^2\theta + f^2\cos^2\theta$, where f is the Coriolis parameter and $\theta$ is the inclination of the lines of constant phase to the horizontal (e.g., A–A)(Gill 1982). Here, the constant phase surfaces were shown by the tilted layers of bunched isotherms, but since the horizontal direction of propagation of the internal wave relative to the submarine track was unknown, the measured tilt, 0.9°, provides only a lower bound of $\theta$ and, hence, of $\sigma$. The local mean buoyancy period measured by CTD profiles was 20 ± 3 min, giving a lower bound of the wave period of about 10 h.

These provide the first clear observations of the horizontal temperature field in internal waves in a lake and complement the observations of the vertical migration of thermal sheets (high gradients) and layers (low gradients) (produced by internal waves in the thermocline) that were found in measurements from fixed moorings by Lazier (1973) and Lazier and Sandstrom (1978). While it is possible that the long near-horizontal layer shown in Fig. 3b was an intrusive layer (Caldwell et al. 1978), it may also have been caused by internal waves. Mixed regions resulting from the propagation and breaking of groups of internal waves are nearly horizontal, provided that the square of the frequency of the waves is much less than $f^2$ (Thorpe 1988, 1999), and this feature may be a scar left by a breaking internal wave group that passed through the region. Without further time history, it is impossible to be sure.

*Convection*—The CTD sections in Figs. 3a and 4a, supplemented by the submarine sections of Fig. 6b, c, show the presence and structure of the cold plume or gravity current running down the slope. This was driven by cooling and more rapid temperature decrease (and density increase) in the shallow waters near the edge of the lake. The thickness of this plume on the slope was about 10 m, and, on reaching the thermocline, it spread into the body of the lake as an intrusion, some 30 m in thickness.

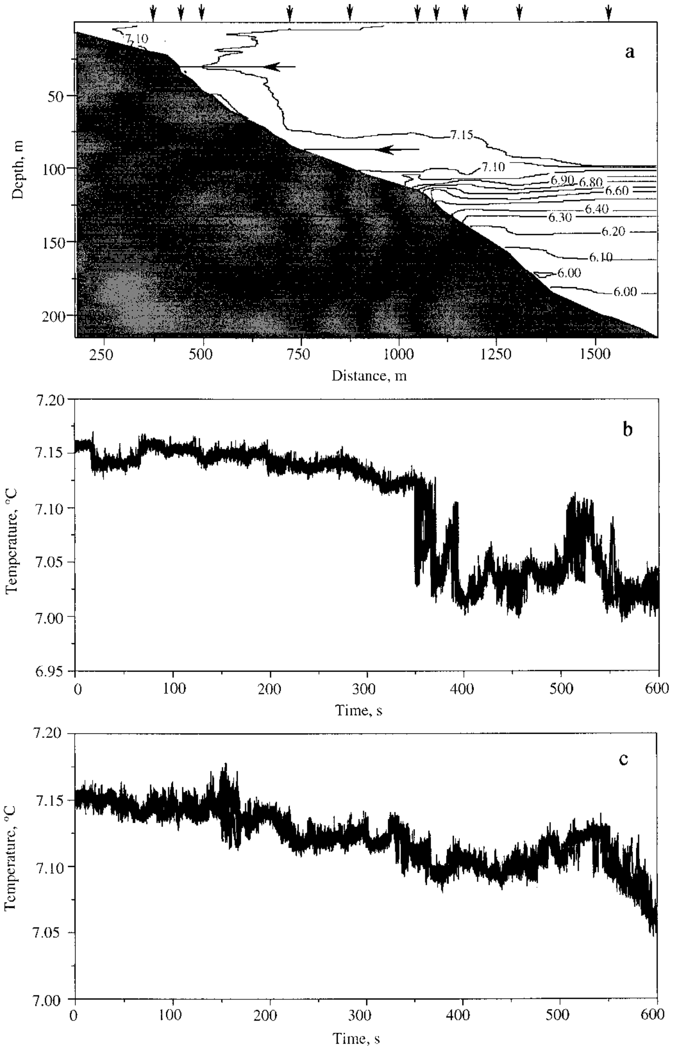


Fig. 6. (a) Isotherm contours as in Fig. 4a but as observed on the afternoon of 22 January 1998. The horizontal lines at 30 and 85 m show the submarine tracks along which the temperature-versus-time data (at 10 Hz) shown in (b) and (c), respectively, are obtained. The submarine speed relative to the ground along these tracks is 0.47 m s$^{-1}$.

Figures 4b and 5 illustrate the thermal structures found in the convective upper layer at 10 m in depth. Two horizontal scales of the structures were evident, the variations in overall temperature over 100 m (or about 200 s) in Fig. 4b and the plumes or convective events, with scales of about 5 m, shown in Fig. 5. Sections made parallel to shore suggested that the larger scales may have been filaments of colder water carried from nearshore in large 100–200-m scale eddies with vertical axes, perhaps associated with the separation of alongshore flow as it passed irregularities in the shoreline or other topographic features in shallow water. The smaller scale features appear to have been convective plumes driven by local cooling at the water surface.

The data presented here provide examples of the measurements that can be made from a submarine. All those observations reported here could probably have been made

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Fig. 5. Temperatures measured by the submarine operating at 10 m in depth in convective mixed layers. The six sensors are at relative heights of 0, 24, 96, 120, 144, and 168 cm above the lowest. Data presented are at 10 Hz. (a) Record starting at 306 s into the record shown in Fig. 4b, with expanded scale. The submarine is moving "normal" to the wind direction at 0.47 m s$^{-1}$. Events A, B, and C are described in text. (b) Record obtained with the submarine moving downwind at 0.54 m s$^{-1}$, shortly after the record a. (c) Record obtained when the wind speed was less than 1 m s$^{-1}$. The submarine is moving at speed of 0.52 m s$^{-1}$. All submarine speeds are relative to the ground.

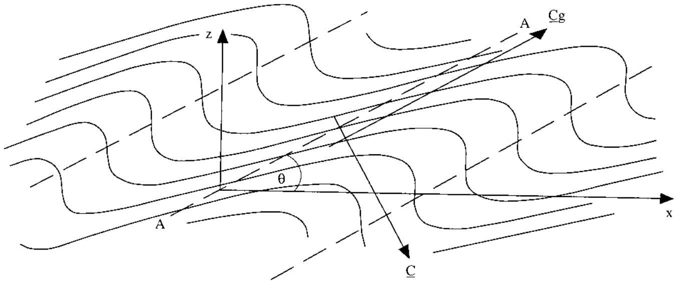

Fig. 7. Isopycnal surfaces in internal waves with slope s = 1 in a fluid with constant mean buoyancy frequency.

by other means, although perhaps with greater difficulty and with less flexibility to respond and to observe, had suitable platforms and facilities been available. In particular, the observations suggest the kinds of measurements that might be made in lakes from suitably instrumented mobile underwater platforms, such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) (e.g., Laval et al. pers. comm.), which may supplement conventional methods of sampling from the surface.

*S. A. Thorpe*

School of Ocean and Earth Science
Southampton Oceanography Centre
European Way
Southampton SO14 3ZH, United Kingdom

*U. Lemmin, C. Perrinjaquet, and I. Fer*
Laboratoire de Recherches Hydrauliques
Ecole Polytechnique Fédérale de Lausanne
CH-1015, Lausanne, Switzerland

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