Journal of the Oceanographical Society of Japan
Vol. 29, pp. 221 to 226, 1973

Observation of the Disturbances Occurring in a Discontinuity Layer of Lake Biwa-Ko*

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Abstract: Short-period temperature fluctuations were observed in the uppermost region of the seasonal thermocline in Lake Biwa-Ko, under the existence of the strong wind-stirring. In the observation period, the temperature profile had a sharp discontinuity at the bottom of the surface mixed layer, and a large gradient in the discontinuity layer of about 2-m thickness. The most dominant disturbances occurred in the discontinuity layer had the period of 2 to 3 minutes and the amplitude of about 1 m. They occurred intermittently with 5- to 15-minute intervals, and the growth and decay cycles were repeated locally. On the basis of these results, it is suggested that they were caused by the shear instability, and that such disturbances may control the erosion process of the seasonal thermocline.

1. Introduction

It is well known that, when the strong wind continues to blow, the surface mixed layer becomes to be apparently bounded from below, by the thin layer, so called discontinuity layer, in which density changes abruptly. This means that the vertical transfer of heat and momentum into the inner region of the ocean is substantially due to the entrainment of underlying water into the surface mixed layer, and resultant deepening of the discontinuity layer. The entrainment process thus seems to be essential to constructing a realistic heat and momentum transport model.

The study of the entrainment process across a density jump has been made experimentally by ROUSE and DODU (1955), TURNER (1968), KATO and PHILLIPS (1969), and others, and some empirical relations on the entrainment rate have been derived. But in spite of their efforts, our understanding of its physical process does not seem to have much increased. For example, we cannot say anything certain about the scale of turbulent eddies in the discontinuity layer, and the manner of their breaking out. The lack of the field observations seems to have prevented further detailed studies on the problem.

The purpose of this paper is to describe the result of an observation of the temperature fluctuations in the discontinuity layer, and to show the characteristics of turbulent eddies

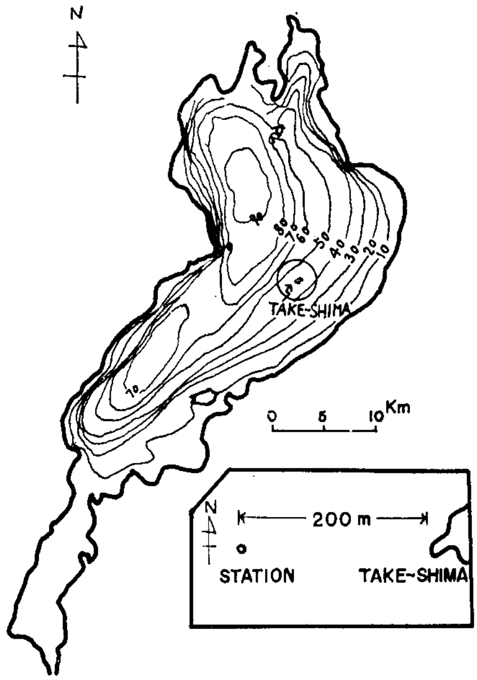

Fig. 1. Bathymetric chart of Lake Biwa-Ko. The location of the station is shown by a circle.

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* Received May 28, 1973

** Geophysical Institute, Faculty of Science, Tohoku University, Sendai, 980 Japan which may control the entrainment process. It is not possible, however, to study this problem quantitatively from the present result since our observation was far from completeness. We must thus confine the present article to qualitative discussion on the characteristics of the large scale disturbances. But it seems to be possible to speculate on the manner of breaking out of turbulence in the discontinuity layer.

2. Observation

The observation was carried out about 200 m west of Take-Shima Island, near the center of Lake Biwa-Ko, as shown in Figure 1, from 10 to 12 June, 1971. The water depth was 20 m at the shore of Take-Shima Island, and gradually increased to 50 m at the station.

In Figure 2 is shown the instrumentation used in the observation. The temperature was measured by six thermistors, which were arranged to locate in the discontinuity layer at the beginning of the observation. The response time of the probes was about 1 second, and the temperature was recorded continuously at Take-Shima Island.

As soon as the observation was begun, the thermocline displaced upward presumably by the internal seiches in Lake Biwa-Ko, and the probes were located, during most of the observation period, in the layer in which the temperature was nearly uniform. It was fortunate, however, that the probe at 12 m continuously stayed in the discontinuity layer for 3 hours from 0:00 to 3:00, June 12, after about 30 hours from the beginning of the observation, and recorded the short-period disturbances which occurred in it. This enables us to speculate on the characteristics of the disturbances occurring in the discontinuity layer without much confusion by the existence of the irregularities of mean temperature profile.

Through the observation period the easterly wind of about 10 m/sec continued to blow, and the water surface was too rough for our small

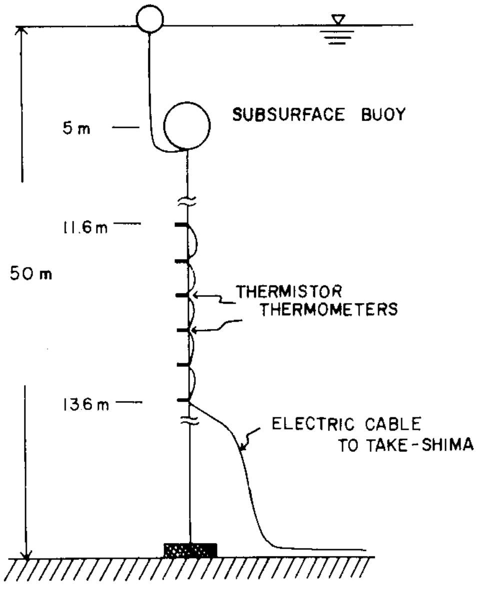

Fig. 2. Arrangements of the instruments at the station.

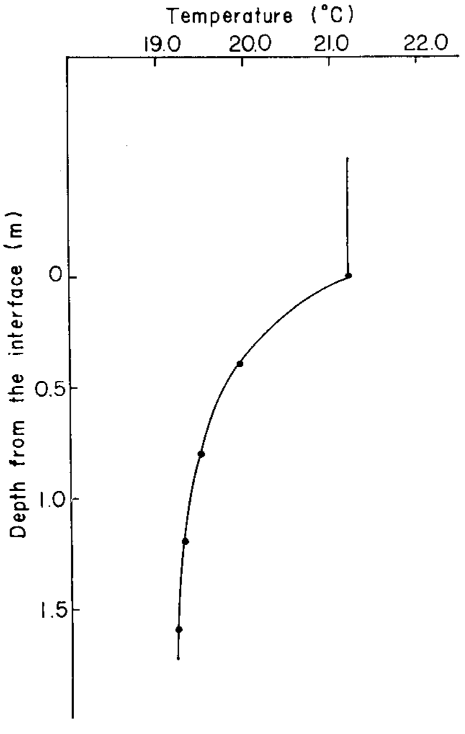

Fig. 3. Temperature profile of the upper region of the thermocline inferred from the part of the temperature series shown in Fig. 4b. The depth is taken from the interface. It was made by the step-by-step calculations of temperature gradients at 40 cm interval, on the assumption that the thickness of the discontinuity layer was not much changed in this time.

motorboat to sail, and so we were not able to obtain the temperature profile from the water surface to the bottom, in the course of the temperature measurement. Our discussion is thus mainly based upon the 3-hour temperature series at 12 m.

3. Data

In Figure 3 is shown the mean temperature profile of the upper region of the thermocline inferred from the temperature series. It was made by the step-by-step calculations of the temperature gradient of 40 cm interval from Figure 4b, on the assumption that, in this period, the discontinuity layer was not much confused and its thickness was retained nearly constant. In the upper mixed layer, the temperature was uniformly 21.2°C, but changed discontinuously at the interface, and decreased to 19.0°C through the discontinuity layer of about 2-m thickness, in which the temperature gradient was considerably great. The mean Brunt-Väisälä period in this discontinuity layer was about 2 minutes. This is a characteristic feature of the seasonal thermocline, when the strong wind continues to blow.

In Figures 4a, b, c are shown three examples of the temperature series obtained from 11.6 m (upper) and 12.0 m (lower). They have been taken from 0:37 to 0:50, 1:07 to 1:20 and 1:42 to 1:55 parts, respectively, of the 3 hours temperature series. We can see from them that the disturbances are apparently classified into two modes. One is the large scale motions of about 2- or 3-minute period which occur sporadically and have the intermittent nature, and the other is the very irregular small scale motions of which the periods are about several tens seconds.

Figure 4a contains the small-scale disturbances which appeared only at 11.6 m, and did not at 12.0 m (shown as (A)), and the large scale 3-

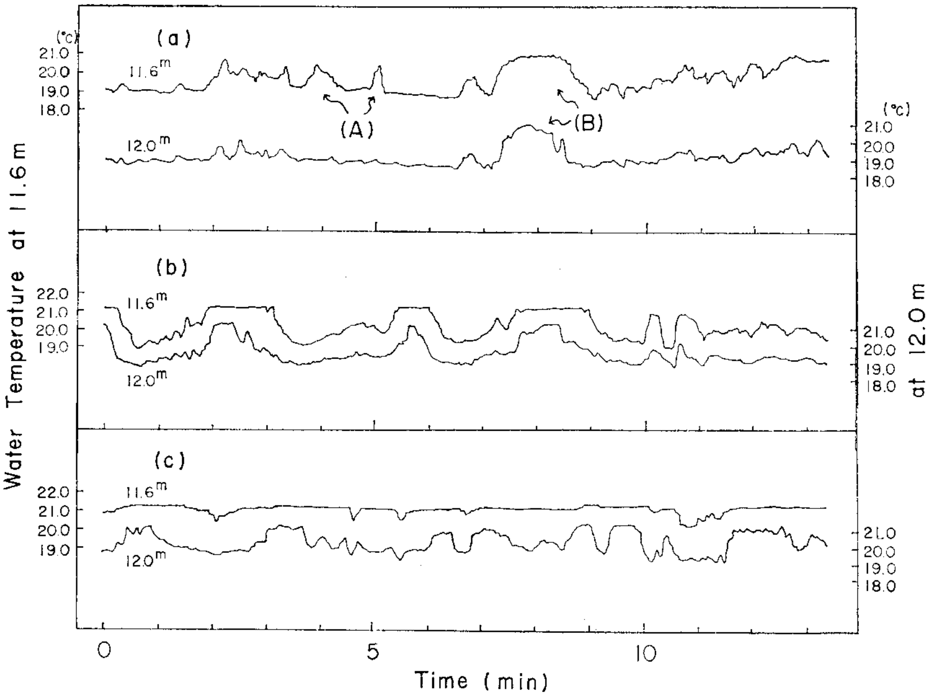

Fig. 4. Examples of the observed temperature series. The records are from 11.6 m (upper) and from 12 m (lower). The 13-minute records shown by a, b, and c have been taken from 0:37 to 0:50, 1:07 to 1:20 and 1:42 to 1:55 parts, respectively, of the 3-hour temperature series.

minute disturbance of amplitude of about 1 m, which occurred suddenly and broke down after the first occurrence (shown as (B)). Through the 3-hour record, the disturbances in the discontinuity layer represent little the regular nature of internal wave, but, more or less, a turbulent nature such as (A) and (B). It seems that the occurrence of (B) greatly contributed to the stirring of the discontinuity layer, since the temperature structure was fairly confused for about 15 minutes after its occurrence.

In Figure 4b, the disturbances of the period of 2.5 to 3 minutes and the amplitude of about 1 m appear in train. They seem to be internal waves, but disappeared suddenly. The temperature at 11.6 m was constant at 21.2°C near the crest of the disturbance, showing that the probe at 11.6 m was in the surface mixed layer. It is interesting that it traversed across the interface, and recorded the detailed temperature structure around the interface. Since the order of the vertical velocity of the displacement of the interface was small as 1 cm/sec, we can see that the temperature changed almost discontinuously at the interface. This shows that the thermocline erosion by the wind stirring was very strong.

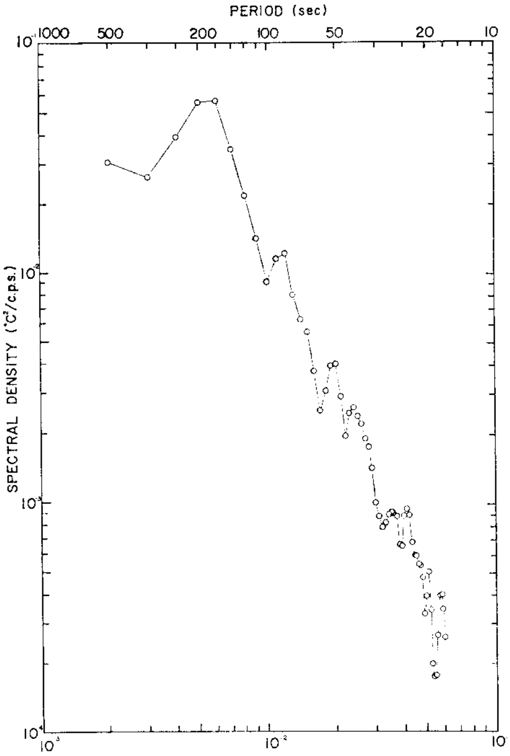

Fig. 5. Power spectrum calculated for the temperature series at 12 m recorded from 0:00 to 2:50, June 12. The total number of data, the sampling interval and the degrees of freedom were 8,100, 1.25 sec and 40, respectively.

As seen in Figure 4c, the probe at 12 m recorded the disturbances just below the interface, while the probe at 11.6 m stayed through the time in the upper mixed layer. We can see from this that the interface is not a smooth surface, but is contaminated by the irregular small scale turbulent eddies or the ripples of about 1 minute and of amplitude of about 20 or 30 cm.

The power spectrum has been calculated for the temperature series at 12 m recorded from 0:00 to 2:50, June 12, and is shown in Figure 5. The spectral density distribution has a dominant peak at 2.8 minutes, which corresponds to the period of large scale disturbances as was seen in Figures 4a and 4b. It may be possible to say that the kinetic energy is supplied at around 2.8-minute, and it caused the sporadic formation of disturbances of large amplitudes. They may soon break down to the smaller eddies, and at last the kinetic energy is transformed to the potential energy through the mixing process. From this point, it seems that the sporadic occurrence of the large scale disturbances is essential to the erosion process of the seasonal thermocline.

4. Discussion

PHILLIPS (1966) suggested that the strong stabilizing effect by the density stratification suppresses the occurrence of the large scale turbulent eddies, and that the entrainment is undertaken by the detachment of the smallest eddies from the underlying denser water. But in our case, it seems that the large scale turbulent-like disturbances occur more vigorously, and that they take an essential part in the entrainment process.

Figure 6 is the dynamic spectrum calculated for the temperature series at 12 m recorded from 0:00 to 2:30, June 12, showing the contours of the amplitude with respect to period and time coordinates. The time-length is about 2.5 hours and the period is from 0.5- to 10-minute. This analysis seems to be favorable to our aim on the point that it can represent the time dependent features of the large scale disturbances. We can distinguish them, in the figure, by the darker closed regions which appear intermittently with components from several tens seconds to 6 minutes in most cases. Their salient characteristics are summarized as follows: (1) the large-scale disturbances appear intermittently, with 5- to 15-minute intervals, (2) they are little dispersing, since all of their Fourier components appear almost at the same time, and (3) the components of maximum amplitudes are restricted to 2- to 3-minute period. On the basis of the above described items (1) and (2), it may be possible to conclude that these disturbances were not propagating as internal waves, but more likely were turbulent eddies, which broke out locally near the probe and soon broke down to irregular small eddies. From their turbulent nature, sporadic occurrence, and the item (3) which suggests the existence of critical wave number, the mechanism of their breaking out is probably due to the local shear instability.

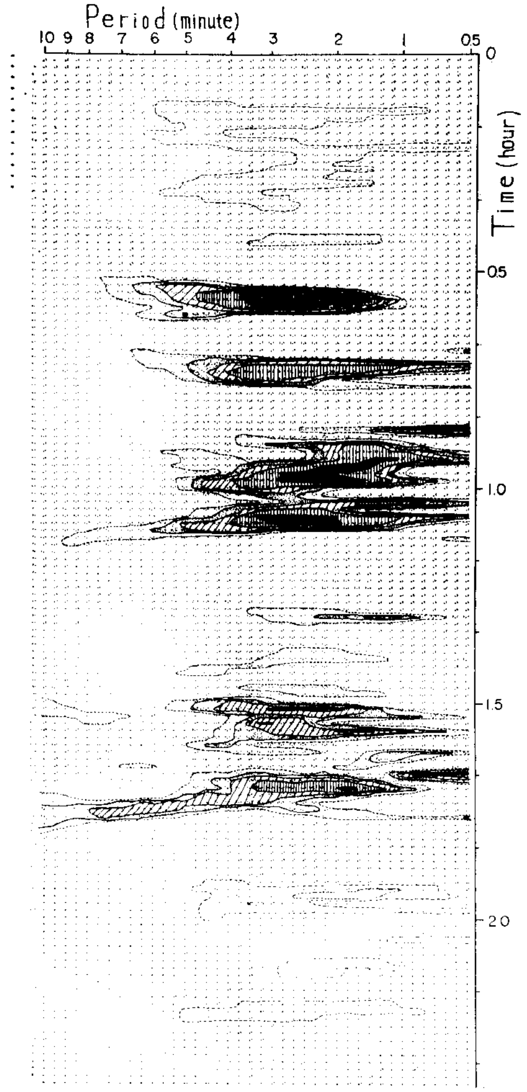

Fig. 6. Dynamic spectrum calculated for the temperature series at 12 m recorded from 0:00 to 2:30, June 12. The amplitude of each component at any time was calculated for the record of the period with its center at that time. The calculations were performed for 40 Fourier components from 0.5- to 10-minute period with 1 minute lag time. Each line represents the contour of the amplitude.

The importance of the shear instability, as the mechanism of breaking out of turbulence in the stably stratified region, has been ascertained by WOODS (1968, 1972) and THORPE (1968). Especially, WOODS showed the importance of the shear induced by the internal waves.

Concerning this, it may be profitable to make some inference on the manner of producing the shear in the discontinuity layer. We can estimate the amplitude of internal waves required to cause the shear instability by the use of Phillips' 1966 formulation on the problem. Internal waves are assumed to be the first mode and trapped in the discontinuity layer. Namely, we get 6- to 7-m for the internal waves of 10- to 60-minute period. In our case, however, we did not find the dominant disturbances which had much longer periods than 2.8 minutes. The maximum vertical travel of the interface through the 3 hours was at most about 3 m. It seems that, though our estimation is rather rough, the internal waves did not take a main part in breaking out of the shear instability. In the discontinuity layer, the stabilizing effect by the buoyany force is very great, but, on the other hand, it suppresses the momentum transport through the layer, and forms a great shear of the wind drift current. It seems to be probable that, when the strong wind continues to blow as in our case, the local Richardson number decreases to the order of 1 in the discontinuity layer mainly by the shear of the wind drift current.

It is suggested that the entrainment process is controlled by the large scale turbulent eddies which break out by the sporadic occurrence of local shear instability, although it is questionable whether it is appreciable to all stages of thermocline erosion process by the wind stirring, and it is not ascertained by quantitative treatment.

Acknowledgments

The author wishes to acknowledge many valuable suggestions and encouragement afforded him by Prof. H. KUNISHI of Kyoto University, Prof. Y. TOBA of Tohoku University and Dr. K. MATSUIKE of Tokyo University of Fisheries. He also indebted to Mr. K. TANAKA and Mr. S. SERIZAWA for the help in making observation, and to Miss Y. KAJIURA for kindful assistance through the data analysis. The observation described in this paper was carrried out while the author was a graduate student at Geophysical Institute of Kyoto University.

References

KATO, H. and O.M. PHILLIPS (1969): On the penetration of a turbulent layer into stratified fluid. J. Fluid Mech., **37**, 643-655.

PHILLIPS, O.M. (1966): The dynamics of the upper ocean. Cambridge University Press.

ROUSE, H. and J. DODU (1955): Diffusion turbulente á travers une discontinuité de densité. La Houille Blanche, **10**, 522-532.

THORPE, S.A. (1968): A method of producing a shear flow in a stratified fluid. J. Fluid Mech., **32**, 693-704.

TURNER, J.S. (1968): The influence of molecular diffusivity on turbulent entrainment across a density interface. J. Fluid Mech., **33**, 639-656.

WOODS, J.D. (1968): Wave-induced shear instability in the summer thermocline. J. Fluid Mech., **32**, 791-800.

WOODS, J.D. (1972): Billow turbulence and ocean microstructure. Deep-Sea Res., **19**, 87-121.

琵琶湖の内部境界層に発生する擾乱の観測

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要旨: 強い風によるかきまぜが存在する時，琵琶湖の季節的なサーモクラインの最上部において短周期の温度変動に関する観測を行った．

観測期間，温度の鉛直分布は混合層の底において不連続的に変化し，そのすぐ下の 2m 程度の厚さの内部境界層において，大きな勾配を持っていた．内部境界層における最も卓越した擾乱は，2分から3分の周期で，振幅は約 1m であった．そして，それらは5分から10分の間隔で間歇的に発生し，生成，消滅を繰り返していた．

このような結果から，それらはシアーによる不安定性機構によって発生したこと，そして，それらが風による季節的なサーモクラインの浸食過程を支配している可能性があることが示唆される．