On the near-shore thermal structure in Lake Huron, Canada

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ABSTRACT

In this paper data which were collected in a near-shore region of a large lake, from a bottom resting tower are presented which reveal certain aspects of the internal thermal structure of the lake. The time scales of the phenomena studied range from forced effects due to wind (greater than one day) to just above the Väisälä period for the thermoclinal region (typically 2 minutes). The dominant free oscillation has a period close to the inertial period for the latitude of the experiments. The data are presented here with limited analysis and limited correlation with theoretical results.

Introduction

This paper is one of a series, either prepared or planned, based on data collected in the near-shore region of lake Huron, Ontario, Canada (see Fig. 1). The first publication in the series was Hale, 1964. Lake Huron is a large lake in the sense that the earth's rotation, as well as the boundaries of the lake, determine the form of the large scale disturbances. In the vicinity of the boundaries, the behavior is extremely complex, and not adequately predicted by any of the (idealized) theoretical models, nor by a simple superposition of the theoretical results.

The near-shore activity is of particular interest because it is in this region that man's activities interact most strongly with the lake environment. The near-shore behaviour is very important in the North American situation where a significant portion of the total industrial activity is carried out along the shores of the North American Great Lakes.

The temporal scales of the phenomena investigated in this paper range from the forced effects due to wind, with periods in excess of one day, down to effects which can be resolved at the shortest interval of data collection, which is 10 minutes. The minimum vertical spacial scale is approximately 0.5 m.

Borrowing terms from meteorology, what is presented here is "weather". Hopefully, the analyses of existing data and data to be collected in the future will allow one to draw conclusions concerning the "internal climatology" of the near-shore region, at least during the segment of the year when experiments are carried out.

These data have been analysed previously to show the possible presence of internal waves of the second vertical mode (Hale, 1969).

Experimental

The data were collected during the summer of 1965 at a bottom resting tower shown in Fig. 2 (Hale, 1965), approximately four km from the shore and six km from the harbour of the Baie du Doré Research Station of the Great Lakes Institute, University of Toronto. The depth of the water at this location at the time of the experiments was approximately 18 m.

A mechanical system carried a thermistor sensor from a storage position near the bottom of the lake, to within 2 m of the surface (the up-leg of the cycle) and then returned the sensor to the bottom storage position (down-leg of the cycle). The time constant of the thermistor was 0.9 s and the rate of travel through the water approximately 0.1 mps.

A timer, with interchangeable cams, determined the interval at which the equipment cycled. A direct current motor, chosen for its "near-uniform" speed-load characteristic, powered the profiling system. The ouput from a

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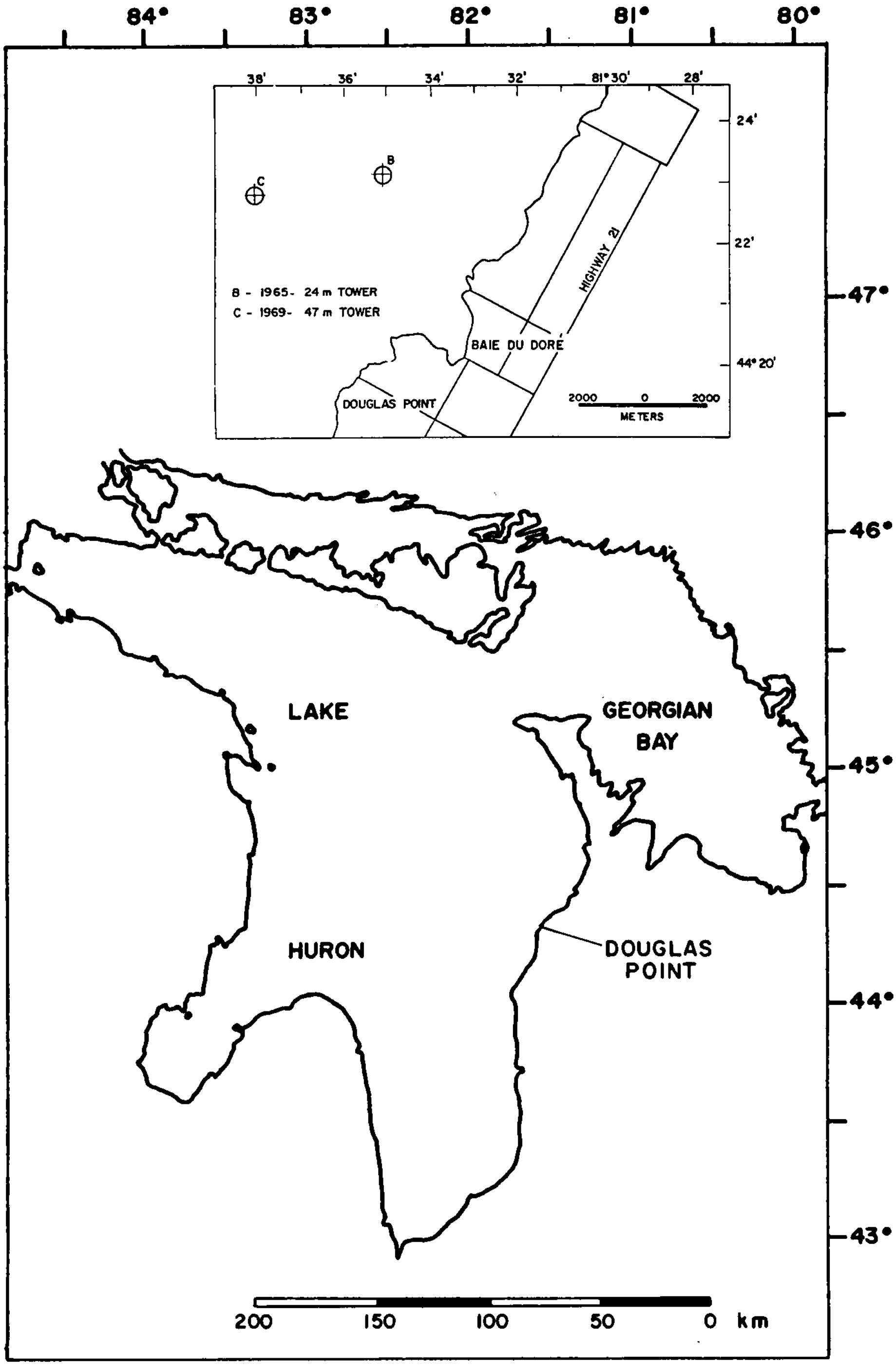

Fig. 1. Lake Huron with an insert showing the location of the limnological tower at which the data were collected.

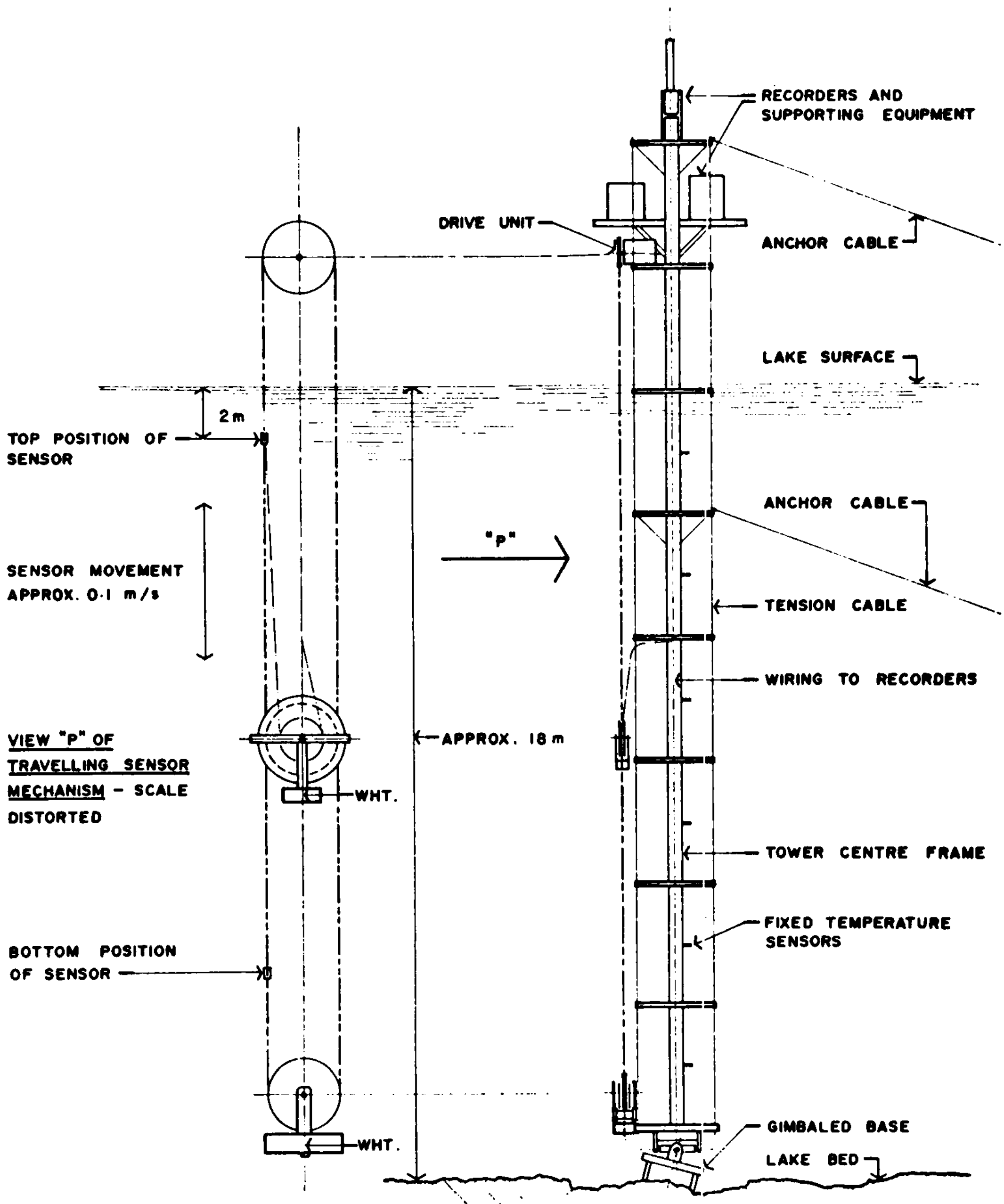

Fig. 2. Details of the limnological tower and data collecting systems. The profiling system was used to collect the data treated in this paper.

bridge circuit, which had the thermistor in one arm, was recorded on a strip chart. Curves were thereby obtained for which one of the coordinates was a function of temperature and the other coordinate a function of depth.

Basic data and data reduction

Data were collected from 1 200, 17 July to 1 300, 26 July at one-hour intervals and from 800, 27 July to 1 500, 28 July at ten minute intervals. A two co-ordinate data abstraction system was used to reduce the recorded information to digital form (Hale, 1968). Calibration information and chart limit co-ordinates were utilized in a computer program to transform the abstracted data (arbitrary scale) to the physical variables, temperature and depth. A number of factors, some of which cannot be quantified, effect the accuracy of the "final" data. Among these are: the variation in the speed of the sensor through the water due to battery condition and change in load, the stability of the bridge circuit, the human error in the abstraction process, and the response of the data collecting system subjected to a varying input. It is felt that temperatures are accurate to approximately $\pm 0.25°C$. The relative temperatures obtained during one profile and at a given depth on successive profiles are more important for the analyses to be made here and are "better" than the above figure would indicate.

Weather data collected on the shore at Baie du Doré were obtained from the Atmospheric Sciences Branch of the Department of the Environment (Canada). These data consisted of the "distance travelled" and the mean direction for one-hour intervals.

Data presentation

In this paper, only the "down-leg" data have been used. The depths of specific isotherms were found by using local curve fitting (least squares). The isotherm history obtained in this way is presented in Figs. 3–8. As well, the temperature-depth information was used to compute the local Väisälä frequency (N) using the relation,

$$N = \frac{1}{2\pi}\left[\frac{g}{\varrho}\left(\frac{dT}{dz}\right)_T\left(\frac{d\varrho}{dT}\right)_T\right]^{\frac{1}{2}} \text{ cps}$$

where $g = 980$ cm/s^2, $\varrho = 1$ gm/cm^3, $(dT/dz)_T$ (°C/cm), is the "local" vertical temperature gradient, obtained by curve fitting, and T is the local temperature, and $(d\varrho/dT)_T$(gm/cm$^{3\circ}$C), is the change in density with temperature at T, obtained from a third degree polynomial, which was fitted to the $T - \varrho$ data contained in the Handbook of Chemistry and Physics, 1948.

This information has been displayed in Figs. 3–8 by plotting curves of depth (ordinate) against Väisälä frequency (abscissa) on a logarithmic scale. To limit congestion the log scale has not been displayed. For the purposes

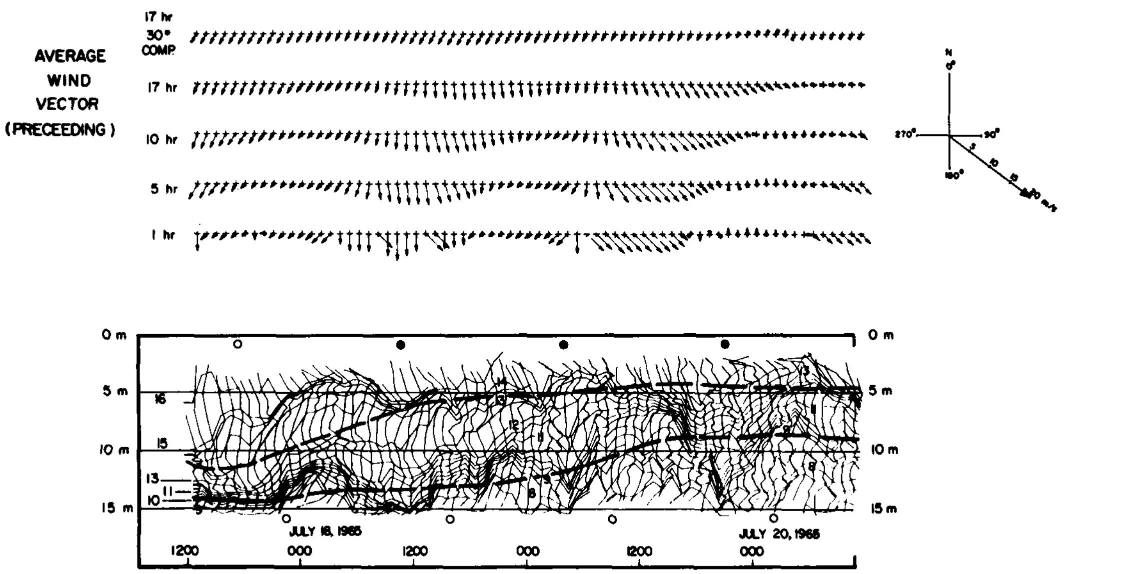

Fig. 3. Data Segment 1 (1 hour interval), displaying: the isotherm-depth histories (0.5°C increments), the mean (17 hour average) positions of the 10°C and 14°C isotherms (heavy dashed lines), the location of the troughs of the near-inertial period free oscillations (dots and circles, see text), the Väisälä frequency dependence on depth ("vertical" lines, see text) and the wind history.

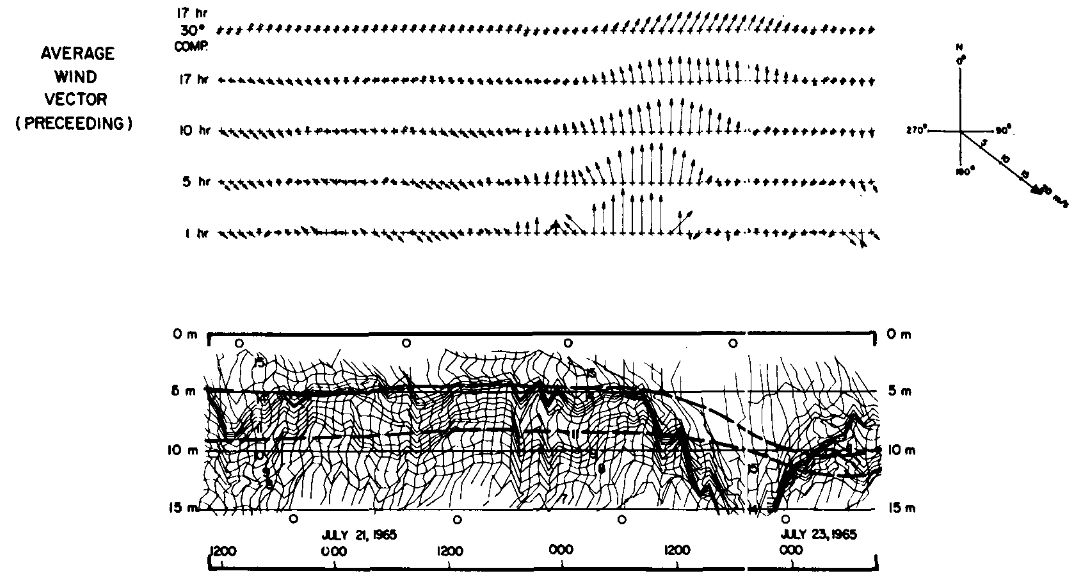

Fig. 4. Data Segment 2 (1 hour interval).

of this paper, the qualitative and relative quantative assessments which can be made based on this presentation are sufficient.

Both isotherm curves and Väisälä frequency curves have been drawn continuously although the calculations were carried out discretely.

The wind information is presented above the thermal data in Figs. 3–8. At the first level above the thermal data the distance travelled in the hour preceding the time of plotting and the mean direction of the wind during that hour are indicated. Above this are plotted the average wind vectors for the preceding periods of five hours, ten hours, and seventeen hours. At the top of each figure the component of the seventeen hour average wind vector in the 30°

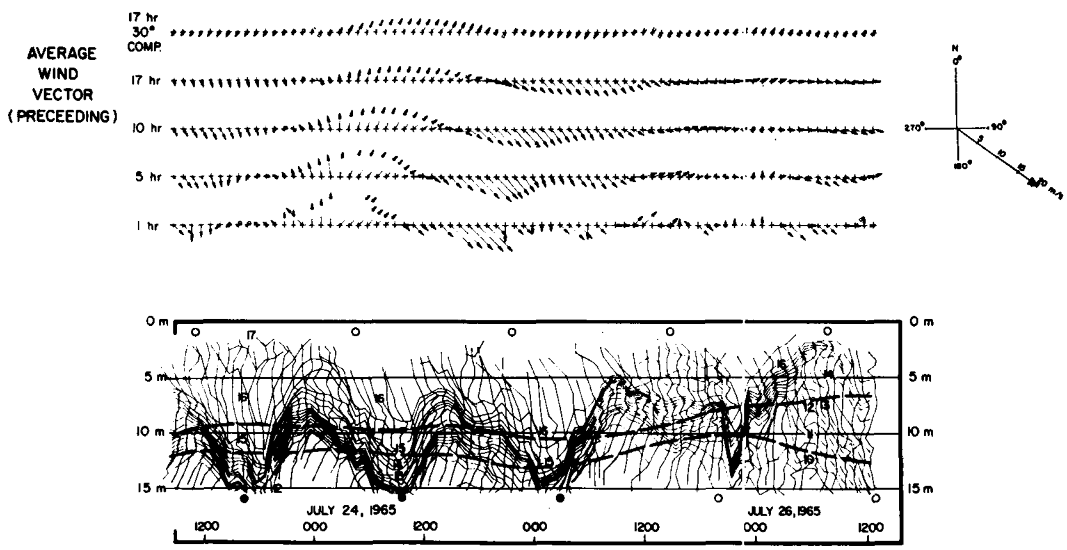

Fig. 5. Data Segment 3 (1 hour interval).

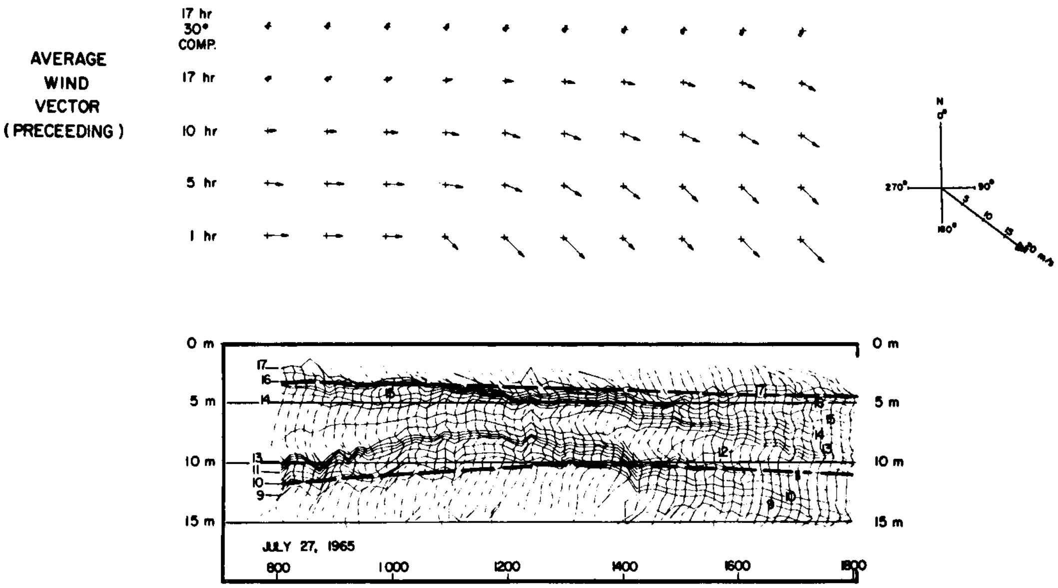

Fig. 6. Data Segment 4 (10 minute interval), displaying: the isotherm-depth histories (0.5°C increments), the mean (17-hour average) positions of the 10°C and 16°C isotherms (heavy dashed lines), the location of the troughs of the near-inertial period free oscillations (circles, see text), the Väisälä frequency dependence on depth ("vertical" lines, see text) and the wind history.

direction (approximately parallel to the shore at Baie du Doré) is presented.

Superposed on the temperature curves are curves of the mean position of specific isotherms. These were obtained by averaging over the preceding seventeen hours (the inertial period at the latitude of Baie du Doré is 17.2 hours). In Figs. 3–5 the 10°C and 14°C isotherms are

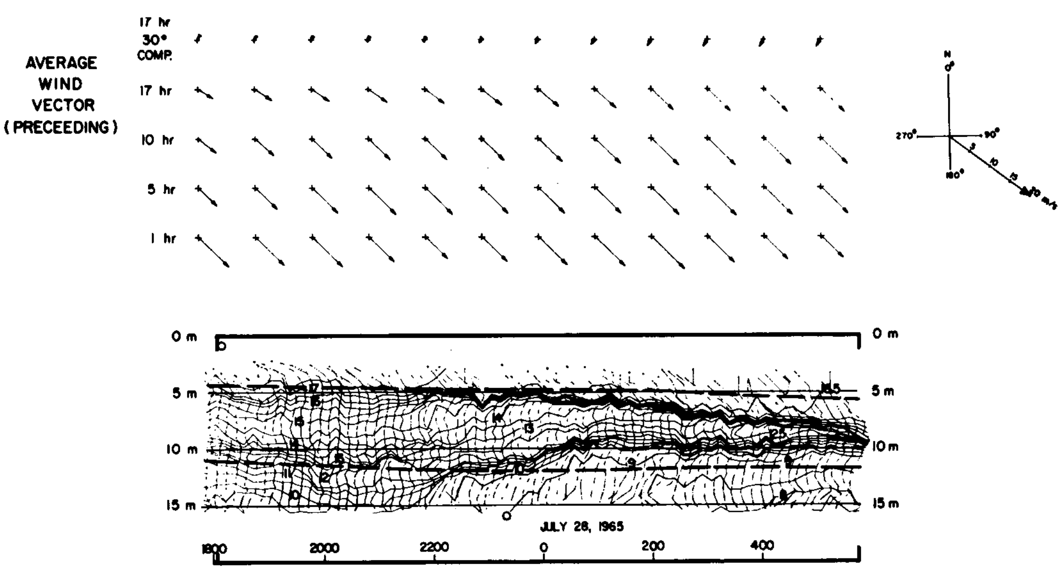

Fig. 7. Data Segment 5 (10 minute interval).

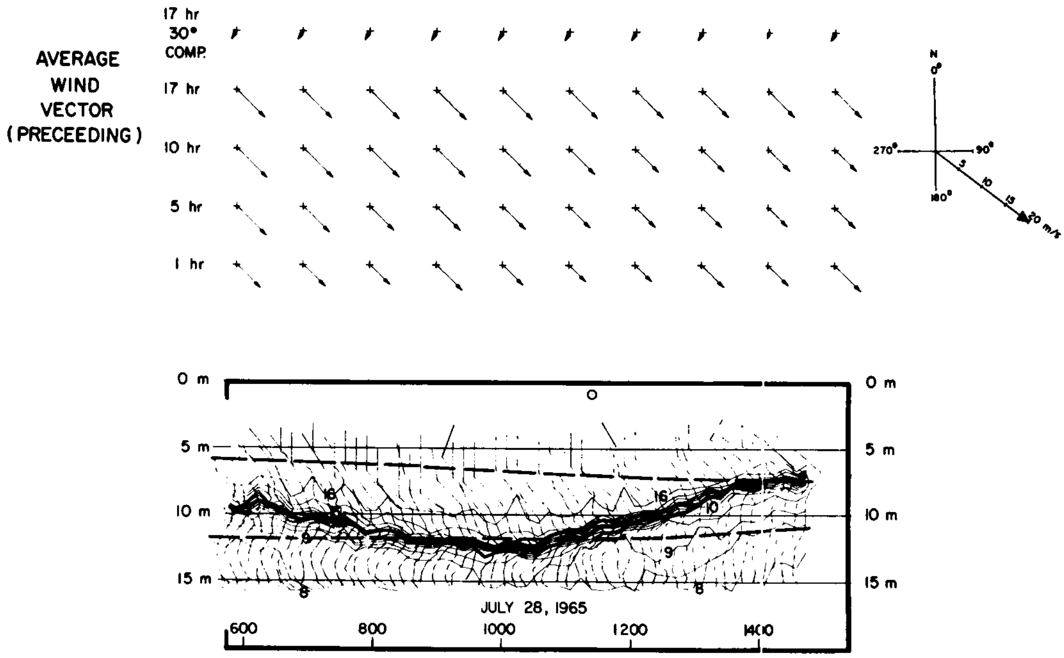

Fig. 8. Data Segment 6 (10 minute interval).

indicated by heavy dashed lines. In Figs. 6–8 the 10°C and 16°C isotherms are indicated by the heavy dashed lines.

Discussion

Quite obviously the thermal behaviour presented in Figs. 3–8 is complex, consisting of forced effects and free oscillations. There may also be a change in the number of vertical modes of motion present in the water column from one time to another. The vertical scale of the phenomena are, in the main, larger than those considered by Woods & Fosberry (1967). Transient behaviour is evident.

It is probably not possible to fully explain all that is contained in the data presentation. However, it is possible to generalize to some extent, and to isolate certain features or combinations of features and proffer explanations for them. An attempt will be made to do this in the following paragraphs.

Throughout the recording interval higher than inertial frequency oscillations embroider the isotherms. These higher frequency oscillations are varied in their form. On occasion they appear to have been caused by a train of waves. The vertical extent of these higher frequency oscillations is quite variable as well. Sometimes extending throughout the water column and at other times being confined to a portion of it. The source and true nature of these higher frequency oscillations is a challenging topic which, however, will not be dealt with in this paper. The shortest interval of data collection was 10 minutes and so the upper frequency "cut off" for the data displayed is below the Väisälä frequency oscillation associated with the thermoclinal region (typically 0.3–1 cpm, period 1–3 minutes).

A general description of the thermal history during the interval 17 July to 28 July will be given. At the beginning of the interval the vertical temperature structure is quite diffuse and perhaps consists of two thermoclines, the lower one being stronger. There are many small scale, transient, vertical features as evidenced by peaks in the Väisälä frequency curves. Some of these features persist for several hours. Throughout most of the interval inertial period oscillations can be discerned in the records. They are better defined in some sections than in others. Data collected independently (Hale, 1968) indicate that, prior to, and following the interval under study here, inertial period oscillations were occurring in the water column at the tower.

The mean position of selected isotherms determined by averaging over the previous inertial period displays considerable character. (Note: the mean position of the isotherms are only correct at and beyond the 17 hour point from the beginning of each of the data segments. This results from the "finite" aspect of the basic data. No such limitation exists in the case of the wind data which are correct averages throughout the intervals.) Part of this character can be explained, at least qualitatively, with reference to the wind history, which will be attempted below, and part of it does not lend itself to simple interpretation at this point.

On 26 July after a interval during which the thermocline was quite sharp, and the inertial oscillation well defined, the thermocline again becomes diffuse and splits into two parts. This condition persists until late on 27 July when the thermocline strongly intensifies.

Let us now consider the inertial oscillations which are particularly evident in the one hour interval curves. The troughs of the inertial oscillations at approximately 1 100, 18 July, 400, 19 July, and 2 100, 19 July have been used to position the inertial oscillation in the time domain. These are indicated in Figs. 3–5 as solid dots plotted above the isotherm and Väisälä frequency information at a "depth" of about 1 m. Open circles have been drawn at positions removed by integral multiples of the inertial period before and after the solid dots.

The mainly north directed winds on the first half of 22 July have quite obviously fed energy into the internal modes. This has resulted in an intensification of the thermocline upon which strong inertial oscillations are evident. The well defined trough at approximately 1 500, 23 July, 1 000, 24 July and 300, 25 July were selected to position this inertial oscillation in the time domain (indicated in Fig. 5 by the solid dots plotted at a "depth" of about 16 m). Again open circles have been plotted preceding and following this interval at times which are removed by multiples of the inertial period. This allows us to compare the two segments of inertial oscillations with respect to phase, and to assess, in part, the effect of the 22 July wind on them. This wind has caused the inertial oscillation trough to be delayed by approximately 6 hours. Speculation on the nature of the large scale internal wave regime and the effects of the winds on this regime will not be undertaken here.

An interesting feature appears in the isotherm curves (Fig. 5) at approximately 2 000, 25 July. It consists of a relatively narrow trough which occurs somewhat after the "predicted" trough of the inertial oscillation. The basic records were re-examined to ensure that there was nothing usual in the data. Both the up-leg and down-leg portions of the cycles involved were similar. The same feature was also evident in the isotherm behaviour determined from independent data (Hale, 1968).

The feature may have been "directly" caused by the winds commencing late on 23 July and ending late on 24 July which swung through approximately 145° (initially at 0° and rotating clockwise to approximately 145°). However, the time scale of this wind feature is perhaps, an order of magnitude greater than the time scale of the isotherm "anomaly" and it seems unlikely that this is a direct forced effect. As well, the time lag between the wind and the effect on the isotherms is perhaps too long (see below).

The explanation proposed by Mortimer (1963) to explain a phenomenon which was detected at a number of locations around the periphery of Lake Michigan may be employed to account for this behaviour. A Kelvintype wave may have been generated in another part of the lake, by the wind stress, which then progressed around the lake. In the absence of data collected at other locations along the shoreline, this is speculative.

An attempt will now be made to relate the mean position of the isotherms (10°C and 14°C in Figs. 3–5 and 10°C and 16°C in Figs. 6–8), to the winds.

The mean positions of the isotherms, for the purposes of this paper, were determined by averaging over the preceding 17 hour interval to remove the "free" inertial oscillations. The winds, of interest here, are those averaged in the same manner. The rationale for this particular averaging technique is based on (1) the fact that it would not be physically realistic to carry out any averaging of the winds which extended into the "future" and (2) the desire to remove the dominant free oscillation.

The dynamics of what may be called the "Ekman effect" (Ekman, 1905) in the near shore region of a fluid in a real basin, with complex and varying density stratification is not fully understood at this time. However, we will utilize the Ekman effect to qualitatively relate the winds to the thermal respone. As justified above, we will be concerned with the 17 hours averages.

If the simpliest approach is taken, one would expect the effects of the winds to be manifest in transports at right angles to the wind direction. With the direction of the shoreline, in the vicinity of the experiment approximately 30° (clockwise) from north, one would select, in this simple-minded approach, the wind component in the 30° direction for correlation with the mean positions of the isotherms.

With the exception of the behaviour from approximately 2 000, 27th July to the end of the experiment, the approach above is adequate to qualitatively explain the main features of the mean isotherm history (up-welling and down-welling). It should be noted that, in the case of the exception, the component in the 30° direction is not large. The influence of the actual shoreline or meteorological conditions not monitored may account for this "anomalous" behaviour. Of course, it may also indicate the inadequacy of this simple approach.

It was felt that the duration of the experiment and the "illconditioned" nature of the wind and thermal histories precluded the use of a formal mathematical approach for the determination of the phase shift between the two histories. A visual technique was, therefore, applied. It consisted of tracing the mean isotherm curves on transparent paper and overlaying them on the 17 hour average, and the 17 hour average 30° component, wind histories. The overlay was positioned visually on the well defined features consistent with the above cause–effect relation and the phase shift determined. It was found to be between 14 and 18 hours. This is consistent with the findings of Jones (1968) who found an 18 hour lag between the winds and the establishment of surface currents in the same region of Lake Huron.

Summary and conclusions

The near-shore internal thermal behaviour of a large lake in a real basin is very complex. Certain aspects of the behaviour can be understood with reference to the results of simple theoretical modeling. It is necessary to combine or superpose the simple results to even approximate the complexity of the actual situation.

Of the possible free modes of motion the inertial period oscillation dominates in the segment of data considered in this paper. This is consistent with results obtained earlier in Lake Huron by the author and with the results obtained by other workers in other large lakes.

As a first approximation, the forced effects can be attributed to Ekman transport. Certainly, a more refined approach than that employed here will be necessary to fully explain the wind–water interaction. It appears that the effect of the wind stress on the dominant inertial oscillation is to delay this oscillation in the time domain.

A Kelvin-type wave was perhaps detected in the segment of data considered here.

The "oscillations" with a frequency above the inertial frequency and below the Väisälä frequency require further investigation. They may be progressive waves, in which case, it will be necessary to install an array of data collecting stations to determine their characteristics.

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О ПРИБРЕЖНОЙ ТЕРМИЧЕСКОЙ СТРУКТУРЕ В ОЗЕРЕ ГУРОН, КАНАДА

В статье представлены данные, полученные на стоящей на дне большого озера в прибрежной зоне мачте, которые показывают определенные особенности внутренней термической структуры озера. Временные масштабы изучаемых явлений простираются от вынужденных ветром эффектов с периодами, большими суток, до периодов, чуть больших периода Вяйсяля для области термоклина, типичное значение которого 2 минуты. Доминирующее свободное колебание имеет период, близкий к инерционному периоду для широты, где проводились наблюдения. Данные представлены здесь с ограниченным анализом и с ограниченным сопоставлением с теоретическими результатами.