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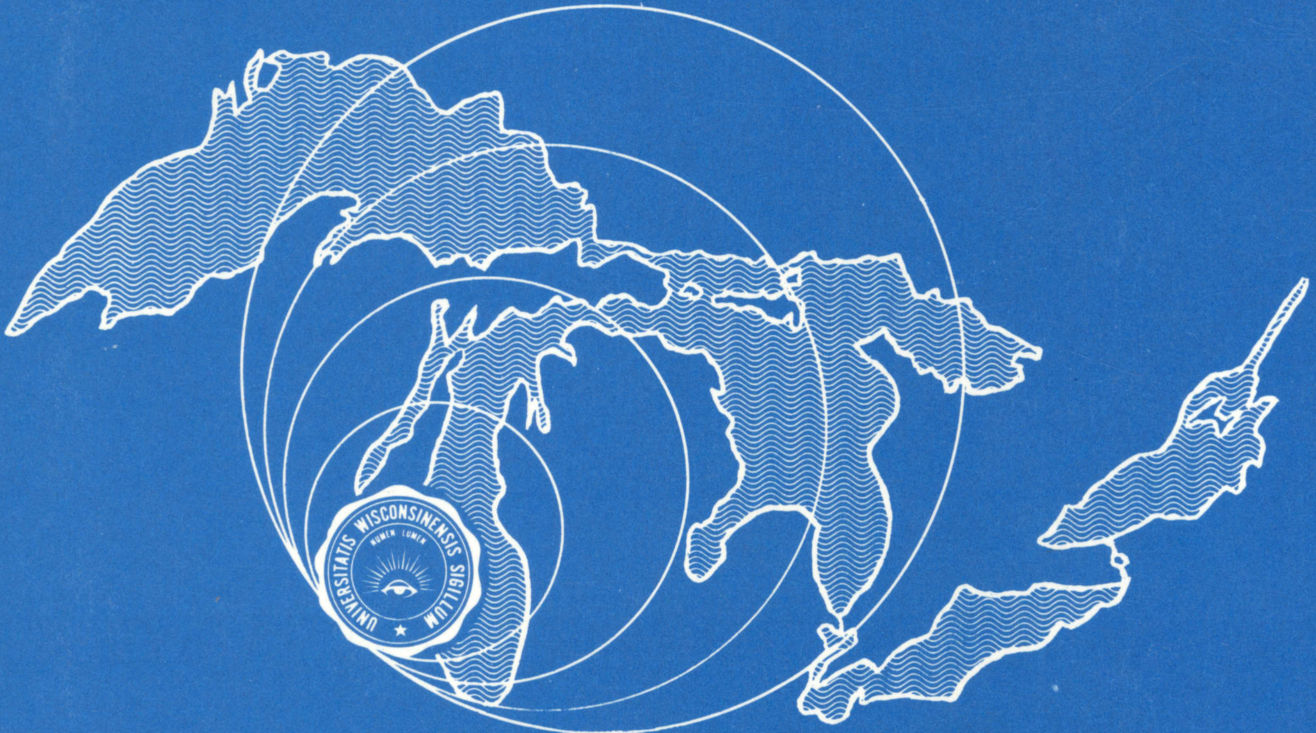

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SPECIAL REPORT NO. 1

Internal waves and associated currents observed in Lake Michigan during the summer of 1963

by

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INTRODUCTION

This report is substantially the same, apart from this introduction and minor improvements in the figures, as the Final Report submitted in November 1967 to the Office of Naval Research under Contract Nonr 1202 (22). It presents, in a series of diagrams, the main part of the data collected by the writer during 1963, but does not include waterworks intake temperatures. Meteorological information, including that for wind presented in figures 8 and 9, was supplied by the U.S. Weather Bureau; and this assistance is gratefully acknowledged. The report referred to on p. 24 under U.S. Department of the Interior was issued by the Department's Federal Water Pollution Control Administration, Great Lakes Region, Chicago, Illinois, under the title "Water Quality Investigation, Lake Michigan Basin: Lake Currents," dated November 1967, 364 pp. Figures 27 and 28 were assembled from information in that report.

To make this more than a data collection, and to indicate the nature of the phenomena upon which the observations throw light, a theoretical interpretation is outlined. (A more thorough theoretical analysis of long internal waves, in collaboration with Dr. M. A. Johnson of the National Institute of Oceanography, England, is being prepared for a later report in this series.)

The main part of the effort was directed to a study of temperature distribution in a region of Lake Michigan, roughly bounded by Lat. 43°00' and 43°30' N, during the period of summer stratification in 1963. Measurements were made with bathythermographs from a railroad ferry vessel (80 cross sections, Milwaukee, Wis.--Muskegon, Mich., 14 July-30 August, see appendix) and from a research vessel (24 July-5 August), which was also used as a platform, at a mid-lake anchor station, to measure the vertical distribution of current speed and direction. Details are given in a later section.

The measurement program was designed to test predictions made by Mortimer (1963) concerning the pattern of internal waves and associated currents anticipated in offshore and inshore regions; and it will aid the presentation and interpretation of the findings if these predictions are outlined first. This can conveniently be done, in non-mathematical language, by selecting and describing some figures from a paper read at the Autumn Meeting of the National Academy of Sciences, Ann Arbor, October, 1967, entitled "A pictorial account of oscillatory responses to wind stress in large lakes, with particular reference to long waves in Lake Michigan." (The abstract, referred to under Mortimer, 1967, on pg. 23, will be published in Bull. Amer. Meteorol. Soc. during 1968.) The extracts used here are placed within quotation marks.

THEORETICAL BACKGROUND

A good starting point is to consider the simplest possible scheme which gives realistic modeling for summer conditions in the central reaches of Lake Michigan. A relatively simple model, but not the only one, takes the form of a rectangular basin of constant depth containing two homogeneous layers of differing density separated by a sharp "thermocline" interface. This interface is shown as a "wave surface" in the following figures, in all of which the currents shown are those for the lower layer (of thickness h_2). Currents in the upper layer (of thickness h_1) are not indicated, but they may be derived from the lower layer currents by turning each vector through 180^o and multiplying the speed by a factor h_2/h_1.

Because of the large dimensions of the basin, the rotational term in the equations of motion (corresponding to the Coriolis parameter) must be taken into account and--to a degree of approximation sufficient for a two-layered constant depth model of Lake Michigan dimensions--the pattern can be built up from the following three classes of component.

1. Geostrophic or quasi-geostrophic currents. These will be relatively steady in direction and with the Coriolis force balanced by the gravity component associated with thermocline (and water surface) slopes directed normal to the direction of flow. These currents, and their associated thermocline slopes, are expected to be most conspicuous near shore and they may be generated in various ways, for instance, as the result of wind-driven Ekman flow and its persistence (with little friction) after the wind stress is removed, or in the form of the "coastal jet" described by Csanady (1967). Such currents are not considered further here, except to voice the expectation that the maximum speeds (and thermocline slopes) will be confined to a coastal strip of some 20 km in width. A similar shore-bound, but reversing, current pattern will be associated with the next component.

2. Internal quasi-geostrophic waves of the Kelvin type, one wavelength of which is illustrated in figure 1. This shows a wave on a thermocline interface traveling from left to right along a shoreline AB. All the associated currents run parallel to the shore and, to achieve this, the wave (and current) amplitude falls off exponentially along a line normal to the shore; and the rate of decrease is such that the component of gravity down the thermocline slope exactly balances the Coriolis force, so that all the currents are shore-parallel. This also meets the boundary condition that the flow can have no component normal to the shore. Under summer conditions in Lake Michigan, this wave is slow-moving (approximately 1.5 km per hour) and the

wave amplitude will fall to half of the on-shore value at a distance of about 4 km from the shore. It will therefore be negligible at 20 km from shore. With wave lengths of the order of the basin length this low wave velocity corresponds to a very long period.

It should be noted that the Kelvin wave solution, and the condition of no transverse motion, is only applicable in the constant-depth basin, and that the whole class of edge waves associated with a sloping bottom is ruled out in this model, but not in nature. However, there is a class of quasi-geostrophic edge waves discussed by Reid (1958) which, as far as wave speed, thermocline slope and current pattern are concerned, will show similarities with the Kelvin wave in figure 1.

Evidence that such slow moving shore-bound waves of this quasi-geostrophic type can be set in motion in Lake Michigan is provided by Mortimer (1963), but as the "period" is very long, more than a small fraction of one cycle of oscillation can rarely be completed before interruption by a fresh wind disturbance.

3. Combinations of internal Sverdrup waves which satisfy the boundary condition at the sides and ends of the basin.

In regions far enough offshore for the amplitudes of quasi-geostrophic waves of the Kelvin type to be negligible, and small enough in extent for the Coriolis parameter to be taken as constant, a type of wave illustrated in figure 2 can occur. This was described by Sverdrup with his (1926) analysis of tides on the North Siberian Shelf. The Sverdrup wave is a progressive wave and is superficially similar to its non-rotating counterpart in that the wave crests and troughs are level. But the effect of rotation is shown in the horizontal projection of the current envelopes. These are no longer straight lines as in the non-rotating case, but ellipses with the major axis lying along the direction of wave travel. The elliptical envelope is produced by a clockwise rotation of the current vectors. The wave speed is greater than that of the non-rotating equivalent; and the speed ratio (rotating/non-rotating) is given by the factor $1/\sqrt{(1-T^2/T_i^2)}$ where T is the wave period and T_i the inertial period, 12/sin ø hrs., ø being the angle of latitude. This factor also defines, for waves of differing periods but equal energy content, the inverse ratio of the wave amplitudes. It follows that, as the wave period increases and approaches that of the inertial period, the wave velocity increases and the wave amplitude decreases. The ratio between the major and minor axes of the current ellipses is given by T_i/T; and this means that, if T approaches T_i (but the energy content remains constant), the ellipses approach circular form; the wave velocity increases markedly; the wave amplitude becomes very small; and the motion then approximates to motion in the inertial circle, with most of the wave energy in kinetic form and little in potential form.

It also follows--because the above factor becomes infinite if T equals T_i--that waves of period greater than T_i cannot exist. T_i corresponds to a low frequency cut-off.

"An inspection of figure [2] makes it clear that no boundary could be introduced without disturbance of the flow pattern. The Sverdrup wave is, therefore, characteristic of offshore waters remote from any boundary. Boundary conditions can only be met . . . by particular combinations of Sverdrup waves in a standing wave pattern, which cancels out any flow normal to the boundaries. In Lake Michigan, as the observations to be discussed later will indicate, the major components of such patterns are Sverdrup waves of wavelength comparable with the basin dimensions. Sverdrup waves of this length travel at high speeds. Their periods are close to the local inertial period (approximately 17.5 hrs in the part of Lake Michigan later to be considered) but never exceed it, by virtue of the period limitations discussed earlier."

It is evident that Sverdrup waves cannot exist in unmodified form in situations where the boundary effects are no longer negligible. But, just as in a non-rotating basin a standing wave pattern can be built up to meet the boundary conditions by combining a pair or pairs of progressive waves traveling in opposite directions, so in the rotating rectangular basin (at least to a good approximation in a basin of Lake Michigan's dimensions) it is possible to produce a standing wave pattern, which does not violate the boundary conditions at the end and sides, by the combination of one pair of Sverdrup waves traveling in opposed directions across the basin and another pair, traveling in opposed directions, along the basin. The respective wavelengths of the pairs are simply related to the transverse and longitudinal dimensions of the basin. This combination produces a pattern of standing Poincaré waves (a standing version of the type of tidal wave described by Poincaré, 1910) which, combined with shorebound Kelvin waves, was the model proposed by Mortimer (1963) for internal waves and associated currents in Lake Michigan, the character of which was largely unknown at that time. Later collaboration with Dr. M. A. Johnson of the National Institute of Oceanography, England, has filled in the quantitative details concerning the amplitude and flow distribution in the pattern as illustrated in the two figures which follow.

The most conspicuous feature of this pattern is its cellular nature; and a system of any desired longitudinal and transverse nodality can be built up as an assembly of unit cells.

"Each unit cell (fig. [3]) contains five nodal points, one at each corner and one in the center. Flow is maximal at the cell center; the current vectors in each cell all point in the same direction at any one instant and execute one clockwise revolution every wave cycle. The wave topographies and corresponding current distribution in such a unit cell are illustrated in figure [3] for quarter cycle intervals. The wave surface may be taken, as in the other figures, to represent either a water surface or a thermocline interface in which case the currents shown in the figure are those for the lower layer. The upper layer currents are not shown.

"The length and breadth, l_y and l_x, may be assigned arbitrary and different values, making it possible to fit a standing wave pattern of any desired longitudinal or transverse nodality to any basin, as long as l_y and l_x are whole number fractions of the basin length and breadth, respectively. [This has been done with a 3 x 3 array of cells in figure 4, as an approximate model of one possible component of the Michigan pattern, taking $l_y = 2l_x$.] There is, however, one important qualification. By combining two pairs of Sverdrup waves alone, it is not possible to meet the boundary conditions at the ends of the basin exactly. The reason is that, with two pairs of Sverdrup alone, the currents of the unit cell boundary walls are not invariably zero (except for the center point), but for low nodalities and for long wave lengths (i.e., periods close to the inertial) they are negligible. For instance, in the figure [4] case, approximated to Lake Michigan conditions, with a transverse nodality of 3 and a period of 16 hrs, the peak current velocity across the unit cell boundaries is 6.5% of the peak current velocity elsewhere in the cell. For a uninodal case, also [anticipated in] Lake Michigan, the percentage is considerably less; but for higher nodalities the percentage rises sharply (M. A. Johnson, personal communication)."

For a complete and universal solution to meet the boundary conditions in a rectangular, rotating, constant-depth basin, it is necessary to combine standing Poincaré waves of various nodalities with at least one of the exponential types of Poincaré wave defined as class IIb in Mortimer (1963, pg. 39), in order that the boundary conditions may be satisfied at the ends of the basin for all wavelengths. But as long as the nodality is low and the wavelength is long--conditions which both appear to apply to Lake Michigan--the figure 4 pattern of alternatively rising and falling "hills and valleys", with an array of nodal points and associated, clockwise-rotating currents, represents one major component of summer thermocline topography and water movement in offshore regions. The figure presents four phases in one complete cycle of a trinodal oscillation, but this is only <u>one</u> of the free modes which may be excited. It will be shown later that another dominant mode is the uninodal one, i.e., with a single node at the central point of the Lake, and corresponding to a single Poincaré cell, in which case the current and elevation pattern would be that shown for the cell in figure 3, or one of the unit cells in figure 4, expanded to extend over the whole basin. In the actual lake there is likely to be a superposition of a uninodal, a trinodal, and perhaps a quintinodal pattern (odd nodes always being preferred because of the shape of the thermocline "distortion" brought about by wind stress), so that nature will probably present a complex mixture, the components of which can only be unravelled by judicious placing of the recording instruments and by spectral and co-spectral (phase) analysis of the records from each station. However, for the long wavelengths anticipated, all the wave periods will be close to, but always less than, the local inertial period.

Near shore, this complex standing wave pattern will be further complicated by the superposition of Kelvin-type edge waves of very long "period" and by quasi-geostrophic currents. All these currents will have a dominant component running parallel to the shore. The offshore currents, on the other hand, will be predominantly rotating; and there will be intermediate patterns in the transition zone between the inshore and offshore regions. An attempt to illustrate this in qualitative fashion is made in figure 5.

THE OBSERVATIONS

Distribution of temperature in the Milwaukee-Muskegon section (see Appendix)

With the facilities kindly made available by the Grand Trunk Western Railroad and with the help of two students from the Department of Physics, University of Wisconsin-Milwaukee (Mr. David Zeitz and Mr. Richard Schumann), bathythermograph casts were made routinely every six minutes (approximately every 2 km) from the Company's car ferries on their regular crossings between Milwaukee, Wis. and Muskegon, Mich. The length of the ferry track (fig. 6), breakwater to breakwater, was 127 km. The maximum water depth was 116 m in the eastern half of the section. The topography of the mid-Lake ridge is shown in more detail in figure 7. Over the interval 14 July--30 August, 1963, pictures of temperature distribution were obtained for 80 crossings (not all complete or consecutive because of rough weather or instrument breakdown) down to a depth of 55 m, i.e., well into the sub-thermocline layer. The results of these measurements, in the form of cross-sectional diagrams of temperature distribution (mainly obtained from the car ferry, but with a few from the research vessel) for the Milwaukee-Muskegon section are assembled in the Appendix. The first (and extensive) use of the Lake Michigan ferries as research platforms was that by Church (1945), whose classic study of the annual temperature cycle in the Lake in 1942 represents one of the first extensive uses of the bathythermograph, then a "classified" instrument. It is of interest to note that the writer of this report found Church's electric winch in the storeroom of the S.S. "City of Milwaukee" and used it for the 1963 survey of the S.S. "Madison" and S.S. "Grand Rapids."

Wind observations

The winds over the interval 17 July to 31 August are illustrated in figs. 8 and 9. The upper sections of the figures present results from an anemometer mounted on a buoy 3 m above the water surface at station 18 (see fig. 6), 7 km north of the ferry track and 39 km from the western shore. This was installed by the Federal Water Pollution Control Administration (U.S. Department of the Interior) in connection with the program to be described later. The observations at station 18, shown as the ranges between maximum and minimum speed for each two-hourly interval (see reference section under U.S. Department of the Interior, 1968) are compared with hourly readings at four land stations (airfields), kindly supplied by the U.S. Weather Bureau. In an attempt to represent the magnitude and timing of the main wind stresses, only wind speeds above 9 knots were included and plotted on a square-law scale, with the principal directions indicated. Direction and timing showed good agreement between all stations; but the speed indications in the figure are considerably higher for station 18 than for the land stations. It must be pointed out, however, that the two-hourly envelopes at station 18 include, by definition, the extreme values, while spot readings at each hour on land did not usually include the extremes. Furthermore, the square-law presentation considerably exaggerates this difference in presentation; but there also seems little doubt that speeds were in fact higher over the water than at the land stations.

Observations at anchor station

During the period 24 July-5 August, 1963, M.V. "Cisco" was chartered from the U.S. Bureau of Commercial Fisheries to make observations of the vertical distribution of temperature and current at anchor stations in the region of M_2 (figures 6 and 7). Three marker buoys were laid at positions M_1, M_2, and M_3, approximately 12 km north of the midpoint of the car ferry track, and about the same distance southeast of a large pyramidal bottom feature rising from deeper water to within 40 m of the lake surface (figure 7). The 60 ft. long vessel was anchored as closely as possible to one position by means of a ship's anchor from the bow and a large concrete sinker from each of the stern quarters. The consistency of the current measurements as shown in later figures, particularly of the low velocities in the hypolimnion, indicate that this method was, perhaps surprisingly, successful in keeping the vessel in a fixed position during calm weather. At wind speeds much in excess of 20 mph, however, the stern anchors were dragging and the anchor stations were, therefore, abandoned. This provided an opportunity of plotting a number of temperature sections, using a bathythermograph, often in a north-south direction and planned to intersect the east-west sections being observed by the car ferry. Some of these results are presented in later figures.

While at anchor station, the vertical distribution of temperature and current velocity and direction was measured approximately every 2 hours using a thermistor thermometer similar to that described by Mortimer and Moore (1953) and a Hydro Products Co. current meter. This was a Savonius rotor and compass system with deck read-out of speed and direction, being a prototype of the Model 460, 465A. The thermometer was reproducible, in calibration, to $\pm$ 0.02 C; the current meter responded to currents as low as 3 cm/sec (1/15 knot), was accurate to $\pm$ 3% of speed reading and $\pm$ 5° of direction reading (according to the manufacturer's specifications).

The thermistor thermometer was usually lashed to and lowered with the current meter, and the routine normally began with the measurement of surface temperature. The vertical temperature profile was measured by setting the thermistor bridge, in turn, to each whole degree in descending order of temperature, while lowering the equipment to determine the corresponding depth of the isotherm, down to the 4.5° or 4° isotherm, followed by a final placement at 50 meters, at which depth a current measurement was made. This was followed by further current measurements while holding the instrument at 40, 30, 25, and 20 meters and then at 2 m intervals up to 2 m depth (at which depth the results were open to question because of magnetic effects of the ship's hull and machinery). As the whole routine normally occupied 30 minutes or more, the "time" allocated to the temperature reading was the time at which the measurement started, and the "time" allocated to the current readings was approximately that (CST) at which the 10 m measurements were made.

Temperatures at the anchor station.--Changes in the vertical distribution of temperature at or near the mid-Lake anchor station M_2 are illustrated in figures 10-14 for the following intervals: 24-28 July (figures 10 and 11), 30-31 July (figure 12), and 3-5 August (figure 13). The thermocline, roughly bounded by the 10° and 15° isotherms, shows a fairly regular oscillation in depth of approximately 16-1/2 hrs in figures 10 and 11, with some oscillations of shorter periods superimposed. A similar oscillation is particularly conspicuous in figure 13 (perhaps at a somewhat longer period nearer 17 hrs) which illustrates the situation at M_2 after the strong southeasterly winds of short duration on 2 August (see fig. 8). Figures 10-13 represent the periods during which it was calm enough to keep the vessel fixed at the anchor station (the original intention was to keep it there for a week or more); and the gaps between them, therefore, represent spells of windy weather, during which the station had to be abandoned and when the opportunity was taken to carry out temperature surveys using the bathythermograph on N-S sections (to be described later), thereby supplementing the E-W runs of the railroad ferry. The contrast between figs. 10 and 13 illustrates the effect of the stronger winds around 2 August in mixing the upper layer and forcing the thermocline to a lower level.

In figs. 10-13, triangles mark the corresponding depths of the 5°, 10°, and 15° isotherms as measured from the railroad ferry when it passed a point on the ferry track 12 km S from M_2. The general correspondence in depth between those triangles and the isotherms at M_2 indicates that the main vertical motion of the thermocline was similar at the two places 12 km apart.

The phase relationships of the main temperature "waves" are illustrated, for the 10° and 15° isotherms and for the interval 24 July to 5 August in fig. 14. The continuous lines represent the isotherm depth at the anchor station M_2, and the circles represent the corresponding isotherm depths at the time of passage of the railroad ferry at 12 km to the south of M_2. Vertical lines in fig. 14 are set at 16.5 hr intervals; and the figure suggests that an internal wave of this period persisted over the whole of the interval 24 July to 1 August, but that after the storm of 2 August, the earlier wave was replaced by one of different phase and of perhaps longer period (17 hrs). It is interesting to note that the secondary "peaks," seen on the 3-5 August wave, approximately coincide with the 16.5 hr intervals in phase with the crests of the 24 July-1 August wave and may therefore represent its persistence into the 3-5 August episode. Whether this is significant or not cannot be established from so short a record.

Currents at the anchor station.--The current patterns observed at the anchor station M_2 are illustrated in figs. 15-20 for the three intervals when it was possible to moor the vessel: 24-28 July (figs. 15, 16, 19); 30-31 July (fig. 17); and 3–5 August (fig. 18). The thermocline region, assumed to be bounded by the 10° and 15° isotherms, is shown shaded; and the period of the main thermocline oscillation, as already noted in fig. 14, was approximately 16.5 hrs until 31 July and perhaps a little longer (17 hrs) during 3-5 August. Waves of shorter period were superimposed. The current vectors are displayed on an isometric projection--which permits directions to be shown--and the length of each arrow is proportional to the speed. Note that, because of the higher speeds encountered during the interval 3-5 August (after the winds of 2 August) the speed equivalent of unit arrow length in figs. 18 and 20 is twice that in the preceding figures. The higher speed was correlated with a greater internal wave amplitude.

A consistent general finding was that the currents above and below the thermocline boundary layer (shaded) were flowing in opposite directions, i.e., approximately 180° out of phase. Such reversal is consistent with the dominance of internal waves of the first vertical mode, i.e., the type appropriate to a system of two homogeneous layers of differing density, with a sharp "thermocline" between them. Also consistent with an internal wave of the first vertical mode is the relative depth uniformity, in speed and direction, of the currents in both upper and lower layers. As the volume transport in each layer must be equal, the ratio of upper to lower layer velocities (approx. 40:10 cm/sec in fig. 18) was approximately the inverse of the ratio of the layer thicknesses.

Another conspicuous feature of the pattern was a general clockwise rotation of the current vectors, in phase with the main thermocline oscillation. This behavior is illustrated in figs. 19 and 20. In the first case, the upper layer portions of figs. 15 and 16 are placed one under the other, so that events on 24-26 July are compared with events 33 hrs (two 16.5 hr periods) later. Similarly, fig. 20 compares two portions of fig. 18, one of which has been displaced by 17 hrs. Figures 19 and 20 serve to illustrate the strong coupling between the current rotation and the internal wave.

The distribution of temperature in sections other than the ferry route

When the winds were too strong to hold the vessel at anchor station, bathythermograph sections were run when steaming to and from port and also in attempts, mainly on N-S sections, to intersect with the runs of the Milwaukee-Muskegon ferry. The results are illustrated, on isometric projection, in figs. 21-26. The temperature structure was investigated in considerable detail along certain portions of the sections (see figs. 22 and 23), i.e., by repeating the bathythermograph casts as quickly as possible. With the vessel steaming at 10 knots and casting the BT every 3 minutes, profiles were obtained every 1/2 nautical mile.

While much of the detail still remains to be interpreted, a general conclusion is that the "waviness" of the thermocline, seen in most of the E-W ferry sections, is also present in the N-S sections;

and there is evidence (for instance, in fig. 22) of internal waves of very long wavelength, which throw some light on the possible three-dimensional topography of the thermocline. Internal waves of shorter wavelength, but of large amplitude, were encountered locally, for instance in figs. 22 and 25. The 30 July portion of the latter figure retraces, some 8-19 hrs later, part of the section run in the preceding figure.

Some interim results from current and temperature surveys by the Federal Water Pollution Control Administration (Department of the Interior)

"By a stroke of good fortune, 1963 also saw the collection of a large body of data on currents and internal waves in Lake Michigan, made by a U.S. federal agency (Great Lakes and Illinois River Basins Project, then of the U.S. Public Health Service, later transferred to the Department of the Interior) by means of a network of self-recording current meters [Geodyne, Richardson type] and thermometers suspended from buoys in Lake Michigan. The impetus for this work arose from the growing concern on the part of federal and public agencies with such problems as the pollution of the Great Lakes and the lack of basic knowledge of water movements and circulation. The group was appointed in 1960 to undertake an extensive study of the mechanisms by which currents are driven and by which pollution-laden waters are transported and diffused. The full results of this study, carried out in all the Great Lakes, awaits publication. The writer has been associated with the interpretation of some of the Lake Michigan findings and has assisted with the preparation of the appendix, "Lake Currents," to the "Report on the pollution in the Lake Michigan basin" now in preparation by the U.S. Department of the Interior, Federal Water Pollution Control Administration [see ref. U.S. Dept. Int., 1968]."

By kind permission of the Administration, some material from the report has been assembled in figures 27 and 28, in which the record of wind at station 18 is compared with observations of temperature at various depths and current speed and direction at one depth, for the two stations nearest to the ferry route (for positions see fig. 6). One station (17) was 4 km from the western shore and 12 km N of the ferry track; the other station (20) was 18 km from the eastern shore and 6 km S of the ferry track. Neither station could be regarded as typically inshore or offshore, but by virtue of their relative positions, they may be exptected to show some features of inshore and offshore current patterns, respectively.

The current data are presented in the form of two-hour envelopes, i.e., vertical lines giving the range of speed and direction during consecutive two-hourly intervals.

The figures assemble a large amount of information, the further analysis of which will be rewarding. Some major features, however, are evident at first glance. At station 20, for instance, the record shows that: "(a) temperature "waves" were evident at various depths for most of the month; the amplitude was greatest at thermocline level at about 15 m, and the waves were generally in phase at various depths, consistent with an internal wave of the first vertical mode corresponding to a predominantly two-layered system; (b) there was a sudden drop in temperature at the 10 m and 15 m levels, corresponding to an upwelling movement after the northerly storm of 13 August; (c) the regular train of waves during the first half of the month permitted a relatively precise determination of period at 17.1 hrs, 2.5% less than the local inertial period of 17.55 hrs and consistent with a Poincaré wave of low nodality; (d) at that time the current vectors at 60 km (in the lower layer) showed a fairly regular rotation, in phase with the internal wave, and associated with a variation in current speed; south-going currents often showed the highest speed, indicating a "looping" of the current track; (e) during the latter half of the month the rotational component of the current was less regular; during the three days commencing 22 August it was a "meandering" rather than a looping current."

At the near-shore station (17), on the other hand, the currents showed a greater tendency to run parallel to the shores, as might be expected, although rotation of the current vectors was by no means absent, for instance 4-9 August. At that time the current envelope was not a simple circle or ellipse, but showed a north-going trend with loops in it, coupled to the internal wave evident on the thermograph traces.

The two stations also showed different responses to wind, consistent with their relative positions. For instance, southerly winds on 27 July and a northerly blow on 9 August produced a strong upwelling and "downwelling" of the thermocline, respectively, at station 17. At station 20 on the other hand, the effects of these winds were small; and it was only after the strong northerly storm on 13 August that upwelling became evident at station 20.

Whereas at station 20 the depth of current measurement (60 m) was well below the thermocline for the whole of the interval covered by figures 27 and 28, the situation at station 17 was variable. On 23-25 July the current meter was above the thermocline and showed a south-going current. Southeast winds during the following two days caused upwelling and raised the thermocline above the current meter, which then showed a north-going meandering current, followed by reversal to a south-going trend on 2-3 August, in turn followed by the looping current already noted. After the wind-induced downwelling at station 17 on 9 August a south-going current persisted for over a week, followed by several reversals later in the month.

During the second half of the month the station 17 current meter (15 m) recorded currents in the upper layer, for, as the temperature records (and also the corresponding railroad ferry sections in the appendix) show, the thermocline remained well below the 15 m level during that interval.

INTERPRETATION

An intensive analysis of the eighty diagrams of cross-sectional temperature distribution (see appendix), and a comparison with various theoretical models, has yet to be made; but some conclusions may be drawn from an initial cursory inspection, particularly when the appendix diagrams are compared with wind speed and direction as illustrated in figs. 8 and 9. For the whole of the study interval, the thermocline appeared to be in a constant state of vertical oscillation, often with ranges of several meters and rising to 10 m or so after windy weather. During spells of predominantly southerly wind, for instance during the last 5 days of July, the layer above the thermocline was transported (as a result of the deflecting force of the earth's rotation) to the right of the wind direction, thereby causing a "downwelling" on the eastern edge and an upwelling on the western edge of the section. This led, after strong wind, to steep thermocline gradients near the shores, typically in a region 15 km or so wide. Examples of this are provided by the ferry run on 27 July (see also the evidence of western upwelling at station 17 in fig. 27); and this type of inshore thermocline topography persisted for several days after the wind "impulse" and was associated with a north-going meandering current at station 17 (below the thermocline in this instance) which changed over to 3 days of south-going current on 1 August.

The main wind disturbances during August took the form of short bursts of strong northerly wind on 9, 13, and 17 August. As was pointed out by Mortimer (1963), the Lake appears to be particularly sensitive to northerly wind impulses which, if strong enough, can produce a marked effect after blowing for only one or two days. The result is a reversal of the usual summer picture of upwelling on the western shore. This changes to a western downwelling, with strong upwelling along extensive stretches of the eastern shore (see fig. 16 and 17 in Mortimer, 1963). Such a reversal can be demonstrated by comparing the ferry cross sections from around 6 August (for instance, run #192) with those around 15 August (for instance, run #212). The strongest winds of the month, from the north on 13 August, provided the main contribution to this reversal, the effects of which are strikingly illustrated by the upwelling at station 20 and the downwelling at station 17 on that day (fig. 28). The strong southeasterly winds on 16 August, backing to northerly the next day, contributed to the disturbance and evidently mixed the upper layer very effectively and sharpened and deepened the thermocline (compare run #214, 16 August, and #222, 18 August).

During the six relatively calm days (18-23 August), which followed the storm, strong western downwelling and eastern upwelling persisted within 20 km of the shores; and the remainder of the thermocline underwent oscillations of large amplitude, typically illustrated for two consecutive ferry sections in fig. 29. These pictures are not synoptic, as the ferry took a little over 5-1/2 hrs to cross the Lake; but the standing nature of the internal waves is strongly suggested by comparing the mid-Lake isotherm slopes in the two halves of fig. 29, particularly in the region 60-70 km from Milwaukee, through which the vessel passed at roughly 2000 hrs on 19 August to return 8 hrs (roughly 1/2 inertial period) later. The thermocline slope had reversed its sign during the 8-hr interval; and this suggests the presence of a nodal point in 60-70 km region. The presence of such a nodal point, at 66 km, is strikingly demonstrated in fig. 30, in which the distribution of a mid-thermocline isotherm (10°) is plotted for nine consecutive runs covering the period 19-22 August.

The nodal point, at 66 km from Milwaukee, corresponds to a point of zero vertical displacement of the thermocline flanked by antinodes (maximum vertical displacement of about 10 m range at around 55 and 80 km). There were also less clear indications of nodes at approximately 41 and 92 km from Milwaukee; and this suggests a mixture of a uninodal and a trinodal standing wave pattern (odd nodalities would, in any case, be preferentially generated by the asymmetrical thermocline topography produced by the storm) in which the uninode and middle trinode happen to coincide and in which the eastern and western trinodes were obscured by the uninodal oscillation. A constant-depth two-layered model of the trinodal component of such a mixture is illustrated in fig. 4; and if the line pq, top right in that figure, coincides with the ferry section, then the anchor station M_2 lies to the left (west) of the 66 km middle trinode, roughly in the position indicated top left in figure 4.

Figure 30 provides no information on the relative phases of the oscillation in the antinodal regions separated by the 66 km node, but some light can be thrown on these relationships by means of a depth/time diagram in which thermocline depth and thickness is plotted (from the information in the appendix) at those points on the ferry track, corresponding to the presumed nodes (41, 66, and 92 km) and antinodes (55 and 80 km) as measured when the railroad ferry passed those points. This has been done in fig. 31 for the ferry runs 221 through 235 (18-22 August); and the thermocline is represented by thick lines joining the depths of the 10° and the 15° isotherms. The picture at 66 km--confirming that shown in fig. 30--is one of small vertical oscillation, whereas at the 55 km and 80 km antinodes there were regular oscillations, each of about 10 m range and 16.5 period, but opposed in phase. This clearly identifies 66 km as a nodal point in a standing wave pattern.

At 41 and 92 km, the thermocline was thicker and its vertical motion greater than at 66 km; but this motion showed no regularity, and a 16.5 hr periodicity could not be seen. Westward from 41 km and eastward from 92 km, there was an indication (not shown in fig. 31) of a 16.5 hr periodicity in thermocline motion during the interval 19-21 August, with phase relationships which appeared to identify 41 and 92 km as the sites of western and eastern trinodes, respectively. This trinodal pattern, if it indeed was such, was obscured near the shore by less regular long-shore motions and, perhaps also by a uninodal standing wave pattern. It is of interest to note that the rough indications (19-22 August) of internal wave crests at station 20 (identified by "temperature troughs" in fig. 28) appeared to be 1/4 cycle in advance of the figure 31 oscillation at 80 km. Phase determinations for internal waves at station 17, for the same interval, is hardly possible, because the thermographs were well above thermocline level; but such slight indications as there are suggest that the wave at station 17 was leading that shown at 55 km in figure 31, again roughly by 1/4 cycle. These results are not inconsistent with the relative positions of the stations and the ferry track (see fig. 6) and with the assumed position of M_2 in the trinodal model illustrated in figure 4.

A much better phase comparison can be made for the interval 4-7 August, because measurements of current and thermocline motion are available from M_2 for part of that interval,and because the instruments at station 17 and 20 showed clear evidence of internal waves with rotating currents at that time.

To assist the interpretation, fig. 32 presents cross-sectional diagrams of 1/4 cycle phases of one oscillation of a uninodal (upper portion) and a trinodal (lower portion) version of a transverse standing Poincaré wave, derived from the fig. 4 model (two-layered), to represent the Milwaukee-Muskegon section, looking north. Nodes are indicated by crosses; the relative positions of station 17, M_2 and 20 are shown; and, for simplicity, internal Kelvin waves or other generators of near-shore currents have been omitted. The fig. 32 currents are solely those produced by the Poincaré wave and are represented by letters to display the direction toward which the current is flowing in the lower layer. The size of the letter indicates current speed, and dots represents zero current at the antinodes. It will be noted that current direction in the upper layer (not shown) will be everywhere 180° out of phase with that indicated for the lower layer; and the relative current speeds in the two layers will be inversely proportional to the layer thicknesses.

The relative phases of thermocline displacements and current directions at station 17, M_2 and 20 can be derived from inspection of figures 18 and 27, but it is convenient to summarize the findings, with other information, in the following table.

Table: Data from three Lake Michigan stations, 4-7 August, 1963.

Station	17	M_2	20
Latitude N	43°08′	43°14′	43°08′
Longitude W	87°51′	87°08′	86°32′
Distance (km) from W shore	4	63	
Distance (km) from E shore			18
Distance (km) from Milwaukee-Muskegon ferry track	12N	12N	6S
Approx. mean thermocline depth (from inspection of ferry sections in appendix) meters	10	18	15-20
Depth (m) of current measurement (all below thermocline at the time)	15	various	16

Table, continued: station		17	M_2	20
Approx. hr (C.S.T.) of occurrence of temperature "troughs," assumed equivalent to internal wave "crests:"		7	6*	
	4th			15
		24	23*	
	Aug. 5th			8
		17		
*observed "crests" at M_2				1
	6th	10		
				18
		3		
	7th			11
		20		
Approx. direction toward which the current was traveling in the lower layer at the above times.		NNE	NNW	SSE
Approx. mean current speed, cm/sec		5	10-15	10

The table permits two conclusions: (i) stations 17 and M_2 form a pair in which thermocline elevations and lower-layer currents were roughly in phase, and (ii) this pair was out of phase with station 20 (8-9 hrs in respect of period and approximately 180° in respect of current direction). Bearing in mind the geographical location of the stations, this result is consistent with the upper part of fig. 32 (and with figure 3), namely a standing Poincaré wave of transverse nodality one, on the assumption that the uninode lies to the east of M_2. This assumption is supported by figure 33, in which the course of the 10° C (thermocline) isotherm was plotted for six railroad ferry sections during the interval 6-9 August,* and suggests the presence of one node only at 76 km from Milwaukee, at which point the depth range of the thermocline did not exceed 2 m during the interval. This "node" was less clearly defined than the 66 km node in fig. 30, and it was also in a different position.

It is also evident that the results tabulated above do not fit the trinodal pattern illustrated in the lower half of fig. 32. A fit with some higher nodality than three is theoretically conceivable; but this is a most unlikely interpretation and, in any case, it appears to be ruled out by consideration of the wave period (very close to inertial), not further discussed here.

*complete runs for the preceding days were not available because of vessel change-over.

If the uninodal picture is therefore accepted, the phases of thermocline elevation and current direction at all three stations may be taken to support the validity of the standing Poincaré wave model. This is an important result and represents the first identification of this type of wave.

CONCLUDING REMARKS

This report should be regarded primarily as a data collection with an initial attempt at interpretation. Further analysis of the material between these covers, and of the results of the Federal Water Pollution Control Administration's survey, should throw more light on the internal wave patterns, both progressive and standing, and on their phase relationships. At some of the FWPCA recording stations, particularly in mid-Lake in the southern half of the basin, the near-inertial rotation of the current vectors (Verber, 1965) was even more striking and persistent than at station 20 (figs. 27 and 28).

Future research should be directed, not only to the analysis of the present data store, but also to the development of more realistic mathematical models, for instance basins of elliptical plan and varying depth. Also the patterns of current and thermocline elevation in waters within a few km of the shore merit further investigation. None of the FWPCA recorders were closer than 3 km from shore; and a better understanding is needed of the circulation patterns and the forces which drive and govern them in the inshore strips of water in the Great Lakes and, indeed, in estuaries and coastal waters of the oceans. The recognition that one or more mechanisms can operate, at certain times, to delay or impede exchange between inshore and offshore water masses, must play an increasing part in the interpretation to be placed on water quality changes and on engineering decisions concerning the location of water intakes and waste disposal points. Power generating stations, both nuclear and conventional, are increasingly being placed on lake and ocean shores, often with inadequate knowledge of the current regime into which the thermal "pollution" will be injected or of the potential ecological effects.

As far as the Great Lakes are concerned, the present state of theory and instrumentation is such that a considerable advance should be possible of the understanding of the dynamics of the coastal strips of water which now receive a variety of waste and nutrient enrichment and from which drinking water is extracted.

"From what is known of oceanic internal waves and their generation, it appears that they differ in several important respects from those here described for the Great Lakes [Mortimer and Johnson, 1967]. This difference arises in the main from the extreme remoteness of oceanic shore boundaries. As far as long waves are concerned and in spite of the dimensions implicit in their title, the Great Lakes exhibit the properties of closed basins. The most conspicuous properties of the long internal wave regime are, as we have seen, boundary-induced. This fact, coupled with the steep gradients of the summer thermocline, gives the internal wave pattern its peculiar character and permits modeling in terms of relatively simple two-layered systems of Kelvin and standing Poincaré waves. These remarks should not suggest that studies of Great Lakes oscillations are not relevant to ocean processes--they have immediate bearing on the study of shelf seas, gulfs, bays, and any areas on which boundaries impinge--but should rather emphasize that the Great Lakes merit study in their own right, as a means of insight into a fascinating corner of geophysics, as a resource of growing importance to midwestern metropolitan man, and not solely as model oceans."

SUMMARY

The program of observations, which produced the data assembled in the report, was designed to test the writer's predictions (Mortimer, 1963) that a dominant component of the internal wave pattern, in Lake Michigan in summer and in regions remote from shores, could be described in terms of Poincaré waves with characteristic periods close to but always less than the local inertial period (17.5 hr) and with associated currents exhibiting clockwise rotation of the same periodicity and following an elliptical track.

The simplest model of summer events in the central reaches of the Lake, and one which is reasonably realistic, takes the form of a rotating rectangular basin of constant depth and containing two homogeneous, immiscible fluid layers of uniform but differing density, separated by a surface of density discontinuity (a "thermocline") which is subject to forced motions, mainly wind-induced, and to free oscillations with periodicities and patterns determined by the dimensions, constraints, and rotational speed of the basin (as expressed by the Coriolis parameter). In such a model basin, with dimensions comparable to those of Lake Michigan and for internal wavelengths of similar order, the patterns of oscillations in thermocline topography, and of the associated currents, can be built up from the following three components: (i) geostrophic or quasi-geostrophic currents, usually most conspicuous as shore-parallel currents

confined to a coastal strip some 20 km wide; (ii) geostrophic boundary waves of the Kelvin type (fig. 1, with associated shore-parallel currents) which exhibit an exponential decrease in wave amplitude and in current speed with increasing distance from shore (for typical Lake Michigan density distributions and water depths, an internal Kelvin-type wave travels at about 1.5 km/hr and experiences a halving of the wave amplitude for every 4 km of distance away from shore); and (iii) particular combinations of Sverdrup waves (fig. 2) which form a pattern of standing Poincaré waves to satisfy the boundary conditions dictated by basin dimensions. The cellular nature of this pattern and the associated clockwise rotation of the current vectors are illustrated in figs. 3 and 4. A family of patterns, each member of which has a different array of nodal points corresponding to different integral numbers of longitudinal and transverse nodes (fig. 4 presents the trinodal case), can be built up from unit cells, the properties of which are illustrated in fig. 3. The solution, represented by figs. 3 and 4 for the rectangular constant-depth model, does not completely meet the boundary conditions at the ends of the basin; but it provides a very close approximation to a complete solution for wavelengths comparable to Lake Michigan dimensions. M. A. Johnson (see Acknowledgements) has made the major contribution to the theoretical development (Mortimer and Johnson, 1967).

Observations of thermocline topography and current pattern in Lake Michigan during the summer of 1963 are compared with the theoretical model just described. The observations consisted of: (i) bathythermograph studies of temperature distribution in the 127 km wide Milwaukee-Muskegon cross-section (fig. 6) on 80 runs of a railroad ferry over an interval of six weeks from 14 July (see Appendix); (ii) current flow (figs. 15-20), temperature measurements (figs. 10-14) from a research vessel at a mid-Lake anchor station; and (iii) temperature and current measurements from instruments moored in the Lake by the FWPCA (figs. 27 and 28, U.S. Department of the Interior, 1968).

The cross-sectional pictures from the ferry runs (Appendix) show a thermocline in a continuous state of oscillation, often with large amplitudes (10 m range) after wind disturbances and often combined with a strong downward tilt of the thermocline on either the western or eastern shore, depending on the previous wind direction, with upwelling on the opposite shore (fig. 29). This phenomenon, mainly confined to an inshore strip of some 15 km in width and associated with long-shore quasi-geostrophic currents, often persisted for several days after the wind disturbance.

In the middle portion of the section, more than 20 km from either shore, the dominant pattern of thermocline oscillation took the form of a standing wave with a period (fig. 14) close to 17 hrs (compared with local inertial period of 17.5 hrs). A nodal point could often be recognized at a distance of about 70 km from Milwaukee (figs. 30 and 33). Phase relationships between thermocline elevation and current direction at the mid-Lake anchor station, and at two FWPCA recording stations (figs. 27 and 28) not far removed from the ferry section, indicated the dominance of a uninodal (transverse) internal standing wave on one occasion (4-7 August), and of a trinodal oscillation on another occasion (19-22 August, figs. 30, 31, and 32), in each case consistent with the theoretical model of a standing Poincaré wave (figs. 4 and 3, respectively).

In line with predictions derived from the theoretical model, the current pattern at the mid-Lake anchor station generally exhibited the following features: clockwise rotation of the vectors in phase with the internal wave; a fairly uniform distribution of velocity in the layers above and below the thermocline; lower velocities in the lower layer, consequent on the greater thickness of that layer; and a direction reversal on passing from one layer to the other.

A clockwise rotation of the current vectors at near-inertial frequency, coupled to an internal wave, was also recorded by the "offshore" FWPCA instruments (figs. 27 and 28). At the same time, an "inshore" buoy (4 km from shore) displayed a current pattern dominated by long-shore motion, although with occasional rotational components.

As it was only possible to examine the temperature distribution on a few longitudinal sections (figs. 21-26 chosen where possible to intersect the ferry runs), all that can be said about the three-dimensional thermocline topography is that the presence of longitudinal internal waves of very long wavelength was indicated.

The observations and theoretical considerations combine to suggest that motion in the Lake is likely to be a complex mixture of uninodal, trinodal, and perhaps higher nodalities of internal standing Poincaré waves, probably combined by internal progressive waves (particularly during periods of wind stress) and further complicated inshore by the presence of slow moving quasi-geostrophic boundary waves of the Kelvin type. These will impose a dominant shore-parallel component on the inshore currents, while the offshore currents, in summer, will be predominantly rotating, with intermediate patterns in the transition zone between the inshore and offshore regions (fig. 5).

ACKNOWLEDGEMENTS

While the main support for this work was provided by the Office of Naval Research--and this is gratefully acknowledged--the subsequent analysis and presentation of the results has depended on the help of persons and institutions too numerous to list in full. Particular gratitude should, however, be expressed to the officers and crew of the Grand Trunk Western railroad ferries, to the captain and crew of M. V. "Cisco" (U.S. Bureau of Commercial Fisheries) and also to Mr. D. McNaught and Mr. K. Stewart, graduate students at the University of Wisconsin, without all of whom the hard work of the field program could not have been completed. The support of Professor A. D. Hasler and his staff in the Laboratory of Limnology, University of Wisconsin, Madison--during the writer's tenure of the Brittingham Visiting Professorship at that University--is also gratefully acknowledged. Thanks are also due to the Wisconsin Alumni Research Foundation for financial support and to the University of Wisconsin-Milwaukee for student help in the field program.

The bulk of the analysis and the preparation of drawings was carried out, after the writer's return to Scotland, with facilities and staff support kindly supplied by the Scottish Marine Biological Association. In particular, the assistance of Miss M. Wright in computation and preparation of drawings should receive mention. The later stages of analysis and presentation have been completed at the Center for Great Lakes Studies at the University of Wisconsin-Milwaukee, and particular thanks are due to Miss M. Pierce and Mr. R. Ristic for document preparation and art work.

It must also be recorded that this interpretation of summer motion in Lake Michigan would have been far less complete without helpful discussions with Dr. J. L. Verber and the data which he supplied, with the kind permission of the Federal Water Pollution Control Administration (Department of the Interior). Finally, the interpretative sections of this report owe much to a collaboration with Dr. M. A. Johnson of the National Institute of Oceanography, England, whose important contribution to theoretical modeling has already been mentioned.

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FIGURES

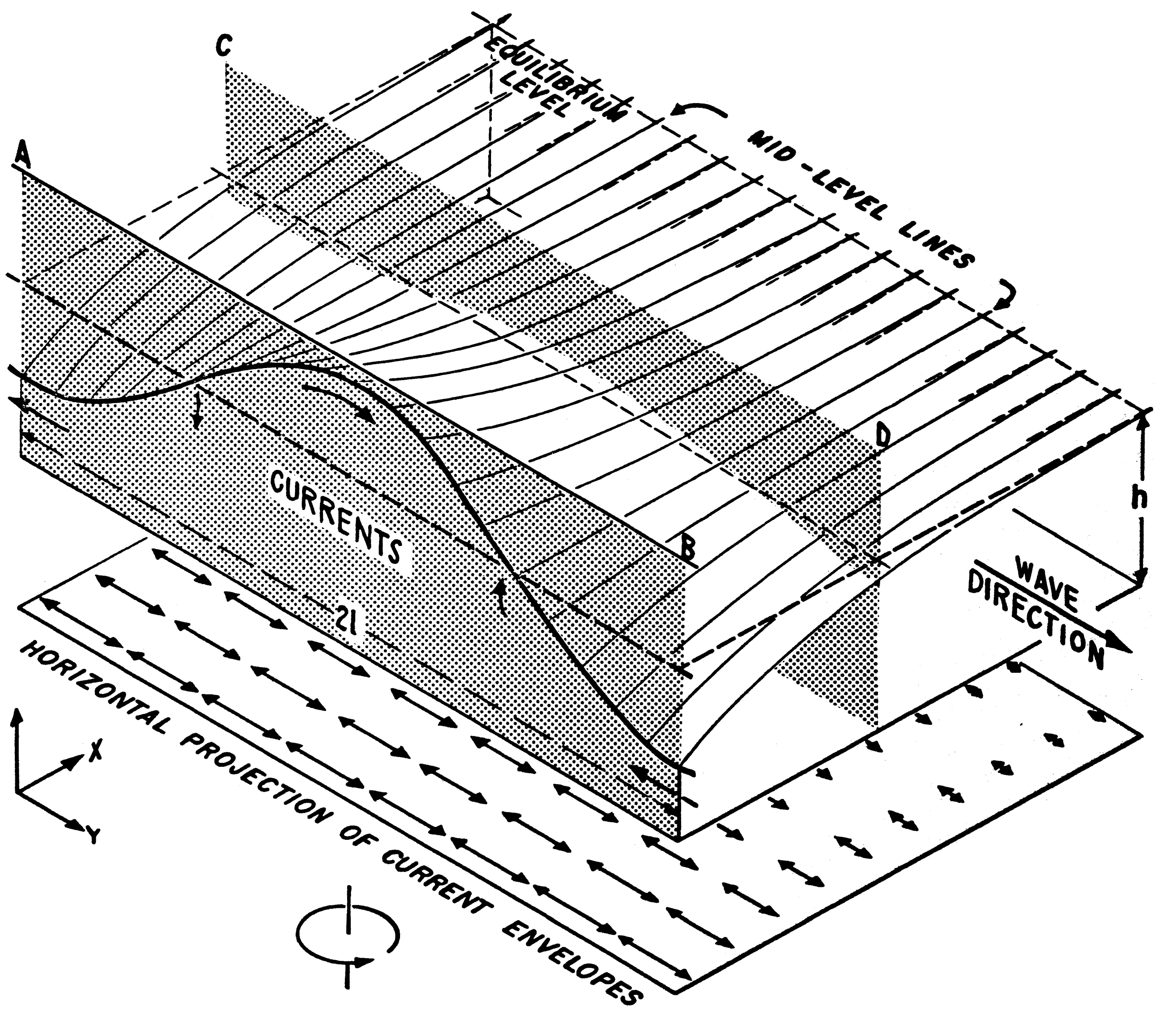


Figure 1 Diagrammatic representation of one wavelength of a Kelvin wave traveling along the shore, AB, of a (counterclockwise) rotating, semi-infinite model of constant depth. A barrier, CD, can be inserted parallel to AB without disturbing the wave, to yield a model of a Kelvin wave in a constant-depth channel.

Fig. 2

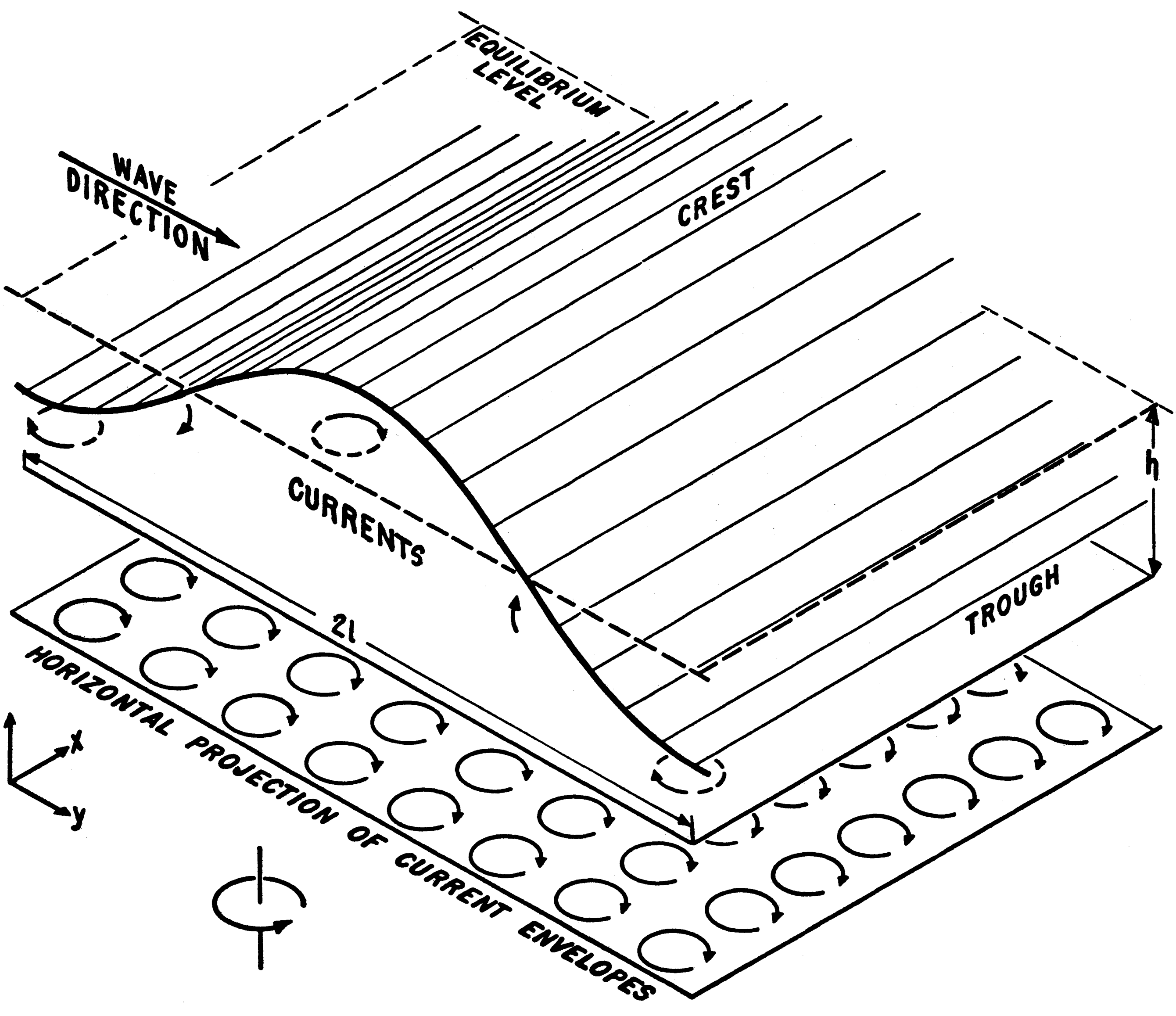


Figure 2 Diagrammatic representation of one wavelength of a Sverdrup wave in a constant-depth, (counterclockwise) rotating ocean of infinite extent. The current directions everywhere undergo one clockwise rotation per wave cycle, and the horizontal projections of the current envelopes (i.e., the track traced out by a water particle) are ellipses.

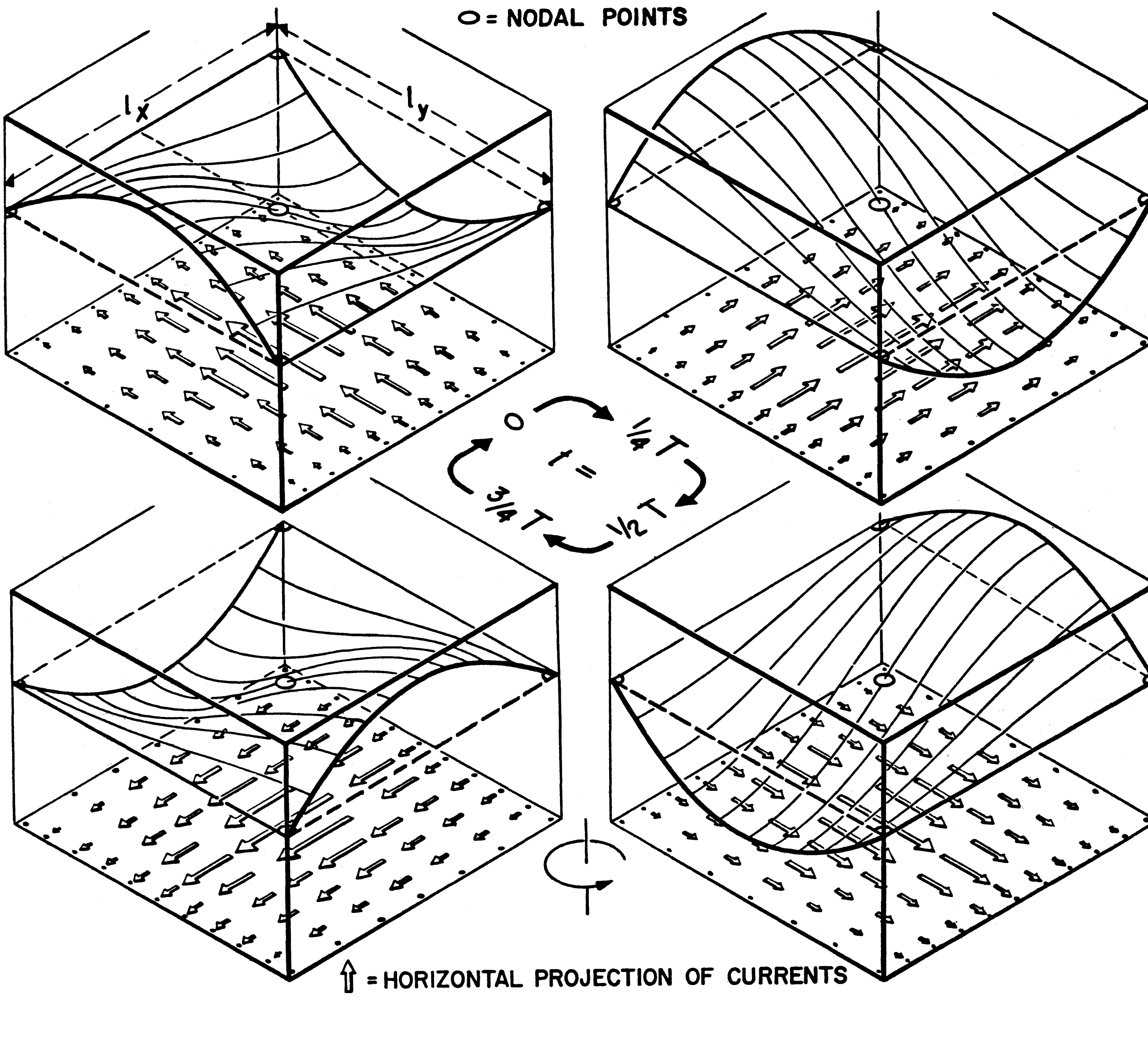


Figure 3 Four phases in one cycle of oscillation of a "unit cell" of a standing Poincaré wave pattern of long wavelength: constant-depth model; counterclockwise rotation; wave period, T.

Fig. 4

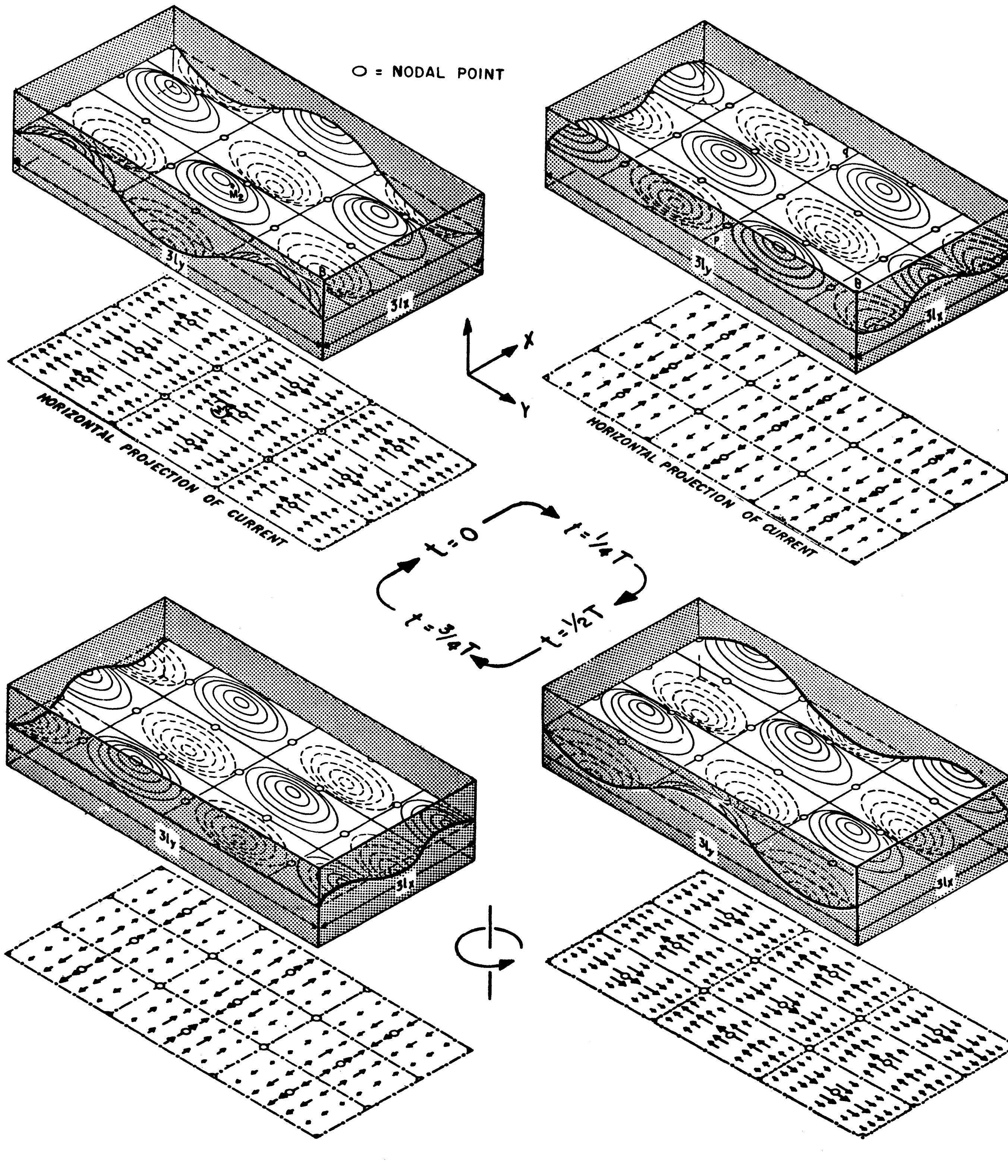


Figure 4 Four phases in one cycle of oscillation of a trinodal standing Poincaré wave of long wavelength: constant-depth model counterclockwise rotation; wave period, T.

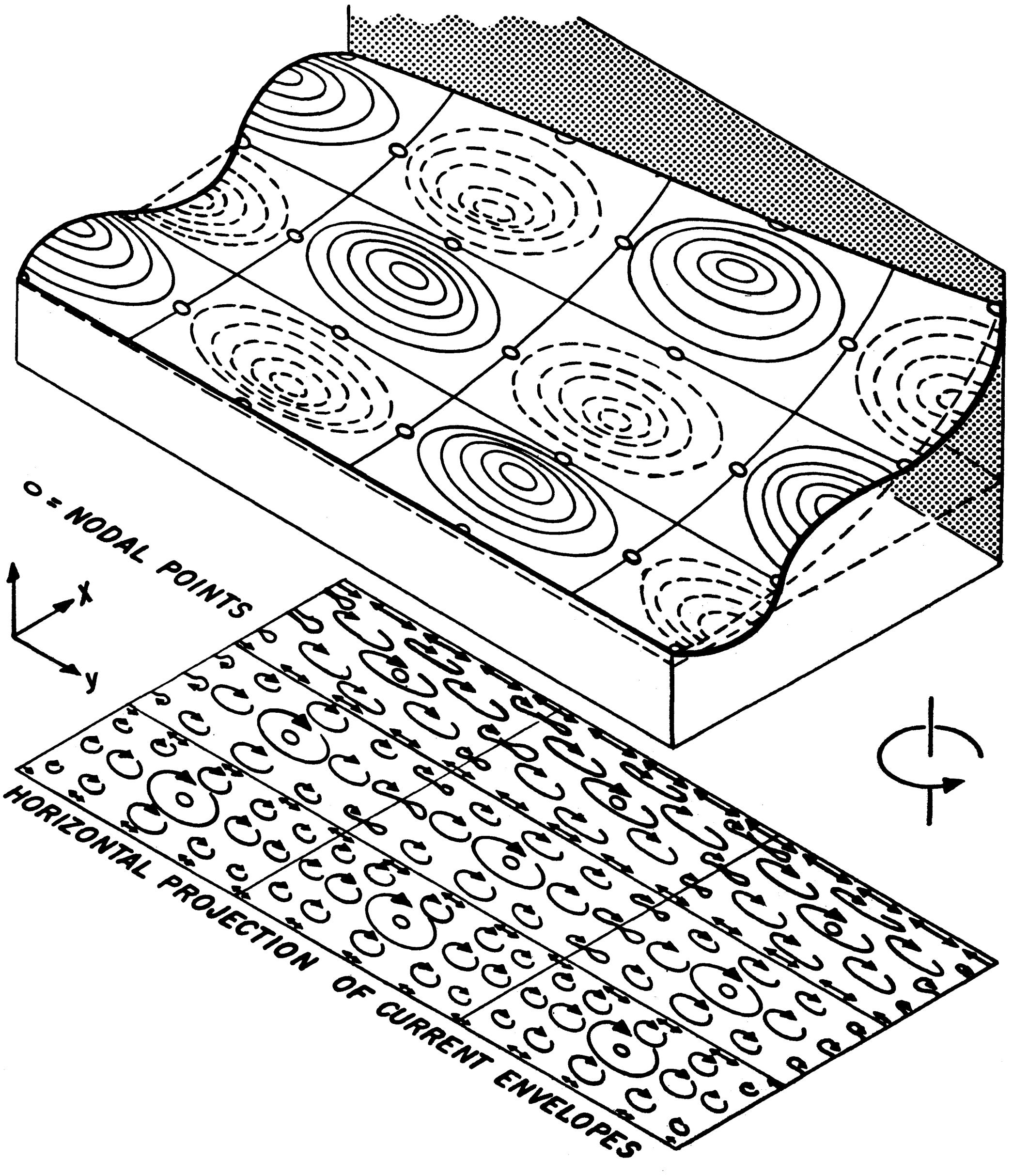


Figure 5 Diagrammatic representation of the combination--in a region of a constant-depth, (counterclockwise) rotating, semi-infinite model--between an "offshore" standing Poincaré wave pattern and an "inshore" Kelvin wave pattern.

Fig. 6

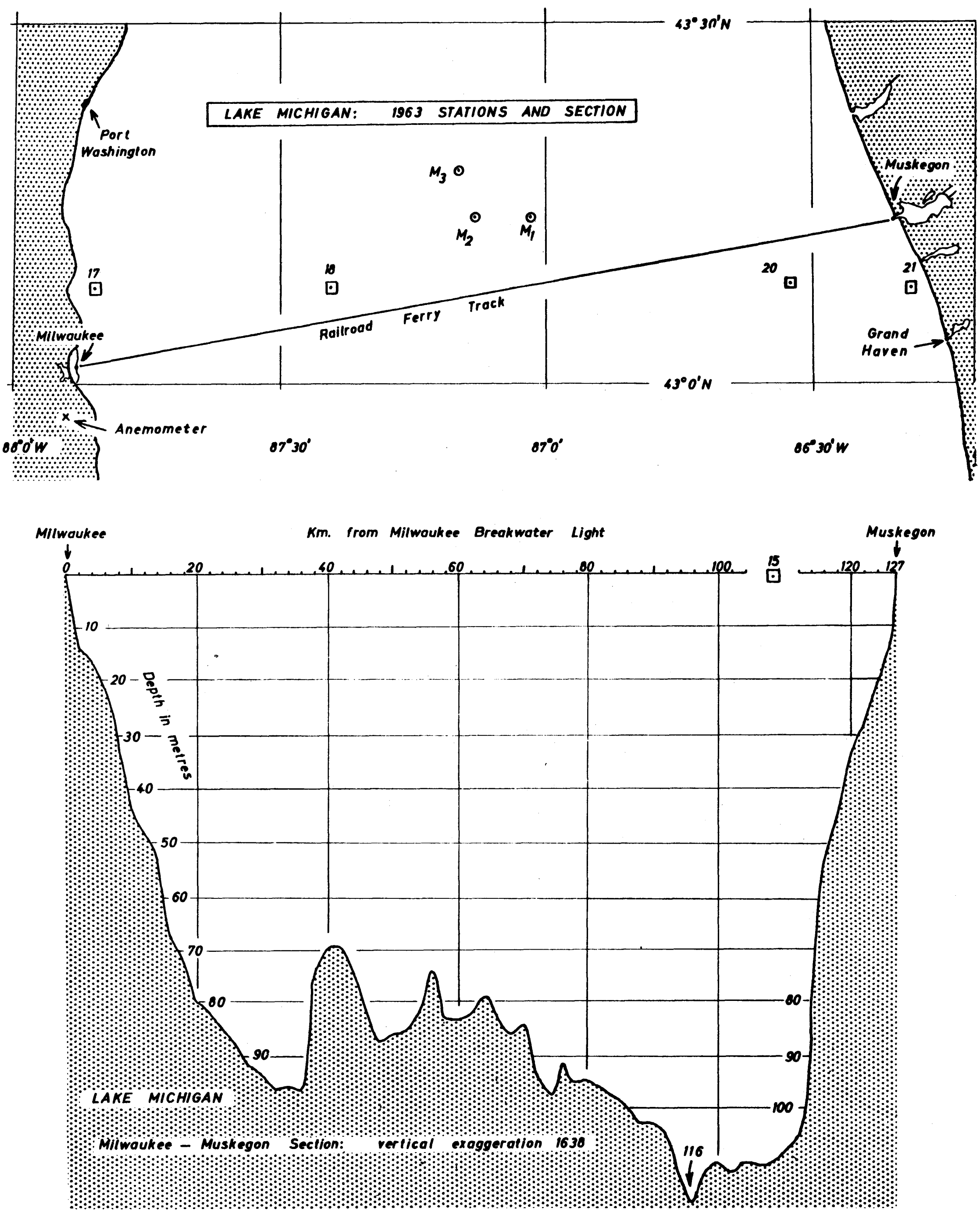


Figure 6 Positions of the Milwaukee, Wis. - Muskegon, Mich. railroad ferry route and of stations 17, 18, M_2 and 20, Lake Michigan, 1963. Water depth along the ferry track is also shown.

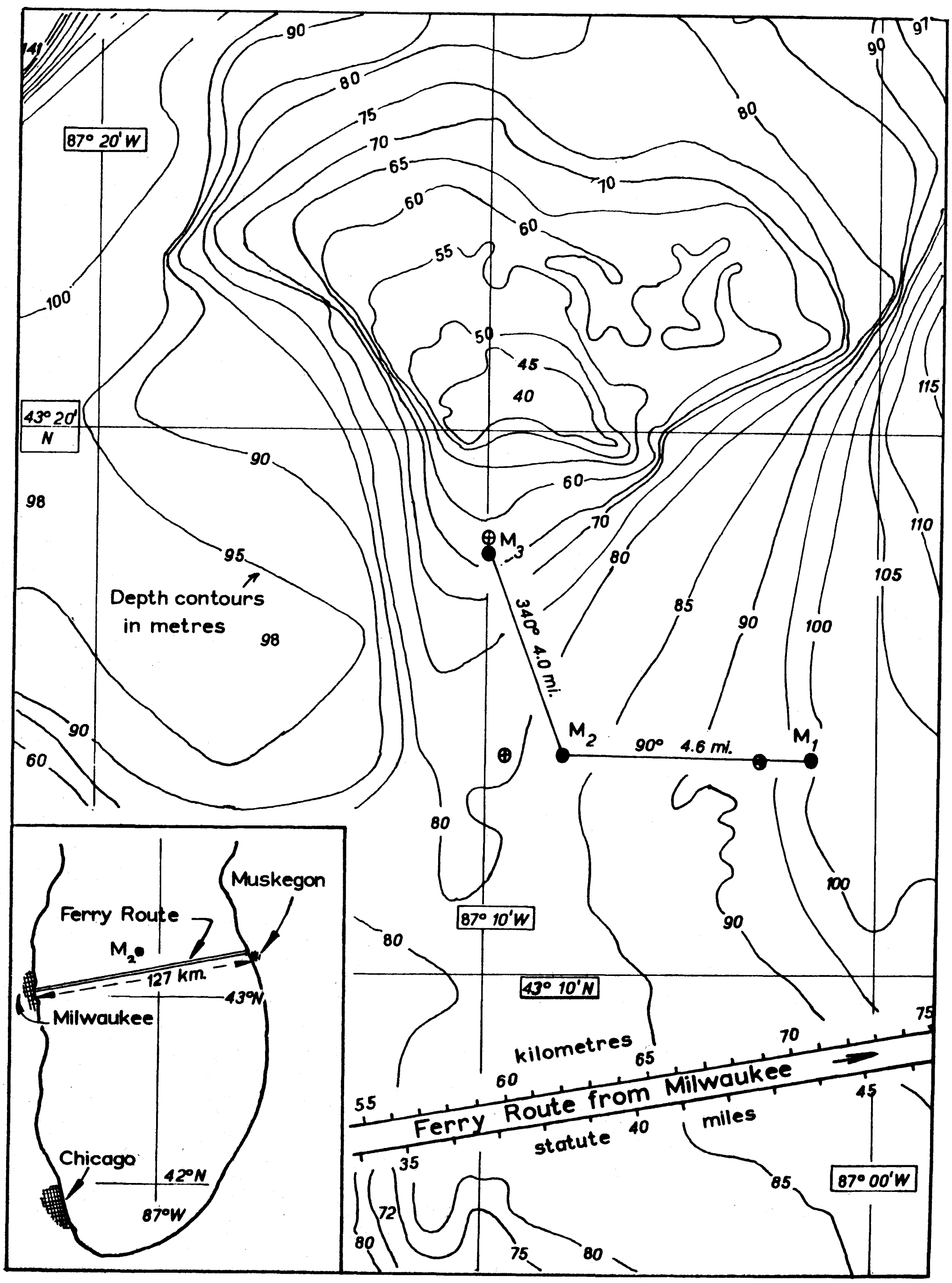


Figure 7 **Positions of the mid-Lake Michigan anchor stations, M_1, M_2 and M_3, and the bottom topography of the region.**

Fig. 8

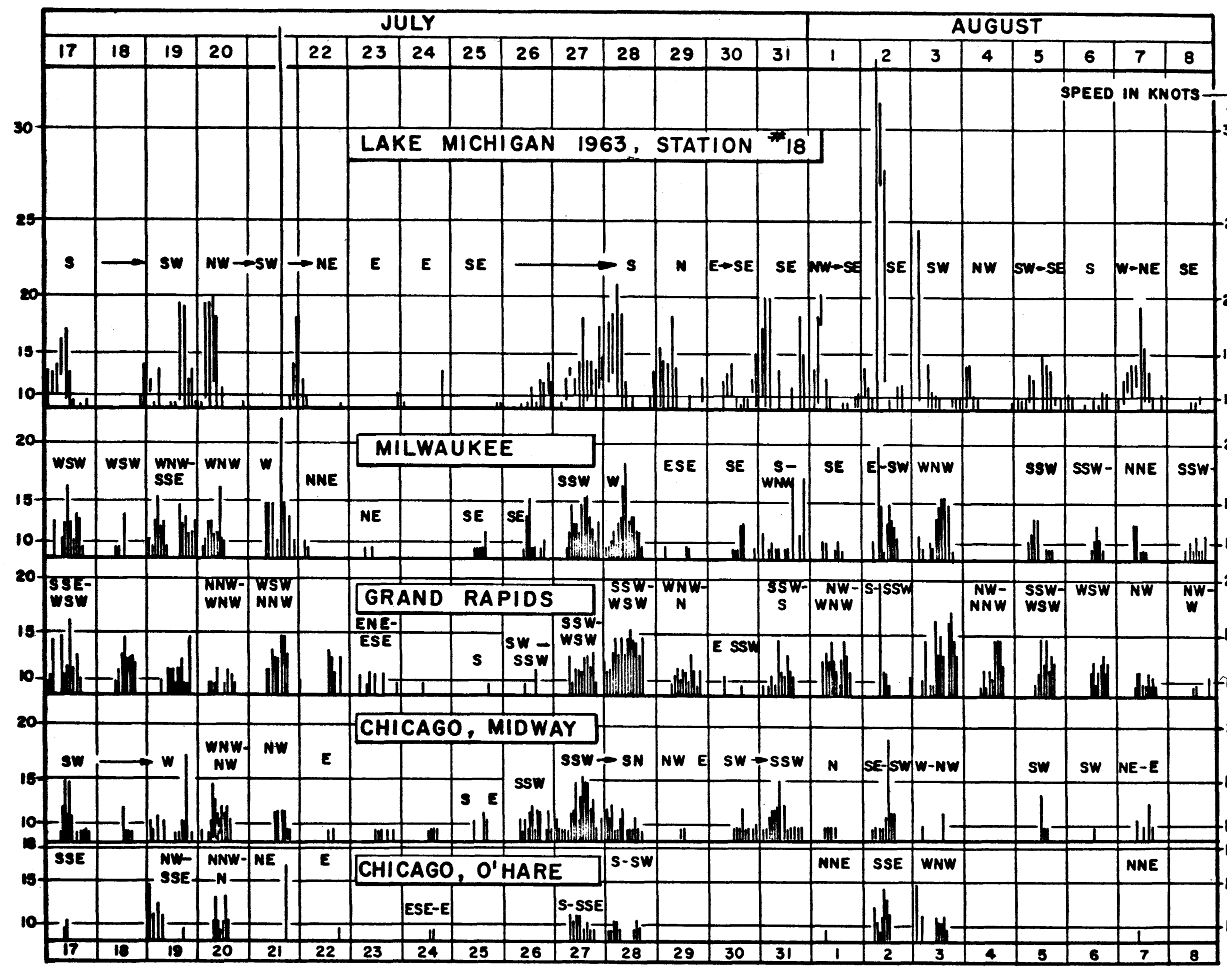


Figure 8 Wind speed and directions at station 18, Lake Michigan (two-hourly ranges between max. and min.), and at four land stations (hourly readings), 1963.

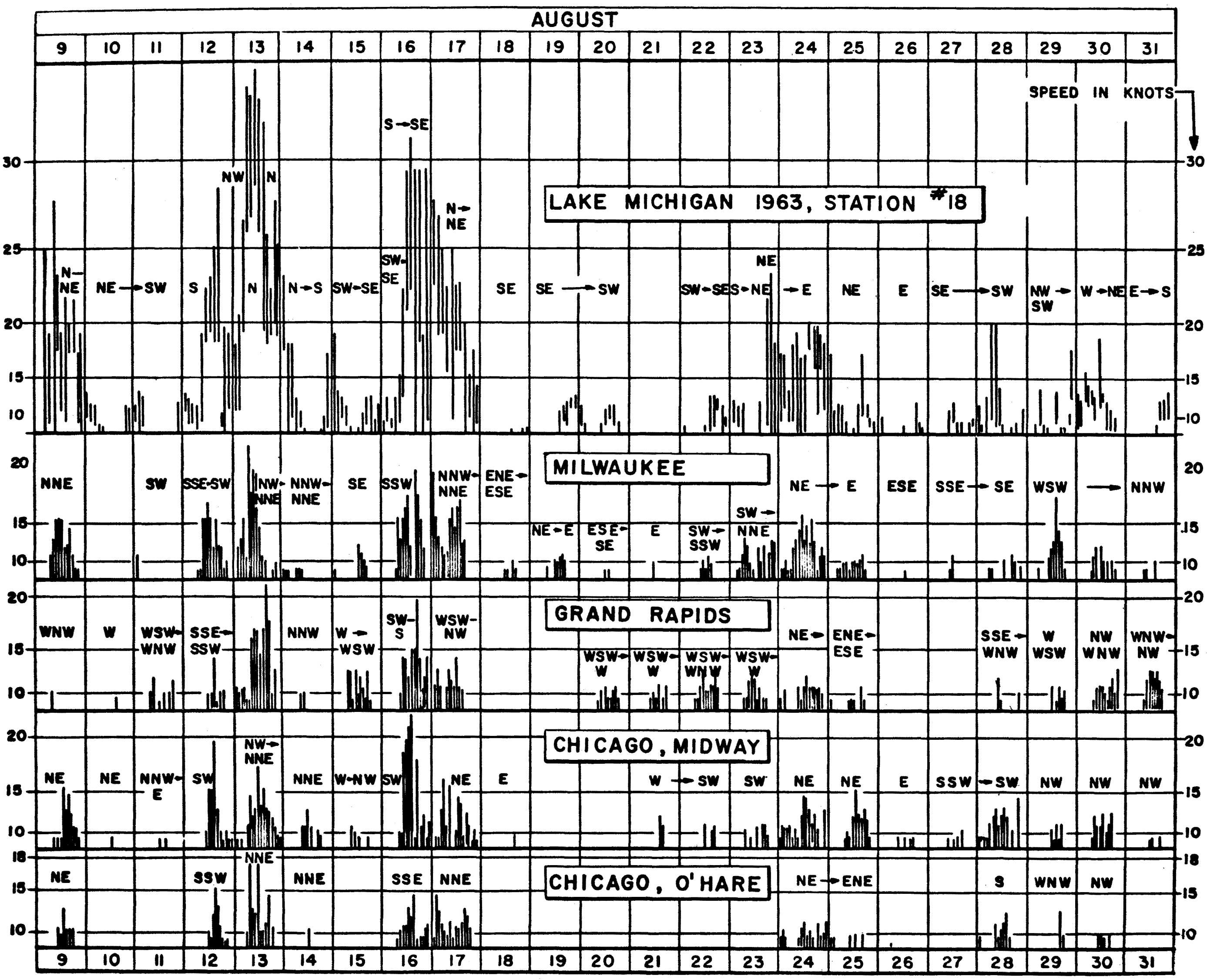


Figure 9 Wind speed and directions at station 18, Lake Michigan (two-hourly ranges between max. and min.), and at four land stations (hourly readings), 1963.

Fig. 10

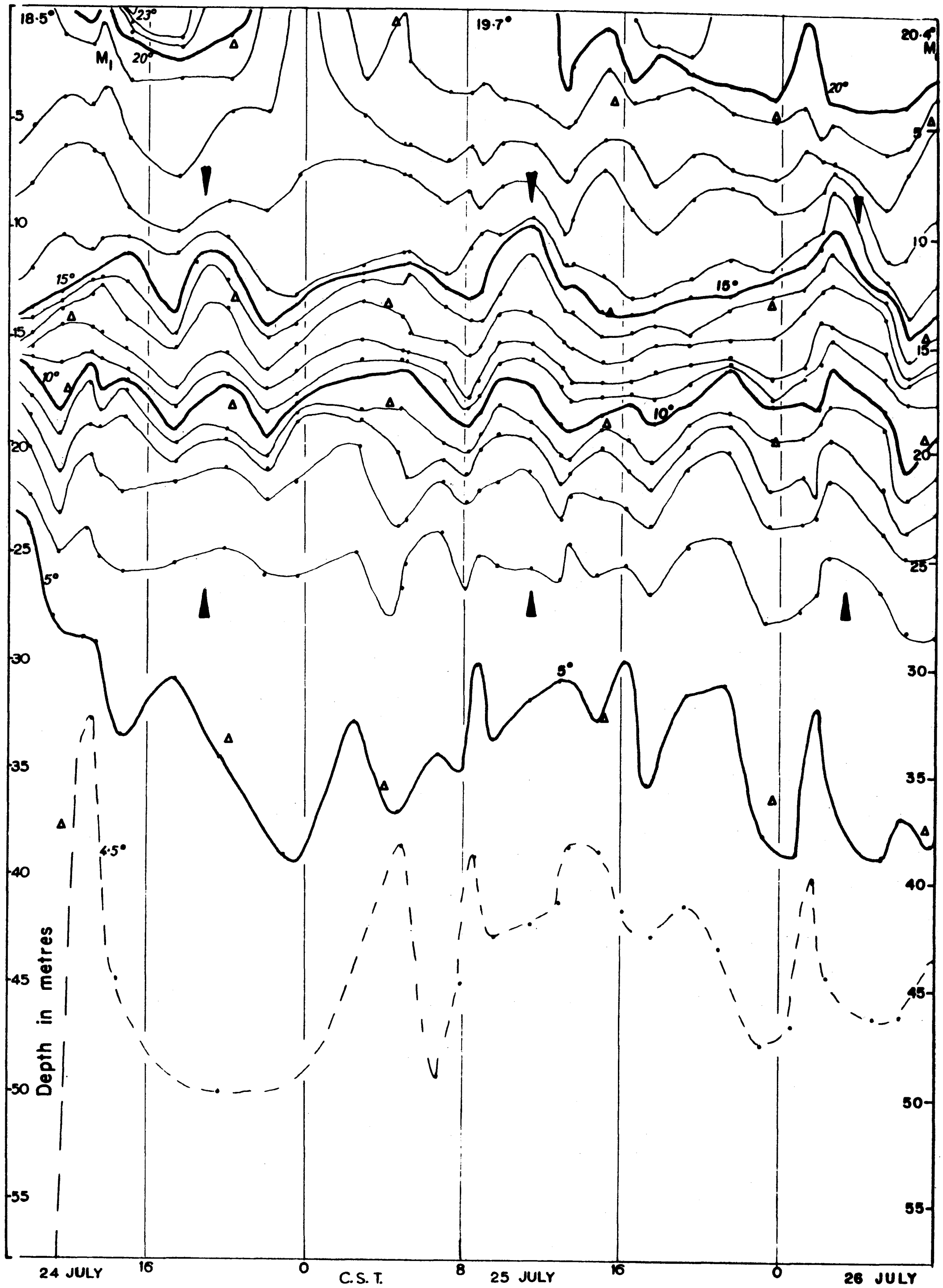


Figure 10 Depth distribution of temperature (°C) at the mid-Lake Michigan anchor station, M_2 (or at M_1 or M_3, where indicated), during the interval 24-26 July, 1963.

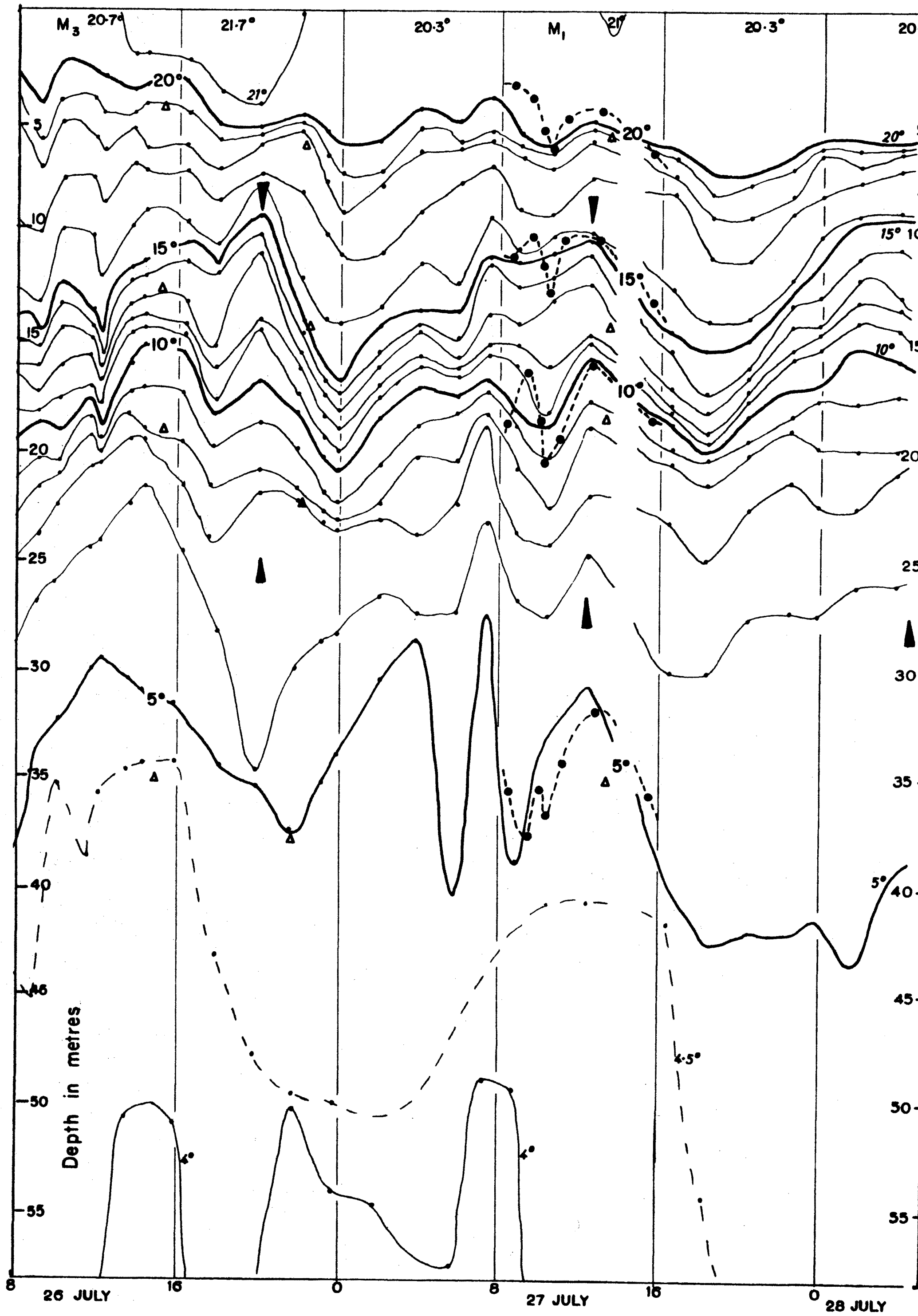


Figure 11 Depth distribution of temperature (°C) at the mid-Lake Michigan anchor station, M_2 (or at M_1 or M_3, where indicated), during the interval 26-28 July, 1963, (continuous with fig. 10).

Fig. 12

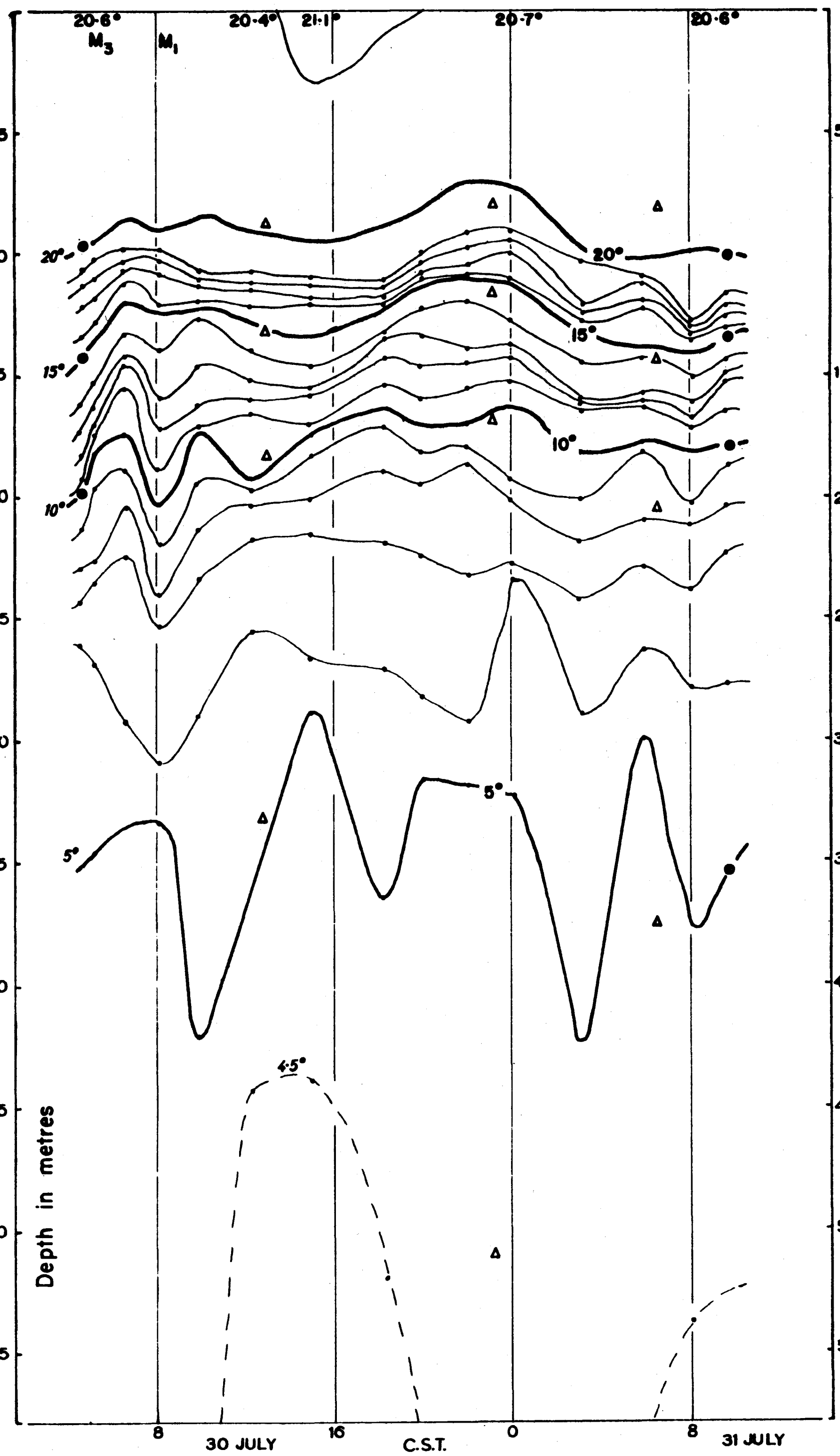


Figure 12 Depth distribution of temperature (°C) at the mid-Lake Michigan anchor station, M_2 (or at M_1 or M_3, where indicated), during the interval 30-31 July, 1963.

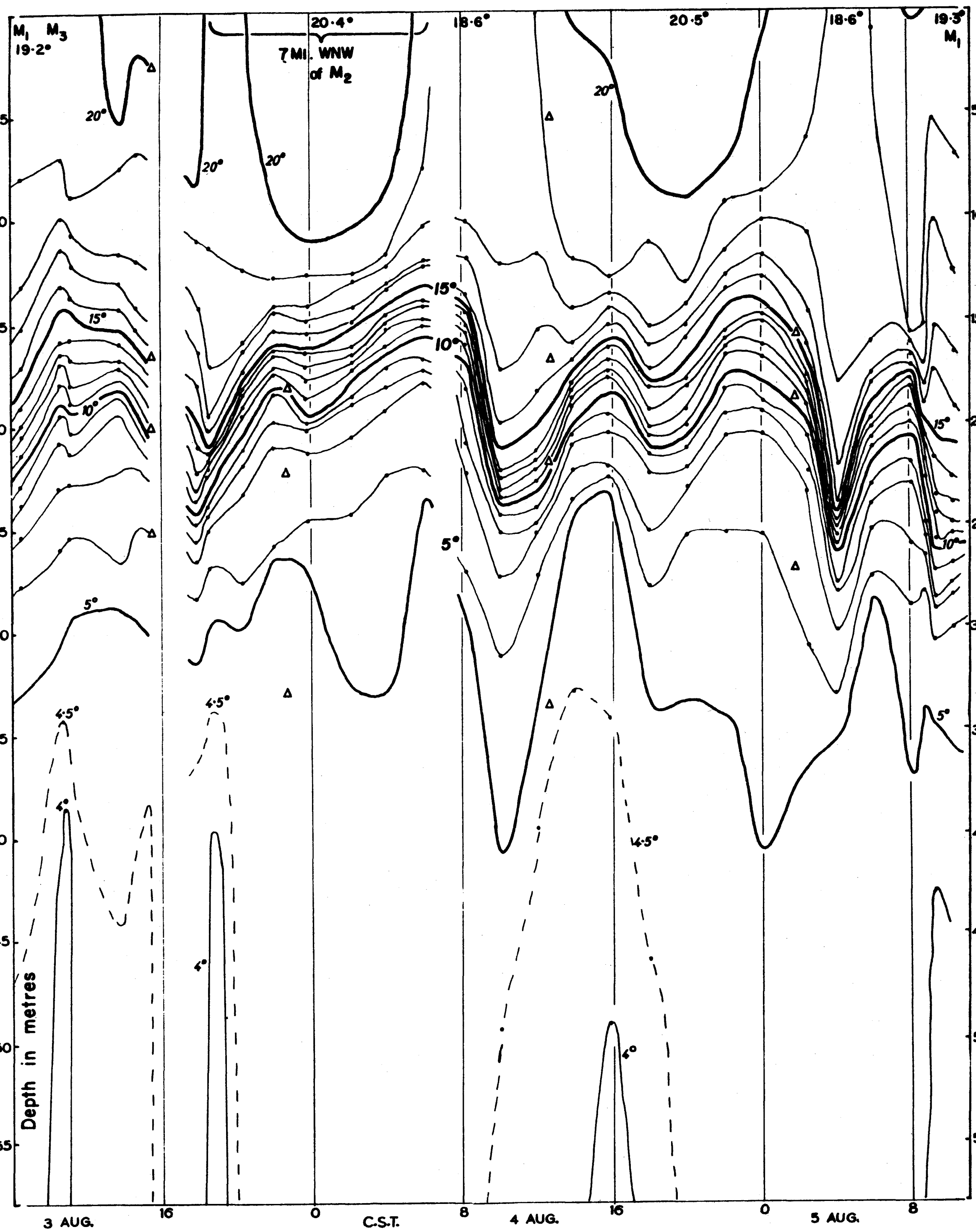


Figure 13 Depth distribution of temperature (°C) at the mid-Lake Michigan anchor station, M_2 (or at M_1 or M_3, where indicated), during the interval 3-5 August, 1963.

Fig. 14

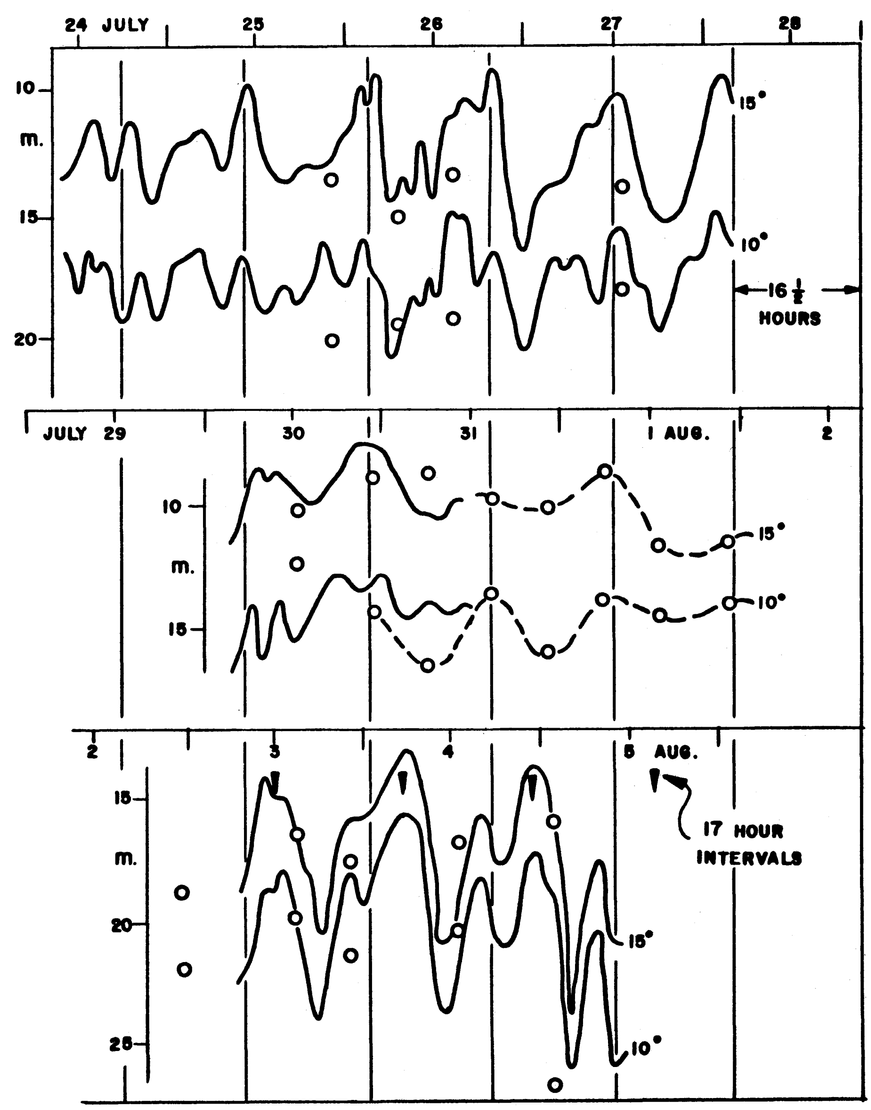
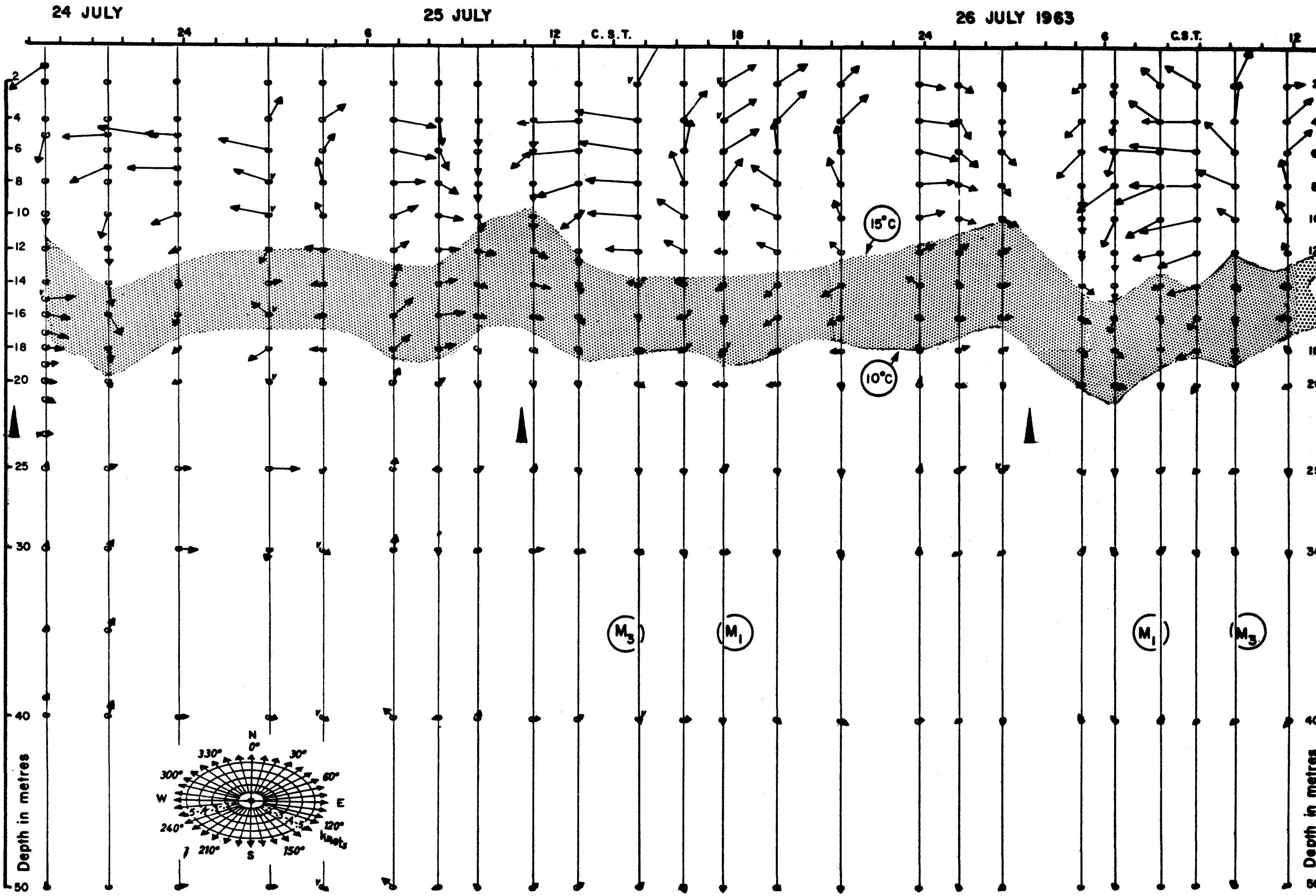


Figure 14 Oscillations in thermocline depth, as indicated by the 10° and 15° isotherms, at mid-Lake Michigan anchor station, M_2, during the interval 24 July-5 August, 1963. The time scale is divided in intervals of 16.5 hours. Further details in text.

Figure 15 Depth-distribution of currents at a mid-Lake Michigan anchor station, M_2 (or at M_1 or M_3, where indicated), during the interval 24-26 July, 1963.[1]



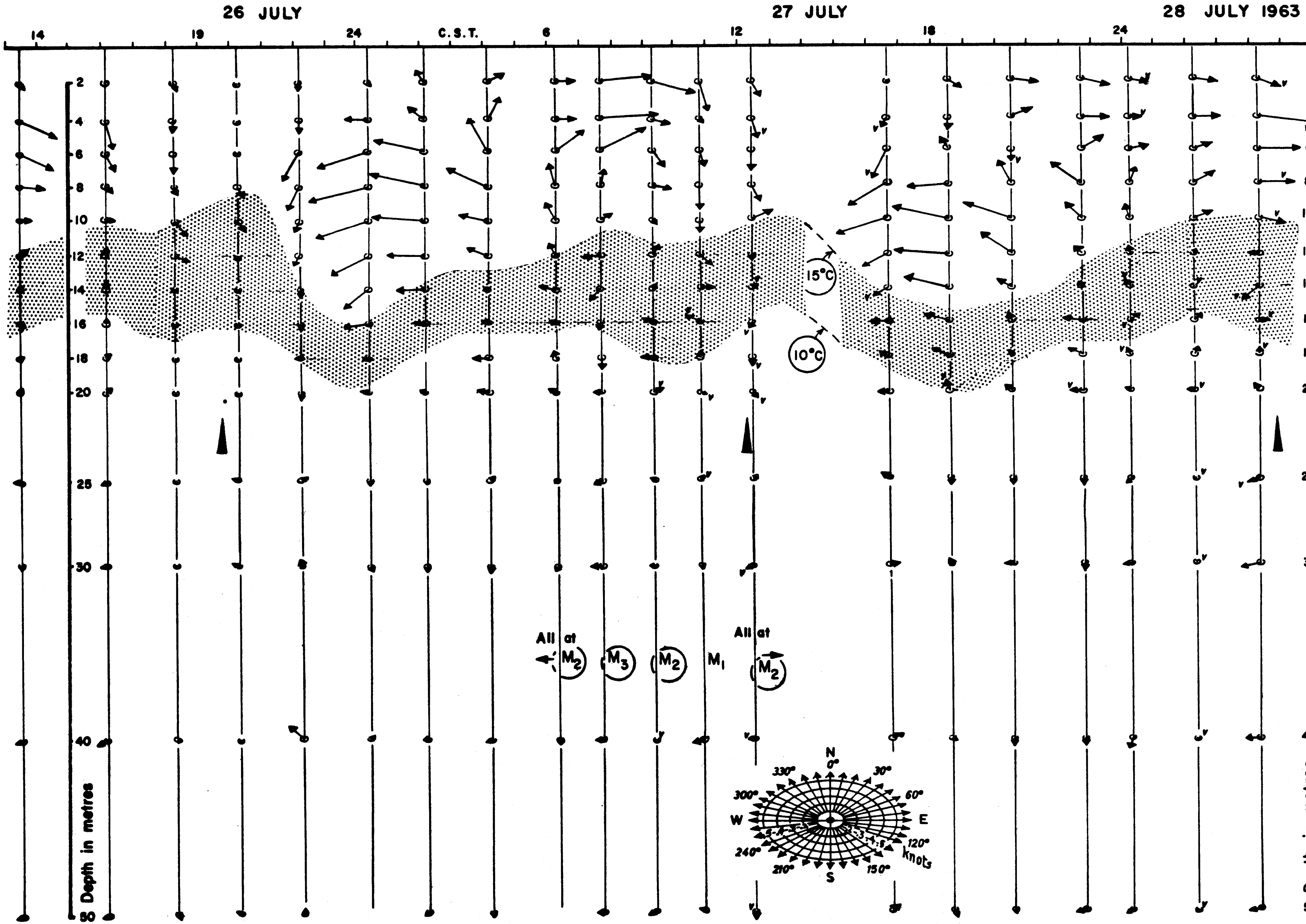


Figure 16 Depth-distribution of currents at a mid-Lake Michigan anchor station, M_2 (or M_1 or M_3, where indicated), during the interval 26-28 July, 1963 (continuous with Fig. 15).

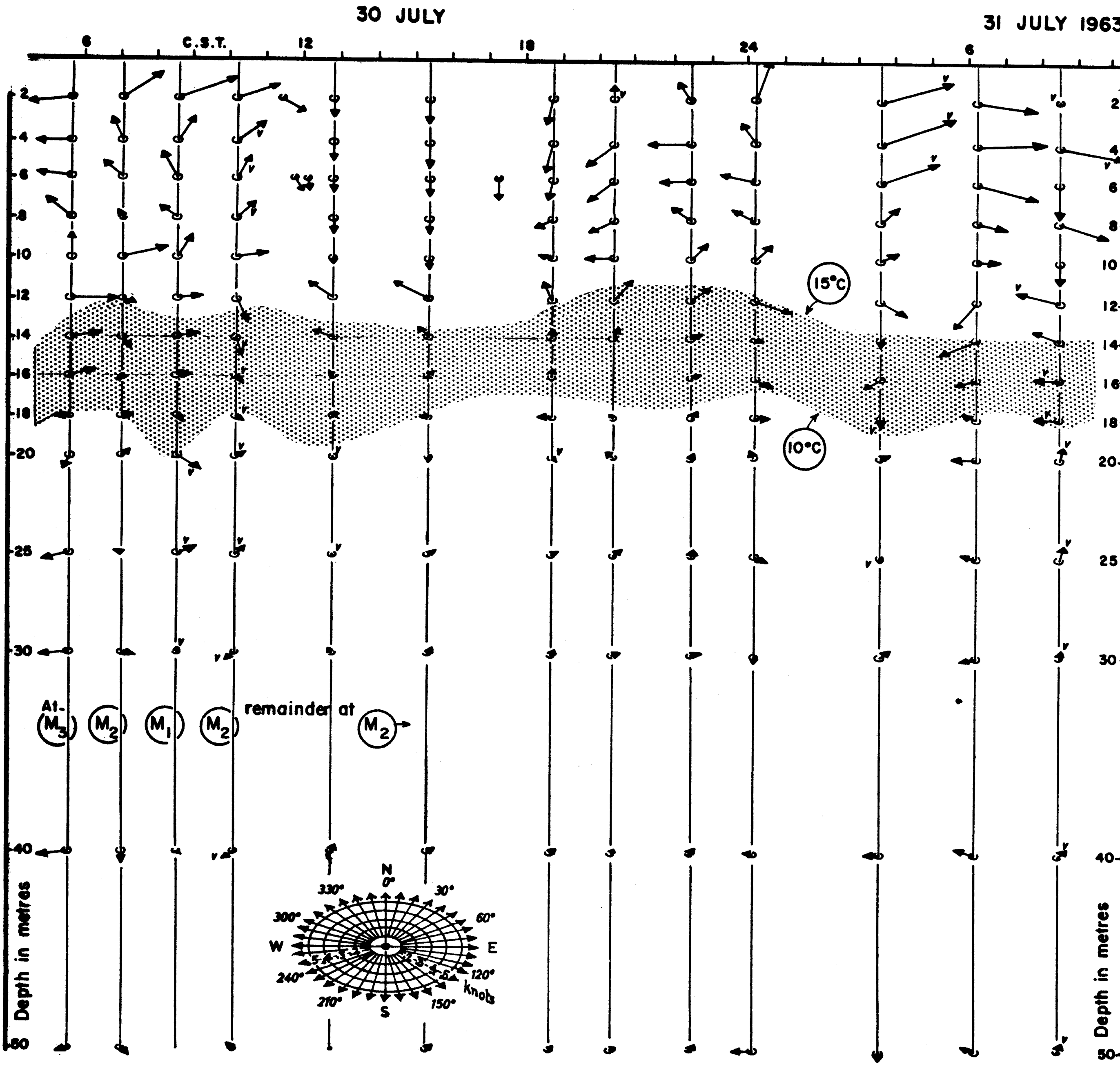


Figure 17 Depth-distribution of currents at a mid-Lake Michigan anchor station, M_2, (or at M_1 or M_3, where indicated), during the interval 30-31 July, 1963.

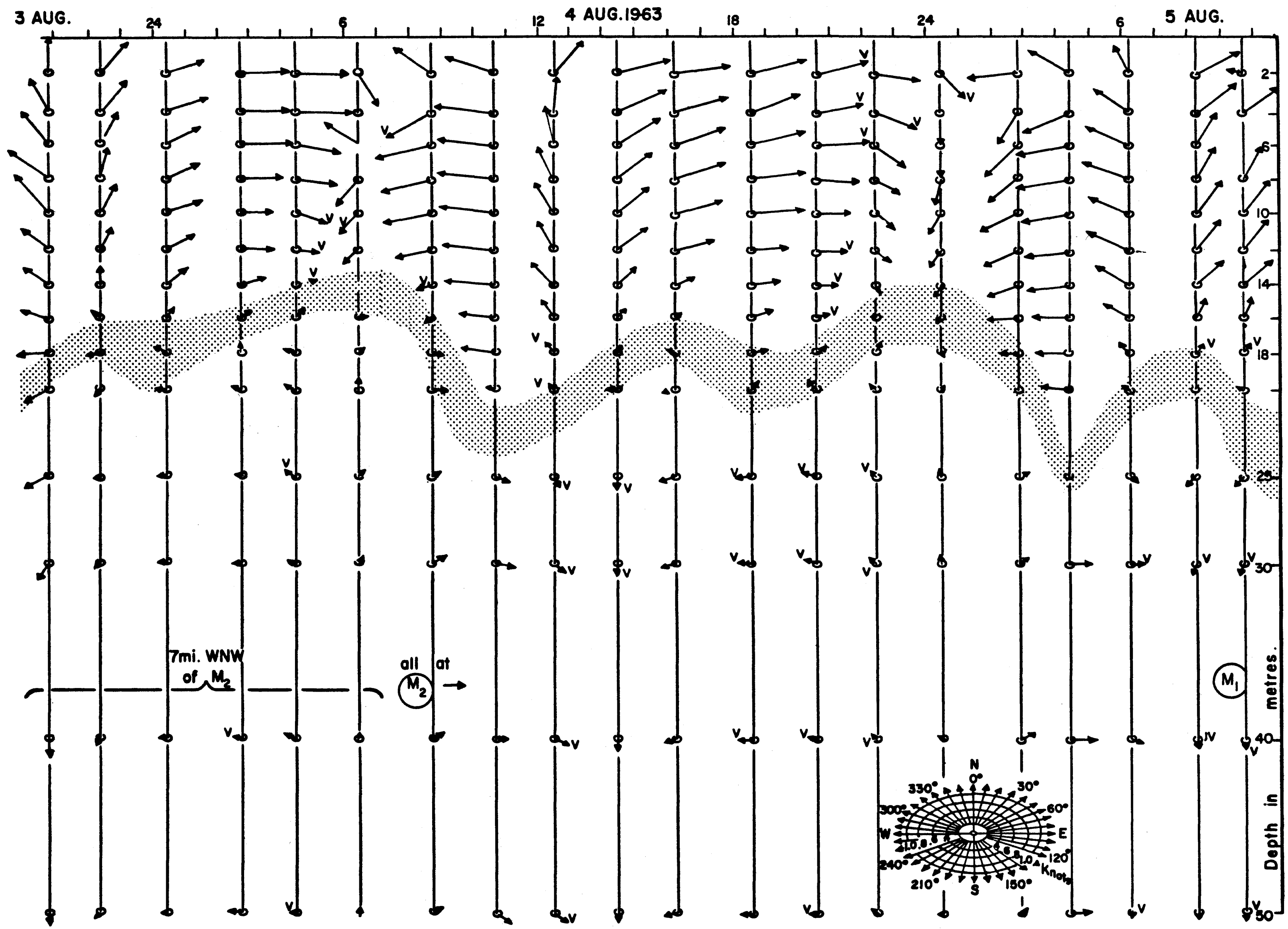


Figure 18 Depth-distribution of currents at a mid-Lake Michigan anchor station, M_2 (or M_1 or M_3, where indicated), during the interval 3-5 August, 1963.

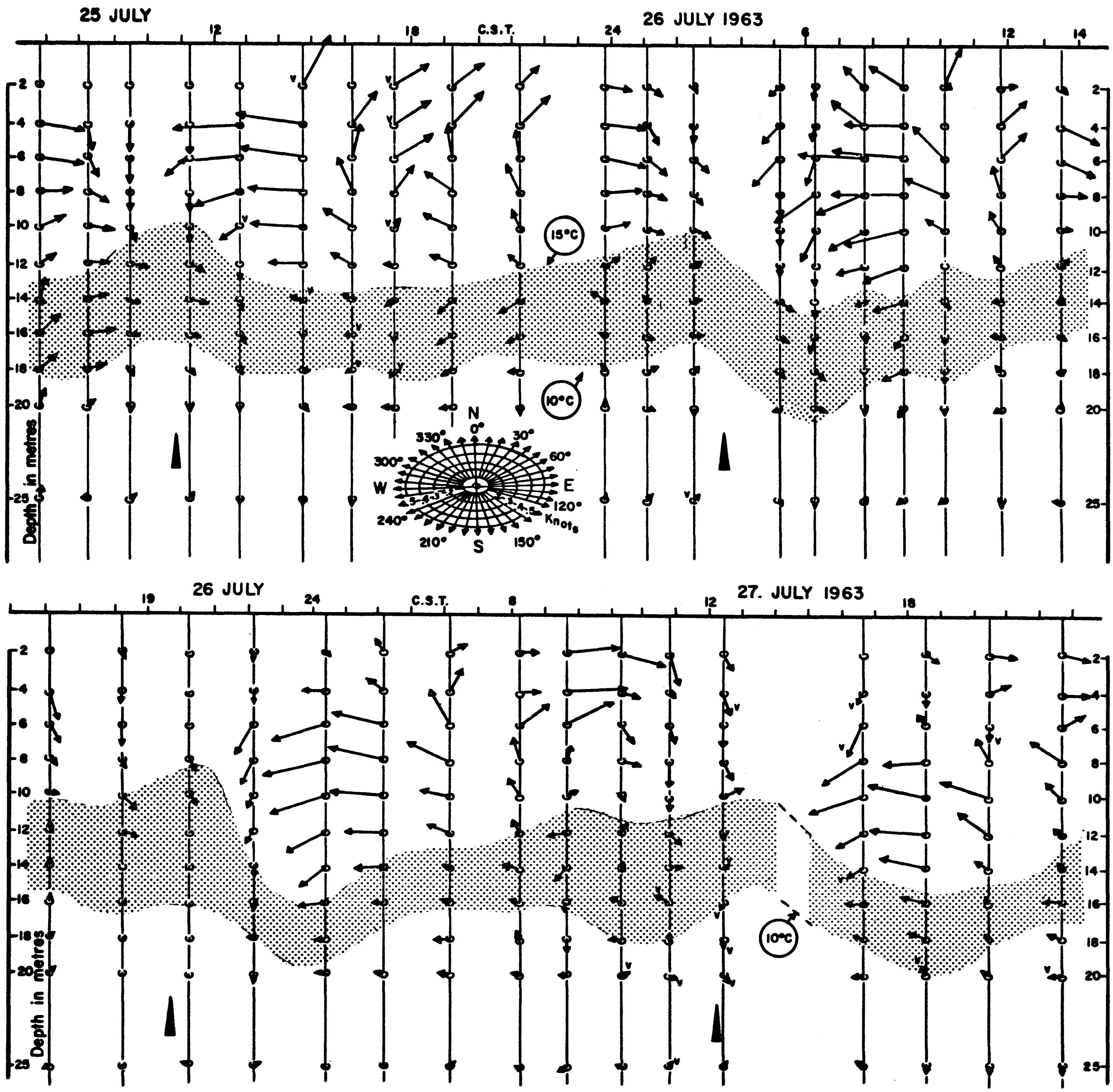


Figure 19 Portions of figs. 15 and 16 arranged to show correlation between the internal wave and the current pattern (at station M_2, Lake Michigan) as described in the text.

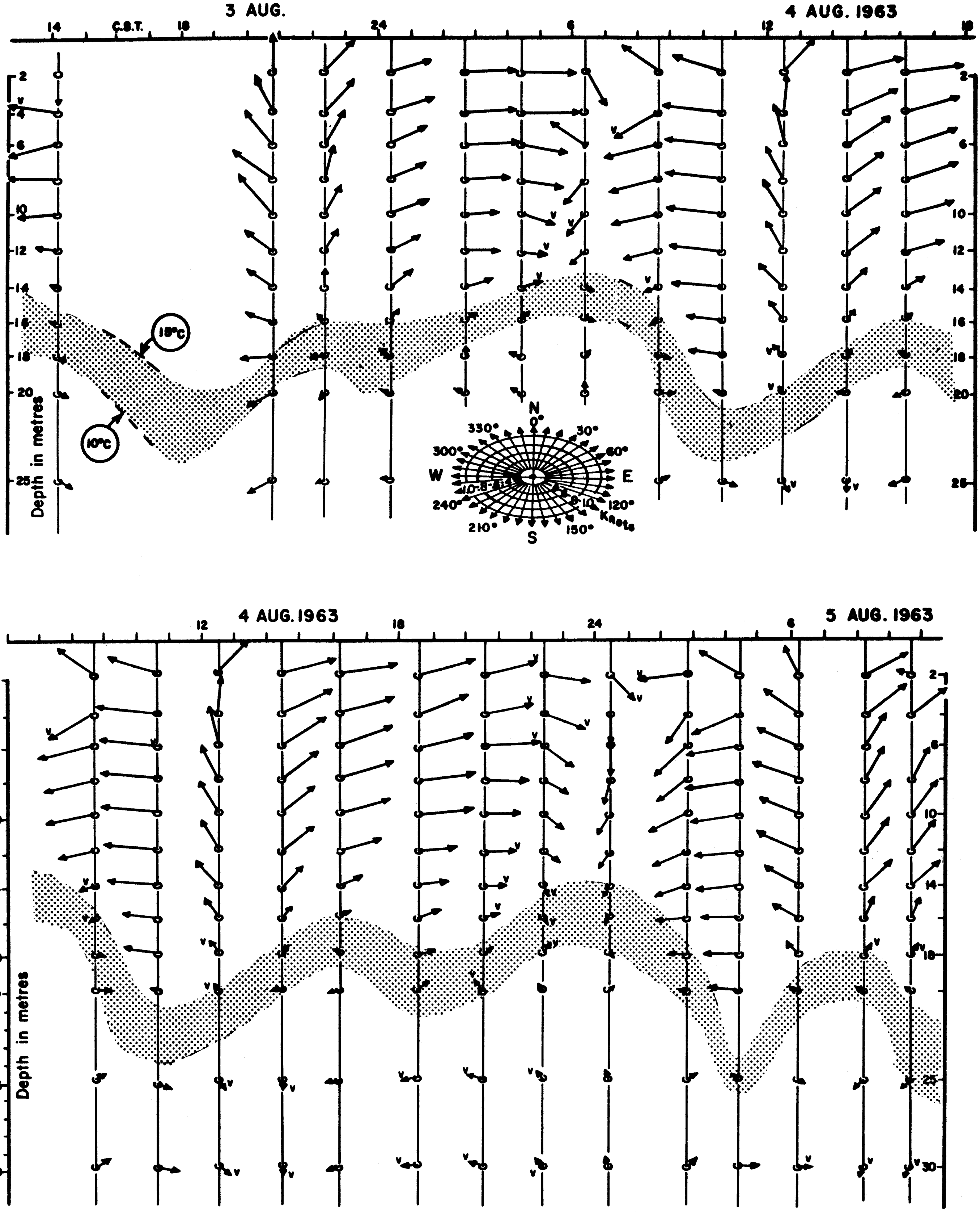


Figure 20 Portions of fig. 18 arranged to show correlation between the internal wave and the current pattern (at station M_2, Lake Michigan) as described in the text.

Fig. 21

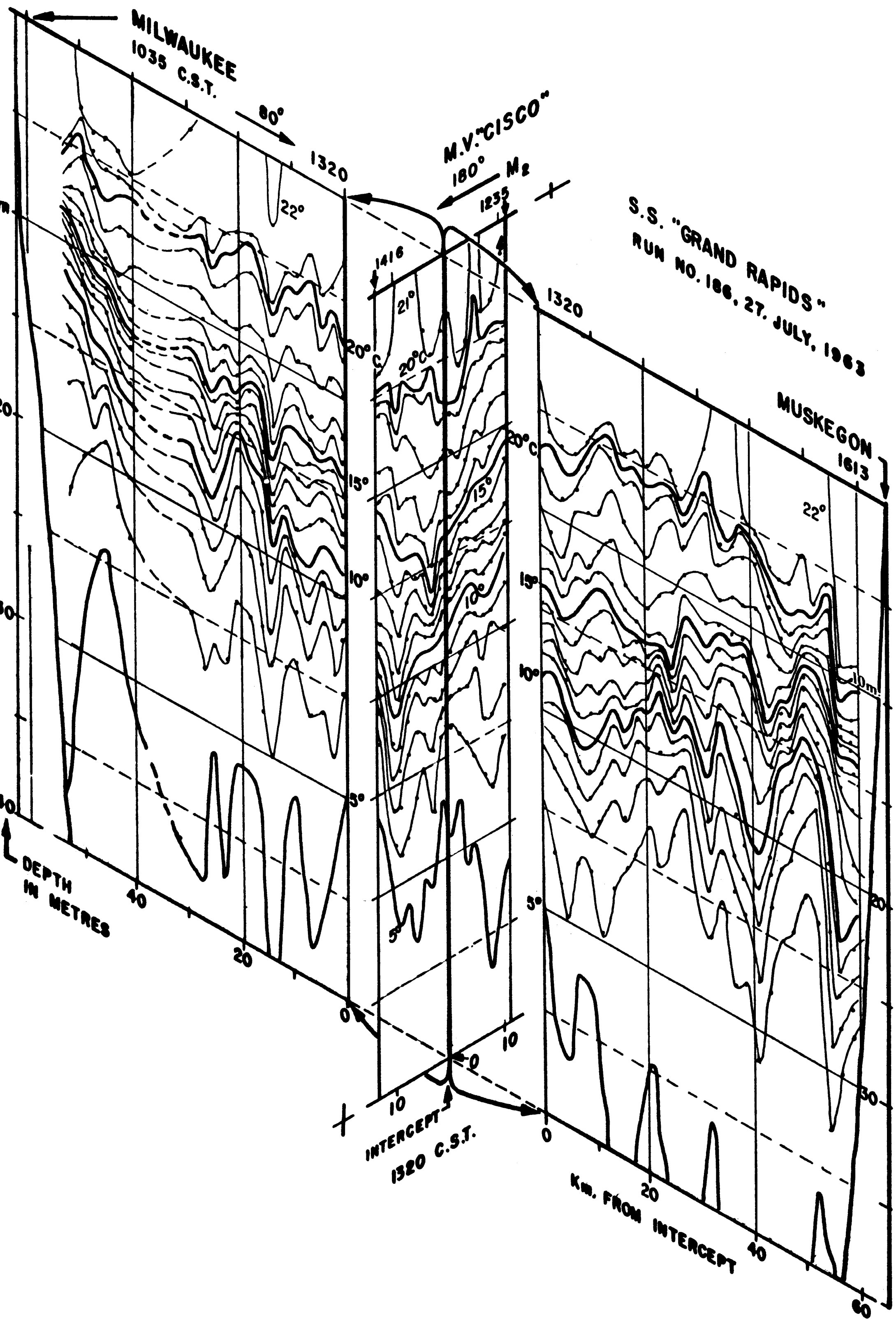


Figure 21 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, 27 July 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V "Cisco"; directions are shown in degrees (true).

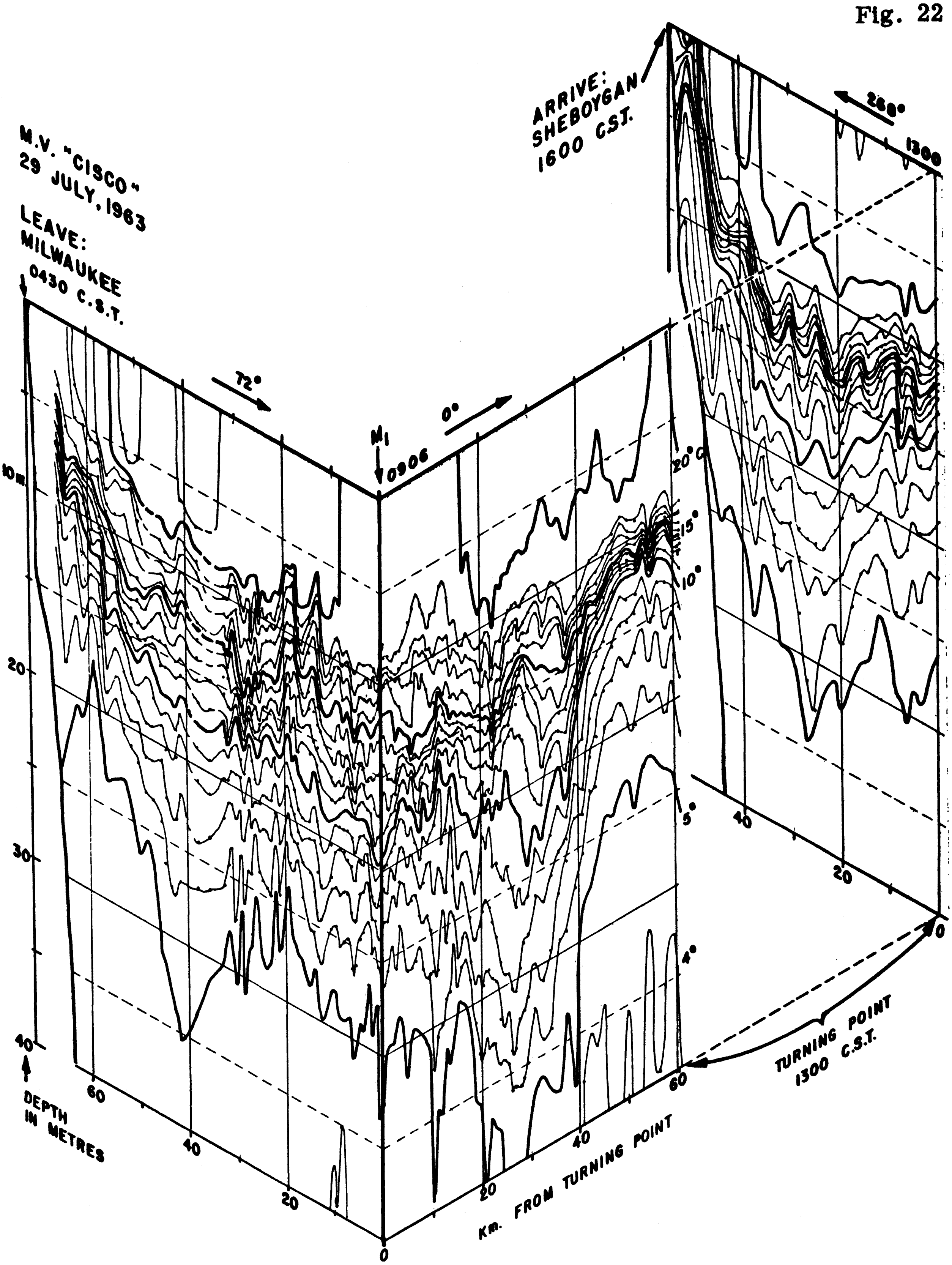


Figure 22 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, 29 July, 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V. "Cisco"; directions are shown in degrees (true).

Fig. 23

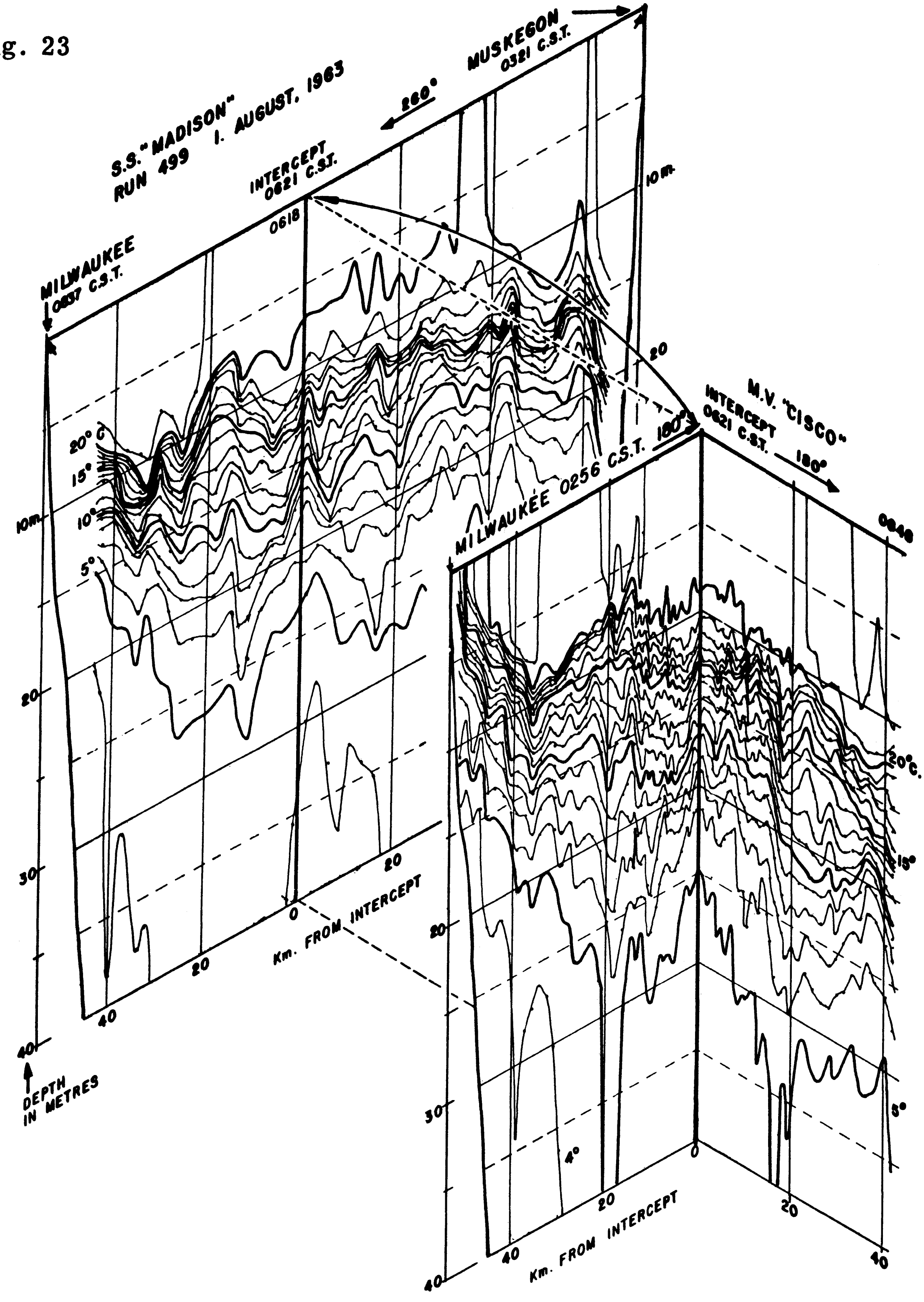


Figure 23 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, a.m., 1 August 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V. "Cisco"; directions are shown in degrees (true).

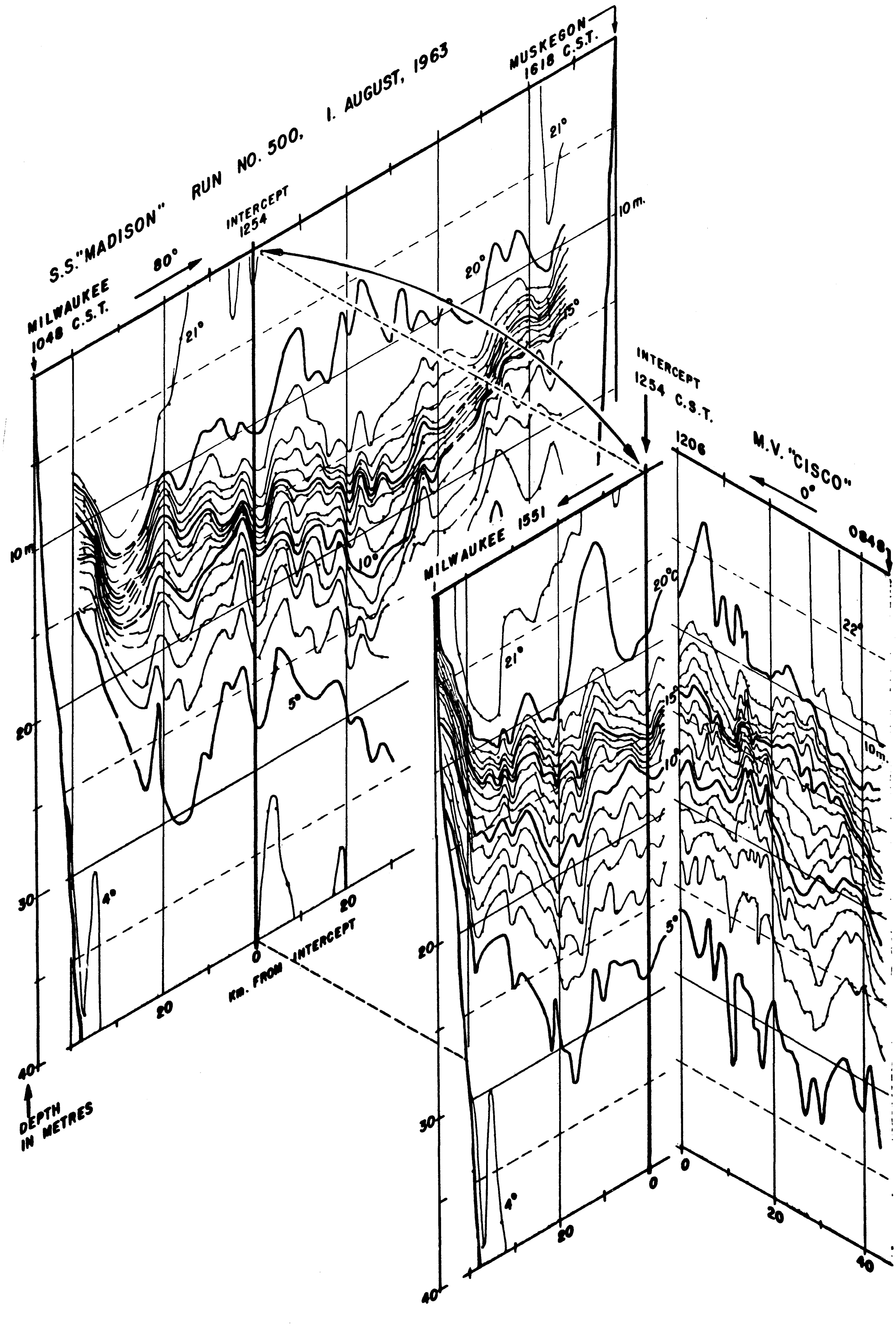


Figure 24 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, p.m., 1 August 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V. "Cisco"; directions are shown in degrees (true).

Fig. 25

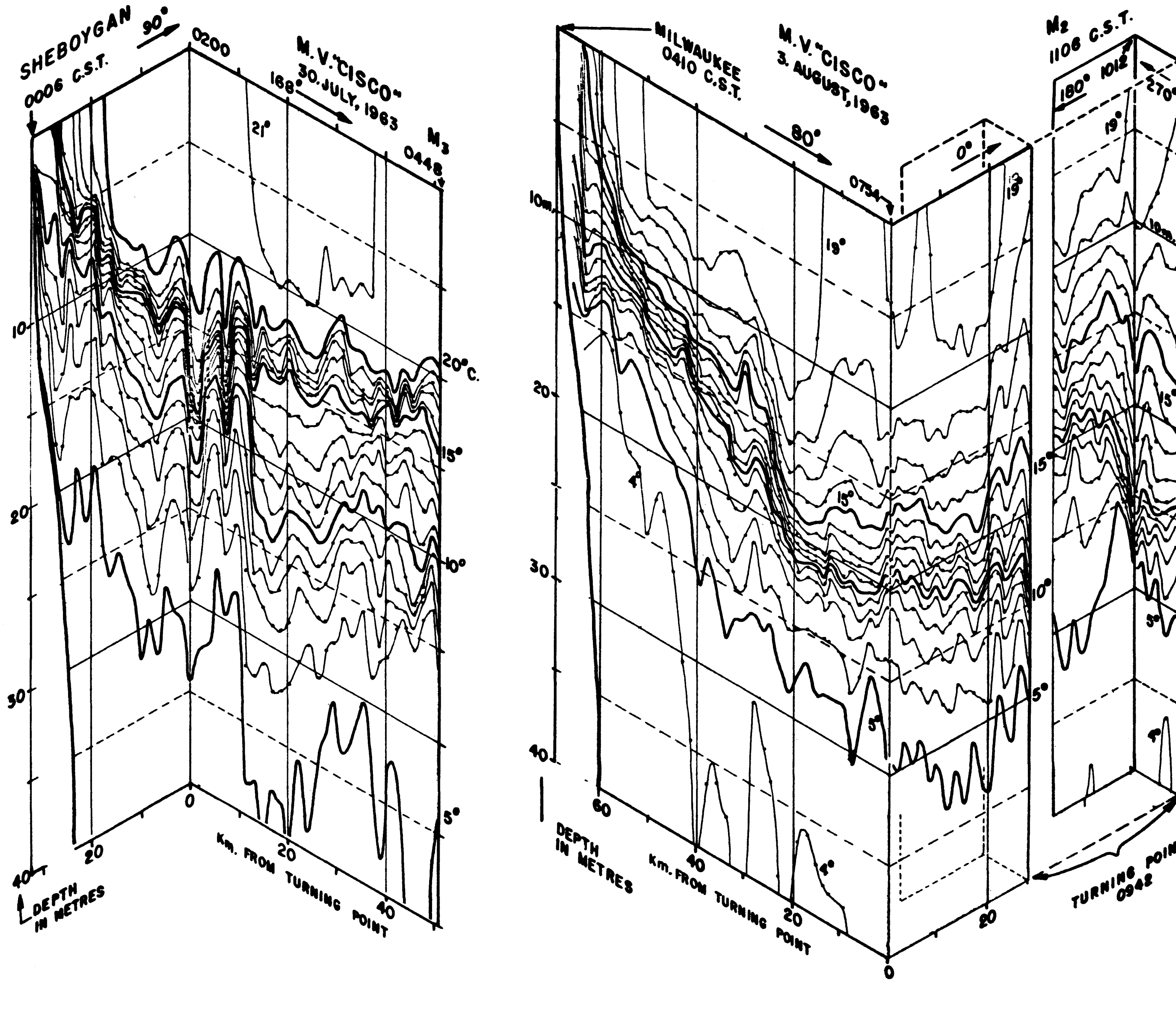


Figure 25 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, 30 July and a.m. 3 August, 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V. "Cisco"; directions are shown in degrees (true).

Fig. 26

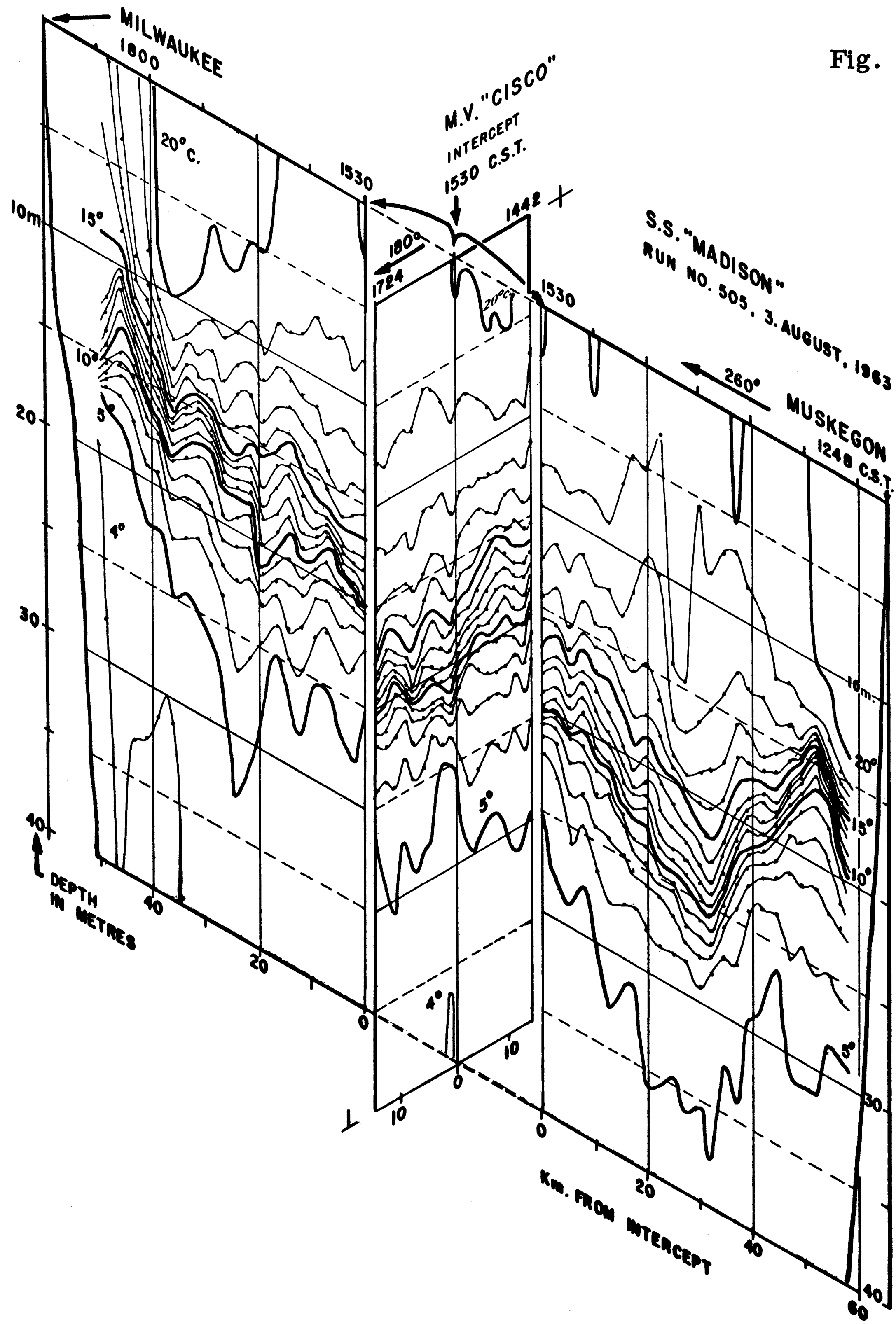


Figure 26 Presentation, on isometric projection, of temperature distributions in connecting or intersecting sections of Lake Michigan, p.m. 3 August, 1963. Run nos. indicate railroad ferry runs on the Milwaukee-Muskegon route; other sections were run by M.V. "Cisco"; directions are shown in degrees (true).

Fig. 27

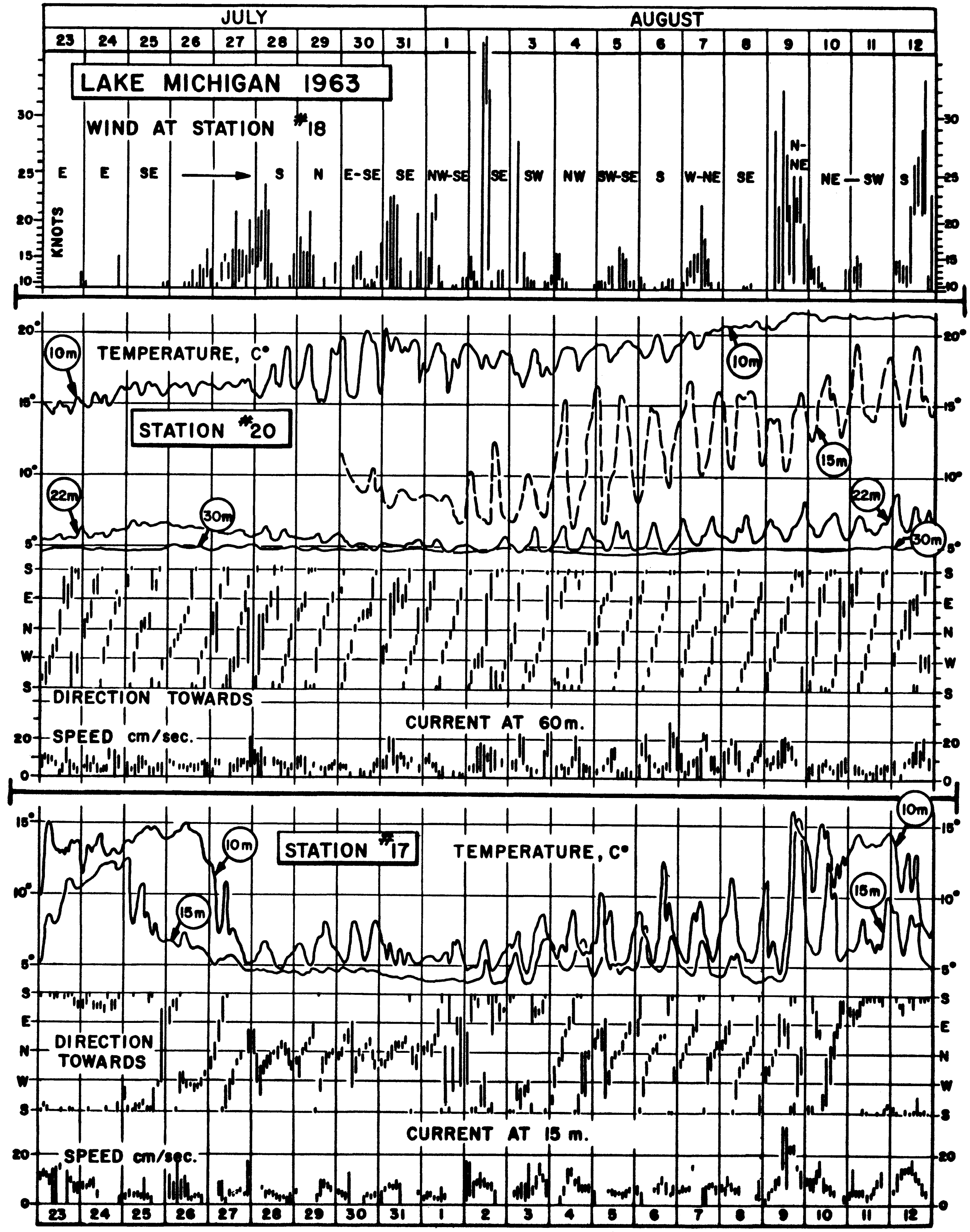


Figure 27 Records of current and temperature at various depths at two stations (17 and 20), and of wind at station 18, in Lake Michigan 1963. These stations were operated by the Federal Water Pollution Control Administration (U.S. Dept. Interior) and their positions are shown in Fig. 6. For further details, see text.

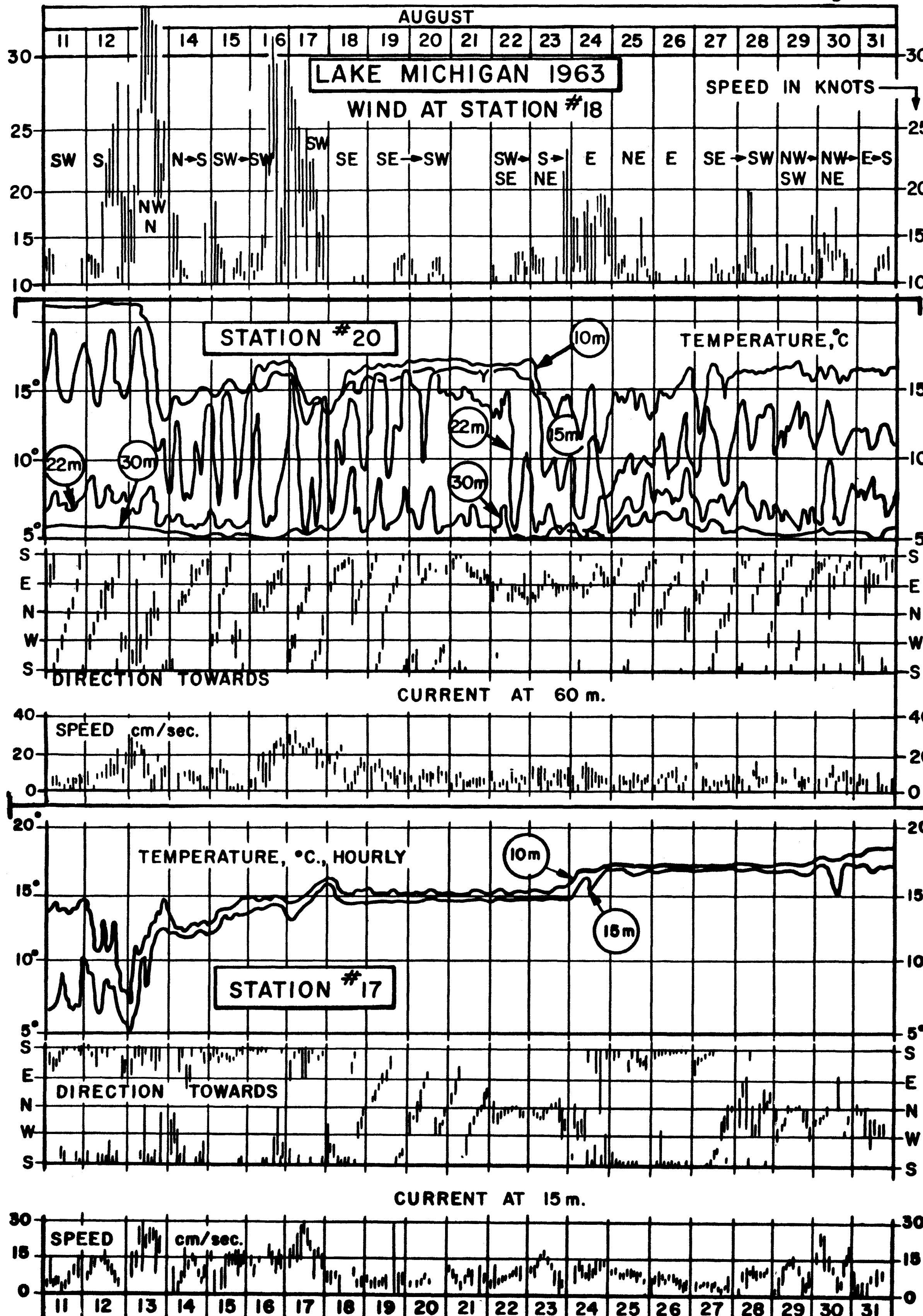


Figure 28 Records of current and temperature at various depths at two stations (17 and 20), and of wind at station 18, in Lake Michigan, 1963. These stations were operated by the Federal Water Pollution Control Administration (U.S. Dept. Interior) and their positions are shown in Fig. 6. For further details, see text.

Fig. 29

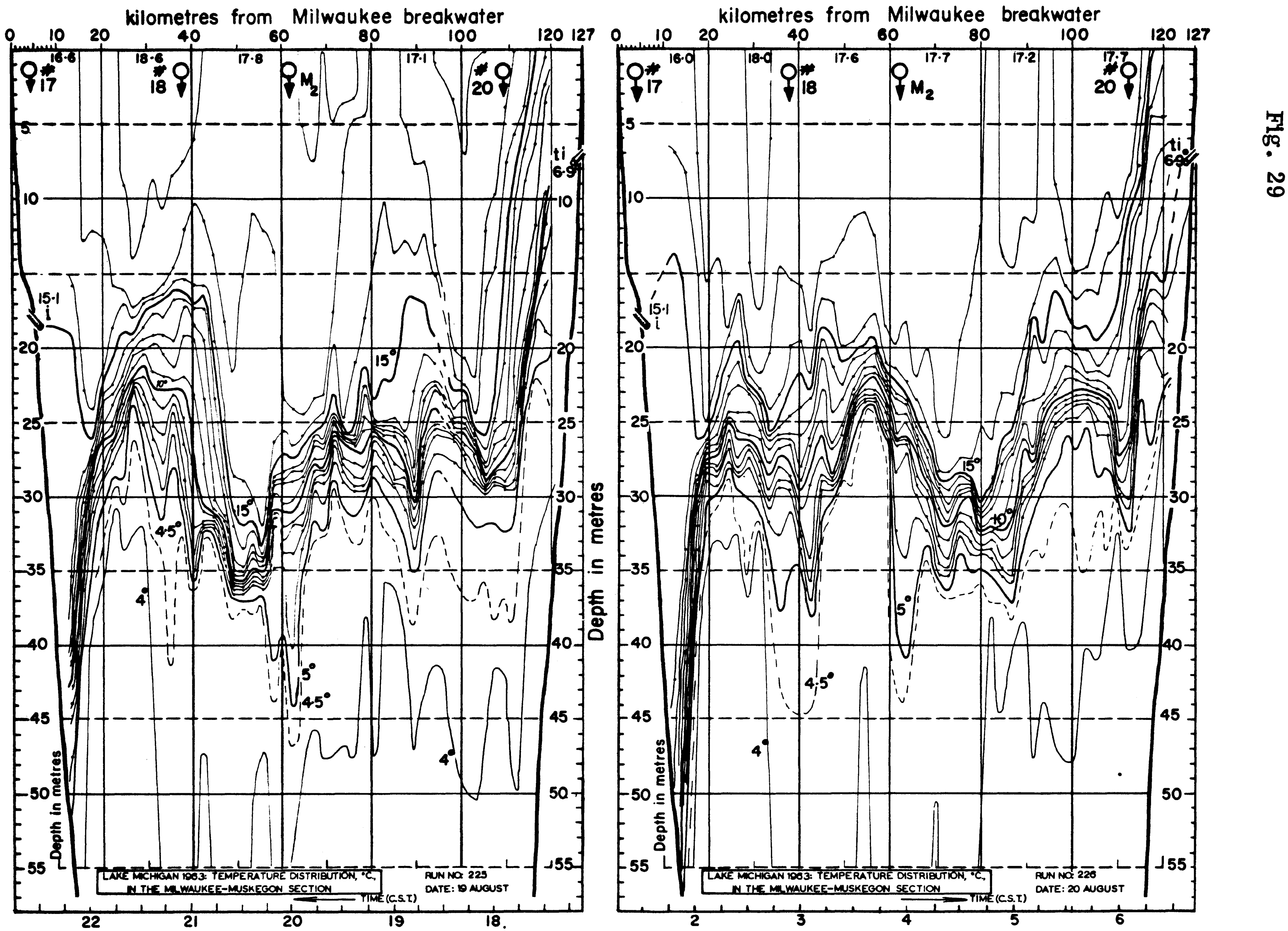


Figure 29 Distribution of temperature (°C) in the Milwaukee-Muskegon cross-section of Lake Michigan during two consecutive runs of the railroad car ferry, S.S. "Grand Rapids," 19-20 August, 1963. Arrows at the top of the figure indicate relative positions of fixed measuring stations (see Fig. 6).

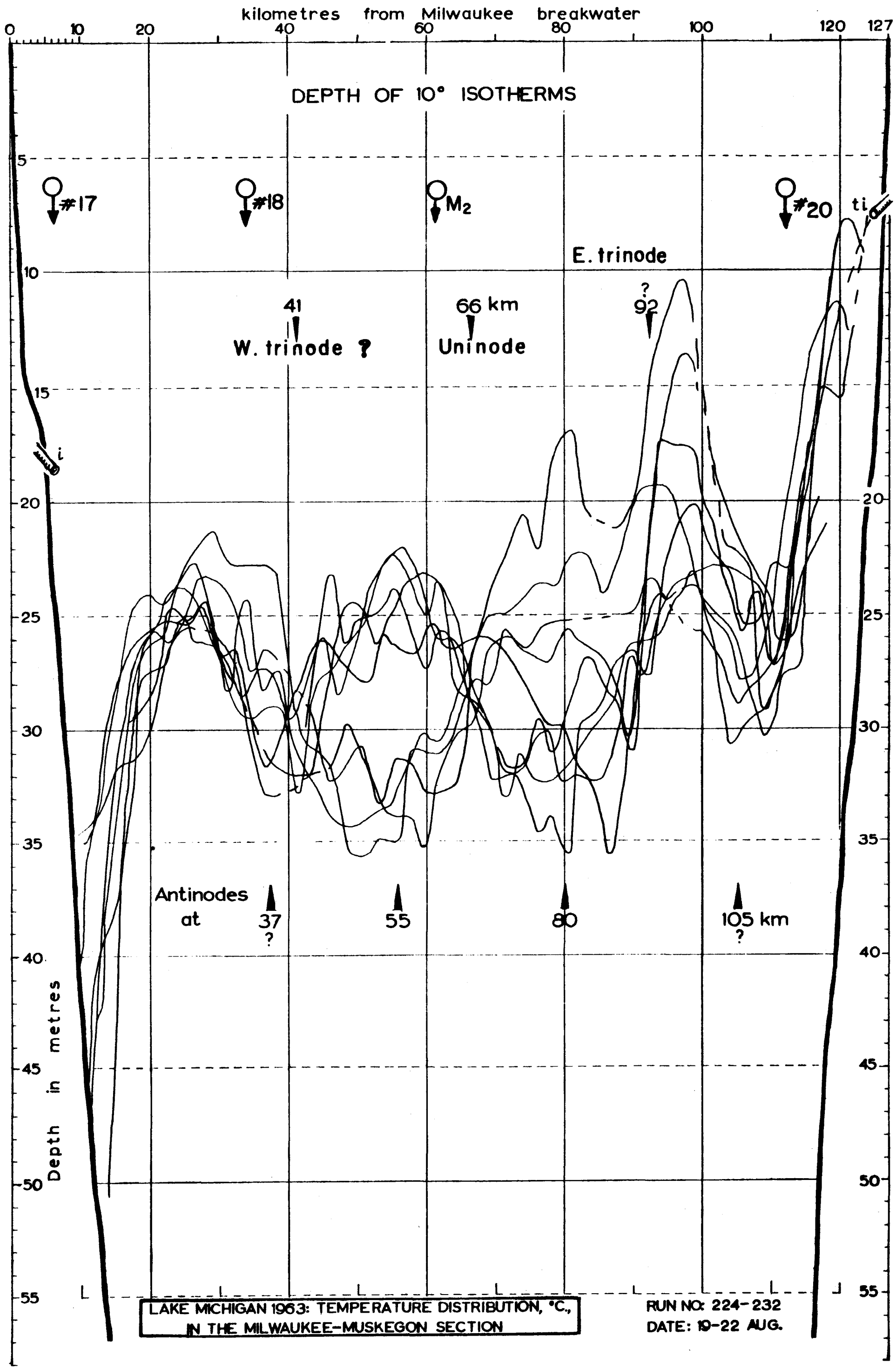


Figure 30 Distribution of the 10° isotherm in the Milwaukee-Muskegon cross-section of Lake Michigan during nine consecutive runs of the railroad ferry, S. S. "Grand Rapids," 19-22 August, 1963.

Fig. 31

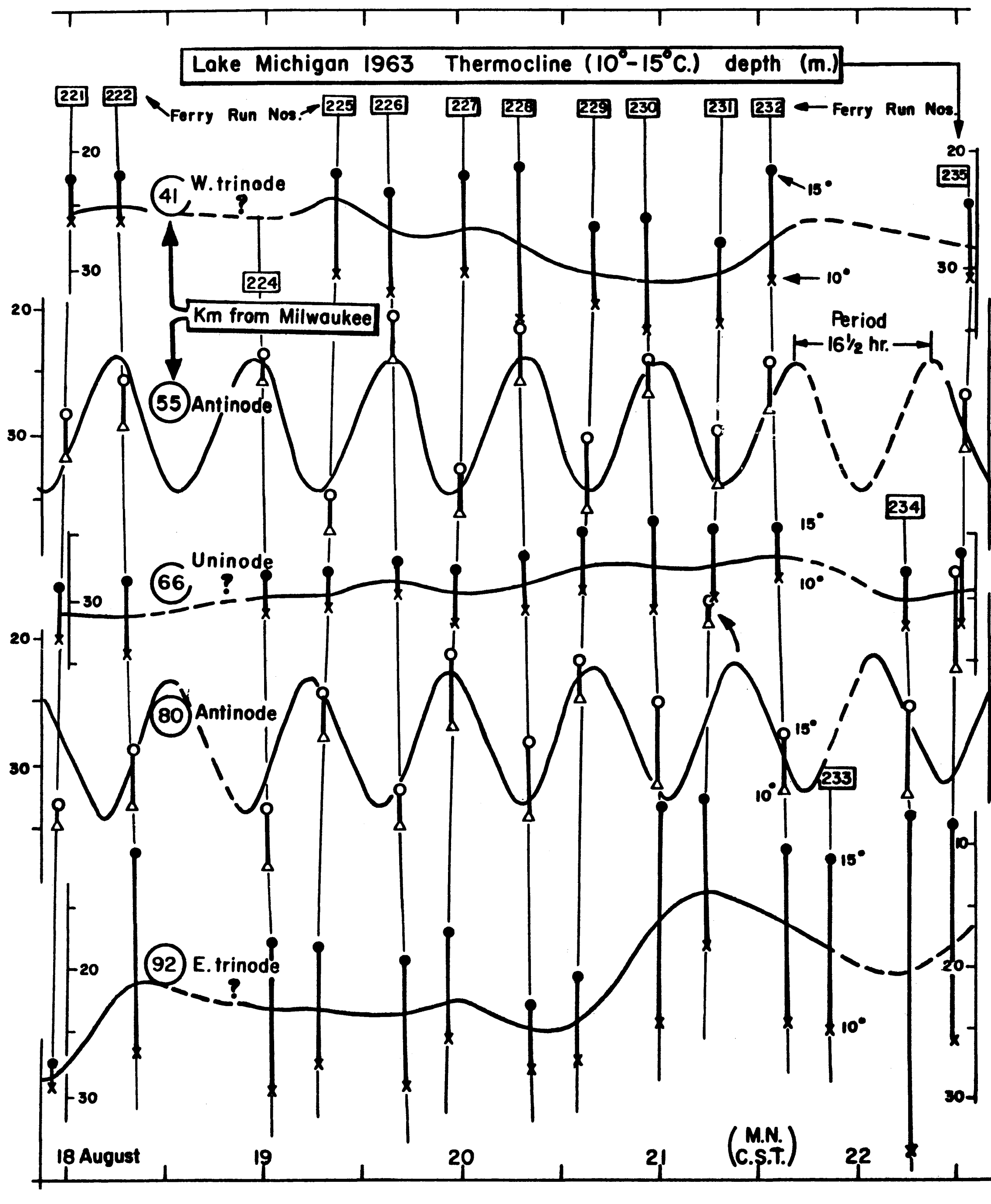


Figure 31 Oscillations in depth of the thermocline (bounded by the 10° and 15° isotherms) at certain points along the Milwaukee-Muskegon cross-section of Lake Michigan, corresponding to presumed nodes and antinodes (details in text), and as observed on the passages of the railroad ferry, S. S. "Grand Rapids," 18-22 August, 1963.

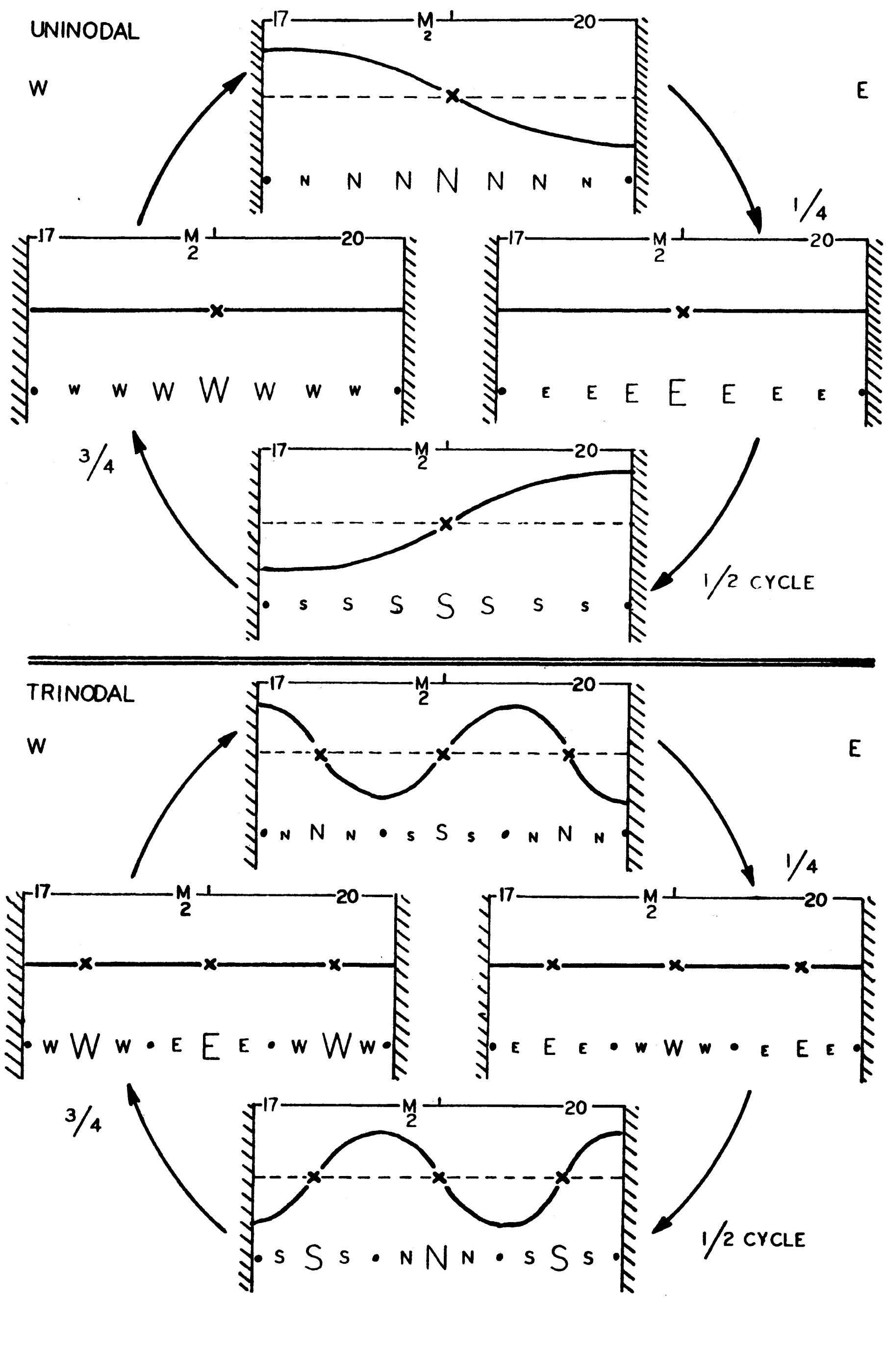


Figure 32 Sections, at quarter-cycle phase intervals, across a uninodal and trinodal standing Poincaré wave in a two-layered model, rotating counterclockwise, and representing the Milwaukee-Muskegon cross-section of Lake Michigan looking north. The lettered directions are those toward which the current is flowing in the lower layer. The relative positions of stations 17, M_2 and 20 are indicated (further details in text).

Fig. 33

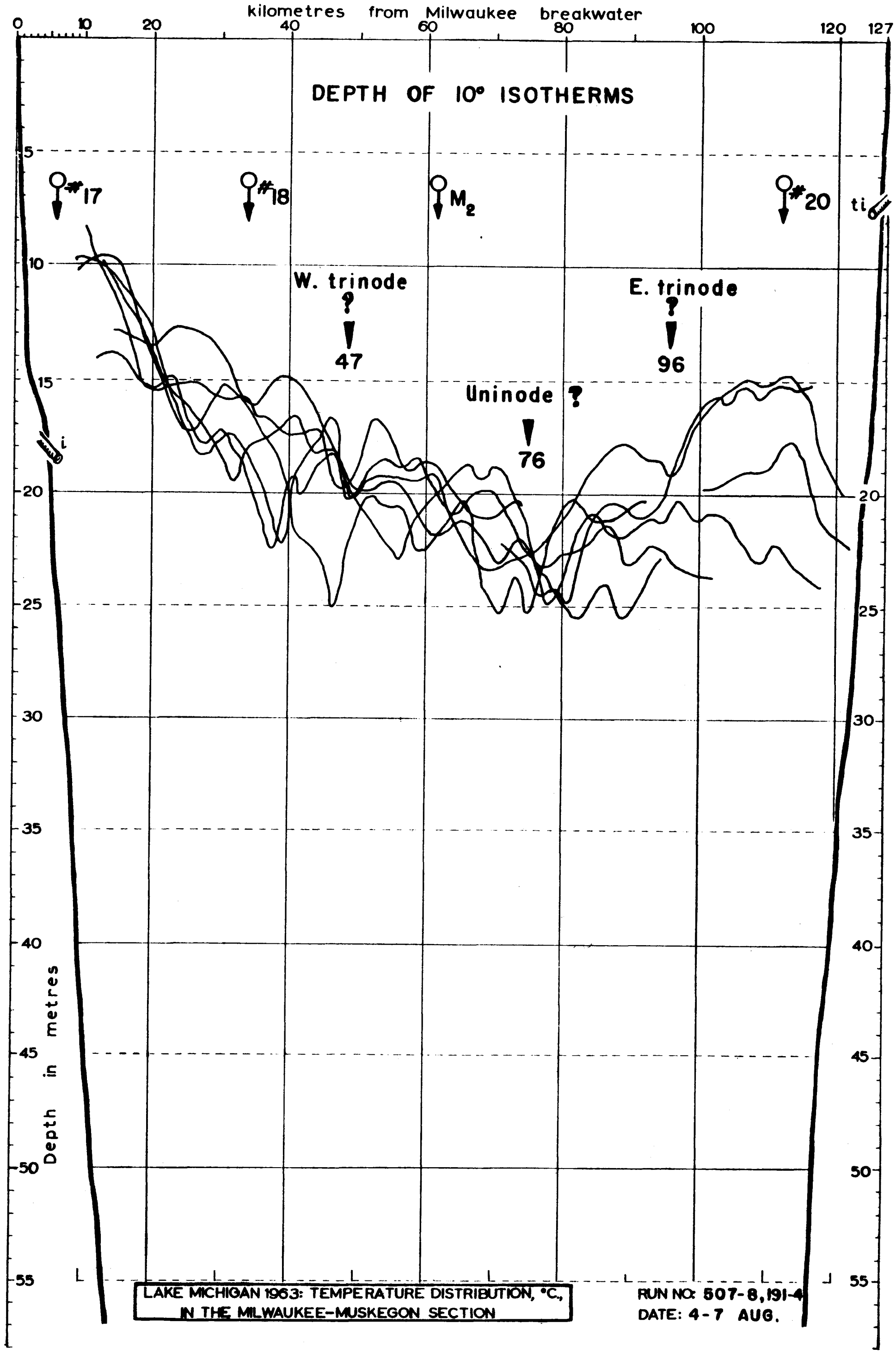


Figure 33 Distribution of the 10°C isotherm in the Milwaukee-Muskegon cross-section of Lake Michigan during eight consecutive runs of the railroad ferry, S. S. "Grand Rapids," 6 - 9 August, 1963.

APPENDIX

Distribution of temperature (°C.), in a cross-section of Lake Michigan corresponding to the railroad ferry route from Milwaukee, Wis. to Muskegon, Mich., during the interval 14 July to 30 August, 1963

The position of the 127 km long section, and the water depth along it, is shown in figure 6.

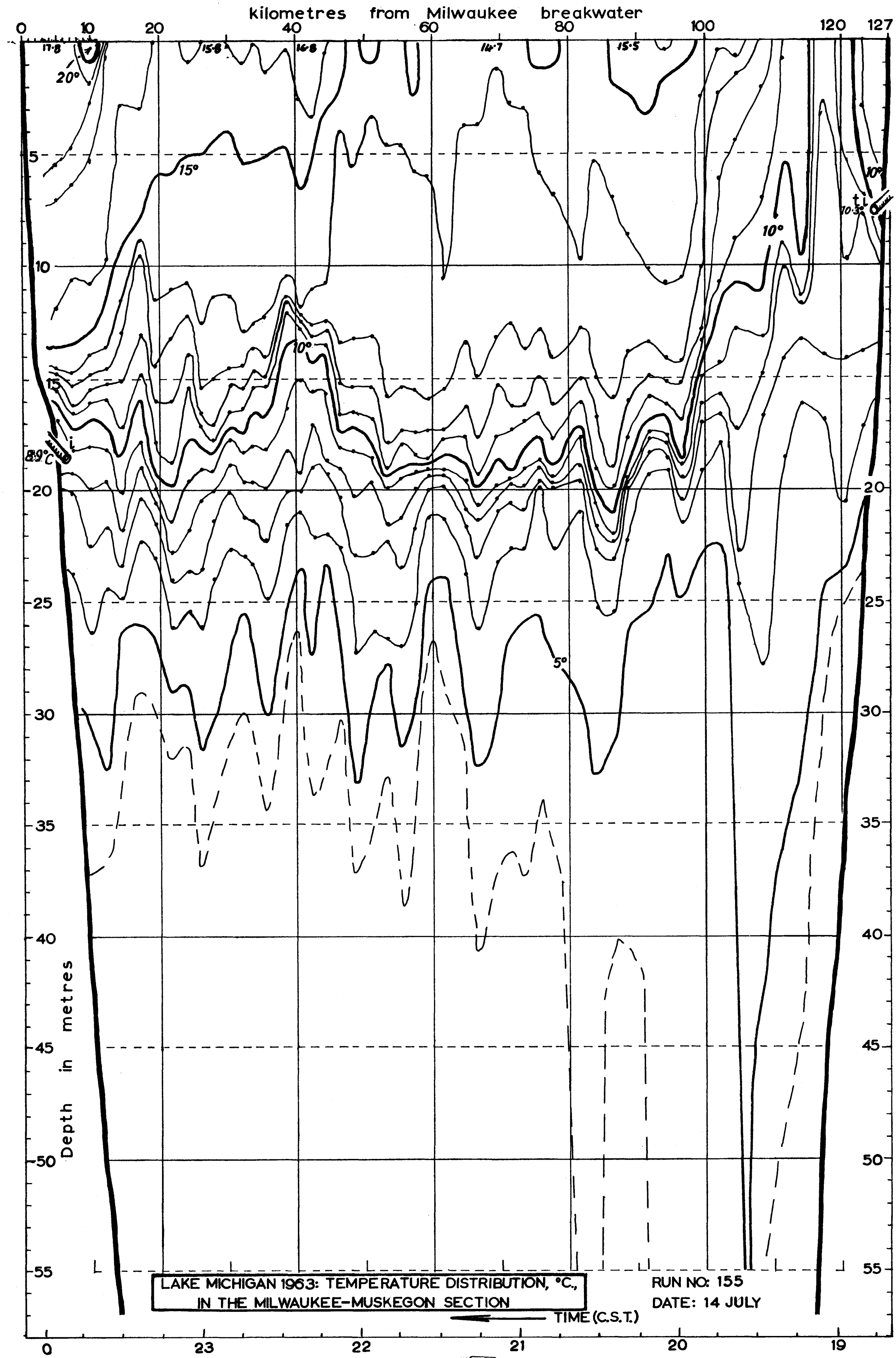
The eighty-seven figures in the Appendix are placed in chronological order and comprise plots of isotherm depths derived from bathythermograph casts on eighty passages of railroad ferries, and on those seven cruises of M. V. "Cisco" which followed the ferry route. On the ferries, the bathythermograph was cast usually every six minutes, corresponding to distance intervals of roughly 2.5 km; but on some of the "Cisco" sections it was cast as frequently as every three minutes, which corresponded to roughly 0.9 km. The ferry sections were not all consecutive or all complete, because of occasional vessel change-over (see below), instrument breakage, or rough weather. The time arrow at the base of the diagram indicates in which direction the section was run.

The run numbers are those logged by two ferries over the following date intervals:

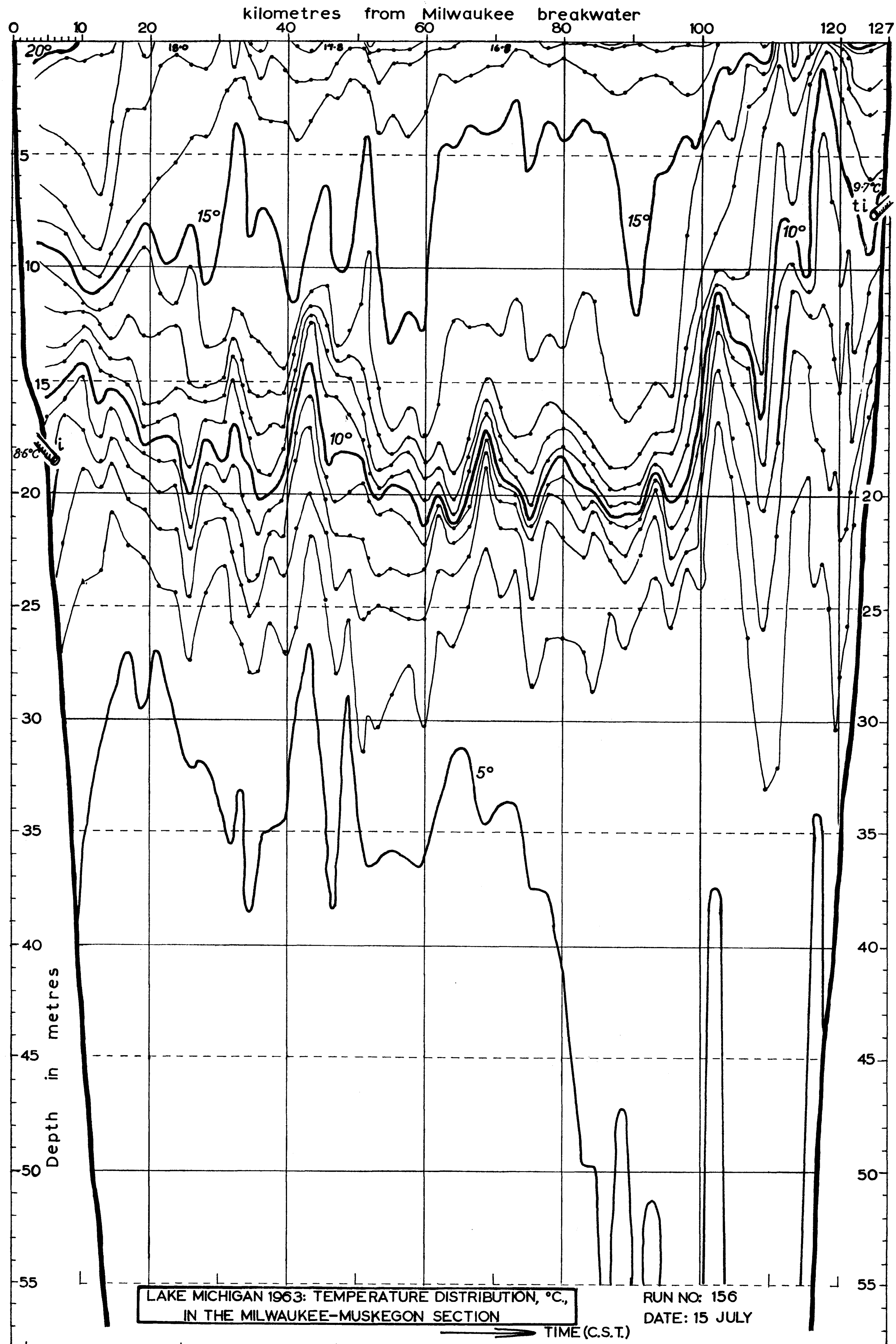
Run Nos.	Vessel	Date Interval
155 - 186	S. S. "Grand Rapids"	14-27 July
494 - 508	S. S. "Madison"	30 July-4 August
191 - 235	S. S. "Grand Rapids"	6-22 August
511 - 524	S. S. "Madison"	24-30 August

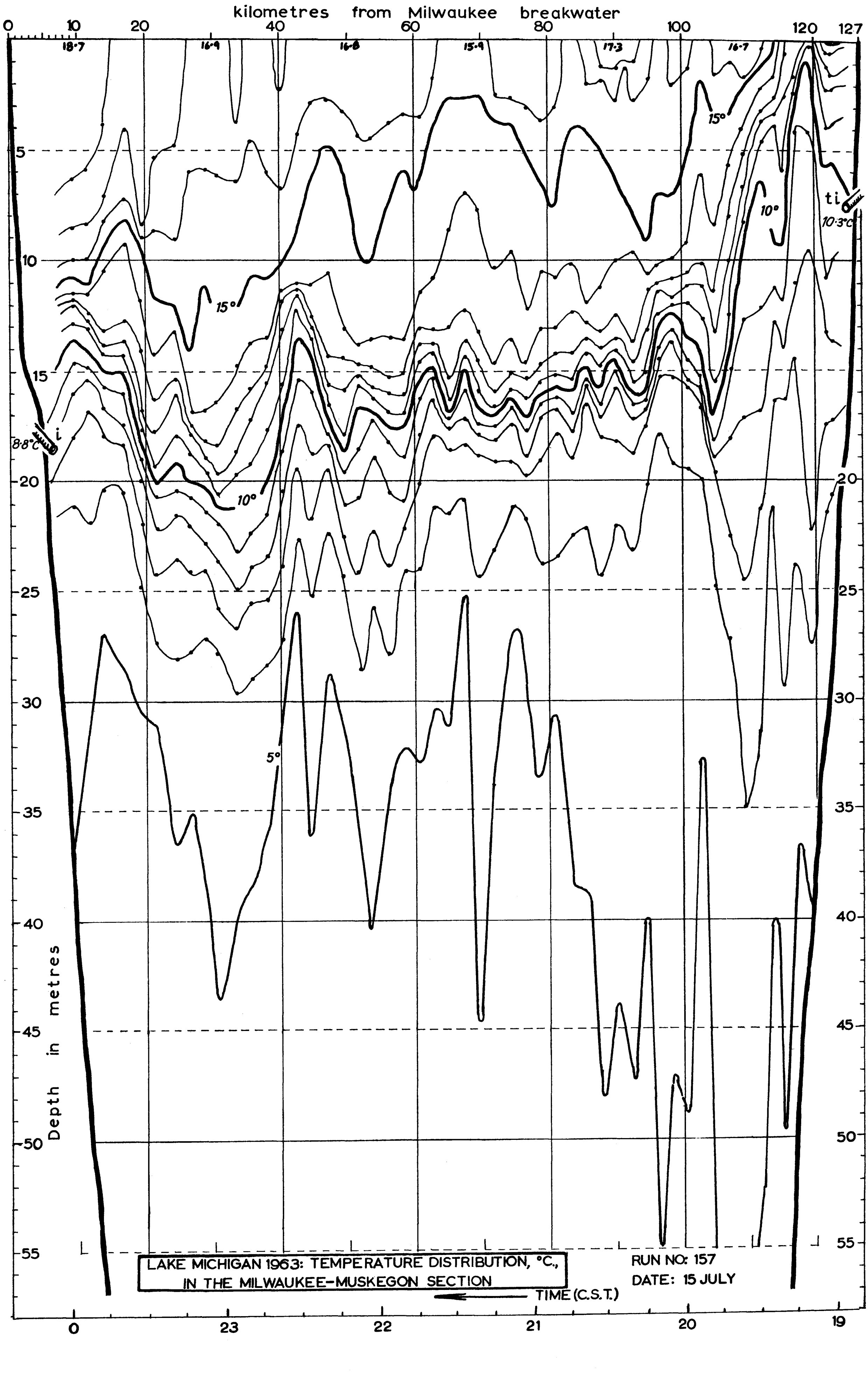
A total of 3461 bathythermograph slides was obtained for the series, not counting those on M. V. "Cisco"; and most of the work on the ferries was done by two students, Mr. D. Zietz and Mr. R. Schuman.

The "pipes," labeled "i" (at 18 m left) and "ti" (at 8 m right) on the section diagrams, represent municipal water intakes at Milwaukee and Muskegon (temporary intake), respectively: and the intake temperatures, corresponding to the nearest hour on the time scale (kindly supplied by the superintendents), are written in.



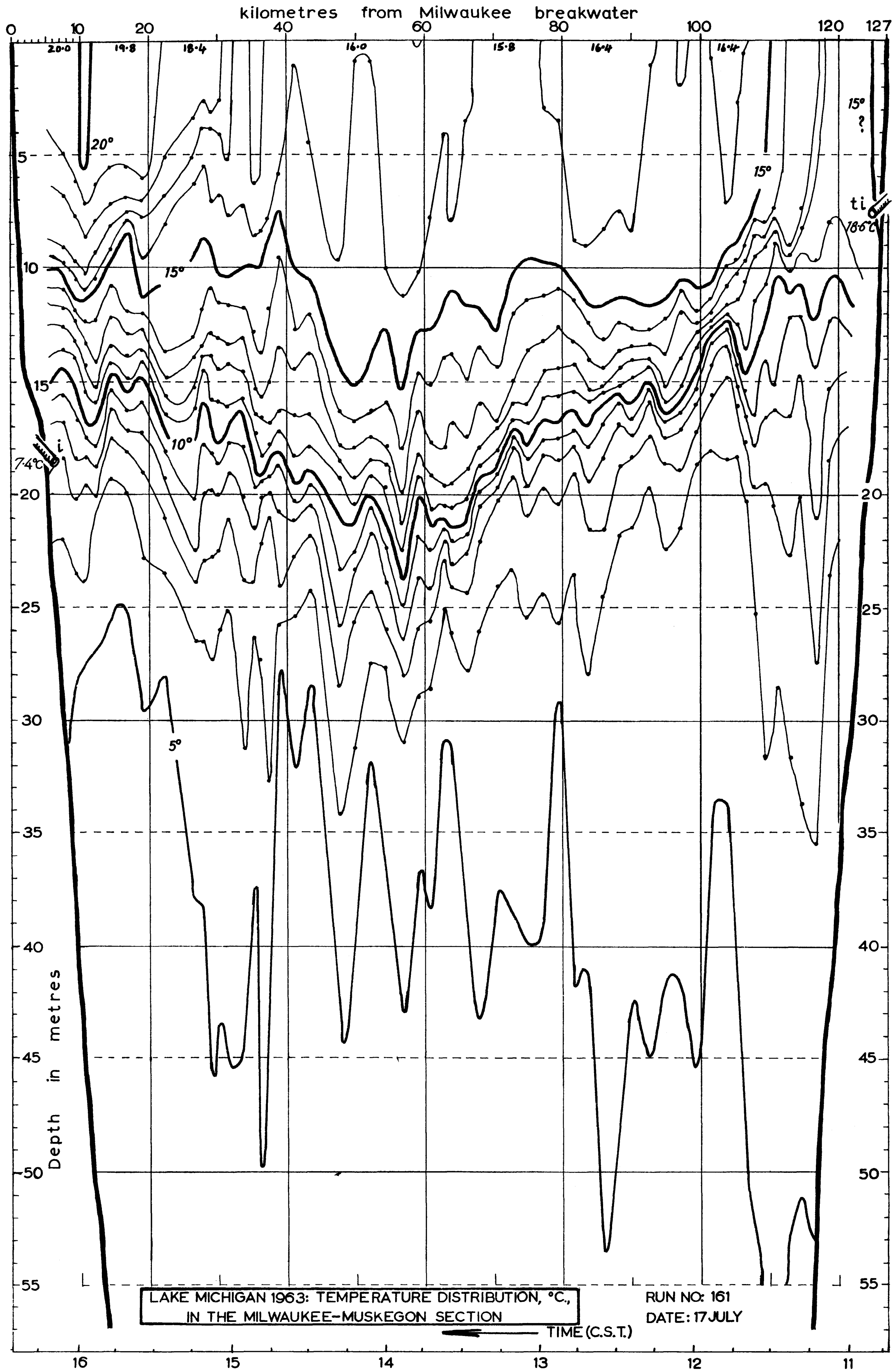
kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
17·8
15·8
14·8
14·7
15·5
20°
15°
10°
10°
10°
10·3°
8·9°C
5°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 155
DATE: 14 JULY
TIME (C.S.T.)
0
23
22
21
20
19

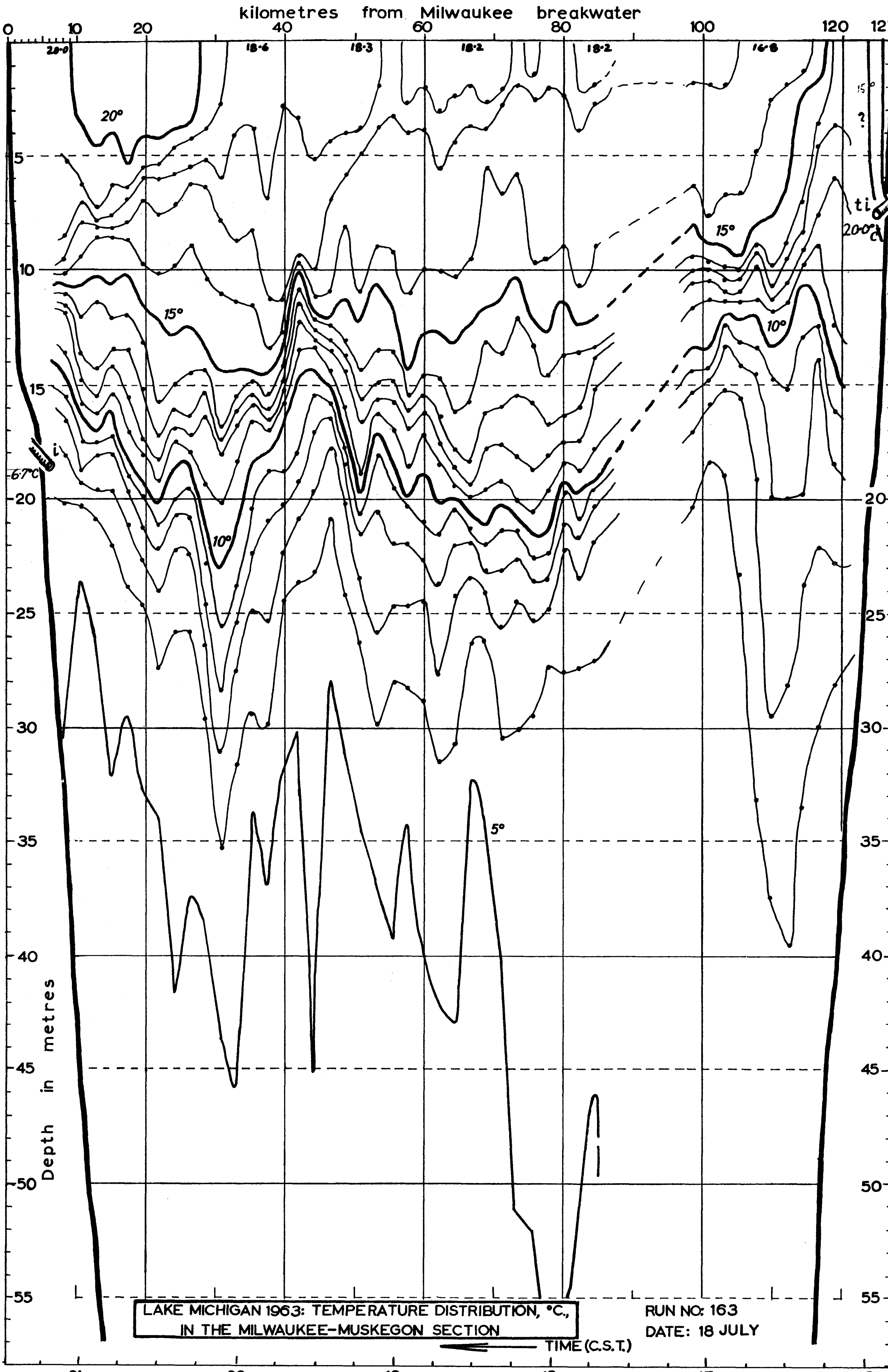

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
20°
18·0
17·8
16·8
15°
15°
10°
10°
5°
8·6°C
i
9·7°C
ti
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 156
DATE: 15 JULY
TIME (C.S.T.)
11
12
13
14
15
16

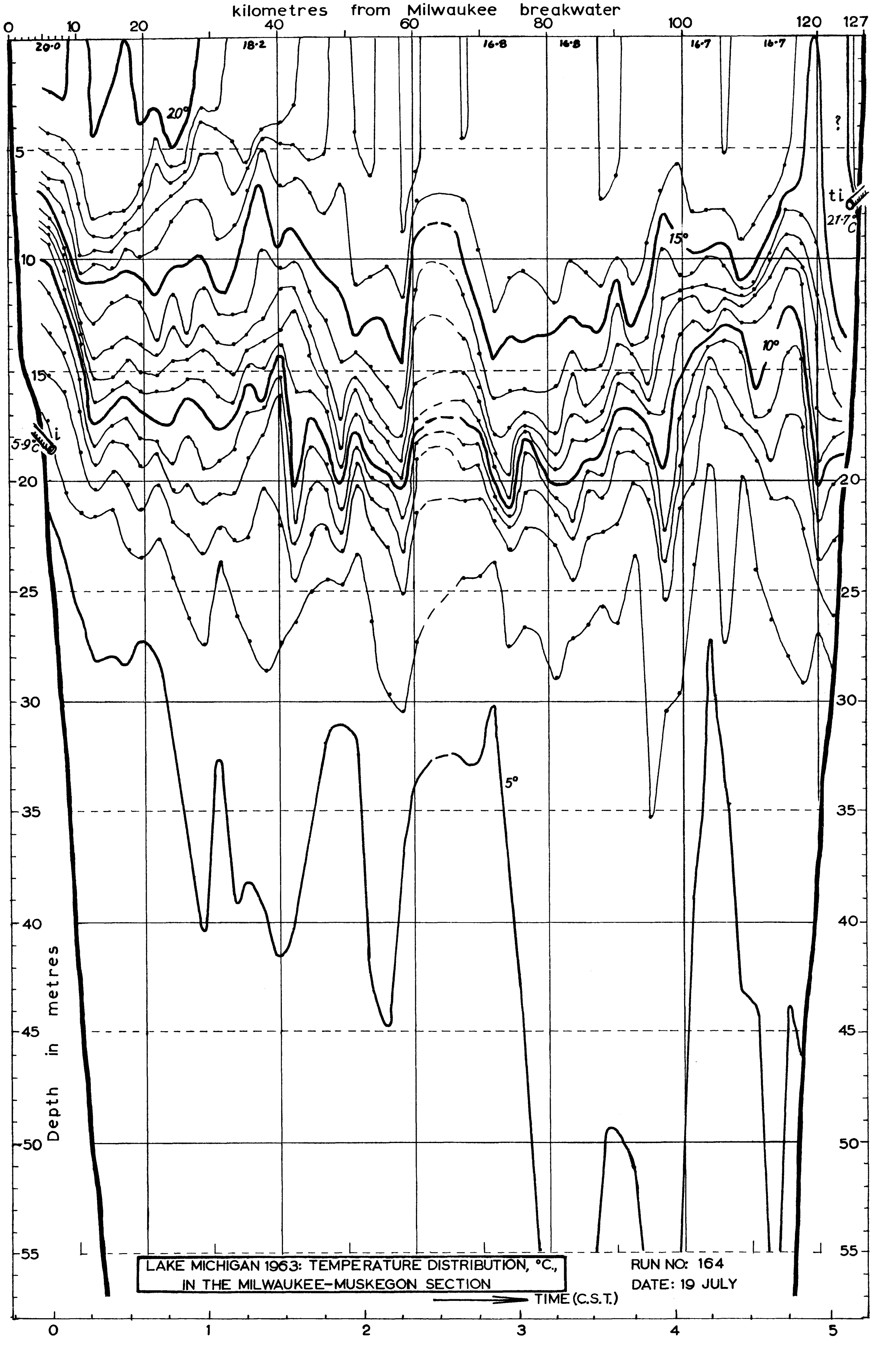


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION

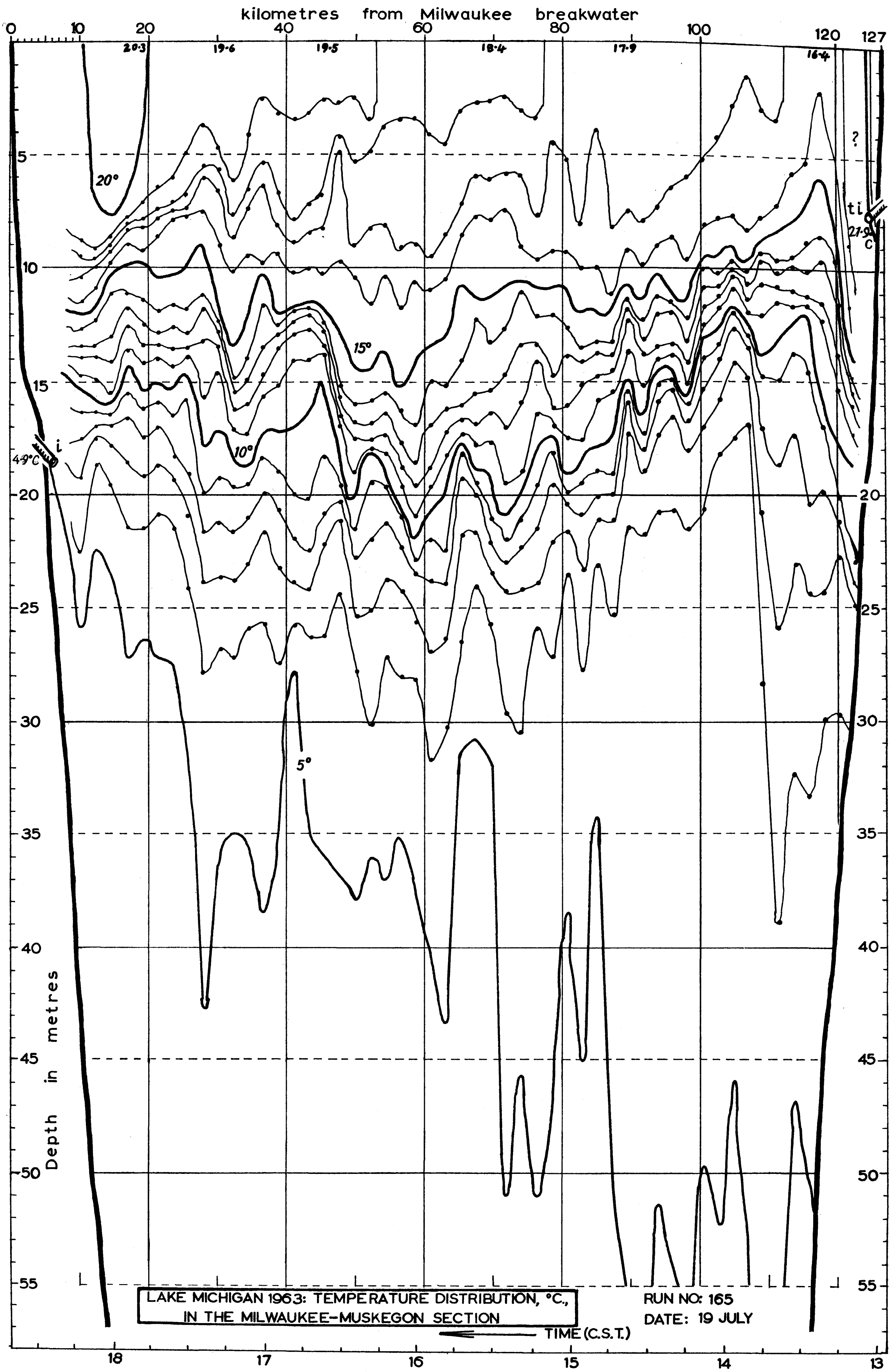
RUN NO: 157
DATE: 15 JULY


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
20·0 19·8 18·4 16·0 15·8 16·4 16·4
20°
15°
10°
5°
15° ?
ti
18·6°C
i
7·4°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 161
DATE: 17 JULY
TIME (C.S.T.)
16 15 14 13 12 11


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
20·0
18·6
18·3
18·2
18·2
16·8
20°
15°
10°
5°
15°
10°
6·7°C
20·0°C
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C.,
IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 163
DATE: 18 JULY
TIME (C.S.T.)
21
20
19
18
17
16

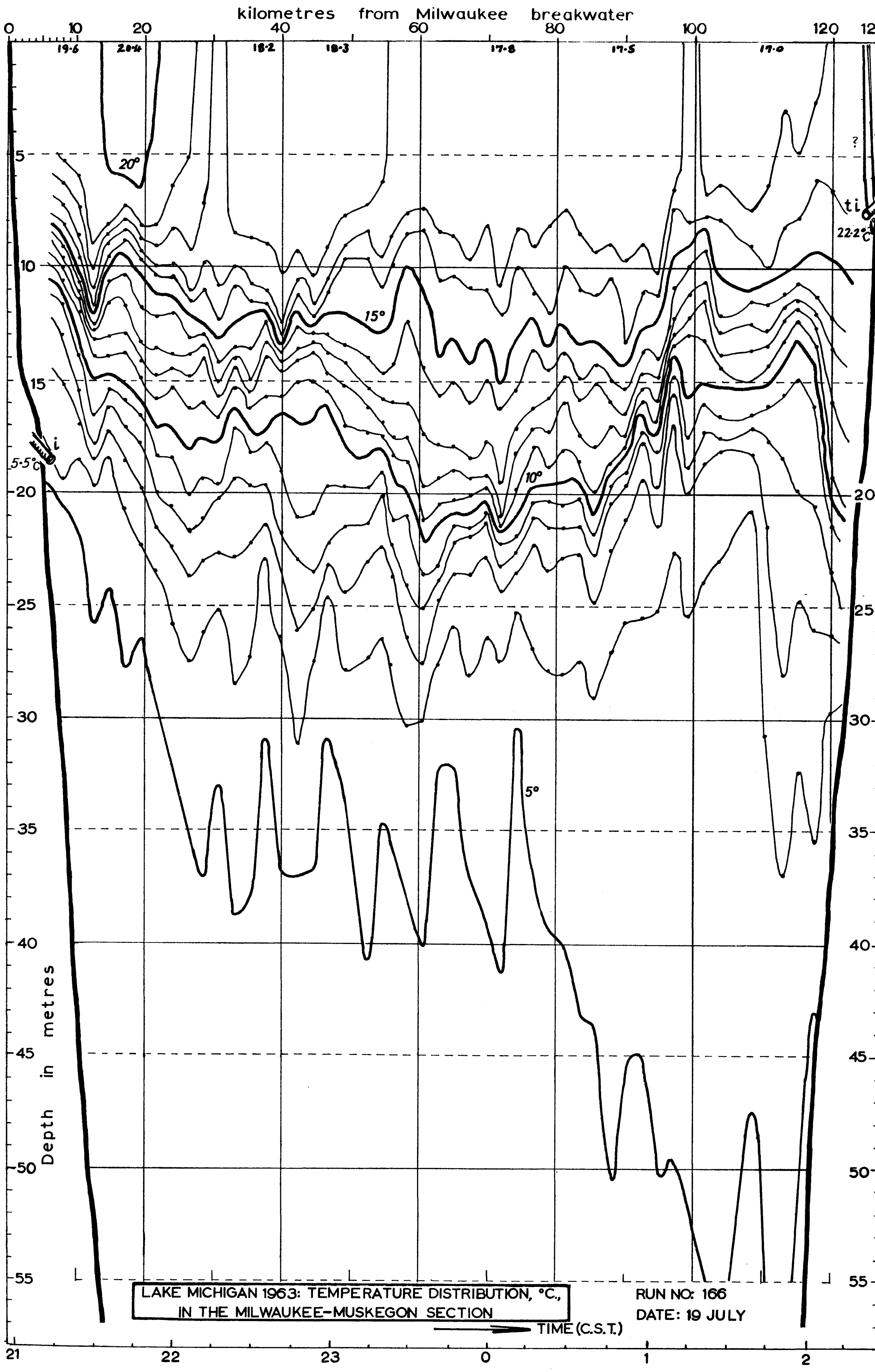


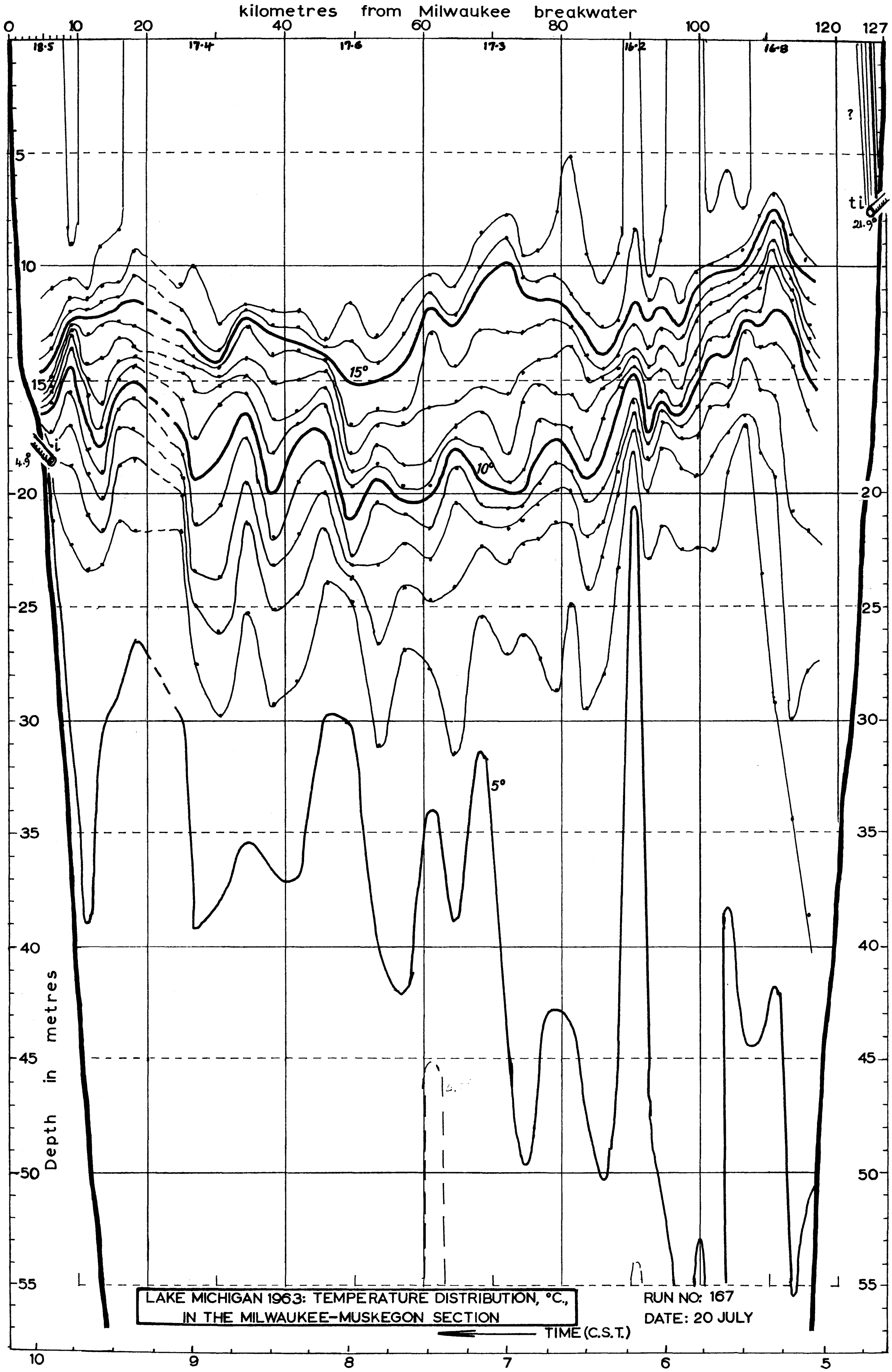
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
20·0 18·2 16·8 16·8 16·7 16·7
20°
15°
10°
5°
?
ti
21·7°C
i
5·9°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 164
DATE: 19 JULY
TIME (C.S.T.)
0 1 2 3 4 5



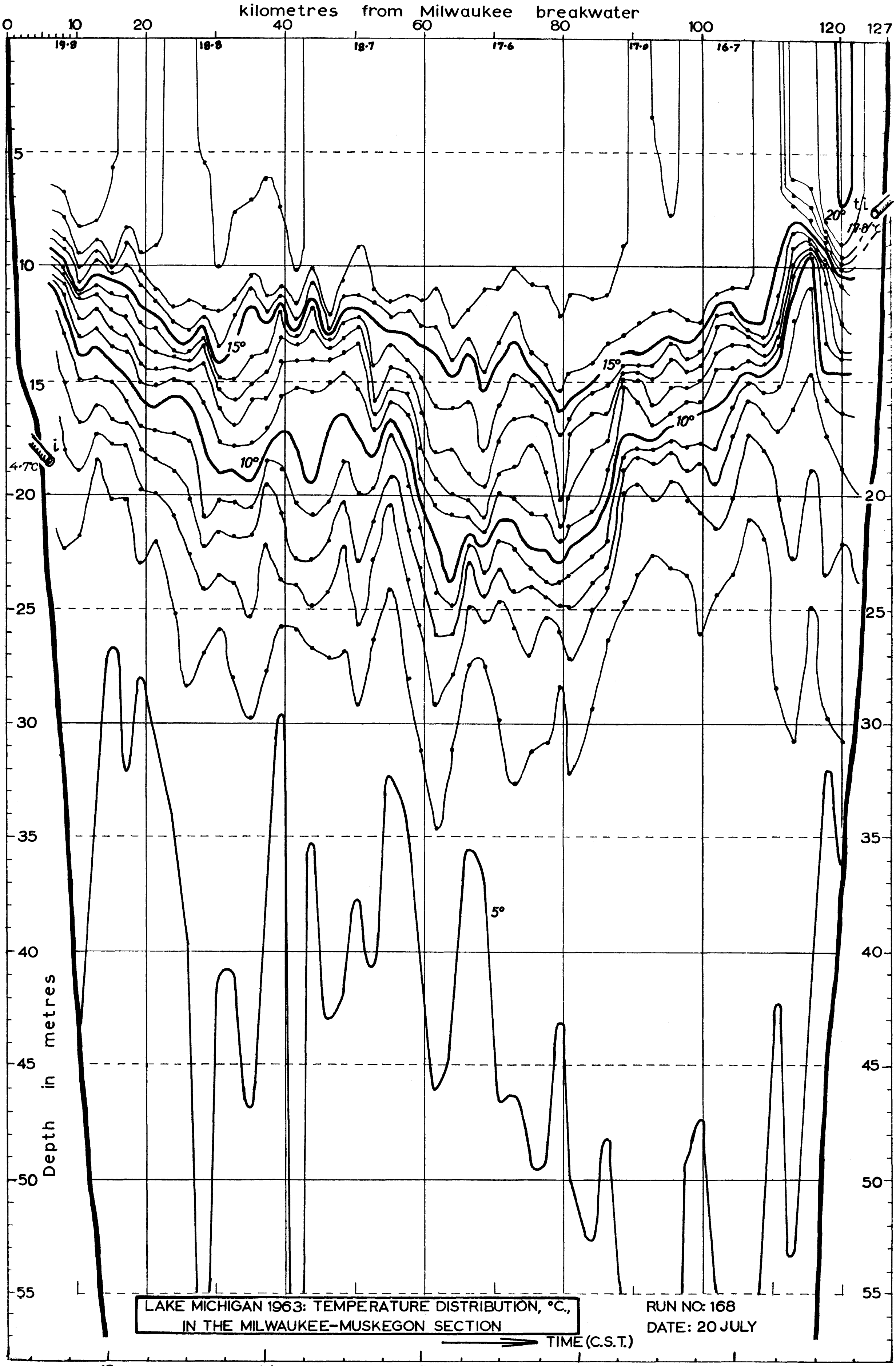
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

RUN NO: 165
DATE: 19 JULY

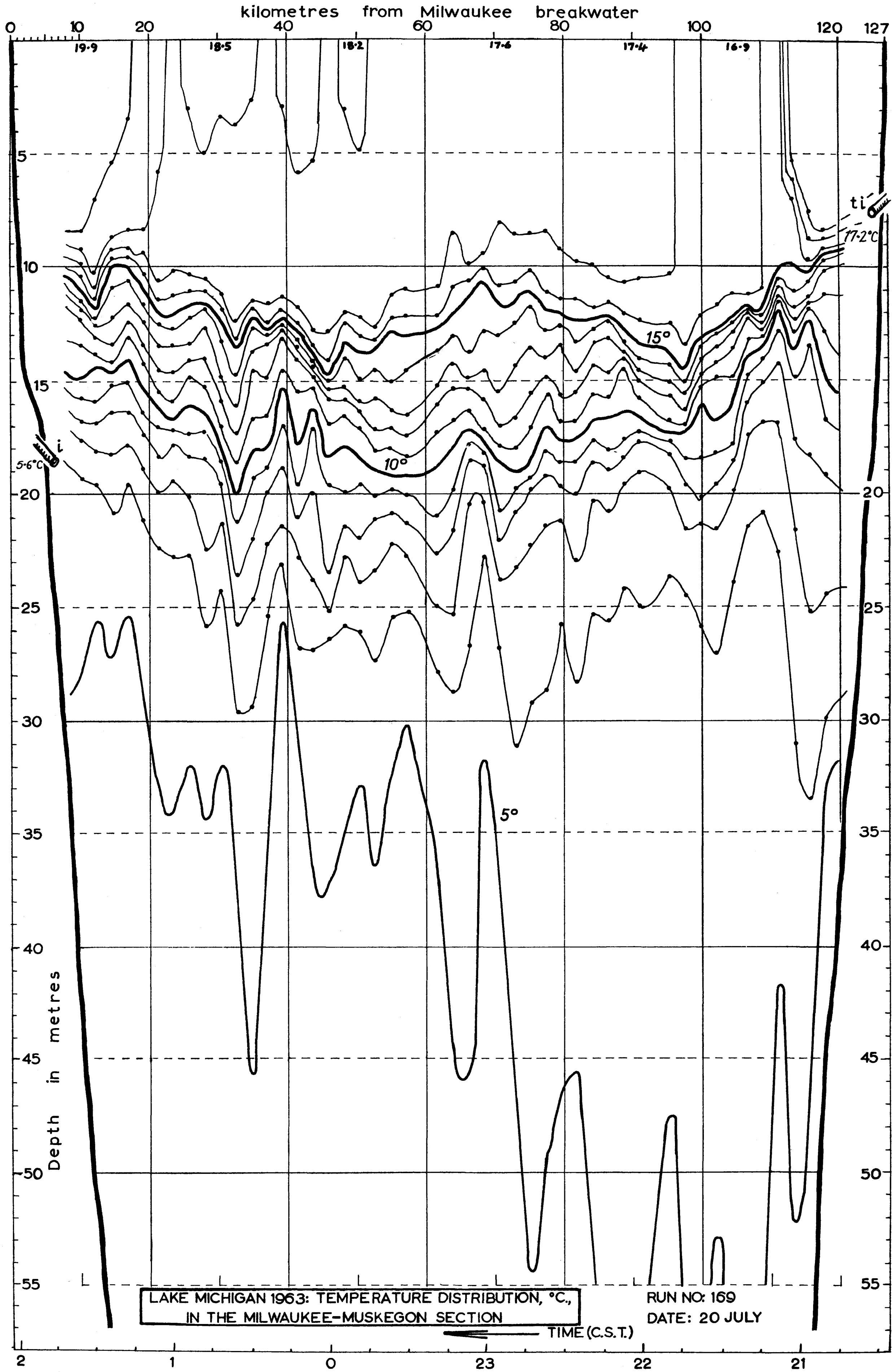

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·6
20·4
18·2
18·3
17·8
17·5
17·0
20°
15°
10°
5°
ti
22·2°C
i
5·5°C
?
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 166
DATE: 19 JULY
TIME (C.S.T.)
21
22
23
0
1
2



kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
18·5
17·4
17·6
17·3
16·2
16·8
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
15°
10°
5°
4.9°
21.9°
?
ti
i
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 167
DATE: 20 JULY
TIME (C.S.T.)
10
9
8
7
6
5



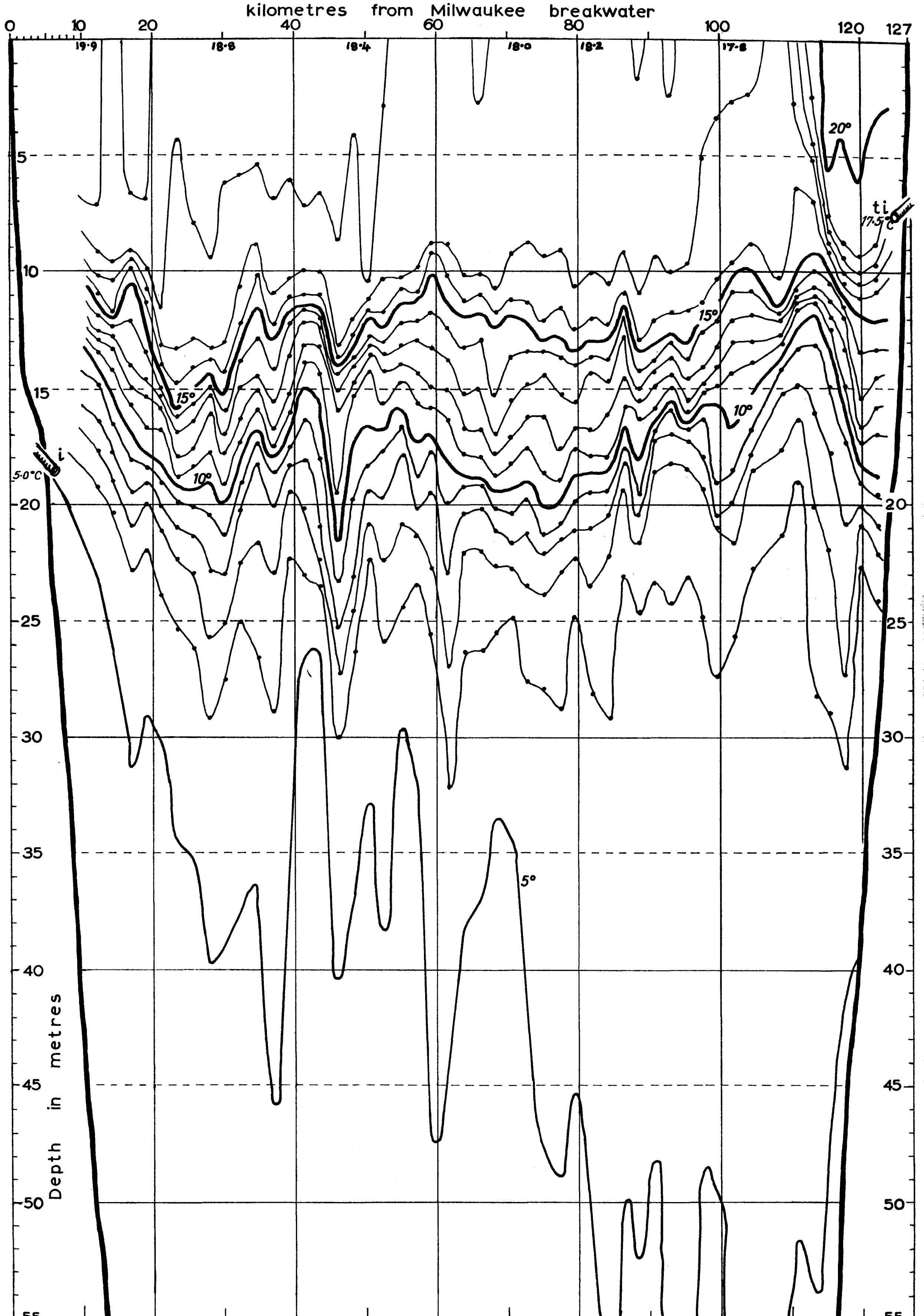
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



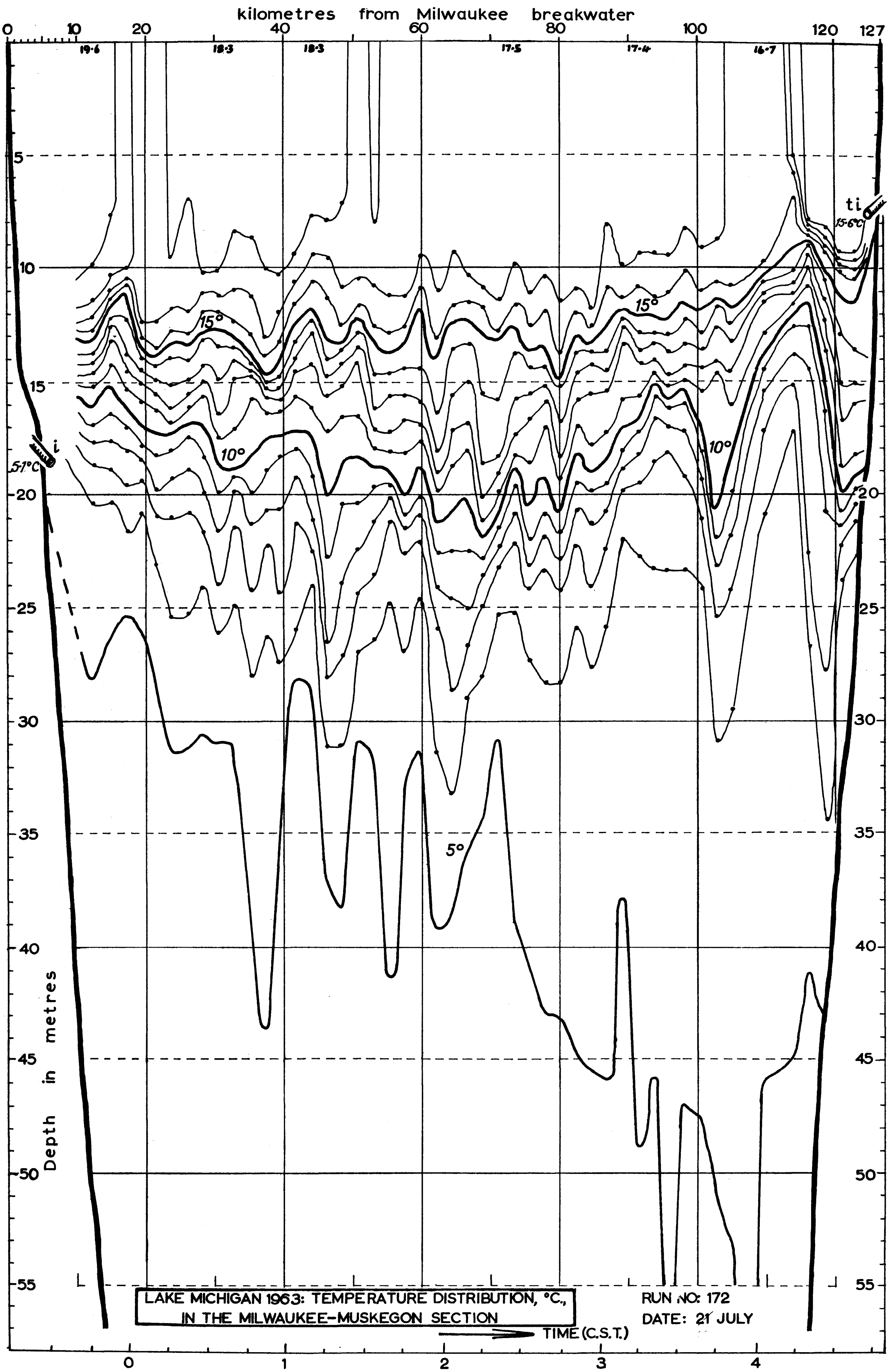
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION

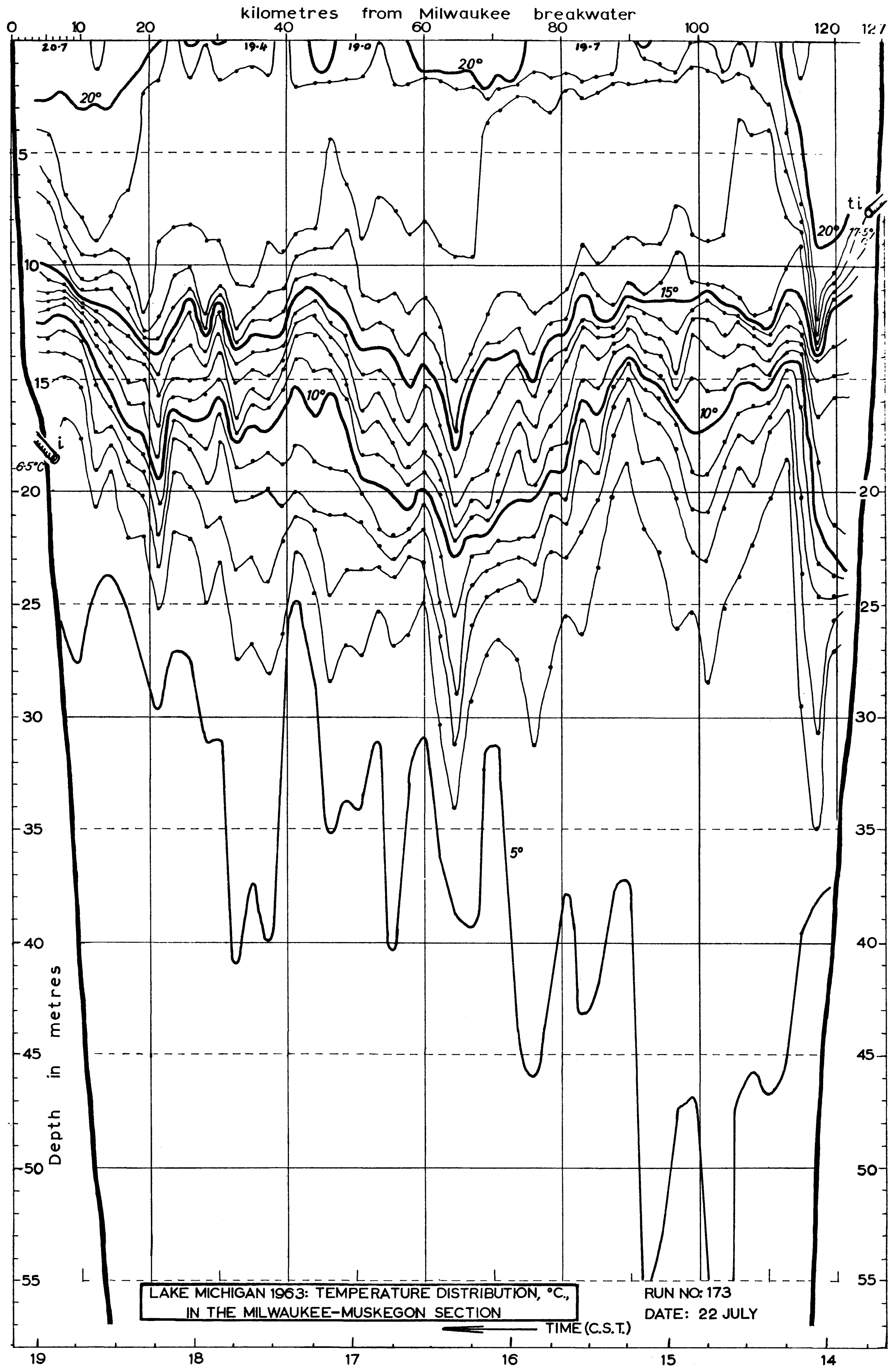
RUN NO: 169

DATE: 20 JULY

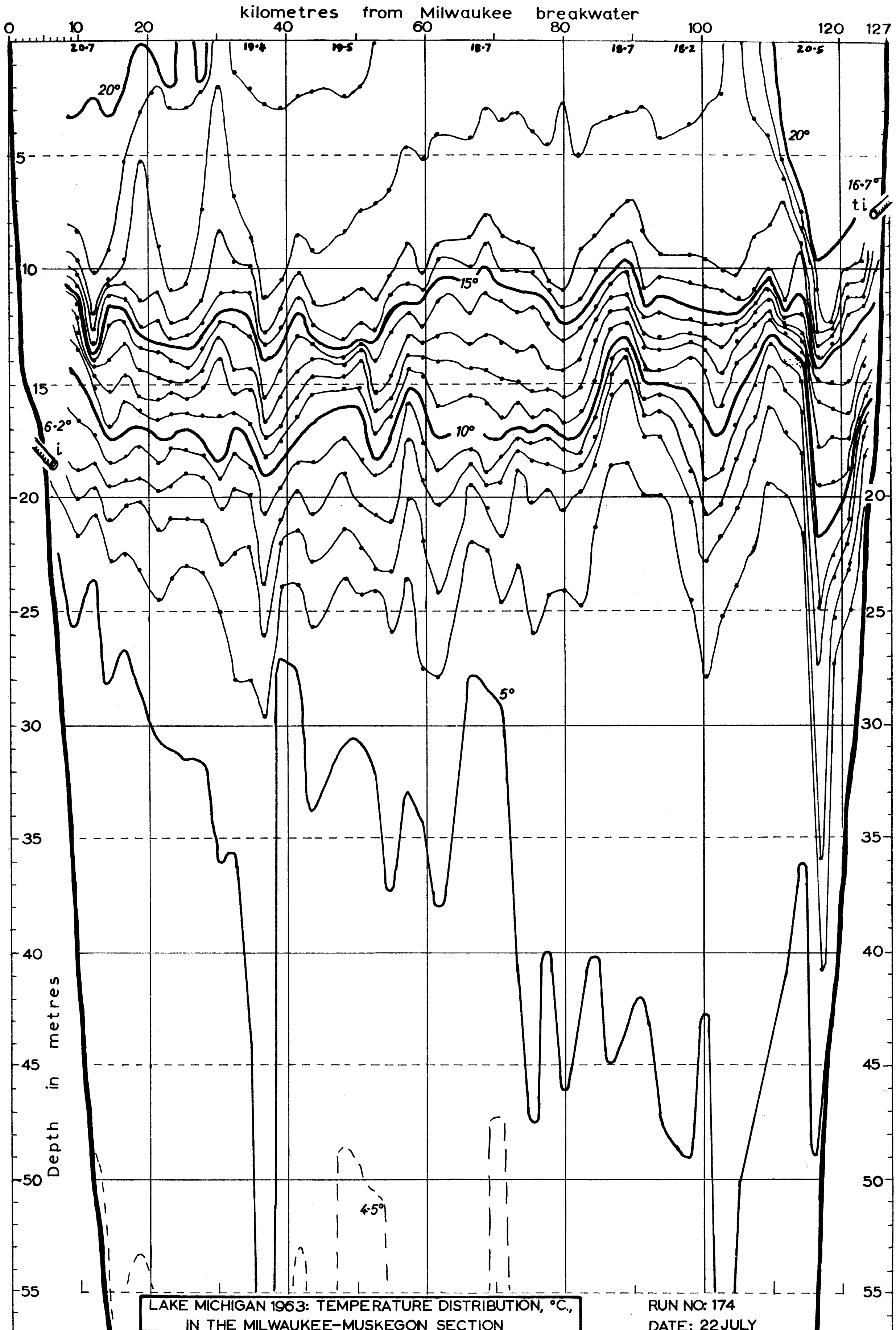


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
19·9 18·8 18·4 18·0 18·2 17·8
20°
ti
17·5°C
15°
10°
i
5·0°C
5°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 170
DATE: 21 JULY
TIME (C.S.T.)
9 10 11 12 13

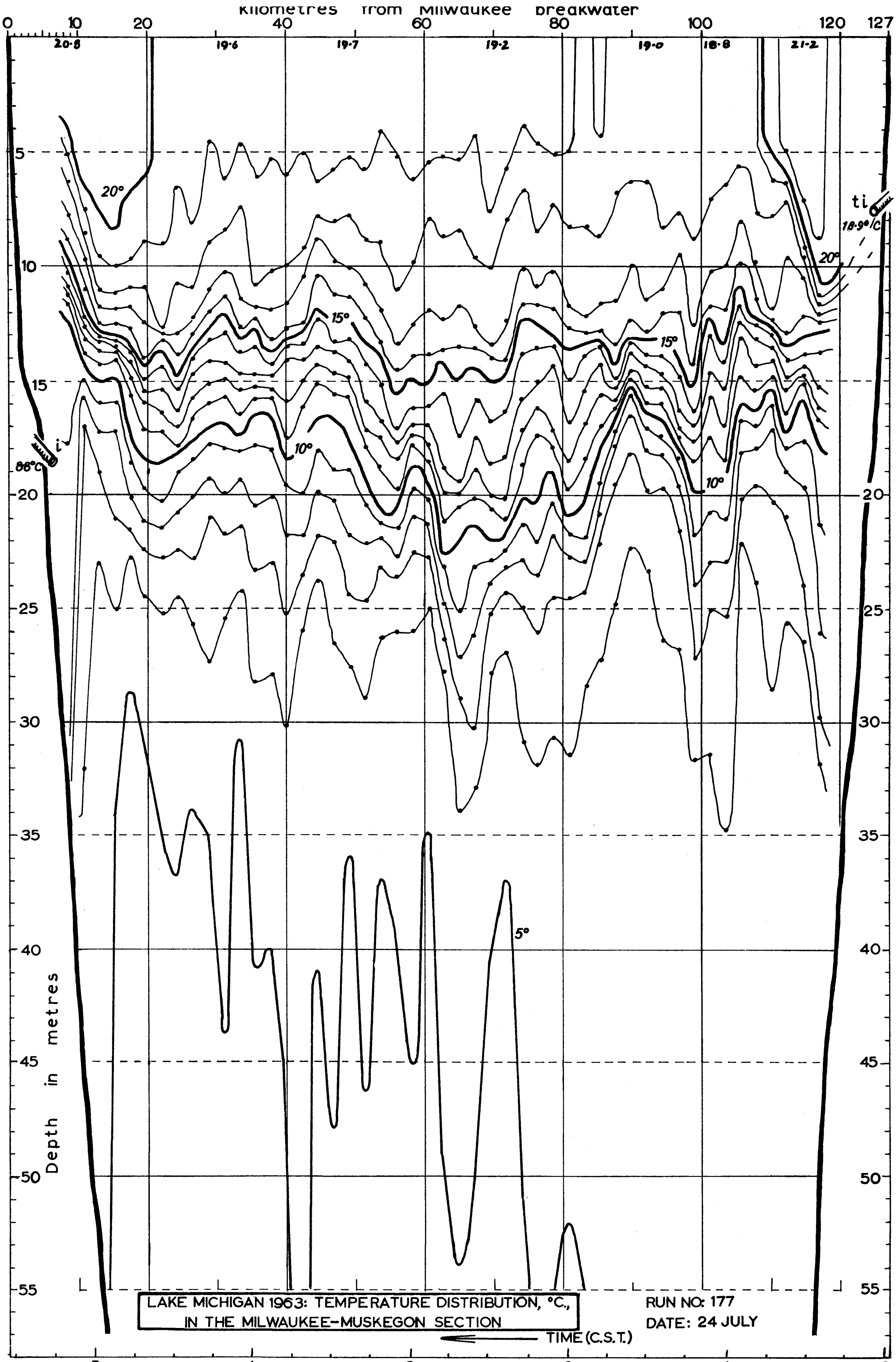

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·6
18·3
18·3
17·5
17·4
16·7
ti
15·6°C
i
5·1°C
15°
10°
5°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 172
DATE: 21 JULY
TIME (C.S.T.)
0
1
2
3
4

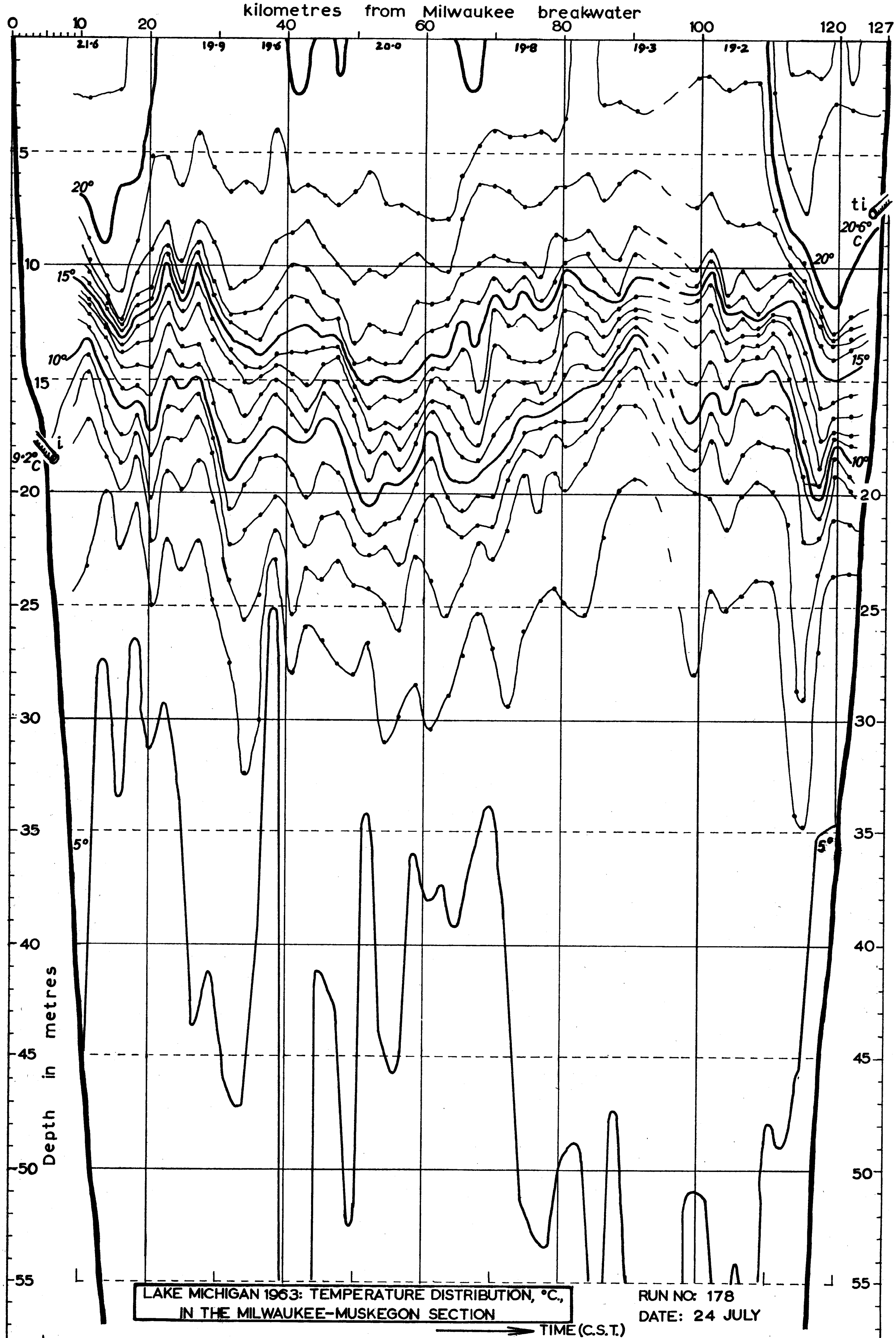


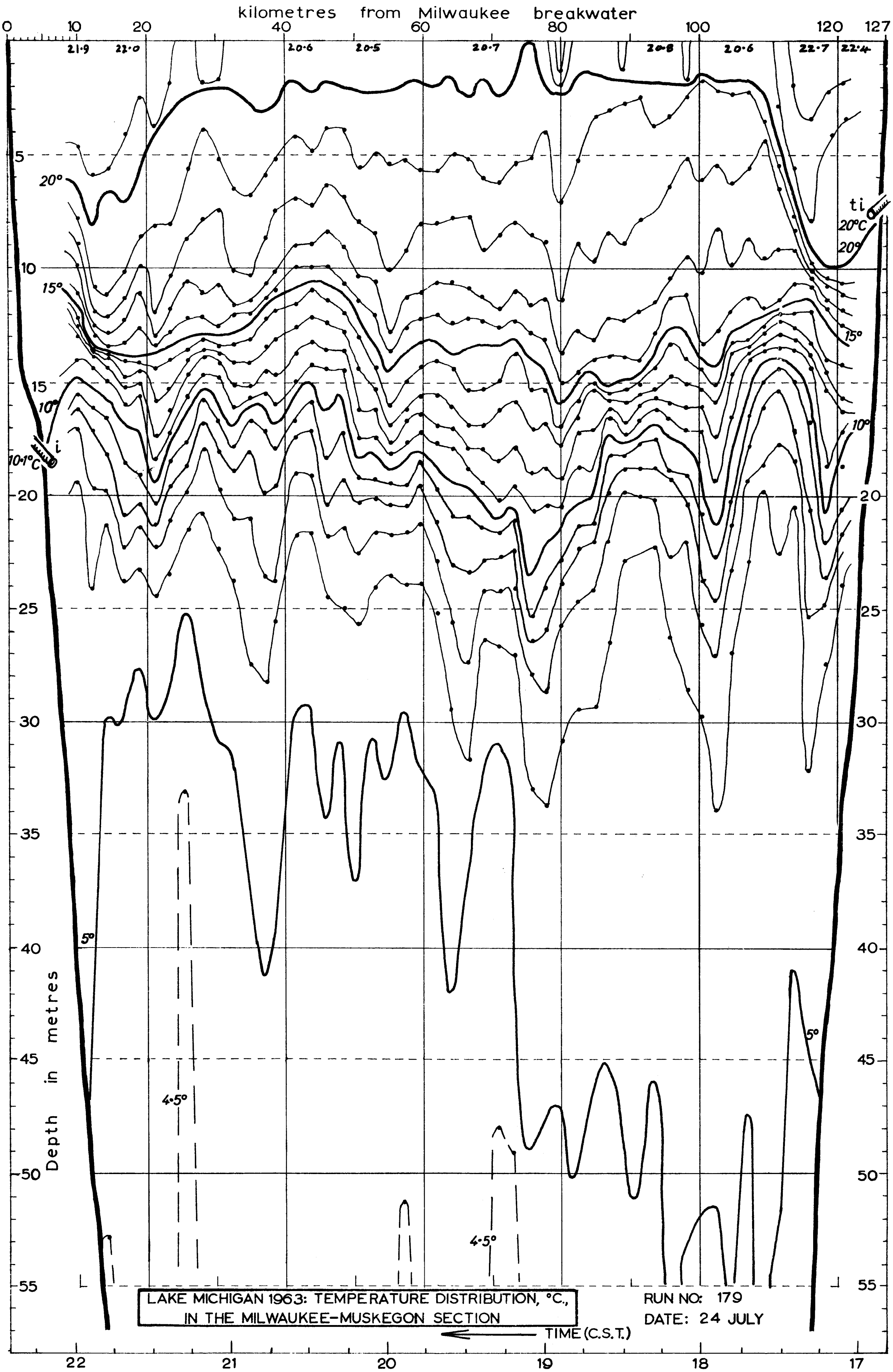
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
20·7
19·4
19·0
19·7
20°
15°
10°
5°
6·5°C
i
ti
17·5°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 173
DATE: 22 JULY
TIME (C.S.T.)
19 18 17 16 15 14

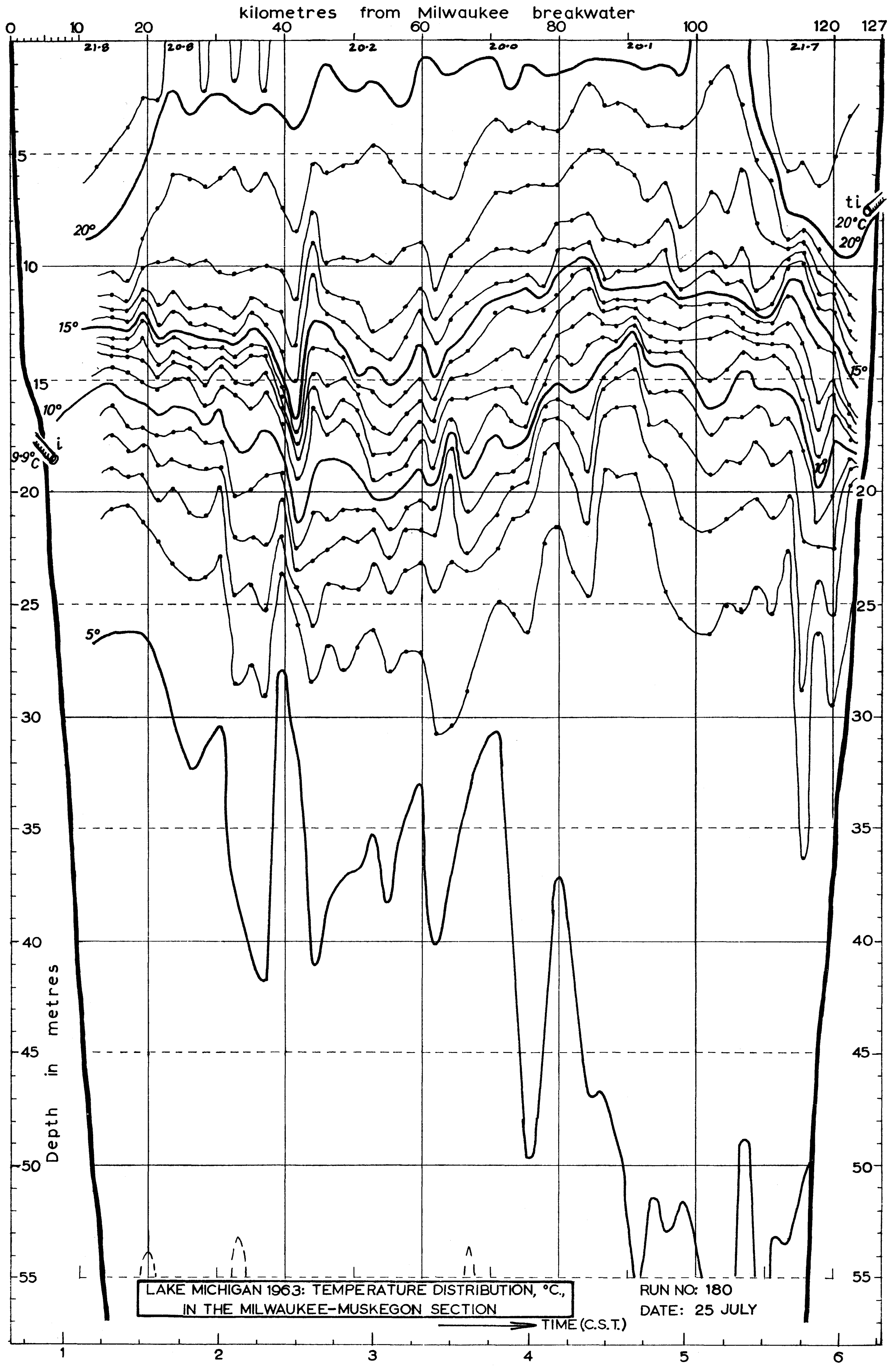


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION


Kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
20·8 19·6 19·7 19·2 19·0 18·8 21·2
20°
15°
10°
5°
ti
18·9°/C
i
8·6°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 177
DATE: 24 JULY
TIME (C.S.T.)
5 4 3 2 1 0

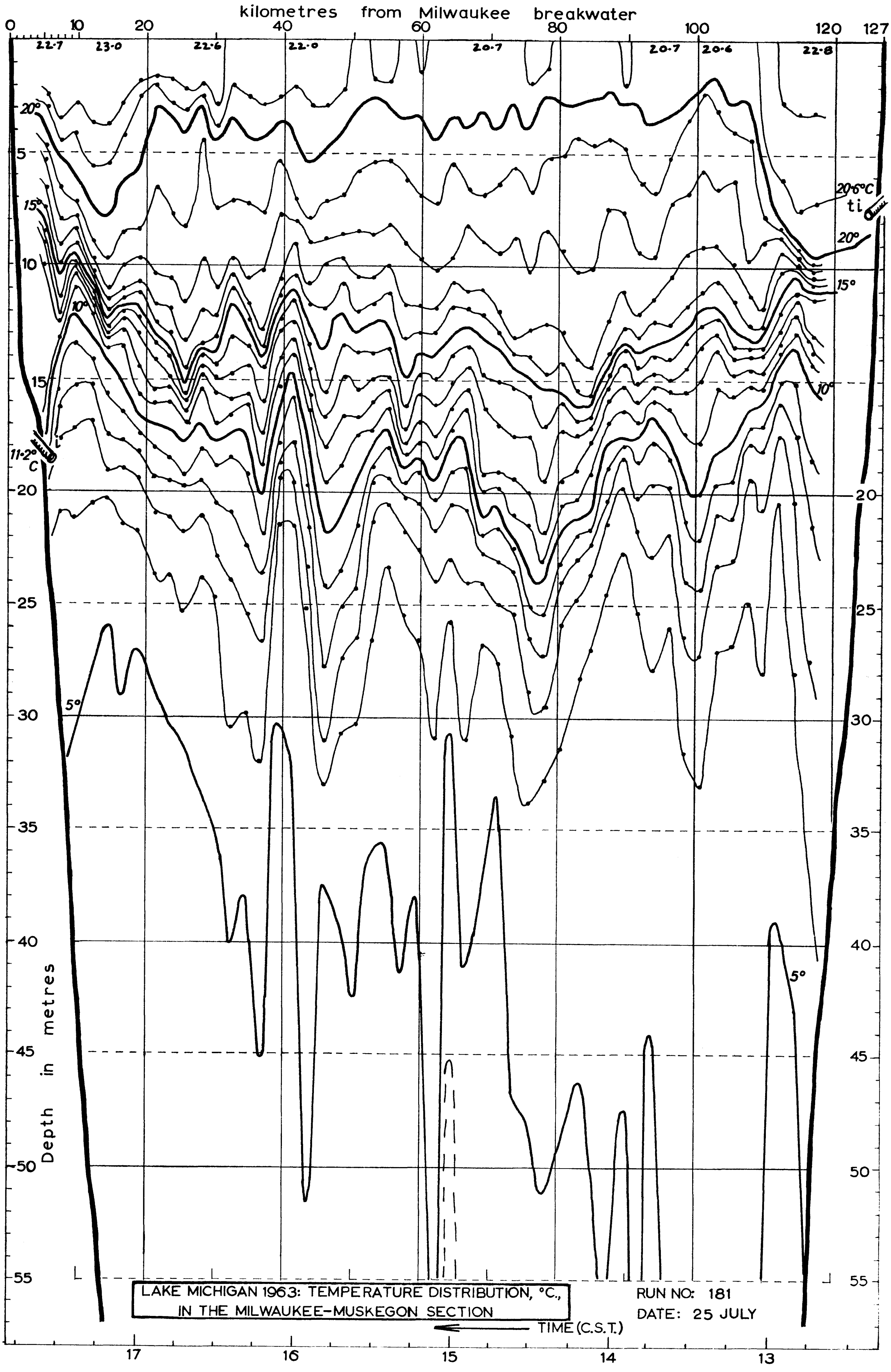

kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
21·6 19·9 19·6 20·0 19·8 19·3 19·2
20° 15° 10° 5°
9·2° C i
ti 20·6° C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 178
DATE: 24 JULY
TIME (C.S.T.)
9 10 11 12 13 14


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
21·9
22·0
20·6
20·5
20·7
20·8
20·6
22·7
22·4
20°
15°
10°
10·1°C
i
ti
20°C
20°
15°
10°
5°
4·5°
4·5°
5°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 179
DATE: 24 JULY
TIME (C.S.T.)
22
21
20
19
18
17

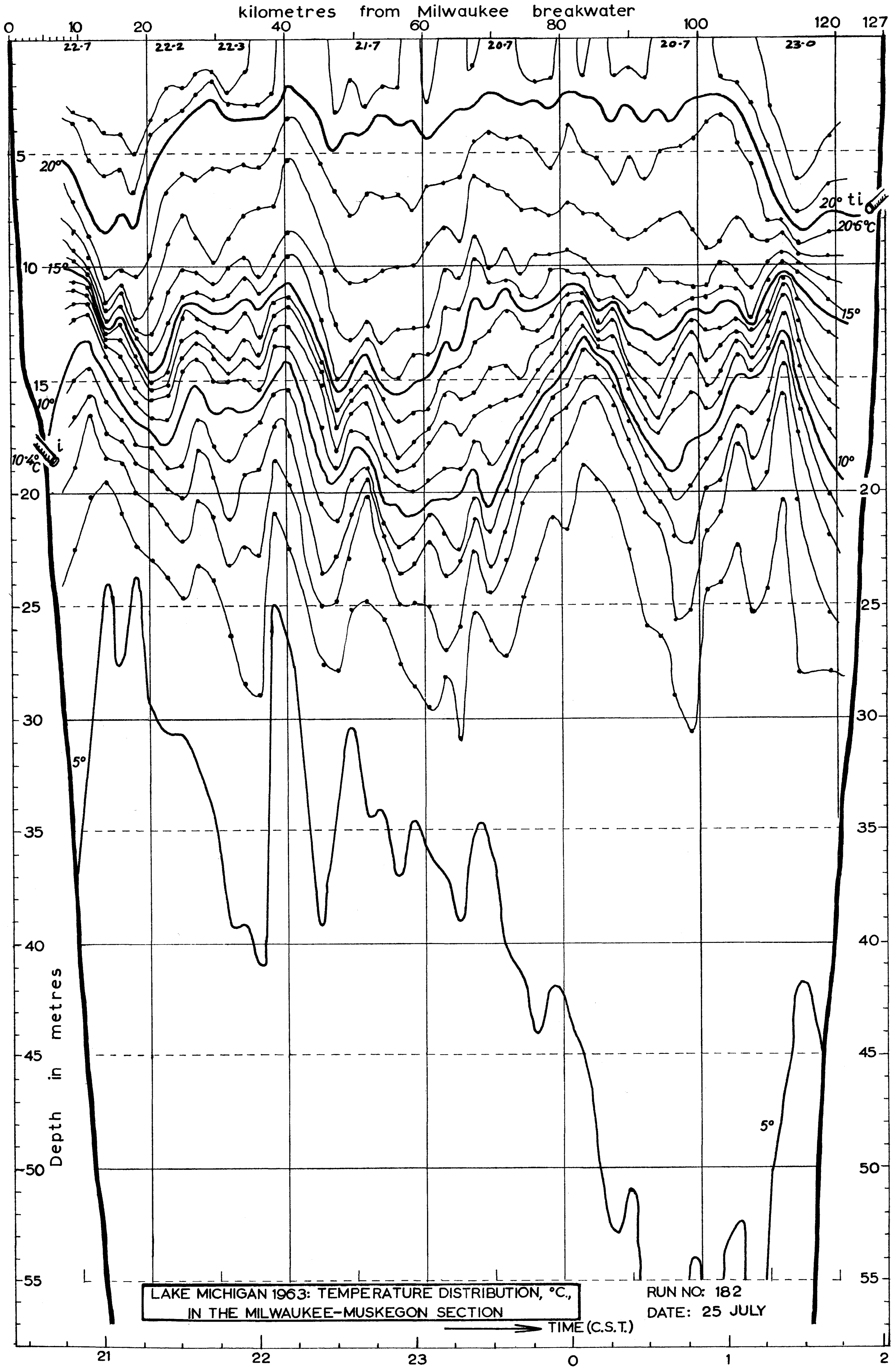


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

RUN NO: 180
DATE: 25 JULY

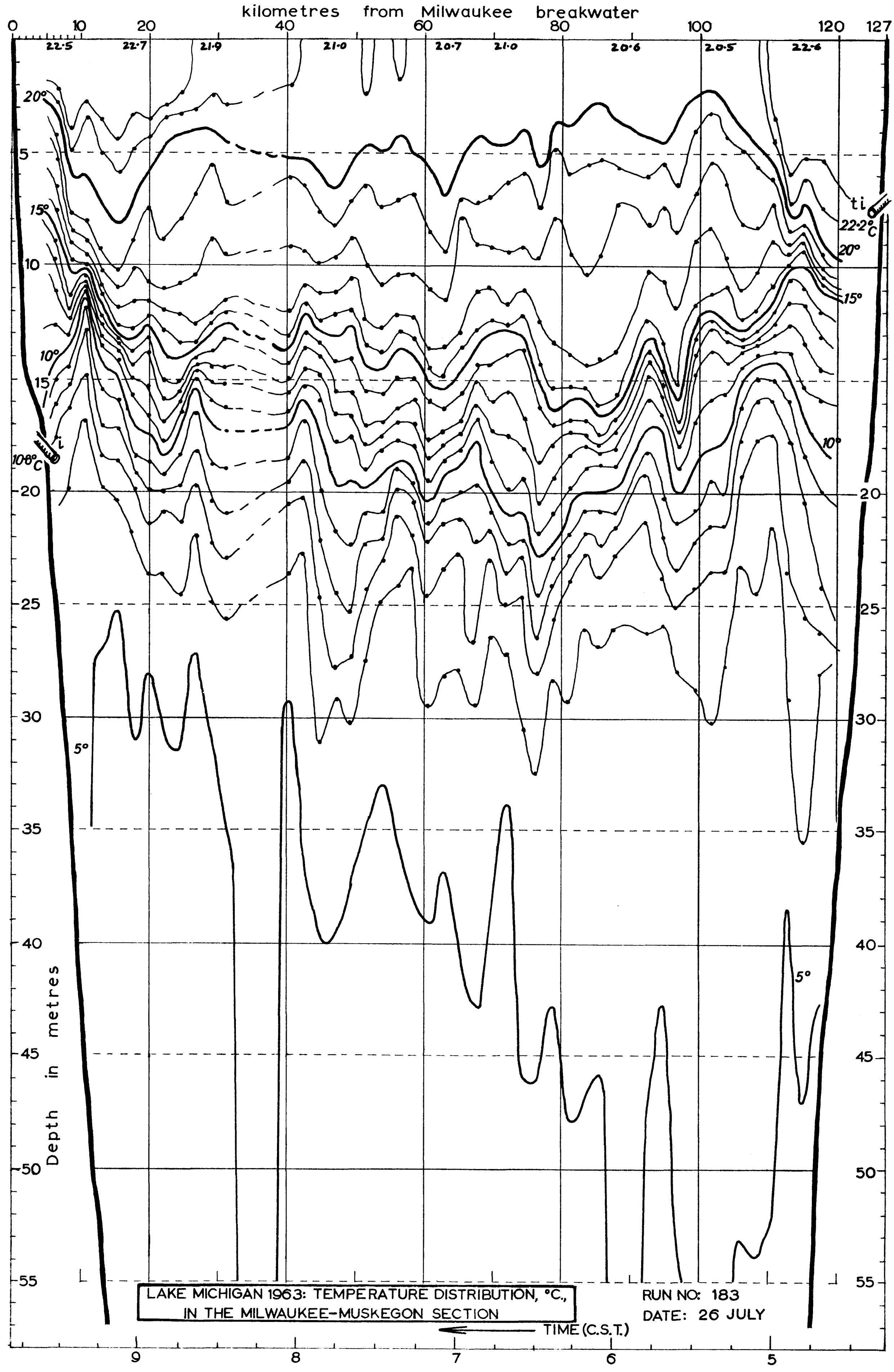


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION



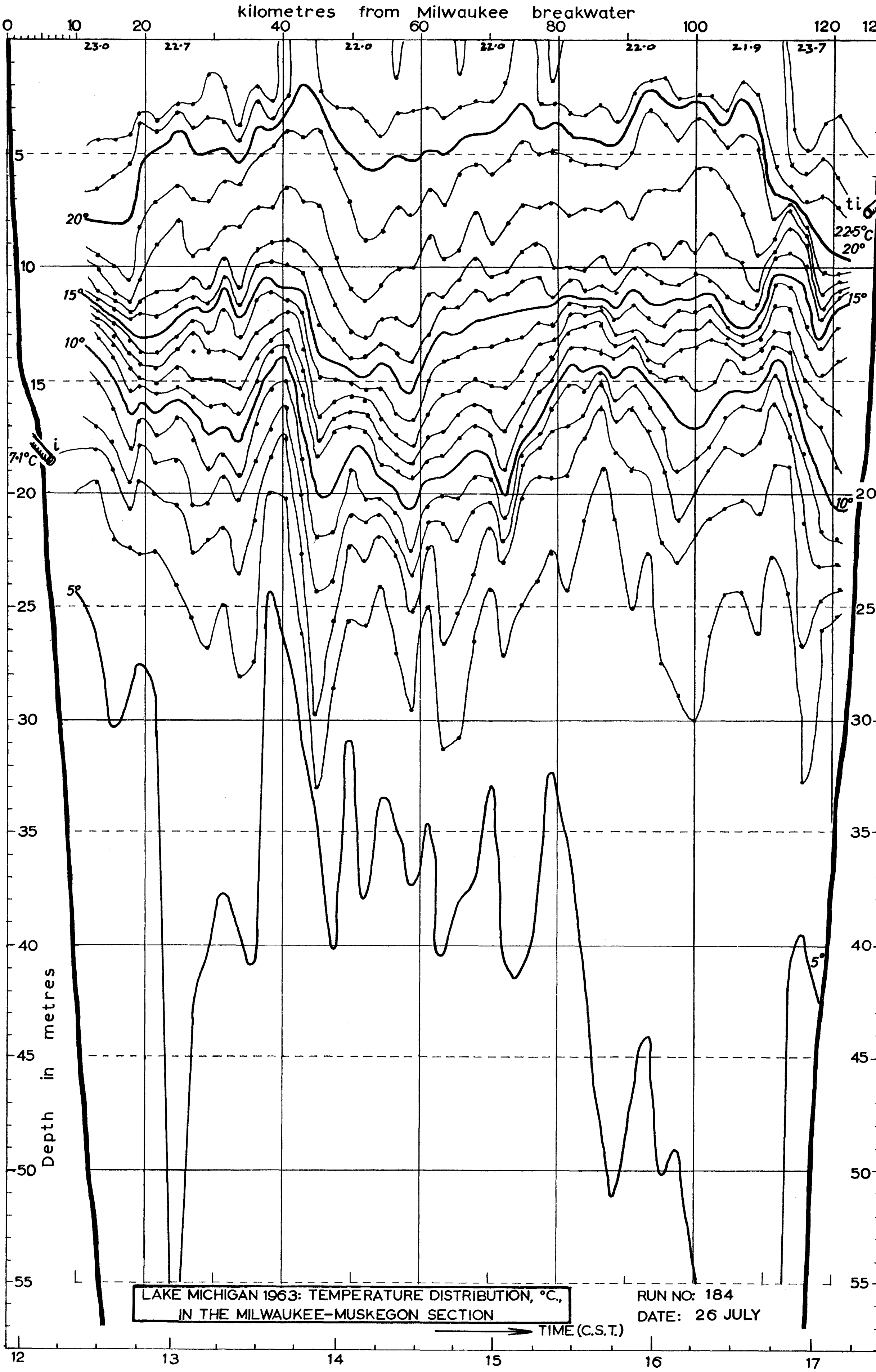
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

RUN NO: 182
DATE: 25 JULY

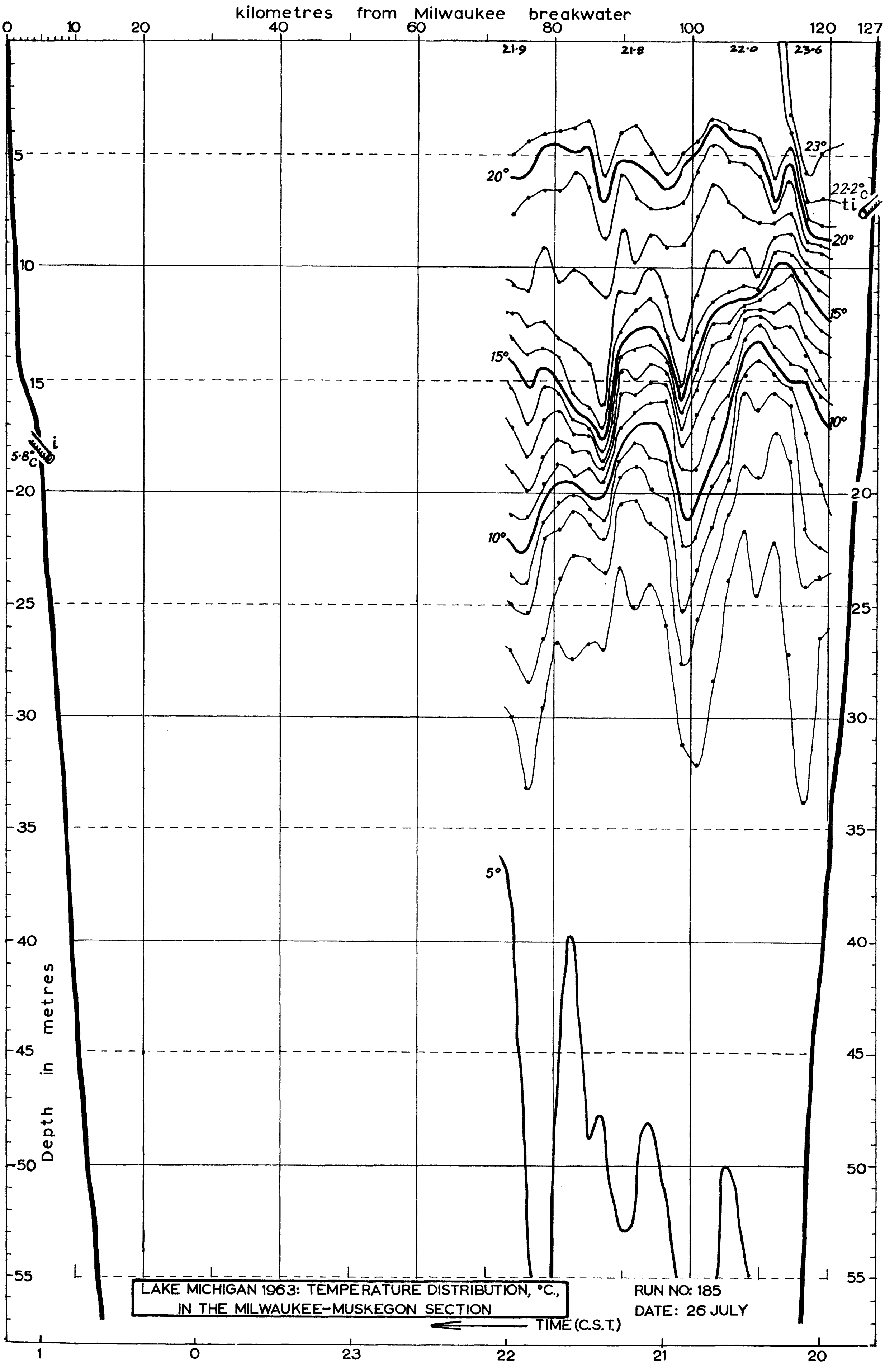


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

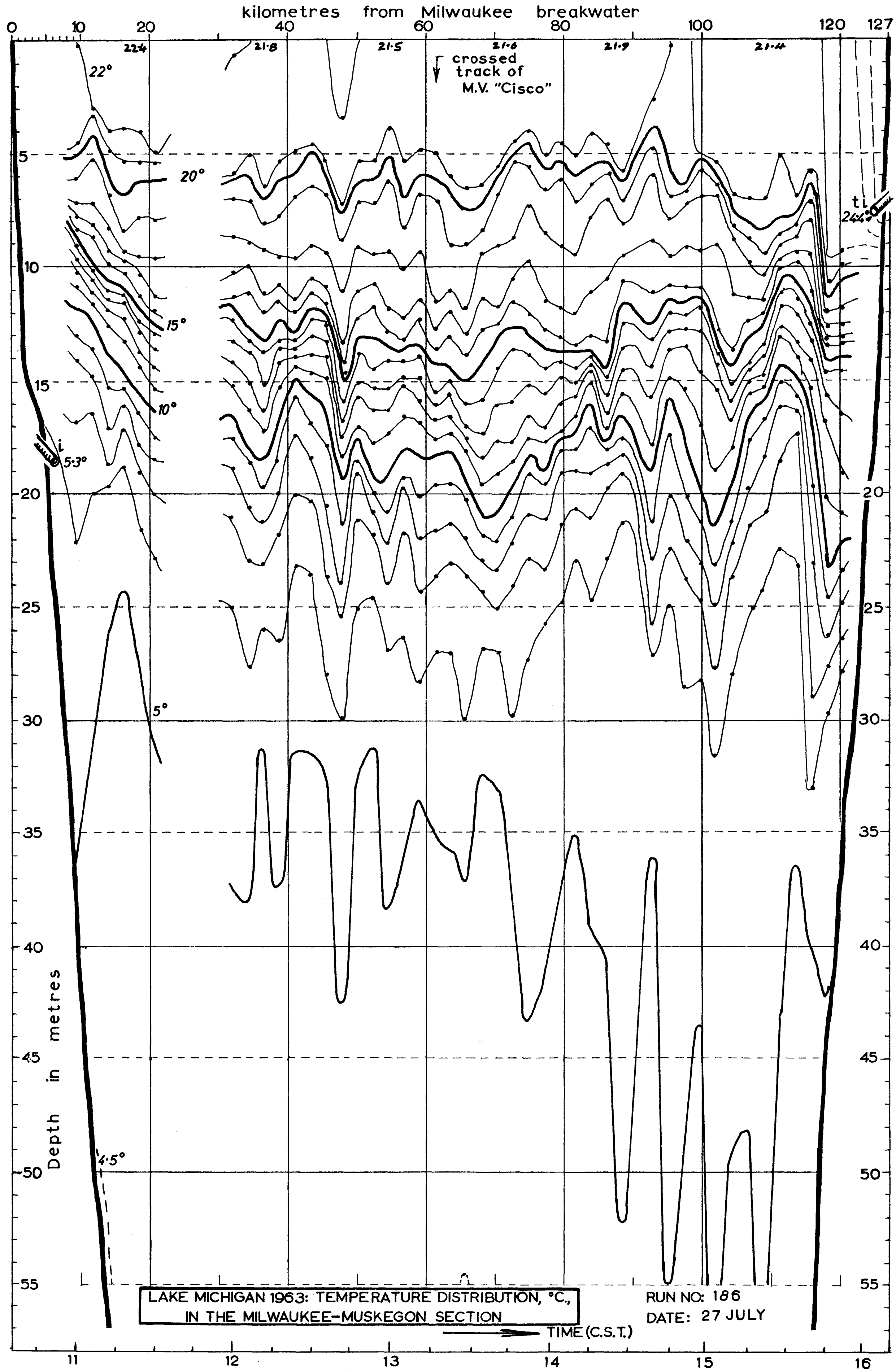
RUN NO: 183
DATE: 26 JULY



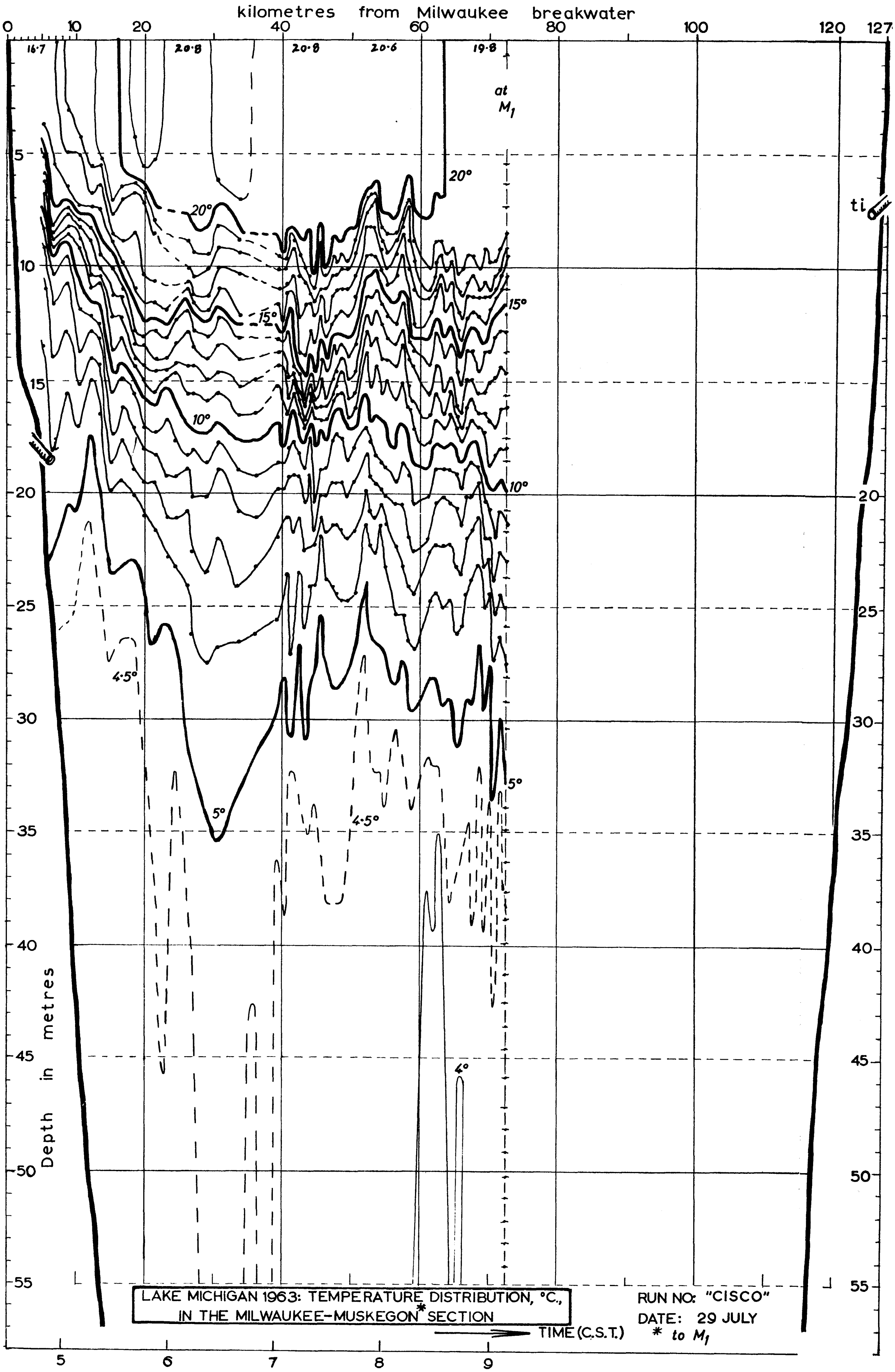
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



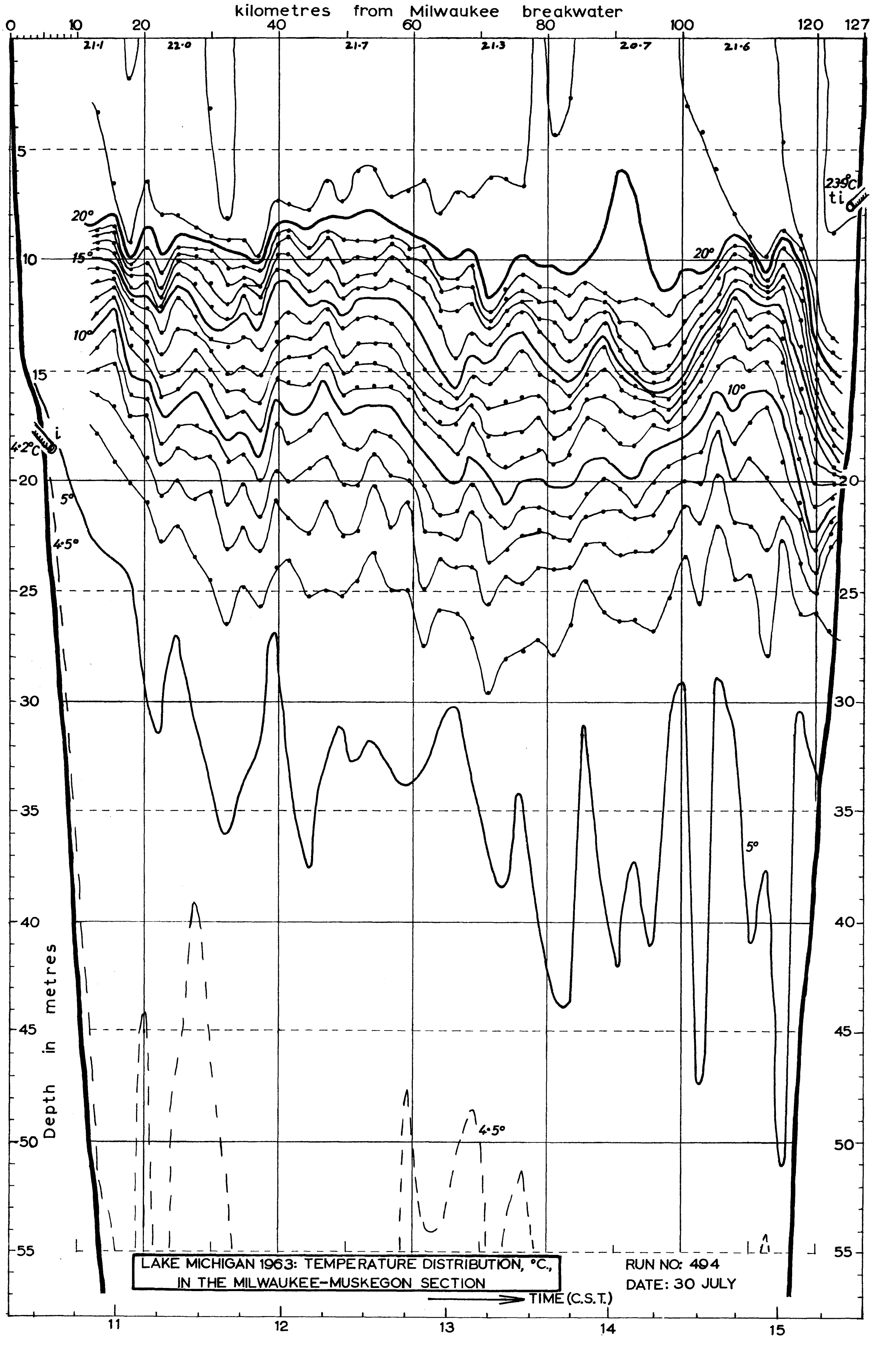
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
21·9 21·8 22·0 23·6
20° 23° 22·2°C ti 20° 15° 15° 10° 10° 5°
5·8°C i
5 10 15 20 25 30 35 40 45 50 55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 185
DATE: 26 JULY
TIME (C.S.T.)
1 0 23 22 21 20



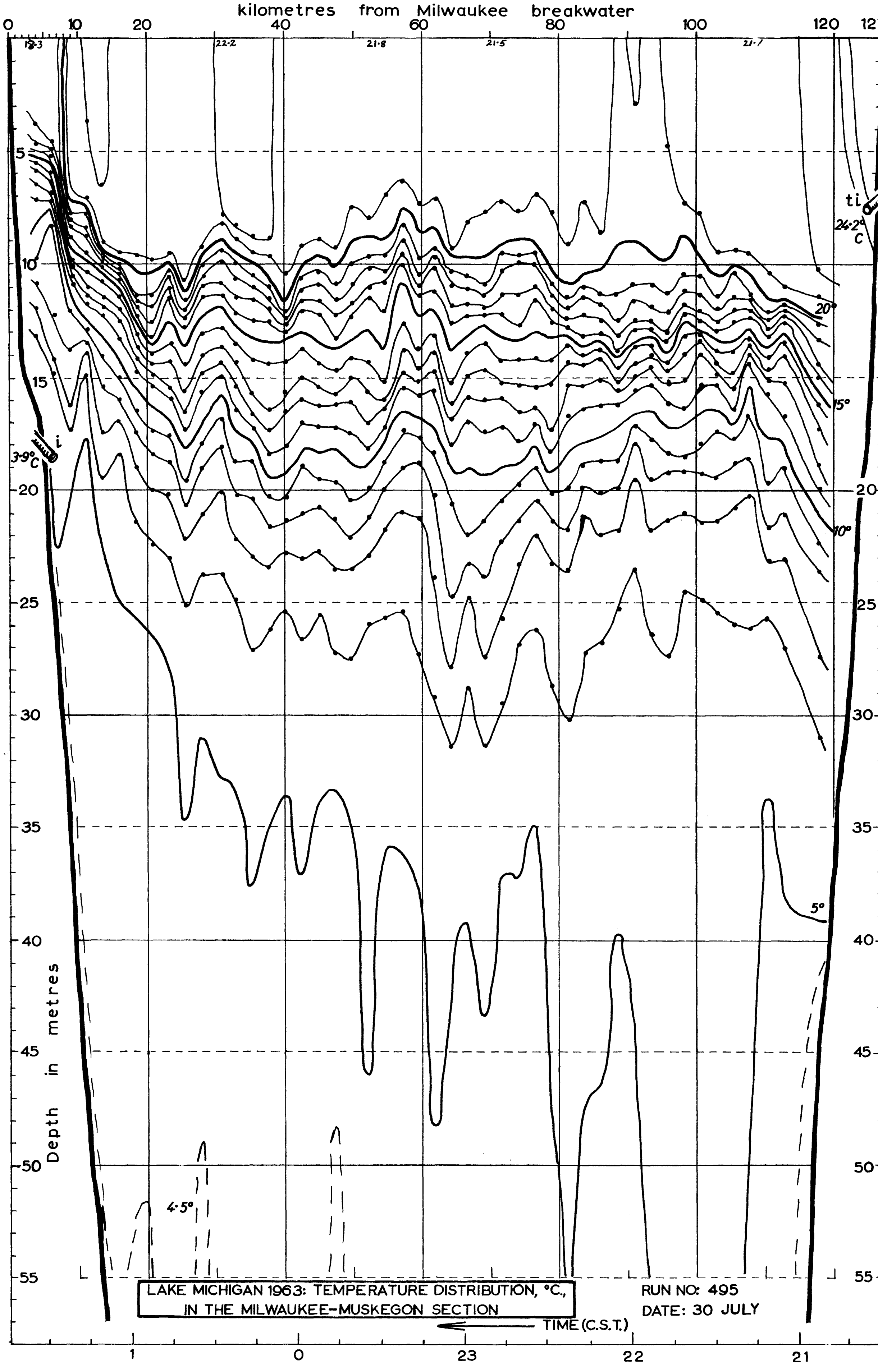
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION



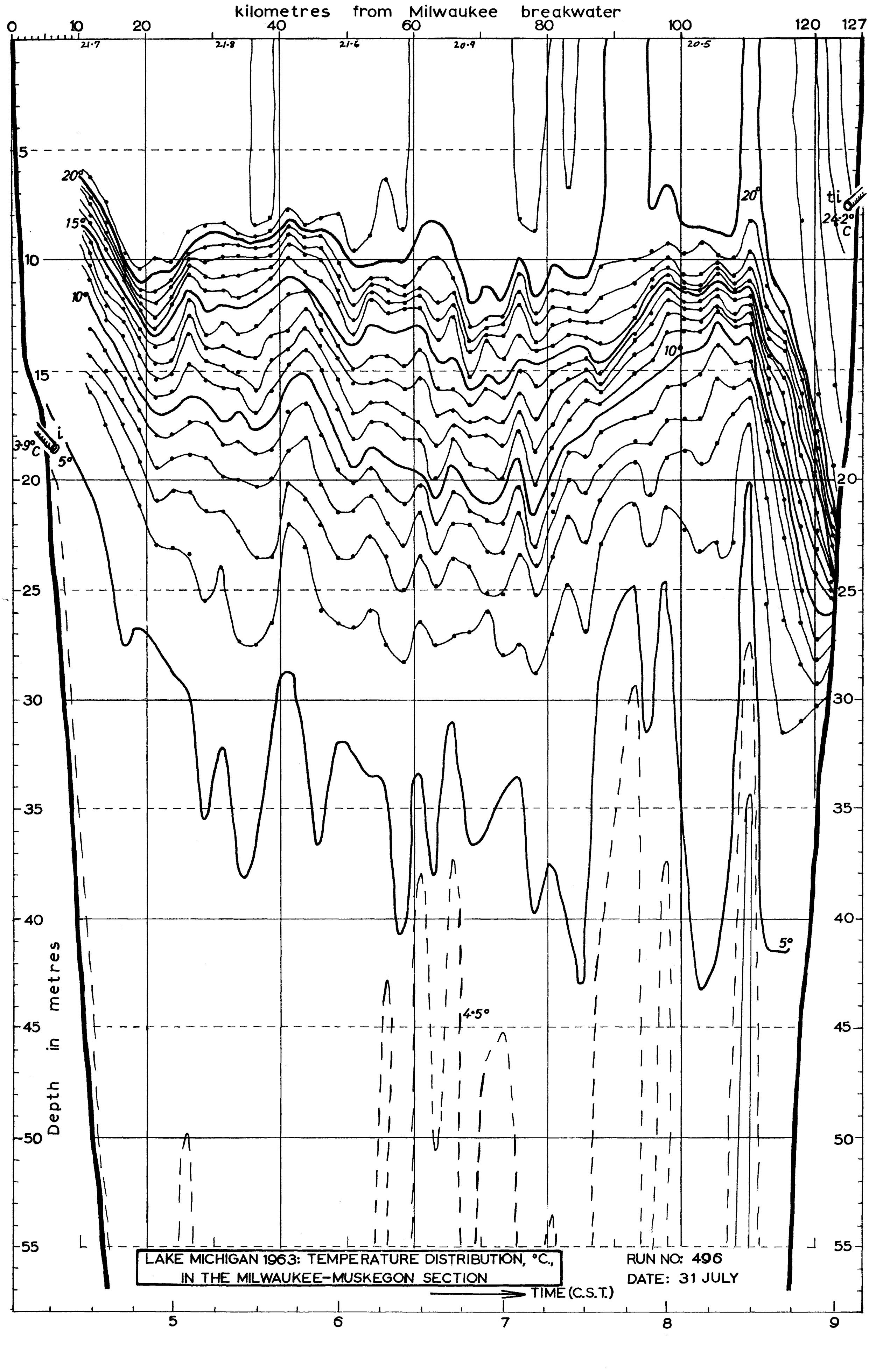
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C, IN THE MILWAUKEE–MUSKEGON* SECTION



LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

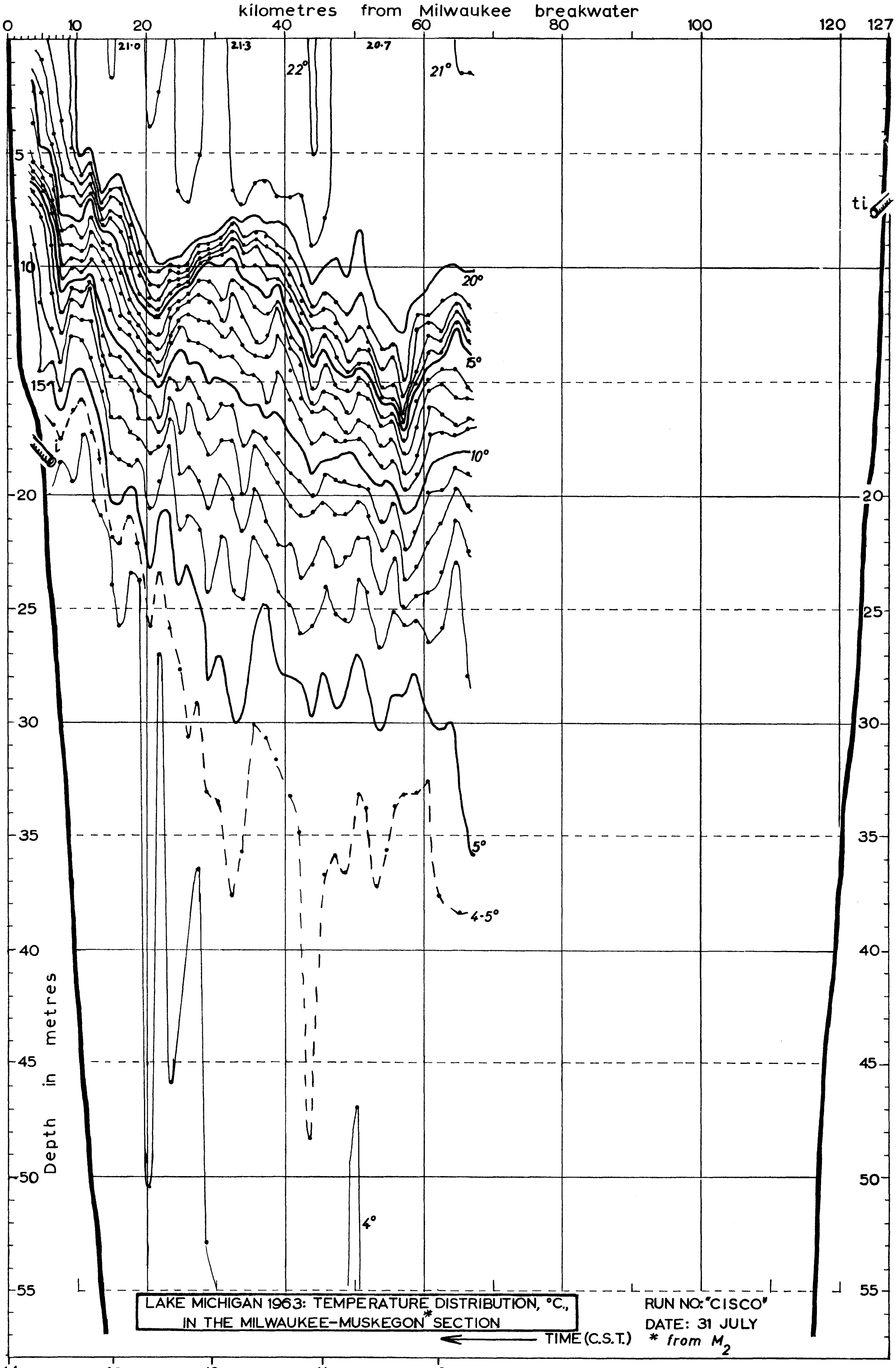


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

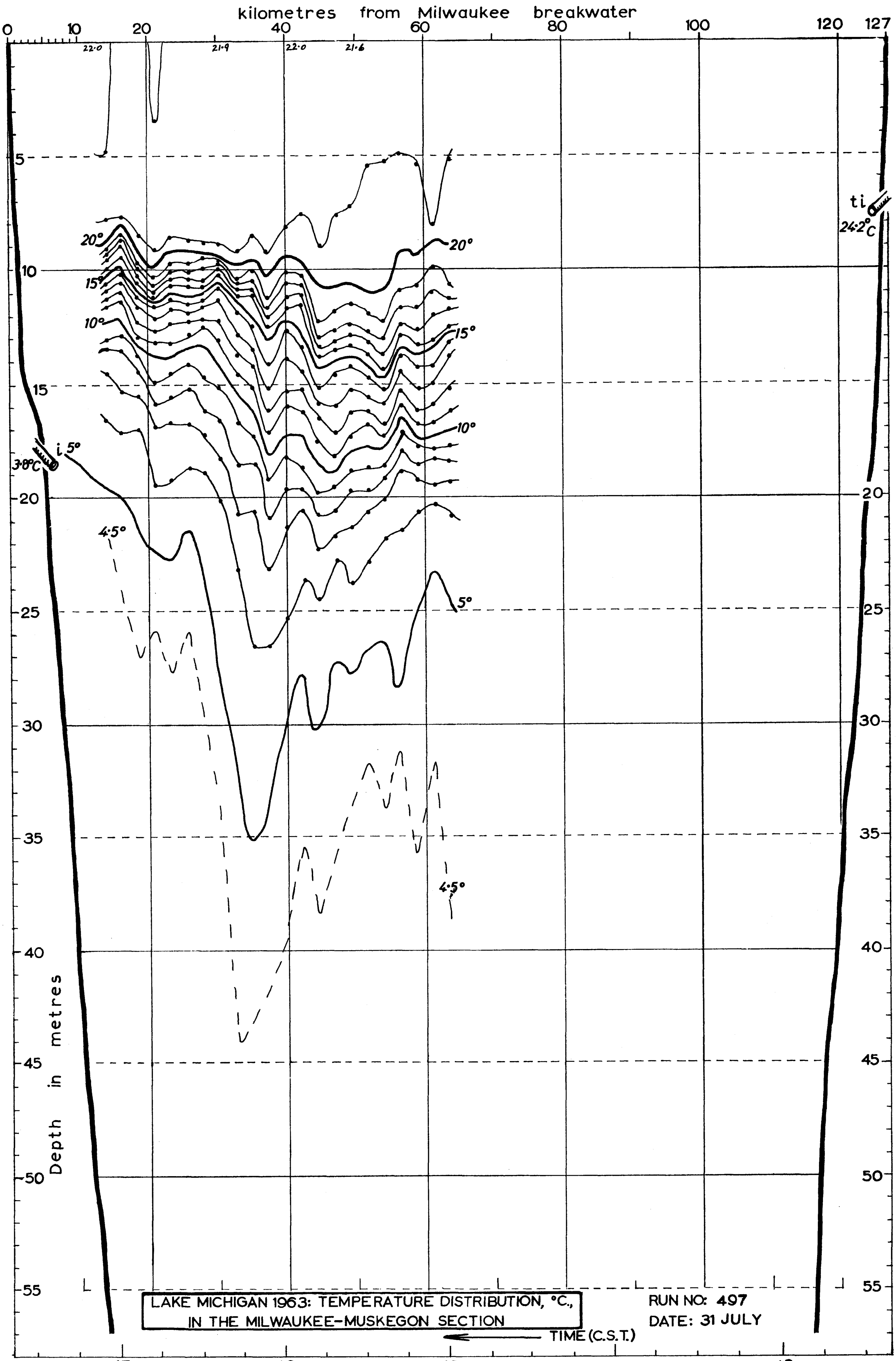


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

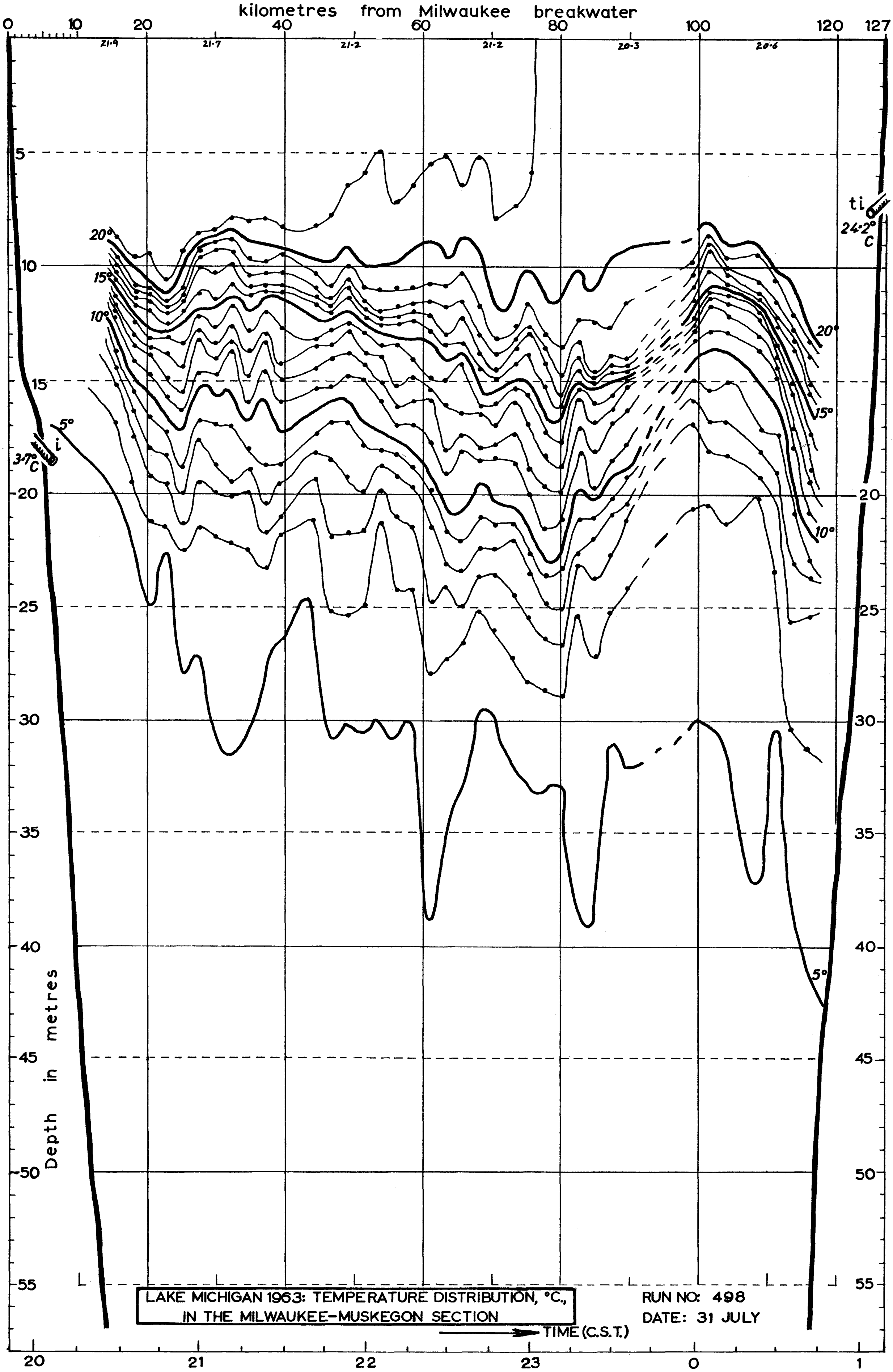
RUN NO: 496
DATE: 31 JULY



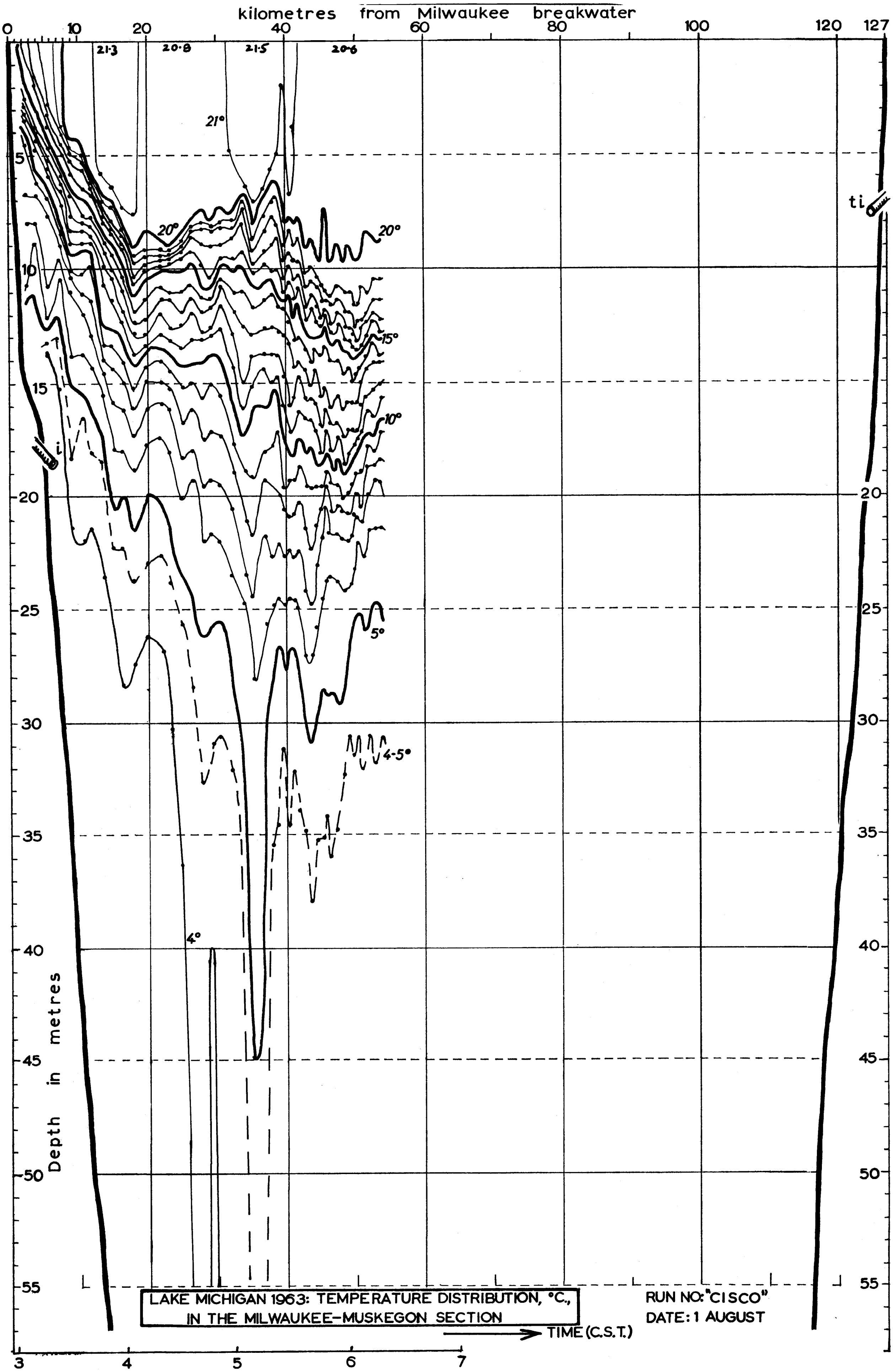
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
21·0 21·3 20·7
22° 21°
20° 15° 10° 5° 4·5° 4°
ti
i
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON* SECTION
RUN NO: "CISCO"
DATE: 31 JULY
* from M2
TIME (C.S.T.)
14 13 12 11 10



LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

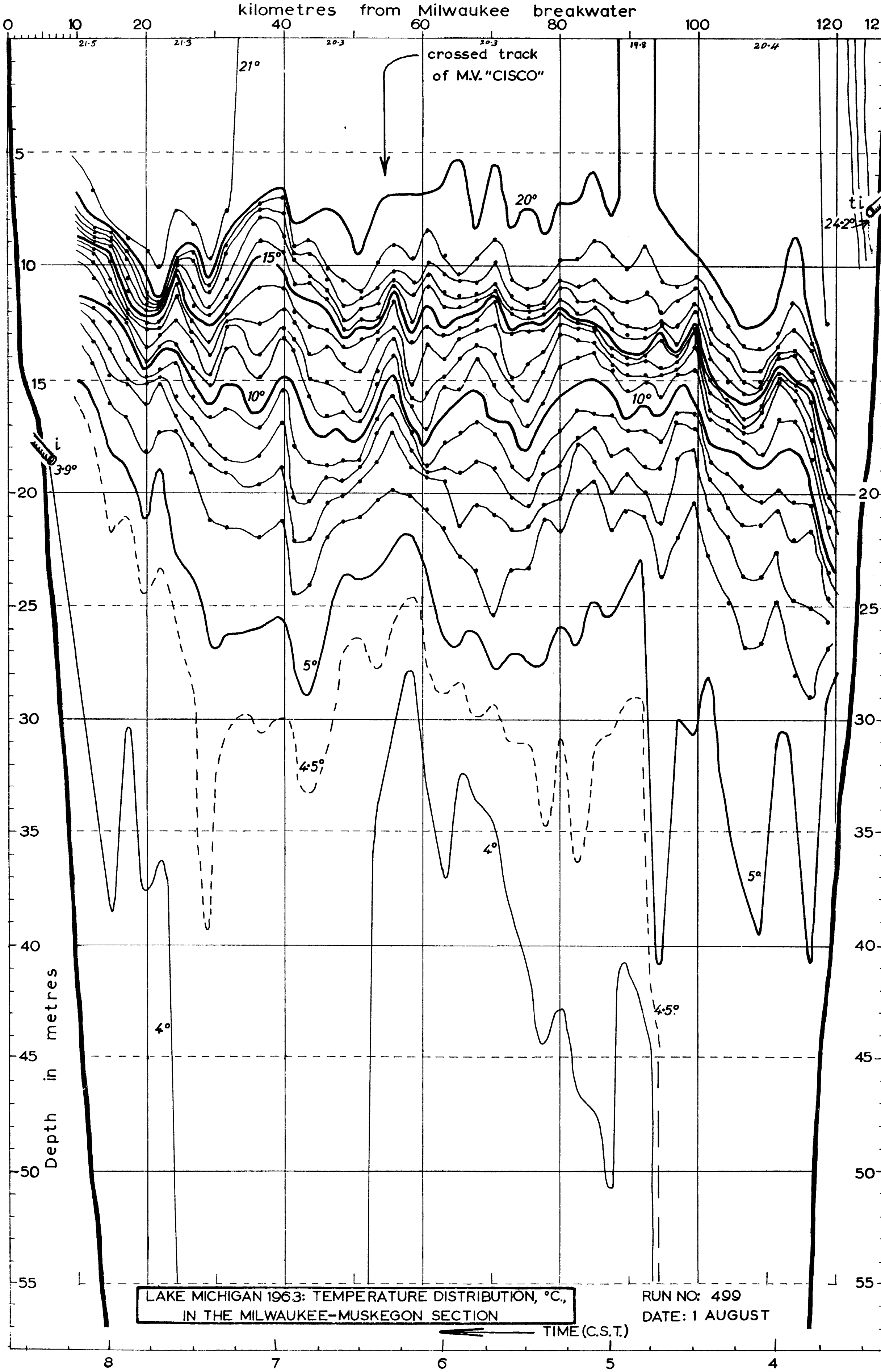


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
21·9 21·7 21·2 21·2 20·3 20·6
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
20° 15° 10° 5°
3·7°C i
ti 24·2°C
20° 15° 10° 5°
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 498
DATE: 31 JULY
TIME (C.S.T.)
20 21 22 23 0 1

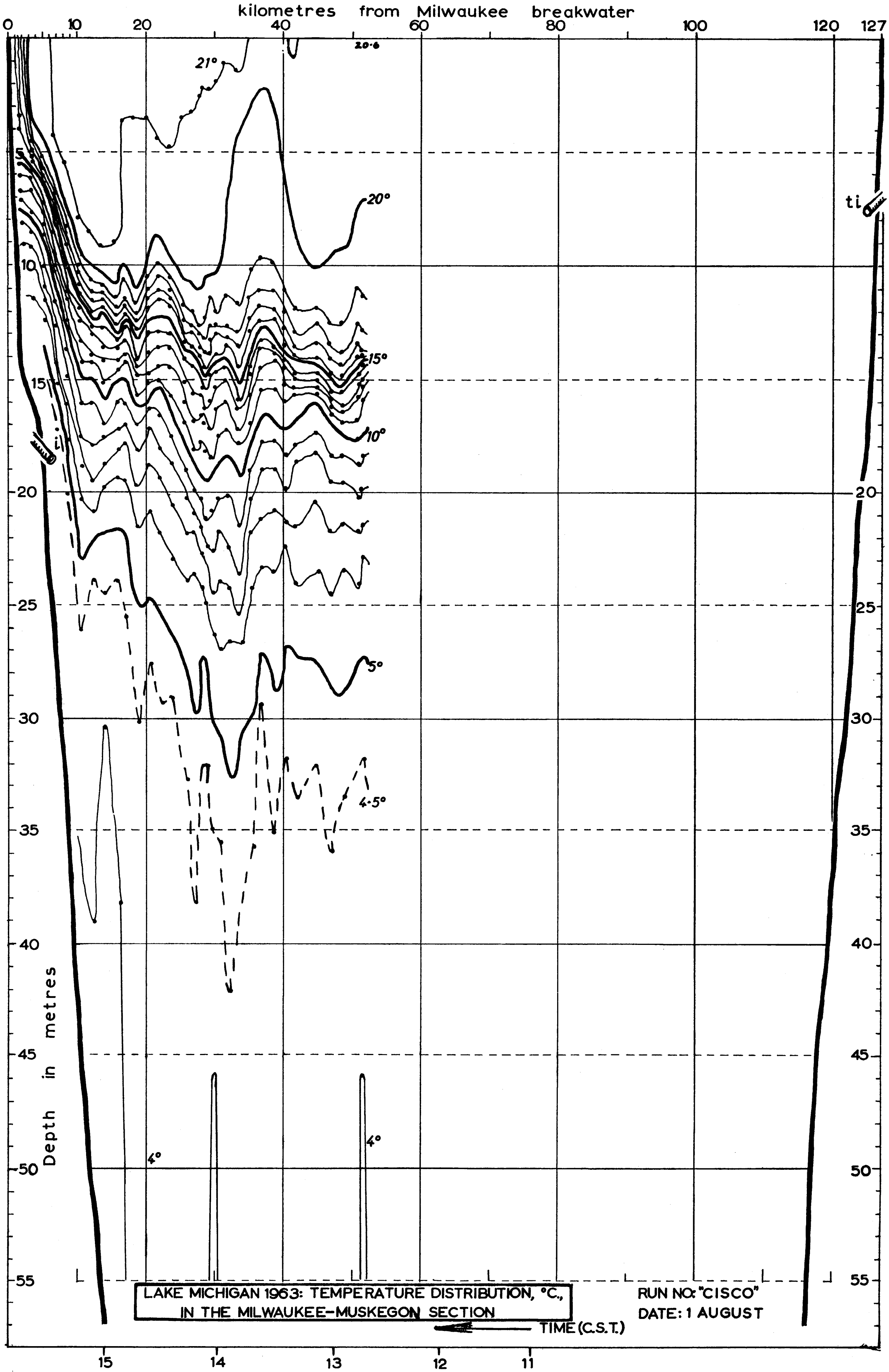


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

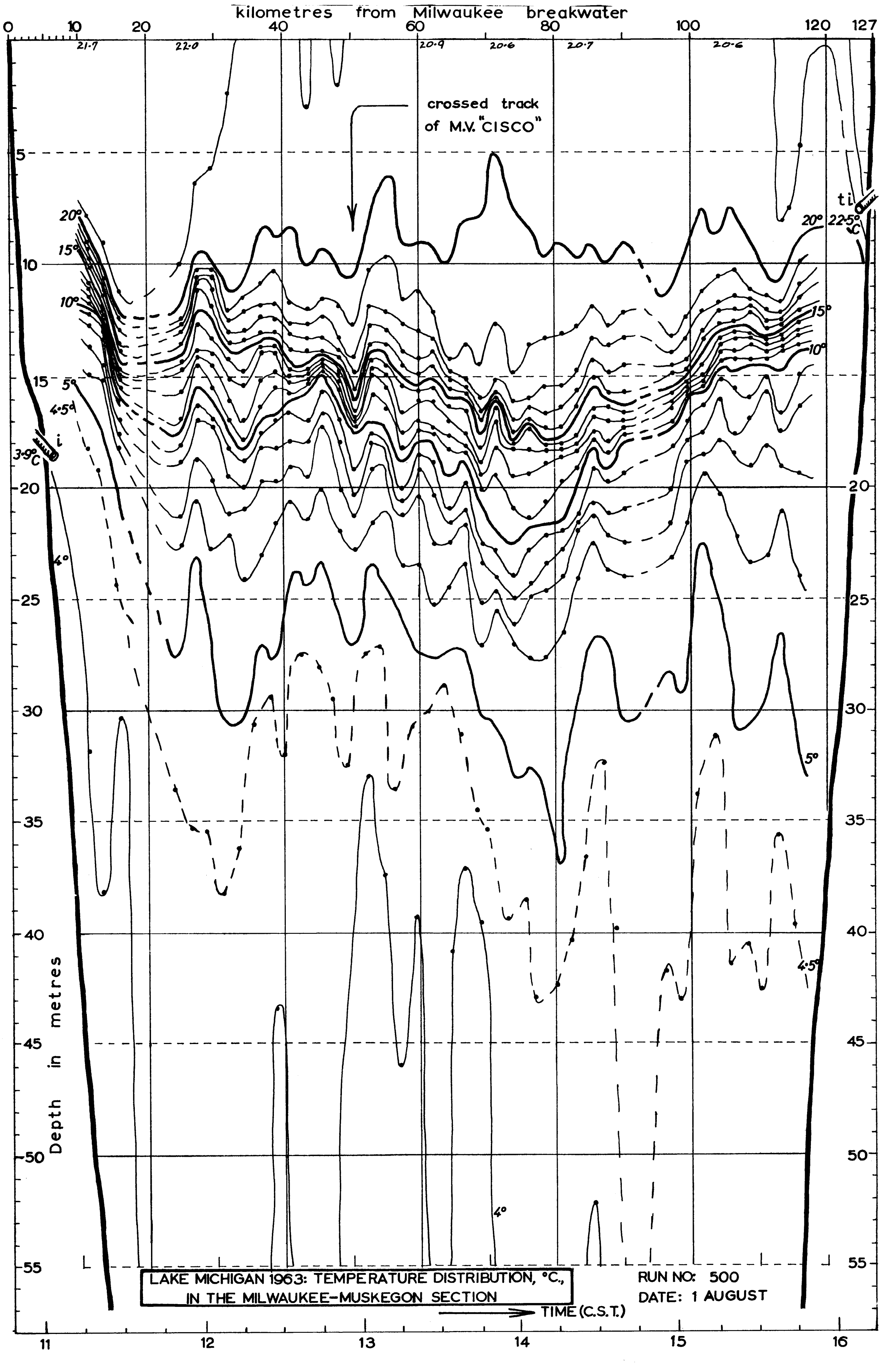
RUN NO: "CISCO"
DATE: 1 AUGUST



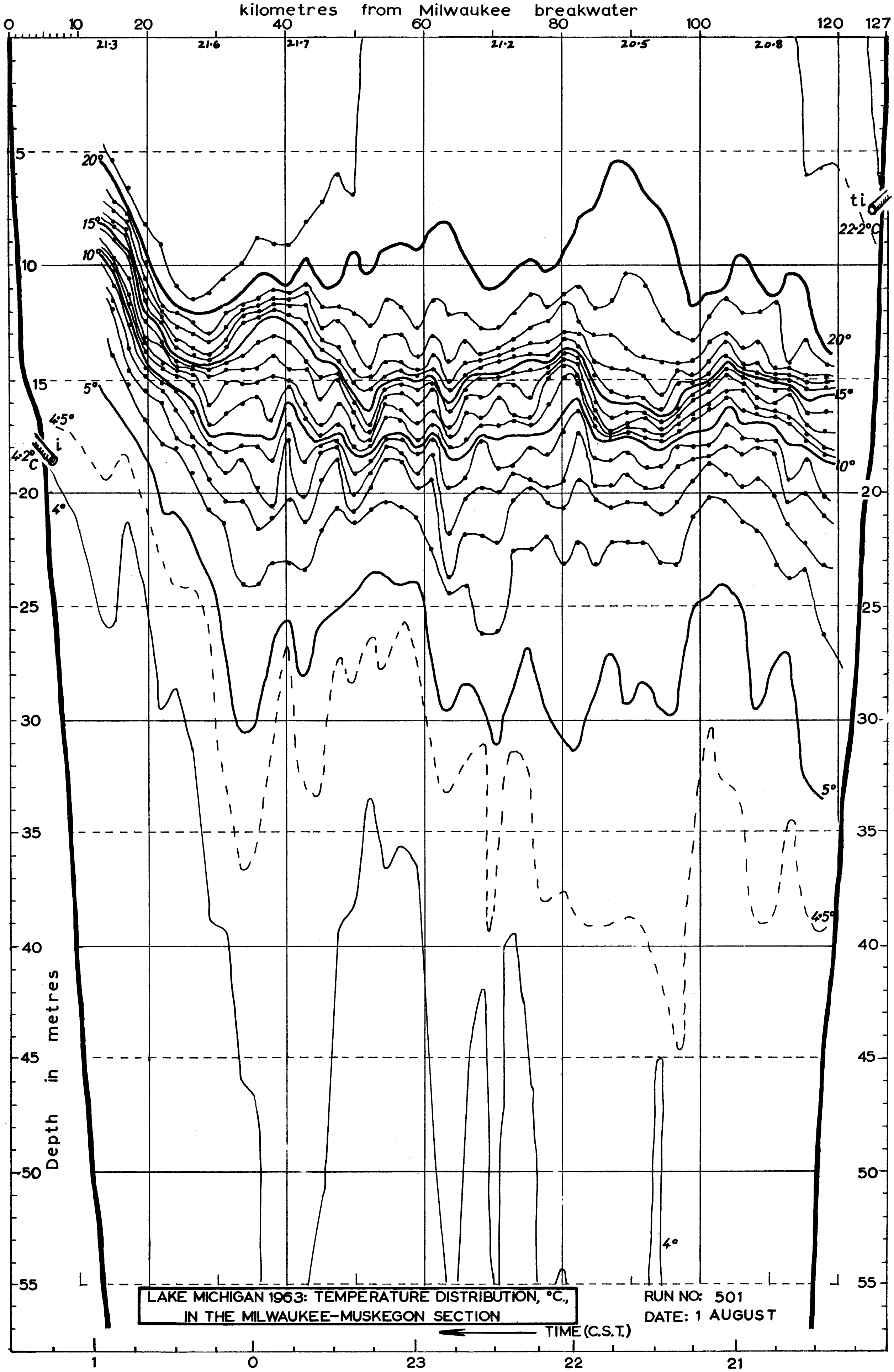
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



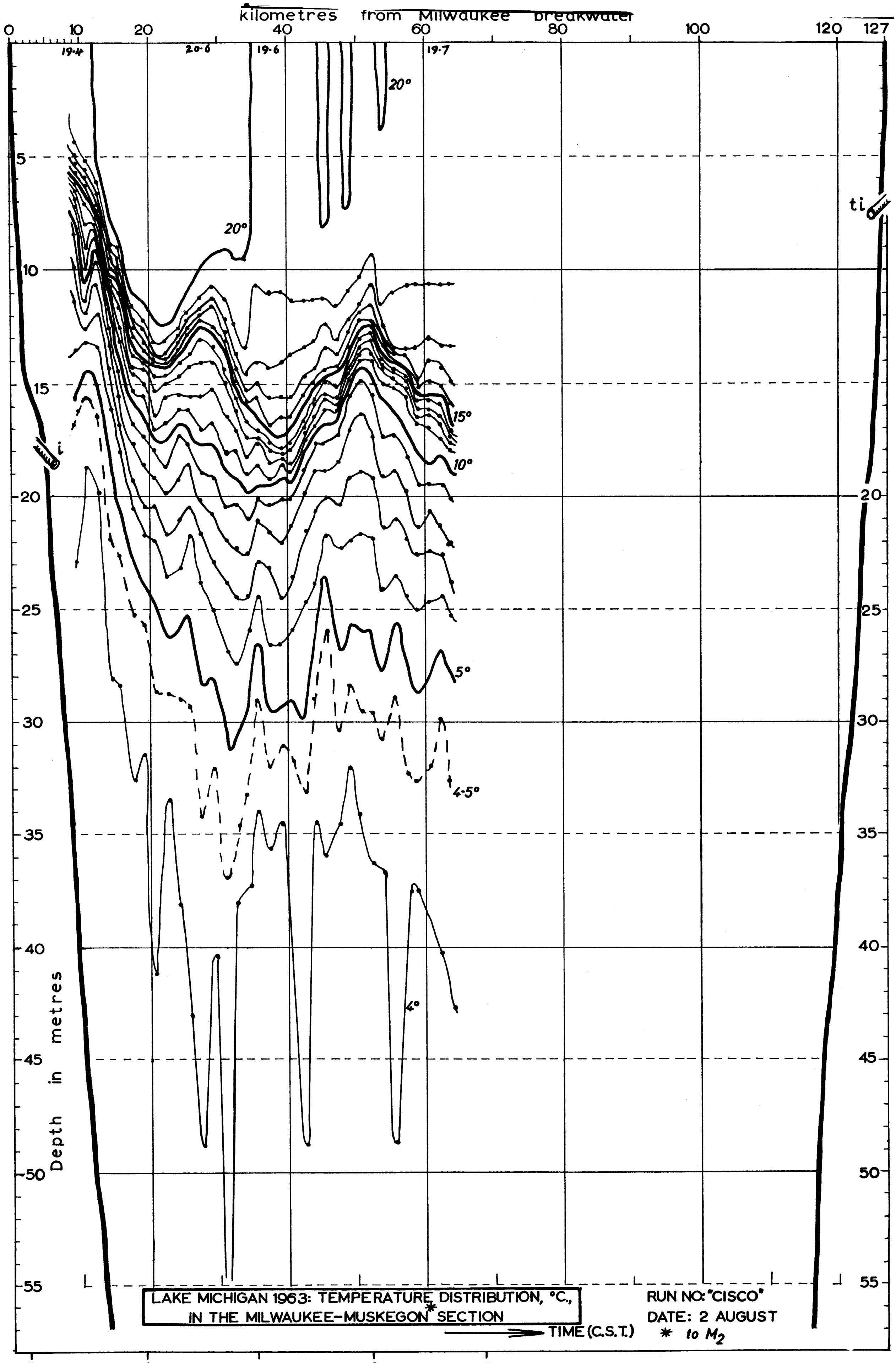
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

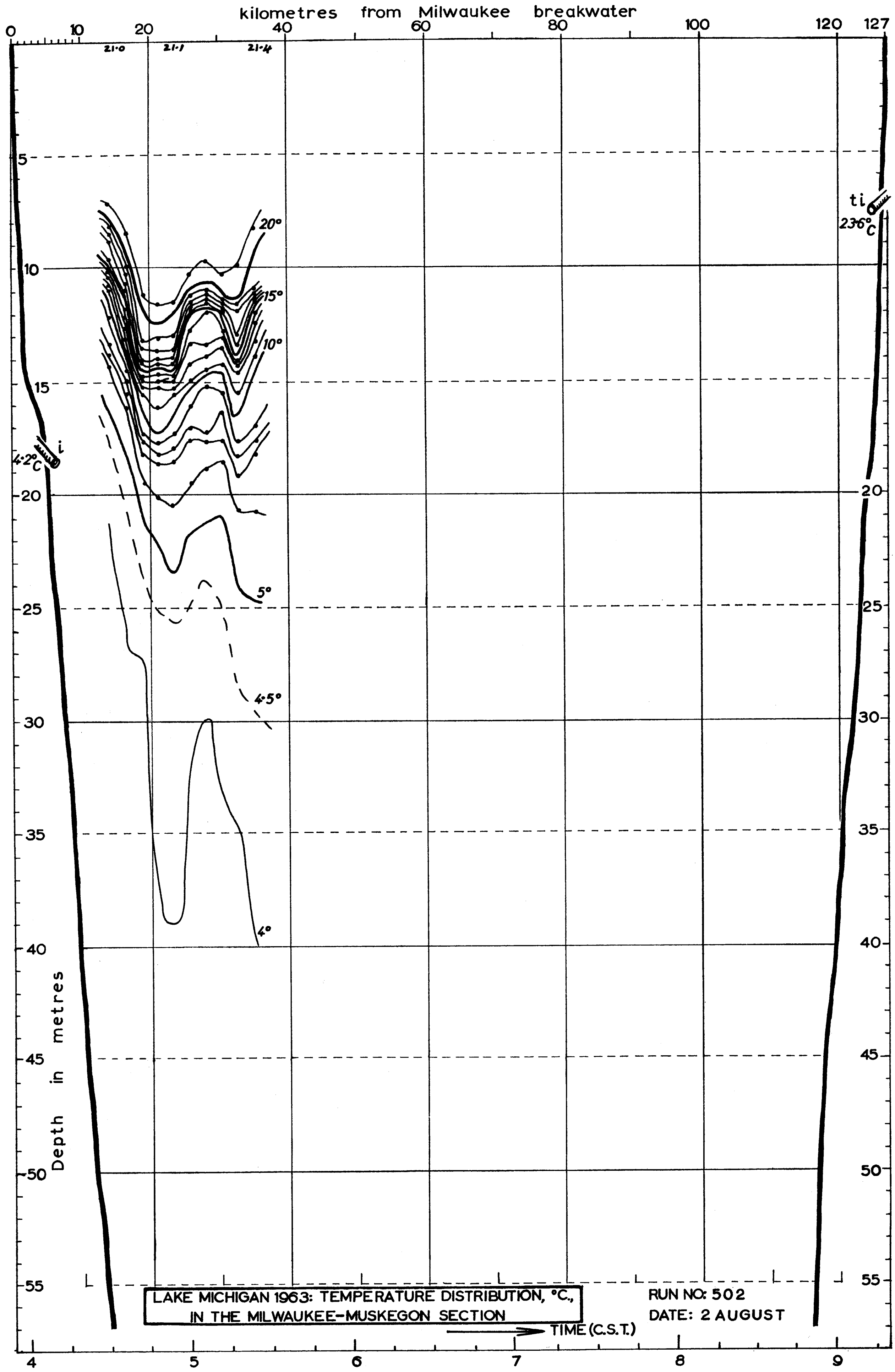


kilometres from Milwaukee breakwater
crossed track of M.V. "CISCO"
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 500
DATE: 1 AUGUST
TIME (C.S.T.)

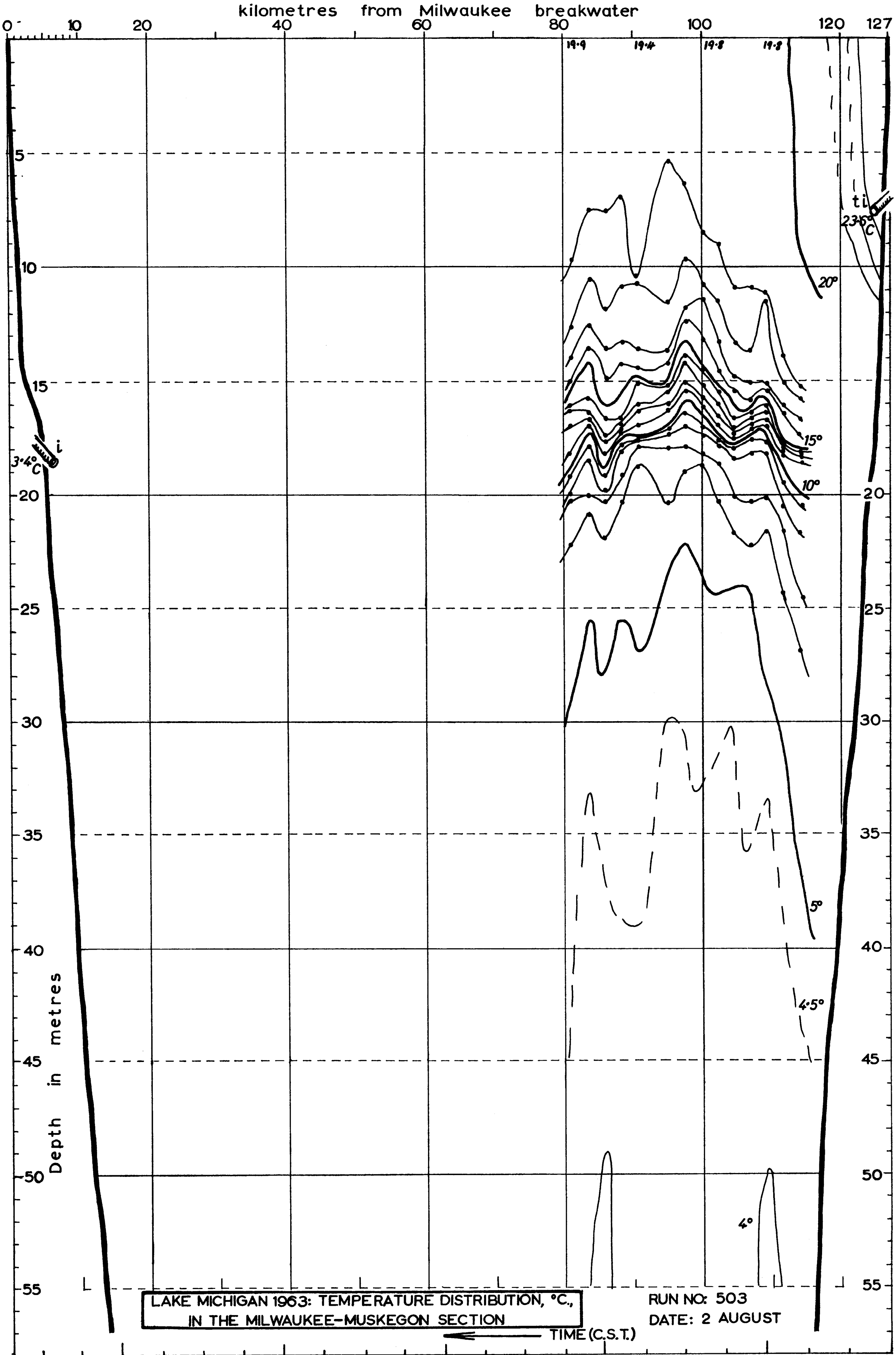


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
21·3 21·6 21·7 21·2 20·5 20·8
20° 15° 10° 5° 4·5° 4·2°C i 4° ti 22·2°C 20° 15° 10° 5° 4·5° 4°
5 10 15 20 25 30 35 40 45 50 55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 501
DATE: 1 AUGUST
TIME (C.S.T.)
1 0 23 22 21

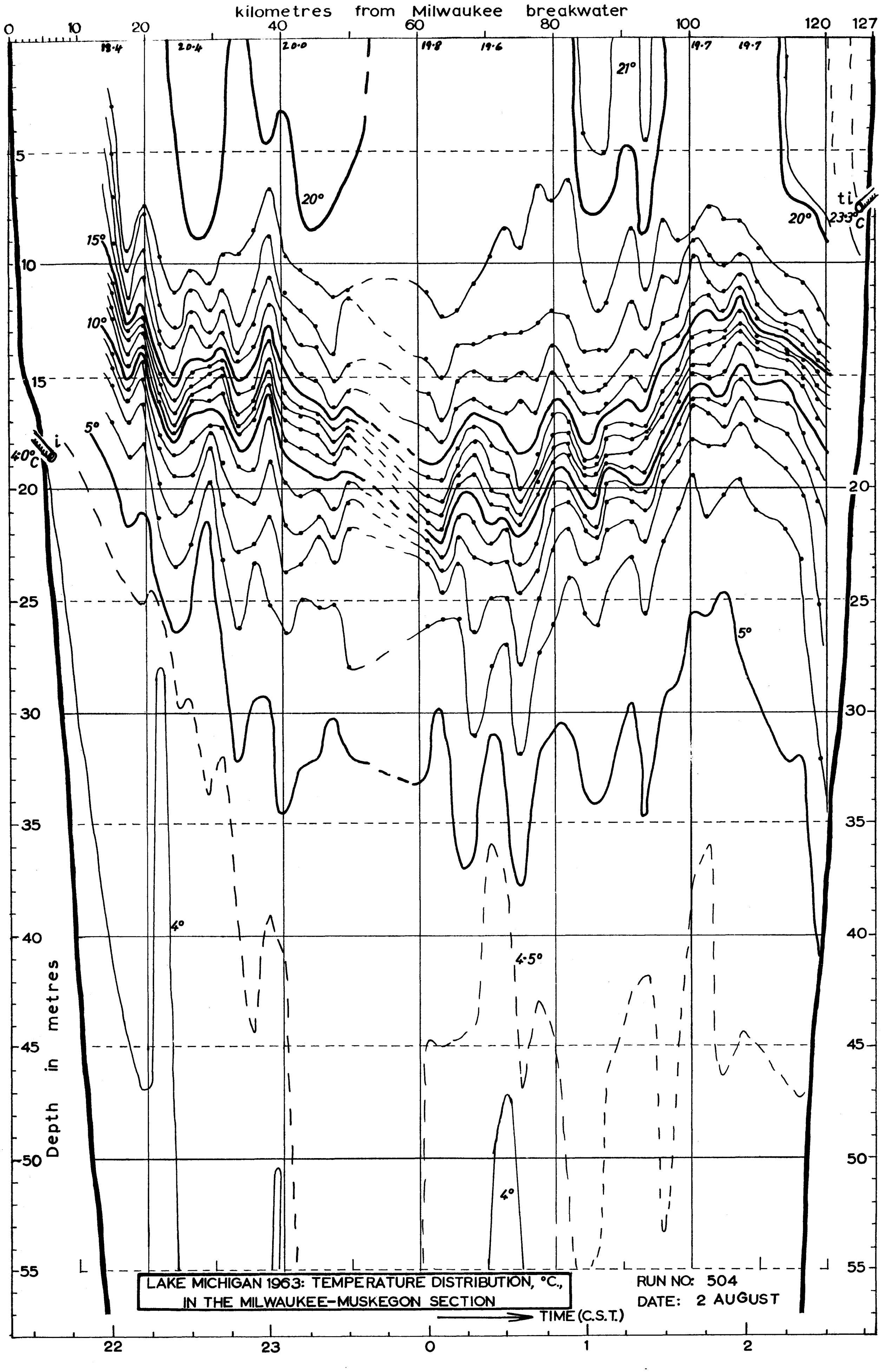

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·4
20·6
19·6
19·7
20°
20°
15°
10°
5°
4-5°
4°
i
ti
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
3
4
5
6
7
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON* SECTION
RUN NO: "CISCO"
DATE: 2 AUGUST
TIME (C.S.T.)
* to M2



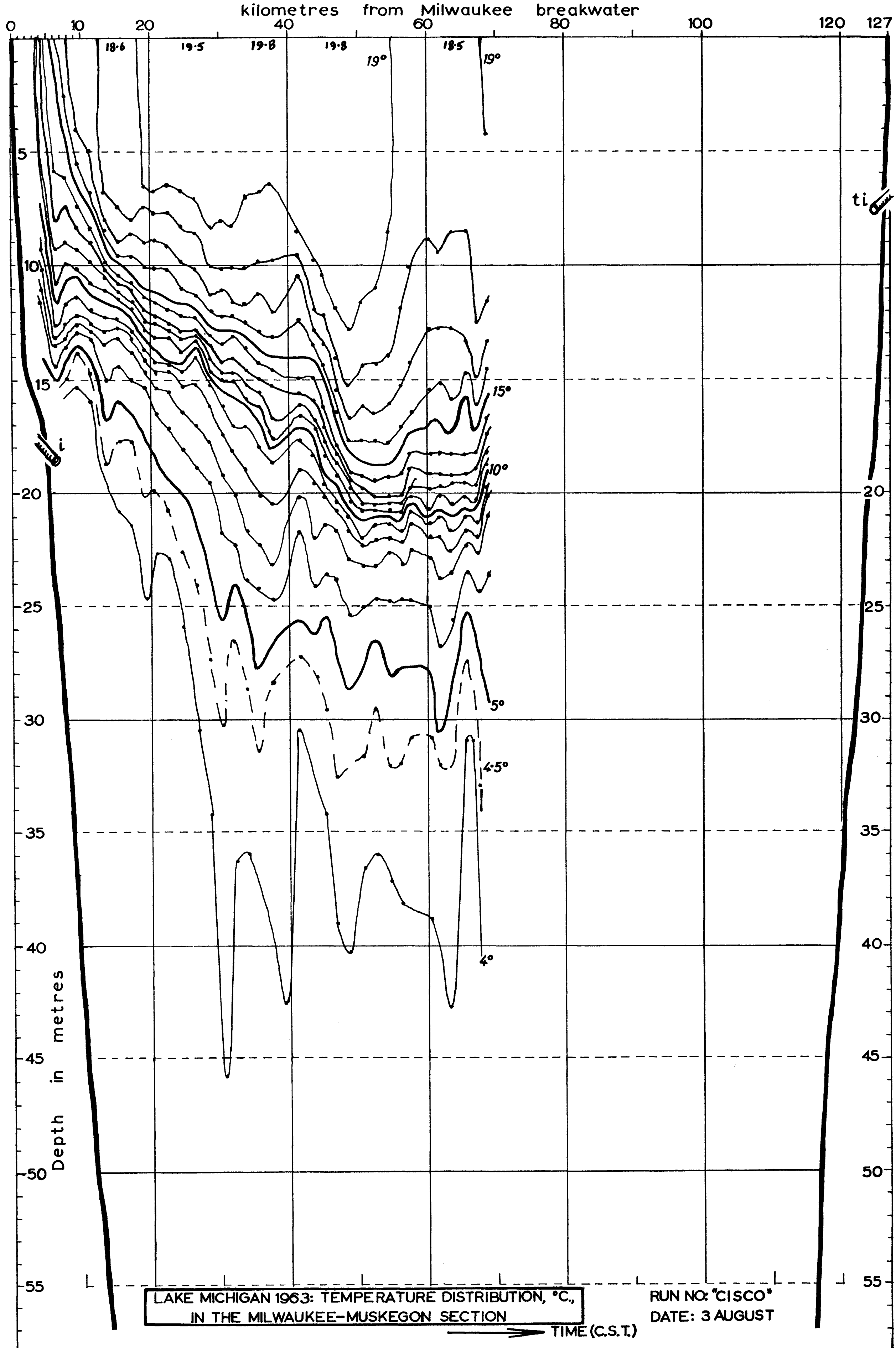
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



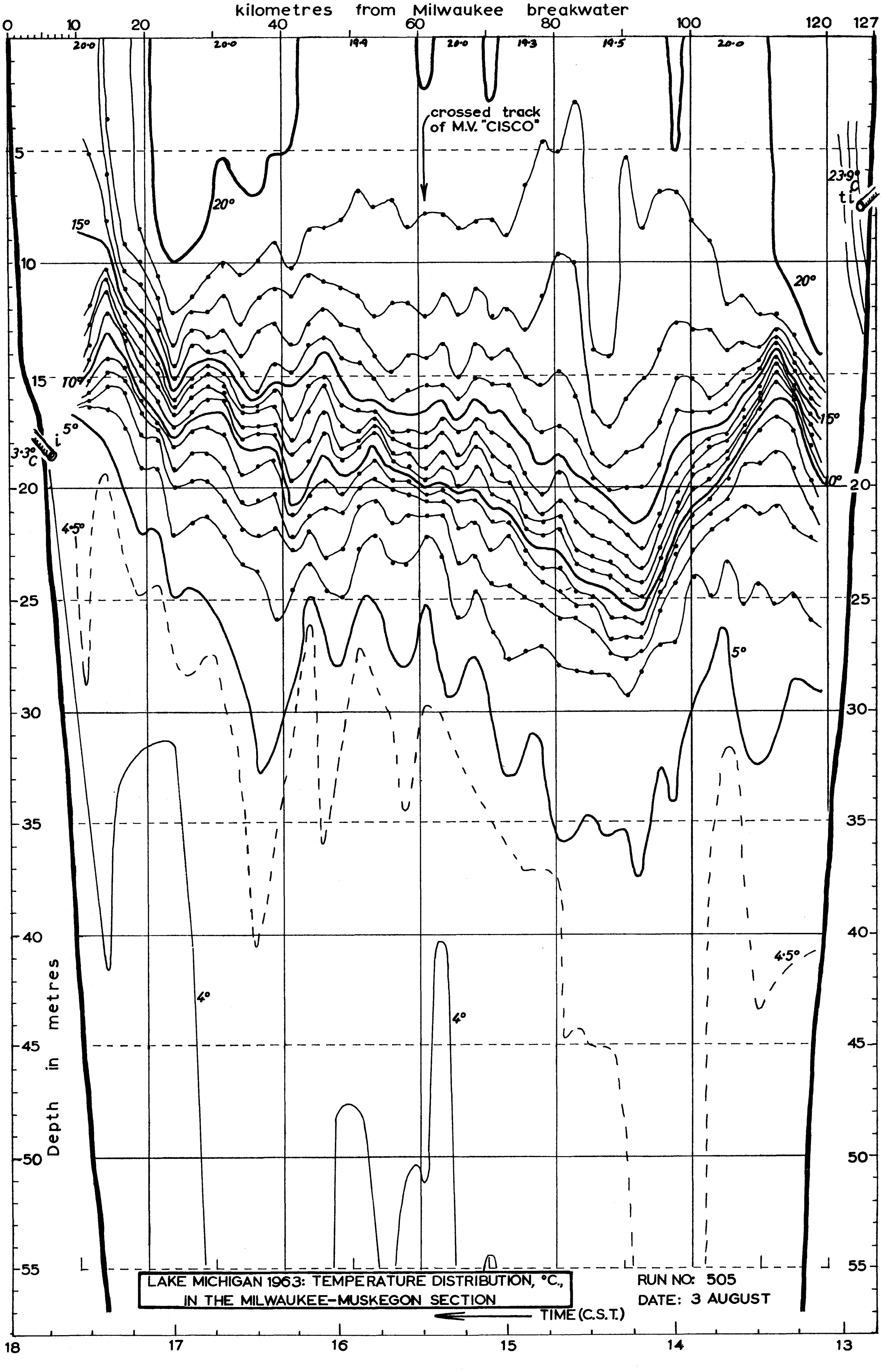
kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·9
19·4
19·8
19·8
Depth in metres
3·4°C
i
ti
23·6°C
20°
15°
10°
5°
4·5°
4°
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 503
DATE: 2 AUGUST
TIME (C.S.T.)
17
16
15
14
13

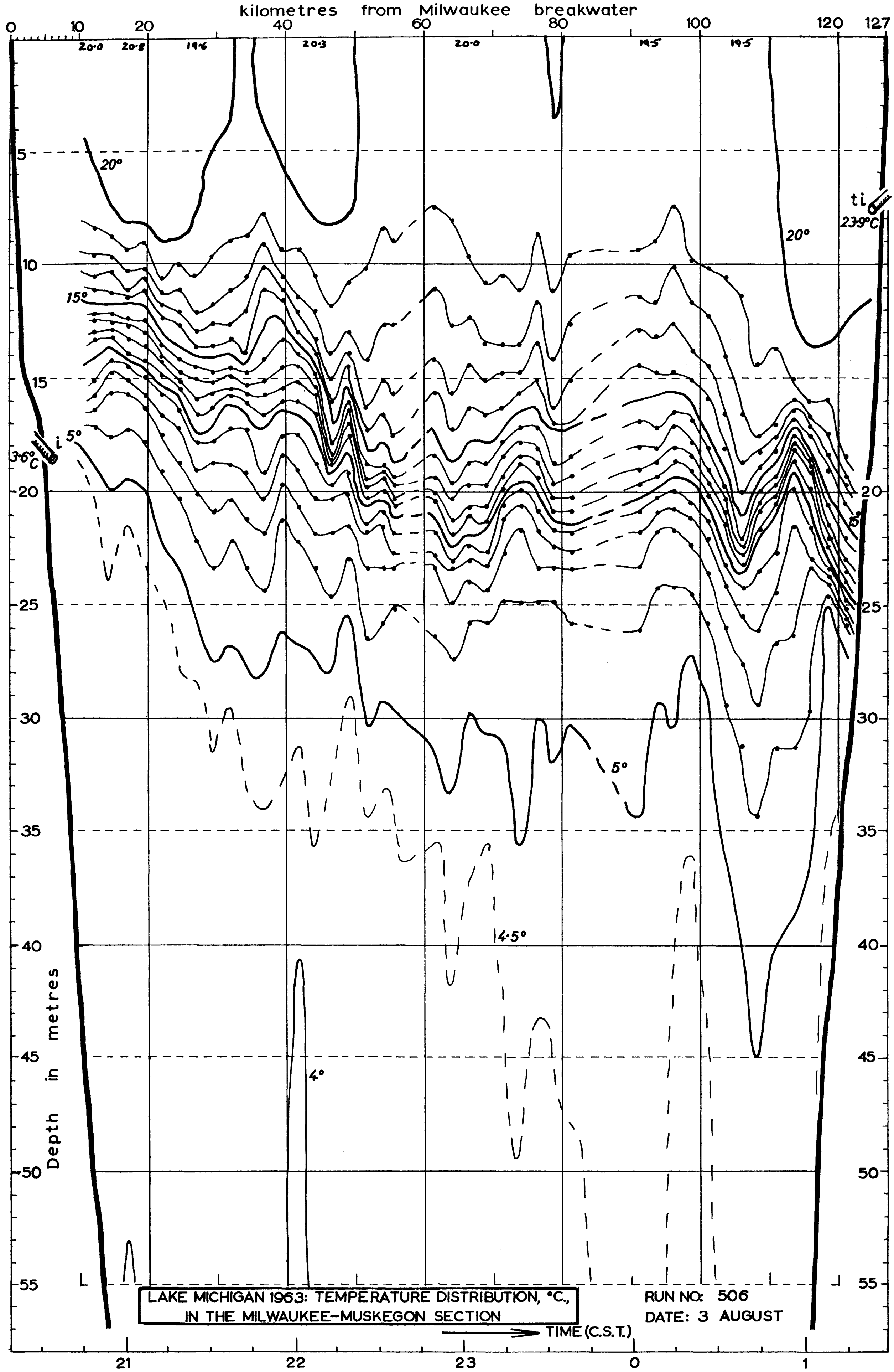


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

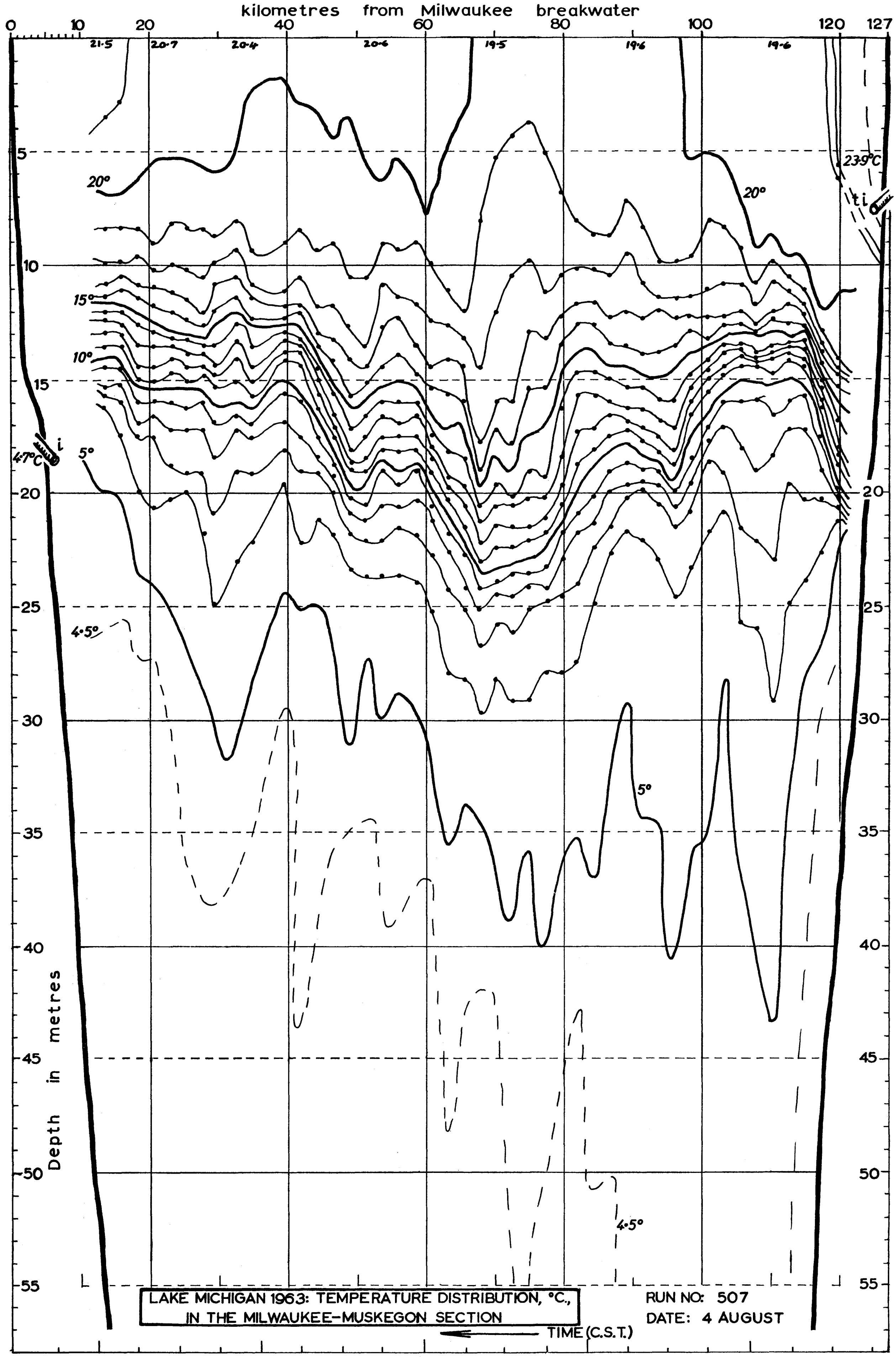


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
18·6 19·5 19·8 19·8 19° 18·5 19°
15° 10° 5° 4·5° 4°
i ti
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: "CISCO"
DATE: 3 AUGUST
TIME (C.S.T.)
5 6 7 8

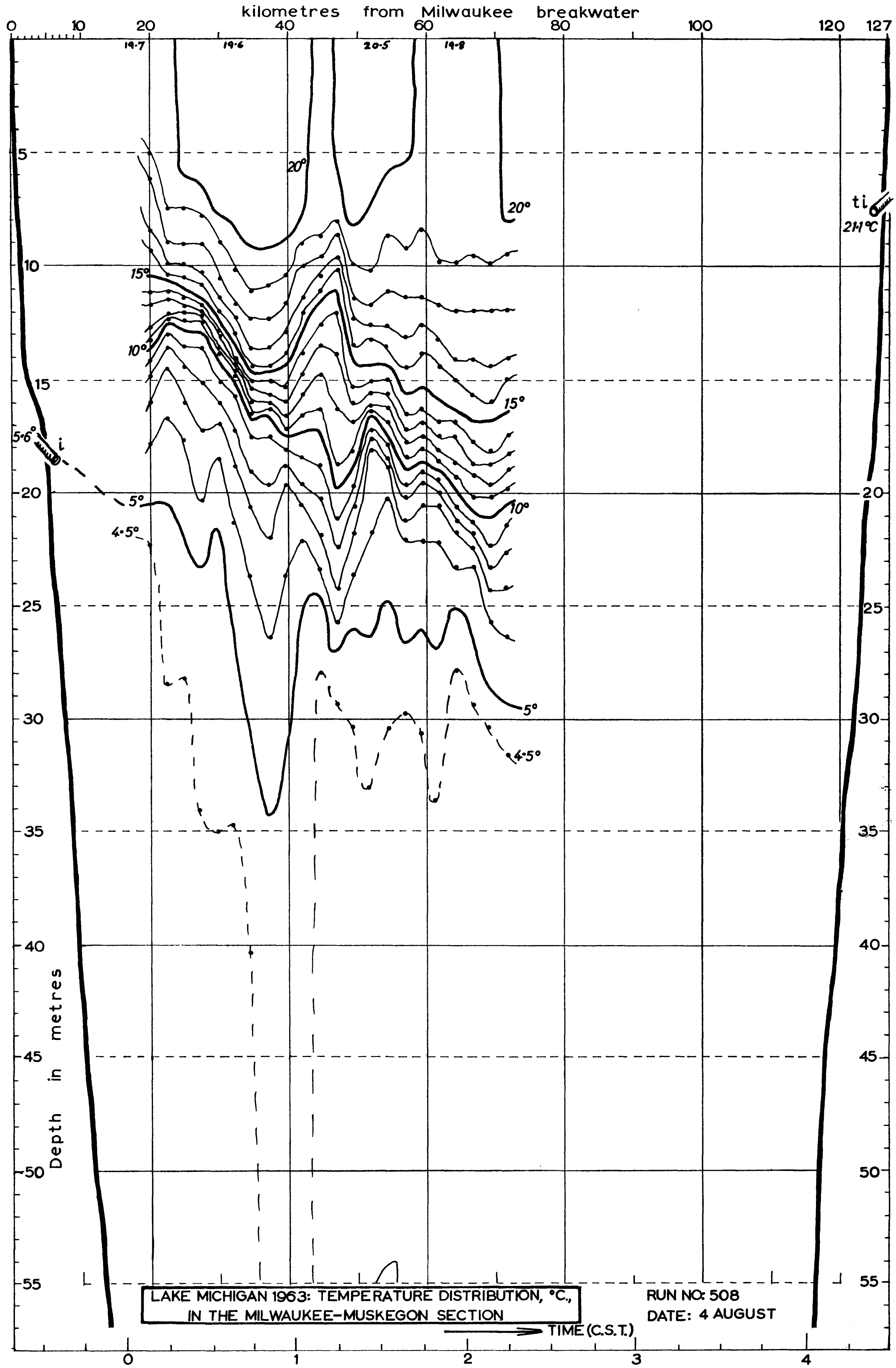

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
20·0
20·0
19·9
20·0
19·3
19·5
20·0
crossed track
of M.V. "CISCO"
20°
15°
10°
5°
3·3°C
i
4·5°
23·9°C
ti
20°
15°
10°
5°
4°
4°
4·5°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C.,
IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 505
DATE: 3 AUGUST
TIME (C.S.T.)
18
17
16
15
14
13



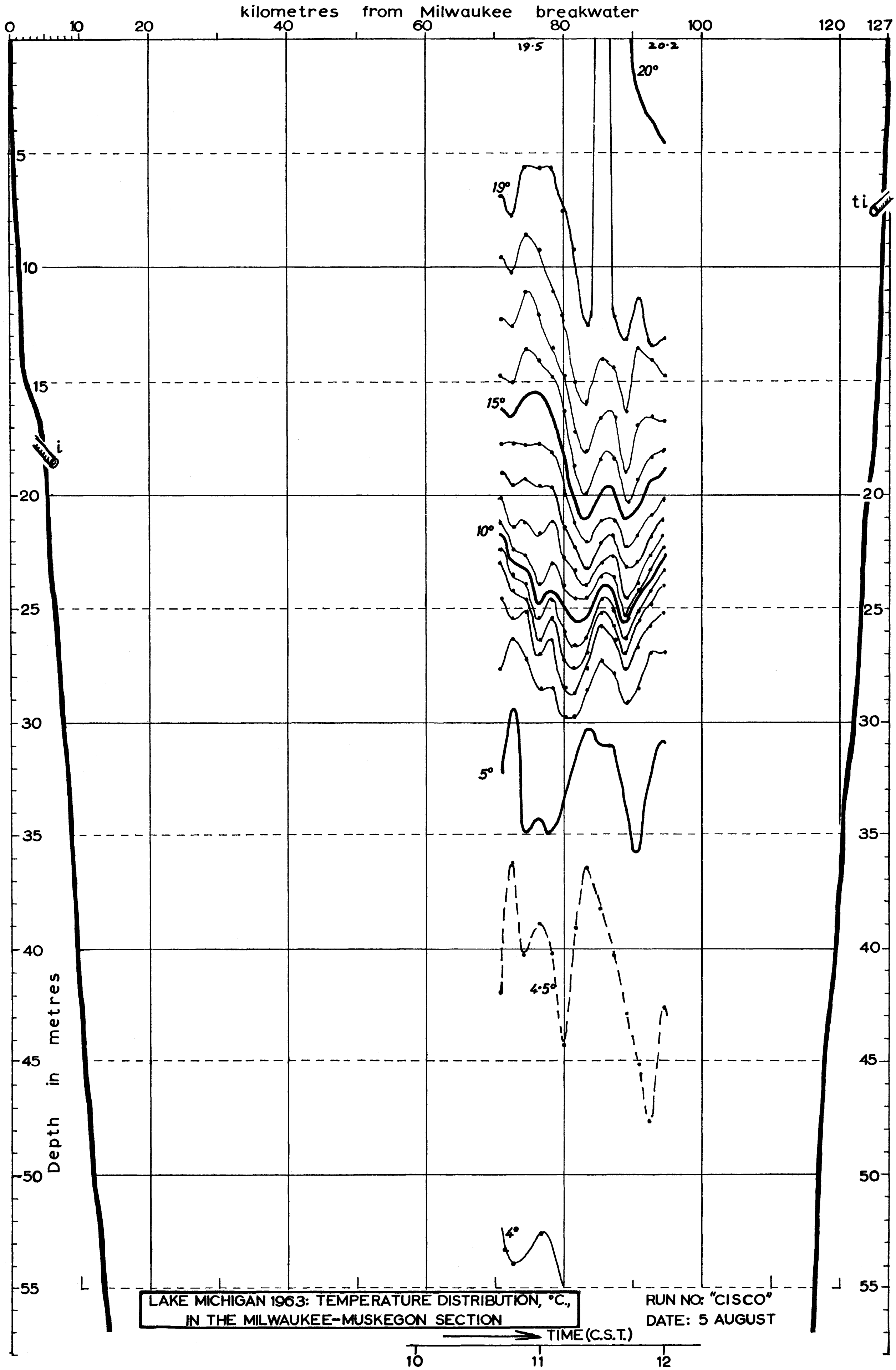
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
20·0 20·8 19·6 20·3 20·0 19·5 19·5
20°
15°
5°
3·6°C
ti
23·9°C
4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 506
DATE: 3 AUGUST
TIME (C.S.T.)
21 22 23 0 1



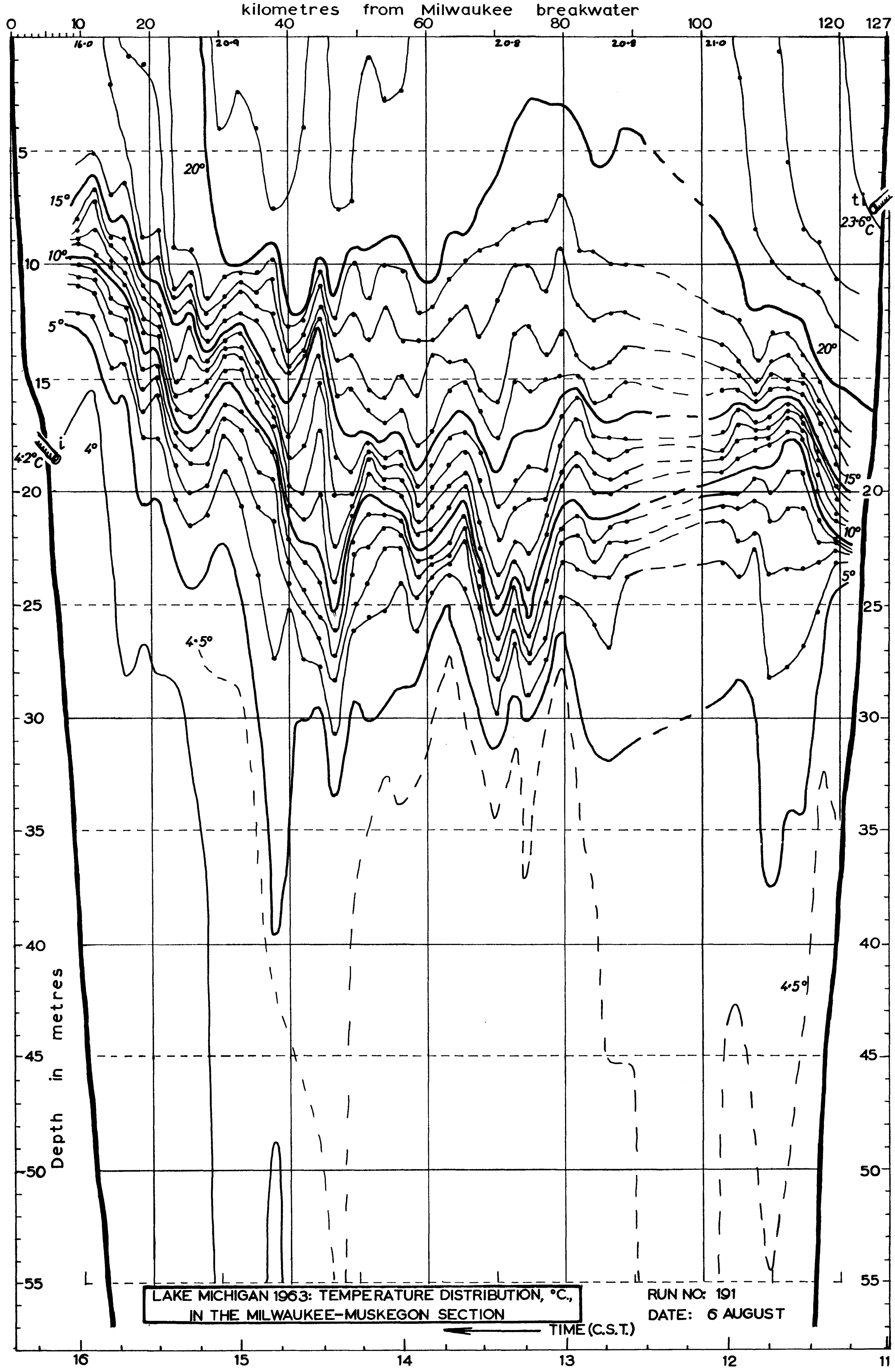
kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
21.5
20.7
20.4
20.6
19.5
19.6
19.6
20°
23.9°C
ti
15°
10°
4.7°C
i
5°
4.5°
5°
4.5°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 507
DATE: 4 AUGUST
TIME (C.S.T.)
15
14
13
12
11



LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

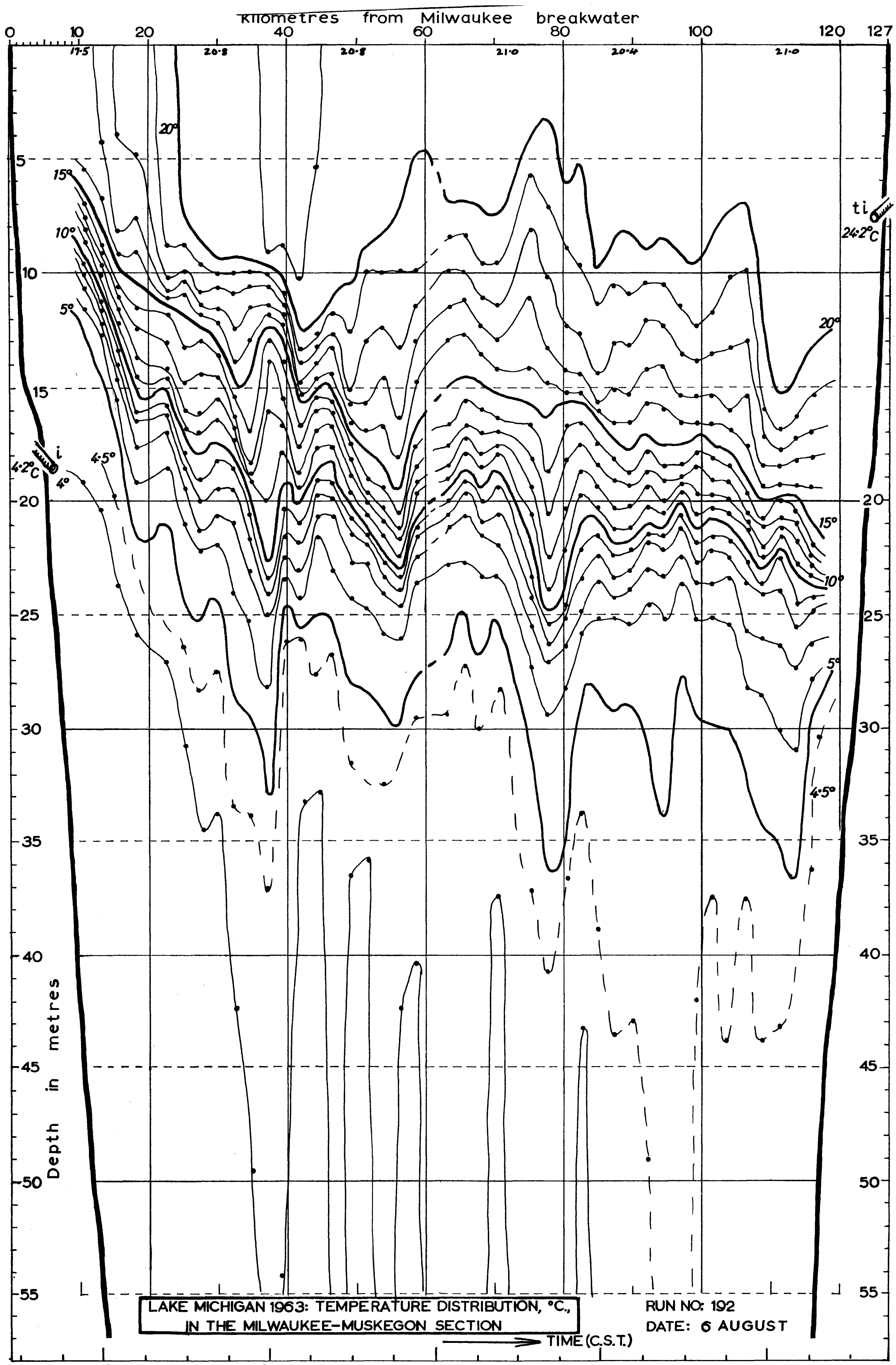


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

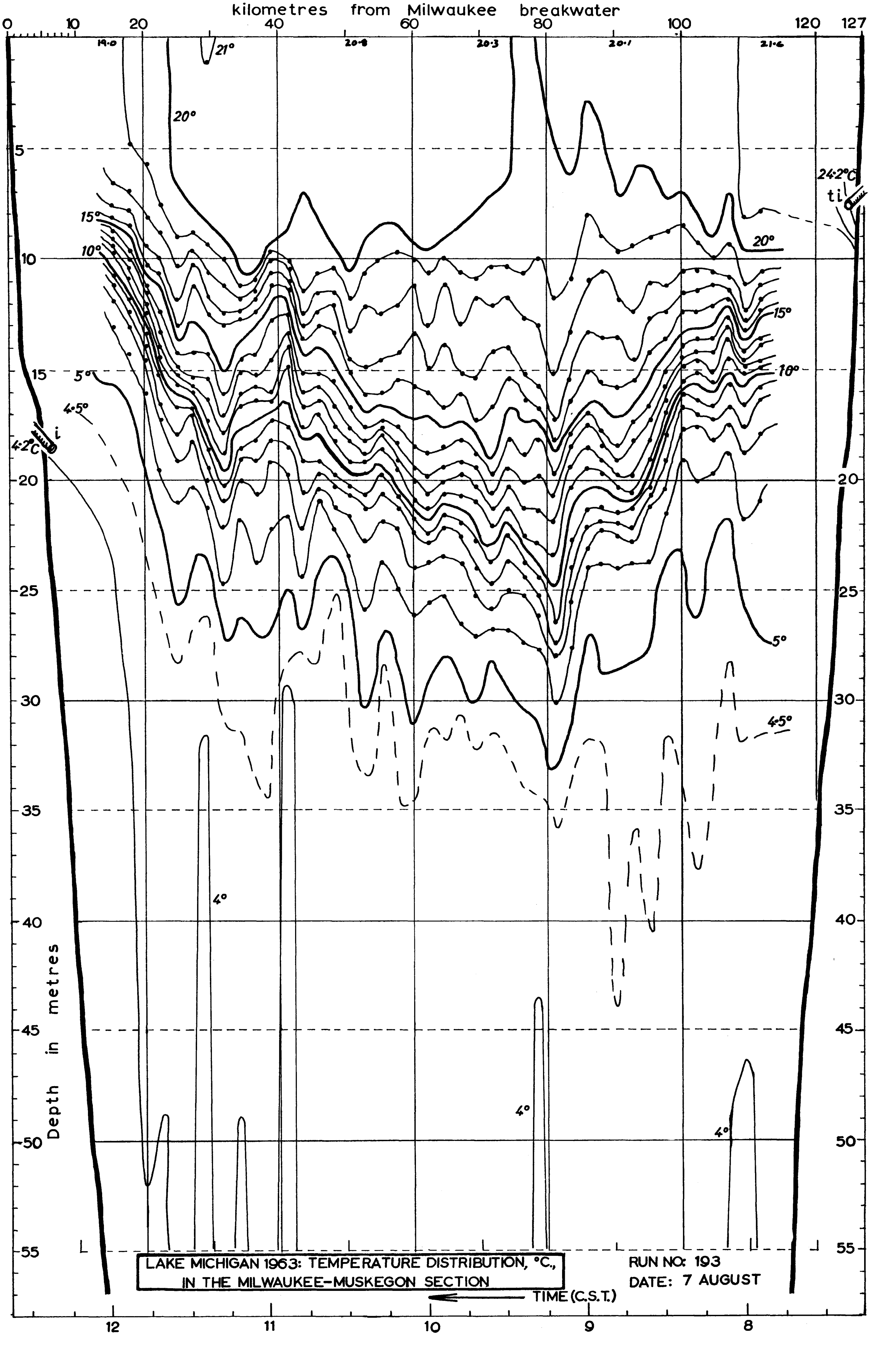


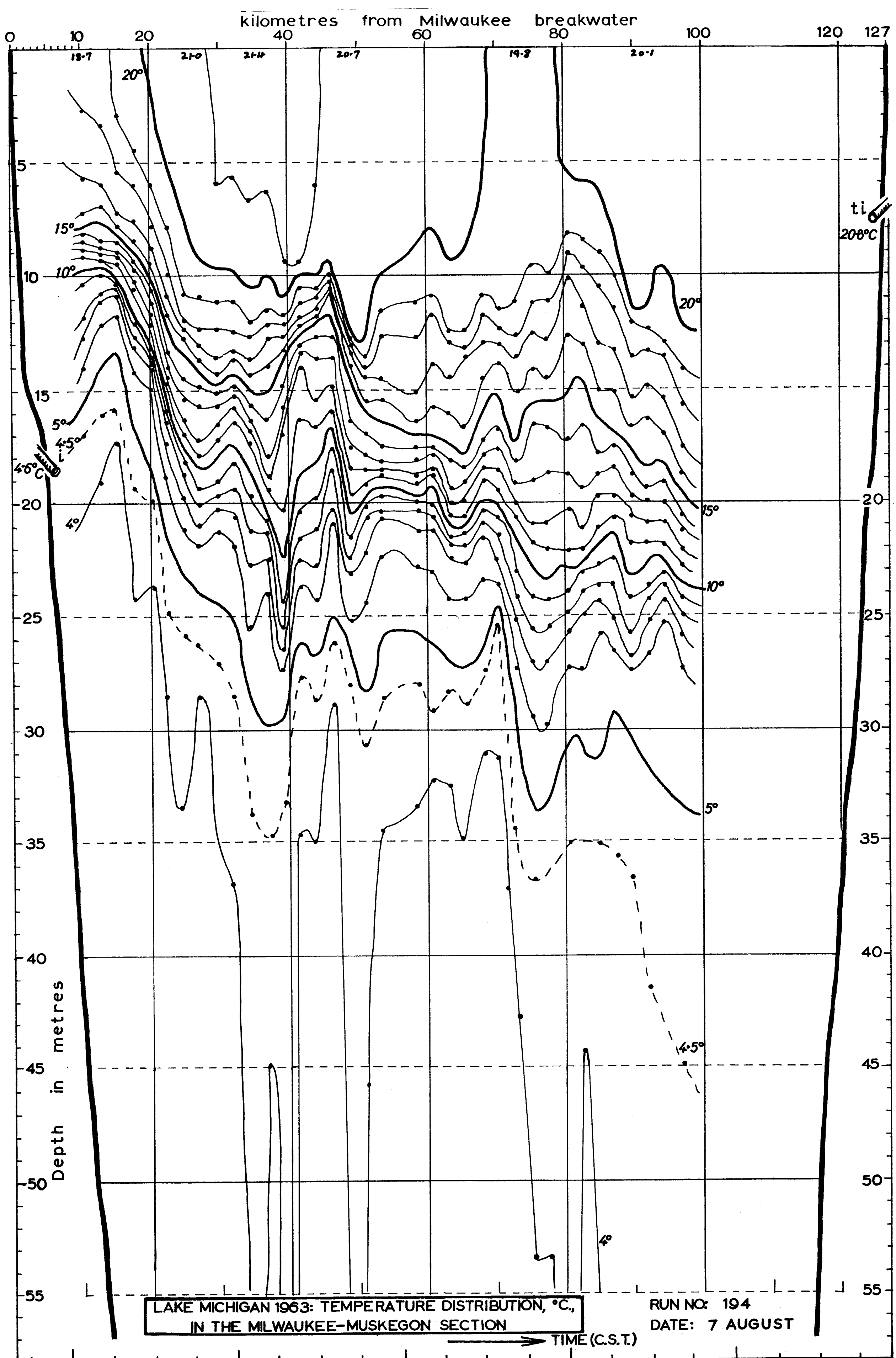
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

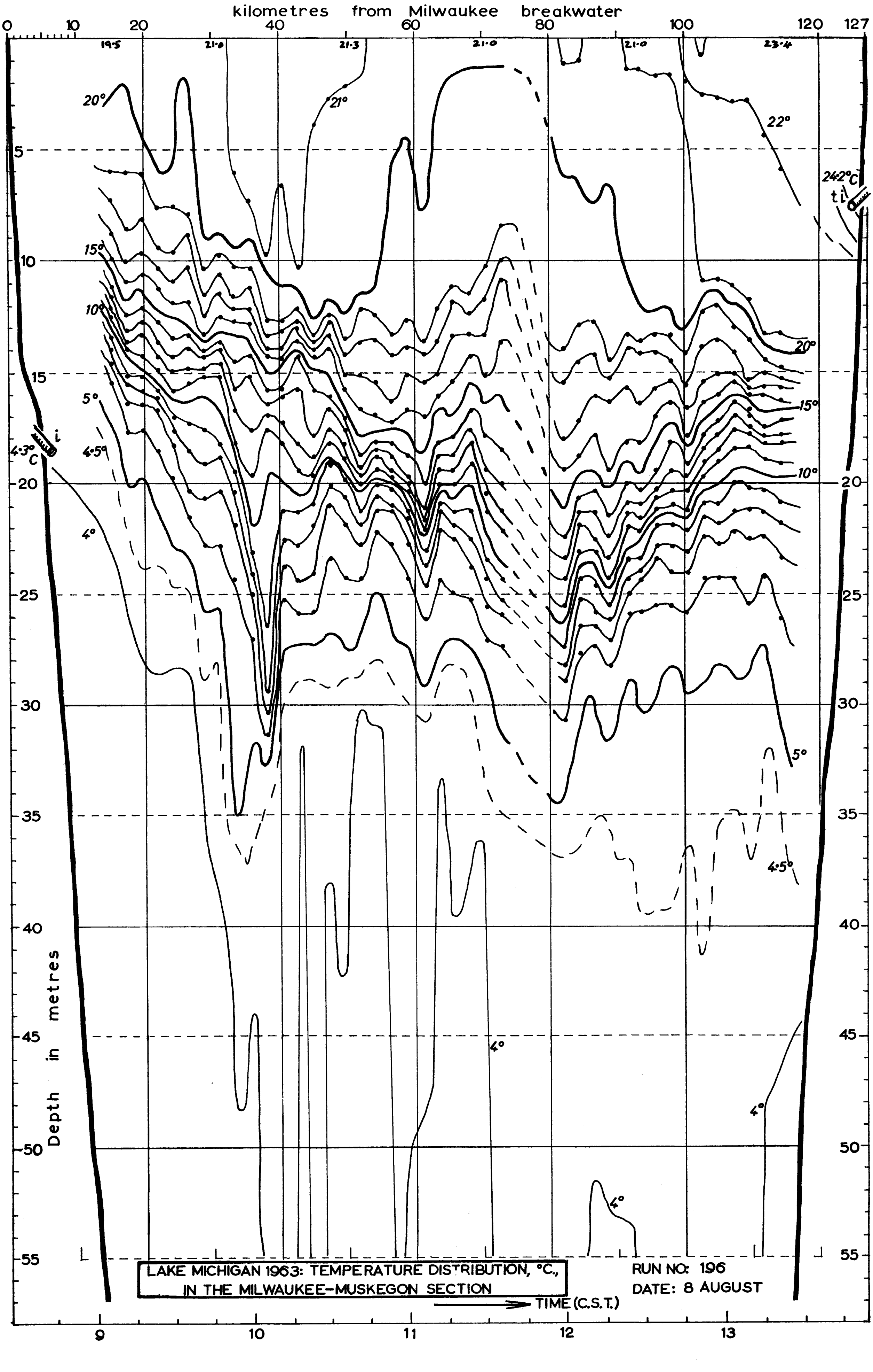
RUN NO: 191
DATE: 6 AUGUST



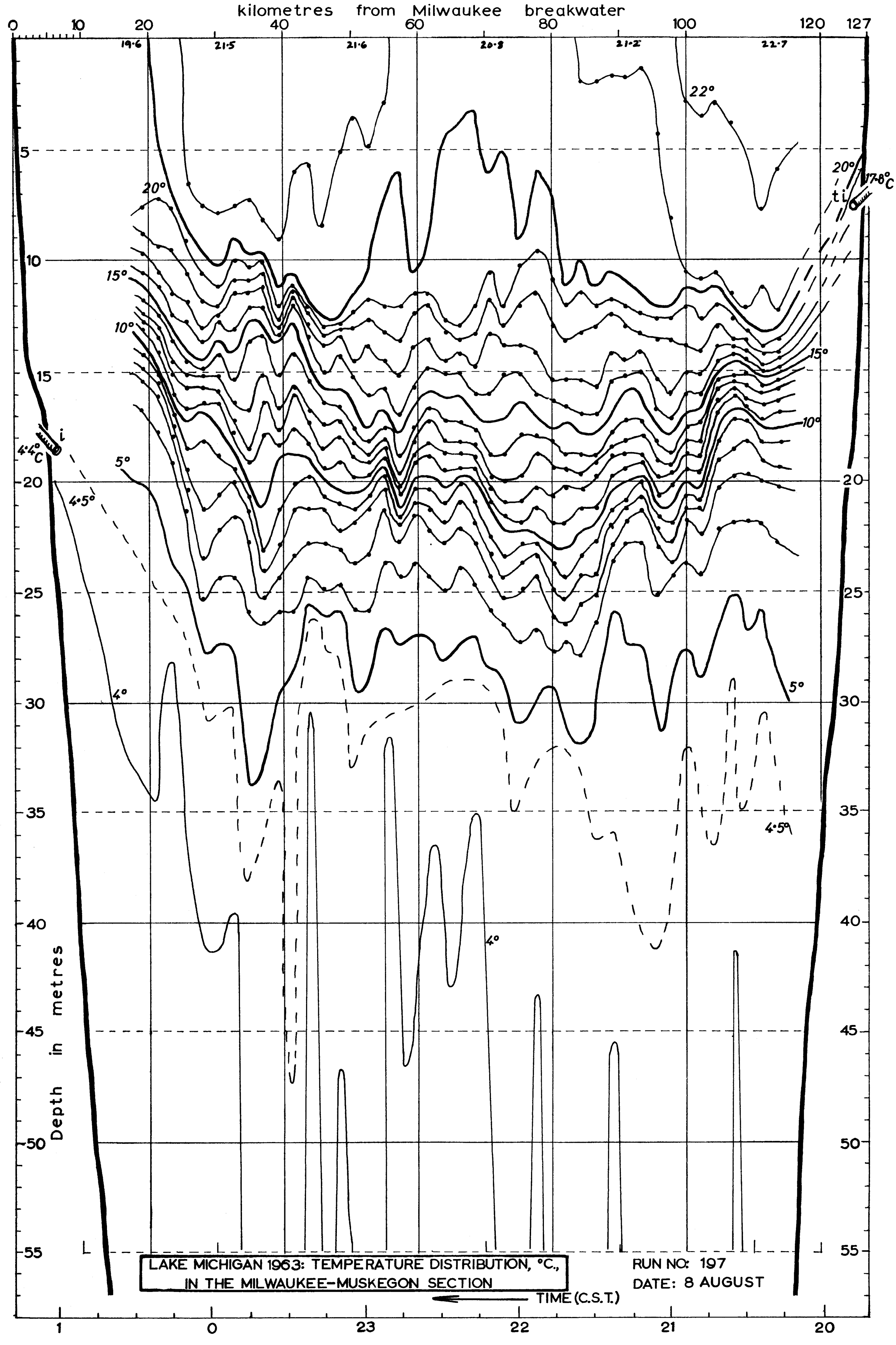
Kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
17·5
20·8
20·8
21·0
20·4
21·0
20°
15°
10°
5°
4·5°
4°
4·2°C
i
ti
24·2°C
20°
15°
10°
5°
4·5°
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 192
DATE: 6 AUGUST
TIME (C.S.T.)
20
21
22
23
0


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19.0
20.8
20.3
20.1
21.6
21°
20°
15°
10°
5°
4.5°
4.2°C
i
24.2°C
ti
20°
15°
10°
5°
4.5°
4°
4°
4°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 193
DATE: 7 AUGUST
TIME (C.S.T.)
12
11
10
9
8

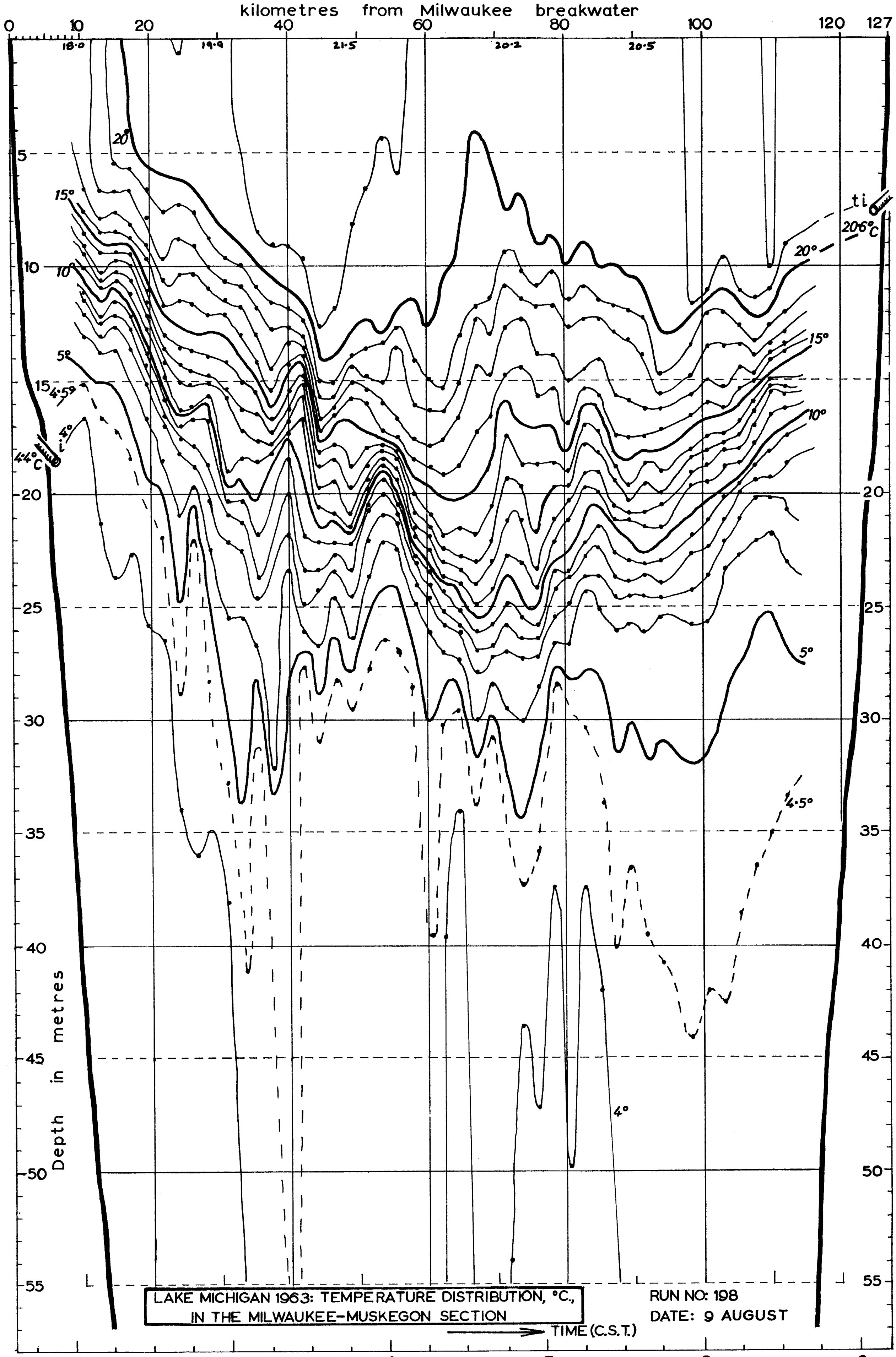

kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
18·7 21·0 21·4 20·7 19·8 20·1
20°
15°
10°
5°
4·5°
4°
4·6°C
20·8°C
ti
i
20°
15°
10°
5°
4·5°
4°
5 10 15 20 25 30 35 40 45 50 55
Depth in metres
15 16 17 18 19
TIME (C.S.T.)
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 194
DATE: 7 AUGUST

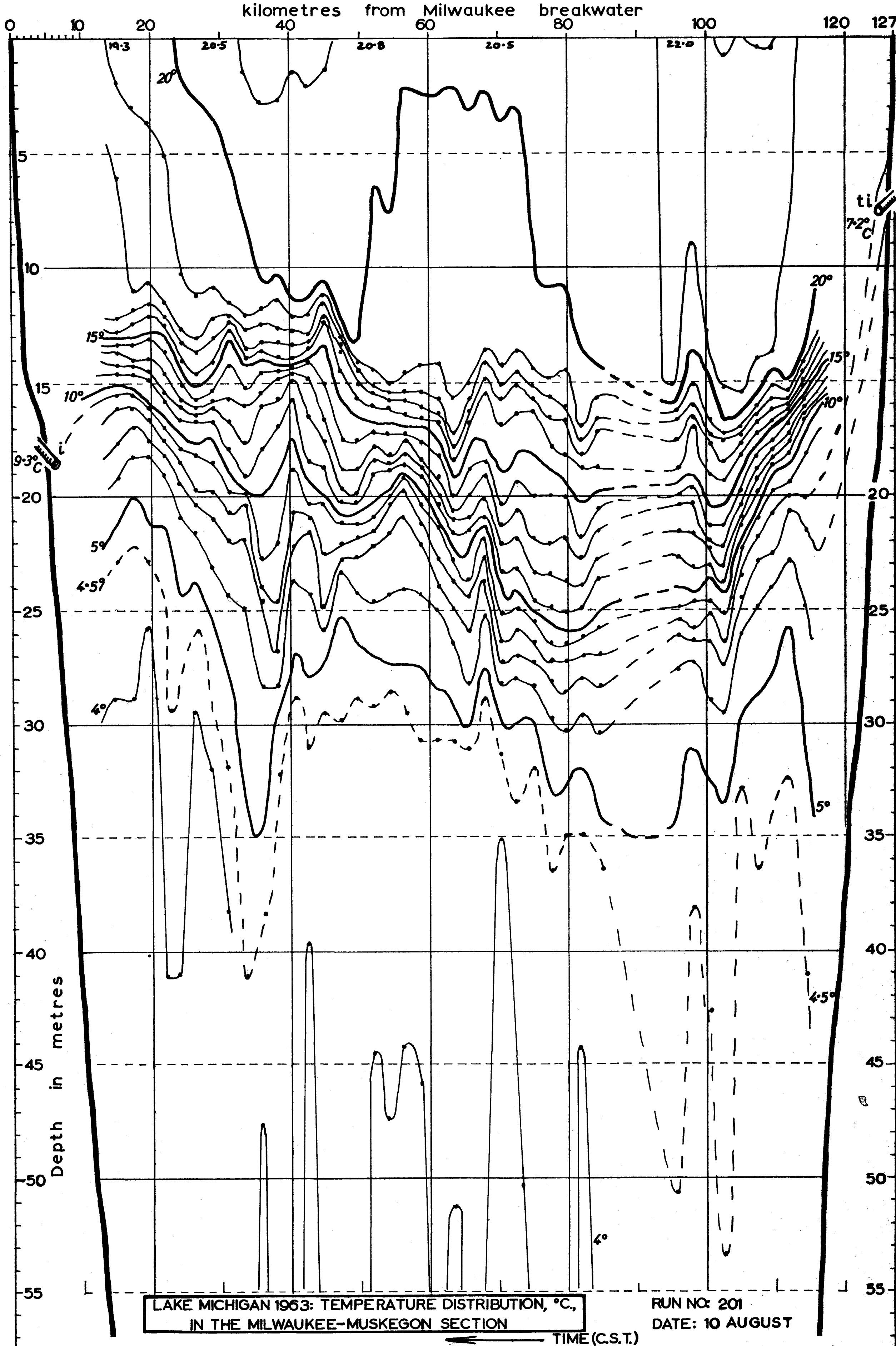


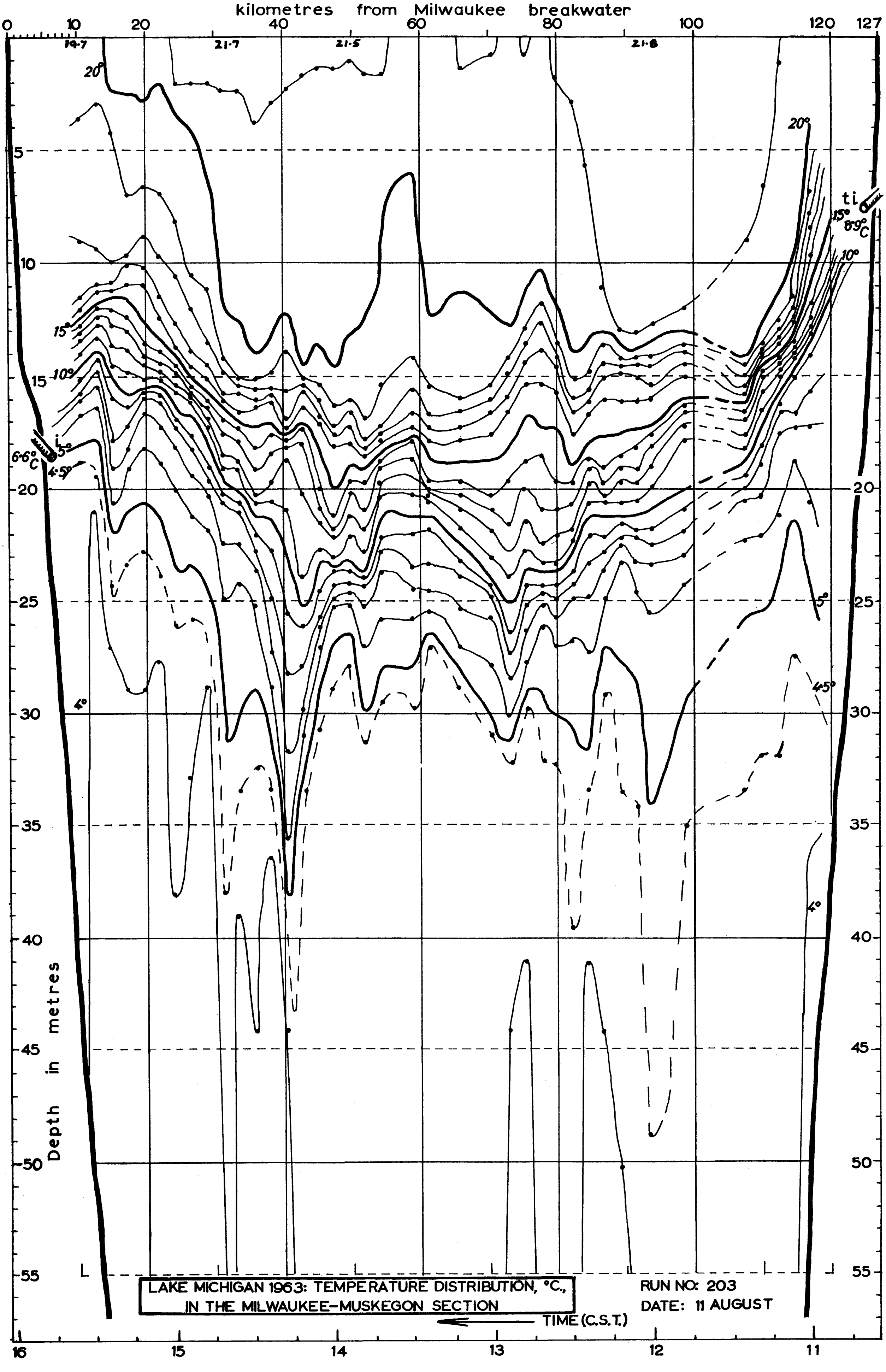
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

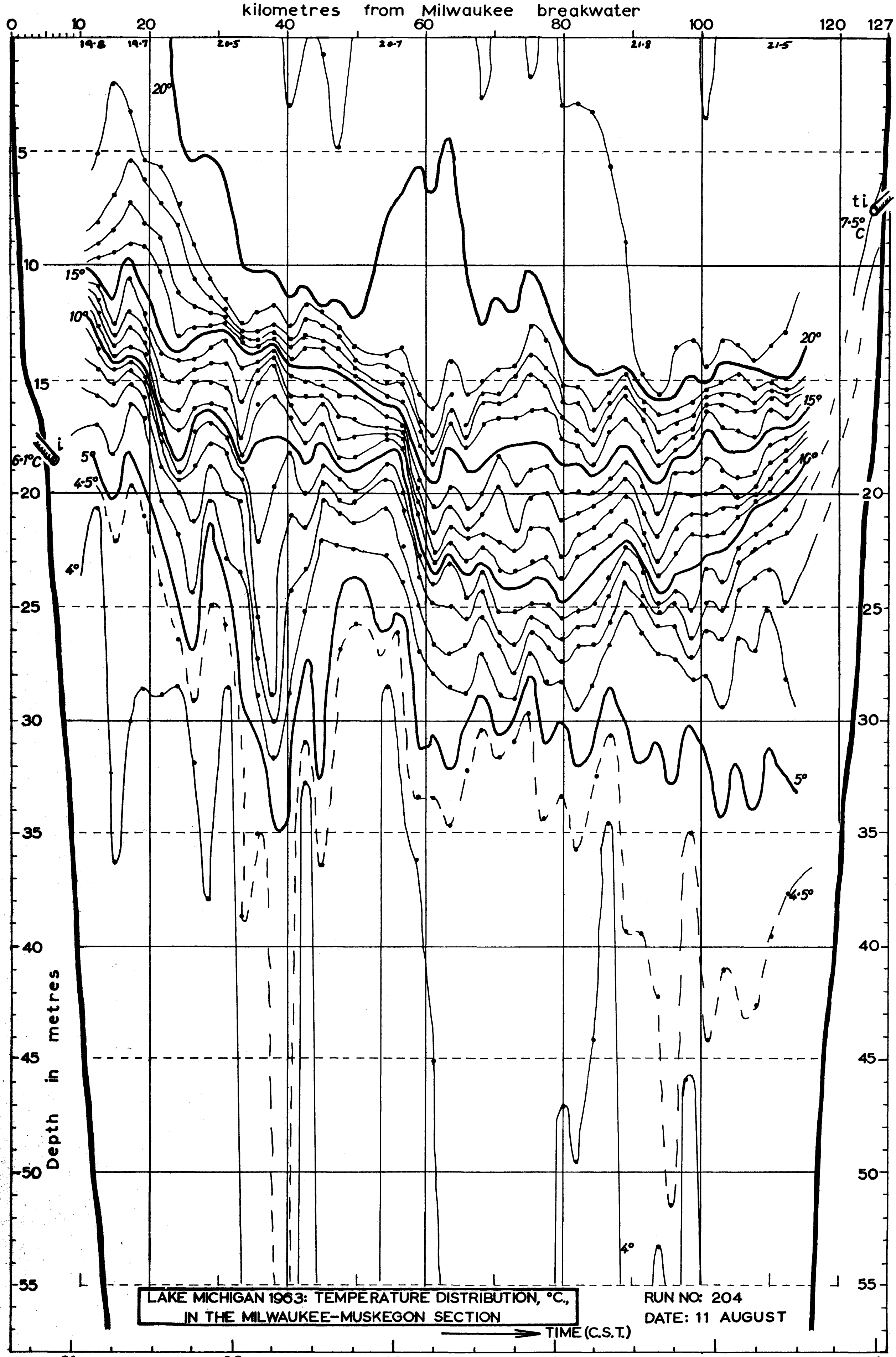


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

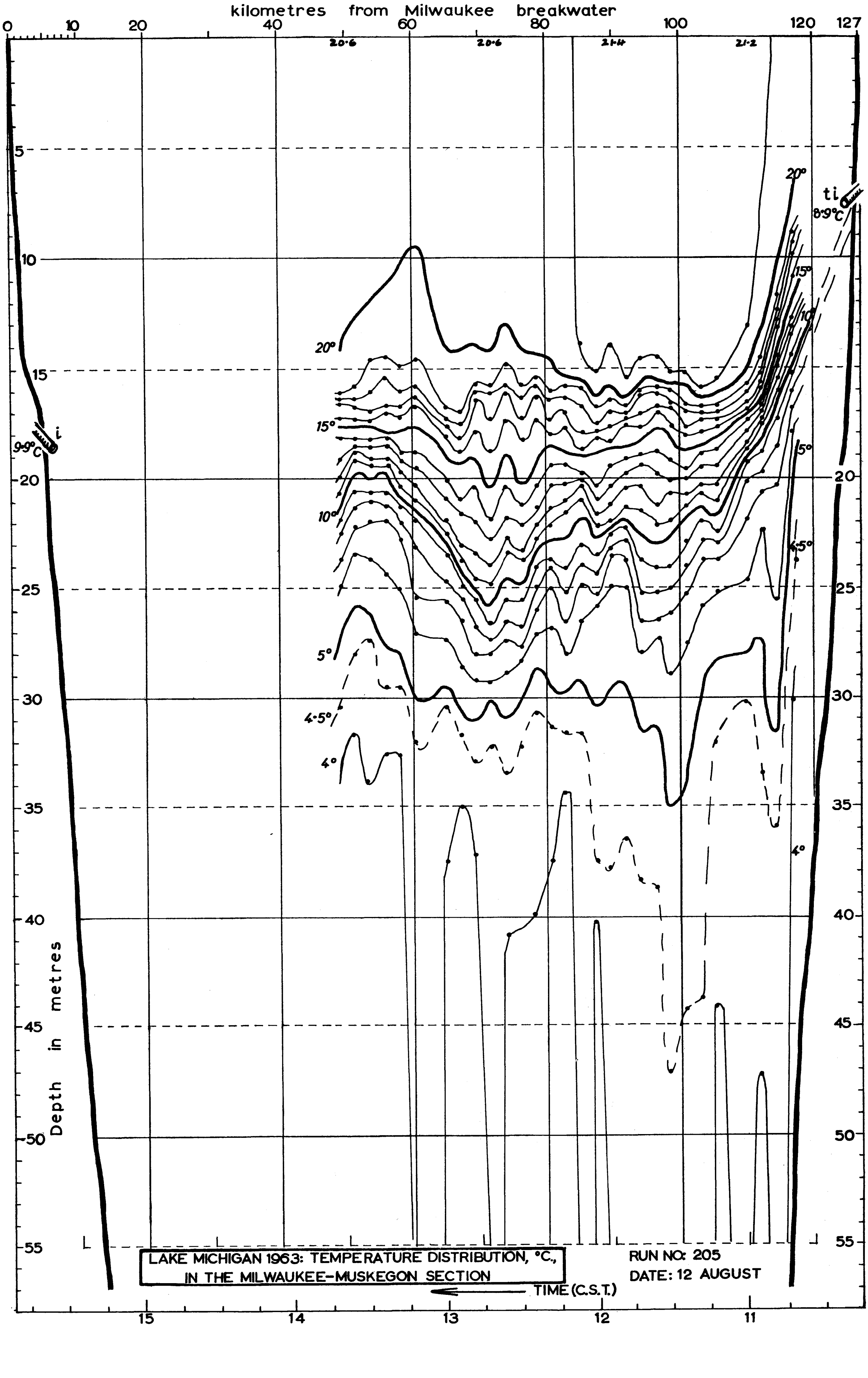

kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
18·0 19·9 21·5 20·2 20·5
20°
15°
10°
5°
4·5°
4°
4·4°C
ti
20·6°C
20°
15°
10°
5°
4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 198
DATE: 9 AUGUST
TIME (C.S.T.)
4 5 6 7 8 9


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·3
20·5
20·8
20·5
22·0
20°
15°
10°
5°
4·5°
4°
9·3°C
i
ti
7·2°C
20°
15°
10°
5°
4·5°
4°
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
15
14
13
12
11
TIME (C.S.T.)
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 201
DATE: 10 AUGUST

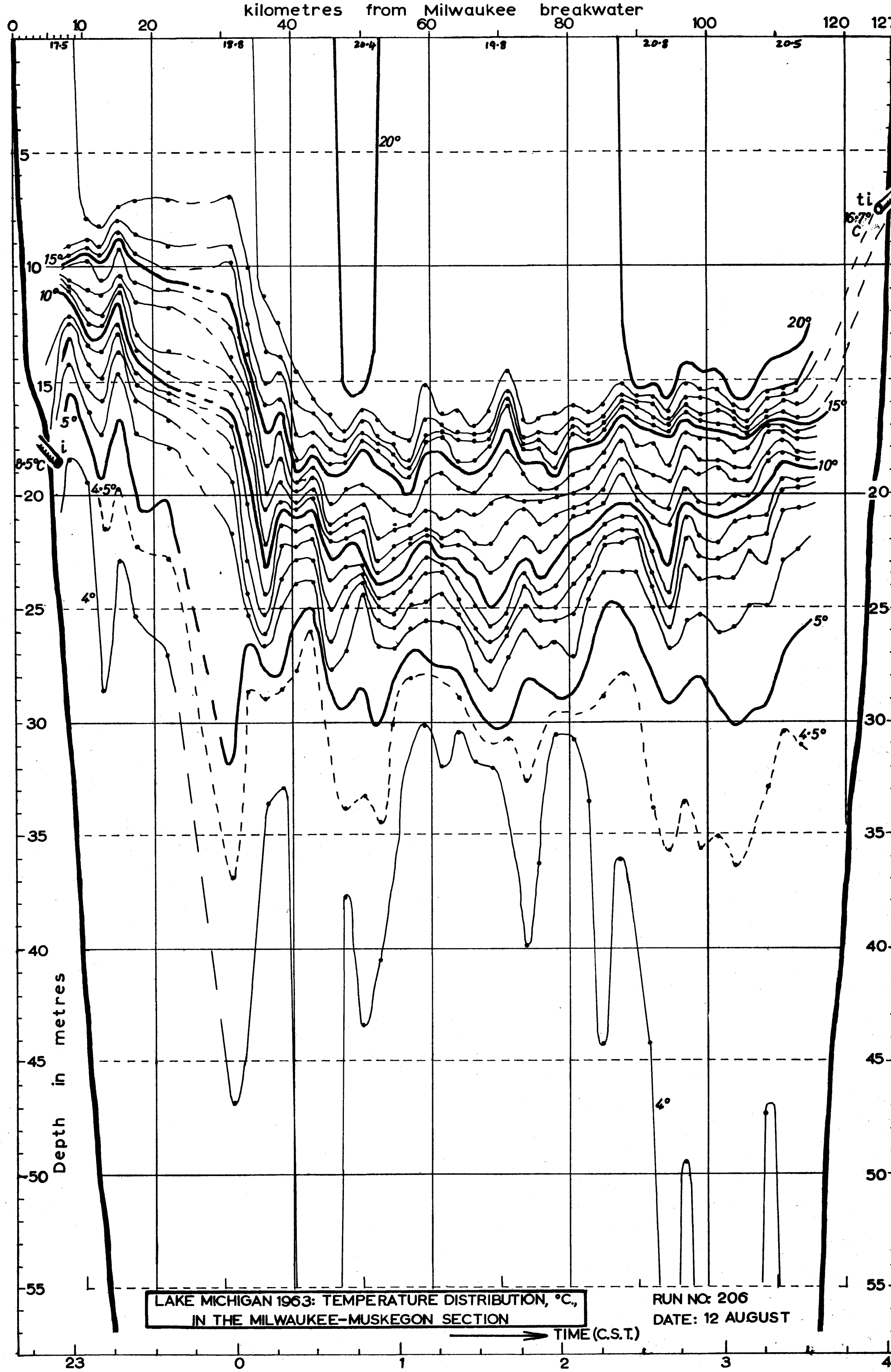

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·7
21·7
21·5
21·8
20°
15°
10°
5°
4·5°
4°
6·6°C
ti
8·9°C
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 203
DATE: 11 AUGUST
TIME (C.S.T.)
16
15
14
13
12
11



kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
19·8 19·7 20·5 20·7 21·8 21·5
20°
15°
10°
5°
4·5°
4°
6·1°C
i
ti
7·5° C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 204
DATE: 11 AUGUST
TIME (C.S.T.)
21 22 23 0 1 2



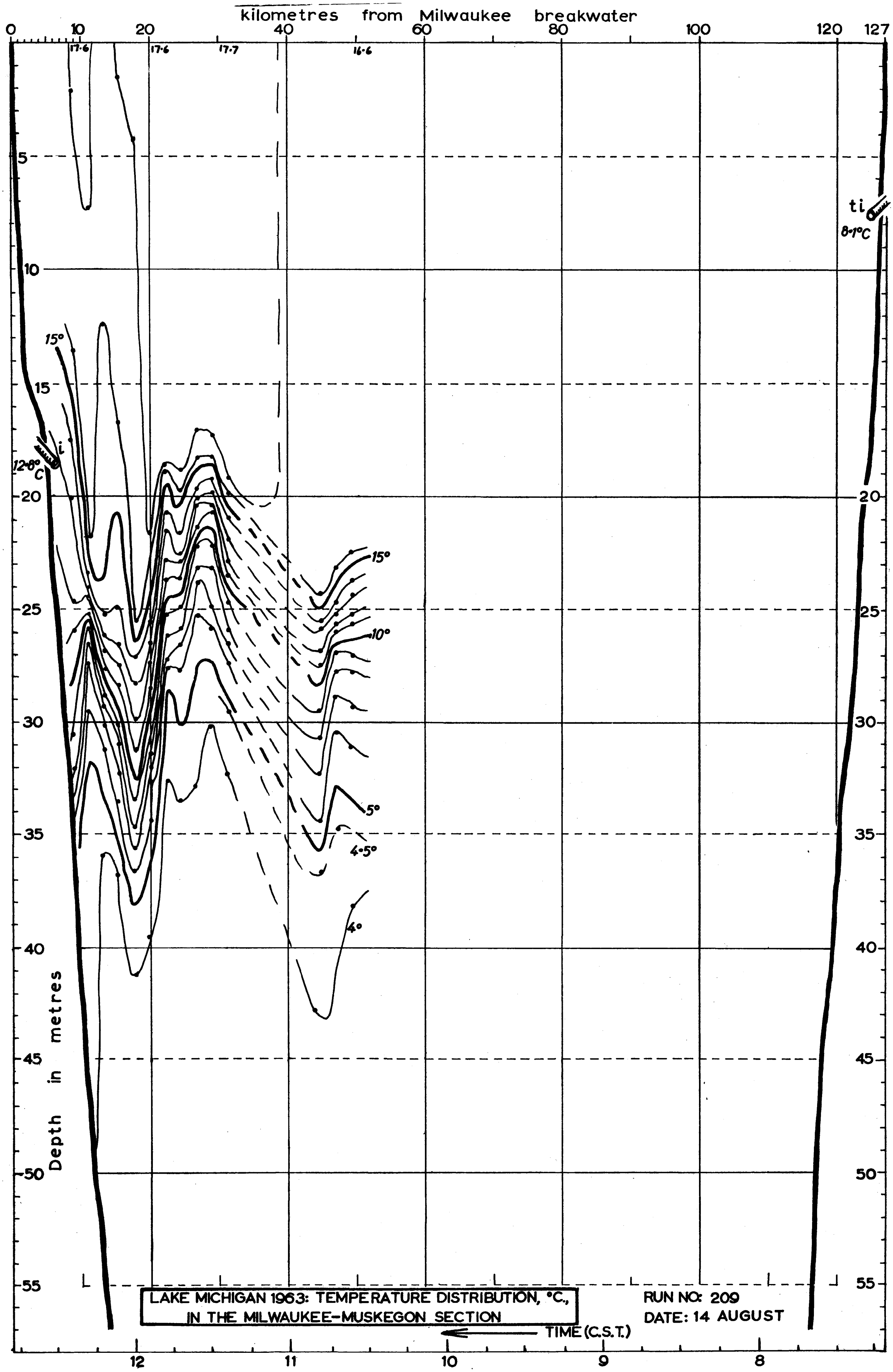
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



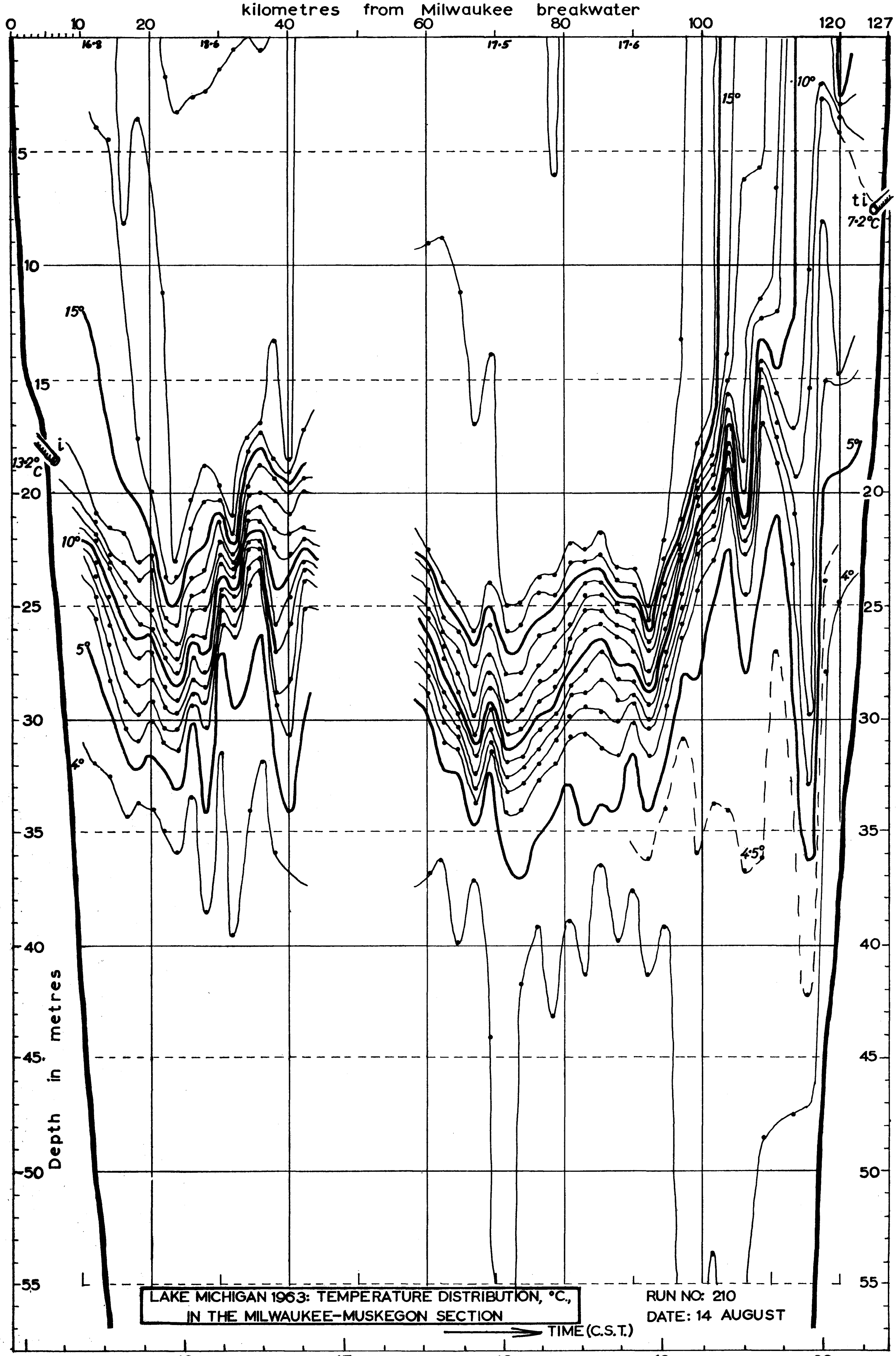
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION

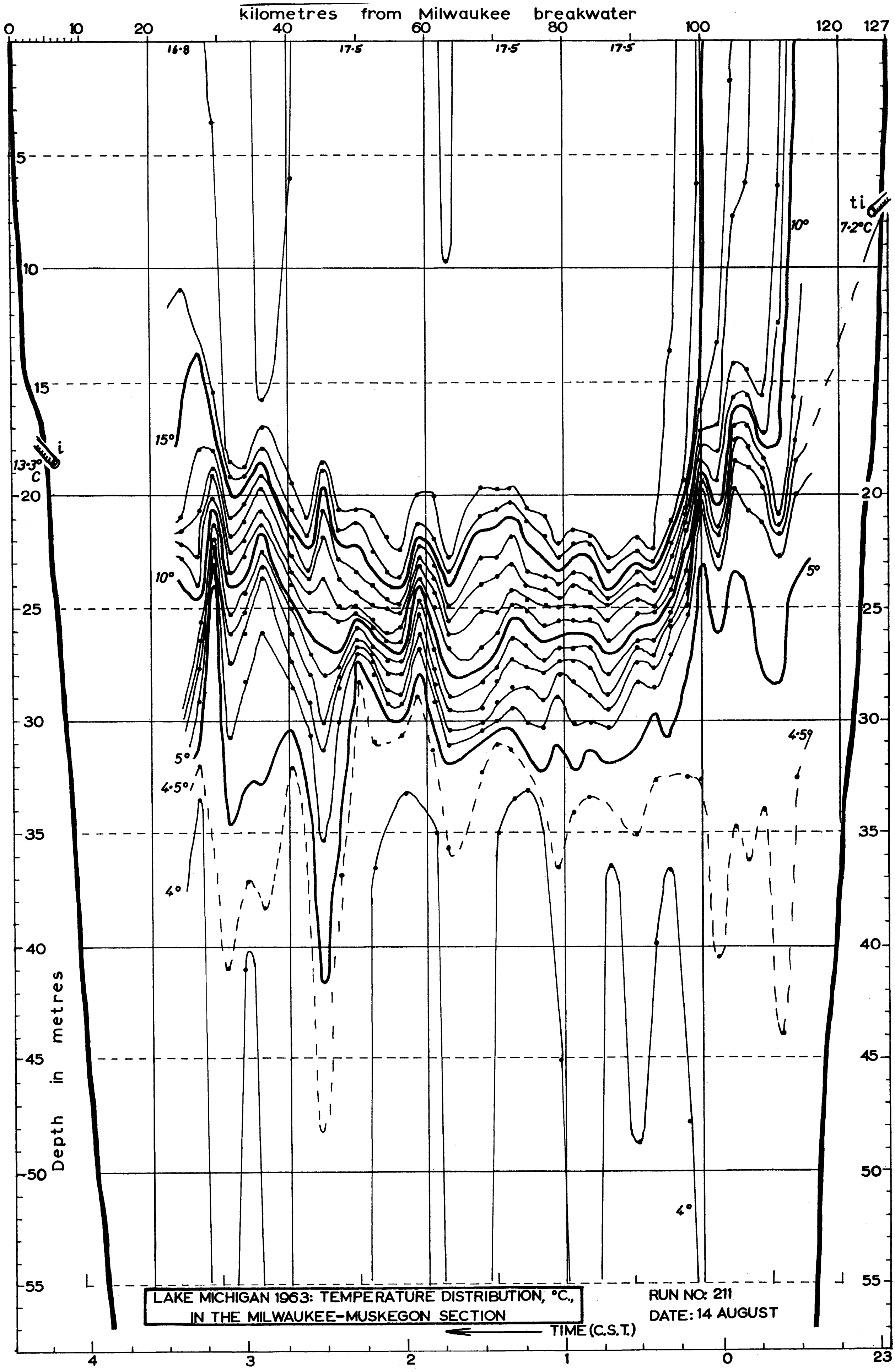
RUN NO: 206

DATE: 12 AUGUST

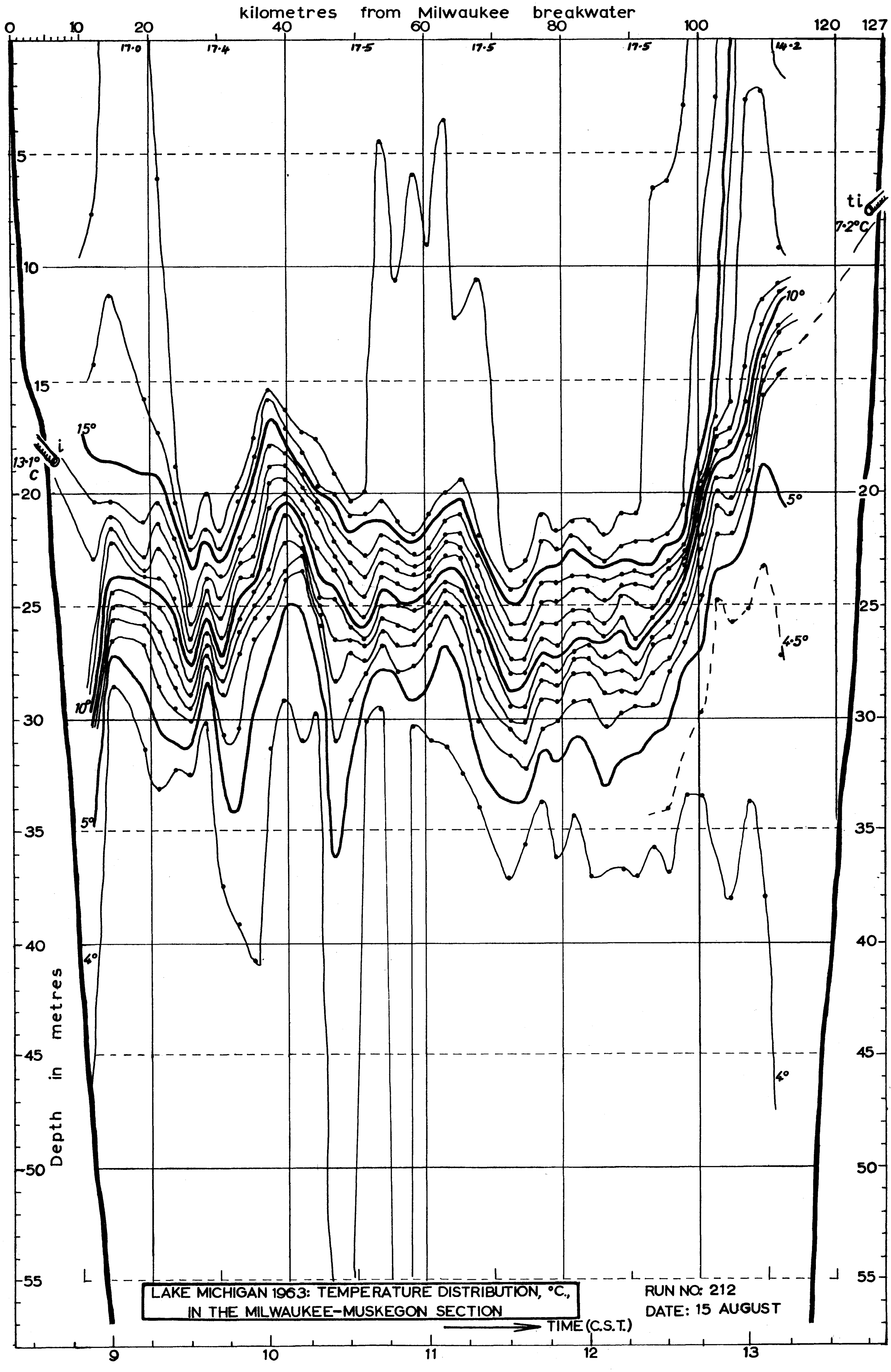


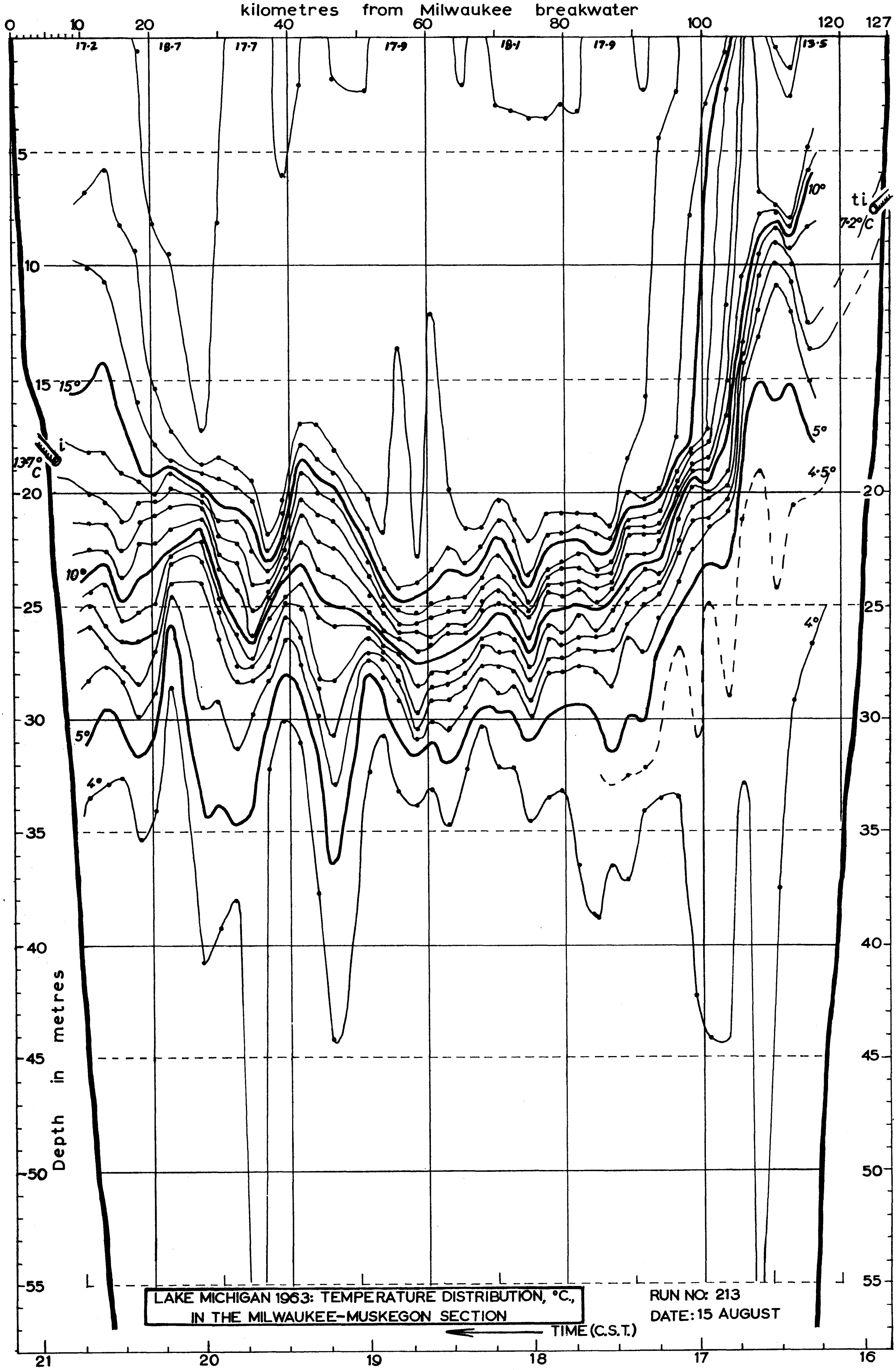
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION


kilometres from Milwaukee breakwater
Depth in metres
TIME (C.S.T.)
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 210
DATE: 14 AUGUST
13·2°C
7·2°C
16·8
18·6
17·5
17·6
15°
10°
5°
4°
4·5°



kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
16·8 17·5 17·5 17·5
15°
10°
5°
4·5°
4°
5°
4·5°
10°
ti
7·2°C
i
13·3°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 211
DATE: 14 AUGUST
TIME (C.S.T.)
4 3 2 1 0 23

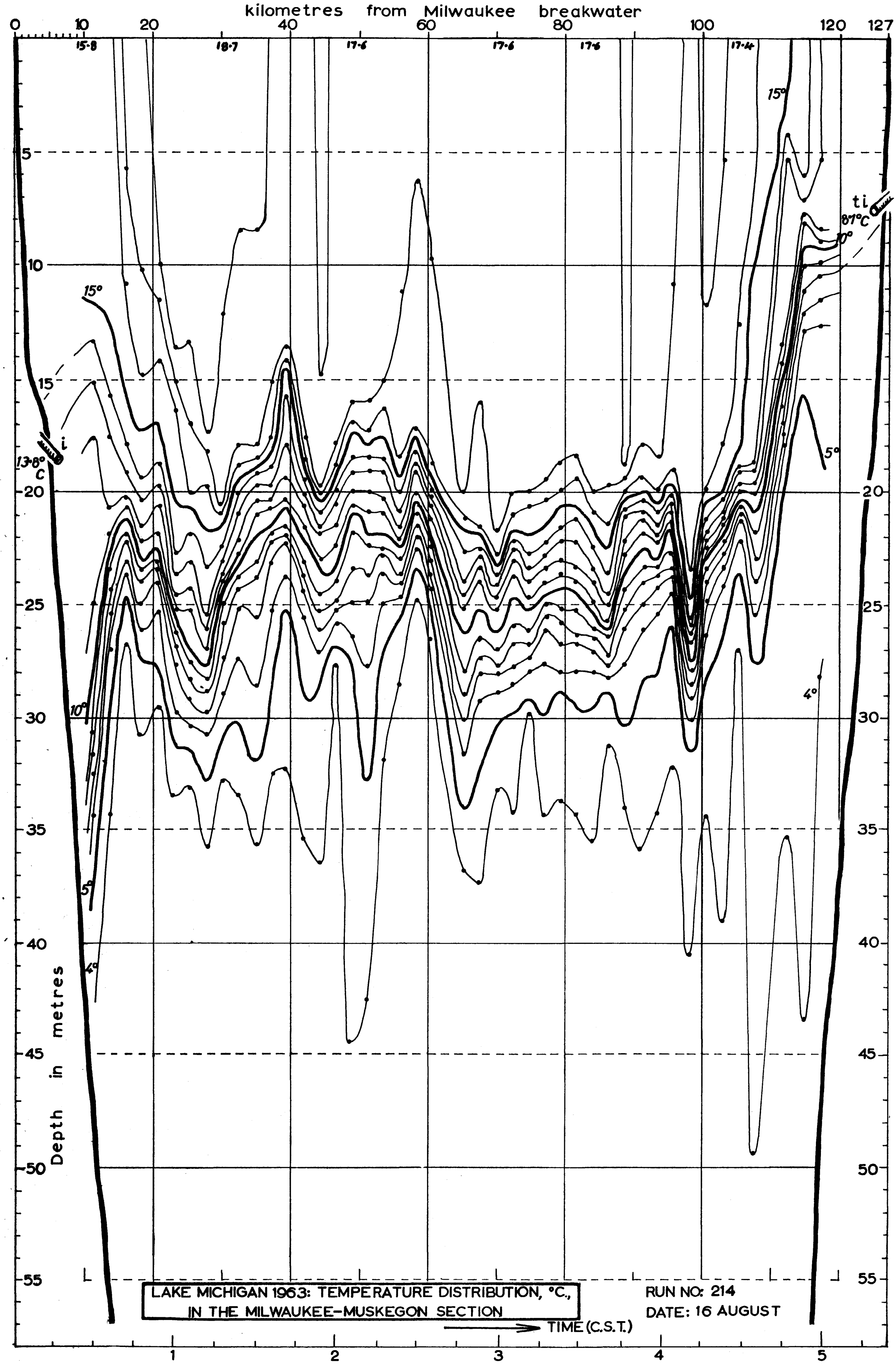

kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
17·0 17·4 17·5 17·5 17·5 14·2
15°
10°
5°
4°
4·5°
i
13·1° C
ti
7·2°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
TIME (C.S.T.)
9 10 11 12 13
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 212
DATE: 15 AUGUST



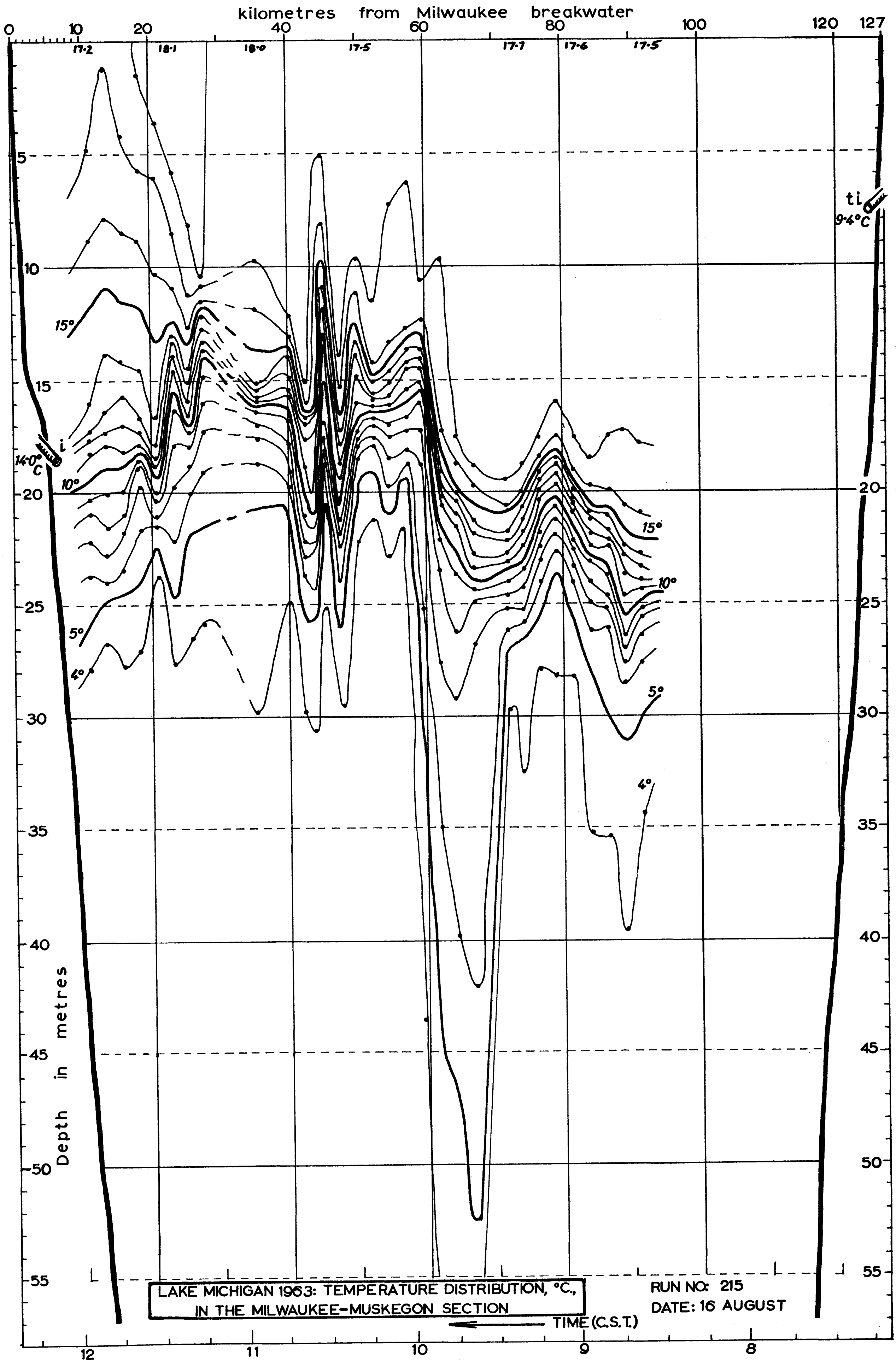
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

RUN NO: 213

DATE: 15 AUGUST

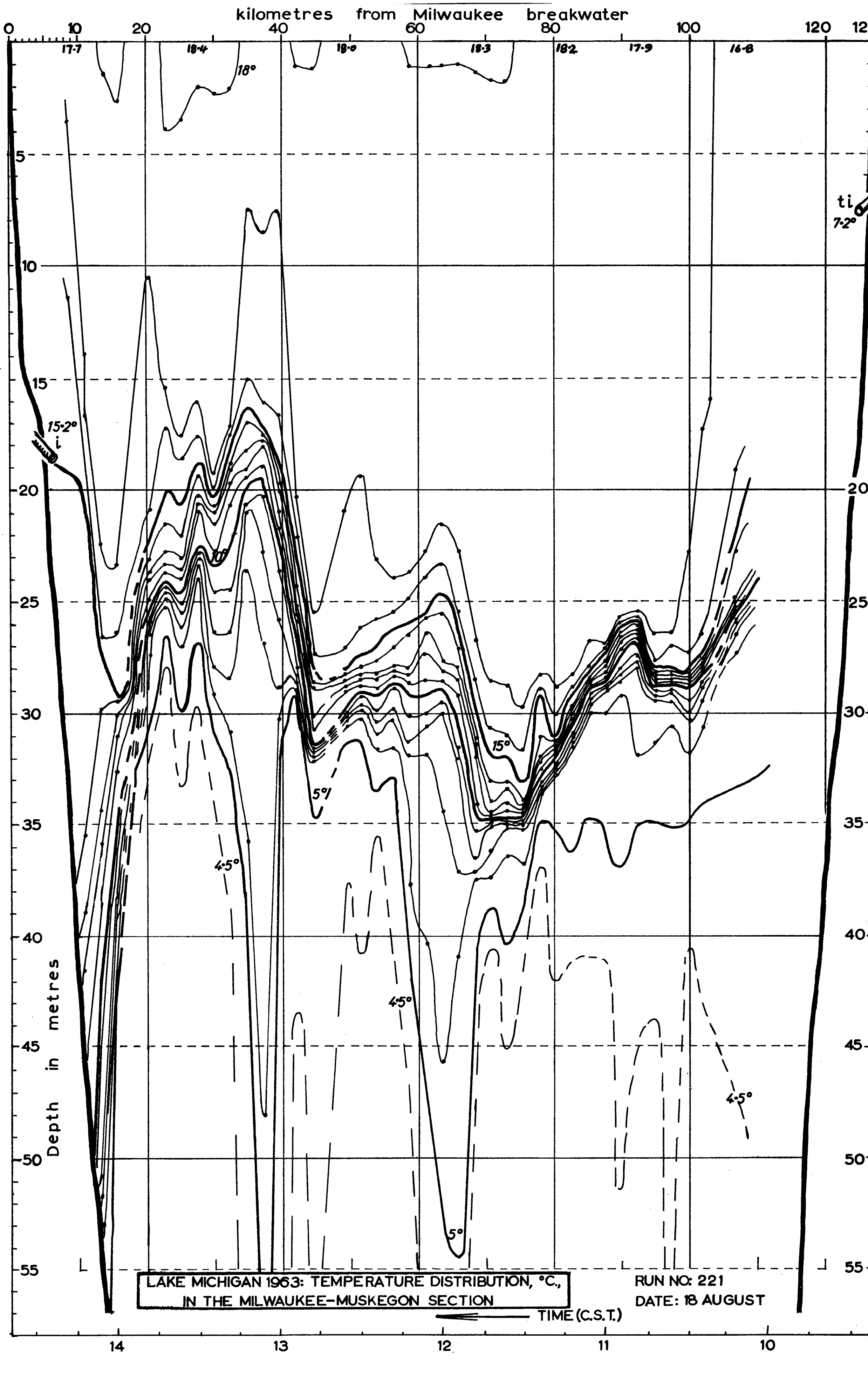


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



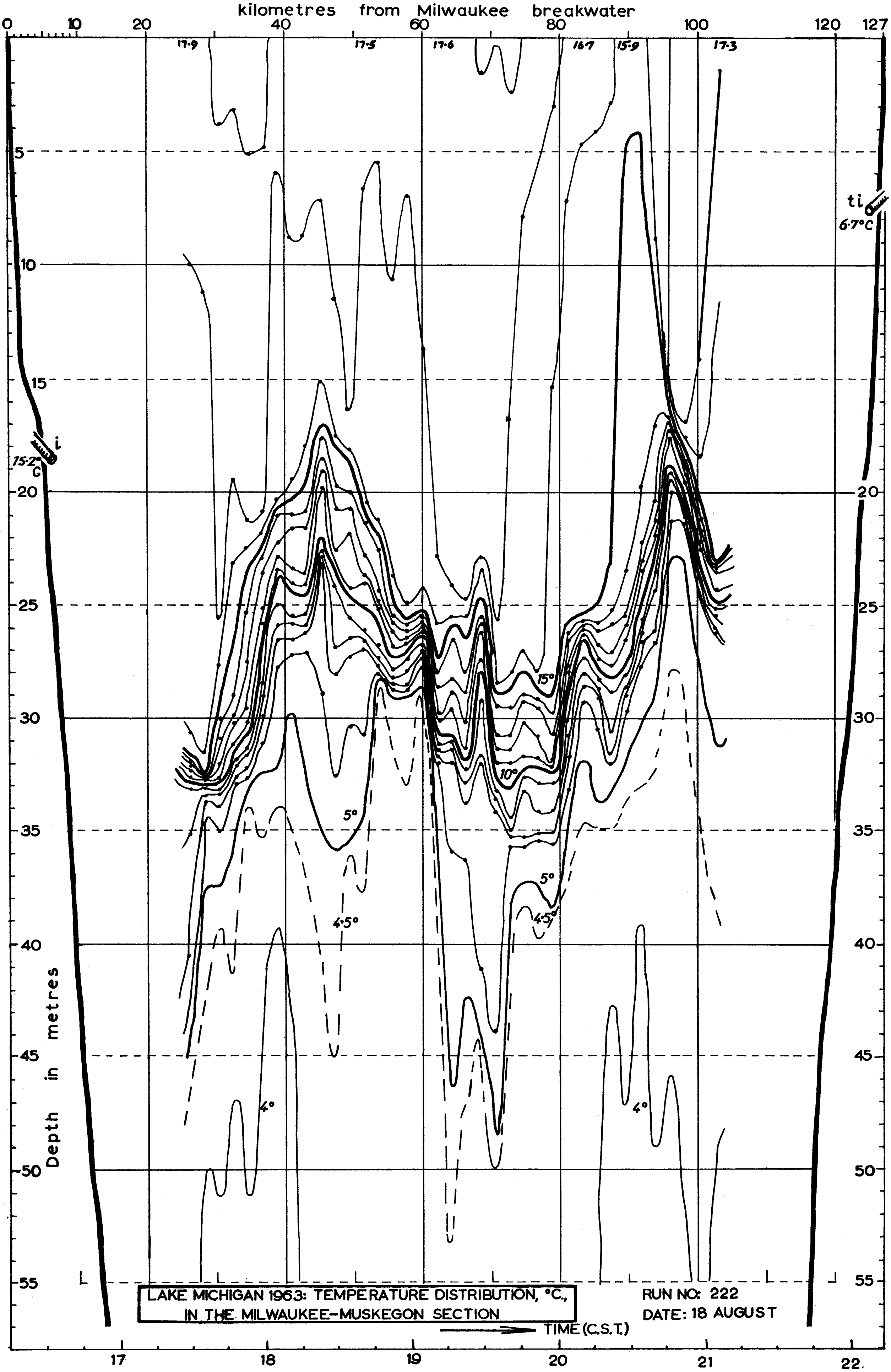
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

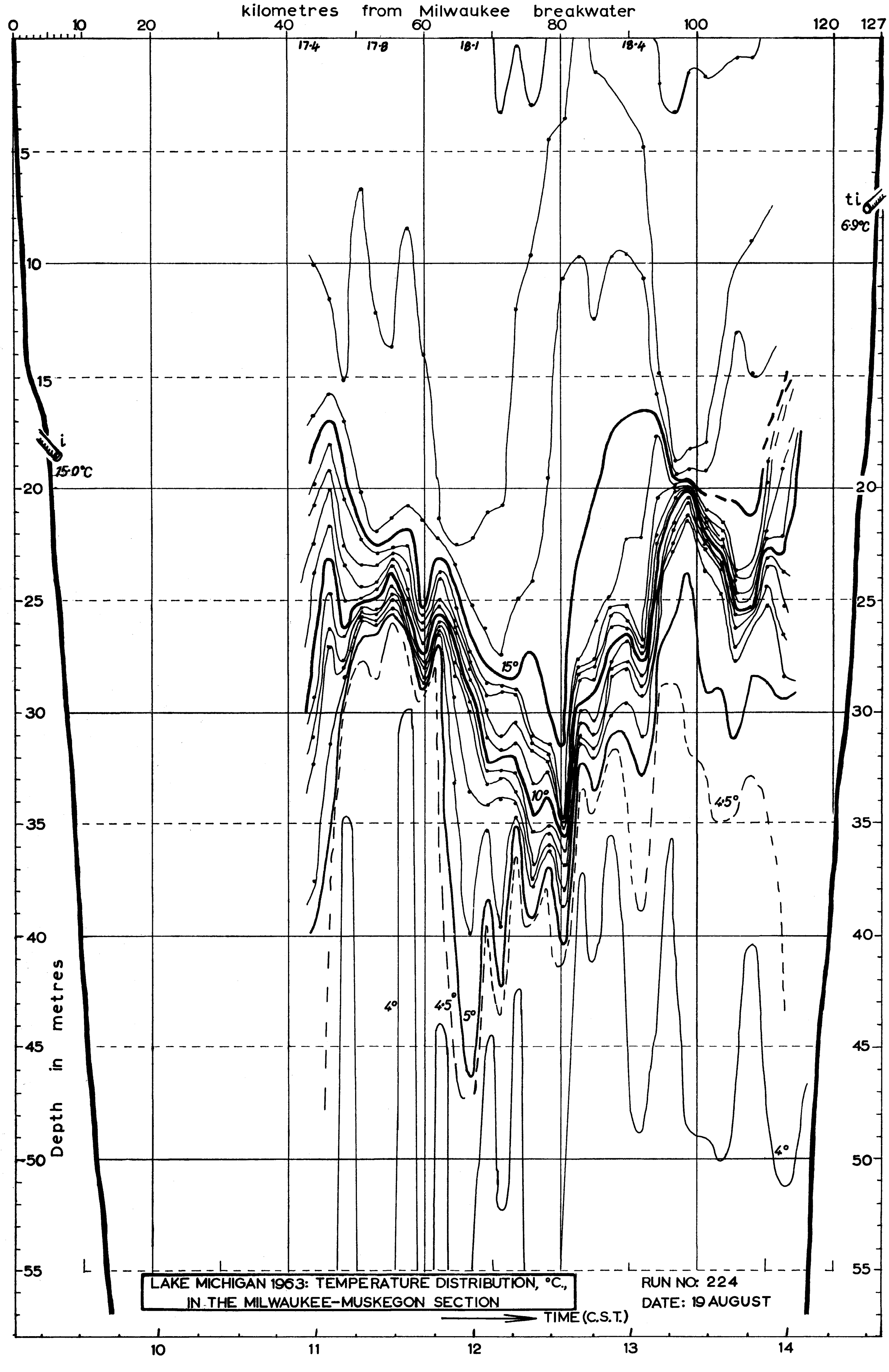
RUN NO: 215
DATE: 16 AUGUST

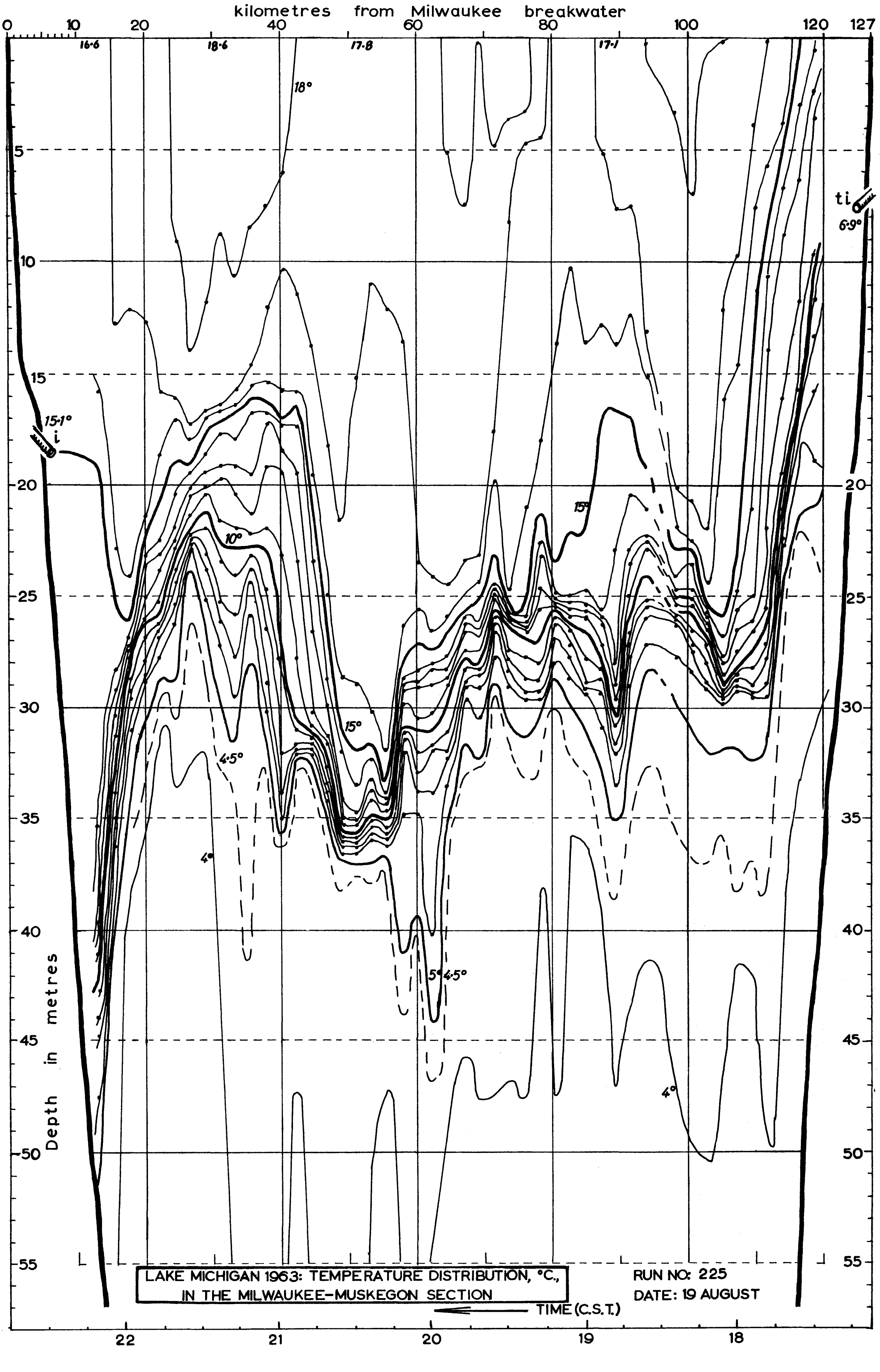


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

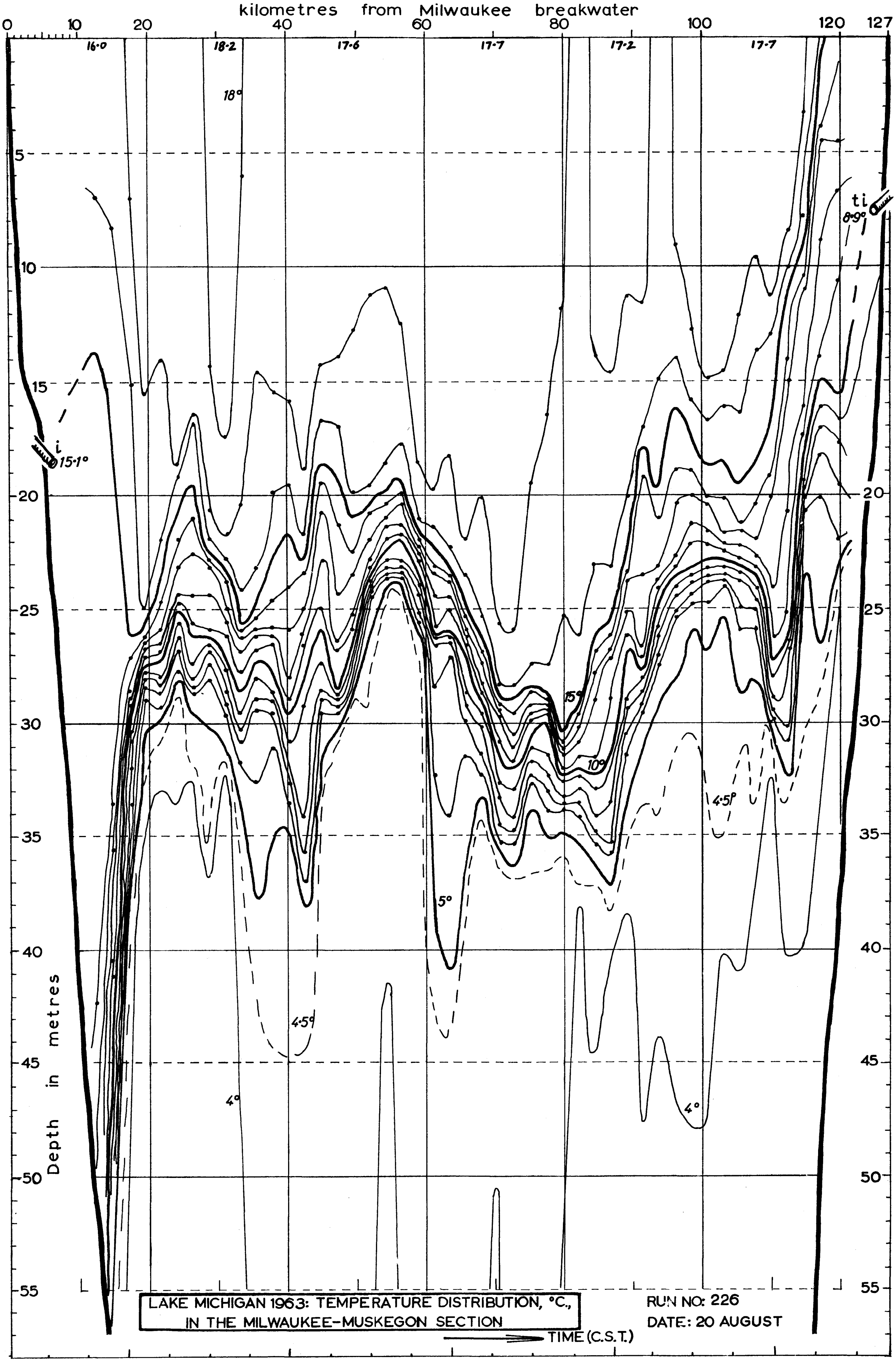
RUN NO: 221
DATE: 18 AUGUST


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
17·9 17·5 17·6 16·7 15·9 17·3
15·2°C
6·7°C
15°
10°
5°
4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
17 18 19 20 21 22
TIME (C.S.T.)
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 222
DATE: 18 AUGUST


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
17·4
17·8
18·1
18·4
ti
6·9°C
i
15·0°C
5
10
15
20
25
30
35
40
45
50
55
15°
10°
4·5°
4°
4·5°
5°
4°
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 224
DATE: 19 AUGUST
TIME (C.S.T.)
10
11
12
13
14



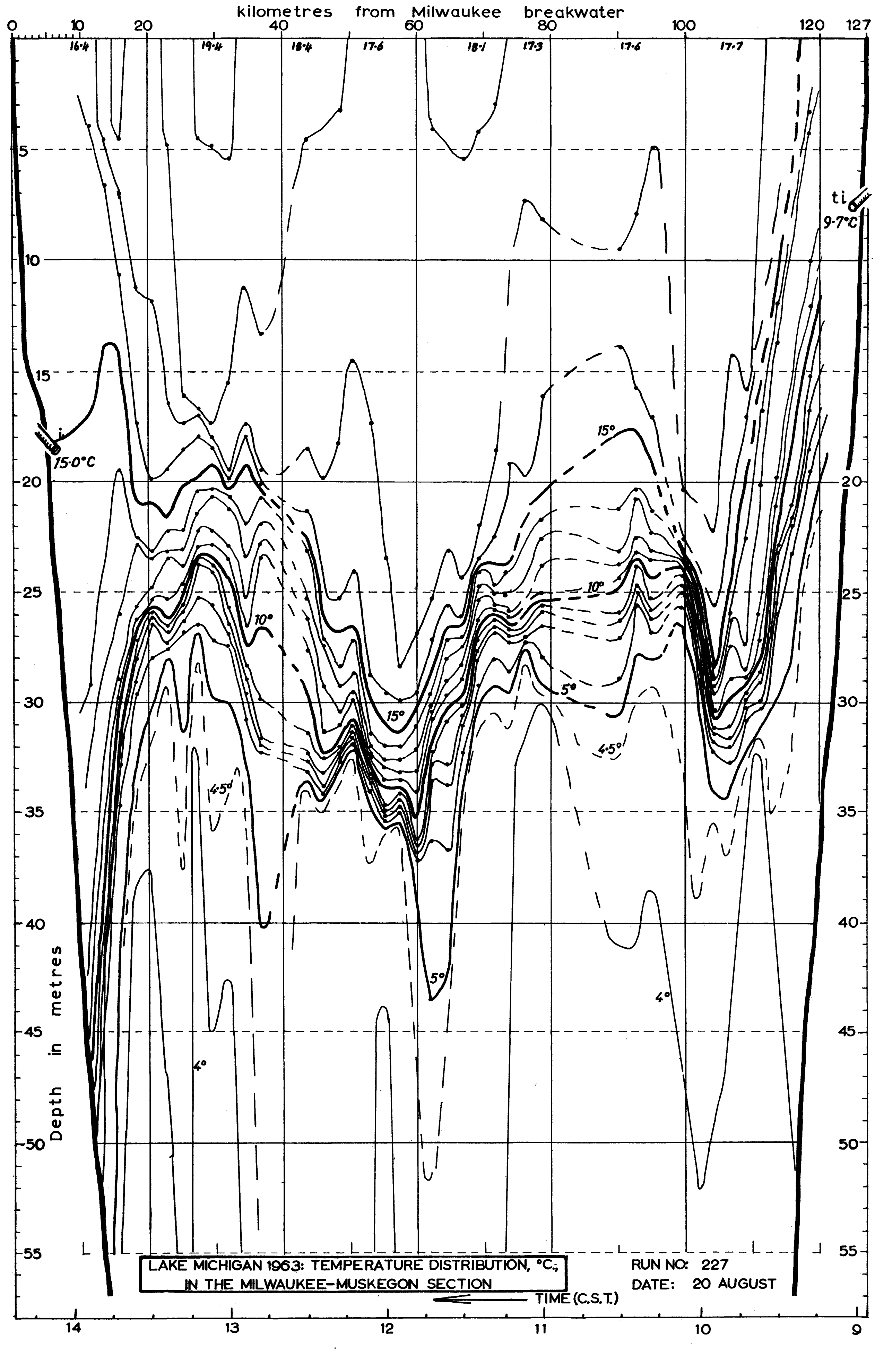
kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
16·6 18·6 17·8 17·1
18°
15·1°
i
ti
6·9°
10°
15°
15°
4·5°
4°
5° 4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 225
DATE: 19 AUGUST
TIME (C.S.T.)
22 21 20 19 18

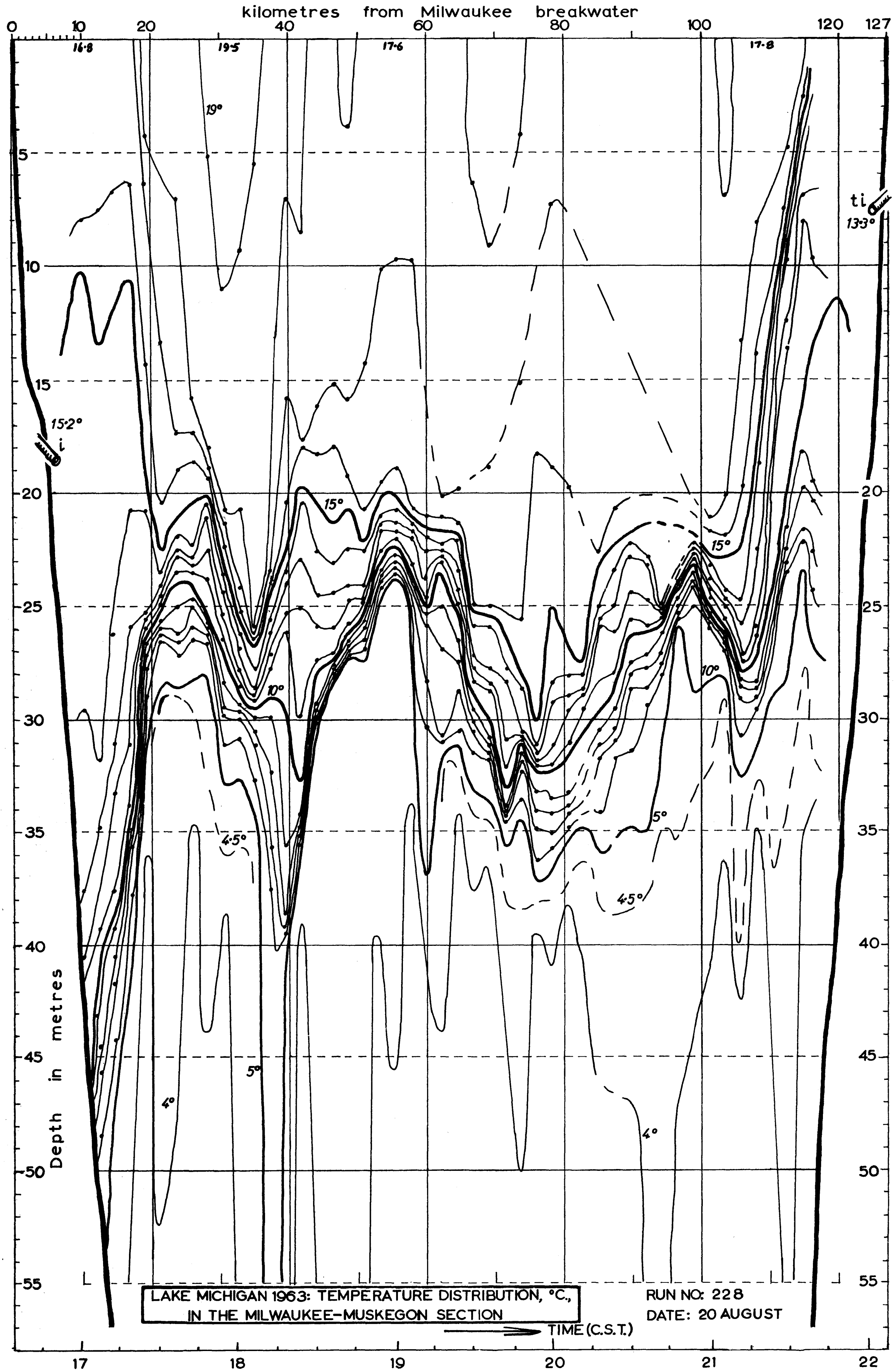


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

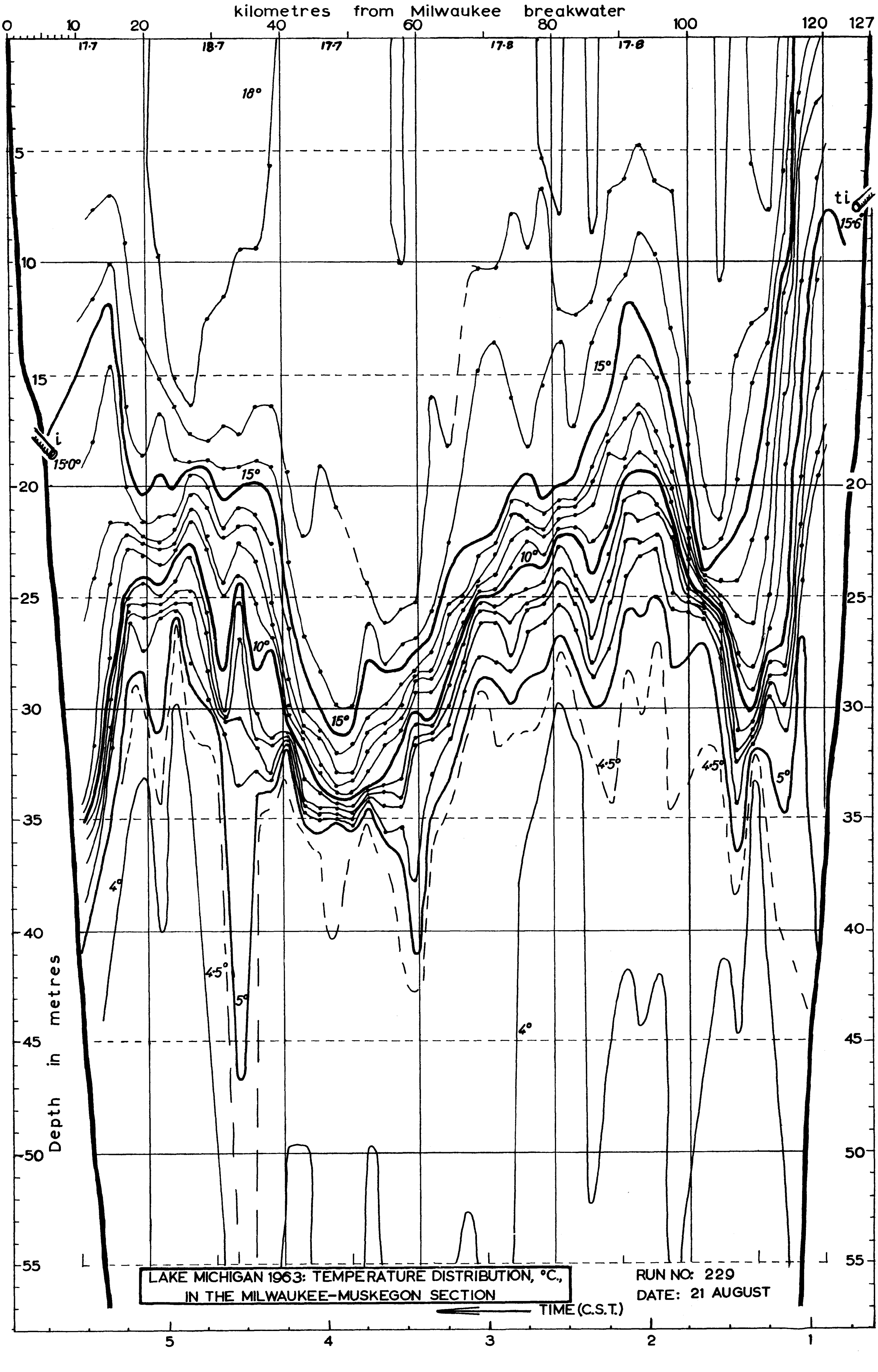
RUN NO: 226

DATE: 20 AUGUST


kilometres from Milwaukee breakwater
16·4
19·4
18·4
17·6
18·1
17·3
17·6
17·7
15·0°C
ti
9·7°C
15°
10°
5°
4·5°
4°
Depth in metres
TIME (C.S.T.)
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C.,
IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 227
DATE: 20 AUGUST

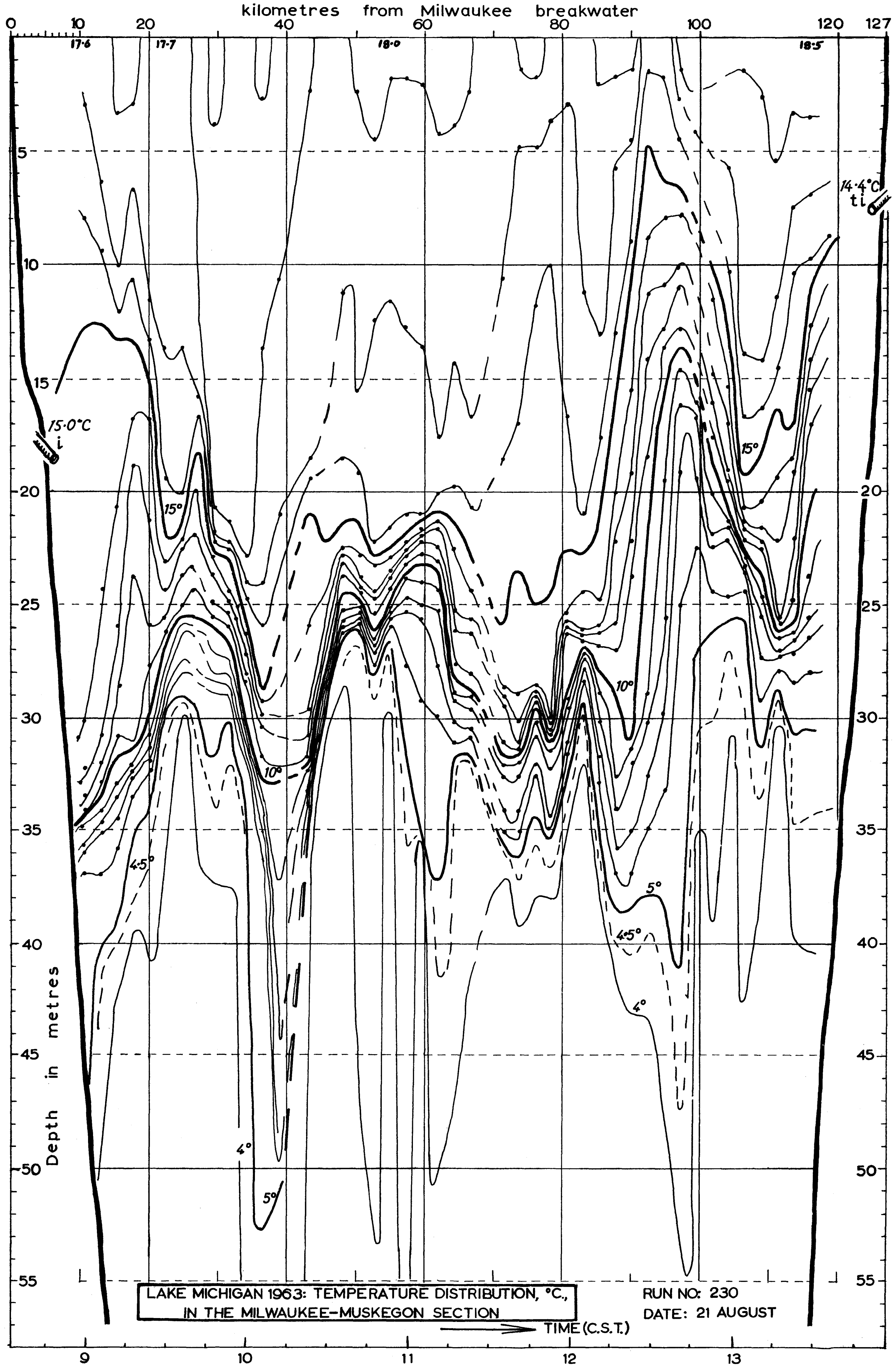


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
16·8 19·5 17·6 17·8
19°
15·2°
ti
13·3°
15°
10°
4·5°
5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 228
DATE: 20 AUGUST
TIME (C.S.T.)
17 18 19 20 21 22

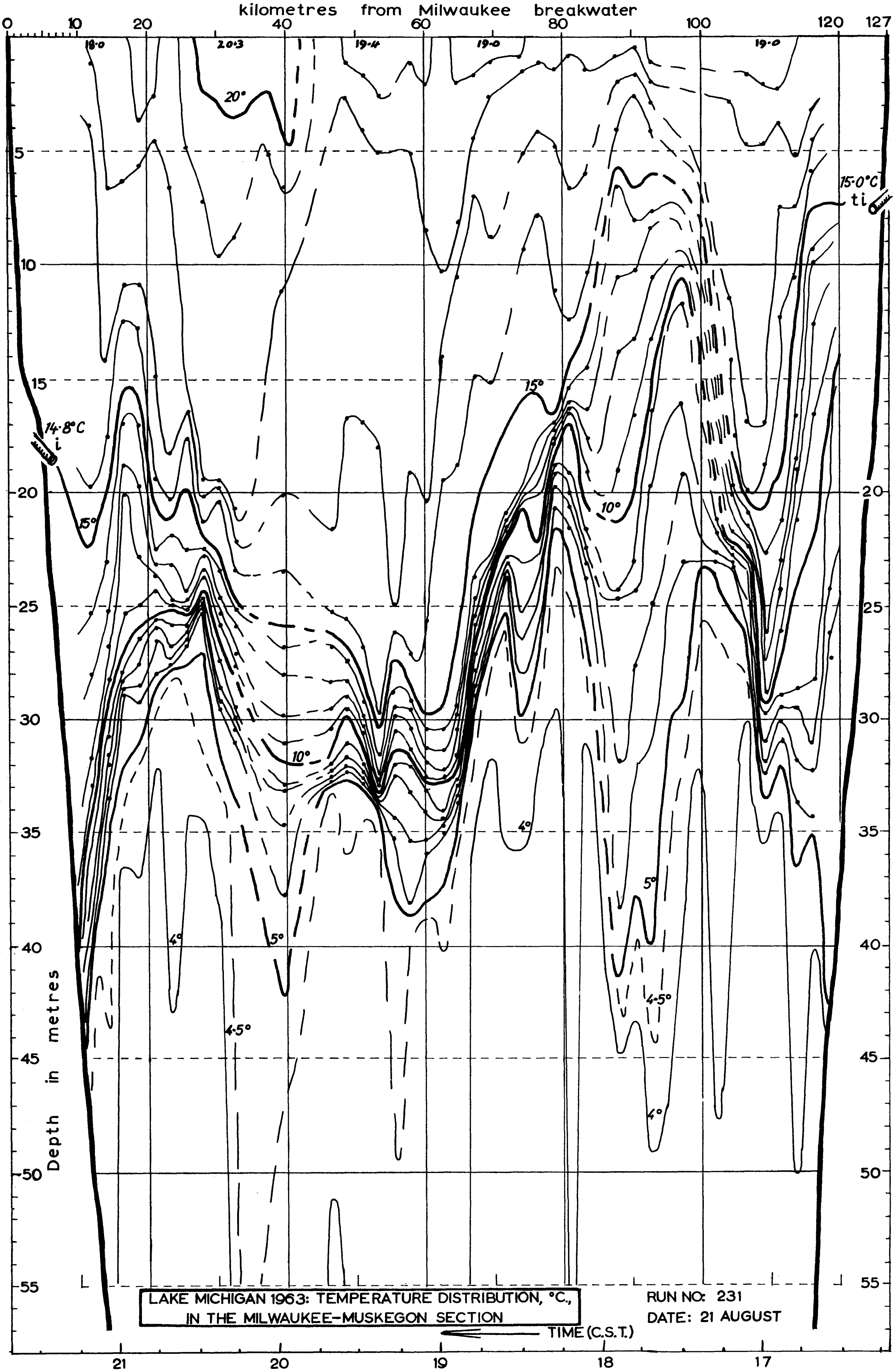


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

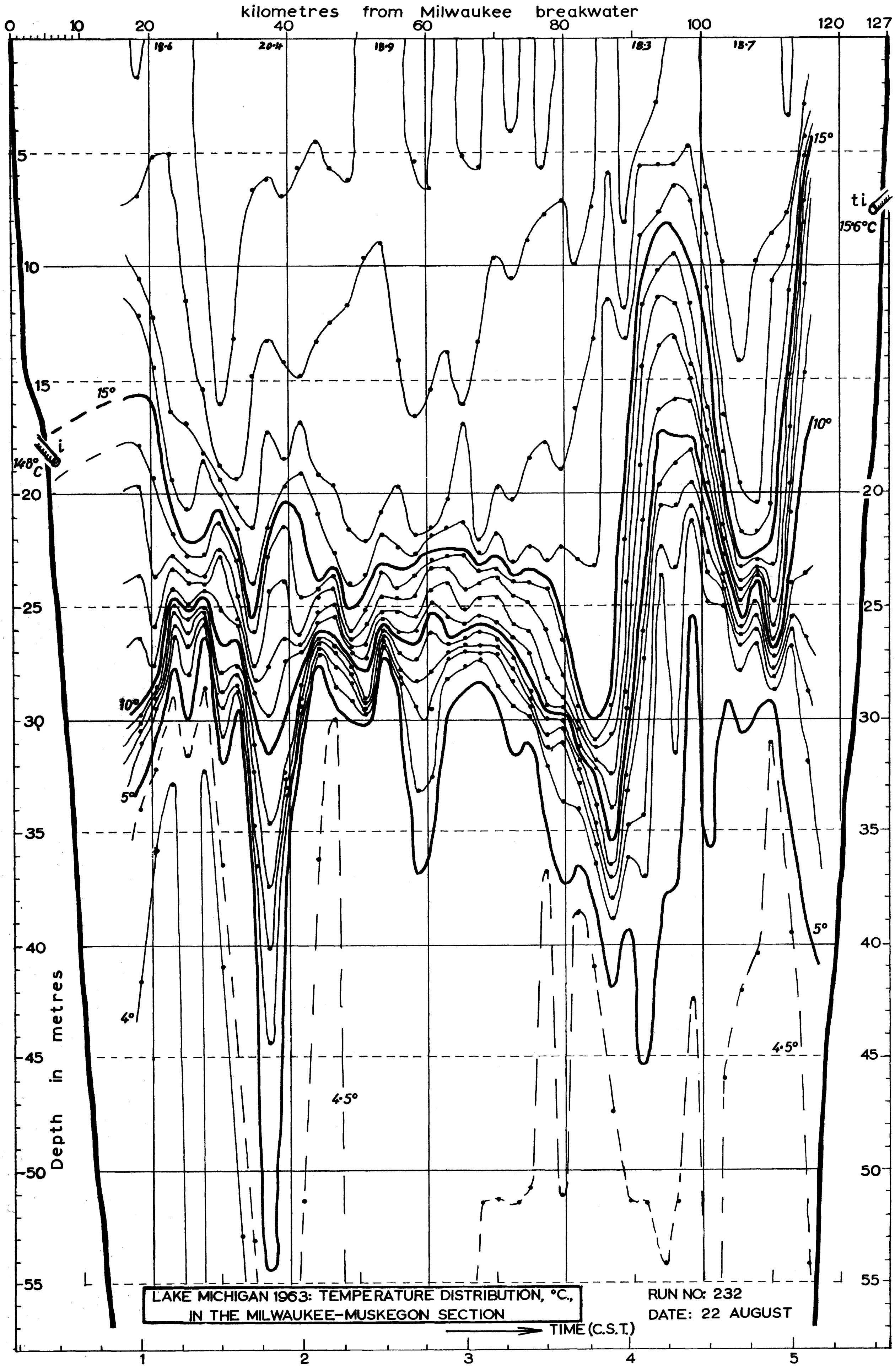
RUN NO: 229
DATE: 21 AUGUST

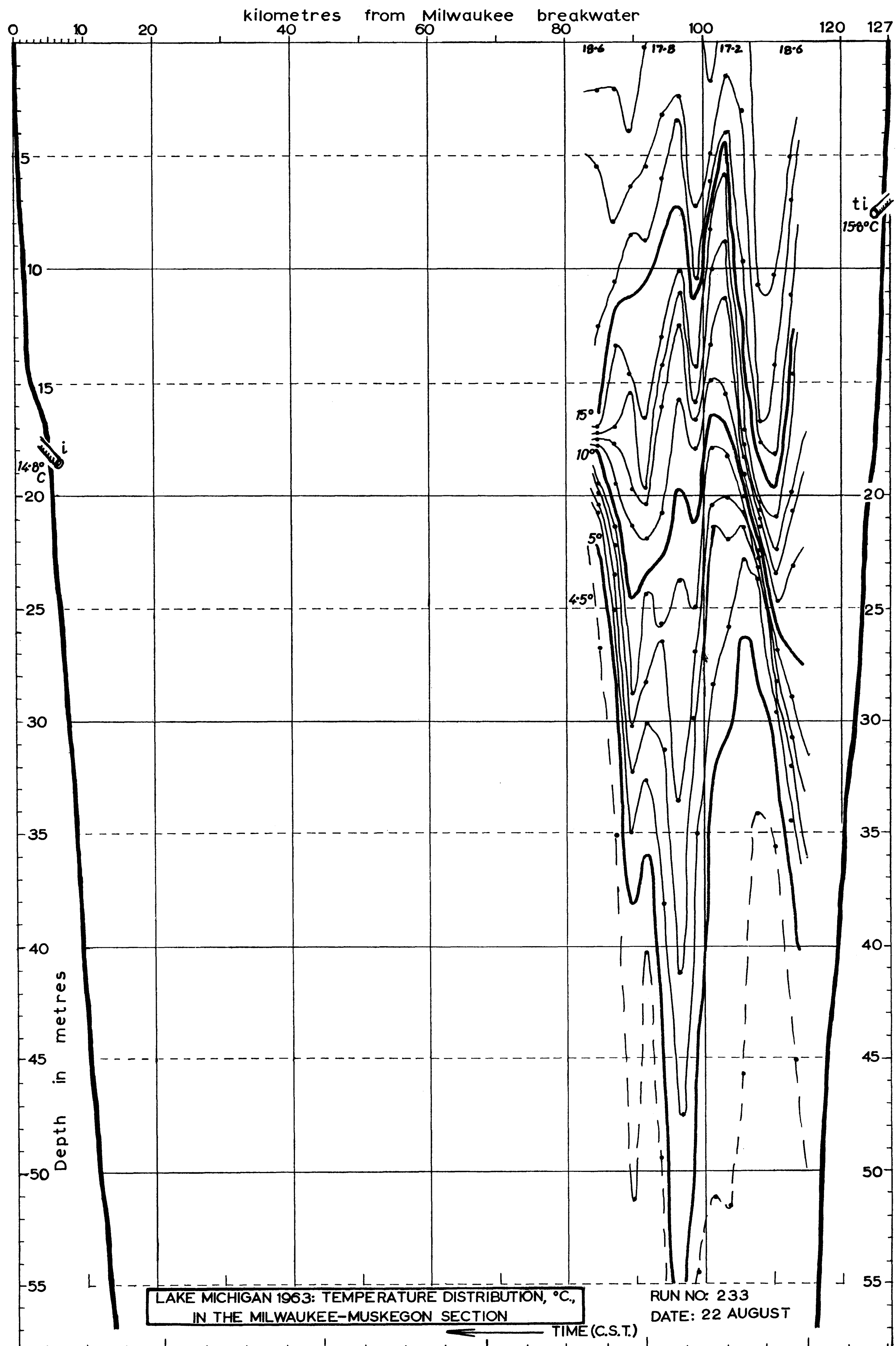


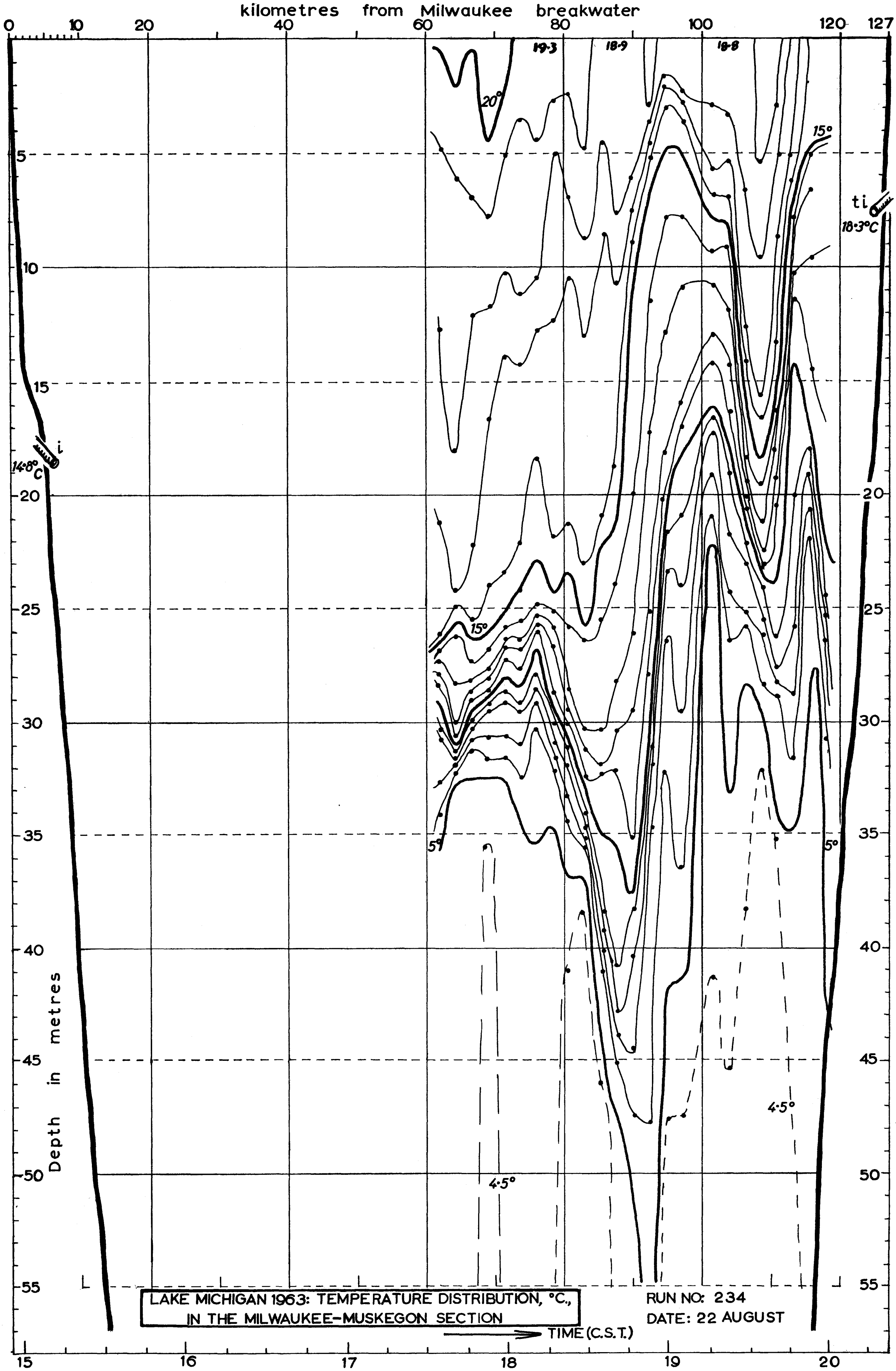
kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
17·6
17·7
18·0
18·5
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
15·0°C
i
14·4°C
ti
15°
10°
4·5°
4°
5°
4·5°
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C.,
IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 230
DATE: 21 AUGUST
TIME (C.S.T.)
9
10
11
12
13

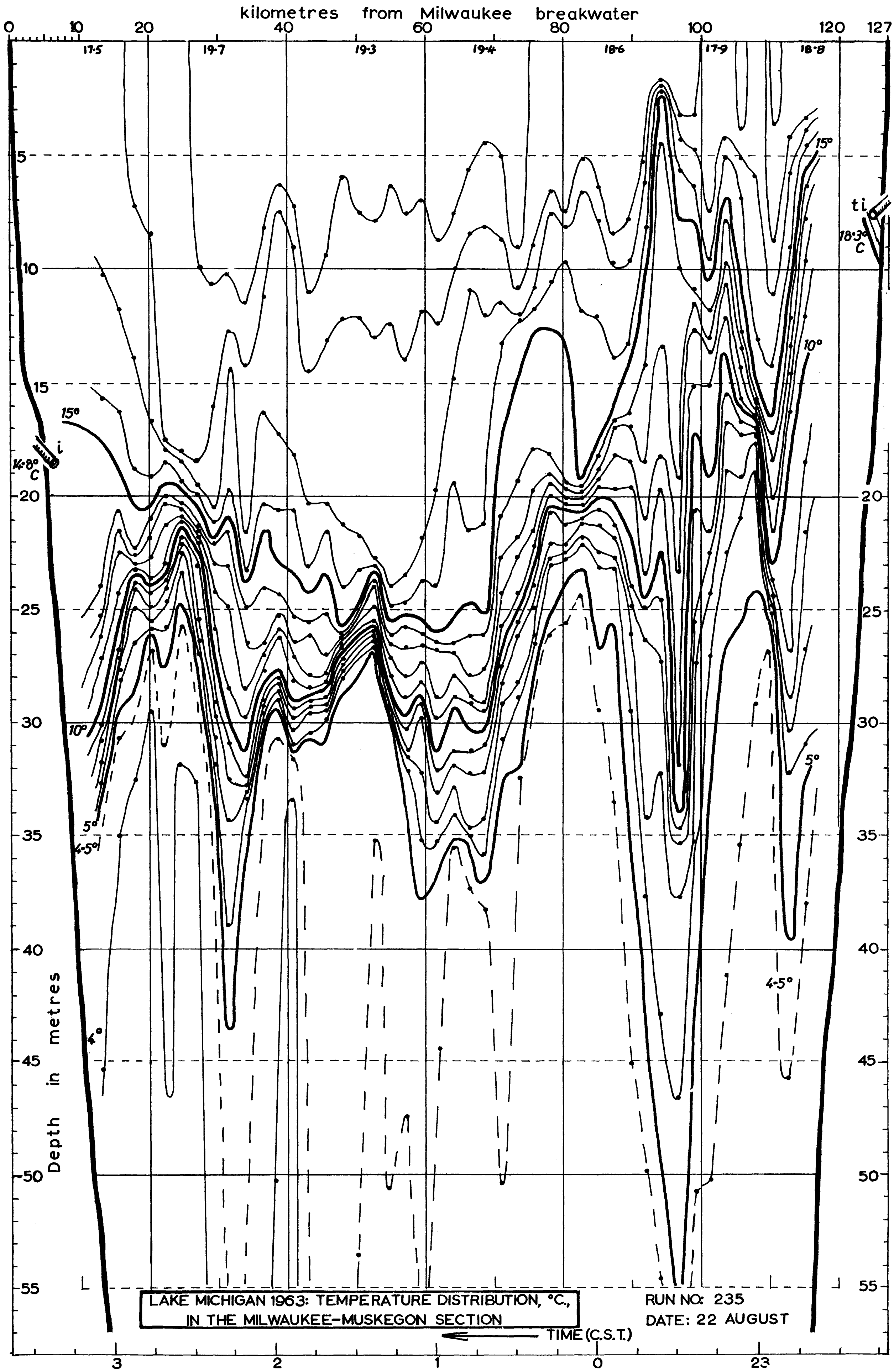


kilometres from Milwaukee breakwater
0 10 20 30 40 50 60 70 80 90 100 110 120 127
18·0
20·3
19·4
19·0
19·0
20°
15·0°C
ti
14·8°C
i
15°
15°
10°
10°
5°
5°
4°
4°
4·5°
4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 231
DATE: 21 AUGUST
TIME (C.S.T.)
21 20 19 18 17

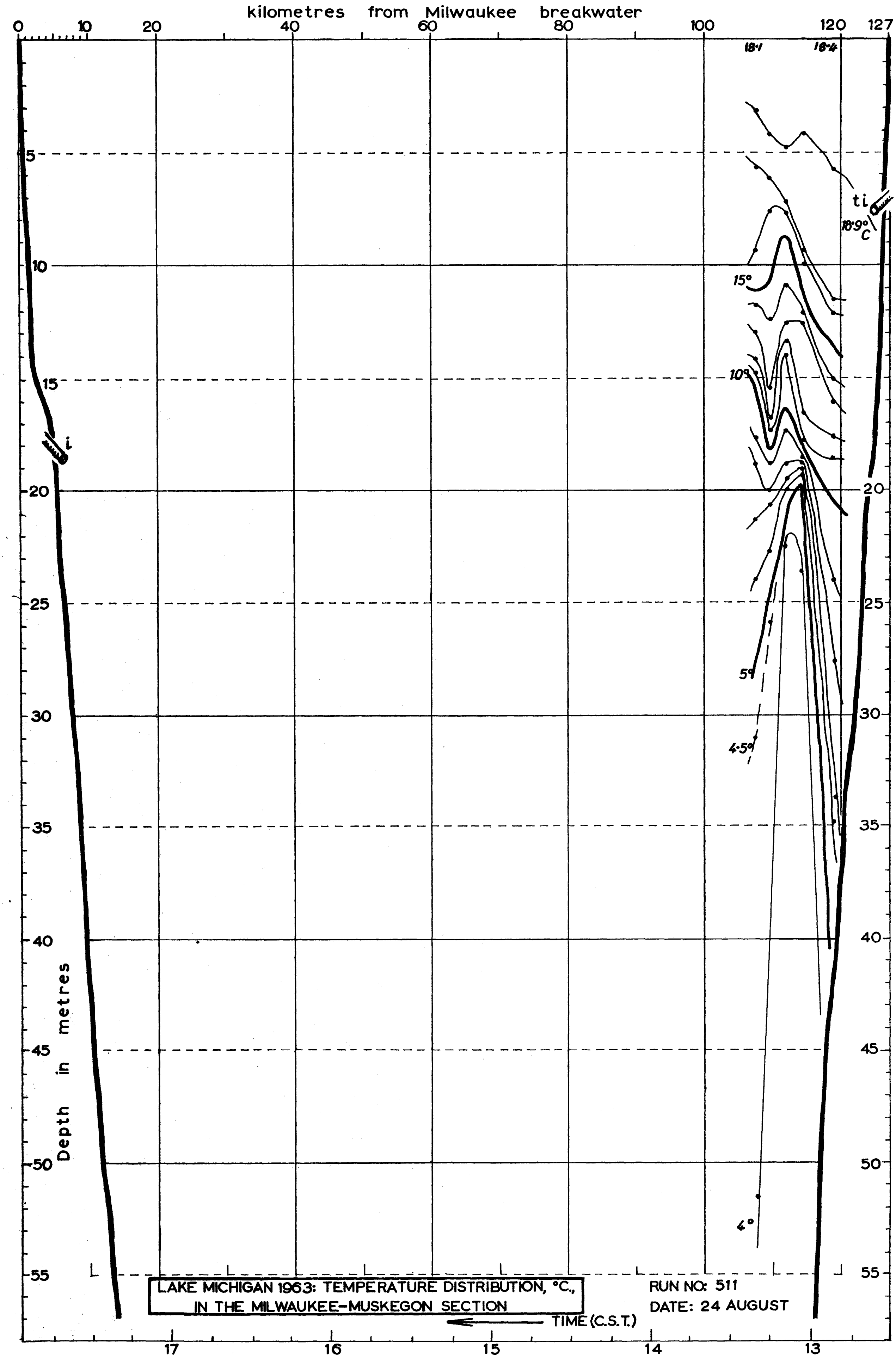

kilometres from Milwaukee breakwater
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 232
DATE: 22 AUGUST
TIME (C.S.T.)
15°
10°
5°
4°
4·5°
14·8°C
15·6°C
18·6
20·4
18·9
18·3
18·7


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
18·6
17·8
17·2
18·6
15°
10°
5°
4·5°
i
14·8° C
ti
15·0°C
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 233
DATE: 22 AUGUST
TIME (C.S.T.)
12
11
10
9
8

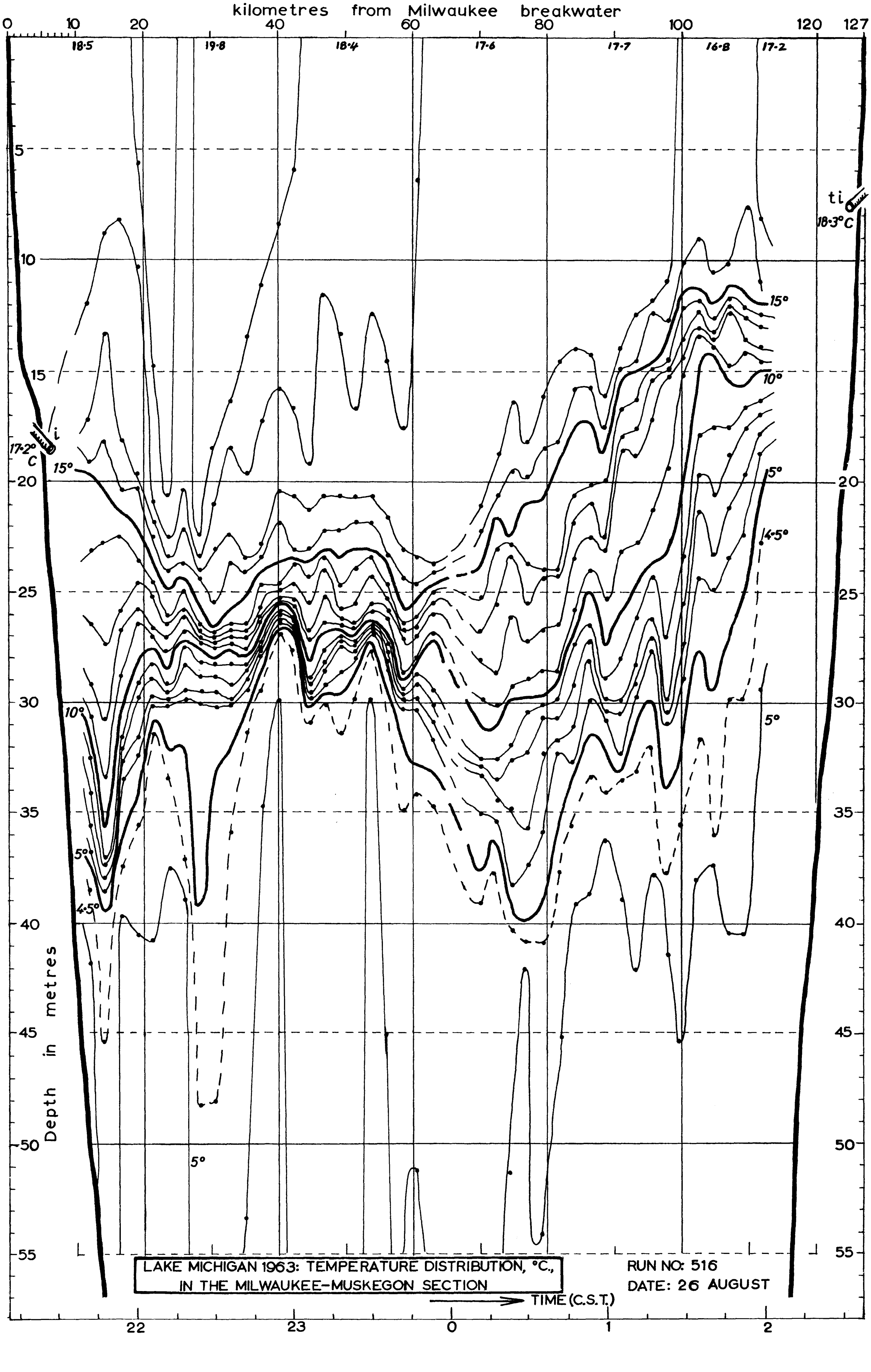

kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
19·3
18·9
18·8
20°
15°
15°
5°
5°
4·5°
4·5°
i
14·8°C
ti
18·3°C
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
TIME (C.S.T.)
15
16
17
18
19
20
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 234
DATE: 22 AUGUST



kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
17·5
19·7
19·3
19·4
18·6
17·9
18·8
15°
10°
5°
4·5°
4°
14·8° C
i
ti
18·3° C
Depth in metres
5
10
15
20
25
30
35
40
45
50
55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 235
DATE: 22 AUGUST
TIME (C.S.T.)
3
2
1
0
23

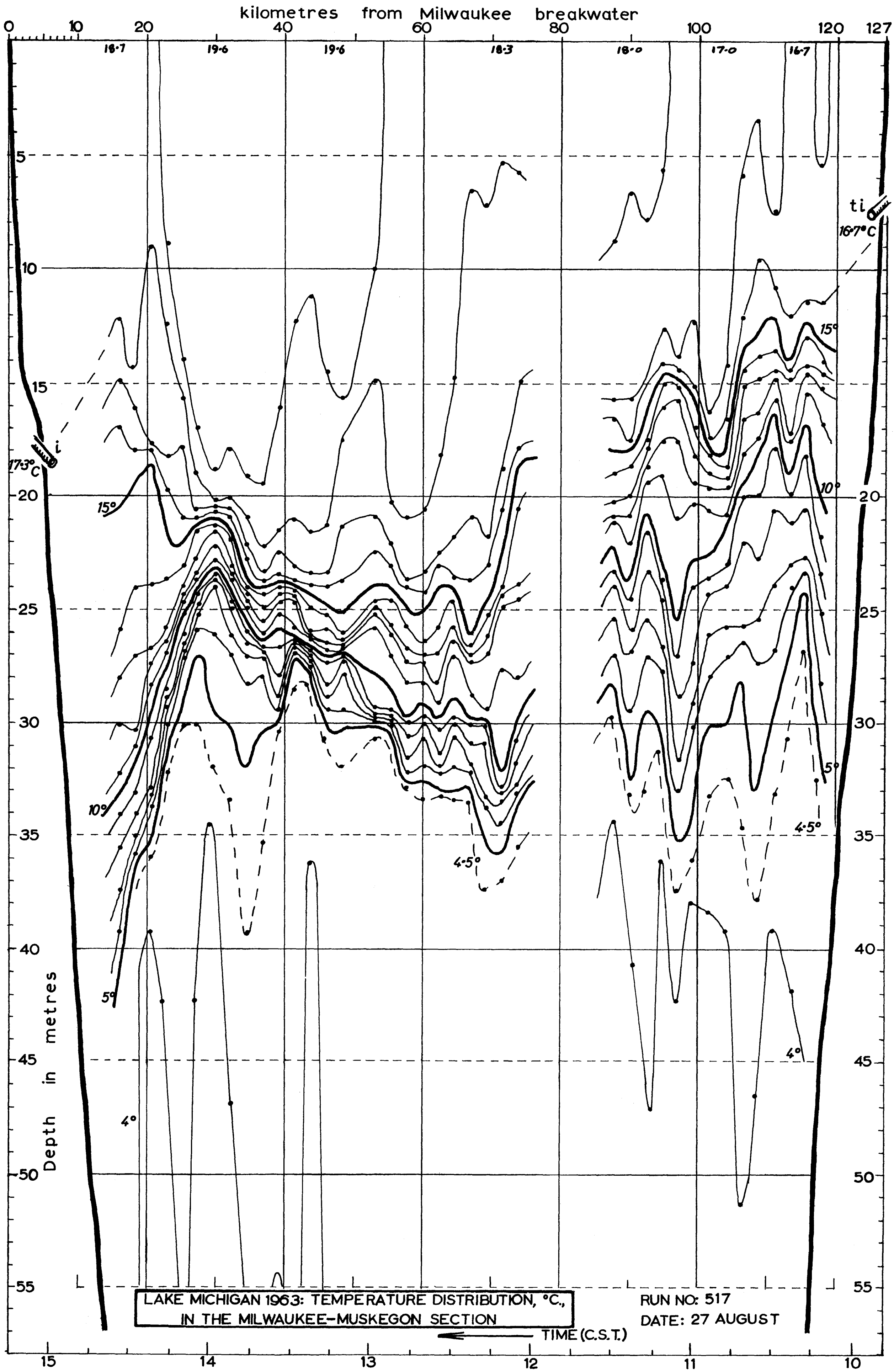


kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
18·1
18·4
ti
18·9° C
i
15°
10°
5°
4·5°
4°
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 511
DATE: 24 AUGUST
TIME (C.S.T.)
17
16
15
14
13

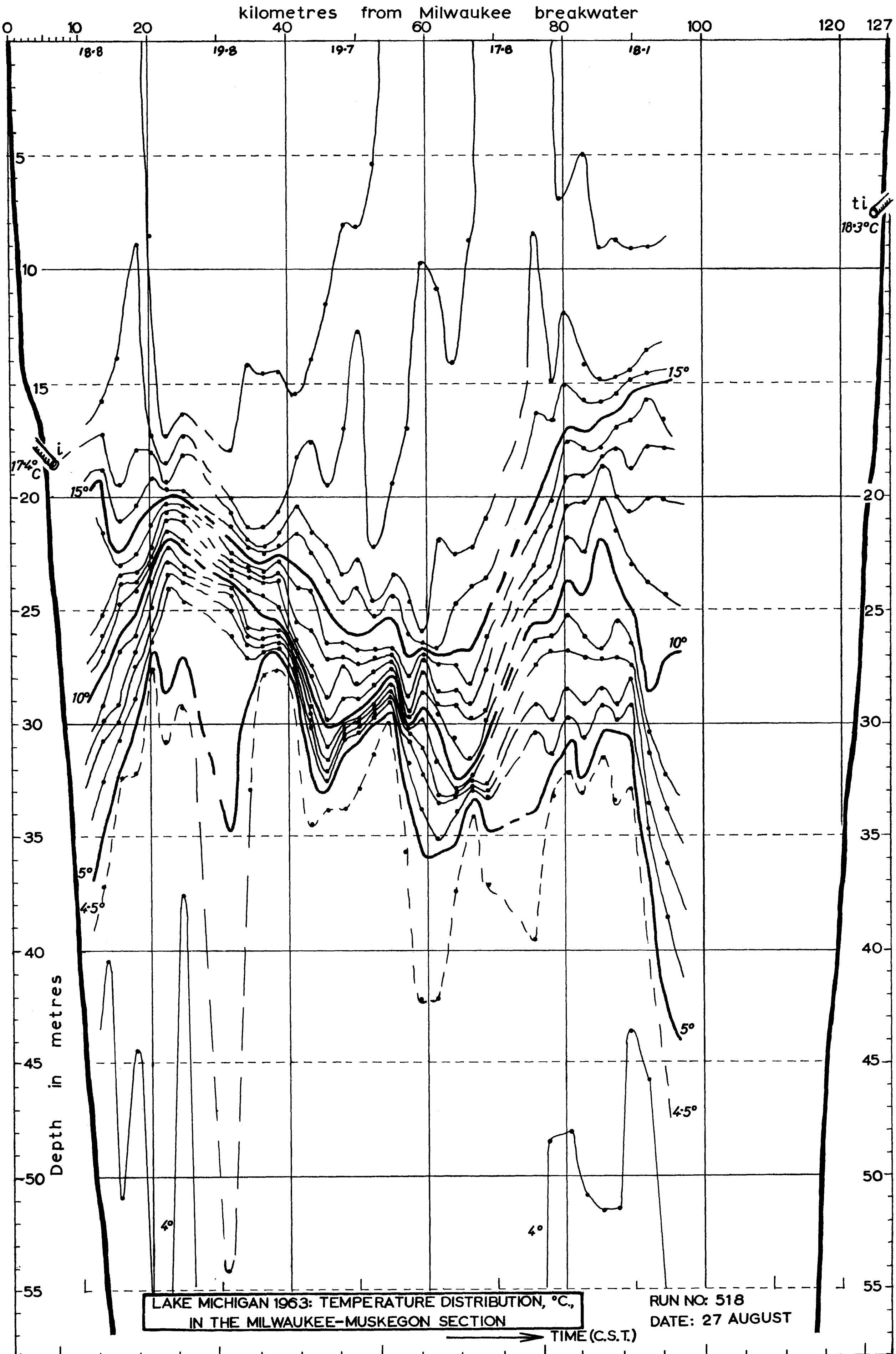


LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

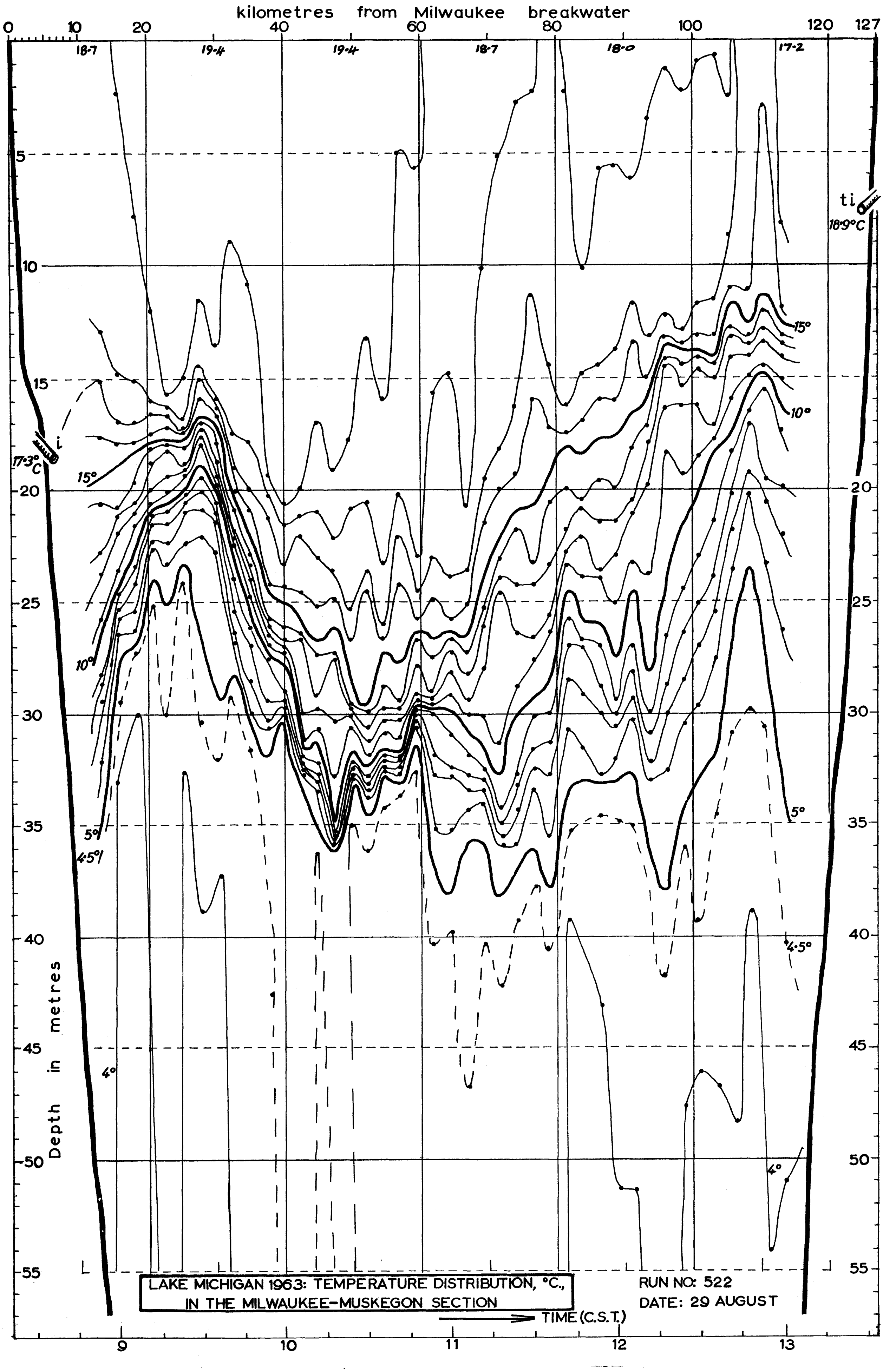
RUN NO: 516
DATE: 26 AUGUST



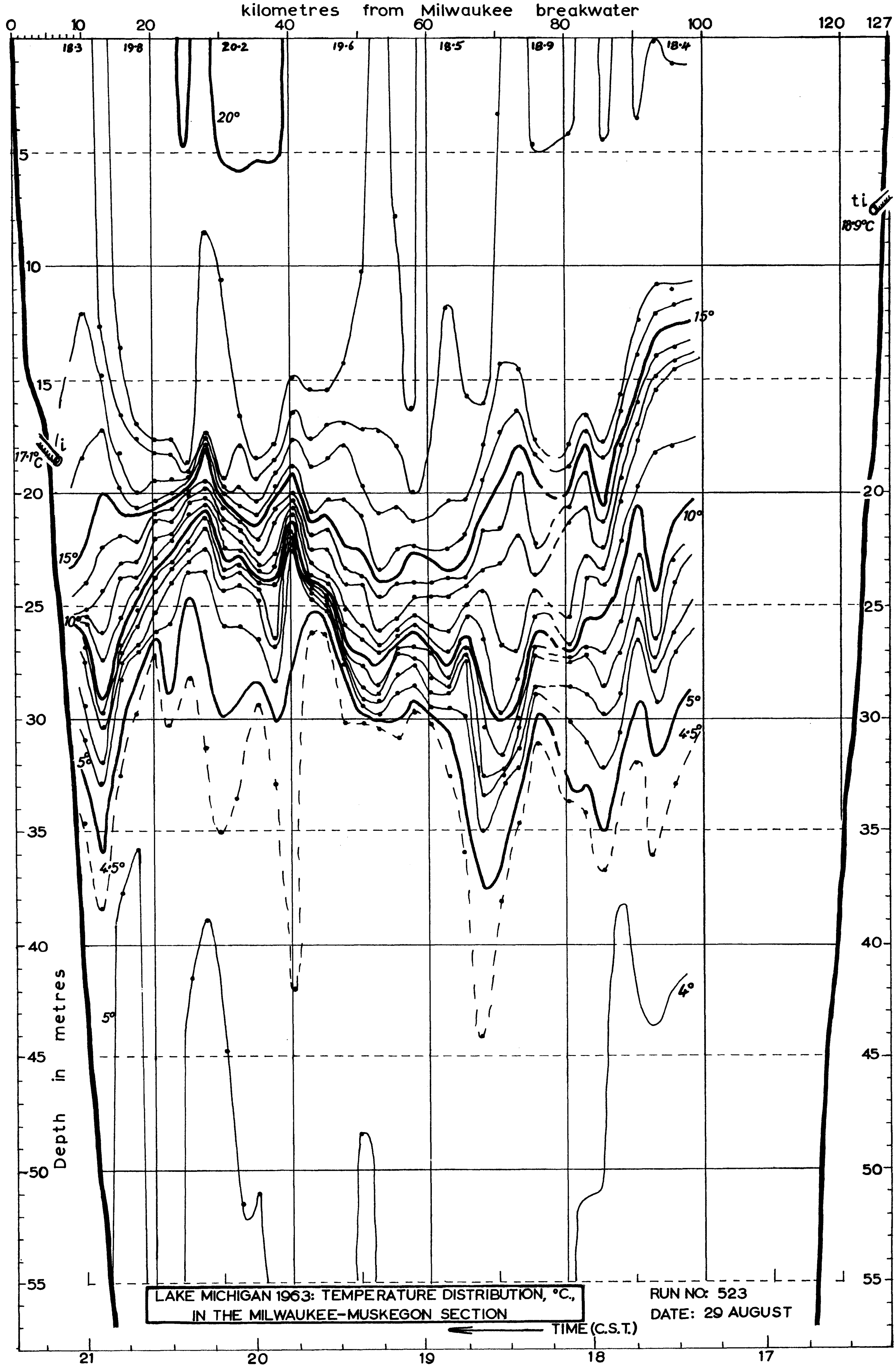
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION



kilometres from Milwaukee breakwater
0
10
20
40
60
80
100
120
127
18·8
19·8
19·7
17·8
18·1
5
10
15
20
25
30
35
40
45
50
55
Depth in metres
17·4°C
i
ti
18·3°C
15°
10°
5°
4·5°
4°
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE–MUSKEGON SECTION
RUN NO: 518
DATE: 27 AUGUST
TIME (C.S.T.)
21
22
23
0
1
2

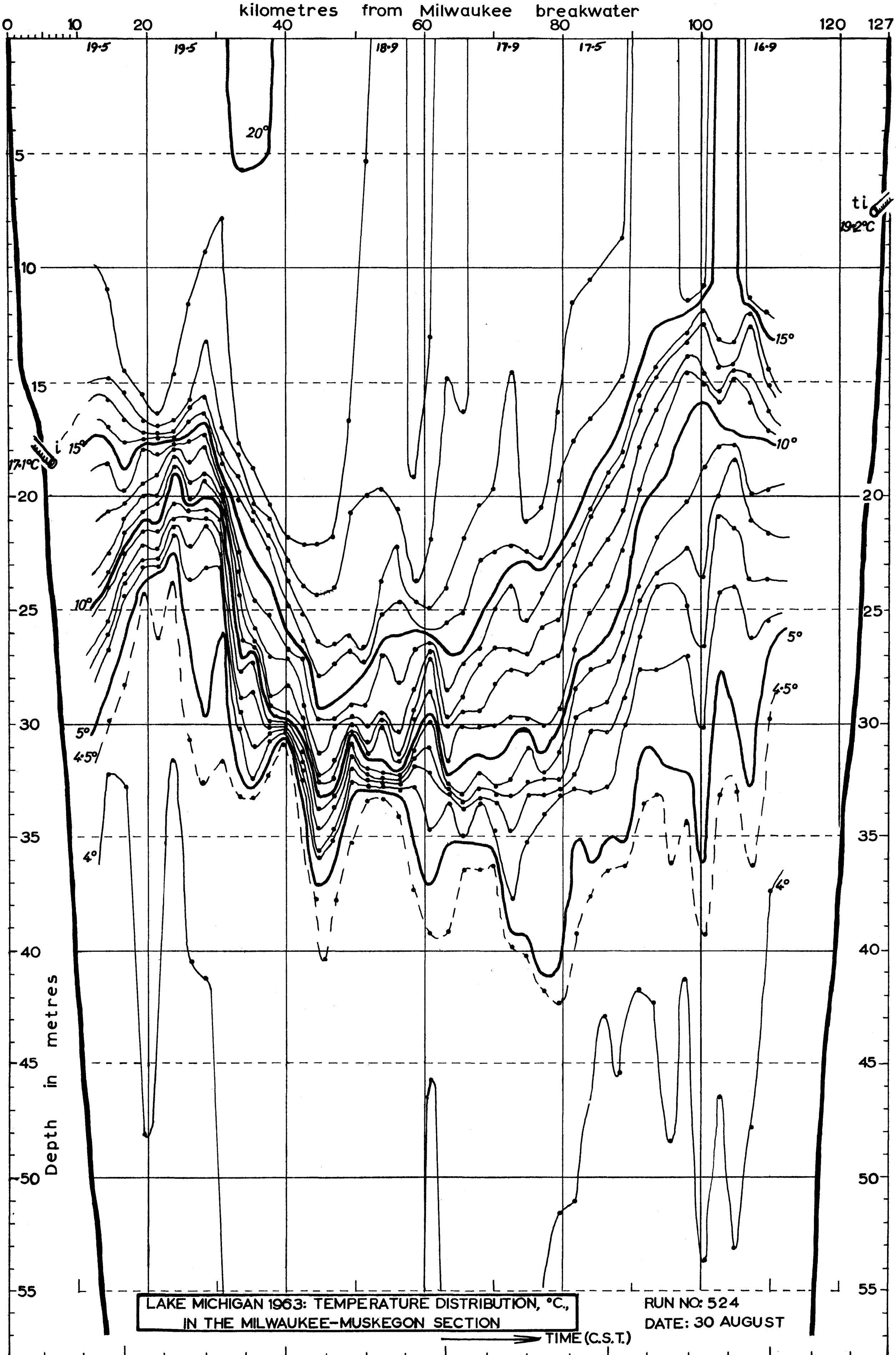


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
18·7 19·4 19·4 18·7 18·0 17·2
ti
18·9°C
i
17·3°C
15°
10°
5°
4·5°
4°
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 522
DATE: 29 AUGUST
TIME (C.S.T.)
9 10 11 12 13



LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION

RUN NO: 523
DATE: 29 AUGUST


kilometres from Milwaukee breakwater
0 10 20 40 60 80 100 120 127
19·5 19·5 18·9 17·9 17·5 16·9
20°
15° 10° 5° 4·5° 4°
17·1°C
19·2°C
Depth in metres
5 10 15 20 25 30 35 40 45 50 55
LAKE MICHIGAN 1963: TEMPERATURE DISTRIBUTION, °C., IN THE MILWAUKEE-MUSKEGON SECTION
RUN NO: 524
DATE: 30 AUGUST
TIME (C.S.T.)
0 1 2 3 4 5