The Coastal Boundary Layer in Lake Ontario: Part II. The Summer–Fall Regime

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ABSTRACT

Field observations on coastal currents near Oshawa on the north shore of Lake Ontario during summer and fall are described. The technique of observations (flag-station chain) has been given in Part I, together with a description of the dynamic regime during the spring period. Observations during summer and fall show that the kinetic energy level of water movements increases considerably from spring to summer and again from summer to fall. Much as in the spring, a nearshore band (some 10 km wide) becomes a unique kind of "boundary layer" in which mid-lake motions adjust to the presence of the shores. In this shore zone, currents are shore-parallel and relatively persistent. During summer and fall, mid-lake motions are wave-like, consisting mainly of near-inertial oscillations. Within the shore zone, the current-like motions are associated with thermocline displacements, upward if the current flows to the east, downward if it flows to the west, so that the pressure gradients caused by the non-uniform density distribution are at least partly balanced by the Coriolis force. The lakewide flow pattern is mainly determined by a few periods of relatively strong winds, which can reverse an opposing current and lead to a complete mass exchange between the shore zone and mid-lake as a consequence of large thermocline movements. Advection of momentum from the outer zone into the coastal zone also plays a significant role in maintaining coastal currents.

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1. Introduction

In an earlier paper [(Csanady, 1972b) to be referred to as Part I] I described some observations on what might be called the "coastal boundary layer" in Lake Ontario during the *spring* period. As a prelude to this description, the general theoretical reasons why flow should have a boundary layer character in the shore zone were also discussed. In the present paper further evidence is presented for this view by describing the flow regime in the coastal zone during summer and fall, as observed in Lake Ontario in the course of the "Coastal Jet Project." The details of the experimental technique, location, etc., have already been given in Part I.

2. General features of the summer–fall regime

By middle or late June a continuous thermocline is usually established in Lake Ontario, at an equilibrium depth of between 10 and 20 m. Long waves of near-inertial period usually distort this into an irregular surface [much as in Lake Michigan (Mortimer, 1968, 1971)], the shore-zone edges of which often show rather more persistent uptilts or downtilts. The uptilts are strong enough on occasion to bring the thermocline to the surface and produce an upwelling. Uptilts are associated along the northern shore of Lake Ontario with eastward flow in the surface layers, downtilts with westward flow [in analogy, respectively, with the lens-shaped and wedge-shaped spring thermocline (Csanady, 1971)], so that quite evidently the Coriolis force is again implicated in their occurrence. The width of the tilting region of the thermocline is usually of the order of 5 km. Easterly or westerly flow is again set up by periods of strong winds of corresponding directions, just as during the spring.

Another fairly general feature of the summer dynamic regime is that most of the water above the thermocline is usually in motion, so that the kind of general stagnation that is sometimes observed in the spring does not occur. Fig. 1 shows the maximum observed velocities (anywhere in the coastal chain, on the occasion of each survey) vs date during the 1969 summer season. In spite of the scatter, the trend to increasing velocities with progress of the season is clear and illustrates one aspect of the transition from "spring" to "summer" regimes.

The thermal structure of the lake in the fall period (from, say, mid-September to late November) is similar to that during the summer in that a continuous thermocline stretches from shore to shore, and is therefore not classed as a separate "regime." With the onset of surface cooling, however, the thermocline begins to move farther downward and the layers above the thermocline become better mixed and are more nearly homogeneous than during the summer. The *dynamic* behavior is also characterized by similar observed maximum velocities as in July, although on one occasion (9 September

1970) a peak speed of 68 cm sec^{-1} was observed, a value more than 50% higher than the highest summer reading. Also, owing to the reversed air-water temperature difference (water now generally warmer than the air), winds close to the water surface become stronger, because upward heat flux enhances atmospheric turbulence. The lake is therefore "rougher" and a greater amount of fair-weather bias in the observations is practically unavoidable. An unbiased "average" current speed is presumably rather higher than during the summer. As we already remarked, the depth of the layer above the thermocline (which is again generally in motion) is also greater, so that the kinetic energy content of the lake is much higher during the fall than during the summer.

Just as during the spring period, the general character of observed currents during summer and fall again show a fairly clear distinction between a coastal boundary layer and an inner zone. The greatest difference is that during the summer in the inner zone we find in place of general stagnation a flow regime dominated by wave-like motions of near inertial frequency, giving rise to current speeds of the same order of magnitude (20 cm sec^{-1}) as in the more persistent coastal currents.

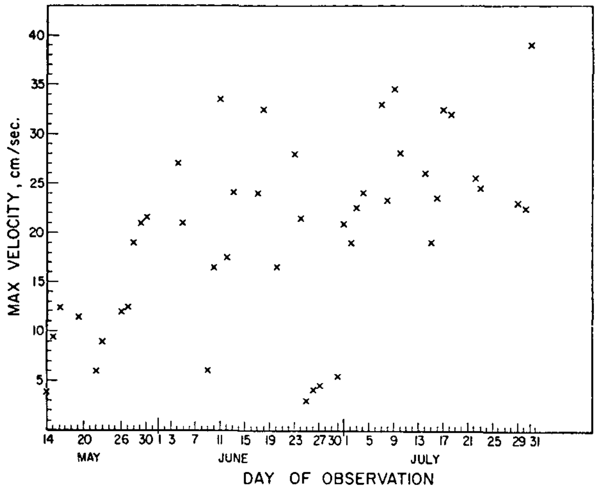

Fig. 1. Maximum observed velocities, 1969 summer season.

a. *Wave-dominated outer zone*

At the outer stations of the coastal chain the influence of long internal waves of near-inertial frequency on observed currents was found to be marked. A clear demonstration of this influence is provided by the

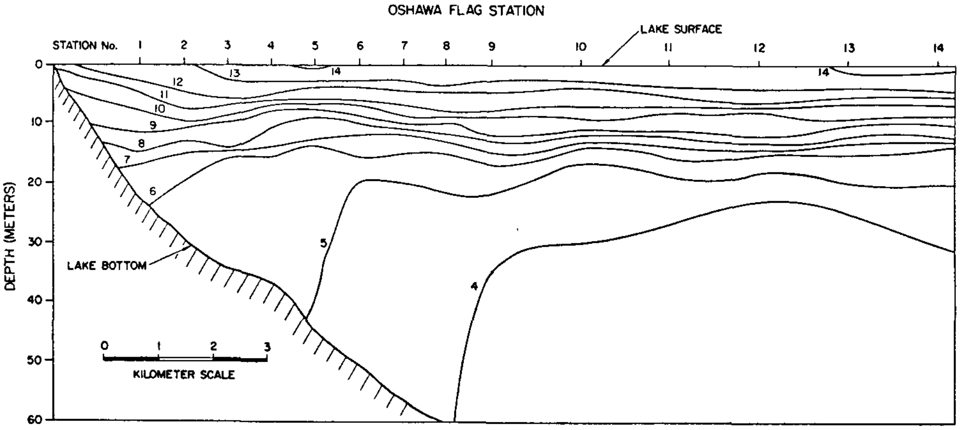

Fig. 2. Isotherm contours, 8 July 1969, from 0915–1315 EDT.

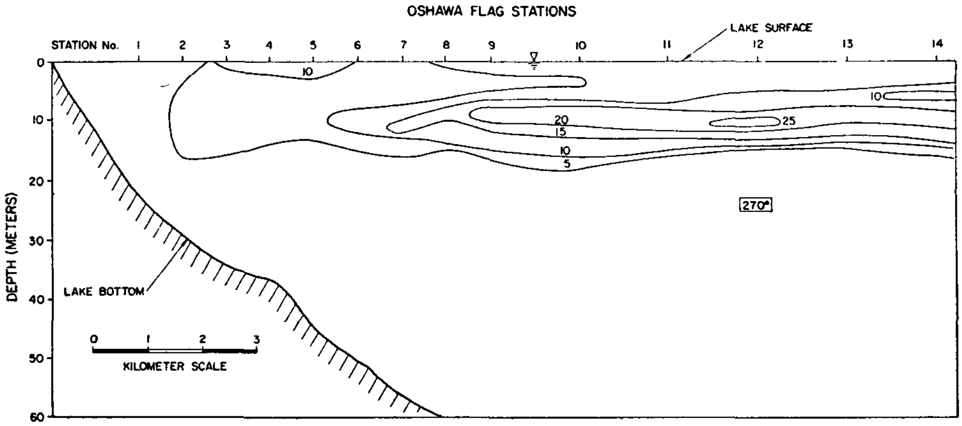

Fig. 3. Constant speed contours for the period shown in Fig. 2.

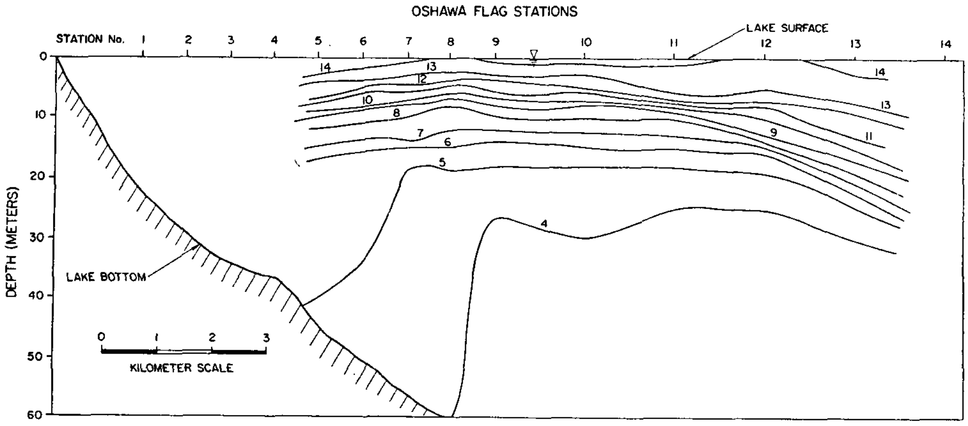

FIG. 4. Same as Fig. 2 except for 1405–1715 EDT.

8 July 1969 surveys (two surveys carried out on this day, separated by an interval of 4–5 hr). Figs. 2–5 show the temperature and velocity structure on these surveys. A high-speed region was observed in the thermocline, at a depth of 8–10 m, 9–17 km from shore (presumably extending farther outward, beyond the coastal chain). Between the first survey and the second, the current direction turned clockwise by 105°, equivalent to a rotation period of 16.5 hr, or slightly less than one-half of a pendulum day. The whole high-speed region also moved slightly closer to shore and its intensity decreased. The changes of the temperature and velocity structure are best exhibited by data at a flag-chain station near the core of the high-speed region (Station 12). Fig. 6 shows the profiles obtained during the first survey, Fig. 7 those during the second. The high-velocity region in the first survey clearly occurred in a "flat spot" of the temperature profile within the thermocline, which was slowly closing up, coincident with a decay of the peak velocity. Simultaneously, the surface layer velocity increased, although not enough to conserve kinetic energy. The horizontal structure of this internal wave may be judged from Fig. 8 showing current vectors at the depth of maximum velocity, at varying distances from shore. Based on this figure one may estimate the horizontal wavelength to have been $\lambda = 20$ km, but if one allows for current rotation between the nonsynoptic flag station measurements, this reduces to 15 km. In any case it is clear that we have here an instance of a "higher" baroclinic wave, associated with pulsations of the thermocline thickness, of moderately long wavelength and near-inertial period [something like the second baroclinic Poincaré wave of a constant-depth model (Csanady, 1972a)]. We note that the depth of water at Station 12 was 83 m, while the high-speed region extended only to a depth of 17 m, so that bottom friction had presumably negligible effects on this wave.

The above example was somewhat atypical, particularly in the relatively short wavelength of the internal wave. On other occasions the observed wavelength was too long for the observations to show much variation in amplitude along the short distance covered by the coastal chain. In most cases, however, the observed current changes at the outer stations were dominated by waves of near-inertial period.

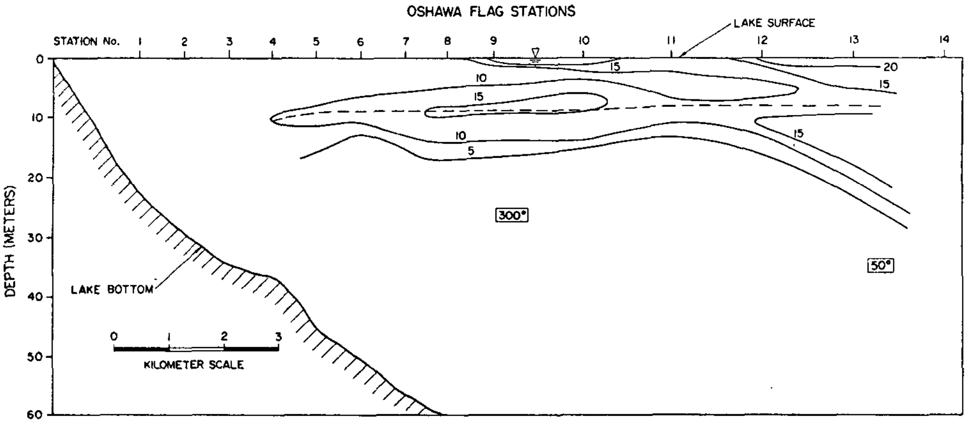

FIG. 5. Constant speed contours for the period shown in Fig. 4. The dotted line marks the core of the high-speed region.

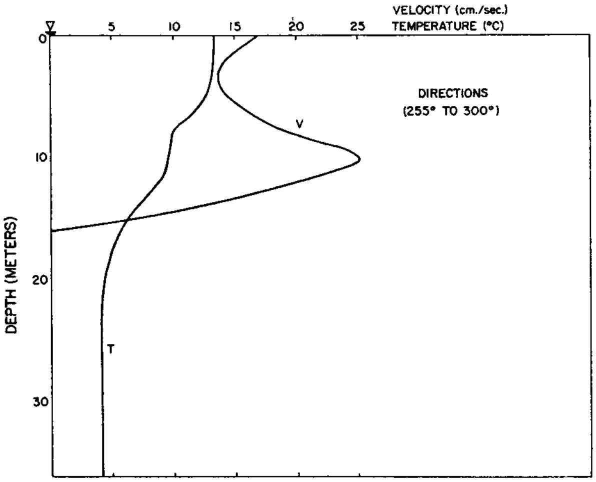

Fig. 6. Velocity and temperature profiles at Station 12 on 8 July 1969, morning.

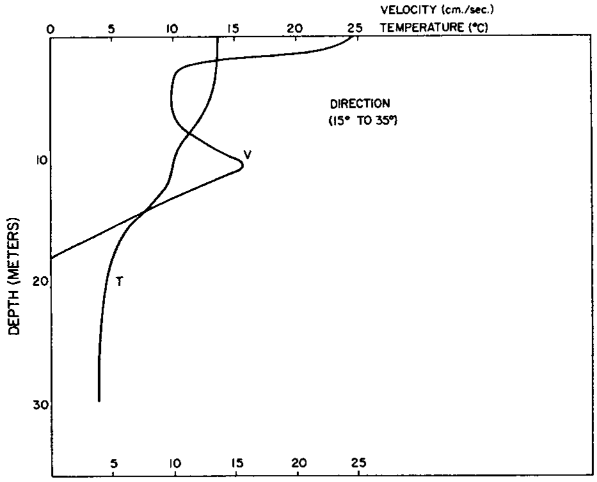

Fig. 7. Same as Fig. 6 except for the afternoon.

Another spectacular fact may be pointed out in connection with Fig. 9. This illustration shows a large high-speed region well below the surface, somewhat offshore from a "coastal jet" (the two high-speed regions in fact touch at 11 m depth, 5 km from shore), observed on 29 September 1970. This region is quite well defined, with its core being at the middle of the thermocline (see the 10C isotherm in Fig. 10), showing peak velocities of 19 cm sec^{-1}. This entire "deep" high-speed region disappeared without trace by the next day, in sharp contrast to the coastal jet lying just above it and having a comparable total kinetic energy. A plausible explanation is that this flow feature was caused by a higher baroclinic, progressive wave, which moved away from the observation area.

The wave-like aspects of the flow are also illustrated by the fixed point records obtained at Station 12 at a depth of 8.2 m. An example is shown in Fig. 11, containing the record for 14–15 July 1970. Note the regular rotation of current direction, with a period of 16 hr or so. This meter was located just above the steepest part of the thermocline on that day.

b. Coastal jets

As we have already remarked, the flow direction closer to shore was more nearly persistent in a "coastal boundary layer." Some effects of the inertial oscillations, however, were also felt in this zone, particularly when the amplitudes were large, or at the edges of a jet where the boundary moved back and forth, as illustrated for a spring jet in Part I. Nevertheless, the separation between the coastal zone and the outer, wave-dominated zone was generally clear enough. A good example of a "coastal jet" is provided by the observations of 27 July 1970 (Fig. 12).

In this illustration the distinction between a 7-km wide shore zone and an outer region is quite conspicuous. The jet in the coastal zone persisted on this occasion for several days; Fig. (13) shows its appearance on 30 July 1970, i.e., 3 days later. Prior to the first survey on 27 July, easterly winds had established the westward flowing current, which then persisted through a period of relatively light winds, some of which opposed the current (west winds up to 7m sec^{-1} occurred on 28 July for a few hours). Outside the coastal jet the current direction rotated with the inertial period.

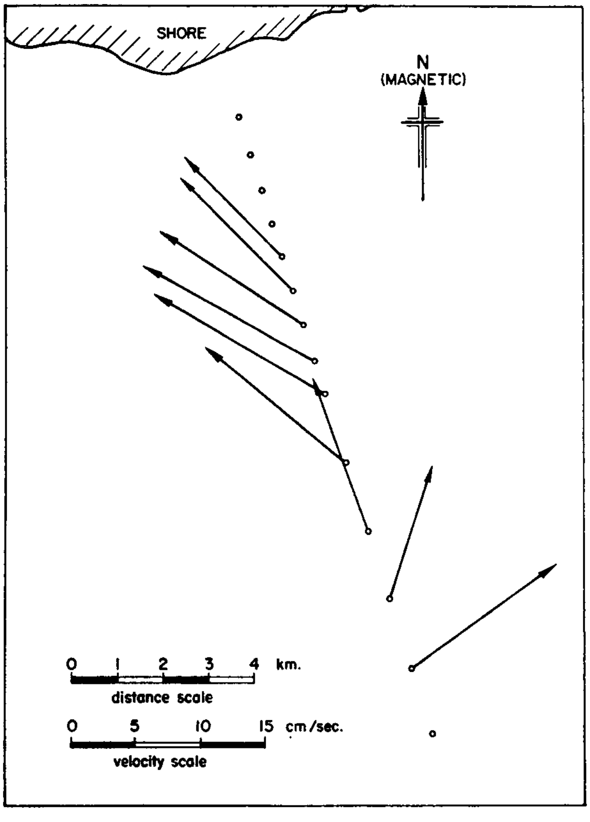

Fig. 8. Current vectors in the high-speed core region (dotted line as in Fig. 5) for 8 July 1969.

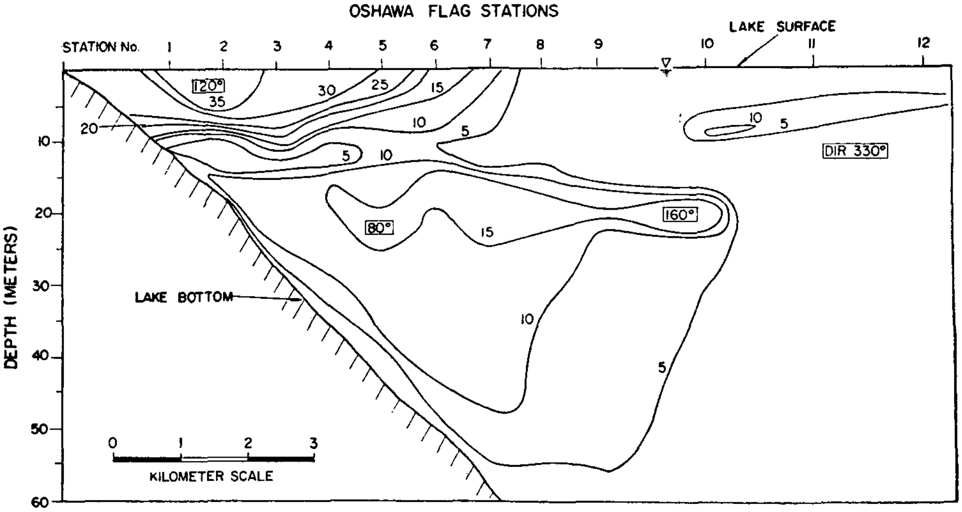

FIG. 9. Constant speed contours for 29 September 1970.

Another example of a coastal jet was already shown in Fig. 9 (29 September 1970). By then this jet had been in existence for two days and persisted for several more, although it drifted outward from the shore, its center being 4 km from shore on 1 October and 7 km on 5 October. The jet could be traced moving with the 14C isotherm, while an upwelling developed near shore. A comparison of the histories of this jet and of that previously described (Figs. 12 and 13) also illustrates the difference between eastward and westward flowing jets: the latter are evidently stabilized by the shore, while the former tend to drift southward, as hypolimnion water progressively occupies the shore zone. Eastward flowing jets were also less frequently observed, presumably on account of their tendency to drift southward, out of the observation area. The lakeward drift of a band of high velocity fluid constitutes appreciable convective momentum transport and underlines the importance of the nonlinear inertial accelerations in the equations of motion.

A third example illustrates the differences between summer and fall conditions in the shore zone. A westward flowing jet occurred on 17 September 1970. Temperature and velocity cross sections for this day are shown in Figs. 14 and 15. This is a rather wider jet (outer edge at 13 km) than any observed in July. It more or less coincides with the 15C isotherm, except that the velocity drops abruptly to zero at the shallow edge, approximately above the thermocline-bottom intersection, and that a weak countercurrent appears on the inshore side of this line. The thermocline shows the downtilt expected with a westward jet. The same jet persisted in a very similar form on the following two days, became weak on the 20th and only a trace of it was left on the 21st. The winds were light easterly on the 17th, but fairly strong southwest winds occurred

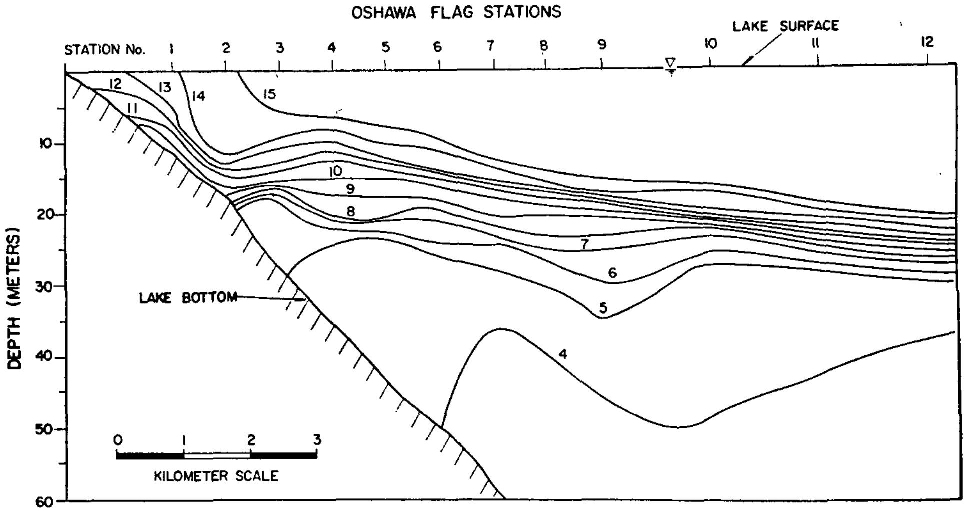

FIG. 10. Isotherm contours for 29 September 1970.

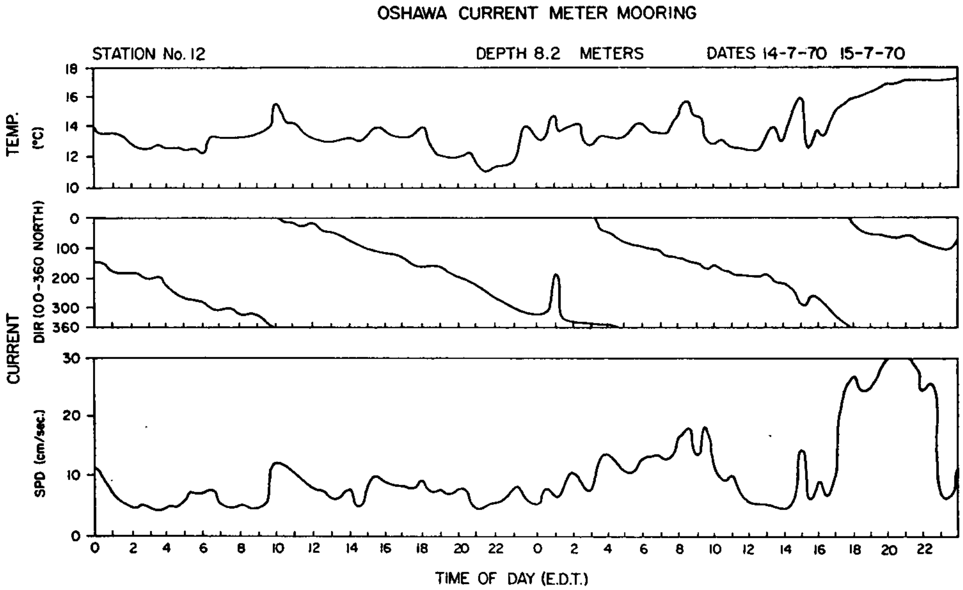

Fig. 11. Fixed point records of temperature, current speed and direction at an outer zone station (No. 12) just above the thermocline (8.2 m depth), 14–15 July 1970.

on the 19th and the 21st, which presumably were responsible for the disappearance of this jet. Vertical temperature and velocity profiles across the core of the jet taken on 17 September are shown in Fig. 16 (at Station 8, where the water depth was 68 m). The bottom edge of the jet appears to be associated with a relatively small step in the temperature profile. By 22 September the thermocline straightened out and an eastward flowing jet was in existence, persisting on the 23rd.

c. Mass exchange

A particularly interesting sequence of observations was obtained on 7 October 1970 and the following day,

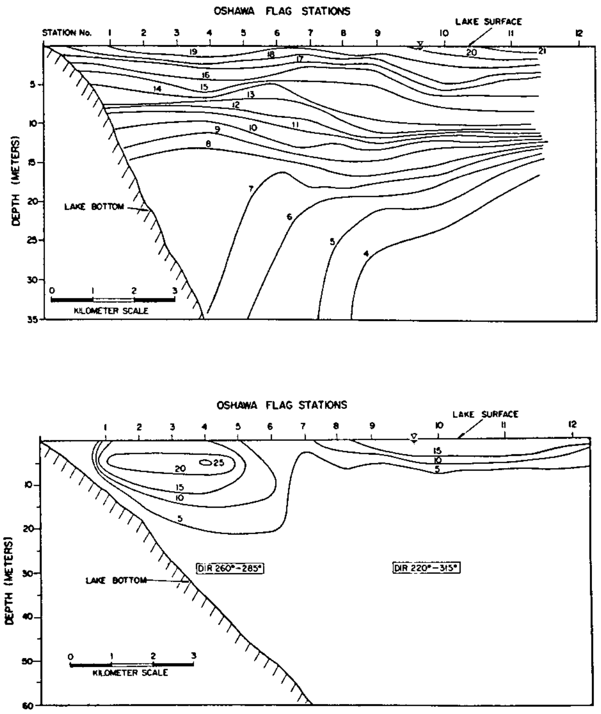

Fig. 12. Isotherms and constant speed contours on 27 July 1970.

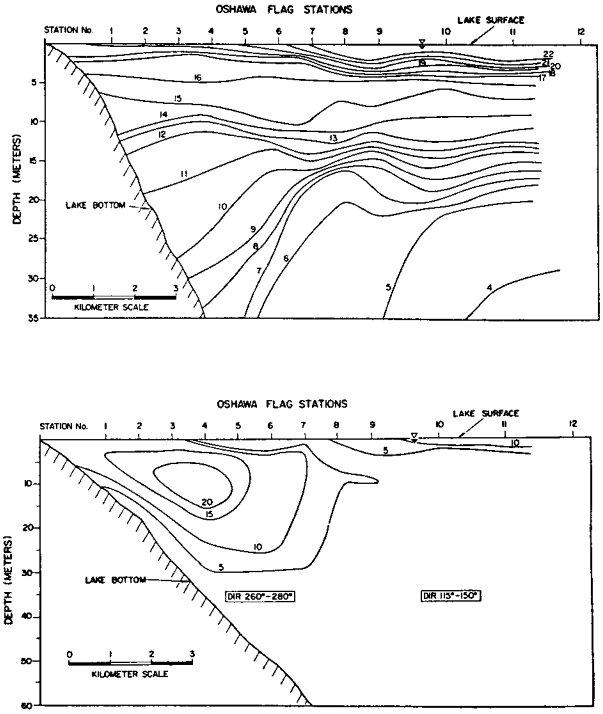

Fig. 13. Isotherms and constant speed contours on 30 July 1970.

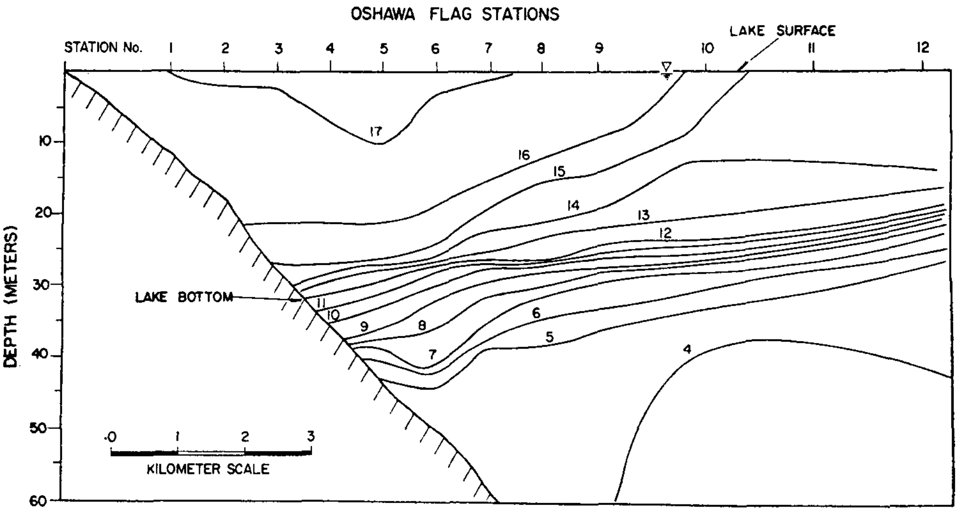

Fig. 14. Isotherms on 17 September 1970.

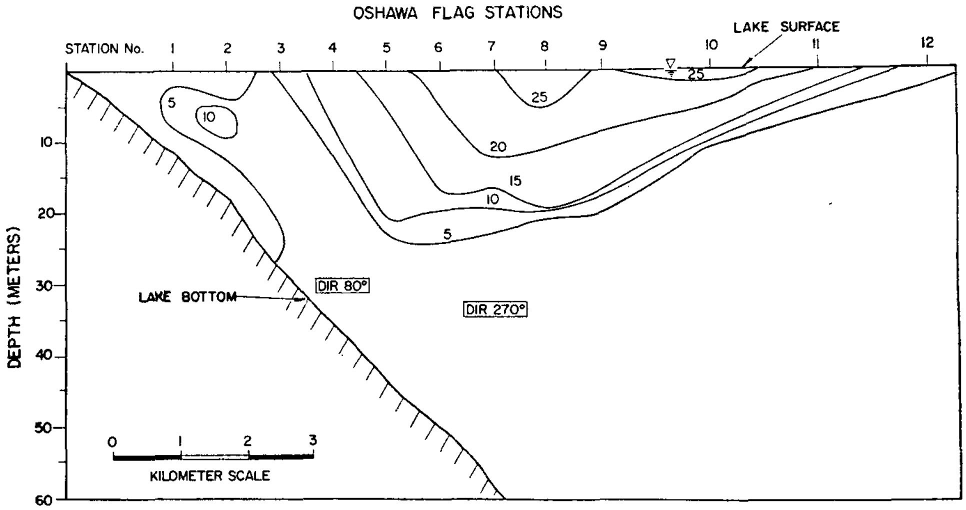

Fig. 15. Constant speed contours on 17 September 1970.

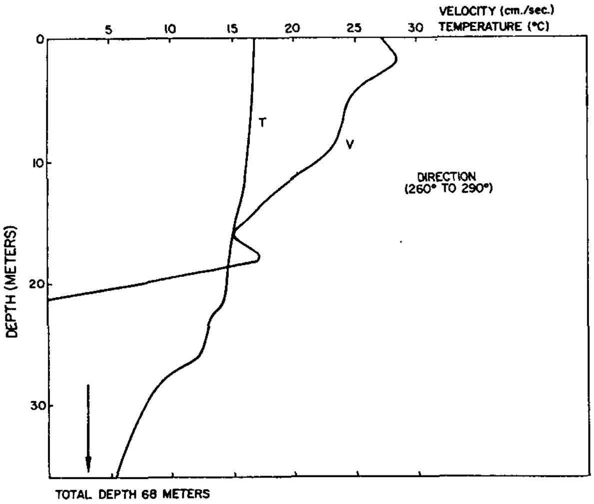

Fig. 16. Velocity profile across the jet core (Station 8) on 17 September 1970.

illustrating phenomena involved in the disappearance of an upwelling. As we have already remarked, a well-developed upwelling was present on 5 October (thermocline coming to the surface 7 km from shore), which remained unchanged on the 6th. On the 7th easterly winds began to blow and became quite strong (12m sec^{-1}) by the 9th. This drove the surface layers inshore and eventually depressed the thermocline, establishing a fairly regular, westward flowing jet by 11 October which persisted until the 14th.

On 7 and 8 October a massive westward jet was present in the cold water on the onshore side of the thermocline, confined mostly to water colder than about 8 or 9C. On the 7th the direction of flow was westerly ($\sim 270°$) but by the 8th a strong southerly component appeared in this cold-water jet. Figs. 17 and 18 show the temperature and velocity sections for 8 October. By the next day (Figs. 19 and 20) all the cold water disappeared from the shore zone, with the 8 or 9C

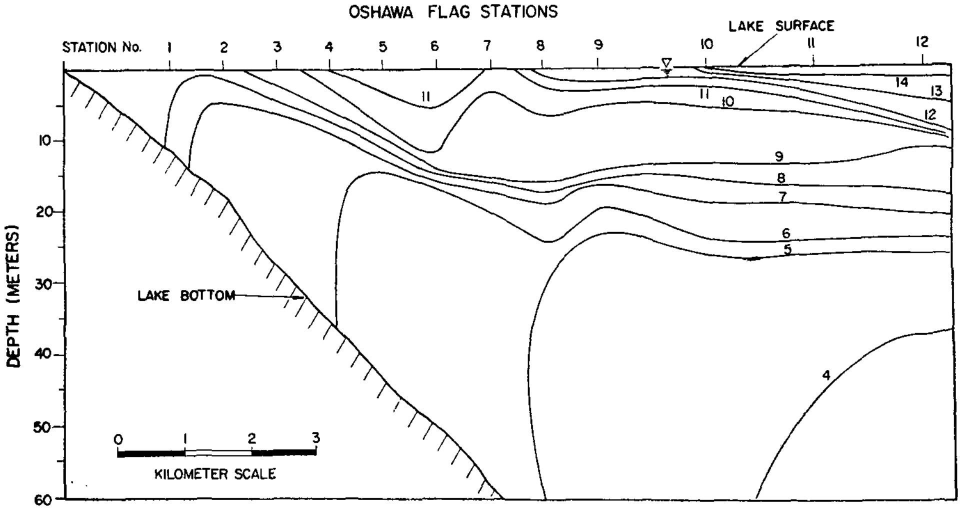

Fig. 17. Isotherms on 8 October 1970.

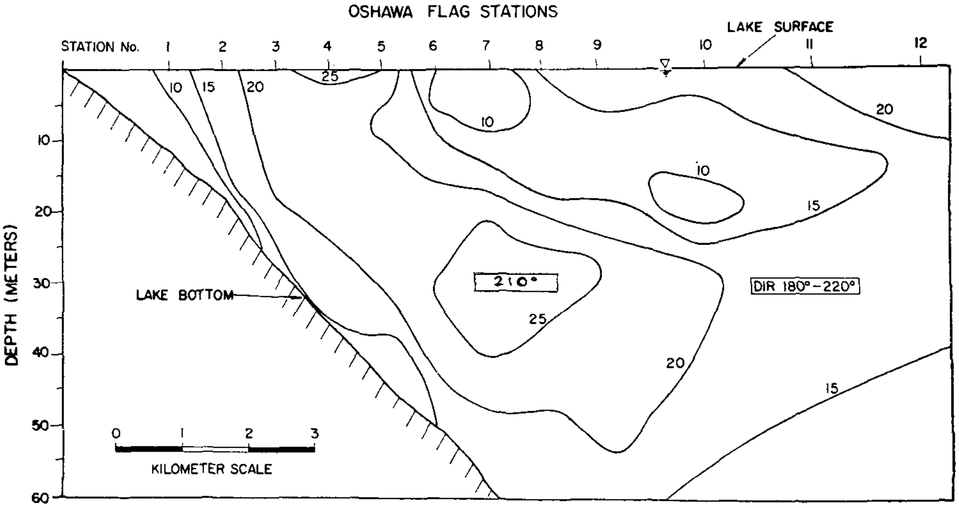

Fig. 18. Constant speed contours on 8 October 1970.

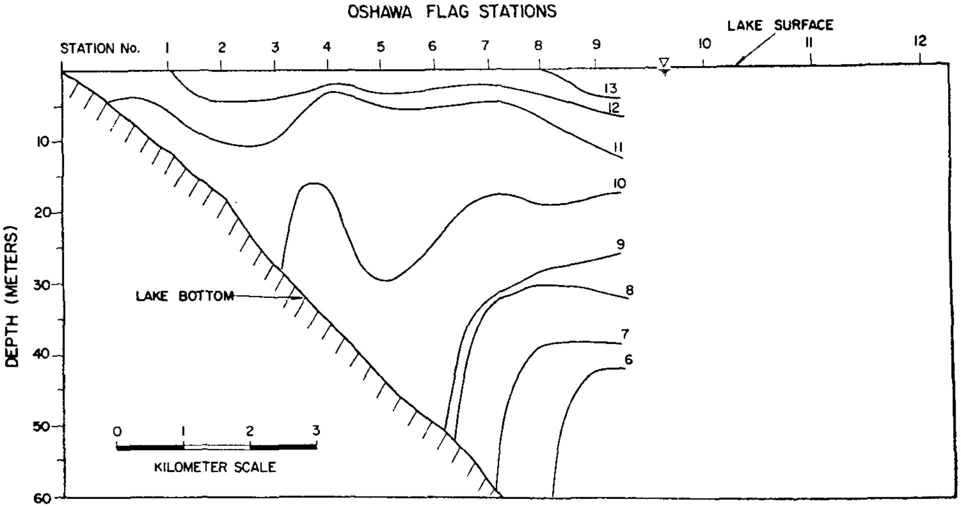

Fig. 19. Isotherms on 9 October 1970.

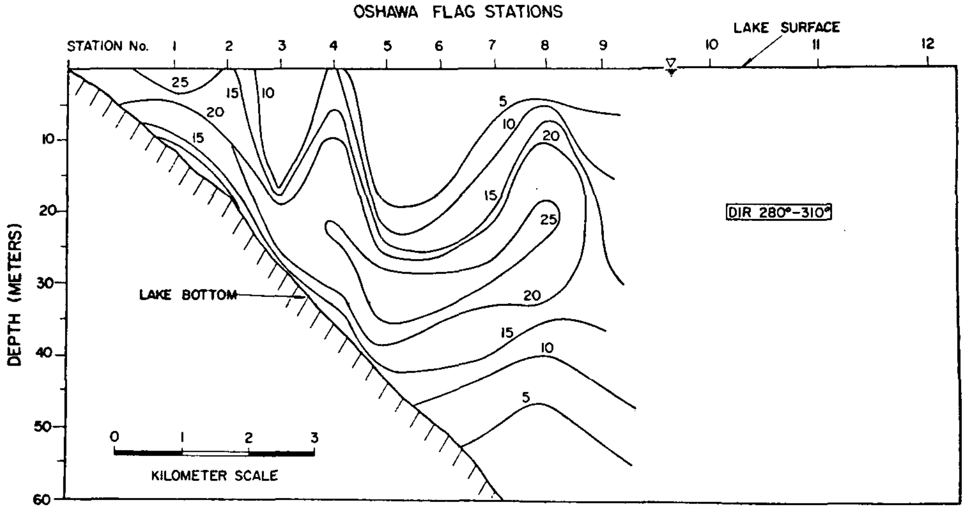

FIG. 20. Constant speed contours on 9 October 1970.

isotherm intersecting the bottom between Stations 6 and 7. The contorted shape of the constant speed contours suggests that an almost closed "eddy" formed in the shore zone as the warm water pushed in on the top. This is sketched in Fig. 21; the illustration assumes that the high momentum of some of this water may be used as a "tracer," because it presumably originated from the surface where the wind had set the water in motion. If this view is correct, it certainly further illustrates the importance of the nonlinear convective accelerations in maintaining shore currents. Following this sequence, a regular westward coastal jet eventually became established as already remarked.

3. Conclusions

From this record of complex phenomena we may distill the following general conclusions in regard to coastal currents during summer and fall:

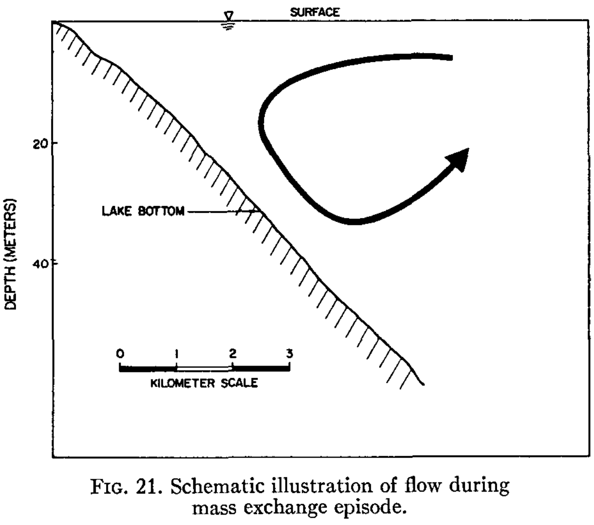

FIG. 21. Schematic illustration of flow during mass exchange episode.

1) A fairly well-defined coastal boundary layer, of some 10 km width, characterized by relatively persistent currents is in evidence.

2) Outside the coastal boundary layer currents are dominated by near-inertial oscillations.

3) Both Coriolis force and inertial accelerations play an important role in maintaining coastal currents.

4) The lakewide flow pattern is mostly determined by relatively brief periods of strong winds. Among their other consequences, such winds often lead to a fairly complete mass exchange between the coastal and outer zones.

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