The Coastal Boundary Layer in Lake Ontario.
Part I: The Spring Regime

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ABSTRACT

Originally prompted by a desire to search for theoretically predicted "coastal jets," an extensive series of observations on currents in the coastal zone near Oshawa, in Lake Ontario, were carried out during 1969 and 1970. The observation technique consisted of anchoring marker flag stations at increasing distances from the shore, forming a "coastal chain" more or less perpendicular to the shore, then collecting current and temperature observations from a small boat by hand-held instruments at a number of depths at each station. During the 1970 season a set of four fixed current meters was also used, providing a temporal history of the currents.

This paper presents the results of observations collected during the "spring" period (May to early June) which showed a current regime different in character from that observed during summer or fall. A near-shore band ($\sim$7 km wide) becomes a unique kind of boundary layer in which mid-lake motions adjust to the presence of the shores. During the spring significant motion is indeed often confined to the vicinity of the coastal boundary layer. Many complex physical factors appear to be involved in determining the current structure in this boundary layer, among them the Coriolis force, inertial accelerations, friction and stratification. The main driving force of these motions is the wind stress at the free surface. A general characteristic of the observed motions is great spatial variability.

1. Introduction

Within recent years the thermal structure of the North American Great Lakes at different times of the year has become known in some detail, as a result of comprehensive studies by Rodgers (1965), Sweers (1969) and others. The considerable seasonal variations of heat content which characterize the yearly thermal cycle of these lakes cause corresponding large changes in the density distribution within the water masses. Questions of considerable practical importance concern the current distributions which are associated with the changing thermal structures and the dynamic regime which accompanies each thermal regime. Experimental evidence on current "climatology" is relatively meager, but what there is (Verber, 1966: Malone, 1968; Birchfield and Davidson, 1967) shows that 1) there are distinct differences between at least "summer" and "winter" current regimes, and 2) at least during the summer months currents in the coastal zones differ significantly from those at mid-lake, the former being more persistent, the latter more wave-like. Similar differences are also exhibited by theoretical studies of simple lake models (Csanady, 1968, 1972).

The currents in the shore zone are especially important for such practical reasons as the dispersal of pollutants and waste heat, and the recreational uses of the lakes. Diffusion studies have revealed a tendency for the "coastal entrapment" (Csanady, 1970) of pollutants, which is presumably linked to the dynamics of coastal currents. On the other hand, the only large-scale and systematic current studies (the Federal Water Pollution Control Administration studies, on which the above quoted references of Verber, Malone and Birchfield, and Davidson were all based) were carried out on a more or less even grid pattern over the lakes with no special attention to the shore zones. Most meters deployed in this study were therefore outside what might be described as the "coastal boundary layer."

An experimental program, code-named "Coastal Jet Projet," was therefore undertaken in an attempt to obtain reasonably detailed information on the structure of near-shore currents. The present paper reports some conclusions pertaining to such currents during the "spring regime" (May to early June) which was found to differ significantly from "summer" or "fall" regimes (no observations were carried out during the winter). Further detail is contained in three reports of limited circulation (Csanady and Pade, 1968, 1969, 1970).

2. Theoretical background

That the shore zone must constitute some kind of boundary layer for currents flowing along the shore is obvious from the results of classical boundary layer theory. However, even if we confine our attention to the effects of friction (more precisely to turbulent momentum transport or Reynolds stresses), it is clear that this boundary layer differs in character from, say, the boundary layer along an aeroplane wing. An idealized shore zone is illustrated in Fig. 1; the bottom slope is typically 1 in 100 or 1000, i.e., very low. Shear stress

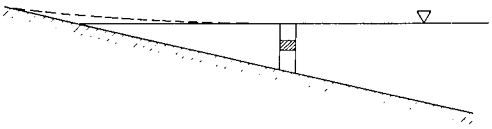

FIG. 1. Idealized shore zone, showing a possible surface elevation distribution accompanying coastal jets or edge waves.

exerted at the solid bottom is transmitted to a fluid element (cross-hatched) by *vertical* momentum transfer, while the flow is maintained against this friction, at least partly by *horizontal* transfer of momentum from the established current further out. By contrast, in the ordinary frictional boundary layer, momentum transport is all in one direction, perpendicular to the boundary.

Theoretically, an explanation for the occurrence of boundary layers of any kind lies in the fact that the highest space derivatives in the governing nondimensional differential equations are multiplied by a small factor (Carrier, 1953). In the case of frictional boundary layers the small factor is the reciprocal Reynolds number in the equations of motion. When the rotation of the earth is important, the equations of motion are best made nondimensional in such a way that the Coriolis force comes to be of order unity (see, e.g., Greenspan, 1968). The shear stress terms are then multiplied by the turbulent analogue of the Ekman number which is again small and suggests the existence of boundary layers both at the bottom and near horizontal boundaries. If we neglect these terms, the next highest space derivatives are in the nonlinear terms, which are multiplied by the Rossby number. This is again a small quantity if the length scale is chosen so as to represent lake-wide motions (Csanady, 1967). Thus, "inertial" boundary layers may be expected to occur near the shores, similar to those discussed by Charney (1955).

If we neglect both frictional and inertial terms, the equations of motion and continuity may be reduced to a linear second-order differential equation for the small displacements ζ of the free surface, (Lamb, 1932). This equation, in a nondimensional form, is

$$\frac{\partial^2\zeta}{\partial t^2}-\frac{R^2}{L^2}\nabla_1^2\zeta+\zeta=0, \qquad (1)$$

where $R=c/f$ is Rossby's "radius of deformation," with $c=(gh)^{\frac{1}{2}}$ the speed of propagation of long waves, h the water depth, L the length scale, and f the Coriolis parameter. The highest space derivatives in this equation are multiplied by the factor R^2/L^2. For barotropic motions this factor is invariably of order unity whether in oceans or in the Great Lakes and therefore the flow does not have a boundary layer character. The ratio R^2/L^2 is, however, small for baroclinic motions, in which case geostrophic adjustment to the presence of the shores occurs in a band of scale width R. This, therefore, becomes a kind of baroclinic boundary layer, in which the "coastal jets" of the theoretical models were found to occur (Csanady, 1971a).

Even for barotropic frictionless motions at low Rossby number, the peculiar geometry of the shore zone (Fig. 1) leads to a singularity at the point where the free surface intersects the sloping bottom. The highest order space derivative in Eq. (1) in this case is multiplied by a factor containing the water depth h, because $R^2/L^2=gh/(f^2L^2)$. Sufficiently close to the shore this becomes small enough to produce singular behavior, one manifestation of which is that "edge waves" may occur.

Thus, it is clear that motion in the shore zone should have a boundary layer character for several reasons. An interplay of the different physical effects referred to above is indeed likely to produce a boundary layer of unusually complex structure. We may add to this that wind stress is often exerted at the free surface. Furthermore, the seasonal changes of stratification observable in the Great Lakes require that we also consider the energy balance. During the warm-up period in the spring the shallow layers near the shores heat up first and produce a thermal boundary layer, the existence of which has some important dynamical consequences (Csanady, 1971b, Huang, 1971).

In the light of this brief survey there is every reason to expect a complex current distribution in the shore zone both along the horizontal and along the vertical. The experimental technique described in the following section was adopted to provide as much spatial resolution as possible with the means at our disposal, concentrating observations in a near-shore band of a width several times the "typical" expected baroclinic width-scale R, i.e., up to a distance of ~15 km from shore.

3. Experimental technique

The bulk of the information was collected by means of the "flag station technique." This consists of taking current and temperature depth profiles by hand-held instruments from a small boat at a number of predetermined locations, where an anchored flag is placed prior to the experimental period. The boat is tied to the flag's anchor and allowed to come to rest before current measurements are taken. Current speed, direction and temperature readings were taken at every meter from the surface down to a depth of 10 m, every 2 m to 30 m, and every 5 m to 60 m (where the water was that deep), in the 1969 and 1970 summer seasons. The observations at a given flag station took typically 10–15 min.

A chain of 12–14 flag stations was laid out early in the season, more or less perpendicular to the shore. The location chosen for the work was just east of Oshawa, Ontario, on the north shore of Lake Ontario, situated along a long and relatively straight shore of the lake, far from the ends, where one would intuitively

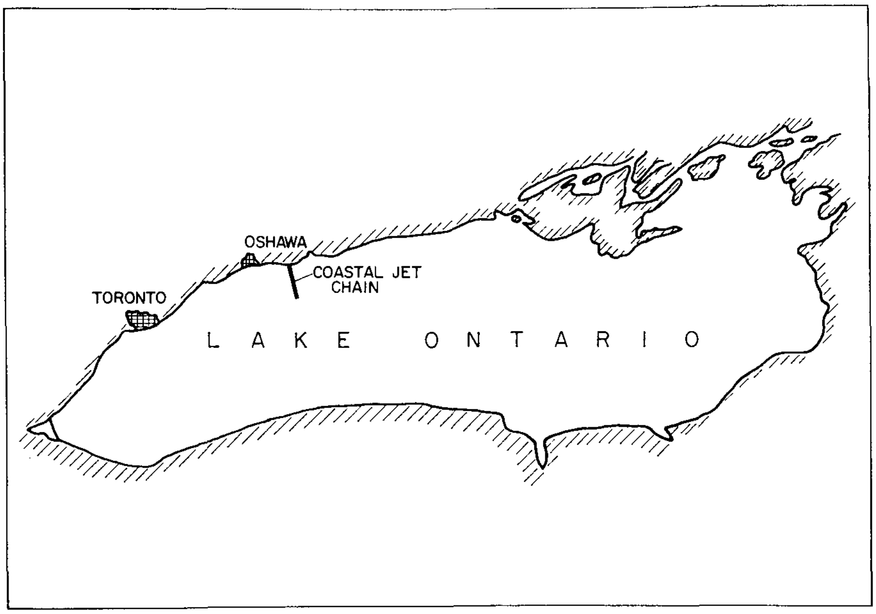

FIG. 2. Lake Ontario, showing location of field study.

expect to find relatively regular coastal currents (Fig. 2). The choice of Lake Ontario was suggested by the coming International Field Year on the Great Lakes (IFYGL, proposed now for 1972), during which it is planned to carry out similar coastal chain studies in Lake Ontario. The 1969 and 1970 observations off Oshawa were intended to play the role of a feasibility study using trial runs, but the results turned out to be sufficiently informative in their own right.

A more detailed plan of the flag station locations (1969 and 1970) is shown in Fig. 3, while Fig. 4 gives a depth profile along the line of the 1969 flag chain. Two boats were used for most observations (when everything was working), one crew collecting data at the inner half of the stations, the other crew at the outer half, in order to obtain simultaneous measurements as nearly as possible. Under ideal conditions an entire survey could be completed within 1 hr, but when only one boat (or one set of instruments) was operational, this could become as long as 4 hr. The "typical" duration of a full survey was perhaps 2 hr, during which the typical change of current direction at the outer stations (when long internal waves dominated the flow regime there) was 45°. Partly for this reason current direction distributions were somewhat less regular than distributions of speed (velocity magnitude) and temperature. As will be seen later, some of the most informative diagrams are those showing observed isotherms and constant speed contours in a cross section along the flag-station chain.

Small boats were used in the experimental work, the more useful one being a pontoon boat. This provided a stable platform, almost devoid of up and down movements at the point where the current and temperature sensors were lowered. On tying up to an anchored flag station, the boat also came relatively quickly to rest in an equilibrium position. No significant influence on the measured data may be attributed to boat motions, because the data were smooth and accurately repeatable.

We have made special efforts to ensure the accuracy of the current meter readings. The instruments were calibrated in the laboratory both before and after field use. The speed was accurate to within 5%, and the direction to the accuracy of reading a compass (±5° or so). There was negligible change over the field observation period.

Previous experience has shown that the change of current speed and direction with depth in the Great Lakes can be quite rapid (Csanady *et al.*, 1964). Consequently, it is essential for accurate fixed-level measurements to use sensors whose vertical dimensions are as small as possible; the conventional Savonius rotor arrangement, suitable for work in the deep ocean, in which the speed and direction sensors are vertically separated by half a meter or more is certainly unsatisfactory. An additional problem is that surface wave orbital motions are often superimposed on current velocities, so that a strictly linear sensor is required with some time-averaging arrangement to provide a current speed reading of acceptable accuracy. The "Q-15" current meter (hand-held, deck-readout model) recently developed by Marine Advisors Co. appears to satisfy these basic needs of current measurements in the Great Lakes and has therefore been used in the Coastal Jet Project. The speed sensor is a ducted vanewheel, 9.5 cm in diameter, with flat vanes, the response of which is quite accurately linear down to a speed of 2–3 cm $\sec^{-1}$. At such low velocities, however, no current

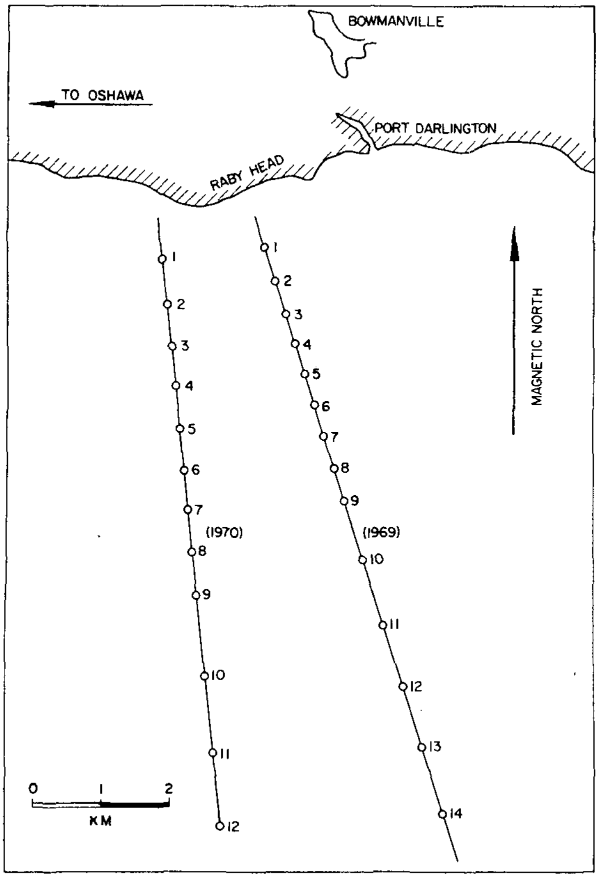

FIG. 3. Location of flag stations, 1969 and 1970.

meter so far available is even remotely reliable, and no particular significance may be attached to observed velocities <5 cm sec⁻¹. The deck readout unit incorporates an appropriate electrical averaging device. The directional vane is mounted level with the speed sensor. After the initial "teething troubles" with this new instrument had been overcome, it performed quite well under field conditions, although it required fairly frequent maintenance. The most practical schedule appears to be to carry out "alert periods" of observations some 4–6 weeks long, after which the meters may be overhauled. This schedule was successfully adopted in the 1970 season (and is proposed for IFYGL) in which three such series of observations were conducted, one in May–June, one in July, and one in September–October. The 1969 observations extended from May to July. In the following only the spring period data are presented and discussed.

During the 1970 season some fixed current meters were also anchored at stations 5 and 12 of the coastal chain, one above and one below the average summer thermocline. This provided a useful complement to the flag-station technique, which yielded data in much greater spatial detail, but at the relatively long intervals of 1 day or occasionally (when repeat runs could be carried out) some 4 hr. These meters also provided a check on the accuracy of the flag-station readings, with satisfactory results. During the spring period, the only significant records were obtained from the current meters anchored at station 5, at a depth of 9.1 m.

The temperature data were obtained with a standard bathythermograph. Meteorological information was available from an anemometer installation in Oshawa harbor, and those at the Oshawa and Malton (Toronto) airports.

4. General description of the spring regime

The *thermal* structure of Lake Ontario in the period May to early June is mainly characterized by an inclined thermocline surface separating somewhat warmer water (8–10C) in a near-shore band from the cold main mass of the lake ($\leqslant 4$C). In a cross section perpendicular to shore the shape of the thermocline surface (which may be taken to coincide with the 7 or 8C isotherm) is either of the "wedge" or of the "lens" type; Figs. 5 and 6 show clear-cut examples of these two possibilities. As the season progresses, the volume of warm water increases along with a rise of the maximum temperature. Thus, the thermocline becomes sharper and moves

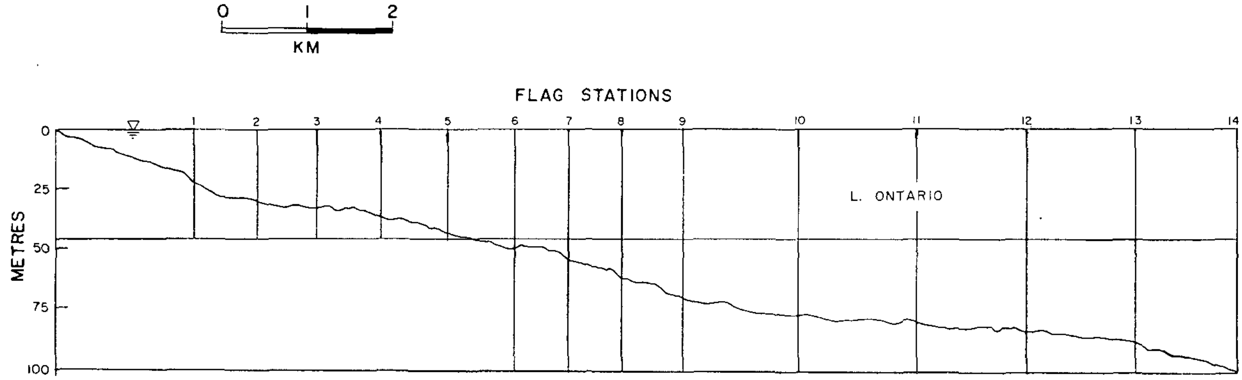

FIG. 4. Depth profile along 1969 flag station chain.

further out from shore. Eventually a "summer" thermocline is established, continuous across the lake.

The *dynamic* regime in the spring is mainly notable for generally low velocities. On several days during the 1969 season the maximum velocity observed anywhere along the chain (i.e., at some 200 different points where current readings were taken) was 5 cm sec^{-1} or less. In 1970, on similar generally stagnant days, occasional velocity peaks of up to 9 cm sec^{-1} have been observed. To appreciate the degree of stagnation involved, Table 1 shows all speed and direction readings obtained on 14 May 1969. By contrast, Table 2 shows the record of 17 May 1970, which was one of the rare days in spring with motion involving most of the coastal water mass. The most common situation is somewhere in between these extremes, but closer to total stagnation such that most of the water mass was stagnant, with only a few bands having more or less well marked currents. In the majority of cases, significant motion is confined to the warmer layers above the thermocline; at least the velocity of these layers is considerably higher than that of any current-bands in the cold water.

a. Coastal jets

Some of the observed current bands resembled the baroclinic "coastal jets" of the theoretical models in that they were narrow, shore-bound, and confined to the warmer layers. Although the correspondence between a simple theoretical model and complex observed phenomenon is marginal, we shall retain the term "coastal jet" for convenience to describe relatively persistent, shorebound bands of current. Some good

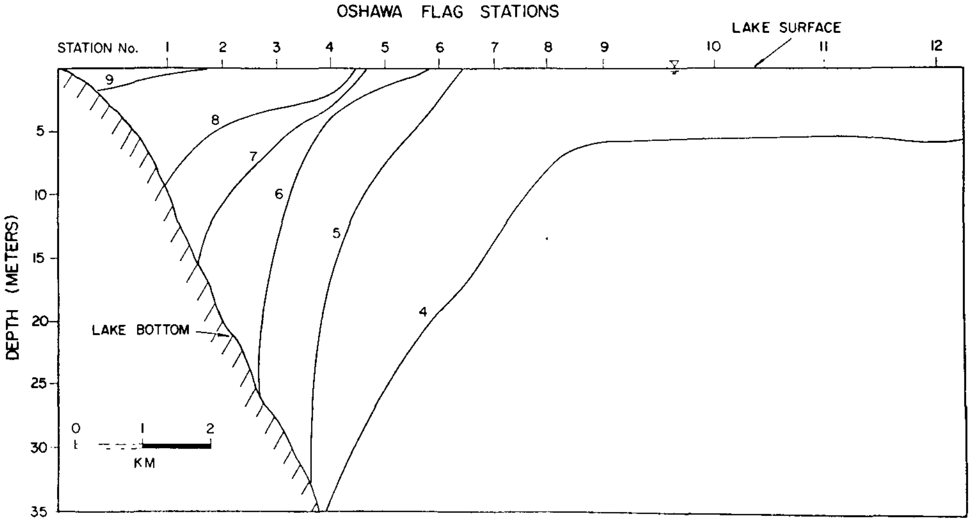

FIG. 5. Isotherm contours (°C) for 26 May 1970, showing wedge-shaped thermocline.

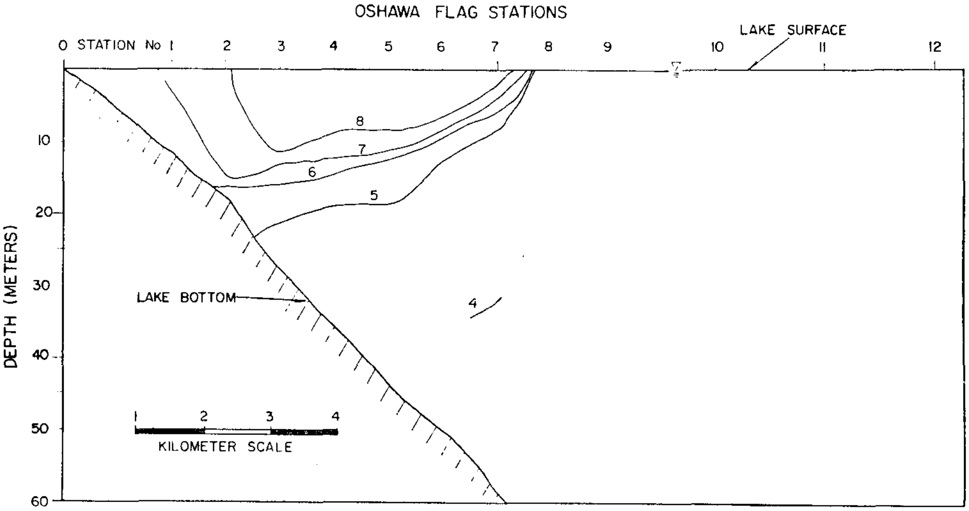

FIG. 6. Isotherm contours (°C) for 27 May 1970, showing lens-shaped thermocline.

TABLE 1. Current data obtained on 14 May 1969 using a chain of 14 stations. (Speeds are in centimeters per second, directions in degrees and depths in meters.)

	Station 1 (1745)		Station 2 (1720)		Station 3 (1643)		Station 4 (1625)		Station 5 (1538)		Station 6 (1442)		Station 7 (1325)		Station 8 (1334)		Station 9 (1442)		Station 10 (1538)		Station 11 (1620)		Station 12 (1715)		Station 13 (1750)		Station 14 (1833)	
Dph	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir	Spd	Dir
1	0	170	0	120	1	160	0	100	4	100	0	90	0	40	0	55	3	62	0	38	0	75	0	78	1	112	0	105
2	2	160	0	108	0	150	2	95	0	95	0	95	1	25	2	55	2	68	1	48	0	68	0	80	0	62	1	103
3	0	160	0	90	0	140	2	95	4	85	0	85	0	15	0	55	3	80	0	75	0	70	0	92	0	69	0	94
4	0	160	0	72	0	138	1	95	2	75	0	80	0	10	0	35	1	95	0	82	0	72	0	98	0	80	0	83
5	0	160	0	80	0	130	0	95	1	75	0	88	0	20	0	40	0	72	0	82	0	72	0	100	0	100	0	68
6	0	155	0	100	0	130	0	95	0	78	0	75	0	40	0	38	0	70	0	78	0	74	0	100	0	100	0	52
7	0	155	0	110	0	130	0	95	0	80	0	82	0	41	0	25	0	60	1	68	0	81	0	102	0	102	0	55
8	0	130	0	112	0	130	0	95	0	75	0	84	0	41	0	28	0	55	0	60	0	80	0	104	0	105	0	58
9	0	130	0	120	0	140	0	90	0	68	0	90	0	45	0	40	0	60	0	65	0	81	0	108	0	108	0	59
10	0	130	0	130	0	140	0	90	0	75	0	70	0	48	0	50	0	28	0	65	0	84	0	82	0	87	0	40
12	0	132	0	130	0	130	0	90	0	80	0	60	0	45	0	78	0	58	0	80	0	81	0	82	0	62	0	26
14	0	140	0	132	0	130	0	90	0	80	0	62	0	40	0	82	0	55	0	78	0	80	0	85	0	64	0	20
16	0	142	0	132	0	125	0	50	0	80	0	69	0	00	0	88	0	55	0	66	0	85	0	89	0	64	0	28
18	0	160	0	132	0	120	0	75	0	70	0	78	0	320	0	86	0	58	0	50	0	82	0	85	0	65	0	34
20	0	180	0	132	0	95	0	75	0	55	0	75	0	300	0	80	0	65	0	38	0	85	0	81	0	42	0	45
22	0	190	0	130	0	85	0	60	0	42	0	60	0	290	0	82	0	85	0	55	0	83	0	80	0	33	0	56
24	0	205	0	120	0	80	0	40	0	35	0	320	0	290	0	88	0	92	0	64	0	83	0	74	0	32	0	52
26			0	100	0	70	0	20	0	15	0	280	0	270	0	80	0	88	0	62	0	75	0	75	0	33	0	42
28			0	62	0	20	0	10	0	340	0	250	0	270	0	30	0	87	0	58	0	80	0	78	0	48	0	12
30			0	22	0	5	0	5	0	310	0	230	0	200	0	338	0	88	0	50	0	85	0	78	0	50	0	350
35					0	5	0	310	0	270	0	200	0	125	0	335	0	90	0	60	0	90	0	82	0	28	0	356
40									0	130	0	100	0	12	0	332	0	100	0	68	0	90	3	78	0	28	0	5
45									0	75	0	330	0	335	0	335	0	30	0	60	0	92	2	75	0	30	0	18
50											0	230	0	320	0	348	0	60	0	52	0	102	0	48	0	25	0	18
55															0	352	0	82	0	54	0	102	0	15	0	28	0	20
60															0	32	0	97	0	40	0	101	2	12	0	38	0	22

examples of such coastal jets were found during the spring period of the 1970 season and are described below.

1) Case I

A jet associated with a wedge-shaped thermocline was found on 17 May 1970. In Table 2 we have already seen that on this day movement extended to quite deep layers and involved all of the surveyed water mass. The isotherm contours are shown in Fig. 7, while Fig. 8 contains contours of constant speed, the direction of the flow being indicated, in this and similar graphs later, only at centers of high-speed regions. Actual compass direction readings are listed in Table 2. Point-to-point variations of these would be difficult to indicate in Fig. 8 and do not appear to be of much significance. We note a velocity maximum of over 20 cm sec^{-1} in the warm layer approximately 4 km from shore. By good fortune, this jet extended to the current meter moored at 9.1 m at station 5 from which we have speed, direction and temperature for the period immediately following the coastal chain survey, shown here in Fig. 9. The temperature trace exhibits slow in and out movements of the warm layer, the direction trace shows the persistence of the flow, while the speed trace demonstrates the jet's decay with a half-time of the order of 20 hr. Particularly in view of the relative permanence of this flow structure, the designation "coastal jet" seems appropriate.

Fig. 8 also shows a second well-marked velocity maximum about 10 km from shore, somewhat below the surface. Furthermore, relatively high velocities (>10 cm sec^{-1}) extend here to a much greater depth

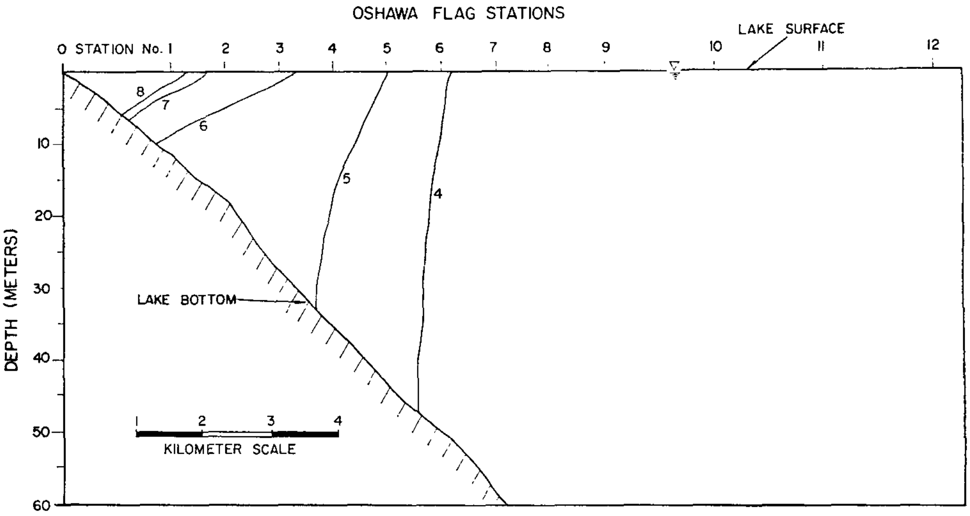

Fig. 7. Isotherm contours (°C) for 17 May 1970.

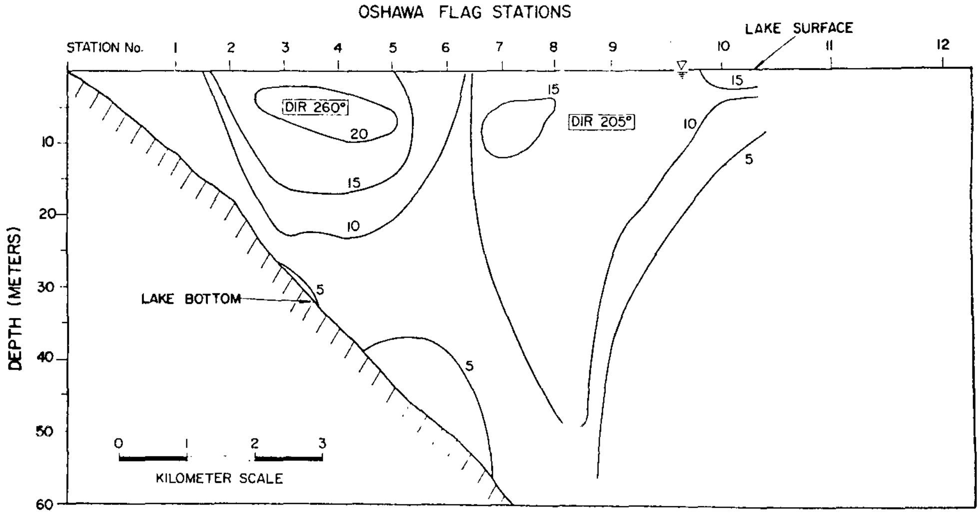

Fig. 8. Constant speed contours (cm sec^{-1}) for 17 May 1970.

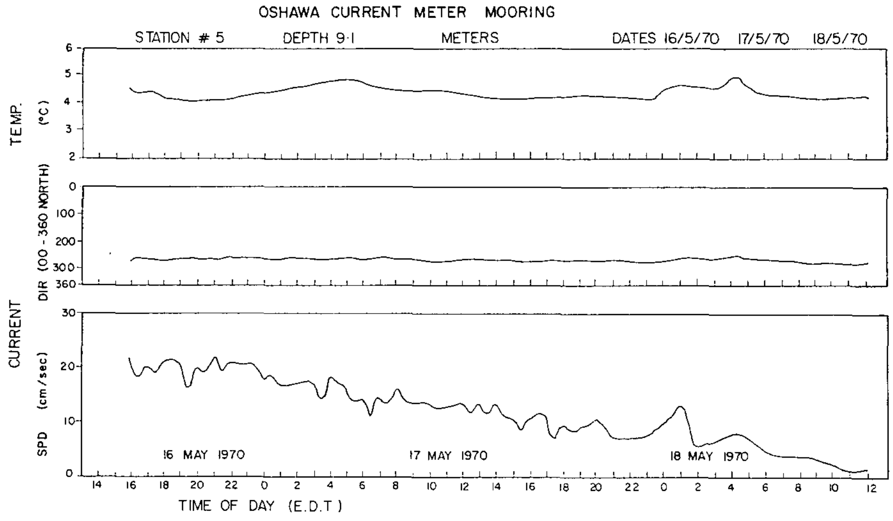

FIG. 9. Record of temperature and current from a fixed meter at Stations 5, 9.1 m depth, 17 May 1970.

than elsewhere. An examination of the isotherm contours in Fig. 7 reveals that this large vertical penetration of momentum occurs close to and on the offshore side of the 4C isotherm. The flow pattern suggests either particularly efficient vertical mixing or sinking motions around stations 7–9. Measured temperatures (Table 2) are, however, not accurately uniform and indicate bodily sinking motions in this region, rather than particularly good mixing (the somewhat irregular minor speed variations listed in the table also point toward the same conclusion).

2) CASE II

Generally similar phenomena were observed on 26 May 1970, the isotherm contours having already been shown in Fig. 5 as an example of a "wedge-shaped" thermocline. The constant speed contours for this day are shown in Fig. 10. The structure of the shore-bound jet is similar to the one previously described, except that it is more complicated at the outer edge. On the offshore side of the thermocline the surface layers are somewhat warmer than 4C (up to 4.5C) and they all move rather faster than the layers below, suggesting little vertical mixing. A tongue of high velocity again extends to greater depths at around station 8, presumably caused by sinking motions.

Particularly illuminating is the record of the 9.1 m moored current meter at station 5 (Fig. 11). As may be seen in Fig. 10, this location was on the edge of the jet. The temperature trace for the period preceeding the flag-chain survey shows inertial oscillations of the isotherm surfaces. Coincident with these oscillations we find velocity fluctuations between a minimum of 5 cm sec^{-1} outside the jet, and a maximum of some

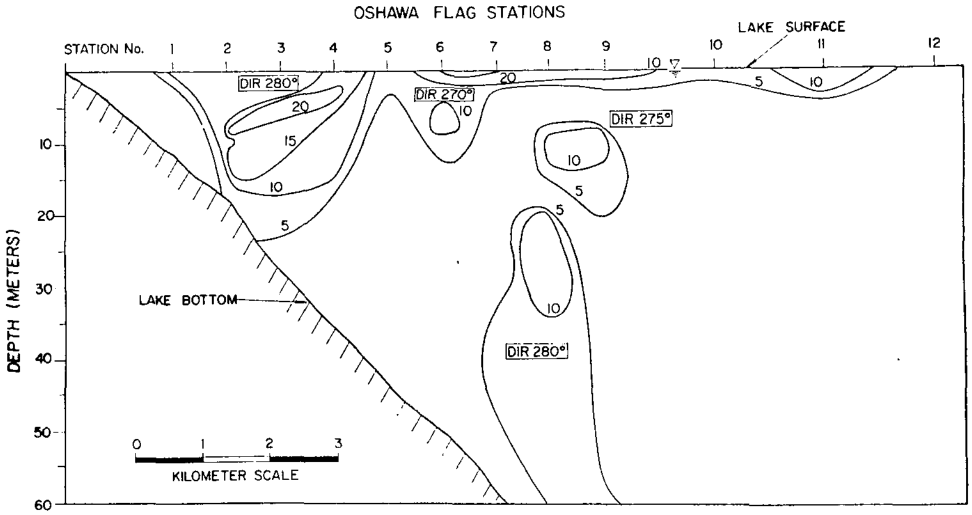

FIG. 10. Constant speed contours (cm sec^{-1}) for 26 May 1970.

TABLE 2. Current and temperature data obtained on 17 May 1970 using a chain of 8 stations. (Speeds are in centimeters per second, direction in degrees, temperatures in degrees Celsius and depths in meters.)*

	Station 1 (1125)			Station 3 (1145)			Station 4 (1210)			Station 6 (1255)			Station 7 (1345)			Station 8 (1430)			Station 9 (1515)			Station 10 (1600)		
Dph	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp	Spd	Dir	Temp
1	1	125	8.1	17	245	6.1	17	260	5.8	3	265	4.1	14	205	3.8	13	250	3.6	11	255	3.6	19	215	3.8
2	2	125	7.7	20	250	6.0	18	260	5.7	6	260	4.1	14	205	3.8	12	250	3.6	10	260	3.6	20	215	3.8
3	1	135	7.1	20	250	5.9	20	270	5.7	7	270	4.1	11	210	3.8	13	245	3.6	12	260	3.6	15	210	3.8
4	0	135	7.0	20	250	5.9	20	270	5.7	8	275	4.1	13	205	3.8	15	250	3.6	12	260	3.6	12	255	3.8
5	0	135	6.7	20	250	5.8	22	270	5.7	7	275	4.0	15	205	3.8	14	250	3.5	12	260	3.6	13	255	3.8
6	0	130	6.3	20	250	5.8	22	270	5.6	9	280	4.0	15	205	3.8	12	250	3.5	11	270	3.6	8	255	3.8
7	0	120	6.1	20	250	5.8	21	270	5.6	9	275	4.0	15	210	3.8	11	250	3.5	12	265	3.6	6	250	3.7
8	0	100	6.1	20	250	5.7	22	275	5.6	10	275	4.0	15	205	3.8	11	250	3.5	12	270	3.6	4	250	3.7
9	0	090	6.0	19	255	5.7	21	280	5.5	10	275	4.0	15	205	3.8	11	255	3.5	12	270	3.6	5	255	3.7
10	0	085	6.0	18	265	5.7	20	280	5.4	10	280	4.0	15	205	3.8	10	255	3.5	12	275	3.6	4	250	3.7
12	0	070	6.0	18	270	5.7	19	280	5.3	8	265	4.0	15	205	3.7	10	255	3.5	12	275	3.6	6	255	3.7
14				17	275	5.7	16	280	5.1	8	255	4.0	14	210	3.7	10	255	3.5	11	270	3.6	5	260	3.7
16				15	285	5.6	15	285	5.1	7	255	4.0	13	210	3.7	10	255	3.5	11	275	3.6	5	260	3.6
18				14	290	5.6	13	280	5.0	8	265	4.0	12	205	3.7	10	255	3.5	11	275	3.6	6	270	3.6
20				13	295	5.6	13	295	5.0	10	275	4.0	12	210	3.7	10	255	3.5	10	280	3.6	4	270	3.6
22				11	295	5.6	11	290	5.0	10	295	4.0	11	210	3.7	10	260	3.5	10	280	3.6	4	280	3.6
24				9	290	5.6	10	285	5.0	8	270	4.0	11	210	3.7	10	260	3.5	10	285	3.6	3	285	3.6
26				7	280	5.6	9	280	5.0	8	260	4.0	10	205	3.7	10	260	3.5	10	285	3.6	3	295	3.6
28				5	270	5.6	9	270	5.0	8	235	4.0	10	210	3.7	10	260	3.5	9	285	3.6	2	300	3.6
30				2	260	5.6	7	265	5.0	7	230	4.0	10	205	3.7	11	260	3.5	8	290	3.6	1	310	3.6
35							7	255	5.0	6	235	4.0	13	205	3.7	11	260	3.5	5	295	3.6	2	290	3.6
40										5	230	4.0	12	205	3.7	12	260	3.5	2	290	3.6	4	285	3.6
45										5	235	4.0	4	210	3.7	11	260	3.5	1	260	3.6	6	295	3.6
50										0	210	4.0	6	210	3.7	9	260	3.5	1	270	3.6	7	295	3.6
55													6	210	3.7	9	260	3.5	0	265	3.6	7	295	3.6
60																								

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* No observations were made at Stations 2, 5, 11, 12, 13, 14.

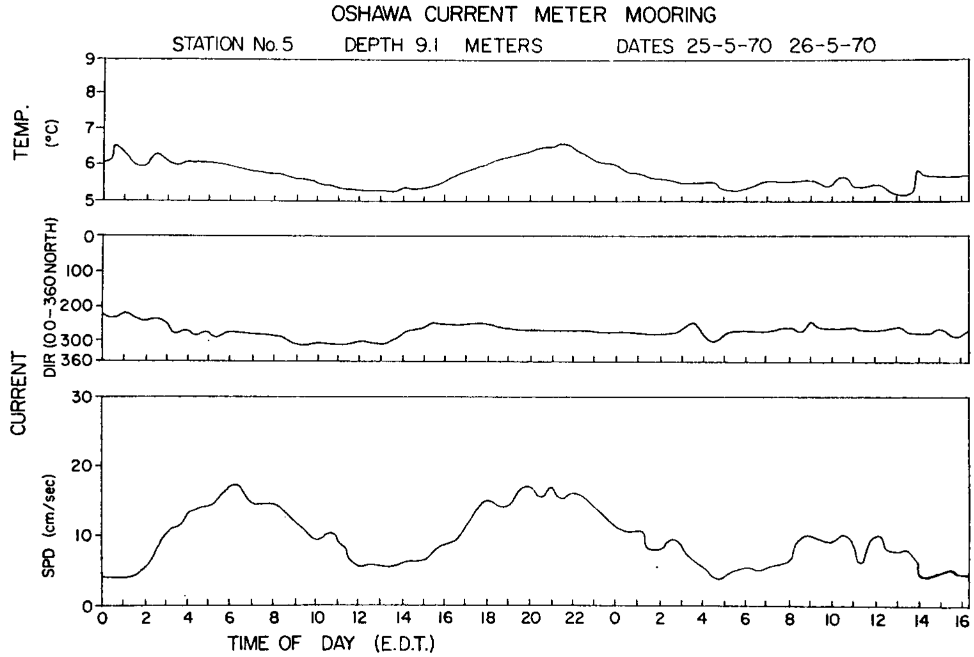

FIG. 11. Record of temperature and current from a fixed meter at Station 5, 9.1 m depth, 25–26 May 1970.

17 cm sec^{-1}, close to the peak velocity of the jet. Clearly, we have here inertial oscillations on the wedge-shaped thermocline moving the jet boundary past the fixed-point instrument.

3) CASE III

The above two coastal jets were directed east to west and the thermocline shape was of the wedge type. A jet in the opposite direction (west to east) was observed on 28 May 1970, associated with a lens-shaped thermocline. The association of lens shape and easterly current, wedge shape and westerly current, held also on all other observed occasions. Isotherms and constant speed contours are shown, respectively, in Figs. 12 and 13. The fixed-point current meter was in a low-speed region and its record is not very informative.

This easterly coastal jet shows some peculiar features in comparison with the two previously described ones. It is rather shallower than the others, although still more or less coincident with the warm band of

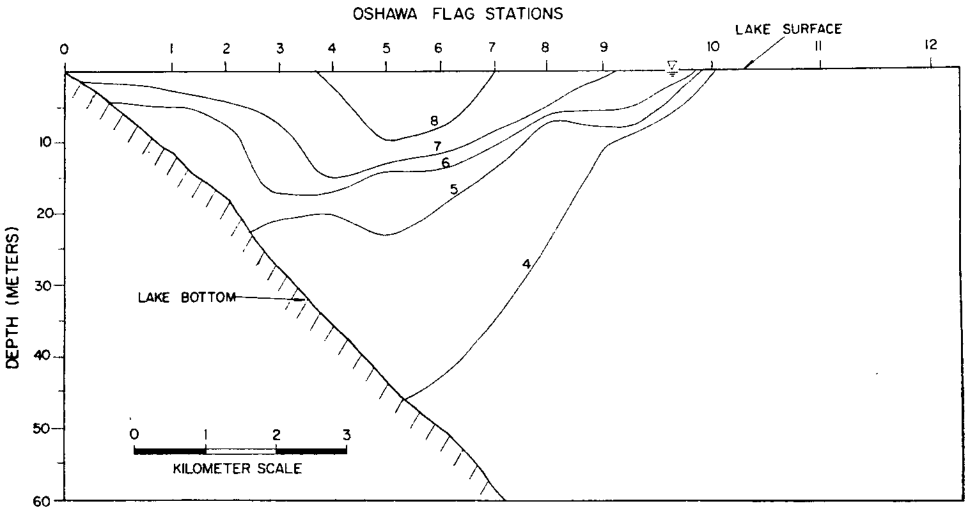

FIG. 12. Isotherm contours (°C) for 28 May 1970, morning (0955–1210 EDT).

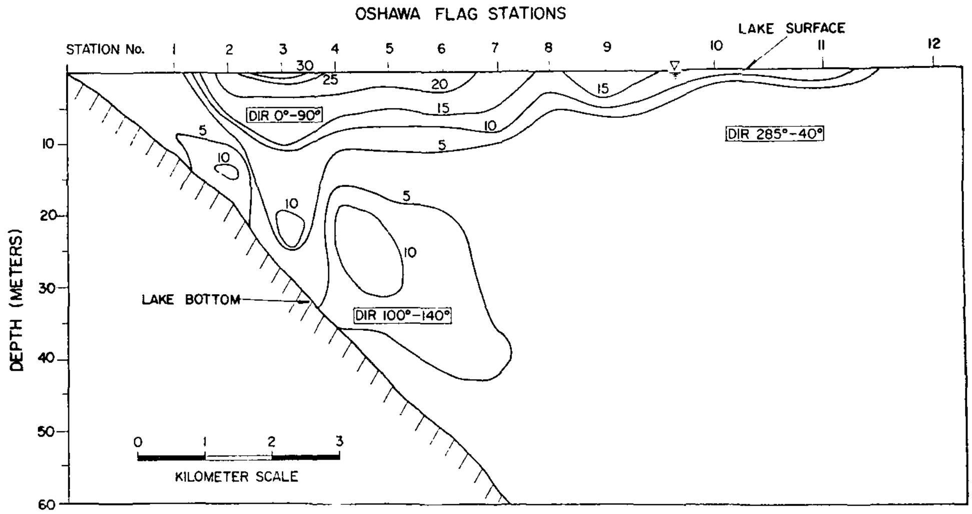

Fig. 13. Constant speed contours (cm sec^{-1}) for 28 May 1970, morning (0955–1210 EDT).

water. On the near-shore side, however, it exhibits a unique velocity peak, with fairly high velocities below, indicating sinking motions in this region. A subsequent survey a few hours later (Fig. 14) showed fairly definite inward movement of the isotherms, which may explain the particular pattern of constant speed contours.

Other fairly well marked coastal jets were observed on 14 and 30 May and 3 June, all of them directed east to west, and accompanied by a wedge-shaped thermocline surface.

b. Physical factors involved

The first question of interest is to what degree the observed velocities can be accounted for as geostrophic motions due to the observed density distributions. In general, velocities calculated from the density distribution (by the "dynamic height" method, i.e., from the "thermal wind" equation) were much lower than those observed: typical calculated velocities were 5 cm sec^{-1} as compared to observed values of 20 cm sec^{-1}. Moreover, although the *direction* of the geostrophic velocity required by the density distribution generally coincided with the observed direction, this was not the case on the offshore side of the lens-shaped thermocline surface, where the baroclinic velocity component was directed to the west. Therefore, one may tentatively ascribe the pronounced difference in velocity magnitude between the inshore and offshore edges of the easterly jet at least partly to the density field. The main component of the current was, however, clearly not an equilibrium current caused by the density field.

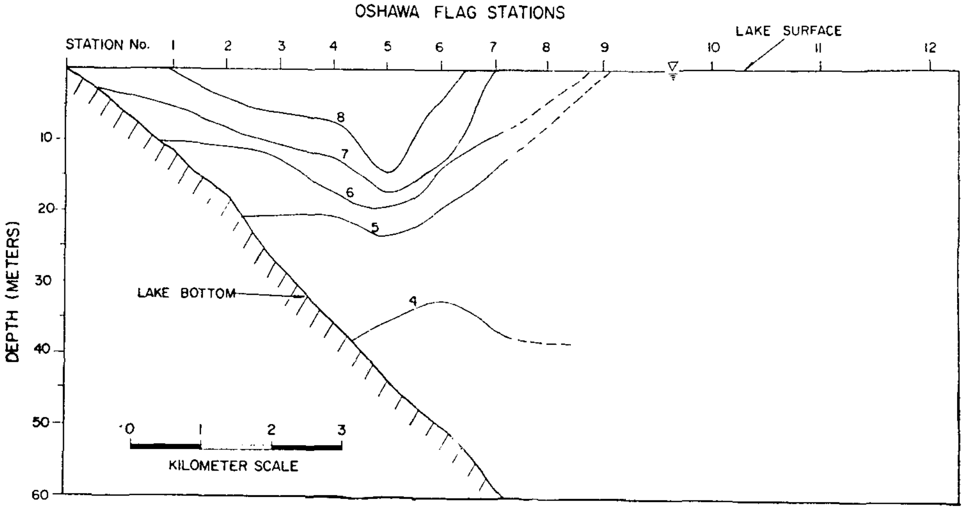

Fig. 14. Isotherm contours (°C) for 28 May 1970, afternoon (1305–1555 EDT).

The lack of correspondence between observed velocities and those calculated from the density field agrees with the conclusions of Scott and Landsberg (1969) in Southern Lake Ontario, and those of Smith and Ragotzkie (1970) in Lake Superior. Nor is this lack of correspondence surprising in light of the observed temporal variability; local current accelerations, $\partial u/\partial t$, were in all observed cases comparable to the Coriolis force per unit mass. Furthermore, the deeper currents near the 4C isotherm (if they were indeed produced by sinking of water which had been set into motion by wind stress at the surface) suggest that convective accelerations were important in their formation. This is not to say, however, that the Coriolis force was in any sense unimportant. We have already seen that the edge of the jet (at the wedge-shaped thermocline surface) oscillated with the inertial frequency, an obvious effect of rotation. Another clear-cut demonstration of the same effect is the association of current direction and thermocline shape: currents flowing east tend to drift in a southerly (offshore) direction, which presumably separates warm water from the shore and produces the "lens-shaped" thermocline. Westerly flow, on the other hand, apparently stabilizes the current at the shore, wedging the warm water in. The lens-shaped thermocline need not continue moving away from shore, because geostrophic equilibrium may be established after an initial displacement following strong winds (Csanady, 1971b). However, it should not come as a surprise that such easterly jets are somewhat less stable flow structures.

So far we have not discussed the influence of the winds on the currents, although a close association is known to prevail in the Great Lakes. This is also easily demonstrated for the period in question. Specifically, the three well-marked jets we described above were apparently set up by three equally well-marked periods of strong winds as follows:

On 17 May the current observations were carried out approximately at midday. From 0200 on the 15th to 1100 on the 16th there were strong east winds (>10 mph, maximum hourly wind 32 mph), followed by a period of light variable winds.

The jet on 26 May was apparently set up by a NE to SE wind (>10 mph, maximum hourly speed 25 mph), lasting from 0600 on the 24th to 0700 on the 25th, picking up again from 1300–1800 on the 25th. This was followed by SW winds up to 14 mph in the early morning hours, which apparently did not yet stop the current flow to the west. SW to NW winds continued, however, later on the 26th (maximum 22 mph) and on the 27th (maximum 14 mph) and finally set up the eastward flowing jet on the 28th. The air temperature was in the neighborhood of 10C on 15 May, 12C on 24 May and again 10C on 27 May, so that the stabilizing air-water temperature difference was only moderate on these occasions.

To summarize, it seems that the coastal current regime in the spring depends in an important way on all three of the physical factors also involved in the dynamics of the planetary boundary layer; namely, Coriolis force, horizontal pressure gradient and friction (the importance of the latter is demonstrated, for example, by the fact that velocities very near the shore tended to be quite low). In the case of the "coastal boundary layer," additional complicating factors are the wind stress at the surface and inertial (convective) accelerations. During the spring period, when the shore zone is warmer than the remainder of the lake, the wind stress is also appreciably higher there on account of reduced atmospheric stability just above the water surface. This may be deduced from the well-known effects of the air-water temperature difference on wind stress (Roll, 1965), and is no doubt partly responsible for the observed fact that motion during the spring is mostly confirmed to the shore-zone warm band.

The evidence of sinking motions on the offshore side of the 4C isotherm supports the notion of a thermally induced circulation in the center part of the lake during spring (by mixing of water masses close to 4C, which become heavier on mixing) as advanced by Rodgers (1965) and others.

5. Conclusions

The above-described observations show that, during spring, the shore zone of a large lake behaves as a rather peculiar kind of boundary layer, whose water movement characteristics differ markedly from those in the "outer zone." The main distinctive characteristic of the shore zone is the dominance of relatively persistent bands of currents, which have been called "coastal jets." The outer zone is nearly stagnant during the spring (more precisely, motions within it are slow compared to those in the shore zone, say 5 cm sec^{-1} and less as against typical velocities of order 20 cm sec^{-1} in the shore zone). The "boundary layer" character of the flow in the shore zone is enhanced during the spring by a surface temperature contrast which (among other effects) increases the intensity of wind stress acting in the shore zone.

A practical point follows from the observed complexity of coastal currents. Clearly, the cost of obtaining temperature and velocity cross sections comparable to those shown here by means of an array of fixed (moored) current meters of conventional design would be entirely prohibitive. On the other hand, setting out a few moored current meters will only yield very incomplete information on current structure. For example, to base estimates regarding the dispersal capacity of a lake (for waste heat or waste materials) on the records of a single or a few fixed current meters may be quite misleading.

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