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DROGUE MEASUREMENTS OF THE UPPER LAYER CIRCULATION IN THERMAIKOS GULF, N.W. AEGEAN SEA (GREECE).

By

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ABSTRACT

Cruciform drogues were used to study the spatial and temporal variability of the upper layer currents in Thermaikos Gulf (N.W. Aegean Sea, Greece). Results from thirty-nine different drogue experiments carried out during the period 1975-1977 indicate that the upper layer water transport is dependent upon the variable discharge of large rivers discharging into the area and the prevailing northerly component winds. In areas of the Gulf away from the rivers, the wind stress and the configuration of the coastline are the most important factors controlling the upper layer currents. Nearshore flow is quasi-parallel to the coasts. The prevailing zonal and meridional water transport are respectively westward and southward. Vertical shear is greater in the upper 5m of the water column.

1. INTRODUCTION

Thermaikos Gulf, in the N.W. Aegean Sea, is of particular interest for environmental studies because it receives domestic wastes and industrial effluents from the city of Thessaloniki, the nearby industrial zone and also from large rivers discharging in the area. However, oceanographic investigations in the area are limited (Balopoulos, 1975, 1976, 1977; Chronis, 1981; Conispoliatis, 1979; Wilding et al., 1980; Robles et al., 1983). In particular, information on water circulation patterns in the Gulf is based mainly on numerical studies (Koutitas and O'Connor, 1980; Ganoulis and Koutitas, 1981).

Physical oceanographic data (hydrographic observations, Lagrangian and Eulerian current measurements) were obtained in Thermaikos Gulf, during 1975-1977, as part of an extensive field programme organized and implemented by the Greek Institute of Oceanographic and Fisheries Research (IOFR).

The overall purpose of this programme was to provide a detailed knowledge of the structure, circulation and mixing of the water masses (Balopoulos, 1982), together with the assessment of their chemical (Friligos, 1977; Friligos and Satsmadjis, 1977; Voutsinou and Satsmadjis, 1983; Chester and Voutsinou, 1981) and biological properties. Such processes are to be considered in the context of the proposed sewage outfalls for the disposal of domestic and industrial wastes from the city of Thessaloniki.

In this contribution, drogue tracking data collected in thirty-nine different experiments are examined (Figure 1) in relation to spatial and temporal variability of the upper layer currents. The nature and degree of influence of several environmental factors (rivers, wind, coastline configuration) in the formulation of upper layer flow patterns are examined.

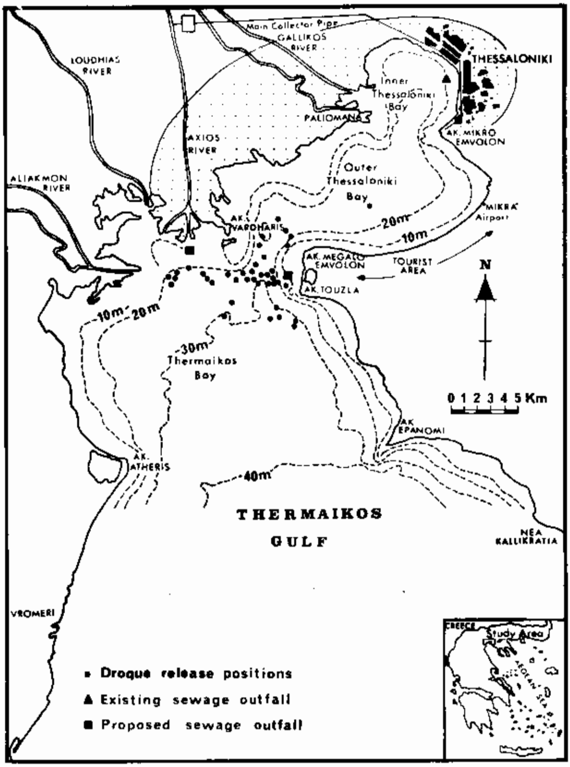

Fig. 1. The study area, showing the tourist beach, the drogue release positions and the locations of the existing and proposed sewage outfalls. The most heavily industrialised coastal regions are indicated by the stippling.

2. AREA UNDER INVESTIGATION

The study area is a shallow semi-enclosed embayment with a total surface area of 320 km^2, which lies in the northwestern Aegean Sea. Geographically, it is subdivided into three interconnecting embayments, that is Inner Thessaloniki Bay (max. depth 23m), Outer Thessaloniki Bay (max. depth 27m) and Thermaikos Bay (max. depth 42m).

Four main rivers (Axios, Aliakmon, Loudhias, Gallikos) discharge into the study area. However, the Rivers Axios and Aliakmon are the most important with regard to water discharge and sediment supply because of their large drainage basins (22,450km^2 and 6,075km^2, respectively). The waters of the large river systems and especially of the River Axios are heavily polluted by pesticides, industrial effluents and domestic wastes. In addition, the study area receives industrial effluents from more than 230 factories and also the domestic wastes (about 20x10^4 m^3 day^{-1}) of the city of Thessaloniki, which has more than 1,200,000 inhabitants.

The tidal range in the Thermaikos Gulf is very small (30 cm at mean Spring tides, reducing to 5 cm at mean Neap tides), although associated meteorological forcing of the water masses has been identified (Wilding et al., 1980). Prevailing wind directions, throughout the year, are the northerly component winds (NW-N-NE), while a high percentage of occurence, during the spring and summer, have and the sea «breezes» (S-SSW-SW) (Livadas and Sahsamanoglou, 1973).

3. METHODS AND ERROR ANALYSIS

Drogue tracking was sellected as the observational method for the Lagrangian determination of the upper layer currents in the Thermaikos Gulf. This method was feasible in terms of ship time and equipment expense and has been used in other regions (Dooley and Steele, 1969; Stevenson et al., 1969; Murray, 1975; Wyatt et al., 1967; Stevenson et al., 1974; De Alteris and Keegan, 1977; Laevastu et al., 1964; Oakley et al., 1980; Saylor and Danek, 1976).

The standard drogues consisted of two cross-placed, 5mm thick, polyvinyl chloride (P.V.C.) sheets, which were suspended through lines from surface floats (Figure 2). In order to minimize wind action on the systems, leaden ballasts were attached under the drogues, so as to confine the unsubmerged surface of the floats. Colour-coded flags attached on the floats were used to identify individual drogues set at different depths for optical tracking. Deployment consisted of dropping the drogues into the ambient current off the stern of the vessel used as the tracking control station.

In each survey, one or two sets of three drogues, corresponding to depths of 1, 5 and 10 metres were followed with the help of a vessel. The positions of

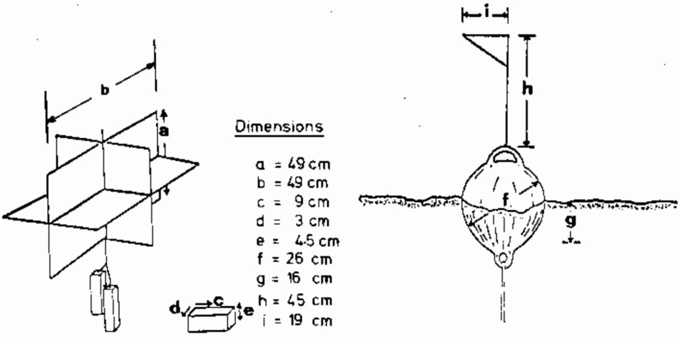

Fig. 2. Type of drogue used.

the drogues, at time intervals, were determined with the aid of the vessel's radar and compass. At the same time intervals, the wind speed was measured with the aid of a mechanical anemometer and the wind direction was estimated by the observer, using the ship's flag and compass. The successive positions of the drogues were defined on a large-scale chart and tracks followed by them were then plotted.

Uncertainties in the results are caused by two types of errors; those due to data aquisition and those in speed estimation due to the wind drag on the surface floats. Maximum error in position fixing, based on the vessel's radar and compass, is estimated to be ±0.1 nautical miles (±0.2 km). On the other hand, errors in the speed estimation, resulting from wind drag on the surface floats, may be examined by neglecting the drag on the suspension line and the submerged part of the surface float. The horizontal balance of forces on the drogue can then be estimated (Murray, 1975) by writing:

$$dU_d/dt = (F_d + F_s)/\rho_w V \tag{1}$$

where U_d is the speed of the drogue relative to the ground, V the volume of water trapped by the drogue ($=b^3$) and .

$$F_d = 1/2\, c_d \rho_w b^2\, U_o |U_o| \tag{2}$$

$$F_s = 1/2\, c_s \rho_a A W^2 \sin\theta \tag{3}$$

In the above equations, F_d is the drag force of the water on the drogue and F_s that component of the drag force of the wind on the surface float, which is transmitted to the drogue as a horizontal force. Further, θ is the tilt angle of the line to the vertical, c_d the drag coefficient of the drogue (1.2), ρ_w the water density, b the length of the side of the drogue (0.49 m), U_o the relative speed between drogue and the water ($U_o = U_d - U$), U water speed, c_s the drag coefficient of the surface float (1.0), ρ_a air density, A the cross-sectional area of the exposed part of the surface float (0.03 m^2), and W wind speed in the current direction.

When the drogue reaches a steady speed, then $dU_d/dt = 0$ and Equation (1) may be written:

$$U_o = [(c_s \rho_a A \ \sin\theta)/c_d \rho_w] \ (W/b) \tag{4}$$

For a maximum value of the angle $\theta = 20°$, Equation (4) yields, at the observed wind speeds 2-10 m s^{-1}), that the maximum error in the speed estimation, due to the wind drag on the surface float, is 0.01-0.06 m s^{-1}. A graphical representation of the speed error, for the type of drogue used and at different wind speeds, is given in Figure 3.

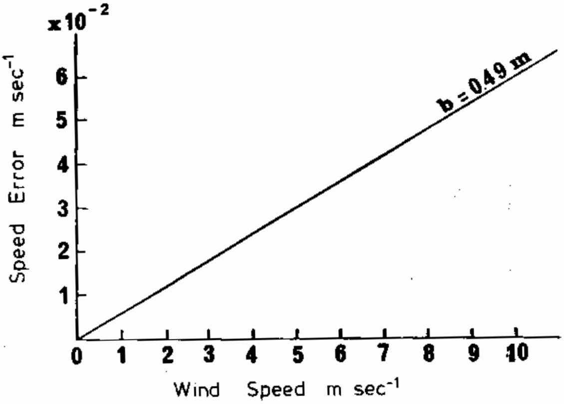

Fig. 3. Speed error of the drogue used, resulting from wind drag on the surface floats, as a function of wind speed.

For each drogue experiment, the average speed, mean velocity and mean velocity components in the northward and eastward direction were calculated (Table 1). The average speed is simply the arithmetic mean of the speeds observed for each drogue and each experiment at the time intervals between observations. Mean velocities for each drogue were computed form their final position, initial position and the corresponding time interval.

The upper layer volume transport for each observational period was estimated by numerical integration of the velocity components (Table 1). These results depent upon two assumptions: that velocity in the upper 1m is uniform; and the horizontal velocity changes linearly with depth between drogues.

Table 1.
Velocities, vertical shears and transports (by experiment and depth interval) computed from drogue observations.

Date-(Expr. No.)	z (m)	V (cm s^{-1})	Mean Velocity Speed (cm s^{-1}) u	v	c	D (°)	Shear ($10^3 \times s^{-1}$) $\partial u/\partial z$	$\partial v/\partial z$	z (m)	Transport ($10^3 \times m^3 s^{-1} m^{-1}$) East Δ	Σ	North Δ	Σ
27	1	7.7	−0.5	−7.4	7.4	184			0				
Aug.							−2.7	5.4		−53		−315	
1975	5	5.1	−1.6	−5.2	5.5	197			5		−53		−315
							−2.4	1.6		−110		−240	
(1)	10	4.7	−2.8	−4.4	5.2	212			10		−163		−555
27	1	12.0	−1.4	−11.6	11.7	187			0				
Aug.							−13.5	3.8		−205		−543	
1975	5	12.8	−6.8	−10.1	12.2	214			5		−205		−543
							1.8	−5.1		−318		−570	
(2)	10	13.9	−5.9	−12.7	14.0	205			10		−523		−1113
28	1	13.9	−2.7	−12.7	13.0	192			0				
Aug.							5.0	−2.0		−85		−655	
1975	5	14.2	−0.7	−13.5	13.5	183			5		−85		−655
							−3.3	0.4		−78		−670	
(3)	10	13.9	−2.4	−13.3	13.5	190			10		−163		−1325
28	1	15.9	−10.9	−8.2	13.6	233			0				
Aug.							7.7	−4.4		−468		−455	
1975	5	16.4	−7.8	−10.0	12.6	218			5		−468		−455
							−6.6	−0.0		−473		−500	
(4)	10	16.8	−11.1	−10.0	14.9	228			10		−941		−955

15	1	16.9	5.5	13.0	14.1	023			0				
Nov.							−4.8	−16.3		228		488	
1975	5	7.4	3.6	6.5	7.4	029			5		228		488
							1.4	−9.6		198		203	
(5)	10	5.3	4.3	1.6	4.6	069			10		426		691
15	1	16.7	9.3	7.0	11.7	053			0				
Nov.							−7.1	−13.8		395		213	
1975	5	6.9	6.5	1.5	6.7	077			5		395		213
							−0.0	−1.9		325		53	
(6)	10	6.5	6.5	0.6	6.5	085			10		720		266
16	1	8.6	4.3	−5.4	6.9	142			0				
Nov.							−5.1	6.6		325		−205	
1975	5	7.1	2.2	−2.8	3.6	142			5		325		−205
							−0.4	−0.3		400		−145	
(7)	10	8.9	2.0	−3.0	3.6	146			10		725		−350
16	1	6.8	6.3	−1.0	6.3	099			0				
Nov.							0.8	14.4		323		95	
1975	5	7.5	6.6	4.8	8.1	054			5		323		95
							−2.5	−3.2		350		200	
(8)	10	6.5	5.3	3.2	6.2	059			10		673		295
18	1	12.2	4.9	2.1	5.4	067			0				
Feb.							7.7	9.9		323		203	
1976	5	11.4	8.0	6.0	10.0	053			5		323		203
(9)													
18	1	9.5	−1.8	−4.1	4.5	204			0				
Feb.							19.0	11.6		200		−180	
1976	5	8.0	5.8	0.5	5.8	085			5		200		−180
							−6.0	3.3		213		65	
(10)	10	5.7	2.7	2.1	3.5	052			10		413		−115

19	1	5.7	−5.3	2.2	5.7	293			0				
Feb.							14.9	7.0		230		198	
1976	5	6.3	0.7	5.7	5.8	007			5		230		198
(11)													
19	1	8.6	−3.6	−6.9	7.8	208			0				
Feb.							2.9	6.0		−153		−245	
1976	5	5.8	−2.5	−4.5	5.1	209			5		−153		−285
							0.0	−0.3		−125		−228	
(12)	10	6.1	−2.5	−4.6	5.2	208			10		−278		−573
20	1	11.7	−5.0	−9.0	10.3	209			0				
Feb.							9.9	13.6		−150		−315	
1976	5	3.8	−1.0	−3.6	3.7	196			5		−150		−315
							−1.4	0.1		−68		−178	
(13)	10	4.3	−1.7	−3.5	3.9	206			10		−218		−493
20	1	11.9	3.4	−4.9	6.0	145			0				
Feb.							0.6	3.1		178		−215	
1976	5	7.1	3.7	−3.7	5.2	135			5		178		−215
							2.2	3.3		213		−143	
(14)	10	7.0	4.8	−2.0	5.2	113			10		391		−358
21	1	42.4	4.4	−42.2	42.4	174			0				
Feb.							2.8	65.2		250		−1458	
1976	5	17.4	5.6	−16.1	17.1	161			5		250		−1458
							−7.5	3.0		185		−768	
(15)	10	15.5	1.8	−14.6	14.6	173			10		435		−2226
21	1	39.0	7.9	−37.1	38.0	168			0				
Feb.							1.2	72.6		408		−1130	
1976	5	16.7	8.4	−8.1	11.6	134			5		408		−1130
							−1.8	7.2		398		−315	
(16)	10	10.4	7.5	−4.5	8.7	121			10		806		−1445

18	1	11.4	4.4	−8.3	9.5	152			0				
May							−22.8	30.3		−8		−113	
1976	5	6.3	−4.7	3.8	6.0	309			5		−8		−113
							−2.2	2.8		−263		225	
(17)	10	8.1	−5.8	5.2	7.7	312			10		−271		112
18	1	11.1	4.1	−7.8	8.8	152			0				
May							−24.2	38.7		−38		−5	
1976	5	12.3	−5.6	7.6	9.4	324			5		−38		−5
							8.1	−2.3		−178		353	
(18)	10	8.8	−1.5	6.5	6.7	347			10		−430		348
19	1	17.4	−14.3	−5.2	15.2	250			0				
May							36.7	3.2		−348		−228	
1976	5	4.2	0.4	−3.9	3.9	174			5		−348		−228
							−5.1	13.5		−43		−28	
(19)	10	5.5	−2.1	2.8	3.6	323			10		−391		−256
19	1	8.2	−6.0	−4.7	7.6	232			0				
May							22.8	8.1		−70		−153	
1976	5	4.3	3.2	−1.4	3.5	114			5		−70		−153
							−6.2	−1.4		83		−88	
(20)	10	2.9	0.1	−2.1	2.1	178			10		13		−241
20	1	34.4	−13.8	−29.6	32.6	205			0				
May							43.2	58.8		−258		−893	
1976	5	7.8	3.5	−6.1	7.0	150			5		−258		−893
							2.2	9.5		203		−185	
(21)	10	5.4	4.6	−1.3	4.8	106			10		−55		−1078

20	1	35.4	−29.3	−19.3	35.4	236			0				
May							29.5	28.1		−1170		−708	
1976	5	20.3	−17.5	−8.5	19.5	244			5		−1170		−708
							3.4	8.6		−833		−318	
(22)	10	16.7	−15.8	−4.2	16.4	255			10		−2003		−1026
23	1	6.0	−2.5	0.9	2.6	290			0				
Aug.							12.5	18.4		0		230	
1976	5	9.2	2.5	8.3	8.6	017			5		0		230
							1.9	−11.6		150		268	
(23)	10	8.2	3.5	2.4	4.3	055			10		150		498
23	1	11.4	−11.2	1.8	11.4	279			0				
Aug.							9.9	1.8		−463		108	
1976	5	9.4	−7.3	2.5	7.7	289			5		−463		108
							−1.9	1.3		−388		143	
(24)	10	10.2	−8.2	3.2	8.8	291			10		−851		251
17	1	25.4	−2.7	−20.5	24.8	214			0				
Jun.							5.9	28.6		−75		−740	
1977	5	9.6	−0.3	−9.1	9.1	182			5		−75		−740
							−6.6	13.8		−98		−283	
(25)	10	5.4	−3.6	−2.2	4.2	239			10		−173		−1023
18	1	19.2	9.1	−16.4	18.7	151			0				
Jun.							−25.5	30.4		200		−515	
1977	5	6.0	−1.1	−4.2	4.4	195			5		200		−515
							14.2	−8.2		180		−313	
(26)	10	13.1	8.3	−8.3	11.8	135			10		380		−828
19	1	12.3	−5.3	−7.0	8.8	217			0				
Jun.							27.8	−4.0		−13		390	
1977	5	10.6	5.8	−8.6	10.4	146			5		−13		−390

							−6.3	10.4		213		−300	
(27)	10	4.7	2.7	−3.4	4.3	142			10		200		−690
13	1	12.2	−3.6	−11.2	11.8	198			0				
Jul.							12.8	10.8		−105		−453	
1977	5	7.7	1.5	−6.9	7.0	168			5		−105		−453
							−2.6	31.2		43		45	
(28)	10	9.5	0.2	−0.2	8.7	001			10		−62		−408
14	1	27.0	−9.2	−21.6	23.5	203			0				
Jul.							17.3	31.2		−288		−768	
1977	5	10.4	−2.3	−9.1	9.4	194			5		−288		−768
							−5.1	14.7		−178		−273	
(29)	10	9.6	−4.8	−1.8	5.1	250			10		−466		−1041
15	1	7.7	−6.5	0.6	6.5	275			0				
Jul.							0.7	8.4		−318		85	
1977	5	8.4	−6.2	2.8	6.8	294			5		−318		85
							−0.6	−5.1		−318		75	
(30)	10	7.8	−6.5	0.2	6.5	272			10		−636		160
23	1	21.8	−7.5	−18.5	19.9	202			0				
Aug.							7.0	28.1		−305		−643	
1977	5	9.7	−4.7	−7.2	8.6	213			5		−305		−643
							2.3	−0.8		−205		−370	
(31)	10	9.7	−3.5	−7.6	8.4	205			10		−510		−1013

24	1	12.0	−0.4	−11.2	11.2	182			0				
Aug.							−3.4	3.6		−53		−525	
1977	5	10.4	−1.7	−9.8	9.9	190			5		−53		−525
							2.4	−0.3		−55		−493	
(32)	10	10.2	−0.5	−9.9	9.9	183			10		−108		−1018
25	1	20.0	3.3	−3.5	4.8	137			0				
Aug.							9.2	−4.3		258		−220	
1977	5	18.0	7.0	−5.3	8.7	127			5		258		−220
							−0.1	0.5		348		−258	
(33)	10	16.5	6.9	−5.0	8.5	126			10		606		−478
26	1	43.6	22.6	−34.8	41.5	147			0				
Aug.							−1.5	2.3		1115		−1718	
1977	5	42.7	22.0	−33.9	40.4	147			5		1115		−1718
							−32.5	51.9		693		−1045	
(34)	10	10.8	5.7	−7.9	9.8	144			10		1808		−2763
17	1	10.7	6.6	−6.8	9.4	136			0				
Sep.							−0.9	7.3		320		−268	
1977	5	7.5	6.2	−3.9	7.3	122			5		320		−268
							1.4	−2.6		328		−228	
(35)	10	9.0	6.9	−5.2	8.6	127			10		648		−496
19	1	18.7	7.8	−14.1	16.1	209			0				
Sep.							13.1	31.1		−260		−395	
1977	5	4.6	−2.6	−1.7	3.1	237			5		−260		−395
							1.9	−0.0		−105		−85	
(36)	10	4.7	−1.6	−1.7	2.3	224			10		−365		−480

22	1	11.7	−9.1	−5.0	10.4	241			0			
Sep.							3.9	1.8		−415		−233	
1977	5	9.4	−7.5	−5.3	8.7	240			5		−415		−233
							−0.2	−0.5		−378		−223	
(37)	10	9.6	−7.6	−4.6	8.9	239			10		−793		−456
23	1	5.8	−2.6	−4.0	4.7	213			0				
Sep.							1.0	3.4		−120		−165	
1977	5	4.5	−2.2	−2.6	3.4	220			5		−120		−165
							4.1	3.5		−58		−88	
(38)	10	3.2	−0.1	−0.9	0.9	188			10		−178		−253
24	1	17.0	−6.1	−15.9	17.0	201			0				
Sep.							9.0	12.7		−215		−668	
1977	5	11.7	−2.5	−10.8	11.1	193			5		−215		−668
							−0.9	0.9		−138		−523	
(39)	10	11.0	−3.0	−10.3	10.8	196			10		−353		−1196

KEY: z is the depth;
V is the average speed;
u is the mean speed eastward;
v is the mean speed northward;
$c^2 = u^2 + v^2$; D is the direction.
Δ shows the transport within the depth interval indicated;
Σ shows total transport from surface to depth indicated.
Speeds are in cm sec^{-1}; directions in degrees true.
Depths in metres; shears in $10^3 \times \mathrm{sec}^{-1}$.
Transport is in $10^3 \times \mathrm{m}^3\mathrm{sec}^{-1}\mathrm{m}^{-1}$.

(α) Characteristics of individual drogue tracks

Each drogue track delinated a well-defined path across the sea surface. The path was simple usually and, in a few cases, almost straight marking clearly the dominance or net drift toward a particular direction. In the vicinity of Ak. Touzla and the passage between Ak. Meg. Emvolon and Ak. Vardharis, however, the drogue trajectories on some occasions exhibited abrupt reversals. On other occasions, they indicated clearly a two-layered velocity structure (Figure 4). All drogues tracked in the rivers discharge area followed courses

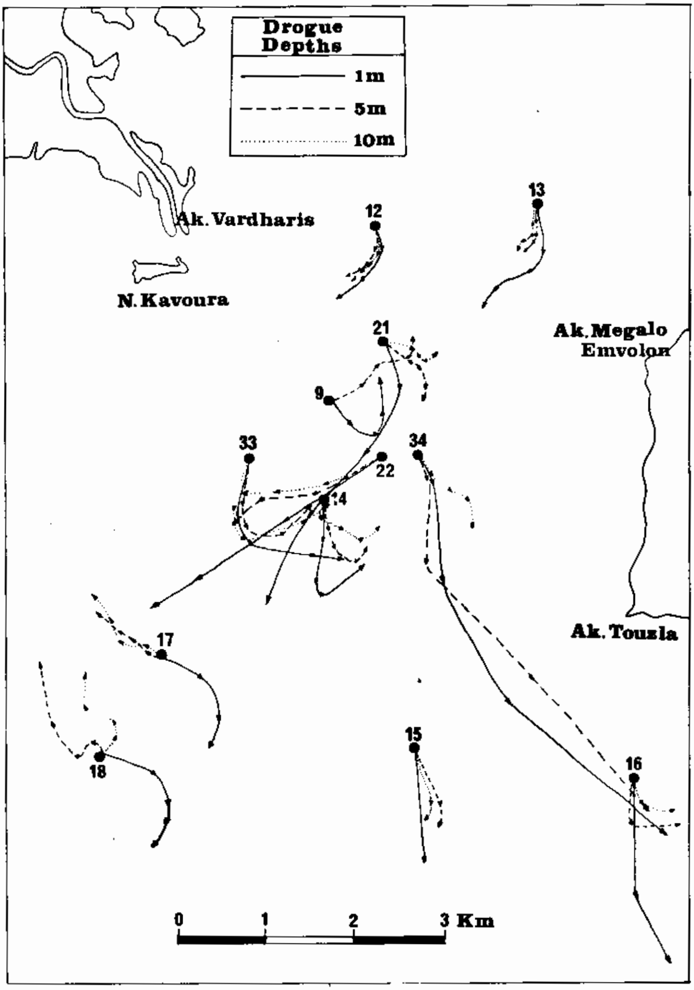

Fig. 4. Drogue trajectories in the vicinity of Ak. Touzla and the passage between Ak. Meg. Emvolon and Ak. Vardharis.

primarily toward the southwest (Figure 5). Nevertheless, in this area the tracks of the drogues at depths of 5m and 10m frequently included variable fluctuations that suggest a complex subsurface eddy structure.

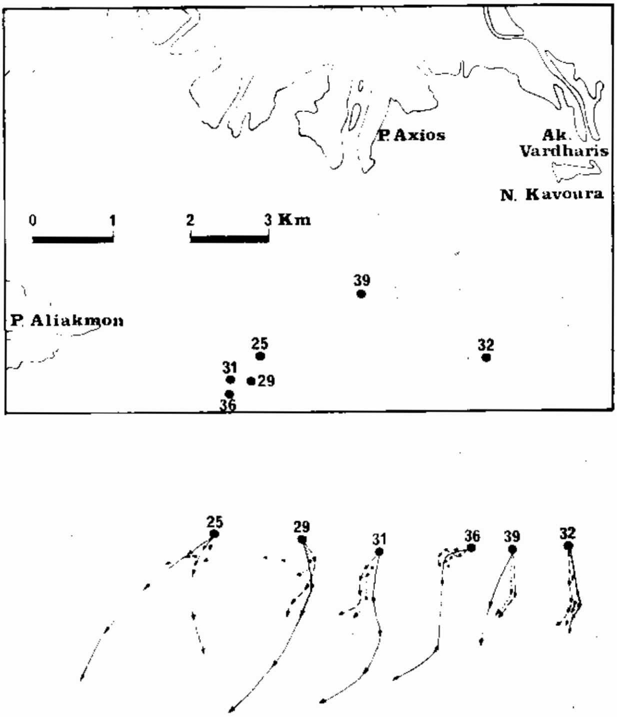

Fig. 5. Drogue trajectories in the rivers discharge area.

(b) Mean currents.

The maximum mean speed observed at 1m depth was 42±2 cm s^{-1} to the southeast, during February 1976 and August 1977. This speed was, in both cases, in the vicinity of Ak. Touzla with northwesterly winds at speeds 2-4 m s^{-1}. Strong northerly component winds had prevailed over the area for several hours prior to the surveys. In the same area, the maximum mean speed at 5m was 40±2 cm s^{-1}. At 10m, the maximum mean speed at no time exceeded 17 cm s^{-1}. Drogue experiments in the river discharge area represented an offshore decay in current speed, with increasing water depth. The speed decay was greater between 1m and 5m. Mean current speeds in this area, ranged between 15 cm s^{1} and 25 cm s^{-1} at 1m. At 10m, they did not exceed 5 cm s^{-1}.

(c) Volume transport.

The largest meridional water transport (2.8 ± 0.2 $m^3s^{-1}m^{-1}$) occured during August 1977, while the smallest (0.1 ± 0.1 $m^3s^{-1}m^{-1}$) was seen during May 1976 and February of the same year. 62% of the total meridional transport occured between the surface and 5m. Beneath 5m and down to 10m, the water transport reduced noticeably. Further, 89% of the total meridional transport was southward. In general, southward water transport was greatest in the upper 5m and it accounted for approximately 64% of the total southward water transport. Northward water transport occured on ten cruises out of thirty-nine. Moreover, from a total of twenty-one drogue experiments, carried out in the summer period, on only three occasions did northwards water transport occur. In all cases, water transport towards the north was relatively small and in no case exceeded $5.0\times10^{-1}m^3s^{-1}m^{-1}$.

Around the mouths of the Rivers Axios and Aliakmon, the meridional transport was in all cases southwards. The mean water transport between the surface and 5m was $6.2\times10^{1}m^3s^{-1}m^{-1}$; between 5m and 10m it was $3.4\times10^{-1}m^3s^{-1}m^{-1}$. Hence, in the aforementioned area, southward water transport between the surface and 5m accounted for about 65% of the total southward water transport between the surface and 10 m. This pattern reflects clearly the effect of freshwater flow mainly from the River Axios.

The meridional transport during only four crusies changed direction with depth. In these cases, a southward water flow was observed between the surface and 1m. There was northward water transport in the layer between 5m and 10m. Prior to these surveys, easterly and southeasterly winds prevailed for several hours over the area, probably transporting water masses from the open sea towards the north.

The largest zonal transport (2.0 $m^3s^{-1}m^{-1}$) occured during May 1976. In the same month, the smallest zonal transport ($10^{-2}m^3s^{-1}m^{-1}$) was also observed. Total zonal transport between the surface and 5m was approximately equal in magnitude to that between 5m and 10m (nearly 52% of the total zonal transport between the surface and 10m). Further, 54% of the total zonal transport was westward. Generally, water transport towards the west was greatest in the upper 5m and accounted for approximately 57% of the total westward water transport. Water transport towards the east occured on seventeen cruises out of thirty-nine. The majority of these experiments took place during winter. From a total of twenty-one experiments carried out in summer, water transport towards the east was observed on only six cruises, On only three occasions did the zonal transport exhibit changes in direction, with depth.

At the mouths of the Rivers Axios and Aliakmon, zonal transport was in all cases westwards. 61% of the total zonal transport in this area occured between the surface and 5m. The mean zonal transport between the surface and 5m was 2.0×10^{-1} $m^3s^{-1}m^{-1}$, while between 5m and 10m, it was 1.3×10^{-1} $m^3s^{-1}m^{-1}$. For this, it is estimated that, during the summer period, the average water transport in the upper 10m, within a distance of 5 km to the east of the mouth of the River Aliakmon, was 5.1×10^3 m^3s^{-1} towards the southwest (Fugure 6).

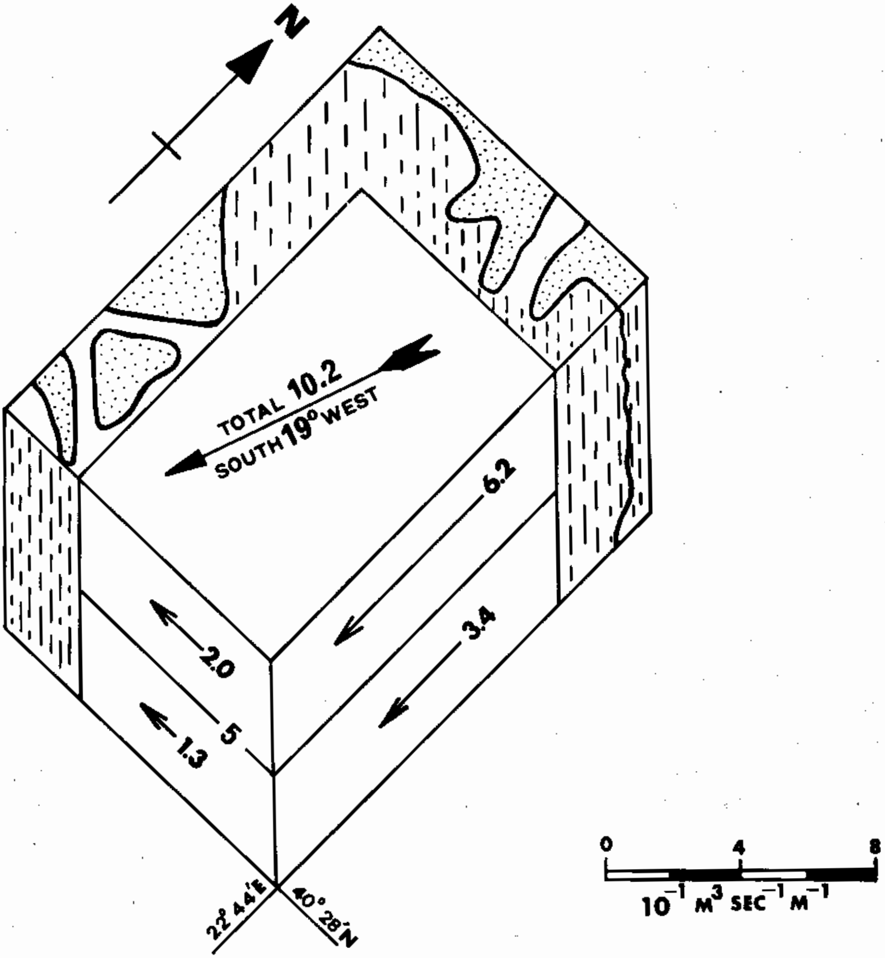

Fig. 6. Schematic diagram of mean transport per second, parallel and perpendicular to the northwestern coast of Thermaikos Bay. Dotted area represents the coastline. Numerals on the sides of block show transport through an area 1m wide and 5m deep, in the direction as shown. Arrow on top of the block (not to scale) represents total mean transport through an area 1m wide and 10m deep.

(d) Vertical shear.

Estimates of the mean velociy shear (e.g., the vertical gradient in horizontal velocity) were obtained from the velocity data (Table 1).

Generally, the shear was larger within the top 5m. Beneath 5m and down to 10m the shear, in most cases, reduced noticeably. Maximum shear within the top 5m occured in the vicinity of Ak. Touzla and Ak. Meg. Emvolon, during February ($7\times10^{\ 2}s^{-1}$) and May ($6\times10^{-2}s^{-1}$) 1976. There was also maximum shear ($5\times10^{\ 2}s^{-1}$) between 5m and 10m in this area in August 1977. Large shear ($3\times10^{-2}s^{-1}$) within the top 5m was, in most cases, in the vicinity of the mouths of the Rivers Axios and Aliakmon. In the aforementioned area, shear in the top 5m accounted for over 70% of that between 1m and 10m in the water column. This shear is due, apparently, to flow caused by freshwater discharge mainly from the River Axios.

The direction of rotation in shear, within the top 10m, occured on twenty of the thirty-nine experiments. This change occured, in all the cruises, carried out in the vicinity of the mouths of the Rivers Axios and Aliakmon. Hence, in this area, when the shear at the top 5m was clockwise, beneath 5m and down to 10m it was counterclockwise. In contrast, when the shear between the surface and 5m was counterclockwise, it was clockwise in the layer between 5m and 10m. Conversely, during only nine of the cruises did the upper layer of water exhibit shear clockwise, with increasing depth. Counterclockwise shear of the upper layer, with increasing depth, occured during ten experiments.

(e) The upper layer currents of Thermaikos Bay

Drogue tracking experiments show clearly that, for most of the observational periods, there was a predominant two-layer current system. This system can be linked to freshwater intrusions from the river systems, which produce the surface or upper water layer. As the area is one of low tidal range, mixing between upper and lower waters is controlled by differential shear at the interface between the layers, caused by atmospheric forcing. Such a two layer system is quite stable until the kinetic energy introduced by shearing is greater than the potential energy increase, that will be caused by complete mixing of top and bottom layers. That is, as a river discharges into an estuary connected to a nearly tideless sea, such as the Aegean Sea, the freshwater overrides the salt water and flows as a nearly undiluted layer into the sea. Salt water intrudes underneath the freshwater layer, in the form of a wedge (Fisher et al., 1979). Moreover, an offshore decay in the flow speed with increasing depth occurs, which is due to shear stress in the interface between the overriding freshwater and the intruding salt water.

All the drogue experiments conducted in the northwestern part of the Thermaikos Bay suggest that the upper layer water transport in this area is dominated by the flow of the freshwater discharged from the rivers. The contribution of the River Axios to this water flow is most important, because of the quantity of its water supply. Further, as a direct effect of the Coriolis force, a diversion of the freshwater flow occurs to the right, which results in a final upper layer water transport towards the southwest. During the summer period, mean current speeds, which may be expected in the river discharge area are 15-25 cm s^{-1} at 1m depth, 8-12 cm s^{-1} at 5m and 2-5 cm s^{-1} at 10m. The highest upper layer current speeds in this area may be expected in winter, due to the increased flow of the rivers and to the usual strong northerly-component winds.

In the vicinity of Ak. Touzla and the passage between Ak. Meg. Emvolon and Ak. Vardharis, upper layer water transport is controlled mainly by the prevailing wind conditions and the coastline orientation. The drogue experiments showed consistently that the nearshore upper layer water flow is quasi-parallel to the coasts, regardless of wind direction and speed. This pattern is in agreement with the theoretical consideration of the mechanics of the processes, which drive the nearshore currents (Murray, 1975). However, the current velocity (speed and direction) is strongly dependent upon both wind speed and direction of the current speed being maximum with strong and parallel to the main axis of the embayment winds (northerly of southerly component winds).

In the passage between Ak. Meg. Emvolon and Ak. Vardharis, in particular, the drogue experiments indicated that northerly component winds result in the formulation of upper layer currents with opposite water flow characteristics. This includes an outflow from Outer Thessaloniki Bay, towards Thermaikos Bay, which occurs nearshore (along both coasts), and an inflow from the Thermaikos Bay towards Outer Thessaloniki Bay, which takes place through the middle of the passage. In the vicinity of Ak. Touzla, outflow along the coast extending between Ak. Meg. Emvolon and Ak. Touzla is divided into two parts. Nearest to the shore, water is diverted to the east and flows along the southern coast of Ak. Touzla. Further offshore, water changes its flow westwards, appearing simultaneously a significant decay in its mean speed. This, suggests probably, that to the south of this area there is water motion characterized by a northward flow component. On the other hand, there was evidence to suggest that southeasterly component winds result in outflow from Outer Thessaloniki Bay towards Thermaikos Bay, which takes place through the middle of the passage between Ak. Meg. Emvolon and Ak. Vardharis.

CONCLUSIONS

Drogue tracking experiments have demonstrated that Thermaikos Bay is characterized, generally, by weak upper layer currents (typically less than 20 cm s^{-1} in the upper 10m layer). In the vicinity of the passage between Ak.

Meg. Emvolon and Ak. Vardharis, however, higher mean speeds (up to 40 cm s^{-1}) may be observed occasionally.

The upper layer water transport in the northwestern part of the Thermaikos Bay is dominated by freshwater dischrage from the rivers. The magnitude of these upper layer currents is affected strongly by variable flow from the River Axios and the northerly component winds. The effect of Coriolis force is seen in the tracks of many of the drogues.

In the passage between Ak. Meg. Emvolon and Ak. Vardharis, the wind stress and the configuration of the coastline are the most important factors controlling the upper layer currents. The nearshore flow here is quasi-parallel to the coastline. Northerly-component winds produce nearshore outflow from Outer Thessaloniki Bay towards the Thermaikos Bay and an inflow between these outflows. Southerly component winds produce a reversal of this situation.

The prevailing zonal and meridional water transport are westward and southward, respectively. The latter accounts for almost 90% of the total meridional transport and it is at a maximum in the top 5 metres. In the northwestern part of the Thermaikos Bay, the average water transport, is towards the southwest. During summer, this has been estimated to be of the order of $10.2\times10^{-1}m^{3}s\ ^{1}m^{-1}$.

Vertical shear is greater in the top 5 metres than in the lower 5 metres of the water column. During summer, shear at the top 5 metre layer, in the northwestern part of the Thermaikos Bay, accounts for over 70% of that between 1 metre and 10 metres depth.

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ΠΕΡΙΛΗΨΗ

Σταυροειδείς ιχνηλάτες ρευμάτων χρησιμοποιήθηκαν για τη μελέτης της χωρικής και χρονικής μεταβολής της ροής στό ανώτερο στρώμα νερού του Θερμαϊκού Κόλπου (Β.Δ. Αιγαίο). Αποτελέσματα από τριάντα εννέα διαφορετικά πειράματα που έγιναν κατά τη διάρκεια της περιόδου 1975-1977 έδειξαν ότι η κυκλοφορία στο στρώμα νερού που προαναφέρθηκε επηρεάζεται από τις μεταβλητές παροχές των ποταμών που εκβάλλουν στην περιοχή και ακόμη από τους επικρατούντες βόρειους άνεμους. Σε περιοχές του κόλπου μακρυά από τις εκβολές των ποταμών, η ένταση του ανέμου και η μορφολογία της ακτογραμμής είναι οι πιό σημαντικοί παράγοντες που επηρεάζουν τα ρεύματα του ανωτέρου στρώματος νερού. Κοντά στις ακτές η ροή

είναι παράλληλη προς την ακτογραμμή. Από τις συνιστώσες κατεύθυνσης ρευμάτων η δυτική και νότια είναι εκείνες που επικρατούν. Η κατακόρυφη σύρση είναι μεγαλύτερη στα ανώτερα πέντε μέτρα της στήλης νερού.

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