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EXPERIMENTAL DETERMINATIONS OF THE HORIZONTAL MIXING COEFFICIENTS ALONG THE ROMANIAN WEST COAST OF THE BLACK SEA

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ABSTRACT:

The space-scale dependence of the turbulent mixing coefficients as determined from turbulent diffusion of dissolved substances, dispersion of finite particles and current velocity fluctuations during 1976-1980 is presented, and the deviations from the "4/3 power law" in the shallow waters are pointed out.

INTRODUCTION

An essential feature of the oceanic motions is their turbulent character, which causes the exchanges of kinetic energy, mass and heat to be several orders of magnitude greater than the corresponding molecular fluxes in the laminar flow.

For the closure of the system formed by the equations of motion and continuity, it is necessary to use auxilliary equations for the terms including dynamic quantity fluctuations. For this purpose, in the semiempirical theories of turbulence, the Reynolds stresses are considered as being directly proportional to the mean velocity gradient, and the coefficient of proportionality is the turbulent exchange coefficient. Similarly, the mass and heat fluxes depend on the mean quantity gradient through a turbulent diffusion coefficient and, respectively, through a tur-

bulent conductivity coefficient. These three coefficients must be determined by data interpretation in the frame of the available theoretical models using supplementary assumptions regarding the dependence of the turbulent coefficients on other parameters- space scale, velocity shear, density stratification, bottom topography, sea state, etc. The paper presents the results concerning the space scale dependence of the horizontal turbulent exchange and the horizontal turbulent diffusion coefficients obtained in the specific conditions of the Romanian nearshore waters.

1. HORIZONTAL TURBULENT EXCHANGE COEFFICIENTS

For determination of the turbulent exchange coefficients (hereafter TEC), several current series recorded with Alexaev type currentmeters were processed by a computer program based on Ertel's algorithm (8). The program allows calculation of the TEC with different averaging periods and also permits the use of different sampling intervals (multiples of the original one) for the same data set.

The obtained TEC for all the series exhibit a strong time variability, with values generally increasing with the extension of the averaging period or of the sampling interval.

According to GEZENTSVEI (3), the dependence of the TEC value A on the averaging period T has the form:

$$A = C\,T^{2/3} \qquad (1)$$

corresponding to the well known "4/3 power law" dependence on the space scale.

But, from the analysis of the data series, it is obvious that the increase of the TEC is limited to the averaging periods of the order of 12-18 hours, the TEC values being almost constant (or even slightly decreasing) for longer periods.

This "saturation effect"- also noticed in some previous papers (1, 6, 10) - is explained by the fact that beyond a certain length scale, there are no larger eddies to contribute to the exchange process, or by the fact that for the length or time scales with external energy input the "4/3 power law" and, consequently, the "2/3 power law" given by (1), is no longer valid.

For this reason, the value of C in (1) was computed only for averaging periods within the range of 1 to 12 hours, and, at the same time, the parameters B and m of a more general dependence:

$$A = B\,T^{m} \qquad (2)$$

have been computed (Table 1).

Table 1

Characteristics of the data series and regression parameters for the TEC (in $m^2\ s^{-1}$) dependence on the averaging period (in hours)

Series	Water depth (m)	Currentmeter depth (m)	Sampling interval (min)	Equation 2		Eq.1
				B	m	C
1	52	10	10	1.78	0.5	2.25
2	52	10	5	3.20	0.9	2.05
3	52	30	5	0.91	0.5	1.30
4	52	10	5	3.38	0.1	10.48
5	52	25	5	6.83	0.2	18.65
6	52	10	5	4.33	1.3	1.12
7	52	50	5	1.53	0.0	6.49
8	10	1	15	1.68	0.6	1.96
9	10	9	15	1.22	1.1	0.50
10	12	6	5	0.61	1.6	0.07
11	12	6	5	0.45	1.0	0.22
12	17	5	5	5.62	0.2	16.61
13	17	5	5	14.08	0.4	27.78

For almost all the series, the curves given by (2) held a better approximation, with the power m ranging between 0 and 1.6, depending on the place and depth of the currentmeter and on the density stratification. In the offshore region the values of m are generally smaller than 2/3 both above and below the seasonal thermocline, decreasing to zero just above the bottom. They are higher than 2/3 only within the thermocline (series 2 and 6). In the nearshore shallow water area, the TEC values depend on the flow orientation as referred to the shoreline and the exponent m varies largely between 0 and 1.6, thus proving that the "2/3 power law" has a limited validity even for averaging periods

smaller than 12 hours.

2. HORIZONTAL TURBULENT DIFFUSION COEFFICIENTS

The methods of determination of the turbulent diffusion coefficients (hereafter TDC) - which allow calculation of the turbulent mass fluxes - were chosen according to the particular contamination sources used in the experiments: continuous or instantaneous mass sources, or instantaneous releases of free floats. The continuous sources were those found in natural mixing zones, while the instantaneous dye and float releases represent experimental simulations of the diffusion process.

MIXING FROM CONTINUOUS SOURCES

The determination of the TDC in the nearshore zones where natural mixing of the fresh or waste waters occurs were made using two analitical steady state solutions for the continuous regime: the FICK solution (5) and the OZMIDOV solution(6). The constant TDC K of the first model and the parameter k of the second one (the proportionality factor in the "4/3 power law") were calculated from the observed salinity or phosphate content distributions according to a method previously presented (7). This method is based on an optimization algorithm, the objective function being the mean square deviation of the computed and measured concentrations.

The results (Table 2) are in good agreement with those published for the other regions of the Black Sea (11), when using the Fickian model, but the values of k are somewhat larger than those presented in the literature, yet representing a better fit for the experimental data. This fact might be explained by the discrepancies between the field conditions and those assumed by the model: uniform flow, no shear, no external energy sources. More work is needed in order to properly relate the apparent TDC to a more complex model including shear, vertical diffusion, density stratification, wave induced turbulence, etc.

INSTANTANEOUS POINT-RELEASE EXPERIMENTS

This kind of experiments are used either as a method to study surface spreading of an accidental pollutant discharge, or as a less expensive method for determination of TDC needed in forecasting the effects of a projected continuous discharge.

Table 2

TDC and k values determined from continuous regime experiments

Exp. no.	Date	Tracer	K ($m^2 s^{-1}$)	k ($10^{-2} m^{2/3} s^{-1}$)
	Constanta (South), waste water, Q = 0.5 $m^3 s^{-1}$			
1	12.05.1977	salinity	2.59	3.20
	Constanta (North), waste water, Q = 0.3 $m^3 s^{-1}$			
1	24.03.1977	salinity	0.39	3.00
		phosphate	0.59	3.10
2	04.04.1977	salinity	0.09	0.32
		phosphate	0.09	0.28
3	12.10.1977	salinity	0.19	2.84
		phosphate	2.89	2.91
4	24.10.1977	salinity	0.09	0.24
		phosphate	0.89	0.87
	Midia, waste water, Q = 1 $m^3 s^{-1}$			
1	06.06.1977	salinity	5.59	2.70
		phosphate	0.69	0.71
2	29.06.1977	salinity	-	0.69
		phosphate	-	5.70
3	14.10.1977	salinity	-	1.00
		phosphate	-	0.18
4	24.04.1978	salinity	2.83	-
		phosphate	2.91	-
5	15.05.1978	salinity	0.70	-
		phosphate	2.64	-
6	23.03.1979	salinity	1.29	3.80
		phosphate	2.12	3.00
7	23.04.1979	salinity	0.19	1.00
		phosphate	0.30	0.30
8	08.08.1979	phosphate	3.00	1.04
9	18.06.1980	salinity	6.91	3.86
		phosphate	0.07	0.51
10	08.07.1980	salinity	3.16	1.30
		phosphate	4.11	1.26
11	29.08.1980	salinity	2.50	3.07
		phosphate	0.57	-
	Periboina, brackish water (Sinoe lagoon), Q=144; 163;76 $m^3 s^{-1}$			
1	13.06.1975	salinity	146.00	1.90
2	25.07.1975	salinity	56.00	1.40
3	29.05.1979	salinity	52.86	15.20
	Sulina, fresh water (Danube river), Q = 1166 and 994 $m^3 s^{-1}$			
1	15.06.1979	salinity	417.80	2.30
2	04.09.1979	salinity	340.00	5.20

DYE AND RADIOACTIVE TRACERS

In these experiments, known quantities of dye (Rhodamine B) and radioisotope (^{82}Br) were simultaneously released as an instantaneous point source. Concentration measurements were made by spectrophotometric analysis of the water samples (for Rhodamine) and by "in situ" radioactivity determination (for ^{82}Br).The detailed results concerning the ^{82}Br releases - carried out in cooperation with a research team of the Institute for Nuclear Physics and Engineering - will be published elsewhere; only the results concerning the Rodamine releases will be dicussed here.

The position of the sampling points were determined with an accuracy of ± 0.5 m by using two shore-based theodolites.

Two types of measurements were used: time sampling of tracer concentration along the patch trajectory and space sampling along the axes of the "instantaneous" patch. The analysis of the experimental data from the first type of measurements was made using several analitical radial-symmetric solutions, for which an optimization procedure yielded the value of the constant parameter involved. The chosen solutions were: K=const. (Fick), $K=k_1 r$ (Joseph-Sendner), $K=k_2 r^{4/3}$ (Ozmidov), $K=k_3 r^{2/3}\, t$ (Okubo), $K=k_4 t$ (Okubo and Pritchard), $K=k_5 t^2$ (Obukhov). The results obtained using Rhodamine concentrations (Table 3) show an irregular time variation of the parameters, which could be due to the fact that not all the sampling points were exactly in the longitudinal axis of the patch.The residual error was essentially the same for all the models and hence no preference for one of them resulted.

The second approach does not require any prior assumption regarding the space scale dependence of the TDC: they are simply defined as the time derivative of the concentration variance:

$$K = \frac{1}{2}\frac{dD^2}{dt} \qquad (3)$$

where:

$$D^2 = \frac{\iint x^2\, C(x,y)\, dx\, dy}{\iint C(x,y)\, dx\, dy} \qquad (4)$$

with the x-axis taken along the patch and the y-axis across it,

the origin being the center of the patch.

Table 3

Parameters of the radial-symmetric solutions determined from fixed-point measurements of Rhodamine concentration*)

Date	25.07.79	11.08.80			12.08.80		
Place	Constanța	Chituc			Chituc		
Point	1	1	2	3	1	2	3
Time**) (min)	24	45	67	89	35	55	81
K ($m^2 s^{-1}$)	27.40	88.00	8.20	131.00	28.70	45.10	97.40
k_1 ($m s^{-1}$)	1.40	1.87	0.47	1.58	1.14	1.16	1.41
k_2 ($m^{2/3} s^{-1}$)	0.62	0.62	0.21	0.43	0.47	0.41	0.41
k_3 ($m^{4/3} s^{-1}$)	0.67	0.67	0.23	0.47	0.52	0.45	0.45
k_4 ($m^2 s^{-2}$)	2.79	3.76	0.93	3.17	2.38	2.34	2.83
k_5 ($m^2 s^{-3}$)	0.82	0.83	0.28	0.58	0.65	0.55	0.55

*) The values given in this table should be multiplied by 10^{-2} in order to obtain the parameters values in the indicated units.

**) Peak arrival time counted from the injection moment.

The obtained results (Table 4) are in good agreement with those presented in the litterature, but they are scattered over a very wide range, due to their dependence not only on the particular region and of the development stage of the process, but also on the hydrological and meteorological conditions during the experiment.

Table 4

TDC values (in $m^2 s^{-1}$) determined from the variance of the Rhodamine B concentrations measured along the patch axis

Date	Place	TDC variation range
25.07.1979	Constanța	0.004 - 0.440
30.07.1979	Constanța	0.167 - 0.669
11.08.1980	Chituc	0.073 - 0.183
12.08.1980	Chituc	0.353 - 0.677

The statistical analysis which is needed for correct interpretation of the results requires a large number of experiments in each study area. The above mentioned tracers are too expensive and the experiments too complicated and costly for such

an approach so that this method was replaced by a simpler and less expensive one- the free float (drogue) dispersion.

FREE FLOATS

The assumed similarity between the dispersion of a float cluster and the diffusion of a dye patch allows calculation of TDC from the time derivative of dispersion $\bar{D}^2$ as in Eq.3, $\bar{D}^2$ being defined as:

$$\bar{D}^2 = \frac{1}{N}\sum_{i=1}^{N} d_i^2 \qquad (5)$$

where d_i is the distance of the i^{th} float from the cluster center of mass ($\underline{2}$).

Between 1978 and 1980 several experiments of this kind were carried out in different littoral zones using 6-12 floats, for dispersion times in the range of 4-6 hours. Positioning of the floats at 6-12 minutes intervals was accomplished using two shore-based theodolites. The results were processed by a computer program allowing calculation of individual float coordinates, interpolation for the positions of all floats at the same moment, calculation of the coordinates of the center of mass and of the dispersion $\bar{D}^2$. Regression parameters a,m,b,t were determined for the time dependence relationships:

$$\bar{D}^2 = a\, t^m \qquad (6)$$

$$\bar{D} = b\, t^p \qquad (7)$$

by the same computer program. From(6),the diffusion coefficient K_D defined as in (3), can be expressed as:

$$K_D = \frac{a\, m}{2}\, t^{m-1} \qquad (8)$$

The dependence of K_D on the scale of the phenomenon can be expressed as:

$$K_D = k\, \bar{D}^n \qquad (9)$$

and the substitution of t from(7)gives the following expressions for the parameters k and n:

$$k = \frac{a\, m}{2}\, b^{\frac{1-m}{p}} \qquad (10)$$

$$n = \frac{m-1}{p} \qquad (11)$$

The obtained values for n(Table 5)are in good agreement with those published for other nearshore zones of the Black Sea. It should be noted, however, that there is no value greater than 1, which proves that for space scales shorter than 2-3 km and diffusion durations shorter than 10 hours,the "4/3 power law" is not valid. The values close to 1 might be explained by a "shear-diffusion" process,while the small value obtained from the second experiment more likely denotes a Fickian diffusion (n=0).

Table 5

Regression parameters for the free float dispersion analysis

Experiment	Eq.6		Eq. 7		Eq.10	Eq.11
	$a.10^{-3}$	m	$b.10^{-2}$	p	$k.10^{-2}$	n
Midia 1978	2.74	1.768	4.60	0.891	2.90	0.860
Tuzla 1978	84.00	1.180	22.70	0.605	7.70	0.297
Eforie 1978	1.27	1.515	3.81	0.733	0.96	0.703
Constanţa 1979	6.19	1.291	8.04	0.636	1.31	0.469
Constanţa 1980	263	1.785	47.00	0.867	0.78	0.905

SUMMARY

Given the importance of the knowledge of the turbulent mixing from a practical point of view, a large number of experiments have been carried out in different nearshore zones: turbulent exchange coefficient determinations from current records and turbulent diffusion coefficient determinations in natural mixing areas of fresh and waste waters from different discharge outlets. The shoreline configuration, bottom topography, meteorological and hydrological conditions varied largely from one experiment to another. A wide range of tracers have been used: salinity, phosphate content, Rhodamine B, radioisotope ^{82}Br, free floats. The diffusion process has been studied either for continuous sources, or for point-instantaneous releases; there were also a few situations when instant releases (Rhodamine B or free floats) were made in the mixing plume from a continuous source.

The resulting turbulent coefficient values are within

the limits published in the litterature, but they also reveal a local character, as well as a strong dependence on space and time scales of the process. This results in a need for statistical analysis for a large number of experiments, and the most suitable method appears to be the use of surface drifters. Also, this inexpensive method does not use pre-set exponent value in the power dependence of K on the space scale (or, alternatively, the dependence of D^2 on the time scale), this value being also determined from experimental data. This is very important if one takes into account the fact that experimental exponent values close to 0,2/3,1 or 4/3 were found, and that a single model using a given exponent value, even though providing analitical solution, cannot be applied in all the experiments. The statistical results concerning the space scale dependence of the turbulent mixing coefficients could be very useful in defining diffusion models in which vertical velocity and density distribution, horizontal nonuniformity of the flow and non-steady state of the process would be included.

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