Estimation of the vertical eddy diffusion coefficient of heat in the Gulf of Trieste (Northern Adriatic)

Heat
Eddy diffusion
Least square fits
Northern Adriatic

Chaleur
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Moindres carrés
Nord de l'Adriatique

Vlado MALAČIČ
Institute of Biology, Marine Biology Station Piran, JLA 65, 66330 Piran, Slovenia, YU.

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ABSTRACT

The vertical eddy diffusion coefficient of heat has been computed from a least squares trigonometric fit of temperatures measured in the Gulf of Trieste ($\sim$21 m depth), at four levels of the water column, from January 1986 to September 1989.

This coefficient is supposed to be in the form of a constant plus a time and depth function. In climatological time scales, the constant coefficient is sufficient for the description of annual temperature changes in the lower part ($\sim$10-21 m depth) of the water column.

For the upper part of the column, the possible range of values of the coefficient for the shallow Gulf of Trieste is discussed.

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RÉSUMÉ

Estimation du cœfficient de diffision verticale turbulente de la chaleur dans le golfe de Trieste (Adriatique nord)

Le coefficient de diffusion verticale turbulente de la chaleur a été calculé par une méthode d'ajustement trigonométrique aux moindres carrés appliquée aux températures mesurées à quatre profondeurs dans une colonne d'eau du golfe de Trieste, de janvier 1986 à septembre 1989.

Ce coefficient se compose d'un terme constant et d'un terme variable avec le temps et la profondeur. Aux échelles climatologiques, le terme constant suffit pour décrire les variations annuelles de la température dans le bas de la colonne d'eau par des fonds de 10 à 21 m.

La gamme des valeurs probables du coefficient de diffusion dans le haut de la colonne fait aussi l'objet de discussion.

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INTRODUCTION

The aim of this paper is to present the estimation of the vertical eddy diffusion coefficient of heat (VEDCH) from temperature measurements at fixed stations in the Gulf of Trieste. This coefficient can also serve as the basis for other estimations of vertical turbulent diffusion parameters, such as the coefficient of turbulent diffusion of nutrients.

The calculation of VEDCH from the time series of temperatures at different depths was first discussed by Fjeldstad (1933) from the annual temperature time series measured in the Biscay gulf. He calculated the variations of VEDCH with depth and also examined its explicit time dependence, but without analyzing its dependence on stability of the water column. These VEDCH values decreased from 0 to 50 m depth, slightly increased back to 200 m depth, and were always below 20 cm^2/s. In Fjelstad's work a Fourier series in time was considered, but only the first term was used in calculations, as was also the case in analyses relative to the Kuroshio area (Sverdrup, 1942).

In more recent times, several expressions connecting the vertical eddy diffusion coefficients (VEDC), the Brünt-Väisälä frequency N^2, and the Richardson number R_i of the water column have been proposed (Munk and Anderson, 1948; Kullenberg, 1971; Kullenberg, 1982; Henderson-Sellers, 1984). Also relations between VEDC, friction velocity u_* and the mixing length 1 for neutral conditions were analyzed (Henderson-Sellers, 1985). But it may be remarked that there is usually a lack of measurements of marine currents in depths continuous enough to obtain reasonable estimates of the velocity shear distribution over at least one year. For this reason there have also been some attempts to describe VEDCH as dependent on N^2 only (Henderson-Sellers, 1984), the shearing (advection) effect being in this case averaged out within several years. Moreover, if vertical salinity changes through the water column can be disregarded, then VEDCH could depend only on the vertical gradient of temperature.

THE GULF OF TRIESTE

Measurements of temperature, salinity (and current) were carried out in the Gulf of Trieste (Stravisi, 1983 *b*) at station D (Fig. 1), about two miles west of Trieste, from July 1980 to December 1982. They were done 29 times during the period mentioned at the surface (0.1 and 0.5 m depth) and at each metre depth from 1 m to the bottom (~22.5 m depth). Stravisi found that the annual mean salinity increases approximately exponen-

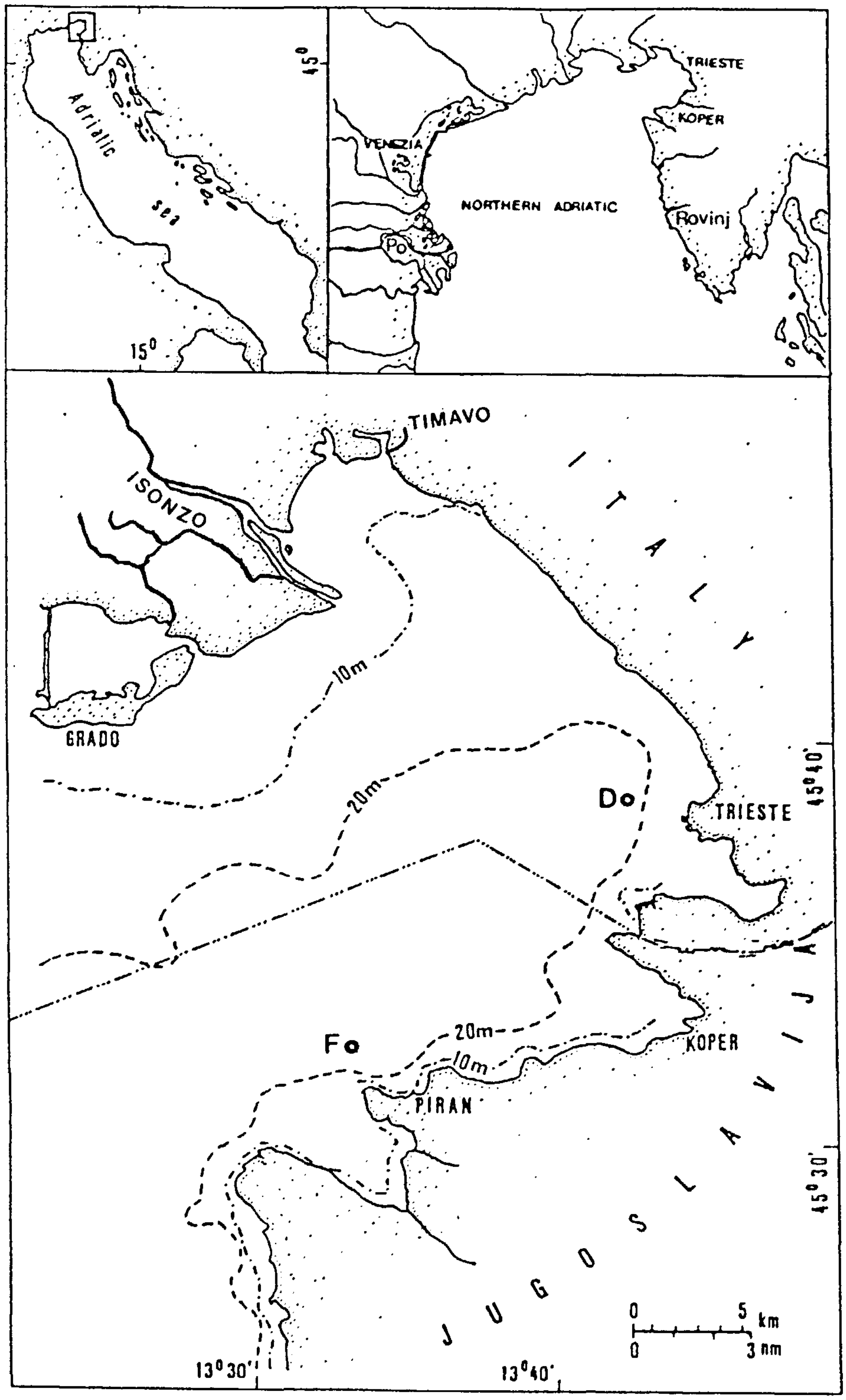


Figure 1

Location map of station F(45°32.33′N, 13°33.10′E) at the entrance of the Gulf of Trieste, and station D(45°38.5′ N, 13°42.5′E). Measurements of temperature and salinity were carried out from 1986 to 1989 at station F and from 1980 to 1982 at station D.

tially with depth at the surface and almost linearly below 5 m depth, while the temperature decreases with depth at station D almost linearly.

For the Italian part of the Gulf of Trieste, Stravisi (1983 *a*) calculated the downward irradiance attenuation coefficient γ from several hundreds of Secchi disc measurements, and found $\gamma = 0.24 \pm 0.05\,\mathrm{m}^{-1}$.

Continuous long-term measurements of currents in the Gulf of Trieste are not available, but from several hundreds of separate measurements of Eulerian and Lagrangian type (Stravisi, 1983 *c*; Stravisi, 1987; Mosetti, 1972; Michelato, 1973), the circulation in the gulf is seen to be mainly wind driven, with the vertically averaged velocity of ~ 10 cm/s. The surface layer of a thickness of ~ 5 m flows clockwise when westerly winds are present (52%), and counterclockwise when easterly winds principally the ENE "bora" (21%) blow. In this last case, the whole water column moves coherently, due to very gusty and quite strong bora wind, occurring, mainly in the winter period (mean velocity 6-15 m/s; Petkovšek and Paradiž, 1976). The bottom layer (below 10 m depth) moves counterclockwise almost permanently, with a typical transport velocity of 2-3 cm/s. Tidal currents (mean velocities 3-10 cm/s, stronger along the open boundary and NW coast) are most significant in calm weather (Stravisi, 1987), merely driving almost the same water mass forward and backward with a run of ~ 1 km. But from annual cycles of salinity, measured from 1955 to 1958 at Rovinj (Fig. 1), and at Fano, ~ 100 km south of the Po river outflow, Orlić (1989) concluded that the residual surface circulation in the central north Adriatic should primarily be of thermohaline origin, especially due to the strong Po river outflow (annual average rate $\sim 1.6 * 10^3\,\mathrm{m}^3/\mathrm{s}$; Degobbis, 1988). However, a serious analysis of the salinity data and river outflows still remains to be carried out in the Gulf of Trieste to estimate properly the density-driven currents.

Using bulk estimates, Stravisi and Crisciani (1986) have estimated the surface heat fluxes, averaged per month for the period 1980-1982 in the Gulf of Trieste. A comparison between the absorbed global solar irradiation and the sum of three major upward surface heat fluxes (IR radiation from the sea surface, latent heat of evaporation and heat transfer by conduction) can be obtained from their work. The sum of these fluxes has the annual mean $\sim 159\,\mathrm{W/m^2}$, with standard deviation (SD) $\sim 14\%$, while the rate of the global solar irradiation, reduced by the mean sea surface albedo (~ 0.35), has annual average $\sim 93\,\mathrm{W/m^2}$ and SD $\sim 57\%$ of the mean. This suggests that the total upward heat flux at the sea surface during the year roughly follows the irradiation minus the annual average sum of three fluxes (*see* also Bowden, 1983). From the rate of the heat storage in the water column per month, with the zero annual mean, one finds that the upward average heat flux from the surface has to be replaced by the advected heat from the south with a maximum during April and a minimum during September and October. The surface heating in early spring due to increased solar irradiation is therefore not considerably reduced by the sum of the surface heat losses, because of the increased input of heat from the south.

FORMULATION OF THE MODEL

Neglecting the advective terms on temperature, the diffusion equation for heat is

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + \frac{1}{c_p \rho}\frac{\partial I}{\partial z}, \tag{1}$$

where ρ and c_p are the sea water density and specific heat (assumed to be constants) and I the irradiance (which may be well replaced by the downward irradiance; Ivanoff, 1977) measured in the northern Adriatic. The common approach to describe the stratification cycle in lakes is to write K as the sum of a constant K_0 and a variable part (Henderson-Sellers, 1984), here assumed to be time and depth-dependent. Suppose the salinity changes along the vertical are not considerably affecting N^2, then the proposed form of VEDCH is

$$K = K_0 + K_1\left(\frac{\partial T}{\partial z}\right)^{-1}, \tag{2}$$

where K_1 is depth-and time-dependent, mostly due to velocity shear.

Global annual irradiance was estimated from the sunshine duration series from 1960 to 1979 and two least squares trigonometric regressions, with one and two harmonic terms (first with the period $t_0 = 365$ days, second with $t_0/2$) were done. In Table 1 the parameter

Table 1

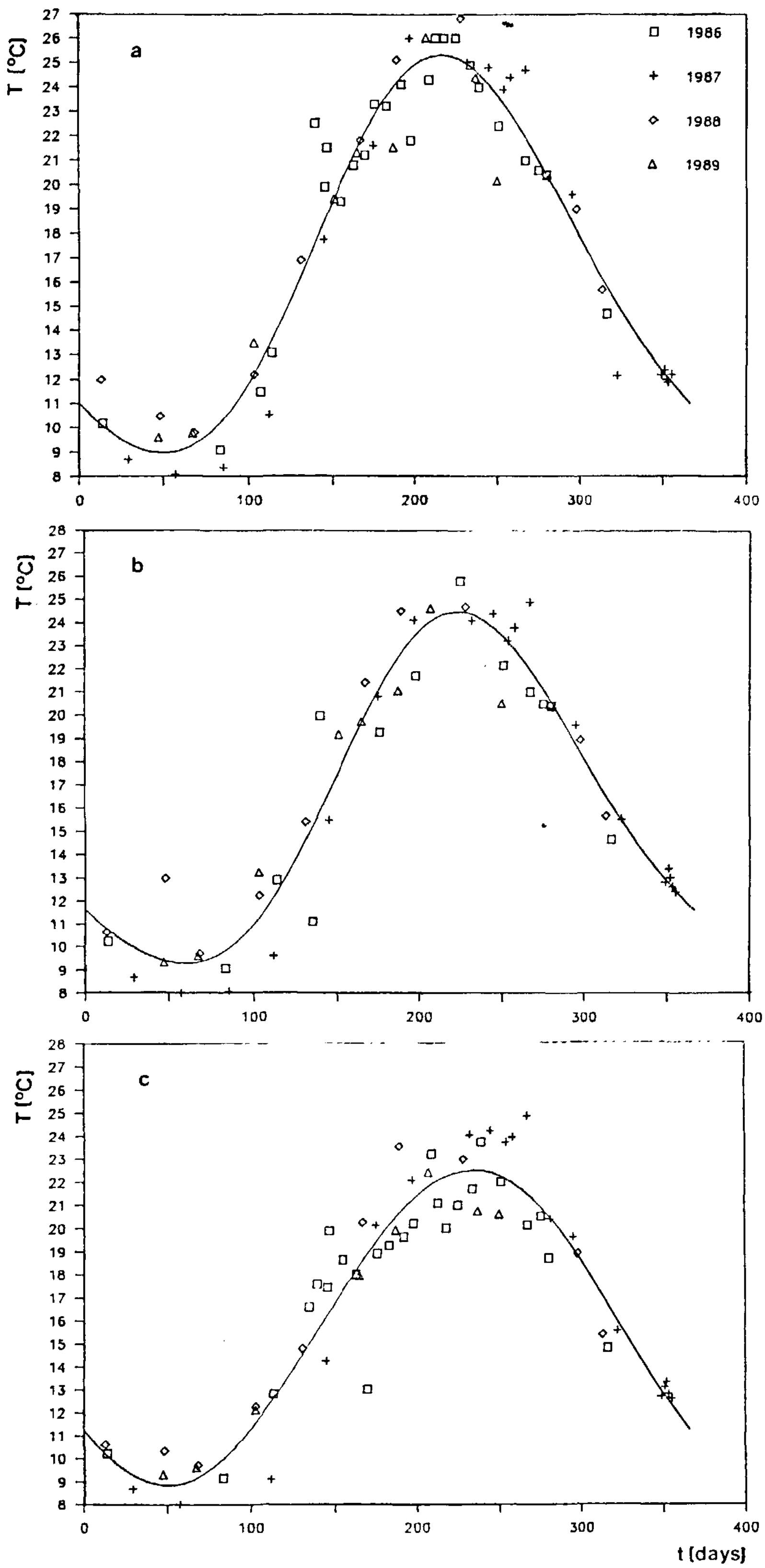
Coefficient values and standard deviations of two least squares trigonometric regressions, with one and two harmonic terms, of the global irradiance (I) estimation, made from the sunshine duration time series from 1960 *to* 1979, *and of the Secchi disk* (D_s) *measurements from January* 1986 *to September* 1989. *The regressions with two harmonic terms were done in a manner similar to fits for temperatures in depth, according to* (4) (*see text*). *Values of calculated irradiance per month, averaged for the mentioned period, have been taken for the least squares trigonometric fit.*

I_0 ($\mathrm{Wm^{-2}}$)	I_1 ($\mathrm{Wm^{-2}}$)	φ_1 (rad)	SD/I_0 10^{-2}	I_0 ($\mathrm{Wm^{-2}}$)	I_1 ($\mathrm{Wm^{-2}}$)	φ_1 (rad)	I_2 ($\mathrm{Wm^{-2}}$)	φ_2 (rad)	SD/I_0 10^{-2}
143.93	107.40	3.05	4.19	143.91	107.41	3.06	4.47	1.38	3.78
D_{s0} (m)	D_{s1} (m)	φ_1 (rad)	SD/D_{s0} 10^{-2}	D_{s0} (m)	D_{s1} (m)	φ_1 (rad)	D_{s2} (m)	φ_2 (rad)	SD/D_{s0} 10^{-2}
10.0	0.4	3.62	30.4	9.8	1.1	2.98	1.9	2.53	28.6

SD is standard deviation.

values of these regressions are presented: I_1 and I_2 are the amplitudes, φ_1 and φ_2 are the phase shifts (from the beginning of the year) of the cosine terms. From Table 1, it is evident that the second harmonic term does not significantly change the parameter values (I_1 and φ_1) of the first one (*see* also Fig. 3*a*), where φ_1 differs from π for <3%. It would thus probably be sufficient to describe the global annual irradiance cycle only with one periodic term having the minimum in time at the beginning of the year, *i.e.* at $t=0$. Supposing that in coastal waters almost all of the IR light is absorbed in the upper layer of thickness ~1 m (Octavio *et al.*, 1977), then the (downward) irradiance absorption may be described by a single exponential function of the depth z. The source term in (1) can then be written as

$$\frac{1}{c_p \rho}\frac{\partial I}{\partial z} = \frac{R\gamma I_0}{c_p \rho}\left(1 - \frac{I_1}{I_0}\cos(\Omega t)\right)e^{\gamma z}, \qquad z<0. \quad (3)$$



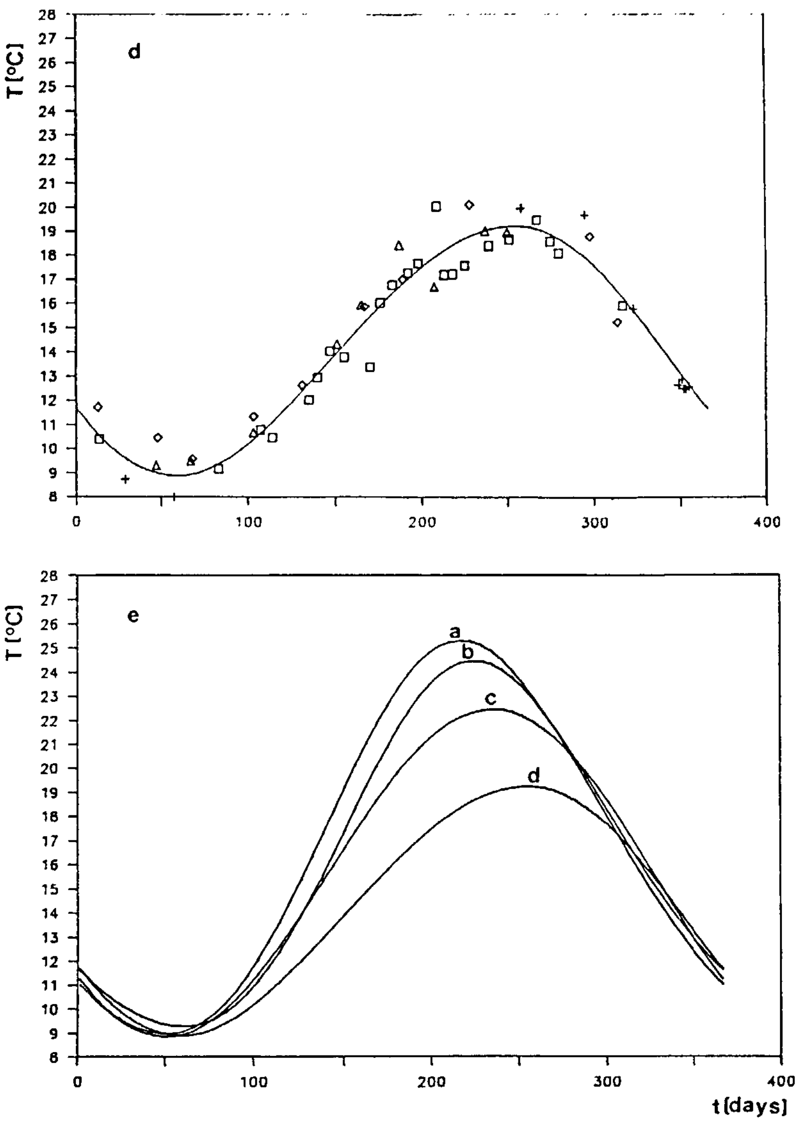


Figure 2

Trigonometric fits of temperatures, according to (4), *taken from four depths at station F from January* 1986 *to September* 1989 *for: a)* 0 *m, b)* 5 *m, c)* 10 *m, d)* 21 *m depths; e) all fits together.*

where I_0 is the annual average irradiance at the water surface, I_1 the amplitude of the irradiance annual variations, γ the attenuation coefficient of irradiance in the water column, and $\Omega = 2\pi/t_0$, where $t_0 = 365$ days. R is a numeric factor ($R \simeq 0.65$, Stravisi and Crisciani, 1986) representing the surface reflection and IR absorption in the surface layer (Octavio *et al.*, 1977).

As proposed solution of (1) we analyze the following function:

$$T = T_0(z) + T_1(z)\cos(\Omega t - \varphi_1(z)) + T_2(z)\cos(2\Omega t - \varphi_2(z)), \tag{4}$$

T_0, T_1, T_2, φ_1 and φ_2 are only depth-dependent.

By inserting (2), (3) and (4) into (1) we obtain five differential equations, connecting K_0 and the derivatives of T_0, T_1, T_2, φ_1, φ_2 and K_1

$$\left(\frac{\partial^2 T_1}{\partial z^2}\right)\left(\frac{\partial T_1}{\partial z}\right)^2 = \frac{T_1^3 \Omega^2}{4K_0^2} \tag{5a}$$

$$\left(\frac{\partial^2 T_2}{\partial z^2}\right)\left(\frac{\partial T_2}{\partial z}\right)^2 = \frac{T_2^3 \Omega^2}{K_0^2} \tag{5b}$$

$$K(\partial^2 T_2/\partial z^2) + \partial K/\partial z + \gamma A(1 - \Delta\cos(\Omega t))\exp(\gamma z) = 0, \tag{6}$$

$$\partial\varphi_1/\partial z = -\Omega T_1(2K_0\,\partial T_1/\partial z)^{-1}, \tag{7a}$$

$$\partial\varphi_2/\partial z = -\Omega T_2(K_0\,\partial T_2/\partial z)^{-1}, \tag{7b}$$

where $A = RI_0/(c_p\rho)$ and $\Delta = I_0/I_1$

In the above system there are more unknowns than equations, some of them being non-linear (5), others non-homogeneous (6); it cannot be uniquely determined. Nevertheless, we may still discuss one particular solution, which is in accordance with that found many years ago (Fjelstad, 1933).

Assuming $K_0 > 0$, nontrivial solutions of the nonlinear homogeneous equations (5 *a*) and (5 *b*), decreasing with depth, may be written as

$$T_i = T_{i0} \exp(\alpha_i z), \tag{8}$$

where $i = 1, 2$ and

$$\alpha_1^2 = \Omega/(2 K_0), \tag{9a}$$

$$\alpha_2^2 = \Omega/K_0, \tag{9b}$$

that avoid oscillations of T_i with depth. Putting (8) and (9) into (7), the linear phase shift changes with depth are found

$$\varphi_i = \varphi_{i0} + \alpha_i z, \qquad i = 1, 2, \tag{10}$$

where φ_{i0} are the phase shifts at the surface. Solutions (8) and (10) are also known for the solution with only one harmonic term ($T_2 = 0$; Fjeldstad, 1933; Sverdrup, 1942). For the solution of the equation (6), two different cases are considered:

A. $T_0'' = 0$, so the average annual temperature is linearly changing with depth. The solution for K_1 can be written in this case as

$$K_1 = K_{10} + A[1 - \Delta \cos(\Omega t)][1 - \exp(\gamma z)], \tag{11}$$

where K_{10} ($= K_1$ at $z = 0$) is time-dependent.

B. $T_0'' \neq 0$. Assuming $T_0 = T_{00} \exp(\gamma z)$, ($T_{00}$ being the surface annual average temperature), then the solution for K_1 follows

$$K_1 = K_{10} + [\gamma^2 T_{00} K_0 + A(1 - \Delta \cos(\Omega t))][1 - \exp(\gamma z)]. \tag{12}$$

One can also require $K_1 \to 0$ as $z \to -\infty$.

Temperatures at fixed depths have been fitted by the least squares method with the following expressions

$$T = T_0 + T_I \cos(\Omega t) + T_{II} \sin(\Omega t) + T_{III} \cos(2\Omega t) + T_{IV} \sin(2\Omega t),$$

which can be rewritten in the form (4).

The same was done for the global solar irradiance and for the Secchi disk depth (Fig. 2). Temperature and salinity measurements at levels 0, 5, 10 and 21 m at station F (Fig. 1) were performed about once per month from January 1986 to September 1989 on calm mornings, between 8 and 10 a.m., local solar time.

In Figure 2 the fits of temperature are shown, related parameter values are in Table 2.

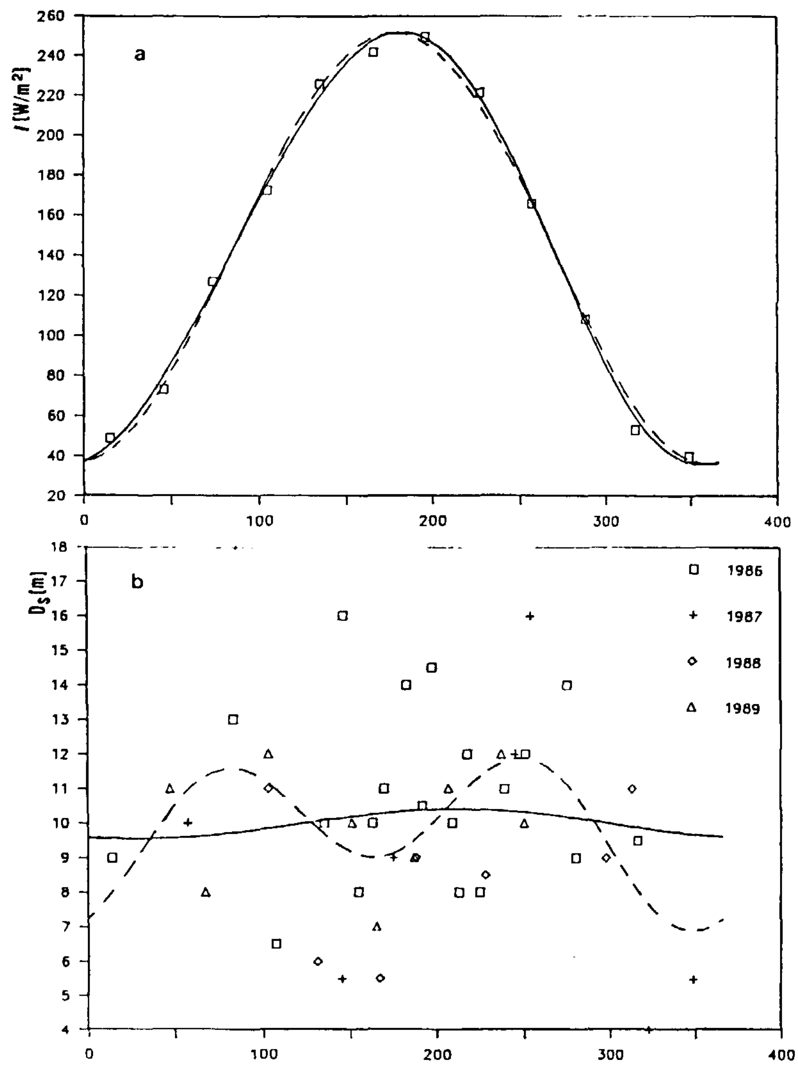


Figure 3

Least squares trigonometric fits of: a) global irradiance per month, averaged for 20 years, b) Secchi disk depth measurements at station F from January 1986 to September 1989. Full lines represent fits with one harmonic term, dashed lines fits with two terms.

Table 2

Parameter values of the least squares trigonometric fits of temperatures, taken at station F from four depths in the period from January 1986 *to September* 1989 *from* 8 *to* 10 *a.m., local solar time. Fits have two harmonic terms, according to* (4) (*see text*).

Depth (m)	T_0 (°C)	T_1 (°C)	φ_1 (rad)	T_2 (°C)	φ_2 (rad)	SD/T_0 10^{-2}	N
0	16.66	8.09	3.82	0.76	0.52	8.68	64
5	16.23	7.51	3.95	0.84	0.88	9.63	51
10	15.71	6.82	4.01	0.06	4.07	10.39	63
21	14.19	5.15	4.23	0.29	4.21	6.42	53

SD is standard deviation and N is the number of measured temperatures at fixed depth.

The sunshine duration was measured with Campbel-Stokes heliographs in Trieste (Stravisi and Jain, 1984) and at the Koper meteorological station (13°43.8′N, 45°32.9′E). Data from the latter station, covering the period from 1960 to 1979, were used for the global irradiance estimation (Hočevar *et al.*, 1982). Calculated irradiance values averaged per month have been taken for the least squares fit (Tab. 1), which was used as a measure for the irradiance in the period from 1986 to 1989 (Fig. 3 *a*).

Downward irradiance decreases more or less exponentially with depth (Ivanoff, 1977) and then, the Secchi disk depth D_s can be the estimation for the attenuation coefficient γ with the simple relation (Holmes, 1970).

$$\gamma \simeq 1.5/D_s,$$

The constant 1.5 was used (Justić, 1988) also for the northern Adriatic.

The measurements of D_s were done at the same location and in the same time interval as temperature measurements (Fig. 3 *b*). These values were fitted with trigonometric terms (Fig. 3) for the estimation of γ, averaged through almost four last years (see Tab. 1). Roughly speaking, the Secchi disk depths are around 10 m with about 30% of tolerance, which means $\gamma \simeq 0.15 \pm 0.05\,\mathrm{m}^{-1}$. This result is somewhere between the estimation mentioned by Justić for the northern Adriatic and that calculated by Stravisi for the Gulf of Trieste.

RESULTS

In Table 3 (Fig. 4), the depth dependency of T_0, T_1, T_2, φ_1 and φ_2 from the least squares fits of trigonometric functions of temperature is presented. The attenuation coefficient of T_0 with depth (linear or exponential) is about 19 times smaller than the average value $\gamma \simeq 0.15\,\mathrm{m}^{-1}$, calculated from the Secchi disc measurements (Tab. 1). Case A described in previous sections is here to be considered: T_0 decreases linearly with depth, which is not in disagreement with the results of the linear least squares fit (Tab. 3).

Although the fit of T_1 with an exponential function gives a bigger standard deviation than that with a linear function, there are two other arguments supporting the exponential decrease estimate (12) with depth of T_1. First, φ_1 changes with depth are almost linear (Fig. 4 and Tab. 3). Second, from the linear regression estimate (Tab. 3) of φ_1 with depth one obtains $\alpha_1 \simeq 0.019\,\mathrm{m}^{-1}$, close enough to the value $0.021\,\mathrm{m}^{-1}$ for the attenuation coefficient for T_1.

The same conclusions do not hold for the parameters of importance for the second harmonic term of the solution (4), φ_2, α_2 and T_2. But the ratio values T_2/T_1 are very small for all four depths, ~ 0.1 at most (Tab. 2).

It remains to calculate VEDCH. From (9 *a*), where for α_1 the value $0.02\,\mathrm{m}^{-1}$ is chosen, the value for K_0 follows

$$K_0 = \Omega/(2\alpha_1^2) \simeq 2.5\,10^{-4}\,\mathrm{m}^2/\mathrm{s}. \qquad (14)$$

K_1 is to be estimated from (13), where $R \simeq 0.65$ Stravisi and Crisciani, 1986), I_0 and I_1 are taken as $143.9\,\mathrm{W/m}^2$ and $107.4\,\mathrm{W/m}^2$ (Tab. 1), c_p as $4 \times 10^3\,\mathrm{J/(kg\,°C)}$ and ρ as $1025\,\mathrm{kg/m}^3$ (Unesco, 1987). Therefore A and Δ can be assumed to be $2.28 \times 10^{-5}\,\mathrm{m\,K/s}$ and 0.75 respectively. $|K_1|$ reaches its maximum value at the surface ($z=0$) for time $t = \pi/\Omega \simeq 183$ days, counted from 1 January. From fitted temperature values at different depths (Fig. 1), it is evident that during summer the temperature roughly decreases with depth for about 10°C per 20 m, or

Table 3

Exponential and linear least squares fits of T_0, T_1, T_2, φ_1 *and* φ_2 *changes with depth. The results found by Stravisi are marked with an asterisk. Fits were done from the mentioned parameters, found from the least squares trigonometric fits of temperatures at four depths* (0, 5, 10 *and* 21 *m*) *from station F, while the results of Stravisi were found from fits of temperatures at each m depth from station D in the Gulf of Trieste. In the exponential case the depth dependency is:* $y = a_0 \exp(a_1 z)$; *and in the linear case:* $y = b_0(1 + b_1 z)$, *where the phase shift* $\alpha = b_0 \times b_1$ *for* φ_1 *and* φ_2.

	Exponential fit			Linear fit					
	a_0 (°C)	a_1 $10^{-3}\,\mathrm{m}^{-1}$	SD/a_0 10^{-3}	b_0 (°C)	b_1 $10^{-3}\,\mathrm{m}^{-1}$	SD/b_0 10^{-3}	b_0^* (°C)	b_1^* $10^{-3}\,\mathrm{m}^{-1}$	SD^*/b_0^* 10^{-3}
T_0	16.82	− 7.8	10.7	16.79	− 7.1	8.8	15.79	− 7.5	4.4
T_1	8.25	−21.4	21.7	8.16	−17.0	9.1	8.77	−11.4	19.4
T_2	0.55	−58.2	707	0.73	−36.9	472			

	a_0 (rad)	a_1 $10^{-3}\,\mathrm{m}^{-1}$	SD/a_0 10^{-3}	b_0 (rad)	b_1 $10^{-3}\,\mathrm{m}^{-1}$	SD/b_0 10^{-3}	α $10^{-3}\,\mathrm{m}^{-1}$	b_0^* (rad)	b_1^* $10^{-3}\,\mathrm{m}^{-1}$	SD^*/b_0^* 10^{-3}	α $10^{-3}\,\mathrm{m}^{-1}$
φ_1	3.83	4.75	5.6	3.83	5.01	5.5	19.2	3.72	6.61	5.1	24.6
φ_2	3.78	5.78	37.2	3.785	6.03	36.0	22.8		$<$	$\leqslant$	$>$

SD is standard deviation.

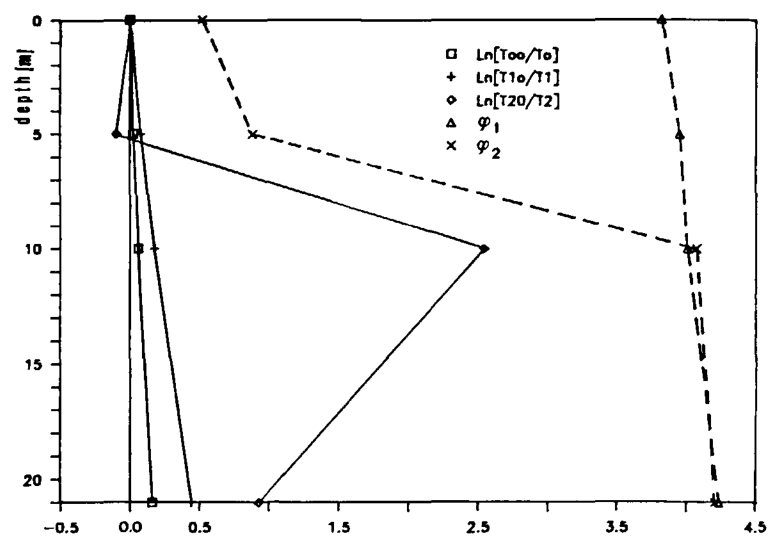


Figure 4
Depth dependency of the parameters of the least squares trigonometric fits of temperature. T_{00}, T_{10} *and* T_{20} *are the surface values of* T_0, T_1 *and* T_2. *Full lines connect* $ln(T_{N0}/T_N)$, $N=0, 1, 2$, *dashed lines connect phase shifts* φ_1 *and* φ_2.

$\partial T/\partial z \simeq 0.5$°C/m. Therefore from (2) the total annual VEDCH at the surface in summer is

$$K \simeq 1.7 \times 10^{-4}\,m^2/s. \qquad (15)$$

From the average Secchi disc depth $D_s \simeq 10$ m, it follows (Holmes, 1970) $\gamma^{-1} \simeq 6.7$ m. Therefore, in the lower part of the water column, for depths from 10 to 21 m, the variable part of VEDCH is almost negligible against the constant part K_0, due to the factor $\exp(\gamma z) < 0.22$ in (13) ($\partial T/\partial z$ is not decreasing with depth with this factor). So, in the lower part of the water column, the annual VEDCH is nearly constant, equal to K_0.

DISCUSSION

It may be asked how the results of the above simple model can be valid, since the advective heat flux from the south, significant in spring (Stravisi and Crisciani, 1986), has not been included. One of the problems is to estimate properly the $\nabla_H T$ and currents in an annual cycle, because no relevant measurements at the entrance of the Gulf of Trieste have yet been done. On the other hand, if there was no heat pumping from the south, temperatures of the upper layer would be significantly lower due to surface heat losses, which are not included in the model. The VEDCH estimation, especially for the upper part of the water column in summer, may contain significant error because of ignored advection.

Annual salinity variations have also been left out of consideration. This effect should be included in the form of the VEDCH (2), where the vertical temperature gradient should be replaced with N^2 (Henderson-Sellers, 1984). K_1 should therefore be replaced with $K_1/(1-R_\rho)$, where the density ratio $R_\rho = \beta\partial S/\partial z \times (\alpha\partial T/\partial z)^{-1}$ (Shay and Gregg, 1986) rep-

Table 4
Daily averages of measured temperatures ⟨T⟩ *and standard deviations* (SD) *at five depths* (0, 5, 10, 15 *and* 21 m) *during the seasons of* 1986 *and* 1987.

Date (dd/mm)	0 m ⟨T⟩ (°C)	0 m SD (°C)	0 m N	5 m ⟨T⟩ (°C)	5 m SD (°C)	5 m N	10 m ⟨T⟩ (°C)	10 m SD (°C)	10 m N	15 m ⟨T⟩ (°C)	15 m SD (°C)	15 m N	21 m ⟨T⟩ (°C)	21 m SD (°C)	21 m N
1986															
24/04	13.55	0.32	44	13.02	0.59	11	–	–	–	11.98	0.47	11	–	–	–
26/05	21.32	0.49	48	–	–	–	17.34	0.63	11	16.16	0.17	6	–	–	–
25/06	23.47	0.30	39	20.37	1.17	12	18.73	1.03	5	17.00	1.15	12	16.09	0.35	12
28/07	24.76	0.24	29	–	–	–	–	–	–	18.89	0.25	11	17.78	0.41	12
22/08	25.10	0.33	35	–	–	–	21.98	0.56	11	20.13	0.79	10	18.86	0.42	11
24/09	21.35	0.29	41	20.92	0.33	12	19.92	0.48	12	19.67	0.30	12	19.45	0.27	12
1987															
22/04	11.81	0.62	28	9.85	1.29	13	9.18	0.42	12	8.80	0.17	12	8.62	0.14	13
25/05	18.64	0.36	41	15.59	0.71	13	14.20	0.25	13	–	–	–	12.34	0.34	12
24/06	22.79	0.60	35	20.84	0.31	11	19.95	0.30	11	15.96	0.27	11	15.29	0.24	11
16/07	25.96	0.27	43	24.90	0.59	13	22.07	0.45	13	19.47	0.80	13	15.98	0.48	13
20/08	25.74	0.41	48	24.40	0.42	13	23.59	0.15	13	21.91	0.43	13	19.92	0.30	13
15/09	24.78	0.38	45	24.11	0.19	12	23.87	0.14	12	22.97	0.30	12	20.18	0.18	12

SD is standard deviation.

resents the relative contributions of the temperature and salinity gradients to the stratification. This, of course, complicates the problem because R_ρ is depth- and time-dependent. From the monthly means of temperature and salinity measurements done by Stravisi (1983*b*) from 1980 to 1982 at station D (Fig. 1) in the Trieste Gulf interior it follows that the Gulf of Trieste is from January to September in the quadrant 2 of the gradient T-S diagram, which means that it is diffusively stable and that the diffusive models can be used within this period. Then $R_\rho<0$ and $K_1/(1-R_\rho)<K_1$, which means that the lower estimation for VEDCH in the upper part of the water column ($1.7\,cm^2/s$) should probably be increased. From the average T and S values for June around 5 m depth, using Stravisi's slopes for T and S at 4-6 m depth (0.5-10 m), the density ratio $|R_\rho|\simeq 1.6$ ($\simeq 1.5$) is found, being bigger near the surface and smaller in depth. Salinity values from 1986 to 1989 at station F are widely dispersed (Fig. 5), but, from the fits of trigonometric functions of salinity at four depths, a rough estimation of $\partial S/\partial z$ could be done. The salinity varies considerably throughout the year in the upper half of the water column (from $\sim 34.8\,^0/_{00}$ at the surface, to $\sim 36.2\,^0/_{00}$ at 10 m depth), which gives $\partial S/\partial z \simeq -0.14\,^0/_{00}\,m^{-1}$ in the summer period. Taking $\partial T/\partial z \simeq 0.5$°C/m, $\alpha \simeq 2.7\times 10^{-4}$/°C and $\beta \simeq 7.4\times 10^{-4}$ for T=21.5°C and $S \simeq 35.6\,^0/_{00}$ (Unesco, 1987), then $|R_\rho|\simeq 0.8$. This should be confirmed with further measurements of better vertical resolution. Whether the variable part due to river discharges actually decreased by the factor 1.8, and the lower estimation of VEDCH at the surface increased to $\sim 2.1\,cm^2/s$, remains to be determined. In the summer, daily and weekly changes in salinity (Fig. 5) are stronger due to local estuaries and outflows, depending on weather conditions. This means that station F is too close to the coast and therefore could not be a very good pattern for the Gulf of Trieste.

Beside annual measurements of temperature once per month, during the seasons of 1986 and 1987 twelve daily measurements of temperature at various depths were done at station F (Tab. 4) with the same experimental method. At the surface from 28 to 48 temperature measurements were done, while in depth usually only ~ 12. From one-day measurements in April and May 1986-1987 the standard deviations (SD) are found to be maximal at 5 m depth. One-day measurements in August 1986-1987 show the SD maximum to be at 15 m depth (in May 1986 and in August 1987 the deviations are the same, due to experimental error). The temperature fluctuates mostly at 10 m depth during one-day measurement in May and September 1986. Unfortunately, measurements at 5 m depth were not done in May 1986. Only from one-day measurements in June and September 1987 it follows that major SD are found at the surface. We can conclude that the daily temperature fluctuations are mostly affected by advection and not by irradiance absorption, which is greatest at the surface. This effect is mainly due to quite strong horizontal temperature gradients near the coast, and the periodical motions with the period within one day (tides, inertial currents) bring warmer (cooler) water from the coastal (open) side to station F. So the phase shift, shown in Figure 3, cannot result from diurnal heating (cooling) processes.

On an annual time scale, the short period motions should be averaged out from proper measurements and the contribution of the residual currents on thermal structure at the entrance of the Gulf of Trieste in the period of the strong horizontal temperature gradient (during early spring?) would be evident. In future work, the diffusion equation (1) will have to be solved numerically to include salinity and advection effects.

CONCLUSION

The overall conclusion of the results described above is that VEDCH at the entrance of the Gulf of Trieste

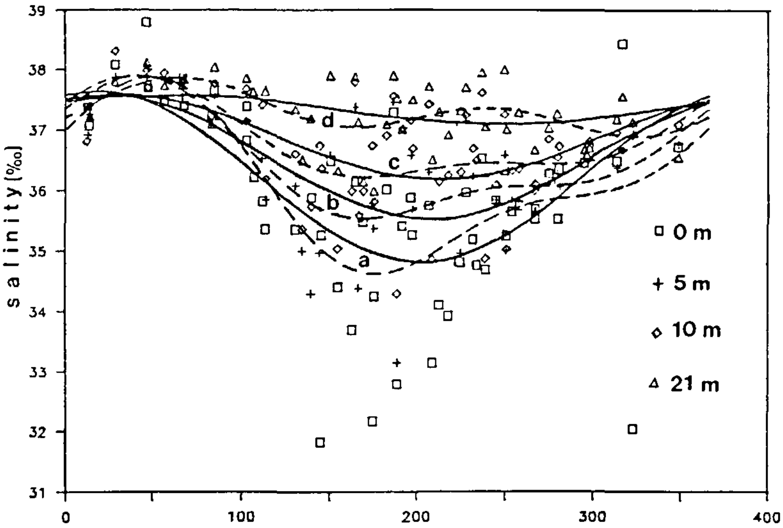


Figure 5

Salinity values at station F from January 1986 to September 1989 and trigonometric fits. Full lines represent fits with one harmonic term, dashed lines fits with two terms for: a) 0 m, b) 5 m, c) 10 m, d) 21 m depths.

has values from $1.7\text{-}2.5 \times 10^{-4}\,m^2/s$, the variations being naturally the greatest at the surface. VEDCH for the upper part of the water column reaches its minimum in the summer, when a strong temperature stratification is present. In the lower part of the water column, the annual variations of VEDCH are almost negligible and VEDCH has greater values than those at the surface.

The above result was obtained from a simple one-dimensional diffusion model of heat, by using a hypothetical solution for temperature and a hypothetical form of VEDCH which for simplicity was dependent only on the temperature stratification. The effect of salinity stratification at the surface, which reduces VEDCH at the surface during the season was described in the discussion section. The solution has been adapted to the least squares fits trigonometric solutions of temperature at the four depths.

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