A model of daily temperature changes in the upper sea layer taking superficial and bulk pollution with petroleum substances (DKTz-3) into consideration

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Abstract

The paper presents a mathematical model of daily temperature changes in the upper sea layer taking into account the time-variable appearance of superficial and bulk pollution by petroleum substances. The model utilizes the expression for the transmission of radiation in the sea given by Czyszek (1985). The effect of temporary pollution was taken into account by modifying the coefficient of seawater absorption. The calculations were performed for the southern Baltic. The effect of pollution by petroleum substances on the evolution and depth of the daily thermocline was examined.

1. Introduction

Heat exchange between the sea and the atmosphere, mixing due to wave action, as well as convective movements, may lead to diurnal water temperature variations. In many oceans these variations are as great as 1.5°C over a two-day period (Perry and Walker, 1982). Mathematical modelling of upper sea layer temperature variations constitutes an important step towards a better understanding of the physical principles of the climate, weather variability and mutual interaction between the atmosphere and the ocean. Today, when analysing temperature distribution, it is necessary to consider pollutants as factors interfering with the interaction of the particular elements of the ocean – atmosphere system. Karbowniczek-Gratkowska (1990, 1991) and Karbowniczek-Gratkowska and Zieliński (1990) have presented mathematical models of seasonal changes in the temperature of the upper layer of a sea polluted superficially or in bulk by petroleum substances (DKTz-1 and DKTz-2). The models were adaptations of the integral, unidimensional model disregarding the effect of pollution presented by Thompson (1976) and called by him DKT to emphasize that it was a continuation of the work by Denman (1973), and Kraus and Turner (1967). They can be relatively easily adapted to the analysis of short-term variations in seawater temperature. In this case one must consider the transmission of the entire range of solar radiation, as well as its dependence on the elevation of the Sun and on weather parameters. It has been demonstrated that in model calculations of the temperature of a calm sea the differences in parametrization of solar energy transmission in seawater may result in significant differences between the results obtained (Simpson and Dickey, 1981). It has been observed that the climate and the global circulation in seas are very strongly dependent on the transparency of ocean waters, and hence, on the transmission of solar radiation (Woods *et al.*, 1984). Czyszek (1985) derived an expression for solar radiation transmission in seawater taking into account its dependence on measured environmental parameters in a more comprehensive way. In the case of long-term temperature variations considering such a dependence is not necessary. This expression has been utilized in the DKTz-3 model of daily variations in the upper sea layer temperature presented in this paper (Karbowniczek-Gratkowska, 1991).

2. Assumptions and description of the DKTz-3 model

The following assumptions have been adopted in the DKTz-3 model:

- the sea is uniformly stratified,
- the depth of the basin examined is greater than the radiation penetration depth,
- the processes of vertical exchange between the sea and the atmosphere and vertical mixing in the sea alter the local conditions in the upper layer to a much greater extent than horizontal advection and diffusion,
- absorption of solar radiation in the sea takes place in the entire water volume,
- the sea surface is smooth and covered with a thin, uniform crude oil layer of thickness h,

- bulk pollution with crude oil is uniform in the upper sea layer,
- the volume concentration of crude oil in water c_k is low and does not affect the seawater density,
- the absorption of light by the petroleum substances and by the remaining components of seawater is additive,
- the occurrence of suspensions and pollutants other than oil is allowed for by changing the value of the light absorption coefficient of sea water.

The upper sea layer is divided into N sublayers. If the initial temperature profile has the form $[T_n(t)]$, where $T_n(t)$ is the temperature of the n-th sublayer ($n = 1, 2, \dots N$), then after a time Δt the profile $T_n(t + \Delta t)$ is obtained. Assuming bulk absorption of solar energy, the following dependences are obtained:

$$\begin{cases} T_1(t+\Delta t) & = & T_1(t) & + & [Q_0 + \eta(0) - \eta(\Delta z)]/(c_p\rho_w\Delta z) \\ T_2(t+\Delta t) & = & T_2(t) & + & [\eta(\Delta z) - \eta(2\Delta z)]/(c_p\rho_w\Delta z) \\ \dots \\ T_{n+1}(t+\Delta t) & = & T_{n+1}(t) & + & \{\eta(n\Delta z) - \eta[(n+1)\Delta z]\}/(c_p\rho_w\Delta z), \end{cases} \tag{1}$$

where
Δz – sublayer thickness,
Q_0 – heat of exchange at the sea – atmosphere boundary,
η – solar radiation dose,
ρ – seawater density,
c_p – seawater specific heat.

Radiant energy doses absorbed in the first and subsequent sublayers are calculated from (Czyszek, 1985)

$$\begin{cases} \eta(0) - \eta(\Delta z) & = & \eta^0\bar{T}_{at}\bar{T}_p[1 - \bar{T}_r(\Delta z)] \\ \dots \\ \eta(n\Delta z) - \eta[(n+1)\Delta z] & = & \eta^0\bar{T}_{at}\bar{T}_p\{\bar{T}_r(n\Delta z) - \bar{T}_r[(n+1)\Delta z]\}, \end{cases} \tag{2}$$

where
$\eta(0)$ – solar energy dose just below the surface,
$\eta(\Delta z)$ – solar energy dose just below the first layer,
$\eta(n\Delta z)$ – solar energy dose just below the n-th layer,
η^0 – solar energy dose reaching the upper atmosphere layer,
T_{at} – transmission of the solar energy dose through the atmosphere,
T_p – transmission of the solar energy dose through the sea surface,
$T_r(n\Delta z)$ – transmission of the solar energy dose through n layers.

Solar energy doses reaching depth z can be calculated from

$$\eta(z) = \eta^0\bar{T}_{at}\bar{T}_p\bar{T}_r(z). \tag{3}$$

Absorption coefficients of seawater polluted with crude oil are calculated from the equation

$$\begin{aligned} a(\Delta\lambda_m) &= c_k a_r(\Delta\lambda_m) + (1-c_k)a_w(\Delta\lambda_m) = c_k[a_r(\Delta\lambda_m) + \\ &- a_w(\Delta\lambda_m)] + a_w(\Delta\lambda_m), \end{aligned} \qquad (4)$$

where

$a_r(\Delta\lambda_m)$ – crude oil absorption coefficient in the $\Delta\lambda_m$ wavelength range,
$a_w(\Delta\lambda_m)$ – seawater absorption coefficient in the $\Delta\lambda_m$ wavelength range,
$c_r = \frac{V_r}{V_r+V_w}$ – volume concentration of crude oil in water,
V_r – volume of oil in water,
V_w – water volume.

The absorption coefficient κ (the virtual part of the complex refraction coefficient), appearing in the expressions for the energetic reflection coefficient R, absorption of radiation in the oil layer A_1, and absorption of radiation in the sea A_2 (Karbowniczek-Gratkowska, 1991), is related to the absorption coefficient by the equation:

$$a(\lambda) = 4\pi\kappa(\lambda)/\lambda. \qquad (5)$$

The heat of exchange Q_0 at the sea-atmosphere boundary in time Δt has been defined in the same way as the concept of radiant energy dose:

$$Q_0 = \int_{\Delta t} Q\,dt = \bar{Q}\Delta t, \qquad (6)$$

where

$$Q = Q_e + Q_h + Q_b + \Pi, \qquad (7)$$

where

Q_0 – mean heat exchange flux at the sea – atmosphere boundary in time Δt,
Q – heat exchange flux at the sea – atmosphere boundary,
Q_e – heat of evaporation flux,
Q_h – flux of heat conducted from sea to the atmosphere,
Q_b – flux of effective heat radiation at the sea – atmosphere boundary,
Π – flux of radiation absorbed by the oil film.

The change in the potential energy of the surface layer due to wind-generated turbulent mixing in time Δt is determined by the empirical formula (Turner, 1969)

$$A = m' c_D \rho_a u_{10}^3 \Delta t, \qquad (8)$$

where

u_{10} – wind velocity at an altitude of 10 m,
ρ_a – density of the atmosphere,
c_D – momentum exchange coefficient,

$m\prime$ – empirical proportionality factor.

The $m\prime$ factor in formula (8) is variable and depends on dimensionless combinations of numerous parameters characterizing the environmental conditions. In this model, both this factor and the momentum exchange coefficient c_D are affected by bulk and surface oil pollution (Byutner and Dubov, 1985). The daily temperature variations of the upper sea layer are determined by the heat fluxes resulting from the absorption of solar radiation, by the intensity of turbulent mixing, heat exchange between the sea and the atmosphere, evaporation and long-wave radiation. All these factors are affected by bulk and surface pollution with crude oil.

Calculations of solar radiation transmission in seawater are performed according to the formula developed by Czyszek (1985):

$$\begin{aligned} T_r(z) &= \frac{\Sigma^m[(1-d_E)p(\Delta\lambda_m)+d_E r(\Delta\lambda_m)]T_p(\Delta\lambda_m)}{\Sigma_m[(1-d_E)p((\Delta\lambda_m)+d_E r(\Delta\lambda_m)]T_p(\Delta\lambda_m)} \times \\ &\times \; exp[-a(\Delta\lambda_{m,z})D_1(\Delta\lambda_{m,}z=0)z], \end{aligned} \tag{9}$$

where

d_E – diffusivity of radiation across the entire spectral range reaching the sea surface,

$p(\Delta\lambda_m)$ – relative energy proportion of the $\Delta\lambda_m$ spectral range in directional radiation reaching the sea surface under given weather conditions and at a given elevation of the Sun,

$r(\Delta\lambda_m)$ – relative energy proportion of the $\Delta\lambda_m$ spectral range in diffuse radiation reaching the sea surface under given weather conditions and at a given elevation of the Sun,

$T_p(\Delta\lambda_m)$ – transmission of radiation from the $\Delta\lambda_m$ range through the sea surface,

$a(\Delta\lambda_m, z)$ – absorption coefficient of radiation from the $\Delta\lambda_m$ range in water at depth z,

$D_I(\Delta\lambda_m, 0)$ – distribution functions of the downward radiation at the $z = 0$ level.

The transmission of solar radiation from the $\Delta\lambda_m$ range through a sea surface covered with an oil film of thickness h can be calculated from

$$\overline{T}_p(h,\Delta\lambda_m) = \frac{A_2(\Theta,h,\Delta\lambda_m)}{A_2(\Theta,0,\Delta\lambda_m)}\overline{T}_p(\Delta\lambda_m), \tag{10}$$

where

$\overline{T}_p(\Delta\lambda_m)$ – transmission of radiation from the $\Delta\lambda_m$ range through a clean sea surface,

$A_2(\Theta, h, \Delta\lambda_m)$ – energy coefficient of absorption of radiation from the $\Delta\lambda_m$ range in a sea covered by a thin film of oil of thickness h for an angle of incidence Θ (in particular $h = 0$).

The transmission of solar energy radiation through the sea surface $\bar{T}_p$ is averaged for the entire wavelength range; this can be done in many ways. In the numerical calculations, the arithmetic mean was adopted:

$$\bar{T}_p(h) = \frac{\Sigma_m \bar{T}_p(h, \Delta\lambda_m)}{m}. \tag{11}$$

Temperature changes in the different sublayers Δz cause the potential energy of the entire surface to change. The solar energy absorbed stabilizes the entire layer by decreasing its potential energy. The main factor destabilizing the layer is turbulent mixing, generated in the surface layer by the wind. The algorithm of the calculations is based on the principle that the energy balance of the influence of the stabilizing and the destabilizing factors is calculated in each time step. The potential energy increases during turbulent mixing. This proceeds in such a manner that the initially uniform first layer is joined by the consecutive layers lying below it. The thickness and the temperature of the mixed layer are calculated in the way reported by Karbowniczek-Gratkowska (1991).

3. Results of numerical calculations using the DKTz-3 model

The values of $p(\Delta\lambda_m, z = 0^-)$, $r(\Delta\lambda_m, 0^-)$ and $T_p(\Delta\lambda_m)$ depend on the elevation of the Sun and on the weather conditions (turbidity of the atmosphere, cloud cover). To determine the instantaneous values of $p(\Delta\lambda_m, z = 0^-)$ and $r(\Delta\lambda_m, z = 0^-)$ is very complicated and requires complex instrumentation. Hence, when calculating the transmission of radiation in water one does better to use the literature values of these coefficients based on long-term measurements. For a clear sky, the distribution coefficients $p(\Delta\lambda_m, z = 0^-)$ and $r(\Delta\lambda_m, z = 0^-)$ were calculated from data (Glagolev, 1970) on the quantity of solar radiation energy in a given spectral range $\Delta\lambda_m$ at the lower boundary of the atmosphere (Czyszek, 1985). The coefficients $p(\Delta\lambda_m, z = 0^-)$ and $r(\Delta\lambda_m, z = 0^-)$ were calculated depending on the elevation of the Sun and atmospheric turbidity. Owing to the lack of data $r(\Delta\lambda_m, z = 0)$ was assumed to have the same value for all atmospheric turbidities in calculations of the solar radiation transmission in the sea. Non-selectivity of solar radiation transmission through the sea surface, $T_p(\Delta\lambda_m) = 0.95$, was assumed for completely and partly overcast skies. Under the so-called mean conditions of radiation to the sea surface (partial cloud cover) a value of $d_E = 0.46$ was adopted (Rusin, 1979). When the sky was completely overcast it was assumed that $d_E = 1$, *i.e.* that only scattered radiation reached the sea surface. The values of $p(\Delta\lambda_m, z = 0^-)$ $r(\Delta\lambda_m, z = 0^-)$, $T_p(\Delta\lambda_m)$, $D_I(\Delta\lambda_m, 0)$ and d_E for various weather conditions are listed in Tables 1–7. Table 8 gives the values of the radiation absorption coefficients in light and heavy oil and in eutrophic water used in calculating the transmission according to equation (9) (Arst and Kard, 1983).

Table 1. Coefficients of relative spectral distribution of directional illumination reaching the sea surface $p_m = p((\Delta\lambda_m, z = 0^-)$ *vs.* solar elevation (clear sky, small opacity) (Czyszek, 1985)

	Solar elevation							
$\Delta\lambda_m$ [μm]	10°	20°	30°	40°	50°	60°	70°	80°
0.30–0.32	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
0.32–0.34	0.0010	0.0020	0.0030	0.0025	0.0020	0.0035	0.0045	0.0055
0.34–0.36	0.0020	0.0040	0.0060	0.0070	0.0080	0.0090	0.0100	0.0105
0.36–0.38	0.0030	0.0060	0.0095	0.0110	0.0120	0.0135	0.0150	0.0165
0.38–0.40	0.0035	0.0075	0.0115	0.0130	0.0145	0.0150	0.0165	0.0195
0.40–0.44	0.0265	0.0310	0.0355	0.0365	0.0375	0.0380	0.0380	0.0385
0.44–0.48	0.0365	0.0440	0.0510	0.0525	0.0540	0.0535	0.0535	0.0530
0.48–0.52	0.0390	0.0470	0.0545	0.0555	0.0565	0.0565	0.0570	0.0570
0.52–0.56	0.0415	0.0500	0.0585	0.0590	0.0595	0.0595	0.0600	0.0600
0.56–0.60	0.0430	0.0515	0.0595	0.0600	0.0605	0.0610	0.0610	0.0615
0.60–0.64	0.0420	0.0500	0.0580	0.0585	0.0590	0.0595	0.0595	0.0600
0.64–0.68	0.0425	0.0505	0.0585	0.0590	0.0595	0.0600	0.0600	0.0605
0.68–0.70	0.0210	0.0250	0.0285	0.0290	0.0290	0.0295	0.0295	0.0300
0.70–0.74	0.0635	0.0575	0.0515	0.0510	0.0500	0.0500	0.0490	0.0490
0.74–0.79	0.0800	0.0730	0.0655	0.0640	0.0620	0.0610	0.0610	0.0600
0.79–0.84	0.0660	0.0605	0.0545	0.0535	0.0520	0.0510	0.0510	0.0500
0.84–0.86	0.0270	0.0240	0.0210	0.0205	0.0200	0.0200	0.0200	0.0200
0.86–0.99	0.0110	0.0525	0.0935	0.0925	0.0910	0.0895	0.0880	0.0865
0.99–1.03	0.0405	0.0360	0.0315	0.0320	0.0320	0.0320	0.0320	0.0320
1.03–1.23	0.0125	0.0570	0.1015	0.0990	0.0960	0.0950	0.0945	0.0940
1.23–1.25	0.0165	0.0140	0.0115	0.0125	0.0130	0.0120	0.0110	0.0105
1.25–1.53	0.0430	0.0390	0.0345	0.0345	0.0345	0.0340	0.0330	0.0320
1.53–2.10	0.0855	0.0780	0.0700	0.0690	0.0680	0.0670	0.0665	0.0655
2.10–3.00	0.0300	0.0275	0.0245	0.0240	0.0230	0.0225	0.0225	0.0220
3.00–4.00	0.0090	0.0085	0.0075	0.0070	0.0065	0.0045	0.0025	0.0005

Table 2. Coefficients of relative spectral distribution of directional illumination reaching the sea surface $p_m = p(\Delta\lambda_m, z = 0^-)$ *vs.* solar elevation (clear sky, medium opacity) (Czyszek, 1985)

	Solar elevation							
$\Delta\lambda_m$ [μm]	10°	20°	30°	40°	50°	60°	70°	80°
0.30–0.32	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
0.32–0.34	0.0015	0.0010	0.0005	0.0015	0.0030	0.0035	0.0045	0.0050
0.34–0.36	0.0020	0.0040	0.0060	0.0060	0.0060	0.0075	0.0090	0.0105
0.36–0.38	0.0025	0.0060	0.0095	0.0095	0.0095	0.0110	0.0130	0.0145
0.38–0.40	0.0025	0.0065	0.0105	0.0110	0.0115	0.0130	0.0145	0.0160
0.40–0.44	0.0265	0.0315	0.0360	0.0370	0.0380	0.0380	0.0380	0.0380
0.44–0.48	0.0365	0.0440	0.0520	0.0535	0.0545	0.0545	0.0545	0.0545
0.48–0.52	0.0380	0.0465	0.0545	0.0560	0.0570	0.0570	0.0570	0.0570
0.52–0.56	0.0400	0.0495	0.0590	0.0600	0.0615	0.0615	0.0615	0.0615
0.56–0.60	0.0415	0.0510	0.0605	0.0620	0.0630	0.0630	0.0630	0.0630
0.60–0.64	0.0405	0.0500	0.0595	0.0605	0.0620	0.0620	0.0620	0.0620
0.64–0.68	0.0410	0.0505	0.0600	0.0610	0.0625	0.0625	0.0625	0.0625
0.68–0.70	0.0410	0.0355	0.0300	0.0310	0.0320	0.0310	0.0300	0.0295
0.70–0.74	0.0665	0.0585	0.0505	0.0500	0.0490	0.0480	0.0475	0.0465
0.74–0.79	0.0830	0.0740	0.0645	0.0635	0.0620	0.0615	0.0610	0.0600
0.79–0.84	0.0690	0.0610	0.0530	0.0525	0.0515	0.0505	0.0500	0.0490
0.84–0.86	0.0270	0.0235	0.0200	0.0195	0.0195	0.0195	0.0195	0.0195
0.86–0.99	0.1190	0.1055	0.0920	0.0905	0.0890	0.0880	0.0870	0.0860
0.99–1.03	0.0420	0.0375	0.0330	0.0325	0.0320	0.0315	0.0315	0.0310
1.03–1.23	0.1295	0.1150	0.1000	0.0985	0.0970	0.0955	0.0945	0.0930
1.23–1.25	0.0140	0.0130	0.0120	0.0115	0.0110	0.0110	0.0110	0.0110
1.25–1.53	0.0435	0.0395	0.0355	0.0350	0.0345	0.0340	0.0335	0.0330
1.53–2.10	0.0890	0.0790	0.0690	0.0680	0.0670	0.0660	0.0650	0.0645
2.10–3.00	0.0300	0.0265	0.0230	0.0225	0.0225	0.0225	0.0220	0.0220
3.00–4.00	0.0090	0.0080	0.0070	0.0070	0.0070	0.0070	0.0070	0.0070

Table 3. Coefficients of relative spectral distribution of directional illumination reaching the sea surface $p_m = p(\Delta\lambda_m, z = 0^-)$ *vs.* solar elevation (clear sky, high opacity) (Czyszek, 1985)

	Solar elevation							
$\Delta\lambda_m$ [μm]	10°	20°	30°	40°	50°	60°	70°	80°
0.30–0.32	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
0.32–0.34	0.0005	0.0010	0.0015	0.0010	0.0005	0.0005	0.0005	0.0005
0.34–0.36	0.0005	0.0020	0.0030	0.0045	0.0060	0.0070	0.0080	0.0090
0.36–0.38	0.0005	0.0030	0.0060	0.0075	0.0095	0.0100	0.0105	0.0115
0.38–0.40	0.0005	0.0040	0.0080	0.0095	0.0105	0.0115	0.0125	0.0140
0.40–0.44	0.0180	0.0250	0.0320	0.0330	0.0340	0.0350	0.0365	0.0380
0.44–0.48	0.0270	0.0345	0.0480	0.0490	0.0500	0.0515	0.0530	0.0545
0.48–0.52	0.0270	0.0385	0.0500	0.0515	0.0530	0.0545	0.0560	0.0585
0.52–0.56	0.0275	0.0405	0.0530	0.0555	0.0585	0.0595	0.0605	0.0615
0.56–0.60	0.0300	0.0425	0.0550	0.0570	0.0595	0.0605	0.0615	0.0625
0.60–0.64	0.0305	0.0320	0.0540	0.0555	0.0575	0.0585	0.0595	0.0610
0.64–0.68	0.0300	0.0415	0.0530	0.0555	0.0585	0.0595	0.0605	0.0615
0.68–0.70	0.0130	0.0325	0.0540	0.0530	0.0515	0.0540	0.0565	0.0590
0.70–0.74	0.0710	0.0620	0.0530	0.0410	0.0500	0.0495	0.0490	0.0485
0.74–0.79	0.0775	0.0730	0.0690	0.0665	0.0640	0.0630	0.0620	0.0610
0.79–0.84	0.0750	0.0645	0.0560	0.0550	0.0540	0.0530	0.0520	0.0505
0.84–0.86	0.0290	0.0250	0.0215	0.0210	0.0205	0.0205	0.0200	0.0200
0.86–0.99	0.1300	0.1150	0.1000	0.0965	0.0935	0.0910	0.0885	0.0860
0.99–1.03	0.0460	0.0400	0.0340	0.0335	0.0330	0.0325	0.0320	0.0310
1.03–1.23	0.1400	0.1230	0.1060	0.1030	0.1000	0.1000	0.0955	0.0955
1.23–1.25	0.0175	0.0150	0.0130	0.0120	0.0110	0.0110	0.0110	0.0110
1.25–1.53	0.0500	0.0430	0.0365	0.0350	0.0335	0.0335	0.0330	0.0330
1.53–2.10	0.0975	0.0855	0.0730	0.0640	0.0555	0.0590	0.0620	0.0655
2.10–3.00	0.0330	0.0290	0.0250	0.0240	0.0230	0.0225	0.0220	0.0215
3.00–4.00	0.0090	0.0080	0.0075	0.0070	0.0070	0.0065	0.0060	0.0055

Table 4. Coefficients of relative spectral distribution of scattered illumination reaching the sea surface $r_m = r(\Delta\lambda_m, z = 0^-)$ *vs.* solar elevation (clear sky) (Czyszek, 1985)

	Solar elevation							
$\Delta\lambda_m$ [μm]	10°	20°	30°	40°	50°	60°	70°	80°
0.30–0.32	0.0055	0.0060	0.0065	0.0075	0.0090	0.0095	0.0100	0.0100
0.32–0.34	0.0055	0.0080	0.0105	0.0270	0.0435	0.0455	0.0480	0.0500
0.34–0.36	0.0300	0.0340	0.0380	0.0480	0.0580	0.0600	0.0615	0.0635
0.36–0.38	0.0390	0.0445	0.0500	0.0560	0.0620	0.0650	0.0675	0.0700
0.38–0.40	0.0275	0.0400	0.0530	0.0575	0.0620	0.0650	0.0675	0.0700
0.40–0.44	0.1330	0.1300	0.1270	0.1265	0.1255	0.1240	0.1230	0.1215
0.44–0.48	0.1400	0.1360	0.1320	0.1315	0.1310	0.1300	0.1295	0.1290
0.48–0.52	0.1155	0.1125	0.1100	0.1100	0.1100	0.1090	0.1085	0.1080
0.52–0.56	0.1015	0.0990	0.0960	0.0960	0.0960	0.0950	0.0940	0.0935
0.56–0.60	0.0855	0.0840	0.0830	0.0830	0.0830	0.0820	0.0810	0.0800
0.60–0.64	0.0730	0.0715	0.0705	0.0705	0.0705	0.0700	0.0690	0.0680
0.64–0.68	0.0640	0.0630	0.0620	0.0620	0.0620	0.0620	0.0620	0.0620
0.68–0.70	0.0300	0.0300	0.0300	0.0295	0.0290	0.0290	0.0285	0.0280
0.70–0.74	0.0115	0.0105	0.0100	0.0090	0.0080	0.0075	0.0070	0.0060
0.74–0.79	0.0200	0.0175	0.0150	0.0140	0.0120	0.0115	0.0110	0.0105
0.79–0.84	0.0110	0.0100	0.0090	0.0080	0.0070	0.0065	0.0060	0.0055
0.84–0.86	0.0055	0.0045	0.0035	0.0045	0.0055	0.0055	0.0060	0.0060
0.86–0.99	0.0170	0.0150	0.0125	0.0110	0.0095	0.0090	0.0085	0.0080
0.99–1.03	0.0060	0.0050	0.0040	0.0035	0.0030	0.0030	0.0030	0.0030
1.03–1.23	0.0130	0.0115	0.0100	0.0090	0.0080	0.0070	0.0065	0.0060
1.23–1.25	0.0025	0.0025	0.0025	0.0015	0.0010	0.0010	0.0010	0.0010
1.25–1.53	0.0025	0.0020	0.0020	0.0015	0.0010	0.0010	0.0010	0.0010
1.53–2.10	0.0030	0.0035	0.0040	0.0035	0.0030	0.0030	0.0025	0.0025
2.10–3.00	0.0010	0.0015	0.0020	0.0015	0.0010	0.0010	0.0010	0.0010
3.00–4.00	0.0005	0.0005	0.0005	0.0005.	0.0005	0.0005	0.0005	0.0005

Table 5. Coefficients of relative spectral distribution of directional and scattered illumination reaching the sea surface $p_m = p(\Delta\lambda_m, z = 0^-)$ and $r_m = r(\Delta\lambda_m, z = 0^-)$ for a partly and completely overcast sky (Czyszek, 1985)

$\Delta\lambda_m$ [μm]	P_m	r_m
0.30–0.32	0.0003	0.0053
0.32–0.34	0.0029	0.0277
0.34–0.36	0.0059	0.0359
0.36–0.38	0.0079	0.0392
0.38–0.40	0.0092	0.0366
0.40–0.44	0.0367	0.1073
0.44–0.48	0.0524	0.1127
0.48–0.52	0.0557	0.0928
0.52–0.56	0.0590	0.0819
0.56–0.60	0.0606	0.0708
0.60–0.64	0.0590	0.0598
0.64–0.68	0.0590	0.0528
0.68–0.70	0.0293	0.0247
0.70–0.74	0.0509	0.0327
0.74–0.79	0.0642	0.0498
0.79–0.84	0.0532	0.0310
0.84–0.86	0.0208	0.0139
0.86–0.99	0.0929	0.0413
0.99–1.03	0.0330	0.0186
1.03–1.23	0.1007	0.0352
1.23–1.25	0.0120	0.0050
1.25–1.53	0.0348	0.0059
1.53–2.10	0.0691	0.0147
2.10–3.00	0.0237	0.0042
3.00–4.00	0.0068	0.0008

Table 6. Values of radiation transmission from the $\Delta\lambda_m$ intervals through the sea surface $T_p(\Delta\lambda_m)$ for medium atmospheric opacity and solar elevation $h_\odot = 30°$ (Czyszek, 1978)

$\Delta\lambda_m$ [μm]	T_p
0.30–0.32	0.938
0.32–0.34	0.938
0.34–0.36	0.938
0.36–0.38	0.938
0.38–0.40	0.938
0.40–0.44	0.935
0.44–0.48	0.935
0.48–0.52	0.935
0.52–0.56	0.935
0.56–0.60	0.935
0.60–0.64	0.935
0.64–0.68	0.936
0.68–0.70	0.936
0.70–0.74	0.931
0.74–0.79	0.931
0.79–0.84	0.932
0.84–0.86	0.931
0.86–0.99	0.933
0.99–1.03	0.931
1.03–1.23	0.934
1.23–1.25	0.933
1.25–1.53	0.936
1.53–2.10	0.935
2.10–3.00	0.935
3.00–4.00	0.935

Table 7. The proportion of scattered radiation d_E in the total radiation reaching the sea surface for a clear sky vs. solar elevation for high, medium and small opacity

Opacity	Solar elevation							
	10°	20°	30°	40°	50°	60°	70°	80°
high	0.663	0.411	0.311	0.247	0.220	0.199	0.182	0.179
medium	0.410	0.251	0.178	0.143	0.126	0.117	0.106	0.107
small	0.330	0.189	0.148	0.122	0.108	0.094	0.092	0.093

Table 8. Spectral distribution of the real and imaginary parts of the complex light refraction coefficient for seawater and crude oil (Arst, 1983)

$\Delta\lambda_m$ [μm]	Eutrophic seawater		Crude oil			
	η_2	$\kappa_2 \times 10^9$	light		heavy	
			η_1	$\kappa_1 \times 10^3$	η_1	$\kappa_1 \times 10^3$
0.30–0.32	1.3565	24.67	1.485	0.965	1.582	60.00
0.32–0.34	1.3524	19.17	1.478	0.675	1.570	40.00
0.34–0.36	1.3491	14.76	1.474	0.480	1.556	25.00
0.36–0.38	1.3465	11.19	1.470	0.340	1.548	17.50
0.38–0.40	1.3440	8.38	1.466	0.246	1.543	14.00
0.40–0.44	1.3412	5.08	1.460	0.146	1.530	9.90
0.44–0.48	1.3382	3.11	1.455	0.089	1.520	6.50
0.48–0.52	1.3360	1.91	1.452	0.059	1.510	4.50
0.52–0.56	1.3342	1.46	1.450	0.039	1.506	3.60
0.56–0.60	1.3318	1.25	1.449	0.025	1.503	3.00
0.60–0.64	1.3308	1.87	1.448	0.016	1.500	2.60
0.64–0.68	1.3304	2.36	1.448	0.011	1.498	2.26
0.68–0.70	1.3302	3.46	1.447	0.009	1.495	2.06
0.70–0.74	1.3295	10.60	1.447	0.007	1.493	1.88
0.74–0.79	1.3288	14.79	1.446	0.005	1.490	1.65
0.79–0.84	1.3277	18.16	1.446	0.005	1.486	1.50
0.84–0.86	1.3271	27.06	1.446	0.004	1.484	1.40
0.86–0.99	1.3280	73.60	1.446	0.004	1.481	1.10
0.99–1.03	1.3260	229.10	1.446	0.005	1.479	0.90
1.03–1.23	1.3230	600.00	1.446	0.009	1.472	0.80
1.23–1.25	1.3190	5260.00	1.446	0.018	1.464	0.74
1.25–1.53	1.3170	$3.00 \cdot 10^4$	1.446	0.030	1.460	0.78
1.53–2.10	1.3180	$3.85 \cdot 10^4$	1.446	0.105	1.448	1.40
2.10–3.00	1.2510	$2.00 \cdot 10^6$	1.412	1.400	1.490	3.20
3.00–4.00	1.1800	$1.20 \cdot 10^9$	1.440	1.000	1.490	2.30

To examine the sensitivity of the DKTz-3 model to changes in its parameter the experimental data from 26 July 1980 from the Gdańsk Deep was used (Czyszek, 1985). These data characterize the environmental conditions, a knowledge of which is necessary to determine daily temperature variations. These data are listed in Table 9.

Table 9. Environmental conditions in Gdańsk Deep on 26 July 1980

Hours		6^{30}–8^{30}	8^{30}–10^{30}	10^{30}–12^{30}
Solar elevation		10°	30°	40°
Cloudiness		clear sky		
$1 - d_E$		0.34	0.69	0.75
u_{10}		5.00	5.25	5.0
$\eta(0^-)^*$		0.419	1.29	1.73
$\bar{T}_p$		0.916	0.939	0.941
Q_0^*		-0.524	-0.529	-0.353
Hours	12^{30}–14^{30}	14^{30}–16^{30}	16^{30}–18^{30}	18^{30}–20^{30}
Solar elevation				
Cloudiness	overcast			
$1 - d_E$	0			
u_{10}	5.0	5.0	6.0	6.0
$\eta(0^-)^*$	4.17	2.08	1.17	0.449
$\bar{T}_p$	0.941	0.941	0.940	0.935
Q_0^*	-0.0515	-0.217	-0.299	-0.385

$\eta(0^-) = \eta(0^-)^* \times 10^6$ [J m^{-2}], $Q_0 = Q_0^* \times 10^6$ [J m^{-2}] $\eta(0^-)$ – radiation dose penetrating directly below the surface.

Figure 1 compares the evolution of mixed layer temperature determined experimentally (Czyszek, 1985) and calculated from the DKT-3 model (in the absence of pollutants). The initial temperature profile in the DKTz-3 model was assumed arbitrarily on the basis of data from the previous day. The time step adopted was 2 h, and the sublayer thickness $\Delta z = 0.25$ m at the number of sublayers $N = 50$. The m/c_D coefficient was selected on the basis of a numerical experiment. Its value in the consecutive stages is (3, 3, 3, 5.5, 9, 3.5, 3)$\times 10^{-6}$. The agreement between the measured and the calculated temperatures can be regarded as satisfactory, the more so, that the measured values are characterized by large errors and should be treated as maxim under the given environmental conditions (Czyszek, 1985). Figure 2 presents a similar comparison for the thickness of the mixed layer. Particularly good agreement was obtained for the time interval $t = 12^{30}$–18^{30}.

The reaction of the DKTz-3 model to the presence of pollutants was examined for light and heavy crude oil as in the cases of the DKTz-1 and

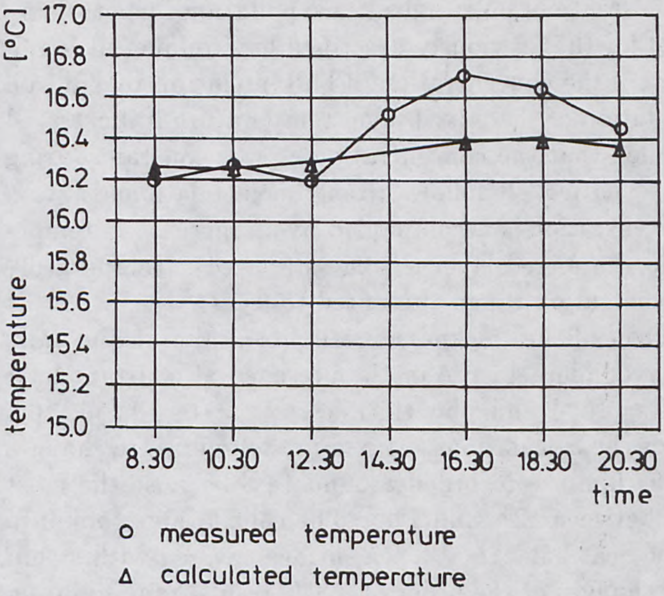

Fig. 1. The daily evolution of the instantaneous mixed-layer temperature (Czyszek, 1985) compared with the temperature calculated using the DKTz-3 model ($c_k = 0$, $h = 0$)

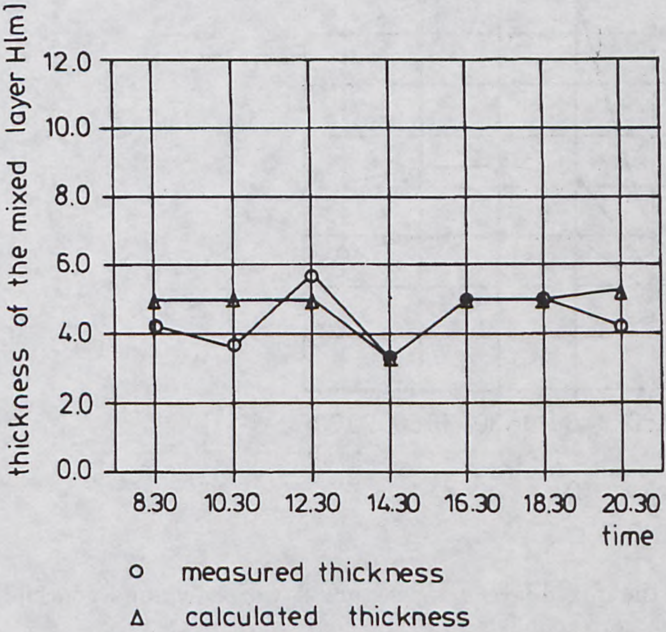

Fig. 2. The daily evolution of the instantaneous mixed-layer thickness (Czyszek, 1985) compared with the thickness calculated using the DKTz-3 model ($c_k = 0$, $h = 0$)

DKTz-2 models. The occurrence of bulk and surface pollution by petroleum substances was simulated for the previously described environmental conditions (Tab. 1). The effect of the concentration of bulk pollution by light oil (Tab. 8) on the daily evolution of the mixed-layer temperature is illustrated in Figure 3. It was assumed that the concentration c_k was constant during the entire period of daily heating. It follows from the calculations that an increase in pollutant concentration is accompanied by an increase in temperature and a reduction in the mixed layer thickness (Fig. 4). Temperature differences over this concentration range amounted to 0.5°C.

Figure 5 shows the effect of the thickness of a light oil film on the daily evolution of the mixed-layer temperature in the presence of constant bulk pollution. A value of $c_k = 10^{-4}$ and film thicknesses h =(0, 10, 50, 100, 1000)μm were adopted for the calculations. Maximum temperature changes due to the presence of the film are recorded around 14^{30} because the most intensive heating occurs between 12^{30} and 14^{30}. The calculations took into account the change in the heat balance at a sea surface covered with a thin film of oil. Temperature changes of the order of 0.8°C result from adopting the greatest thickness of the film occurring the entire daily period of heating.

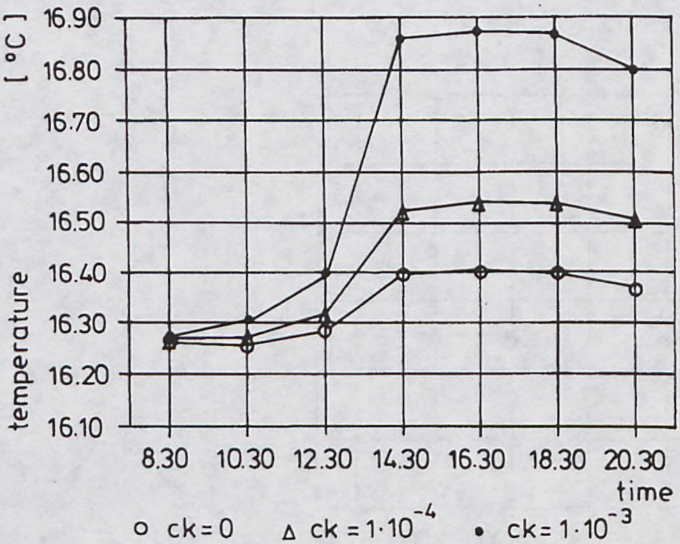

Fig. 3. Daily evolution of the mixed-layer temperature at various volume concentrations of light oil ($1.E - n$ corresponds to 10^{-n})

The change in the heat balance in the presence of an oil film significantly influences the calculations of temperature values. This is illustrated in

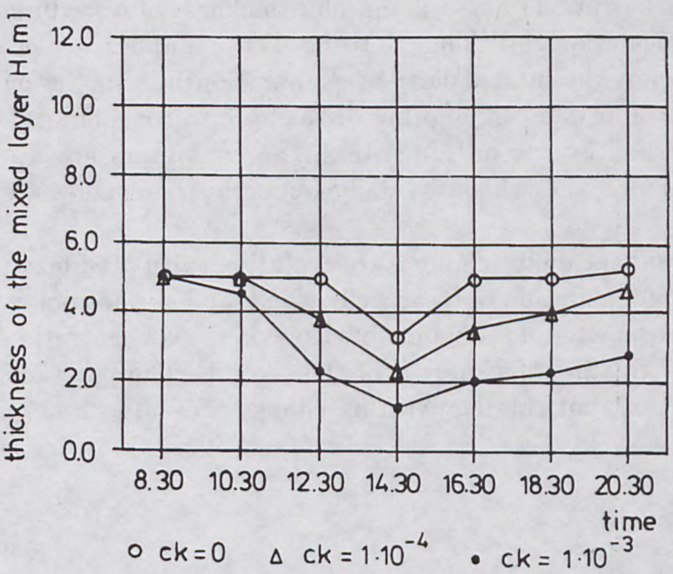

Fig. 4. The daily evolution of the mixed-layer thickness at various concentrations of light oil

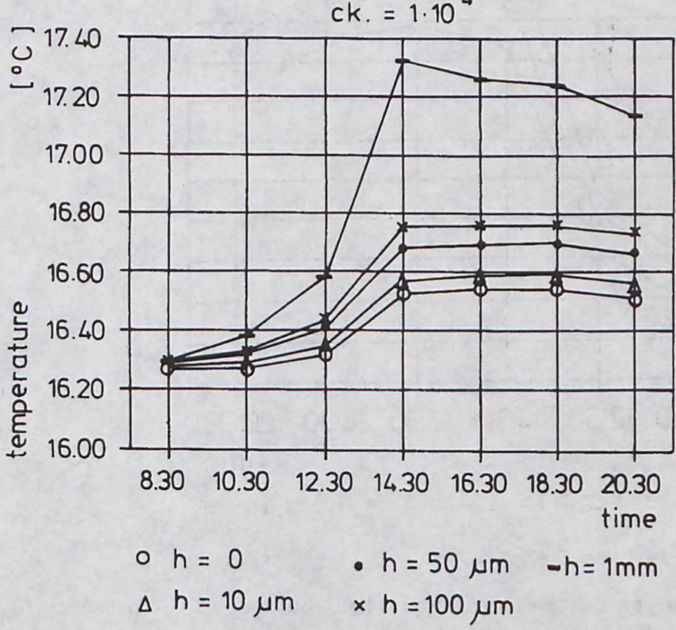

Fig. 5. Daily evolution of the mixed-layer temperature at various thicknesses of light oil film and constant concentration of bulk pollution with light oil $c_k = 10^{-4}$

Figure 6. A volume concentration of $c_k = 0$ and film thickness of $h = 10\mu m$ were adopted in the calculations. Taking k_1 to be 0 or 1 implies neglecting or taking into account the limited heat of evaporation due to the oil film, while values of $k_2 = 0$ or 1 mean ignoring or taking into consideration the radiation flux absorbed by the oil film. If the above factors are not included in the heat balance, the calculated daily temperature changes are underestimated.

Figures 7 and 8 present the daily temperature evolution calculated using the DKTz-3 model for bulk pollution only, as well as bulk and surface pollution by heavy oil. The parameter of the family of curves is the concentration c_k in the first case, and the film thickness h in the second. The plots are similar to those for light oil, but the temperature changes are larger.

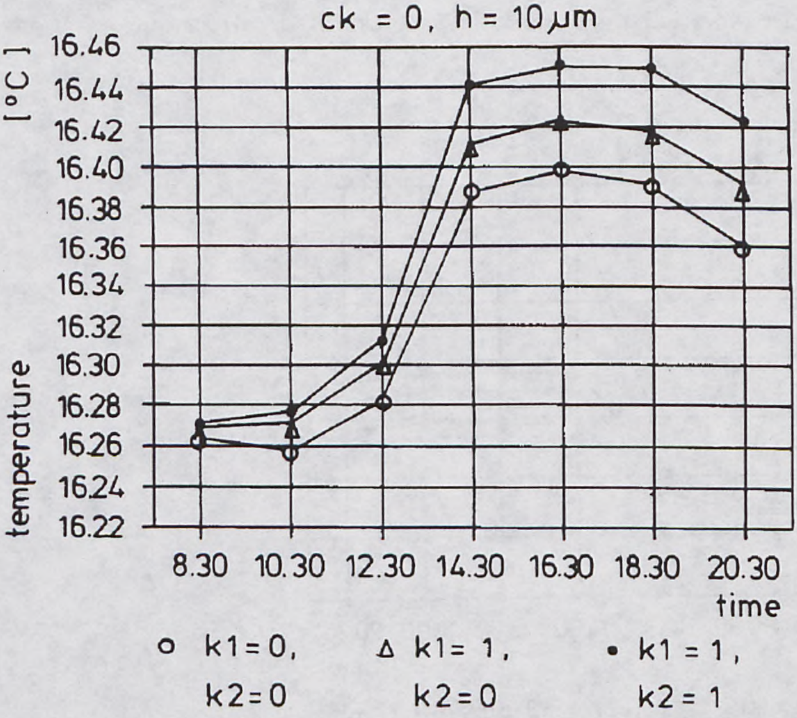

Fig. 6. The effect of the manner of calculating the heat balance in the presence of a light oil film of thickness $h = 10\,\mu m$ on the daily evolution of temperature from the DKTz-3 model

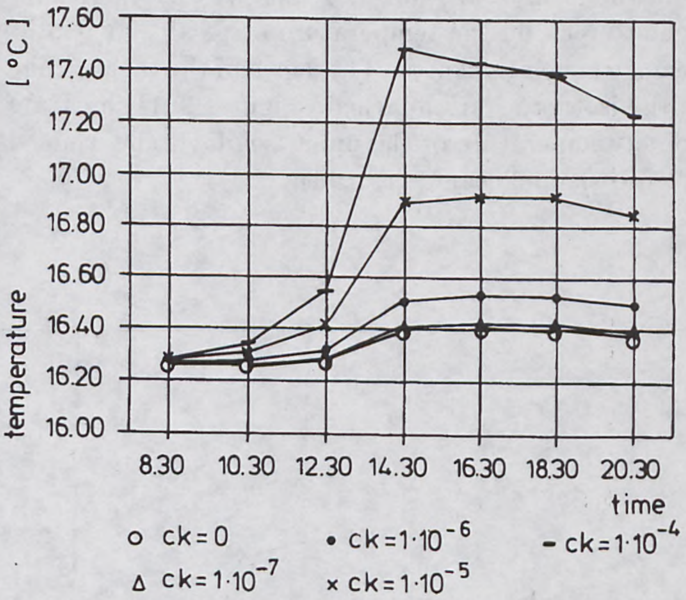

Fig. 7. Daily evolution of the mixed-layer thickness at various concentrations of heavy oil (bulk pollution)

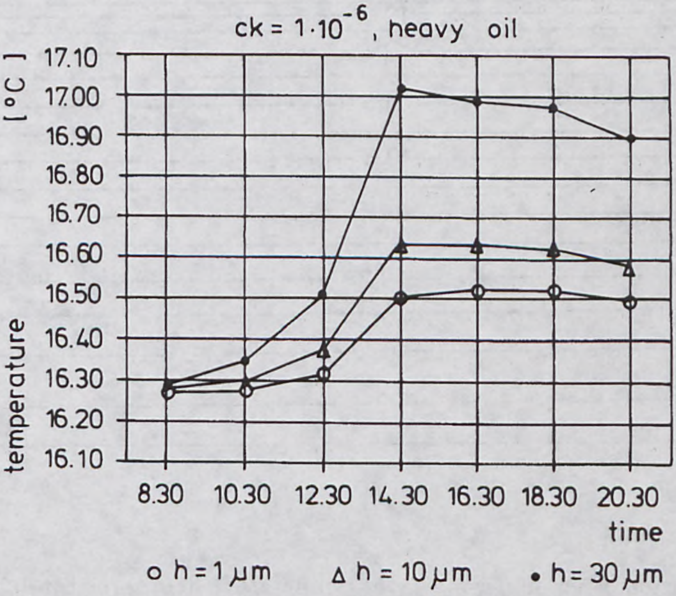

Fig. 8. Daily evolution of the mixed-layer temperature at various thicknesses of heavy oil film and constant concentration of bulk pollution with heavy oil $c_k = 10^{-6}$

The time-space temperature variations of the upper sea layer may be conveniently presented in the form of contour diagrams with isotherms indicated. They enable one to read off the temperature at particular depths and the evolution of the mixed layer thickness. The depth of the thermocline is clearly visible where the isotherms are bunched. Figures 9–11 illustrate the time-space evolution of temperature of the upper sea layer determined using the DKTz-3 model for the pollutants described.

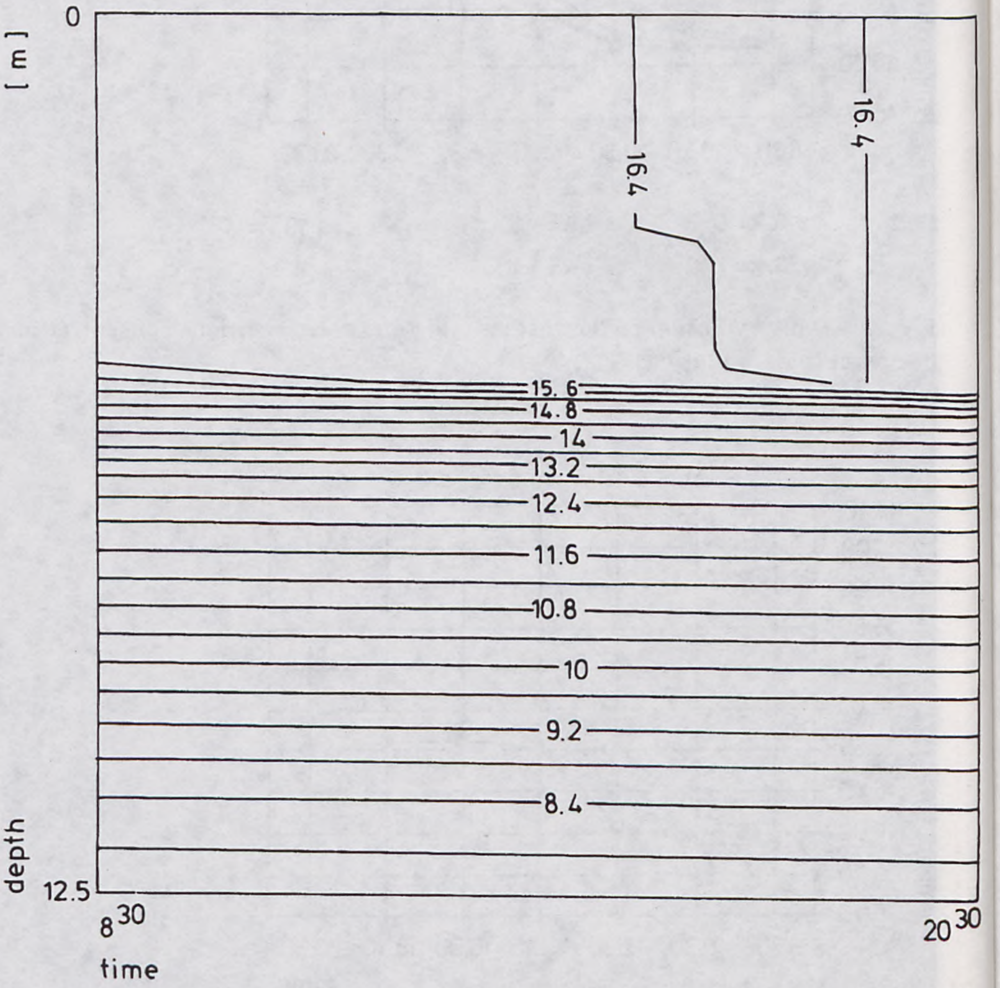

Fig. 9. Time-space evolution of the upper-sea-layer temperature determined from the DKTz-3 model for $c_k = 00$ and $h = 0$

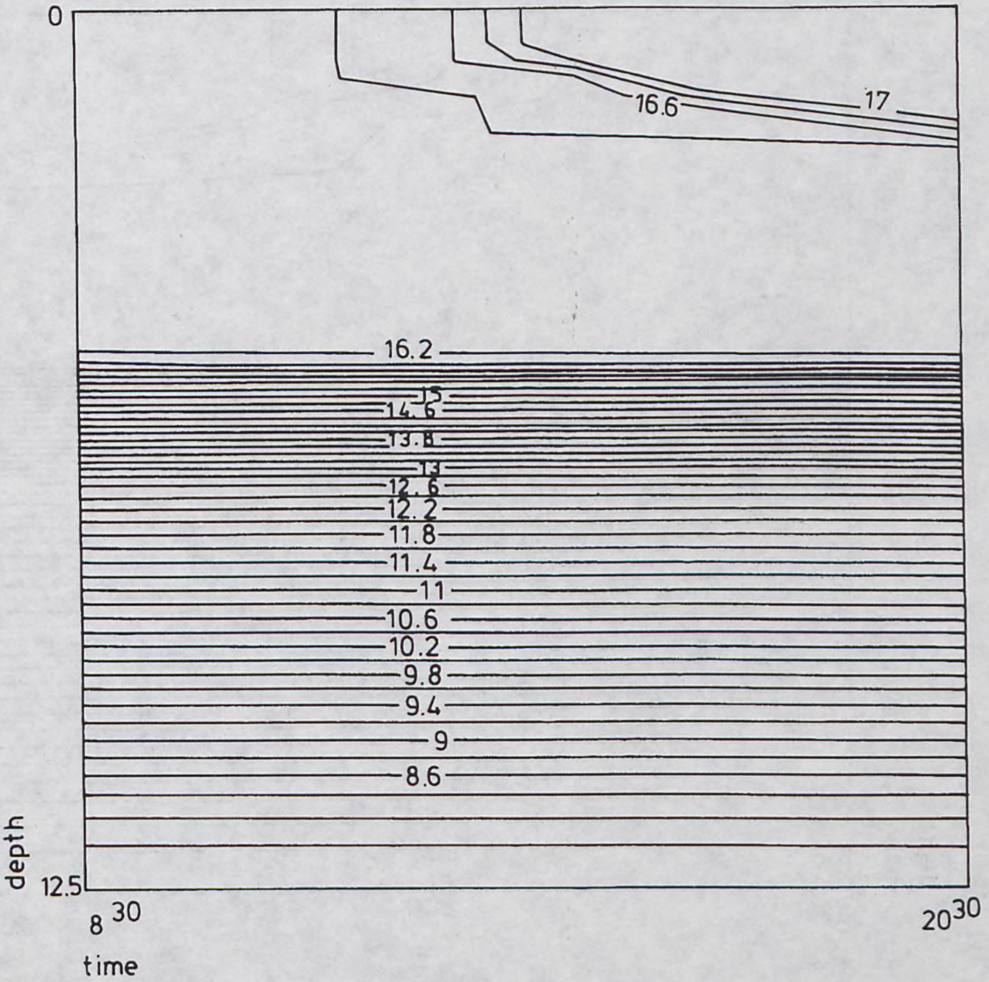

Fig. 10. Time-space evolution of the upper-sea-layer temperature determined from the DKTz-3 model for $c_k = 10^{-4}$ and $h = 1$ mm (light oil)

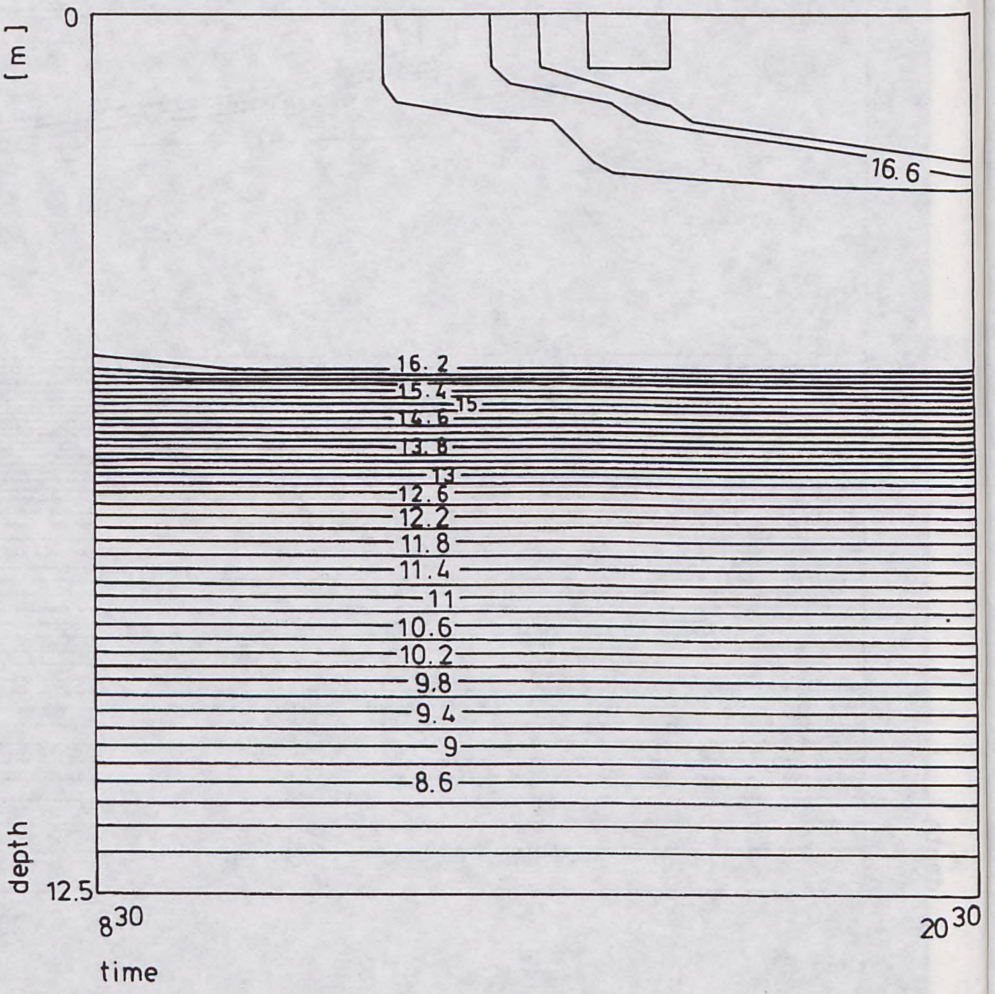

Fig. 11. Time-space evolution of the upper-sea-layer temperature determined from the DKTz-3 model for $c_k = 10^{-6}$ and $h = 30\,\mu$m (heavy oil)

4. Conclusions

The integral, unidimensional mixed-layer DKT model was used to develop mathematical models of the seasonal and daily temperature changes in an upper sea layer polluted by petroleum substances: DKTz-1, DKTz-2 and DKTz-3. The DKTz-1 model enables seasonal temperature changes to be analysed and forecast for the occurrence of any petroleum substances whose volume concentration in the sea is time-variable. A modification of this model, mainly affecting the way in which the transmission coefficient of light absorption in sea water and heat balance are determined, leads to the DKTz-2 model, which provides for the simulation of seasonal temperature variations in the presence of both bulk and surface pollutants in the time-variable concentration. In limiting cases the model enables the temperature and thickness of the mixed layer in the presence of only bulk or only surface pollution to be determined. The DKTz-3 model permits the analysis of short-term temperature variations in the presence of bulk and surface pollution. This model is a further modification of the previous ones, and enables the effect of pollution on the evolution of daily temperature changes and the mixed layer thickness to be analysed numerically. This is possible because the model takes into account the transmission of the entire solar radiation spectrum and its dependence on the elevation of the Sun and weather conditions. The model was verified by numerical simulations for the southern Baltic. The results of these simulations were compared with experimental data for this region of the Baltic (Czyszek, 1985). The agreement between the calculated and real temperature variations and mixed-layer thickness was satisfactory. The results of these calculations allow the following conclusion to be drawn:

1. The model presented in this paper is very versatile and permits a ready analysis of the temperature field of any marine environment (polluted or not), owing to the introduction of parameters generally used in modelling thermodynamic processes related to ocean-atmosphere interaction, and to the restriction of the number of empirical coefficients. It thus fulfils the necessary condition for inclusion in the global model describing ocean-atmosphere interaction.

2. The occurrence of petroleum pollutants in seawater can be taken into consideration by an alteration in the absorption coefficient of the seawater – petroleum substances system. The effective value of this coefficient is the sum of the absorptions of the individual elements of the system, whereas its spectrum is a superimposition of partial spectra.

3. The coefficient of solar radiation transmission in seawater was determined from equation (9), which takes into account the entire spectrum of solar radiation penetrating directly below the sea surface and the variability of hydrometeorological conditions.
4. The effect of environmental conditions on the temperature and thickness of the mixed layer is also taken into account by the change in the value of the m/c_d coefficient (mixing parameter). The values of this coefficient were determined in a numerical experiment by comparing the calculated and real temperature and thickness of the mixed layer.
5. When bulk pollution occurs, any increase in its concentration raises the temperature and reduces the thickness of the mixed layer. With surface pollution, the direction of changes remains the same with increasing film thickness.
6. At similar concentrations, different kinds of crude oil (light and heavy) cause different changes in the temperature mixed-layer thickness with respect to unpolluted water:smaller in the case of light oil, greater in the case of heavy.
7. Maximum changes in the mixed-layer temperature occur when pollutants are introduced during the period of the most intensive heating.
8. The effect of surface pollutants in the form of a flat, uniform oil layer on the evolution of the temperature and thickness of the mixed layer can be allowed for in the model by altering the values of the transmission coefficients in such a way that the absorptive and reflective properties of the atmosphere – oil layer – seawater system are taken into account.
9. The occurrence of surface pollution with petroleum substances changes the thermal conditions of the atmosphere – oil layer – sea water system with respect to the atmosphere – seawater system, a fact which should be taken into account in the heat balance. Disregarding this phenomenon results in underestimated temperature values.

Further investigations into the development of unidimensional models should deal with the effect of solar radiation scattering by petroleum pollutants (Mrozek-Lejman, 1984) on the evolution of the mixed-layer temperature and thickness. Such studies should also take into account the change in the distribution function of bulk pollutants in seawater (Gurgul *et al.*, 1990). It does not seem, however, that these modifications will significantly change the calculated values of the parameters. It is more important to develop models for two- and three-dimensional cases. These should additionally take into account the wave motion of the free sea surface, on which patches of petroleum substances of finite dimensions and time- and space-variable thickness may occur. The two-, and particularly the three-dimensional model would more accurately describe the real variations in the temperature and thickness of the mixed layer, which significantly influence the micro- and macroclimate.

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