Nonstationary heat transfer and interstitial solute diagenesis in disturbed sediments

Heat transfer
Solute diagenesis
Marine coastal sand
Mathematical model
Mediterranean
Transfert de chaleur
Diagenèse de solutés
Sable marin côtier
Modèle mathématique
Méditerranée

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ABSTRACT

The results of continuous temperature versus time measurements obtained simultaneously 7.0 cm below and 10 cm above the sediment/seawater interface in the proximity of the Revellata headland (Corsica, Mediterranean Sea) over a 6.5-day period are presented. The bottom of the 7 m deep water column undergoes distinct thermal events of advective origin and a strong stirring owing to a weather alteration.
Heat propagation in the sand 7.0 cm below the interface in a nonstationary state is described by means of a mathematical model based on the heat conduction equation and with the assumption that the heat is conservative. This description is achieved without any adjustment of the model to the data.
Since the K_s value characteristic of unconsolidated clastic sediments in undisturbed environments, *i.e.* 3.5×10^{-3} cm^2.s^{-1}, is successfully used for this description, we suggest that overlying water stirring did not promote any appreciable increase of the heat transfer across the sand/seawater interface. This evidence could invalidate the previous hypothesis of an interstitial solute transfer increase owing to that kind of turbulent mixing. The analysis of the damping with depth and time of the thermal shock illustrates a model application that might constitute a physical reference frame for future studies of the extension of thermal stresses imposed on benthic burrowing organisms.

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RÉSUMÉ

Transfert non stationnaire de chaleur et diagenèse de solutés interstitiels dans les sédiments perturbés.

Nous présentons les résultats de mesures de la température en fonction du temps, réalisées en continu sur une période de 6,5 jours, simultanément à 7,0 cm en dessous de l'interface sédiment/eau de mer et à 10 cm au-dessus, à proximité du rivage de la pointe de la Revellata (Corse, Méditerranée). La base de la colonne d'eau d'une profondeur de 7 m, est le siège de divers événements thermiques d'origine advective et est soumise à une forte agitation liée aux conditions météorologiques.
La propagation de la chaleur dans le sable à 7,0 cm sous l'interface est décrite dans un état non-stationnaire, au moyen d'un modèle mathématique basé sur l'équation de la conduction thermique, en admettant que la chaleur est conservative. Cette description est réalisée sans aucun ajustement du modèle aux données.
Étant donné que la valeur de K_s caractéristique des sédiments meubles clastiques dans des milieux calmes, soit 3.5×10^{-3} cm^2.s^{-1}, est utilisée avec succès dans cette description, nous proposons que l'agitation de l'eau de mer surnageante ne devrait provoquer aucune augmentation appréciable du transfert de chaleur à travers l'interface sable/eau de mer. Ce fait pourrait infirmer la précédente hypothèse d'un accroissement du transfert de solutés interstitiels dû à ce type de mélange turbulent.

L'analyse de l'amortissement en fonction de la profondeur et du temps du choc thermique illustre une application du modèle, qui pourrait servir de cadre de référence physique pour de futures études sur la portée de contraintes thermiques imposées à des organismes benthiques fouisseurs.

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INTRODUCTION

Near-interface concentration gradients of solutes have been extensively documented in pore waters of unconsolidated sediments over a broad variety of environments (Manheim, 1976). These vertical gradients are commonly thought to represent the net component borne from the combined action of diagenetic chemical (or biochemical) reactions and fluxes across the sediment/seawater interface. The mechanisms which account for these fluxes are referred to as advection and diffusion (Berner, 1980).

Vertical advection is the upward relative motion of pore water owing to sediment compaction. Its magnitude depends on the burial rate.

Diffusion in unconsolidated coastal marine sediments can be divided into: molecular diffusion and turbulent dispersion (bioturbation and overlying water stirring).

Molecular diffusion in pore water obeys Fick's first and second laws (Berner, 1980). The former is most useful in assessing fluxes across the sediment/water interface, whereas the latter allows the description of concentration changes occurring with time at any given depth below the interface. The application to bulk sediment (water + particles) involves the correction of the molecular diffusion coefficient for the sediment porosity and tortuosity (Manheim, 1970; Li, Gregrory, 1974; Berner, 1980).

Bioturbation includes various phenomena caused by benthic burrowing activity, which lead to the homogeneization of the upper bulk sediment.

Overlying water stirring (bottom current, wave motion, tidal pumping) has been recently identified as a possible mechanism enhancing the escape of interstitial solutes to the overlying seawater as suggested by the vanishing of the solute vertical gradient over the upper sediment (Vanderborght *et al.*, 1977 *a*; 1977 *b*; Rutgers Van Der Loeff, 1980). Experimental evidences support this view (Billen, 1982).

A two-layer steady-state mathematical model was applied by Vanderborght *et al.* to nutrient diagenesis in disturbed near-shore sediments exempt form bioturbation. From curve best-fitting of the model, they were able to show that to account for the observed concentration gradients the mass transfer coefficient in the 3.5 cm — thick upper layer should be 100 times the molecular diffusion coefficient value.

We propose here an alternative approach in the study of solute transfer enhancement across the sediment/seawater interface attributable to overlying water stirring, through the application of the heat conduction theory. Heat conduction theory is well understood and permits the description of thermal events in natural systems by means of mathematical models substantially simpler than those related to solute diagenesis, since heat can be regarded as conservative in the sediment in the range of depth considered here (Matisoff, 1980). Given the turbulent nature of the pore mixing generated by seawater stirring, it is reasonable to assume that any transfer enhancement owing to this stirring should affect both solutes and heat. An increase of the mass transfer coefficient and of the apparent thermal diffusivity should thus occur simultaneously.

We applied a simple mathematical model based on the heat conduction theory to the description of the heat transfer between a near-shore marine sand and the overlying seawater. Our field observations are related to a sudden invasion of a cold seawater mass in a small cove in West Corsica as a result of a local weather alteration.

The study of the upper sediment response to discrete temperature changes in the overlying seawater should provide basic information on thermal stresses, whether anthropogenic or natural, and on burrowing benthic organisms. This will illustrate possible extensions of the heat conduction theory application to environmental studies.

METHODS

The area of study (Pointe de la Revellata, western edge of the Calvi Bay, Corsica, Mediterranean Sea) was chosen because its surrounding waters are frequently subjected to advective motions. At the end of the summer, seawater masses interchanges can be improved by northerly winds.

In situ temperature measurements were performed simultaneously in the sediment and the overlying water (depth: 7 m) at the end of September, 1978, in the immediate vicinity of the Oceanographical Station of the University of Liège (Stareso).

The examination of raw sediment samples under a polarizing microscope showed that their upper 20 cm consist of very poorly sorted coarse sand made of crystaline rock fragments, quartz, feldspars, brown mica, calcareous test fragments and siliceous sponge spicules. This composition is essentially the same as that reported in the area (Caschetto *et al.*, 1976). Local patches of conglomeratic sand are also present in the area. From rapid visual inspection of sediment cores and sea bottom, we estimated the density of the burrowing organism population to be very small.

A thermistor temperature micro-probe (about 0.1 cm in diameter) was plugged into the bottom sand at $+7.0 \pm 0.5$ cm depth (coordinate system fixed to the sediment/seawater interface, distances counted positively downward) by Scuba divers (the authors). Special care was taken to minimize sediment disturbance and preferential water circulation along the connection wire wall. A second thermistor temperature probe was fixed at -10 ± 0.5 cm above the bottom, about 0.5 m distant from the sand-plugged one. The connection wires were anchored alongside the bottom. Twice daily, the *in situ* fastening of the probe was checked and the seawater temperature was measured by means of a thermometer ($\pm$ 0.05°C accuracy) for gross control. Both temperature measuring devices were specifically designed in our laboratory. The signal from the sensors (micro-thermistances aged until reaching a drift <0.1°C/year) was transmitted in the frequency mode to two independent electronic converters connected to two paper chart recorders located onshore. The measuring devices were calibrated in our laboratory from 0 to 24°C in 0.1°C steps (precision: 0.01°C, accuracy: 0.05°C, time-response: <12 s).

The temperature was recorded continuously over a total period of 16 days. The first four days data were disregarded to provide extra safety against any bias due to possible artificial stress of the medium.

RESULTS

The data obtained from the continuous temperature measurements over a total 12-day period show that, except for a continuous 6.5-day period characterized by heavily disturbed conditions, the temperature of the sediment and the overlying seawater was quite stationary.

Since our prime interest lies in the description of the heat transfer in a nonstationary disturbed system, we shall present herein the observations related to this continuous 6.5-day period only (Fig. 1). This figure represents the temperature evolution with time observed simultaneously within the sediment at $+7.0 \pm 0.5$ cm and within the overlying water at -10 ± 0.5 cm. The time coordinate has been arbitrarily set to zero at the beginning of the 6.5-day period.

Comparison between the patterns of the two curves suggests that closely related trends characterize the temperature evolution with time in both media.

Four basic events (E_1 to E_4) can be singled out from our data observed in the seawater (Fig. 1). They occur successively within the time intervals (0-48 h), (48-90 h), (90 h-100 h) and (100-156 h).

On a 48-hour time-scale, E_1 reflects a slow alteration of the stationary state which prevailed for the first 6 days. The same trends towards a relatively small but significant temperature drop is observable within the sediment.

During E_2, the seawater temperature rises to 17.80°C and reaches 17.55°C in the sediment. E_3 is characterized by a sudden drop in the seawater temperature (about 1.4°C). The corresponding sediment temperature decrease is close to 1.0°C. The mean rate of temperature decrease is 0.19°C/h and 0.07°C/h in the seawater and the sediment respectively.

Accordingly, a temperature inversion occurs between times 93 h and 102 h approximately (Fig. 1 and 2) and explains why the subsequent temperature minima exhibit different values (16.45 against 16.60°C) and are outphased in the two media.

During E_4, the temperature tends to increase in both media. The system resulting from the described temperature stress is characterized by an oscillatory evolution.

The existence of a diurnal periodicity is easily drawn from the data reported in Figure 1. Both curves exhibit the occurrence of minimum and maximum values at respectively 6 a.m. and 6 p.m., which we relate to the sun heating diurnal cycle assuming a 6 h outphase.

The sea conditions changed during this 6.5-day period as a consequence of a sudden weather alteration. At about time 40 h, northerly winds started to blow. The sea turned to exhibit swell and surge (Beaufort 5). The wind decreased around time 110 h, but the initial weather conditions were not yet restored at time 140 h. Between times 80 and 110 h, centimetric back and forth motions of sand particles and posidonia fragments due to seawater stirring were observed on the bottom, by divers.

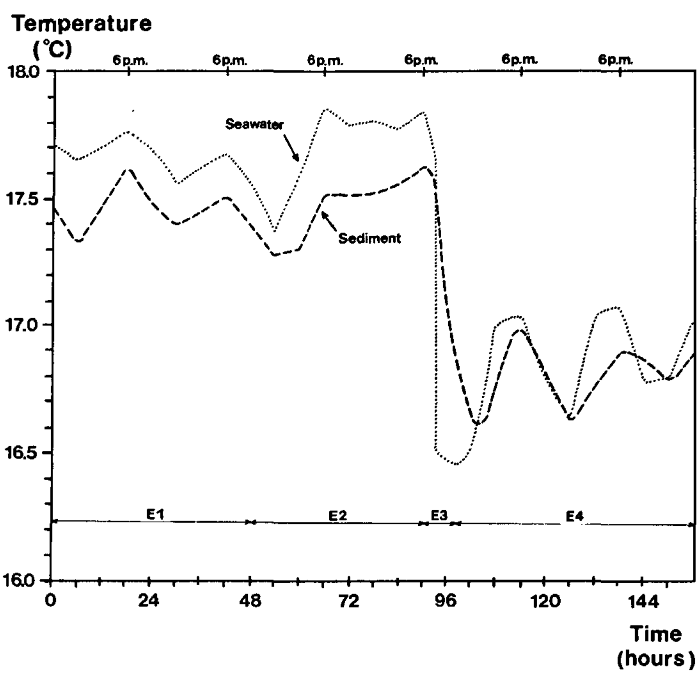

Figure 1

Temperature evolution with time measured over a 6.5-day period by means of two independent probes within the overlying seawater 10 cm above the sediment/seawater interface (......), and within the sediment 7 cm below the interface (------) (Revellata headland, Western edge of the Calvi Bay, Mediterranean Sea). E_1, ..., E_2 refer to successive thermal events (see text).

Évolution en fonction du temps de la température mesurée au cours d'une période de 6.5 jours au moyen de deux sondes indépendantes, simultanément dans l'eau de mer à 10 cm au-dessus de l'interface sédiment/eau de mer (......) et dans le sédiment à 7 cm en dessous de cet interface (——) (pointe de la revellata, bordure occidentale de la Baie de Calvi, Méditerranée). E_1, ..., E_2 symbolisent les événements thermiques successifs (*voir* texte).

MATHEMATICAL MODEL

Let the sediment be a semi-infinite isotropic medium whose interface undergoes the temperature changes with time occurring in the overlying seawater. We shall further assume that no heat is produced or consumed within the sediment and that the heat flow due to the geothermal gradient is negligible.

Advection due to sediment compaction being ignored, the mathematical description of the heat transfer in the sediment can be written as (Carslaw, Jaeger, 1973):

$$\partial_t \theta = K_s \partial^2_{zz} \theta, \qquad (1)$$

Where θ is the temperature, t is the time, z is the depth coordinate and K_s is the apparent (or bulk sediment) thermal diffusivity given by:

$$K_s = k/s\rho,$$

where k is the thermal conductivity, s is the specific heat, and ρ is the density.

Assuming now that K_s is independent of temperature and depth (Matisoff, 1980) and with the following boundary condition:

$\theta = \lambda(t)$ for $z = 0$

and initial condition:

$\theta = \theta_0(z)$ for $t = 0$

For $\lambda(t) = \gamma(t)$, where $\gamma(t)$ is the Heaviside function or unit step function, the solution of equation (1) becomes (Carslaw, Jaeger, 1973):

$$\theta(z,t) = \frac{2}{\sqrt{\Pi}} \int_{z/(2\sqrt{K_s t})}^{\infty} e^{-\eta^2} d\eta,$$

which is known as the complementary error function, commonly symbolized as:

$$\theta(z,t) = \operatorname{erfc}\left(\frac{z}{2\sqrt{K_s t}}\right). \qquad (2)$$

The solution $\theta(z,t)$ corresponding to a general evolution of the temperature at the sediment/seawater interface $\lambda(t)$ can be obtained by means of the superposition principle. This consists merely of summing up the effects produced by every unitary discrete drop in temperature. Mathematically, for N events:

$$\lambda(t) \cong \sum_{i=1}^{N} \gamma(t-t_i)(\theta_i - \theta_{i-1}) + \theta_0.$$

Hence:

$$\theta(z,t) = \sum_{i=1}^{N} \gamma(t-t_i) \qquad (3)$$

$$\times (\theta_i - \theta_{i-1}) \operatorname{erfc}\left(\frac{z}{2\sqrt{K_s t}}\right) + \theta_0$$

This expression of $\theta(z,t)$ has been used for:

$z = +7$ cm and $t_{i+1} - t_i = 3$ h

to describe the time related temperature evolution we observed within the sediment under nonstationary conditions. The $\lambda(t)$ boundary conditions has been drawn from our measurements taken within the overlying seawater assuming that its temperature evolution at the interface is identical to that observed at -10 cm.

To check the sensitivity of our model, we compared the results computed thereby to describe the above mentioned temperature evolution with time for various $\theta_\infty[\theta_0(z=\infty)]$ values ranging from 12 to 17°C. The time-temperature graphs exhibited no significant differences for values between 12 and 15°C.

The mean seawater temperature recorded in the surrounding area below the thermocline is close to 13° (Caschetto, Wollast, 1979; Loffet, 1981). Other measurements achieved close to Stareso at about -10 m (Bay, pers. comm.) suggest that the annual mean seawater temperature is close to 15°C. We thus introduced 14°C in our model as a representative value of θ_∞.

On the other hand, the K_s value in our model has been chosen from the litterature as 3.5×10^{-3} cm^2.s^{-1}. The reason for this choice will be discussed later.

DISCUSSION

The evolution with time of temperature observed from time zero above and below the sediment/seawater interface shows that the system is in a near-equilibrium state as long as the hydrodynamical conditions in the overlying seawater undergo only minor changes. This is in accordance with our observations carried out during E_1 and E_2 (Fig. 1).

A sudden and significant seawater temperature change such as the discrete event E_3 (Fig. 1) results in a temperature inversion and in an outphazing. Given the rate of the seawater temperature change owing to advection, the sediment temperature change is delayed since it is controlled by a relatively slower process (conduction).

Figure 2 shows the theoretical sediment temperature evolution with time calculated using equation (3) (for $z = +7.0$ cm, $\theta_\infty = 14$°C and $K_s = 3.5 \times 10^{-3}$ cm^2.s^{-1}) together with the temperature values observed in the sediment and the overlying water during a period of well-established disturbed conditions (swell throughout the Calvi Bay; surge and seawater column stirring nearshore the Revellata headland).

Reported thermal diffusivity values for lacustrine and marine undisturbed sediments are in the range of 1.8×10^{-3} cm^2.s^{-1} (Matisoff, 1980).

Considering pure water diffusivity to be 1.4×10^{-3} cm^2.s^{-1} (Carslaw, Jaeger, 1973), the above value of 1.8×10^{-3} cm^2.s^{-1} seems rather low. Typical values for soils are (Carslaw, Jaeger, 1973):

2.0×10^{-3} cm^2.s^{-1} (sandy dry soils),
3.3×10^{-3} cm^2.s^{-1} (sandy moisted soils) and
$4.6. \times 10^{-3}$ cm^2.s^{-1} ("mean" soils).

We suggest that among these values only three (*i.e.* 3.2, 3.3 and 4.6×10^{-3} cm^2.s^{-1}) are applicable to the sediment studied here. Therefore, we used 3.5×10^{-3} cm^2.s^{-1} to test the sand thermal response by means of our model.

In order to evaluate the magnitude of the effect of the K_s parameter, we introduced various K_s values ranging from 1.0 to 10.0×10^{-3} $cm^2.s^{-1}$ in our model, all the other parameters being set to their previous value. The results (Fig. 3) suggest that the sediment temperature evolution with time computed by means of our model is basically the same (considering the accuracy of our measurements), no matter which value in the range of the three values selected above form the literature K_s is given. The residual standard deviation (RSD) calculated from equation (3) for various K_s values confirms this view (RSD is 0.05°C, i.e. our temperature measurement accuracy, for K_s values from 3.0 up to 4.9 × 10^{-3} $cm^2.s^{-1}$).

The agreement between the observed and the theoretical sediment temperature evolution with time appears reasonably good (the RSD is 0.05 ± 0.01°C for $K_s = 3.5 \times 10^{-3}$ $cm^2.s^{-1}$ and z = +7 cm). However, for times between 100 h and 108 h, and to a lesser extent for times between 70 h and 84 h our model appears less satisfactory.

The thermal response of the studied sand can be described according to the heat conduction equation (1) through a simple mathematical model whose boundary conditions are drawn from observed data using a K_s value which is definitely not higher than the typical thermal diffusivity value for undisturbed clastic sediments.

If the turbulence observed at the sediment/seawater interface induces a significant effect within the pore water, then the heat transfer between the sediment and the seawater could be expected to be enhanced, which is not pointed out by our results.

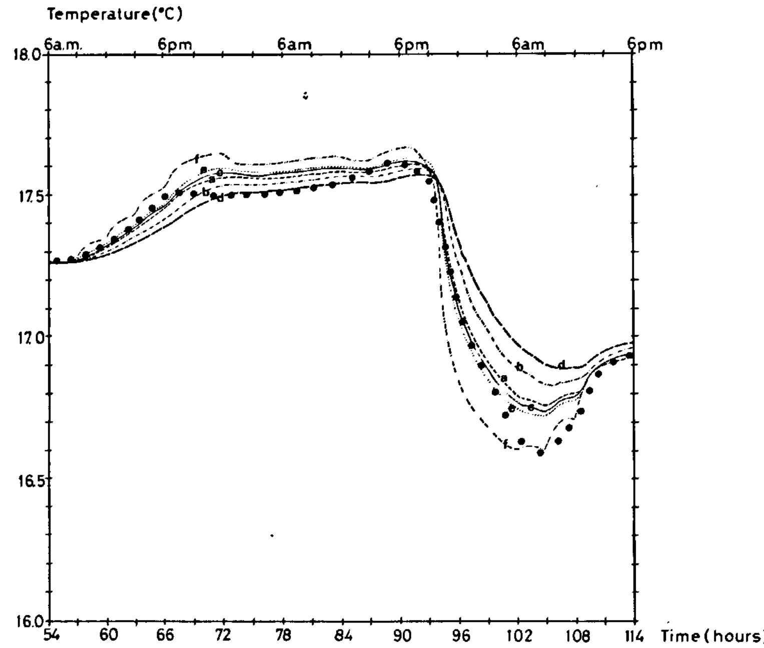

Figure 3

Sediment temperature evolution with time calculated by means of a model based on the heat conduction equation, for various K_s values: d = 1.4; b = 2.0; a = 3.0; c = 3.5; e = 4.0; f = 10.0 (values given in 10^{-3} $cm^2.s^{-1}$) and for z = +7.0 cm, θ_∞ = 14°C. The dotted curve (...) represents the temperature measured in the sediment at +7 cm.

Évolution temporelle de la température dans le sédiment calculée par un modèle basé sur l'équation de la conduction thermique pour différentes valeurs de K_s : d = 1.4; b = 2.0; a = 3.0; c = 3.5; e = 4.0; f = 10.0 (valeurs données en 10^{-3} $cm^2.s^{-1}$) et pour z = +7.0 cm, θ_∞ = 14°C. La courbe pointillée (...) représente la température mesurée dans le sédiment à +7 cm.

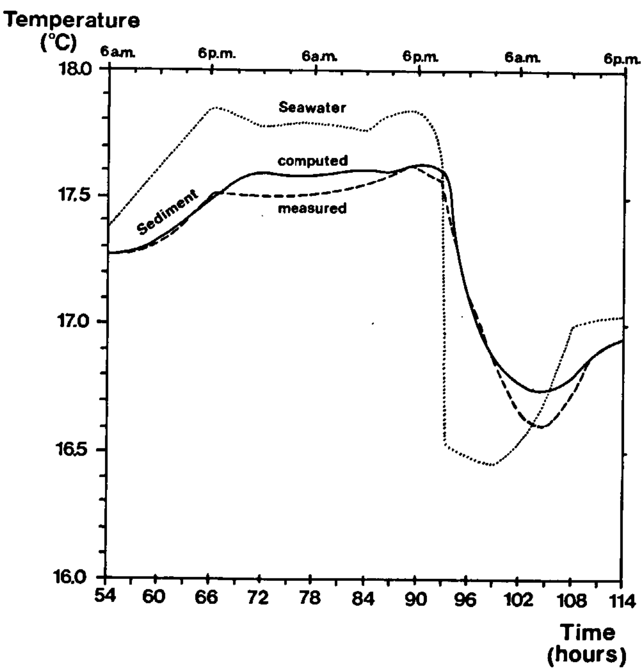

Figure 2

Comparison between the observed (----) and the calculated (————) sediment temperature evolution with time in a nonstationary state. The theoretical curve is computed from a model based on the heat conduction equation, for $K_s = 3.5 \times 10^{-3}$ $cm^2.s^{-1}$, z = +7.0 cm, and θ_∞ = 14°C. The overlying seawater measured temperature is also shown (.......).

Comparaison entre l'évolution mesurée (----) et l'évolution calculée (————) de la température du sédiment en fonction du temps, dans un état non stationnaire. La courbe théorique est calculée par un modèle basé sur l'équation de la conduction thermique, pour $K_s = 3.5 \times 10^{-3}$ $cm^2.s^{-1}$, z = +7.0 cm, et θ_∞ = 14°C. La température de l'eau de mer surnageante est aussi montrée (.......).

Therefore, although typical nonstationary disturbed conditions prevailed during the thermal event studied, we suggest that the overlying water stirring effect reported for solutes (Vanderborght *et al.*, 1977 *a*; 1977 *b*; Rutgers Van Der Loeff, 1980; Billen, 1982) seems invalidated by the description of the heat transfer in sands in the considered area given the limits of the accuracy of our field observations and of our model capacity.

Nevetheless, we admit that the overlying water stirring might actually facilitate the heat transfer between the sediment and the seawater, but then the effect of this mechanism would be to increase the K_s value only up to about 5×10^{-3} $cm^2.s^{-1}$. This figure could appear very small when compared with the 100 times increase of the dispersion coefficient for solutes observed in disturbed muds [Vanderborght *et al.*, 1977 *a*; 1977 *b* (actually, the molecular diffusion coefficient becomes negligible in front of the two orders of magnitude higher dispersion coefficient because of turbulent mixing)]. Perhaps this difference could be related to the nature of the sediments.

Any sudden thermal environmental shock, either natural or anthropogenic, might be expected to affect preferentially those of the burrowing benthic organisms that live in the very upper part of the sedimentary column.

The knowledge of the sediment temperature evolution with depth and time generated by a sudden change in the bottom seawater temperature is useful in approaching quantitatively the biological effects possibly produced by such a thermal stress.

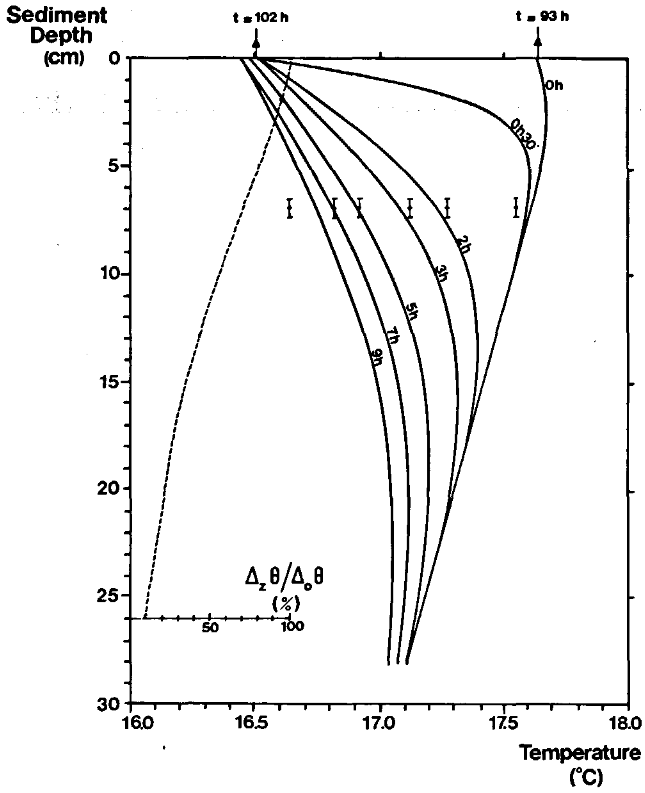

Figure 4

Vertical distribution of temperature in the sediment calculated in function of time by means of a model based on the heat conduction equation during a thermal shock occurring form time 93 h to time 102 h. Measured temperature values are also reported for the overlying water (Ɪ) and for the sediment (▲). The dashed line represents the thermal shock relative amplitude variation with depth $\Delta_z\theta/\Delta_0\theta$, where $\Delta_0\theta$ is 1.05°C.

Distributions verticales de la température dans le sédiment calculées en fonction du temps par un modèle basé sur l'équation de la conduction thermique au cours d'un choc thermique se produisant entre 93 h et 102 h. Les valeurs mesurées de la température dans l'eau de mer surnageante (Ɪ) et dans le sédiment (▲) sont également montrées. La courbe en trait interrompu représente la variation de l'amplitude relative du choc thermique en fonction de la profondeur $\Delta_z\theta/\Delta_0\theta$, où $\Delta_0\theta$ vaut 1.05°C.

With this aim, we calculated temperature vertical profiles in the sediment at different times between 93 h and 102 h (the duration of the thermal shock occurrence) by means of our model for $K_s = 3.5 \times 10^{-3}$ $cm^2.s^{-1}$ and $\theta_\infty = 14$°C.

It can be seen from the results (Fig. 4) that the temperature gradient $G_t = -(\partial_z\theta)_t$ decreases drastically with depth for any given time considered, especially near the interface. Also, this gradient decreases with time for any given depth.

Accordingly, the relative amplitude of the thermal shock $\Delta_z\theta/\Delta_0\theta$ ($\Delta_z\theta$ is the difference between the temperature at the beginning of the shock, *i.e.* 0 h, and the temperature at the end of it, *i.e.* 9 h, for any given depth z; in particular, $\Delta_0\theta$ represents the shock amplitude at the interface) is substantially reduced with depth. For example, $\Delta_z\theta/\Delta_0\theta$ (Fig. 4) is 40% for z = 15 cm, and only 10% for z = 26 cm.

Thus, similar applications of the heat conduction theory might be tentatively used to determine critical depths below which a given burrowing benthic organism could be significantly affected by a given thermal shock, provided that a biologically critical threshold value of $\Delta\theta$ is known for the specific organism. Also, this kind of application might provide valuable information on the kinetic aspect of the biological effect of such stresses.

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