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Seasonal variations of heat flux at the water-sediment interface in very shallow lagoons

Heat flux
Lagoons
Sediments
Temperature
Shallow waters

Flux de chaleur
Lagunes
Sédiments
Température
Eaux basses

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ABSTRACT

During 1980, six experiments, one every two months were made, to quantify the yearly cycle of heat flux at the water-sediment interface. Temperature measurements were taken at five levels in a homogeneous zone of silty sediments and very shallow water, 1 m as a maximum in the northern part of the Lagoon of Venice. This depth is characteristic of 80 % of the whole lagoon surface. The total excursion of the temperature decreases as the depth increases. A penetration depth of 230 cm and a phase lag between maxima of the temperature at various levels are observed and confirmed from typical values of thermal diffusivity for silty muds. The energy stored in the water from late winter to late summer is about 2×10^3 cal cm^{-2}, while, in the same period, the energy stored in the sediment down to the penetration depth is about $1.7 \times$ cal cm^{-2}. The theoretical value of energy stored in the whole sediment is 2.1×10^{-2} cal cm^{-2}.
Simple calculations based on our assumed conductivity of silty mud, indicate that the heat flux through the water-sediment interface is on the order of 10^{-4} cal cm^{-2} sec.$^{-1}$, that is 1/10 of the annual excursion of the incident solar flux, at Venice's latitude. A very rough comparison with other fluxes in the heat balance equation, indicates that the flux at the water-sediment interface is not negligible.

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RÉSUMÉ

Variations saisonnières du flux de chaleur à travers l'interface eau-sédiment dans des lagunes peu profondes

Durant l'année 1980, six expériences ont été effectuées, à raison d'une tous les deux mois, s'efforçant de quantifier le cycle annuel du flux de chaleur à travers les interfaces eau-sédiment. Des mesures de température ont été réalisées à 5 niveaux, dans une zone homogène d'argile silteuse et à très faible profondeur : 1 m d'eau environ, dans la partie nord de la lagune de Venise. Cette profondeur maximale est celle de 80 % de la surface de la lagune.
On observe une diminution de la température avec la profondeur, une profondeur de pénétration de 230 cm et une distorsion entre les maxima de température à différents niveaux. Ces valeurs sont confirmées par les valeurs types de diffusion thermique des argiles silteuses. L'énergie emmagasinée dans l'eau de l'hiver à l'été suivant, avoisine 2×10^3 cal cm^{-2}, alors que durant la même période l'énergie stockée dans le sédiment jusqu'à la profondeur de pénétration est d'environ 1.7×10^{-3} cal cm^{-2}. La valeur théorique de l'énergie emmagasinée dans l'ensemble du sédiment est de 2.1×10^{-3} cal cm^{-2}.
Des calculs simples, basés sur notre hypothèse de conductivité de l'argile silteuse, montrent que le flux de chaleur à travers l'interface eau-sédiment, est de l'ordre de 10^{-4} cal cm^{-2} sec.$^{-1}$, c'est-à-dire 1/10^e du flux solaire annuel correspondant, à la latitude de Venise. Une comparaison très approximative avec d'autres flux dans l'équation du bilan de chaleur, montre que le flux de chaleur à l'interface eau-sédiment n'est pas négligeable.

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INTRODUCTION

The Venice Lagoon is a well-known hydrological system of channels and flats connected with the Adriatic Sea by three inlets (Fig. 1). Our paper describes the heat exchanges of this system with its underlying sediments. It is a matter of fact that very little is known from this point of view about the Lagoon of Venice and this is a contribution to improve our knowledge in this field. From the point of view of thermal exchanges, the lagoon system interacts with the sea through the water exchange during the tidal cycle, with the atmosphere through back radiation, evaporation, sensible heat exchange and, as we shall see later, on conductive exchanges with the bottom sediment.

We have a number of data from our field studies in the lagoon which show that the effect of the semidiurnal tide on water temperature is prevailing in the deep channels (10 m depth) in direct communication with the sea, and where current velocities are greater ; the effect of solar cycle prevails in the shallow flats (1 m depth), becoming larger when farther from the inlets and channels. This effect is greater in summer than in winter.

In particular, the data of October 1976 from the San Felice channel (Arcari *et al.*, 1978 *a*) near point 2 of Figure 2 show that the temperature has a semidiurnal period and is in phase with the tide for the whole depth. The data of June 1977 from the Malamocco Channel (Arcari *et al.*, 1978 *b*) and of July 1979 from the San Felice channel, in points 1-2-3 of Figure 2, show a more complex behaviour of the

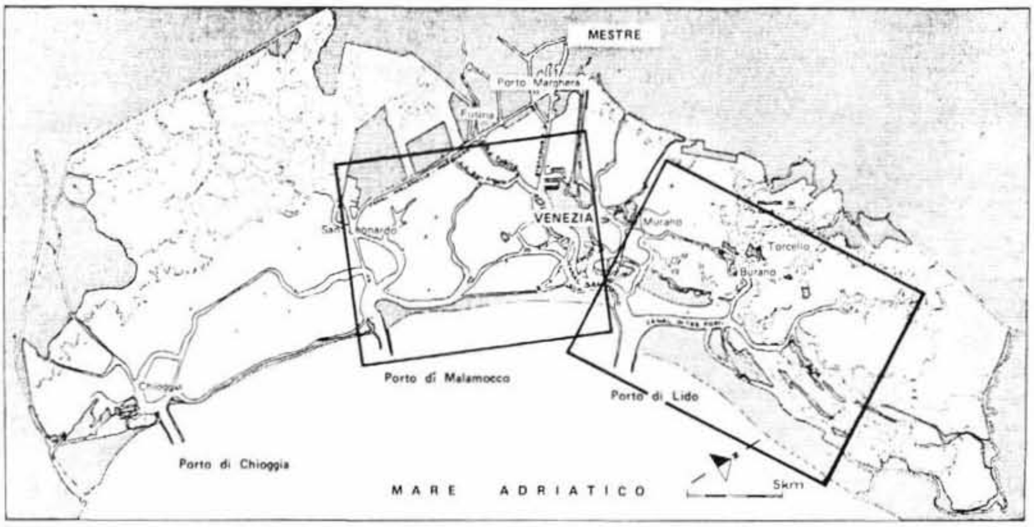

Figure 1

General schematic picture of the Venice Lagoon. The zones inside the rectangles are respectively reproduced, the left in Figure 4 and the right one in Figure 2.

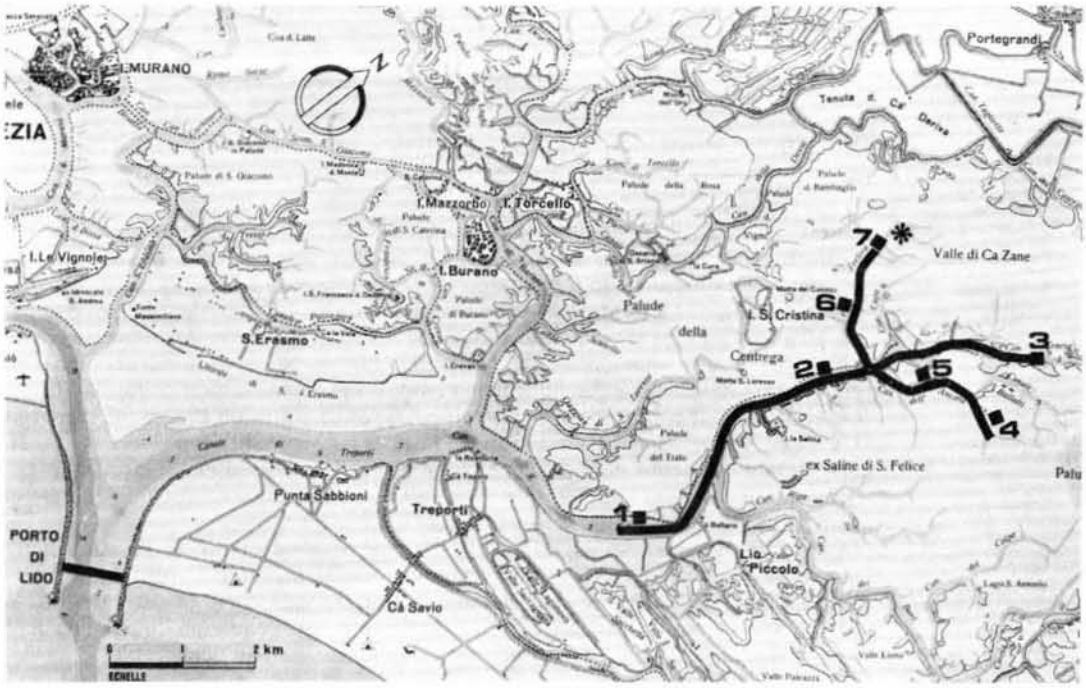

Figure 2

Location of measurements, indicated with an asterisk, during « pole » campaigns, 1, 2, 3 and 4, 5, 6, 7 are the measurement points of the 1976 and 1979 field studies respectively.

Figure 3

Points A, B, C, D, E, F and the one indicated by the name " San Nicolo " are the measuring points during the field study of 1977 in the Malamocco channel, see Arcari et al., *1978* b.

temperature. In the Malamocco channel the temperature measured in three points A, B, C near the inlet (Fig. 3) has almost a 12 hour period, but is in opposition to the tide phase (Fig. 4). In the San Felice channel which is less deep than the preceding one, the measuring points were farther apart from each other and farther from the Lido inlet. Here the temperature seems to have a behaviour which is the result of a diurnal and a semidiurnal period (Fig. 5).
The diurnal, or solar component, is prevailing passing from point 1 to point 3 toward the inner part of the lagoon. At point 1 the temperature has two maxima corresponding to the afternoon low tide and another attenuated maximum in between. At points 2 and 3, the two principal maxima are very pronounced and the smallest maximum becomes a minimum. Near the principal maxima of point 1 the temperature is in opposition to the tide phase as in the Malamocco channel. Considering now the inner points 4, 5, 6, 7 of Figure 2, where the influence of the channel is very reduced, the temperature has a diurnal period (Fig. 6). The tide-water temperature phase relation in opposite seasons, winter and summer, becomes more evident at the inlets (Arcari *et al.*, 1978 *b* and *c*). It is very evident here that the water temperature is in phase with tide in winter (Fig. 7) and in opposition of the phase in summer (Fig. 8). This can be condensed saying that on the mean, the water of the lagoon is colder in winter and warmer in summer than the water of the sea.

A FIRST APPROXIMATION

We have shown some examples of the actual behaviour of water temperature in various locations of the lagoon, channels and flats and at different time scales. This behaviour can be organized in the following first approximation scheme. While in the channels the temperature depends on the tidal mechanism, the very shallow zones show a temperature behaviour essentially determined by the solar cycle. Therefore the mean temperature in the vertical of such a layer of water has a yearly cycle with its maximum in late summer and minimum in winter. Superimposed to this cycle are diurnal fluctuations, which are, in general, more regular and with greater amplitude in summer, when the solar heating is maximum.

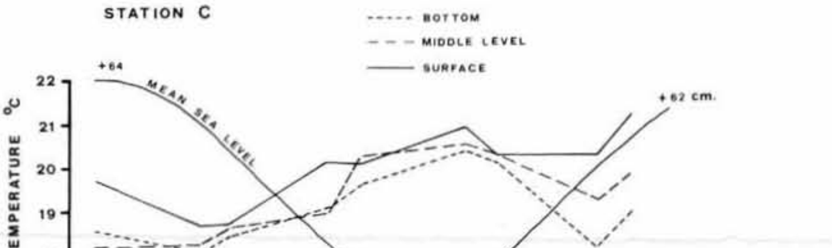

Figure 4

Behaviour of temperature at three levels in point C of Figure 4 during a tidal cycle.

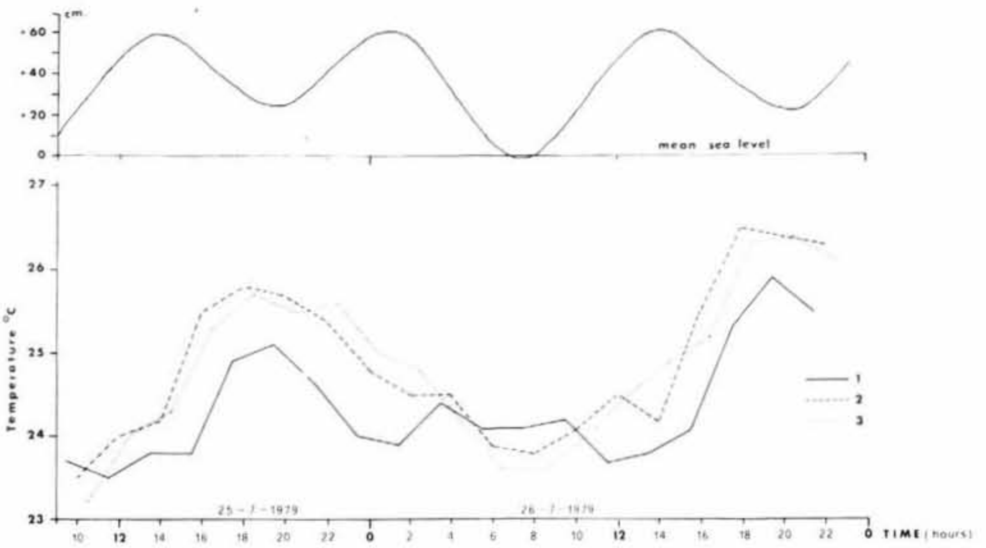

Figure 5
Behaviour of temperature at points 1, 2, 3 of Figure 2 with respect to tidal period and phase.

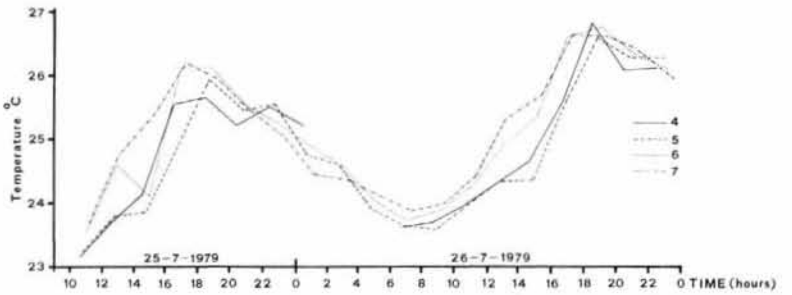

Figure 6
The behaviour of temperature at points 4, 5, 6, 7 of Figure 2, clearly shows a diurnal cycle.

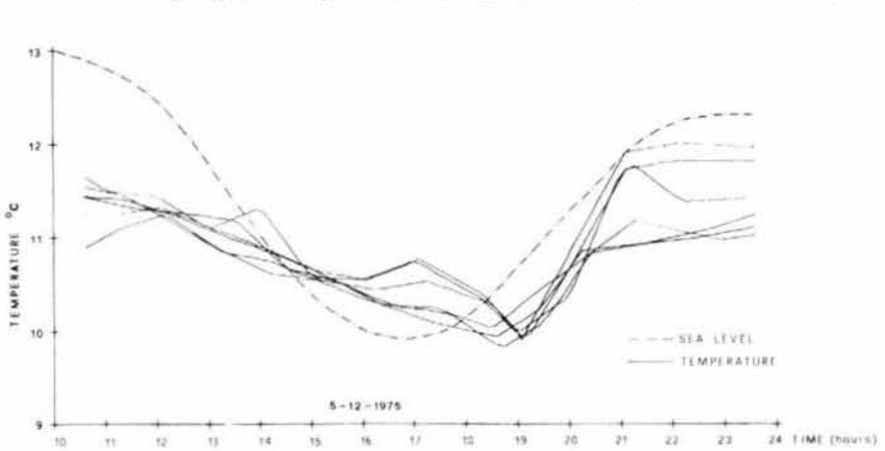

Figure 7
Behaviour of the mean temperature on 6 vertical profiles taken along the line between the jetties of the Lido inlet (see Fig. 2), i. e. along a cross-section of the channel (see Arcari et al., *1978* c).

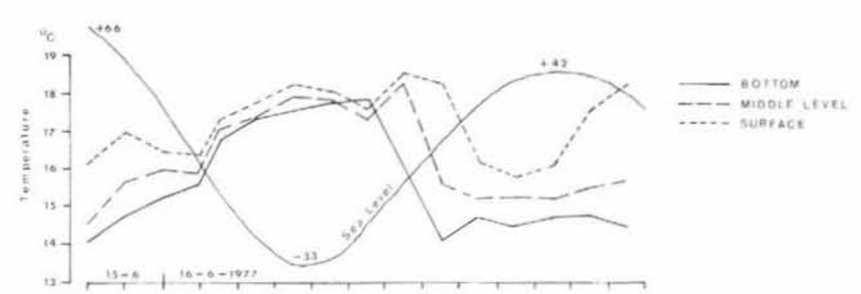

Figure 8
Behaviour of temperature on a vertical representative of a cross-section in the Malamocco inlet.

Table 1

Mean temperatures in °C taken at various levels during the year. Note the strong temperature gradients.

			Sediment temperatures, 1980					
		cm	January 3rd decade (1)	March 3rd decade	May 3rd decade	July 3rd decade	September 3rd decade	December 1st decade
Level	I	(− 20)	6.9	9	17	23.5	23.3	7
	II	(− 70)	7	9.5	15.5	21.5	22.7	9.2
	III	(− 120)	8	10	14.2	20	21.7	11
	IV	(− 170)	9.3	11	13.7	18.5	21.5	14.5
	V	(− 220)	10.5	11.7	13	19.5	19.5	15.7

(1) The month being divided into three decades.

We can say that the situation of the shallow zones tends to that of a salty lake with the same depth of water, when the exchanges with the sea become negligible. In the actual situation, sea water with its own characteristics enters the lagoon through the channels, interacts with water of the surrounding flats, then goes back to the sea in a modified state. But the point is that this interaction is not due to the tidal advection, as is deducible from the diurnal and not tidal behaviour of temperature, it is instead a horizontal turbulent diffusion mechanism (Battiston *et al.*, 1980) which acts on a much longer scale of time, that is on a seasonal one. So that in general we can separate in these zones processes of heating and cooling which act on a diurnal scale of time and are essentially local and processes which involves the interaction whith the sea and are seasonal. In this paper we are dealing with the latter.

The total yearly thermal excursion in these inner zones is about 20-25 °C, that is appreciably greater than the corresponding value for the CNR platform in the Adriatic Sea (CNR stands for the National Research Council), roughly 15 km offshore where the depth is ~ 16 m. In fact here the winter temperature, constant with depth, is about 10 °C and the July thermocline goes typically from 15 °C at the bottom to 25 °C at the surface. The difference between these thermal excursions appears thus strongly related to the presence of the shallow areas in the lagoon. We have proposed that the bottom in contact with these shallow layers is an important factor in their temperature excursion on a seasonal time scale.

THE 1980-1981 POLE EXPERIMENT

To quantify the interaction of the lagoon water with the bottom, we made during 1980 and also during 1981, 2 series of measurements, the last of them still in elaboration. We have measured the temperature of bottom sediments during a 3-4 day period at regular two month intervals during one year in a typical shallow area which is called Valle Cà Zane (see asterisk, righthand side of Fig. 2). For this purpose the " measurement team " of our institute, which carried out all the field measurements previously mentioned, constructed a polypropylene tube, 3.5 m long and 8 mm thick with a 60 mm diameter. On the external surface, housings were made for the thermistors (Fenwal Electronik 2381 h 88/uua 4151 Unicurve 10 k — 25 °C — 0.2 °C). The six thermistors, spaced every 50 cm along the tube, have been protected by a PVC bar with little holes for each thermistor to attain the best thermal contact with the sediment and the best protection.

The smooth internal and external surfaces of the tube and the oblique cut of the penetration end, made both the penetration and the extraction in the bottom sediments easy without the aid of any special means.

When the pole is immersed, the highest sensor is at an average of 20-30 cm under the water-sediment interface. During all these field studies the water temperature, its salinity, the relative humidity of the air and its temperature are measured.

From temperature data records at the 5 levels in the sediments from − 30 to − 230 cm, it is possible to estimate the 3-4 day average temperature as a function of depth every two months (Table 1). The first level is nearest the water-sediment interface.

From these data it is possible to obtain Figure 9, in which a tentative temporal evolution of temperature at various levels is described. The various curves show an amplitude attenuation and a phase lag with depth. Due to the limited number of data of the first cycle, these curves are only a first approximation of the two parameters. It should be noted that the first three curves of Figure 9 show a very large

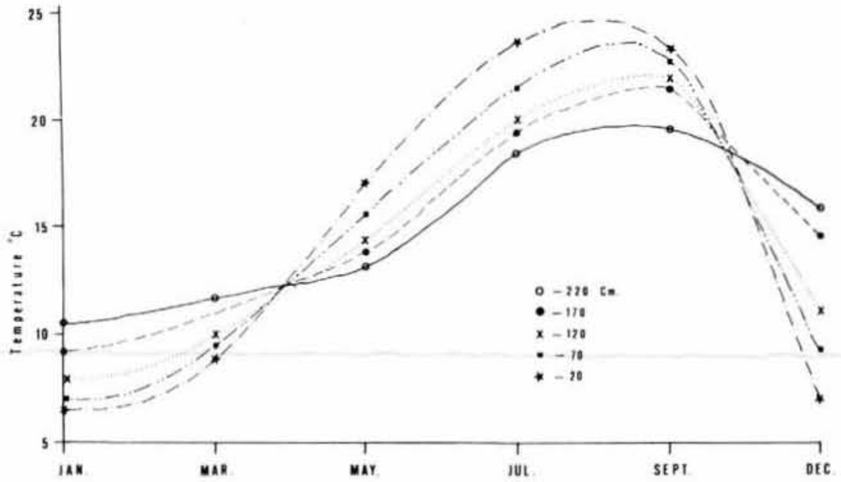

Figure 9

Experimental behaviour of the sediment temperature at 5 levels taken during a yearly cycle in the point shown in Figure 2.

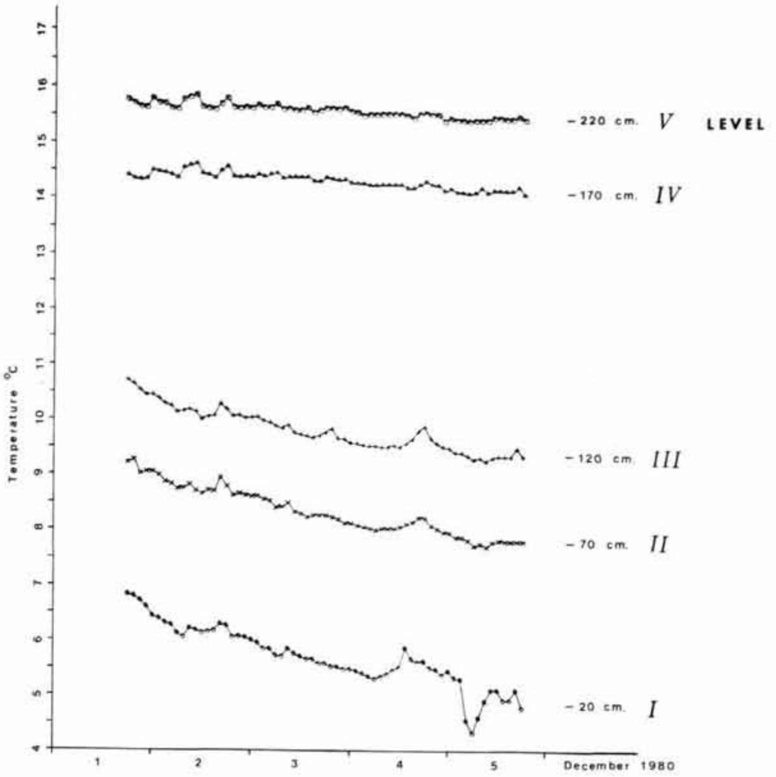

Figure 10

Typical behaviour of the sediment temperature at various levels. This case of 5 days during December 1980 falls within a period characterized by a sudden drop in air temperature. Strong temperature gradients are present.

temperature variation between September (3rd decade) and December (lst decade). This is due to the large thermal gradient which is present in this period of 1980 in the upper half of the sediment (Fig. 10). This can be related to a decrease in temperature, which starts from level I and penetrates to the levels underneath.

In general, any sudden change in atmospheric conditions generates rapid variations in the energy fluxes at the air-water and water-sediment interfaces, and then rapid variations in the sediment temperatures at various levels. These changes are described here as fluctuations with respect to a mean sinusoidal behaviour. If we neglect these fluctuations, we are left with a sinusoidal behaviour and with this approximation we shall investigate the phenomenon.

THE HEAT FLUX

The bottom sediment is nearly homogeneous for almost all of the lagoon, especially in the northern part, and here it is comprised of a silty-clay, very poorly compacted and with a large water content (Ricceri, Butterfield, 1974 ; Neglia, 1971-1972 ; Barillari, Rosso, 1975).

In regard to heat transport, we assume that the sediment has the following characteristics :

density $\rho = 2$ g cm^{-3}
specific heat $c = 0.37$ cal g^{-1} °C^{-1}
thermal conductivity $k = 3.77\ 10^{-3}$ cal cm^{-1} sec.$^{-1}$°C^{-1}
thermal diffusivity $\chi = 0.51\ 10^{-2}$ cm^2 sec.$^{-1}$,

for a water content of 40 % (Monteith, 1973).

With these values, we can calculate the average heat flux from the first level to the second one, assumed positive downward. These are summarized in Table 2.

Assuming a sinusoidal behaviour for the flux at the water sediment interface, $\Phi^* \sin \omega t$, the temperature in the sediment at depth z_i is :

$T(z_i, t) = (\Phi^*\delta/k) \sin (\omega t - \pi/4 - z_i/\delta\sqrt{2}) \cdot \exp(-z_i/\delta\sqrt{2})$,

where $\omega = 2 \times 10^{-7}$ rad sec.$^{-1}$ is the yearly frequency $\delta = \sqrt{\chi/\omega} = 160$ cm,

and $d = \delta\sqrt{2} = 230$ cm is the so-called penetration depth. From this relation one obtains a phase lag $\varphi = \Delta z/\delta\sqrt{2} \simeq 0.88$ radians, or 1 month and a half between level I and level V. This is in good agreement with the value we deduce from the intersection of the curves of Figure 9 with the horizontal axes (i.e. when the temperature assumes the mean value of 15 °C). The amplitude of temperature at level I is $\Delta T^* \simeq 9$ °C, but because $\Delta T^* = \Phi^*\delta/k$, one gets $\Phi^* \simeq 0.21 \cdot 10^{-3}$ cal cm^{-2} sec^{-1}, and this value is consistent with the maximum value of Table 2.

The theoretical behaviour of $T(z_i, t)$ is sketched in Figure 11. Here the beginning point is the last decade in January, and the phase is chosen so that theoretical and experimental curves assume the same mean value of 15 °C contemporaneously. The theoretical behaviour is in good agreement with the 1980 experimental data (Fig. 9) in the interval of March-September, but not so good outside of this interval.

This can be attributed to the meteorological fluctuations we have spoken about before. The maximum excursion of water temperature during the year, as we have mentioned in Section 2 is between 20 and 25 °C. Assuming for instance

Table 2

The fluxes are downward in May, July and September and upward in January, March and December.

	Water-sediment conductive fluxes					
	January	March	May	July	September	December
Cal cm^{-2} sec.$^{-1}$ 10^{-3}	− 0.037	− 0.037	0.11	0.16	0.10	− 0.17

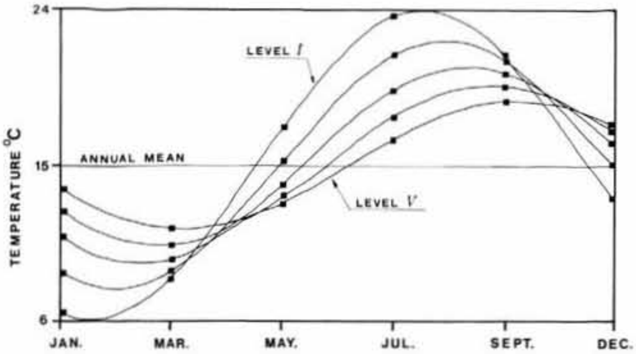

Figure 11

Theoretical behaviour of the temperature of the sediments, assuming a sinusoidal flux at the water-sediment interface. This behaviour is to be compared with the experimental one of Figure 9. On the y-axis, the amplitude of the temperature is 9 °C and the mean is 15 °C.

$\Delta T_w = 20\,°C$ and $h = 1$ m as the mean depth for the layer of water, the average variation of heat content from late winter to late summer, for the water column is:
$\Delta E_w/\Delta t = \Delta(\rho_0 c_0 hT)/\Delta t = 0.13 \cdot 10^{-3}$ cal cm^{-2} sec.$^{-1}$,
where ρ_0 and c_0 are the density and specific heat of the water. We can compare this value with the corresponding experimental value for the sediment $\Delta E_s/\Delta t$ down to the penetration depth d:

$$\Delta E_s/\Delta t = \Delta\left(\rho c \int_0^{\tau/2}\int_0^{d} T(z_i,\ t)\ dz\ dt\right)/\Delta t$$
$$\simeq 0.11 \cdot 10^{-3}\ \text{cal cm}^{-2}\ \text{sec.}^{-1}$$

The theoretical value for the whole sediment is

$$\Delta E_{sw}/\Delta t = \int_0^{\tau/2} \Phi^* \sin \omega t dt = 2\,\Phi^*/\omega$$
$$= 0.136 \cdot 10^{-3}\ \text{cal cm}^{-2}\ \text{sec.}^{-1}$$

$\tau/2$ is a half year period.
From these figures it is evident that the energy stored in the sediment during the heating period is roughly equal to that stored in the layer of water. According to the values of the conductive fluxes we have illustrated previously, this energy is released in winter to the water.

THE YEARLY HEAT BALANCE

The yearly heat balance for the water column of unit area section can be schematized in this way:
$dE_W/dt = \varepsilon(\Phi_0 + \Phi_1 \sin \omega t) - F_s - F_n - Q$,
where F_s is the flux from water to the atmosphere (including sensible and latent heat fluxes, longwave radiation);
F_n is the flux from water to the bottom;
$Q = \int_0^h \text{div}\, F_T dz$, F_T the flux normal to the column of water due to horizontal transport (horizontal turbulent diffusion);
$\Phi_0 + \Phi_1 \sin \omega t$ is the incident solar flux (the origin of time being at spring equinox);
ε is the absorption coefficient with respect to the whole water column.
For the numerical values of Φ_0 and Φ_1 (respectively mean value and amplitude of the incident solar flux) it can be assumed at the latitude of Venice:
$\Phi_0 = 3.5 \times 10^{-3}$ cal cm^{-2} sec.$^{-1}$
$\Phi_1 = 2.3 \times 10^{-3}$ cal cm^{-2} sec.$^{-1}$.
These numbers are obtained from insolation records taken in Venice in 5 preceding years (Janeselli, 1975; 1977 *a* and *b*; 1978; 1979).
An example of the value of F_s for the third decade of October, in a zone very similar to the present and for clear days, is given in Arcari *et al.*, 1978 *a*).
$F_s = 2.10^{-3}$ cal cm^{-2} sec.$^{-1}$.
If $\varepsilon = 90\,\%$ and $\sin \omega t$ is calculated for that period, it results:
$\varepsilon(\Phi_0 + \Phi_1 \sin \omega t) - F_s = 10^{-4}$ cal cm^{-2} sec.$^{-1}$.
We argue that this is an indication of the order of magnitude of this difference during the whole year.
As described in the introduction, the Venice Lagoon is effectively releasing heat to the sea in summer and receiving in winter, so that the presence of the term Q in the balance equation is meaningful.
With the definition of Q given before, it can be written (in two dimensions):
$Q = \rho_0 c_0 h \cdot K_X(\partial^2 T/\partial X^2)$,
where K_x is the coefficient of turbulent diffusion. If one looks at the data of Figure 6, filtered of the diurnal trend, one has an idea of the smallness of the difference of temperature in a typical distance of 500 m. Taking $h = 100$ cm, $K_x = 10^3$ cm^2 sec.$^{-1}$, and $(\partial^2 T/\partial X^2) \simeq 10^{-9}$-$10^{-10}$ it results
$Q \simeq 10^{-4}$-10^{-5} cal cm^{-2} sec.$^{-1}$.
The heat balance appears at this point roughly established between terms of the same order of magnitude, in particular F_n cannot be neglected.

CONCLUSIONS

Notwithstanding the complexity of the problem of thermal exchange in the lagoon system, the analysis of the temperature data taken in the water and in the bottom sediment in a typical very shallow zone, brings to some interesting conclusions:
a) sediments at all levels to a depth of 230 cm show a distinct seasonal variation. Sediments at a shallower depth show additional higher frequency variations in response to weather related variations in water temperatures;
b) the temporal variation of the storage term for sediment, the temporal variation of the storage term in the overlying layer of water, and the conductive heat flux into or out of the sediment are of the same order of magnitude.
This suggests a strong interaction between lagoonal waters and the uppermost sediment layer;
c) the flux at the water-sediment interface is 1/10 of the annual excursion of the incident solar flux but its contribution to the balance equation for the water column cannot be neglected.

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