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HEAT TRANSFER AND THERMAL PROPERTIES OF THE SUBSOIL IN BELÉM

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Temperature profiles with depth were monitored in two neighboring boreholes at a site in Belém, Pará, 400 m from a river, at five-day intervals during a one year cycle of observations. The first borehole was cased with galvanized steel pipe closed at its lower end and filled with water. Three thermistor thermometers were fixed to a thin aluminium rod at depths of 1, 3 and 6 meters within this hole. The second borehole was cased with a plastic (PVC) pipe open at the bottom and consequently filled with water to the local water table level. Temperature profiles in the second hole were determined with a thermistor sonde to 16 meters depth. These observations were complemented with measurements of temperature at 0.02, 0.1, 0.2, 0.3 and 0.5 meters, using mercury soil thermometers and with solar radiation flux incident at the surface, determined by an actinograph. The temperature profiles for months of the same season show a remarkable resemblance, while between the rainy and dry season one notices very different features. The daily amplitudes of the temperature at 0.5 m reached 0.1°C in the rainy season and 0.34°C during the dry season. The seasonal temperature ranges at these depths were found to be approximately 5.0°C at 0.02 m and 4.0°C at 0.5 m. The temperature profiles in both seasons show changes of sign of the gradient at different depths. As expected, the amplitude of temperature variations decreases rapidly with depth but it is appreciable down to 16 meters and certainly at lower depths. A high correlation was observed between the variations of the temperature measured at 1 m and the solar radiation flux incident at the surface. The rare cases in which this correlation was not observed could be explained by an increase of the pluviometric precipitation at the site. Continuous sediment sampling during drilling allowed the laboratory determination of the profiles of specific heat, thermal conductivity and density. These parameters were used to determine the thermal diffusivity profiles. The heat flow near the surface was calculated from 0.1 to 8.0 meters. The estimates for 9:00 AM and 6:00 PM, local time, showed an almost symmetrical behaviour down to 0.5 m, with relation to the zero flux line. The estimated heat flow presents a rapid decay of amplitude with depth, and sudden changes of sign, due to the stored heat from previous periods of surface exposure to insolation.

Foi realizada uma atividade de monitoramento de perfis de temperatura em dois furos localizados na cidade de Belém, Pará. Os furos distam cerca de 400 m da margem de um rio. O monitoramento térmico foi efetuado em intervalos de cinco dias durante um ciclo de período de um ano. O primeiro furo foi revestido com tubo metálico galvanizado, fechada sua extremidade inferior e, posteriormente, preenchido com água. Em seu interior foi inserida uma fina vara de alumínio na qual foram afixados três termômetros de termistor, às profundidades de 1, 3 e 6 metros. O segundo furo foi revestido com tubo plástico (PVC), permanecendo abertas suas extremidades, consequentemente, preenchido com água até a profundidade atinente ao nível freático. Os perfis de temperatura referentes ao segundo furo foram determinados até a profundidade de 16 metros, utilizando-se uma sonda de termistor. Estas observações foram complementadas com medidas de temperaturas, às profundidades de 0,02, 0,1, 0,2, 0,3 e 0,5 metros, obtidas com uso de termômetros de mercúrio, e com valores de fluxo de radiação solar incidente na superfície, determinados por um actinógrafo. Os perfis de temperatura correspondentes aos meses de uma mesma estação mostram uma boa semelhança entre si, enquanto que os relativos às estações seca e chuvosa apresentam feições muito diferentes. A 0,5 m de profundidade, a amplitude diária da temperatura atingiu 0,1°C durante a estação chuvosa e 0,34°C durante a estação seca. Nesta profundidade a variação sazonal observada foi de 4,0°C, enquanto que a 0,02 m registrou-se o valor de 5,0°C. Em ambas as estações os perfis de temperatura mostram a ocorrência de

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mudanças de sinal do gradiente a diferentes profundidades. Como esperado, a amplitude das variações de temperatura decresce rapidamente com a profundidade mas continua sendo apreciável a 16,0 m e certamente a maiores profundidades. Foi observado uma excelente correlação entre as variações da temperatura medida a 1,0 m de profundidade e o fluxo de radiação solar incidente na superfície. Os raros casos em que esta correlação não é observada podem ser explicados pelo incremento da precipitação pluviométrica local. Obteve-se através de testemunhos de sondagem uma amostragem contínua dos furos em estudo, o que tornou possível a determinação, em laboratório, de perfis de calor específico, condutividade térmica e densidade. Estes parâmetros foram usados para a determinação de perfis de difusividade térmica. O fluxo de calor próximo a superfície foi calculado desde 0,1 até 8,0 metros. Até a profundidade de 0,5 m, os resultados concernentes às 9:00 e 18:00 h local mostram um comportamento quase simétrico, com relação a linha de fluxo zero. O fluxo de calor calculado apresenta um rápido decaimento da amplitude com a profundidade e mudanças súbitas de sinal. Isto é devido ao calor armazenado em períodos anteriores em que a superfície esteve exposta a insolação.

INTRODUCTION

Studies of thermal properties of the subsoil as well as the thermal regime near the surface in the Amazon Region have so far been restricted to soil thermometer observations up to 1 m depth (Decico et al., 1977; Diniz & Bastos, 1980), and inferences of the geothermal gradient based on bottom hole temperatures (BHT) of oil exploration wells (Uyeda & Watanabe, 1970; Meister, 1973; Carvalho et al., 1986). Nevertheless, heat transfer may play an important role in rock weathering and microclimatic changes, wherever the vegetation cover is removed. With this environmental concern, a monitoring program of the soil and subsoil temperatures at a site approximately 400 m away from a riverside was started. This site is in the outskirts of the city of Belém, within the University of Pará campus, which has more than 50 hectares of unpaved, sparsely vegetated area.

The site under study presents a well defined pluviometric regime with the rainy season occurring between January and May and the "dry" season between July and November (Cunha & Bastos, 1973; Rocha & Souza, 1982; Souza et al., 1984). This regime is largely controlled by the presence of the Intertropical Convergence Zone (ITCZ) periodically passing over the site. The thick nebulosity caused by the ITCZ significantly diminishes the global solar radiation flux incident at the surface (Diniz et al., 1984). The climatological normals for different segments of the time series of observations are shown in Fig. 1 (Cunha & Bastos, 1973; Serviço de Meteorologia, 1968) and have presented little change over an 80 year observation period (Cunha & Bastos, 1973; EMBRAPA, 1983).

Considering the relative regularity of the thermal and pluviometric regimes at the surface of the area under study, one year cycle of monitoring may give a reasonable idea of the variability and extremes to be expected at this humid tropical site.

The solar radiation flux incident at the earth's surface is partially absorbed by the solid or liquid materials, resulting in the heating of the surface during

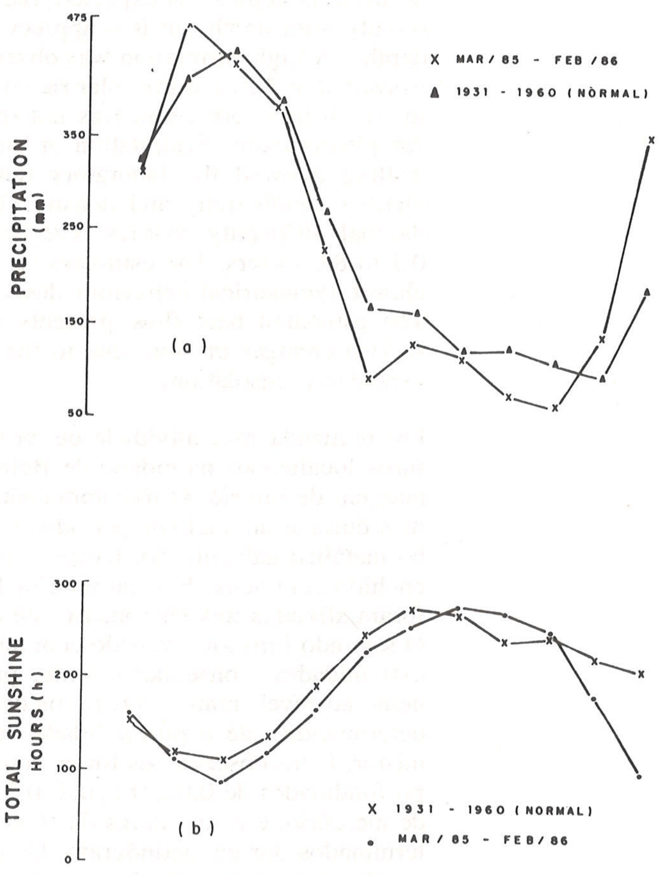


Figure 1. Climatological normals in Belém; total sunshine hours and precipitation: period 1931–1960 (from Cunha & Bastos, 1973; Serviço de Meteorologia, 1968); March/85 to February/86 data.

the sunshine hours. The heat transfer efficiency to deeper layers by conduction will depend among other factors on the amplitude of the temperature changes at the surface, the vertical distribution of thermal diffusivity of the ground and the loss of energy at the surface (through radiation, sensible and latent heat fluxes) to the atmospheric boundary layer.

It has been frequently reported in the literature that the ground temperature changes due to the daily solar heating at the surface are strongly attenuated in depth and may be negligible at about 1 m depth and beyond (Carslaw & Jaeger, 1959; Kézdi, 1974; Sellers, 1974; Jaeger, 1965; Courtillot & Francheteau, 1976). However the same authors suggest that the seasonal thermal variations may reach depths around 20 m. It should be pointed out that these studies were not conducted in the humid tropics. Temperature observations with a thermistor thermometer at 1.0 m depth at our chosen site had indicated sizeable daily changes; and this fact encouraged the author to pursue a temperature monitoring program at 13 selected depths from 0.02 to 16.0 m.

NEAR SURFACE OBSERVATIONS OF THE THERMAL PROPERTIES AND REGIME

The data collection involved the periodic observation of the temperature profiles (Table 1) and the determination of the thermal properties of the core samples obtained at various depths of the boreholes (Table 2) used in this experiment. The period of study covers a one year cycle and includes observations of the incoming solar radiation flux and the pluviometric precipitation at the area under study.

Temperature profiles

Soil thermometers were used for the temperature monitoring at depths 0.02, 0.1, 0.2, 0.3 and 0.5 m. These mercury thermometers have specified errors within a $\pm$ 0.2°C range. However, this low precision does not imply a large relative error considering the sizeable temperature variations at such depths.

The measurements of temperature at 1 m and beyond were made using thermistor thermometers with their resistance determined by a precision Wheatstone

Table 1. Monthly averages of the temperatures measured within the 0.02 to 10.0 m depth interval in Belém: a) 9:00 AM; b) 6:00 PM (local time).

Z (m)	MAR/85	APR/85	MAY/85	JUN/85	JUL/85	AUG/85	SEP/85	OCT/85	NOV/85	DEC/85	JAN/86	FEB/86
	TEMPERATURE (°C)											
0.02	27.0	26.9	27.5	27.5	27.3	27.6	28.6	31.5	30.5	28.2	27.6	27.0
0.10	27.2	27.1	27.7	27.8	27.7	28.0	28.5	29.6	29.2	27.8	27.5	27.0
0.20	27.5	27.5	28.2	28.3	28.3	28.5	29.2	30.8	29.9	28.3	28.1	27.6
0.30	28.1	28.1	28.7	29.0	29.0	29.2	29.7	31.1	30.5	28.6	28.4	27.9
0.50	28.7	28.5	29.4	29.7	29.8	–	31.0	31.8	31.1	29.2	28.9	28.4
1.00	27.44	27.26	27.53	27.77	28.51	28.92	29.52	31.10	30.67	28.73	28.30	27.71
3.00	28.34	28.14	28.00	27.97	28.06	28.25	28.38	28.64	28.94	28.88	28.62	28.41
6.00	27.67	27.34	27.43	27.26	26.86	26.84	27.70	27.82	27.89	27.46	27.68	27.20
8.00	27.65	27.48	27.41	27.24	26.98	27.06	27.56	27.67	27.72	27.53	27.61	27.28
10.00	27.57	27.53	27.46	27.37	27.20	27.25	27.56	27.63	27.67	27.56	27.61	27.39

(a)

Z (m)	MAR/85	APR/85	MAY/85	JUN/85	JUL/85	AUG/85	SEP/85	OCT/85	NOV/85	DEC/85	JAN/86	FEB/86
	TEMPERATURE (°C)											
0.02	29.2	28.8	29.8	30.5	30.5	30.9	31.2	32.7	31.7	29.2	29.4	29.2
0.10	29.3	29.1	30.3	30.8	31.1	31.5	32.2	34.0	32.9	29.8	29.8	29.7
0.20	29.3	29.0	29.9	30.0	30.5	30.5	31.2	33.7	32.8	29.9	30.0	29.5
0.30	28.7	28.6	29.4	29.6	29.7	29.9	30.7	32.6	31.7	29.3	29.2	28.8
0.50	28.6	28.5	29.4	29.8	29.7	–	30.8	31.9	31.0	29.1	28.8	28.4
1.00	27.42	27.24	27.51	27.74	28.47	28.89	29.52	31.08	30.68	28.62	28.38	27.80
3.00	28.34	28.14	28.01	27.97	28.06	28.25	28.38	28.64	28.95	28.92	28.70	28.41
6.00	27.67	27.34	27.43	27.26	26.86	26.84	27.70	27.82	27.89	27.46	27.68	27.26
8.00	27.65	27.48	27.41	27.24	26.98	27.06	27.56	27.67	27.72	27.53	27.61	27.28
10.00	27.57	27.53	27.46	27.37	27.20	27.25	27.56	27.63	27.67	27.56	27.61	27.39

(b)

Table 2. Lithological composition and physical properties of the core samples from the boreholes – percentage of sand, clay and water; density (ρ), specific heat (C), thermal conductivity (λ) and thermal diffusivity (k).

Z (m)	% SAND	% CLAY	% WATER	ρ (10^3 kg.m^{-3})	C (10^3 J.kg^{-1}.^{o}C^{-1})	λ (W.m^{-1}.^{o}C^{-1})	k (10^{-6} m^2.s^{-1})
0.45	66.94	22.50	10.56	2.30	1.204	2.19	0.791
1.00	65.51	24.34	10.18	2.32	1.192	2.54	0.918
2.50	1.87	72.15	25.98	1.84	1.776	1.33	0.407
5.30	0.34	52.41	47.25	1.42	2.470	1.11	0.316
8.50	4.34	52.40	43.26	1.48	2.334	1.06	0.307
10.50	7.75	45.72	46.53	1.51	2.438	0.95	0.258
15.00	66.95	16.81	16.24	1.98	1.389	2.19	0.796
16.00	12.63	54.58	32.79	1.83	1.986	1.38	0.380

bridge, adapted to operate with continuous current of 20 μA, which was mantained throughout all the measurements. This arrangement allowed temperature determinations with precision of the order of ± 0.02^{o}C.

Two boreholes were made, one next to a meteorological station, A, and another 500 m away, B. Both had continuous core sample collection down to 12 and 18 m, respectively. The lithological analysis of the samples showed similar features at boreholes A and B. Considering this fact plus the identical meteorological conditions, and the same surface and water table levels, the temperature profiles obtained from 1.0 to 6.0 m in hole A were connected to the temperature profiles determined from 8.0 to 16.0 m in hole B.

In order to minimize errors in the temperature determinations near the surface, caused by loss of thermal contact with the ground or the pesence of convection within the unsaturated zone; hole A was cased with a galvanized water pipe closed at the lower end. Three thermistors were attached to a thin aluminium rod and inserted in this pipe remaining fixed at 1.0, 3.0 and 6.0 m depth. The pipe was then filled with fresh water and closed at the top in order to avoid evaporation of the fluid. The measurements were performed by switching the thermistor thermometers terminals at the Wheatstone – type bridge.

Hole B was cased with an open ended PVC plastic pipe in which the static groundwater level remained around 4 m depth. In that condition the temperature profiles were obtained by lowering a single thermistor thermometer from 8.0 to 16.0 m with measurements at each 2.0 m depth interval.

Thermal Diffusivity Determinations

The thermal diffusivity was calculated at half meter intervals along the borehole A. The core samples collected provided material for the laboratory determinations of thermal conductivity, density and specific heat, used for the thermal diffusivity determinations.

The thermal conductivity measurements were performed by a transient heat conduction method using a needle system as described by Von Herzen & Maxwell (1959), Langseth (1965) and Smith (1973). This system permitted conductivity measurements within a ±0.15 W.m^{-1} ^{o}C^{-1} error range.

In order to determine the density of each sample, they were placed in a graduated cylinder filled with distilled water. The water volume displaced by the sample volume was determined with ± 0.5 ml error. The masses were determined through a digital balance with ± 10^{-4} g error.

The same samples were dried, crushed and sieved in order to separate their sand, clay and silt fractions. The specific heat of each sample, C, was calculated using a weighted mean of the average specific heat of each fraction $\bar{c}_i$ (obtained from Rzhevsky & Novik, 1971; Kézdi, 1974)

$$C = \sum_{i=1}^{3} m_i \bar{c}_i \Big/ \sum_{i=1}^{3} m_i$$

where m_i are the masses of each fraction in the sample.

Solar Radiation and Precipitation

The incoming global solar radiation flux at the surface was continually recorded by a Robitzech-type bimetallic actinograph with a ± 8% error of the registered values.

The daily pluviometric precipitation height was determined by means of a Ville de Paris-type pluviometer with the water volume collected measured in a graduated cylinder with 0.1 mm scale.

DISCUSSION OF THE RESULTS

Time Variations of Soil Temperature at 1 m Depth

Within the year of observations, we selected two months of the rainy season (March and April) in order to display and compare the time behaviour of the following parameters: a) the five-day averages of the daily incident global solar radiation flux at the surface; b) the registered soil temperatures at 1 m depth, daily at 9:00 AM, local time; c) the five-day averages of the daily precipitation. As one can verify in Fig. 2 where these parameters are displayed the temperature varies considerably at 1 meter from one day to another. Therefore, in the area under study the daily changes of the temperature are not strongly attenuated with depth and cannot be neglected at such depths.

It is clear from Fig. 2 that a direct relationship exists between the solar radiation flux at the surface and the temperature at 1 m depth. In the same figure one can observe a delay of approximately 1 day between the maxima and minima of the soil temperature at 1 m with regard to those of the solar radiation flux. This delay can be explained by considering a mean speed over 4.0 $cm.h^{-1}$ for the transmission of the daily radiation pulse within the 1 m surface layer. It is also evident from Fig. 2 that precipitation plays a significant role on the observed 1 m depth temperatures. One observes a persistent inverse relationship between precipitation and the two parameters already considered. Within the observation period considered in Fig. 2, which includes the equinox and the occurrence of the largest indexes of nebulosity and precipitation over the region, the largest increments of the solar radiation flux observed from one day to the other were of about 30 $W.m^{-2}$. The temperature increases related to the radiation increments were around 0.2°C at 1 m depth.

The same parameters shown in Fig. 2 were plotted at five-day intervals in Fig. 3, for the whole year-cycle of observations. One observes in Fig. 3 that the largest short-term variations of the radiation flux occur from January to May in this region, which has a substantially regular climatic regime. The radiation flux varied from 127 to 264 $W.m^{-2}$ while the temperature range at 1 m depth was from 27.08 to 31.96°C.

It is apparent from Fig. 3 that the direct relationship between solar radiation flux and soil temperature already mentioned, persists for the whole year. However, such relationship is even better observed during the dry season. This is explained by the fact that during the rainy season most of the incoming solar radiation energy is consumed as latent heat for evaporation in a tropical moist region (Sellers, 1974). On the other hand during the dry season a larger portion of this energy source can be used for the heating of the soil. This may explain the large temperature gradients observed during the months of September to November. In the few instances where a direct response of the soil temperature to the solar heating is not observed, one can verify the following: 1) the solar radiation flux increases while the soil temperature may decrease if there is a simultaneous increment of the precipitation or this parameter remains at high levels (periods of November 10 to 15 and January 20 to 25, respectively); 2) in the absence of precipitation and for high values of solar energy input, the soil temperature may continue to rise during small decrements of the solar energy flux (periods of September 15 to 30 and October 25 to 30).

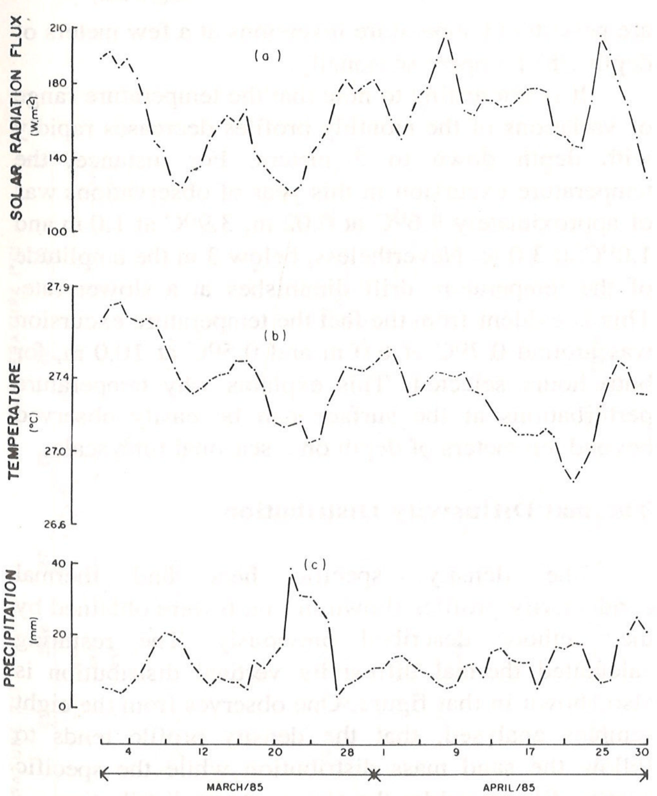
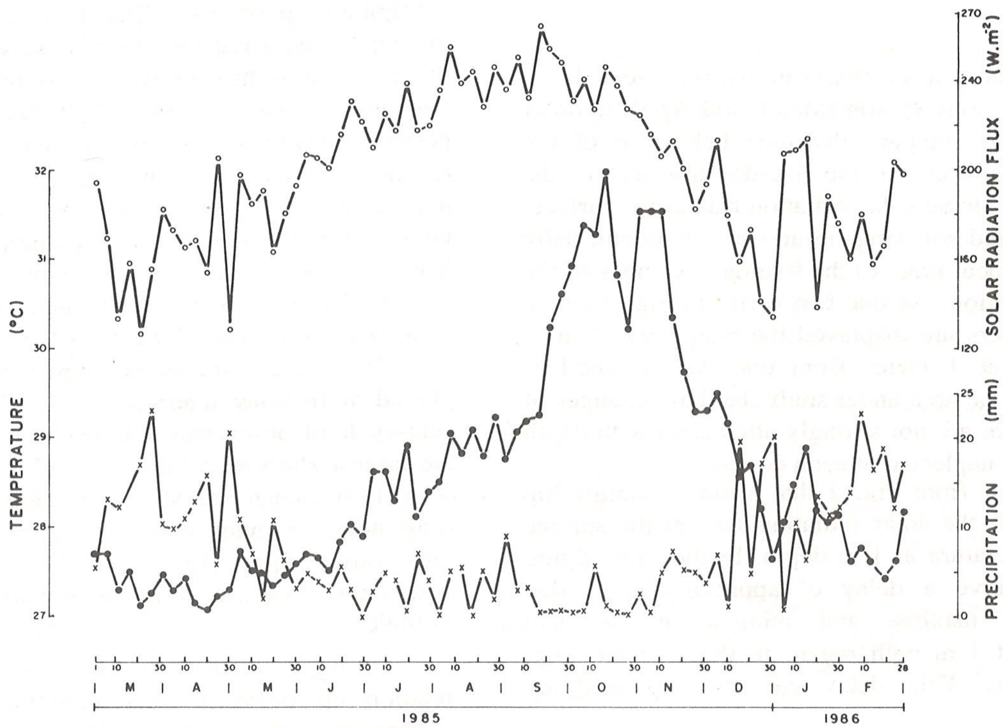


Figure 2. Time behaviour of: a) five-day averages of the solar radiation flux incident at the surface; b) soil temperature at 1.0 m depth, taken at 9:00 AM, local time; c) five-day averages of the daily precipitation. Period: March and April, 1985

Annual Variation of the Temperature Profiles within the 0-10 m Depth Zone

The monthly mean temperature profiles for the 0-10 m depth zone during the year of observations are shown in Figs. 4a, 4b, 5a, and 5b. In order to better display the results, the data pertaining to two depth intervals, namely from 0.02 to 0.5 m and from 0.5 to 10.0 m are shown separately. The measurements were performed at 9:00 AM and 6:00 PM, local time, at five-day intervals. These observation hours were

Figure 3. Time behaviour of: precipitation (–x–); temperature at 1.0 m depth (–.–); solar radiation flux (–o–). Period: March/85 – February/86.



selected because, at this tropical site, on clear days, at 9:00 AM the incident solar radiation flux has already begun to raise the surface's temperature and at 6:00 PM this source of energy may be considered to vanish. In these figures, each profile displayed represents the average of six profiles observed during the month considered.

One observes in Figs. 4a and 4b corresponding to the measurements made at 9:00 AM that the evolution of the profiles present somewhat parallel displacements within the same pluviometric season, as well as substantial changes and even inversions of temperature gradients between the local rainy and "dry" seasons. The same behaviour can be observed in Figs. 5a and 5b which display the results of measurements made at 6:00 PM. However, one notices an almost symmetrical profile configuration within the 0.02 to 0.5 m zone in these figures. For greater depths, the profile differences at these two selected hours are not so remarkable and both the magnitudes and temperature gradients are similar at a given depth interval.

At a given hour of the day the monthly profiles drift toward greater temperature values during the May to October period. With few exceptions, at certain depths the profiles drift toward lower temperature values in the period of November to March.

The changes of sign of the temperature gradients are not only due to daily effects or restricted to the 0-0.5 m zone. It is clear from these figures that there are persistent temperature inversions at a few meters of depth which appear seasonally.

It is interesting to note that the temperature range of variations of the monthly profiles decreases rapidly with depth down to 3 meters. For instance, the temperature excursion in this year of observations was of approximately 4.6°C at 0.02 m, 3.9°C at 1.0 m and 1.0°C at 3.0 m. Nevertheless, below 3 m the amplitude of the temperature drift diminishes at a slower rate. This is evident from the fact the temperature excursion was around 0.7°C at 6.0 m and 0.5°C at 10.0 m, for both hours selected. This explains why temperature perturbations at the surface can be easily observed beyond ten meters of depth on a seasonal time scale.

Thermal Diffusivity Distribution

The density, specific heat and thermal conductivity profiles shown in Fig. 6 were obtained by the methods described previously. The resulting calculated thermal diffusivity vertical distribution is also shown in that figure. One observes from the eight samples analysed, that the density profile tends to follow the sand mass distribution while the specific heat profile resembles the clay contents distribution.

The specific heat profile shows a behaviour with depth opposite to that of the sample density. In fact the specific heat distribution is directly related to the water content of the sample. The samples with larger percentages of clay retain more water, as shown in

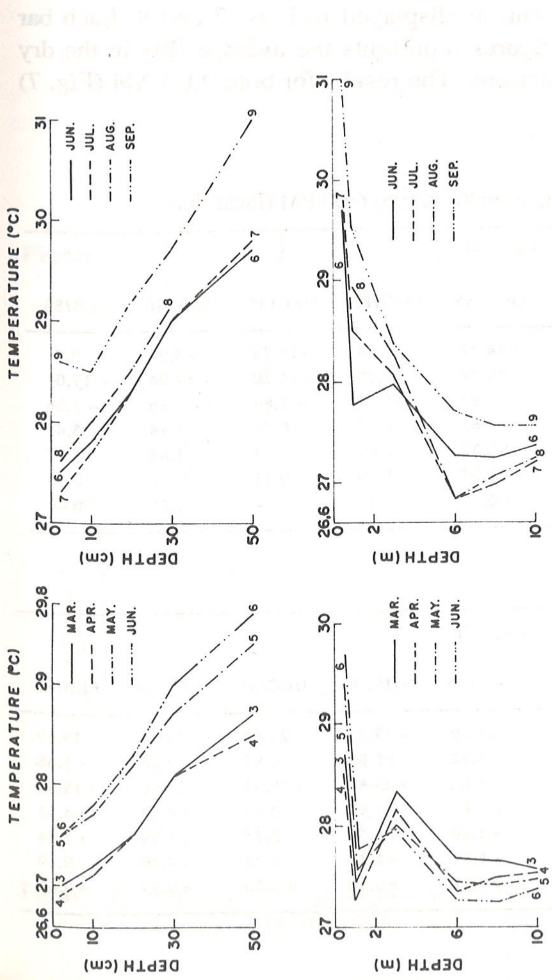


Figure 4.a. Temperature profiles – 9:00 AM (local time).

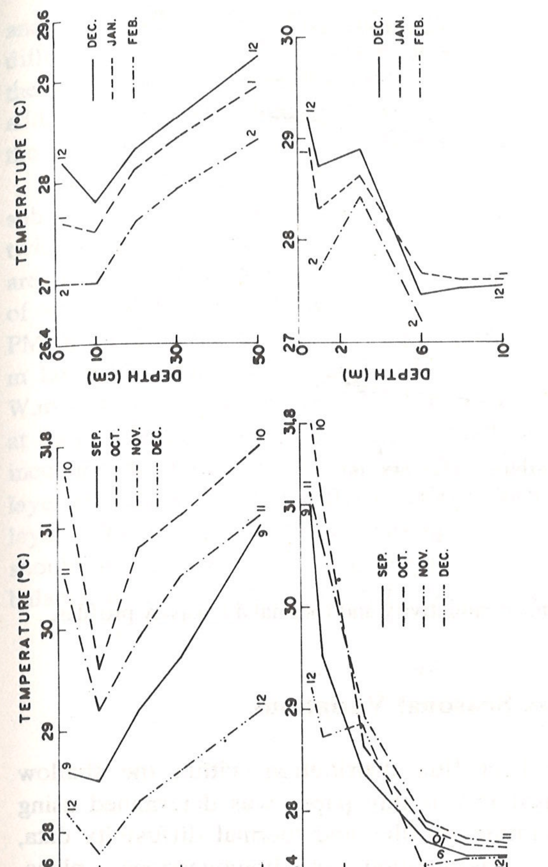


Figure 4.b. Temperature profiles – 9:00 AM (local time).

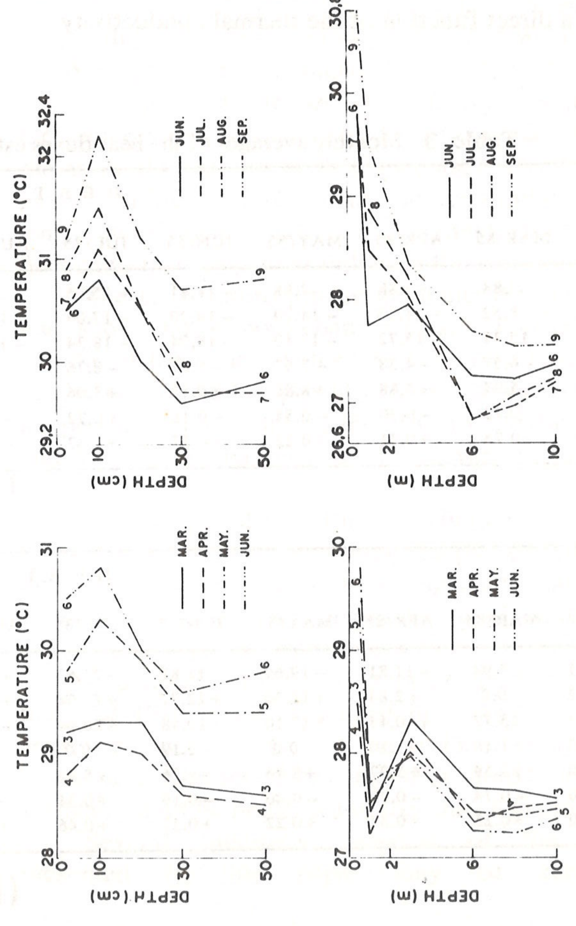


Figure 5.a. Temperature profiles – 6:00 PM (local time).

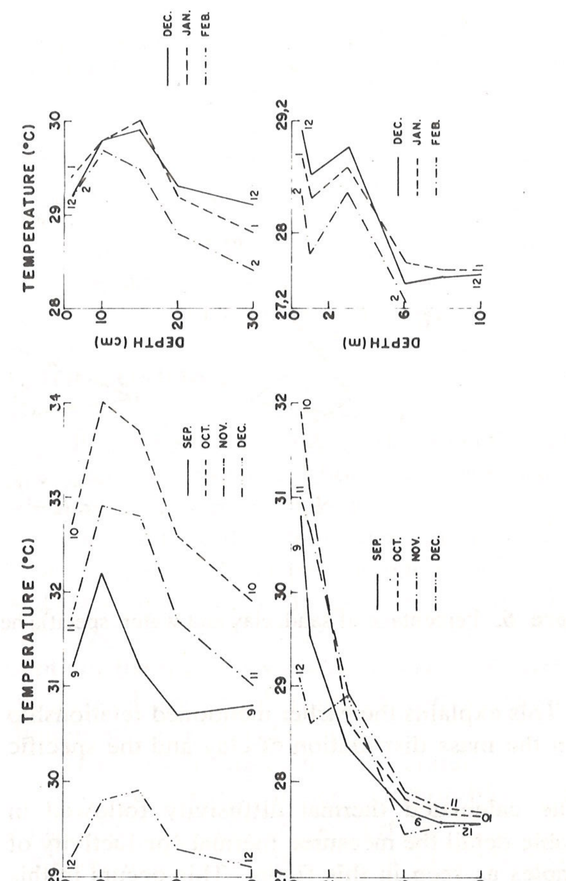


Figure 5.b. Temperature profiles – 6:00 PM (local time).

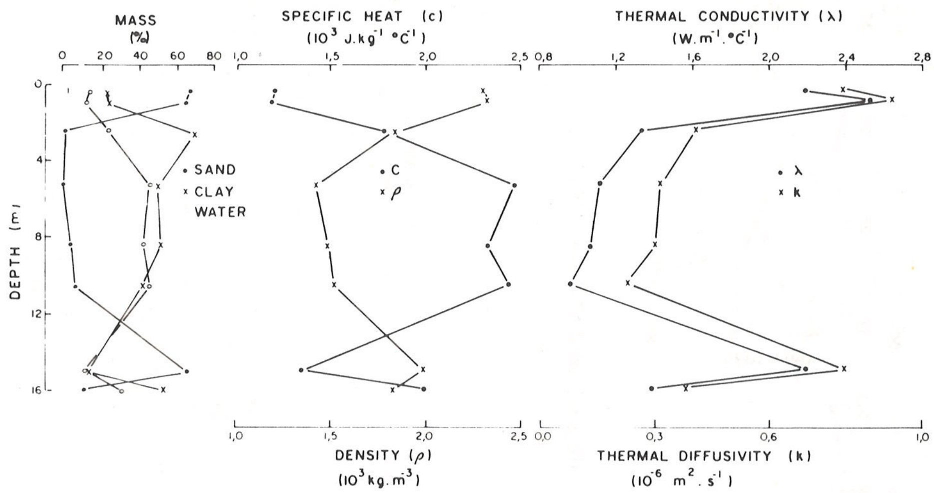


Figure 6. Percentage of sand, clay and water; specific heat, density, thermal conductivity and thermal diffusivity profiles.

Fig. 6. This explains the earlier mentioned relationship between the mass distribution of clay and the specific heat.

The calculated thermal diffusivity followed in remarkable detail the measured thermal conductivity of the samples as seen in this figure. This occurs in this case because the density and specific heat have inverse distributions with depth, so that the product of these two parameters remain nearly constant within the layer considered. Therefore the thermal diffusivity becomes simply a direct function of the thermal conductivity.

Heat Flux Seasonal Variations

The heat flux distribution within the shallow zone considered in this paper was determined using the temperature profiles and thermal diffusivity data, under the assumption of homogeneous, plane, stratified layers. Within a given layer the flux may be considered as constant and represented by a vertical line segment, as displayed in Figs. 7 and 8. Each bar in these figures represents the average flux in the dry or rainy seasons. The results for both 9:00 AM (Fig. 7)

Table 3. Monthly averages of the heat fluxes estimates in Belém: a) 9:00 AM; b) 6:00 PM (local time).

	HEAT FLUXES ($W.m^{-2}$)											
Δ Z (m)	MAR/85	APR/85	MAY/85	JUN/85	JUL/85	AUG/85	SEP/85	OCT/85	NOV/85	DEC/85	JAN/86	FEB/86
0.02 – 0.1	−7.88	−7.88	−7.88	− 11.81	− 15.75	− 15.75	+3.94	+74.81	+51.19	+15.75	+3.94	0.0
0.1 – 0.2	−8.52	− 11.36	− 14.20	− 14.20	− 17.04	− 14.20	− 19.81	− 34.08	− 19.88	− 14.20	− 17.04	− 17.04
0.2 – 0.3	− 15.72	− 15.72	− 13.10	− 18.34	− 18.34	− 18.34	− 13.10	− 7.86	− 15.72	− 7.86	− 7.86	− 7.86
0.3 – 0.5	− 6.57	− 4.38	− 7.67	− 7.67	− 8.76	–	− 14.24	− 7.67	− 6.57	− 6.57	− 5.48	− 5.48
0.5 – 1.0	+5.97	+5.88	+8.86	+9.15	+3.06	–	+7.02	+3.32	+2.04	+2.23	+2.84	+3.27
1.0 – 3.0	− 0.72	− 0.70	− 0.54	− 0.16	+0.72	+0.54	+0.91	+1.97	+1.39	− 0.13	− 0.26	− 0.56
3.0 – 6.0	+0.25	+0.31	+0.22	+0.27	+1.37	+0.54	+0.26	+0.31	+0.40	+0.54	+0.35	+0.46

(a)

	HEAT FLUXES ($W.m^{-2}$)											
Δ Z (m)	MAR/85	APR/85	MAY/85	JUN/85	JUL/85	AUG/85	SEP/85	OCT/85	NOV/85	DEC/85	JAN/86	FEB/86
0.02 – 0.1	− 3.94	− 11.81	− 19.69	− 11.81	− 23.63	− 23.63	− 39.38	− 51.19	− 47.25	− 23.63	− 15.75	− 19.69
0.1 – 0.2	0.0	+2.84	+11.36	+22.72	+17.04	+28.40	+28.40	+8.52	+2.84	− 2.84	− 5.68	+5.68
0.2 – 0.3	+15.72	+10.48	+13.10	+10.48	+20.96	+15.72	+13.10	+28.82	+28.82	+15.72	+20.96	+18.34
0.3 – 0.5	+1.10	+1.10	0.0	− 2.19	0.0	–	− 1.10	+7.67	+7.67	+2.19	+4.38	+4.38
0.5 – 1.0	+5.59	+5.97	+8.96	+9.76	+5.83	–	+6.07	+3.89	+1.52	+2.28	+1.99	+2.84
1.0 – 3.0	− 0.74	− 0.72	− 0.40	− 0.19	+0.34	+0.51	+0.91	+1.95	+1.39	− 0.24	− 0.26	− 0.50
3.0 – 6.0	+0.25	+0.31	+0.22	+0.27	+0.46	+0.54	+0.26	+0.31	+0.40	+0.56	+0.39	+0.43

(b)

and 6:00 PM (Fig. 8) data, show considerable differences between the average flux distributions in the rainy and dry seasons up to 3.0 m depth. In addition, the amplitudes of flux variations are larger in the dry season than in the rainy season in this zone.

One observes that the computed fluxes vary substantially in amplitude and can change sign at least twice within the upper 6.0 m depth. The heat fluxes are strongly attenuated with depth, reaching extremes of +74.8 $W.m^{-2}$ at 9:00 AM and -51.2 $W.m^{-2}$ at 6:00 PM in the 0.02 to 0.1 m layer; while at the 3.0 to 6.0 m layer the range was from +1.4 $W.m^{-2}$ and +0.2 $W.m^{-2}$ at those hours (Table 3). The computed fluxes at these selected hours may reach around 30% of the incoming solar energy flux within the 0.02 to 0.1 m layer and about 4% of that flux within the 0.5 to 1.0 m layer. Therefore, the energy storage in the ground should not be neglected, when estimates of the energy balance at the surface are made, for this region.

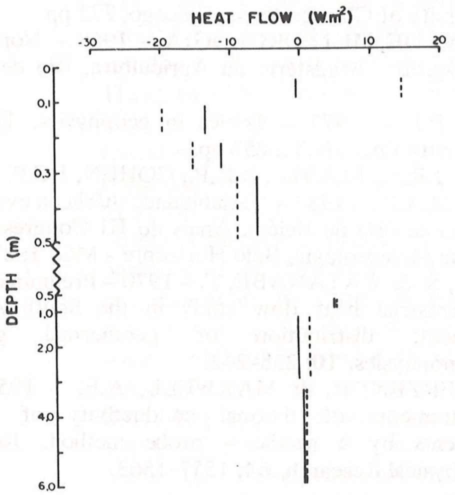


Figure 7. Average heat flux in the dry (⁄) and rainy (/) seasons – 9:00 AM (local time).

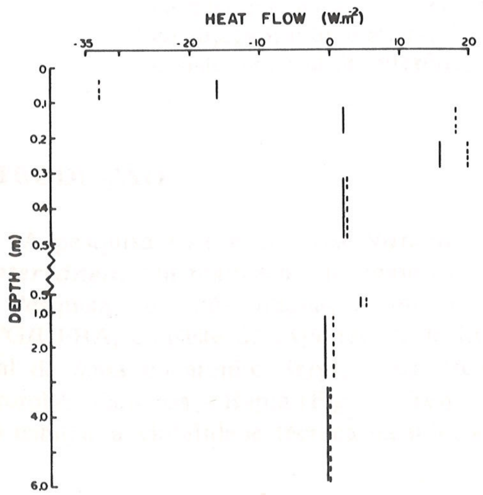


Figure 8. Average heat flux in the dry (⁄) and rainy (/) seasons – 6:00 PM (local time).

The symmetrical aspects of the flux distributions in Figs. 7 and 8 up to 0.5 m depth were expected, since at 9:00 AM the soil has just begun its daily heating, while at 6:00 PM its heat loss to the atmosphere is already appreciable in the region under study. It is evident for the selected hours that, in the 1.0 to 3.0 m layer, a negative average flux prevails during the rainy season while during the dry season the opposite is true. This indicates that heat storage may occur seasonally below such layer.

CONCLUSIONS

It is possible to study shallow geothermics with conventional instrumentation as long as certain precaution measures are taken.

At least in the humid tropical site studied the solar heating of the 0-10 m depth zone is significant and certainly can be monitored at greater depths.

The results presented show a strong decay with depth of the thermal perturbations at the surface, down to 3 m. However this decay rate is substantially diminished beyond that depth.

The monitoring of the temperature at 1 m depth showed a strong direct relationship with the temperature changes at the surface. The temperature response at 1 m depth however presents a delay of nearly one day, with regard to the times of occurrence of the extremes registered at the surface. This would correspond to a temperature pulse propagation over 4.0 $cm.h^{-1}$ average speed.

During a year of observations, the solar radiation flux at the surface varied from 127 to 264 $W.m^{-2}$ while the temperature at 1 m ranged from 27.08 to 31.96°C.

Exceptionally, in periods of heavy precipitation, the temperature at 1 m may decrease while the solar radiation flux at the surface increases. On the other hand, during periods with no precipitation that temperature may rise, for constant (or slowly decaying) incoming solar radiation fluxes.

The temperature profile gradients down to 10 m may show two or more changes of sign during several months of the year. At this site at a given hour of the day, the monthly profiles drift toward greater temperature values during the May to October period and the inverse happens in the November to March period.

The computed heat flux distributions with depth show considerably larger average amplitude during the dry season. These fluxes are strongly attenuated with depth and following the temperature gradient reversals may change sign twice or more within 6 m of depth.

The results show that at given hour of the day the heat flux to the soil must be considered in the energy balance equation at the surface. On the other hand, on a seasonal basis, the heat stored below the surface cannot be neglected in the same equation.

Several qualitative aspects of the results presented in this paper may be considered representative of other geographic areas. Certainly independent measurements should be made whenever important climatological and/or lithological differences exist.

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