

A New Method for Estimating the Turbulent Heat Flux at the Bottom of the Daily Mixed Layer

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A new method is presented for estimating the vertical turbulent heat flux at the bottom of the daily mixed layer from the temperature data in the mixed layer and net solar irradiance data at the sea surface. We assume that fluctuations in the divergence of advective heat flux have longer than daily time scales. The method is applied to data from the eastern tropical Pacific, where the daily cycle in the temperature field is confined to the upper 10–25 m. The night-to-day difference of the turbulent heat flux calculated from the data obtained during nine daily cycles in November 1984 agrees well on average with the same quantity estimated from microstructure observations. The night-to-day difference of the turbulent heat flux, estimated at several mooring stations near the equator (an average over 100 to 300 daily cycles), varies from 120 to 220 W/m² with larger values on the equator. Equatorial turbulence measurements show that the turbulent heat flux is much larger during nighttime than daytime. Therefore the present estimates give approximately the nighttime average, which is the major part of the turbulent heat flux. From the daytime heat budget we obtain divergence of the low-frequency horizontal heat advection at 1°30'S, 140°W; it is governed by equatorial mesoscale fluctuations having a predominant period of 15–20 days.

1. INTRODUCTION

Recent observations of the significant nighttime increase of turbulent dissipation at 140°W longitude on the equator [Gregg *et al.*, 1985; Moum and Caldwell, 1985] suggest that the formation of the daily thermocline occurs during daytime periods of weak turbulence and its erosion occurs during nighttime periods of strong turbulence. Individual temperature profiles should demonstrate this difference of the vertical transport process. However, the time scale and amplitude of these processes in the open ocean are comparable to the time scales and amplitudes of random internal waves, and thus a description of the daily heat budget or the night-to-day differences in the temperature profiles requires a large data set. In the Tropic Heat and Equatorial Pacific Ocean Climate Studies (EPOCS) programs [Eriksen, 1985; Hayes *et al.*, 1986], highly vertically resolved temperature time series of 6 months and longer together with simultaneous surface heat flux estimates make such a daily heat budget study practicable.

During the sunlight hours, the upper 25–40 m of the ocean is heated directly by solar radiation and cooled by latent and sensible heat fluxes and by longwave radiation. Near the equator a daily thermocline is established on most days because heating is larger than cooling over a significant portion of the afternoon. During nighttime the cooling persists, and so some of the stored heat is given back to the atmosphere almost at the same rate as during the daytime before. But because strong turbulence is found at night, some of the stored heat also mixes vertically. Therefore in a water column of fixed thickness, the change in heat content from sunrise to sunset less the change in heat content from sunset to sunrise should

reflect, principally, the sum of the shortwave radiation absorbed in the column during daytime and the heat transported out of the bottom of the column during nighttime. Such a simple balance, of course, assumes that persistent and significant night-to-day differences in divergence of advection or surface cooling do not occur (we show later that night-to-day differences in surface cooling rates are not significant). It is the purpose of this paper to demonstrate, from observations of ensemble averages of daily heat content changes and surface radiation budgets, that the upper 25 m of broad areas of the equatorial Pacific loses significantly more heat during nighttime than during daytime. Because no significant night-to-day bias is found in atmospheric cooling, the implication is that an increase of nighttime mixing occurs over broad areas of the equatorial Pacific in all seasons. This phenomenon was discovered by detailed turbulence measurements over a few days at 140°W.

2. METHOD

The equations governing the conservation of heat in the daily mixed layer during daytime and nighttime are

$$\bar{H}_t^D = \bar{Q}_{\text{sol}}^D - \bar{Q}_{\text{surf}}^D - \bar{Q}_{\text{adv}}^D - \bar{Q}_{\text{turb}}^D \quad (1)$$

$$\bar{H}_t^N = -\bar{Q}_{\text{surf}}^N - \bar{Q}_{\text{adv}}^N - \bar{Q}_{\text{turb}}^N \quad (2)$$

respectively (see Figure 1). Here H is the heat content of a water column with a unit area and constant thickness h and is calculated from $H = \int_{-h}^0 \rho c T dz$, where ρc is the specific heat capacity per unit volume, T is the temperature, and z is the vertical coordinate. The subscript t denotes the local rate of change in time. Q_{sol} is the net solar irradiance (heating) at the sea surface, and Q_{surf} is the surface cooling term, which consists of the net outgoing longwave radiation, latent heat flux, and sensible heat flux. The principal component to Q_{adv} is expected to be the vertically integrated divergence of advective heat flux in the horizontal direction; Q_{turb} is the vertical turbulent heat flux at the bottom of the column. The divergence of horizontal turbulent heat flux as well as the divergence of vertical advective heat flux are both additional components of

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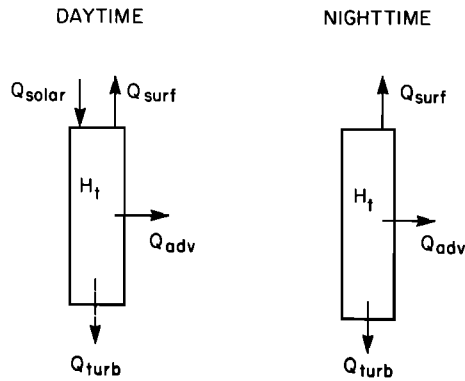


Fig. 1. Schematic diagram of heat balance in the daily mixed layer during (left) daytime and (right) nighttime.

the divergence of advective heat flux (Q_{adv}). Expressions \bar{Q}^D and \bar{Q}^N mean the daytime (from 0600 through 1800 local mean time) average and the nighttime (from 1800 through 0600 the next morning) average of Q , respectively.

In the present paper, we are interested in the daily cycle, and in the beginning, we assume that the divergence of advective heat flux varies with a time scale much longer than the daily cycle; the average divergence of advective heat flux (\bar{Q}_{adv}^N) during nighttime is assumed to be equal to that (\bar{Q}_{adv}^D) during daytime. Of course, internal waves do advect heat, but their contribution to the day-to-night differences in the divergence should average out over several daily cycles. There is a daily acceleration of currents in the upper ocean as stratification builds up during the day in the surface layer and momentum flux from the wind becomes distributed over shallower mixed layer depths. We have tried to compute the night-to-day difference in the divergence of north-south advection of heat on 150-km spatial scale and find it to be a very noisy signal. In our paper we assume it to be small *ab initio* and find later that this assumption makes sense. As we shall see later, the contribution of motions with a time scale of several days to the divergence of advective heat flux is important, and we will estimate it also. We proceed, however, with the assumption that there is no night-to-day bias in the divergence of the horizontal advection. With this assumption, the subtraction of (2) from (1) gives

$$\bar{H}_t^D - \bar{H}_t^N = \bar{Q}_{sol}^D - (\bar{Q}_{surf}^D - \bar{Q}_{surf}^N) + (\bar{Q}_{turb}^N - \bar{Q}_{turb}^D) \quad (3)$$

The day-to-night difference ($\bar{H}_t^D - \bar{H}_t^N$) of the local heat content change is given by the vertical integral of the day-to-night difference of temperature change as: $\rho c \int_{-h}^0 (\Delta T_D - \Delta T_N) dz / \Delta t$, where ΔT_D is the temperature difference between 0600 and 1800, ΔT_N is the temperature difference between 1800 and 0600 the next morning, and Δt is the time difference of 0.5 day.

Therefore, using (3), measurements of the temperature changes in the upper layer, the net solar irradiance, and the night-to-day difference of the sea surface cooling, we can estimate the night-to-day difference of turbulent heat flux at the base of the layer. From the limited hourly meteorological time series we have near the equator at 140°W, it is found that the term $\bar{Q}_{surf}^D - \bar{Q}_{surf}^N$ in (3) is not only small in comparison with \bar{Q}_{sol}^D (see section 4), but is also small in comparison with the sum of all other estimated terms. So we assume this to be the case over other areas of the eastern tropical Pacific.

Direct measurements of turbulent activity and estimates of turbulent flux near the equator at 140°W [Gregg *et al.*, 1985] show that the turbulent heat flux in the upper layer is much larger during night than during the day. For example, at 25-m depth it is 30 W/m² at noon and 240 W/m² at midnight. Therefore we anticipate that the night-to-day difference of the turbulent heat flux is almost equal to the nighttime average, or the major contribution to this flux.

With the assumption that the divergence of advective heat flux varies with a time scale much longer than the daily cycle, the daily mean divergence of advective heat flux (\bar{Q}_{adv}) is estimated by

$$\bar{Q}_{adv} = -\bar{H}_t^D + \bar{Q}_{sol}^D - \bar{Q}_{surf}^D \quad (4)$$

Here we neglect the turbulent heat flux during daytime appearing in the right-hand side of (1) because it is much smaller than other terms (or any sum terms). The divergence of advective heat flux is related to the spatial mean velocity (u, v, w) and temperature gradient (T_x, T_y, T_z) as

$$Q_{adv} = \rho c \int_{-h}^0 (uT_x + vT_y + wT_z) dz + \text{horizontal diffusion} \quad (5)$$

In the present case, the divergence of vertical advective heat flux is considered to be small because the bottom of the layer is close to the sea surface, vertical velocity is small, and the vertical gradient of temperature is also small in the layer. Horizontal "diffusion" is due to those space and time scales which are not resolved. Here we simply neglect this contribution. Therefore an approximation to (5) is

$$Q_{adv} = A\rho ch(uT_x + vT_y) \quad (6)$$

where the horizontal velocities and temperature gradients are estimated at 10-m depth, h is 25 m, and A is a coefficient of order unity (to be determined using a least squares method). Since we do not totally resolve v in z and T in y , A is a coefficient which models replacing (5) by (6). The divergence of advective heat flux estimated from the heat budget on the right-hand side of (4) will be compared with that estimated kinematically from (6). Strong vertical velocities have been measured on the equator [Bryden and Brady, 1985] with a mean over a season of about $\bar{w} = 1 \times 10^{-5}$ m/s, at 25-m depth. The variations about the mean are the same size. Because a vertical temperature gradient builds up during the daytime, the daytime average of the divergence of vertical advection is about $\rho ch \bar{w} \bar{T}_z^D$ (about 20 W/m²). Again, this term is much smaller than those kept in (3) or (4)

3. DATA

Three general data sets from the Tropic Heat and EPOCS programs are used in this study. The air-sea interaction data come from R/V *Wecoma* shipboard hourly observations of bulk meteorological parameters and measurements of net shortwave and longwave fluxes at (0°, 140°10'W) from November 19 to December 1, 1984 (Figure 2). Also, 15-min average time series of wind, air temperature, humidity, and sea surface temperature (SST) were recorded at mooring station TH10 (1°30'S, 140°30'W) from December 1984 to June 1985 [Payne, 1988]. Latent and sensible heat fluxes were estimated from these observations by bulk methods (for methodology, see *Large and Pond* [1982] for *Wecoma* observations and *Ste-*

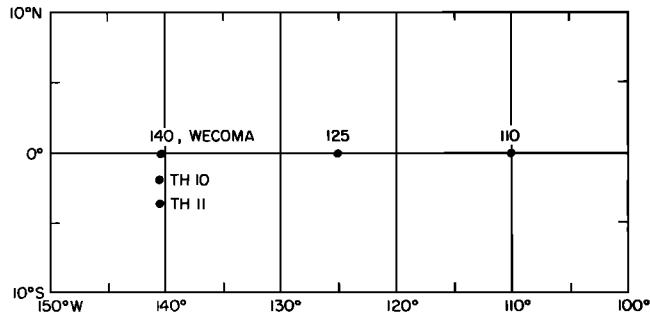


Fig. 2. Locations of ship observation (R/V *Wecoma*) and mooring stations.

venson [1982] for mooring station TH10). At mooring station TH10 the net longwave budget was considered to vary only because of the change in humidity and SST, and it was estimated by the bulk method [Stevenson, 1982]; at the *Wecoma* station it was directly measured by radiometers. The net hourly shortwave budget was measured directly at the *Wecoma* station. The net shortwave budget was also computed from GOES 6 satellite irradiances on a daily basis at mooring stations 140, 125, and TH10 [Gautier et al., 1986]; the shortwave data were sampled on 14×14 km pixels and averaged over 42×42 km² areas around each location. Comparison of *Wecoma* data with the remotely sensed shortwave irradiance data at station 140 over a 12-day average yields a -6 W/m² bias and a 12 W/m² rms difference.

The temperature and velocity data come from vector averaging current meters, or VACMs (for technique see Halpern [1987]), and temperature recorders on surface moorings from various periods in 1984 and 1985. Table 1 lists the mooring locations and periods of data used. Typically, data were recorded every 15 min on moorings and arithmetically averaged hourly values are used here. The nominal depths of upper ocean temperature data are 1, 10, 25, and 45 m; currents were measured at 10, 25 and 45 m. Moorings T44, T46, and T50 have additional temperature sensors at 35-m depth. The velocity and temperature data used in estimation of daily mean advective heat flux divergence were further processed through a Godin filter with bandwidth of 71 hours [Godin, 1972] to eliminate the high-frequency fluctuations, and were subsampled once a day. The daily cycle of advection was thus also filtered.

The third data set was obtained from the rapid sampling vertical profiler, or RSVP [Caldwell et al., 1985]. Vertical profiles of temperature and turbulent dissipation rates were measured on the equator at 140°10'W, 5–10 times in an hour over

a period from November 19 to December 1, 1984, from R/V *Wecoma*. From these data the vertical profile of the daytime and nighttime average turbulent heat fluxes is estimated in the upper layer (0- to 100-m depth) for 12 days; the technique is described by J. N. Moum et al. (Processes in the equatorial mixed layer, submitted to *Journal of Geophysical Research*, 1988, hereinafter, Moum et al., 1988). Daily values of $\bar{H}_t^D - \bar{H}_t^N$ are also calculated from hourly averaged profile data obtained by the RSVP. The RSVP station, or *Wecoma* station, was about 1 n. mi (1.9 km) east of mooring station 140.

4. RESULTS

The turbulent heat flux at 25-m depth estimated from mooring station 140 temperature data and *Wecoma* heat flux observations is first compared with that estimated from the RSVP measurements during the period of November 19 to December 1, 1984. Figure 3 shows vertical profiles of a half of the daytime minus nighttime temperature change $[(\Delta T_D - \Delta T_N)/2]$ from mooring station 140. This is equivalent to the average amplitude of daytime and nighttime temperature changes because the nighttime temperature change is usually negative, while the daytime value is positive. The individual daily profile variability is quite large, especially below 20-m depth. This is probably due to the advection associated with high-frequency internal waves or small-scale fronts which exists even in the daily thermocline. The ensemble average over the observation of 10 daily cycles, however, yields a significant amplitude only in the upper 20- to 30-m layer. (The profile on year day 328 is excluded from the average because of its extreme value but is shown in Figure 3.) Below, the error of the mean is as large as the ensemble mean. We note that the average depth of the surface mixed layer during nighttime observed by the RSVP is about 25 m (Moum et al., 1988).

Figure 4 displays an intercomparison of the time series of several terms appearing in (3) during the *Wecoma* observations, computed from the mooring station data (sparse vertical sampling and continuous time sampling) and the RSVP data (continuous vertical sampling and sparse time sampling). The day-to-night difference $(\bar{H}_t^D - \bar{H}_t^N)$ of the local heat content change is calculated by the integration of the day-to-night difference of temperature change shown in Figure 3 from the sea surface to 25-m depth. These separate estimates agree very well except on year days 328 and 329, when the upper layer temperatures at mooring station 140 were unusually low at sunset (328) and those at the RSVP station were unusually low at the next sunrise (329). A small-scale front must have existed between 140 and the RSVP station. Comparison of the continuous profile estimates from the RSVP with the discrete

TABLE 1. Location and Duration of Temperature and Velocity Data From Mooring Stations

Station	Mooring	Program	Location	Data Period
TH10	TH10	Tropic Heat	$-1^{\circ}30'N, 140^{\circ}30'W$	Dec. 6, 1984, to June 13, 1985
TH11	TH11	Tropic Heat	$-3^{\circ}10'N, 140^{\circ}23'W$	Dec. 9, 1984, to April 30, 1985
140	T44	EPOCS	$-0^{\circ}02'N, 140^{\circ}09'W$	Oct. 26, 1984, to April 28, 1985
125	T40	EPOCS	$-0^{\circ}02'N, 124^{\circ}33'W$	April 22 to Sept. 26, 1984
	T46	EPOCS	$-0^{\circ}01'N, 124^{\circ}34'W$	Oct. 20, 1984, to May 5, 1985
	T50	EPOCS	$-0^{\circ}01'N, 124^{\circ}35'W$	May 5 to Oct. 5, 1985
110	T38	EPOCS	$0^{\circ}00'N, 109^{\circ}13'W$	Nov. 2, 1983, to April 17, 1984
	T42	EPOCS	$0^{\circ}03'N, 109^{\circ}51'W$	April 18 to Oct. 16, 1984
	T47	EPOCS	$0^{\circ}04'N, 110^{\circ}04'W$	Oct. 17 to Nov. 29, 1984
	T51	EPOCS	$0^{\circ}06'N, 110^{\circ}01'W$	May 9 to Sept. 17, 1985

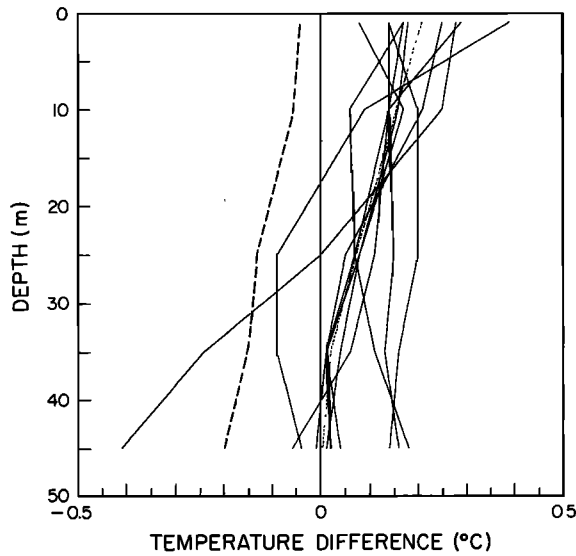


Fig. 3. Vertical profiles of a half of the daytime minus nighttime temperature change $[(\Delta T_D - \Delta T_N)/2]$ observed at mooring station 140 during the 11 daily cycles of *Wecoma* observation. Solid lines are for individual daily profiles, and the dotted line is for the 10 daily cycle average. The dashed line is the extreme value omitted (year day 328).

profile estimates from the mooring data, shows that the mooring data at discrete depths are adequate for the present analysis. The day-to-night difference of the local heat content change averaged over nine daily cycles (with the 328 and 329 year days excluded) is $691 \pm 81 \text{ W/m}^2$ from the mooring data and $644 \pm 87 \text{ W/m}^2$ from the RSVP data. If all 11 daily cycles are included, the mooring data yields $592 \pm 137 \text{ W/m}^2$ and the RSVP yields $670 \pm 127 \text{ W/m}^2$.

Figure 4 also displays the net solar irradiance (\bar{Q}_{sol}^D) mea-

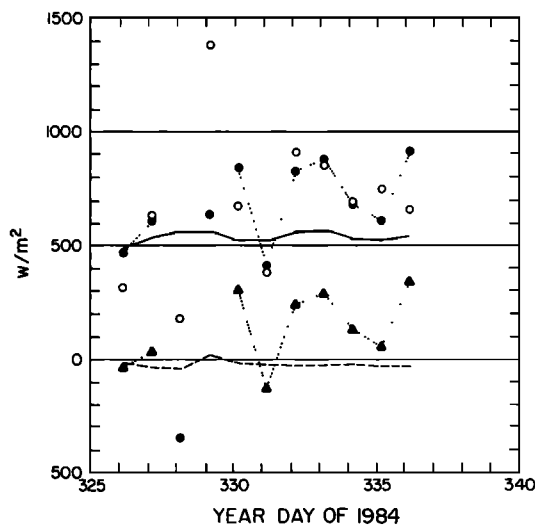


Fig. 4. Heat budget estimated during the *Wecoma* observation. The day-to-night difference ($H_p^D - H_p^N$, dots) of the local heat content change, the net solar irradiance (\bar{Q}_{sol}^D , solid line), and the day-to-night difference ($\bar{Q}_{\text{surf}}^D - \bar{Q}_{\text{surf}}^N$, dashed line) of the net surface heat flux are shown. The triangles are the night-to-day difference ($\bar{Q}_{\text{turb}}^N - \bar{Q}_{\text{turb}}^D$) of the turbulent heat flux calculated from these quantities (solid symbols are from mooring station data). Open circles are the day-to-night difference of the local heat content change calculated from the RSVP data.

sured on board R/V *Wecoma*. It is fairly steady with an average of $535 \pm 10 \text{ W/m}^2$ over 11 days of daylight hours. Also shown is the day-to-night difference of the turbulent and longwave heat flux components through the sea surface, $\bar{Q}_{\text{surf}}^D - \bar{Q}_{\text{surf}}^N$. The 11-daily cycle average value of \bar{Q}_{surf} is quite significant, having a daytime average of $135 \pm 14 \text{ W/m}^2$, and nighttime average of $160 \pm 13 \text{ W/m}^2$. However, its day-to-night difference is small, having an average of $-25 \pm 6 \text{ W/m}^2$.

From these quantities we can now estimate the night-to-day difference of the turbulent heat flux ($\bar{Q}_{\text{turb}}^N - \bar{Q}_{\text{turb}}^D$) (triangles in Figure 4) using (3). An estimate over a single day does not make sense because both weak negative and large positive values occur, mostly due to the high-frequency fluctuation of the day-to-night difference of the local heat content change. Apparently, internal waves or small-scale advective features are present in the daily thermocline. The average of ($\bar{Q}_{\text{turb}}^N - \bar{Q}_{\text{turb}}^D$) average over nine daily cycles from mooring station 140 is $131 \pm 74 \text{ W/m}^2$; the average from *Wecoma* RSVP temperature profiles is $87 \pm 77 \text{ W/m}^2$.

Estimates of vertical heat flux due to turbulent mixing were also made from RSVP dissipation measurements. The nighttime mean of the turbulent heat flux at 25-m depth is 112 W/m^2 on an average over 9 daily cycles (with year days 328 and 329, excluded, and the daytime one is 47 W/m^2 , the latter occurs mostly from 0600 to 1000 local time (Moum et al., 1988). Therefore the night-to-day difference of the turbulent heat flux is 65 W/m^2 . The above estimates based on the heat budget from temperature and net solar irradiance data agree with this value within estimated errors.

A similar analysis is now done at the mooring stations in the eastern tropical Pacific, which have sufficient resolution of temperature in the upper ocean. Here the day-to-night difference ($\bar{Q}_{\text{surf}}^D - \bar{Q}_{\text{surf}}^N$) of the net surface heat flux is neglected everywhere, because it is small where the data exist to estimate this quantity. Figure 5 shows the time series of daytime mean (\bar{Q}_{surf}^D) and nighttime mean (\bar{Q}_{surf}^N) of the net surface heat flux at mooring station TH10. Fluctuations of these two are strongly correlated, having a correlation coefficient of 0.92. The day-to-night difference is very small; it is -6 W/m^2 on an average with the rms fluctuation of 23 W/m^2 .

The monthly ensemble averages of a half of the daytime

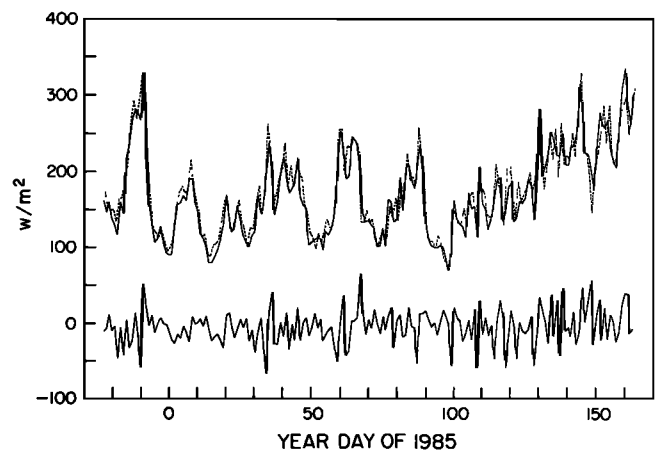


Fig. 5. Time series of daytime mean (\bar{Q}_{surf}^D , top solid line), and nighttime mean (\bar{Q}_{surf}^N , dotted line) of the net surface heat flux at mooring station TH10, and also their difference ($\bar{Q}_{\text{surf}}^D - \bar{Q}_{\text{surf}}^N$, bottom solid line).

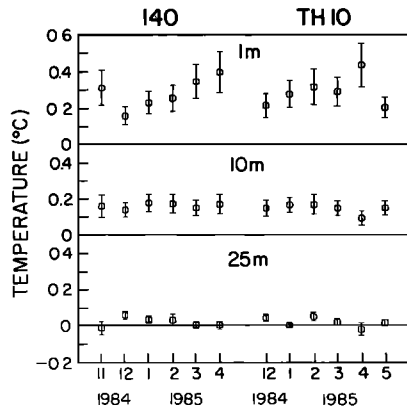


Fig. 6a

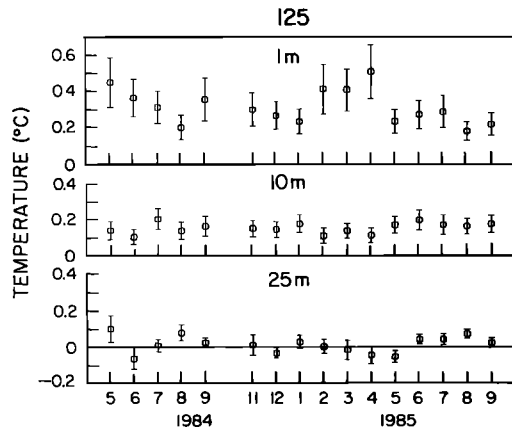


Fig. 6b

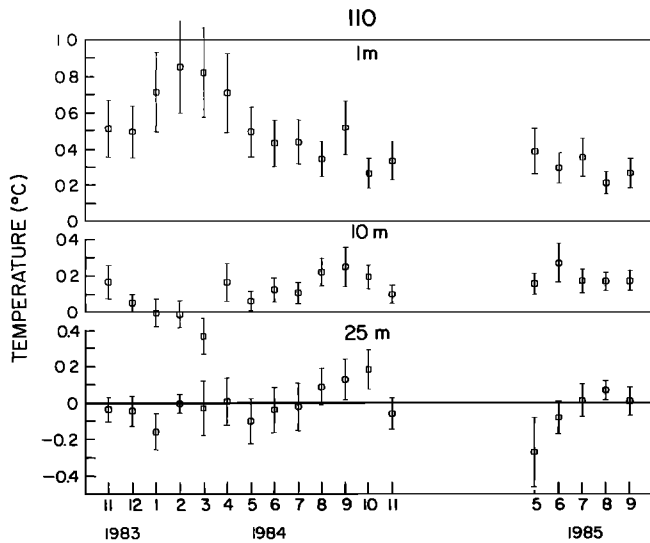


Fig. 6c

Fig. 6. The monthly mean of a half of the daytime minus nighttime temperature change $[(\Delta T_D - \Delta T_N)/2]$ observed at three depths (1, 10, and 25 m) at mooring stations (a) 140 and TH10, (b) 125, and (c) 110 (see Figure 2 for locations). The bars are the errors of the mean. The abscissa is time in months from 1983 to 1985.

minus nighttime temperature changes at the upper three depths (1, 10, and 25 m) are shown in Figure 6 (the values which lie outside 3 standard deviations of the original data set are excluded). The data during the *Wecoma* observations are

included in the November 1984 value at mooring station 140 (Figure 6a). At 140°W (Figure 6a) the daily fluctuation of temperature is restricted to the upper 25-m layer on average, and the amplitude of sea surface (1-m depth) temperature fluctuation is 0.2°–0.4°C. (Results from mooring station TH11 are not shown here because the sea surface temperature data are missing, but amplitudes at 10-m and 25-m depths are similar in amplitude to those at mooring stations 140 and TH10.) Moving to the east, the situation becomes different. At 110°W (Figure 6c) there seems to be a seasonal change of the upper ocean temperature cycle. In January through April, the daily fluctuation does not penetrate deeper than 10-m depth and the amplitude of the sea surface temperature is as large as 0.7°–0.8°C; this is the period of warming sea surface temperature and weakening wind. In July through October, wind strength increases, the daily cycle penetrates deeper than 10-m depth, and the sea surface temperature change is reduced to 0.2°–0.5°C. At 110°W the fluctuations at 25-m depth, which are reflected in the estimated errors, are larger than these at 140°W because at 110°W the main thermocline is closer to the surface, and internal waves are larger at a shallower depth. It is interesting to note that a warming of the deeper levels at night occurs both at 125°W and 110°W (Figures 6b and 6c) when maximum heating occurs during the day in the upper layers. This could conceivably be explained by the coincidence that the sensors were in that part of the upper layers which were warmed at night by vertical mixing.

The monthly mean day-to-night difference of the local heat content change is calculated from the temperature change difference to 25 m (Figure 6) and is shown in Figure 7. Results are not shown for mooring station 110, partly because it is apparent that vertical resolution of the temperature data available is not sufficient to resolve the shallower daily cycle, and partly because the net solar irradiance data are not available at that longitude. In Figure 7 the monthly mean net solar irradiance, as estimated from satellite data, is also shown. It is quite uniform in time and space over the moored array.

From these two quantities we calculate the monthly mean night-to-day difference of the turbulent heat flux at the bottom of the layer by use of (3), neglecting the net surface heat flux terms. At mooring station 125, even monthly ensemble means fluctuate, mostly owing to the large temperature fluctuation at the sea surface (Figure 6b); there a seasonal signal is not evident in the present data. The record length averages of the terms in (3) are tabulated in Table 2. A 6-month mean is well defined at each station because the error of the mean is much smaller than the mean. The night-to-day difference of the turbulent heat flux is smaller at mooring station TH10, which is off the equator, than at equatorial stations. We resist the temptation to infer a quantitative seasonal cycle, based on less than 2 years of data. Nevertheless, it is suggested qualitatively and might be resolved with longer records especially at 110°W.

The daily mean divergence of advective heat flux (\bar{Q}_{adv}) is calculated at mooring station TH10 (at 1°30'S) by use of the heat budget equation (4), and its components are shown in Figure 8a neglecting about 50 W/m² for \bar{Q}_{turb}^D . The daily data are smoothed by a Gaussian three-point filter with weights (0.25–0.5–0.25) to emphasize the lower-frequency fluctuations. The largest contribution is due to the heat storage change. The divergence of heat advection has a predominant period of 15–20 days from the beginning of the observation to year day 75. This is primarily north to south movement of the edge of

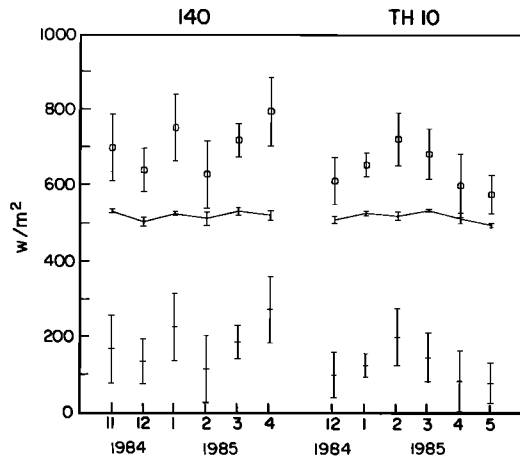


Fig. 7a

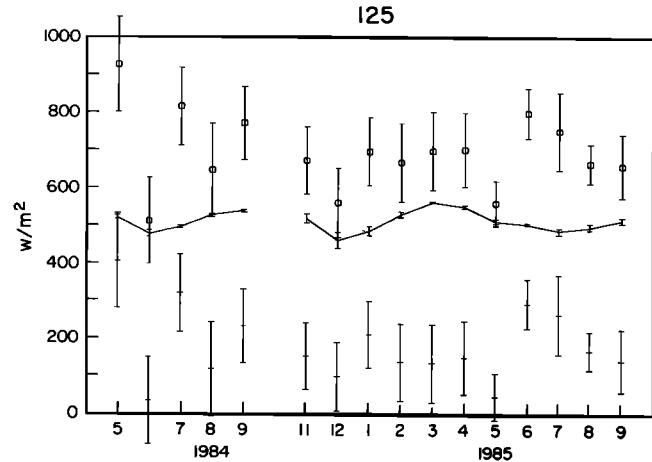


Fig. 7b

Fig. 7. Monthly mean heat budget estimated at mooring stations (a) 140 and TH10 and (b) 125. The day-to-night difference ($\bar{H}_t^D - \bar{H}_t^N$, open circles) of the local heat content change, the net solar irradiance (\bar{Q}_{sol}^D , solid line), and the night-to-day difference ($\bar{Q}_{turb}^N - \bar{Q}_{turb}^D$, crosses) of the turbulent heat flux are shown. The bars are the errors of the mean. The abscissa is time in months from 1984 to 1985.

the cold pool and is related to the equatorial mesoscale fluctuation, which is clearly seen in satellite AVHRR sea surface temperature data [Legeckis, 1977] and moored current meter data [Philander et al., 1985].

The part of the divergence of advective heat flux associated with the meridional velocity, $A\rho chvT_y$, is estimated from daily velocity data at 10-m depth at mooring station TH10 and from daily temperature data at 10-m depth at mooring stations 140 and TH11 (Figure 8b). The divergence of advective heat flux (\bar{Q}_{adv}) (Figure 8a) estimated as a residual of heat budget (equation (4)) and this divergence of meridional advective flux ($A\rho chvT_y$) are correlated very well with each other (correlation coefficient 0.72). The least square regression gives A of 1.3, which indicates possible underestimation of T_y from moorings 3° apart. The record length average of the divergence of advective heat flux estimated from (4) is 53 ± 33 W/m^2 . The record length average of daily mean divergence of meridional advective heat flux estimated from current meter data and (6) is 48 ± 24 W/m^2 . It comes largely from the southward flowing mean meridional velocity \bar{v} and the southward increasing mean temperature gradient T_y ; $A\rho ch\bar{v}T_y = 61$ W/m^2 . At this longitude it appears that the excess heat at $1^\circ 30'S$ is transferred away from the equator by the mean southward flow. The divergence of the eddy heat flux is a smaller quantity.

5. DISCUSSION

It should be noted that in the present heat budget estimates, only relative accuracies of temperature measurements are required; systematic bias errors in temperature sensors do not cause an error in estimation of the local heat content change. The estimated error δH is proportioned to the calibration error γ (in per cent) of sensor sensitivity; namely, $\delta H = \gamma(\bar{H}_t^D - \bar{H}_t^N)$. Therefore temperature sensors having a 5% accuracy give usable estimates (with an error of 35 W/m^2) of the day-to-night difference of the local heat content change (provided that the true value is some 700 W/m^2).

The most important issue about the accuracy of the technique is the vertical resolution and number of daily cycles averaged. Let N temperature sensors be deployed evenly throughout the layer of thickness h , each sensor have a measurement accuracy of $\alpha(^{\circ}C)$, and averages be made over M daily cycles; then the random error δH in the estimate of the day-to-night difference of the local heat content change is given by

$$\delta H = \frac{(6)^{1/2} \rho c h \epsilon}{\Delta t (NM)^{1/2}}$$

Note that if the depth is doubled, four times the number of sensors are required to keep the error the same. For $h = 25$ m, as in the present case, $\delta H = [4.85 \times 10^3 \epsilon / (NH)^{1/2}]$ W/m^2 .

TABLE 2. Average Heat Budget

Station	Observation Period	Number of Cycles	$\bar{H}_t^D - \bar{H}_t^N$	\bar{Q}_{sol}^D	$\bar{Q}_{turb}^N - \bar{Q}_{turb}^D$
140	Oct. 1984 to April 1985	178	705 ± 32	523 ± 4	181 ± 32 (149-213)
TH10	Dec. 1984 to June 1985	185	638 ± 25	519 ± 4	119 ± 25 (94-144)
125	April-Sept. 1984	145	728 ± 53	510 ± 4	218 ± 53 (165-271)
125	Oct. 1984 to Oct. 1985	331	674 ± 26	513 ± 4	161 ± 26 (135-187)

Values are given as mean \pm error in watts per square meter. Ranges in parentheses are mean + error to mean - error.

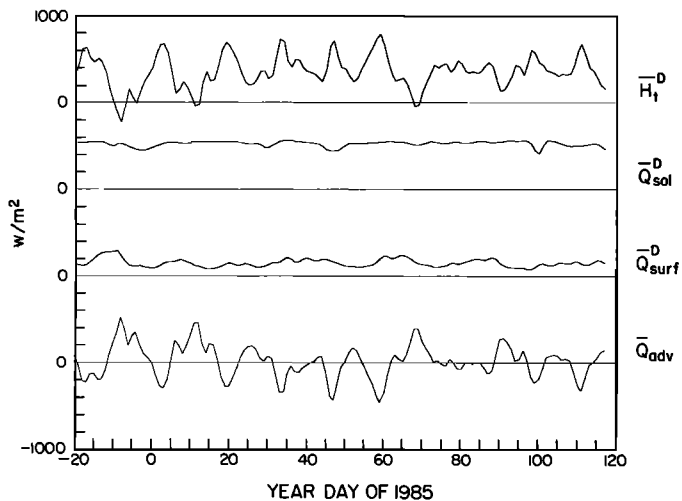


Fig. 8a

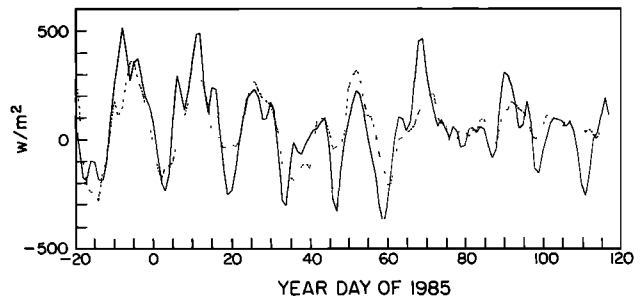


Fig. 8b

Fig. 8. Time series of daily mean divergence of advective heat flux (\bar{Q}_{adv}^D) at mooring station TH10, (a) shown together with components from which it is estimated by use of the heat budget equation (4) and (b) shown (the solid line) together with the divergence of the meridional advective heat flux (dotted line) estimated directly from the velocity and temperature data by use of (6).

Since the calibration errors of the VACM temperature sensors are 0.02°C (P. Bedard, personal communication, 1987) and $N = 3$ in the present case, the estimated accuracy is 56 W/m^2 for daily estimates and 10 W/m^2 for monthly averages. The latter seems satisfactory. The sensor number of three is the minimum requirement for the present purpose and should be increased in future. For example, if a thermistor chain having five sensors with measured accuracy of 0.05°C is deployed in the upper 25-m layer, the estimated error is 20 W/m^2 for monthly averages, which is also reasonable. It should be kept in mind, however, that the actual estimates contain large temporal fluctuations due to high-frequency advective processes, and the error due to those fluctuations is generally much larger than the error due to measurements.

In the present paper the solar irradiance is assumed to be absorbed completely in the surface mixed layer (to 25-m depth), but actually some of it penetrates to deeper layers. We do not have the measurements from which the water type at the sites can be specified accurately, but 4–11% of the solar irradiance at the sea surface is expected to penetrate to 25 m (the estimate is based on the equation by Paulson and Simpson [1977] and water classifications by Simonot and Le Treut [1986]). The net solar irradiance absorbed in the surface layer (shown in Table 2 and Figure 7) should be reduced by 4–11%, which results in a 20- to 60-W/m^2 increase in the night-to-day difference of the turbulent heat flux.

The present method depends upon the assumption that significant and persistent day-to-night differences of the advective heat flux divergence and the sea surface cooling do not exist. If internal wave activity has a day-to-night bias, then our interpretation of $(\bar{H}_t^D - \bar{H}_t^N - \bar{Q}_{sol}^D)$ as the increase of nighttime turbulence is flawed. The suggestion to view the moored array data in this manner came, of course, from turbulence measurements during the *Wecoma* observations which showed significant night-to-day differences in the turbulent dissipation activity [Moum and Caldwell, 1985]; in the *Wecoma* observations, two thirds of the vertical flux occurred during the night.

The present results suggest that such a night-to-day difference of turbulence is prevalent over the entire eastern tropical Pacific.

There is also a suggestion that the estimated nighttime turbulent heat flux is a little larger on the equator (mooring station 140) than at $1^\circ 30'S$ (mooring station TH10). It might be related to the strong vertical shear associated with the South Equatorial Current and the Equatorial Undercurrent on the equator. Recently, Newell [1986] has suggested that El Niño conditions in the eastern Pacific can be caused by dramatic changes of the upper ocean vertical turbulent fluxes (rather than horizontal heat advection). Our computations at 110°W lend credence to this hypothesis as they suggest a seasonal cycle in night-to-day differences in the daily heat storage and a concomitant change in vertical turbulent transports.

The most advantageous point of this method is that it does not require the net surface heat flux data, which requires several meteorological measurements at the sea surface. Only hourly-averaged upper layer temperature profiles are required twice a day (at 0600 and 1800 local time), as well as an accurate estimate of the net solar shortwave flux at the sea surface. The former can be obtained more easily than the meteorological data, for example, by drifting or moored thermistor chains, provided that a sufficient number of sensors with adequate accuracies are installed in the daily thermocline. The latter can be obtained from routine satellite observations.

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