# Field-Observation Analysis of Sea-Bottom Effects on Thermal Environments in a Coral Reef

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## ABSTRACT

To understand the effects of sea bottom on thermal environments in a coral reef with shallow water depth and high transparency of water, we performed an intensive field observation at Shiraho reef located in the south-east coast in Ishigaki Island, Okinawa, Japan. The heat balance for reef water indicates that the sea bottom has a crucial importance on thermal environments in a coral reef. A heat budget analysis for reef water also demonstrates that the treatments of the sea-bottom effects affect appreciably the results of the heat budget analysis.

KEY WORDS: Coral reef; field observation; thermal environments; sea-bottom effects; radiative process.

## INTRODUCTION

Coral reefs in tropical and subtropical ocean systems have recently experienced severe environmental problems due to mass coral bleaching events which occurred worldwide in 1997 and 1998. Water temperature has been known to be a main factor of coral bleaching (*e.g.*, Glynn, 1993; Berkelmans and Oliver, 1999; Nadaoka et al., 2001a), and hence it is therefore quite important to clarify thermal environments and heat balance in coral reefs. The thermal environments in coral reefs are significantly influenced by heat fluxes through sea surface and bottom due to shallow water depth and high transparency of water in coral reefs. The thermal influences from inland and offshore are also dominant on the heat balance for reef water.

Nadaoka et al. (2001b) made a field observation on hydrodynamic and thermal environments of coral reefs with the special emphasis on the connections with offshore and terrestrial waters under typhoon and normal atmospheric conditions. The details of the thermal environments in coral reefs were examined by a heat budget analysis for reef water with the observed data. In the heat budget analysis for a water column, however, the heat flux through the sea bottom was evaluated using the simple formulation without directly observed data. Furthermore transmission and reflection processes of solar radiation in seawater and on sea bottom have not been taken into consideration explicitly in the heat budget analysis. Therefore we have poor information for the effects of sea bottom on thermal environments, which may play an important role on water temperature fluctuations in coral reefs with shallow water depth and high transparency of water.

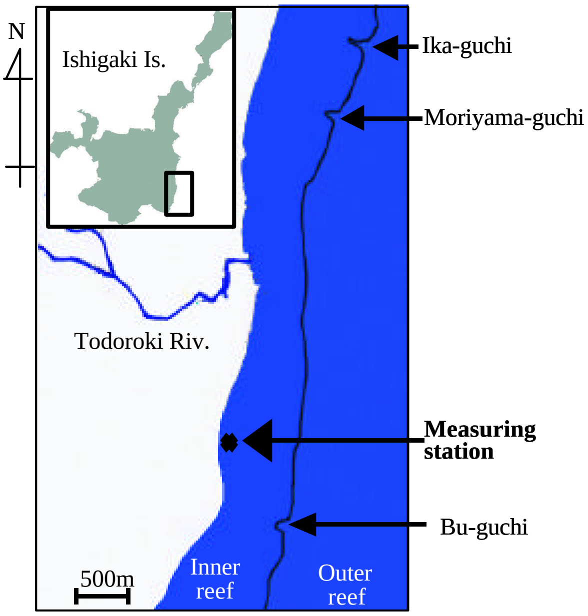
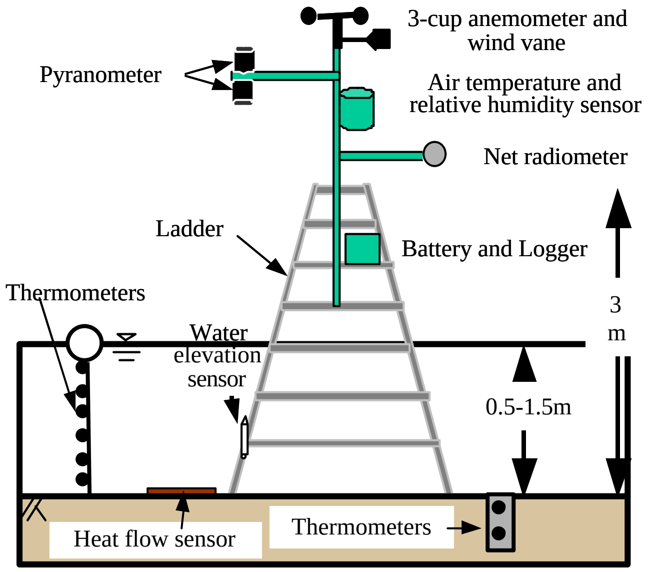
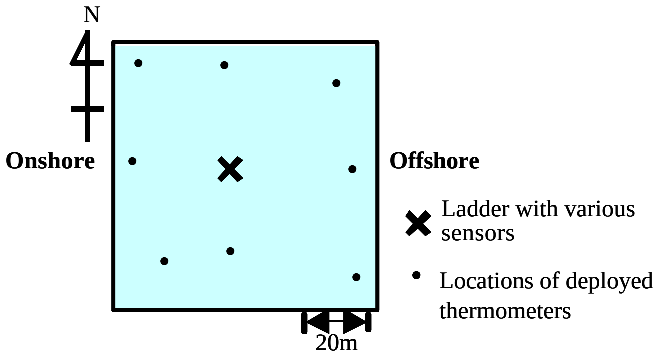


**Fig. 1** Location of a measuring station.

This paper focuses on the effects of sea bottom on thermal environments in a coral reef. For this purpose, we conducted an intensive field observation at Shiraho reef located on the south-east coast of Ishigaki Island, Okinawa, Japan. We performed the heat budget analysis for reef water with special attention to the sea-bottom



**(a)** Vertical array of various instruments in the ladder



**(b)** Locations of thermometers around the ladder

**Fig. 2** Outline of the intensive field survey on thermal environments.

effects.

## FIELD OBSERVATION

We conducted an intensive field observation at Shiraho reef, which is a well-developed fringing reef of about 800m in width, from September 3 to 5 in 2000. **Figure 1** depicts the measuring station at which a ladder with various measuring sensors, as shown in **Fig. 2(a),** was located. The mean water depth at the station was about 1.0m.

In this field survey, we measured the climate factors (wind speed and direction, air temperature, humidity and short and long wave radiations in upward and downward directions), temperatures in seawater and sea bottom at various heights, water elevation and heat flux through the sea bottom. In the heat budget analysis with these observed data, we can treat more accurately the radiative process in seawater using data of two pyranometers recording shortwave radiation in upward and downward directions, and in addition we can directly evaluate the heat flux to the sea bottom with a heat flow sensor (MF-81, EKO Instruments Trade Co., Ltd. in Japan) mounted on the sea bottom. Although a heat flow sensor has a slight error in measuring a heat flux due to the difference of thermal properties in the sensor and its surrounding soil (Philip, 1961), any correlation for the heat flux obtained here was not done for simplicity. We installed a vertical array of 17 thermometers to obtain the detailed vertical temperature profile in seawater and sea bottom, and also deployed thermometers at 8 stations around the location of the ladder, as shown in **Fig. 2(b)**, to clarify the horizontal gradient of water temperature. The water temperature was measured with three kinds of thermometers; TidbiT (Optic Computer Corp. in U.S.A.), MIDS-T and MDS-MkV-T (Alec Electronics Co., Ltd. in Japan).

## HEAT BUDGET ANALYSIS WITH ATTENSION TO SEA-BOTTOM EFFECTS

### Treatment of Radiation Balance in Seawater

Before showing the method of heat budget analysis, we outline the treatment of radiative process in seawater in the present analysis. **Figure 3** indicates the schematic illustration of transmission and reflection processes of shortwave radiation in seawater (Kobatake et al, 1997). $S_d$ in the figure means a shortwave radiation in downward direction. While the albedo on sea surface $a_1$ was used to be 0.06 as a standard value for sea surface, the albedo on sea bottom $a_2$ was given to be 0.25 by a laboratory measurement for

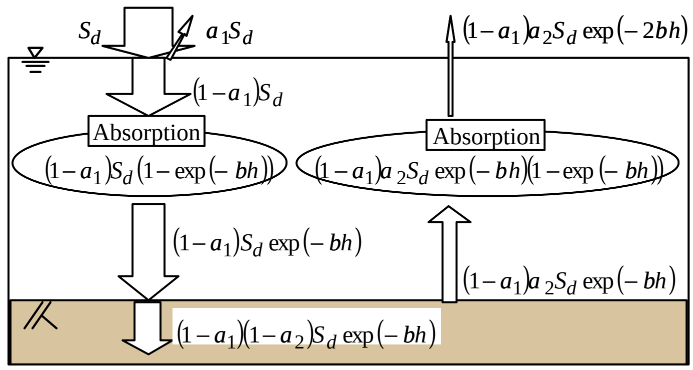


**Fig. 3** Treatment of radiative processes in seawater.

the coral sands obtained from the field site. The extinction coefficient of shortwave radiation in water, $b$, was calculated with the measured shortwave radiation and the equations for the heat budget analysis described below. Since the longwave radiation has been known to be absorbed in a quite thin layer near sea surface, we consider the contribution of longwave radiation only to sea surface in the heat budget analysis.

## Equations of Heat Balance for Sea Surface, Sea Bottom and Water Column

The heat balances for sea surface, sea bottom and water column are formulated with the treatments of the radiation balance described above. We first express the heat balance on sea surface as

$$L_d - L_u = H + lE + G\,, \tag{1}$$

where $H$ and $lE$ denote the sensible and latent heat fluxes from sea surface to atmosphere, respectively, $G$ represents the heat flux to the seawater through sea surface and $L_u$ and $L_d$ mean the longwave radiation in upward and downward directions, respectively. The left-hand side of the above equation corresponds to the net radiation consisting of only the longwave radiation in upward and downward directions. Among these fluxes, the net radiation was obtained with the observed data of longwave radiation, and the sensible heat and latent heat fluxes, $H$ and $lE$, were evaluated with bulk formula. The heat flux to the seawater $G$ was calculated as the residual in Eq. 1.

In the heat balance on sea bottom, the net shortwave radiation on sea bottom is equal to the summation of the sensible heat flux from sea bottom to the water column $H_{soil}$ and the heat flux to the sea bottom due to thermal conduction $G_{soil}$, as indicated in the following equation

$$(1-a_1)(1-a_2)S_d \exp(-bh) = H_{soil} + G_{soil}\,. \tag{2}$$

For evaluating these heat fluxes in Eq. 2, the solar radiation in the downward direction $S_d$ was given by measured data and the heat flux to the sea bottom $G_{soil}$ was directly obtained from the observed data of the heat flow sensor. The sensible heat flux from the sea bottom $H_{soil}$ was finally calculated as the residual in Eq. 2.

The heat balance for a water column with a unit horizontal area is schematically illustrated in **Fig. 4**; the temporal change rate of heat storage in the water column $\Delta Q$ equals the summation of the heat fluxes through each surface bounding the water column and the gain of heat by radiative processes in the water column $S_{abs}$. The equation of the heat balance for the water column is given by

$$\Delta Q = G + H_{soil} + \Delta F + S_{abs}\,, \tag{3}$$

where $\Delta F$ denotes the divergence of heat fluxes due to horizontal advection and diffusion processes of coastal current, referred to here as 'horizontal advective heat flux'. $\Delta Q$ was calculated with measured water temperature and water elevation, and $\Delta F$ was given as the residual in Eq. 3. In the following discussion, each term of Eq. 3 was evaluated as a depth-averaged value for removing their dependence on the water depth. Eq. 3 may be also reformulated with Eqs. 1 and 2 as

$$\begin{aligned}\Delta Q = {} & G + \Delta F - G_{soil} \\ & + (1-a_1)S_d[(1-\exp(-bh))(1+a_2\exp(-bh))\,. \\ & \qquad + (1-a_2)\exp(-bh)]\end{aligned} \tag{4}$$

It should be noted that the effect of the heat flux through sea bottom is reflected on the third term of the right-hand side in Eq. 4, and the radiative process in seawater is incorporated into the fourth term of the right-hand side in Eq. 4.

## RESULTS AND DISCUSSIONS

### Water Temperature Fluctuations

**Figure 5** shows the time variations of solar radiation and temperatures in air, seawater and sea bottom from September 3 to 5, 2000. We

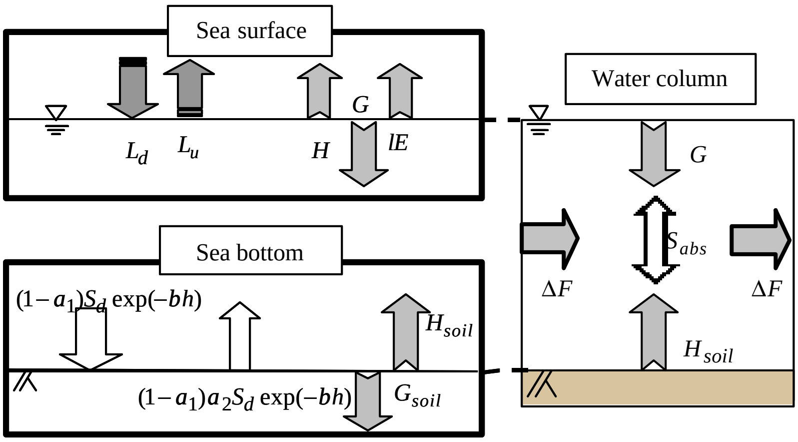
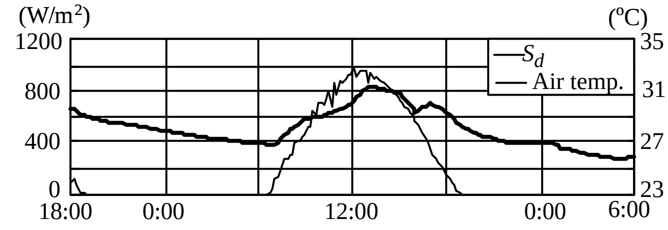
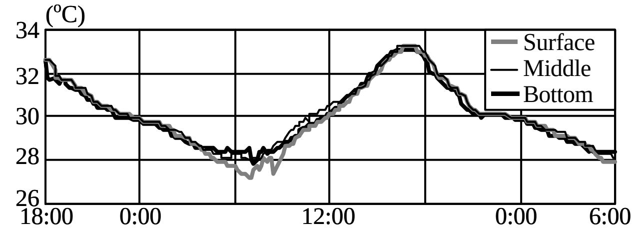


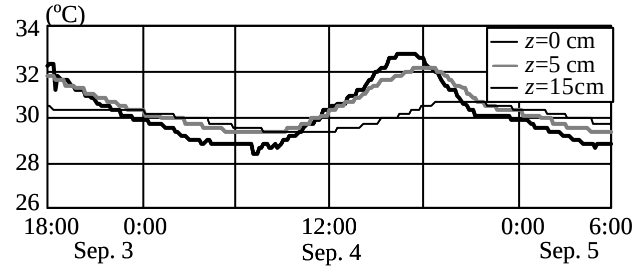
**Fig. 4** Schematic illustration of the present heat budget analysis.



**(a)** Solar radiation ($S_d$) and air temperature

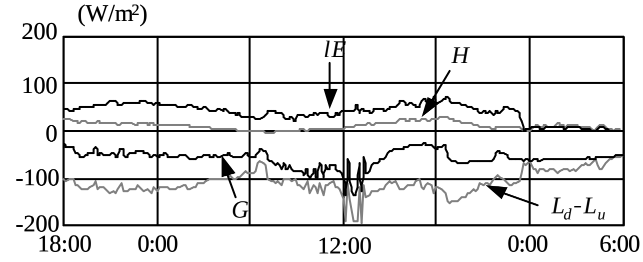


**(b)** Water temperature

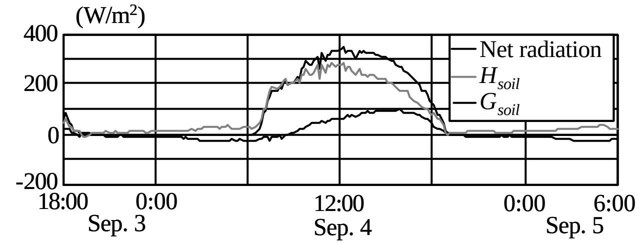


**(c)** Temperature in sea bottom

**Fig. 5** Time variations of solar radiation and temperatures in air, seawater and sea bottom ($z$: vertical coordinate with the origin at the sea bottom being positive downward).



**(a)** Sea surface



**(b)** Sea bottom

**Fig. 6** Time series of heat fluxes for sea surface and bottom.

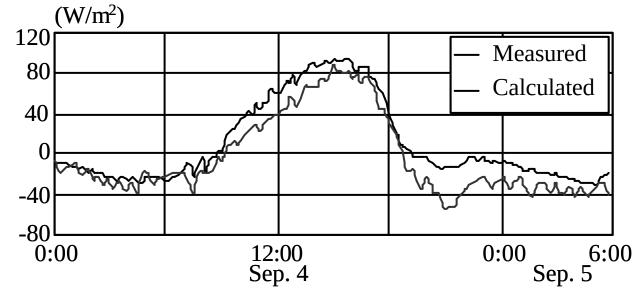


**Fig. 7** Comparison of the calculated and measured heat flux into the sea bottom. ( $a_G$ =5.9*10$^{-7}$[m$^2$/s])

conducted the field survey under a typical fine weather in summer with the wind speed of less than 5 m/s and the solar radiation up to 1000 W/m$^2$. The values of water temperature at three different depths in seawater had low and high peaks in early morning and evening, respectively, and hence water temperature increased in daytime and decreased in nighttime. It is noted that the distinct differences of water temperature in the vertical direction was deformed only for early morning.

The time variations of temperature in sea bottom were similar to those of water temperature. However the amplitude of the temperature fluctuations in sea bottom was much smaller as the depth at measuring stations increases. Furthermore the phase lag of the temperature in sea bottom appeared remarkably. We may find from these facts that the temperature fluctuations in the sea bottom give qualitatively agreements with fundamental features of thermal conduction processes.

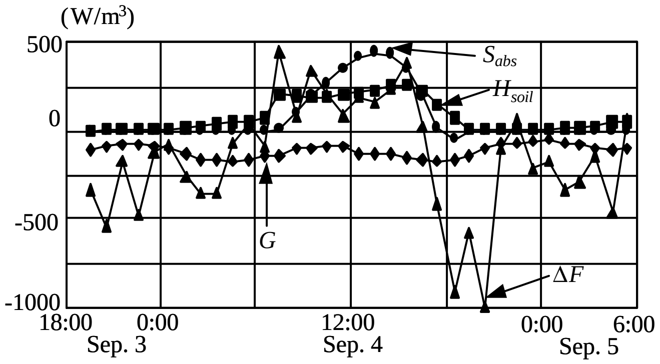
## Heat Balance for Sea Surface and Bottom

**Figure 6(a)** represents the results of the heat balance for sea surface evaluated with Eq. 1. The absolute value of heat flux to the water column $G$ was smaller than those of the latent heat flux $lE$ and the net radiation on sea surface $L_d - L_u$. Since the sign of $G$ was always negative mainly due to the negative value of the net radiation, $G$ had a cooling effect on the water column. **Figure 6(b)** indicates the time series of the heat fluxes on sea bottom described in Eq. 2. The net shortwave radiation on sea bottom increased rapidly in the early morning in September 4 due to abrupt increase of solar radiation, and the sensible heat flux $H_{soil}$ increased almost at the same time. Although the heat flux into the sea bottom $G_{soil}$ also increased from early morning in September 4, the absolute value of $G_{soil}$ is relatively smaller than that of $H_{soil}$.

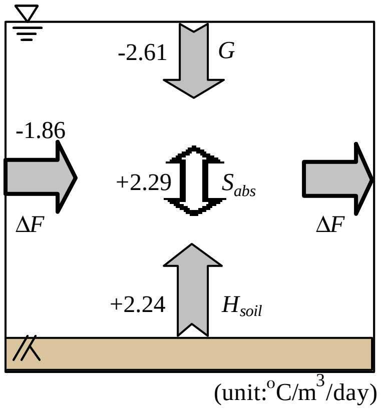
To evaluate the heat flux into the sea bottom $G_{soil}$, Nadaoka et al. (2001b) adopted the analytical solution of temperature in sea bottom $T(z,t)$ obtained with 1-D thermal conduction equation in the vertical direction

$$T(z,t) = T_b(0) + \int_0^t \frac{z}{2\sqrt{\pi a_G (t-x)^3}} \times \exp\left\{-\frac{z^2}{4a_G(t-x)}\right\}(T_b(x)-T_b(0))dx \quad , \tag{5}$$

where $a_G$ is a diffusion coefficient of temperature in sea bottom, $z$ is the vertical coordinate with the origin at the sea bottom being positive downward, $T_b(t)$ is the time-varying water temperature at the sea bottom ($z$=0). In the derivation of this solution, the initial temperature in the sea bottom is assumed to be uniform vertically with the value equal to the initial temperature at $z$=0. With the vertical distribution of time-varying temperature estimated with Eq. 5, the heat flux into the sea bottom $G_{soil}$ can be written in the form



**(a)** Time series of 1h-averaged heat fluxes



**(b)** 24h-averaged heat fluxes

**Fig. 8** Heat balance for a water column.

$$G_{soil} = \int_0^\infty r_G c_G \frac{\partial T}{\partial t} dz \,, \qquad (6)$$

where $c_G$ and $r_G$ is specific heat and density of sea bottom. **Figure 7** shows the comparison of the calculated heat flux into the sea bottom with the observed results of the heat flow sensor, indicating that the calculated heat flux into the sea bottom gives acceptable agreements with the measured results. This fact demonstrates the fundamental validity of Eqs 5 and 6 to evaluate the heat flux into the sea bottom.

## Heat Balance for a Water Column

**Figure 8(a)** illustrates the time variations of the 1 hour (1h)-averaged heat fluxes for the water column evaluated with Eq. 3. The temporal change rate of the heat storage $\Delta Q$ was positive and negative in the daytime and nighttime, respectively, corresponding to the water temperature fluctuations as shown in **Fig. 5**. The positive value of $\Delta Q$ in the daytime was caused not only by the horizontal advective heat flux $\Delta F$ and the radiative absorption process $S_{abs}$, but also by the sensible heat flux from the sea bottom $H_{soil}$. On the other hand, the negative $\Delta Q$ in the nighttime occurred mainly due to the horizontal advective heat flux $\Delta F$.

To clarify the overall contributions of the heat fluxes on the heat balance for the water column, the 24h-averaged heat fluxes are summarized in **Fig. 8(b)**. In this figure, each heat flux is represented as a temporal change rate of water temperature of the water column with unit volume. These results indicate that the seawater in the reef was cooled by the heat flux through the sea surface $G$ and the horizontal advective heat flux $\Delta F$ but was warmed by the gain of heat by the absorption of shortwave radiation in the water column $S_{abs}$ and the sensible heat flux from the sea bottom $H_{soil}$. It should be noted that the absolute value of 24h-averaged sensible heat flux from the sea bottom $H_{soil}$ was comparable to those of the other fluxes. These results manifest that the sea bottom has a significant influence on the heat balance of reef water.

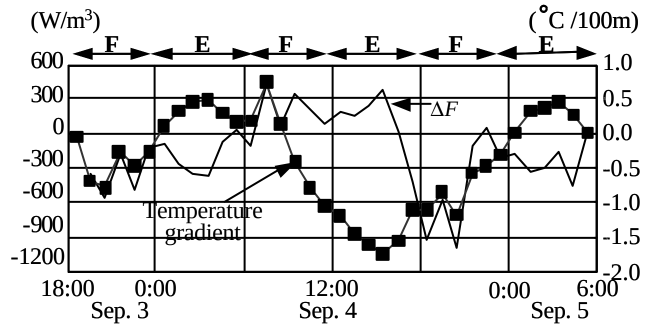


**Fig. 9** Horizontal gradient of water temperature in on-off shore direction. (F=Flood tide, E=Ebb tide)

It is also noteworthy from **Fig. 8** that the horizontal advective heat flux $\Delta F$ plays an important role in the fluctuations of the temporal change rate of the heat storage $\Delta Q$ and the water temperature. To understand the cause for the time variation of $\Delta F$, we have attempted to examine the horizontal fluctuation patterns of water temperature using measured data of the thermometers deployed around the ladder as shown in **Fig. 2(b)**. **Figure 9** indicates the time histories of the horizontal gradient of water temperature in on-off shore direction, which is positive if the water temperature in offshore points is higher than in onshore points, with the horizontal advective heat flux $\Delta F$. Since the water temperature gradient in cross-shore direction was small compared to that in on-off shore direction, it is not depicted in the figure. The water temperature gradient in the on-off shore direction had an appreciable diurnal fluctuation with the amplitude of more than $1\,^\circ C/100m$. We here consider the advective heat flux transported by tidal current in on-off shore direction; if the gradient of water temperature is negative in a flood tide, the heat flux transported by tidal current simply from offshore to onshore should be negative. We may find from this figure at this viewpoint that the fluctuation of the horizontal advective heat flux $\Delta F$ was qualitatively consistent with that of the heat flux associated with water movements in on-off shore direction by tide. This result reveals that the fluctuations of $\Delta F$ may be closely related to the movements of water mass in the on-off shore direction due to tidal current.

### Comparison of Heat Budget Analysis with and without Sea-Bottom Effects

In the heat balance for reef water, the effects of sea bottom are reflected on the radiative process in seawater and the heat flux through sea bottom. We have examined the influence of the treatments of these sea-bottom effects on results of heat budget analysis. For this purpose, we conducted the heat budget analysis with and without these two effects of sea bottom on thermal environments. We first employ the heat budget analysis for a water column without the two sea-bottom effects, in which the shortwave radiation transmitting sea surface is completely absorbed in the water column and the heat flux into the sea bottom is neglected, that is,

$$\Delta Q = G + \Delta F + (1 - a_1) S_d \,. \qquad (7)$$

**Table 1** Comparison of heat budget analysis with and without sea-bottom effects.

| | Eq.3 | Eq.7 | Eq.8 |
|---|---|---|---|
| $G$ | -2.61 | -2.61 | -2.61 |
| $H_{soil}$ | 2.24 | | |
| $G_{soil}$ | 0.35 | | 0.35 |
| $\Delta F$ | -1.86 | -1.86 | -1.86 |
| $S_{abs}$ | 2.29 | 5.47 | 5.47 |
| $\Delta Q$ | 0.07 | 1.00 | 0.65 |

(unit:$^{o}$C/m$^3$/day)

Furthermore we also perform the heat budget analysis only without the effect of the radiative process in seawater, but with the heat flux through sea bottom, that is,

$$\Delta Q = G + \Delta F - G_{soil} + (1 - a_1)S_d \, . \qquad (8)$$

We calculated the heat balance for the water column with Eqs. 3, 7 and 8 as a temporal change rate of water temperature for the water column with a unit volume. We evaluated $G$ and $\Delta F$ with Eqs.1 and 3, respectively, and used the measured data for $S_d$ and $G_{soil}$. The difference of the treatment of sea-bottom effects on the heat budget analysis is therefore reflected on the value of the temporal change rate of the heat storage in the water column $\Delta Q$. **Table 1** represents the values of $\Delta Q$ and the heat fluxes evaluated with Eqs. 3, 7 and 8, indicating that the differences of evaluated heat balance for the water column appear appreciably by whether the equations in the heat budget analysis involve the sea-bottom effects. These results demonstrate that the treatments of the radiative processes in seawater and the heat flux through the sea bottom influence remarkably the results of the heat budget analysis for reef water.

## CONCLUSIONS

To investigate the effects of sea bottom on the thermal environments and heat balance in coral reefs, we have attempted to perform an intensive field observation at Shiraho reef located in Ishigaki Island, Okinawa, Japan. In the field observation, we used a heat flow sensor and two pyranometers to accurately incorporate the effects of sea bottom in a heat budget analysis for reef water. We performed the heat budget analysis for reef water with special attention to the sea-bottom effects, indicating a significant importance of sea-bottom effects on the heat balance of reef water. The heat budget analysis also reveals that the treatments of the sea-bottom effects affect appreciably the results in the heat budget analysis.

## ACKNOLEDGEMENTS

The present study was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B) (No.12450198 and No.12555147) and for Scientific Research (C) (No.12895008) and by the funds from Heiwa-Nakajima Foundation.

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