Radiative heat exchange in a tropical Chwaka bay, east coast of Zanzibar

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Radiative heat fluxes were measured from a platform during the period 18 January through 9 February 1996. Cloud cover ranged from clear skies to overcast while the air temperature was near 28°C. Sea surface temperature varied between 27 and 34°C and air vapour pressure from 26 to 39 mb. Measured values of both short-wave and net long-wave radiative fluxes were compared with those computed from empirical formulas. The net long wave radiative fluxes were obtained by taking the difference between simultaneous measurements of net all-wave and net solar heat fluxes. The agreement between the observations and the formulas varied between 1 to 20% for short-wave radiation and from 0.3 to 15% for long-wave radiation. The formulas by Reed (1977) and Budyko (1963) have been found to be the most appropriate for estimating the two fluxes, respectively. It is concluded that the empirical formulas, used for Chwaka bay, gives results that are similar to those obtained elsewhere.

The radiative heat exchange through the sea surface consists of net short-wave solar radiation $Q_s$ and loss of heat by net outgoing long-wave radiation $Q_b$. Over the tropics, $Q_s$ contributes significantly to net heat gain while $Q_b$ contributes towards net heat loss. Sheltered waters like those of Chwaka bay play an important ecological role in providing a warm, nutrient-rich and highly productive environment conducive to the prosperity of both fauna and flora. Knowledge of the ocean-atmosphere heat exchange of such an ecosystem is relevant to the biology of these areas, as it provides a vital input in linking physical and biological processes. The objectives of this paper are to describe observations of radiation over Chwaka bay and to compare the observations with suggested parameterisations of radiative fluxes ($Q_s$ and $Q_b$) at the sea surface.

Materials and Methods

Chwaka bay is located on the east coast of Zanzibar Island in Tanzania, between 39° 22' to 39° 30' E and 6° 8' to 6° 15' S (Fig. 1). The bay is shallow, having an average depth of 2 m at mean sea level. The bay also experiences a semi-diurnal tide, with a mean spring tidal range of 3.2 m. During low water, large intertidal flats are exposed. The surface area of the bay varies from 20 km² at low water spring to 50 km² at high water spring.

Radiation measurements were from 18 January to 9 February 1996. The incoming short-wave radiation (0.3-2.5μ), outgoing short-wave radiation (0.3-2.5μ), net radiation (0.3-60 μ), air temperature, air pressure, relative humidity and sun duration were measured from an Aanderaa Automatic Weather Station 2700. The weather station was mounted on a tripod, which was anchored on a flat bottom in the middle of the bay, at a depth of 0.5 m during spring low water. The sensors were positioned at the same level on a
mast, which projected 1 m from the apex of the tripod, and approximately 11 m from the bay bottom. A downward-looking solar radiation sensor (for measuring upward short-wave radiation) was mounted separately on a boom extending 2 m from the mast, slightly below the other sensors. A temperature sensor was attached to a surface buoy, also connected to the data storage unit of the Weather Station. All sensors were set to record at 20 min intervals. The outputs of the weather station are in raw form. These are converted to physical units using sensor-specific calibration coefficients, as specified by the manufacturer. The sensors were calibrated in 1995 while their specifications are shown in Table 1. In this work, the atmospheric variables are averaged over 24 h periods while day-time observations of sun duration are used to obtain daily estimates of the fractional cloud cover. If $S_d$ is the observed sun duration (min) in a 20 min observation interval, then the fractional cloud cover $C$ is equal to $1 - \frac{S_d}{20}$. The daily estimate is obtained by averaging $C$ over the period from sunrise to sunset. However, no visual observations of cloud cover were made during the study period.

Records of the incident short-wave, upward short-wave and net radiation were used to obtain net long-wave radiation. The net short-wave radiation ($Q_s$) is the sum of the incident short-wave solar radiation and the upward short-wave solar radiation. The net long-wave radiation ($Q_b$) is the sum of the long-wave radiation emitted down from the atmosphere and that emitted up from the sea surface. The net radiation sensor measures direct and scattered solar radiation as well as infrared radiation from the sea surface and the atmosphere, which is simply the sum of $Q_s$ and $Q_b$. The net radiation sensor measures $Q_b$ directly at night, since the incident short-wave radiation and hence $Q_s$ during this time is zero. This method of measuring $Q_b$ is similar to that used by previous authors\footnote{\textsuperscript{2,6}}. They all used a pyranometer to measure short-wave radiation (0.28-2.8 $\mu$m) from the sun and sky, and a net radiometer to measure radiation of wavelengths from 0.3 to 60 $\mu$m. In addition to this indirect method, $Q_b$ was also measured directly, using various instruments.

**Net short-wave solar radiation ($Q_s$)** — Table 2 shows some of the empirical formulas\footnote{\textsuperscript{7-10}} that have been advanced for computation of the cloud correction factor ($F$). In Table 2 $C$ refers to the fractional cloud cover (tenths) while $\alpha$ is the noon solar altitude (degrees). The formulas of Kimball\footnote{\textsuperscript{7}}, Laevastu\footnote{\textsuperscript{8}}, Tabata\footnote{\textsuperscript{9}} and Reed\footnote{\textsuperscript{10}} have been applied to estimate $Q_s$ for comparison with the measured values at Chwaka bay. It is worth-noting that over the recent years, the formula by Reed\footnote{\textsuperscript{10}} has widely been applied for computation of $Q_s$. Reed\footnote{\textsuperscript{10}} compared several formulae for estimating clear-sky insolation with coastal and oceanic observations and concluded that

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Range</th>
<th>Accuracy</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>Solar radiation</td>
<td>0:2000 Wm$^{-2}$</td>
<td>$&lt; 0.02 \text{ Wm}^{-2}$</td>
<td>4 Wm$^{-2}$</td>
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<tr>
<td>Net radiation</td>
<td>-2000:2000 Wm$^{-2}$</td>
<td>1% of full scale</td>
<td>4 Wm$^{-2}$</td>
</tr>
<tr>
<td>Air temperature</td>
<td>-43:48$^\circ$C</td>
<td>1% of full range</td>
<td>1% of full range</td>
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<tr>
<td>Air pressure</td>
<td>920:1080 mb</td>
<td>0.2 mb</td>
<td>0.2 mb</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>400:1100 min</td>
<td>-</td>
<td>1 min</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0:100%</td>
<td>3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Air temperature</td>
<td>-7.5:41$^\circ$C</td>
<td>0.1% of range</td>
<td>0.1% of range</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>-8:40$^\circ$C</td>
<td>0.1$^\circ$C</td>
<td>0.05$^\circ$C</td>
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</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>Formula</th>
<th>Bias (Wm$^{-2}$)</th>
<th>Error (%)</th>
<th>Corr. coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimball\textsuperscript{7}</td>
<td>$1 - 0.71C$</td>
<td>-58.2</td>
<td>20</td>
<td>0.73</td>
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<tr>
<td>Laevastu\textsuperscript{8}</td>
<td>$1 - 0.60C^3$</td>
<td>13.8</td>
<td>5</td>
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<tr>
<td>Tabata\textsuperscript{9}</td>
<td>$1 - 0.716C + 0.00252\alpha$</td>
<td>6.7</td>
<td>2</td>
<td>0.73</td>
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<tr>
<td>Reed\textsuperscript{10}</td>
<td>$1 - 0.62C + 0.0019\alpha$</td>
<td>3.4</td>
<td>1</td>
<td>0.73</td>
</tr>
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the relation by Seckel & Beaudry was one of the most reliable. The sea surface albedo for Chwaka bay is obtained as the ratio of outgoing to incoming radiation. Since the bay is shallow, the outgoing radiation also includes a small portion of solar radiation reflected at the bay bottom, especially during spring low water.

Net long-wave radiation—As is the case with short-wave solar radiation; the net long-wave radiation is usually estimated by empirical expressions, which use sea surface temperature, air temperature, air pressure and relative humidity as inputs. The empirical formulas of Budyko, Budyko and Anderson (Table 3) are frequently used in the estimation of net long-wave radiation under clear skies. It may be noted that Budyko’s formulas were derived from observations over land while that of Anderson was derived exclusively from observations over a lake. These formulas have been employed in this study for comparison with the measured values at Chwaka bay.

Results and Discussion

The various atmospheric variables observed during the 23-day study period are presented in Fig. 2. The air temperature was near 28°C while sea surface temperature varied between 27°C and 34°C and relative humidity from 63% to 91%. Cloud cover obtained from measurements of sun duration ranged from clear skies to overcast, with a mean value of 0.42 (Fig. 3). The observed incoming solar radiation, net radiation and outgoing short-wave radiation within the same period are shown in Fig. 4. The three variables had mean values of 291, 237 and 15 W m⁻², respectively.

Figure 5 shows the mean daily albedo values that were computed from measurements taken from sunrise to sunset. These values were obtained as the ratios of outgoing to incoming short-wave solar radiation, and had a mean value of 0.053. Plots of observed mean daily insolation (i.e. albedo values were not applied), together with predictions of the

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<tr>
<td>Budyko</td>
<td>εσ(T_s+273.16)⁴ (0.39-0.05ε_a⁵) + εσT_s³(T_s-T_a)</td>
<td>0.1</td>
<td>0.33</td>
<td>0.67</td>
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<tr>
<td>Budyko</td>
<td>εσ(T_s+273.16)⁴ (0.254-0.00495ε_a)</td>
<td>-5.5</td>
<td>15</td>
<td>0.64</td>
</tr>
<tr>
<td>Anderson</td>
<td>εσ(T_s+273.16)⁴ (0.260-0.0049ε_a)</td>
<td>-3.1</td>
<td>8</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 3—Empirical formulas for estimation of net long-wave radiation under clear skies and their error estimates.
four empirical formulas, are presented in Fig. 6. Apart from February 6, when there was a complete overcast sky (Fig. 3), the observed insolation was fairly constant over the whole period.

Results of the observed values of long-wave back radiation $Q_b$, together with the empirical estimates, are presented in Fig. 7. The mean value of the observed net infrared radiation was $38.0 \text{ W m}^{-2}$. The estimated values by the formulas of Budyko$^{14}$, Budyko$^{15}$ and Anderson$^{15}$ were $38.1$, $32.5$ and $34.9 \text{ W m}^{-2}$, respectively.

The mean value of the absorbed short-wave solar radiation was $275.5 \text{ W m}^{-2}$. This was obtained by assuming an albedo value of $0.053$ obtained from observations. For the latitude at Chwaka, the widely used tabulations for sea surface albedo by Payne$^{16}$ suggest a value of $0.06$. Payne’s observations were taken from a fixed platform in a bay off the coast of Massachusetts, USA. Considering that the outgoing solar radiation combines also light reflected from the bottom, the observed mean albedo value at Chwaka bay is relatively small.

On estimating insolation, the formula by Kimball$^7$ has greatly underestimated the observations while the rest have given higher values than those observed. The reason for the appreciable overestimation of Kimball’s formula might be due to the fact that the formula was primarily derived from data obtained over an inland location where height and density of clouds are generally different than at sea$^{10}$. The deviations of estimates of the various insolation formulas from the observations are shown in Table 2. Whereas the formula by Laevastu$^8$ has given the best correlation coefficient, Reed’s$^{10}$ formula has given the smallest bias. Since the accuracy of the solar radiation sensors were within $20 \text{ W m}^{-2}$, biases within this range cannot be considered as significant. Thus, the formulas by Laevastu$^8$, Tabata$^9$ and Reed$^{10}$ (Table 2) have given reasonably good insolation estimates.

Whereas Budyko’s$^{14}$ formula has given results that agree considerably with the observed values of net long-wave radiation, Budyko’s$^{14}$ formula and Anderson’s$^{15}$ formula have underestimated $Q_b$ (Table 3). The correlation between observed and predicted values of net long-wave radiation are not large because of the scatter, which may be ascribed to the approximation made in the prediction formulas that the flux depends on surface temperature, air temperature and relative humidity which fluctuate considerably.

The three radiation sensors that were used to obtain $Q_b$ have biases of $20 \text{ W m}^{-2}$ (7.2% of the mean) for each of the downward and upward looking solar radiation sensors, and 1% for the net radiation sensor. This implies therefore that Budyko’s$^{14}$ formula and Anderson’s$^{15}$ formula provides realistic estimates of net long-wave radiation. Since the three sensors have given good predictions of net long-wave radiation, this is a strong indication that there were no serious errors for either instrument.

In order to make analytical remarks, the estimated results obtained from the empirical formulas must be compared to those of previous studies. When analysing radiation measurements collected in the Northeast Pacific (near $35^\circ\text{N}$ and $155^\circ\text{W}$), Simpson & Paulson$^5$ observed that Kimball’s formula underestimated insolation by 18% (about what we have obtained here), whereas Reed’s formula overestimated insolation by 6%.

![Fig. 4—Time series of 20-min averages of measured incident solar radiation, net all-wave radiation and upward radiation](image)

![Fig. 5—Daily-averaged values of albedo obtained as a ratio of outgoing to incoming short-wave solar radiation](image)
Fig. 6—Plots of daily-averaged values of observed and computed short-wave solar radiation by the formulas of Kimball⁷, Laevastu⁸, Tabata⁹ and Reed¹⁰.

Fig. 7—Plots of daily-averaged values of observed and computed long-wave solar radiation by the formulas of Budyko¹¹, Budyko¹² and Anderson¹³.
Godfrey et al.\textsuperscript{5}, using Reed's formula, found that values computed using Reed's formula were about 5% higher than the observed values. Their data were collected in the Western Equatorial Pacific (near 4°S and 149°E), Reed & Brainard\textsuperscript{17}, using data collected during the summer period of 1975 in the Pacific Ocean (near 45°N and 125°E), observed the same bias of 5% as Godfrey et al.\textsuperscript{5}, with the estimated values being higher than the computed values.

Using radiation data off central California coastline, Frouin et al.\textsuperscript{18} observed that Laevastu's\textsuperscript{6} formula overestimated insolation by 24.5 Wm\textsuperscript{-2}. Reed\textsuperscript{19} has presented results which show that Tabata's formula gives somewhat larger values at small cloud amounts than Reed's formula (which is also true in this case).

The following studies on long-wave radiation have given results that concur with our predictions. Reed\textsuperscript{4} noted that Budyko's\textsuperscript{14} formula gives lower values than Anderson's\textsuperscript{15} formula. Simpson & Paulson\textsuperscript{3}, using Budyko's\textsuperscript{14} formula, found a good agreement between the mean of the estimates and the mean of the observations. Their predictions using Budyko's\textsuperscript{14} formula gave values that underestimated the observations by 15%. Godfrey et al.\textsuperscript{5} used a 13 day record of radiation measurements and noted that Budyko's\textsuperscript{13} formula agreed closely with their observations. They also noted that Budyko's\textsuperscript{13} formula consistently underestimated the observed values.

In view of the above discussion, our solar radiation predictions conform to those observed elsewhere. This implies therefore that the clear-sky insolation formula that we have used, and the method for the derivation of albedo, were both appropriate. Although no visual observations of cloud cover were made, it seems reasonable to comment that the records of sun duration from the instrument we used can reliably be applied to derive cloud cover amounts that may be used in empirical formulations for insolation predictions. The method we have used for estimation of cloud cover may however need to be validated through comparison with data obtained using visual observations, although such observations have also been reported to have inherent large errors\textsuperscript{10}.

From the above discussion, it is concluded that the various radiation prediction formulas that we have used for Chwakwa bay gives results that are similar to those obtained elsewhere. For best prediction results, the formulas by Reed\textsuperscript{10} and Budyko\textsuperscript{13} have been found to be the most appropriate for estimating short-wave and net long-wave radiations, respectively. This study has involved data collected only for one month. To investigate the radiative heat energy exchange over a full range of time scales, observations must extend through a full year to quantify seasonal variations.

**Acknowledgement**

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**Appendix**

*Estimation of net short-wave solar radiation (Q*)*

The empirical formulas for estimation of \( Q * \) are generally expressed in the form:

\[
Q = Q_o F(1-A)
\]  

(1)

where \( Q_o \) (W m\textsuperscript{-2}) is the clear-sky mean daily insolation and \( A \) is the sea surface albedo. \( F \) is the cloud correction factor, which represent the attenuation of solar radiation by clouds. To estimate \( Q_o \) we use a formula adopted by Reed\textsuperscript{10}. The formula, which was first proposed by Seckel & Beaudry\textsuperscript{11} and has acquired general acceptance, is expressed as follows:

\[
Q_o = A_o + A_1 \cos \phi + B_1 \sin \phi + A_2 \cos 2 \phi + B_2 \sin 2 \phi \]  

(2)

where

\( \phi = (t-21)/(2 \pi/365) \)  

(3)

\( t \) in Eq. (3) is the time of year (days). For the latitude band 20°S-40°N, the coefficients in Eq. (2) have the following expressions:

\[ A_o = -15.82 + 326.87 \cos L \]  

(4a)

\[ A_1 = 9.63 + 192.44 \cos (L+\pi/2) \]  

(4b)

\[ B_1 = 3.27 + 108.70 \sin L \]  

(4c)

\[ A_2 = 0.64 + 7.80 \sin 2(L-\pi/4) \]  

(4d)

\[ B_2 = 0.50 + 14.42 \cos (L-\pi/36) \]  

(4e)

where \( L \) is the latitude of a place (degrees).

In the formulas by Tabata\textsuperscript{7} and Reed\textsuperscript{10}, the noon solar altitude \( \alpha \) for the computation of \( F \) in Eq. (1) is given by the relationship\textsuperscript{20},

\[ \alpha = 23.45 \sin \left( \frac{360}{365} \left( \frac{t-21}{283} + \frac{1}{2} \right) \right) \]  

(5)

where \( t \) is in days.
\[ \sin \alpha = \sin L \sin \delta + \cos L \cos \delta \] ... (5)

where \( \delta \) is the sun declination which is expressed in terms of \( t \) as:
\[ \delta = 23.87 \sin \left[ \frac{2 \pi (t - 82)}{365} \right] \] ... (6)

Estimation of net long-wave radiation \( (Q_b) \)

In the formulas for estimation of \( Q_b \), \( \varepsilon \) is the emissivity of the sea surface (taken as 0.97 \(^{21} \)), \( \sigma \) is the Stefan-Boltzmann constant \( (5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) \), \( T_s \) is the sea surface temperature (\(^\circ\text{C}\)), \( T_a \) is the air temperature (\(^\circ\text{C}\)), and \( e_a \) is the air vapour pressure (mb) given by
\[ e_a = \left( \frac{r_h}{100} \right) e_v \] ... (7)

where \( r_h \) is the relative humidity (percentage) and \( e_v \) (mb) is the saturation vapour pressure at the sea surface expressed as \(^{21} \):
\[ e_v = 0.98 \left[ 1 + 10^{4.5 + 0.006T_s} \right] \times 10^7 \] ... (8)

where \( P \) is the air pressure (mb), and
\[ \gamma = (0.7859 + 0.0347T_s)/(1 + 0.00442T_s) \] ... (9)

The frequently used cloud correction factor \((1-BC)\) is that recommended by Reed\(^4\). \( B \) is a factor that depends on the cloud type. For the higher clouds typical of the tropics, \( B \) is taken as 0.7.

References