Balance of surface, advective and up-welling heat fluxes in the Gulf of Aden

Yasser O. Abualanaja*, Fazal Ahmad, & Nwaf A. Al-mtairi

Marine Physics Department, faculty of Marine Science, King Abdulaziz University, p.O Box 80207, Jeddah, 21589, Saudi Arabia

*Red Sea Science & Engineering Centre, King Abdullah University of Science and Technology (KAUST), P.O Box 55455, Jeddah, 21534, Saudi Arabia

[E mail-Yasser.abualnaja@kaust.edu.sa]

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Based on International Comprehensive Ocean Atmosphere Data Set (ICOADS), monthly summary groups (1960-2008), covering 1° boxes in the Gulf of Aden, the surface advective and up-welled heat fluxes are calculated. Annual averages of evaporative, net long wave radiation and sensible heat fluxes are respectively 143, 55 and 2 W/m². Annual average of absorbed solar radiations at the sea surface based on the Smithsonian formula is 249 W/m². Advective heat transport to the Red Sea from Gulf of Aden at Bab-el-Mandab Strait is 35 W/m² giving a surplus of 14 W/m². Compared to the available recorded solar radiations it seems that the Smithsonian formula over-estimates the incoming solar radiations perhaps because of the neglect of aerosols. Up-welled heat flux during the southwest monsoon is $1.0 \times 10^{13}$ W.

[Keywords: Gulf of Aden, Red Sea, Surface heat fluxes, Advective heat transport].

Introduction

The Gulf of Aden is located between Yemen on the southern coast of the Arabian Peninsula and the northern coast of Somalia in Africa. It is bounded to the east by approximately 51° E longitude and in the northwest it connects with the Red Sea through the narrow Bab-el-Mandab Strait (Fig. 1). Gulf of Aden is considerably wider than the Red Sea and the approximate surface area is $220 \times 10^3$ km². The area is heavily influenced by the Indian Ocean monsoon system: winds from the east to northeast during the winter monsoon (October to April) and from the southwest during the summer monsoon (May to September).²

Surface circulation is mainly dependant on the changing monsoon winds. During the NE monsoon, winds drive the surface water towards Bab-el-Mandab Strait, particularly along the Arabian coast. Along the Somali coast there is some occasional local up-welling but generally the currents are weak and variable. During SW monsoon the surface water generally moves in the Easterly direction. The longshore wind stress causes strong up-welling of subsurface water at different locations along the Arabian coast. During this time three up-welling regions with varying intensity and mechanisms have been identified in the Arabian Sea³,⁵. Because of the strong up-welling the surface water temperature along Arabian coast of the Gulf of Aden varies considerably. Maximum temperatures occur in May/June and September/October with lower temperature in July and August. During the peak of coastal up-welling temperature may be 7-10 °C lower. However, the extent of cooling depends on the intensity and duration of up-welling which vary from one year to another. A striking feature of the up-welling along the Arabian coast of the Gulf of Aden is its extent over a wide area⁵,⁶. As a consequence the up-welled waters are supplied from a much greater depth than is usual in other coastal up-welling regions⁶.

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*For correspondence

Fig. 1—Map of the study area; showing the Gulf of Aden connects with the Red Sea through the narrow Bab-el-Mandab Strait at the northwest side. (www.aquarius.ifm-geomar.de).
The Gulf of Aden is a unique environment having very special dynamics and thermodynamics due to its size and geographic location. It exchanges water with the Red Sea and the Arabian Sea. Up-welling is also very important along its northern coast during SW monsoon. Therefore the main factors that control the heat balance of the Gulf of Aden are: balance of surface heat fluxes at the air-sea interface; exchange of heat with the Red Sea at Bab-el-Mandab and the Arabian Sea; up-welling process which suppresses the out-going heat fluxes especially the evaporative heat flux at the sea surface.

For the computation of surface heat fluxes the present study is based on the International Comprehensive Ocean Atmosphere Data Set (ICOADS). The Monthly Summary Groups (MSG) of the parameters; sea surface temperature, air temperature, scalar wind, relative humidity, cloudiness and sea level pressure are available for each year covering 1° boxes. The averages of the data and standard deviations for the above parameters for the Gulf as a whole, based on data from 1960-2008 are given in Table 1.

**Materials and Methods**

**Surface heat flux**

Surface fluxes of heat (latent and sensible) are estimated using Bulk Aerodynamic method\(^7,8\), the equations are:

\[
Q_e = \rho_a \ L \ C_E \ (q_s - q_a) \ w
\]

\[
Q_h = \rho_a \ C_p \ C_T \ (T_s - \theta) \ w
\]

Here \(q_s\) and \(q_a\) are the surface and near surface atmospheric specific humidity respectively. \(\rho_a\) is density of moist air, \(C_p\) is specific heat of air at constant pressure, \(L\) is latent heat of evaporation, \(C_E\) and \(C_T\) are Bulk transfer coefficients determined from Bunker\(^9\), Bunker *et al.*\(^10\), Bourassa *et al.*\(^11\), Fairall *et al.*\(^12\) and Yu *et al.*\(^13\), \(T_s\) is sea surface temperature; \(\theta\) is near surface air potential temperature, and \(w\) is the wind speed. \(q_s\) is computed from saturation humidity \(q_{sat}\) for pure water at \(T_s\); \(q_s = 0.98 \ q_{sat} (T_s)\), as the salinity of about 35‰ reduces the vapor pressure by 2%. \(\theta\) is calculated from \(\theta = T_s + \gamma \ z\), where \(\gamma\) is the adiabatic temperature lapse rate and \(z\) is the height for air temperature \(T_a\). Based on the data given in Table 1, the evaporative heat flux \(Q_e\) and the sensible heat flux \(Q_h\) are given in Table 2.

The net long wave radiation (\(Q_b\)) at the sea surface is the result of emission, absorptions and scattering in the atmosphere. It is common to derive \(Q_b\) with the aid of various bulk formulas. Bulk formula assumes that the surface properties of temperature and humidity represent those of atmospheric column and they introduce various parameterization schemes with constants derived from regression fitting to certain sets of observations. In general only the cloud fraction is taken into consideration and the cloud type (high, medium or low) is ignored. This increases the uncertainty\(^14\). The formula for \(Q_b\) given by Berliand and Berliand\(^15\) and Bignami *et al.*\(^16\):

<table>
<thead>
<tr>
<th>Month</th>
<th>(T_o) (°C)</th>
<th>(T_s) (°C)</th>
<th>Wind (m/s)</th>
<th>RH %</th>
<th>C (okta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.90 ±0.33</td>
<td>25.17 ±0.30</td>
<td>6.30 ±0.55</td>
<td>70.50 ±3.25</td>
<td>2.40</td>
</tr>
<tr>
<td>2</td>
<td>25.82 ±0.50</td>
<td>25.09 ±0.25</td>
<td>5.55 ±0.57</td>
<td>71.55 ±2.25</td>
<td>2.28</td>
</tr>
<tr>
<td>3</td>
<td>26.87 ±0.25</td>
<td>26.16 ±0.18</td>
<td>5.88 ±0.51</td>
<td>75.25 ±3.30</td>
<td>2.10</td>
</tr>
<tr>
<td>4</td>
<td>28.65 ±0.36</td>
<td>28.00 ±0.33</td>
<td>5.32 ±0.50</td>
<td>80.10 ±3.50</td>
<td>2.16</td>
</tr>
<tr>
<td>5</td>
<td>30.45 ±0.37</td>
<td>30.21 ±0.15</td>
<td>5.17 ±0.60</td>
<td>79.05 ±2.20</td>
<td>2.00</td>
</tr>
<tr>
<td>6</td>
<td>29.90 ±0.40</td>
<td>30.10 ±0.32</td>
<td>6.89 ±0.65</td>
<td>78.60 ±2.80</td>
<td>2.47</td>
</tr>
<tr>
<td>7</td>
<td>28.67 ±0.28</td>
<td>29.35 ±0.19</td>
<td>7.55 ±0.62</td>
<td>79.10 ±2.35</td>
<td>3.53</td>
</tr>
<tr>
<td>8</td>
<td>28.00 ±0.35</td>
<td>28.50 ±0.21</td>
<td>7.25 ±0.55</td>
<td>80.45 ±3.32</td>
<td>2.98</td>
</tr>
<tr>
<td>9</td>
<td>28.84 ±0.33</td>
<td>29.00 ±0.32</td>
<td>5.31 ±0.54</td>
<td>81.00 ±3.35</td>
<td>2.54</td>
</tr>
<tr>
<td>10</td>
<td>28.90 ±0.41</td>
<td>28.03 ±0.15</td>
<td>5.46 ±0.60</td>
<td>75.65 ±2.75</td>
<td>2.10</td>
</tr>
<tr>
<td>11</td>
<td>27.71 ±0.32</td>
<td>27.10 ±0.31</td>
<td>5.62 ±0.55</td>
<td>76.21 ±3.00</td>
<td>1.94</td>
</tr>
<tr>
<td>12</td>
<td>26.92 ±0.28</td>
<td>26.31 ±0.24</td>
<td>6.31 ±0.50</td>
<td>74.12 ±2.80</td>
<td>2.56</td>
</tr>
</tbody>
</table>
Table 2—Computed monthly values of evaporative heat flux $Q_e$, sensible heat flux $Q_h$, net long wave radiation flux $Q_b$, and incoming short wave radiation $Q_s$ for the Gulf of Aden.

<table>
<thead>
<tr>
<th>Month</th>
<th>$Q_s$ (W/m²)</th>
<th>$Q_b$ (W/m²)</th>
<th>$Q_h$ (W/m²)</th>
<th>$Q_c$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>185 ±11</td>
<td>6 ±3</td>
<td>63 ±2</td>
<td>211</td>
</tr>
<tr>
<td>2</td>
<td>142 ±8</td>
<td>5 ±2</td>
<td>68 ±2</td>
<td>235</td>
</tr>
<tr>
<td>3</td>
<td>145 ±9</td>
<td>5 ±1</td>
<td>61 ±1</td>
<td>258</td>
</tr>
<tr>
<td>4</td>
<td>124 ±6</td>
<td>4 ±1</td>
<td>54 ±1</td>
<td>271</td>
</tr>
<tr>
<td>5</td>
<td>135 ±6</td>
<td>2 ±1</td>
<td>48 ±2</td>
<td>272</td>
</tr>
<tr>
<td>6</td>
<td>145 ±8</td>
<td>-2 ±2</td>
<td>49 ±1</td>
<td>269</td>
</tr>
<tr>
<td>7</td>
<td>135 ±7</td>
<td>-6 ±3</td>
<td>47 ±2</td>
<td>269</td>
</tr>
<tr>
<td>8</td>
<td>116 ±5</td>
<td>-5 ±2</td>
<td>48 ±2</td>
<td>271</td>
</tr>
<tr>
<td>9</td>
<td>105 ±4</td>
<td>-1 ±1</td>
<td>47 ±2</td>
<td>264</td>
</tr>
<tr>
<td>10</td>
<td>158 ±8</td>
<td>6 ±2</td>
<td>56 ±3</td>
<td>243</td>
</tr>
<tr>
<td>11</td>
<td>148 ±8</td>
<td>4 ±1</td>
<td>59 ±2</td>
<td>218</td>
</tr>
<tr>
<td>12</td>
<td>177 ±10</td>
<td>5 ±2</td>
<td>59 ±2</td>
<td>204</td>
</tr>
<tr>
<td>AVG</td>
<td>143±8</td>
<td>2 ±2</td>
<td>55 ±2</td>
<td>249</td>
</tr>
</tbody>
</table>

$Q_b = \sigma_{SB} \delta T_o^4 (0.39 - 0.05 e_n^{1/2}) (1 - C)^2$

is used to compute net long wave radiation flux. Here $\delta$ is the coefficient of emissivity = 0.98517, $\sigma_{SB}$ is Stefan-Boltzman Constant $5.74 \times 10^{-8}$ J.s⁻¹.m⁻².K⁻⁴, $n$ is the fraction of cloud cover, $C$ is a function of latitude and runs from 0.5 at the equator to 0.82 at 75° latitude, $T_o$ is the absolute sea surface temperature, and $e_n$ is the vapor pressure at the air temperature in mb. The computed values are given in Table 2.

**Incoming short wave radiations**

The incoming short wave radiations under clear sky $Q_s$ in W/m² are estimated¹⁸, nineteen as:

$$Q_s = (A_0 + A_1 \cos \phi + B_1 \sin \phi + A_2 \cos 2\phi + B_2 \sin 2\phi)$$

where $A_0$, $A_1$, $B_1$, $A_2$, and $B_2$ are functions of latitude ($\phi$) and are given as:

$A_0 = -15.82 + 326.87 \cos \phi$

$A_1 = 9.63 + 192.44 \cos (\phi + 90)$

$B_1 = -3.27 + 108.70 \sin \phi$

$A_2 = -0.64 + 7.80 \sin 2(\phi - 45)$

$B_2 = -0.50 + 14.42 \cos 2(\phi - 5)$

and $\phi = (360/365)(t - 21)$ where $t$ is time of the year in days. From the clear sky values $Q_s$, the insolation under cloudy condition is normally calculated as:

$$Q_c = Q_s (1 - C_n n + 0.0019h)$$

$h$ is the noon solar altitude in degrees, $C_n$ is 0.62, and $n$ is the fraction of cloud cover.

It is seen that the equation for calculating insulation under cloud condition is valid for cloud cover of about 0.3 and higher. Under conditions of cloudiness <0.3 a reduction of 5% is suggested¹⁸. Because of the presence of aerosols in the area Da Silva et al.²⁰ suggests a turning parameter of 0.92 on the clear sky radiation and 1.04 on the cloudiness coefficient. Also not all radiations are absorbed at the sea surface and the reflection coefficient $\alpha$ depends on the time of the day. Therefore the absorbed solar radiations $Q_c$ can be computed as:

$$Q_c = 0.92 Q_s (1 - 1.04 C_n n + 0.0019)(1 - \alpha)$$

Ahmad and Sultan²¹ suggest a constant reflection coefficient of 6%. The monthly values of $Q_c$ are given in the Table 2.

**Advective heat transport from Gulf of Arden to Red Sea.**

During the last decade there have been various estimates of the exchange flow at Bab-el-Mendab from direct oceanographic measurements and the indirect air-sea flux data²²-²⁶. Sofianos et al.²⁷ data of inflow/outflow volumes at Bab-el-Mendab Strait with the average salinity and temperature of their volumes is reproduced in Table 3. Based on the in and out flows the heat advected $Q_v$, to the Red Sea is;

$$Q_v = \rho_i V_i C_p (T_i - \rho_o V_o C_p T_o)$$

where the subscript i and o stand for inflow and outflow respectively. $\rho$ is the density, $V$ is the volume, $C_p$ is the specific heat of water, and $T$ is the water temperature. The formula gives the total net advective heat to the Red Sea. Considering the area of the Gulf of Aden as 220,000 km² the monthly advected heat transport to the Red Sea is given in Table 4.

**Upwelled heat**

The upwelled heat along the length of the coast is given as;

$$Q_{upw} = \tau \ell f^{-1} \Delta T C_p$$

$\tau$ is the wind stress, $\ell$ is the length of the coast along which upwelling occurs; Here $\ell = 330$ km, $\Delta T$ is the difference in temperature between the coast and the
width of upwelling. \( \Delta T = 3 \, ^\circ C \), \( C_p \) is specific heat, \( f = 2\Omega \sin\phi \); where \( \phi \) is the latitude (13.5\(^\circ\) N), \( \tau = \rho_a \kappa_a \omega \) (\( \kappa_a \) depends on the wind speed), \( \tau = 0.087 \text{ N.m}^{-2} \) based on wind speed 7 m/sec. Therefore the up-welled heat flux \( Q_{\text{upw}} \) is equal \( 1.0 \times 10^{13} \) W. Cool up-welled waters are brought to the surface and are presumably advected eastward by a wind driven coastal current. However, most of the up-welled water may spread in the Gulf of Aden and become part of the anti-cyclonic eddies. The up-welling considerably suppresses the evaporative heat flux due to the lowering of temperature and affects net back radiations and sensible heat flux as well.

If the up-welled heat of \( 1.0 \times 10^{13} \) W is approximately the same as has been suppressed due to reduced evaporative heat flux, net back radiation flux and sensible heat flux; the under estimation of these terms amounts to \( = 45 \) W/m\(^2\), which comes from \( \left[ \frac{Q_{\text{upw}}}{\text{Area of the Gulf}} \right] \). As up-welling does not occur throughout the year (\( \approx 4 \) months), therefore for comparison with other heat balance terms (annual basis) the suppression in heat amounts to 15 W/m\(^2\).

**Error estimation**

The error estimation in the individual surface heat flux is made according to wear et. al.\(^{28} \)

\[
S = \left( \left( \frac{\partial v}{\partial x} \right)^2 S_x + \left( \frac{\partial v}{\partial y} \right)^2 S_y + \left( \frac{\partial v}{\partial z} \right)^2 S_z \right)^{1/2}
\]

where \( v \) is the dependant variable and are \( x, y, z \) possible independent variables. The uncertainties in the sensible and evaporation heat fluxes and that of net back radiation were estimated from the annual ± averages standard deviations in sea surface temperature, vapor pressure at the air temperature, sea surface and air temperatures differences, differences in atmospheric specific humidity at the surface and near surface, wind speed and bulk transfer coefficients. The computed standard deviations of these parameters are given in Table 2.

**Results and Discussion**

The annual averages of surface heat fluxes at the
air sea interface for the Gulf of Aden are: absorbed short wave radiations 249 W/m²; net back radiation 55 ± 2 W/m²; evaporative heat flux 143 ± 8 W/m² and sensible heat flux 2 ± 2 W/m². Annual average of heat advected to the Red Sea from the Gulf of Aden is 35 W/m². Total upwelled heat of 1.0 × 10¹³ W is equivalent to a suppression of 15 W/m² considering the area of the Gulf and 4 month duration of upwelling during summer. Overall it seems that the surplus of heat based on fluxes at the air-sea interface and the advective heat transport to the Red Sea is 14 W/m² (249-55-143-2-35=14 W/m²). This surplus is of the same order as the suppression of heat (15 W/m²) due to up-welling. Most of the surface fluxes of heat and momentum studies are carried out for the Indian Ocean or the Arabian Sea which include the Gulf of Aden²,³. However, not many studies have been carried out for the Gulf of Aden separately. Yu et al.²⁰, have computed latent and sensible heat fluxes from the global data sets. The values are about 130-140 W/m² for latent heat flux and around zero for sensible heat flux near Gulf of Aden.

Banks et al.³⁰ have shown that sensible heat flux values in the Indian Ocean are generally 5-15 W/m² with lower values occurring in regions with coastal upwelling. Latent heat flux values of 140-180 W/m² are observed in the Arabian Sea. Sultan and Ahmad¹ calculated the heat budget of the Gulf of Aden and showed annual averages of –16, 43 and 52 W/m² respectively for sensible, latent and net back radiation fluxes. Their incoming observed short wave radiations were 192 W/m² which they obtained from a nearby recording station. This gives a heat surplus of 113 W/m². However, their data were from one coastal station only against the present data for 1 degree boxes for the whole Gulf. The present value of 55 ± 2 W/m² for the net back radiation compares favorably well with 52 W/m² value computed by Sultan and Ahmad¹. However, there is a substantial difference between their values of sensible heat flux (~16 W/m²) and latent heat flux (43 W/m²) against the present values of 2 ± 2 W/m²² and 143 ± 8 W/m²². It seems that Sultan and Ahmad¹ under estimated the latent heat flux as the present value compares well with 140 W/m²² by Banks et al.³⁰. The main discrepancy seems to lie in the estimation of absorbed solar radiations of 249 W/m² against their value of 192 W/m² for the Gulf of Aden and a value of 210 W/m² for the nearby southern Red Sea²¹ and 225 W/m² for Port of Sudan¹⁰. This over estimate may be due to the neglect of aerosol (abundantly present in the area such as duststorm) in computing the solar radiation. The computed values of 2 ± 2 W/m²² for the sensible heat flux and 143 ± 8 W/m²² for the latent heat flux compare favorably well with Banks et al.³⁰, Grassl et al.³¹ and Yu et al.³. However, Hastenrath and Lamb³² value of latent heat flux is almost 20% lower.

Overall it seems that the main factors in balancing the heat budget of the Gulf of Aden are; surface heat fluxes; advection of heat at Bab-el-Mandab and the suppression of heat due to up-welling. The exchange of heat with the Arabian Sea may not play a major role in this balance.

The over estimation of the incoming solar radiations seem to be 15%. However, it is very difficult to conclude the over estimation in the absence of recorded stations around the area.

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