Water column conditions in a coastal lagoon near Jeddah, Red Sea

doi:10.5697/oc.54-4.675
OCEANOLOGIA, 54 (4), 2012.
pp. 675–685.

KEYWORDS
Red Sea
Lagoon
Water column

Alaa M. A. Albarakati*
Fazal Ahmad

Faculty of Marine Sciences,
King Abdulaziz University,
Jeddah, Saudi Arabia;

e-mail: aalbarakati@kau.edu.sa

*corresponding author

Received 25 October 2011, revised 14 April 2012, accepted 16 July 2012.

Abstract

Water column conditions in a lagoon near Jeddah are investigated on the basis of changes in potential energy. Three major factors including balance of surface heat at the air-sea interface, wind and tidal mixing are considered. A negative potential energy change $\frac{dv}{dt}$ will develop stratification, whereas positive $\frac{dv}{dt}$ will tend to mix the water column. The tidal effect is greater in summer with wind mixing showing no great variations. The buoyancy effect of the heat balance at the surface is negative from April to October. This negative buoyancy effect will tend to develop stratification but the positive contributions of wind and tide counteract this and the water column remains mixed except in September and October, when a weak stratification may develop. Generally, the water column remains practically mixed throughout the year. The change in heat content of the water column from mid-April to mid-September is about 3.3×10^8 J. During this period the net heat input at the air interface is about 2.0×10^8 J, which is about 40% less than the

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

heat content of the water column, showing that the heat is advected towards the central area from the shallower periphery of the lagoon.

1. Introduction

Water column conditions in coastal lagoons depend on a number of factors, including the balance of surface heat fluxes at the air-sea interface, the contribution of fresh water discharge or runoff, wind stress and tidal mixing (Simpson & Hunter 1974, Simpson & Bowers 1981, Bowers & Simpson 1987, Simpson 1997, Yanagi et al. 2001, Buranapratheprat et al. 2008). Positive surface heat flux and fresh water discharge strengthen the vertical stability, whereas tidal currents and wind stress increase water mixing and turbulence. However, these factors are modified in each area. Therefore, it is necessary to understand the controlling factors and their role in order to know the mechanism of water column stability in the area of interest.

The Red Sea (Figure 1) lies in an arid zone where evaporation is very high > 2 m year^{-1} (Morcos 1970) and precipitation very low. Consequently

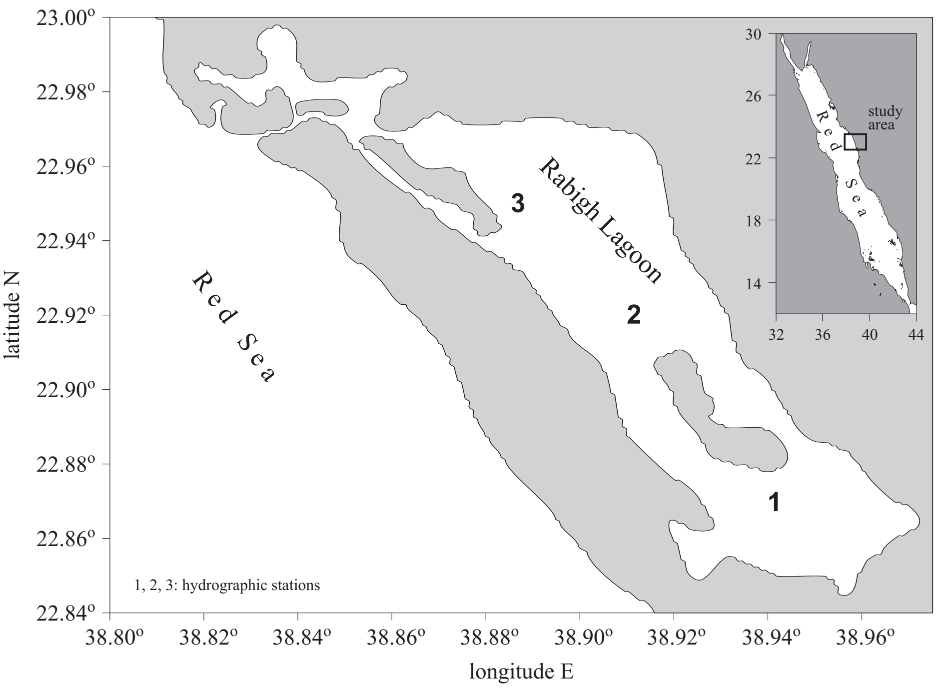

Figure 1. Map of the Red Sea and Rabigh Lagoon

there are no river discharges in the area. Many studies have been carried out regarding the surface heat fluxes in the Red Sea (Bunker 1976, Bunker & Goldsmith 1979, Hastenrath & Lamb 1979, Ahmad & Sultan 1987, 1989, Ahmad et al. 1989, Tragou et al. 1998), most of them referring to the main body of the Red Sea. However, a study by Ahmad et al. (1989) calculated the monthly variations in heat fluxes at the air-sea interface in coastal waters near Jeddah, Red Sea.

The Red Sea possesses an irregular bottom topography. The coastline is bordered by shallow fringing reefs, the edges of which slope gently into lagoons bordered by an offshore barrier reef system (Morley 1975). The basic shape is formed by a wave-built barrier on a gently sloping shoreline and is parallel to the coast. Current velocities in these lagoons are functions of size of the lagoon, its shape, size of the inlet and tidal range etc. Tides are of primary importance, providing periodic exchange. Wind stress plays a sometimes dominant but variable role, depending on the strength of the local tide and the characteristic wind speed (Sultan & Ahmad 1990, Ahmad & Sultan 1992).

The tides in the Red Sea are probably a combination of an independent oscillation of the water within the basin and a forced co-oscillation induced by the tides in the Gulf of Aden (Morcos 1970). The independent oscillations are semidiurnal and of small amplitude. Towards the central part of the Red Sea the tidal range decreases (Edwards & Head 1987); at about 20°N there is a nodal point. Between 19°N and 21°N the tidal currents are weak and variable. However, at the inlets of the coastal lagoons, the tidal currents may be as high as 1 m s^{-1}. But in the main body of the lagoons the currents are weak and vary depending on the spring-neap cycle and the variation in sea level.

The Red Sea level is strongly influenced by the rate of evaporation and balance between in- and outflowing water at Bab-el-Mandab. In winter the inflow exceeds the combined effect of outflow and loss by evaporation in spite of the fact that evaporation is higher in winter, at least in the central Red Sea (Ahmad & Sultan 1989). Consequently, the mean sea level rises over the entire Red Sea in winter. In summer the reverse occurs and mean sea level is lower (Morcos 1970, Ahmad & Sultan 1993, Smeed 2004).

The use of some coastal lagoons as discharge areas for industrial and municipal waste and some others as sea water intakes for desalination purposes in Saudi Arabia makes an assessment of water column stability indispensable. Lying to the north of Jeddah (Figure 1), Rabigh Lagoon is over 17 km long and has an average width of about 4 km. Urban and industrial development has begun to exert an impact upon the lagoon's ecology. The objective of this study is to predict the water column conditions in Rabigh Lagoon. It is generally shallow but in some parts depths may reach about 20 m.

2. Water column potential energy change

The mean rate of change of the potential energy of the water column is applied to evaluate the water column condition, i.e. whether it is stratified or vertically mixed (Simpson & Hunter 1974, Simpson et al. 1978, Simpson & Bowers 1981, Yanagi & Takahashi 1988, Yanagi & Tamaru 1990, Simpson 1997). The potential energy 'v' is relative to the mixed conditions, and positive and negative signs are assigned to the term that increases and decreases water column mixing. The equation is:

$$\frac{dv}{dt} = -\frac{\alpha\, g\, Q\, H}{2c_p} - \frac{\beta\, g\, S\, H\, R}{2A} + \frac{4\epsilon\, K_b\, \rho_w (u_t)^3}{3\pi} + \delta\, K_s\, \gamma\, \rho_a\, w^3\,. \qquad (1)$$

The 1st term is the contribution of the surface heat flux, while the 2nd, 3rd and 4th terms are the respective contributions of fresh water discharge, tidal mixing and wind mixing.

As there are no river discharges in the area, only three factors – the balance of heat fluxes at the air-sea interface, tidal mixing and wind mixing – are considered.

Here,

α is the thermal expansion coefficient, taken to be 3.2×10^{-4} °C^{-1} and $c_p = 3.98$ J g^{-1} °C^{-1} (salinity ≈ 39.5‰ and temperature 28.5°C);

g is 9.8 m s^{-2};

Q is the balance of heat at the air-sea interface in [w m^{-2}];

H is the water depth in [m] (here 20 m);

β is the coefficient of saline contraction;

S is the salinity in [‰];

R is the river discharge in [m^3 s^{-1}];

A is the surface area under river discharge influence in [m^2];

ϵ is the efficiency of conversion from turbulence to potential energy for tidal mixing ≈ 0.015 and is calculated from $\epsilon = \frac{3\pi\, \alpha\, g\, Q}{8\rho\, k'\, c_p}\left(\frac{H}{u^3}\right)$ (Simpson & Hunter 1974, Bowden 1983), where k' is the modified drag coefficient from bottom to surface, and $\log \frac{H}{u^3}$ varies from 2 to 3;

K_b is the bottom drag coefficient $\approx 2.5 \times 10^{-3}$;

ρ_w is the density of sea water ≈ 1026 kg m^{-3};

u$_t$ is the tidal current velocity [m s^{-1}];

δ is the coefficient of conversion of turbulent to potential energy, as wind mixing depends on the wind speed, and is ≈ 0.039 (Buranapratheprat et al. 2008). Bowden (1983) considers that the efficiency of mixing falls as stratification increases, implying that δ will be higher when the stratification starts to develop;

K_s is the surface drag coefficient, $1000K_s = 0.29 + \frac{3.1}{w_{10}} + \frac{7.7}{w_{10}^2}$ (Yelland & Taylor 1996);

γ is the ratio of wind induced current to wind speed $\gamma = \frac{v}{w} = \frac{0.0127}{\sqrt{\sin\varphi}}$;

ρ_a is the density of air ≈ 1.18 kg m^{-3};

w is the wind speed in [m s^{-1}].

Various studies relating to water column conditions have been carried out in different areas. Holloway (1980) considers thermal stratification in a water body subjected to atmospheric heating and wind-induced vertical mixing. Simpson et al. (1990) discuss how buoyancy input as fresh water exerts a stratifying influence in estuaries and adjacent coastal waters. Liu (2007) found that, in the Bohai Sea, stratification comes into existence in April, peaks in July and decays towards October. Buranapratheprat et al. (2008) discuss the water column conditions in the upper Gulf of Thailand based on surface heat flux, river discharge, tidal and wind mixing. They show that stratification develops in May because of surface heating and is dominant in October due to the large river discharge.

3. Data sources and analysis

Monthly variations of the surface heat fluxes are taken from Ahmad et al. (1989) and the results are reproduced in Figure 2 along with the net surface heat flux. Wind speed data (1990–2000) for Jeddah airport are provided by PME (Presidency of Meteorology and Environment) of Saudi Arabia. The monthly averages of wind speed are plotted in Figure 3a. The hydrographic data and the tidal current speeds are from Ahmad et al. (1997). The measured tidal current velocities are also plotted in Figure 3b and the temperature and salinity for the months of April and September 1997 for three stations are shown in Figure 4.

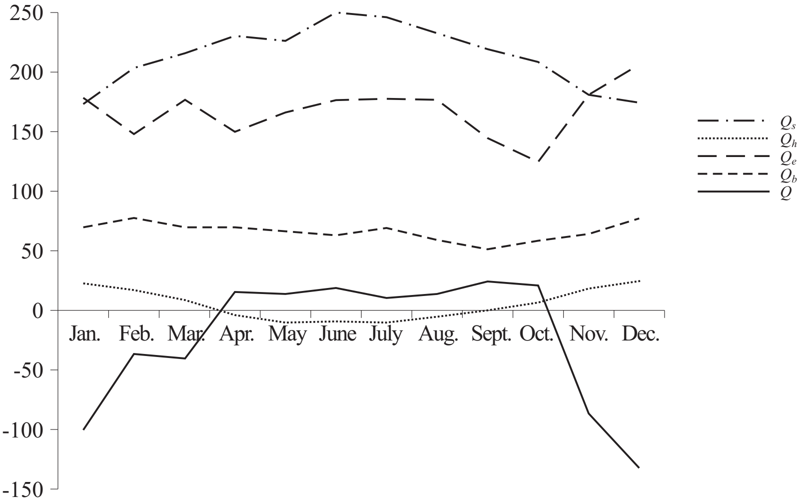

Figure 2. Plots of surface heat fluxes (monthly values) (after Ahmad et al. 1989); Q_s is the solar radiation absorbed at the sea surface, Q_h is the sensible heat flux, Q_e is the evaporative heat flux, Q_b is the net backward radiation and Q is the net surface heat flux

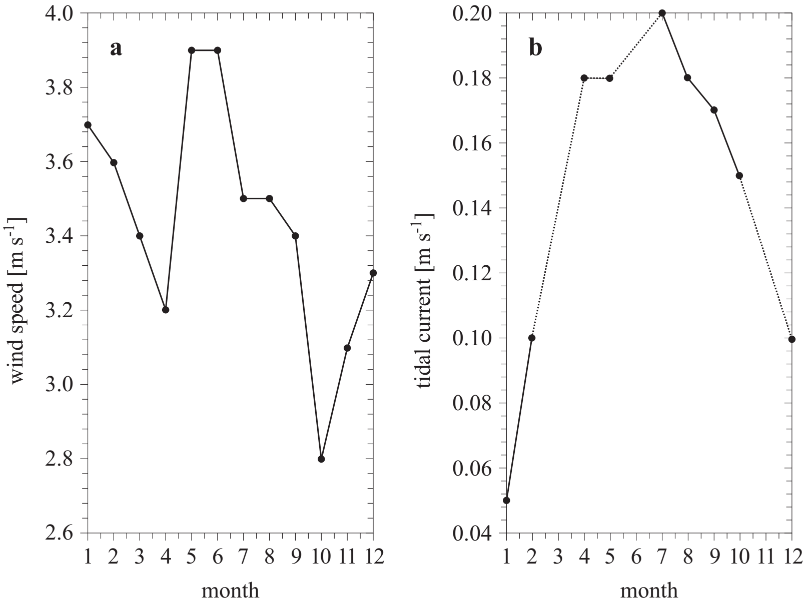

Figure 3. Monthly averages of wind speed (1990–2000) for Jeddah (a), and tidal current velocities (1997) for Rabigh Lagoon (b)

The tidal current velocity in the main body of the lagoon varied from about 0.05 m s^{-1} to about 0.2 m s^{-1} depending on the spring-neap cycle

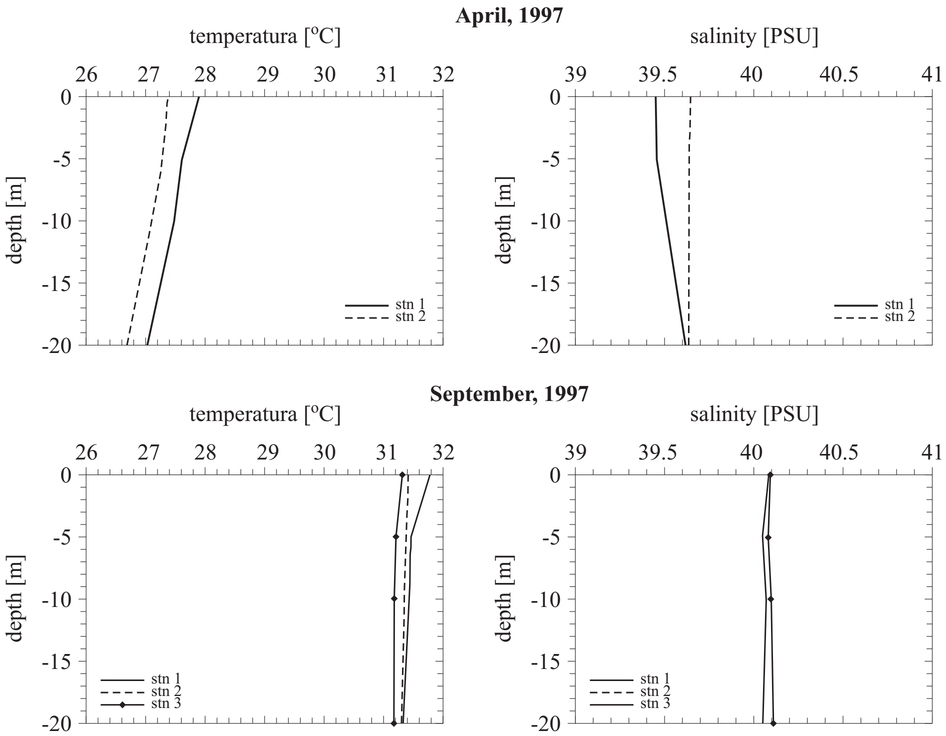

Figure 4. Temperature and salinity profiles at stations, in Rabigh Lagoon

and the seasonal variations of the mean sea level in the Red Sea. The tidal currents at the inlet were faster owing to the narrowness of the entrance.

When the net heat at the air-sea interface $Q < 0$, from November to March (Figure 2), then the potential energy due to the surface heat flux will not contribute to stratification and the water column is mixed. When the heat balance $Q > 0$, surface heating will contribute to stratification and tidal and wind mixing will be opposed, so stratification will depend on their net contribution. The calculations are therefore made for April to October only. The net surface heat flux at the air-sea interface from April to October, as well as the tidal current velocities and the wind speeds for this period are listed in Table 1. Based on this data $\frac{dv}{dt}$ is computed for surface heat flux, tidal and wind mixing terms. The values are given in Table 2 along with the net changes in potential energy.

From the hydrographic data at three stations in the Rabigh Lagoon (Ahmad et al. 1997) the change in the heat content of the water column from mid-April to mid-September was calculated as $\sum_{i=1}^{n} \rho_i \, c_{pi} \, t_i \, dz_i$, where dz is the depth interval. The average change in heat content over 5 months is

Table 1. Net surface heat flux at the air-sea interface, wind speed and tidal current velocities from April to October

Month	Q heat input [w m^{-2}]	Wind speed [m s^{-1}]	Tidal currents [m s^{-1}]
4	16 ± 3	3.2 ± 0.2	0.18
5	13 ± 2	3.9 ± 0.3	0.18
6	19 ± 3	3.9 ± 0.2	–
7	10 ± 2	3.5 ± 0.1	0.20
8	13 ± 2	3.5 ± 0.1	0.18
9	24 ± 3	3.4 ± 0.2	0.17
10	21 ± 4	2.8 ± 0.1	0.15

Table 2. $\frac{dv}{dt}$ [10^{-3} kg s^{-1}] for heat flux, wind and tidal mixing terms and the net $\frac{dv}{dt}$ from April to October

Month	Heat flux	Wind mixing	Tidal effect	Net $\frac{dv}{dt}$
4	-0.126 ± 0.024	0.065 ± 0.027	0.096 ± 0.043	0.035 ± 0.023
5	-0.102 ± 0.016	0.108 ± 0.045	0.096 ± 0.043	0.102 ± 0.066
6	-0.150 ± 0.024	0.116 ± 0.050	–	–
7	-0.079 ± 0.016	0.078 ± 0.034	0.131 ± 0.058	0.130 ± 0.084
8	-0.102 ± 0.016	0.085 ± 0.036	0.096 ± 0.043	0.079 ± 0.050
9	-0.189 ± 0.024	0.072 ± 0.030	0.080 ± 0.0396	-0.037 ± 0.024
10	-0.165 ± 0.032	0.044 ± 0.020	0.055 ± 0.025	-0.066 ± 0.042

3.3×10^8 J. For the same period the heat input at the air-sea interface is 2×10^8 J, which is about 40% less than the change in the heat content of the water column. This indicates that heat is advected to the deeper water from shallow parts of the lagoon.

3.1. Error analysis

In general it is assumed that where the standard deviations of the individual terms are not available, a 20% variation is considered:
$\epsilon = 0.015 \pm 0.003$,
$K_b = 2.5 \times 10^{-3} \pm 0.5 \times 10^{-3}$,
$u_t = 0.2 \pm 0.04$,
$\delta = 0.039 \pm 0.0078$,
$\gamma = 0.0212 \pm 0.00424$,
$K_s = 1.87 \times 10^{-3} \pm 0.374 \times 10^{-3}$.

The uncertainties in the calculated values are due to the choice of the coefficients and to the errors that are inherent in oceanographic and meteorological data. The standard deviations in $\frac{dv}{dt}$ for the heat flux, wind and tidal mixing are determined using an equation of the form (Wear et al. 1981):

$$s = \left[\left(\frac{\partial \gamma}{\partial x} \right)^2 s_x^2 + \left(\frac{\partial \gamma}{\partial y} \right)^2 s_y^2 + \left(\frac{\partial \gamma}{\partial z} \right)^2 s_z^2 \right]^{1/2}, \tag{2}$$

where s is the standard deviation, γ is the dependent variable and x, y, z are independent variables.

4. Results and discussion

Variations in water column conditions are investigated by considering three forcing factors, namely, surface heat flux, wind and tidal mixing. The effect of wind mixing (positive $\frac{dv}{dt}$) changes from 0.044×10^{-3} kg s^{-1} in October to 0.116×10^{-3} kg s^{-1} in June, whereas the contribution of tidal mixing varies from 0.055×10^{-3} kg s^{-1} in October to 0.131 kg s^{-1} in July. The balance of the surface heat flux Q is positive (downwards) from April to October and negative (upwards) from November to March. Surface heating contributes to stratification. Tidal and wind mixing act in opposite directions, so stratification will depend on their net contribution. The $\frac{dv}{dt}$ due to the net surface heat flux at the air-sea interface varies from -0.079×10^{-3} kg s^{-1} in July to -0.189×10^{-3} kg s^{-1} in September. The net $\frac{dv}{dt}$ is positive from April to August, which will not favour stratification of the water column. However, in September–October $\frac{dv}{dt}$ is somewhat negative, which may favour a slight stratification. In general it seems that the water column will remain almost mixed throughout the year.

The change in heat content, 3.3×10^8 J, of the water column from mid-April to mid-September is about 40% higher than the heat input, of 2.0×10^8 J, at the air-sea interface for the corresponding period. This shows that the heat energy from the shallower parts of the lagoon is advected to the deeper parts.

Acknowledgements

We are grateful to the Presidency of Meteorology and Environment (PME), Saudi Arabia, for providing the wind data.

References

Ahmad F., Sultan S. A. R., 1987, *On the heat balance terms in the central region of the Red Sea*, Deep-Sea Res., 34 (10), 1757–1760, http://dx.doi.org/10.1016/0198-0149(87)90023-9.

Ahmad F., Sultan S. A. R., 1989, *Surface heat fluxes and their comparison with the oceanic heat flow in the Red Sea*, Oceanol. Acta, 12 (1), 33–36.

Ahmad F., Sultan S. A. R., 1992, *The effect of meteorological forcing on the flushing of Shuaiba Lagoon on the eastern coast of the Red Sea*, J.K.A.U.: Marine Sci., 3 (1), 3–9, http://dx.doi.org/10.4197/mar.3-1.1.

Ahmad F., Sultan S. A. R., 1993, *Tidal and sea level changes at Jeddah, Red Sea*, Pakistan J. Marine Sci., 2 (2), 77–84.

Ahmad F., Sultan S. A. R., Abdelrahman S. M., 1997, *Flushing time scale, effect of meteorological forcing and hydrographic variation in two coastal lagoons of the central Red Sea*, Report project, 065/1415, Scientific Council, KAAU, Jeddah, Saudi Arabia.

Ahmad F., Sultan S. A. R., Moammar M. O., 1989, *Monthly variations of net heat flux of the air-sea interface in the coastal waters near Jeddah, Red Sea*, Atmosphere-Ocean, 27 (2), 406–413, http://dx.doi.org/10.1080/07055900.1989.9649343.

Bowden K. F., 1983, *Physical oceanography of coastal waters*, E. Horwood Ltd., Chichester, 302 pp.

Bowers D. G., Simpson J. H., 1987, *Mean position of tidal fronts in European shelf seas*, Cont. Shelf Res., 7 (1), 35–44, http://dx.doi.org/10.1016/0278-4343(87)90062-8.

Bunker A. F., 1976, *Computation of surface energy flux and annual air-sea interaction cycles of North Atlantic Ocean*, Mon. Weather Rev., 104 (9), 1122–1140, http://dx.doi.org/10.1175/1520-0493(1976)104<1122:COSEFA>2.0.CO;2.

Bunker A. F., Goldsmith R. A., 1979, *Archived time series of Atlantic Ocean meteorological variables and surface fluxes*, WHOI Tech. Rept. WHOI-79-3, 54 pp.

Butanapratheprat A., Yanagi T., Matsumura S., 2008, *Seasonal variation in water column conditions in the upper Gulf of Thailand*, Cont. Shelf Res., 28 (17), 2509–2522, http://dx.doi.org/10.1016/j.csr.2008.07.006.

Edwards A. J., Head S. M., 1987, *Red Sea*, Pergamon Press, 441 pp.

Hastenrath S., Lamb P. J., 1979, *Heat budget atlas of the tropical Atlantic and eastern Pacific Oceans*, Univ. Wisconsin Press, Madison, 104 pp.

Holloway P. E., 1980, *A criterion for thermal stratification in a wind mixed system*, J. Phys. Oceanogr., 10 (6), 861–869.

Liu H., 2007, *Annual cycle of stratification and tidal fronts in the Bohai Sea: A model study*, J. Oceanogr., 63 (1), 67–75, http://dx.doi.org/10.1007/s10872-007-0006-9.

Morcos S. A., 1970, *Physical and chemical oceanography of the Red Sea*, Oceanogr. Mar. Biol., 8, 73–202.

Morley N. J. F., 1975, *The coastal waters of the Red Sea*, Bull. Mar. Res. Centre, 5, 1–19.

Simpson J. H., 1997, *Physical processes in the ROFI regime*, J. Marine Syst., 12 (1–4), 3–15, http://dx.doi.org/10.1016/S0924-7963(96)00085-1.

Simpson J. H., Allen C. M., Morris N. C. G., 1978, *Fronts on the continental shelf*, J. Geophys. Res.-Oceans, 83 (C9), 4607–4614, http://dx.doi.org/10.1029/JC083iC09p04607.

Simpson J. H., Bowers D. G., 1981, *Models of stratification and frontal movements in shelf seas*, Deep-Sea Res., 28 (7), 727–738, http://dx.doi.org/10.1016/0198-0149(81)90132-1.

Simpson J. H., Brown J., Matthews J., Allen G., 1990, *Tidal straining, density currents and mixing in the control of estuarine stratification*, Estuar. Coast., 13 (2), 125–132, http://dx.doi.org/10.2307/1351581.

Simpson J. H., Hunter J. R., 1974, *Fronts in the Irish Sea*, Nature, 250, 404–406, http://dx.doi.org/10.1038/250404a0.

Smeed D. A., 2004, *Exchange through the Bab-el-Mandab*, Deep-Sea Res., 1 (49), 1551–1569.

Sultan S. A. R., Ahmad F., 1990, *Flushing of a costal lagoon in the Red Sea*, Estuar. Coast. Shelf Sci., 31 (3), 345–349, http://dx.doi.org/10.1016/0272-7714(90)90108-4.

Tragou E., Garrett C., Outerbridge R., Gilman C., 1998, *The heat and fresh water budgets of the Red Sea*, J. Phys. Oceanogr., 29 (10), 2504–2522, http://dx.doi.org/10.1175/1520-0485(1999)029<2504:THAFBO>2.0.CO;2.

Weare B. C., Strub P. T., Samuel M. D., 1981, *Annual mean surface heat fluxes in the tropical Pacific Ocean*, J. Phys. Oceanogr., 11 (5), 705–717, http://dx.doi.org/10.1175/1520-0485(1981)011<0705:AMSHFI>2.0.CO;2.

Yanagi T., Takahashi S., 1988, *A tidal front influenced by river discharge*, Dynam. Atmos. Oceans, 12 (2), 191–206, http://dx.doi.org/10.1016/0377-0265(88)90025-5.

Yanagi T., Tamaru H., 1990, *Temporal and spatial variables in a tidal front*, Cont. Shelf Res., 10 (7), 615–627, http://dx.doi.org/10.1016/0278-4343(90)90041-J.

Yanagi T., Sachoemar S. I., Takao T., Fujiwara S., 2001, *Seasonal variation of stratification in the Gulf of Thailand*, J. Oceanogr., 57 (4), 461–470.

Yelland M., Taylor P. K., 1996, *Wind stress measurements from the open ocean*, J. Phys. Oceanogr., 26 (4), 541–558.