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Thermal structure in coastal waters of central Bushehr (Iran/Persian Gulf)

Seyed Ali Azarmsa*
Faculty of Marine Sciences, Tarbiat Modares University, Gisha Bridge, P. O. Box: 14115-111, Tehran, I.R. Iran
*[E-mail: azarmsaa@modares.ac.ir]

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Thermal structure was studied in the northern coastal part of the Persian Gulf in Iranian southern province of Bushehr. Temperature measurements revealed that the morning–afternoon temperature variations were in the range of 0.2 – 4°C at deeper layers and 0.2 – 1.7°C near the sea surface. The range of the morning–afternoon temperature variations was also time dependent and reduced from a maximum value of 4°C in August to its minimum value of 0.2°C in November. Monthly average of the seawater temperature decreased about 7.4°C in the temperature decreasing period of August to November; with the maximum thermal gradient of about 3.8°C / month occurred in transition from October to November. Cross shore distribution of the sea surface temperature was almost constant. Moreover, both the maximum (36.8°C observed in August) and minimum (26.5°C observed in November) water temperatures were recorded at the surface layer, indicating that the temperature field in the study area is mainly affected by the air-sea heat fluxes. Water column was not thermally stratified at shallow waters (h < 24 m). In November, intense heat losses at the air–sea interface cause the water column become well mixed in the study area and thus, thermal stratification disappeared even at deeper waters.

[**Key words:** Temperature, thermal stratification, mixing, Bushehr, Persian Gulf, Iran]

Introduction

Temperature is a key oceanographic parameter. In most of oceanographic studies conducted in the Persian Gulf, however, it has been poorly recorded in northern coastal waters, including the Bushehr coastal area, and especially during September-November period[1-5]. A comprehensive CTD sampling carried out during the *Mt Mitchell* surveys in winter (late February-early March) and spring (late May-early June) of 1992. The collected data covered some regions of the Persian Gulf that were poorly sampled by other expeditions, including the Strait of Hormuz and the shallow southern banks[2-4]. Follow-up CTD surveys were done in April of 1994 and March-April of 1996, but the area investigated by these cruises is not as wide as that covered by the *Mt Mitchell.* In other studies, data included CTDs obtained mainly along a deep axial basin extended from the Oman Sea to Tigris-Euphrates-Karun River delta off Iraq[1]. Therefore, thermal structure has not been properly investigated at shallow northern banks, including the Bushehr coastal area. The distribution of recorded data as a function of seasons also indicates few data in summer, almost no data in autumn, and a bias towards winter and spring.

The objective of this research is to study morning to afternoon, daily and monthly variations of seawater temperature and thermal stratification in the central Bushehr coastal waters at the northern part of the Persian Gulf (Fig. 1) during the temperature decreasing period of August-November. Therefore, the results of this research not only are useful in developing our understanding of the oceanography of the Bushehr coastal area, but also can be used as a complementary set for other results to have a better investigation on temporal and spatial variation of temperature in the whole Persian Gulf. Moreover, temperature plays a key environmental,

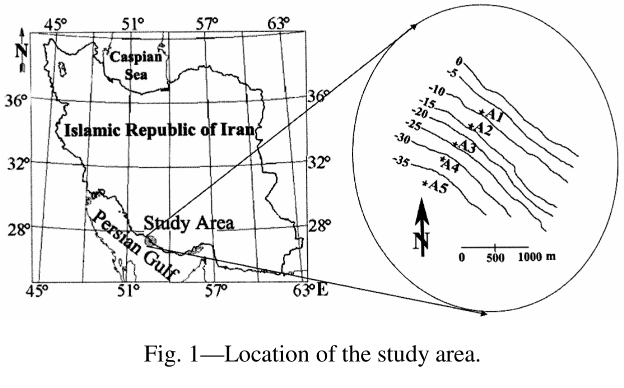

Fig. 1—Location of the study area.

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*Phone: ++98-122-6253101
Fax: ++98-122-6253499

morphological and ecological role within the Bushehr coastal area. Information on the temperature range is even important in determining the range of fauna and flora[6-8]. Temperature is also a critical parameter in designing cooling water systems used in the huge industries developed along the Bushehr coasts. Therefore, investigation of temperature, its structure and variability in the study area during the temperature decreasing period of August-November is quite requisite and useful.

Material and Methods

Bushehr coastal area is located at the northern coastlines of the Persian Gulf (Fig. 1); the shallow marginal part of the Indian Ocean. The atmospheric forcing plays an essential role in driving the circulation and maintaining the water properties in the Bushehr coastal area. It has a hot and humid climate. The evaporation rate in the Bushehr coastal area is pretty high[1,9]. It is next to desert land masses and is subjected to dry winds that intensify evaporation from the water. The winds are predominantly northerly or northwesterly throughout the year[10]. The summer winds are mild and continuous. In contrast, the winds in winter often associate with synoptic weather systems. They usually break out suddenly and violently[2,11]. Wind speed ranges from 0 to 10 m/s as alternating sea and land breezes. The lower wind speeds usually occur at about midnight and the higher ones occur at around noon[10,12]. In the Bushehr coastal area, mean tidal range[13] is about 2 m. Moreover, the significant wave height (Hs) varies from 0.1 to 1.8 m throughout the year, and the mean zero-up crossing period (Tz) is in the range of 3.56 to 4.95 s[12,14]. The mean air temperature in summer is 50° C and in winter 6°C. During hot seasons, the sea surface temperatures (SSTs) of the Persian Gulf are high, and a huge thermal trough system is usually dominant over the region[15]. The summer SSTs of the Persian Gulf are known to be the highest in the world[16].

Temperature measurements were conducted from 6 Aug. to 6 Dec. 2001, to cover the seawater temperature. Sampling times were chosen to be twice a day, with the intention of highlighting morning to afternoon and daily variations and relating them with air temperature and wind velocity variations in the temperature decreasing period (August-November), rather than performing weekly or biweekly measurements and investigating average monthly and seasonal variations. Time schedule and number of measurements carried out from morning to afternoon is presented in Table 1. Measurements were not taken during rough sea conditions.

Measurements of water temperature were made in the study area along one transect, at five stations A1 to A5 positioned from the shoreline to an approximate water depth of 40 m (at about 1730 m from the coastline), and at different depths. In this way, characteristics of water temperature in both shallow and deep waters could be studied and

Table 1—Number of measurements carried out from morning to afternoon in Aug.-Dec. 2001. R: Rough sea conditions.

Date	Months				
	Aug.	Sept.	Oct.	Nov.	Dec.
1	—	R	2	R	2
2	—	R	R	R	2
3	—	2	R	R	2
4	—	2	2	2	2
5	—	2	2	2	2
6	2	R	2	2	2
7	2	R	1	R	—
8	3	2	1	2	—
9	2	R	R	R	—
10	2	2	2	R	—
11	2	3	1	2	—
12	2	2	2	1	—
13	2	3	2	R	—
14	2	2	2	R	—
15	2	2	2	R	—
16	2	2	2	R	—
17	2	3	2	2	—
18	2	1	2	R	—
19	2	1	2	R	—
20	2	2	1	R	—
21	2	2	R	2	—
22	2	2	1	2	—
23	2	1	2	2	—
24	2	1	2	1	—
25	2	2	2	R	—
26	2	2	1	2	—
27	3	2	1	2	—
28	2	2	1	2	—
29	2	2	2	1	—
30	2	R	2	2	—
31	2		1		—

compared. The number of measuring points was determined according to the total water depth at each station. The measurements were carried out on-aboard a fishing vessel. A Magellan 3000, Global Positioning System (GPS) was used for locating stations. A Valeport direct reading current meter (Model 108 Mk III) equipped with temperature and conductivity sensors and was used during the measurements. Water temperature was measured with an accuracy of ±0.1°C.

To investigate the influences of air temperature and wind velocity on water temperature, a Skye's MiniMet meteorological station was mounted close to the shoreline at (52° 32' 35" E, 27° 33' 25" N) and meteorological data were measured at an altitude of 10 m every 30 minuets during the measurement period. Daily averages of these parameters were used to observe their changing trends from August to November.

Results

Temperature time series

Time series of water temperature at various stations and depths was derived based on the data recorded in the morning and afternoon of each day during the measurement period (Fig. 2). The morning–afternoon temperature variations were in the range of 0.2° – 4°C at deeper layers and 0.2° – 1.7 °C near the sea surface. The range of the morning–afternoon temperature variations was also time dependent and reduced from a maximum value of 4°C in August to its minimum value of 0.2°C in November.

Seawater temperature decreased from 36.8°C in August to 26.5°C (approximately) in November, resulting in a total decrease of ΔT = 10.3°C. It is notable that both the maximum (36.8°C) and minimum (26.5°C) temperatures were recorded at the surface layer at shallow station A1 in the afternoon of August 15 and morning of November 30, respectively (Fig. 2a). This reveals that water temperature in the study area is intensively influenced by atmospheric conditions. Temperature variations with depth are negligible at shallow water stations A1 to A3 (Figs. 2a-2c) . At deep water stations A4 and A5 (Figs. 2d and 2e), however, temperature variations with depth were observed in the range of 8 – 1°C from August till November. The decreasing rate of water temperature intensified in November at all stations and depths (Fig. 2). Moreover, temperature variations with depth became negligible even at deep water stations A4 and A5. The reason can be related to the loss of heat from the sea surface in November. Sea water temperature remained nearly constant during 1-6 December 2001.

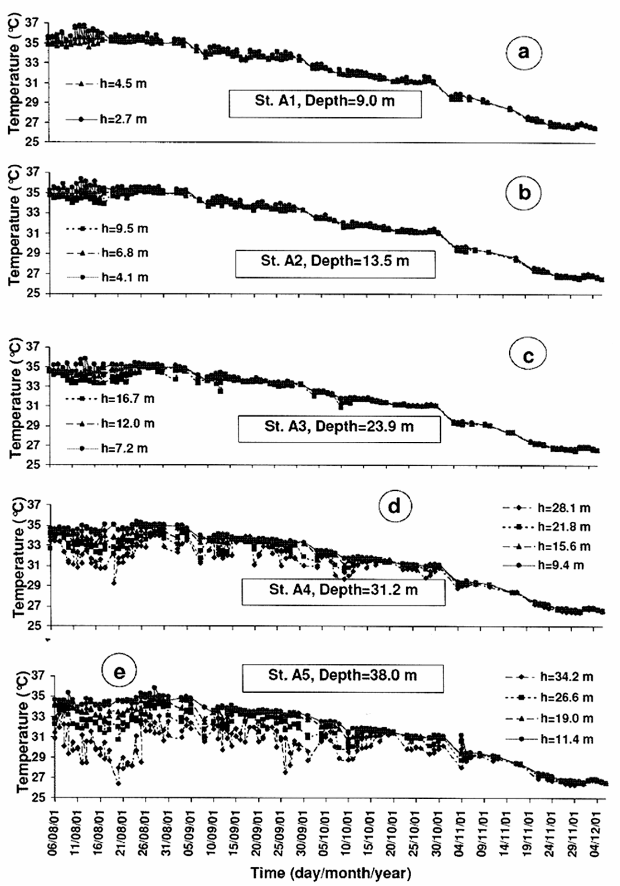

Fig. 2—Time series of the observed temperature at different stations (a-e) and depths

Variation of temperature along the transect

Results reveal that in most of the cases, gradient of temperature was low in cross shore direction. However, differences are noticed in the temperatures at different depths. In general, two patterns are distinguished for thermal structure of water column (Fig. 3). Investigations reveal that these patterns were developed under two different weather conditions as follows:

Figure 3a-c depict the characteristic situation for conditions following a period of warm weather ($T >$ 27°C, where T is the water temperature) and low wind speeds ($U < 4.5$ m/s, where U is the wind speed) (Fig. 4). Thermal stratification resulting in significant

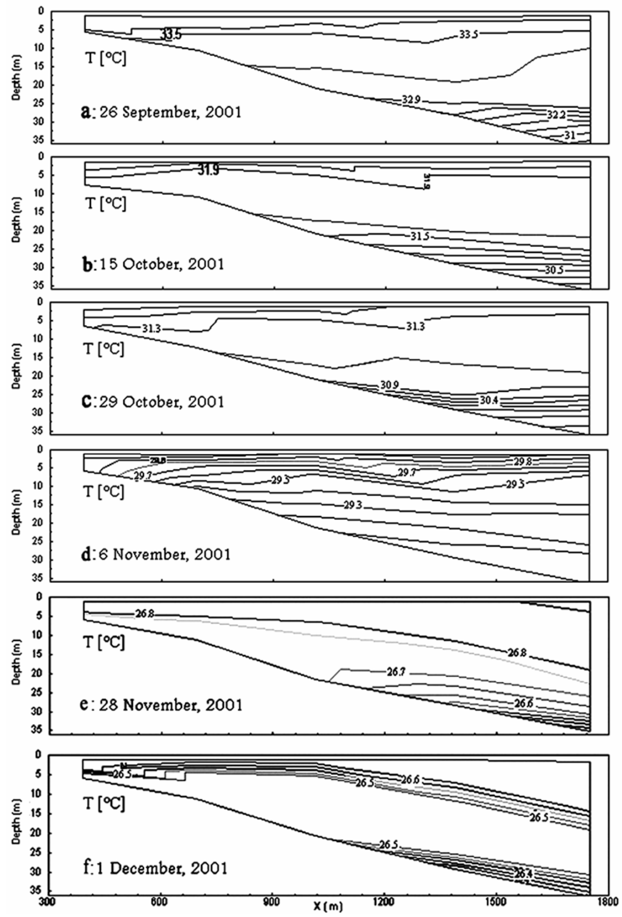

Fig. 3—Longitudinal distributions of water temperature in warm and calm (a, b, c) and cold and windy (d, e, f) conditions, typical samples

temperature differences between surface and near seabed water layers can be observed. Under such conditions, thermal structure of water column is characterized by significant temperature gradient maintained in the upper boundary region (between the sea surface and the depth of 10 m) and also in the lower boundary region (between the depth of 25 m and the seabed at about 40 m depth), and weaker temperature gradient in between these two regions. In contrast, Fig. 3 d-f show the characteristic thermal structure for conditions following a period of relatively colder weather (T < 27°C) and moderate to strong winds (U ≥ 4.5 m/s) (Fig. 4), that homogenize the temperature in the water column and make it thermally mixed. Under strong winds, upwelling may also occur in the study area. As typical samples, pattern of temperature contours in Figs 3e and f depict occurrence of upwelling during 28 November and 1 December, 2001.

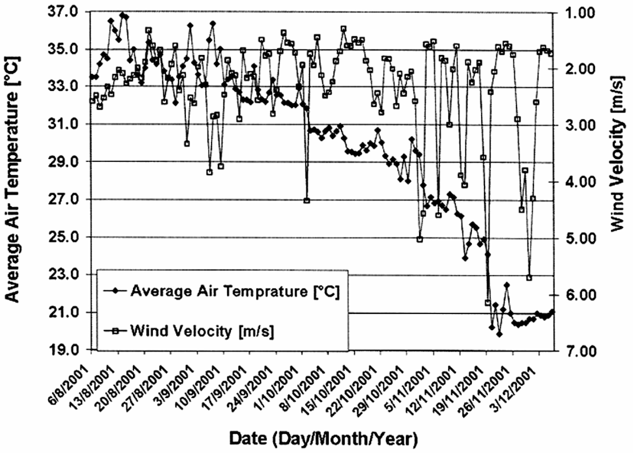

Fig. 4—Daily variations of average air temperature and wind velocity during measuring period.

Discussion

Morning-afternoon variations

At shallow water stations A1–A3 (Figs. 2a-c), the morning–afternoon temperature variations were observed till late August when the radiation inputs may well be more than the latent heat loss and the sensible heat flux. The range of these variations was quickly damped with time so that from October to early December when air temperature decreases, winds become stronger (Fig. 4) and thus heat loss from the sea surface increases in the study area, such variations were rarely observed. The range of the morning–afternoon temperature variations was not considerably changed with depth at shallow water stations A1–A3, because the water column was thermally mixed at these stations and the influence of the temperature rise in the afternoon could reach the shallow sub-layers, too.

At deeper stations A4 and A5 (Fig. 2 d and e), the range of the morning–afternoon temperature variations depends on both the time and depth. From August to October when the weather was hot or warm, winds were light or absent (Fig. 4), and water column was thermally stratified (Fig. 2 d and e), the morning–afternoon temperature variations were depth dependent so that the range of these variations near the seabed was interestingly greater than that observed near the sea surface. Under such conditions, radiation inputs to the sea surface may well be balanced by the latent heat loss and a vertical heat flux toward the deeper and cooler layers. The later increases the range of the morning–afternoon temperature variations near the bottom levels at the expense of decreasing its value at the surface level. The temperature variations near the bottom levels may also be strengthened and amplified by the internal waves at diurnal periods [17-22]. In November when weather was colder, winds were stronger (Fig. 4), and the water column was thermally mixed (Fig. 2d and e), depth dependency of the morning–afternoon temperature variations was removed and the range of these variations reduced to its minimum (0.2°C). It can be generally concluded that the occurrence of morning-afternoon warming is mainly governed by the wind and air temperature variability and for this reason; the significant morning-afternoon warming observed in the study area corresponds to the overheating of the sea surface during calm and hot afternoons.

Monthly variations of sea surface temperature

Table 2 shows the monthly average values of the sea surface temperature, MASST, at different stations during the measurement period. The MASST decreased from shallower waters at the site A1 toward offshore at the site A5 in August (0.9°C), September (0.3°C) and October (0.2°C), but MASST values were almost constant along transect in November and also in measured period in December. Besides, MASST decreased about 7.4°C (in average) from August to November; with the maximum thermal gradient of about 3.8°C / month occurred in transition from October to November.

In general, Table 2 reveals that cross shore advection of thermal energy is negligible and SST is in a localized equilibrium. This confirms the situation often expected and considered for shallow seas at mid-latitudes[23].

Thermal stratification

At station A1 (Fig. 2a), a considerable difference was not observed between the temperatures recorded at different depths during the measurement period. In September, October, November and early December, this difference was practically zero, but it was a little larger in the order of 0.5 ~ 1°C in the beginning of August. Similar situations were observed at stations A2 and A3 (Figs 2b and c). Only at station A3, temperature slightly changed (about 1°C to 2°C) with depth in the middle of August. Therefore, it can be concluded that water column was not thermally stratified at stations A1-A3 during the measurement period.

Table 2—Monthly averages of the sea surface Temperature in°C at each station

	A1	A2	A3	A4	A5
August	35.5	35.3	35.0	34.7	34.6
September	34.1	34.1	33.9	33.8	33.8
October	31.9	31.8	31.7	31.7	31.7
November	28.1	28.1	28.0	28.0	28.0
December	26.7	26.7	26.7	26.7	26.7
Grand Average	32.6	32.5	32.3	32.2	32.2

By contrast, at stations A4 and A5 (Fig 2 d and e), where depth was more than 30 m, variation of temperature with depth was often noticeable. Nevertheless, temperature time histories obey a similar pattern at different layers of water column. In fact, the warm weather and low wind speed conditions observed in the Bushehr coastal area, and also in other places in the Persian Gulf, cause the sea surface temperature to be more than water temperature at deeper layers in August, September and October. Therefore, thermal stratification intensifies as the water depth increases. As weather become colder and winds become stronger ($U \geq 4.5$ m/s) in November (Fig. 4), however, intense heat losses from the sea surface result in considerable decrease in the sea surface temperature (Fig. 2a-e). Consequently, the temperature difference between the shallow and deep layers decreases, and thermal stratification in water column weakens or disappears even at stations A4 and A5. Lack of stratification in the northern Arabian Sea during late fall and winter months was also reported in the literature[24-27].

The results of this study make clear that the thermal structure in the study area is sensitive to the atmospheric conditions. It was shown that the combination of wind speed and air temperature has a significant effect on water temperature and thermal stratification in Bushehr coastal waters. In general, it can be concluded that in the Bushehr coastal area, and in other coastal areas in the Persian Gulf subjected to similar atmospheric conditions, shallow waters ($h<24$ m) are thermally mixed from middle of August to November, and deep waters ($h>30$ m) are stratified in August–October period and mixed in November.

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