Seasonal cycles of temperature, salinity and water masses of the Western Arabian Gulf

Temperature
Salinity
Water masses
Saudi Arabian coast
Arabian Gulf

Température
Salinité
Masses d'eau
Côte d'Arabie Saoudite
Golfe Arabique

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ABSTRACT

Temperature and salinity were measured from May 1985 to April 1988 at fifteen locations in the Western Arabian Gulf. High temperatures, excessive evaporation, and limited mixing and transport with Western Arabian Gulf waters result in hypersaline conditions in the Gulf of Salwah, in the southernmost sector of the study area. Salinities in the Gulf of Salwah were among the highest that have been measured in marine waters. Surface salinities reached 57.7, during winter and bottom salinities were as high as 59.2 during summer. The highest salinities occurred in this area during summer months when nearshore evaporation was at its maximum.

Offshore salinities north of the Gulf of Salwah generally varied from 38-45. High-salinity bottom water masses from the Gulf of Salwah could be traced during summer as far as Ras Tanura, about 92 km north of the entrance to the Gulf of Salwah. Surface salinities at stations further north along the Saudi Arabian coast were as low as 37.9 during spring months when southeastward currents and strong northwest winds bring low-salinity water from the northern gulf.

The highest surface temperature in the Gulf of Salwah waters was 34.9°C during the summer of 1985. However, the highest surface temperature 35.5°C occurred further north, near Abu Ali island during the same season. The lowest surface temperature (15.9°C) occurred in the Gulf of Salwah during the winter of 1988, while the lowest surface temperature reached 17.5°C in the northern part of the study area.

The thermocline and pycnocline are poorly developed in most areas of the western Arabian Gulf except in the area immediately north of the entrance to the Gulf of Salwah. Here, a strong pycnocline occurs due to the northward movement of highly saline Gulf of Salwah bottom water into the open gulf. Otherwise, stratification is absent in the western gulf; this is due to shallow depths, high and persistent winds, moderate waves, and strong currents which rapidly destabilize any density gradient.

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RÉSUMÉ

Cycles saisonniers de température, salinité et masses d'eau dans l'ouest du Golfe Arabique

La température et la salinité ont été mesurées de mai 1985 à avril 1988 en quinze stations, dans l'ouest du Golfe Arabique. Des températures élevées, une forte évaporation et les échanges limités avec les eaux du Golfe Arabique, créent des conditions hypersalines dans le secteur le plus méridional de la région étudiée, le Golfe de Salwah : 57,7 pour les eaux superficielles en hiver et 59,2 pour les eaux de fond en été. Les salinités les plus fortes sont observées en été, lorsque l'évaporation est maximale, à proximité de la côte.

Au large, au nord du Golfe de Salwah, les salinités varient généralement entre 38 et 45. En été, les masses d'eau de fond très salées du Golfe de Salwah peuvent être suivies vers le Nord jusque vers Ras Tanura, à 92 km de l'entrée du Golfe de Salwah. Plus au Nord, le long de la côte saoudienne, les salinités superficielles descendent jusqu'à 37,9 au printemps, lorsque de l'eau peu salée arrive du nord du golfe sous l'effet des courants et des vents forts.

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La température superficielle atteint 34,9°C dans le Golfe de Salwah durant l'été 1985. Cependant, la valeur maximale est enregistrée plus au Nord, vers l'île Abu Ali, pendant la même saison. La température superficielle minimale de 15,9°C est observée dans le Golfe de Salwah au cours de l'hiver 1988, tandis que dans le nord de la région étudiée elle est de 17,5°C.
La thermocline et la pycnocline sont peu développées dans la plupart des zones occidentales du Golfe Arabique, à cause des faibles profondeurs, des vents forts permanents, de la houle modérée et des courants forts, qui effacent rapidement les gradients de densité. En revanche, au voisinage immédiat de l'entrée nord du Golfe de Salwah, un fort gradient de densité est créé par l'eau de fond très salée en mouvement vers le Nord, en direction du Golfe Arabique.

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INTRODUCTION

The Arabian Gulf is of interest to ocean scientists and engineers due to its high annual temperature variations and high salinities. However, only limited temperature and salinity data were available on the western Arabian Gulf until the present study was undertaken in 1985. A previous study of temperatures and salinities in open gulf waters (Emery, 1956) showed nearly uniform summer surface temperatures throughout the gulf of around 32.2°C with a general decrease in temperature to about 23.9°C in the Arabian Sea. Salinities generally ranged from 38-42 in open waters, but have been known to reach as high as 70 in embayments at the southernmost part of the Gulf of Salwah (Purser and Siebold, 1973; Basson *et al.*, 1977). A study by Schott (1918) showed that salinity in winter was slightly higher than in summer. Observations of temperature, salinity and chemical properties in the entire gulf for the month of February and March of 1977 were made by Brewer *et al.* (1978). Some nearshore salinity measurements in the Gulf of Salwah off the Qatar coast (Beltagy, 1980) showed salinities increasing from 53 off Dukhan to 58 off Abu Sanura, the southernmost station in the Gulf of Salwah. Hypersaline waters were also found in the Dowhat As Sayh lagoon, Arabian Gulf, where salinities in its outer part ranged from 53-56 and from 54-70 in its inner part during 1974-1975 (Jones *et al.*, 1978). El Samra (1988) found salinities ranging up to 43 in open waters off the western and southern Gulf coasts. By reviewing previous studies, Hunter (1984) concluded that horizontal density variations were roughly the same in both winter and summer off the Saudi Arabian coast, but rather smaller in summer in the southeastern Arabian Gulf. The results of Hunter's (1984) study indicated high evaporation rates and consequent high salinities and densities in the shallow waters of the southwest and south coasts of the Gulf.

The conclusions proposed in these previous studies were based on limited data measured over short periods of time. This paper describes the first comprehensive study of the seasonal variations of temperature, salinity and water masses along the entire Saudi Gulf coastline.

STUDY AREA

The Arabian Gulf is very shallow, with an average depth of 35 m, and rarely exceeding 100 m. Coastal and nearshore oceanographic processes in the Arabian Gulf are complex, with significant temporal and spatial variations.

The offshore water depths of the western gulf from Safaniya to Salwah are generally less than 35 m, and the sea bottom is generally sandy. Depths in nearshore waters up to 50 km offshore rarely exceed 25 m and increase very gradually with distance from shoreline.

Winds in the western gulf blow predominantly from a north-northwesterly direction. In June and early July, high-speed northerly winds known as "Shamal" are common (Williams, 1979; Perrone, 1979). During Shamal, wind speeds range from 40-50 km/hh with gusts up to 100 km/h. October and November are transitional months during which temperatures start to drop and relative humidity rises. Winter storms begin to affect this area in November and occasionally create southeast or south winds followed by northwesterly winds. February is usually the windiest month, and December and January are the coldest. During spring (March and April), storms are less frequent; strong thunderstorms may however, occur. Summer lasts from May to September, the hottest months being June through August.

METHODS

Temperature and salinity were measured on 24 cruises over a three-year period from May 1985 to April 1988. Measurements were made at fifteen stations along the Saudi Arabian coast, from the southern Gulf of Salwah to Safaniya near the Kuwait border. The survey stations were arranged along five transects, four perpendicular to the shoreline at the Manifa, Ras Al Ghar, Jubail, and Ras Tanura areas, and one parallel to the shoreline in the Gulf of Salwah (Fig. 1). Stations were established using satellite navigation techniques, and an echo sounder was used to verify appropriate (5, 10 or 20 m) depths. These instruments were also used to relocate the stations during each site visit.

The number of visits to stations north of the Gulf of Salwah ranged from 5 to 10 and were distributed over all seasons. Sampling was more intensive in the Gulf of Salwah (stations 13 to 15), where 10 to 15 sampling visits were made. Sampling during site visits was done

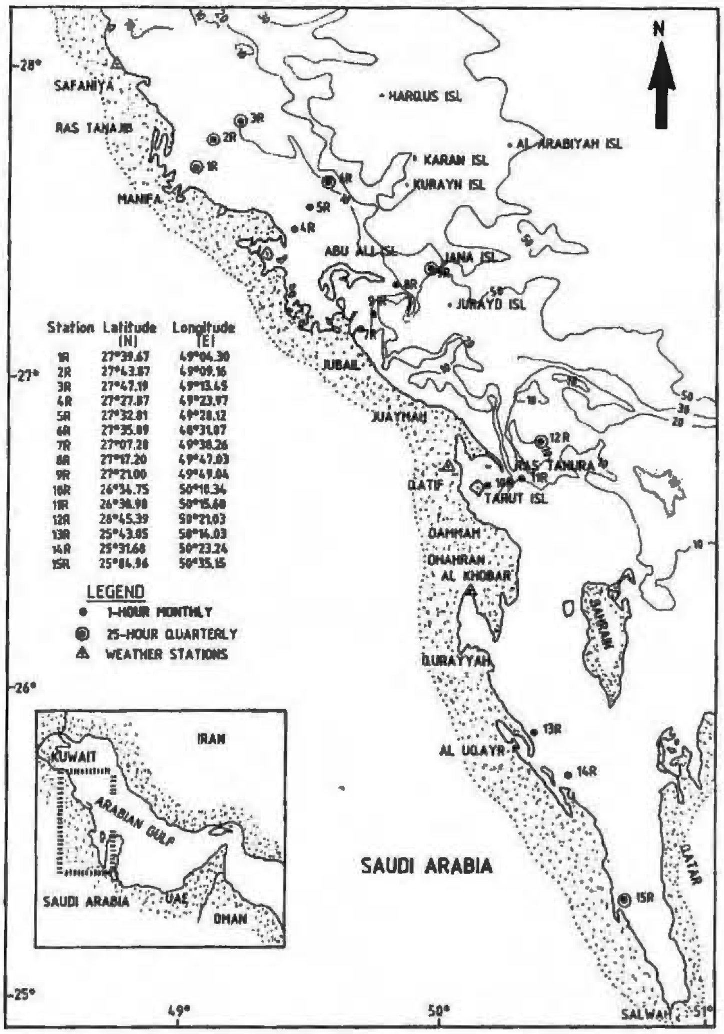

Figure 1
Location map of cruise stations.

either on a single sample basis or hourly over a 24-hour period.

Temperature and salinity were measured using calibrated instruments and standardized methodologies (Grasshoff, 1983). Sea-water temperature during cruises was measured either with protected reversing thermometers or *in situ* with an Inter-Ocean 513D CSTD probe. Salinity was determined either by using a Beckman induction model RS7-C salinometer for the water samples collected from Nansen bottle casts or *in situ* using the Inter-Ocean model 513D CSTD probe, modified by the manufacturer to measure hypersaline conditions. The basic principle of salinity analysis by the CSTD probe is the same as for laboratory induction salinometers. Sea-water conductivity was measured by comparing the current induced to flow by a known applied electrical current.

Temperature and salinity data collected from quarterly cruises were plotted for each station, and the resulting diagrams were used to eliminate spurious values. Temperature and salinity data were grouped by season according to the following seasonal classifications: December to February: winter; March and April: spring; May to September: summer; October and November: autumn. Mean monthly wind speed and predominant direction for three nearshore stations (Dhahran, Ras Tanura and Safaniya) are shown in Table 1. Mean values of temperature and salinity were plotted as horizontal isopleths for each season (Fig. 2 *a* to *d* and 3 *a* to *d*). All temperature and salinity data were used in drawing T-S diagrams for each season (Fig. 4). Vertical profiles of salinity have been drawn (Figs. 5 and 6) for stations (2R, 6R, 9R, 12R, 13R, 14R and 15R) for March and April (spring) and September (summer).

RESULTS

Water temperature

The minimum water temperature during the winter season occurred during February 1988, when the temperature reached 15.9°C at station 13R. In the open gulf waters further north the surface temperatures were higher, and the lowest recorded temperature during February 1988 was 17.5°C at station 1R. Generally, nearshore and Gulf of Salwah temperatures were lower than offshore temperatures in winter.

During spring, water temperature started to increase with increasing air temperature. This process occurred more rapidly nearshore, resulting in lower mean temperatures offshore except at stations 1R-3R (Fig. 2 *b*). In the northern part of the study area, intrusion of colder water from the north probably occurred due to northwest prevailing winds and a nearshore southeastward current (Fig. 2 *b*). The water temperatures for this season varied from 17.7°C at station 1R to 25°C at station 4R.

Table 1
Mean wind speed (km/h) and predominant direction.

Month	January	February	March	April	May	June	July	August	September	October	November	December	#Years
							Dhahran						
Speed	19	21	21	21	22	24	19	19	19	16	19	19	24
Direction	NW	NNW	N	N	N	NNW	N	NNW	N	N	NW	NW	24
							Ras Tanura						
Speed	17	17	18	17	17	18	15	15	13	13	15	17	17
Direction	NW	N	N	N	NNW	NNW	N	NNW	NNW	NNW	WNW	WNW	17
							Safaniyah						
Speed	15	15	17	15	15	15	12	13	10	13	15	17	6
Direction	NW	N	N	N	NNW	NNW	N	NNW	NNW	NNW	WNW	WNW	6

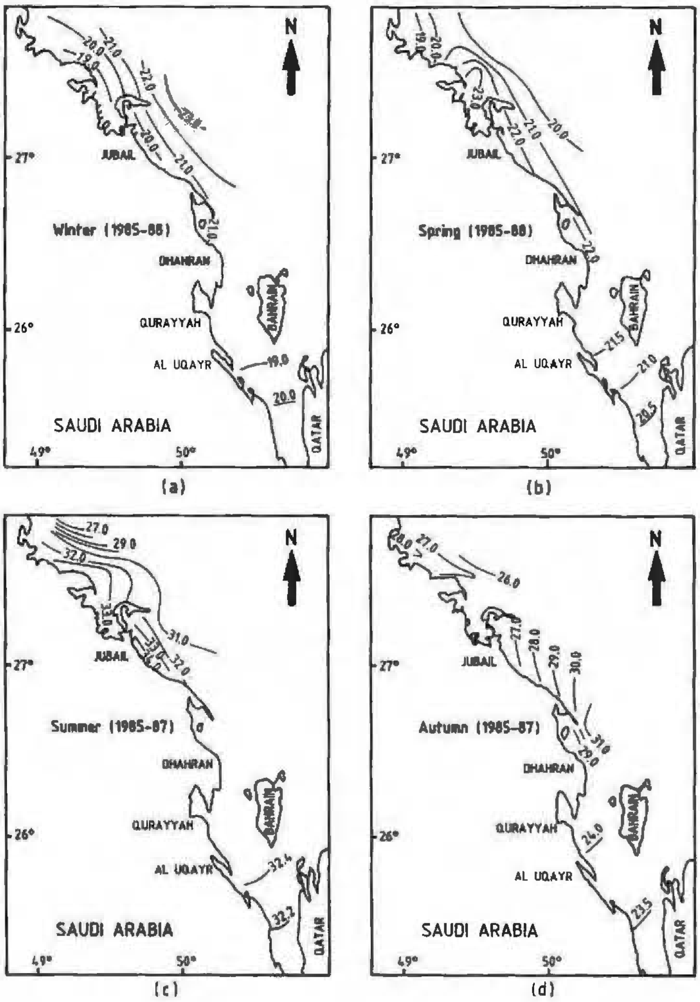

Figure 2
Horizontal profiles of vertically averaged temperature: (a) winter; (b) spring; (c) autumn; (d) summer.

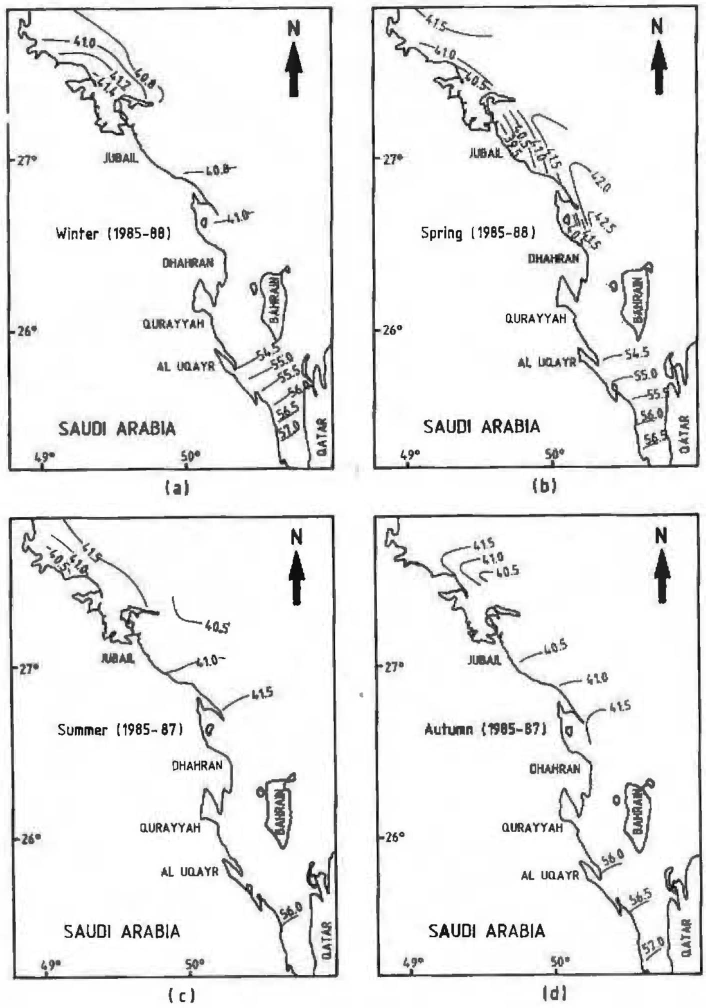

Figure 3
Horizontal profiles of vertically averaged salinity: (a) winter; (b) spring; (c) autumn; (d) summer.

During summer, open-water temperatures reached a maximum of 35.5°C at station 7R near Abu Ali island. Generally, surface water temperature decreased in the seaward direction, and water temperature was high in the Gulf of Salwah, ranging up to 35.0°C.

During autumn, the maximum and minimum temperatures observed were 33.10°C at station 11R and 22.85°C at station 1R. Mean temperatures were substantially lower in the Gulf of Salwah than in other stations, indicating that the more shallow and restricted waters in this area are more rapidly influenced by evaporative cooling processes and decreasing air temperatures than areas further north.

Salinity

During winter, offshore salinities ranged between 40.0 and 41.8 at stations 1R to 12R, and Gulf of Salwah salinities ranged from 52.3-57.7 (Fig. 3 *a*). Generally, the mean salinity in the Gulf of Salwah increased southward from 54.1 at station 13R to 57.3 at station 15R.

During spring, the salinity distribution showed the influence of low-salinity water coming from the northwestern Arabian Gulf (Fig. 3 *b*), with salinities ranging from 37.9-38.9 at nearshore stations 1R, 4R, 7R and 10R. Wind (KFUPM/RI, 1988 *a*; 1988 *b*) and current meter data (John, 1990) collected during this period indicate that Northwest winds (Tab. 1) and Southeastward currents caused this low salinity water to flow south near the coast. Outside the Gulf of Salwah, maximum salinity was observed at station 12R offshore of Ras Tanura (43.6).

During summer, salinities north of the Gulf of Salwah ranged from 39.5-44.9. In the Gulf of Salwah, salinities were at their annual highest, with a maximum of 59.2 occurring near the bottom at station 15R during this season. Northward movement of this water is also indicated with the maximum mean salinity outside of the Gulf of Salwah occurring at station 11R off Ras Tanura.

During autumn, the salinity distribution north of Gulf of Salwah showed less variation when compared to summer, with salinities ranging from 40.07-42.97. Gulf of Salwah water had salinities ranging from 56.0-57.1.

The denser saline water from the Gulf of Salwah was observed as high salinity bottom water at station 12R further north at Ras Tanura (Fig. 5 and 6). At this station a well-defined two-layer system exists, the top mixed layer up to 10 m (salinity 41) and a bottom layer of salinity 44.5 being separated by a strong halocline.

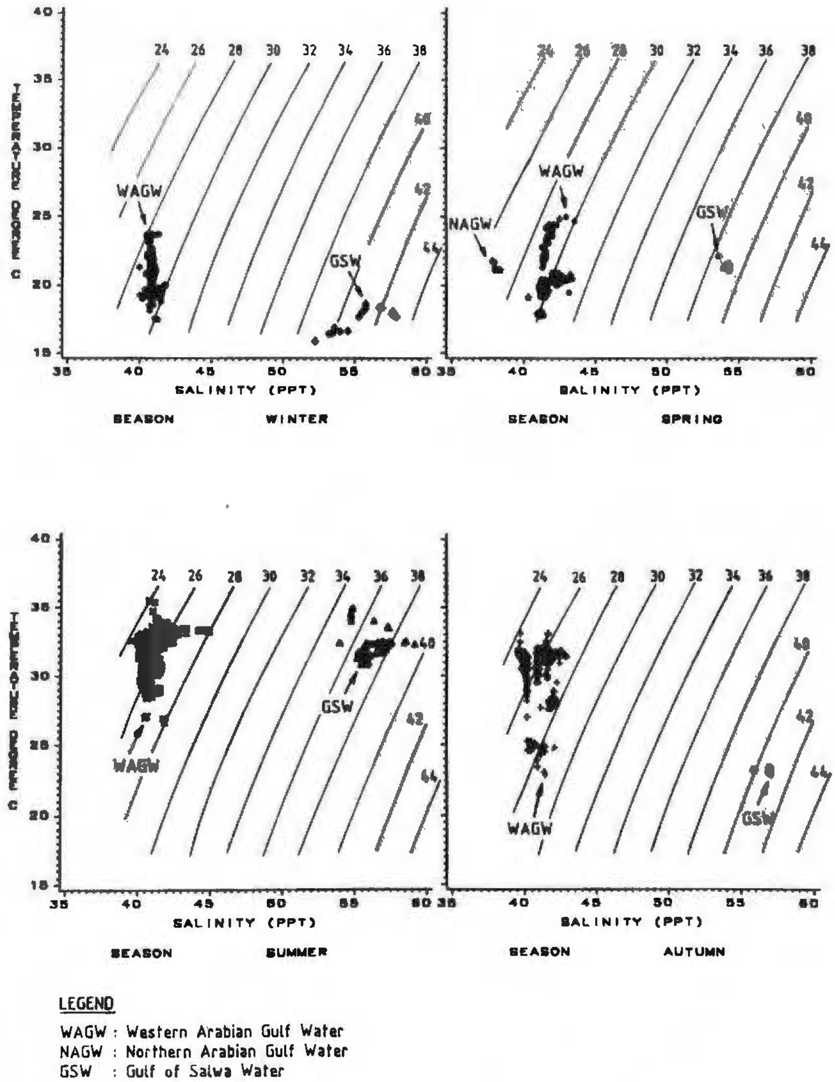

Figure 4
Composite T-S plot and water masses: (a) winter; (b) spring; (c) autumn; (d) summer.

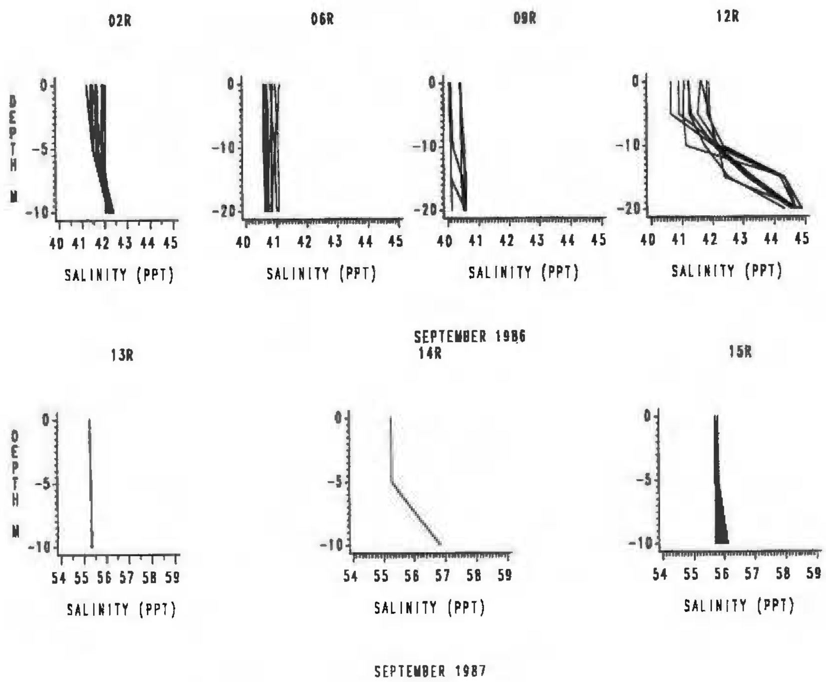

Figure 5
Vertical profiles of salinity for March and April.

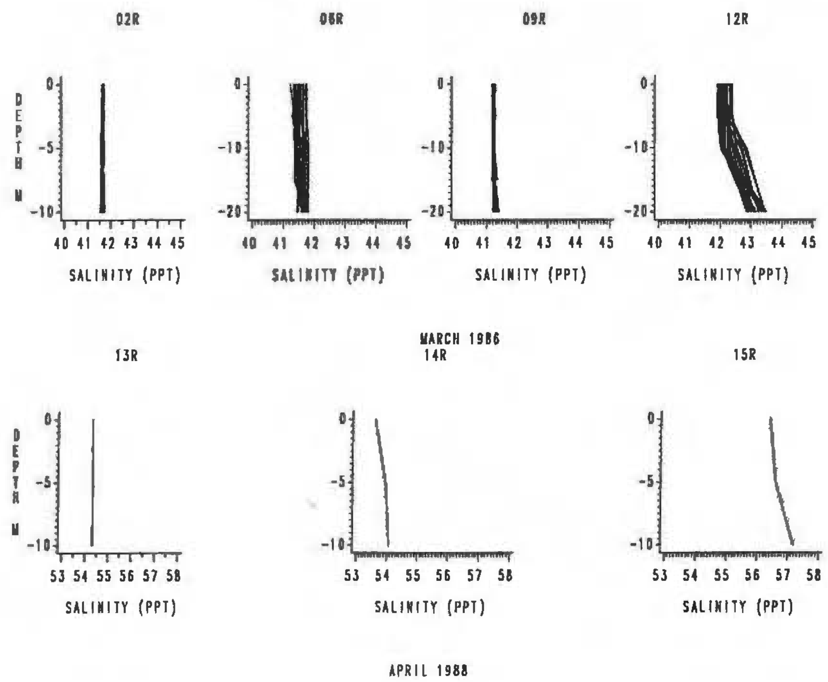

Figure 6
Vertical profiles of salinity for September.

Seasonal variation of water masses

The seasonal temperature-salinity relationship of open gulf water to the Gulf of Salwah is presented in Figure 4. Basically, there are two distinct water masses in the study area: the Western Arabian Gulf Water (WAGW) and the Gulf of Salwah Water (GSW). The characteristics of these two water masses in different seasons are shown in Figure 4. WAGW extends along the Saudi Arabian coastline from Safaniya to Ras Tanura and has an annual temperature range of 17.5-35.5°C and salinities 37.9-44.9. The salinity of WAGW shows relatively little changes, compared to the seasonal temperature range, which is the largest contribution to the change in density. GSW has slightly cooler temperatures with an annual variation of 15.9-34.9°C and substantially higher salinities of 52.3-59.2. The density difference between these two water masses is largely due to the high salinity of GSW, which is about 40% more saline than WAGW. Sigma-*t* values have an annual variation of 24.0 to 31.2 for WAGW and 35.0 to 43.0 for GSW.

During spring, a low salinity water mass, Northern Arabian Gulf Water (NAGW) is observable in the Safaniya to Manifa region, with salinity of around 37.9. This is due to the freshwater flow from the Shatt Al-Arab being carried southward by the prevailing southward and southeastward coastal currents and strong north west winds.

DISCUSSION

The results indicate that the thermocline and pycnocline are poorly developed in most areas of the western Arabian Gulf, despite the rapid heating and cooling of surface waters that occur seasonally and the intense evaporation that results from a high air-sea interface temperature differential (Privett, 1959). This lack of a well-developed thermocline can be attributed to the shallowness of the area, strong persistent winds, moderate waves, and strong currents that disturb density stratification.

Other factors, such as freshwater input, that might enhance stratification probably exert a relatively minor effect on the western gulf as a whole. Freshwater inflow from the Tigris-Euphrates at the Shatt al-Arab, the only significant freshwater source, has been estimated (Grasshoff, 1976) at a maximum of 180 km^3 per year in April and minimum of 22 km^3 per year in October and the lowest annual discharge of 5 km^3 per year was reported by Hartman *et al.* (1971). This represents only about 15%, on average, of the water loss due to evaporation (Lehr, 1984). Annual precipitation is an even less important source, averaging only 5 cm annually (Evans, 1966). The effects of freshwater input on gulf salinities were only measurable in the present study at nearshore sites during spring months, and these effects were transient.

The distribution of mean salinity values (Fig. 3) suggests gradual mixing of GSW with WAGW. However this effect is not measurable beyond Ras Tanura. Studies of moored current measurements at six locations on the western Arabian Gulf (KFUPM/RI, 1988 *a*; 1988 *b*; John, 1990) have indicated a northward near-bottom residual current at Abu Safah (21 km northeast of Ras Tanura) opposite to the residual current at all other locations. This suggests that this high salinity GSW flows as a near-bottom current and is probably diverted to the right by the Coriolis force. GSW eventually joins the near-bottom water mass flowing eastward along the Trucial coast and Strait of Hormuz. GSW therefore plays an important role in the residual circulation of the gulf.

Table 2
Seasonal summary statistics of temperature.

	Winter season (1985-1988)				Spring season (1985-1988)				Summer season (1985-1987)				Autumn season (1985-1987)			
Station	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
01R	17.45	19.80	19.27	0.69	17.72	24.00	18.58	1.97	31.91	32.95	32.25	0.30	22.85	29.50	28.06	0.95
02R	18.80	23.72	19.92	0.99	19.39	23.57	19.65	0.73	28.79	34.80	31.26	1.55	–	–	–	–
03R	19.90	21.50	20.50	0.71	19.11	22.94	20.57	1.74	23.50	33.01	26.41	2.30	–	–	–	–
04R	17.56	20.02	18.78	1.41	21.77	24.98	23.34	1.81	32.38	33.60	32.94	0.65	23.05	28.35	26.05	2.69
05R	–	–	–	–	23.21	23.38	23.29	0.09	32.60	33.55	32.89	0.41	24.90	30.00	26.96	2.69
06R	19.40	22.75	21.97	0.58	19.17	22.48	19.78	0.42	27.00	33.03	30.99	0.94	24.95	25.10	25.01	0.06
07R	18.50	20.89	19.65	1.25	21.07	24.20	22.48	1.58	32.34	35.50	34.06	1.60	25.20	28.20	26.41	1.46
08R	–	–	–	–	19.61	22.61	20.89	1.42	29.94	32.24	31.08	1.19	–	–	–	–
09R	22.00	23.55	23.54	0.75	19.17	22.76	19.78	0.46	28.39	32.94	30.54	1.36	–	–	–	–
10R	18.16	23.67	20.91	3.18	21.07	24.21	22.65	1.78	26.66	34.15	30.44	4.23	23.40	31.10	28.27	3.61
11R	19.95	23.58	21.29	0.43	20.00	24.39	20.51	0.78	30.21	34.70	31.42	1.15	24.30	33.10	31.17	1.21
12R	18.70	22.70	21.69	0.46	19.46	24.65	20.58	0.76	30.59	33.90	31.63	1.17	24.60	32.00	31.27	1.10
13R	15.89	20.52	18.09	1.87	21.42	21.55	21.48	0.09	30.87	34.25	32.32	1.34	23.19	25.30	23.91	1.21
14R	16.61	22.97	19.72	2.50	21.27	22.14	21.70	0.62	31.50	34.90	32.39	1.26	24.90	24.90	24.90	–
15R	17.90	21.10	20.36	0.69	19.60	20.75	20.30	0.36	31.09	34.90	32.12	0.60	23.04	25.60	23.32	0.56

Table 3
Seasonal summary statistics of salinity.

	Winter season (1985-1988)				Spring season (1985-1988)				Summer season (1985-1987)				Autumn season (1985-1987)			
Station	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
01R	40.38	41.30	40.99	0.32	38.86	42.10	41.09	0.78	40.02	41.93	40.39	0.56	41.36	42.30	41.95	0.22
02R	40.04	41.56	40.94	0.23	41.54	41.82	41.64	0.05	40.13	42.40	41.17	0.64	–	–	–	–
03R	40.78	40.89	40.82	0.05	40.38	41.64	41.20	0.61	40.30	41.92	40.89	0.56	–	–	–	–
04R	41.10	41.84	41.45	0.40	37.88	43.04	40.35	2.85	40.84	42.10	41.44	0.68	41.39	41.43	41.41	0.03
05R	–	–	–	–	41.66	41.70	41.68	0.02	40.97	41.50	41.27	0.25	40.38	40.43	40.41	0.03
06R	40.02	40.99	40.85	0.10	41.22	41.82	41.53	0.15	40.05	41.56	40.65	0.25	40.71	40.77	40.74	0.03
07R	40.44	40.98	40.70	0.20	38.00	41.66	39.48	1.98	40.24	41.13	40.65	0.38	40.20	40.41	40.26	0.10
08R	–	–	–	–	41.30	41.48	41.40	0.09	40.56	40.88	40.72	0.14	–	–	–	–
09R	40.52	40.77	40.63	0.05	41.18	41.40	41.23	0.04	39.54	40.70	40.36	0.14	–	–	–	–
10R	40.74	41.24	40.99	0.29	38.42	41.98	40.20	2.04	41.31	41.84	41.57	0.28	40.92	41.76	41.32	0.44
11R	40.88	41.14	40.98	0.05	41.60	43.00	42.52	0.21	41.01	43.32	41.65	0.41	41.09	42.97	41.67	0.30
12R	40.72	41.02	40.87	0.07	41.24	43.62	42.34	0.55	40.62	44.90	41.55	1.07	40.07	42.67	41.45	0.59
13R	52.28	55.54	54.09	1.59	54.32	54.34	54.33	0.01	54.76	57.39	55.63	0.95	55.98	55.98	55.98	–
14R	53.64	55.82	55.14	1.03	53.60	53.96	53.78	0.25	54.75	56.97	55.96	0.77	–	–	–	–
15R	56.80	57.69	57.26	0.48	56.40	56.60	56.50	0.14	53.96	59.17	56.31	0.90	57.02	57.10	57.06	0.02

Table 4
Seasonal water mass characteristics.

	Western Arabian Gulf water			Gulf of Salwah water		
Season	Température (°C)	Salinity	Sigma-*t*	Température (°C)	Salinity	Sigma-*t*
Winter	17.5-23.7	40.0-41.8	28.0-30.2	15.9-23.0	52.3-57.7	39.2-43.0
Spring	17.7-23.2	37.9-43.6	26.6-31.2	21.0-22.0	53.6-56.6	38.3-39.4
Summer	23.5-35.5	39.5-44.9	24.0-28.1	30.9-34.9	54.0-59.2	35.0-39.4
Autumn	22.9-33.1	40.1-43.0	24.1-28.9	23.0-25.6	56.0-57.1	40.0-40.9

Nearshore measurements of salinity by Beltagy (1980) in the Gulf of Salwah off the Qatar coast are in general agreement with the results of this study in salinity values and determination of an increasing salinity gradient towards the inner Gulf of Salwah.

Density stratification in the western gulfs occurs only near the entrance to the Gulf of Salwah, where the northward movement of highly saline Gulf of Salwah bottom water intrudes under less saline western gull water, forming the density structure of a typical reverse estuary (Sverdrup *et al.*, 1942). The high salinities in the Gulf of Salwah result from its restricted exchange of water with the rest of the gulf, its relative shallowness and its resulting limited heat capacity. These factors promote high evaporation both during the summer months when sea temperatures are high, and in winter when the sea-air temperature-differential is at its maximum.

This same pattern of a highly saline, reverse estuary driven by net water loss from high evaporation applies to the Arabian Gulf when compared to the adjacent Arabian Sea (Emery, 1956; Hunter, 1984). The Gulf of Salwah may therefore be viewed as a smaller but more extreme model of the Arabian Gulf as a whole which may be very important in the net circulation of the latter. Hunter (1984) has developed a model of gulf circulation that proposes that the pressure gradients arising from evaporation-induced variations are the dominant forcing function of the net circulation. The inflow of low salinity surface water at the Strait of Hormuz is balanced by the outflow of deep saline water that can be measured outside the strait as a deep layer in the northern Arabian Sea (Sundararaman *et al.*, 1967). The present study indicates that the formation of high-salinity water in the Gulf of Salwah may be one of the most important sources of the salinity-related density gradient proposed by Hunter (1984) to drive circulation in the Arabian Gulf. Further work is required to measure the residual circulation, mixing processes, and to determine a net salt balance of the Gulf of Salwah to verify this hypothesis.

CONCLUSIONS

Due to the high annual range of temperatures and high salinities, waters of the Arabian Gulf are almost unique in the world. This oceanographic programme provides the first extensive baseline oceanographic data base for the area. The western Arabian Gulf is characterized by very shallow coastal bays and offshore waters. High temperatures, excessive evaporation and limited mixing and transport with open Arabian Gulf waters cause hypersaline conditions in the nearshore bays, especially in the Gulf of Salwah. Salinities of up to 59.2 have been recorded in the Gulf of Salwah open waters during these surveys, one of the highest surface salinities found in the world's oceans. In disagreement with the results found by Schott (1918), summer salinities observed during this study (1986-1988) were higher than those observed during winter.

Waters north of the Gulf of Salwah have offshore salinities which generally vary from 38-45 and also have annual surface temperature maxima up to 35.5°C. The results also show a poorly developed thermocline and pycnocline except near the mouth of Gulf of Salwah, where a strong pycnocline occurs due to northward movement of highly saline Gulf of Salwah bottom water. This can be attributed to the shallowness of the western Arabian Gulf, strong persistent winds, moderate waves and strong currents.

Although oceanographic monitoring has been carried out in most areas of the western Arabian Gulf, the results have shown the need for detailed investigation in certain areas, the most important being study of residual circulation, mixing processes, and flushing time of Gulf of Salwah water and its impact on open gulf waters.

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