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SPREADING OF PERSIAN GULF WATER IN THE NORTHWESTERN ARABIAN SEA DURING THE MONTH OF JANUARY

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ABSTRACT: The presence of different water masses in the North Arabian Sea continues to remain of interest to scientists and researchers. Focus on these water masses is due to the unique monsoonal reversal features of the Arabian Sea. The encroachment of Persian Gulf water into the Arabian Sea has been acknowledged and traced. This paper presents the results of an investigation on the spreading patterns of Persian Gulf water in the northwestern Arabian Sea. The study incorporated two different techniques: The core-layer method and the constant sigma-theta surface method on data collected during the North Arabian Sea Environment and Ecosystem Research (NASEER) programme. Horizontal curves of temperature and salinity plotted by both methods show that the Persian Gulf water reduces in concentration as it moves from west to east, whereas the major direction of flow is along the coast of Oman. The results of the study indicate that features of the Persian Gulf water in the northwestern Arabian Sea are so pronounced that either of the method can be used to study and identify the water mass fairly well.

KEY WORDS: Water mass, Persian Gulf water, North Arabian Sea, sigma-theta surface, core layer.

INTRODUCTION

The unique monsoon characteristics of the Arabian Sea have distinguished it from other ocean basins of the world. The Arabian Sea experiences extreme in atmospheric forcing that lead to semi-annual seasonal changes (Arshad *et al.*, 1995). The monsoonal effect is predominantly felt on the surface layers. Thus the water masses of the surface layers are subjected to seasonal changes (Ramam *et al.*, 1968). The characteristic water masses are formed primarily at the sea surface of the source area by various meteorological factors. Usually this occurs in partially isolated seas or on continental shelves. The analysis of world water masses has taken a new turn since the introduction of the temperature-salinity (T-S) diagram as a tool by Helland - Hansen (1916). A salinity maxima is defined as that point on a T-S curve that has a salinity value greater than the value obtained by the mixing of the water above and below it on the curve. One example of the formation of water masses can be seen in the Persian Gulf, which has been accepted as the origin of the highest salinity values present in the northern Arabian Sea. The excessive evaporation over the sum of precipitation and river run-off form the Persian Gulf water. High evaporation in the Persian Gulf causes a loss of freshwater, which suggests an out flow of $0.18X10^6$ m^3/s (Olson *et al.*, 1992). The dense water that forms in the Gulf, enters the Arabian Sea with a salinity 36.9 PSU (Practical Salinity Unit) (Banse, 1990) and with slightly higher values of temperature and oxygen.

Determining the temperature-salinity relationship of the Arabian Sea is complex and requires closely spaced and carefully chosen sampling depths. Rochford (1964) deduced that in the North Arabian Sea, Persian Gulf water is found at depths of about 300 meters.

He grouped the salinity maxima of the water masses of the Arabian Sea, as A to D. B corresponds to the Persian Gulf water mass. After entering the Arabian Sea it sinks to a specific density surface, which can be identified as the intermediate subsurface salinity maxima. Further southward, salinity decrease due to strong mixing with lower salinity water (Ivanov-Frantskevich, 1961). A general description of the Persian Gulf water in the Arabian Sea has also been given by Wyrtki (1971).

The National Institute of Oceanography, Pakistan, undertook an oceanographic research programme entitled the "North Arabian Sea Environment and Ecosystem Research (NASEER)" in collaboration with scientists from the United States and the U.S. Office of Naval Research. The first cruise of NASEER, from 8-25 January 1992, covered a track of 1700 nautical miles (Fig. 1), Data related to physical, biological, and chemical oceanography were collected.

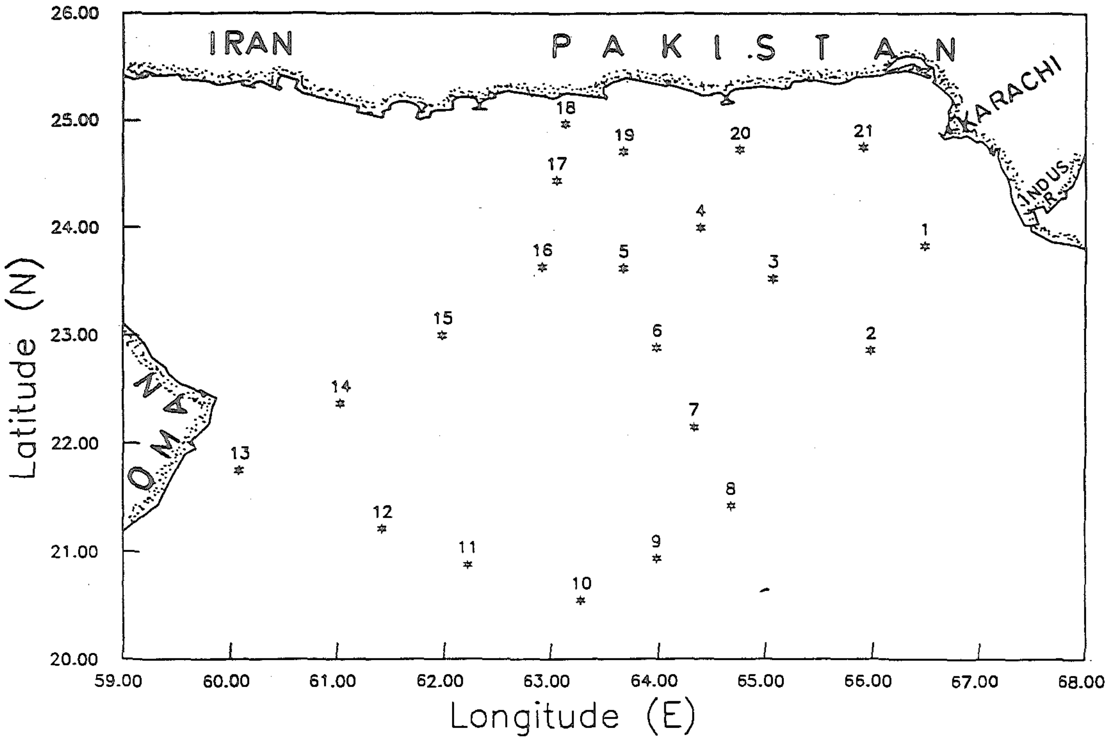

Fig. 1. CTD stations. NASEER January 1992 cruise.

This paper describes the synoptic view of Persian Gulf water spreading in the northwestern Arabian Sea using the core-layer and sigma-theta methods. The study is mainly based on conductivity, temperature and depth data, collected during the first cruise of NASEER. Earlier studies available in the literature used historical data as well as water-bottle data. The objective of this study is to enhance knowledge of the Persian Gulf water mass in the northwestern Arabian Sea using the sigma-theta surface and core layer methods.

Sigma-theta is the potential density of seawater when temperature is converted into potential temperature. This surface method is a very useful tool to study the lateral mixing and spreading of water masses because it is depth free and eliminates the short-term vertical displacement in a water column such as internal waves. Generally, extreme values of water mass, least affected by mixing, are found in this area. Charting this value of a given property consequently defines a core layer of a water mass, as it is in this layer that the original properties of the water mass are best preserved.

MATERIALS AND METHODS

The first cruise of NASEER took place from 8-25 January 1992. During the cruise a track of 1,700 nautical miles (Fig. 1) was surveyed, and data related to physical, biological, and chemical oceanography were collected.

Conductivity, temperature, and depth (CTD) measurements on board the M/V *Aghyar-S* were made with Sea Bird's SBE 9/11 plus CTD profiler with a 11 bottler General Oceanic Rosette sampler fitted with reversing protected and unprotected thermometers. The M/V *Aghyar-S* , a cargo vessel, was specially converted into a research vessel by adding an "A" frame with a motorised winch supported by a wire length digital meter, and an observation platform on the port side. During the transect, the CTD profiler was lowered at 21 stations and data were recorded in the assembly during the downcast with a sampling frequency of 8 Hz and a lowering speed of about 1m/s. During the up cast, bottles were triggered at selected depths to collect water samples and temperature for calibration of the CTD sensors as well as for chemical and biological analyses. The CTD profile is accurate to +-0.01 °C and +-0.003 PSU for temperature and salinity, respectively. Recorded data were retrieved in the computer through a RS232 cable.

The temperature data were converted to potential temperature and the density to potential density because they do not change adiabatically. The T-S curves of converted potential values and vertical profiles of different seawater parameters were plotted to determine the values of all properties at each core layer as well as depth of the core. Co-salinity and co-temperature charts were prepared and plotted for core layer and on a 26.6 sigma-theta surface.

Since the data are obtained from the CTD profiler that has an accuracy of depth $\pm$ 1 meter, the core was sampled precisely. The quality of CTD data was checked from the data recorded by reversing thermometer for temperature and by analyses of water samples using an inductive salinometer for salinity values.

RESULTS AND DISCUSSION

Vertical profiles of temperature and salinity (Fig. 2a,b) display pronounced maxima of the respective values in the middle of the thermocline and halocline regions. The same type of maxima is also visible in the profile of oxygen (Fig. 2c). However, the high values of salinity and temperature at the surface are due to the high rate of evaporation in the North Arabian Sea.

The temperature-salinity diagrams plotted for Station 16 (Fig. 3) and Station 2 (Fig.4), show the strong presence of a Persian Gulf water tongue during the observation period in the northwestern Arabian Sea. Extreme values of temperature and salinity in

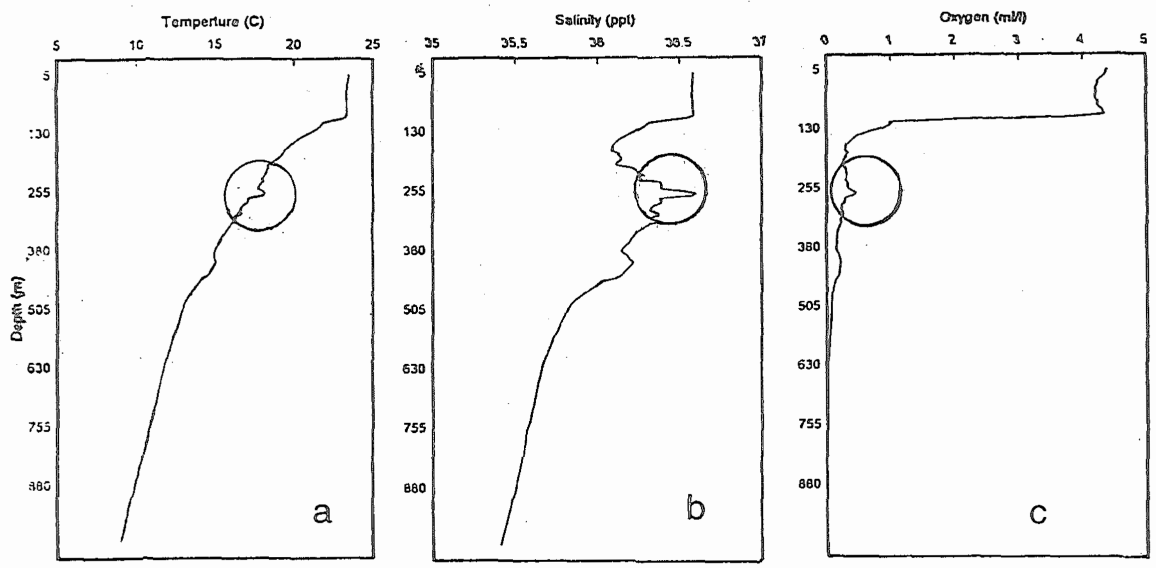

Fig. 2. Vertical profile of (a) temperature (°C), (b) salinity (PSU) and (c) oxygen (ml/l) data collected at Station 16 by CTD.

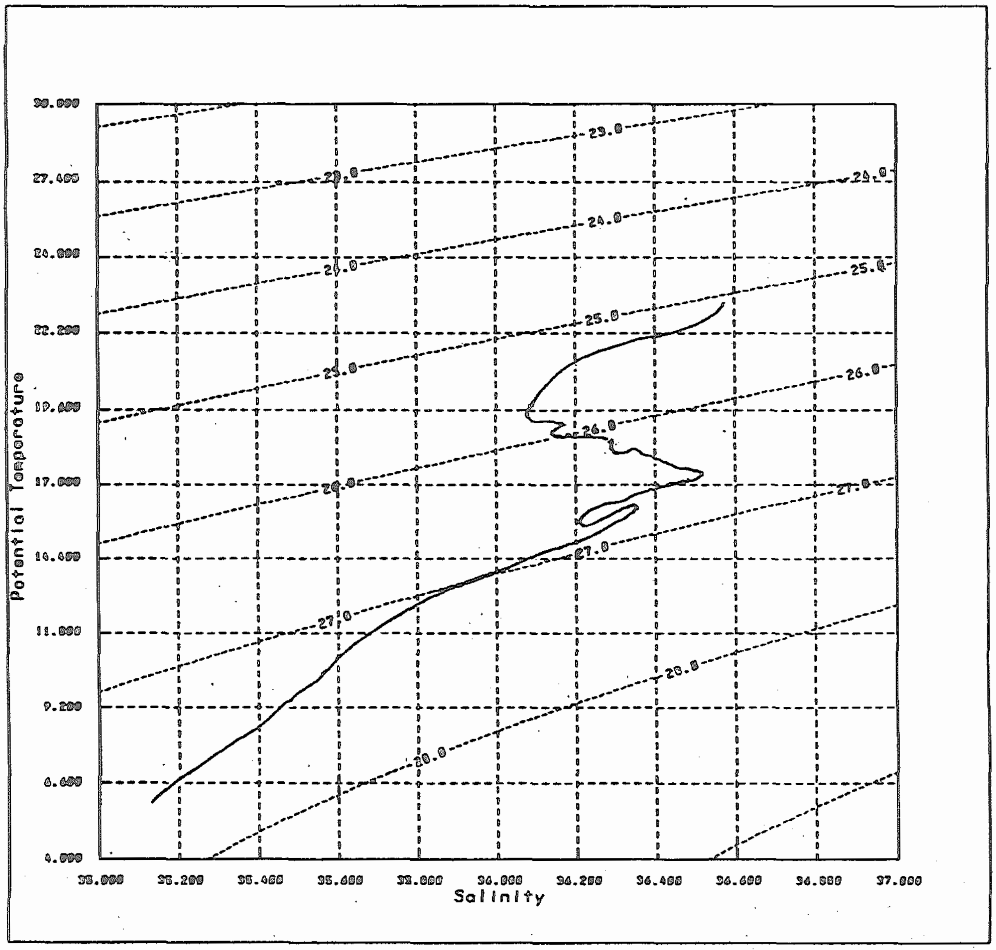

Fig. 3. Temperature-salinity diagram of CTD data collected at Station 16.

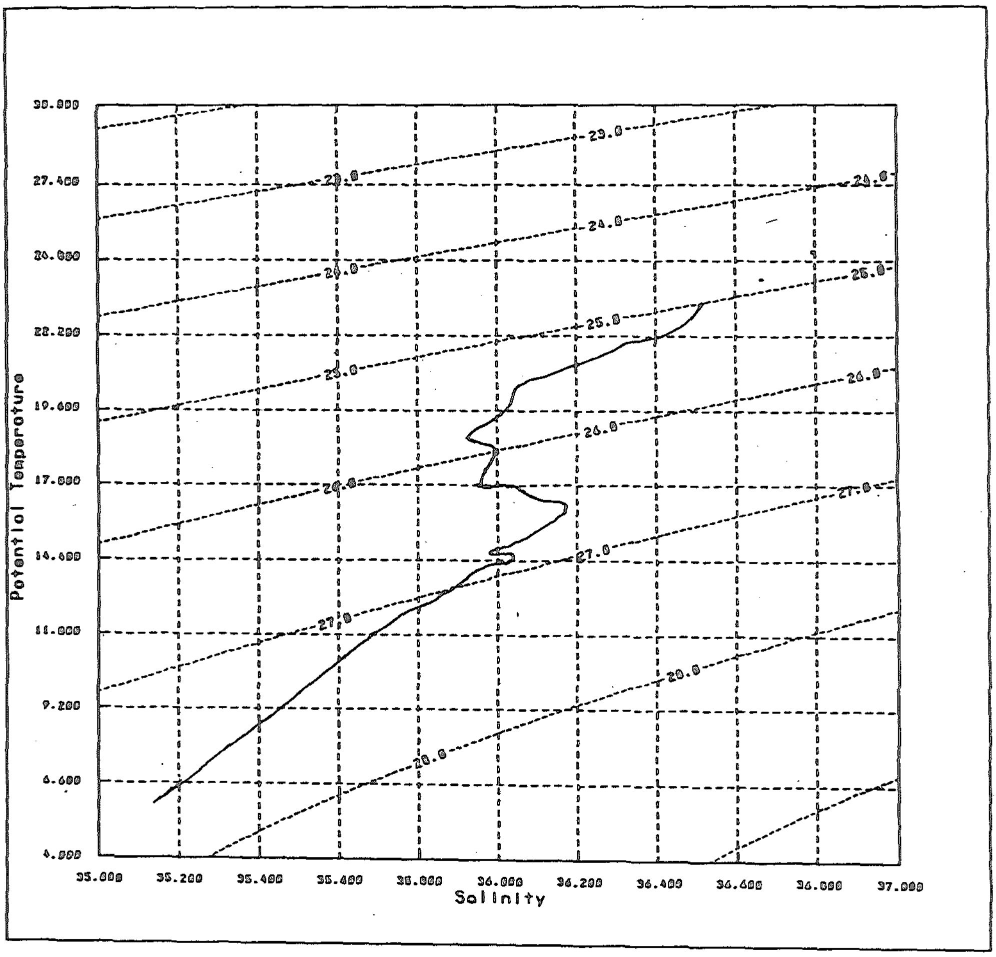

Fig. 4. Temperature-salinity diagram of CTD data collected at Station 2.

the T-S curves correspond to the 26.6 sigma-theta level. The higher salinity values at Station 16, located near the Oman coast, indicate its presence near the entrance of the Arabian Sea, while Station 2, located at the far eastern side of the northwestern Arabian Sea, reflects reduction of the salinity level due to strong mixing, confirming the interpretation made by Ramam *et al.*, (1968).

Potential temperature and salinity on the 26.6 sigma-theta surface (Figs. 5,6), and in the core layer (Figs. 7,8), show that the Persian Gulf water after entering the northwestern Arabian Sea, spreads in two directions. Due to the winter monsoon's anticlockwise general circulation pattern in the Arabian Sea, one path is towards the south while another is towards the east, on its way from west to east, mainly by reduction. The salinity in the sigma-theta surface (Fig. 6) varies from 36.5 to 36.2 PSU, whereas in the core layer, slightly higher values (Fig. 8) are observed on the eastern side. Temperature by both methods varied from 17.5 to 16.5 °C. The lowest concentration of Persian Gulf water is found near the Pakistan coast with a salinity of 36.16 PSU and a temperature of 16.5 °C (Fig. 4).

The depths of the Persian Gulf water obtained by the core-layer method (Fig. 9) vary

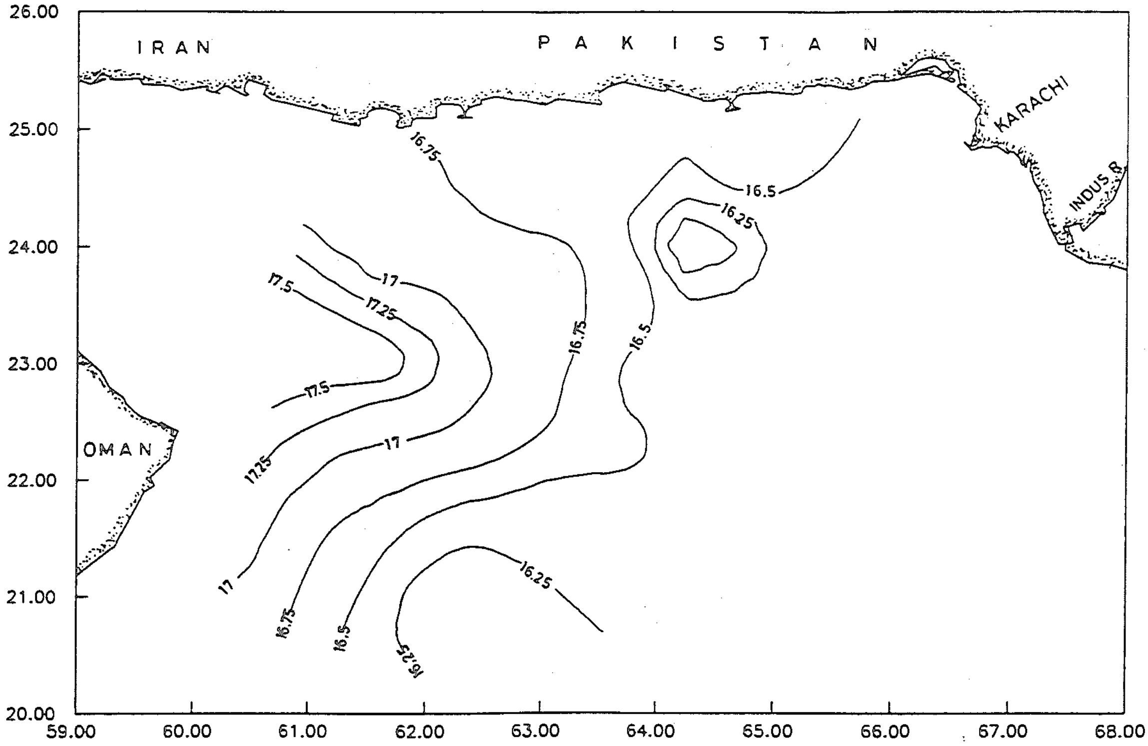

Fig. 5. Co-temperature (°C) lines along the 26.6 sigma-theta surface.

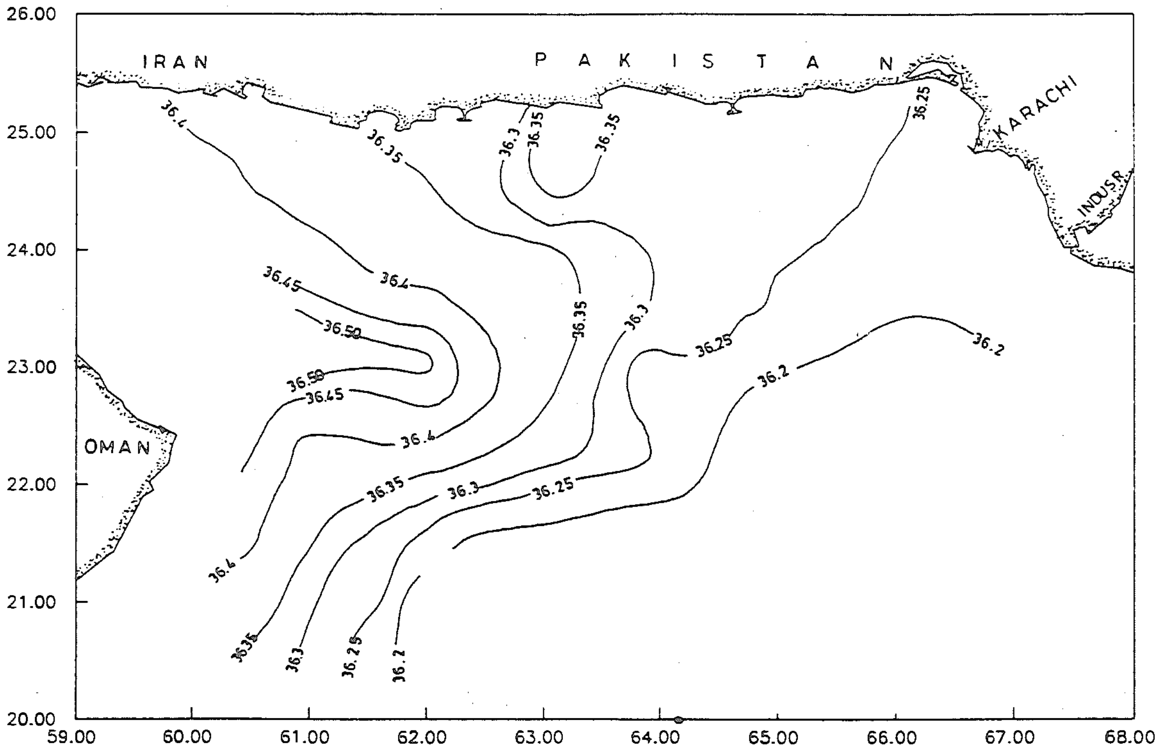

Fig. 6. Co-salinity (PSU) lines along the 26.6 sigma-theta surface.

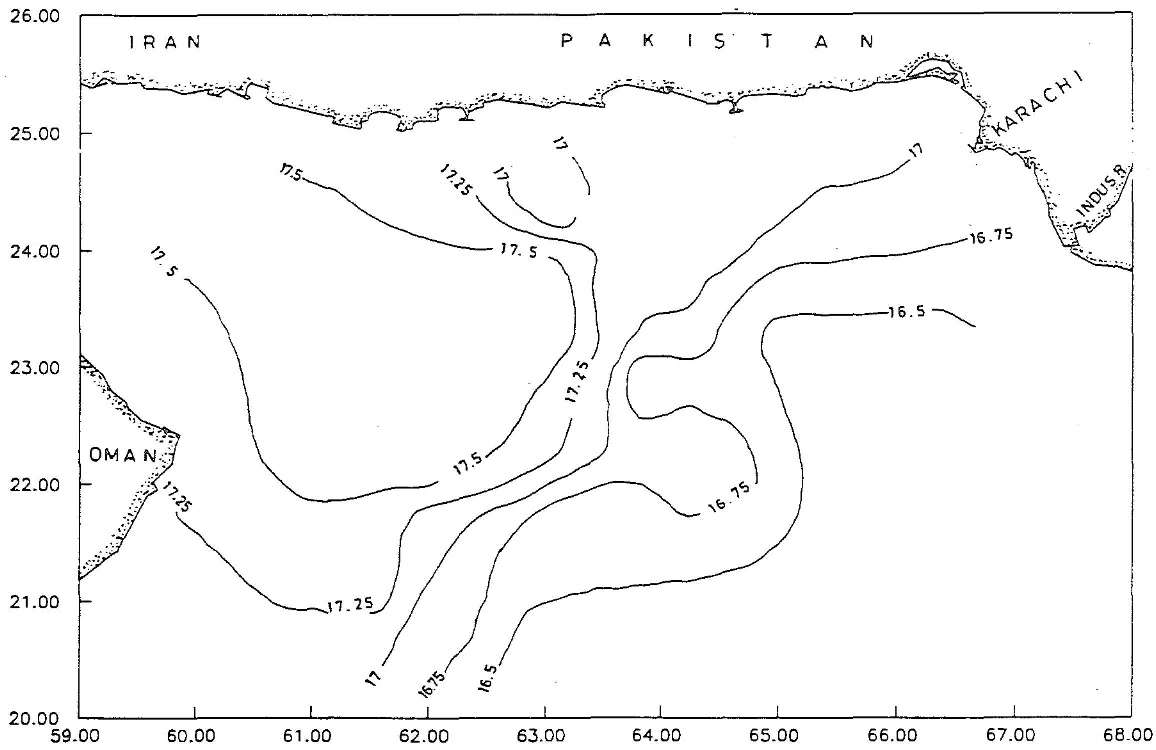

Fig. 7. Co-temperature (°C) lines in the core layer.

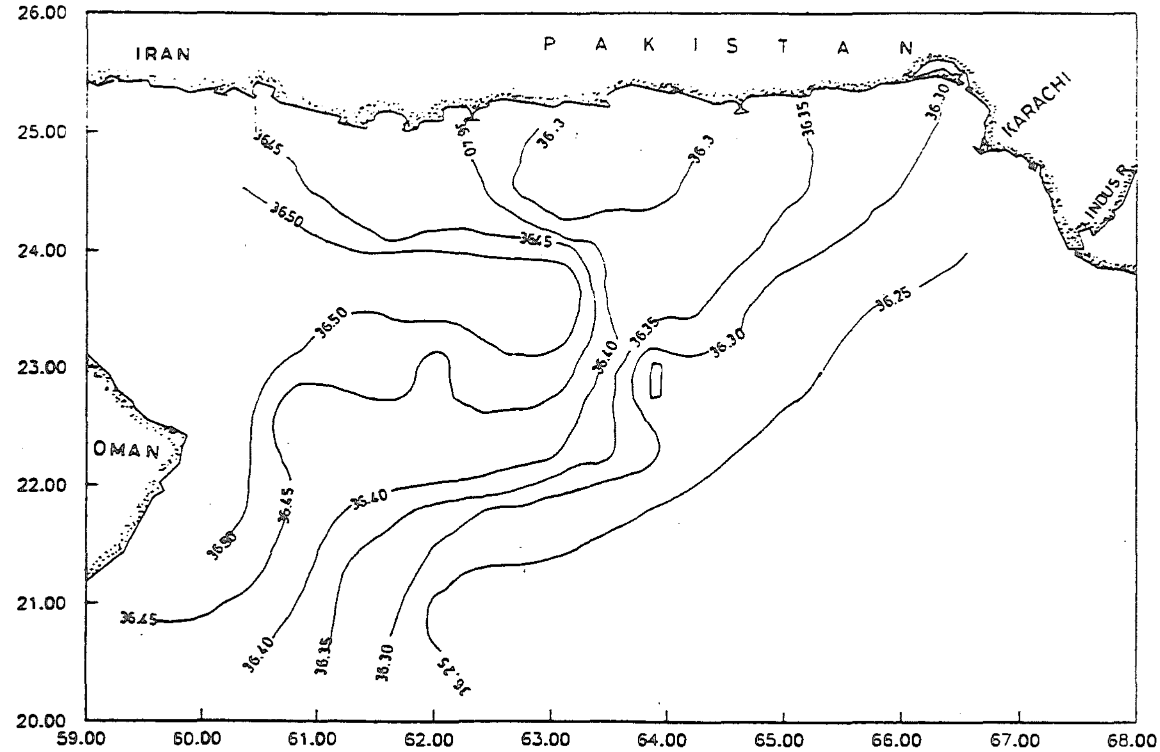

Fig. 8. Co-salinity (PSU) lines in the core layer.

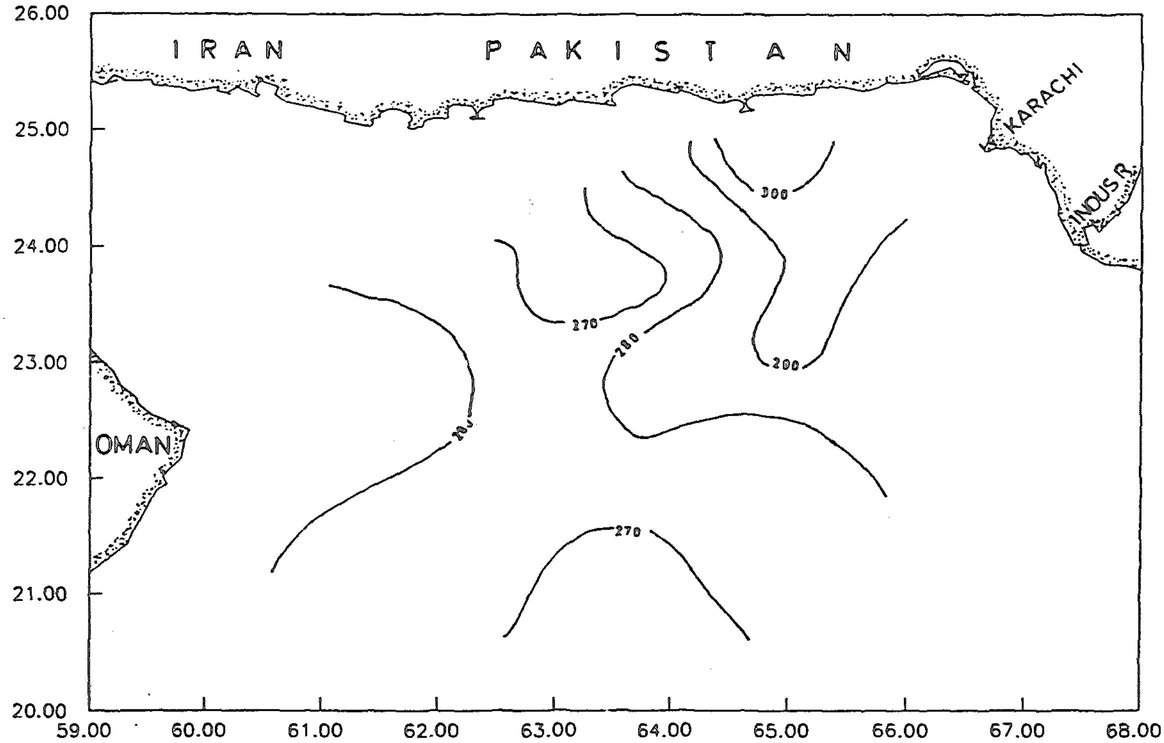

Fig. 9. Depth (m) of Persian Gulf water determined by the sigma-theta method.

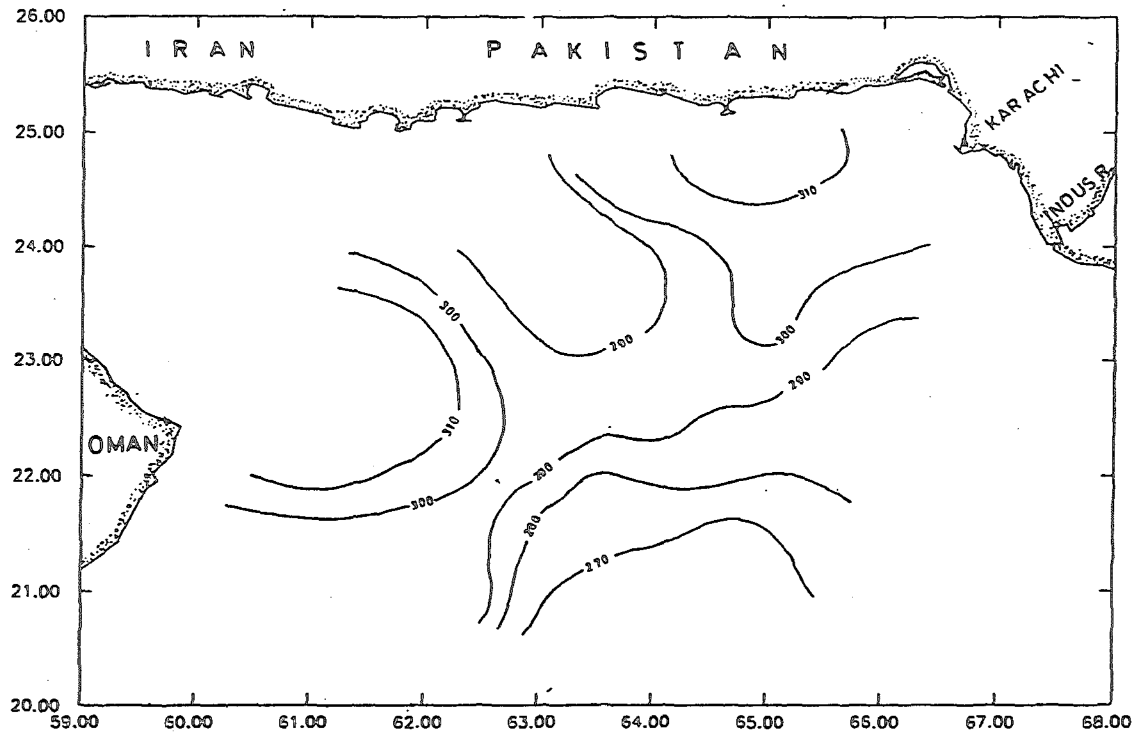

Fig. 10. Depth (m) of Persian Gulf water determined by the core-layer method.

from 270 to 300m. Whereas depths taken by the constant sigma-theta surface method (Fig. 10) vary from 270 to 310m. These depths, are in good confirmation to earlier studies, which state that in the northern part of the Arabian Sea, Persian Gulf water sinks to a depth of 300m (Rochford, 1964). The results of our investigation also show that the data resulting for the sigma-theta and core-layer methods used in the study of the Persian Gulf water are very similar as it spreads in the northwestern Arabian Sea.

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