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Irregular flow of Persian (Arabian) Gulf water to the Arabian Sea

by Karl Banse[1]

ABSTRACT

The bottom outflow from the Persian (Arabian) Gulf, which intrudes in the Gulf of Oman as an intermediate salinity maximum and spreads in the northern Arabian Sea, was inferred to be seasonal. Also, based on particular expedition, single values of temperatures, salinities, and oxygen concentrations were assumed as end members for this core layer. From historical data it is shown here that the salinity of the water exiting at depth from the Gulf is first reduced to <40 ppt by mixing with Gulf of Oman water in the shallow Strait of Hormuz with its strong tides. The core layer acquires its characteristics when the mixing product descends the outer shelf at the head of the Gulf of Oman and entrains upper-thermocline water with an intermediate to low oxygen content above the outflow. After leaving the seabed, when mixing with water also below the intrusion begins, the maximal values observed in the core layer for salinity, density (sigma-*t*), and oxygen saturation ranged between 37.5 and 38.0 ppt, 26.30 and 26.95 g dm^{-3}, and approximately 20 and 60%, respectively (eight expeditions, with two for oxygen; in all, 15 temporally separated cruises). Rules about this variability could not be recognized, except that the oxygen content in the freshly formed core layer seems to be highest in spring and lowest in fall.

At the head of the Gulf of Oman, one intrusion was always present; at least three times, two intrusions of nearly the same density were encountered, as is common also several 100 km away from the source region. Persistent presence of the core layer at the head, but absence near the mouth of the Gulf of Oman in the spring of one year, and presence during the following spring (five cruises between May 1975 and August 1976) do not indicate a marked seasonal pattern of the outflow. Within at least 1,000 km from the Strait of Hormuz, advection clearly participates in the lateral spreading of the core layer.

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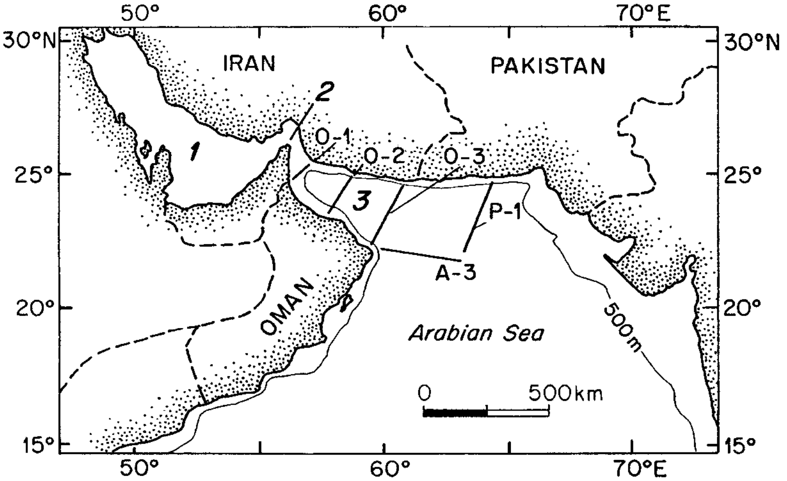

Figure 1. Map of study area with sections by *Dr. Fridtjof Nansen* run between March 1975 and September 1976. Sections referred to in this paper: O-1 to O-3, Gulf of Oman; A-3, off Arabia in the Arabian Sea; P-1, off Pakistan. Sea areas labelled by large italic digits: 1, Persian (Arabian) Gulf; 2, Strait of Hormuz, with Musandam I. (not shown) below the end of the arrow; 3, Gulf of Oman.

1. Introduction

Owing to the marked excess of evaporation over the sum of runoff and precipitation in a shallow water body, the Persian (Arabian) Gulf acts as a negative or inverse estuary. Water flows in at the surface from the Arabian Sea via the Gulf of Oman and the Strait of Hormuz; high-salinity water exits first as a bottom current and, then, in the deeper part of the inner Gulf of Oman, forms an intrusive, pronounced intermediary salinity maximum of slightly elevated temperature and oxygen content. This core layer is widely encountered in the northern Arabian Sea between a sigma-*t* of 26.2 or 26.3 and 26.8 g dm^{-3}.

Previously for the Persian Gulf, it was assumed from its large meteorological seasonal range that the outflow would be principally seasonal, similar to the Red Sea. For the open Arabian Sea, seasonality in the core layer was also inferred from differences of salinity between expeditions, but it is not clear whether, actually, differences between years were seen. Finally, for budgeting the effect of the outflow on the intermediate waters of the Arabian Sea, single values of salinity and oxygen rather than ranges were assumed, because the variability at the origin of the intrusion could not be assessed or was not even realized. From historical data comprising 15 cruises of eight expeditions to the Strait of Hormuz and the Gulf of Oman, this paper will first describe the mixing processes during the outflow in more detail than done previously, and then show that none of the above assumptions or inferences are justified.

The Strait of Hormuz (Fig. 1) bends around Musandam I., the northernmost island off the Arabian Peninsula; sometimes the nearby region is referred to as Musandam Peninsula. Broadly, the Strait is roughly 90 m deep, but a narrow valley of $>$100 m depth exits into the upper Gulf of Oman. To the west, well inside the Gulf near 55E and beyond the region considered herein, is the minor East Sill (77 m deep, but possibly with a deeper cut, Seibold and Vollbrecht, 1969), which separates the 80–100 m deep central basin of the Gulf from the Strait. There also appears to be a minor sill of 80 or 90 m depth outside the Strait, just south of 26N (Map No. 62028, 12th ed., 1980; Defense Mapping Hydrographic/Topographic Center, Washington, D.C.).

For the eastern Persian Gulf and the Strait of Hormuz, the principal observational papers on horizontal and vertical distributions of temperature, salinity and, in part, oxygen are by Emery (1956), Koske (1972), Rabsch (1972), Simmonds and Lamboeuf (1981), Brewer and Dyrssen (1985), and Reynolds (1993). In addition, there are the atlases by Wooster *et al.* (1967) and Wyrtki (1971) for the distributions of variables mostly at the surface. For the outer Gulf of Oman and the northern Arabian Sea, the intrusion was mapped by Rochford (1964) and Sabinin (1964), followed with quarterly maps of temperature, salinity, and oxygen by Wooster *et al.* (1967). Düing and Schwill (1967) argued for the region beyond the mouth of the Gulf of Oman that the spreading of the high salinity in the core layer can be described by only considering eddy diffusion. Wyrtki (1971: his charts 282, 283) again averaged all data and depicted an average depth of 260–270 m of the core layer poleward of 20N and to the head of the Gulf of Oman. A subset for two expeditions with closely spaced stations during spring 1961 was used by Premchand (1982) and Premchand *et al.* (1986) for mapping the core layer. Das *et al.* (1980) and Varma *et al.* (1980) depicted the geographical distribution of the intrusion on the basis of even more closely-spaced measurements, including CTD data, for spring 1974 but excluded the Gulf of Oman. Because of inadequate coverage, all these authors could not consider temporal dependence of the geographic distribution in the outer Gulf of Oman and the adjacent northwestern Arabian Sea except in very general terms, if at all. Five cruises between May 1975 and August 1976 by *Dr. Fridtjof Nansen,* however, with closely-spaced stations on sections in the Gulf of Oman and the northwestern Arabian Sea (Fig. 1), permit a temporal treatment and demonstrate short-term (months) variability, including apparent nonseasonal cessation of spreading of the core layer. Observations on these five cruises so far were merely sketched in some technical reports; e.g., Kesteven *et al.* (1981), or discussed in an unpublished master's thesis by Sandven (1979), who briefly treated the intrusion due to the outflow from the Persian Gulf.

2. Methods

First, newly reviewed are observations by *Meteor* during March/April 1965 (Brettschneider *et al.,* 1970) and *Requisite* during January/March 1961 (Peery, 1965; without oxygen) in the eastern Persian Gulf, the Strait of Hormuz, and the innermost Gulf of Oman over what sometimes is called the Biaban Shelf. Scant data from other years and seasons, including summer, are considered. For the Gulf of Oman and the Arabian Sea, the data for temperature, salinity, and oxygen by *Dr. Fridtjof Nansen* were obtained from the

Norwegian Oceanographic Data Center in Bergen. Being unpublished, they need to be described in detail as follows.

On the sections (Fig. 1) made by the 150-foot converted stern trawler *Dr. Fridtjof Nansen,* the station closest to the shore generally was placed in water of 20 to 30 m depth, and the next few stations were 20 to 30 km apart. In the open sea, the distance between stations varied between approximately 55 and (rarely) 110 km. The longest section used herein, P-1, extended for almost 500 km from the shore.

Water bottles with protected reversing thermometers were deployed at standard depths to 500 m (see Fig. 6), and salinity was determined onboard with an inductive salinometer. The quality was checked here by comparison with *T-S*-relations from *Meteor* (March 1965, Dietrich *et al.,* 1966), *Atlantis II* (March 1965), and *Mikhail Lomonossov* (summer 1966) for samples from 400 and 500 m in the same area (data of the latter two ships from the U.S. National Oceanographic Data Center, Washington, D.C. [NODC]). Seasonal variation in the depth interval was presumed to be small. These observations and the *Nansen* data generally deviated by not more than 0.05 ppt S from the average relation, without any obvious regularity. Even in this depth range, however, periods occurred when the scatter was larger and showed patterns among stations, suggesting real changes rather than artifacts (spring 1965, *Meteor* and *Atlantis II;* November 1975, *Dr. Fridtjof Nansen*). Because of the wide spacing of bottles at the depths of concern (150, 200, 250, 300, and 400 m), the core of the intrusion may not have been sampled accurately. Therefore, salinities herein often are rounded to the nearest 0.05 or 0.10 ppt; also, statistics are generally eschewed.

Concentrations of dissolved oxygen to 300 m depth were determined onboard by the Winkler method. The quality is excellent, since removed from the Gulf of Oman and in the sigma-*t* range of 26 to 27 g dm^{-3} where oxygen ranges between 0.1 and 0.2 (or 0.3) ml l^{-1}, the Gulf water intrusion is recognizable on almost every station by an intermediate increase of 0.05 to 0.10 ml l^{-1}.

The nominal depths were not corrected to true depths. Large wire angles visible at the surface, however, could be largely avoided (Dr. J. Blindheim, Bergen, *in litt.,* 1989). The hydrographic winch and davit of the ship were situated just aft of the bridge, with the wire clearly visible from there; also, the ship had two side thrusters. As a result, the densities on the full sections (A-3, O-3, see Fig. 1) at nominally 400 and 500 m depth are similar to those of other expeditions in the region. More importantly, the 500-m density is equal to or less than the 400-m value on an adjoining station only on 3 out of the 56 stations on the two sections, although the ship worked also during the southwest monsoon. Therefore, the main purpose of this paper, to sketch temporal changes in the occurrence of the Gulf water in the Arabian Sea, can be easily accomplished.

Descriptions of methods for other expeditions can be found in the papers cited. For *Lemura,* however, temperature and salinity for November 1977, April/May 1978, and August/September 1978 had to be read from sections and maps in Simmonds and

Lamboeuf (1981). Reversing bottles were used at 0, 10, 20, 50, 75, and 100 m on stations located at 37-km intervals on transects 110 km apart.

3. Mixing and the formation of the intrusion

a. Principles. In the absence of wind and tides, the outflow from the Persian Gulf would be a density-driven undercurrent. It and the concomitant surficial inflow through the Strait of Hormuz and the immediately adjoining waters would become irregular on a scale of days to weeks once wind-forced set-up on either side of the Strait is admitted. The actual currents around the Strait, however, are principally tidal as first noted in the context by Emery (1956). The velocities a few meters above the bottom largely exceed 0.5 m sec^{-1} and often are between 1 and 1.5 m sec^{-1} (see Hartmann *et al.,* 1971). These velocities suffice to destroy the stratification completely at least at times (Matsuyama *et al.,* 1994), which further interrupts a regular outflow, perhaps with a bi- or four-weekly periodicity.

The most drastic effect of tidal vertical mixing in the Strait was observed in December 1993 north of Musandam I., apparently during spring tides (Matsuyama *et al.,* 1994). A water column with a top-to-bottom density gradient <0.1 g dm^{-3} to the sea bed at 70 m was separated from the Persian Gulf by a sharp top-to-bottom salinity front, the salinity changing from about 37.6 to 38.4 ppt (ca. 1.0 g dm^{-3} in density). Other winter measurements in the Strait of Hormuz reviewed below suggest well-stratified water (cf. Figs. 2, 3), with the isopycnals deepening toward the Iranian coast. For none of these is the state of the tide known. However, as to be shown, in any season deep water of ≥40 ppt S rarely can travel around Musandam I.

b. Winter/spring observations of 1965. The exchange processes creating the intrusion of Persian Gulf water are principally illustrated by *Meteor* data from winter and early spring and are described in detail to make several points at the outset. In mid-April, around the Musandam Peninsula and to 26N, a 30- (up to 50-) m thick upper layer with a salinity nearly that of the Gulf of Oman overlay a wide pycnocline caused by salinity (GO and open and dotted circles in Fig. 2). The stratified lower part of this layer (very clear water, Ziegenbein, 1966, his Fig. 5b) indicated its origin from the Arabian Sea by a weak oxygen minimum (63 and 68% of saturation at the bottom of the layer at a sigma-*t* of 25.4 to 25.5 g dm^{-3}). In contrast, Gulf of Oman water was not present in the Persian Gulf in the same season of 1961 (cf. Fig. 3). At depth in 1965, water >40.0 ppt S did not extend around Musandam I. although it was present inside the Strait of Hormuz at 70 m (Fig. 2).

As observed on the shelf to the south and southeast of the Strait between the middle and the end of March 1965, Gulf of Oman water was encountered at 80 to mostly 100 m, below of which the about 25 m thick bottom current entrained ever cooler and less oxygenated water (cf. crosses in Fig. 2). Therefore, an intermediate oxygen minimum was present at the bottom of the top layer (see discussion of Fig. 4). The salinities in the bottom current had been reduced to 37.8 to 39.2 ppt, below a halicline with gradients of 2 ppt $(3\ m)^{-1}$ and 1.5 ppt $(2\ m)^{-1}$ (from Koske, 1972, his Figs. 11, 12). Marked horizontal density gradients

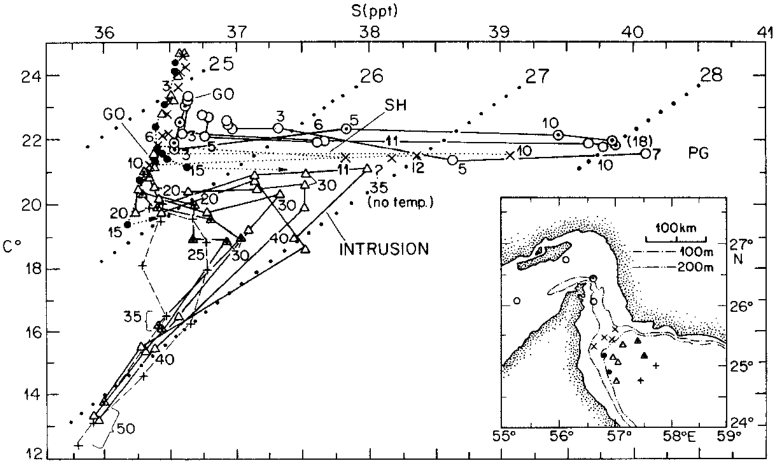

Figure 2. Temperature-salinity diagram for selected stations of *Meteor*, March-April 1965, with isopycnals (sigma-*t*; data from Brettschneider *et al.*, 1970). Inset, station locations with isobaths from Seibold and Ulrich (1970: Fig. 4). Open circles, stas. 272, 372, 380 (with inserted dot), 381; lying crosses and dotted lined, stas. 268–270, 382; filled circles and dotted lines, stas. 254, 255; triangles, stas. 256–259, 261, 262 (stas. 258, 259 with inserted dots, plotted from 100 m downward); upright crosses, stas. 265 (southwestern), 266 (northeastern; both plotted from 150 m downward). Numbers near station symbols, decameters. GO, surface water of the Gulf of Oman; PG, water of the Persian Gulf; SH, water on the shelf southeast of the Strait of Hormuz.

at 110 m suggest a strong south-setting bottom current. Off the Iranian coast, Gulf of Oman water of the same temperature as that at 100 m on the Arabian side was present to 200 m (not shown). Farther away from the Strait at 190 m bottom depth, the salinities had been reduced to 37.2 to 37.6 ppt (filled circles in Fig. 2).

To the east and southeast of these stations, with bottom depths ≥320 m, the upper layer extended to 200 m (triangles in Fig. 2). The modified outflow water had separated from the bottom (at 220 m depth, Ziegenbein, 1966, from CTD casts), permitting mixing with water below. The typical shape of the intrusion had formed: Salinity, temperature, and oxygen increased with depth in the upper part.

The maximal salinity of the newly-formed intrusion in late March 1965 was ≤38.0 ppt; sigma-*t* ranged from about 26.5 to 26.8 g dm^{-3}. In this range, clearly two intrusions were present at nearly the same density. The median temperatures, salinities, sigma-*t* values, and oxygen concentrations were, respectively, 18.85 and 20.74°C, 37.00 and 37.53 ppt, 26.49 and 26.60 g dm^{-3}, and 1.21 and 2.46 ml l^{-1}; only the ranges of density of the two groups of stations overlapped. Finally, at the southeastern-most stations (upright crosses in Fig. 2), the intrusion was poorly expressed although the proper density range had been sampled. The high-salinity, well-aerated water seemed to hug the western slope (right hand for the current) of the Gulf of Oman.

Thus, in 1965, (a) water ≥40.0 ppt did not leave the Gulf in spite of the absence of a marked sill, presumably because of tidal mixing; (b) The salinity of the water traveling

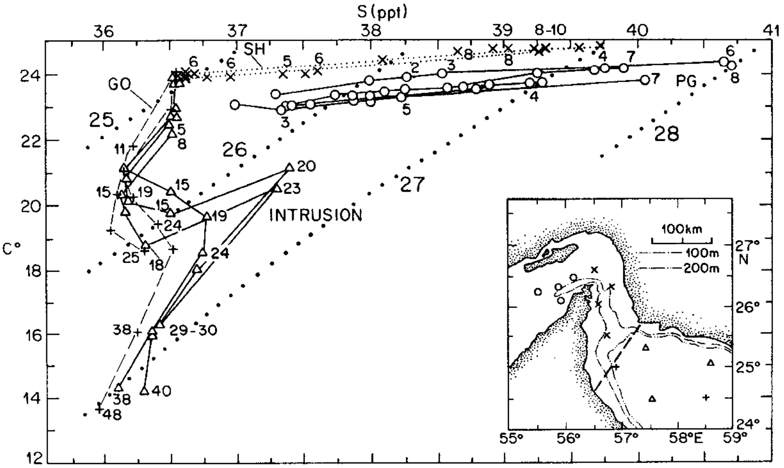

Figure 3. Temperature-salinity diagram for selected stations of *Requisite,* January 1961 (PG for Persian Gulf in Peery, 1965) and mid-March 1961 (AS for Gulf of Oman and Arabian Sea), with isopycnals (sigma-*t*). Open circles, stas. PG 28, 30–32; lying crosses, PG 36 (repeated series), 37, 41, 42 (repeated series); upright crosses, PG 43 (bottom near 250 m), AS 4 (southeasternmost station of inset with least prominent intrusion, at 280 m); triangles, AS 1-3. See also Figure 2. Broken line across the Gulf of Oman in inset, section O-1 of *Dr. Fridtjof Nansen.*

downslope was 38 to 39 ppt, and the approximate density of the intrusion was being established at about 100 m bottom depth within and just outside the Strait of Hormuz; (c) After the saline water separated from the sea bed, the density gradient continued to be relatively marked at the upper side, more so than on the underside of the intrusion, as is true also in the open Arabian Sea; (d) Below the intrusion to almost 500 m, the vertical gradient of density was very small, in contrast to winter 1961 (cf. Figs. 2 and 3).

c. Winter/spring observations of 1961. Qualitatively, *Requisite* in January encountered the same situation as described for winter 1965, the principal quantitative differences being as follows. (a) The water in the eastern Persian Gulf was warmer by about 1°C than in 1965. Also, the mixing product in the inner Gulf of Oman (lying crosses, of mid-March 1961) was warmer by another degree, so that source water for the intrusion, flowing down the slope, in the winter of 1961 had about a 2°C higher temperature than in 1965. (b) North and east of Musandam I., the dilution of the outflowing water (lying crosses in Fig. 3) had not proceeded as far as in 1965, salinities at the northernmost station reaching 39.7 ppt in one out of eight casts at an anchor station (range, 38.6–39.7, median 39.6 ppt). As in 1965, water $\geq$40.0 ppt S had not made it around Musandam I. (c) The intrusion interleafed at a depth 70–100 m shallower than in 1965 because of lower density (26.3 to 26.4 g dm^{-3}).

In May 1961 inside the Strait of Hormuz, *Commandant Robert Giraud* recorded a bottom water density (sigma-*t*) of up to 28 g dm^{-3}, as in January (Fig. 3), but now due to low salinities near 39.5 ppt and low temperatures between 21 and 22°C (data from NODC).

On the Omani end of an approximately north-south section just east of 57E, a salinity as high as 37.97 ppt at 21.4°C was observed near 300 m (bottom near 350 m). Near 24N, 59E, the highest measured salinity in the core layer was 37.4 ppt. The intrusion spread at a density (sigma-*t*) about 0.2 g dm^{-3} greater than in March 1961, but similar as in winter/spring of 1965.

d. Winter observations of 1967. A February section by *Atlantis II* yielded essentially the same picture as the 1961 observations (stas. 2365 and 2366, Brewer *et al.,* 1978; cf. Brewer and Dyrssen, 1985, their Fig. 4). Once again, water ≥ 40 ppt from the western end of the Strait of Hormuz did not mix directly with the Gulf of Oman water at 250 to 300 m depth, but first was transformed within the Strait of Hormuz and on the shelf to the southeast into water with a sigma-*t* of ≤ 27 g dm^{-3}. This time, a salinity as high as 39.3 ppt (sigma-*t*, 27.76 g dm^{-3}) had reached 150 m depth, and the density of the core layer, once formed, was near 26.4 g dm^{-3} (36.9 ppt S, 290 m depth; the only datum of the cruise).

e. Seasonal data by Lemura. The measurements, made in November 1977, April/May 1978, and August 1978, extended only to 100 m. They suffice to show that outflow was present during all cruises but water of ≥ 40 ppt S did not traverse the Strait of Hormuz. In August, water with ≥ 38 ppt S in the easternmost Persian Gulf ranged between 27 and 34°C so that the *T-S* diagram did not resemble Figures 2 and 3.

f. Winter and summer cruises by "Mt Mitchell," 1992. In early March, the highest salinity close to the bottom near 85 m north of Musandam I. was about 39.5 ppt (sigma-*t*, 28 g dm^{-3}). The salinity in two lenses of intrusion of similar density in the Gulf of Oman at about 25N was just above 37 ppt. The temperatures in these lenses were ≥ 19 and ≥ 21°C. In early June on a north-south section at about 57°15′E, just west of the tip of the Arabian Peninsula, water with slightly above 40 ppt S and as cold as 19–20°C was present between 70 and 85 m close to the sea bed. A few ten kilometers farther to the east, the salinity had declined to approximately 37 ppt (from Reynolds, 1993, Figs. 12, 14). On the same days, however, the highest salinity in the intrusion in the middle of the Gulf of Oman near 25N, 150 km removed and certainly subjected to further mixing with low-salinity water, was somewhat above 37.5 ppt.

g. Summer observations of 1948. The only other summer section was occupied by *Massey* in mid-August 1948 (Emery, 1956; data in Dubach, 1964). Samples were taken to ≤ 100 m except at one station in the Gulf of Oman and Station 10, above the hole of about 200 m depth off Musandam I. (not shown on the inserts of Figs. 2 and 3). The critical stations, 16 km apart, are the more northwesterly Station 10, immediately north of the island and station 9, to the east on the western slope of the valley exiting the Strait of Hormuz (bottom depth, 123 m). The upper layer of Station 9 was essentially the same as that farther down the Gulf of Oman, but it was separated from Station 10 by a salinity difference of ≥ 0.7 ptt (a front ?). The *T-S* diagram for the two stations suggests marked differences also at depth, similar salinities (40.3 ppt at Station 9, 90 m; 40.1 ppt at Station 10, 100 m [40.5 ppt, 200 m]) being accompanied by temperatures that differed by 1.6°C (24.2 and 22.8 [22.8] °C, respectively). This is the only observation of water >40.0 ppt having traversed the Strait of Hormuz.

h. Five cruises between May 1975 and September 1976. The unpublished observations by *Dr. Fridtjof Nansen* concern only the already-formed core layer at or just beyond the shelf break in the upper Gulf of Oman (section O-1, Fig. 3, insert). The highest salinities on the O-1 (and O-2) sections during the cruises were 37.50 (and 37.75) in May and 37.65 in October 1975, 37.75 (and 37.85) in March, 37.60 in June (only O-2), and 38.00 ppt in September 1976. (For September, see also below.) The densities (sigma-*t*) for these samples ranged between 26.30 and 26.65 g dm^{-3}. Clearly, the intrusion was always present.

Possibly during late summer at the head of the Gulf of Oman, advection and mixing can work differently than described so far: A 150-m deep O-1 station on the Omani slope in early September 1976 at 140 m yielded 38.30 ppt S (!), 26.30 g dm^{-3} (sigma-*t*), and 1.7 ml l^{-1} of oxygen (36% saturation, see Fig. 5c); the temperature was 23.6°C, clearly unusual (cf. Figs. 2, 3). Apparently, saline water from the Strait of Hormuz, of perhaps 24°C, had mixed with Gulf of Oman water of 22°C, the only source available at this depth, instead of with the normally entrained colder water farther down the slope. In contrast, the adjoining 289-m station, 52 km seaward, showed normal intrusion water from mixing of the same Hormuz source (or one almost as saline) with Gulf of Oman water of 18 or 19°C. The deepest sample (250 m; sigma-*t*, 26.65 g dm^{-3}) had a temperature of 21.5° and a salinity of 38.0 ppt and is presumed to be near or in the core of the intrusion. The salinities of 38.0 and 38.3 ppt are the highest intrusion values in the present data sets (cf. one other like value in Fig. 3). The warm water of 1976 is similar to that in August 1948, when >40 ppt S had passed beyond the Strait of Hormuz.

As the conclusion of the entire section, the formation of the water type spreading into the Gulf of Oman and the Arabian Sea as an intermediate salinity maximum takes place in two stages, first during the tidal mixing in the Strait of Hormuz, second, by further entrainment while traversing the continental slope at the head of Gulf of Oman. There is neither a single salinity at the origin of the intrusion that may be used as an end member for studies of the spreading of the Persian Gulf water in the Arabian Sea, nor a single value or narrow range for density. The salinity range is 37.5–38.0 ppt, and that of density, 26.30–26.95 g dm^{-3}. Grand averages cannot be calculated in view of the bottle spacing and the likelihood, on all expeditions, of not having encountered the very center of the core layer(s). Therefore, the maximal value at least for salinity at the head of the Gulf of Oman may be even higher.

There is marked short-term (months) variability inside and outside the Strait of Hormuz, making the prediction of the water composition at the point of origin of the intrusion (the end member value) difficult. Examples come from winter/spring 1961 (Fig. 3, lying crosses *versus* triangles at about the same density), less so from the same period of 1965, again strongly from 1975/1976, and from 1992. The synoptic data within cruises from the Gulf of Oman demonstrate the complexity of the outflow regime and point to the danger lurking in interpretations, owing to the confounding of time and space for any along-Gulf section.

4. Initial ventilation of the intrusion

Aside from *in situ* consumption, the oxygen concentration in the intrusion is due to the initial charge from the relatively well-oxygenated high-salinity water of the Persian Gulf, its mixing with, at first, poorly-ventilated subthermocline water above it and, after lift-off from the bottom, entraining deeper water of the Gulf of Oman that is even lower in oxygen content. Only the stations of *Meteor* and *Dr. Fridtjof Nansen* can be used.

Figure 4a for March 1965 illustrates the initial mixing product on the shelf outside the Strait of Hormuz (open circles and lying crosses; see also Fig. 2), followed downstream by the establishment of the oxygen minimum between the saturated surface water and the intrusion. The same minimum is apparent in Figures 4b, c.

As expected, oxygen saturation in the intrusion during all cruises correlates with salinity, the variable with a high signal/noise ratio (Figs. 4 a–c). The same trend holds for the oxygen concentrations (not shown). However, oxygen concentrations at a given salinity varied greatly between cruises. In October 1975, the saturation was about $^4\!/_{10}$ that in May 1975 at the same salinities, and the slope of the S-O_2 relation had also changed. Because of the generally observed, relatively rapid changes of water masses, it is suggested that this difference does not reflect consumption of oxygen, but differing initial concentrations during formation of the intrusion. In fact, the change of slope was not observed during 1976, although also then, the highest oxygen concentrations and saturations occurred in spring (Fig. 4c). Thus, the apparently seasonal differences in oxygen in the newly-formed intrusion seem to be caused principally by varying supply from the Persian Gulf.

The supply may vary seasonally, but the properties of the mix will also depend on the density of interleafing into the intrusion. Note that the oxygen minimum in the Arabian Sea proper is at temperatures well below those in Figure 4 (Wyrtki, 1971, his chart 318). Thus, a higher density of the newly-forming intrusion would lead to interleafing at greater depth, hence, to colder and less-oxygenated water above the intrusion. The lowest saturation values in the oxygen minimum above the intrusion were encountered during the late- and post-southwest monsoon seasons of 1975 and 1976, while the highest were found in March 1965 and spring 1976 (Figs. 4a–c). For the post-monsoon, a similarly low value of 21% saturation at 37.45 ppt was observed by *Charles Darwin* in late September 1986 somewhat to the east of the middle of the O-1 section (Mantoura *et al.*, 1993, Station 11). The winter highs of saturation are supported by the one relevant *Atlantis II* Station 2366 of February 1977. Indeed, among the six cruises (with two intrusions for *Meteor,* see Section 3; thus, $n = 7$), the median and the minimal temperatures at the oxygen minimum are negatively correlated with the density at the maximal salinity in the intrusion during a cruise

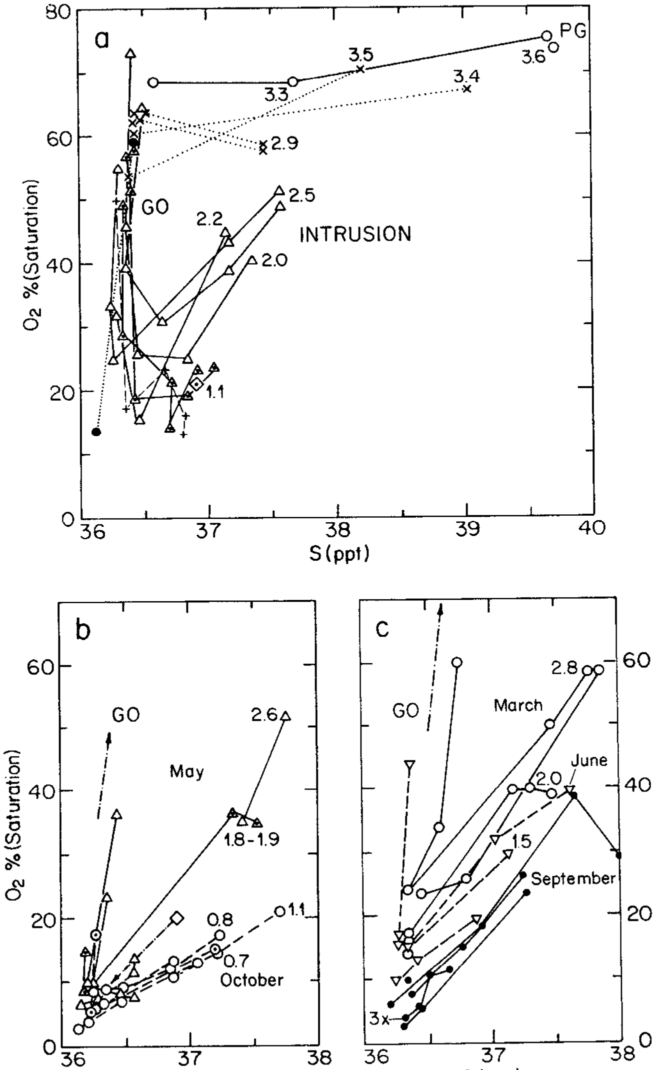

Figure 4. Oxygen saturation in the inner Gulf of Oman plotted on salinity for densities (sigma-t) > 25.50 g dm^{-3} (>25.45 for *Meteor*) for stations where the high-salinity water had lifted off the bottom, except for the circles and lying crosses in Figure 4a. Values from below the salinity intrusion usually omitted. For clarity, not all symbols are connected by lines. Numbers within panels, O_2 (ml l^{-1}, rounded). (a), *Meteor*, March 1965. Data source and symbols as in Figure 2 for the same stations, except circle for Station 381 southeast of the tip of the Arabian Peninsula (not on insert in Fig. 2); diamond, *Atlantis II*, February 1977, Station 2365 (middle Gulf of Oman, near 57E; from Brewer *et al.*, 1978). (b, c), *Dr. Fridtjof Nansen*, 1975/76, O-1 and O-2 sections for indicated months. Symbols varied for clarity; arrows in left upper corners of panels point to surface layer. (b) 1975. triangles, May; diamond, maximum at Station 210 on P-1 section, arrow pointing to the sample from the oxygen minimum above the intrusion; circles, October. (c), 1976. Open circles, March; inverted triangles, June; filled circles, September; 3×, three samples.

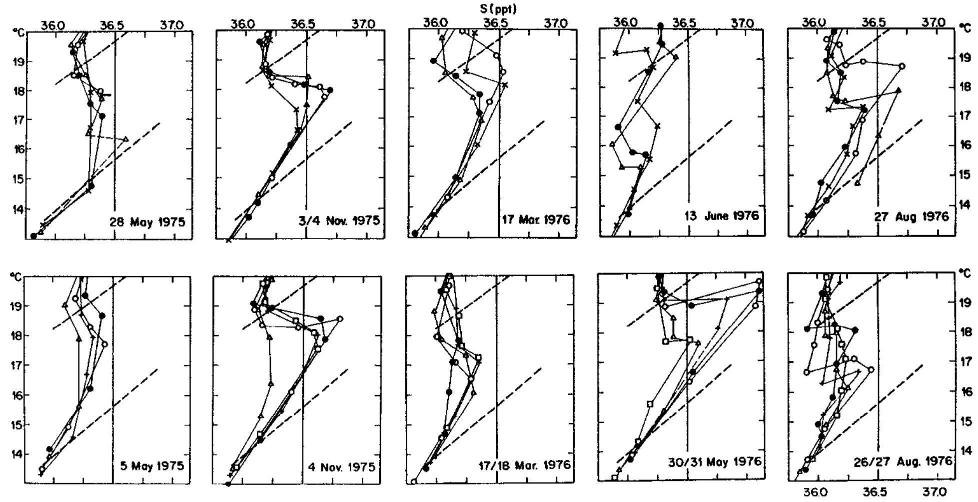

Figure 5. Temperature-salinity diagrams for the sigma-*t* range bracketing the Persian Gulf intrusion (26 and 27 g l^{-1}) on the four southern stations of section O-3 (upper panels) and the five western stations of section A-3 (lower panels). For locations of sections, see Figure 1. From the shore outward, stations on O-3 are signified by open circles, filled circles, triangles, and lying crosses. The sequence for A-3 is squares, upright crosses, open circles, filled circles, and triangles.

($r = -0.934$ and -0.955, respectively; for both, $P < 0.01$). Also here, seasonality is apparent.

Like for salinity, the variability within cruises in the mixing products is apparent for oxygen; e.g., the two high values of 2.85 and 3.5 ml/l in March 1976 (Fig. 4c) near a density of 26.3 g dm^{-3} for one station each at the O-2 and O-1 sections, 80 km apart. Both samples occupied nearly the same position in the *T-S* diagram.

In conclusion, there is no single end member value for the oxygen concentration in the core layer at the origin. Future oxygen budgets for the Arabian Sea will have to operate with ranges.

5. The Gulf intrusion in the outer Gulf of Oman and the open Arabian Sea

The new hydrographic data of *Dr. Fridtjof Nansen* of 1975/76 permit the first treatment of the temporal aspects of the intrusion across the mouth of the Gulf of Oman and on an adjoining west-east section into the Arabian Sea (Fig. 1). Figure 5 shows that most stations on the five cruises sampled the density range of the core layer. Therefore, the failure to observe the high-salinity water on some cruises is not an artifact of water bottle spacing. Also, with the close proximity of stations nearshore, a bottom current hugging the slope of Oman would have to have been of small cross section to escape observation in terms of salinity.

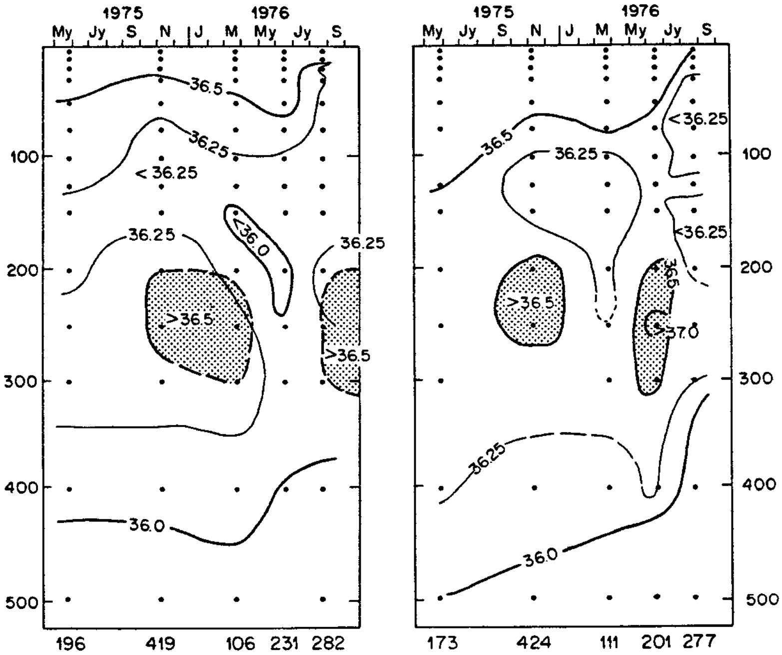

Figure 6. Isopleths of salinity (ppt) for one station each on section O-3 (fourth station, about 120 km from the shore; left panel) and section A-3 (second station, about 30 km from the shore; right panel); both stations are signified by filled circles in Figure 5. Darkened areas, >36.5 ppt. Broken 36.5-isohalines in the left panel indicate conditions on the offshore part of the section. Station numbers below panels.

a. May–June 1975. At the end of May on section O-2, peak salinities on all stations were ≥36.6 ppt. In contrast, the salinity of the core layer on A-3 (early May) and O-3 (late May) did not exceed 36.45 ppt except possibly on O-3 off the Omani slope at 400 m (36.60 ppt, see Figure 5, 28 May, triangle; 100 m deeper than elsewhere, including the slope stations of the same day). Otherwise, the intrusion was weakly expressed or absent (Figs. 5, 6).

One month later, however, one station away from the offshore end of the P-1 section, the salinity in a pronounced core layer at 250 m reached 36.90 ppt, being accompanied by an oxygen saturation of 22% (1.11 ml l^{-1}). The salinity and oxygen saturation at 300 m were also high, 36.71 ppt and 14%, respectively. Both salinities exceeded any other below the mixed layer of the station so that false tripping of the bottles is not involved. This relatively little diluted Gulf water, almost 1,000 km from the Strait of Hormuz, was neither present on the adjoining stations 55 km to the north and south even though the density at 250 m was almost identical to that at the station at issue, nor on sections O-3 and A-3 (cf. Fig. 5 for parts thereof).

b. November 1975. The intrusion was well established on the O-3 and A-3 sections (Figs. 5, 6), median salinities in the intrusion being 36.45 ppt ($n = 7$; one sample each with

36.65 and 36.70 ppt) and 36.65 ppt ($n = 4$; max., 36.80 ppt), respectively. Off Pakistan (P-1 section, one station from the offshore end), salinity reached 36.30 ppt at a few depths and a maximal value of 36.55 ppt (with 0.43 ml l^{-1} O_2, 8% saturation; sigma-*t*, 26.43 g dm^{-3}).

c. March 1976. The salinities on the O-3 and A-3 sections had appreciably declined, especially on A-3 (Figs. 5, 6). The medians of the intrusion on the two sections were 36.40 ppt ($n = 7$) and 36.35 ($n = 4$), respectively. On the innermost station of A-3 (open circle in Fig. 6, lower panel), however, the core of intrusion occurred at lower density and depth than at the other stations; the oxygen content was appreciably higher (10 and 12% saturation) than that at the same density or in the core of the intrusion on the other stations of the section, which signifies different water. Off Pakistan, high salinity values of note were not recorded in the salinity maximum, the median being 36.25 ppt ($n = 10$).

d. May/June 1976. In late May 1976, a large part of the A-3 section was conspicuously occupied by intrusion water with a median salinity of 36.70 ppt ($n = 7$), which was separated from high-salinity water in the inner Gulf of Oman by the low-salinity water on the O-3 section (Fig. 5). On A-3, the maxima on two stations reached 37.10 ppt (2 samples on one of the stations) and 37.15 ppt on Station 201 (Fig. 6), but neither these, nor the one station with a relatively high core salinity on O-3 were those nearest to the Omani shore, as one might expect from a south-setting current. The density (sigma-*t*) in the core on the A-3 section ranged from about 26.45 to 26.70 g dm^{-3}, higher than in March. The oxygen concentrations from several depths on A-3 exceeded 1 ml l^{-1} (up to 1.49 ml l^{-1}, 29% saturation). A pronounced intrusion was encountered in June off Pakistan only on the station next to the offshore end of the P-1 section, accompanied by elevated oxygen (36.60 ppt, 12% saturation).

e. August/September 1976. In late August 1976, the salinities in the core layer on the A-3 section were much lower than on O-3, the medians being 36.40 ppt ($n = 6$; two stations with 36.70 ppt) and 36.35 ppt ($n = 4$), respectively. No change was observed off Pakistan.

f. Summary. The principal feature of the observations by *Dr. Fridtjof Nansen* is the rapid (on the scale of a few months) change of salinity in the mouth of the Gulf of Oman, as well as on the A-3 section that extends far into the northern Arabian Sea. The intrusion was very weakly pronounced or absent on sections O-3 and A-3 during May 1975, but was strongly present on A-3 and weakly on O-3 during June 1976 (Figs. 5, 6). During March 1976, the intrusion was clearly present on O-3, but weakly developed on A-3; the situation was again reversed in August 1976. As seen from Figure 5, the spacing of water bottles was adequate. The interpretation, thus, is intermittent, relatively rapid but brief advection of relatively well-ventilated water at depths of roughly 250 to 300 m into the open northwestern

Arabian Sea. Because of the difference between the two pre-monsoon seasons of 1975 and 1976, this advection is unlikely to be a seasonal feature.

6. Discussion

The first point to be made concerns the salinity and oxygen concentrations of the Persian Gulf intrusion at the origin. Any consideration of the intrusion or core layer in respect to its maintenance in, and its role for, the Arabian Sea will hinge on the salinity, as well as the effective volume in the inner Gulf of Oman when the intrusion lifts off the bottom. However, there is no single salinity that may serve as the end member for studies of mixing, etc., in the outer Gulf of Oman or the Arabian Sea. The salinity certainly may range between 37.5 and 38.0 ppt. Apparently, water $>$ 40.0 ppt S rarely makes it around the Musandam Peninsula. The densities (sigma-t) at the depths of the maximal salinities for the six cruises in Figure 4 ranged from 26.29 to 26.94 g dm^{-3} (for *Requisite,* 26.30 g dm^{-3}, Fig. 3; 26.65 for *Commandant Robert Giraud,* not shown). The maximal oxygen values in the core layer ranged between 0.8 and 2.8 ml l^{-1} (Fig. 4). The corresponding range of saturation was approximately 20–60%. It is not clear which roles variability in volumes of Persian Gulf water, including spring-neap tide periodicity (cf. Matsuyama *et al.,* 1994), vagaries of subsequent entrainment and other mixing on the shelf in the inner Gulf of Oman, and sampling variability may have played for the described data of the various expeditions.

Regrettably, nothing can be said about the volumes at the origin of the intrusion to which the above property ranges refer. Previous authors estimated annual transport volumes valid in or near the Strait of Hormuz from a water balance of the Persian Gulf by choosing salinity values for the in- and outflowing water. For example, Hartmann *et al.* (1971) used 39.70 ppt S for the outflow from *Meteor* data of 1965 for the shelf southeast of the Strait. Hassan and Hassan (1989, from a manuscript by H. M. Hassan) cited a mean of 37.5 ppt for the outgoing water "close to the Arabian side of [the Strait of] Hormuz," which I believe to have been on the low end. Both papers, however, were concerned with the Persian Gulf. For an oxygen balance in the oxygen minimum of the central Arabian Sea, Olson *et al.* (1993, p. 678) used an end member of 38.2 ppt S (from Koske, 1972, for winter/spring 1965) and (p. 680), an O_2 concentration of 3.5 ml l^{-1} (based on Wyrtki, 1971, in turn based on Brettschneider *et al.,* 1970, also for winter/spring 1965). This last number is in my view on the high side, since it was the concentration in the Strait of Hormuz (see Fig. 4a herein, open circles and lying crosses). Judging the role of the outflow from the Persian Gulf for the Arabian Sea in quantitative terms will require repeated cruises by an investigation like that by Price *et al.* (1993) for the Mediterranean outflow.

The second point concerns the sites of entrainment of Gulf of Oman water into the outflow. From Figures 2 and 3 and the reduction of density by about 1 g dm^{-3} across a tidal front in the Strait of Hormuz (Matsuyama *et al.,* 1994) it appears that part of the entrainment takes place in the Strait, presumably greatly and periodically modulated by the tides. The other part occurs when the outflow travels downslope across the outer shelf toward the depth of separation from the bottom. In contrast, Price and Baringer (1994) had suggested for such outflows that the principal entrainment occurs during the down-slope travel and modeled only a single layer or bottom current moving through an ocean at rest.

The third point concerns the downstream irregularity of occurrence of the intrusion in space and time, which results at least in part from the vagaries of formation in the Strait of Hormuz and on the shelf to the southeast. Side-by-side presence of two water masses near the head of the Gulf of Oman was noted in August 1948, late March 1965, March, June and August/September 1976, and March 1992, which is very frequent relative to the total number of observations. The instances depicted in Figure 6 for the mouth of the Gulf of Oman and southwest of it are further evidence and point to a strong *temporal* component of advection. Perhaps, the offshore movement of high-salinity water into less saline water of very similar density is comparable to the processes at the exit of the Red Sea ("Reddies," Shapiro *et al.,* 1994). In contrast, Baringer and Price (1997) for the Mediterranean outflow showed the role for the mixing product of *spatial* differentiation, since outflowing water hugging a slope over some vertical distance will mix with different ambient water, depending on the particular depth considered (cf. the discussion herein of the processes during descending the shelf for 1965, and Fig. 2).

For the mouth of the Gulf of Oman, the drastic effect on temperature stratification of the advection of water of slightly variable density is illustrated by *T-S* diagrams from CTD traces of *Charles Darwin* near the Arabian ends of sections A-3 and O-3 (Currie, 1992, his Fig. 12). This vertical inhomogeneity of water masses persists even farther from the origin of the core layer. For example, interleafing was recorded near 23N, 63E, about 350 km from the shoreward origin of section A-3 in Figure 1 (Somayajulu *et al.,* 1980; salinity in the core approximately 36.2 ppt), and even in the upwelling region off Arabia near 16N, 55E, approximately 800 km from the end of section A-3 (Hamon, 1967: Fig. 4a; core layer salinity only 35.8–36.0 ppt).

Massive horizontal advection of lenses, however, might be relatively rare, since oxygen values >1 ml l^{-1} apparently are not common in the core layer of the Gulf water at about 22.5N, the approximate latitude of the A-3 section (e.g., Das *et al.,* 1980, for spring 1974; *Atlantis II* data for March 1965, as reviewed herein but not shown). Yet, near the offshore end of the P-1 section of *Dr. Fridtjof Nansen* almost 1,000 km from the Strait of Hormuz and about 450 km from the northeastern tip of the Arabian Peninsula, the core salinity at 250 m in May 1975 was 36.90 ppt (oxygen concentration, 1.11 ml l^{-1}). Note that this apparently rare event occurred deep in the principal pycnocline. There is nothing like it in earlier data sets, the nearby values in the core layer reaching $\leq$36.4 ppt ppt (1961, from water bottles, Premchand, 1982; 1963, from water bottles, Düing and Koske, 1967; 1974, from CTD traces, Das *et al.,* 1980, and Varma *et al.,* 1980; averages in Wyrtki, 1971: chart 283). Such an instance of advection argues against modeling the spreading of Persian Gulf water in the Arabian Sea only by eddy diffusion, as done by Düing and Schwill (1967).

The fourth and last point is the lack of an obvious seasonality in the overall result of the processes at the source region or at the mouth of the Gulf of Oman (cf. the two May/June cruises in Fig. 6), except the trend in oxygen content of the core layer near its origin. This is in contrast to the outflow from the Red Sea, which in winter was stated to be approximately ten times that in summer (Shapiro *et al.,* 1994). For the open Arabian Sea, though, the quarterly means for 2.5° by 2.5° squares (Wooster *et al.,* 1967) indicated the widest southward extent of the 36.0 ppt isohaline during March-May. Shenoi *et al.* (1993), using Levitus' (1982) compilation, detected differences in the spreading of the Persian Gulf intrusion between November-January, the period with the greater horizontal extent, *versus* May-July.

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