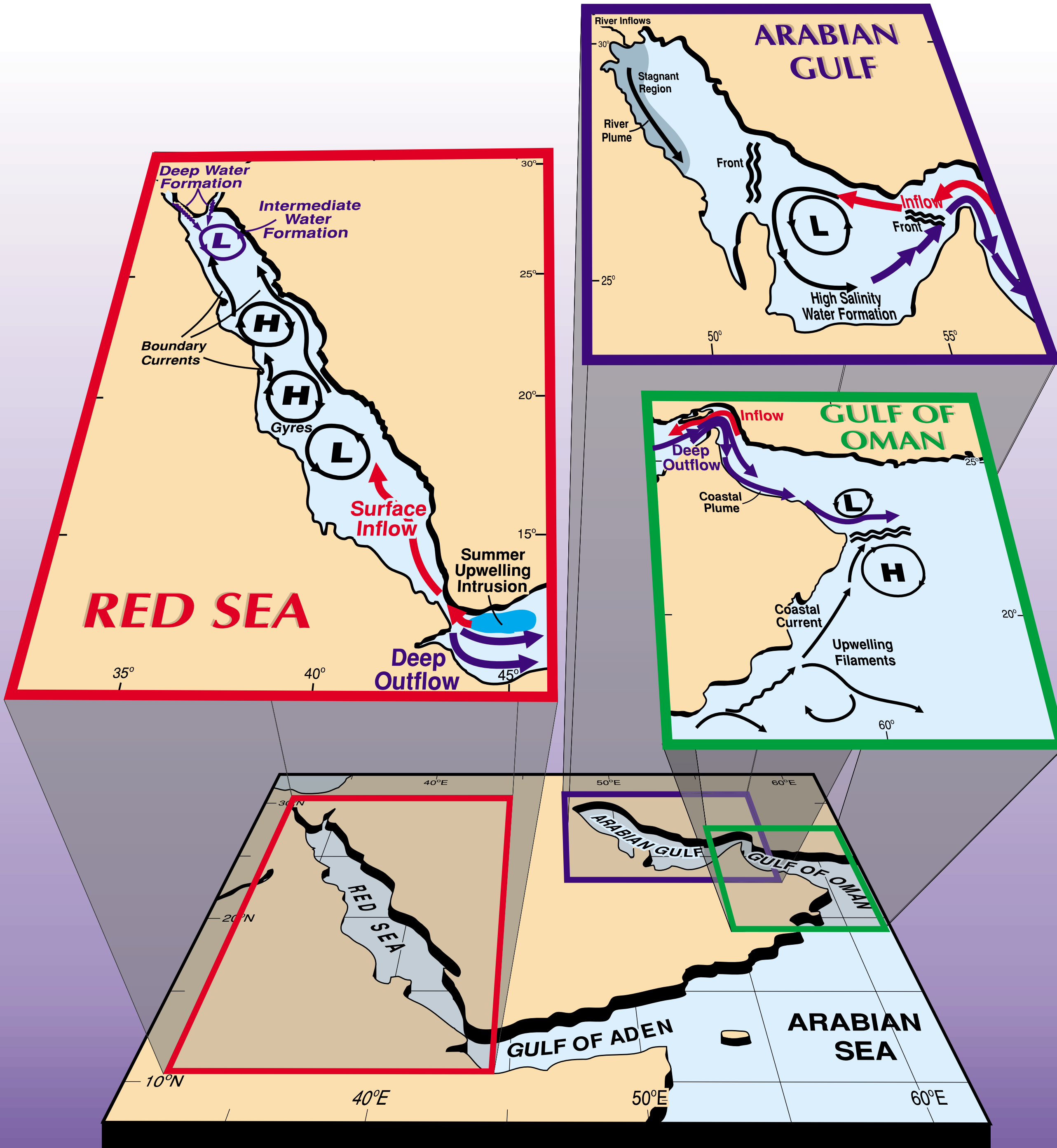
Arabian Marginal Seas and Gulfs



Report of a Workshop Held at Stennis Space Center, Mississippi

May 11 - 13, 1999

Sponsored by the Office of Naval Research

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Executive Summary

The region of the Arabian Marginal Seas and Gulfs (AMSG) continues to be of paramount importance to the world community for a variety of economic and political reasons. The immense petroleum resources and their maritime export from the region and the complex evolution and conflict of competing political entities are constantly demanding attention.

With the African continent to the west, Mediterranean Europe to the north and Pakistan-India-China to the east, the AMSG region is a striking geopolitical crossroads. Unquestionably, the dominant geophysical phenomena affecting the oceanography and meteorology of the region is the Arabian Monsoon which extends from the African coast, half way up the Red Sea, all along the Yemeni-Omani coast, affects the entire Arabian/Persian Gulf and reaches eastward into India, thus binding together - at least at the large scale - the political and geophysical environments. Net evaporation rates of several meters a year also characterize these marginal seas by generating high salinity/high density water masses which fill most of their interior volumes. The air-sea interaction physics of this hyperdense water mass formation, its rate and areas of location, and the details of its exit through the bounding straits and its cascade into the surrounding basins remain some of the most challenging problems of physical oceanography.

In May 1999, over 50 atmospheric and oceanic scientists gathered together at the Stennis Space Center to assess our knowledge of this region and identify pathways forward in understanding the physical system regulating these marginal seas and gulfs. Each of the key components of the region is individually important and each presents complex scientific questions unto itself. One of our primary intentions, however, was to seek connectivity across the AMSG region.

On the western side of the AMSG region lies the elongated trench of the Red Sea extending north-south over 18° of latitude. Its deep central channel of over 2000 m depth is interrupted by its relatively narrow and shallow entrance strait at Bab el Mandeb which leads into the deep bounding Gulf of Aden providing the link into the Indian Ocean. At the eastern end of the AMSG region the Arabian/Persian Gulf differs notably in that it is quite shallow (less than 50 m deep) over its entire extent and its entrance strait (Hormuz) notably has no blocking sill. Interestingly, the Arabian Gulf/Hormuz complex also has a deep gulf (Gulf of Oman) linking it to the Indian Ocean which is surprisingly similar bathymetrically to the Red Sea's Gulf of Aden. The long littoral region of the southern Arabian Peninsula (now well known for intense upwelling filaments) stretches along the Yemeni and Omani coasts and links the marginal sea complexes. An obvious first order question then is: ’Has the unifying influence of the Arabian Monsoon and the intense regional evaporation impressed some order on the dynamics controlling the circulation across the AMSG’? The Workshop steering committee posed a more focused central theme, i.e., to determine ”what is needed in terms of model development, theory, and observations to significantly improve capabilities for modeling to marine environment and variability of the AMSG region”.

Key factors emerge from the exhaustive review of existing knowledge in this document. With regard to the atmospheric forcing, the interaction of the monsoon winds with the high mountains bordering much of the AMSG appears critical to obtain correct model driving. The high moisture flux of globally significant magnitude from the AMSG seas to the atmosphere is enhanced by the extreme aridity of the bordering lands and leads to the thermohaline exchange believed to be the primary driving mechanism for the large scale circulation. What are perceived to be strong seasonal variations in wind strength and moisture fluxes remain largely unresolved.

Arabian/Persian Gulf - Strait of Hormuz

Due its shallow nature the Arabian/Persian Gulf appears to be influenced by both wind driven and thermohaline forces. The persistent southward wind stress, at least in the northern half of the Gulf, appears to set up coastal current regimes along both the Saudi (downwelling) and Iranian (upwelling) coasts. A persistent thermal front across the Arabian Gulf about the latitude of Qatar appears related to the thermohaline exchange through the Hormuz Strait. Freshwater input from the Iraqi Shatt-al-Arab waterway is expected to amplify the Saudi-Emirate coastal current. Modeling results suggest a number of sources for the deep-water formation that dominate the thermohaline field but observations are required to validate and direct the modeling premises. Despite years of high profile visibility it is surprising to learn that the details of the interior circulation of the Arabian/Persian Gulf remain essentially unobserved, not only for the coastal currents but also in the broad interior. The Hormuz Strait has recently been the subject of a reconnaissance level study that has identified an important circulation feature in the surface layer. The surface inflow layer, rather than being laterally uniform, appears from satellite data to preferentially outflow on the western (Omani) side into an organized coastal current that transits along the Emirate and Omani coast to the major promontory of Ras al Hadd. A major front and accompanying jet form at the collision of this Gulf outflow and the eastward flowing coastal current along the southern Arabian margin. The Ras al Hadd front appears to be the major thermal-optical-acoustical feature in the region. After transiting the Strait of Hormuz the Arabian/Persian Gulf deep water strongly influences the northern Gulf of Oman. After its cascade down the slope into the Gulf of Oman the deep outflow is suspected to be dominated by sub-mesoscale eddies as it equilibrates and moves toward the Indian Ocean. It was concluded that definitive observational studies to not just validate models but to identify key physics and physical processes necessary for inclusion into models are sorely lacking in the Arabian/Persian Gulf - Gulf of Oman complex.

Red Sea - Gulf of Aden

The Red Sea is similar to the Arabian/Persian Gulf in that it also acts as an inverted estuary. Dense salty water formed by evaporation is involved in deep convection in the northern Red Sea eventually flowing out into the Gulf of Aden underneath a fresher inflowing layer. In contrast to the Arabian Gulf, however, the exchange flow in the Red Sea entrance strait is highly seasonal with maximum outflow in winter. The seasonal reversal of the monsoon and local coastal configuration combine in summer to force a radically different circulation pattern composed of a thin surface outflow, an intermediate inflowing layer of Gulf of Aden thermocline water and a vastly reduced (often extinguished) outflowing deep layer. The dense outflow is known to spill down into the Gulf of Aden and is thought to evolve into mesoscale eddies (Reddies). The horizontal circulation inside the Red Sea based only on drifters and model results appears to be a number of energetic gyres or eddies distributed along the length of the basin.

The Gulf of Aden itself is seen in satellite images to be 'choked up' with large eddies, mostly anticyclones. These features appear to propagate westward from the mouth of the Gulf toward the Red Sea and their origin may be linked to the propagation and decay of eddy features in the western Arabian Sea.

Arabian Margin

Upwelling favorable winds along the coasts of Somalia, Yemen and Oman typically begin in May and ship drift records reveal the resulting presence of a northeastward flowing Oman Coastal Current (OCC) whose speeds reach 40 cm/s and extend 200 km offshore.

This current turns offshore to the east off Ras al Hadd and is associated with the Ras al Hadd front. Filaments and jets escape the Omani coast in this location capable of exporting cool, optically active, upwelled waters hundreds of km offshore.

The reversal to the Northeast or winter monsoon in November significantly alters the dynamical picture by causing the reversal of the Oman Coastal Current to southeastern flow. It is inferred from available evidence that a southward current now extends all along the northeast coast of Oman, successfully turns the corner at Ras al Hadd, and continues south until it is entrained into offshore-directed squirts and jets south of 20°N. SST images suggest that eddies are generated from the breakdown of the previous current system that then propagate southward along the coast. Studies have shown that eddy kinetic energy dominates over that of the mean flow and is confined to the littoral region. Obviously strong mesoscale variability in water mass properties, e.g. optical and acoustic transmission must be expected in this region.

With respect to connectivity across the AMSG region, our review of existing knowledge has to now emphasized differences rather than similarities, e.g., the variation in the atmospheric forcing and especially the vastly different bathymetric constraints between the Red Sea complex and the Persian Gulf complex. Another example: tidal currents will be of first order importance inside the Arabian/Persian Gulf but of second order inside the Red Sea, and first order in both entrance straits. Hypersaline deep-water production appears to occur in totally different areas of the two marginal seas due largely to bathymetric contrasts.

Outstanding Questions and Recommendations

The final two sections of the report are a detailed listing of important scientific questions identified by the assembled specialists followed by a list of recommendations to push forward our understanding of the processes controlling the AMSG environment. In the topical area of exchanges between the marginal seas and the Indian Ocean the surface buoyancy fluxes are of paramount interest. Evaporation rates near extremely arid coasts, at very high sea surface temperatures and at low wind speed are critical questions to be answered. Spatial gradients and seasonal and interannual variability in the evaporative flux in the marginal sea basins are also identified as key questions. The Red Sea outflow is now well documented but the physics determining the seasonal cycle remains unclear, as does the role of hydraulic control and its possible transient nature. At Hormuz, the fundamental exchange cycle itself, its lateral variability and seasonal structure remain key questions.

The science panels also highlighted questions concerning water mass formation in both the Red Sea and Arabian/Persian Gulf. The generation areas and production rates of both deep and intermediate water remain unclear. The role of hypersaline water mass production in the shallow coastal waters of the Arabian/Persian Gulf appears critical to resolve for improvement of model thermodynamics. The horizontal circulation in the operationally important surface layer is poorly known due to lack of modern focused studies all through the region. Locations of gyres, eddies, and mesoscale features such as coastal boundary currents are suspected from anecdotal data but remain unverified or poorly resolved, both spatially and temporally. The pathways into the Indian Ocean and dynamical characteristics of both the Red Sea and Arabian/Persian Gulf deep outflow likewise pose important remaining questions after the initial descent stage. Large surface intensified eddies, probably optically and acoustically active, are known from satellite imagery to clog the Gulf of Aden. Questions concerning their origin, decay, effect on transport through the Strait, and effect on the deep outflow were all cited as important by the panel. The presence and behavior of such eddies in the Gulf of Oman remain unknown. The role of external influences on the AMSG region is highlighted by the 'great whirl' that forms south of Socotra during the Southwest Monsoon. Is the annual breakup of the great whirl the source of the eddies in the Gulf of Aden? Do the whirl waters advect primarily eastward and affect the Gulf of Oman, and thence via the exchange flow the Arabian/Persian Gulf?

The region poses many fascinating and complex questions dealing with biophysical interactions. The Ras al Hadd frontal region is thought to be a key element in the largest unexploited potential fishery in the world, involving interactions, not yet understood, between the coastal circulation, the filaments, and the front. The behavior patterns of critically important planktonic copepods that dominate the vertically migrating scattering layers demand attention. The effect of the presence of an extensive oxygen minimum zone (greatly diminishing biological activity), the large biomass of acoustically actively fish via their swim bladders, and the role of atmospherically delivered dust from the Omani deserts and the Indian subcontinent are among many other key questions.

The concluding section on Recommendations explicitly addresses the needs of models for improved surface fluxes and wind fields, improved climatology for model initialization, and establishment of metrics and observational benchmarks for model performance. A strong consensus indicated a hierarchy of model approaches is needed to advance understanding of the AMSG region and in particular the interconnectivity of the marginal seas, connecting gulfs, and the Arabian littoral zone that links them together. Both semi-enclosed seas models and regional models are recommended for a program of process studies involving: varying dynamical forcing (wind, buoyancy flux, strait flows), examination of mesoscale variability and eddy formation, and the relative roles of local and remote forcing. Specific modeling targets include the Shatt-al-Arab plume inside the Arabian Gulf, the deep outflow plumes, the formation of Reddies and Peddies, and the Ras al Hadd frontal jet.

A surprising and important outcome of this meeting was the realization that many aspects of the AMSG general circulation are poorly understood and in many cases lack even a basic description of their essential features to serve as model benchmarks. Thus Lagrangian measurements were thought to offer the quickest return of understanding for investment. Surface layer drifters and subsurface floats in the deep outflow plumes from the marginal seas were recommended to add significantly to basic understanding of circulation in these basins. A strong remote sensing program including SST, ocean color, surface winds, and altimetry must be an essential part of a modern observational program. A program to obtain better estimates of surface momentum and buoyancy fluxes was considered a priority. Such a marine boundary layer observation program consisting of intensive localized measurements to guide and validate standard meteorological prediction packages should be combined with a larger scale VOS program. Areas targeted by the panels as in need of intensive observation are (1) the Arabian Gulf - Strait of Hormuz region (including the mid-Gulf front off Qatar and the western boundary coastal plume) with moorings, HF-radar and MBL stations, (2) the Ras al Hadd frontal region where an interdisciplinary effort would be especially rewarding scientifically, and (3) the Red Sea-Gulf of Aden where both mooring lines and drifter studies are candidates. Other potential sites include the Omani coast, the area around Socotra, and the western Gulf of Oman.

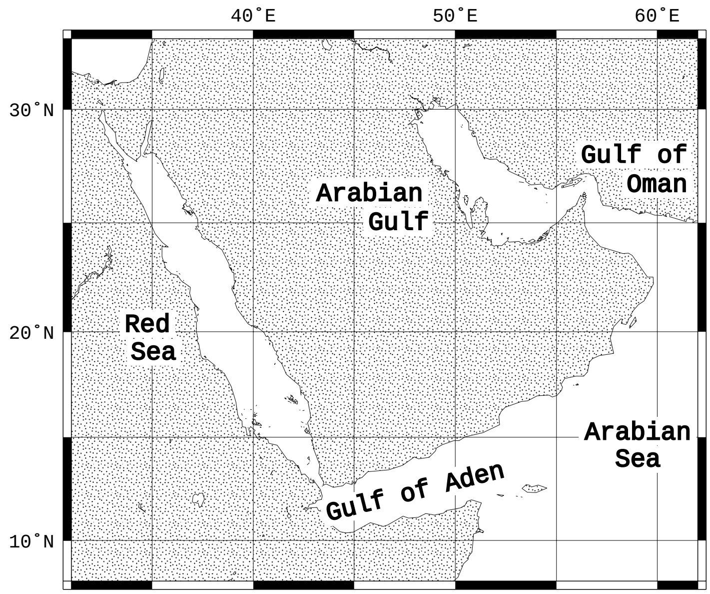
It was emphasized that any serious study in this critical, but remote, data poor region must include, in addition to the ocean observations, a meteorological component, a remote sensing component, a strong dynamically oriented numerical modeling effort, and must be of a 2 year minimum duration.

The Arabian Marginal Seas and Gulfs

1. Introduction

On 11-13 May 1999, a workshop was held at the Stennis Space Center on the topic of the "Arabian Marginal Seas and Gulfs". The workshop was sponsored by the U.S. Office of Naval Research and hosted by the Naval Research Laboratory.

The purpose of the workshop was to conduct a thorough scientific review of the dynamics and circulation of the Arabian Gulf, Red Sea, Gulf of Oman, and Gulf of Aden, and the coastal regions of the Indian Ocean which they closely interact with. The workshop was motivated in part by recent field programs in the northwestern Arabian Sea and in the key straits connecting the marginal seas and gulfs, which have provided a basis to better understand the forcing and linkages between these regions. Several modeling efforts are also underway to help understand the air-sea interaction processes and the causes and variability of the regional circulation.



The workshop participants included theoreticians, observationalists, and numerical modelers who are active in the region and who could speak for needed improvements in each of these areas to help advance our physical understanding and predictive capabilities. In addition to conducting a scientific review of the AMSG region, the workshop was intended to serve as a forum for bringing together the expertise of the various Navy labs (NRL, NAVOCEANO) and academic institutions working in the region and to help promote enhanced collaboration between them. The workshop focused primarily on the physical oceanography and air-sea interaction of the AMSG region but also considered biophysical interactions in the region.

The central question which served as the focus of the workshop was:

- "What is needed in terms of model development, theory, and observations to significantly improve capabilities for modeling the marine environment and variability of the Arabian Marginal Seas and Gulfs region?"
- A number of specific topics were proposed for focused discussion, among them:
    1. General Circulation and Exchanges with the Indian Ocean
    2. Atmospheric Forcing and Air-Sea Fluxes
    3. Short-Term Responses to Atmospheric Forcing
    4. Water Formation Processes and Deep Outflow Plumes
    5. Productivity and Physical/Biological Coupling

Following research presentations on these topics by several of the meeting participants (Appendix 2), the workshop was organized into two working group sessions. In working group session 1 the participants broke into three groups divided by region and were tasked with summarizing what is known about the circulation in these regions and determining what the most important remaining scientific questions are. These regions were (i) the Arabian Gulf and Gulf of Oman, (ii) The Red Sea and Gulf of Aden, and (iii) the coastal Arabian Sea. The latter group also considered the interactions of the Arabian Sea with the bordering Gulf of Oman and Gulf of Aden so that there was some overlap between the groups. The second working group session broke up into two groups which were charged with forming recommendations for future research in the region and suggesting possible approaches to this research. These groups divided along the lines of (i) Modeling and (ii) Observational approaches but there was considerable overlap in the expertise and range of discussion on these topics within each of the groups.

This report contains a summary of the principal features of the circulation in these regions as known from previous research, which are presented by region in Section 2. Highlights of recent research in the region shown by the meeting participants, much of which is as yet unpublished, are presented in Section 3 of the report. Important scientific questions for these regions as outlined by the working groups are listed in Section 4, followed by a summary and recommendations for future research in Section 5.

2. Scientific Background

Atmospheric Forcing

Atmospheric conditions over the Arabian marginal seas and gulfs region are strongly influenced by the seasonally reversing Arabian monsoons (Fig. 1). The monsoon forcing is most intense over the coastal Arabian Sea and southern Red Sea, while continental patterns become more dominant over the northern Red Sea and Arabian Gulf. The coastal Arabian Sea experiences the largest seasonal forcing with the shift from the strong SW winds of the summer monsoon to the NE winter monsoon winds (Fig. 1). The SW monsoon pattern is confined mostly to the Somali coast and northern part of the Arabian peninsula, and the intensity of these winds diminishes greatly into the Gulf of Aden and Gulf of Oman. Conversely, the winter monsoon pattern extends well into the Gulf of Aden and southern Red Sea, causing a seasonal reversal in the winds over this entire region.

Orographic influences on the atmospheric circulation are very significant due to the high mountains bordering much of the coastline in this region (Fig. 2). The Ethiopian highlands and coastal mountain range of northern Somalia act to focus the SW monsoon winds offshore of Somalia and the Arabian peninsula. Simultaneously they shield much of the Gulf of Aden from strong SW monsoon forcing. In winter these mountains are responsible for steering the NE monsoon winds into the Gulf of Aden and southern Red Sea. The Red Sea is bordered along its full length by high mountain ranges that cause the winds to be closely aligned along the axis of the Sea except at a few locations in the central Red Sea where gaps in the mountains exist. The Zagros Mountains of Iran and the Jebel al Akhdar range in northern Oman play a similar role in focusing the winds over the Arabian Gulf and southern Gulf of Oman.

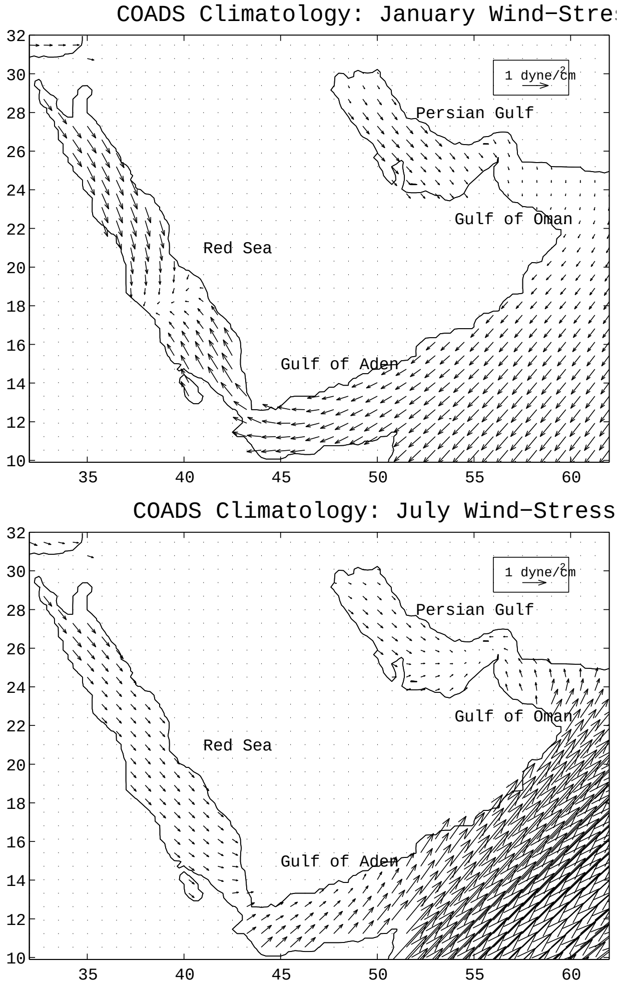


Fig. 1: Climatological winds over the AMSG region, for January and June at the height of the NE and SW monsoon seasons (from COADS).

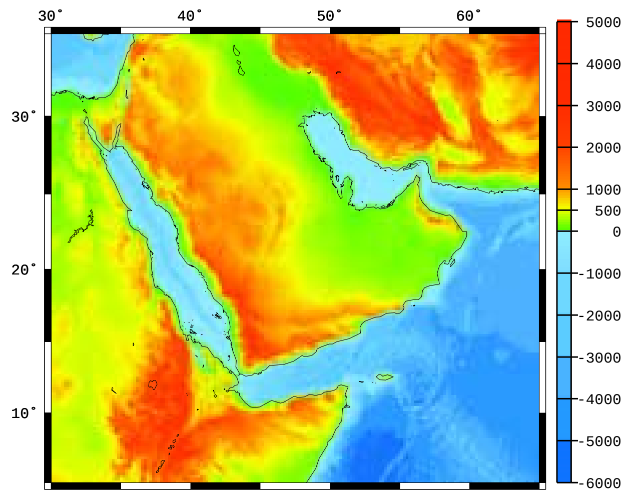


Fig. 2: Orography and bathymetry of the Arabian Peninsula region.

Winds over the southern Red Sea are southeasterly during the winter monsoon (October-May) and change to northwesterly north of about 18°N where a strong convergence zone exists. This convergence zone marks the boundary between the monsoon dominated atmosphere in the south and continental atmosphere in the north. The winter winds over the northern Red Sea are strongly event dominated by frontal passages which move southward from Egypt and the southern Mediterranean and decay near the latitude of the convergence zone. During summer (June - September) this convergent wind pattern is replaced by weaker northwesterly winds over the entire Red Sea. The Arabian Gulf is less influenced by the monsoons and is characterized by northwesterly or westerly winds throughout the year. These winds are strongest in late fall and winter when the intense "shamal" events propagate down the Gulf to the central and southern Gulf. During summer the winds are weaker and less variable, especially in the southeastern Gulf.

The region as a whole is characterized by high annual evaporation, and the net evaporation (E-P) rate becomes very large over the Arabian Gulf and Red Sea. Moisture exchange across the air-sea interface is enhanced by the extremely arid nature of the bordering lands, particularly for the marginal sea areas. The annual evaporation over the Red Sea is estimated at between 1.4 to 2.0 m/yr, and a similarly high or perhaps even larger value occurs over the Arabian Gulf (Privett, 1959; Hastenrath and Lamb, 1979). This freshwater loss constitutes the main annual buoyancy forcing for these basins as both the Red Sea and Arabian Gulf experience relatively small annual heat losses of O(10 W/m^2). Both the evaporation and heat exchange are subject to strong seasonal variations due to the changing seasonal wind patterns and wind strengths. The thermohaline exchange forced by freshwater loss is generally believed to be the primary driving mechanism for the large-scale circulation in these seas and exchange with the bordering gulfs and Indian Ocean.

2.2 Regional Circulation

The following regional summaries attempt to provide relevant background on known circulation features and processes in the region as well as some of the major unknowns. Accompanying "circulation cartoons" for the region are shown in Figs. 3a-d which schematically indicate the major features.

2.2.1 The Arabian Gulf

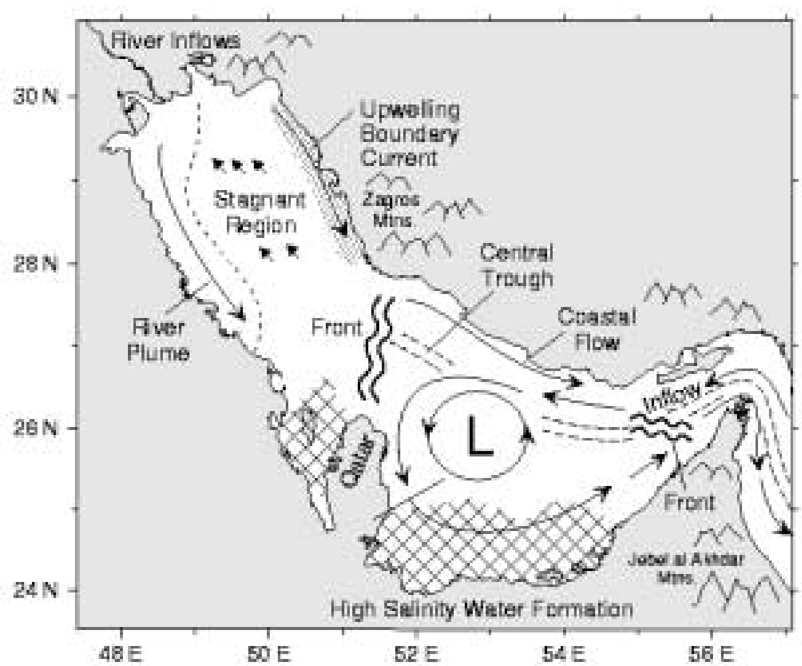


Fig. 3a: Circulation schematic for the Arabian Gulf.

The basic features of the Arabian (or Persian) Gulf can be divided into a northern and southern or eastern regime (Fig. 3a). The northern regime is dominated by wind forcing to the south along the axis of the Gulf and the riverine input at the Gulf's head. The wind-driven response of the Gulf appears to be the typical adjustment of the pressure field such as to produce a down-wind flow, i.e. there is downwelling on the western coast and upwelling on the coast of Iran, and evidence for a southeastward flowing coastal current along both the northern and southern coasts (Reynolds, 1993).

The flow along the Kuwait and Saudi coast is augmented by the freshwater input from the north which forms a riverine plume. The river inflows are approximately split between the flow out of the Shalat Ariabi (Tigris and Euphrates) and rivers flowing out of the highland of Iran (the Hendijan, Hilleh, and Mand). In current times the flow of the Shalat Ariabi is much smaller than it once was because of massive dam projects in Turkey. It is not clear what changes this decline in freshwater input has made. The center of the northern Gulf appears to be fairly stagnant (Reynolds, 1993). The southern end of this regime corresponds roughly to the longitude of Qatar and Bahrain, although the termination of the northern circulation is poorly understood. The flow along the Iran coast seems to continue into the southeastern basin as a tightly trapped coastal current extending perhaps as far as the Strait of Hormuz. This flow becomes very complex in proximity to the island of Jazareh in the northern portion of the Strait.

The northern Gulf is separated from the southern regime by a front that typically is found off Qatar (Fig. 3a). This front is most intense in summer and weakest, at least in sea surface temperature, in the late winter and spring. The location of this front appears in both climatological hydrographic data and remotely sensed SST to be tied to the penetration of fresh inflow into the Gulf from the Strait of Hormuz. The available data suggests that much of this inflow may terminate in a counter-clockwise, cyclonic flow to the east of the mid-Gulf front (Fig. 3a). This cyclone appears in circulation climatologies and appears as a coherent SST anomaly in satellite imagery. East of this front the available data suggest a flow out of the Gulf around the tip of the Musandem peninsula and into the northern Gulf of Oman. The large evaporation over the Gulf leads to an inverse estuarine circulation with the highly saline waters leaving the Gulf through the deep part of the Strait of Hormuz and being replaced by a fresh surface inflow from the Gulf of Aden. The saline bottom waters that flow out through the Strait may originate from several locations in the Gulf. Historical salinity data and SST data implicate a broad region of high salinity waters extending from Qatar eastward along the Emirate coast (hatched region in Fig. 3a). Waters in this shallow region can reach very high salinities (>42 psu) and appear to form a warm and salty endpoint of the Gulf outflow. The temperature salinity relationships of the observed outflowing waters imply a fairly complicated set of water mass modifications in the Gulf. Colder and somewhat fresher waters are also found in the deep outflow from the Gulf and suggest another source, probably from the northern Gulf. Modeling results (Horton et al., 1994) suggest that some of the outflow arises from sinking in the shallow high salinity area off the Emirates, but that further sinking occurs in the vicinity of the variable mid-Gulf front.

The deep water arising from these sources exits the Gulf on the southern (deepest) side of the Strait of Hormuz at a maximum depth of ~100 m. Unlike the Mediterranean or Red Sea the Gulf is shallow (<100 m) and there is no prominent sill to constrain the outflow. The annual mean outflow of the deep waters and compensating fresh surface inflow is estimated from the Knudsen relations to be approximately 0.2 Sv, assuming a mean evaporation rate of approximately 1.5 m/yr (Privett, 1959; Hastenrath and Lamb, 1979) and net freshwater input from rivers of ~0.2 m/yr (Wright, 1974). Estimates of the exchange rate from available models span a range from 0.1 Sv to nearly 0.4 Sv (Chao et al., 1992, Horton et al., 1994). Seasonal variability of the deep outflow and surface inflow is not clearly established, although recent measurements (Johns and Olson, 1998) suggest that the deep outflow may be fairly steady throughout the year.

2.2.2 The Red Sea

The Red Sea is similar to the Arabian Gulf in that it acts as an inverted estuary, with dense, salty water formed by evaporation and deep convection in the northern Red Sea flowing out into the Gulf of Aden underneath a fresher inflowing layer from the Gulf of Aden (Fig. 3b). Unlike the Arabian Gulf, however, the exchange is known to be highly seasonal, with maximum exchange occurring in winter. Indirect estimates of the transport of Red Sea water through the Bab el Mandeb Strait suggest an annual mean transport of 0.33 Sv (Siedler, 1968), varying from approximately 0.6 Sv in winter to nearly zero in late summer (Patzert, 1974). The winter period (November-May) is characterized by a classical two-layer exchange flow (Siedler, 1968). However, in summer the northwesterly winds apparently drive a three-layer exchange, consisting of a thin surface outflow from the Red Sea, an inflowing layer of Gulf of Aden thermocline water, and a weak outflowing deep layer (Maillard and Soliman, 1986).

Estimates of the annually averaged rate of Red Sea deep water formation range from 0.06 Sv (Wyrtki, 1974) to 0.16 Sv (Cember, 1988). This water forms in the northern Red Sea predominantly during winter, and fills the deep basin below the Bab el Mandeb Strait sill depth (approximately 160 m) with a nearly homogeneous water mass of temperature 21.7°C and salinity 40.6 psu (Neumann and McGill, 1962). A second source of somewhat less dense Red Sea water, or Red Sea "intermediate" water, is believed to be formed also predominantly in winter by an open sea convection process in the northern Red Sea that remains poorly understood (Morcos, 1970).

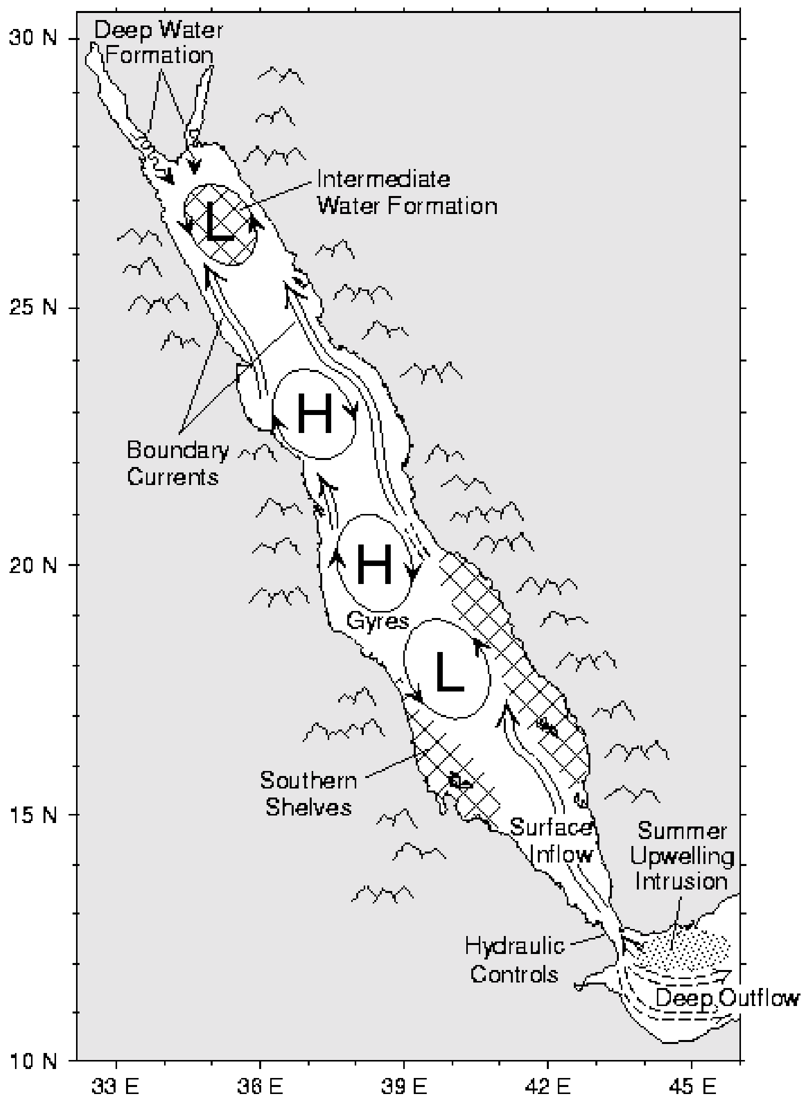


Fig. 3b: Circulation schematic for the Red Sea.

This process appears to be distinct from the Red Sea deep water formation process that occurs in the northern gulfs of the Red Sea (Gulf of Suez and Gulf of Aqaba) and that fills most of the deep volume of the Red Sea. Another class of intermediate waters may be formed on shallow shelves in the southern Red Sea (Maillard, 1974). Volumetrically, the rate of intermediate water formation appears to be greater than the rate of deep water formation, and is thought to supply the main contribution to the lower layer outflow from the Red Sea through Bab el Mandeb.

The seasonal cycle of the Red Sea exchange through the Bab el Mandeb is driven primarily by the seasonal change in winds over the southern Red Sea and Gulf of Aden (Fig. 1). In winter the southeasterly winds act to reinforce the thermohaline circulation of upper layer inflow and deep outflow. Conversely, in summer the northwesterly winds act in opposition to the thermohaline forcing and this may partly explain the reversal to outflow in the surface layer of the strait in summer. Upwelling in the western Gulf of Aden during summer is also believed to play a role in forcing the surface current reversal in the Strait and thermocline layer intrusion into the Red Sea, by changing the stratification and sea level in the western gulf and hence affecting the alongstrait pressure gradient (Patzert, 1974). The relative importance of these two wind-forced effects, one direct and one indirect, is not yet clear. Seasonal changes in surface buoyancy forcing may also affect the seasonality of the exchange, but this possibility has yet to be investigated.

The Red Sea water exits the Bab el Mandeb strait with a sill depth of ~160 m and spills down the topography of the western Gulf of Aden where it entrains resident Gulf waters and sinks to an average depth of about 600 m. Hydraulic control of the outflow is much debated and there is as yet no consensus on the exact nature of hydraulic controls that may govern the exchange. The overflow character of the outflowing Red Sea water is suggestive of hydraulic control. However, there is no evidence of a Gibraltar-like internal bore, a feature that would serve as indirect evidence for hydraulic control. Recently, Smeed (1999) has constructed a three-layer hydraulic model that reproduces the gross characteristics of the stratification and exchange in both summer and winter. However the critical conditions required in the summer and winter solutions differ considerably from direct wave speed calculations by Pratt et al. (1999 a,b) based on data collected by Murray and Johns (1998) at the sill and narrows.

The horizontal circulation of the Red Sea appears to consist of a number of gyres or eddies distributed along the length of the Sea (Fig. 3b), of which some may be semi-permanent (Quadfasel and Baudner, 1993). There is little detailed information on this circulation as most studies have tended to treat the Red Sea as a two-dimensional basin. Most oceanographic measurements are therefore confined to its central axis. In the northern Red Sea, drifter trajectories point to a cyclonic gyre at least in winter (Clifford et al., 1997). This gyre may be linked to the aforementioned intermediate water formation process in the northern Red Sea, and could possibly serve in a preconditioning role for the intermediate water formation. In the central Red Sea the circulation appears to be dominated by anticyclones that occur most regularly near 23-24°N and 18-19°N. These locations may be tied to coastline and topography variations (Quadfasel and Baudner, 1993). Both cyclonic and anticyclonic features are found in the southern Red Sea but no persistent gyre pattern seems to exist there. When present, these gyres usually span most of the width of the Red Sea and can have horizontal velocities of 0.5 m/s or more. Thus they are energetic compared to the ~0.1 m/s mean flows in the surface layer associated with the large scale thermohaline circulation of the Red Sea.

Coastal boundary currents may exist both in the southern Red Sea off Yemen and in on both sides of the northern Red Sea (Eshel and Naik, 1997). Little direct evidence is available for these currents, however. Particularly in the northern Red Sea, the opposing influences of the wind and thermohaline forcing throughout the year make it unclear what sense should be expected for these boundary currents.

2.2.3 Gulf of Oman

The northern Gulf of Oman is strongly influenced by outflow from the Arabian Gulf. From fall through mid-spring, satellite SSTs suggest a plume of Gulf water flowing as a coastal current along the Oman and Emirate coast to Ras al Hadd at the edge of the Arabian Sea (Fig. 3c). This would imply that at least through part of the year the outflow from the Gulf consists of a deep water (PGW) layer and a modified surface layer that must together balance the inflow component.

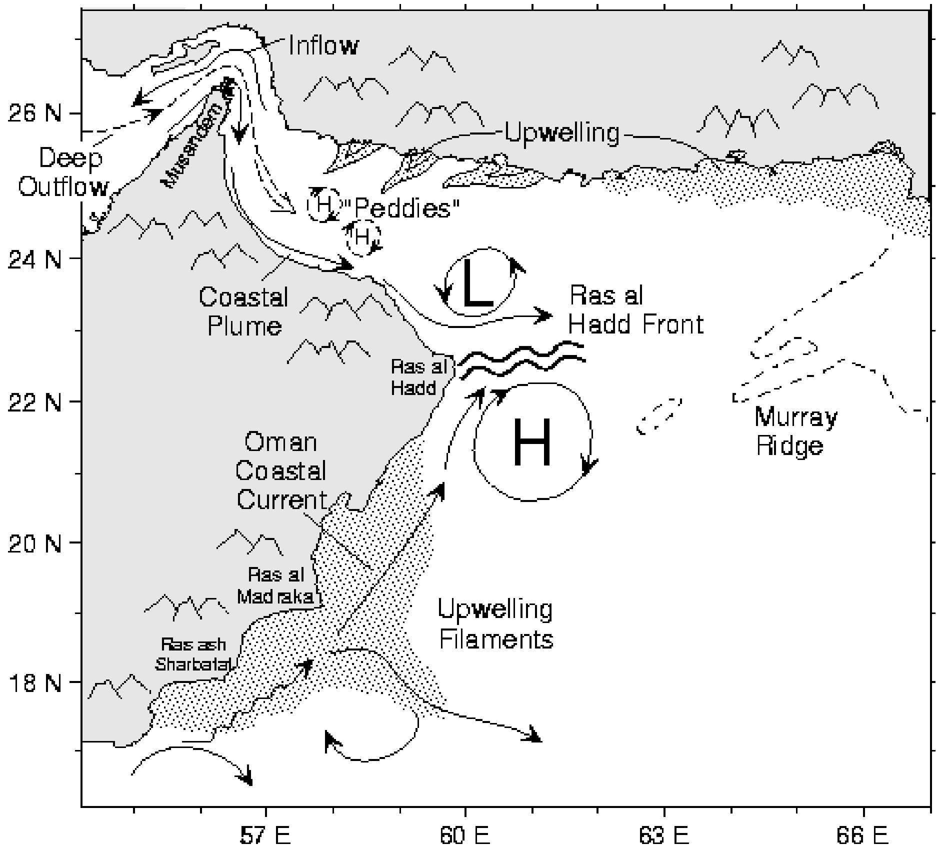


Fig. 3c: Circulation schematic for the Gulf of Oman and northern Arabian Sea.

This and the absence of any sill to confine the flow differentiates the Gulf from marginal seas such as the Red Sea and Mediterranean. The manner in which the PGW enters the deep Gulf of Oman is not clear from available data. Data from the U.S. and German WOCE cruises in 1995 and Navoceano AXBT surveys suggest that the PGW layer is dominated by sub-mesoscale eddies. Are these formed at the outfall of the paleo-river channel at the shelf edge or by shelf edge meandering as the plume proceeds southeastward down the shelf break? What are the range of sizes and dynamics of the resulting Peddies? The final issue is the nature of the PGW and associated surface flows. Is the flow a coherent shelf break one or a train of eddies? The interaction of these with the other elements of the Gulf of Oman circulation is also of interest.

Other important elements involved in the Gulf of Oman's circulation are the seasonal upwelling along the coast of Iran to the north and the complicated mesoscale dynamics associated with the extension of the south coastal Oman upwelling system into filaments extending off Ras al Hadd. The latter is complicated by the shallow Murray Ridge that extends across the mouth of the Gulf (Quraishee, 1984). The Ras al Hadd jet (Fig. 3c) is highly variable, sometimes extending out to the east as shown in the figure and extending northeastward or southeastward at other times. This feature is also referred to as the Ras al Hadd front because it forms the seasonal boundary between the northern Arabian Sea and the Gulf of Oman. During the SW monsoon the transport of the Ras al Hadd jet is believed to be at least 10 Sv (Elliot and Savidge, 1990). Flagg and Kim (1998) discovered that the Ras al Hadd jet intensified in August 1995 following the reversal of the flow along the northeastern Oman coast from northward to southward, thereby adding to the flow along the Ras al Hadd front. They speculated that the reversal of the flow along the northeastern Oman coast in August is related to the intensification and/or propagation of a cyclonic eddy in the Gulf of Oman during this period. Similarly, Baker et al. (1996) suggested that such an eddy can play a role in the dynamics of the Ras al Hadd Jet, which may become tied to a double vortex as it extends offshore. It is speculated that to the south, an anticyclonic eddy forms, while to the north in the Gulf of Oman, a cyclonic eddy forms, both of which are driven by the extension of the Ras al Hadd jet into the open Arabian Sea. While the anticyclonic eddy to the south has been observed (Flagg and Kim, 1998; Simmons et al., 1988), no direct connection has yet been established between the Ras al Hadd jet and the cyclonic eddy in the Gulf of Oman. The interaction of the Ras al Hadd front with the coastal flow, the Murray Ridge and the eddies are not well understood. In some of the remote SST data, shifts in the dipole lead to its breakup and the propagation of the cyclonic component northwards into the Gulf of Oman. The interaction of these surface intensified features with the thermocline layer Peddies and the PGW outflow is probably complicated. The interannual variations are large, as are those in the interactions with the Murray Ridge and upwelling on the Iranian coast.

The seasonal and interannual variations in the circulation in the Gulf of Oman appear to be significant. The nature of the flow along the southern side of the Gulf of Oman appears to be better organized in June through December although this may be tied to the lower thermal contrast in January through May. The northern side of the Gulf has consistent upwelling associated with the SW monsoon along the Pakistani coast (Fig. 3c). Upwelling along the western, Iran coast is more variable. In 1995, for example, this coast was associated with upwelling filaments that moved to the west and even entered the outer edges of the Strait of Hormuz. Other years suggest less extensive upwelling although there is localized upwelling at the mouth of the Strait in all years examined. One clear need is a better depiction of winds over the Gulf of Oman in relationship to this variability.

2.2.4 Gulf of Aden

The Gulf of Aden is influenced at depth by the outflow of Red Sea waters moving toward the Indian Ocean (Fig. 3d), and at the surface by inflow from the Arabian Sea. The signature of the Red Sea outflow is seen throughout the Gulf of Aden and northern Indian Ocean as an intermediate salinity maximum near 600 m depth, spreading southward along the western boundary as far as 20°S (Wyrtki, 1971).

As the Red Sea water spills over the Bab el Mandeb sill, it appears to follow at least two pathways in the western Gulf of Aden, one along the southern boundary of the Gulf in the expected sense, and another along the central or northern part of the Gulf (Siedler, 1968; Federov and Meschanov, 1988). These different pathways appear to be related in part to the complicated topography of the western Gulf, including the Tadjura Rift that extends westward to just outside the Bab el Mandeb (Siedler, 1968). Different mixing behavior along these flow pathways may lead to different penetration depths between 400-1200 m and varying properties of the Red Sea water in the Gulf of Aden (Bower et al., 1999). Little detailed knowledge is available on the eastward spreading of Red Sea water in the central Gulf of Aden or how this takes place, either in the form of continuous boundary currents or isolated eddies. The pathways by which surface waters navigate their way westward through the Gulf to provide the required surface layer inflow to the Red Sea are also poorly known.

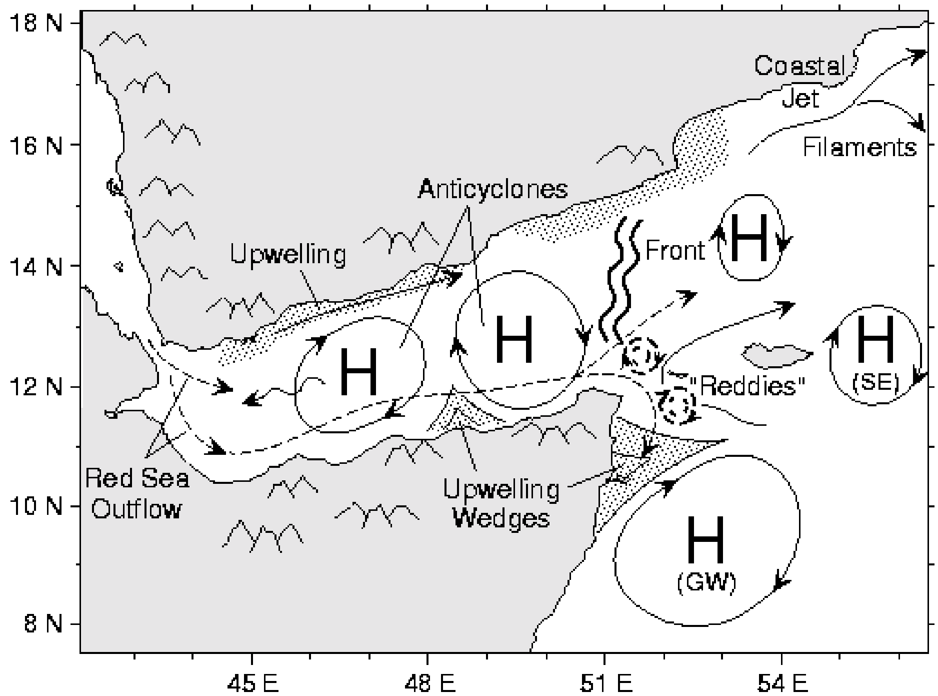


Fig. 3d: Circulation schematic for the Gulf of Aden and western Arabian Sea.

The upper layer circulation of the Gulf of Aden appears in remotely sensed SST imagery and a few available AXBT survey data to contain large eddies - mostly anticyclones - that are comparable in size to the width of the Gulf (Fig. 3d). These features appear to propagate westward from the mouth of the Gulf toward the Red Sea, and their origin may be linked to the propagation and decay of eddy features generated in the western Arabian Sea. In addition, the seasonally reversing winds over the Gulf may generate localized responses consisting of gyres and seasonal boundary currents along the northern and southern boundaries of the Gulf. Direct evidence for these gyres, eddies, or seasonal boundary currents from in situ observations is almost entirely lacking, however.

Seasonal upwelling with the onset of the SW monsoon is quite pronounced in SST imagery in the western Gulf of Aden. Cool upwelled waters are brought to the surface along the southern coast of Yemen beginning in May and are presumably advected eastward by a wind driven coastal current. The lifting of the thermocline and depression of the sea surface in the western part of the Gulf caused by this seasonal upwelling process is believed to play a major role in the reversal of the surface flow in the Bab el Mandeb Strait in summer, and the associated intrusion of Gulf of Aden thermocline water into the Red Sea. A front is often observed near the mouth of the Gulf (Fig. 3d) during the SW monsoon which marks a water mass boundary between the cool upwelled waters advected northward along the Somali coast and the warmer waters in the Gulf of Aden.

Similar to the situation for the Red Sea, very little is known of the 2-dimensional circulation of the Gulf of Aden or its causes.

2.2.5 Coastal Arabian Sea

Knowledge of the monsoon-forced circulation off the Arabian Peninsula has increased considerably following the recent ONR/WOCE/JGOFS surveys. Upwelling favorable winds along the coasts of Somalia and Oman typically begin in May, although ship reports (Fieux and Stommel, 1977) indicate that the onset of upwelling favorable winds along the Oman coast can actually begin in April. While the winds along the Oman coast in April- May are not as strong as during the primary SW monsoon period, they appear to be sufficient to generate a coastal upwelling response as detected in AVHRR imagery.

Historical ship drift records reveal the existence of the Oman Coastal Current (OCC; Fig. 3c) north of approximately 14°N by early May (Cutler and Swallow, 1984). Ship drift records (Elliot and Savidge, 1990) show a northeastward flowing OCC during the SW monsoon of around 0.4 m/sec in magnitude and extending to 200 km offshore. The current turns abruptly to the east off Ras al Hadd (Fig. 3c). However, direct measurements of the coastal flow from ADCP instruments during 1987 showed that the northeastward coastal flow weakened toward the southwest from an estimated transport of ∼10 Sv near Ras al Hadd to weak and variable flow at 17-18°N (Elliot and Savidge, 1990). Additionally, the ADCP data analyzed by Flagg and Kim (1998) for the 1995 southwest monsoon displayed no mean coastal current to the northeast, but rather the presence of variable flow characterized by current reversals over relatively small scales. Flagg and Kim (1998) hypothesized that these differences between direct observations of the OCC and historical ship drift data may be accounted for by a systematic bias in the ship drifts due to the persistently high winds and seas state during this period. Clearly, questions remain about the nature of the Oman Coastal Current. While we know that it leaves the coast at Ras al Hadd, its southeastern most extent has not been documented, and we know little of its origins. Is the OCC comprised of several distinct flows of limited alongshore extent during the SW monsoon, or does it exist in the mean but is simply disrupted by the pronounced mesoscale variability?

Among the most prominent SW monsoon features along the Oman coast are filaments and jets (Fig. 3c) that are capable of exporting cool, nutrient rich, upwelled coastal waters hundreds of kilometers offshore (Brink et al., 1998). The first direct measurements of these features were described by Elliot and Savidge (1990) who discovered plumes of cold water extending offshore from the coast in the region between Ras ash Sharbatat (∼18°N) and Ras al Madraka (∼19°N). This is approximately the same region where a major filament was observed during the 1995 SW monsoon (Brink et al., 1998; Flagg and Kim, 1998; Arnone et al. (1999); Lee et al., 1999; and Manghnani et al., 1998). Some properties of the filaments have been described as similar to those off the U.S. pacific west coast (Elliot and Savidge, 1990; Brink et al., 1998). However, Flagg and Kim (1998) view the offshore-directed plumes as part of a major anticyclonic feature that remains essentially in place for approximately six months, thereby extending through the SW monsoon into the winter season. Manghnani et al. (1998) hypothesize that the plume is not part of the offshore deflection of a coastal current, but rather results from an interaction between the wind field and anticyclonic mesoscale features that may have existed prior to the onset of the SW monsoon. A definitive description of these important features and an understanding of their origins are still lacking.

The circulation off the coast of Somalia during the SW monsoon and Fall intermonsoon periods has been the subject of numerous studies during the past 30 years (e.g., Schott, 1983; Knox and Anderson, 1986). With the onset of the intense southwesterly winds during the summer monsoon, the Great Whirl (GW) spins up in June and July between 5°N - 9°N (Fig. 3d). A second anticyclonic gyre, known as the Socotra Eddy (SE), forms to the east and north of the GW during the latter stages of the SW Monsoon. It is generally believed that the Socotra Eddy forms because of a large amplitude meander of the eastward extension of flow from the GW (Knox and Anderson, 1986). The timing of the eastward extension of flow from the GW, the generation of a pronounced meander and the formation of the separate SE may be quite variable from year to year. In addition to the eastward extension of flow from the GW to form the SE, a northward flow of through the Socotra passage into the Gulf of Aden is also a regular occurrence (Bruce, 1980; Molinari et al., 1990; Fischer et al., 1996) (Fig. 3d). In August 1993, the northward transport through the Socotra passage was estimated to be ∼13-14 Sv. This flow may extend sufficiently far north to form a large anticyclonic eddy at the eastern end of the Gulf of Aden (Fig. 3d), as detected by XBT measurements from the R/V *Marion Dufresne* in April-May of 1981 (Bruce, 1990). This eddy, referred to as the "North Socotra Warm Eddy" by Simmons et al. (1998), can be as large as 200 km in diameter and can extend across the full width of the Gulf of Aden.

The onset of the Northeast or winter monsoon occurs in November. In the northern Arabian Sea the primary circulation response to the onset of the northeasterly winds is the reversal of the Oman Coastal Current to southeastward flow, thereby yielding a continuous southward current that extends along the northeast coast of Oman, turns the corner at Ras al Hadd, and continues southward along the coast until it is entrained into offshore directed squirts and jets south of ∼20°N (Flagg and Kim, 1998). Anticyclonic features that were once directly connected to the coastal circulation during the SW monsoon now appear in SST imagery to evolve into separated eddies that exhibit a tendency to propagate southward along the coast. Among the key results of the analysis by Flagg and Kim (1998) is that the eddy kinetic energy in the northern Arabian Sea dominates that of the mean flow, is primarily confined to the near coastal region, and does not exhibit a pronounced seasonal variation. The generating mechanisms for the eddy field remain to be determined.

The wintertime circulation near the Somalia-Socotra region is characterized by a bifurcation of the westward flowing Northeast Monsoon Current at the Somali coast near 5-7°N, producing a northward transport through the Socotra Passage and a weak eastward transport just south of Socotra. According to Schott and Fischer (1999) the northward transport through the Socotra Passage is weaker than during the SW monsoon, and there is a southward transport of some 1 Sv of Persian Gulf water below the surface layer in the 200-500 m depth range, and ∼0.5 Sv of Red Sea water below 500 m. This contrasts with measurements during the SW monsoon which show negligible deep southward transport through the Socotra passage. Schott and Fischer (1999) conclude that Red Sea water enters the Somali basin primarily through the Socotra passage during the NE monsoon. Spreading of Red Sea Water in the form of "Reddies" that propagate along pathways eastward from Socotra and southward along the coast of Somalia have also been identified (Rochford, 1964). The mechanisms that drive the sub-surface circulation in the northern Arabian Sea - particularly the exchange of waters between the Somali basin, the Gulf of Aden, and the Gulf of Oman - are not yet well understood.

3. Recent Results

In recent years there have been several new field programs carried out in the Arabian Sea and the coastal margins and straits surrounding the Arabian peninsula. Among these are the WOCE/ONR/JGOFS intensive sampling program in the northwestern Arabian Sea during 1995-1996, and new long-term measurements of the exchange through the two major straits in the region, the Bab el Mandeb and Strait of Hormuz. A number of new results have also emerged from remote sensing, modeling, and studies of surface forcing fields in the region. Some highlights from the research presentations by workshop participants are included here to give an overview of these recent results and ongoing work in the AMSG region.

3.1 Strait Exchanges

Steve Murray and Bill Johns reported on two recent measurement programs in the Bab el Mandeb and Strait of Hormuz that have provided the first long-term direct measurements of seasonal variations in the strait exchanges.

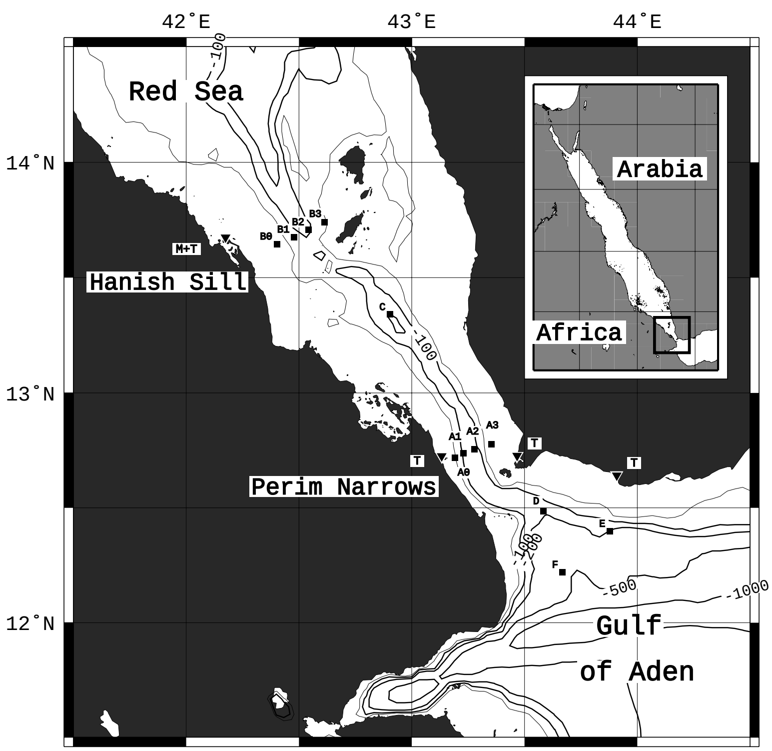


Fig. 4: The 1995-96 Bab el Mandeb experiment. Locations of ADCPs and current meter moorings are shown near the Hanish Sill in the north and the Perim Narrows in the south.

Steve Murray described a comprehensive Bab el Mandeb experiment during 1995-1996 involving moored ADCPs and T-S sensors (Fig. 4), that revealed the annual cycle of the exchange in a detail that had not been available before (Fig. 5). The inflow and outflow transports of the exchange flows were well resolved and showed a very repeatable transition between the winter two-layer regime and summer three layer regime over the 17 months of continuous observation (Fig. 6). The changing inflow/outflow conditions were clearly reflected in the salinity variations in the strait, which documented for the first time the extent and timing of the summertime intrusion of fresh Gulf of Aden thermocline water into the Red Sea. The annual mean outflow of Red Sea deep water through the strait was estimated to be 0.39 Sv, with maximum exchange reaching 0.7 Sv in February and average summer outflow of ~0.05 Sv.

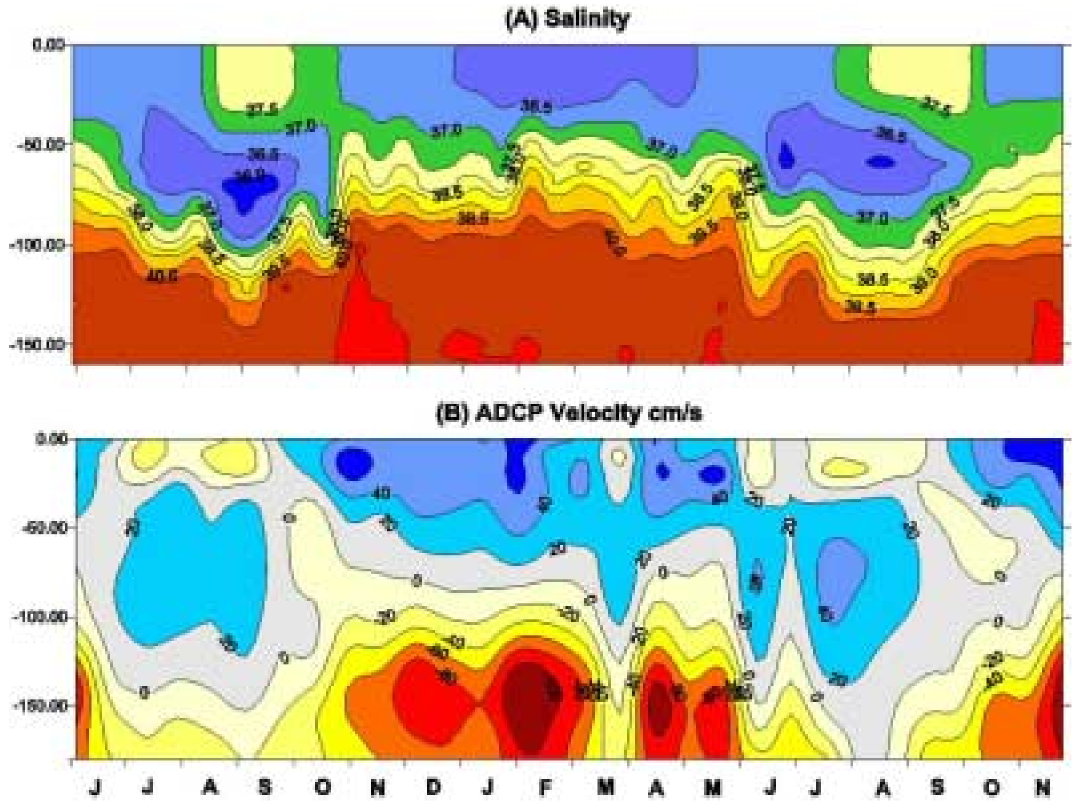


Fig. 5: Time series (June 1995 - November 1996) of salinity at the Hanish Sill (top) and ADCP alongchannel velocity at the Perim Narrows (bottom); negative velocities are outflow from the Strait. Note modulation of deep summer mid-depth intrusion, as well as a reversing surface layer.

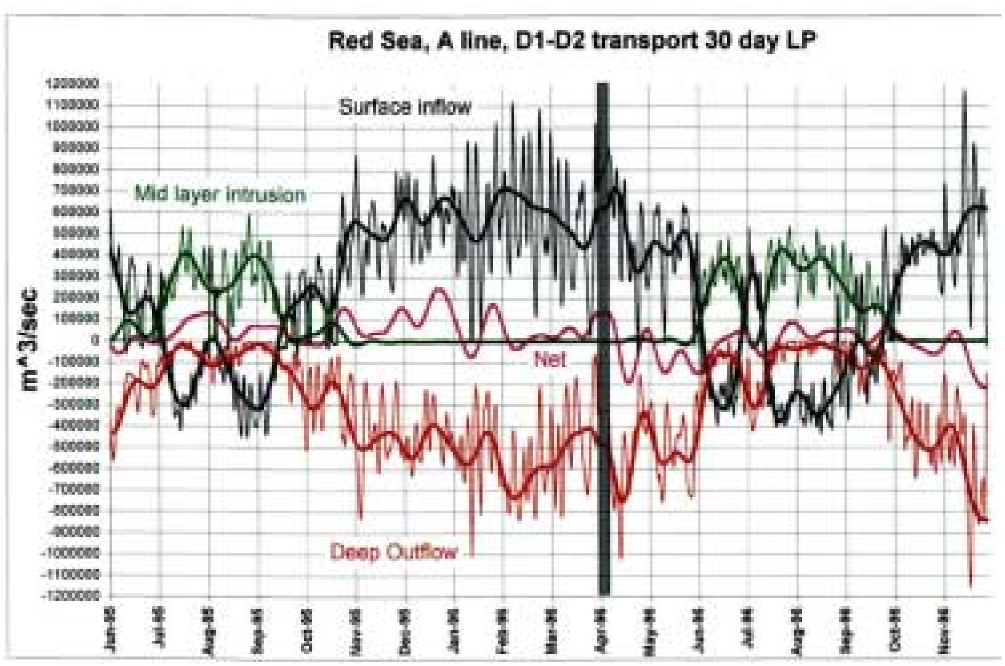


Fig. 6: Volume transports for the surface layer, the deep outflow layer, and the mid-depth summer intrusion in the Bab el Mandeb. The two-layer exchange in February reaches 0.7 Sv. Deep outflow diminishes to 0.05 Sv in summer. Annual average deep outflow ∼0.39 Sv. Net flow into the Red Sea over one year (April 1995-1996) ∼36,000 m^3/s.

Bill Johns showed new measurements from a similar but less extensive experiment in the Strait of Hormuz, which was confined to the Omani side of the Strait (Fig. 7, Fig. 8). Currents in the near-surface layer of the Strait were highly variable and exhibited large amplitude short-term variations, especially during winter (Fig. 7). Monthly averages suggest a mean outflow through the southern part of the Strait during fall and winter and a weak residual inflow during late winter and spring. The near-surface salinity variations showed lower salinity (< 37 psu) during spring (Fig. 8), characteristic of inflow from the Gulf of Oman. Measured currents in the deeper part of the Strait were steadier and did not indicate a significant seasonal modulation of the deep outflow. However, the salinity of the deep outflow varied considerably, with pulse-like events of high salinity outflow (> 40 psu) occurring during both winter seasons. A preliminary estimate of the annual mean deep outflow from the Strait from these data is 0.25 ± 0.5 Sv, with an additional $\sim$0.07 Sv of annual mean shallow outflow occurring in the southern half of the Strait.

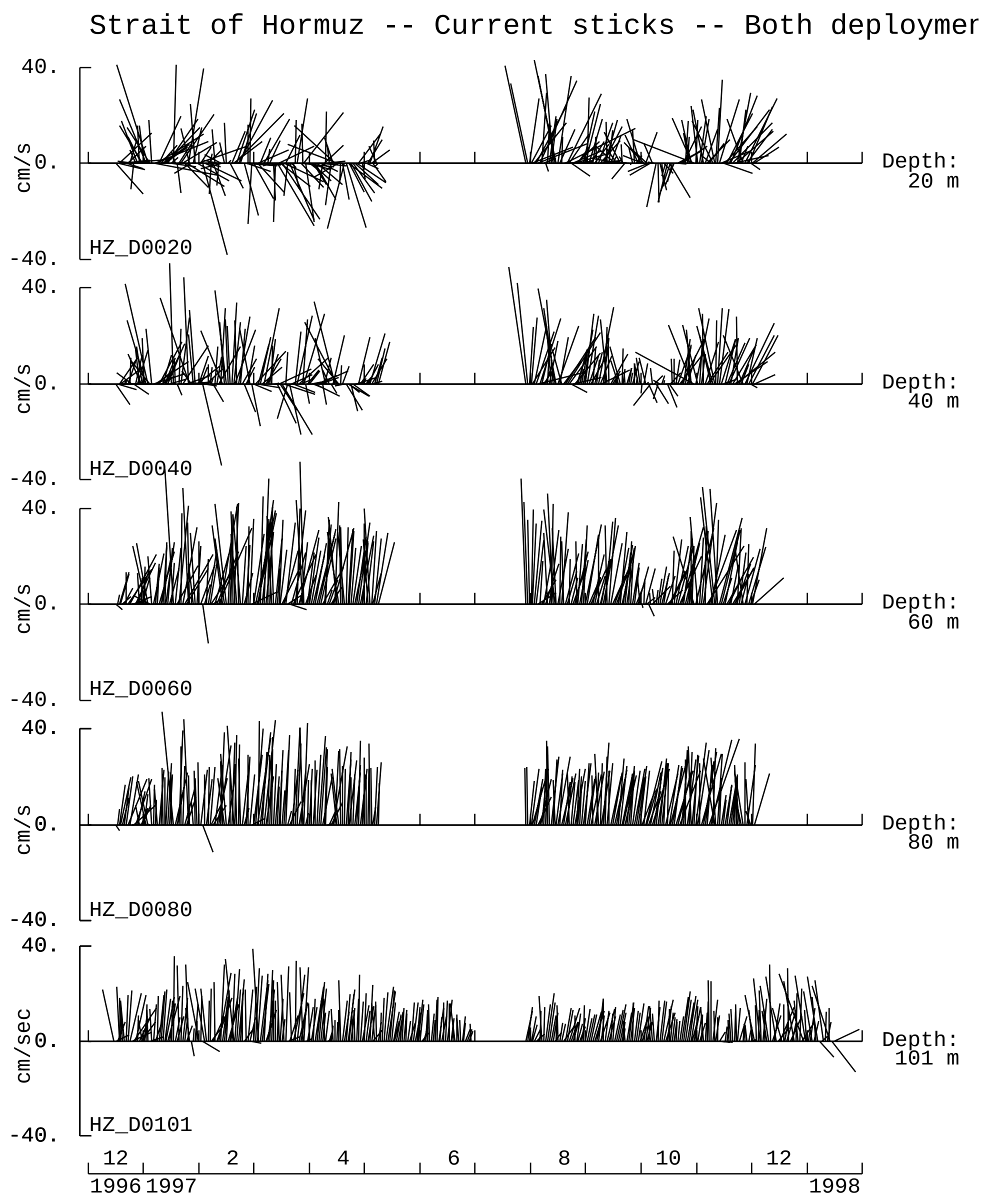


Fig. 7: Lowpass filtered current vectors from ADCP mooring in the Strait of Hormuz. Depth levels are 20, 40, 60, and 80 m from the ADCP, and 101 m from a near-bottom conventional current meter. Currents are rotated, up is 055° true, out of the Strait.

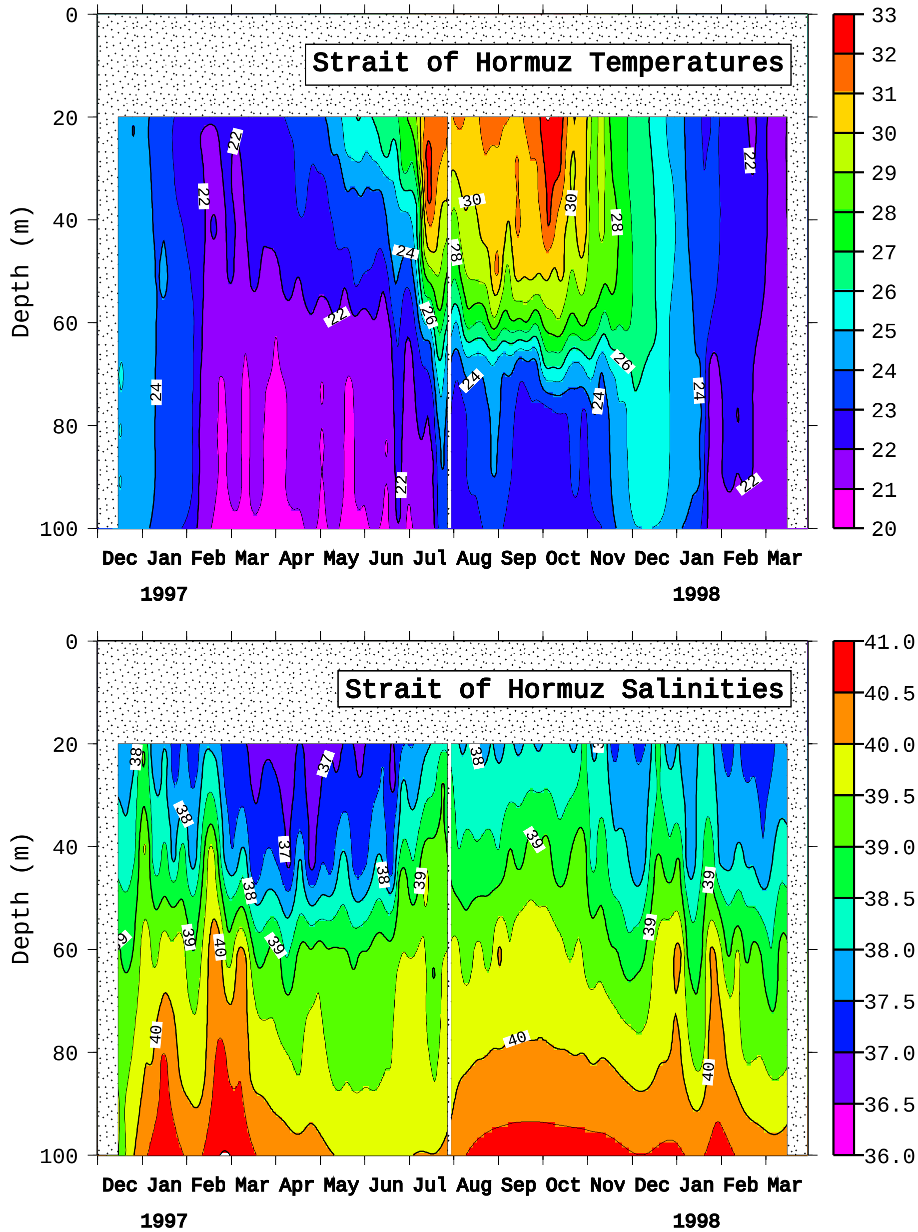


Fig. 8: Contours of temperature (top) and salinity (bottom) profiles in the Strait of Hormuz.

Larry Pratt showed the results of a hydraulic analysis of the Murray and Johns field data (Pratt et al., 1999 a,b). Preliminary results had suggested the sill as the most likely section of critical flow and the object was to calculate the speeds of the lowest mode internal gravity waves there to determine whether the flow is, in fact, hydraulically critical. Wave speeds were found by solving a version of the Taylor-Goldstein equation extended to incorporate effects of the cross-channel topography at the sill. Surprisingly, the wave speeds based on monthly mean velocity and stratification at the sill showed that the flow is marginally subcritical with respect to the first and second internal modes (Fig. 9a). However the monthly mean results are deceptive, since the flow is strongly modulated by tides and subtidal disturbances (Fig. 9b). The flow can range from subcritical to supercritical over a tidal period. Another interesting feature of the sill flow is that all wave speed pairs lie outside the range of the fluid velocity over the fluid depth (the velocity extremes are indicated by circles in Figs. 9a and 9b. Critical levels in the water column are therefore avoided, suggesting that mixing processes may be at work. Mixing is also suggested by profiles of Richardson number at the sill with values often near 1/4.

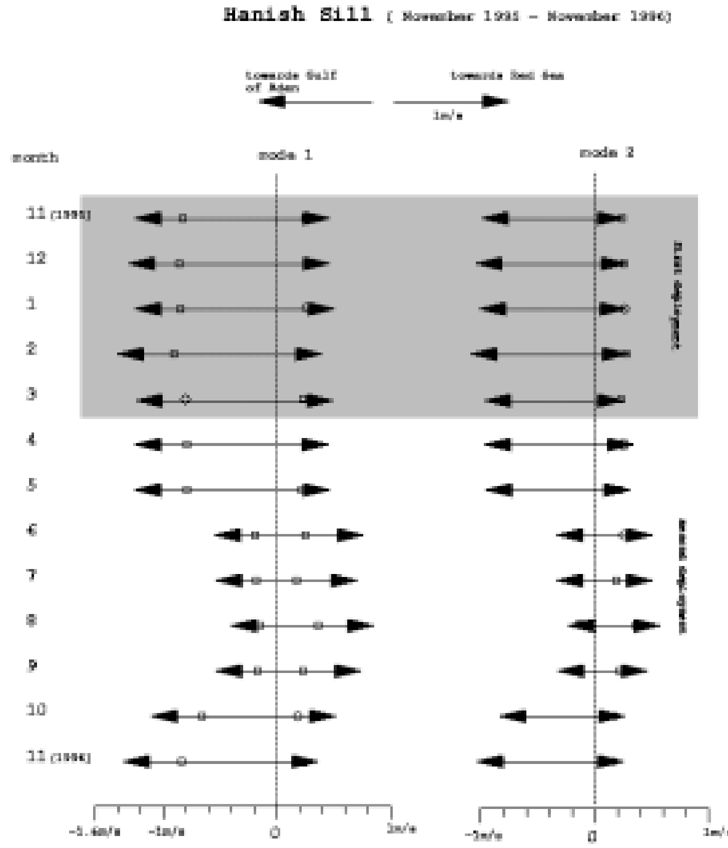


Fig. 9a: Wave speeds of the first and second internal mode gravity waves in the Bab el Mandeb at the Hanish Sill. The wave speeds are shown by a pair of arrows for each mode and each month, representing the forward and backward propagating waves. A pair of arrows pointing in opposite directions indicates subcritical flow, such that information can propagate in either direction (from Pratt et al., 1999 a, b).

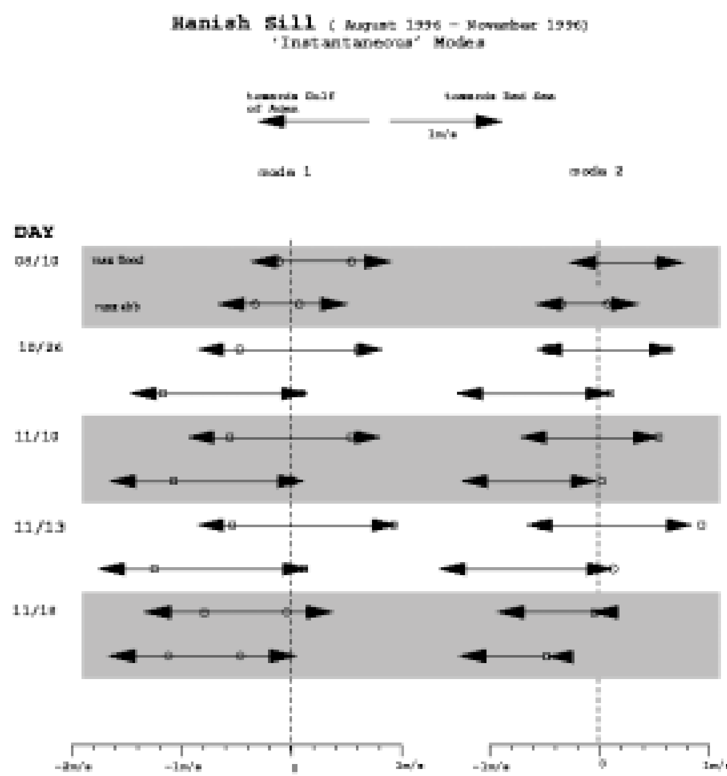


Fig. 9b: As for Figure 9a, but for instantaneous wave speeds at extremes of flood and ebb tide on a few selected days (from Pratt et al., 1999 a, b).

3.2 Deep Outflows

Amy Bower presented some intriguing new views of the deep outflows from the Arabian Gulf and Red Sea from repeated AXBT surveys of the Gulf of Oman (Fig. 10) and Gulf of Aden (Fig. 11). While the resolution of these surveys is relatively low, T-S correlations allow these surveys to be used to map the main flow patterns of the high salinity outflows. In the Gulf of Oman, there are numerous eddy features present in all seasons at the main PGW equilibration depth (∼250 m), and evidence for a boundary-following undercurrent along the western and southern boundaries of the Gulf is seen during the spring (March 1993 and March 1994). In the Gulf of Aden (Fig. 11), there is evidence of a boundary-following undercurrent of the warm Red Sea Water, particularly in June 1993, as well as a large, mid-gulf patch of relatively pure Red Sea Water in the same survey. This would be just after the season of maximum outflow transport of Red Sea Water. Temperature patterns at shallower depths in these basins also clearly reveal near surface gyre and eddy patterns; for example, the presence of large, transient warm and cold eddies along the Gulf of Aden (Fig. 12), with diameters of the same order as the width of the gulf. The eddy features were particularly evident in March 1993 and March 1994.

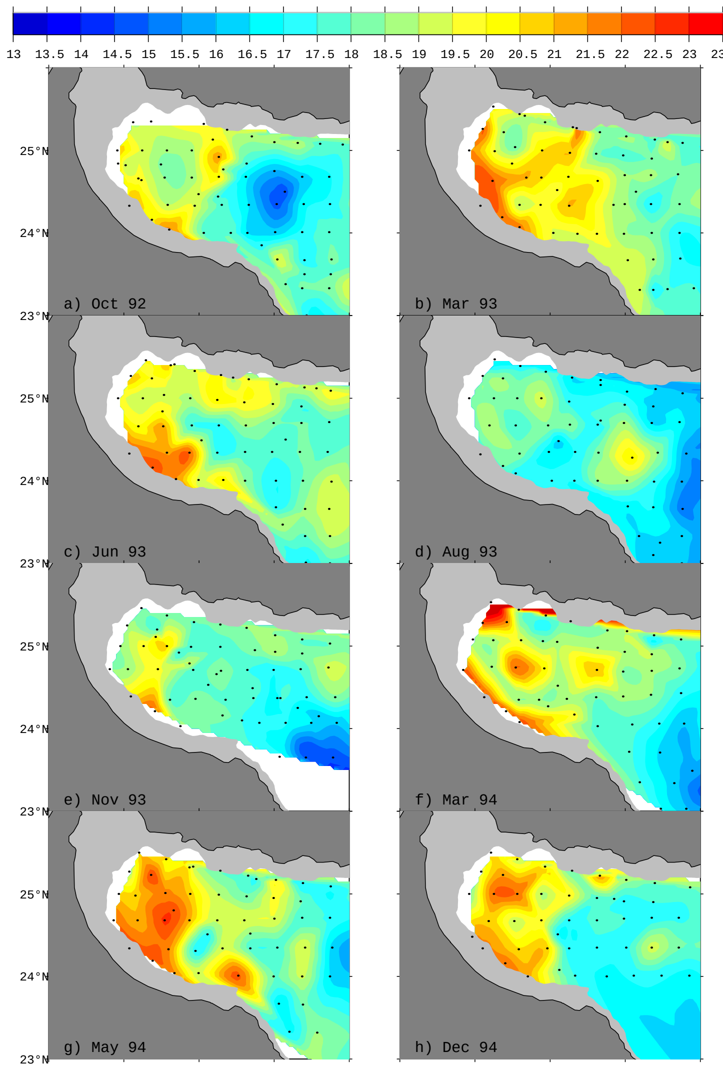


Fig. 10: Temperature at 250 m in the Gulf of Oman from repeated AXBT surveys conducted by NAVOCEANO. Color shading indicates temperature in 0.5°C intervals, and small dots show AXBT positions.

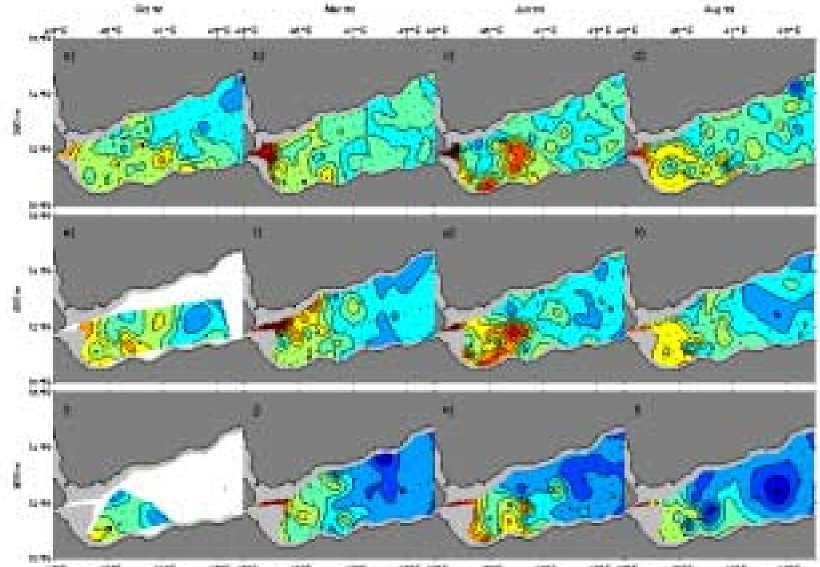


Fig. 11: Temperature at 350, 600 and 800 m for four AXBT surveys in the Gulf of Aden conducted by NAVOCEANO. Contour interval is 1°C. Warmer water in the western gulf is indicative of Red Sea Water.

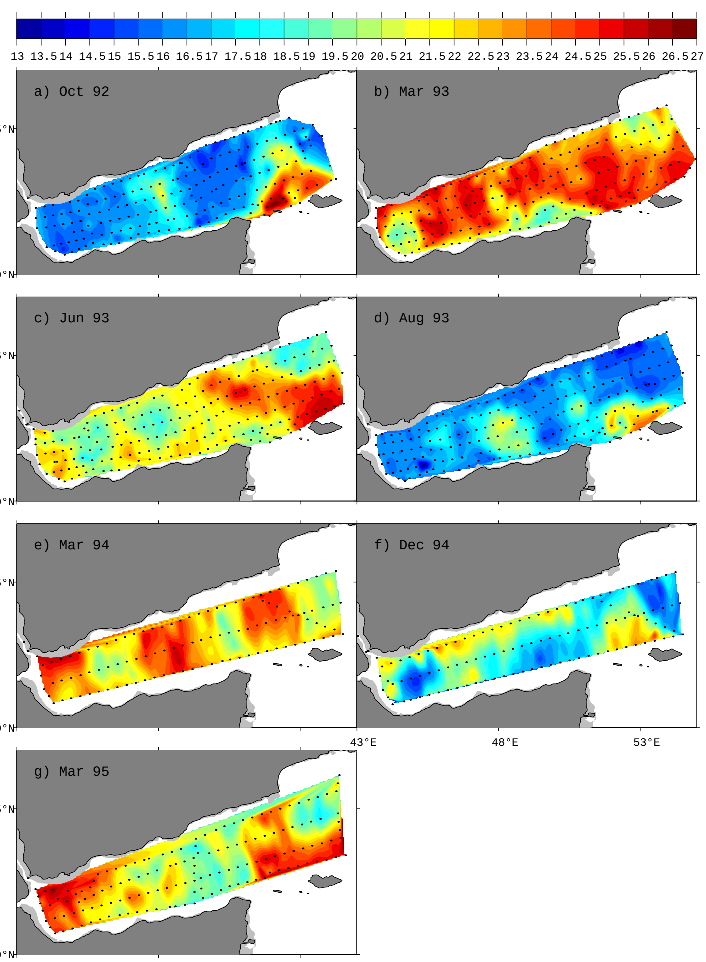


Fig. 12: Temperature at 100 m in the Gulf of Aden from repeated AXBT surveys conducted by NAVOCEANO. Color shading indicates temperature in 0.5°C intervals, and small dots show AXBT positions.

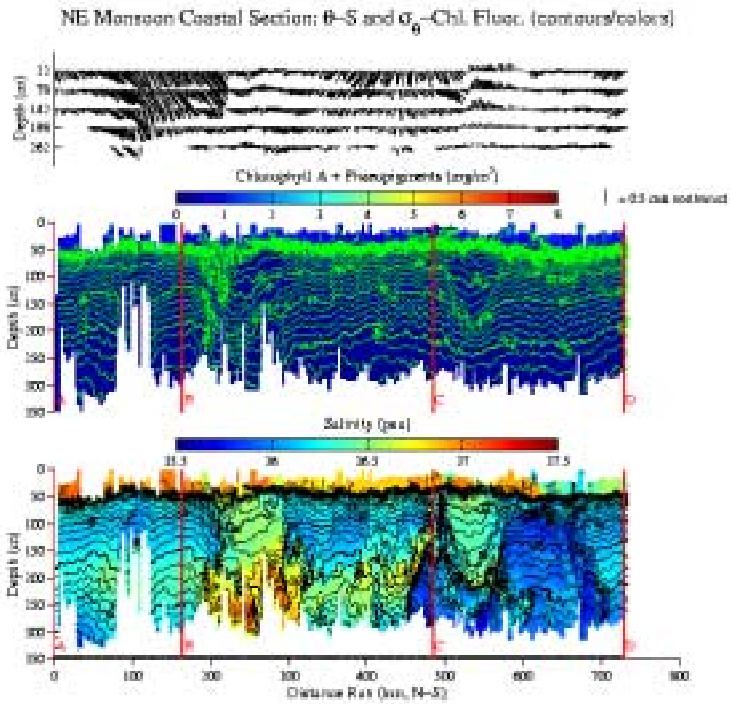


Fig. 13a: Sections of: (top) velocity, (middle) sigma-theta (in contours) and chlorophyll fluorescence (in colors), and (bottom) temperature (in contours) and salinity (colors) from the Northeast Monsoon. The section runs roughly parallel to the Omani coast. Point ‘A’ is within the Gulf of Oman, point ‘B’ is near Ras al Hadd and the remainder of the section runs southwestward along the coast well offshore of the shelfbreak. A large region of elevated salinities sits beneath an eddy at 250 km, and elevated salinities extend southward to ‘C’ at 500 km.

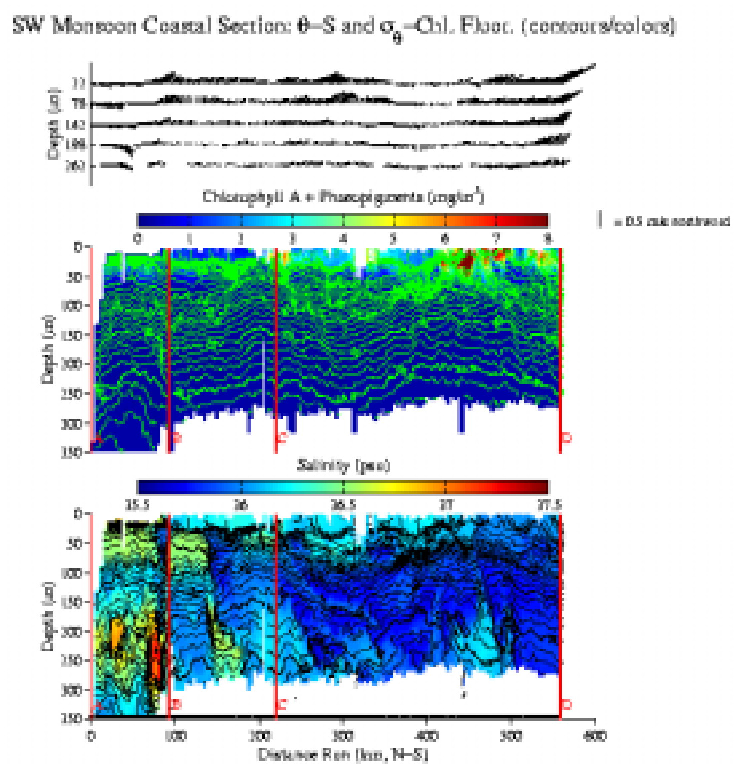


Fig. 13b: As for Fig. 13a, section along the Omani coast, but for the southwest monsoon. Two distinct high-salinity features appear north of Ra’s al Hadd (left of ‘B’).

Craig Lee showed results from four cruises sampling upper ocean variability in the Northern Arabian Sea through the 1994-1995 Monsoon cycle (Fig. 13a, Fig. 13b). Physical and biological measurements were carried out using both traditional hydrographic profiling and high resolution underway sampling with SeaSoar and shipboard ADCP. Both SeaSoar and hydrographic sampling revealed evidence of Persian Gulf outflow extending along the Omani coast as far as 300 km south of Ras al Hadd. SeaSoar/ADCP transects along the northeast Omani Coast showed in great detail the presence of high salinity lenses with length scales of O(50 km) at the PGW core depth of 200-300 m, along with numerous other high salinity features outside the lenses with smaller O(10 km) scales. During the NE monsoon (Fig. 12) the strongest signature of PGW appeared to be found south of Ras al Hadd, while during the SW monsoon the PGW water was mostly confined north of Ras al Hadd, suggesting a strong seasonal advective pattern at the PGW core depth related to the monsoon forcing.

3.3 Air-Sea Interaction and Surface Fluxes

Recent evaluations of the available surface flux climatologies over the Arabian marginal sea areas have revealed what appear to be large biases in net surface heat flux over these regions. Elina Tragou presented a recent analysis of COADS forcing over the Red Sea that was constrained by heat and freshwater fluxes through the Bab el Mandeb. Significant errors in several heat flux components led to a large estimated heat gain for the Red Sea of some 80 W/m^2, versus a heat loss of $\sim$10 W/m^2 estimated from the strait fluxes. A large portion of the difference was attributed to the overestimated shortwave radiation due to neglect of aerosols. Similar biases are also believed to exist in the COADS fluxes for the Arabian Gulf. Tragou also presented evidence for interannual variations in the surface forcing of the Red Sea (Fig. 14), which may be related to recently discovered variations in Red Sea deep water production (Woelk and Quadfasel, 1996).

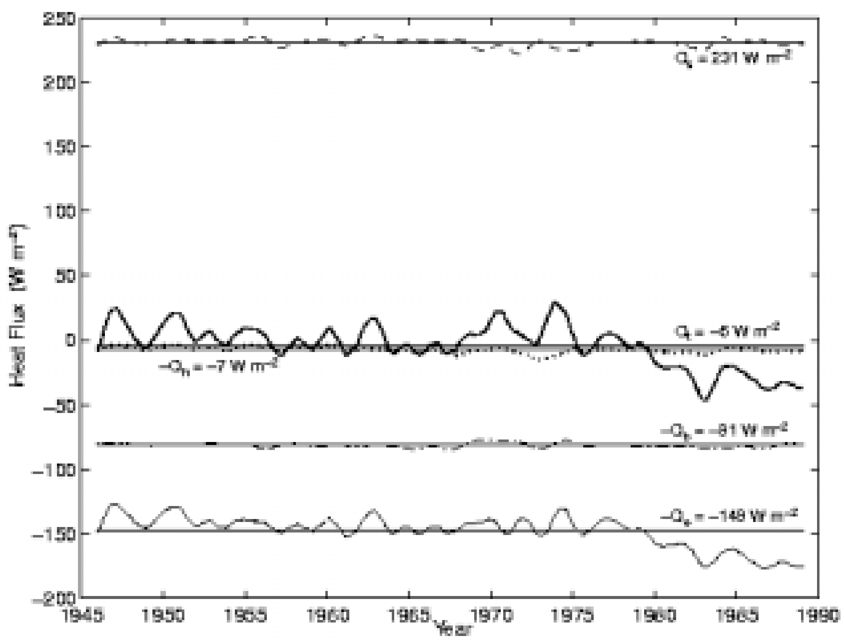


Fig. 14: Interannual variation of total heat flux and heat flux components in the Red Sea, after correction for systematic biases in the components.

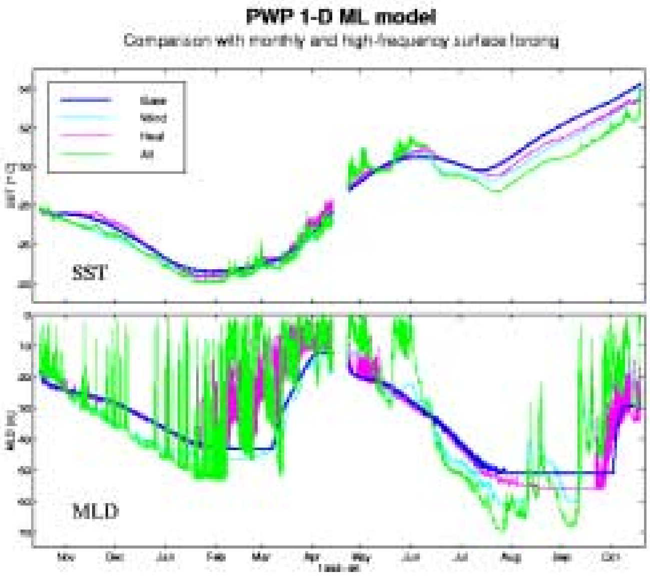


Fig. 15: Comparisons of results from the Price Weller Pinkel 1-D mixed layer model at the WHOI Arabian Sea mooring site, for monthly mean and high-frequency surface forcing. The base case (blue) is forced with monthly mean wind stress and heat flux, and no salt flux. The runs marked 'Wind' (cyan) and 'Heat' (purple) add high-frequency wind and heat forcing to the base case. The run marked 'All' (green) includes high frequency wind, heat, and salinity forcing. High-frequency forcing introduces both short term and low-frequency rectified effects on the SST and mixed layer depth.

Albert Fischer presented results from the WHOI air-sea interaction mooring in the Arabian Sea (Fig. 15) and related modeling studies (Fig. 16), stressing the importance of diurnal and high-frequency atmospheric forcing on the regional mixed layer response. He also noted the large range of surface fluxes derived from available climatologies in comparison to the Arabian Sea buoy fluxes (Weller et al., 1998).

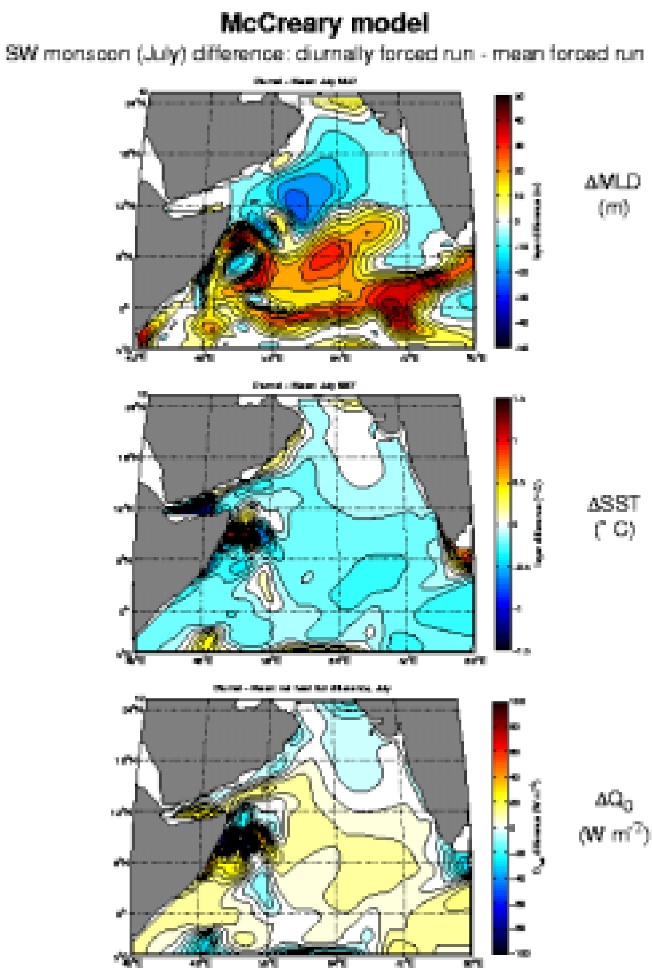


Fig. 16: Spatial differences in the mixed layer depth, sea surface temperature, and net surface heat flux between runs with a diurnally-varying heat flux and a monthly mean heat flux, for July. Over the course of a full model year the net surface heat flux over the Arabian Basin was increased in a model run with a diurnally-varying heat flux.

3.4 Remote Sensing

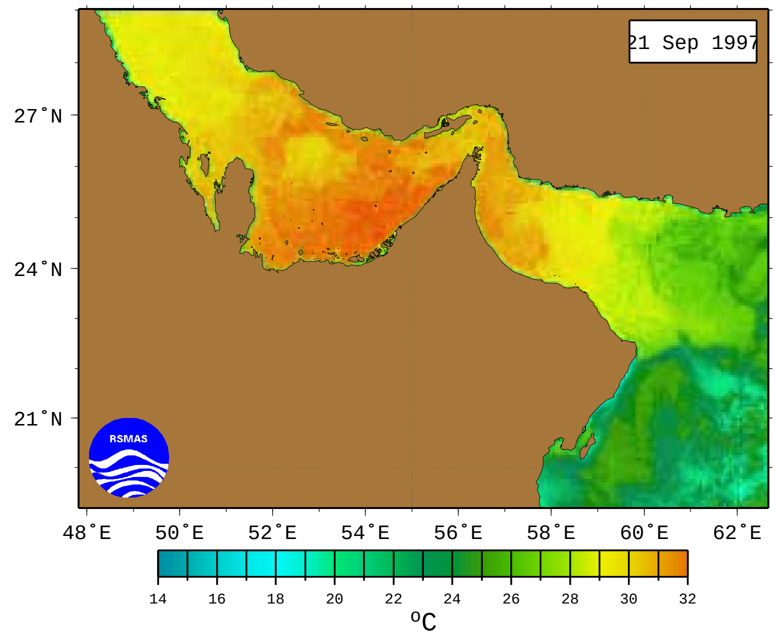


Fig. 17: AVHRR SST image for the Arabian Gulf and Gulf of Oman for September, 1997, showing evidence of a warm coastal plume emanating from the Strait of Hormuz.

Bob Arnone and Don Olson presented new remote sensing results for the region and summarized the tools now available for sensing of properties in the surface layers. The thermal patterns in these seas provide information on the basic patterns of water mass formation and outflows (Fig. 17) and the development of upwelling along the coast of the southern peninsula (Fig. 18). For example, the evidence from SST imagery for a seasonal outflow of surface waters from the Strait of Hormuz feeding a coastal plume along northeastern Oman coast (Fig. 17) has recently been confirmed by the direct observations in the Strait mentioned above.

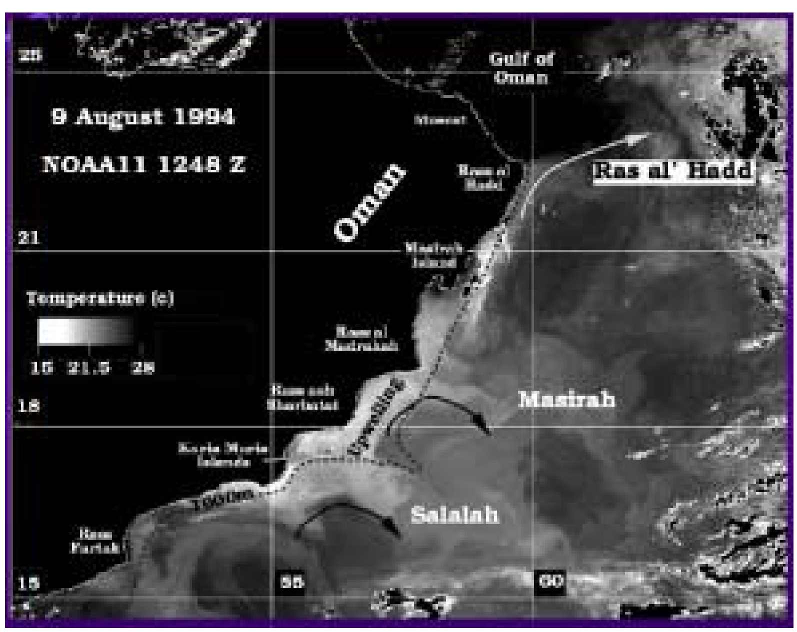


Fig. 18: AVHRR SST image for the Oman coastal region during the 1995 SW monsoon.

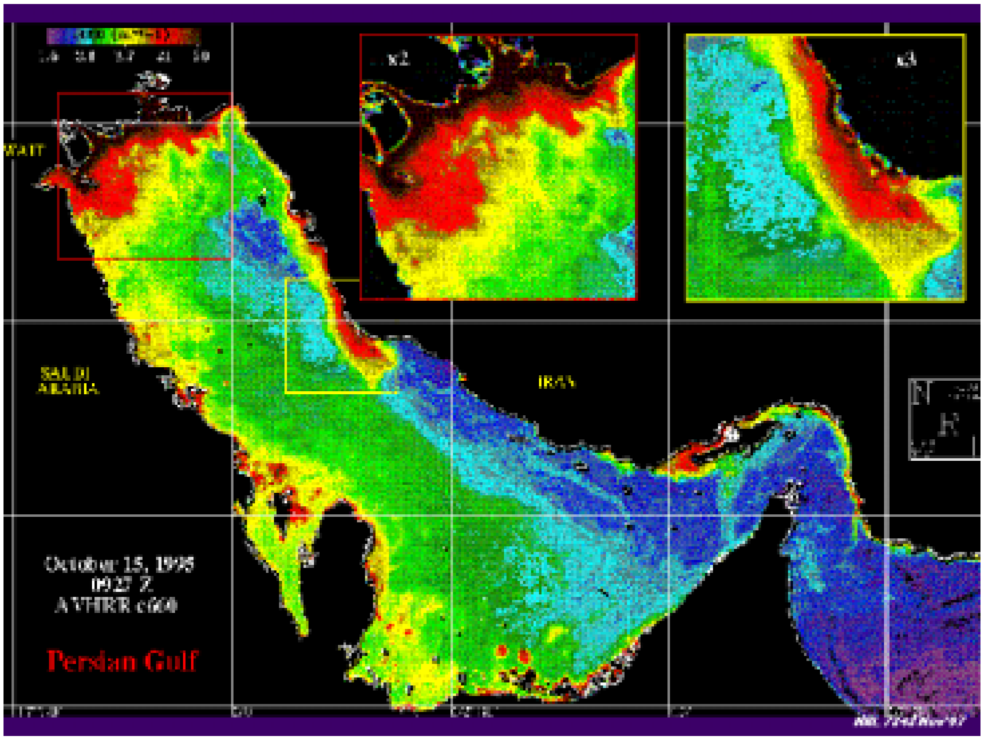


Fig. 19: AVHRR 660 nm band image of the Arabian Gulf for October, 1995. Strong signatures of the river outflow in the north and the coastal upwelling plume along the northern Iran coast are evident.

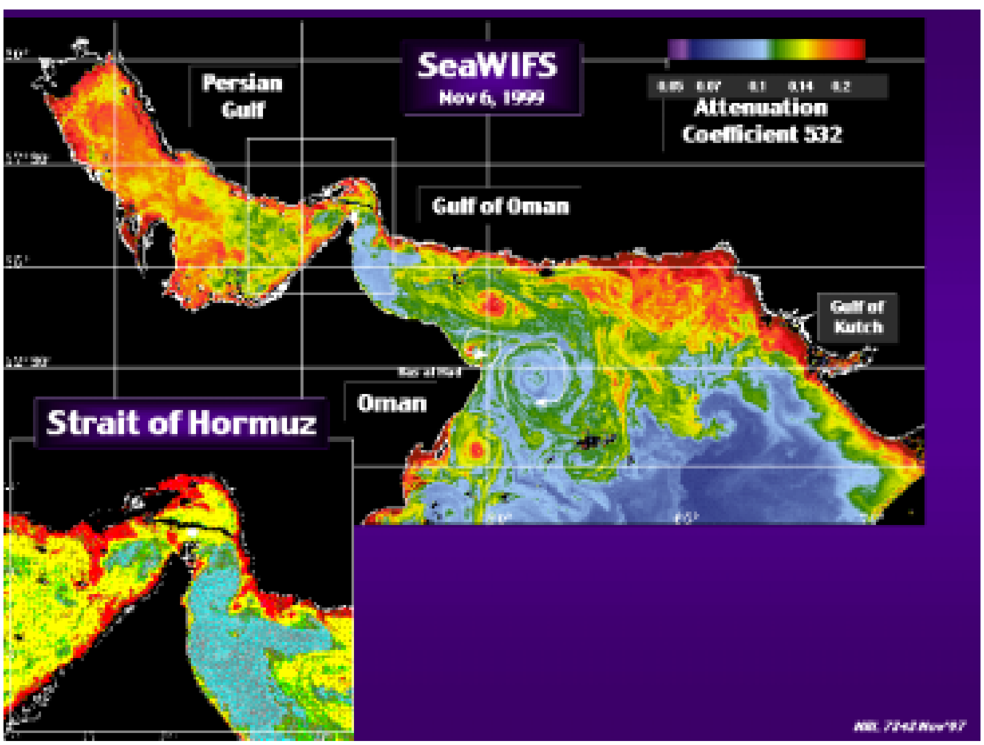


Fig. 20: SeaWifs image of the northern Arabian Sea and Arabian Gulf for November, 1998. The filaments off southern Oman as well as the dipole vortex pair off Ras al Hadd are clearly discernable.

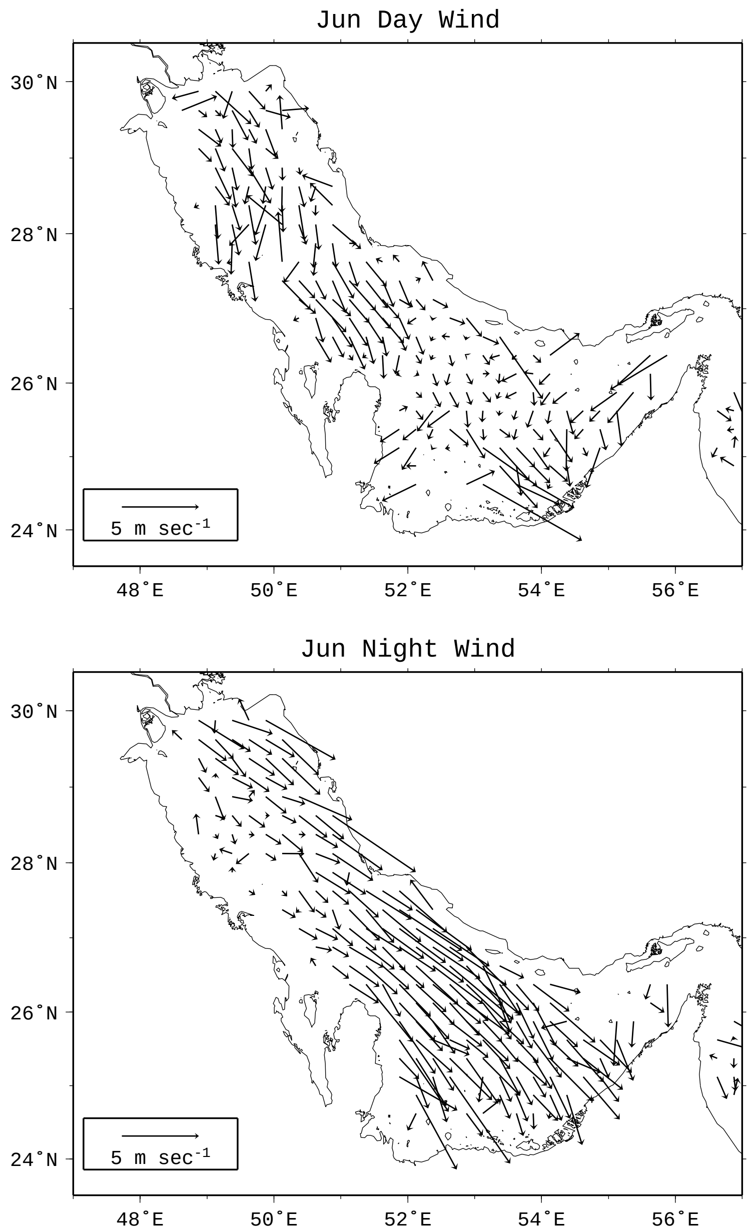
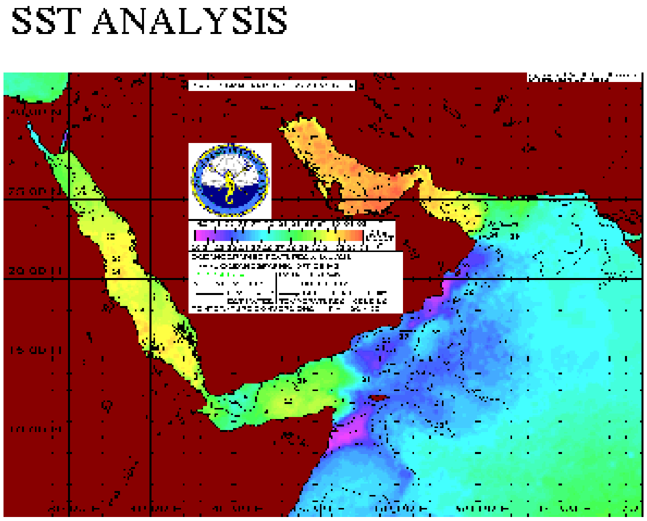


Fig. 21: Average day (top) and night (bottom) winds over the Arabian Gulf for June 1997 from the NSCAT mission.

These same sensors can be used to deduce surface optical properties (Fig. 19) and the details of features such as the coastal plume along the Iran coast in the northern Arabian Gulf (see also Fig. 23). In terms of passive sensing there are also the new color scanners and the upcoming hyperspectral missions. SeaWifs images of this region are spectacular and reveal many interesting features such as the vortex pair off Ras al Hadd (Fig. 20).

New active sensors also provide spatial information on winds over these seas. Figure 21 shows day and night winds over the Arabian Gulf for June. Of major interest is the large difference in wind strength between day and night. While it is crucial to have local wind estimates at higher temporal resolution than the twice per day satellite passes to understand the exact form of these significant diurnal forcing changes, the ability of scatterometers and upcoming passive wind sensors to provide spatial structure will be important in future work.

3.5 Modeling



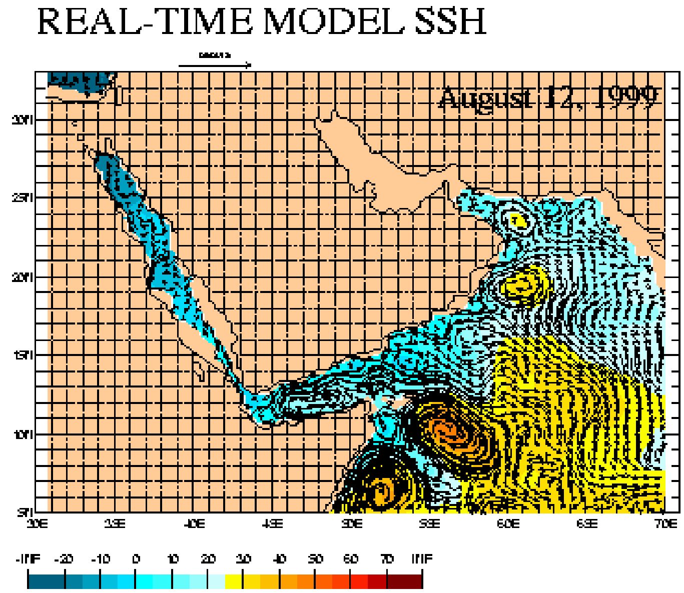


Fig. 22a (left): SST analysis in the northern Arabian Sea from NAVO for 12 August 1999.

Fig. 22b (right): The corresponding model day from the real-time NRL global model that assimilates altimeter data. The NAVO SST composite shows the position of the Great Whirl and what appears to be the Socotra Eddy just to its northeast. The model SSH and layer 1 currents show the Great Whirl in the same position as the NAVO SST analysis, as well as a very clear depiction of the Socotra Eddy (in approximately the same location as the analysis), and several other eddies along the Oman coast.

New high resolution models of various configurations have considerable promise for understanding the dynamics of the Arabian marginal seas. Results from several of these models were presented at the workshop, including the quasi-operational NAVO marginal sea models (Horton/Clifford) and Kantha POM model, and from the Navy layered ocean model (Kindle/Rhodes; Fig. 22). Figure 22 shows a composite SST analysis in the northern Arabian Sea from NAVO for 12 August 1999, and the corresponding model day from the real-time NRL global model that assimilates altimeter data. The NAVO SST composite shows the position of the Great Whirl and what appears to be the Socotra Eddy just to its northeast. The model SSH and layer 1 currents show the Great Whirl in the same position as the NAVO SST analysis, as well as a very clear depiction of the Socotra Eddy (in approximately the same location as the analysis), and several other eddies along the Oman coast. In addition to the good agreement shown by this comparison, the figure reveals the present ability of real-time models to augment interpretation of images derived purely from SST information. Other active simulations include MICOM and POM (Eshel and Naik, 1997) runs in the Red Sea and a new finite-element code applied to the Arabian Gulf (Cheryl Ann Blain; Fig. 23). Preliminary comparision of features in the Blain model, such as the northern boundary current in the Gulf, with the remote sensing results are very promising although much work remains to be done in comparing them. This model is now being used to explore the possible short time response to the diurnal wind changes discussed above.

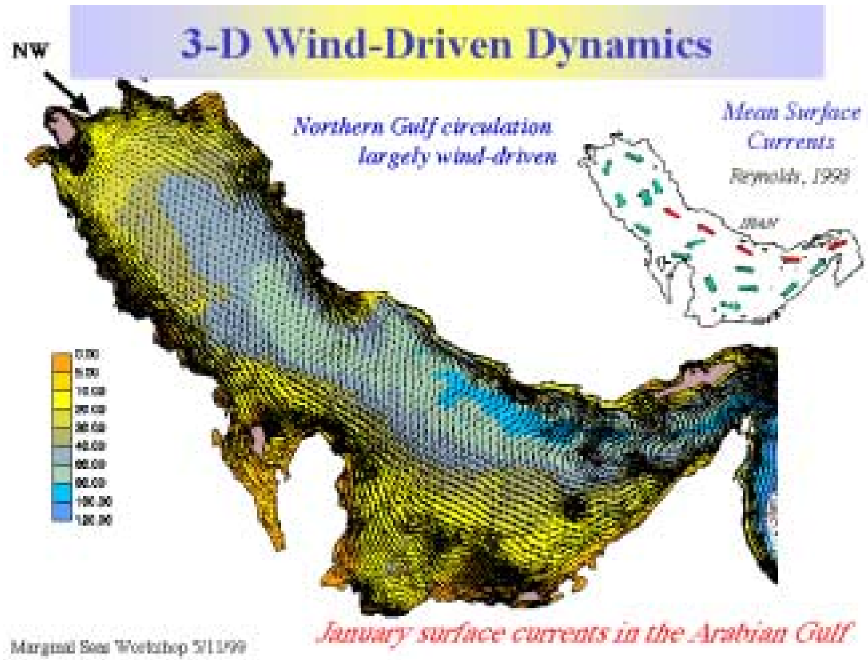


Fig. 23: Circulation snapshot from preliminary run of the NRL finite element Arabian Gulf model. The northern coastal boundary currents and general cyclonic circulation in the southeastern Gulf are clearly present, in general agreement with observations. (Forcing of thermohaline inflow from the Strait of Hormuz is not included in this model.)

4. Important Scientific Questions

The following scientific questions were posed by the workshop participants as some of the most important remaining questions for the region. These questions are broken into two sets of regional questions, grouped by common phenomena (where possible), and a third set of selected questions on biophysical interactions.

4.1 The Red Sea and Arabian Gulf

Exchanges with the Indian Ocean

4.1.1. What are the magnitudes and seasonal variations of the surface buoyancy fluxes that drive the overall exchanges between the marginal seas and the Indian Ocean? These fluxes are still poorly known and recent studies have shown that there are considerable biases in existing flux climatologies such as COADS. The evaporation rates that are occurring adjacent to the very arid coasts, at very high ocean temperatures, and frequently at relatively low wind speeds, are poorly determined from observations and may also be poorly accounted for by conventional bulk formula estimates. Are significant spatial gradients present in the evaporation rates and heat flux that impact water formation processes? Do significant interannual variations in these fluxes occur that cause associated interannual changes in water mass formation and exchange rates?

4.1.2. What is the cause of the seasonal cycle in the exchange flow system through the Bab el Mandeb at the entrance to the Red Sea? It has been well-documented that there is a two-way exchange flow during winter (NE monsoon), and a three-layer scheme in summer. The latter includes a thin outflow layer at the surface, and an intrusion of cool, fresher Gulf of Aden water at intermediate depths into the strait and Red Sea. Deep water outflow is a minimum in summer. Several hypotheses have been proposed to explain some or all of the seasonal changes in the strait flow: a) surface outflow in summer is driven by northwesterly wind; b) upwelling favorable winds in the western Gulf of Aden in summer alter the stratification there and cause a change in the along-strait pressure gradients at different depths in the strait. This suggests that the Gulf of Aden intrusion is driven by processes mainly external to the Red Sea. Such an adverse pressure gradient may also result in a weaker outflow of deep Red Sea Water.

4.1.3. What is the role of hydraulic control in the Bab el Mandeb? Recent studies suggest that in the mean, the flow in the strait may be subcritical, but that synoptically, it may be supercritical. What does it mean for a flow to be subcritical in the mean, but supercritical on short (perhaps tidal) time scales? Is there a hydraulic jump downstream of Perim Narrows that has not yet been observed? This would be in the downward sloping shelf/slope region in the western Gulf of Aden.

4.1.4. How does mixing along the strait transform the water properties of the inflow and outflow? Bab el Mandeb strait is unusually long (150 km), and mixing processes in the strait may significantly affect the properties of the waters entering the Red Sea and the Gulf of Aden. The observed low Richardson numbers and lack of critical levels are strongly suggestive of mixing.

4.1.5. What is the magnitude and seasonality of the exchange between the Arabian Gulf and the Gulf of Oman? Do winds have any significant role in the exchange as in the Red Sea? The limited available data from the Strait of Hormuz suggest a steadier deep outflow than the Red Sea but one with strongly varying properties on both seasonal and shorter time scales. Seasonal wind variations are significant over the Arabian Gulf though perhaps not as extreme as in the southern Red Sea. What are the essential physics behind the different characteristics of these exchanges?

4.1.6. What is the detailed nature of the surface exchange flow through the Strait of Hormuz? Is the inflow from the Gulf of Oman always concentrated on the Iranian side of the strait as in the accepted picture? Is there a narrow and shallow outflowing wind-driven current close to the Iran coast, inshore of the thermohaline driven inflow? What causes the seasonally varying countercurrent that is apparent in the southern part of the strait?

Water Mass Formation

4.1.7. What is the rate of Red Sea Water mass formation and where are the deep waters formed? It is generally believed that high evaporation in the northern Red Sea leads to intermediate and/or deep convection. Where does this take place? The Gulf of Suez has been identified as a probable location for deep water mass formation, but the rates are still uncertain. Intermediate water may be formed by various processes including deep winter convecton in northern Red Sea and evaporative intrusions from the southern Red Sea shelves. How do these water masses vary in their formation rates and contributions to the total export from the Red Sea?

4.1.8. Where are the dense waters formed in the Arabian Gulf and how do they flow out of the Gulf? What role does the river plume play in the watermass formation process? How important is the southeastern shelf region to the total watermass formation compared to that in the northern Gulf? What causes the observed variability in the outflow properties on seasonal as well as shorter time scales?

Horizontal Circulation

4.1.9. What is the horizontal circulation of the Red Sea? Observations suggest that there may be several semi-permanent gyres in the Red Sea that are maintained by as yet unknown causes. Modeling studies suggest that there is significant eddy activity, as well as strong boundary flows, especially in the upper ocean. But there have been few transverse hydrographic sections, and no subsurface direct velocity observations in the Red Sea. The value of $\beta L^2/u$ (where L is the Red Sea length and U is a typical velocity) is >1, suggesting that the beta effect is important. However, formulation of simple models which might anticipate the effect of beta on the horizontal circulation are hampered by the lack of sufficiently resolved wind fields. As a result, most studies have focused on the two-dimensional, thermohaline circulation, and not the wind-driven circulation. Are there seasonal changes in the Red Sea horizontal circulation caused by the prominent wind reversal over the southern Red Sea? How do the gyre and eddy features affect the propagation of Gulf of Aden surface and intermediate waters into the Red Sea and their conversion to deep outlfow waters?

4.1.10. Why is there a large axial horizontal density gradient of about 4 kg/m^3 in the Red Sea? Is friction responsible for the observed slow thermohaline circulation and the associated large density gradient, and if so, is it bottom or internal friction?

4.1.11. What features of the Arabian Gulf circulation are permanent versus seasonal (e.g., gyres, northern coastal boundary currents)? Do winds control the horizontal circulation in the Gulf (e.g., cyclonic gyre(s)), or does the thermohaline circulation partly drive it? What path does the inflow of fresh Gulf of Oman waters take in the Gulf? Does the fresh inflow penetrate into the northern Gulf, or mostly wrap around the cyclone in the southern Gulf and feed back toward the Strait of Hormuz? How does this relate to the SST front often observed near Qatar?

4.1.12. What kind of mesoscale variability occurs in the Gulf? Are there sub-gyre scale mesoscale eddies present? What is their energy source (winds, instabilities along the inflow/outflow front in the Strait or elsewhere)?

4.2 The Gulf of Oman, Gulf of Aden, and Coastal Arabian Sea

The Red Sea and Arabian Gulf Outflow Plumes

4.2.1. What is the nature of the downstream evolution of the Red Sea outflow plume after exiting the Bab el Mandeb Strait? There is reason, based on both theory and observations, to believe that both the Red Sea and Arabian Gulf outflows start out as defined, bottom-hugging currents, but that they rapidly break up into a string of eddies that move outward from the source region. There remain a number of questions about how this general pattern works out in practice, and these issues ultimately involve flow at a range of depths, not just the core depth of the outflow eddies themselves. For the Red Sea outflow, there are suggestions in sparse data of a boundary-following undercurrent along the western and southern boundaries of the Gulf of Aden, but the detailed cross-stream and along-stream structure of such a boundary current are completely unknown. This includes the breakdown of a possible coherent boundary current into eddies. Do isolated patches of Red Sea Water have the characteristics of Meddies (Reddies) or are they more benign blobs of outflow water? Where are these 'Reddies' formed? Do they form in the Gulf of Aden itself, or near Socotra where the Red Sea waters enter the Arabian Sea, or even from mid-ocean fronts in the western Arabian Sea?

4.2.2. How is the Arabian Gulf outflow water dispersed/mixed? What role do 'Peddies' play? How are Peddies formed (e.g., do they result from an instability of the quasigeostrophic plume after main entrainment has taken place, or from pulses of outflow from the Strait of Hormuz)? Once the eddies break off, are the water properties within the eddies modified during the time the eddies pass through the Gulf?

4.2.3. Are the deeper (eddy core depth: 200-500m) and shallower flows coupled in the Gulf of Oman and the Gulf of Aden? That is, is the behavior of the deep outflow water uncoupled from shallower influences? **4.2.4.** In either Gulf, how do ambient eddies affect the outflows from the evaporative basins?

Coastal boundary currents

4.2.5. Is there a continuous alongshore current off the Arabian peninsula, or is the system better characterized as simply a field of eddies? Observations (at best cross-shelf slices at a small number of locations) are inconclusive. Model results (e.g. Young and Kindle, 1994) suggest some continuity of alongshore flow during the southwest Monsoon, but the flow is not continuous along the entire slope edge. Presumably, alongshore flow over the shelf proper, being less influenced by eddies, will be more continuous. How far back toward the southwest does any continuous alongshore flow extend?

4.2.6. To what extent is the western boundary flow - both along Somalia and Yemen/Oman - a Sverdrup-like response to the interior wind stress curl (analogous to the Gulf Stream and other western boundary currents) versus a coastal upwelling/downwelling response to the alongshore winds? What is the impact of the seasonally reversing wind-stress curl on the time-dependent Sverdrup response? What is the magnitude of the directly forced response to that of the eddy field?

4.2.7. Are there clear-cut seasonal reversals in the general flow field in the Arabian Sea? If they are present, they were not obvious in the recent WOCE/ONR/JGOFS field effort.

4.2.8. What is the mean/seasonal circulation in the northern Gulf of Oman? Very little is apparently known of this region. How are the upwelling events forced that are evident in SST imagery there, and what are the associated mean or transient coastal currents?

Gyres, mesoscale eddies, and filaments

4.2.9. What is the origin of the eddy field in the Arabian Sea? Hypothesized mechanisms include westward propagation from the eastern boundary response along the west Indian coast, instabilities of interior jets driven either by the rapid onset of the atmospheric Findlater Jet or the offshore extension of the coastal currents, and direct wind-stress curl forcing.

4.2.10. How do the cyclonic/anticyclonic gyre pair at Ras al Hadd develop and evolve seasonally? Do these spin up in response to the offshore separation of the Oman Coastal Current or do they partly drive the separation of the OCC at Ras al Hadd? How do these break down after the southwest monsoon?

4.2.11. What is the origin of the large, surface-intensified mesoscale eddies observed in the Gulf of Aden? SST and SSH observations suggest mainly anticyclonic (warm) eddies in the Gulf of Aden, sometimes with diameters similar to the width of the Gulf. Presumably, these eddies propagate westward in the Gulf until they reach the head of the Gulf near Bab el Mandeb. How do these eddies decay? Through surface fluxes? Boundary mixing? What, if any, impact do they have on the exchange flow through the strait? How do they impact the spreading and mixing of Red Sea water? Basic characteristics of these eddies are unknown beyond typical diameters and associated temperature anomalies. What is their vertical structure? How deep do they penetrate? Is there seasonality in their presence in the Gulf of Aden?

4.2.12. What is the fate of the "Great Whirl" waters? The whirl forms south of Socotra during the southwest monsoon, and it appears to be a refugium for various forms of organisms including copepods. Does the eddy break up and shed eddies into the Gulf of Aden? Do the whirl waters find their way primarily eastward?

4.2.13. What is the fate of coastally upwelled water in the Arabian Sea? Cool, nutrient rich waters are upwelled near the Arabian peninsula coast during the southwest monsoon. These waters appear to dominate the upper ocean nutrient supply in the basin as a whole, and their influence is known to be felt at least as far offshore as the 1994-1995 WHOI surface mooring (under the core of the climatological Findlater jet, about 500 km offshore). It is not clear exactly how this water gets so far offshore, but it does appear to penetrate through the eddy field, forming filaments. What is the seasonality of the eddy field, and how does this affect the offshore transport? How do the patterns of offshore transport relate to life strategies for copepods?

4.3 Biophysical Interactions

4.3.1. What are the important biophysical interactions involved in the fisheries at Ras al Hadd, for example, the role of circulation in aggregating mesopelagic fish and yellowfin tuna? The largest unexploited potential fishery in the world is thought to be the mesopelagic resources of the Gulf of Oman, northern Arabian Sea, and maybe Gulf of Aden. These fish have a one year life cycle, driven by the strong seasonal signals of the reversing monsoon winds. Their biomass is largest in spring, and their spawning follows the southwest monsoon. They are food for the yellowfin tuna which are often aggregated in the Ras al Hadd region, inshore of the Ras al Hadd Jet. We know very little about distributions of the fish, and nothing about how the coastal circulations act to create the fishing center at Ras al Hadd. The connection of the upwelling areas all along the coast of Yemen and Oman and the mesopelagic fish is also unknown, as is the reproduction and growth of the mesopelagic fish outside the Gulf of Oman.

4.3.2. What controls the primary productivity cycle in the southern Red Sea and Bab el Mandeb region? The western Gulf of Aden and southern Red Sea have seasonal peaks in primary productivity that are opposite to those of the Arabian Sea. Phytoplankton blooms occur on both sides of Bab el Mandeb during winter when cooling deepens the mixed layer and entrains nutrients into a euphotic zone with sufficient sunlight. Although upwelling occurs along the coast of Yemen during summer and some blooms due to this are observed near Bab el Mandeb, the summertime circulation of the Gulf of Aden and southern Red Sea is mostly oligotrophic with deep chlorophyll maxima (Results of the Netherlands Indian Ocean Expedition, 1992-1993). Whether the entire food webs of the Gulf of Aden and southern Red Sea show seasonality opposite that of the Arabian Sea is unknown at this time. It is clear that Bab el Mandeb is an important biogeographic boundary (F. Ferrari, Smithsonian Institution) but the details of how this faunal choke-point operates are not understood. The nature and fate of plankton exchanged at Bab el Mandeb are of great interest.

4.3.3. What are the life strategies of plankton in the Gulf of Aden and upwelling areas, and can they serve as tracers of deep flows? The Gulf of Aden and coasts of Oman and Somalia contain a particular planktonic animal (the copepod *Calanoides carinatus* which is at the surface only during the upwelling season, when it comprises almost 50% of the plankton biomass. Grazing by this copepod may control phytoplankton blooms early in the upwelling season, and it in turn is probably a major food source for the fishes mentioned above. When upwelling is not active, the copepod is found at depths of 500-1500 m or more where it is dormant. Therefore, this dormant phase functions as a small deep drifter during winter. We know that this copepod is most abundant in the deep water at Bab el Mandeb during the northeast monsoon season. Why this is so is unknown; is it advected in from Somali coastal waters or does it complete its life cycle in the Gulf of Aden? It does not survive in the Red Sea.

4.3.4. What is the seasonal productivity along the Arabian peninsula and what role does convection play in enhancing productivity in the northeast monsoon season? The contrast in primary production and standing stock of chlorophyll-a between southwest and northeast monsoon seasons in 1995 was much less than previous measurements had indicated, and the standing stocks and productivity were higher in both seasons than had been reported previously. The higher productivity of the northeast monsoon season seems to be supported by nutrients brought into the euphotic zone by convective mixing caused by the cold dry air from the Tibetan plateau blowing over the region. The dramatically reduced seasonal contrast in chlorophyll-a also suggests that the CZCS (1978-1986), and possibly now SeaWiFS, need a re-evaluation of their algorithms for this region. The published composites of CZCS data for this region may include dust and aerosols as chlorophyll-a, leading to an areal distortion in the extent of the biological response of the upper ocean in this region.

4.3.5. What is the role of the extensive oxygen minimum zone in the nitrogen cycle and distribution of pelagic and benthic organisms in this region? The oxygen minimun zone (OMZ) in this region is intense and persistent, caused in part by source waters that are poor in oxygen and by the degradation of organic material arising from the upwelling areas, eddies, and convective mixing. In the oxygen minimum zone, denitrification converts nitrate and nitrite to nitrogen gas which escapes to the atmosphere. The suboxic conditions of the OMZ cause the sediments of the shelf and slope where it impinges to be devoid of normal benthic organisms and to have unusual geochemical constituents. In the pelagic realm, some layers of the water column are also mostly devoid of organisms (and have peculiar geochemistry), while other layers contain fish and euphausids which migrate to the surface on a daily basis. The fish that are thought to dominate the migrating biomass contain swim bladders, giving a strong daily acoustic backscatter signal. The actual biomass of fish and its areal distribution are not well known outside the Gulf of Oman. The physiological adaptations which allow the organisms to inhabit the OMZ for 12 or more hours each day have not been investigated.

4.3.6. Mother Nature's Iron Experiment: What is the role of dust and anoxic sediments in enhancing primary productivity? We know that iron is a crucial micronutrient for phytoplankton growth, particularly diatoms and nitrogen-fixing cyanobacteria. The dust sources in this region are in Oman and India, with Oman dust delivered during the southwest monsoon and Indian dust delivered then and in the northeast monsoon as well. The winds of the southwest monsoon deliver dust at the same time they drive upwelling of nitrate and silicate for diatom growth. Sorting out the dust delivery is complicated by the scavenging of dust by salt put into the atmosphere during the rough seas of the southwest monsoon. A systematic study of source regions and seasonal delivery to the air and sea surface are necessary to quantify the role of dust. It is also possible that iron arises from the anoxic or nearly anoxic shelf sediments and is carried to the surface during upwelling. An increase in iron at the sea surface during the southwest monsoon has been measured; measurements connecting that to the sediments or the atmosphere have not been quantitative. Physiological experiments demonstrating that the in situ iron stimulates increased productivity have also not been done.

5. Summary and Recommendations

5.1 Recommended Modeling Studies

A strong consensus was reached at the workshop that a hierarchy of model approaches is needed to advance basic understanding of the region, and in particular the interconnectivity between the marginal seas, gulfs, and open Arabian Sea. Simple models will provide some basic insight into the composition of the circulation features within each basin. There remains a need for very basic theoretical studies and scaling analyses to determine the importance of various dynamical processes. Useful approaches in numerical modeling will include closed model domains to ascertain the importance of local versus remote forcing, and process studies to examine the contribution of individual forcing mechanisms to the overall circulation within the basins. Sensitivity studies for various forcing mechansims are needed to motivate observational data collection and to justify the need for, and requirements of, high resolution meteorological models for the region. The group felt that the availability of high resolution mesoscale atmospheric models which could accurately account for orographic effects would likely be crucial to improving ocean models for this region. As more observational data and more accurate real-time forcing for the regions becomes available, the models can progress to include full physics and examine shorter time-scale phenomena, that is, to move beyond annual mean and seasonal dynamics to study mesoscale and forced synoptic scale variability. Finally, it was emphasized that coupled atmospheric and oceanic models will ultimately be needed to truly represent the dynamical processes at work in these regions.

Modeling Needs:

The following items were identified as major modeling needs for the region:

1. Improved climatological surface fluxes and wind forcing fields
2. Improved hydrographic data bases for model initialization and comparison
3. Validated atmospheric model products for forcing of synoptic scale circulation studies
4. Establishment of metrics for model performance, including well-determined observational benchmarks such as:
    - strait exchanges and transports (Hormuz, Bab el Mandeb)
    - coastal current transport and seasonal cycle off the Omani coast

Theoretical/Laboratory Models:

The following theoretical/laboratory models and process studies were recommended:

1. Extend some of the recent Red Sea thermocline laboratory models (Finnigen and Ivey, Grim and Maxworthy) to include rotation and possibly the beta effect. This would provide some notion of what the horizontal circulation would be if there were no wind. In addition, it would provide insight into what determines the deepest Red Sea waters that are able to spill out over the sill.
2. Initiate simple analytical/numerical studies with the purpose of looking at the leakage of eddies through gaps in straight walls.
3. Initiate process-oriented numerical studies of continuously stratified exchange flow over a sill with the purpose of clarifying the role of the inevitable critical layer that forms when an exchange flow is hydraulically controlled.
4. Use analytical and process-oriented numerical models to examine the influence of the far field (i.e., winds over the Arabian Sea) on the Red Sea/Indian Ocean exchange.
5. Determine how the relative importance of wind and buoyancy forcing depends on the dimensions of the basin and strength of surface fluxes in semi-enclosed seas, i.e. when is a 2-d model a good approximation? Where do the Red Sea and Persian Gulf lie in this parameter domain?
6. Determine the relative importance of interior versus boundary transports in carrying the thermohaline circulation of the semi-enclosed seas from the straits to the regions of intermediate and deep water formation. This could also be asked in terms of a potential vorticity budget, i.e. is lateral friction or diapycnal mixing balancing the meridional advection of the planetary vorticity by the thermohaline circulation?

Numerical Models:

In addition to basin scale OGCMs covering the full domain of interest, at least two types of smaller model configurations are recommended to study specific aspects of the regional circulation.

1. Semi-enclosed sea model(s) with specified strait exchanges.

These models can be used to study the general circulation and watermass formation processes in the Red Sea and Arabian Gulf, and to check the consistency of surface forcing fields with the internal state of the basins as determined from hydrographic climatologies.

2. Regional models.

Several kinds of regional models were recommended. One type of regional model would be a semi-enclosed sea model including part of its neighboring Gulf. Such models could be used to study, e.g., the seasonal cycle of exchange through the Bab el Mandeb Strait (believed to be forced in part by the winds over the Gulf of Aden), and effects of propagating eddies in the gulfs on the strait exchanges. Another type of regional model could include the Arabian Sea and adjacent gulfs with specified exchange boundary conditions at the straits. These models could be used to study the origins of eddy features in the gulfs and the connectivity of the coastal currents along the Arabian peninsula.

Recommended Process Studies

A number of general process and/or sensitivity studies are envisioned to help understand the forcing mechanisms responsible for various elements of the regional circulation. Among these are:

1. Sensitivity studies with partitioned dynamical forcing.

For the Red Sea and Arabian Gulf, simulations could be performed with various portions of the total forcing turned on or off, including (i) the wind forcing, (ii) surface buoyancy forcing, and (iii) inflows/outflows through the Strait, to help understand what forcing elements are responsible for specific aspects of the circulation.

2. Process studies to examine mesoscale variability and eddy formation.

The mechanisms responsible for generating transient circulation in the basins can be investigated by performing parallel simulations with mean winds, seasonal winds, and synoptically varying winds, to see what variability is internally generated (through instabilities of the mean or seasonal circulation) or externally generated by direct wind forcing.

3. Process studies with local and remote forcing.

The effects of local and remote wind forcing on the coastal current regime off the Oman/Yemen coasts could be examined with suitable models and forcing schemes, including the details of the generation and propagation of Rossby waves off the Indian coast that is involved in the remote response.

4. Sensitivity studies to model resolution and resolved/unresolved processes.

Model simulations should be carried out to determine the sensitivity of the modeled circulation to horizontal (and vertical) resolution, and to determine what processes may interact with each other on different time and space scales (e.g., tidal mixing effects on mean circulation, impact of diurnal wind variations).

Process modeling studies were also recommended for the following specific areas or phenomena:

- The River plume in the northern Arabian Gulf (effects on circulation and watermass formation)
- Dynamics and entrainment/mixing processes in RSW and PGW outflow plumes hierarchy of models ranging from 1-d slab layer models to fully 3-d plume models)
- Formation of Reddies/Peddies (theoretical/numerical models)
- The Ras al Hadd jet and frontal region (effects of wind stress curl resolution vs. coastal geometry)

5.2 Recommended Observations

An important outcome of this meeting was the realization that many aspects of the general circulation in this region are poorly understood and in some cases lack even a basic description of their essential features. The Red Sea is a good example of this situation, where almost nothing is known about the structure of the gyres, eddies, and boundary currents that are thought to exist there. Similarly, there are large knowledge gaps on the coastal flow in the northern Gulf of Oman, the eddy features in the Gulf of Aden, and the Ras al Hadd region off the Omani coast. Given this rudimentary state of knowledge, a consensus was reached that Lagrangian measurements offered perhaps the most promising near-term payoff toward an improved description of the circulation features and scales of variability in the region. For example, even modest drifter programs carried out in the Red Sea and Arabian Gulf could be expected to add a great deal to the basic understanding of the circulations in these basins. Similarly, subsurface floats launched in the outflow plumes from these basins within the Gulf of Oman and Gulf of Aden would help to understand the mechanisms by which these high salinity waters are mixed and dispersed in the Indian Ocean. Certain regions were also identifed where focused Eulerian measurement programs would be highly useful to constrain transports or exchanges between basins, such as in the Strait of Hormuz, off the central Omani coast, and near the Ras al Hadd jet/front.

A focused remote sensing effort will also be an essential part of any observational program, including SST, ocean color, altimetry, and surface winds. Altimetry in particular has barely been exploited in this region and its extension into the coastal and marginal sea areas needs to be aggressively pursued even with the new challenges it brings. A great need for the region is better estimates of surface momentum and buoyancy fluxes, and measurements of these quantities should be included as part of any observational program. A combination of intensive localized measurements in selected locations as well as broader scale VOS measurements to validate marine boundary layer products for the region is necessary. It was felt that a very useful start on this problem could be made by taking advantage of the high marine traffic in areas such as the

Arabian Gulf, where oil supply vessels or oil platforms could be instrumented with IMET or other similar boundary layer observation packages. Merchant vessels running regular routes in the Red Sea or along the Arabian peninsula could also perhaps be utilized for this purpose.

In addition to these large scale observations, several regions were recommended as areas where focused in-situ field studies should be conducted to explore specific processes or important dynamics. It is emphasized that any serious study done in any of these regions ought to include the following attributes: (i) multi-year duration (2 years minimum), (ii) meteorology, especially surface water and momentum fluxes, (iii) remote sensing (the exact suite depends on location), and (iv) a strong, dynamically oriented numerical modeling effort. In general, meeting participants were happy with the idea of using numerical models to guide the thinking and a priori planning for any field study (which worked well in the recent Arabian Sea field study), but uncomfortable with the idea of having the day-to-day activities of the field effort be directed by data-assimilative models.

These regions and processes were:

1. Red Sea and western Gulf of Aden region.

The horizontal circulation patterns here are not known, and the overturning pattern is known only schematically. It will be important to gain some exploratory idea of the horizontal circulation at a range of depths. For this reason, surface drifters, PALACE floats and ship-of-opportunity ADCP work will be valuable. The southern end of this region seems to be a biogeographical boundary, but it is not known exactly why. The mechanisms that drive the interesting annual cycle of exchange through the Bab el Mandeb are not fully understood, nor is the specific location of hydraulic control of the outflow, if one exists. A dedicated observational program will probably be required to sort out the hydraulic issues in the strait. It is not really known where deep convection happens in the Sea, yet it is known that it does occur. It would be desirable to place an array of moorings across the Red Sea and western Gulf of Aden in order to understand the scales, means, and cohesiveness of flow in the area. Presumably, the time series could be used to diagnose driving agencies. For the time being, however, Lagrangian measurements are seen as having a higher payoff that Eulerian current measurements.

2. Ras al Hadd region.

This is another area where important biophysical interactions take place and an interdisciplinary field experiment would be especially valuable. We do not understand more than the broad-brush biology here. Copepods do not get into the Gulf of Oman in large numbers. Mictofids consume the copepods, and the tuna consume the mictofids. Tuna congregate in large numbers (seasonally) near this front. What processes make this an attractive place for tuna to aggregate and (presumably) feed? In terms of measurement techniques, some important elements would be (i) drifters and Lagrangian fluorometric measurements, (ii) resolved frontal surveys, including oxygen measurements, (iii) vertical velocity (subduction) estimates near the front, and (iv) surveys of copepods and mictofids. Because of the strong contrasts, this would be a good location for developing satellite remote sensing algorithms.

3. Arabian Gulf and Strait of Hormuz region.

Exchanges through the Strait of Hormuz are not well measured and there appears to be a complicated system of horizontal exchange through the strait in addition to the vertical (overturning) exchange. Water mass formation regions and transformations in the Arabian Gulf are also poorly understood. Suggested measurement include: (i) moorings across the Strait of Hormuz similar to the recent intensive Bab el Mandeb measurement program utilizing bottom-mounted ADCPs and Seacats (or such) moored in the water column), (ii) surface current radar imaging (CODAR or OSCR) in carefully selected locations. At present it is not clear what the highest priority locations (besides the Strait of Hormuz) should be, although the river plume region and frontal zone off Qatar are obviously key areas of interest.

Other areas discussed for possible field emphasis were:

- The area near Sallalah on the Omani coast where a "straight" coast study could be done of the alongshore boundary current and upwelling regime and to document the seasonal cycle of the coastal current (structure/transport) in relation to the monsoon cycle.
- The eastern Gulf of Aden/Socotra region. The focus here would be on the relationship of the surface eddy field in the western Indian Ocean (e.g. the Great Whirl and Socotra Eddy) with eddies in the Gulf of Aden, and with the subsurface outflow of Red Sea water and Reddy formation.
- The western Gulf of Oman in the area of the southeastward flowing coastal plume and the descending outlfow plume from the Arabian Gulf. Here the focus would be on the structure and continutiy of the coastal plume between the Gulf and Ras al Hadd and the dynamics and formation of Peddies from the deep Gulf outflow.

Concluding Remarks

At the close of the meeting the participants expressed the feeling that they had learned a great deal about the region, and especially about the connectivity between the various basins by exchange flows and eddy processes. Many of the participants were familiar with certain parts of this region or with individual basins. However, few had had an opportunity to consider the region as a whole with colleagues and to share ideas on the common forcing and important linkages between the regions. The attempt at bringing together personnel involved in both research and operational aspects of Naval oceanography and meteorology with their counterparts in academia studying this region was entirely successful, and has helped already in several cases to maximize the sharing of available resources and information among the groups. The scientific exchange was very productive and is expected to lead to new partnerships and new plans for research in the region.

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8. Appendix 1. Contributed presentations

Real-time Nowcast of Indian Ocean Circulation from a 1/4 degree Global Ocean Model **(R. Rhodes)**

Synoptic and Mesoscale Atmospheric Forcing: High-resolution Model Simulations and Satellite Observations **(S. Chen)**

Overview of NAVOCEANO Operations and Products in the AMSG region **(M. Carron)**

Basic questions about the buoyancy forcing and dynamical response of the Red Sea **(E. Tragou and C. Garrett)**

Annual Cycle of volume and salt exchange between the Red Sea and Indian Ocean - Recent Observations 1995-1997 **(S. Murray)**

Hydraulic processes in the Bab el Mandab **(L. Pratt)**

Modeling the Bab el Mandeb Strait **(M. Inoue)**

A Review of the Results from Three Recent Cruises in the Arabian Gulf: The Mt. Mitchell Cruise in 1992, the Umitaka-Maru Cruises in 1993-94 **(M. Reynolds)**

The Shallow Water Analysis and Forecast System (SWAFS) in the Persian Gulf **(C. Horton and M. Clifford)**

Applications of a Finite Element Coastal Ocean Model to the Arabian Gulf **(C. Blain)**

Seasonal exchange through the Strait of Hormuz **(W. Johns)**

Remote Sensing of the Arabian Gulf Outflow Plume **(D. Olson and B. Arnone)**

Seasoar Measurements in the Gulf of Oman, 1994-1995 **(C. Lee, K. Brink, B. Jones)**

The Red Sea and Persian Gulf Outflows: Results from Historical Data Analysis and Modeling **(A. Bower)**

Where does dense water sink? **(M. Spall)**

The splitting of dense outflows and the formation of Reddies **(D. Nof)**

A Real Time Prediction System for the North Indian Ocean **(L. Kantha and J. Kindle)**

A Brief Overview of the Major Findings of the U.S. JGOFS Arabian Sea Process Study of 1995 **(S. Smith)**

The Arabian Sea response to high-frequency wind and buoyancy forcing **(A. Fischer and R. Weller)**

Influence of Persian Gulf water on the water mass formation in the Indian Ocean **(W. Han)**

On the upper ocean circulation of the Arabian Sea: Features I'd like to know more about **(J. Kindle)**

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