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Overview of physical oceanographic measurements taken during the Mt. Mitchell Cruise to the ROPME Sea Area

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Abstract

The NOAA research vessel *Mt. Mitchell* operated in the ROPME Sea Area, Strait of Hormuz, and Gulf of Oman from February to June, 1992. Of the six official legs and one unofficial leg on the homeward journey, four were devoted to physical oceanography, geology, and other large-scale processes. A variety of physical oceanographic observations were taken: (1) over 500 CTD casts were taken, (2) seven current meter moorings were deployed and six were recovered yielding eleven quality current meter records at different depths, (3) thirty-six drifting buoys with Argos positioning were deployed throughout the RSA, (4) continuous shipboard measurements of meteorological and oceanographic variables were recorded. The data base continues to grow as new data are continually added. The measurements are reviewed from the experimental point of view. Data accuracy, resolution, and precision are estimated. Quality assurance of the measurements is reviewed. The complete data set covers the important seasonal transition from mid-winter to early summer. During this period of time, the RSA develops an intense thermocline which decouples the surface mixed layer from the interior water. The data are reviewed in the light of prior measurements and recent modeling results.

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1 Introduction

The ROPME Sea Area (RSA) (Fig. 1) is one of the most important commercial waterways in the world. In peak periods, one ship passes the Strait of Hormuz each six minutes (Al-Hajri, 1990), and approximately 60% of the world's marine transport of oil comes from this region.

However, for its commercial importance, the number of direct oceanographic observations is small. Many investigations have been undertaken by countries of the RSA along their specific coastline, but only two basin-wide studies are commonly cited (Emery, 1956; Brewer and Dyrssen, 1985). The primary reason for the dearth of basin-wide data is that internecine conflicts between many countries bordering the sea prevent scientific access. The effect of war on the environment is considerable.

1.1 The Oil Spill

The deliberate discharge, by Iraqi soldiers, of 6.3 million barrels (Mbbl) of crude oil during the 1991 war against Kuwait has been called "environmental terrorism" (Williams, 1991). From 19–28 January, 1991, oil poured from two major sources: three Iraqi tankers anchored at Kuwait's port of Mina Al-Ahmadi, and the Mina Al-Ahmadi Sea Island terminal area. The valves at the Al-Ahmadi terminal, 16 km offshore, were opened on 22 January, 1991, and were left open for four days until U.S. Air Force precision bombs partially closed the manifold. Five other tankers and several other terminals added more oil throughout the spring and early summer. Estimates of the oil spilled at Al-Ahmadi, were based on duration and typical flow rates. In addition, 0.28 Mbbls were spilled at Kafji and 0.19 Mbbls were spilled at Mina Bakr.

This spill was the largest oil spill in history. It was about twice the size of the next largest spill, Ixtoc, but on a much smaller time and space scale. The third largest spill occurred in the Nowruz field in the RSA during the Iran-Iraqi war. The Nowruz spill came to 2–4 Mbbls, and was also an Iraqi creation.

Estimates of the volume spilled at Al-Ahmadi are widely variable. Side Looking Aerial Radar (SLAR), made just after the spills, did not reveal the large mass expected, and later estimates were reduced to 2.5 Mbbls.

Several factors complicated cleanup activity and/or affected the oil trajectory. Strong NW Shamal winds (Sec. 2.3) were twice interrupted by southerly blows which halted spill advance and raised wave heights to as much as 3 m. The winter sea temperature of approximately 16°C reduced evaporation rates. NW-SE tidal currents sheared off large sections of the spill and produced windrows that washed ashore intermittently over several weeks.

The oil fouled over 300 km of Kuwait and Saudi Arabian coastline as far south as Abu Ali peninsula. Abu Ali acted as a natural trap and prevented further southward movement of the oil. Thus important coastal seawater intakes for desalinization plants and industrial cooling/process water were spared. For example, Jubail has the largest desalinization plant in the world (> 5 Mbbls per day) and supplies 80% of the water for the Saudi capital, Riyadh.

The over 600 oil well blowouts and fires, started by Iraqi soldiers as they retreated from Kuwait, added further pollution to the RSA, and over a much broader area. It is estimated that oil fallout from the smoke plumes doubled the size of the spill (Congressional Research Service, 1992).

1.2 The *Mt. Mitchell* Cruise

Later, in the same year, an international program to study the effects of the oil spill on the environment began. The program was sponsored by the Regional Organization for the Protection of the Marine Environment (ROPME), the Intergovernmental Oceanographic Commission (IOC), and the National Oceanic and Atmospheric Administration (NOAA). ROPME is an environmental consortium of states surrounding what was formally called the Persian Gulf (or Arabian Gulf). NOAA provided a research vessel, the *Mt. Mitchell* (described below) which operated in the Inner Gulf, Strait of Hormuz, and Gulf of Oman from February to June, 1992. The expedition has been named the "*Mt. Mitchell* Expedition."

Aside from obvious studies of the environmental consequences of the war, the cruise was seen as an important opportunity to make a comprehensive physical oceanographic study of the entire region. All ROPME countries, with the exception of Iraq, supported the cruise and gave permission for the *Mt. Mitchell* or its small boats to enter into all coastal waters. An ambitious study was designed, and the required instrumentation had to be procured, prepared, and loaded onto the ship during three months before its sailing date on 15 January 1992.

The R/V *Mt Mitchell*, named for Mount Mitchell in the Blue Ridge Mountains of western North Carolina, was commissioned in 1968 in Jacksonville, Florida, as a hydrographic survey vessel. In 1987, she was refitted for surveying the nation's Exclusive Economic Zone (EEZ), and was equipped with a new swath sounding system called Seabeam. Table 1 presents specifications for the 70 m, 1631 tonne (displacement) vessel.

An intensive preparation for the RSA cruise was undertaken: (a) several scientific vans were placed on the already limited deck area; (b) new instrumentation was purchased or upgraded including five new CTD units, a scientific-grade weather station, and an underway thermosalinograph; (c) two rigid hull inflatable boats (RHIBs) were bought and outfitted with lights, radios, and redundant navigation equipment; (d) a complete scientific shipboard computer (SCS) system was installed so all ship measurements and navigation could be monitored continuously; (e) below deck adjustments to living areas were made to accommodate the large complement of scientists. (f) a personal computer network was installed and interfaced with the ship's Vax-based system. The ship crew graciously made way for an anticipated scientific party of up to 22 which would change each leg.

The cruise period lasted from 26 February to 12 June, 1992 (Julian days 57-160) during seven at-sea periods (Table 2). Figure 2 shows the approximate locations of the different physical oceanographic measurements made from the *Mt. Mitchell*, and Table 3 lists the most important measurements.

This paper is organized in the following way. Section 2 reviews the meteorology and the physical oceanography of the RSA, Strait of Hormuz and Gulf of Oman. The discussion includes three recent modeling efforts. Section 3 presents the main results from the CTD survey taken during Leg I and Leg VI. The Leg III intensive CTD survey is beyond the scope of this paper and will not be discussed. However, the Iranian coastal flow is easily seen in the satellite images and shuttle photos¹. Section 4 is a discussion of the basic results from the current meter time series. Section 5 reviews the drifting buoy tracklines. Section 6 provides a short review of the shipboard computer system data, and Section 7, proposes important directions for future research. The *Mt. Mitchell* study was necessarily broad, merely touching on areas of interest and lighting the way for future detailed investigations.

¹The project was supported by the NASA shuttle photography program (Ackerman *et al.*, 1993)

2 Physical Oceanography of the ROPME Sea Area

2.1 Geology and Bathymetry

The ROPME Sea Area (Fig. 1) has evolved by the interaction of the African and Eurasian plates. Arabia has been gradually moving northeastward, underthrusting Eurasia, for a considerable time. These movements have led to the slow closure of a vast waterway which once linked the Mediterranean and Indian Ocean, and in which a thick column of oil and gas bearing sediments, in excess of 10,000 m, has accumulated.

In the northwest, the closure of the ancient seaway has been completed, and the former marine area is covered with the flat alluvial lands of the fertile crescent of Iraq and Iran. This lowland has been formed by the deposition of the load of sediment supplied by the Tigris-Euphrates-Karun fluvial system attracted to the low depression between the stable Arabian Shield and mobile fold belt of Iran, a composition for major river systems (Fig. 3).

In the south, the history has been more complicated and the movements of the plates transporting Arabia and the adjacent Indian Ocean floor to the north-east has resulted in the anomalous Oman mountain range on the Arabian side of the depression.

The movement of the plates continues today, as the slow inexorable movement of Arabia to the northeast causes underthrusting, adjustment in the basement, and associated earthquakes and volcanoes in Iran. On the stable, Arabian Shield, movement has continued along basement faults, many with N-S trends, and this has resulted in gentle warping and the production of broad gentle anticlines and synclines in the cover rocks, in marked contrast to the highly folded structures found in Iran.

The Gulf is a flooded-valley estuary. The evidence for the changing landscape of the region is provided by: drowned physiographic features obviously formed above or close to sea level such as valleys, coastal beach dune complexes, and abrasion platforms; and also by the presence of sediments with textural and compositional properties which indicate a shallow water origin (e.g., shallow water oolitic sands). Faunas found in the sediments show shallow-water characteristics at present depths well below their original levels of formation.

At approximately 7000-6000 BP, the advancing waters of the rising sea engulfed the coastal deserts and depressions, and the RSA had an outline very similar to that seen today. The exact position of the shoreline in the northwestern part of the region is still poorly known. Beach ridges and related features on the Arabian shoreline indicate that the coastline has in places prograded seaward 4-5 kilometers since 4500 BP.

The bathymetry of the Gulf (Fig. 1) shallows to the north and to the west coasts. A deep trough extends in through the Strait of Hormuz and along the Iranian coast approximately 300 km. There is no sill at the mouth of the Gulf in the Strait of Hormuz; the trough simply deepens to more than 100 m through the Strait and drops quickly to more than 2000 m within 200 km outside the Strait. The surface area of the Gulf is approximately $2.39 \times 10^5 \text{ km}^2$ and a mean depth of 36 m implies an average volume of $8.63 \times 10^3 \text{ km}^3$. (By comparison, the area and depth for the Red Sea is $4.38 \times 10^5 \text{ km}^2$ and 491 m, and for the Baltic Sea is $4.22 \times 10^5 \text{ km}^2$ and 55 m).

2.2 Fresh Water Exchange

Most river inflow into the RSA occurs in the north and primarily on the Iranian side (Fig. 3). Recent flow measurements from Iran allow a better estimate of outflow than has hitherto been available. The Shatt Al-Arab is a nexus of three major rivers: the Tigris and Euphrates rivers together provide an annual average of $708 \text{ m}^3 \text{ s}^{-1}$ and the Karun adds $748 \text{ m}^3 \text{ s}^{-1}$. Thus, the total average outflow of the Shatt Al-Arab is $1456 \text{ m}^3 \text{ s}^{-1}$. Other major rivers are the Hendijan ($203 \text{ m}^3 \text{ s}^{-1}$), the Hilleh ($444 \text{ m}^3 \text{ s}^{-1}$), and the Mand ($1387 \text{ m}^3 \text{ s}^{-1}$).

The total runoff into the Gulf is $1.1 \times 10^2 \text{ km}^3 \text{ yr}^{-1}$, equivalent to 46 cm yr^{-1} of depth. This estimate is considerably greater than earlier published estimates. Al-Hajri (1990) uses a value of 16 cm yr^{-1} . Industrial and agricultural development are having a pronounced effect on the outflow from the Shatt Al-Arab.

New models of the circulation are sensitive to the runoff amount. While river outflow is considerably less than evaporation, its concentration in the northern, closed end supports a counterclockwise circulation (Chao *et al.*, 1992).

Annual rainfall in the arid climate of the RSA is small, of the order of 7 cm yr^{-1} .

Evaporation in the Gulf is much higher than both river inflow and precipitation and the net loss of water creates the Mediterranean, reverse-flow, estuarine circulation. Estimates of evaporation vary from 500 cm yr^{-1} to 144 cm yr^{-1} . The lower figure from Privett (1959) is in agreement with Meshal and Harsan (1986) who estimated 200 cm yr^{-1} .

2.3 Winds

The RSA is located between latitudes $24\text{--}30^\circ\text{N}$ in which are located most of the Earth's deserts. This region, north and south of the equator, marks the boundary between tropical circulations (Hadley Cell) and the synoptic weather systems of mid-latitudes. Descending dry air in these latitudes produces clear skies and arid conditions.

The local climate is influenced by orography. The Taurus and Pontic mountains of Turkey, the Caucasus mountains of Iran, and the Hejaz mountains of the Arabian Peninsula together with the Tigris-Euphrates Valley form a northwest-southeast axis that strongly influences the tracks of extra-tropical storms to a southeast direction.

The climate in the Gulf of Oman is markedly different than the climate in the RSA. While the RSA is mainly affected by the extra-tropical weather systems from the northwest, the Gulf of Oman is at the northern edge of the tropical weather systems in the Arabian Sea and Indian Ocean. This monsoon circulation produces southerly winds in the summer and strong northerlies in the winter. In the Gulf of Oman, winds are NW/SE variable in the winter but prefer a SE direction in the summer months. The Strait of Hormuz approximates a boundary between the two systems.

The most well-known, and notorious, weather phenomenon in the Inner Gulf is the Shamal, a NW wind which occurs year round (Perrone, 1981). Shamal is an Arabic word meaning north. The Winter Shamal is a wind that sets in with great abruptness and force, and is related to synoptic weather systems to the NW. It seldom exceeds 10 m s^{-1} ($< 5\%$ frequency) and lasts several days. On the other hand, the summer Shamal is practically continuous from early June through July. It is associated with the relative strengths of the Indian and Arabian thermal lows.

The winter Shamal brings some of the strongest winds and highest seas of the season to the RSA region. Winds in the area ahead of an approaching cold front blow from the southwest. These winds are called *Kaus* in Arabic or *Shakki* in Persian, and slowly increase in intensity as the front approaches. They may reach gale force before the passage of the front and the onset of the Shamal. Due to the channeling of the low-level air flow by the Zagros mountains of western Iran, the strongest of the southerly winds occur on the eastern side of the RSA. Usually, the Shamal occurs first in the northwest and then spreads south.

A strong sea breeze occurs along the entire coastline, especially along the Arabian peninsula. Driven by the intense temperature difference between the land and water surfaces, the sea breeze circulation adds a landward component to all winds. The effect of these winds is to drive surface pollutants to the beach much faster than they would move otherwise. Examples of on- or off-shore winds as high as 15 ms^{-1} are evident in coastal meteorological stations.

2.4 Currents – tides, wind-driven, and density-driven

The energy in the water motion can be related to three forcing processes: tidal forces, wind force, and density differences. The kinetic energy of the water velocity can be partitioned between the three terms approximately as 100, 10, 1 respectively. Each of the different currents has a different scaling time: tides vary over a few hours at diurnal or semidiurnal periods; wind-driven currents develop and subside over a few days; and density-driven currents take weeks to change in response to seasonal forcing. The selection of averaging times and filter types affects the computed proportions considerably.

2.4.1 Tides

The tides in the Inner Gulf are co-oscillate with those in the narrow Strait of Hormuz which opens into the deep Gulf of Oman (Fig. 4). The tides in the Gulf of Oman are co-oscillating tides with those in the Arabian Sea. The tides in the Gulf are complex and vary from semi-diurnal to diurnal throughout the Gulf. The tidal range is large with values greater than 1 m everywhere (Lehr, 1984). The dimensions of the Gulf are such that resonance amplification of the tides can occur and the result is that the semi-diurnal constituents have two amphidromic points, in the northwest and southeast ends, and the diurnal constituents have an amphidromic point in the center near Bahrain.

As large as the tides are, they do not make an important contribution to the overall circulation of the RSA. Averages longer than a day have negligible residual energy, and as a result, tides are not considered by oil trajectory models or general circulation models. Tides are important on small scales of horizontal length ($< 10 \text{ km}$) and time ($< 24 \text{ hrs}$). The KFUPM has developed a detailed tide model of the Gulf (Lardner *et al.*, 1982).

2.4.2 Residual Circulation – wind-driven and density-driven

The net freshwater loss to the atmosphere is replaced by a surface inflow in the Strait of Hormuz. Throughout the year and against prevailing Shamal winds, relatively low-salinity water enters the Gulf through the Strait of Hormuz to freshen the hypersaline Gulf water. As it enters it undergoes evaporation, becomes more dense and sinks to exit the Gulf as a high-salinity undercurrent through the deeper portion of the Strait of Hormuz. This circulation is called

“reverse estuary flow” and is similar to the circulation of the Mediterranean Sea.

An early sketch by Hunter (1983) is given in Fig. 5. The sketch shows the main features of the residual circulation in the RSA: (a) high- and low-salinity water exchange in the Strait of Hormuz; (b) density-dominated circulation in the central and southern Gulf; (c) frictional-balanced, wind-dominated regime in the NW Gulf; (d) and evaporation-induced bottom flow. The actual pattern of circulation is more complex than that in the sketch as can be seen by the patterns of sea-surface temperature shown in Fig. 6.

Figures 7 to 12 indicate that the surface inflow occurs year round, but is more pronounced and extends deeper into the Gulf in the summer. However, in the winter (Fig. 11) the density difference is primarily due to the lower salinity of the water of the Gulf of Oman where in summer (Fig. 12) both temperature and salinity strengthen the density difference.

Wintertime cross sections at A and B shown (Fig. 13 and Fig. 14) indicate how the bottom water exits the Strait of Hormuz. In Section B, very dense water ($\sigma_T > 27$) fills the bottom and banks slightly upwards towards Oman. This water spills down the mouth of the Strait of Hormuz (there is no sill there), mixes with Gulf of Oman water, and ultimately settles out as a density layer at about 200 m ($\sigma_T \approx 26$).

An, important, secondary current in the Gulf is a coastal reverse circulation along the Iranian coast. Driven by the density differences that result from river runoff, the coastal currents along the Iranian coast are southerly, against the inflow water. The reverse currents are evident in shuttle photographs and AVHRR images (Fig. 6). The interface between the two currents is a region of horizontal current shear and often shows evidence of waves, some breaking, indicative of a shear instability.

As summer approaches, the intense solar heating creates a surface mixed layer and a thermocline which decouples the surface layers from bottom mixing. Figures 11 and 12 demonstrate the differences in the structure. The density contours (σ_T) indicate the combined effect of temperature and salinity. As the temperature increases, the water density decreases. Thus solar heating creates a surface mixed layer separated by the thermocline (at about 20 m depth in Fig. 12). Countering this stabilization, evaporation increases surface salinity, which increases density, which creates an unstable situation and causes the surface water to sink to some lower depth.

The vertical density structure of the RSA has the following striking features: (a) In the wintertime, north of Qatar, the water column is almost perfectly mixed top to bottom. (b) In the summertime, the northern end of the Gulf becomes a two-layer system with a well-mixed surface layer and a well-mixed bottom layer which is a residual of the winter water. (c) At the southern end of the Gulf, a two-layer system persists year round. The upper layer is warmer, fresher water intruding from the Gulf of Oman to replace water lost by evaporation, and the lower water is colder, more-saline water which is exiting the Gulf as part of the reverse-estuarine, Mediterranean-like circulation.

There are three dominant mixing processes: (1) the strong tides induce mechanical turbulence at the bottom, (2) winds create waves and mechanical turbulence at the surface, and (3) the high evaporation enhanced by wintertime cooling generate a vertical mixing near the surface. Internal waves at density interfaces, and topographic features such as island also contribute to mixing but their contribution is unknown and probably small. The mixing forcing is opposed by stabilizing effects of surface warming in the summertime and locally, along the coastlines by river runoff.

2.4.3 Residence Times

The estuarine circulation exchanges water into and out of the Gulf via the Strait of Hormuz. Simple box models predict the residence time for a water parcel in the Gulf. (Assuming a long-term steady state, the residence time is the ratio of volume of water to the volume exchange rate (in or out) of the Gulf. It is a measure of the mean amount of time a particle of water will remain in the volume. We assume the same measure applies to passive pollutants.) Up to now, the circulation in and out of the Strait of Hormuz has been poorly defined, and as a result estimates of residence times vary in the approximate range of 2-5 years (Hughes and Hunter, 1979; Hunter, 1983). However, knowledge of the circulation in the Strait of Hormuz plays a key role in understanding the basin-wide behavior of the Gulf.

2.4.4 Surface Pollutant Trajectories

Many pollutants float on the ocean surface. Oil is a notable example. Water at the surface is strongly influenced by the winds over the water, and a rule of thumb is that the wind-induced surface flow is 3% of the mean wind speed and 15° to the right of the wind direction (northern hemisphere). In a 10 ms^{-1} Shamal wind this amounts to an 0.3 ms^{-1} added current which is considerably larger than the residual currents (approximately 0.1 ms^{-1}). Thus, over several tidal periods, the wind-induced surface current plays a significant role in predicting where surface pollutants will go.

In an enclosed basin such as the Gulf, the situation becomes more complex. Sustained winds such as Shamals generate a secondary, wind-induced circulation over the entire Gulf. The secondary flow can go in all directions, depending on its location, and in some regions, theoretically, can oppose or nullify the residual and wind-induced currents.

2.4.5 Modeling Studies

The ROPME Sea Area suffers from an extreme dearth of comprehensive physical oceanographic measurements. Probably no other body of water of comparable size is so un-investigated. Modeling efforts have been carried as far as they can with the current spotty data base. Winds, hydrography and resulting currents are highly seasonal, and data sets for all seasons are another dimension to the problem.

Modeling efforts can be divided between tidal models and circulation models. There are several excellent tidal models for the RSA and the paper by Le Provost (1984) is a good review. Three modeling efforts currently exist: (1) The U.S. Naval Oceanographic Office (Horton, et al., 1992); (2) The Catholic University of America (Chao et al., 1992); and (3) King Faud University of Petroleum and Minerals (KFUPM) (Lardner *et al.*, 1988a; Lardner *et al.*, 1988b; and Lardner *et al.*, 1993).

The models differ in type and construction. The Navy model is a three-dimensional, primitive-equation circulation model with complete thermodynamics and imbedded turbulent-closure submodels. It uses terrain-following vertical coordinates and has a horizontal grid size of approximately 8 km and 14-22 levels in the vertical. The Catholic University model uses 20 km grid size and 11 levels in a diagnostic model. The KFUPM model covers the gulf with a rectangular grid of approximately 10 km size. The it is three-dimensional, but has the option of being run in two-dimensional mode. The algorithm uses a mode-splitting method by which the

depth-averaged equations are first solved for the barotropic mode, then the momentum equations are stepped forward to compute the velocity profiles. The bottom friction and advective terms are computed for use in the depth-averaged equations on the next step.

The models have the same general findings: (a) The inflow current along the Iranian coast is weakened by Shamal winds in the winter, but in the summer it strengthens and extends almost to the head of the Gulf. (b) A cyclonic circulation gyre fills the southern Gulf and is driven by the inflowing surface water through the Strait of Hormuz. (c) Runoff from Shatt Al-Arab in the northwest Gulf maintains a cyclonic circulation there that would otherwise be anti-cyclonic. (d) A southward coastal jet exists between the head of the Gulf and Qatar, and extends east of Qatar depending on the wind.

Oil spill models have been developed for the Gulf. Galt (1983) and Galt *et al.* (1983) describe a finite-element circulation model developed during the Nowruz spill and subsequently updated for the recent spill.

3 Hydrographic Measurements

3.1 Instrumentation

Legs I, III, and VI were dedicated to physical oceanography, and CTD measurements were a major part of them. CTD casts were made from the ship and two Rigid Hull Inflatable Boats (RHIBs). To meet the expected requirements and provide backup, two Seabird Electronics Company SBE-9 real-time shipboard instruments and two SBE-19 Seacat internally recording CTD instruments, to be used primarily on the RHIBs, were provided. An additional SBE-19 Seacat was used as a backup unit. Because of an early requirement for dissolved oxygen (DO) profiles concurrent with the CTD casts, one SBE-9 was retrofitted with a DO sensor and associated electronics and the new SBE-19 was ordered with a DO sensor. The requirement for a DO sensor was later removed, and as a result, the DO sensors were not calibrated or maintained.

The SBE-9 CTD was housed in a protective cage and installed in a General Oceanics rosette sampler configured to accept 12, 1.7 l, Niskin bottles. The CTD was electrically connected through slip rings on the winch to a PC computer in the oceanographic laboratory. Raw data, downloaded into this computer, were processed and quality controlled with Seabird software before being sent to the Scientific Computer System (SCS). The rosette was deployed from the oceanographic winch on the port side of the fantail through the portside A-frame. By comparing the CTD pressure to the ship's precision depth sounder, the instrument was lowered to within 3 m of the bottom.

The SBE-19 Seacats were housed in a small protective cage. They were deployed from the RHIBs using an electric winch to aid in lowering and raising the instrument. The winch incorporated a metering device and this was used in conjunction with the depth sounder on the RHIBs to lower the CTDs to within 2 m of the bottom. In addition, the cages were fitted with a feeler rod that was attached to a lower corner of the cage and kept the cage from contacting the bottom in case the meter and sounder method failed. At the end of each day's casts the SBE-19 data were downloaded to the IBM computer in the oceanographic laboratory. The data were then treated in the same manner as those from the SBE-9.

Two 17-foot RHIBs were outfitted with 100 hp outboard motors, fathometers, HF and VHF radios, hand-held GPS and LORAN-C navigation receivers, and extra fuel tanks carrying a total

of 54 gallons of gasoline. Each RHIB was fitted with a small electric winch with 123 m of 60-kg test-tensile-strength, stainless steel wire to aid in the deployment and recovery of the CTD units.

Quality Assurance of the CTD measurements was maintained by several methods: (1) Intercomparison casts were taken with at least one Seacat accompanying each cast by the shipboard unit. In general, temperature and salinity intercompared to ± 0.02 ($^{\circ}\text{C}$ or psu respectively). (2) Intercomparison soaking of several units were regularly made. The differences between units was as indicated by the intercomparison casts. (3) Water samples were taken from 23 different stations during the legs. Two samples were taken at each of calibration cast, one at the deepest point of the cast and the second at the surface.

The general performance of the equipment was good, but the quality of the soundings noticeably declined over the duration of the cruise. Most importantly, strong temperature and salinity gradients produced spiking in the computed salinity and σ_t profiles. Strong gradients in temperature or salinity are known to induce spiking as a result of differing time constants in the temperature and conductivity sensors. All casts are currently undergoing a spiking removal analysis.

3.2 CTD Data Processing

Initial cast processing was performed by the ship survey department using Seabird-provided software on a PC computer. The output of the initial processing was an ASCII "avg" file that was sent via Ethernet to the ship's mainframe VAX computer.

The "avg" files were then transferred to a Macintosh computer for further processing (Reynolds, 1992a and 1992b). A complete and robust set of Matlab routines were developed to perform the following tasks: (1) Convert "avg" files to vector time series. (2) Find and remove outlier data from electrical spikes or data dropout. (3) Extract downcast samples. (4) Remove and interpolate over slow samples. Slow samples were those samples that occurred when the CTD unit was moving downward at a speed less than 0.25 m s^{-1} . When the speed was less than this, the sensors are not suitably washed for good results. This procedure also removed cases when the fish was moving upwards from the heave of the ship. (5) Plot profiles. (6) Write output files. Standard, ASCII, output files were produced and in addition, standard, OceanAtlas². ASCII files were created.

The CTD profile plots were used to construct hand-drawn, cross-section diagrams of the density structure of the RSA. Examples of CTD sections for temperature, salinity, and density are shown in Figures 11 to 23. Both winter sections (Feb/Mar) and early summer sections (May/June) are shown. The sections reveal drastic changes to the stability structure of the Gulf. While winter conditions are largely homogeneous in the vertical, summer conditions feature an intense thermocline at approximately 20 m depth. The thermocline shows waviness and variation in thickness, evidence of internal wave action. Penetration of surface water from the Gulf of Oman as far as station 88 is evident. The salinity sections are similar from winter to summer; salinities of 39-40 psu are found in the bottom water at the Strait of Hormuz. However, the tongue of slightly fresher water indicative of the Gulf of Oman is evident to station 66. Densities in the Gulf reflect the effects of salinity and secondarily temperature. Values of σ_T at the Strait

²OceanAtlas is a Macintosh-based software package for the display and visualization of CTD data. Today, OceanAtlas is a mature (though routinely updated and improved) software package which is used throughout the oceanographic community. Because of its utility and because it is public domain software, we elected to use it for CTD analysis.

of Hormuz are approximately 28 for both summer and winter.

4 Current Meter Measurements

4.1 Instrumentation

Five anchored moorings (Fig. 24) were provided by the NOAA Pacific Marine Environmental Laboratory (PMEL). With the benefit of equipment loaned by the University of Qatar, two additional moorings were deployed. The moorings were placed near the Iranian coast with the goal of better identifying the Oman inflow water mass (Fig. 2). Of the seven moorings and sixteen current meters deployed, five moorings with eleven operating meters were recovered (Reynolds, 1992b): Mooring M6 was lost due to failure of some of the flotation spheres, possibly from collision with a deep-draft ship; Mooring M1 was never found and it is suspected it fell victim to the heavy bottom-trawl fishing in that area; and finally, the top meter of mooring M7 failed to advance its tape. Table 4 is a summary of the recovered current meter data.

All current meters were Aanderaa Model RCM-5 with magnetic tape recording. The meters measured current speed by counting rotations of a savonius rotor, current direction by recording a magnetic compass bearing, temperature from a thermistor resistance bridge, conductivity by an inductive sensor, and pressure from a capacitive sensor. All measurements except speed were taken once at the end of the speed counting period, which for this experiment was set to 20 minutes. The accuracy of the speed, direction, temperature, conductivity, and pressure are estimated to be 1 cm s^{-1} , 2° , 0.1°C , 0.01 S m^{-1} , and 1 dbar respectively. The corresponding recorded resolutions are 1 cm s^{-1} , 1° , 0.1°C , 0.01 S m^{-1} , and 0.1 dbar. The accuracy and resolution of the computed salinity is 0.1 psu and 0.01 psu respectively.

The PMEL meters were carefully prepared prior to shipment in the PMEL current meter facility. Because of the short preparation time, a complete calibration was not done prior to deployment. The recovered meters were sent directly to the Northwest Regional Calibration Center in Bellevue Washington, USA for a complete calibration of the compass (including an accounting for residual case magnetism), temperature, conductivity, and pressure, and these calibration results were used in the data processing. The Qatar meters were purchased in 1982 and were never used prior to the *Mt. Mitchell* cruise. These meters remained in the Middle East and could not be calibrated. Thus, the manufacturer's original calibration equations were used. Any discrepancies between the two sets of meters will be identified during future detailed analysis of the data.

Algal growth developed on all meters during the three-month deployment. The densest growth was found on near-surface meters, and all conductivity measurements taken more than a few weeks after deployment are questionable. In no case was the savonius rotor impeded, and it is felt that the speed measurements did not deteriorate over the deployment time.

4.2 Data Processing

All current meter tapes were processed in the PMEL current meter processing group. The procedures and computer programs used at PMEL have been developed for these current meters over the past fifteen years in hundreds of applications. However, even though the quality control is high, only after detailed analysis by physical oceanographers can they be considered completely reliable.

Preliminary analysis of the current meter data was performed using the Matlab statistical software programs. Residual currents were estimated by use of a low pass filter designed by the Woods Hole Oceanographic Institute (WHOI). The filter (Flagg *et al.*, 1976) is called the PL133 low-pass filter. The sharp-cutoff filter is a symmetric convolution window with 65 elements in the time domain (Fig. 25). The 10-db cutoff frequency is equal to the O_1 tide frequency of 0.04 hr^{-1} . All frequencies from 0 – 0.02 hr^{-1} (DC to 2 day period) are passed with negligible attenuation. The filter represents a compromise which suppresses most tidal fluctuation, yet passes short period wind induced fluctuations with periods of a few days. The filtered data exhibit some oscillations of near-diurnal period which may be a leaked tidal signal or internal waves with frequencies below the filter cutoff.

4.3 Preliminary Mooring Results

Important features of the Gulf circulation are apparent in preliminary analysis. Progressive vector diagrams (cumulative sums) of the filtered current vectors reveal the density-driven, reverse-estuary circulation pattern (Fig. 26). The general pattern of inflowing surface current and outflowing bottom current can be seen in records from M2, M3, M4, and M7. Overall mean currents are in the neighborhood of 5 cm s^{-1} . A weak, cross-basin flow of about 2 cm s^{-1} is evident in the records of M3, M4, and M5. The northward bottom current at M3 (71 m) is surprising. This record is currently being re-examined for errors.

The temperature records (Fig. 27) reflect the estuarine circulation and the onset of the summer thermocline. Surprisingly, the bottom temperatures at M2, M3, and M4 actually *decrease* by approximately 1°C during the transition from winter to summer. The surface waters increased by about 7°C during this time period. The bottom cooling occurs when the thermocline sets up and the winter bottom water flows southward, downhill into the deeper areas. The motion is apparent when comparing Figures 11 and 12.

5 Drifting Buoys

5.1 Instrumentation

Thirty-two, Argos-tracked, drifting buoys were deployed in the *Mt. Mitchell* study (Table 6). Twenty-two drifters were deployed during Leg I, four were deployed during Leg III, and five were deployed during Leg VI. Five different types of buoys were used (Fig. 28) (a) Davis Design – based on a special design by Davis (1985a, 1985b), this buoy has negligible error from wind drift and wave rectification. It is considered to be the most accurate buoy for surface current measurements. (b) CMOD – air-deployable design manufactured by the Metocean Company. When this compact buoy enters salt water a spherical float inflates, the antenna extends, and a holey-sock drogue drops to eight meters. (c) ECOCAP type – a large FGGE-style buoy manufactured by the French agency CEIS ESPACE. This buoy incorporated a two-meter square window shade drogue centered at approximately 3 m. (d) Low cost drifter (LCD) – a very small buoy manufactured by Aanderaa Inc. based on a design from Draper Laboratories. This buoy has no drogue and is specially weighted in hopes it will properly represent the drift of an oil slick. (e) Spherical surface drifter (SSD) – a small spherical-shaped buoy also with the purpose of simulating oil slicks.

The Davis drifter buoy is an exceptionally accurate current follower in the presence of wind and surface waves. It was inexpensive, so a large number could be deployed to provide

complete coverage of the RSA. The hull design minimized rectification of drag forces induced by short wave motion; drag averages to near zero over a wave cycle. Wind drag was also minimal since the antenna was the only thing exposed above the water. Tests by Davis (1985a) verified that design goals were achieved. The buoy motion agreed with the water motion at a depth of approximately 0.5 m, and typical slip velocity was less than 1 cm s^{-1} and never exceeded 1.5 cm s^{-1} .

The Davis drifters were manufactured by Brightwaters Instrument Co., Brightwaters NY. The hull was made from PVC plumbing parts which were inexpensive yet robust and reliable. Each PTT (Portable Telemetry Terminal) was assigned a unique identification code, a data format, and a repetition rate. The PTTs were model ST-5 manufactured by Telonics Inc. A six-month battery pack and quarter-wave whip antenna completed the electronics. The Argos transmission frequency was 401.650 MHz. The 32-bit message length included water temperature and battery voltage. The repetition rate was 90 seconds. The Argos User Manual (Argos, 1988) estimates the number of daily passes over a platform at the latitude of the Gulf (30°N) to be 8–12 times with a mean of 9. The time window during which the satellite can receive messages has an average duration of ten minutes. Latitude and longitude computations have standard RMS errors of 200 m and 600 m respectively.

Six Compact Meteorological and Oceanographic Drifter (CMOD) buoys were provided by the U.S. Navy. The sonobuoy-size CMOD buoys were self-contained units designed for three to four months operation. The buoys were 0.917 m long, 12.3 cm in diameter, and weighed 12.7 kg. The flotation was an inflatable collar and the antenna was a two-part telescopic mast. The drogue was an eight-meter holey sock drogue resulting in a center of drag at approximately 4 m depth. On three occasions, CMOD buoys were released concurrently with Davis buoys for intercomparison purposes.

Four ECOCAP buoys were donated to the program by the Marine Environmental Protection Agency (MEPA) of Saudi Arabia (Tawfiq, 1987). The buoys were large cylindrical buoys (approximately 30 cm dia. $\times$ 2 m long. A one-meter piece of chain and a 2×2 m window-shade drogue were suspended beneath the buoy. The combination cylinder, chain, and window shade resulted in a center of drag between 2 and 3 m.

Two oil-spill buoys were provided by the U.S. Minerals Management Service (MMS). Oil-spill buoys are designed to have the right combination of wind and water drag so they will drift in the same direction as an oil spill. These buoys are small, have no drogue, and are designed to operate only a few days while they are in the vicinity of the spill. The LCD is a discus shaped buoy approximately 0.5 m in diameter. The SSD is approximately the same volume as the LCD, but is spherical and depends on a 1 kg fishing weight to keep it upright.

5.2 Data Processing

Satellite location data were transferred automatically from CLS/Argos to the NOAA computer by FTP (file transfer protocol). Daily data files were collected into raw time-series files for further analysis. Missing data blocks and any other errors were corrected as they occurred. Over the course of the experiment, the mean arrival time between consecutive location fixes was 2.2 hours or 10.9 positions per day. There were some gaps of as much as 12 hours, and these are expected to complicate detailed analysis because of the aliased tidal signal.

The time series were interpolated to a common three-hour time base (0, 3, 6 . . . , 21) with a cubic fit interpolation routine. A group of four consecutive observations of latitude/longitude

and time defined three line segments. A cubic curve was derived for the interior segment. The curve passed exactly over the end points of the segment and its slope at the end points equaled the slope of the corresponding outside line segments. The cubic curve was used to compute positions for times falling in the interior time segment. This technique preserved the original position and velocity information and had much less overshoot than standard cubic spline techniques.

Each buoy record was examined carefully, and only free-drift data were retained for further analysis. The drifting buoys had a variety of fates: some ran aground; some were picked up by fishing boats; and some ceased transmitting without reason.

5.3 Preliminary Results

The deployment sites for all the buoys are located in Figure 2. The buoys were launched in various combinations for a variety of goals. All other deployments were designed simply give a general overview of the circulation patterns in the RSA.

Figure 29 provides an overview of the buoy behavior throughout the RSA. There is indication of a clockwise gyre in the western Gulf of Oman with a counter-clockwise to the east. Two buoys deployed in the Strait of Hormuz stopped transmitting within a few hours. All buoys in the southern side of the central Gulf drifted in a southerly direction and either landed on shore or were heading that way before they terminated. However, in the northern part of the central Gulf almost no net drift was recorded over many days. Mean drift in this region ranged from 0.6 to 2.5 cm s^{-1} .

While it is generally accepted that the circulation in the northern Gulf follows a counter-clockwise circulation, some computer models have predicted a reverse direction. The four ECOCAP buoys followed a counter-clockwise circulation pattern and substantiated the counter-clockwise circulation theory (Fig. 30). Spreading was exceptionally small: during the first 33 days of their deployment (after which buoy 5238 went off the air) the mean spread between the buoys was less than 4 km. Later the pattern broke apart: one buoy drifted onto the beach and the other two continued down the coast towards Qatar. We expect a similar behavior by an oil spill, and previous spills along the Iranian coast, especially the Nowruz spill and a spill at Kharg Island, did indeed drift westward to impact the Kuwait and Saudi Arabian coast.

A complex, double-gyre circulation pattern in the Gulf of Oman was verified by buoys 9450, 9451, and 9460 (Fig. 32). Buoy 9450 was released near the coast of Oman and it followed a complex path. During the first weeks it wandered around the western Gulf of Oman alternating between clockwise and counter-clockwise cycles. At one point it was swept into a large clockwise path that took it from Iran almost to Oman, and then out into the Arabian Sea. Buoy 9451 was released near the coast of Iran, and it was swept into a basin-scale counter-clockwise gyre before it too was carried out to sea. Buoy 9460, released in June, also moved in a clockwise direction along the coast of Oman and into the Strait of Hormuz. The intersection of the two counter-rotating gyres is a well-known region of coastal upwelling along the Iranian coast. The gyres pull cold coastal water offshore of Iran in a spout-like feature which is a common feature along cusped coastal upwelling coastlines.

Intercomparisons between the different buoys provided some confidence in the usability of the tracklines. We were given two oil spill tracking buoys, and took the opportunity to compare these buoys with the Davis and the CMOD buoys. Figure 31 is the result of the intercomparison. The Davis buoy reflects the water motion at a depth of 0.5 m while the CMOD buoy was drogued deeper. Nevertheless, the two buoys tracked very well. The two oil spill buoys tracked almost

identically, but went in a much different direction, reflecting the much stronger wind component.

A surprise was the almost negligible drift and dispersion displayed by the six buoys which were deployed together in the north central Gulf, at CTD station 94. In spite of strong wind events and 20 km tidal excursions, these buoys remained tightly grouped for weeks after deployment. This apparent "low energy" area is described in a detailed paper by Lehr *et al.* (1983).

6 Shipboard Meteorological Measurements

It seems to be a cliché to say that the weather during the expedition was unusual, but that is the appropriate description. The winter of 1991-92 was one of the coldest ever registered in that area of the world. In February it snowed in Israel and Lebanon for the first time in most people's memory and Turkey recorded extensive cold and snow. The temperature in the western middle east has a strong effect on the RSA.

The winter temperatures in the northern RSA were 4-5°C colder than normal (Fig. 21) reaching almost 14°C in the far north. These low temperatures are suspected to be a reason for extensive coral devastation in this region.

Shipboard surface measurements were collected by the SCS and bridge measurements. The *Mt. Mitchell* data, while of good quality, suffers from the fact that the ship was not in a fixed locations, and thus requires extensive interpretation. The ship SCS data were averaged to hourly samples and culled for "at-sea" periods (Table 2) so they are most representative of over-the-water values. Figure 33 is an example of the scope of the resulting SCS data. Data from legs III and VI have not been processed at this time.

Processed meteorological data from the SCS provide an interesting overview of the weather conditions through which the ship passed. An example of the air and water temperatures and the true wind speed are given in Figure 33. Approximately from days 57-100, the air-sea temperature difference was negative (air colder than the water) which implies an unstable and convective boundary layer with enhanced evaporation. After day 100 approximately, the air is considerably warmer than the water. This implies the atmosphere near the sea is stable which has a pronounced effect on heat flux and evaporation.

The cases of Shamal-type winds were numerous during the cruise. High winds (> 30 kts) were reported on the ship five times between days 57-137. On many occasions winds exceeded 40 m s^{-1} and the duration of the wind outbreaks generally lasted from two to several days. These experiences are not in agreement with Feteris (1973) who states "winds of more than 30 kt are uncommon over the Gulf; when they do occur, they rarely last longer than a few hours."

7 Conclusions

The circulation in the RSA is seasonally dependent and strongly dependent on winds. The mean wintertime surface circulation (Fig. 34) is the best known pattern. The flow in the southern part of the Inner Gulf is predominantly density driven with surface flow inward from the Strait of Hormuz and adjacent to the Iranian coast.

A southward coastal flow is present along the entire southern coast of the Inner Gulf. The flow stagnates east of Qatar, where high evaporation and sinking forms a dense, bottom flow to the northwest and out of the Strait of Hormuz.

The northern Gulf circulation is predominantly wind driven, with surface flow along both coasts in a southerly direction. Along Iran, the coastal flow is intensified by baroclinic forcing produced by river outflow. In the north-central Gulf a northerly return flow completes the wind-induced secondary circulation. In the north-central Gulf, the secondary circulation balances wind-drift in the surface water and creates a region of very low net drift. Circulation north and south of this low-energy region (marked by double arrows in Fig. 34) is variable and sensitive to winds. Flow at the north end can be easterly or westerly and to the south of the low-energy area will move northerly or southerly.

The north extent of the surface inflow marks a balance between the baroclinic forcing toward the north and the southward wind stress. Dashed lines in Fig. 34 mark the approximate position of the inflow water. In the summer, the inflow is recognizable as far north as 28°N. Circulation in the Gulf of Oman is dominated by a clockwise gyre in the west and a counter-clockwise gyre in the east. The interface between the two counter-rotating gyres is a region of upwelling along the Iranian coast. The circulation patterns seems to exist in winter and summer, but its strength, and the upwelling depend on prevailing winds.

Outflow from the Shatt Al-Arab are carried by the counter-clockwise circulation in a westerly direction and down the Kuwait and Saudi Arabian coast.

Recommendations: During the First Scientific Workshop on the results of the *Mt. Mitchell* Cruise, held in Kuwait from 24–28 January, 1993, oceanographers met to review the physical oceanographic findings of the cruise and to produce a prioritized set of research goals for the future. The result of that meeting is given below.

1. Strait of Hormuz. The flow in and out of the Strait of Hormuz reflects the estuarine exchange of the Inner Gulf with the world's oceans. Very little is known of the currents here. Models depend heavily on knowledge of conditions, and until this region is better understood, models and flushing estimates will be inaccurate.

This goal is both terribly important and extremely difficult to accomplish. High volume of ship traffic combined with extensive bottom-trawl fishing make this region very risky for moored instrumentation. The strong tides mask weaker residual currents and the currents vary widely across the Strait. Any current measurements from a ship would be extremely difficult to interpret.

2. Northern Inner Gulf. We need to define the circulation here for different winds and seasons. The variability of the Iranian coastal flow must be better understood.

This task requires more moored current-meter studies over all the seasons of a year. Wind measurements (below) are a necessary part of such a study.

3. Wind Stress. We need over-the-water, scientific-quality meteorological measurements at several locations in the RSA. Accurate evaporation estimates are required to compute flushing and residence times. Wind stress drives oil spill dispersion and the very important secondary flow in the north. Over-the-water records of a year or longer can be correlated with coastal stations so accurate transfer functions can be derived.

Of all the tasks listed here, quality, over-the-water, meteorological measurements are the easiest to achieve. Instrumentation is available, excellent platforms are available, and satellite measurements are seldom troubled by clouds. Immediate steps should be taken towards this goal. A numerical model should be developed in parallel to the measurement

study. In this way the model would be tuned by the measurements so that it will be able to make good quality estimates of wind fields in the absence of measurements.

4. Central Inner Gulf. Identify the seasonal variation in the Gulf of Oman surface in flow and associated cross-basin circulations.

Same as the northern Gulf study above. A combination of current-meter moorings and wind stations are required in a multi-year study.

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ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
BNL	Brookhaven National Laboratory
BP	Before present
CTD	Conductivity, Temperature, and Depth instrument
DO	Dissolved oxygen
EEZ	Exclusive Economic Zone
IOC	Intergovernmental Oceanographic Commission
KFUPM	King Faud University of Petroleum and Minerals
LCD	Low Cost Drifter
MEPA	Marine Environmental Protection Agency
NOAA	National Oceanographic and Atmospheric Administration
PMEL	Pacific Marine Environmental Laboratory
RHIB	Rigid-Hull Inflatable Boat
ROPME	Regional Organization for the Protection of the Marine Environment
RSA	ROPME Sea Area
SCS	Shipboard Computer System
SLAR	Side-looking aerial radar
SSD	Spherical Spill Buoy
SST	Sea-Surface Temperature
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNEP	United Nations Environmental Protective

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Several key persons in NOAA management contributed enormously, both towards the cruise itself and towards data analysis afterwards. A special acknowledgement goes to Dr. John Knauss, who was NOAA Administrator during this period, for having the vision to recognize the importance of this research and the tenacity to put forward the ship and personnel, in times of restricted budgets, to make it a success. John Robinson, Director of the Gulf Program Office, worked extremely hard to accommodate the scientific needs and attend to endless logistical issues. Ms. Lisa Symmons provided thorough logistical support for the crew and scientists. Funding for research leading to this paper was provided by a grant from NOAA and with services support from Brookhaven National Laboratory.

Table 1: Specifications for *Mt. Mitchell*

DISPLACEMENT	1631 tonne (1798 ton)
LENGTH	70.3m (231 ft)
BEAM	12.8m (42 ft)
MAX DRAFT	4.2 m (14.3 ft)
NET TONNAGE	524 tonne (578 ton)
RANGE	5,920 nm
CRUISE SPEED	12.5 kt
ENDURANCE	22 days

Table 2: The 'at sea' times for the various legs of the *Mt. Mitchell* cruise. The times specify when the ship was away from the dock according to the ship log. Times in universal coordinated time (UTC).

LEG	START	STOP	PRIMARY ACTIVITIES
1	57 0700	71 1800	Muscat-Jubail: CTD, drifter survey, moorings, sediments
2	77 0900	91 1000	Jubail-Jubail: Oil impact at Abu Ali
	92 1200	97 0800	Jubail-Manamma
3	105 1300	111 0800	Manamma-Kuwait: Intense CTD arrays on Iran coast
4	115 1400	116 1300	Kuwait-Kuwait: Fisheries
	116 1500	124 0700	Kuwait-Doha
5	128 1300	137 0600	Doha-Kuwait: Reef ecology, benthic biology
6a	141 0900	151 0600	Kuwait-Abu Dhabi: Repeat Leg I CTD survey, sediments, microfauna
6b	154 0600	158 0600	Abu Dhabi-Muscat: Complete Leg VI survey
7	160 0600	164 1300	Muscat-Salallah: Hydrographic and biological study of the Oman eastern seaboard.

Table 3: Physical Oceanography measurements taken during the *Mt. Mitchell* cruise.

MEASUREMENT	NUMBER	DESCRIPTION
CTD - basin wide	≈ 300	Large scale temperature, salinity and density fields in winter (Feb-Mar) and early summer (May-June).
CTD - Iran coast	≈ 225	Intensive survey of three Iranian coastal regimes where river out-flow creates a unique coastal circulation.
Moored current meters	11	Seven moorings with 17 meters deployed and five mooring with 11 records recovered. Study focussed on estuarine surface inflow-along the Iranian Coast.
drifting buoys	32	Argos-tracked buoys to sample circulation patterns and investigate mixing processes.
satellite AVHRR	≈ 120	AVHRR images (4 bands) for the year days 57-165 provide qualitative picture of circulation and mixing processes.
shuttle photography	≈ 120	Film and electronic still camera images taken during shuttle flight STS-45 provide visible, high-resolution pictures of coastal features.
SCS	90 days	Continuous digitized time series of weather, navigation, and oceanographic measurements.

Table 4: Current meter information (cm table)

METER SN	DEPTH (m)	START DAY (ddd hhmm)	END DAY (ddd hhmm)
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Mooring M2: 26 22.44N, 55 45.66E, depth=94.4 m

2265	10	61 2228	150 0908
7251 [†]	30	62 2216	150 0916
2171	84	61 2207	150 0927

Mooring M3: 27 03.79N, 52 22.75E, depth=81 m

5988	10	65 0733	148 1233
5431	24	65 0732	148 1251
6674 [†]	40	65 0727	148 1247
3214	71	65 0731	148 1251

Mooring M4: 26 50.40N, 51 58.57E, depth=69 m

3176	15	64 2247	148 0927
2512	59	64 2229	148 0909

Mooring M5: 25 59.67N, 52 00.13E, depth=33 m

6670 [†]	21	64 1026	149 1506
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Mooring M7: 27 11.09N, 51 19.46E, depth=76 m

7027 [†]	56	65 1645	148 0425
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[†] Qatar meters

Table 5: Special drifter studies

STUDY	BUOY IDS	CLOSEST CTD STATIONS
Gulf of Oman Circulation	9450, 9451, 9460, 9727	2, 5, 6301, 6301
Intercomparison (Davis,CMOD,LCD,SSD)	9460, 1727, 9825,14684	6301
Intercomparison (Davis,CMOD)	2049/9462, 2048/9461	75, 73
N. Gulf Circulation	3390, 5237-5239	104
Dispersion and turbu- lence, N. Central Gulf	9464-9469	94

Table 6: Statistics of the drifter program. The drogue depths for Davis, CMOD, and ECOCAP are 0.5, 5, and 3 m respectively. The LCD and SSD are oil spill drifters and are designed to move as a surface slick.

ID	TYPE	DDHH	LAT	LONG	T	ΔL	$\int dL$	$\bar{V}$	$\bar{S}$	$(\bar{V}/\bar{S})$
9450	Davis	5821	24 45.5	57 07.3	1950	1479	278	3.96	21.07	0.19
9451	Davis	5903	25 23.8	57 56.5	453	495	188	11.56	30.37	0.38
9452	Davis	6009	26 41.8	56 12.5	42	13	4.4	2.89	8.59	0.34
9453	Davis	6009	26 23.8	56 11.4	15	9	8	14.93	17.51	0.85
9454	Davis	6012	26 29.4	54 56.0	33	8	3	2.64	7.12	0.37
9455	Davis	6015	25 57.1	55 08.0	729	542	15	0.56	20.65	0.03
9456	Davis	6018	25 39.4	55 17.9	6	45	45	208	208	1.0
9457	Davis	6500	26 16.7	52 47.4	552	367	118	5.93	18.45	0.32
9458	Davis	6500	26 40.9	52 09.0	144	73	13	2.52	14.05	0.18
9459	Davis	6500	27 07.3	52 33.9	456	237	20	1.22	14.43	0.08
9460	Davis	15612	24 57.2	56 49.8	444	350	129	8.05	21.89	0.37
9461	Davis	7000	27 38.3	50 36.6	1203	784	144	3.32	18.09	0.18
9462	Davis	7012	27 53.2	40 59.2	273	195	21	2.10	19.83	0.11
9463	Davis									
9464	Davis	6621	28 48.8	49 25.2	2379	1529	194	2.26	17.85	0.13
9465	Davis	6621	28 48.8	49 25.2	1155	858	13	0.32	20.63	0.02
9466	Davis	6621	28 48.8	49 25.2	99	57	9	2.53	12	0.16
9467	Davis	6621	28 48.8	49 25.2	1347	965	16	0.33	19.89	0.02
9468	Davis	6621	28 48.8	49 25.2	1227	870	7	0.17	19.69	0.01
9469	Davis	6621	28 48.8	49 25.2	1755	1193	56	0.88	18.89	0.05
1723	CMOD	6212	24 57.9	53 44.9	270					
1725	CMOD	6203	25 39.2	55 50.1	240	184	26	3.04	21.25	0.14
1726	CMOD									
1727	CMOD	15800	24 57.2	53 47.3	405	334	145	9.97	22.93	0.43
2048	CMOD	7200	27 38.3	56 49.8	1155	559	168	4.05	13.43	0.30
2049	CMOD	6921	27 53.2	50 36.6	435	315	125	8.01	20.10	0.40
3380	ECOCAP	10921	29 35.0	40 59.2	1134	877	156	3.82	21.49	0.18
5237	ECOCAP	10921	29 35.0	40 59.2	1494	1174	242	4.50	21.83	0.21
5238	ECOCAP	10921	29 35.0	40 59.2	747	546	58	2.15	20.30	0.11
5239	ECOCAP	10921	29 35.0	40 59.2	1494	1183	222	4.12	22.00	0.19
9825	LCD	15621	24 57.2	56 49.8	123	99	58	13.12	22.39	0.59
14684	SSD	15621	24 57.2	56 49.8	123	105	58	12.99	23.82	0.55

ID = buoy identification number.

TYPE = design name.

DDHH = year day and hour of the first 'hit'.

LAT = deployment latitude (dd mm.m N).

LONG = deployment longitude (dd mm.m E).

T = total operation time (hrs)

ΔL = net displacement (km).

$\int dL$ = integrated path length (km).

$\bar{V}$ = vector average velocity (cm s^{-1}).

$\bar{S}$ = mean scalar speed (cm s^{-1}).

$(\bar{V}/\bar{S})$ = ratio of speeds.

Figure 1: Bathymetric map of the RSA showing CTD section lines. The main bodies of water are the Inner Gulf, Strait of Hormuz, and the Gulf of Oman.

Figure 2: Map of physical oceanographic stations. Map of the RSA showing locations of the physical oceanography stations. Solid dots indicate CTD stations, larger dots indicate the current meter moorings M1-M7, and solid triangles mark deployment sites for Argos drifters. CTD stations were aligned in transverse sections labeled A-Q.

Figure 3: Map showing the major rivers into the northern RSA.

Figure 4: The M₂, S₂, and K₁ tidal constituents in the Gulf (Lardner *et al.*, 1982).

Figure 5: Early schematic of the Gulf density-driven circulation. (Hunter, 1983)

Figure 6: Color enhanced of AVHRR images for winter and summer conditions.

Figure 7: Surface temperature and salinity measured by Brewer (1978)

Figure 8: Summertime surface temperature and salinity measured by Emery (1956).

Figure 9: Maps of surface temperature and salinity for winter, Leg I.

Figure 10: Maps of surface temperature and salinity for early summer, Leg VI.

Figure 11: CTD cross section along the axis of the RSA from Leg I survey.

Figure 12: CTD cross section along the axis of the RSA from Leg VI survey.

Figure 13: CRD cross section along line A during Leg I (winter).

Figure 14: CTD cross section along line B during Leg I (winter).

Figure 15: CTD cross section along line C during Leg I (winter).

Figure 16: CTD cross section along line D during Leg I (winter).

Figure 17: CTD cross section along line H during Leg I (winter).

Figure 18: CTD cross section along line I during Leg I (winter).

Figure 19: CTD cross section along line J during Leg I (winter).

Figure 20: CTD cross section along line P during Leg I (winter).

Figure 22: CTD cross section along line P during Leg VI (winter).

Leg VI

Section Q

Sec.6Q

Figure 23: CTD cross section along line Q during Leg VI (winter).

Figure 24: Diagram of the current meter mooring M1. The mooring was specially designed for high ship traffic areas with a backup recovery system comprised of the acoustic release and several sub-surface floats distributed along the line. In the case that the upper float is flooded, enough additional buoyancy is available from the other floats to bring the entire mooring to the surface.

Figure 25: Frequency response of the PL133 filter.

Figure 26: Progressive vector diagrams for filtered current meter records. The upper meters indicate flow towards the NW while bottom meters show return flow towards the Strait of Hormuz. The bottom meter at M3 appears to be erroneous.

Figure 27: Unfiltered (raw) temperature time series from current meters M2, M3, M4, M5, and M7.

Figure 28: Five different types of drifter buoys used in the study.

Figure 29: Schematic of the tracks of the drifter buoys. The end of the tracks are marked by an arrow and the number of days of valid data. Buoys 9450 and 9451 drifted out to the Arabian Sea. Buoys 9464-9469 remained in the same location for almost three months until, finally, one buoy drifted away and landed ashore south of Abu Ali Peninsula.

Figure 30: Counter-clockwise circulation in the northern Gulf evidenced by ECOCAP buoys (3380,5237,5238,5239). Top inset shows the displacement of the center of the group during the first 33 days of operation while they were still relatively together. The lower inset shows the mean spread of the buoys around the center.

Figure 31: Comparison tracklines of four types of buoys released at the same time in the Gulf of Oman. Tick marks mark the days and the associated number identifies the Julian day for that mark. Top inset shows the separation distance of the Davis and CMOD buoys over a 16-day period. Bottom inset charts separation of the two oil spill buoys during their four-day lifetime.

Figure 32: Buoys 9450, 9451, and 9460 indicate a double gyre circulation in the Gulf of Oman. A clockwise circulation in the western provides surface water along the Oman coast and into the Strait of Hormuz. A counter-clockwise circulation exists in the central Gulf. The junction of the two gyres creates a cold water filament (hatched area) that is evident in satellite sea surface temperature images. Boxed numbers mark the deployment days. Other numbers along the tracks mark the position of the buoys on subsequent Sundays.

Figure 33: (upper) Comparison of air and water temperature measured on the *Mt. Mitchell*. Only data taken while the ship was at sea are shown. During Leg I and Leg II, water temperature was greater than air temperature which creates an unstable surface layer. During Leg IV and Leg V the air was warmer than the water implying a stable surface layer. (lower) A scatter plot of hour-average, wind vectors (in the direction of the wind flow) shows a preferred NW and SE direction, and occasional Shamal occurrences of winds greater than 40 ms^{-1} .

Figure 34: Schematic of surface currents and circulation processes.

END

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