Oceanography

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Introduction

The physical oceanographical features in the Gulf can be related to three different forcing processes: tidal forces; wind forces; and density differences. The kinetic energy of the water can be partitioned among the three forcing processes approximately as 100, 10, 1 respectively, and each component has a different scaling time: tides vary over a few hours at diurnal or semi-diurnal periods; the seich period of the Gulf is approximately 21 hours; wind-driven currents develop and subside over a few days; and density-driven currents take weeks to change in response to seasonal forcing.

The number of direct oceanographic observations from this region is small, at least it was before 1992. Comprehensive studies that are commonly cited include a 1948 summer cruise by the German ship R/V Meteor (Emery, 1956), another German expedition taken a decade later (DHI, 1960), and a 1976 wintertime expedition of the R/V Atlantis from Woods Hole Oceanographic Institution (Brewer et al., 1978; Brewer and Dyrssen, 1985). Data indicated a counter-clockwise mean circulation in the Gulf, and this was confirmed by ship drift data (Hunter, 1983).

The dominant feature of the data was an inflow surface current of 0.1-0.2 m s⁻¹ flowing in from the Strait of Hormuz and continuing along the Iranian coast for 200-300 km before turning in a counter-clockwise gyre. Fig. 1 presents a summary of what we know today of the mean circulation and active processes in the Gulf. The arrows indicate the surface current, and are in basic agreement with the Hunter’s observations a decade prior.

In the past eight years there have been several international, multi-disciplinary studies and the results of these have promise of significantly improving our understanding of the region (Johns et al., 2000). In 1992, the National Oceanic and Atmospheric Administration ship R/V Mt. Mitchell conducted a comprehensive study of the Gulf, Strait of Hormuz, and Gulf of Oman from January to June (Price and Robinson, 1993). Soon after, three cruises by the Tokyo University of Fisheries R/V...
Umitaka-Maru were carried out in the Gulf of Oman, Strait of Hormuz and Southern Gulf during 1993-1994 (Otsuki et al., 1998). Following the Japanese study, the University of Miami and U.S. Navy deployed a year-long current study in the Strait from December 1996 to March 1998 (Johns and Zantopp, 1999), which provided a much-needed look at summer conditions.

An extensive modelling effort for the Gulf has developed over the past 16 or so years. Tidal models have worked well for smaller regions (e.g., Lardner et al., 1982; Hunter, 1984a), but only recently have the numerical algorithms and computer hardware been sufficiently developed that robust tide models of the entire Gulf have been successful, e.g. Blain (1998). Basin-wide models of the long-term circulation are beginning to come into use with the models of Lardner et al. (1988b), Clifford et al. (1992), and Blain (2000). These models all produce similar large-scale patterns which are summarised in the discussions below.

**Tidal currents**

Tidal range in the Gulf varies from about 1.4 m near Qatar to 3 m in the extreme northwest and to 2.8 m in the extreme southeast. When onshore winds are strong, the level of the coastal waters, particularly in the southern Gulf may rise by as much as 2.4 m above tidal levels and cause extensive flooding of the low sebkhas. Tidal currents are strong (1 m s\(^{-1}\)) near the western end of the Strait of Hormuz, but elsewhere--except between islands or in estuaries and lagoon entrances--rarely exceed 0.2-.4 m s\(^{-1}\).

As late as 1984, Dr. J. R. Turner stated that “at present little is known of the tidal motions in Kuwait waters” (Hunter, 1984a). The simple model introduced by Dr. Hunter was followed by a good many other modellers and as computers improved and techniques advanced, the models grew in scope until today they seek to describe all the Gulf, the Strait of Hormuz, and even extend to the Gulf of Oman (Blain, 1998; Lo and Al-Salem, 1999; Blain, 2000).

The tides in the Gulf, Strait of Hormuz, and Gulf of Oman are a complex mixture of diurnal and semi-diurnal standing waves. The dimensions of the Gulf are such that resonance amplification of the tides can occur and the result is that the tide heights are strongly diurnal in the northern Gulf near Kuwait and in the southern Gulf off the UAE coast, and they are strongly semi-diurnal in the central Gulf north of Qatar. On the other hand, the tidal currents are most diurnal in the central Gulf and mixed or mixed-diurnal elsewhere.

**Residual currents**

Residual currents are those currents that persist over long periods of time after the oscillatory motions from turbulence, waves, and tides have been removed by averaging. Residual currents are the most significant means for transporting pollutants, but, until the past decade, have been quite difficult to assess.

Tides, while important for stirring and mixing waters vertically and for horizontal mixing on a scale of 10 km, do not make a significant contribution to the residual
circulation of the Gulf. Model results by Blain (1998) produced tidal residual velocities of 0.02 m s\(^{-1}\) or less, which is in agreement with observations, and although the currents increased somewhat near certain headlands with broad shallow shelf bathymetry, and around island passages, they are not considered in an overall analysis of the Gulf. Blain (2000) also reproduced these residual current patterns.

The primary contributors to the mean (residual) currents of the Gulf are the winds and density flows. It is generally stated that the northern Gulf is dominated by wind forcing and the southern Gulf by density currents. Actually, the two flows are comparable in both regions, and both processes must be considered to achieve a reasonable picture of the observed circulation.

Discussions of the expected wind-induced currents in the Gulf were given by Lardner et al. (1988a) and Chao et al. (1992). Originally, modellers had a theory that the Shamal winds in the northern Gulf produced a complex pattern of southerly jets on both Kuwait and Iran coasts, and a return flow along the central axis. But models were two-dimensional. Winds force a slope in the water surface that produces a pressure-driven secondary flow. In actuality, the circulation is three-dimensional and 3D model results indicate that with Shamal (northwest) winds, the surface flow of the whole of the northern Gulf is towards the southeast, with average annual velocities of 0.1-0.3 m s\(^{-1}\) (Lardner et al., 1988a). The return flow (necessary to balance the total water mass) occurs at deeper levels of the water column. Drifting buoy studies all indicate a surface flow to the southeast along both coasts, and a divergent circulation in the far northern Gulf which supports this model result. Nevertheless, the central area of the northern Gulf is in need of continued research.

When averaged over the area of the Gulf, evaporation, river inflow, and rainfall are approximately 200, 46, and 7 cm respectively (see Section 2.3). However, it should be noted that while evaporation and precipitation are distributed over broad regions, river inflow is concentrated in the far northern end, and has a pronounced effect on the density-driven circulation there. The northern Gulf, more shallow and well mixed, is much more dependent on the wind forcing and less dependent on temperature or salinity forcing, with the exception of the river outflow region near to the Shatt Al-Arab.

When models are run with no river input, the resulting currents at the north end of the Gulf favour a clockwise rotation, from Kuwait to Iran and south along the coast of Iran. However, the river fresh water inflow forms a strong coastal current, of width approximately 20 km, along the Kuwait and Saudi Arabian coast (Fig. 2), and forces a counter-clockwise circulation that is evident in some models (Chao et al., 1992; Blain, 2000).

Water exchange with the Gulf of Oman dominates the circulation of the southern Gulf. Maps of the surface temperature and salinity for January and June 1992 from the Mt. Mitchell expedition (Fig. 2) clearly demonstrate the processes (Reynolds, 1993). Fig. 3, from the same cruise, shows cross-sections of the temperature and salinity vertical structure down the central axis of the Gulf. Throughout the year and against prevailing Shamal winds, relatively low-salinity water enters through the Strait of Hormuz to balance the salt excess from evaporation. The fresher surface water enters the Gulf and holds close to the Iranian coast. As the water flows northward its salinity increases as it evaporates and mixes with more saline water below. In the winter, the water cools, which enhances the density gain until a point is reached, about 300 km into the Gulf, where it sinks to the bottom and the water column becomes well mixed.
Fig. 1. A diagram of the major oceanographic processes in the Gulf, Strait of Hormuz, and Gulf of Oman.

Fig. 2. Surface temperature and salinity in the Gulf and Strait of Hormuz in January and June from the Mt. Mitchell cruise (Reynolds, 1993). The intrusion of surface water from the Gulf of Oman is defined by the temperature in the winter and by salinity in the summer.
Fig. 3. A cross section of temperature and salinity along the main axis of the Gulf and Strait of Hormuz in January and June from the Mt. Mitchell cruise (Reynolds, 1993). The northern Gulf is very well mixed in winter but highly stratified in summer. The arrows show the directions of the thermosaline circulations.
The boundary between the northern and southern Gulf is marked at the point where the wintertime water column becomes vertically mixed. Satellite photographs often show this point as a distinct frontal line that stretches almost across the basin.

In the summer, the surface inflow increases but is not so apparent from surface temperature maps. It is evident by the contours of salinity. The temperature warms under the intense solar radiation, so much that even though evaporation is three times more than in the winter, the density increase is not sufficient to offset the warming. Thus a strong thermocline develops. With the reduced vertical mixing, the salinity front extends an additional 100 km northward than its winter extent.

Bottom flow in the southern Gulf is generally a motion of more saline and colder water out, primarily through the deep channels around the southern side of the Strait of Hormuz (Fig. 1). An interesting feature of the bottom water (Fig. 3) is that the cold dense water that is generated in the northern Gulf continues to move into the deeper troughs throughout the summer so that in June the bottom water is colder than it was in January.

Areas of intense evaporation and sinking are the Gulf of Salwa, south of Bahrain, and the broad shallow shelf along the UAE coast. Salinities here are known to exceed 45 ppt routinely. There are very little data available from this region, and speculation on the importance of evaporation here and the induced thermosaline circulation is based on model results. However, some current meter evidence near the entrance to the Strait of Hormuz suggests that the theory of sinking and outflow is correct (Matsuyama et al., 1998; Johns and Zantopp, 1999).

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 satellite images. The interface between the coastal jet to the south and the northward surface flow from the Strait of Hormuz is a region of horizontal current shear which often shows evidence of wavelike shear instability.

Exchange through the Straits of Hormuz

The currents in the Strait of Hormuz are do not have any perceptible dependence on the winds there. Currents are dictated by the density-driven exchange between the Gulf and the Gulf of Oman.

Simple box models have been used to predict the residence time for a water parcel in the Gulf. To predict residence times, the exchange through the Strait of Hormuz and the surface exchange with the atmosphere, mainly evaporation, must be known. (Assuming a long-term, steady state, instantaneous mixing, the residence time is the ratio of the volume of the Gulf to the net volume exchange rate (in or out) of the Gulf. It is a measure of the mean amount of time a parcel of water will remain in the Gulf. 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 from two to five years (Hughes and Hunter, 1979; Hunter, 1984b). Knowledge of the circulation in the Strait of Hormuz plays a key role in understanding the basin-wide behaviour of the Gulf.
The surface inflow through the Strait is about 40-50 m deep. In the winter this is well defined in both temperature and salinity. The deep water enters the Gulf of Oman and sinks to about 200 m before it reaches its neutral density point (Fig. 1). The Gulf water is apparent throughout the Gulf of Oman and well into the Arabian Sea. There is some evidence that the deep outflow current pulsates and the water emerges as lenses rather than a continuous layer. The studies of Matsuyama et al. (1998) and Senjyu et al. (1998) describe a “Peddy” that was seen in the Gulf of Oman at a depth of 250-400 m with horizontal and vertical scales of 50 km and 150 m respectively. In a very recently recovered year-long mooring in the Gulf entrance to the Strait (Johns and Zantopp, 1999), there were two pulses in the deep outflow that suggested that some of the outflow water comes from the northern Gulf. The exact makeup of the outflow water is uncertain and more research is needed in this area.

Observations in the Gulf of Oman suggest that Gulf water forms a plume along the UAE and Oman coast out to the Ras al Had, at the Arabian Sea (Bower et al., 2000). Evidence from recent cruises indicate the Gulf water mixes into the Gulf of Oman as large eddy circulations. A complete description of the Peddy will not be available without additional observational data.

Other features of the circulation in the Gulf of Oman are upwelling along the coast of Iran (Brock et al., 1992; Reynolds, 1993; Arnone et al., 1998), and a permanent front at Ras al Had that forms a barrier between the Gulf of Oman and the Arabian Sea (Brink et al., 1998). Winds are quite different from one side of the front to the other (Arnone et al., 1998).

Gaps in knowledge

As models become ever more detailed and refined, they demand more and better data with which to work. The various physical processes such as tides, wind forced circulations, evaporation, heating and stratification, and density flows, all combine in complex interrelated ways that result in the observed oceanographic features.

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 prioritised set of research goals for the future. The recommendations of that meeting are still crucial seven years later and they are given, with some modification, below.

1. Strait of Hormuz. The flow in and out of the Strait of Hormuz reflects the estuarine exchange of the Gulf with the world’s oceans. The goal of direct measurements in the Strait of Hormuz is both terribly important and extremely difficult to accomplish. The high volume of ship traffic combined with extensive bottom-trawl fishing make this region very risky for moored instrumentation. The two Strait mooring sites (Johns and Zantopp, 1999; Matsuyana et al., 1998) were not in the Strait, but rather well out into the Gulf. Interpretations from these moorings are difficult.

2. Northern Gulf. The circulation here must be defined 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 are a necessary part of such a study. Accurate and verified river
flow information is crucial in determining the correct residence times and flushing rates.

3. Wind stress and energy fluxes. We need over-the-water, scientific-quality meteorological measurements at several locations in the Gulf. 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.


**Summary and conclusions**

Measurements and 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 counter-clockwise current 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 counter-clockwise circulation there that would otherwise by clockwise if based solely on wind forcing. (d) A southward coastal jet exists between the head of the Gulf and Qatar, and extends east of Qatar, depending on the wind.

The mean wintertime surface current pattern in the southern Gulf (Fig. 1) is the most widely known current pattern. The flow 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 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 low-density, river outflow. In the north-central Gulf a weak northerly return flow completes the wind-induced secondary circulation. 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. 1) is variable and sensitive to winds. Flow at the north end can be easterly or westerly, clockwise or counterclockwise circulation, and to the south of the low-energy area will move northerly or southerly. The northern extent of the surface inflow marks a balance between the baroclinic forcing toward the north and the southward wind stress. Dashed lines in Fig. 1 mark the approximate limit of the inflow water. In the summer, the inflow is recognisable as far north as 28° N. Outflow from the Shatt Al-Arab is carried by the counter-clockwise circulation in a westerly direction and down the Kuwait and Saudi Arabian coast.

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 pattern seems to exist in winter and summer, but its strength and the upwelling depend on prevailing winds.

References


