Three-dimensional flushing times of the Persian Gulf

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Received 4 May 2004; accepted 19 October 2004; published 16 December 2004.

[1] A three-dimensional hydrodynamic model is employed in a fully prognostic mode to derive flushing times of the Persian Gulf—an evaporation-driven inverse estuary that is governed by import of surface water from the adjacent ocean and export of saline bottom gulf water through the Strait of Hormuz. During spring and summer, a cyclonic overturning circulation establishes along the full length of the Gulf. During autumn and winter, this circulation breaks up into mesoscale eddies, laterally stirring most of the Gulf's surface waters. As a result of this, 95% flushing times of surface waters are shortest (1–3 yr, increasing with distance from the Strait) along the Iranian coast, but are much longer (>5 yr) along the coasts of Kuwait and Saudi Arabia. Owing to density stratification introduced by the surface inflow of ocean water, flushing times of bottom waters are ~6 yr in most parts of the Gulf. *INDEX TERMS:* 4235 Oceanography: General: Estuarine processes; 4243 Oceanography: General: Marginal and semienclosed seas; 4255 Oceanography: General: Numerical modeling; 4599 Oceanography: Physical: General or miscellaneous. **Citation:** Sadrinasab, M., and J. Kämpf (2004), Three-dimensional flushing times of the Persian Gulf, *Geophys. Res. Lett.*, *31*, L24301, doi:10.1029/2004GL020425.

1. Introduction

[2] The Persian Gulf, sometimes incorrectly referred to as the Arabian Gulf (for a historical discussion, see *Niebuhr* [1772]), is an important military, economic and political region. The countries of United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, and Iraq border the Gulf along its southern coastline and Iran is situated along the Gulf's northern coastline (Figure 1). This area contains ~65% of the world's oil reserves and is one of the most important shipping lanes in the world. Approximately one ship in every six minutes passes through the Strait of Hormuz. An estimated quarter of a million barrels of oil pollutes the Gulf each year [*Ackleson et al.*, 1992]. Knowledge of the Gulf's circulation is of great significance for sound management of frequent oil spill events. The Gulf is ~990 km long and has average and maximum depths of 36 m and 120 m, respectively. It is broadest (370 km) in its middle and narrowest (56 km) across the Strait of Hormuz. The Gulf is a semi-enclosed marginal sea in an arid sub-tropical region. Estimates of net evaporation rates vary between 336 km^3/yr to as large as 1200 km^3/yr [*Privett*, 1959; *Meshal and Hassan*, 1986; *Johns et al.*, 2003; *Ross and Stoffers*, 1978]. Evaporation exceeds precipitation (~23 km^3/yr) by far [*Reynolds*, 1993]. Major river discharges are the Shatt-al-Arab (Arvand Roud) and Bahmanshir rivers being located at the northwestern extremity of the Gulf. Estimates of river discharge vary between 36- and 110-km^3/yr [*Hartmann et al.*, 1971; *Reynolds*, 1993]. The current discharge rate is unknown owing to a lack of field data acquired after the introduction of major river regulations such as, the Atatürk Dam built by Turkey in the Euphrates River in 1990. Strong evaporation makes the Gulf an inverse estuary that is governed by outflow of saline Gulf water through the Strait and inflow of low salinity surface water from the adjacent Gulf of Oman [*Swift and Bower*, 2003]. *Ackleson et al.* [1992] estimate the rate of the dense outflow at ~3110 km^3/yr (0.099 Sv) and that of the surface inflow at ~3360 km^3/yr (0.107 Sv). Recent estimates give a volume transport of the dense outflow of 0.15 ± 0.03 Sv [*Johns et al.*, 2003]. The net flow through the Strait makes up the excess of evaporation over precipitation plus river discharge that the Gulf experiences on an annual basis.

[3] On the basis of a comprehensive suite of hydrographic data acquired a year after the Gulf War in 1991, *Reynolds* [1993] proposed a sketch of the Gulf's general circulation (Figure 2) that has been confirmed by most subsequent studies. Influenced by the Earth's rotation, inflow of surface water from the Gulf of Oman leans against the Iranian coastline whereas the bottom outflow escapes the Gulf along the coasts of United Arab Emirates and Oman. This creates an overall cyclonic circulation in the Gulf with a salinity front separating in- and outflow regimes. This front roughly follows the 40-m depth contour (see Figure 1) but, for unknown reasons, experiences a seasonal variation of its location. It should be noted that only few field measurements have been taken during autumn and early winter [see *Alessi et al.*, 1999], so that the fate of the salinity front is basically unknown for several months of the year. Spatial salinity distributions shown by *Johns et al.* [2003] suggest that the cyclonic circulation extend the full length of the Gulf during summer. In addition to this general circulation, the combined discharge from the Shatt-al-Arab and Bahmanshir rivers creates a classical river plume that typically runs along the coasts of Kuwait and Saudi Arabia. Year-round northwesterly winds, known as the Shamal, are believed to create a southeastward coastal upwelling jet along the Iranian coast between 28°–29°N, but observational evidence thereof is sparse. During summer a quiescent region establishes in the centre of the Gulf's western portion. As far as the authors are aware, comprehensive modelling studies of the Gulf's general circulation are lacking; that is, previous studies were either highly simplified [*Chao et al.*, 1992], or have focussed exclusively on tides [e.g., *Najafi*, 1997].

[4] Flushing time is the time it takes for a semi-enclosed sea to exchange its volume with ambient ocean water. Flushing times of 3–5.5 yr have been reported for the Gulf

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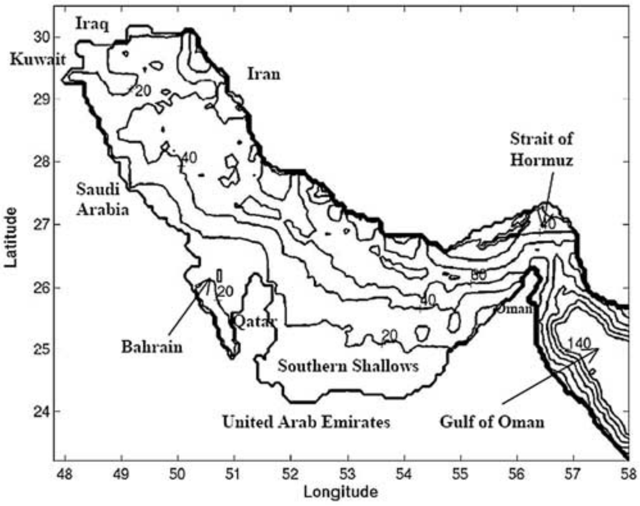

Figure 1. Bathymetry (m) of the Persian Gulf (CI = 20 m; ETOPO-2 data smoothed). Maximum water depth is set to 150 m.

[*Koske*, 1972; *Hunter*, 1986; *Hughes and Hunter*, 1979]. Spatial distributions of flushing times in the Gulf are unknown. The principle objective of this paper is to derive a three-dimensional spatial distribution of flushing times for the Persian Gulf using a regional numerical model under realistic forcing.

2. Methods

[5] This study employs the three-dimensional hydrodynamic model COHERENS (Coupled Hydrodynamic-Ecosystem Model for Regional Seas) [*Luyten et al.*, 1999] based on sigma coordinates. We use 5 sigma levels on an ETOPO-2 bathymetry (see Figure 1), being interpolated and slightly smoothed onto a 4-minute grid. Maximum water depth is set to 150 m, which only modifies the topography of the Gulf of Oman and has no impact on the resultant circulation in the (Persian) Gulf. Cartesian lateral grid spacings are 6.6 km (north-south) and 7.4 km (east-west). The model is forced by climatologic monthly mean atmospheric forcing (wind speed, air temperature, humidity, cloud cover and precipitation) derived from 54 years of NOAA data. The annual rate of evaporation minus precipitation in the Gulf resulting from the applied forcing is ~480 km^3/yr, which is within the range of previous estimates. The annual-mean surface heat flux experienced by the Gulf is relatively small (-17 W/m^2). We use a reduced river discharge of ~10 km^3/yr as an estimate of flow rates after dam construction. Monthly mean vertical profiles of temperature and salinity, extracted from previous hydrographic data [*Alessi et al.*, 1999], are prescribed at the eastern open-ocean boundary. Tidal boundary forcing is included using the four major constituents: M_2, S_2, O_1, and K_1. The tidal part of the model has been calibrated against previous tidal studies [*Najafi*, 1997]. The simulated annual-mean volume transport of the outflow through the Strait of Hormuz is 0.163 Sv (the inflow rate is 0.177 Sv), which is close to estimates by *Johns et al.* [2003]. Simulations cover a total period of 18 years including an initial spin-up period of 5 years. The model is run in a fully prognostic mode for all variables. The salt balance of the Gulf is crucially dependent on the numerical advection scheme employed for scalars. Highly diffusive advection schemes (that is, the upwind scheme) resulted in artificial entrainment of ambient saltier water into the surface inflow from the Gulf of Oman yielding a dramatic increase in the Gulf's average salinity of 0.5 psu/yr. Best results were achieved by the Total Variation Diminishing (TVD) scheme [see *Luyten et al.*, 1999] that removed unwanted longer-term trends in salinity and temperature (Figure 3). Simulated seasonal and spatial variations in temperature and salinity in the Gulf are in general agreement with field data [*Alessi et al.*, 1999]. A discussion of this, however, would go beyond the scope (and page limit) of this paper.

[6] After 10 years of simulation, the entire Gulf of Oman (east of 56°20′E) is filled with passive Eulerian tracers of a concentration of unity, kept constant thereafter, whereas the (Persian) Gulf is initially void of tracers. Flushing times

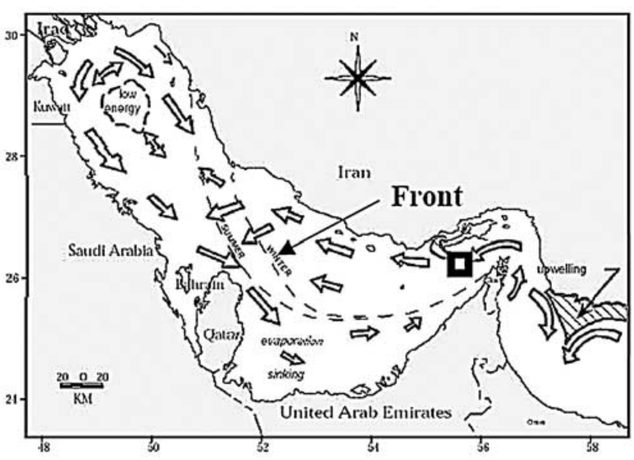

Figure 2. Sketch of the general circulation in the Persian Gulf. Modified from *Reynolds* [1993] with permission from Elsevier. The square gives the location used in Figure 3.

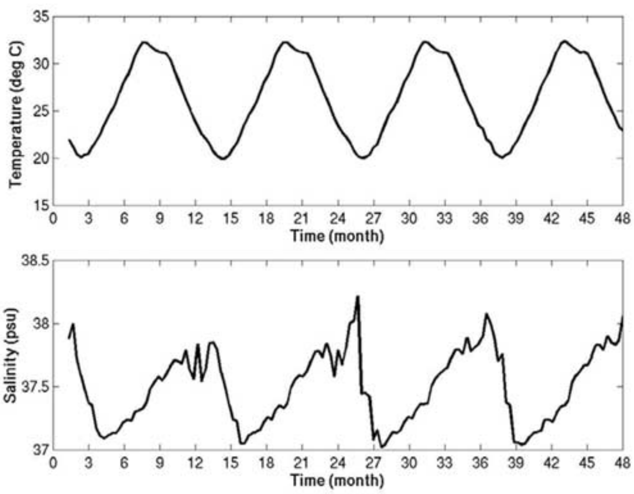

Figure 3. Time series of vertical averaged temperature and salinity for the last 4 years of an 18-year simulation. The location is shown in Figure 2.

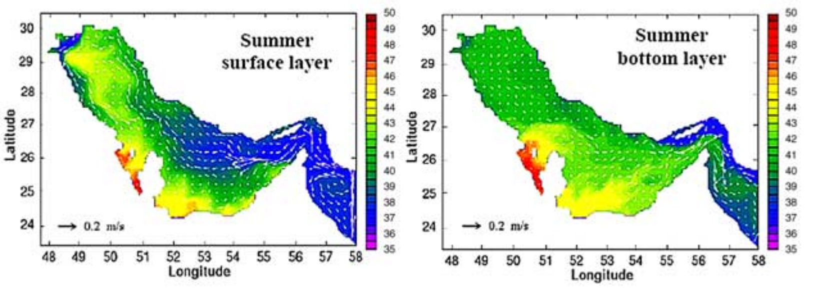

Figure 4. Distributions of monthly-mean salinity (colour shading) and currents (arrows) in surface and bottom layers during summer (July) for the 18th simulation year.

are calculated in each grid volume of the model domain as the time that it takes until the tracer concentration exceeds 95% locally. This concept is based on initial volume and ignores subsequent dilution by riverine discharge. Technically, this is achieved by treating rivers as closed boundary points in the tracer prediction scheme, whilst river discharge is maintained in all other parts of the model. Accordingly, tracer concentrations in the Gulf's interior can only increase with time (owing to continual inflow of tracers through the Strait) and, eventually, the conservative 95% flushing threshold will be exceeded everywhere in the Gulf. It is noteworthy that dense bottom water outflow can remove positive tracer concentration from the Gulf, thus yielding prolonged flushing times in the interior of the Gulf.

3. Discussion and Conclusions

[7] By mid-summer (July), surface inflow of low salinity surface water from the Gulf of Oman, leaning against the Iranian coastline, reaches the far northwestern extremity of the Gulf, where it combines with the river plume to form a cyclonic gyre (Figure 4). Saline water of a salinity of 42–45 psu drives the dense bottom outflow. This water forms in quiescent central parts of the Gulf's western portion, off Bahrain, and in the Southern Shallows. Thus, a Gulf-wide cyclonic overturning circulation establishes during summer in agreement with observational evidence [*Johns et al.*, 2003]. As a result of this evaporation-driven circulation, a salinity front is created roughly running along the 40-m depth contour in agreement with the sketch of *Reynolds* [1993] and salinity distributions shown by *Johns et al.* [2003]. Across this front, salinity varies from 38 to 42 psu over a distance of a few tens of kilometers. Notice that the model also predicts a river plume running along the coasts of Kuwait and Saudi Arabia. During autumn and into winter, on the other hand, the Gulf's cyclonic circulation becomes dynamical unstable and breaks up into mesoscale eddies of $\sim$30 km in diameter. These eddies operate as vigorous lateral mixing agents to remove the summer salinity front by mid-winter (Figure 5). Eddies are confined to the upper $\sim$50 m of the water column, so that the bottom salinity field remains largely unaffected (not shown). Note also that the shallow regions south of Bahrain maintain a high salinity (>48 psu) throughout the year, which is an indicator of weak exchange with ambient Gulf water. The reason of the break-up of the cyclonic circulation into eddies is a slight intensification of the baroclinic exchange circulation through the Strait during autumn when cooling of saline waters produces the densest water south of the salinity front. Nevertheless, despite this seasonal collapse of the cyclonic circulation in the Gulf's interior, the exchange circulation through the Strait persists throughout the year with only minor variations in strengths of <30%, in agreement with *Johns et al.* [2003].

[8] Flushing of the Gulf's surface layers occurs via two distinct mechanisms: a) direct advective flushing provided by the Gulf-wide cyclonic surface circulation that establishes during spring and summer, and b) indirect turbulent flushing by intense mesoscale eddy activity during autumn and winter. As a result of this, 95% flushing times of surface waters range from 1 to 3 yr along the Iranian coast (Figure 6) with longer times reflecting increased distance from the Strait. This relatively short flushing is associated with the direct advective flushing mechanism provided by the gulf-wide cyclonic circulation that establishes during spring and summer. Flushing of other parts of the Gulf is more dominated by lateral stirring of mesoscale eddies being created during autumn and winter. The 4-year flushing-time contour running along the axis of the summer salinity front (see Figure 4) separates the advective flushing regime from the turbulent flushing regime. Surface flushing times of >4 yr are located south of this front with the longest flushing times (>5 yr) occurring along the coastlines of Kuwait and Saudi Arabia. Interestingly, the Southern Shallows display relatively short ($\sim$3.5 yr) flushing times of surface waters, for this region occasionally becomes flooded with lower salinity ocean inflow water (not shown). Owing to density stratification introduced by the stably

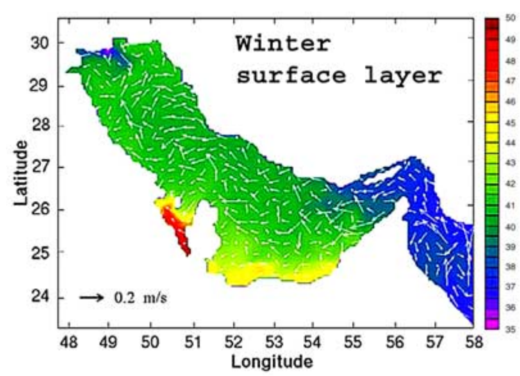

Figure 5. Distributions of monthly-mean salinity (colour shading) and currents (arrows) in the surface layer during early winter (December) for the 18th simulation year.

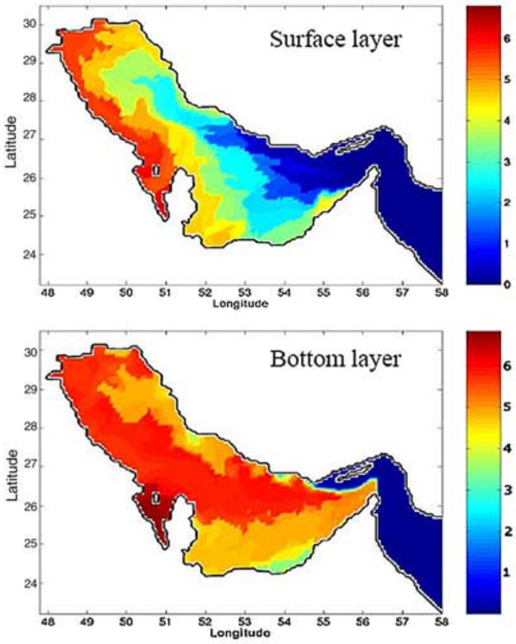

Figure 6. Lateral distributions of flushing time (years) in surface and bottom layers.

stratified inflow, the Gulf's bottom water displays flushing times of ∼6 yr in most parts of the Gulf. The longest bottom flushing times (7–8 yr) establish in the shallows around Bahrain as a signature of limited exchange with ambient water. Interestingly, an extended region near the Southern Shallows attains a local minimum (3.5–5 yr) in bottom flushing times. This minimum relates to a convective conversion of surface water (which is flushed on time scales of 3.5 yr) into bottom water and the advective export thereof by means of the dense bottom outflow. Bottom water escaping the Gulf has a flushing time of ∼5 yr. Objectives of our future research are to: 1) explore the circulation and flushing of the Persian Gulf prior to the introduction of river regulations, and 2) collect comprehensive field data during autumn and early winter to fill previous data gaps.

[9] **Acknowledgments.** This work was supported by an international postgraduate scholarship awarded by Khorramshahr University of Marine Sciences & Technology, Iran. We are grateful to Matthias Tomczak for helpful suggestions that improved this work.

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