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A model of the general circulation in the Persian Gulf and in the Strait of Hormuz: Intraseasonal to interannual variability

Stéphane Pous [a,d], Pascal Lazure [b], Xavier Carton [c,*]

[a] Sorbonne Universités (UPMC, Univ Paris 06)-CNRS-IRD-MNHN, LOCEAN Laboratory, 4 place Jussieu, F-75005 Paris, France
[b] DYNECO, IFREMER, BP 70, 29280 Plouzané, France
[c] LPO, IUEM, Univ. Bretagne Occ., 6 Av. Le Gorgeu, 29200 Brest, France
[d] Department of Oceanography, University of Cape Town, South Africa

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ABSTRACT

Previous studies modeling the circulation and thermohaline structure in the Persian Gulf have suggested that interannual variability and vertical mixing processes could explain the model biases when compared to the few observations available. Here, a realistic, interannual, high-resolution model of the Persian Gulf is presented, validated against observations and then used to describe the intraseasonal to interannual variability in the circulation, water mass formation and exchange through the Strait of Hormuz. Sensitivity experiments to model settings, in particular vertical mixing parameterizations, have been performed in order to have the best comparison with all available observations. Main circulation and water mass characteristics correspond well to observations and previous modeling studies on the seasonal timescale. A barotropic cyclonic gyre dominates the general circulation in the Gulf from April to July then breaks down into smaller features as wind intensifies and stratification decreases due to winter cooling. Dense salty water is formed in the northwest part of the Gulf and in the southern banks, but the latter reaches the Strait of Hormuz from November to April only. While temperature fluctuations are mostly seasonal, salinity has substantial fluctuations on the interannual timescale that cannot be directly related to atmospheric fluxes because of the importance of the exchanges at Hormuz for the salt budget within the Gulf. This advocates the use of atmospheric conditions including interannual variations when running models of the Persian Gulf. On the other hand, the interannual variations in the net transport at Hormuz directly follow variations in the evaporation minus precipitation over the Gulf. Thermohaline structure and circulation also vary on intraseasonal timescale, induced by the high-frequency tidal and atmospheric forcings. Finally, some biases remain in the simulations presented here, mostly due to the lack of observations of the evaporation rate, precipitation and river discharges.

1. Introduction

The Persian Gulf, hereafter called the Gulf, is a shallow, semi-enclosed sea which is bounded to the northwest by the delta of Iraki and Iranian rivers, to the south by a wide desert along the Iraq, Kuwait, Bahrain, Qatar, Saudi Arabia and United Arab Emirates coasts and to the north by the tall Zagros mountains along the Iranian coast. The average depth of the Gulf is 40 m, the maximal depth is 120 m near the Strait of Hormuz (hereinafter referred as the strait) which connects the Gulf to the Gulf of Oman. The Gulf is about 1000 km long, and at most 350 km wide. Its area is about 239,000 km^2 and its volume is about 8780 km^3. The Gulf is influenced by tides, winds, heat and freshwater fluxes (including from rivers), which are reviewed below.

The direct effect of forces generating tides is very weak within the Gulf, but tides propagate into it from the Indian Ocean. Due to its dimensions, the Gulf has a self-oscillation period between 21.6 and 27 h (Defant, 1960). The semi-diurnal and diurnal waves generate resonance oscillations in this basin, and create amphidromic points of Kelvin–Taylor type. The tidal forcing is important for the instantaneous circulation, especially in the Strait of Hormuz and along the Iranian coast but generates weak residual currents (Hugues and Hunter, 1980; Pous et al., 2012).

The Gulf is also driven by dominant northwesterly winds called Shamal. Other winds, called Kaus or Suhaili and blowing from the south, or Nashi blowing from the northeast, are more localized, more seasonal and often occur in bursts.

Horizontal temperature gradients within the Gulf are often weaker than those of salinity, in terms of corresponding density gradients. Salinity gradients can result either from river fluxes, from precipitation and evaporation or from exchanges between

* Corresponding author. Fax: +33 298016468.
E-mail addresses: spolod@locean-ipsl.upmc.fr (S. Pous), xcarton@univ-brest.fr (X. Carton).

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the Gulf and the Gulf of Oman. The Tigris, Euphrates and Karun river which form the Shatt-al-Arab have a seasonally variable discharge, but an annual mean of 1400 m^3/s (18 cm/year) is now usually admitted. Less information is available on the discharge of the Iranian rivers Hendijan, Hilleh and Mand, for which estimates of 2000 m^3/s have been quoted (Reynolds, 1993). The annual rainfall is very weak in this region; it is estimated at 15 cm/year, two times less than the total river discharge. Evaporation is strong and a value of 200 cm/year is most often quoted. With the values of evaporation, precipitation and river discharge quoted here, the Gulf has a 416 km^3/year water deficit and is an evaporation basin.

The water deficit is compensated for by the inflow of Indian Ocean Surface Water (IOSW) through the Strait of Hormuz; denser, more saline, waters exit the Gulf near the bottom (these are called Persian Gulf Water or PGW, Emery, 1956; Koske, 1972; Brewer et al., 1978; Horton et al., 1994). There is also a seasonal surface outflow of intermediate salinity on the southern side of the strait (Johns et al., 2003). The volume transport of the inflow and the total outflow has been estimated by Johns et al. (2003) at 0.23 ± 0.04 Sv and 0.21 ± 0.05 Sv.

IOSW has a temperature range of 23–26 °C in winter, and 30–32 °C in summer, and a salinity range of 36.5–37.2 psu (Pous et al., 2004a; Swift and Bower, 2003). Observations show that, in a yearly average, the surface waters follow a cyclonic route. The formation of dense PGW ($\sigma_t > 29.5$) occurs essentially in the northern part of the Gulf in winter (Swift and Bower, 2003) and in the southwestern part of the Gulf in winter and early summer (Yao, 2008), while in summer, more buoyant, warm and hypersaline water is formed in the southwestern part (Johns et al., 2003). The dense water from the northern formation site is advected towards the strait all year long, whereas the export of the salty water from the southwestern evaporation site is more sporadic in winter and creates salinity peaks; in late summer and fall, it is exported as an outflow of warm and salty seawater at intermediate depth (Yao and Johns, 2010). Nevertheless, the details of the circulation in the Gulf are more complex than a simple cyclonic gyre, because of the influence of seasonal variations of the exchange at Hormuz, of the river discharge, of wind forcing and because of topographic anomalies.

Observations (Johns et al., 2003) indicate that the PGW outflow shows substantial changes in temperature and salinity characteristics. Salinity is minimum in summer (39.3 psu) and maximum in winter (40.8 psu). Temperature is minimum in February (21 °C) and maximum in December (25 °C). The PGW outflow transport was measured over a year, and ranged between 0.08 Sv in December and 0.18 Sv in March (Yao, 2008), but without a clear pattern of seasonal variation (Johns et al., 2003). Tidal motions and internal tidal waves can lead to a density front in the Strait of Hormuz and to high-frequency variations in the outflow (Matsuyama et al., 1994).

The first attempts to model numerically the circulation in the Gulf (Lardner et al., 1982; Chao et al., 1992) used three-dimensional models, with horizontal Cartesian coordinates, a mesh size of about 20 km, and vertical geopotential coordinates. They had either rigid lid or free surface, and simplified thermohaline and mechanical forcings. These models reproduced essential characteristics of the circulation and also evidenced the elements which should be improved (seasonal variations of forcings, increased resolution). The operational model SWAFS by Horton et al. (1994) assimilated real-time temperature and salinity data to reproduce the general circulation. The model developed by Blain (2000) diagnosed the circulation induced by tide, heat fluxes, winds and density gradients for two extreme situations (January and July). But these models did not provide a detailed description of the seasonal variations. The circulation model by Kämpf and Sadrinasab (2006), based on free-surface three-dimensional dynamical equations, with 7 km horizontal resolution and five vertical levels, and climatological forcing provided the first description of the seasonal variation of the Gulf.

This study was followed by that by Yao and Johns (2010, 2010); it investigated the circulation in the Gulf with the same hybrid coordinate model (HYCOM), with 5 km horizontal resolution and 13 vertical levels. This study evidenced that the seasonal variations of the surface salinity in the Gulf are chiefly due to the balance between the advection of IOSW and vertical salt fluxes induced by mixing, while the mechanical forcing only plays a weaker role. It also showed that high frequency atmospheric forcings provide more realistic surface temperatures.

A higher-resolution (1 km horizontally and 16 layers), primitive equation model was used by Thoppil and Hogan to model the Gulf and the Strait of Hormuz. A first study (Thoppil and Hogan, 2009) reproduced salinity pulses of short duration, as observed, in the Strait of Hormuz. These pulses were related to the formation of cyclonic eddies upstream in the strait, due to the barotropic instability of the exchange flow in this region, and to fluctuations in the wind stress forcing. This study was followed by an investigation of the seasonality of the general circulation of the Gulf (Thoppil and Hogan, 2010); it showed that a cyclonic gyre develops in spring in the eastern basin. In summer, this gyre becomes unstable and breaks into mesoscale eddies. This study attributed a large importance to the Ekman dynamics in the extension of the IOSW intrusion into the Gulf.

All these previous studies have shown different biases when comparing the main features (water mass properties and circulation) of the Gulf to the few (synoptic) observations available. Indeed, among these discrepancies, the simulated salinity of the PGW outflow was too salty (Kämpf and Sadrinasab, 2006 and Yao and Johns, 2010) or too fresh (Thoppil and Hogan, 2009) compared to observations. Actually, these studies suggest that interannual variability or vertical mixing processes (impacted by heat fluxes, induced by tidal forcing in the strait, and affected by model resolution) could explain most of the model biases. However, none of these studies describes the interannual variability of the circulation or thermohaline properties, nor combines all drivers of variability in the Gulf.

The objective of this study is to present a realistic, interannual model of the circulation in the Persian Gulf and at the Strait of Hormuz, to validate it against observations, and then to describe the variability of the circulation, water mass formation and exchange through the Strait of Hormuz on intraseasonal to interannual timescale. We use a primitive-equation, sigma-coordinate model forced by mechanical and thermohaline atmospheric fluxes, river discharges and tides. Model set up and sensitivity experiments run to optimize the realism of the solution are described in Section 2. The model is first run for 14 years with climatological forcing then for years 1994–2001 with interannual forcing. The seasonal variations are studied for an average year of the climatological run once the model has reached its steady state (Section 3). The interannual variability is then detailed for years 1994–2001 (Section 4). Intra-seasonal variability of the model is illustrated in Section 5. Finally, the results of the model at higher resolution (3 km grid size instead of 9 km) are discussed in view of the former results (Section 6), before drawing conclusions (Section 7).

2. Model setup

2.1. The numerical model, initial and boundary conditions

The numerical model is composed of two parts: a 2D model of the north western Indian Ocean to provide the boundary conditions to a 3D model of the Persian Gulf and the Gulf of Oman. Both