

Physical Oceanography of the Gulf of Aden

Thesis

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Marine Sciences

by

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بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ
"وَقُلْ رَبِّیْ زِدْنِیْ عِلْمًا"

to my parents

my wife

Hagar and Ebrahim

Statement

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Physical Oceanography of the Gulf of Aden* is my original contribution and it has not been submitted on any previous occasion.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

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Certificate

This is to certify that the thesis entitled *Physical Oceanography of the Gulf of Aden*, submitted by Mohammed Ali Yahya Al Saafani to Goa University for the degree of Doctor of Philosophy, is based on his original studies carried out under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

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Synopsis

The Gulf of Aden presents a unique ecosystem that deserves scientific attention. In addition to its extraordinary biotic richness, the Gulf of Aden also serves as a highway for international trade between east and west. At present, approximately 3 million barrels of oil are being transported daily through the gulf. Traditionally, the Gulf of Aden has provided considerable amounts of sea food for the inhabitants of the surrounding arid lands. It will continue to do so in future if the fisheries are developed using modern scientific knowledge and techniques. In spite of the importance of the Gulf of Aden, very little information is available on its physical oceanography. Most of the investigations in this area were either aimed at understanding the exchanges between the Red Sea and the Gulf of Aden [Maillard and Soliman, 1986; Murray and Johns, 1997; Aiki et al., 2006], or at the spreading of Red Sea outflow into the Gulf of Aden [Fedorov and Meshchanov, 1988; Bower et al., 2000, 2002, 2005; Ozgokman et al., 2003; Peters and Johns, 2005; Peters et al., 2005] and its pathway into the Arabian Sea [Beal et al., 2000]. A few studies have used the available hydrographic data to describe the water masses in the Gulf of Aden [Rochford, 1964; Khimitsa, 1968; Piechura and Sobaih, 1986; Nasser, 1992; Mohamed et al., 1996; Mohammed, 1997]. All these studies, however, are either localized in space and time or have devoted themselves to describing the Red Sea outflow. Hence, they fall short of providing a comprehensive picture of the structure of water masses in the Gulf of Aden as they evolve round the year. These studies have also not succeeded in providing quantitative estimates of the different types of water masses that occupy the Gulf of Aden.

Often, the definition of water masses (the temperature–salinity– σ_θ ranges) vary drastically depending on the limited data used for the study. Similarly, the earlier studies did not deal in detail with the circulation and eddies in the Gulf of Aden.

This thesis aims at the synthesis of various data sets (hydrography, sea levels, winds, and model outputs) to describe the circulation and water masses in the Gulf of Aden more precisely than before. The main objectives of the study are: (i) to describe the seasonal cycle of circulation and hydrography in the Gulf of Aden, (ii) to describe the interannual variability of circulation in the Gulf of Aden, and (iii) to identify the possible mechanisms that control the circulation.

After presenting an introduction to the thesis in Chapter 1, Chapter 2 deals with the data used in this thesis. A new climatology of hydrography was prepared by assembling the data available from the National Oceanographic Data Center (NOEC), USA, Japanese Oceanographic Data Center (JODC), and a few other data centres and individuals because the existing climatology [Stephens et al., 2002; Boyer et al., 2002] was found to be insufficient for deciphering the fine features in the Gulf of Aden.

The satellite altimeter derived sea level data used in this thesis were obtained from CLS Space Oceanography Division. The merged gridded TOPEX/Poseidon, Jason, and ERS-1/2 sea level anomaly (SLA) data for January 1993 to December 2003 were available for every 7 days on a 1/3 degree Mercator grid projection. These data have low mapping errors and better spatial coverage than the TOPEX/Poseidon data alone [Ducet et al., 2000; Volkov, 2005].

Chapter 3 describes the hydrography and water masses in the Gulf of Aden. The newly prepared climatology of hydrography was used to identify and describe the water masses in the Gulf of Aden and their variability in space and time. Four water masses have been identified based on their θ – S characteristics. The Red Sea Water (RSW) that flows from the Red Sea is the most prominent water mass in the Gulf of Aden; it occupies about 37% of the total volume of the Gulf of Aden. The Gulf of Aden Surface Water (\sim

3%) forms as a mixture of local water and the water from western Arabian Sea during winter and Red Sea Surface Water during summer. The intermediate water, identified as Gulf of Aden Intermediate Water (GAIW), occupies about 9% of the total volume of Gulf of Aden; a characteristic salinity minimum is associated with it at $\sigma_\theta = 26.50 \text{ kg m}^{-3}$. The northward spread of Sub-tropical Subsurface Water from the south appears to be the major source of GAIW. The bottom water, named Gulf of Aden Bottom Water (GABW), showed the least variability. It was formed by mixing of Red Sea Water and water of southern origin. Mixing triangles have been used to analyze the composition of water in the Gulf of Aden.

Chapter 4 deals with the seasonal and interannual variability of circulation in the Gulf of Aden. Mean monthly variability of circulation in the Gulf of Aden is described using several data sets: hydrography, ship drifts, and satellite-derived sea levels. All data sets showed the dominance of eddies in the seasonal cycle. During winter (November–March), the net flow is westward all over the gulf, with a host of cyclonic and anticyclonic eddies embedded in it. The flow inside the gulf during the transition periods, April and October, is similar to that during the winter months. During May, the flow inside the gulf is dominantly geostrophic because the Ekman drift is weak. During June, when the summer monsoon establishes over the gulf and the northwestern Arabian sea, the flow is eastward along the northern side of the gulf and is towards west along the southern side. Later in July–September, an eastward flow establishes all over the gulf. An anticyclonic eddy is seen at the centre of the gulf during June-September.

The vertical structure of circulation is described using the geostrophic currents derived from hydrographic data. The circulation pattern at 300 and 600 m during November to March is similar to that at the surface. The cyclonic and anticyclonic eddies seen at the surface extend up to $\sim 600\text{--}800$ m. During summer, the eastward flow extends till 600–700 m during June, July and September, but only till 200 m in August. In August, the flow below 200 m is westward.

Merged altimeter SLA for 11 years is used to describe the interannual variability of surface circulation. Several techniques are available to resolve the signals at different periodicities hidden in the time series; wavelet analysis is one among them. To determine the dominant modes of variability in the SLA time series we have used the Morlet wavelet. This method allowed us to estimate the wavelet power due to the variability in SLA at different periods ranging from high-frequency (2 weeks) to interannual (5 years) periods. The annual and high-frequency signals dominate the sea level variability in the Gulf of Aden. The SLA variability in the gulf at interannual frequency is minimum and insignificant at 99% confidence level. It is significant at 95% confidence level only over a patchy area inside gulf. Since the variability in SLA is prudential to the geostrophic currents at the surface, the interannual variability in the surface geostrophic currents inside the gulf also are insignificant at 95 and 99% confidence levels.

Chapter 5 describes the mesoscale eddies that influence the circulation in the gulf and their origin. Inside the gulf, the eddies move at a speed of $\sim 6.0\text{--}8.5 \text{ cm s}^{-1}$, comparable to the first-mode baroclinic Rossby wave speed of 7.2 cm s^{-1} . The eddies, which enter the gulf from the Arabian Sea, owe their existence to more than one mechanism. Local Ekman pumping in the western Arabian Sea is important during the summer monsoon (June–September). During the winter monsoon (November–March), the dominant mechanism involves the westward propagating Rossby waves generated either in the Arabian Sea by Ekman pumping or along the west coast of India by poleward propagating Kelvin waves. These Rossby waves from the Arabian Sea propagate slower on entering the gulf because of a shallower thermocline in the gulf. Analysis shows that the SLA signal consists of low (annual and inter-annual) and high ($\sim 100\text{--}180$ days) frequencies. The low-frequency signal (mainly annual) shows a discontinuity between 52° E and 60° E . Though the high-frequency signal is seen at all longitudes, a wavelet analysis shows that it is significant only west of 60° E . An energy analysis, based on model simulations, suggests that barotropic instabilities are important during the entire year and that baroclinic

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The results described above are summarized in Chapter 6.

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