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Three-Dimensional Numerical Modelling Study of Sound Speed in the Persian Gulf

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Abstract: The three-dimensional variability of sound speed in the Persian Gulf is investigated. In this study, a three-dimensional hydrodynamic model (COHERENS) is employed in a fully prognostic mode to derive sound speed profiles in the Persian Gulf, an evaporation-driven inverse estuary that is governed by the import of surface water from the adjacent ocean and the 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. Results of the model show that sound speed in the Persian Gulf depends mainly on the temperature in the surface layer whereas the bottom layer as well as the southern part of the Gulf depends on temperature and salinity. Maximum sound speed occurs during the summer in the Persian Gulf which decreases gradually moving from the Strait of Hormuz to the north western part of the Gulf. A gradual decrease in sound speed profiles with depth was commonly observed in almost all parts of the Gulf. However, an exception occurred in the Strait of Hormuz during the winter. The results of the model are in very good agreement with earlier observations.

Key words: Sound velocity, mathematical models, seasonal variations, Indian Ocean, Strait of Hormuz

INTRODUCTION

Because of its natural resources, the Persian Gulf is an important military, economic and political region and is one of the world's busiest waterways. Countries bordering the Persian Gulf are Iraq, Kuwait, Saudi Arabia, Qatar Bahrain, the United Arab Emirates and Oman, on one side and Iran on the other side (Fig. 1). The Persian Gulf is ~990 km long and has a maximum width of 370 km. The average depth of the Gulf is 36 m. The Persian Gulf occupies a surface area of ~239,000 km^2 (Emery, 1956). Extensive shallow regions, with depths below 20 m, are found along the coast of the United Arab Emirates, around Bahrain and at the head of the Gulf. Deeper portions, with depths over 40 m, are found along the Iranian coast continuing into the Strait of Hormuz, which has a width of ~56 km and connects the Persian Gulf to the northern part of the Indian Ocean via, the Gulf of Oman. The narrow Strait of Hormuz restricts water exchange between the Persian Gulf and the northern part of the Indian Ocean.

The Persian Gulf is a semi-enclosed, marginal sea that is exposed to an arid, sub-tropical climate. It is located between latitudes 24-30°N and is surrounded by most of the Earth's deserts.

The Gulf experiences evaporation rates of ~2 m year^{-1} (Privett, 1959; Hastenrath and Lamb, 1979; Meshal and Hassan, 1986; Johns *et al*., 2003) that exceed by far the net freshwater input by precipitation (~0.15 m year^{-1}) and river discharge (Johns *et al*., 2003). The major river source of the Persian Gulf is the Shatt-Al-Arab (called Arvand Roud by some countries), being located at the head

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of the Gulf and being fed by the Euphrates, Tigris and Karun rivers. The salinity distribution in the Persian Gulf experiences significant seasonal variations.

The inflow of Indian Ocean seawater strengthens in late spring and summer and moves further up the Iranian coastline and closer to the coast of the United Arab Emirates (Reynolds, 1993). As a result of this, surface Gulf waters are saltier in the winter than in the summer. Theoretical and experimental studies on sound transmission have been carried out for different sea and ocean conditions. So far different equations with some limitations have been given by scientists. These equations slightly differ from each other due to some limitations. The sound speed in the ocean is a function of depth, salinity and temperature.

Sound waves propagate much better in the ocean than in the air. The average speed of sound in the air with a temperature of 20° centigrade is 334 m sec^{-1} but the average sound speed in the sea is about 1500 m sec^{-1}.

Usually, in the sea sound speed is increases with arise in temperature, depth and salinity. Due to large seasonal variation in the temperature and salinity in the Persian Gulf, the study of sound speed profiles seems to be of great interest to oceanographers.

Brewer and Dyrssen (1976) and Emery (1956) observed winter and summer hydrographic conditions, respectively in the Persian Gulf. This data was scattered over certain areas, whereas the observations of RV *Mt. mitchell* (Reynolds, 1993), provided an intensive and comprehensive data set for the entire Gulf. As far as sound speed in the Persian Gulf is concerned little has been published with regard to its acoustic properties. Earlier attempts have utilized temperature data only and neglected the effects of salinity. These results have been used to investigate seasonal variations in the acoustic properties of the Persian Gulf. However, the data was scattered, giving neither acoustic information for the northern part of the Gulf nor the vertical variations across and along its entirety.

This study focuses on the distribution of sound speed profiles in the Persian Gulf by employing a three dimensional hydrodynamic model, COHERENS (Luyten *et al*., 1999) which has not been addressed before. Characteristics of seasonal changes of sound speed have been investigated using the combined effect of temperature and salinity, in order to compare their relative importance.

MATERIALS AND METHODS

We employed the hydrodynamic part of COHERENS [COupled Hydrodynamical Ecological model for REgioNal Shelf seas] (Luyten *et al*., 1999), which is based on a vertical sigma coordinate. The model is run in a fully prognostic mode with Cartesian lateral coordinates on the f-plane, using geographical latitude of 27°N. The model is based on hydrostatic versions of the Navier-Stokes equations that embrace conservation equations for momentum, volume, heat and salt. We employ 10 sigma levels and Cartesian lateral grid spacings of $\Delta x = 7.4$ km (east-west direction) and $\Delta y = 6.6$ km (north-south direction). Bathymetry and coastline locations are based on ETOPO-2 data that has been interpolated and slightly smoothed onto a 4 min grid (Fig. 1). Minimum water depth is chosen at 5 m and maximum water depth is restricted to 150 m. The latter applies only to the Gulf of Oman and has no significant impact on the results. Note that restriction to 10 sigma levels is a compromise to maximize model efficiency with relatively fine lateral resolution and long simulation times (~20 years).

The model is initialized in winter when vertical stratification is weak throughout the Gulf using uniform temperature and salinity fields with values of 20°C and 38 PSU, respectively, which are reasonably close to observational evidence (Alessi, 1999). The model is forced by climatologic monthly mean atmospheric forces (wind speed, air temperature, humidity, cloud cover and precipitation) derived from 54 years (1952-2006) of NOAA data.

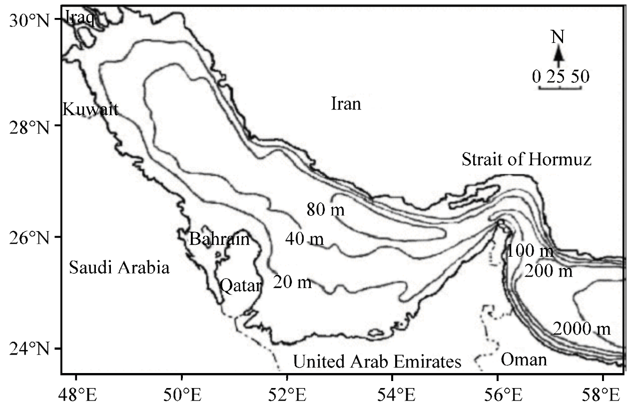

Fig. 1: Map of the Persian Gulf

River discharge is implemented in the model by means of inflow of a low-salinity (10 PSU) surface layer of 1.5 m in thickness and 700 m in width. Riverine inflow is assumed to vary in a sinusoidal curve with minimum values of 350 m sec^{-1} in October and a maximum of 650 m sec^{-1} in April. This gives an annual-mean river discharge of 500 m sec^{-1}, which we deem a realistic estimate of current discharge rates. River temperatures are assumed to vary between minimum value of 16°C in December and a maximum value of 32°C in July.

At the open-ocean boundary we prescribe 2-layer profiles of temperature and salinity, derived from earlier numerical modelling in the Persian Gulf (Kaempf and Sadrinasab, 2006) on a monthly basis. Temperature and salinity do only vary significantly in the upper 60 m of the water column. The water column underneath does not experience significant temporal variations and is kept at a temperature of 22°C and a salinity of 36.5 PSU throughout the simulations.

Amplitudes and phases of the four major tidal constituents, M_2, S_2, O_1 and K_1, are prescribed as constant values along the eastern open-ocean boundary in the model.

In order to simulate sound speed, Lorans equation is employed and added to the model to calculate sound speed in the domain as a function of temperature, salinity, depth and latitude, that is:

$$c(x,s,t) = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + (1.333 - 0.126t + 0.009t^2)\times(s-35) + \Delta(x)$$
$$\Delta(x) = 16.3x + 0.1$$

As the Lorans equation is defined for latitude 45°, we replace x with $x(1-0.0026\cos\varnothing)$ in the mentioned equation.

In this equation s, t, $\varnothing$ and x denote salinity in PSU, temperature in Celsius degree, latitude in degree and depth in kilometers.

RESULTS AND DISCUSSION

In order to simulate seawater properties as well as circulation of the Gulf, the model was run for 15 years and has reached its steady-state. Present findings, which are in good agreement with observational evidence, suggest that the Persian Gulf experiences a distinct seasonal cycle in which a gulf-wide cyclonic overturning circulation establishes in summer, but this disintegrates into mesoscale eddies in winter. In other words, water from the Indian Ocean enters from the surface into the Persian Gulf via the Strait of Hormuz during summer time and reaches to the head of the Gulf, but during the winter the Indian Ocean water reaches only near the middle of the Gulf. Moreover, top to bottom temperature gradients exceed 11°C during the summer and diminish to 1- 2° in the winter. As a result of this a seasonal thermocline establishes during the summer which is in a very close agreement with Emery (1956). The model also predicts the vertical mixing of the water in winter in the entire Gulf. It is due to the passing of cold air over the surface of the Gulf, resulting in an increase of density in the surface layer of the water and creating a vertical movement from top to bottom.

Figure 2 shows last 4 years of the simulated Gulf-averaged salinity, temperature and sound speed which attain a robust, steady seasonal cycle. Gulf-averaged temperature follows the seasonal cycle of incident solar radiation with a time lag of 1-2 months. Gulf-averaged salinity, on the other hand, attains

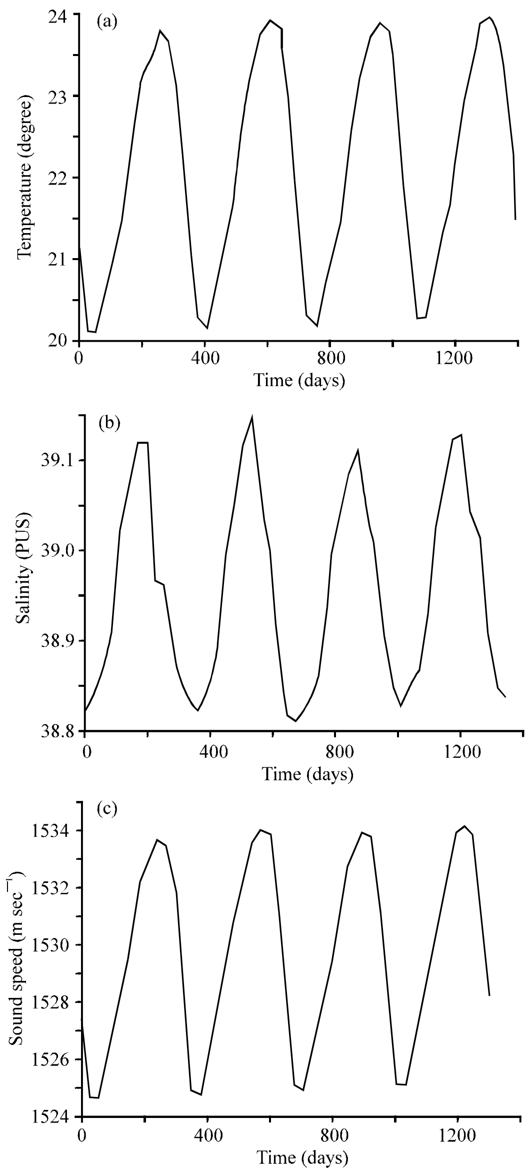

Fig. 2: Time series of Gulf-averaged; (a) temperature; (b) salinity and (c) sound speed from the model results

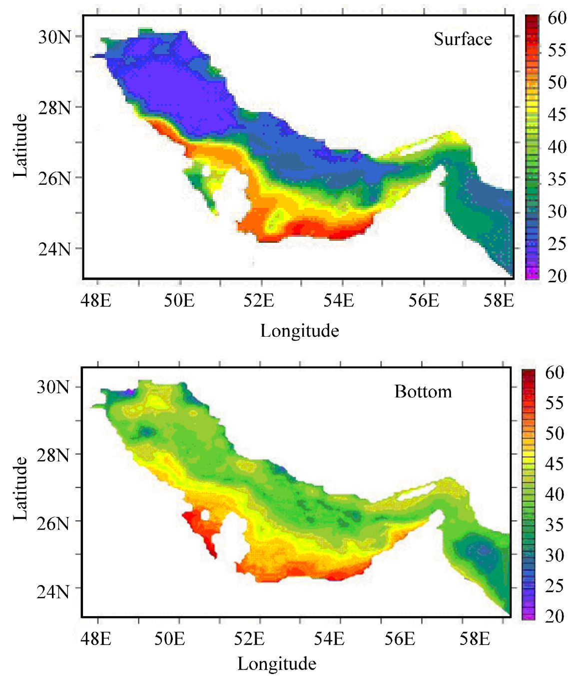

Fig. 3: Sound speed (from 1500 m sec^{-1}) in surface and bottom layers during summer in the Persian Gulf

minimum values during March-May each year. Effects of precipitation and river run-off on salinity changes are negligible on a gulf-wide scale. Decreases in salinity can be fully attributed to inflow of Indian Ocean surface water which is in agreement with observational evidence, peaks in spring. Maximum salinities occur during October-December when the evaporative surface salinity flux dominates over injection of low-salinity water through the Strait of Hormuz.

As mentioned earlier maximum water temperature as well as the maximum difference between surface and bottom temperatures occurs during the summer. Hence, maximum sound speed occurs during summer in the Persian Gulf (Fig. 2).

From the model results we have constructed sound speed profiles in surface and bottom layers of the whole domain in winter and summer. During the summer due to lack of vertical mixing maximum stratification of temperature occurs in this region.

As can be shown from Fig. 3, sound speed is maximum during the summer (~1560 m sec^{-1}) in the southern part of the Persian Gulf. Also sound speed in the northern part of the Gulf varies from 1524-1528 m sec^{-1} in the bottom and from 1547-1552 m sec^{-1} in the surface. These show that sound speed has a 20 m sec^{-1} difference from surface to bottom during the summer.

In the southern part of the Gulf except for the region surrounding Bahrain, sound speed varies from 1548-1552 m sec^{-1} in the bottom layer and from 1553-1557 m sec^{-1} in the surface layer. This location is shallow and the difference between surface and bottom temperature is negligible and sound speed is a function of both temperature and salinity.

Findings of the model also suggested that around Bahrain, sound speed varies from 1539-1544 m sec^{-1} in the bottom and from 1554-1558 m sec^{-1} in the surface.

In this part of the Gulf, sound speed varies more than in the other parts because this region is shallow and salinity has more effects on sound speed than temperature.

Figure 4a and b, respectively show vertical profiles of sound speed constructed from the model output and field observation in the Strait of Hormuz during the summer by Abdelraman (1998).

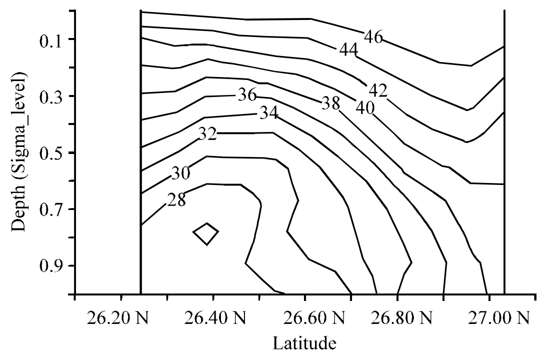

Fig. 4a: Vertical profile of sound speed (from 1500 m sec^{-1}) from the model results in the Strait of Hormuz during summer

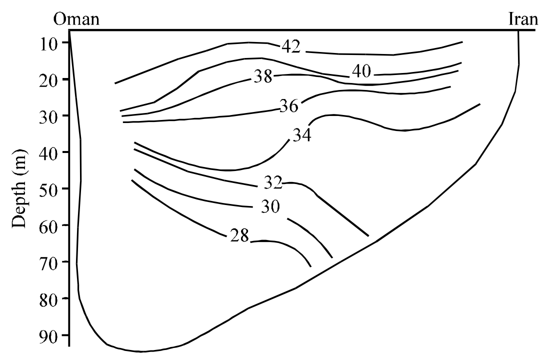

Fig. 4b: Vertical profile of sound speed (from 1500 m sec^{-1}) from field measurement in the Strait of Hormuz during summer 1996 (Abdelraman, 1998)

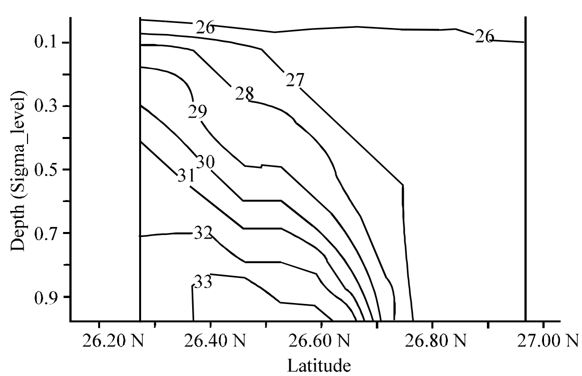

Fig. 5a: Vertical profile of sound speed (from 1500 m sec^{-1}) from the model results in the Strait of Hormuz during winter

Figure 4a and b show that the sound speed profile in the Strait of Hormuz decreases from surface to bottom i.e., varies from 1546-1528 m sec^{-1} during the summer. It is seen that the correspondence between model and observations is very good in the deeper layers. The model produces slightly higher

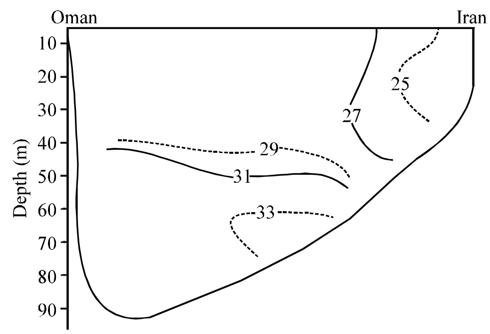

Fig. 5b: Vertical profile of sound speed (from 1500 m sec^{-1}) from field measurement in the Strait of Hormuz during winter 1996 (Abdelraman, 1998)

sound speed at the surface and does not place the strongest gradients in the uppermost layer, but the general structure is reproduced quite well.

Figure 5a and b, respectively show vertical profiles of sound speed constructed from the model output and field observation in the Strait of Hormuz during the winter by Abdelraman (1998). As can be seen from the figures variation of sound speed is very small during winter at the Striate of Hormuz. Moreover, sound speed in the Strait of Hormuz has negligible changes during the winter. These figures also show that sound speed in the Strait of Hormuz increases from surface to bottom in the winter, which is the only exception in the Persian Gulf.

Comparing Fig. 4a with b and also 5a with b shows that the results of the model are in very good agreement with the observations.

CONCLUSION

- Sound speed is a function of temperature, salinity and depth in the Persian Gulf but the effect of salinity and temperature is more than the effect of depth
- Because the Persian Gulf is shallow, depth can not affect sound speed and is negligible
- The temperature is the main factor that affects sound speed in the Persian Gulf, so that we can conclude that sound speed is a strong function of temperature in the Persian Gulf
- Sound speed in the Persian Gulf has higher values during the summer than the winter because of higher water temperature
- From the results of this model we can simulate the sound wave propagation in the Persian Gulf. This is of great importance in underwater communication applications
- Changes in the seasonal pattern of sound-speed, particularly in the Strait of Hormuz are evident

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