

Sound speed structure in the Arabian Sea and the Bay of Bengal

S Prasanna Kumar, G S Navelkar, T V Ramana Murty, Y K Somayajulu & C S Murty
National Institute of Oceanography, Dona Paula, Goa 403 004, India
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Sound speed computed from annual mean temperature and salinity data of Levitus reveals that spatial variation in the Arabian Sea is greater than that in the Bay of Bengal. Maximum spatial variation of sound speed in the Arabian Sea noticed between the depth levels 200 to 1500 m is due to the combined effect of variation in the salinity (to a larger extent) and temperature. In the Bay of Bengal though the spatial variation of sound speed is marginal, variations observed between 1500 and 2800 m are brought about by warm Andaman Sea waters. The depth limited nature of annual mean sound speed profile for 2 marginal seas suggests that the effective acoustic channel lies much below (~ 300 m) the surface. This results in acoustic propagation in the form of surface-refracted bottom-reflected (RBR) rays within the SOFAR channel. Acoustic ray arrival pattern, obtained from the ray-tracing software, reveals that in the Arabian Sea middle order rays with launch angles from $\pm 6.5^\circ$ to $\pm 7.5^\circ$ reach the receiver early. These are followed by rays with flat angle or near-axial rays and the RBR rays. The purely refracted rays with steep as well as flat angles can adequately be resolved in time—a characteristic that make the ray identifications easier at the experimental stages. On the contrary, in the Bay of Bengal, near axial, flat angle rays with launch angles from -4° to $+4^\circ$ reach the receiver faster than the purely refracted steep angle rays. Further, flat angle rays arrive almost simultaneously making the ray identification complex and difficult. The rays with launch angles between $\pm 4^\circ$ and $\pm 7^\circ$ undergo total refraction and have a better spread as far as travel time is concerned. The early arrival of the middle order rays in the Arabian Sea has been attributed to the frequent scanning of warm and high saline waters in the depth range of 500-1200 m by these rays. The early arrival of the axial rays in the Bay of Bengal results from weak gradients within the SOFAR channel.

Ocean acoustic tomography is a tool for synoptic monitoring of large scale oceanographic features¹. The most important parameter that one is interested in and measures in ocean acoustic tomography is the travel time of an acoustic pulse. The sequential arrival of these acoustic pulses at any receiver location, for a given source-receiver configuration depends mainly on the acoustic field of that region. Hence a *priori* knowledge of the sound speed field enables one to understand and identify the eigen rays from the multipath propagation and obtain maximum information about the oceanic interior. Previously there have been some attempts to study the sound speed field and its variability in the Arabian Sea² and the Bay of Bengal³⁻⁵ using limited data sets. The present study aims at understanding sound speed structure of waters of the 2 marginal seas - Arabian Sea and Bay of Bengal - using a comprehensive data set and to highlight its implications to ocean acoustic tomography.

Materials and Methods

The quasi-synthetic environmental data of Levitus⁶ for the Arabian Sea and the Bay of Bengal

have been utilised to obtain annual mean values of temperature and salinity at 33 standard depths. From these data, sound speeds were computed⁷. Annual mean sound speed and minimum and maximum values at each of the standard depths were obtained. These mean profiles were used for acoustic ray-tracing program⁸ for computation of travel time. Ray-tracings were carried out for launch angles from $+10^\circ$ to -10° , over a range of 300 km keeping the acoustic source at 1600 m depth.

Results and Discussion

Sound speed field in the Arabian Sea - In the Arabian Sea the sound speed distribution at the surface (Fig. 1a) shows a decrease in value from 1543 m.sec⁻¹ in the south-eastern region to 1538 m.sec⁻¹ towards the western boundary. The contours are oriented parallel to the western boundary up to 50 m depth. At 75 m depth (Fig. 1b) a high sound speed region is seen at the central Arabian Sea with a core value of 1540 m.sec⁻¹. This is well developed at 100 m depth (Fig. 1c) where the core value is 3 m.sec⁻¹ higher than the ambient sound speed. Beyond 150 m (Fig. 1d) the core dissipates and contours start

orienting zonally with sound speeds increasing from equator to north. Thus the zonal gradients seen up to 150 m depth changes into meridional gradients beyond this depth. This trend continues upto 1500 m (Fig. 1e), beyond which (Fig. 1f) gradients are much less.

Sound speed field in the Bay of Bengal — Sound speed at the surface (Fig. 2a) decreases from 1542 m.sec⁻¹ in the southern Bay to 1536 m.sec⁻¹ near the head of the Bay with the contours oriented zonally. This pattern remains up to 50 m. At 75 m depth (Fig. 2b) 2 high sound speed regions are noticed, one near the equator and other at the central Bay. This is well developed at 100 m depth (Fig. 2c). The waters of the Andaman Sea at this depth are characterised by a low sound speed as compared to the Bay of Bengal. Beyond 150 m (Fig. 2d) the high sound speed core dissipates and the gradients become very weak. In the depth range between 1500 m (Fig. 2e) and 2000 m (Fig. 2f) the magnitudes of sound speed in the Andaman Sea region are higher (by about 2 m.sec⁻¹) compared to the corresponding values in the Bay of Bengal. This is due to the warm waters prevailing at this depth range. Below 2000 m depth the variations in sound speed are marginal.

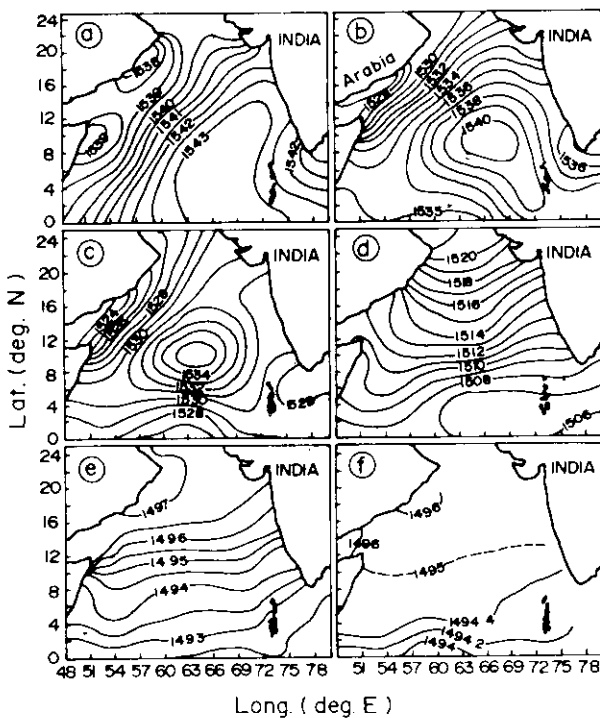


Fig. 1—Spatial distribution of sound speed at (a) surface, (b) 75 m, (c) 100 m, (d) 200 m, (e) 1500 m and (f) 2000 m in the Arabian Sea. [Note the change in contour interval at surface and 1500 m (0.5 m.sec⁻¹) and at 2000 m]

Characteristics of annual mean sound speed profile— The annual mean sound speed profile (Fig. 3) shows uniform values in the upper 40 m of the Arabian Sea while an increase with depth is seen in the Bay of Bengal, indicating the presence of a surface duct with weak gradients. An interesting feature common to the Arabian Sea and the Bay of Bengal is the depth limited nature of the profile i.e. surface sound speed exceeds the near bottom sound speed. This has an

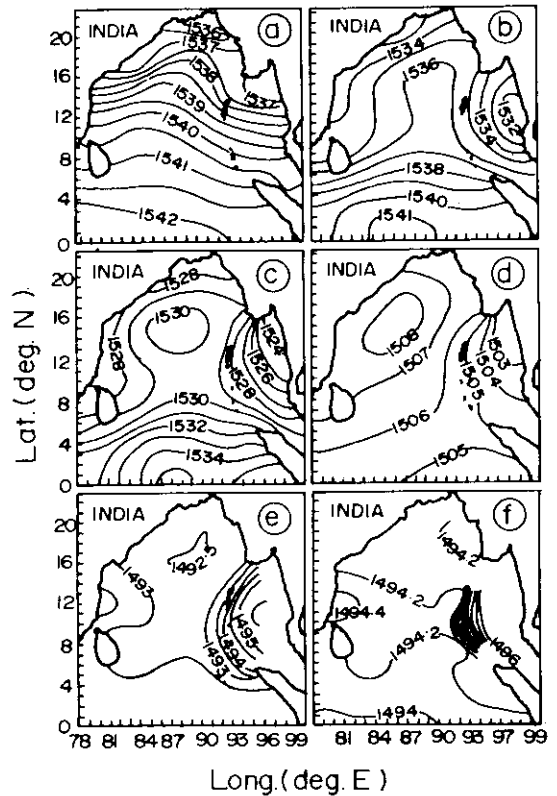


Fig. 2—Spatial distribution of sound speed at (a) surface, (b) 75 m, (c) 100 m, (d) 200 m, (e) 1500 m and (f) 2000 m in the Bay of Bengal [Note the change in contour interval at 1500 m (0.5 m.sec⁻¹) and 2000 m (0.2 m.sec⁻¹)]

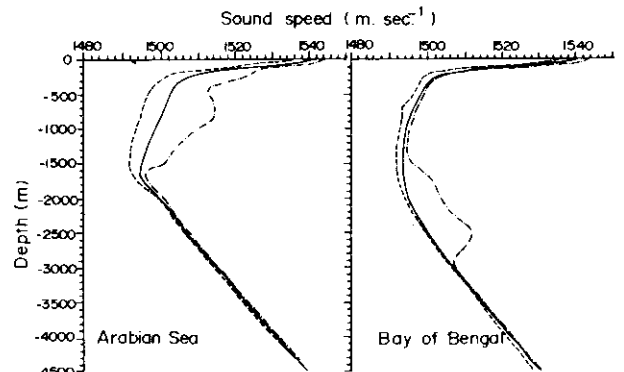


Fig. 3—Annual mean (—) sound speed profile along with the minimum (---) and the maximum (·-·-·) values

important implication to sound propagation. Acoustic rays in an ocean with depth limited profile will propagate as surface-refracted bottom-reflected (RBR) rays. In the Arabian Sea, sound speed shows maximum spatial variations between the depth levels 200 to 1500 m. This is due to a combined effect of variations in salinity (to a larger extent) and temperature. In the Bay of Bengal spatial variations of sound speed are marginal as seen from the mean profile and the associated minimum and maximum values. However, between 1500 m and about 2800 m the observed sound speed variations are due to the effect of the Andaman Sea water which is warmer than the Bay of Bengal water. In general, at any depth sound speed values in the Arabian Sea are higher than the corresponding values in the Bay of Bengal.

Spatial variations of channel parameters— Considering the importance of channel parameters such as axial sound speed, channel axis depth, conjugate depth and sound speed at the conjugate depth on acoustic propagation, the spatial distributions of these are examined and presented. The conjugate depth (depth below the sea surface at which the sound speed equals the near bottom values) in the Arabian Sea presents variation from 75 to 300 m while in the Bay of Bengal the variation is from 100 to 300 m (Fig. 4). These variations of over 200 m in conjugate depth is primarily due to the spatial variations in bottom depth. As a result, the effective sound channel lies much below the sea surface. Sound speeds at the conjugate depths also show wide variations from 1540 $m.sec^{-1}$ at 75 m to 1497 $m.sec^{-1}$ at 300 m in the Arabian Sea and 1532 $m.sec^{-1}$ at 100 m to 1497 $m.sec^{-1}$ at 300 m in the Bay of Bengal (Fig. 5). The depth of sound channel axis varies between 1450-1950 m in Arabian Sea as compared to 1100-1750 m in Bay of Bengal (Fig. 6). In general, the depth of the channel axis increases towards the northern latitudes in the Arabian Sea, while it decreases in the Bay of Bengal. The mean depth of the channel axis in the Arabian Sea and the Bay of Bengal are 1750 m and 1500 m. The sound speed at the axis shows variations up to 4 $m.sec^{-1}$ and 2 $m.sec^{-1}$ respectively (Fig. 7). The eastern Bay and the Andaman Sea, are characterised by low axial depth and high axial sound speeds.

Ray arrival structure— Acoustic ray arrival pattern (Fig. 8), obtained from ray-tracing reveals that in the Arabian Sea the rays with emergence angle between $\pm 6.5^\circ$ and $\pm 7.5^\circ$ reach the receiver first followed by the flat angle near axial rays and the surface-refracted bottom-reflected (RBR) rays. In the Arabian Sea the purely refracted steep as well as flat angle rays are adequately resolvable in time. This feature makes ray

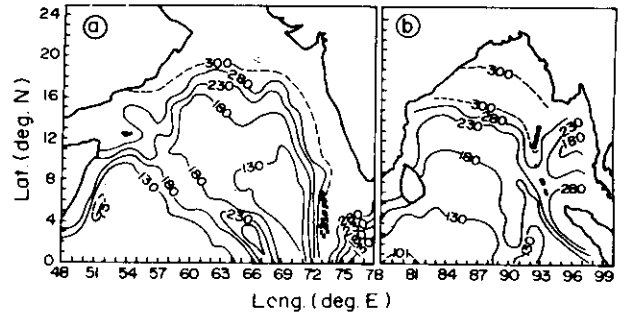


Fig. 4—Variation in conjugate depth (m) (a) Arabian Sea and (b) Bay of Bengal

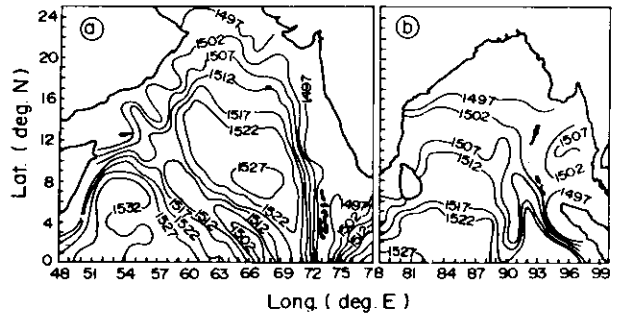


Fig. 5—Sound speed ($m.sec^{-1}$) at the conjugate depth (a) Arabian Sea and (b) Bay of Bengal

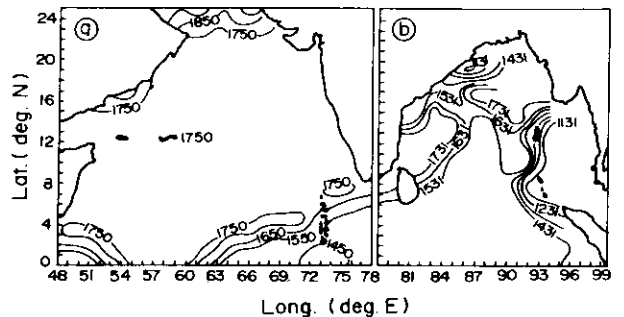


Fig. 6—Variation in the SOFAR Channel axis depth (m) (a) Arabian Sea and (b) Bay of Bengal

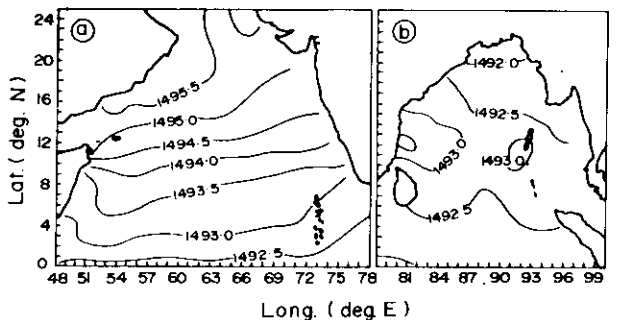


Fig. 7—Sound speed ($m.sec^{-1}$) at the SOFAR axis (a) Arabian Sea and (b) Bay of Bengal

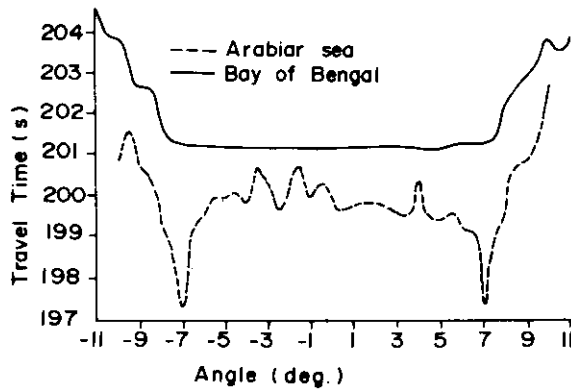


Fig. 8—Launch angle versus travel time of acoustic ray over 300 km range

identification - the crucial aspect of tomography - easier. In the Bay of Bengal the near axial flat angle rays (-4° to $+4^{\circ}$) reach the receiver faster than the purely refracted steep angle rays. Further, the flat angle rays arrive almost simultaneously ($< 10 \text{ m. sec}^{-1}$) making the ray identification difficult. The rays with launch angles between $\pm 4^{\circ}$ and $\pm 7^{\circ}$ are purely refracted and have better travel time spread with well defined arrival pattern. However, rays with angle of emergence $> \pm 7^{\circ}$ undergo bottom bounces - appearing as kinks in the curve (Fig. 8) and lead to enhanced loss of energy at the bottom boundary. Due to the depth limited nature of the acoustic profile, the steep angle rays undergo reflection at the lower boundary and refraction at the upper boundary without undergoing surface reflection.

The observed arrival pattern of the acoustic pulse has been analysed in the light of the prevailing oceanographic features in this region. For example, the early arrival of $\pm 6.5^{\circ}$ to $\pm 7.5^{\circ}$ rays in the Arabian

Sea is due to the frequent scanning of the warm, high saline waters in the depth range of 500-1200 m by these rays. Since the sound speed in this layer is more, the travel times of the above rays are reduced. The warm, high saline waters of the Red Sea origin⁹ intrude into the Arabian Sea at depth interval of 500-800 m. The early arrivals of the axial rays in the Bay of Bengal result from the characteristic weak sound speed gradients prevailing within the SOFAR channel. Eigen ray computations for source at 1600 m and receiver at 1500 m show a time span of 495 millisecond in the Arabian Sea which is longer compared to that in the Bay of Bengal (344 millisecond).

Acknowledgement

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