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Transmission Loss Variability Associated with Upwelling and Downwelling Off the Southwest Coast of India

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ABSTRACT

Fine resolution spatial survey carried out off the west coast of India during June and December 2004 was utilised to study the transmission loss (TL) variability associated with the upwelling and downwelling processes in this region. During June, the upwelling was confined to the upper 80 m. Downsloping of isotherms below this depth towards the coast and the occurrence of low saline waters indicated the presence of undercurrent. Between the periods of upwelling and downwelling, temperature and salinity in the surface layers increased by 1-2 °C and 2 PSU, respectively, while at the sub-surface levels, the corresponding increase was ~8 °C and ~0.5 PSU. A range-dependent acoustic propagation model based on parabolic equation method was utilised to compute TL for these two periods. The model was run with a source frequency of 3 kHz kept at 5m depth for different environmental setup, viz. propagation along the constant-depth contour, range-independent and range-dependent environment, and upslope/downslope propagation. The computations revealed significant variability in the TL characteristics between the upwelling and downwelling scenario, though bathymetry and geo-acoustic properties were the same. The analysis also stressed the need of range-dependent acoustic propagation model for realistic prediction of transmission loss variability.

Keywords: Transmission loss, upwelling process, downwelling process, acoustic propagation model, upslope propagation, downslope propagation, bathymetry

1. INTRODUCTION

Upwelling and downwelling are the two prominent features appearing off the west coast of India on an annual cycle. Generally, upwelling is noticed during the summer monsoon season[1-4] and downwelling during winter[1,5]. Even though upwelling starts in the deep waters in February[2,6,7], it is discernable off the southwest coast of India only by May, and then extends northward along the coast with the progress of the monsoon. Upwelling is usually associated with the shoaling of mixed layer towards the coast and increase in the gradients below the mixed layer. The converse process, downwelling is characterised by deep mixed layers in the continental shelf.

In the presence of surface-mixed layer, sound travels in ducted manner which enables a larger distance of propagation in the surface layers. Within the mixed layer, since the temperature and salinity are almost uniform, the sound velocity increases with depth due to pressure effects, while below this layer, the sound velocity decreases as the temperature decreases. As a result, at the base of the mixed layer, maximum sound velocity is noticed. Moreover, it is believed that the mixed layers are of interest only for high-frequency acoustic propagation, as there is a cut-off frequency below which ducted propagation in the surface layer is not possible. Hareesh Kumar[8,9], *et al.* showed that the variability in the temperature profiles due to internal waves and Arabian Sea mini warm pool have profound influence on the acoustic propagation. Similarly, the seasonally occurring features like upwelling and downwelling vary the thickness of the surface-mixed layer and vertical gradients below this layer. Hence, in this study the influence of these two contrasting features on acoustic propagation has been utilising a range carried out dependent propagation model based on parabolic equation method.

2. MODEL AND DATA USED

2.1 Model

The propagation of acoustic pressure field in underwater environment is governed by Helmholtz equation. In a cylindrical coordinate system, this equation[10] can be written as

$$\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}+\frac{\partial^2 p}{\partial z^2}+k_0^2 n^2 p=0 \qquad (1)$$

Here, the azimuthal symmetry is assumed. $P(r,z)$ is the acoustic pressure, $k_0=\omega/c_0$, c_0 is the reference sound speed and $n(r,z) = c_0 / C_{(r,z)}$ is the index of refraction. $p(r, z)$ is expressed equal to $u(r,z)\ v(r)$, where $v(r)$ is strongly dependent on r while $u(r,z)$ is only weakly dependent on r. For an out going wave $v(r)$ is given by the zero^th order Hankel function of first kind as.

$$p(r,z) = u(r,z)\ H_0^{(1)}(k_0 r) \qquad (2)$$

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Applying far-field approximation $(k_0 r) >> 1$

$$H_0^{(1)}(k_0 r) = \sqrt{\frac{2}{\pi k_0 r}} e^{i(k_0 r - \frac{\pi}{4})} \quad (3)$$

Substituting Eqn (2) in Eqn (1) one gets

$$\frac{\partial^2 u}{\partial r^2} + 2ik_0 \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2} + k_0^2 (n^2 - 1)u = 0 \quad (4)$$

Assuming that the operators $\frac{\partial}{\partial r}$ and $\frac{\partial}{\partial z}$ are commute, i.e.

$$\frac{\partial}{\partial r}\frac{\partial}{\partial z} u = \frac{\partial}{\partial z}\frac{\partial}{\partial r} u$$

The Eqn (4) becomes

$$\left[\frac{\partial^2}{\partial r^2} + \frac{\partial^2}{\partial z^2} + 2ik_0 \frac{\partial}{\partial r} + k_0^2 (n^2(r,z) - 1)\right] u = 0 \quad (5)$$

Let $P = \frac{\partial}{\partial r}$ and $Q = \sqrt{n^2 + \frac{1}{k_0^2}\frac{\partial^2}{\partial z^2}}$

then the elliptical wave equation is of the form

$$\left[P^2 + 2ik_0 P + k_0^2 (Q^2 - 1)\right] u = 0 \quad (6)$$

which can be factorised as

$$(P + ik_0 - ik_0 Q)(P + ik_0 + ik_0 Q)u - ik_0 (PQ - QP)u = 0 \quad (7)$$

for a weak range-dependence, the last term of this equation becomes zero. Selecting only the outgoing wave component, one has

$$PQ = ik_0 (Q - 1)u \quad (8)$$

$$\text{or,} \quad \frac{\partial u}{\partial r} = ik_0 \left(\sqrt{(n^2 + \frac{1}{k_0^2}\frac{\partial^2}{\partial z^2}} - 1 \right) u \quad (9)$$

This is the generalised parabolic wave equation, which can be solved by implicit finite difference method to get the acoustic field values. This model is utilised to simulate the acoustic fields in this study.

2.2 Data

INS Sagardhwani carried out a spatial survey off the southwest coast of India during June and December 2004 (Fig. 1). The survey was carried out along 3 transects in June (separated by 30 nautical miles and up to an offshore distance of 120 nautical mile from 30 m depth contour) with stations at every 10 nautical mile intervals and along 13 transects in December (separated by 5 nautical miles between 30 m and 200 m depth contours) with stations at every 5 nautical mile intervals. Vertical profiles of temperature and salinity (using Mini CTD system) were collected from all the stations. In addition, the daily wind data from Quick SCAT corresponding to the above periods was also utilised to explain its role on upwelling and downwelling.

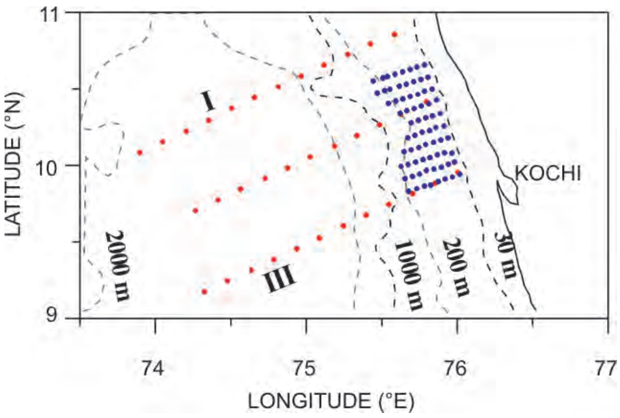


Figure 1. Station location.

3. RESULTS AND DISCUSSION

As the main objective was to study the influence of coastal upwelling and downwelling on the transmission loss variability, it was better to have an understanding of the prevailing atmospheric and oceanic conditions in these regions during these periods. The observed winds were strong (>7 m/s) and west-northwesterly during June, while they were weak (<5 m/s) and northeasterly during December. The alongshore component of the wind stress (τ_y), after applying the coastal inclination, was equatorward during June [Fig. 2(a)] and poleward during December [Fig. 2(b)]. Moreover, during June, the absolute magnitude of τ_y near the coast (<-0.025 Nm^{-2}) was three times lesser than τ_x (>0.075 Nm^{-2}). Compared to other famous upwelling regions like off Somalia and Peru, the upwelling off the southwest coast of India was found to be very weak. During December, τ_x and τ_y were almost equal in magnitudes but significantly different from June. The positive values of τ_y favours downwelling in these regions.

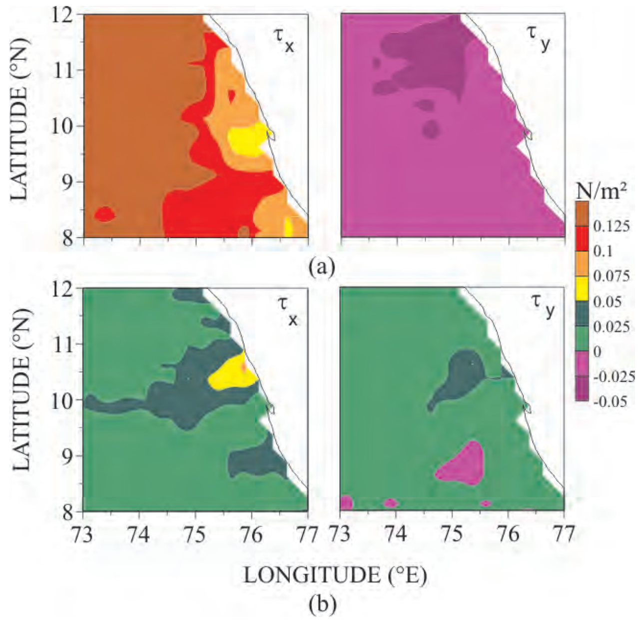


Figure 2. Wind stress components during: (a) June 2004, and (b) December 2004.

To highlight the environmental conditions during the periods of upwelling and downwelling, the vertical sections of temperature along two transects for the corresponding periods are presented (Fig. 3 and 4). The figures clearly indicated upsloping of isotherms towards the coast during June (Fig. 3), but was mostly confined to the upper 80 m of the water column. As a result, the surface isothermal layers shoaled by > 45 m along transect II (from 50 m at a distance of 220 km to < 5 m at the 30 m depth contour) and by < 30 m along transect III. This highlights the spatial

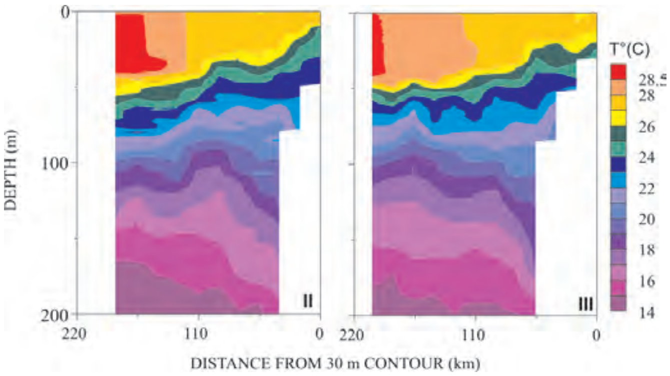


Figure 3. Depth-space sections of temperature at the transects II and III during June 2004.

variability of upwelling within a short distance. The two facts, viz., equatorward component of τ_y and upsloping of isotherms towards the coast, suggest windinduced eastern boundary upwelling off the west coast of India during June. In the continental slope, downward sloping of isotherms were very prominent at sub-surface levels along the two transects (below 60 m and 90 m along transects II and III, respectively), which are the typical signatures of undercurrent in the wind-driven eastern boundary upwelling regions. Within the region of undercurrent, the vertical temperature gradient was very weak, due to the increased shear mixing between the southerly surface currents and northerly sub-surface currents[11]. The scenario completely changed in December (Fig. 4), when the water column became nearly isothermal (~28 °C) up to bottom in the shelf, whereas in

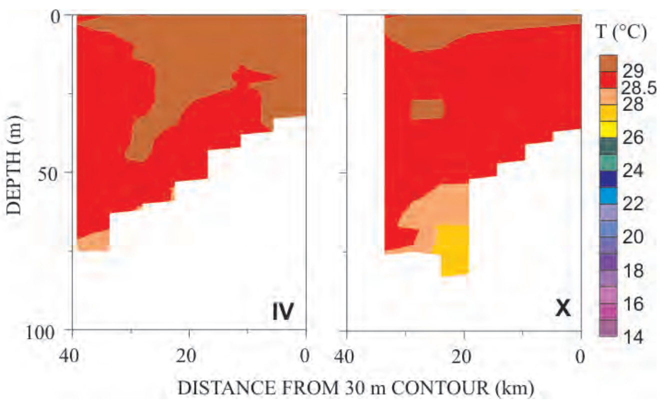


Figure 4. Depth-space sections of temperature at the transects IV and X during December 2004.

the slope, thermocline (> 0.25 °C/m) was noticed below 75 m depth.

To understand the observed variability in the temperature and salinity profiles between the periods of upwelling and downwelling, the data collected from the same locations during June and December 2004 along a transect is presented (Fig. 5). Between the two periods, temperature in the surface layers increased by 1-2 °C and by > 8 °C at the sub-surface levels. In the coastal region, the shallow isothermal layer (< 10 m) observed during June 2004 deepened and the water column became fully isothermal by December 2004. Moreover, features like step structure, tri-layer structure, and strong thermocline gradient noticed in the temperature

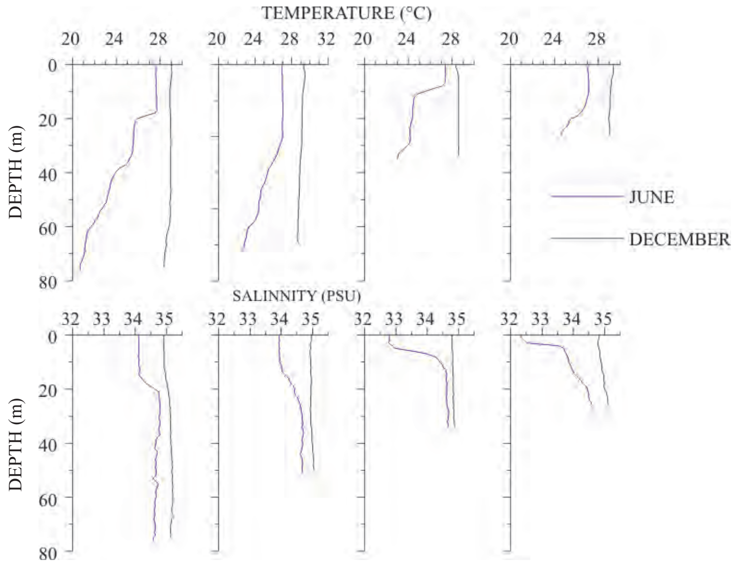


Figure 5. Vertical profiles of temperature and salinity during June and December 2004.

field during June 2004 vanished by December 2004, as the water column became fully isothermal.

It is a well established fact that during the north-east monsoon season, the east Indian coastal current brings low-salinity water from the Bay of Bengal[1,12-14] and occupy the continental shelf of the south-west coast of India. In spite of this, salinity in the water column increased between June 2004 and December 2004. This was due to the fact that dilution in the surface layers due to freshwater influx is much more than the influx of water from the Bay of Bengal, which is having a salinity of ~35 PSU. Difference in salinity was maximum in the surface layers of the coastal regions (>2.5 PSU), where the fresh-water influx was more compared to offshore. At the sub-surface levels, the difference was < 0.5 PSU. The excessive rainfall and river discharge during the summer monsoon compared to winter[4] is responsible for the low surface salinity during June, and hence, the big difference in salinity. The tri-layer structure observed in the temperature profile during June 2004 was also evident in the salinity profile, especially near the coastal region. Moreover, the halocline noticed in June 2004 disappeared and salinity increased with depth in December 2004.

3.5 Transmission Loss Variability due to Upwelling and Downwelling Processes

Analysis of data collected from the coastal waters showed that during the transition from upwelling to downwelling, not only the mixed layer in the continental shelf deepened by more than 50 m, but followed by a considerable reduction in the vertical gradient. The presence of deep isothermal layer supports the fact that the medium characteristic during downwelling is favourable for the acoustic propagation in the surface layers for a source within the sonic layer than the upwelling scenario. Hence, it is important to monitor the variability in the acoustic characteristics of the medium due to the changes in oceanic environment for better deployment/utilisation of underwater sensors. The variability in the temperature field between June and December is sufficient to alter the acoustic character of the same acoustic path significantly.

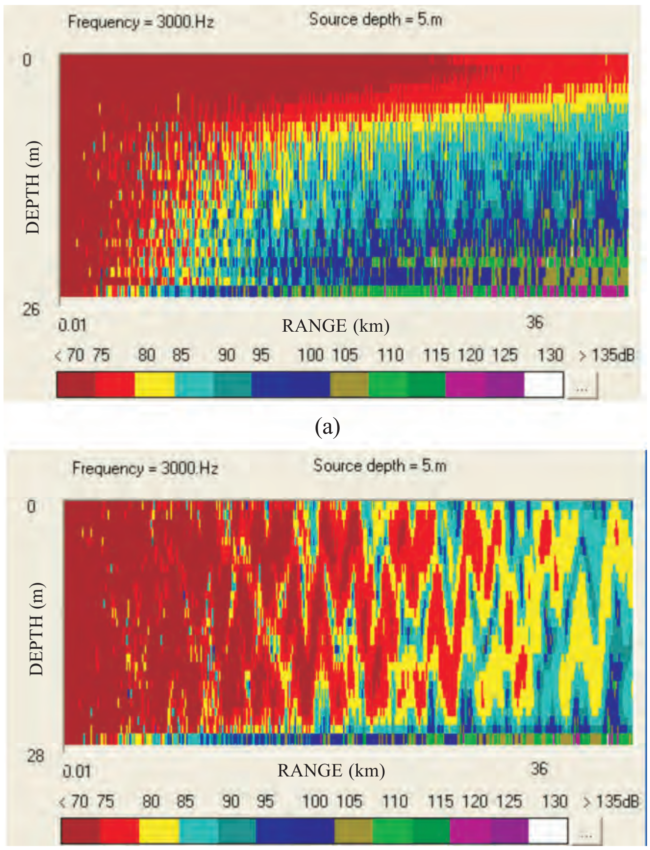
A range-dependent transmission loss (TL) model[10] based on parabolic equation method was utilised to study the influence of upwelling and downwelling on sound transmission loss variability. This model is a powerful approach for solving range-dependent propagation problems in laterally-varying media in ocean acoustics and was utilised to study the range-dependent transmission loss variability in the presence of tri-layer structure[8] and warm pool[9]. For this study, data along transect II, which was covered during the two periods (June and December) was considered. The sound speed profiles computed from the vertical profiles of temperature and salinity collected from different stations along this transect were given as the range-dependent environmental input to the model. The bathymetry and geo-acoustic parameters obtained along this transect were also the input to the model. The model computations were carried out to a range of 36 km from the 76 m depth contour to 26 m depth contour (upslope propagation) and vice versa (downslope propagation). A 3 kHz source at 5 m depth was used for transmission loss computations. The model was run to compute the TL for the following different environmental conditions:

(a) *Case 1:* single sound speed profile in the shallow water along the same depth contour,
(b) *Case 2:* single sound speed profile in the deep water and along the same depth contour,
(c) *Case 3:* single sound speed profile in the upslope propagation,
(d) *Case 4:* variable sound speed profiles in the upslope propagation, and
(e) *Case 5:* variable sound speed profile in the downslope propagation.

In Case 1 (Fig. 6), a profile in the shallow water was considered and the model was run along the same depth contour up to a range of 36 km. In the case of upwelling [Fig. 6(a), a well-defined ducted propagation with TL < 80 dB was noticed in the upper 8 m water column. Below this layer, a shadow was present (TL > 85 dB). During the period of downwelling, the propagation pattern changed significantly. In this case, the ducted propagation was absent and the entire water column was insonified (<75 dB) up to a range of 20 km. These features can be directly linked to the presence of a shallow isothermal layer during the period of upwelling and fully isothermal condition during the period of downwelling.

In Case 2 (Fig. 7), a profile in the continental shelf was considered, where the depth was 76 m and the model was run along this depth contour up to a range of 36 km. In this case also, during the period of upwelling, a well-defined ducted propagation was noticed in the upper 15 m water column, but with a slightly increased TL compared to the case 1. For example, the 80 dB TL mosaic extended only up to a range of 20 km in the surface layers compared to > 36 km in the first case. Moreover, below this layer, i.e., in the shadow zone, the TL increased to > 95 dB. In the downwelling propagation, the range of full insonification (< 75 dB) reduced to < 15 km. Another notable observation compared to the Case 1 was the appearance of a shadow zone with TL in excess of 90 dB below a depth of 35 m.

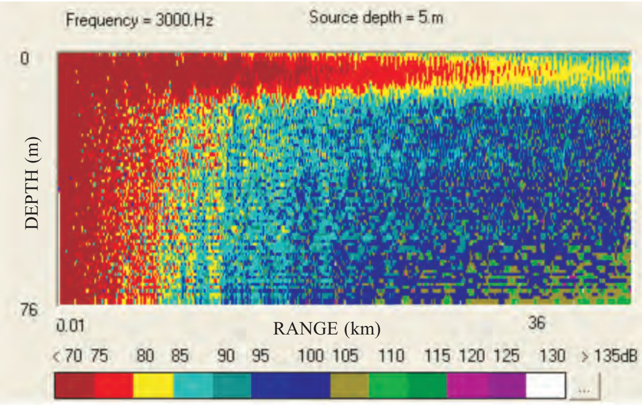
Further, the model was run for the upslope condition considering a single sound speed profile from the off-shore region (Case 3) and the corresponding TL mosaics are presented in Fig. 8. In this case, significant variations were noticed in the TL between the upwelling and downwelling situations. During the period of upwelling, the ducted



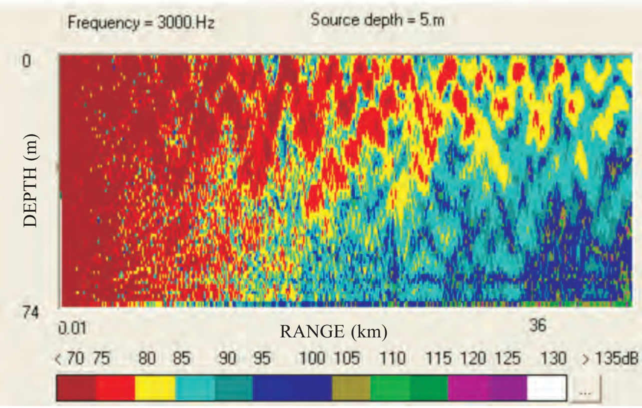
(a)

(b)

Figure 6. Transmission loss variability along the same depth contour during: (a) upwelling and (b) downwelling with single input profile in the shallow water.

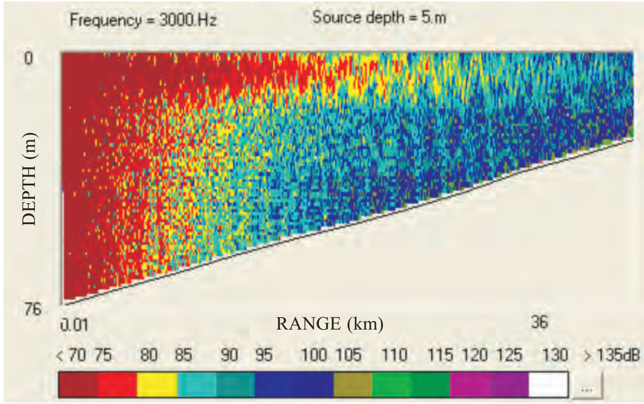


(a)

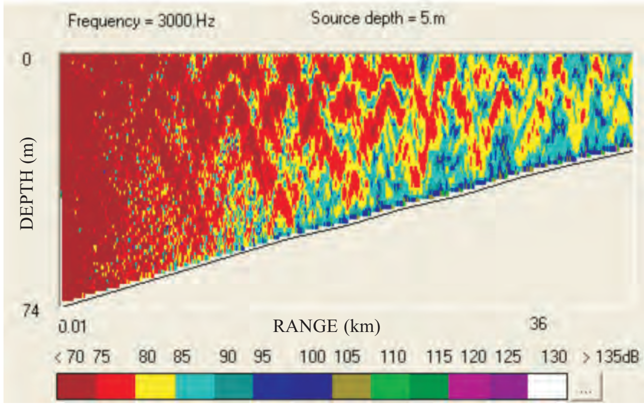


(b)

Figure 7. Transmission loss variability along the same depth contour during: (a) upwelling, (b) downwelling with input profile in the deep water.



(a)



(b)

Figure 8. Transmission loss variability with a single profile in the upslope scenario during: (a) upwelling, (b) downwelling.

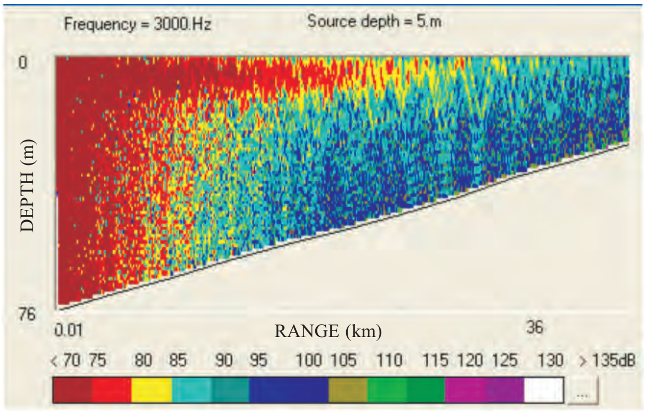
propagation in the surface layer was confined to the upper 15 m, where the TL < 80 dB was noticed only up to a range of 15 km. Beyond this range, the TL increased and at a range of 36 km, the TL was found to be more than 95 dB. As observed in Cases 1 and 2 previous cases, a shadow zone was present in this case also. During the period of downwelling, the entire water column was found to be insonified (< 80 dB) up to a range of < 15 km. Beyond this range, the TL increased to > 85 dB.

In all the above TL runs, only a single profile was considered. The data collected during the periods of upwelling showed large spatial variability, both in the off-shore and alongshore directions. Therefore, the model was further run for the same 3 kHz frequency for the upslope (Fig. 9) and downslope propagation (Fig.10) considering the profile variations with range. During the periods of upwelling [Fig. 9(a)], the TL mosaics pattern appeared to be the same compared to Case 3 but with a different magnitude of TL. On the other hand, during the periods of downwelling [Fig. 9(b)], TL increased in the entire water column (> 85 dB), especially beyond 15 km. A notable observation in this case was the low TL values (< 80 dB) close to the bottom. Increase in TL within the surface layer could be due to the fact that even though the water column was fully isothermal, the sonic layer was very shallow. This is due to the presence of low saline water in the Bay of Bengal in the surface layers near the coast[4,13] has resulted in the formation of a salinity gradient in this region, thereby shoaled the sonic layer.

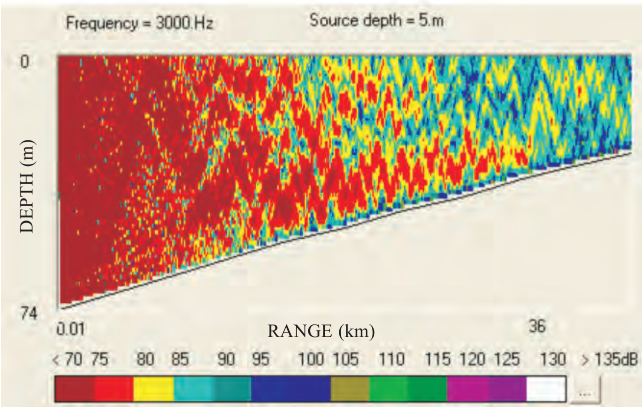
In the downslope scenario (Fig. 10), the ducted propagation in the surface layers became well pronounced and the 80 dB TL contour was extended to more than 25 km. Below the surface duct, a low TL region (< 75 dB) was noticed close to the bottom and was extended up to 15 km. This feature was absent in the range-independent scenario. In the downwelling situation, the downslope propagation was found to be similar to that of the upslope propagation with increased TL.

4. CONCLUSIONS

A fine-resolution spatial survey was carried out off the south-west coast of India during June and December 2004 to study the upwelling and downwelling situations. The period of upwelling was characterised by upsloping of isotherms towards the coast resulting in the disappearance of isothermal layer near the coast. In the slope, downsloping of isotherms below 80 m indicated the presence of undercurrent. On the other hand, the period of downwelling was characterised

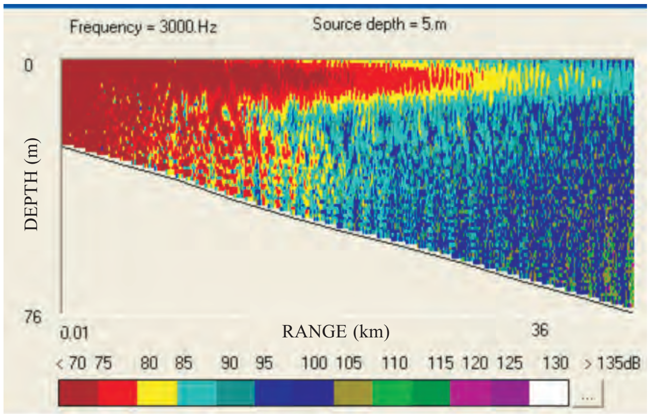


(a)

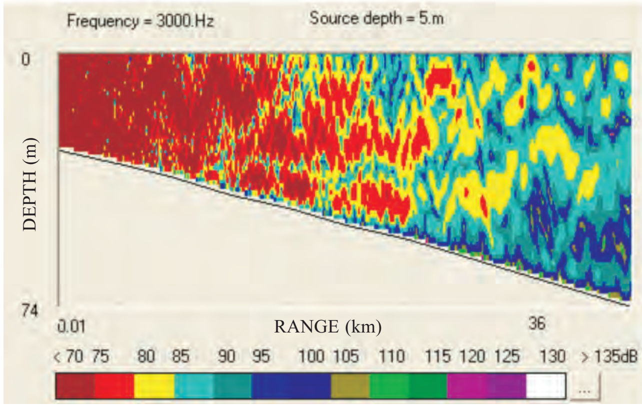


(b)

Figure 9. Transmission loss variability in the upslope scenario with variable profiles during: (a) upwelling, and (b) downwelling.



(a)



(b)

Figure 10. Transmission loss variability in the downslope scenario with variable profiles during: (a) upwelling, and (b) downwelling.

by nearly homogeneous temperature up to the bottom in the continental shelf and upto 60 m in the slope. Between June and December 2004, the surface temperature increased by 1-2 °C and surface salinity by 2 PSU. At the sub-surface levels, the corresponding increase was ~8 °C and ~0.5 PSU.

A range-dependent acoustic propagation model based on parabolic equation method was utilised to study the influence of upwelling and downwelling on the TL variability. The model was run with a source frequency of 3 kHz kept at 5 m depth for different environmental setup. The simulation revealed significant variability in the TL between the two scenarios, though bathymetry and geo-acoustic properties were the same. When a single profile was used in the model along a constant-depth contour during the period of upwelling, a well-defined ducted propagation with TL < 80 dB was noticed in the upper 8 m water column. On the other hand, the entire water column was insonified (< 75 dB) up to a range of 20 km during the period of downwelling. This shows the influence of environmental variability on the propagation characteristics. When the model was run for the upslope condition considering a single sound speed profile from the off-shore region, significant variations were noticed in the TL characteristics between the upwelling and downwelling situations. During the period of upwelling, the ducted propagation in the surface layer was confined to the upper 15 m whereas the water column up to 15 km was insonified during the period of downwelling. The model run was repeated for the upslope scenario considering the profile variations with range. In this case, the pattern of TL variation appeared to be same during the period of upwelling, but its magnitude was found to be different. In the down-slope scenario, the ducted propagation in the surface layers became well pronounced during upwelling and a low TL region (< 75 dB) was observed close to the bottom. On the other hand, TL increased during the period of downwelling. Moreover, the presence of a low TL values (< 80 dB) was observed close to the bottom of the sea.

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