Retraction Notice

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The paper is withdrawn from "Open Journal of Marine Science" due to personal reasons from the corresponding author of this paper.

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The Effects of Internal Waves on Propagation Behavior of Sound in the Sea

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Abstract

The process of generation of internal waves and their propagation mechanism are studied, separately. However, the effect of internal waves on sonic waves behavior is a discussion that has not received much attention in our country. Marine environments are generally stratified by density. This stratification can normally be continuous or step-like. Stratified structure in oceans and seas is important from computations of sound and heat transition in horizontal and vertical directions. Due to existence of some regions in Iranian naval territory which has stratified density and internal waves, it is necessary to study the interaction of these two on sound propagation which can be applied in many purposes. In this research, we have tried to study the effect of internal waves motion on propagation, refraction, and scattering of sonic waves under water and find out how these waves affect sound propagation and point out the parameters that sonic waves are influenced by using Caspian sea data. We compute parameters such as sound speed, buoyancy frequency, displacement variance, relative perturbations in sound propagation associated with vertical displacement and horizontal particle velocity, phase & amplitude function, internal waves phase & amplitude spectrum. In general, $N(z)$ is maximum just below the mixed layer and near the top of the main thermocline. Internal-wave-induced sound velocity fluctuations are concentrated where $N(z)$ is greatest. The phase function N_+ is seen to be monotonously decreasing as β increases. By comparing relative induced perturbations in sound propagation associated with vertical displacement, we find that the latter effect is much smaller. Also, we can see that with increasing depth and decreasing buoyancy frequency, wavenumber and vertical displacement predominantly will be increased. We find a maximum value of buoyancy frequency and induced perturbations in sound propagation associated with vertical displacement in near surface which is due to thermocline, and in this region, we can see the minimum value of vertical displacement.

Keywords

Internal Waves, Sound Speed, Buoyancy Frequency, Displacement Variance, Relative Perturbations

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1. Introduction

Ocean surface is always waving, and we cannot control its shape. In the water column, there are hydrodynamic perturbations: internal wave, large scale turbulence, inhomogeneities of fine structure. Thus, we need use the statistical description of hydrodynamic parameters of ocean such as $\xi(x,y,t)$, random function of space co-ordinates and time with zero mean value, and $\mu(X,z,t)=c(X,z,t)/c_0(z)$, fluctuations of sound speed field in water column [1].

The velocity of sound in the sea is an oceanographic variable that determines many of the peculiarities of sound transmission in the medium. It varies with depth, the seasons, geographic location, and time at a fixed location. In the method yield the expressions for the velocity of sound are in terms of the three basic quantities: temperature, salinity, and pressure. Although these are the only three physical variables, no other physical properties have been found to affect the velocity of sound in sea water, the dependence of velocity on them is by no means a simple one. We can show mixed effects of these with approximation equation [2] [3]:

$$C=1449+4.6t-0.055t^2+0.0003t^3+(1.39-0.012t)(s-35)+0.017d.$$

For sound speed fluctuations, there are also models, for example, Garrett-Munk spectrum of internal waves. Parameters of the models depend on region and season, so that we need carefully test the region of interest to obtain the statistical description of sound speed field inhomogeneities. The sound-velocity fluctuation is related to the vertical displacement by [4] and [5]:

$$\mu(x,y,z,t)\equiv\delta c/c=GN^2(z)\xi(x,y,z,t)$$

where $G=\sigma/g$ depends slightly on ocean regions and on depth and $N(z)$ is Brunt-Wasala (buoyancy) frequency.

$$N^2(r,z)=\frac{-g}{\rho}\frac{\partial}{\partial z}\rho(r,z)=g\left[h\frac{\partial T}{\partial z}-s\frac{\partial S}{\partial z}\right] \quad (1)$$

The quantities h and s are the coefficient of thermal expansion and saline contraction, respectively.

$$\sigma=\alpha(1+dTu)/a(1-Tu)$$
$$d\equiv a/(\beta\alpha b)$$

where $Tu=b\partial_z S/a\partial_z T$ is "Turner number".

On the basis of myriad observations, Garrett and Munk have contrived successive models (GM72, GM75) of internal wave spectra. We use the GM75 spectrum, somewhat modified for the Cairns observations [6] [7]:

$$\langle\mu^2(z)\rangle=\int_f^{N(z)}\mathrm{d}\omega\sum_{j=1}^{\infty}\phi_\mu(\omega,j;z),$$

$$\phi_\mu(\omega,j;z)=\langle\mu^2(z)\rangle G(\omega)H(j)$$

$$G(\omega)=\frac{4}{\pi}\frac{f(\omega^2-f^2)^{\frac{1}{2}}}{\omega^3},\quad \int_f^{N(z)}G(\omega)\mathrm{d}\omega\approx 1.$$

And we have equivalence:

$$\sum_1^{\infty} H(j) = \frac{2}{\pi}\int_0^{\infty} \frac{\mathrm{d}\beta}{\left[1+\left(\frac{\beta}{\beta_*}\right)^2\right]\beta_*} = 1.$$

Therefore, the index of refraction spectrum can be written [8]:

$$\Phi_\mu(\omega,\beta) = 2\times\left(\frac{2}{\pi}\right)^2 \langle\mu^2\rangle f \frac{\left(\omega^2-f^2\right)}{\beta_*\omega^3} \frac{1}{\left[1+\left(\frac{\beta}{\beta_*}\right)^2\right]} \tag{2}$$

$$\langle\mu^2\rangle = GN^2\langle\zeta^2\rangle$$

Here $\langle\mu^2\rangle$ is the mean-square index of refraction at the particular depth under consideration; β_* is a wavenumber given by $\beta_* = t\left(n^2-\omega^2\right)^{\frac{1}{2}}$ where t is a constant characteristic of the internal wave field with values of the order 1 - 2 cpm[1]/Hz.

From measurements one can deduce a vertical wave number spectrum [8]:

$$\phi_\xi(\beta) = \int_f^n \mathrm{d}\omega\phi_\xi(\omega,\beta) \approx \left(\frac{2}{\pi}\right) tn\langle\xi^2\rangle\left[\beta^2+t^2n^2\right]^{-1}.$$

The results of measurements consist typically of time series of amplitude and phase from which various spectra and cross spectra are calculated, but here we act other way. The Fourier transforms of amplitude (χ) and phase (s) given by:

$$\bar{s}(x;\beta,\omega) = (1/2\mathrm{i})\left[\bar\psi(\beta,\omega)-\bar\psi^*(-\beta,-\omega)\right], \tag{3}$$

$$\bar\chi(x;\beta,\omega) = \frac{1}{2}\left[\bar\psi(\beta,\omega)+\bar\psi^*(-\beta,-\omega)\right], \tag{4}$$

or, since $\bar{v}^*(-\beta,-\omega) = \bar{v}(\beta,\omega)$,

$$\begin{Bmatrix}\bar{s}\\ \bar\chi\end{Bmatrix} = 2k\pi\int_0^x \bar{v}(x';\beta,\omega)\begin{matrix}\cos\\ \sin\end{matrix}\left[\frac{\pi\beta^2(x-x')}{k}\right]\mathrm{d}x' \tag{5}$$

The power spectrum of (χ) at range L, $\phi_\chi(L;\beta,\omega)$, is defined by:

$$\begin{aligned}\langle\bar\chi(L;\beta,\omega)\bar\chi(L;\beta',\omega')\rangle &= \phi_\chi(L;\beta,\omega)\delta(\beta+\beta',\omega+\omega')\\ &= (2\pi k)^2\int_0^L \mathrm{d}x'\int_0^L \mathrm{d}x''\langle\bar{v}(x';\beta,\omega)v(x'';\beta,\omega)\rangle\\ &\quad\times\sin\left[\pi\beta^2(L-x')/k\right]\sin\left[\pi\beta^2(L-x''/k)\right].\end{aligned}$$

It is shown in the appendix that index of refraction correlation can be expressed as:

$$\langle\bar{v}(x';\beta,\omega)\bar{v}(x'';\beta',\omega')\rangle = \phi_\mu(\omega,\beta)J_0(2\pi\alpha\chi)\delta(\beta+\beta',\omega+\omega') \tag{6}$$

where ϕ_μ is the power spectral density, such that:

$$\langle\mu^2\rangle = \int_f^n \mathrm{d}\omega\int_0^\infty \mathrm{d}\beta\phi_\mu(\omega,\beta)$$

and

[1]Cycle per meter.

$$\begin{aligned}&\alpha \equiv \beta\left[\left(\omega^2 - f^2\right)/\left(n^2-\omega^2\right)\right]^{\frac{1}{2}}\\ &X = x' - x''\end{aligned} \tag{7}$$

Substituting (7) into (6), changing the variables x', x'' to $X = x' - x'', \zeta = \frac{1}{2}(x' + x'')$ performing the integration over the variable ξ, and proceeding similarly for the spectrum ϕ_s, we obtain:

$$\begin{matrix}\phi_S(\omega;\beta)\\ \phi_\chi(\omega;\beta)\end{matrix} = 4(K/\beta)^4 \phi_\mu(\omega,\beta)\Im_\pm\left(\tilde{L},\Gamma\right) \equiv N_\pm \phi_\mu \tag{8}$$

where:

$$\begin{aligned}&\tilde{L} = \pi\beta^2 L/k\\ &\Gamma = \left(\frac{2k}{\beta}\right)\left[\left(\omega^2 - f^2\right)/\left(n^2-\omega^2\right)\right]^{\frac{1}{2}}\\ &N_\pm \equiv 4(k/\beta)^4 \Im_\pm\\ &\qquad \left(\tilde{L} \pm \cos\tilde{L}\sin\tilde{L}\right)/\Gamma\\ &\Im_\pm = \begin{cases} 2\tilde{L}/\Gamma \\ 2\tilde{L}^3/(3\Gamma) \end{cases} \quad \tilde{L} \ll 1\\ &\qquad \tilde{L}/\Gamma \qquad \tilde{L} \gg 1\end{aligned} \tag{9}$$

If integrate from Equation (8) over all wavenumbers, we can estimate amplitude and phase spectrum as fallow:

$$\begin{matrix}\phi_s\\ \phi_\chi\end{matrix} = \int_0^\infty N_\pm(\omega,\beta)\phi_\mu(\omega,\beta)\,\mathrm{d}\beta \tag{10}$$

We have seen that most of the contributions to the phase spectrum come from the very lowest wave numbers, for which $\tilde{L} < 1$.

Substitute Equations (9), (2) into (10) then we will gain for phase as follow:

$$\varphi_s = \frac{16 f\left\langle \mu^2 \right\rangle K^2 L}{t\pi\omega^3} \ln\left|\frac{\beta^2}{\beta_*^2 + \beta^2}\right|_{\beta\min}^{\beta\max} \tag{11}$$

Proceeding similarly for amplitude, thus:

$$\varphi_x = \frac{16\pi L^3\left\langle \mu^2 \right\rangle f\left(\omega^2 - f^2\right)^{\frac{1}{2}}\left(n^2-\omega^2\right)t}{3\omega^3}\left[\left(\beta^2 + \beta_*^2\right) - \beta_*^2\left[\ln\left(\beta^2+\beta_*^2\right)\right]\right]_{\beta\min}^{\beta\max} \tag{12}$$

In computations of amplitude and phase, choose $L = 15000(\mathrm{m})$ (range between images fixed transmitter and receiver) and $\sigma = 100(\mathrm{Hz})$ (images sound frequency).

To compute maximum and minimum value of β, we use "Richardson number":

$$\begin{aligned}&R_i = (2\pi n)^2/\left\langle U_z^2\right\rangle = \left[24\pi\left\langle \zeta^2\right\rangle tn\beta\right]^{-1}\\ &\left\langle U_z^2\right\rangle = 96\pi^3\left\langle \zeta^2\right\rangle tn^3\beta_{\max}\end{aligned} \tag{13}$$

A measure of the stability of waves is given by the Richardson number and instability is likely to occur if $R_i < 0.25$. Then by using of critical value $(R_i = 0.25)$ for minimum of n, can compute maximum value of β and converse.

The internal wave displacement can be written as [6]:

$$\langle \zeta^2 \rangle = \iint n_0^{-2} \overline{Z^2(z)} E(\alpha, \omega) \mathrm{d}\alpha \mathrm{d}\omega$$
$$\overline{Z^2(z)} = n_0 \left(\omega^2 - f^2\right) / n(z) \omega^2, \quad f < \omega < n(z) \tag{14}$$

where $\overline{Z^2(z)}$ is root-mean-square of normalized wave function.

G&M have proposed the frequency-wave number energy density $E(\alpha, \omega)$ under conditions of a stationary, homogeneous, and horizontally isotropic gravity wave field as follow:

$$E(\alpha, \omega) = 4b^3 n_0^3 E f^2 \mu^{-1} \omega^{-1} \left(\omega^2 - f^2\right)^{-1/2}$$
$$\alpha^{(1)}(\omega) < \alpha(\omega) < \alpha_c(\omega) \tag{15}$$

where

$$\mu(\omega) = j\pi \left(\omega^2 - f^2\right)^{1/2}$$
$$\alpha_c = \mu(\omega) / 2\pi b n_0 \tag{16}$$

Here $\alpha^{(1)}(\omega)$ is the dispersion relation for the lowest order mode, j is the number of propagating modes at the inertial frequency f, and b is the $1/e$ depth defined as the stratification depth. In fitting this spectrum to observation, G&M have chosen $E = 2\pi \times 10^{-5}$ that we also have used same value in our computations.

Defining a displacement spectral density $F_\delta(\omega)$, we have

$$\langle \zeta^2 \rangle = \int F_\delta(\omega) \mathrm{d}\omega \tag{17}$$

or

$$F_\delta(\omega) = \int n_0^{-2} \overline{Z^2(z)} E(\alpha, \omega) \mathrm{d}\alpha \tag{18}$$

Using Equation (14) and Equation (15) and integrating yields

$$F_\delta(\omega) = 2\pi^{-1} b^2 n_0 n(z)^{-1} E \omega^{-3} f \left(\omega^2 - f^2\right)^{1/2} \tag{19}$$

Now from Equation (17), can be given displacement variance as follow:

$$\overline{\zeta^2} = \frac{-2n_0 b^2 E f}{\pi n(z)} \left[\sin^{-1} \left(1 - \frac{f^2}{\omega^2}\right)^{1/2} - \frac{f}{\omega} \left(1 - \frac{f^2}{\omega^2}\right) \right] \tag{20}$$

We find that $b = 37(\mathrm{m})$ and $\omega = 0.5(\mathrm{cph})$ therefore will substitute these values for displacement variance computations.

In what follows for comfort, all frequencies of internal waves are expressed in cycles per hours (cph) and acoustic signals are in Hertz.

Also by following equations, can gain horizontal and vertical ranges [9]:

$$L_H = \frac{\pi (n_0 / f) B}{8 j_* \left[\log(n/f) - \frac{1}{2} \right]} \tag{21}$$

$$L_V = \frac{B n_0 / n}{\pi j_* - 1} \tag{22}$$

In upper relations, B is depth scale.

Setting $f = 0.03780\ \mathrm{cph}\left(37.55^\circ \mathrm{N}\right)$, $n_0 = 21.3377(\mathrm{cph})$, $B = 0.1(\mathrm{km})$, $j_* = 3$ into

Equation (21) and Equation (22), gives the values in Table 1. As showed in the Table, L_H and L_V will be increased when depth increase and buoyancy frequency decrease.

To compute of buoyancy frequency by Equation (1), assume to be have given values as follow and temperature and salinity data of the southern section of Caspian Sea at 37.55˚N latitude and 50.69˚E longitude.

$$a \cong 1.1\times10^{-4}\left({}^{\circ}\mathrm{C}\right)^{-1},\ \alpha \cong 0.96\times10^{-3}\left(‰\right)^{-1}$$
$$b \cong 0.8\times10^{-3}\left(‰\right)^{-1},\ \beta \cong 3.16\times10^{-3}\left({}^{\circ}\mathrm{C}\right)^{-1}.$$

Also, the *rms* horizontal velocity component associated with internal waves (GM75) given by [10]:

$$rms\left(u\right) = rms\left(u_0\right)\left(n/n_0\right)$$

Assuming $u_0 = 4.7\left(\mathrm{cm/s}\right)$, we have done our computations. For comparison, we show typical values from defined equations associated with vertical wave number, rms displacement, vertical displacement and horizontal particle velocity, respectively in Table 2. The last two columns give relative perturbations in sound propagation of vertical displacement and horizontal particle velocity.

2. Conclusions

We find following results from studying and investigation about the internal wave effects on the sound propagation in the Caspian Sea over its southern area.

The model predicts a phase spectrum decreasing like the cube of the frequency, proportional to the square of the acoustic frequency and to the range; the amplitude spectrum similarly behaves like ω^{-3}, but is proportional to the acoustic frequency and to the square of the range.

Table 1. Typical values for buoyancy frequency (n), horizontal (L_H), and vertical (L_V) ranges with j^* = 3, f = 0.03780 cph (37.55˚N), n_0 = 21.3377 (cph), B = 0.1 (km).

	Z (km)	n (rad/s)	n (cph)	L_H (km)	L_V (km)
Thermocline	−0.02	3.72E−02	21.3337	3.29	0.01
	−0.075	8.24E−03	4.7236	4.59	0.05
	−0.5	1.56E−03	0.8936	8.40	0.27
Bottom	−0.8	9.45E−04	0.5417	11.18	0.46

Table 2. Typical values associated with vertical wave number, rms displacement, relative perturbations in sound propagation of vertical displacement and horizontal particle velocity.

	Z (km)	β (cpm)	n (cph)	$rms\ \zeta$ (m)	$rms\ \mu = rms\ \delta c/c$	$rms\ u/c$
	−0.02	3.21	21.3337	0.177	6.86E−04	3.1E−05
Thermocline	−0.075	14.5	4.7236	0.801	1.40E−05	6.87E−06
	−0.5	76.59	0.8936	4.23	9.30E−06	1.3E−06
Bottom	−0.8	143.06	0.5417	8.69	1.88E−06	7.88E−07

If the spectral distribution of the internal-wave field is random, the phase and amplitude will also be random. Thus, while both amplitude and phase spectra are random, phase information is simply related to causative environmental parameters, but amplitude is not.

The functions $N_\pm$ are plotted on **Figure 1**. The phase function N_+ is seen to be monotonously decreasing as β increases. The corresponding amplitude factor, N_-, has a maximum around $\tilde{L}=1$ ($\beta=(k/\pi L)^{1/2}$) and, for larger wavenumbers becomes equal to N_+ (**Figure 2**).

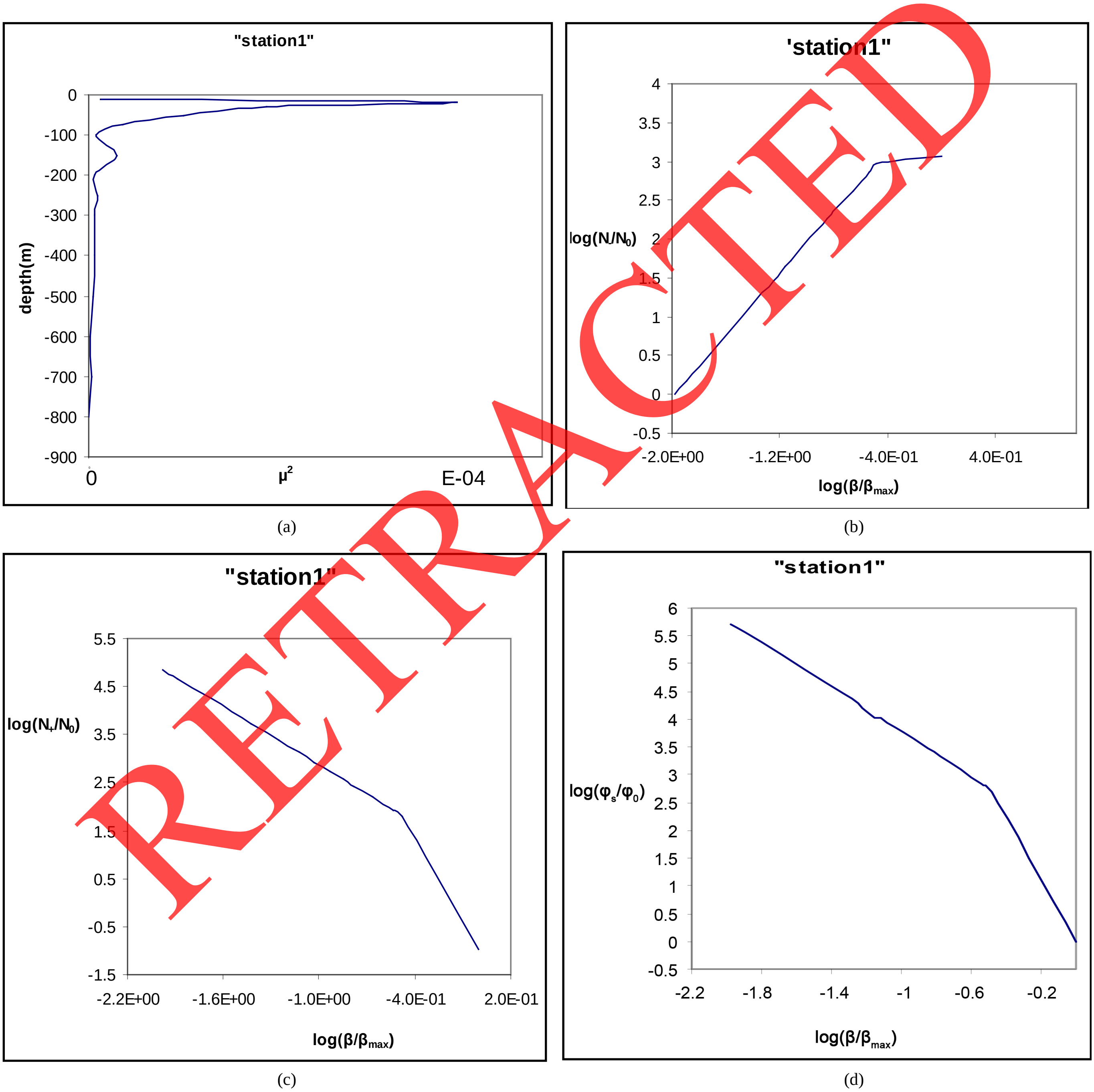

Figure 1. (a) Induced perturbations by internal waves in the vertical speed. (b)-(c) The amplitude and phase functions defined by Equation (11) and (12), respectively. (d) The phase-wavenumber spectrum.

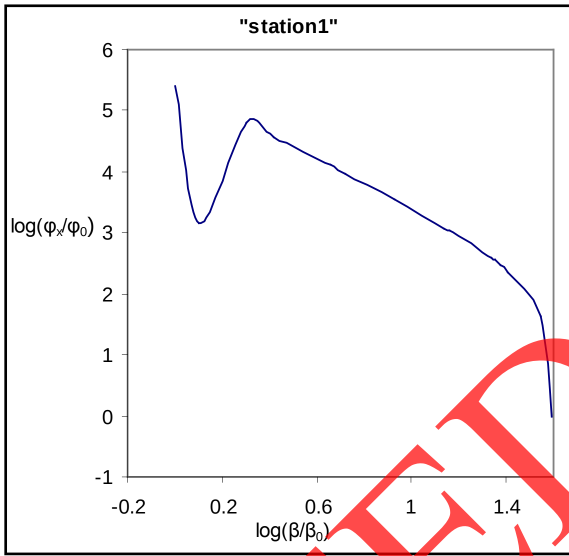

Figure 2. The amplitude-wavenumber spectrum.

The phase fluctuations are overwhelmingly dominated by the lowest mode of internal waves. Most of the contributions to the phase spectrum come from the very lowest wave numbers, for which $\tilde{L} < 1$.

By comparing relative induced perturbations in sound propagation associated with vertical displacement, we find that the latter effect is much smaller (except in very deep water), then they can be ignored. On the other hand, the u effects dominate at and below inertial frequencies, so that planetary waves with their quasihorizontal particle motions affect sound transmission. Also, we can see that with increasing depth and decreasing buoyancy frequency, wavenumber and vertical displacement predominantly will be increased. We find a maximum value of buoyancy frequency and induced perturbations in sound propagation associated with vertical displacement in near surface which is due to thermocline, and in this region, we can see the minimum value of vertical displacement. In general, $n(z)$ is maximum just below the mixed layer and near the top of the main thermocline. Near the surface, stability is quite variable.

The rms vertical wave displacement increases with depth as $n^{-1/2}$. Thus, from Equation $\mu = n^2(z)\zeta\sigma/g$, sound velocity fluctuations increase with depth as $(n^{3/2})$. Therefore, internal-wave-induced sound velocity fluctuations are concentrated where $n(z)$ is greatest, *i.e.*, in the main and seasonal thermoclines because there, we have maximum value of density changes. Thus, internal waves occur in this region with maximum frequency and minimum period (Figure 3).

In the velocity profile, we can see that just below the sea surface is the surface layer, in which the velocity of sound is susceptible to daily and local changes of heating, cooling, and wind action. The surface layer may contain a mixed layer of isothermal water that is formed by the action of wind as it blows across the surface above. We can see thermocline existence both in thermocline graphs and in the speed profiles as a negative thermal or velocity gradient (temperature or velocity decreasing with depth). Below the thermocline and extending to the sea bottom is the deep isothermal layer having a nearly constant temperature near 5˚C, in which the velocity of sound increase with depth because of the effect of pressure on sound velocity (Figure 4).

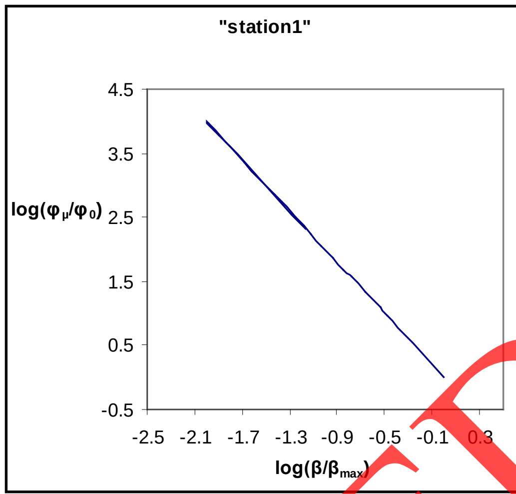

Figure 3. Internal wav-wavenumber spectrum.

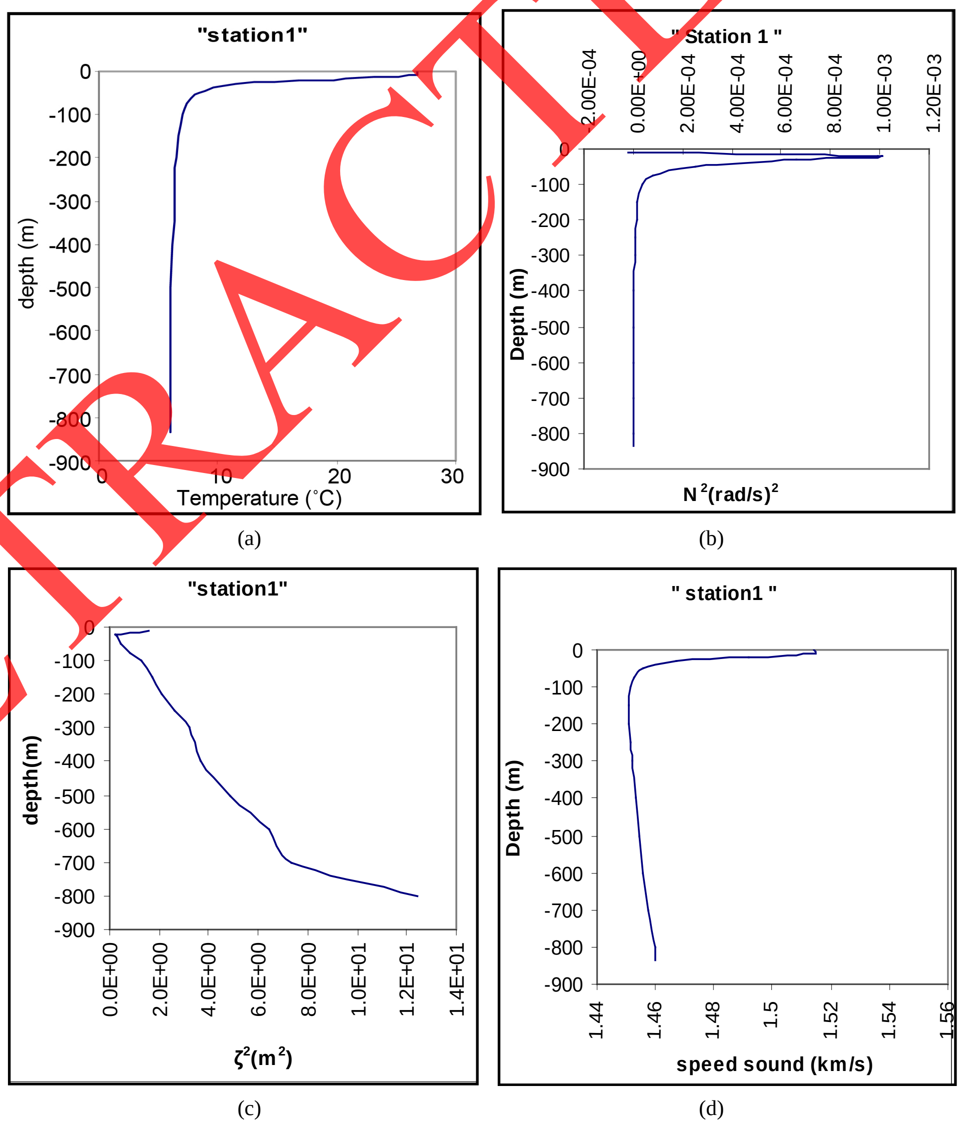

Figure 4. (a) Thermocline graph. (b) Depth-dependent buoyancy frequency. (c) Sound-speed profile as a function of ocean depth. (d) Depth-dependent vertical displacement square.

In the shallow waters of coastal regions, the velocity profile is greatly influenced by surface heating and cooling, salinity changes, and water currents. The occurrence and thicknesses of these layers vary with latitude, season, time of day, and meteorological conditions. The shallow-water profile is complicated by the effects of salinity changes caused by nearby sources of fresh water.

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