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Internal Tides in the Coastal Waters of NE Arabian Sea: Observations and Simulations

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Time series of temperature and salinity collected from a station in the NE Arabian Sea during March, April, May, October, and November was utilized to explain the behavior of internal tides. Analysis revealed the existence of semi-diurnal internal tides and high frequency (HF) internal waves (IW). It was observed that the amplitudes of HF IWs were determined by the degree of stratification in the thermocline. Corresponding to an increase in the density gradient in thermocline (0.016 kg/m³ in April to 0.14 kg/m³ in October), the temperature fluctuations due to internal tides increased from <0.2°C to >1.5°C, respectively. Brunt-Väisälä frequency also showed similar variations (~10 cph to 22 cph). Within the thermocline, semi-diurnal internal tides caused fluctuations of >10 m in the isotherm depths. A linear regression equation was fitted to parameterize the amplitude of HF IWs and its upper frequency limit in terms of thermocline gradient. The IW and one-dimensional models simulated the presence of internal tides and diurnal cycling in the temperature field, respectively. Coupling of these models showed improvement in the simulation of temperature.

Keywords Internal tides, one-dimensional and internal wave model, coupled model

1. Introduction

Internal waves with tidal periodicity are quite ubiquitous in the stratified waters over continental shelf. These waves occupy a vast continuum of spatial and temporal scales (Garrett and Munk 1972, 1975), with horizontal scales ranging from few tens of meters to few kilometers and temporal scales from inertial to local Brunt-Väisälä frequency. In the deep ocean, internal wave spectrum is consistent everywhere, except in regions, close to the source of generation. Based on the field measurements, Garrett and Munk (1975) developed an energy-frequency spectrum, popularly known as the Garrett-Munk (GM) spectrum. As this spectrum model was formulated based on a considerable amount of observations, it was well accepted by the scientific community. The main assumption here is that the distribution of energy over modes and frequencies are independent of each other. This spectrum model provides the distribution of waves in frequency–wavenumber domain. It also considers the
fact that there exists a frequency-wavenumber distribution that appears to be “universal” in space and time. The limitation of this model is its genesis developed mainly based on the data collected from deep water.

In the coastal and deep waters of the Indian seas, internal tides are prominent and cause large variability in the thermo-haline fields, which have been reported by several researchers including LaFond and Rao (1954), LaFond (1961), Antony et al. (1985) Murthy and Hareesh Kumar (1990), Sarma et al. (1991), Murthy (2002), Unnikrishnan and Antony (2004), Krishnakumar and Balasubramaniam (2005), and Hareesh Kumar et al. (2006). The studies, though limited, were mostly confined to the internal tides, which may be due to the lack of sufficient fine temporal resolution data. Hence, specific experiments were conducted at a location in the shallow water, and fine resolution data is collected to study the characteristics of these internal tides. Moreover, the efficacy of a merged model, based on the GM spectrum internal wave model and the one-dimensional model of Price, Weller, and Pinkel (1986) in simulating the temporal evolution of temperature profiles in this region, was also investigated.

2. Data

Short time-series measurements (3–5 hrs with sampling interval of 5–10 min duration) of temperature and salinity profiles were carried out from a station in the continental shelf of the northeast coast of India (22° 8.226′N and 68° 37.450′E, bottom depth ≈ 52 m) during the periods March 2003, April 2003, May 2002, October 2002, and November 2002. In addition, a vertical array of temperature sensors at selected depths (sampling interval 10 s) was moored within the close vicinity of the time series station (~5 km away) to capture and delineate the internal tide characteristics. In simulating the temporal evolution of temperature profiles, two models were considered, the GM spectrum model and the one-dimensional model of Price, Weller, and Pinkel (1986), hereinafter referred to as PWP for simulating the vertical temperature profiles. The vertical displacements for different modes of internal waves were simulated utilizing the GM model. Then PWP was utilized to simulate the temporal evolution (for a period of 48 hrs) of the vertical temperature and salinity profiles. Finally, the vertical displacement obtained from the GM model for different modes were incorporated in the simulated temperature profiles as a function of time. The data collected during the field campaign in November were utilized to validate the coupled one-dimensional and internal wave model.

2.1. The GM Model

The dispersion relation for the internal waves in the density stratified rotated ocean (Gill 1982) can be represented as:

$$\frac{d^2 W_{\omega,j}(z)}{dz^2} + k^2 \left[ \frac{N^2(z) - \omega^2}{\omega^2 - f^2} \right] W_{\omega,j}(z) = 0 \quad 0 \leq z \leq H$$

(1)

Here, $H$ is the water column depth, $f$ is the inertial frequency ($f = 2\Omega \sin \phi$), $\Omega$ is the angular frequency, $\phi$ is the latitude, and $N$ is the buoyancy frequency (popularly referred to as Brunt-Vaisala frequency), defined as:

$$N(z) = \left( -\frac{g}{\rho} \frac{d\rho}{dz} \right)^{1/2}$$

(2)
where \( g \) is the gravitational acceleration and \( \bar{\rho} \) the mean density of the medium. This equation is solved using the boundary conditions \( W_{\omega,j}(0) = W_{\omega,j}(H) = 0 \) to obtain the normal modes. As each frequency \( \omega \) has its own set of depth dependent vertical modes \( W_{\omega,j}(z) \), where \( j \) indicates the number of mode, the vertical displacement of the linear internal wave field is finally expressed as a combination of plane waves as a weighted sum over mode number \( j \) and frequency \( \omega \) in the form:

\[
\xi(x, z, t) = \int_0^N \sum_{j=1}^{\max} A(\omega, j) W_{\omega,j}(z) e^{i(k_{\omega,j} x - \omega t + \psi)} d\omega
\]  

(3)

Here \( A(\omega, j) \) is the \( j^{th} \) mode amplitude associated with GM spectrum and \( k_{\omega,j} \) the corresponding wave number, \( x \) the range, \( t \) the time, and \( \psi \) the phase. The amplitude \( A(\omega, j) \) in Eq. (3) is expressed in terms of the GM spectrum (Saunders and King 1991) as:

\[
A(\omega, j) = \left[ 2 r B(\omega) H(j) \int_0^H N(z) dz \right]^{1/2}
\]  

(4)

where \( r \) is an energy parameter dependent on the season and location. The parameters \( B(\omega) \) and \( H(j) \) of GM model as advocated by Jackson and Elliott (2002) can be represented as:

\[
B(\omega) = \frac{2 f}{\pi \omega \sqrt{\omega^2 - f^2}} \int_f^{N_{\max}} B(\omega) d\omega = 1
\]  

(5)

\[
H(j) = \frac{(j^2 + j_0^2)^{-\frac{\pi}{2}}}{\sum_{j=1}^{M} (j^2 + j_0^2)^{-\frac{\pi}{2}}} \sum_{j=1}^{M} H_M(j) = 1
\]  

(6)

\( M \) and \( H_M(j) \) indicate the finite number of modes. If few modes are used, the relative energy distribution between the lower order modes changes significantly. As a corrective measure, the modal bandwidth parameter \( j_0 \) is chosen to depend on the number of modes \( M \).

\[
j_0 = \begin{cases} 
1, & M \leq 2, \\
2, & M = 3, \\
3, & M \geq 4.
\end{cases}
\]  

(7)

The vertical displacement \( \xi(x, z, t) \) is modified by the sum over a finite number of modes and frequencies. In this case, we postulate 15 sets of frequencies encompassing the range between inertial frequency \( f \) and the maximum buoyancy frequency \( N_{\max} \). For each frequency, Eq. (1) is solved for a number of \( M \) modes (Elliot and Jackson 1998), which are denoted by \( W_{\omega,j}(z) \). Integral over frequencies was approximated by the sum and phase independent \( e^{i(k_{\omega,j} x - \omega t)} \) is approximated by \( \sin(k_{\omega,j} x - \omega t) \) to obtain the final expression for the vertical displacement as a function of range, depth, and time.

\[
\xi(x, z, t) = \sum_{\omega = f}^{N_{\max}} \sum_{j=1}^{M(\omega)} A(\omega, j) W_{\omega,j}(z) \sin(k_{\omega,j} x - \omega t) \sqrt{\Delta \omega}
\]  

(8)

The term \( \sqrt{\Delta \omega} \) is obtained from the approximation of the integral by summation.
Eq. (1) is solved to obtain the exact dispersion relations of the internal wave field. The internal wave modes are normalized so that

$$\int_0^H \left( \frac{N^2(z) - \omega^2}{\omega^2 - f^2} \right) W_i(z) W_j(z) dz = \delta_{ij}$$

(9)

The weight function \(\left( \frac{N^2(z) - \omega^2}{\omega^2 - f^2} \right)\) can be both positive and negative depending on the buoyancy frequency profile \((N)\) and the frequency at which the equation is being solved. Therefore, the conventional methods like shooting can lead to instabilities and hence fail. Hence an alternative numerical scheme that is robust and reliable has been used here (Krishnakumar and Balasubramaniam 2005).

A finite difference approximation of the eigen-value problem in Eq. (1) is obtained by dividing the interval \([0, H]\) into \(N\) parts of size \(\Delta z = H/N\). Hence Eq. (1) can be expressed as

$$\frac{d^2 W(z)}{dz^2} + \lambda b^2(z) W(z) = 0 \quad 0 \leq z \leq H$$

(10)

where \(W(0) = W(H) = 0\), \(b^2(z) = \left( \frac{N^2(z) - \omega^2}{\omega^2 - f^2} \right)\) and \(\lambda = k^2\). By defining \(b^2_n = b^2(n\Delta z)\) and \(W_n = W(n\Delta z)\) for \(n = 0, N\) and applying the three-point central differencing to Eq. (10), we obtain:

\[
[-W_{n+1} + 2W_n - W_{n-1}] = \lambda \Delta z^2 b^2_n(z) W_n, \quad n = 1, \ldots, N
\]

(11)

where \(W_0 = W_N = 0\) is the boundary condition. A matrix of the form \(AW_n = \lambda_m W_n\) is obtained from Eq. (11). Here \(\lambda_m\) is the mth eigen-value of \(A\), \(W_m\) is the \(N \times 1\) eigenvector approximating the mode function, and \(A\) is the \(N \times 3\) nonsymmetric tri-diagonal matrix. The diagonal entries in the tri-diagonal matrix \(A\) are \(A_{i,i} = -\frac{2}{b_i(\Delta z)}\) while the entries in the super-diagonal and sub-diagonal are \(A_{i,i+1} = \frac{1}{b_i(\Delta z)}, \quad A_{i,i-1} = \frac{1}{b_i(\Delta z)}\), \(i = 1, 2, \ldots, n - 1\), respectively.

The eigen-values and eigenvectors are found using the QR technique (Press et al. 1999), which is robust and stable. The QR techniques means a matrix is first is written as two matrixes called Q and R, where Q is an orthogonal matrix and R is an upper triangular matrix and solved them for eigen values and vectors. The eigenvectors on the depth grid are thereby estimated and normalized using Eq. (9) to obtain the internal wave modes.

3. Results and Discussion

An essential prerequisite for the formation of internal tide is presence of a highly stratified layer. As the degree of stratification varies both spatially and temporally, characteristics of these internal tides also exhibit variability in these scales. Moreover, the degree of stratification in the thermocline determines the Brunt-Vaisala frequency \((N)\), which is considered the upper frequency limit of internal waves. Therefore, it is essential to first study the evolution of vertical stratification before investigating the details of internal tides.

The density of water column was calculated from the in situ temperature and salinity records collected from time series measurements at station during the periods April, May, October, and November, and the mean profile is presented in Figure 1a. The evolution of the pycnocline, where maximum density gradient occur, can be clearly seen in this figure. During April, the surface density was \(\sim 1023.8\) kg/m\(^3\) and increased with depth to slightly above 1024.6 kg/m\(^3\) close to the bottom (variation of 0.8 kg/m\(^3\) within 50 m). During the
month of May, increased surface heating resulted in decrease of the surface density (1023.4 kg/m³), while at the subsurface levels, not much change was observed. During this period, a pycnocline of 10 m thickness (variation of 0.7 kg/m³ within 10 m) was found sandwiched between weakly stratified upper and bottom layers. This type of vertical structure was named as tri-layer structure and was common in the Indian coastal waters (Hareesh Kumar et al. 2005, 2006). During October, even though change in density of surface layers was only marginal, the subsurface density increased to more than 1025.6 kg/m³ thereby increasing the pycnocline gradient (∼2.1 kg/m³ within 15m). As a result, the tri-layer structure is prominently evident. The decrease in density at the sub-surface levels (1025 kg/m³) during November resulted in the reduction in pycnocline gradient compared to October. Moreover, the initiation of winter cooling resulted in the deepening of pycnocline up to 30 m.

The degree of stratification can be explained in terms of the stability parameter E (\( E = -\frac{1}{\rho} \frac{\partial \rho}{\partial z} - \frac{g}{c^2} \)), where \( \rho \) is the average density, \( \frac{\partial \rho}{\partial z} \) is the vertical density gradient, \( g \) is the acceleration due to gravity, \( c \) is the sound speed, and \( z \) is the depth) (Pond and Pickard 1986). In this study, \( E \) was estimated utilizing short time series measurements of temperature and salinity profiles collected from the location (5–10 min sampling interval for 4–5 hrs) during April, May, October, and November, which is shown in Figure 2.

A notable observation from the depth-time sections of the stability parameter (Figure 2) is the presence of highly stratified layer sandwiched between weakly stratified upper and bottom layers. In general, the water column was statically stable during all the four months with a varying stratification, as indicated by the positive value of the stability parameter (\( E > 0 \)). Hence, a parcel of water displaced a short distance vertically will try to return back to its original position. During April, even though the water column was weakly stratified, a peak in \( E \) was noticed around 45 m (∼ > 10 × 10⁻⁵/m). With the progress of time, the vertical stratification in the water column gradually increased, as indicated by the values of \( E \) greater than 10 × 10⁻⁵/m centered at 20 m depth in May (∼5 m thickness) and 15 × 10⁻⁵/m centered
at 15 m depth in October (∼10 m thickness). The vertical migration of the region to shallower depths corresponding to maximum stratification between April and October (10 m in April to 45 m in October), can be attributed to the dominant mechanism of upwelling prevailing in this region. Beyond October, this stratified layer was noticed migrating to deeper depths, that is, from 15 m during October to more than 30 m in November, with a considerable reduction in the vertical gradient. The deepening of this stratified layer can be attributed due to the downwelling process, which is a well-established process in the northeastern Arabian Sea during winter months. The presence of this thin and highly stratified layer at this location between May and October was very much conducive for the formation of internal waves. Here, it is worthwhile mentioning that in the north-eastern Arabian Sea, salinity is very high (>36 PSU) in the entire water column and its variability both in the vertical and temporal scales are very less compared with that of temperature. Hence, the density (or the vertical stratification) depends more on temperature rather than salinity.

The vertical profiles of temperature and salinity collected during these periods were utilized to compute the mean profiles of Brunt-Väisälä frequency $N (N^2 = gE$, where $g$ is the acceleration due to gravity and $E$ is the stability parameter) for each month. The depth where maximum value of $N$ occurred (Figure 1b) coincided with the region of maximum stratification (Figure 2). In general, $N$ varied from ∼10 cph (6 min) during the periods of weak stratification (in April) to values over 22 cph (2.7 min) when stratification was maximum (in October). This suggests a direct relationship exist between $N$ and stratification, that is, increase/(decrease) of $N$ with increase/(decrease) in stratification. Moreover, it can also be seen that when the stratification is maximum, internal waves with minimum periodicity (2.7 min or 22 cph) are formed in this region and vice versa.

Internal waves can be better resolved utilizing data from moored sensors having high-resolution sampling intervals. The short time series data (∼7 hrs at 10 sec sampling interval) collected from these sensors moored in the thermocline region during April, May, October, and November (Figure 3) indicate periodic fluctuations in the temperature field with varying magnitudes. The observed temperature fluctuations per unit distance were in the order of 0.2°C in April and May, 1–2°C in October, and 0.5–1°C in November. On comparing with the stability parameter $E$ (Figure 2), it can be seen that minimum amplitude in
temperature fluctuations (in April) coincided with the periods of minimum stratification in the thermocline region and vice versa.

From the above analysis, it can be inferred that there exists a direct relationship between (i) the degree of vertical stratification and the amplitude of high frequency internal tides and (ii) the degree of vertical stratification and maximum $N$, as expected. To highlight this, the scatter diagrams between (i) thermocline gradient versus the amplitude of internal tides (Figure 4a) and (ii) thermocline gradient versus $N$ (Figure 4b) are presented. In both the

![Figure 3. Time series of temperature variations in the thermocline at the time series station during April, May, October, and November.](image)

![Figure 4. Scatter diagram between (a) gradient in the thermocline versus amplitude of internal wave and (b) gradient in the thermocline versus Brunt-Väisälä frequency ($N$).](image)
cases, a good relationship was noticed, as indicated by the coefficient of determination 0.98 and 0.95, respectively. Moreover, it can be advocated that the Brunt-Vaisala frequency, N increased with increase in the thermocline stratification. One of the notable observations was that, when the gradient was less than 0.1°C/m, amplitudes of the internal tides were found to be near zero (Figures 3, 4a) with a coefficient of determination less than 0.4. However, for gradients greater than 0.16°C/m, a well-defined linear relationship was evident; that is, the amplitudes of internal tides increased with increase in the thermocline gradient.

An attempt was made to fit a linear equation with amplitude as independent value (A) and thermocline gradient as dependent value (G) by considering 67 data points (Figure 4a). The respective equations finally obtained can be expressed as:

\[
A = 1.020 \times G + 0.74; \text{ for } G > 0.16°C/m \quad (12)
\]

\[
A = -0.055 \times G + 0.034; \text{ for } G < 0.10°C/m \quad (13)
\]

It is found the buoyancy frequency (N) also increased with increase in the thermocline gradient indicating a very good linear relationship (Figure 5b). N was found to be less than 14 cph (4 min) when the gradient was weak (<0.16°C/m), whereas for gradients greater than 0.4°C/m, the value of N increased to more than 20 cph (<3 min). Also in this case, a linear equation was fitted based on the observed gradient and N utilizing 67 data points (Figure 4b). The obtained resulting equation was:

\[
N = 21.58 \times G + 11.13 \quad (14)
\]

To verify the efficacy of the above equations, an independent data set was utilized. A good match was noticed between the observed and estimated amplitude of internal waves and maximum Brunt-Vaisala frequency. However, as the number of data points utilized to fit the regression equations listed above was less, an extensive validation campaign has to be carried out to assess the performance of the above regression equations before they are put into use.

3.1. Solitons

"Internal solitary waves" or "solitons" are ubiquitous wherever strong tides and stratification occur over an irregular topography. These waves are a class of nonsinusoidal, nonlinear, isolated waves of complex shape that occur frequently in nature. Solitons occur in stratified coastal waters as groups or packets of oscillations, with the number of cycles varying from a few to a few dozen, depending on time and distance from the generation point. They are usually produced by tidal currents flowing normal to the local bathymetry (An Atlas of Oceanic Internal Solitary Waves 2002). These wave groups are generated approximately every 12 hrs during the spring tide phase of the fortnightly (14-day) tidal current. During the neap tide phase, they are often absent. Apel (1979) noticed the occurrence of internal waves of high energy packets at regular interval of time in the Andaman Sea with spatial velocity scales much larger than that in the continental shelf of New York. Many experiments were conducted (Osborn and Burch 1980; Apel et al. 1985; New and Pingree 2000) at various locations to establish the nature of these waves and delineated some of its properties. Korteweg and deVries (1895) derived some of the mathematical properties of these waves and developed the soliton solutions. Even though, many theories are available in literature on the generation of these solitons (Apel et al. 1985), the exact mechanisms that generate these waves are not understood, even today.
Figure 5. Time series of (a) observed temperature from thermocline during November, (b) low frequency filtered using Wavelet decomposition technique, (c) sorted for 6 hrs from (b), (d) sorted for 1 hr from (c), and (e) sorted for 30 min from (d).

High-resolution (10s sampling interval) data collected from a shallow water mooring site at the continental shelf in the northeast coast of India for a period of 48 hrs (Figure 5) indicated the dominance of internal waves with semi-diurnal (∼12 hrs) and diurnal (∼24 hrs) tidal periodicities in the temperature field. In addition, many high frequency components were also observed. From this figure it can be seen that internal tides caused fluctuations in the order more than 3°C in the temperature field, while it was less than 0.4°C in the case of internal waves with less than tidal periodicity. The figure also revealed the presence of many high energy pockets with large amplitude temperature oscillations that appear and disappear (Figure 5b) at regular intervals of time. These pockets were found overriding the internal tides.

To separate out the high frequency internal waves from the tides dominated original data, wavelet decomposition technique was utilized. These high energy pockets resembled the soliton suggested by several researchers. These high frequency packets caused
fluctuations of $\sim 0.4^\circ\text{C}$ in the temperature field. On further investigating these packets, it was found that one group contains many smaller packets (Figures 5c–e). Using the decomposition technique and sorting for 30 min, we find 5 such packets were obtained. The frequency of this oscillation coincided with the Brunt-Vaisala frequency at that location, $\sim 12 \text{cph}$. Further decomposition at higher time intervals do not show the presence of any such events. This suggests that the maximum frequency at which these events exist is the Brunt-Vaisala frequency. Another interesting and notable observation is that each soliton packet was made up of many such soliton packets with $N$ as the maximum frequency. This study improves the overall understanding of the existence of solitons in shallow waters and signifies their importance in thermo-haline fields.

3.2. Simulation of Internal Tides Using Coupled Model (PWP and GM Spectrum)

Two models were utilized to simulate the temporal evolution of temperature profiles. The first one is the GM spectrum model for simulating the internal tides and the second is the one-dimensional PWP model for simulating the temporal evolution of vertical temperature profiles. In the PWP model, short-term variability in temperature due to one-dimensional forcing and different mixing processes based on Richardson number criteria was well accounted. In the GM model, the amplitudes associated with the GM modal spectrum and corresponding vertical displacements were computed from the initial temperature profile. These two individual models were coupled for a better simulation of temperature profiles that included the upper ocean mixed layer processes and subsurface internal wave phenomena. During the process of coupling, simulated amplitudes and vertical displacements of internal waves were imposed on PWP simulated profiles to generate the final temperature profiles, which include both the mixed layer and internal wave dynamics.

The vertical temperature profiles collected from the stationary location during November (for a period of 48 hrs at 5-min sampling intervals) is presented as composite anomaly profiles (Figure 6a). The figure indicate minimum spread in temperature within the surface mixed layer ($<0.75^\circ\text{C}$), that is, in the upper 25 m, and large spread in the thermocline

![Figure 6](image_url). Composite temperature anomaly profiles of (a) measurement and (b) simulated using merged GM and PWP models.
Figure 7. Depth-time section of temperature obtained from (a) ground truth measurement and (b) coupled GM and PWP models.

region (>2°C at 35 m depth), which suggest that the internal tide activity was mostly confined to the thermocline region. As the sampling interval was high, the larger spread can be attributed to the prevailing internal tides (Figure 7a). When the GM model was run independently, the simulated profiles showed large spread in the thermocline but could not reproduce the temperature variability within the surface mixed layer as observed in the case of in situ profiles. This can be attributed due to the fact that within the surface layers, variability on a short time scale is controlled mainly by the air-sea interaction processes rather than due to internal waves. In the second run we utilized the PWP model, where suitable one-dimensional physical parameterization for the temperature variability on a short time scale was incorporated. In this case, the model was able to capture the diurnal cycling in the surface layers, which the GM could not reproduce. However, in this case the model failed to capture the variability in the thermocline zone. Keeping this under consideration, for the third run the PWP model was coupled with the GM model, and the simulation was again carried out (Figure 6b). In this case, significant improvement was noticed in the simulated temperature profiles both in the surface mixed layer as well in the thermocline.

In order to have a better presentation, the depth-time sections of the observed and simulated temperature profiles using the coupled model are presented in Figure 7. It is well known that the thermohaline variability in the coastal waters of the northeastern Arabian Sea, India, is influenced by the tides. This can be clearly seen from the observed temperature field, which clearly demonstrates the dominance of internal waves with tidal periodicity (12 hrs) in the thermocline zone. These internal tides caused fluctuations of more than 10 m in the depth of isotherms.

The simulated results indicated that diurnal cycling in the surface layers and the rhythmic oscillations in the thermocline was well simulated through numerical experiment. It could be emphasized here that the coupled model could capture the diurnal scale variability within the surface homogeneous layer, where the one-dimensional process are significant and also the temperature fluctuations due to internal waves in the thermocline zone, with a reasonable degree of accuracy. The analysis suggested that the coupled PWP and GM model provided a better simulation of the temperature variability rather than using GM and PWP models in isolation.

The dynamics in the Indian coastal waters, especially off the northeast coast of India, are highly complex. Even then, the coupled model was able to simulate the diurnal variations in temperature profiles both in the surface layer and the thermocline region reasonably well;
the results obtained are quite encouraging. Smaller differences noticed in the simulated profiles could be attributed due to the lack of proper physical parameterization other than the local processes.

4. Conclusions

Short time series data collected from a location in the shallow waters of the northeastern Arabian Sea during different months are utilized to demonstrate the temporal variability of the internal wave characteristics. The results signify that the degree of stratification in the thermocline determined the characteristics of high frequency internal waves. Amplitudes of these internal waves increased with the increase in thermocline gradient and vice versa. A linear regression equation was fitted to parameterize the amplitude of internal waves and its upper frequency limit based on the thermocline gradient. This regression equation can be used to estimate directly the amplitude of internal waves and the Brunt-Vaisala frequency from a single temperature profile. In this study we notice many high energy pockets emerging and vanishing periodically at regular intervals, which cause large amplitude temperature oscillations (~0.4°C). These high energy pockets were found to override over the internal tides. It was also seen that that the maximum frequency at which these events are possible is the local Brunt-Vaisala frequency. Two models, the GM spectrum model and the one-dimensional PWP model, were utilized to simulate the temporal evolution of temperature profiles. The observed temperature field clearly indicate the dominance of tidal activity (~12 hrs ~24 hrs periodicity) prevalent in this region. In the thermocline region, the semi-diurnal internal tides induced fluctuations of more than 10 m is evident in the depth of isotherms. The PWP model and the GM model were separately run to simulate the temporal evolution of the temperature field. The GM model was able to simulate internal tides in the thermocline region reasonably well, whereas the PWP model was able to reproduce the diurnal cycling in the temperature field, especially within the mixed layer. On coupling these two models, the results improved significantly in simulating both the surface mixed layer and processes in the thermocline region. However, the lack of proper physical parameterization, such as advection, remote forcing, and so forth, in the coupled model led to small differences between the observed and simulated profiles. Although coastal waters off the northeast coast of India are well known for their complexity, this coupled model could simulate well the diurnal scale variability in the temperature field with a reasonable degree of accuracy.

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References


