Bay of Bengal is characterised by a seasonally changing thermocline depending on monsoon winds and circulation. Vertical and horizontal eddy mixing play an important role in the upper layer dynamics. Mean seasonal (north east monsoon) eddy coefficients (Kz and Kh) are worked out for a 2° square zone (4.5° to 6.5°N and 93° to 95°E) using mean vertical temperature profiles computed from all available historical data. Kh values showed 5 orders (10^5 to 10^{10} cm^2/sec) of variations from 15 to 275 m with a conspicuous increase (>10^8) just below the main pycnocline (75-125 m). Vertical profile of Kz showed high values (>120 cm^2/sec) at the upper half (75-100 m) of the pycnocline. High values of Kz and Kh
along with the high shear cause intense vertical mixing at
the pycnocline where high stratification prevails.

Introduction

Bay of Bengal constitutes the eastern adjacent sea of the
Indian subcontinent with a surface area of \(3 \times 10^6\) \(\text{km}^2\) (north
of 5°N) including Andaman Sea. It is well known that the Bay
and the equatorial Indian Ocean experience seasonally
reversing wind and current systems. The rivers in the
hinterland, including Burma, bring \(943 \times 10^9\) \(\text{m}^3\) and \(104 \times 10^9\)
\(\text{m}^3\) of fresh water during southwest monsoon (June + July +
August) and northeast monsoon (December + January + February)
respectively (VARKEY and SASTRY, 1992). High salinity water
masses flow into the Bay from the northern and equatorial
Arabian Sea. In this background the turbulent mixing
properties of the thermocline layer (Fig. 1) in the Bay
acquire special significance. An attempt is made here to
evaluate the mixing properties in the thermocline layer
during the northeast monsoon.

Data And Methods

For this work, a 2° square zone (93° to 95°E and 4.5° to
6.5°N) which has sufficient data for the northeast monsoon
(NEM) months of November, December, January and February is
selected (Fig. 2). This zone is divided into a grid (4 x 4)
of 0.5° squares. But two grids did not have any data for the
NEM months. This problem is circumvented by interpolating
profiles using profiles of the adjoining squares. From this
data mean profiles of temperature are computed upto a depth
of 400 m (Fig. 2) pooling all available profiles from the NEM
months only. These seasonal mean temperature profiles, are
used to evaluate the mean \(K_z\) and mean \(K_h\) values using a
method as described below.
The conservation equations for heat and salt neglecting sources of heat due to dissipation of kinetic energy of motion are (FOFONOFF, 1962),

\[
\frac{\partial T}{\partial t} + \frac{v}{\partial x} + \frac{u}{\partial y} + \frac{w}{\partial z} = \frac{K_h}{Pr} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + \frac{K_z}{Pr} \left( \frac{\partial^2 T}{\partial z^2} \right) \quad \ldots \quad (1)
\]

\[
\frac{\partial S}{\partial t} + \frac{v}{\partial x} + \frac{u}{\partial y} + \frac{w}{\partial z} = \frac{D_h}{q} \left[ \frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} \right] + \frac{D_z}{q} \left( \frac{\partial^2 S}{\partial z^2} \right) \quad \ldots \quad (2)
\]

Assuming steady state conditions and taking \( Cp \) as unity eqn. (1) becomes;

\[
\frac{v}{\partial x} + \frac{u}{\partial y} + \frac{w}{\partial z} = \frac{K_h}{Pr} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + K_z \left( \frac{\partial^2 T}{\partial z^2} \right) \quad \ldots \quad (3)
\]

Heat flux across the sea surface is not taken into consideration here since this component would have only small effects; 25% at 10 m, and 11% at 25 m (ROLL, 1965). Assuming eqn. (3) to be valid for different individual layers of standard depths (like 400 to 300 m, ..., 100 to 75 m, etc.) the depth dependence of \( K_z \) and \( K_h \) are worked out from the mean seasonal profiles as follows. Geostrophic velocities (zonal and meridional) are calculated using the mean temperature and salinity data, with a reference level at 400 m. Vertical velocity \( w \) is evaluated using the equation of continuity in the form (LEENDERTSE et al, 1973);

\[
W_z^\text{(up)} = W_z^\text{(low)} + \frac{\partial (vh)}{\partial x} + \frac{\partial (uh)}{\partial y} \quad \ldots \quad (4)
\]

The lowest boundary value of \( w \) at 400 m was taken as 0.49 x 10^{-4} \text{ cm/sec} (VARKEY, 1986).

Now in eqn. (3), \( K_z \) and \( K_h \) are unknown. Once \( K_z \) is specified by some means \( K_h \) can be worked out. This is done following GARGETT (1984) in which he suggested an \( N \) (static stability) dependent relationship for \( K_z \) as;

A - 3
\[ K_z = a_0 \ N^{-Q} \]  

... (5)

This is strictly valid only in the interior of the oceans wherein horizontal advection is of insignificant nature in balancing the vertical density structure. For the present, \( N \) is replaced by \( Ri \) (dynamic stability) and \( q \) is taken as 1 for physical reasons and based on Gargett's review. Hence,

\[ K_z = a_0 \ Ri^{-1} \]  

... (6)

\[ = \frac{a_0 \ (dc/dz)^2}{N^2} \]  

... (7)

where the method dependent \( a_0 \) is assumed to be 2900 (VARKEY, 1986). Now the vertical profile of \( K_z \) is known. Hence \( K_h \) can be evaluated from equ. (3).

Results And Discussion

Figure 4 shows the computed vertical profile of \( K_z \) in the study zone. Here, it is necessary to be aware that only the relative vertical variations in \( K_z \) are of topical significance in relation to the mixing in the thermocline (see Fig. 1 also). The most important feature in the figure is the very high values within the depth range 50-100 m observed in the pycnocline region (50-150 m). This brings out the intense vertical mixing across the density discontinuity caused by the thermohaline effects. BUCH (1982) noted that the vertical mixing in the pycnocline is shear generated. From Fig. 6 it can be observed that the current shear is high within the depth range 50-150 m.

Figure 5 depicts the vertical variations of \( K_h \). Disregarding the values above 25 m wherein some minor effects of heat flux across the sea surface exists and those below 300 m due to
approximations in equation (6) the most important feature is the high values within the range 100 to 175 m. High values of shear and stratification also occur within depth range of 50-150 m (Fig. 6). But the Kh peak at 140 m is below the shear peak (90 m) and stratification peak (110 m). The Kh values show a wide range from $2 \times 10^5$ cm$^2$/sec at 275 m to $2 \times 10^7$ cm$^2$/sec at about 25 m. Here it should be kept in mind that these absolute values of Kh can vary 2 or 3 times, but the emphasis is only on the relative vertical variations. BENNETTE (1970) estimated Kh in the northern Indian Ocean from Red Sea salinity maximum (27.2 $\sigma_t$) as $7 \times 10^7$ cm$^2$/sec for bimonthly horizontal distribution and as $3 \times 10^8$ cm$^2$/sec for mean annual horizontal distribution. DEFANT (1955) found a value of $5.5 \times 10^7$ cm$^2$/sec for Mediterranean water tongue which flows into the Atlantic. GARRETT (1979) found a wide range of $10^3$ to $10^4$ for Kh estimated by various workers.

From Figs. 4 and 5 it is clear that in the pycnocline region Kz and Kh values are large. From Fig. 6 it is seen that a region of high current shear exists above the layer of maximum static stability with some overlapping. Even though high N inhibits vertical mixing, the current shear induces instability and intense breaking of internal waves resulting in low Ri. This in turn results in high Kz and vertical transfer. This feature of high Kz, Kh and shear explains vertical mixing in the Bay across the well stratified thermocline.

References


GARRETT, C., 1979; Mixing in the ocean interior, Dyn. of atmosphere and oceans, 3: 239-265.


Fig 1 Thermal structure in the Bay of Bengal (88° to 90°E & 5° to 6.5°N)

- O March,
- X-----X July,
- □-□ September,
- △-△ December

Λ = 7
Fig. 2 Study area with half degree zones and depths at which computations are carried out. X = Seasonal mean hydrographic profiles. Θ = V(→) & U(↑) profiles, Δ = R↓, W & N profiles.
Fig. 3 Co-ordinate system for computations.

Fig. 4 Vertical profile of $K_z$ computed using equation 6.
Fig. 5 Vertical profile of Kh computed using equation 3

$K_h (C_m^2 \text{Sec}^{-1})$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

DEPTH (m)

0

50

100

150

200

250

300

350

400

A = 10
Fig. 6 Vertical profiles of $Ri$, $N$, $dc/dz$, $dv/dz$ and $1/Ri$