

MEAN TURBULENT MIXING PROPERTIES IN THE THERMOCLINE LAYER
OF THE BAY OF BENGAL

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SYNOPSIS

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 (K_z and K_h) 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. K_h 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 K_z showed high values (>120 cm^2/sec) at the upper half (75-100 m) of the pycnocline. High values of K_z and K_h

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 (4×4) 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),

$$\frac{\partial T}{\partial t} + \frac{v \partial T}{\partial x} + \frac{u \partial T}{\partial y} + \frac{w \partial T}{\partial z} = \frac{K_h}{\rho C_p} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + \frac{K_z}{\rho C_p} \left(\frac{\partial^2 T}{\partial z^2} \right) \dots (1)$$

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

Assuming steady state conditions and taking C_p as unity equ. (1) becomes;

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

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 equ. (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);

$$W_z (\text{up}) = W_z (\text{low.}) + \frac{\partial (vh)}{\partial x} + \frac{\partial (uh)}{\partial y} \dots (4)$$

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

Now in equ. (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;

$$K_z = a_0 N^{-q} \quad \dots (5)$$

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,

$$K_z = a_0 Ri^{-1} \quad \dots (6)$$

$$= \frac{a_0 (dc/dz)^2}{N^2} \quad \dots (7)$$

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 K_h peak at 140 m is below the shear peak (90 m) and stratification peak (110 m). The K_h values show a wide range from 2×10^5 cm²/sec at 275 m to 2×10^7 cm²/sec at about 25 m. Here it should be kept in mind that these absolute values of K_h can vary 2 or 3 times, but the emphasis is only on the relative vertical variations. BENNETTE (1970) estimated K_h in the northern Indian Ocean from Red Sea salinity maximum ($27.2 \sigma_t$) as 7×10^7 cm²/sec for bimonthly horizontal distribution and as 3×10^8 cm²/sec for mean annual horizontal distribution. DEFANT (1955) found a value of 5.5×10^7 cm²/sec for Mediterranean water tongue which flows into the Atlantic. GARRETT (1979) found a wide range of 10^2 to 10^4 for K_h estimated by various workers.

From Figs. 4 and 5 it is clear that in the pycnocline region K_z and K_h 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 R_i . This in turn results in high K_z and vertical transfer. This feature of high K_z , K_h and shear explains vertical mixing in the Bay across the well stratified thermocline.

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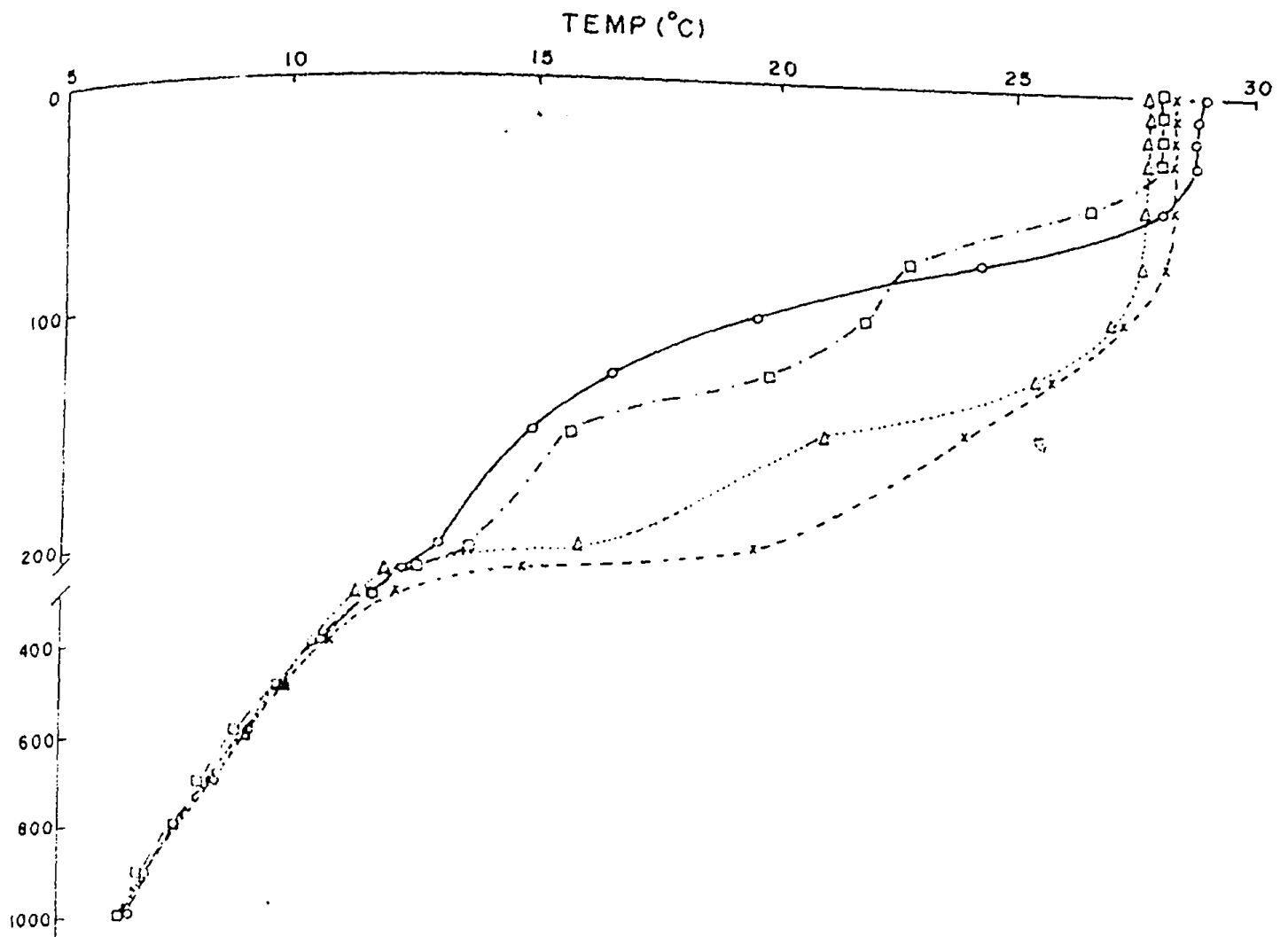


Fig 1 Thermal structure in the Bay of Bengal (88° to 90° E & 5° to 6.5° N)
 ○—○ March, x—x July, □—□ September, Δ—Δ December

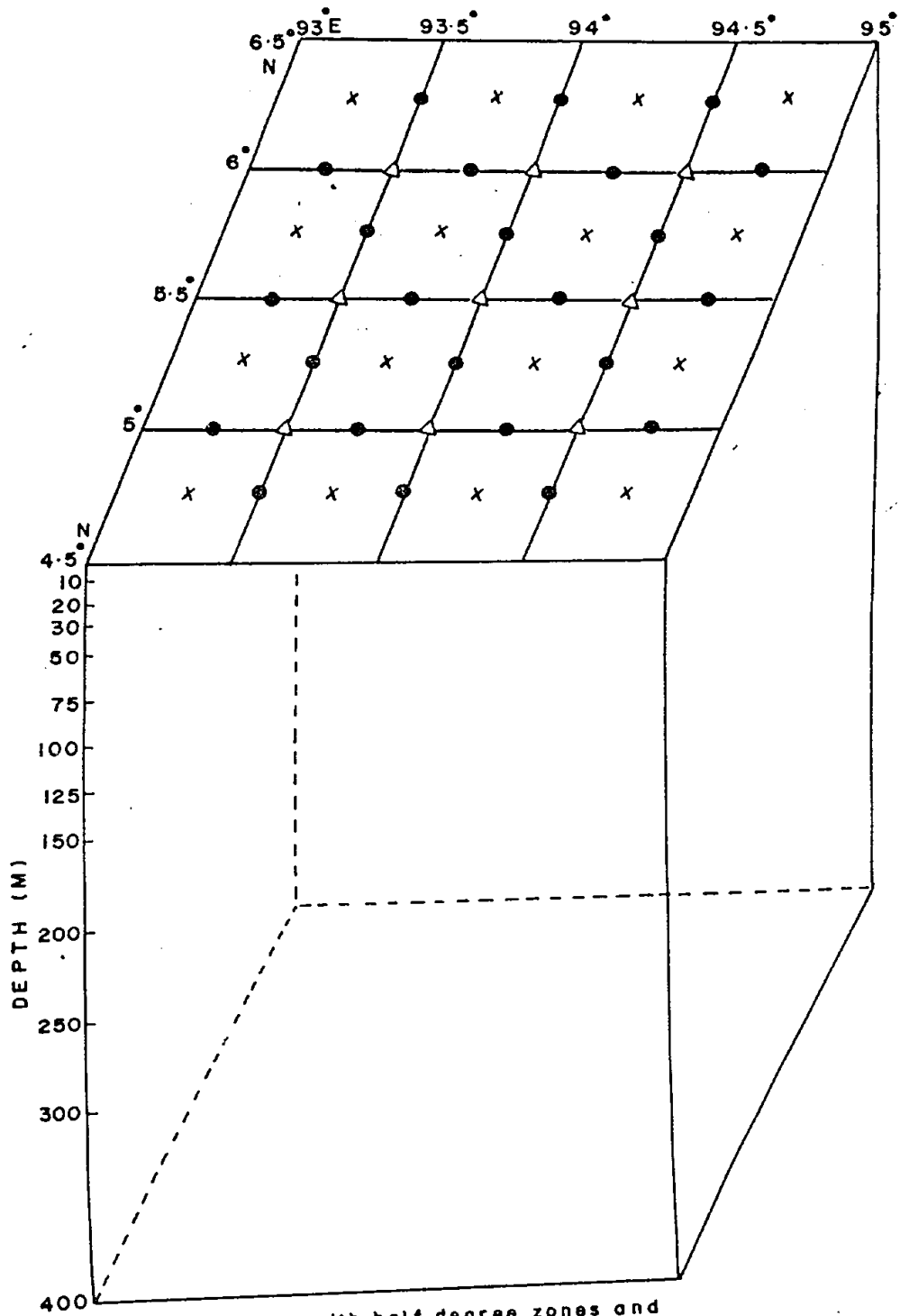


Fig. 2 Study area with half degree zones and depths at which computations are carried out. X = Seasonal mean hydrographic profiles
 ⊙ = V (→) & U (↑) profiles, Δ = R, W & N profiles.

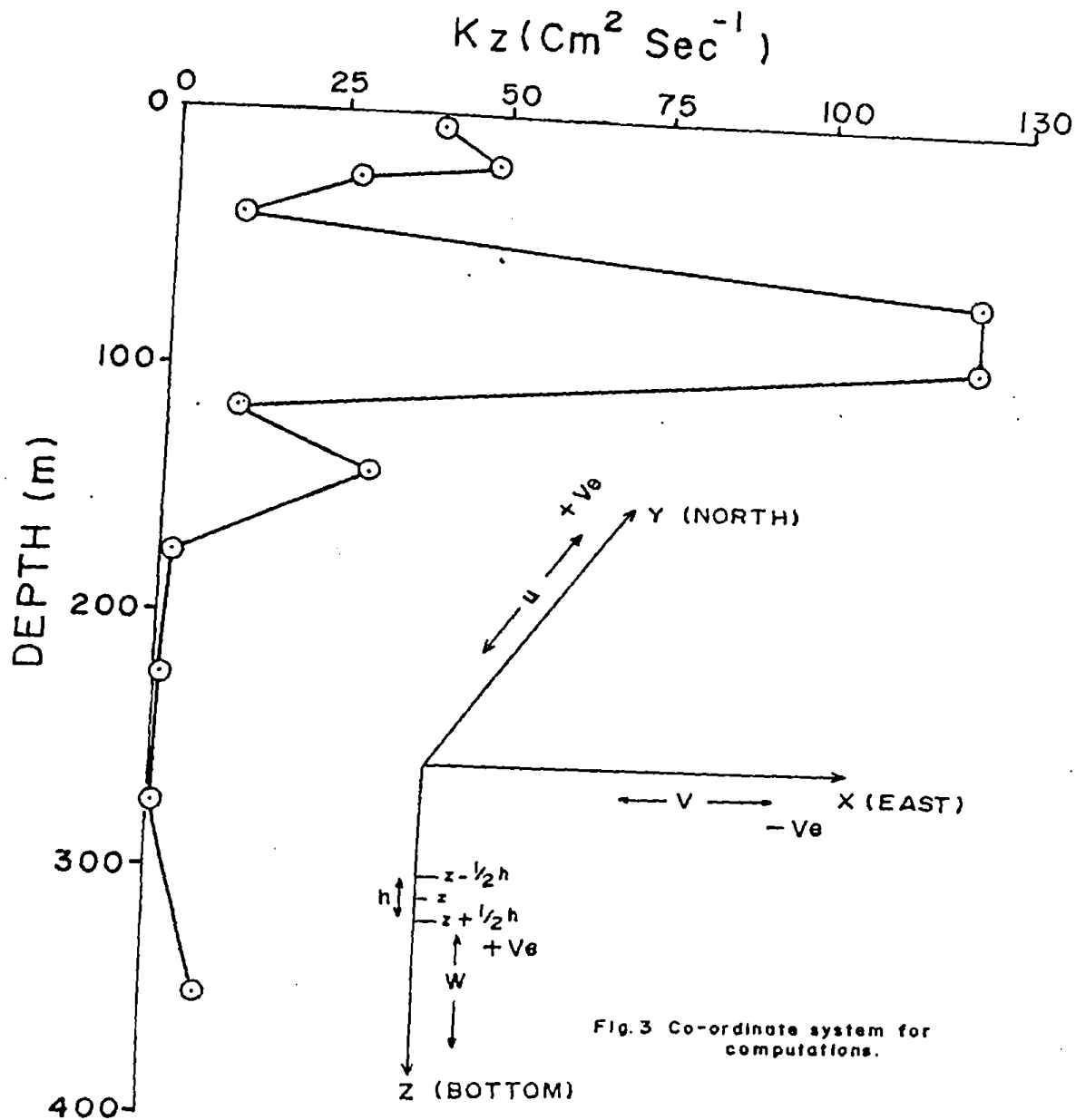


Fig. 4 Vertical profile of K_z computed using equation 6.

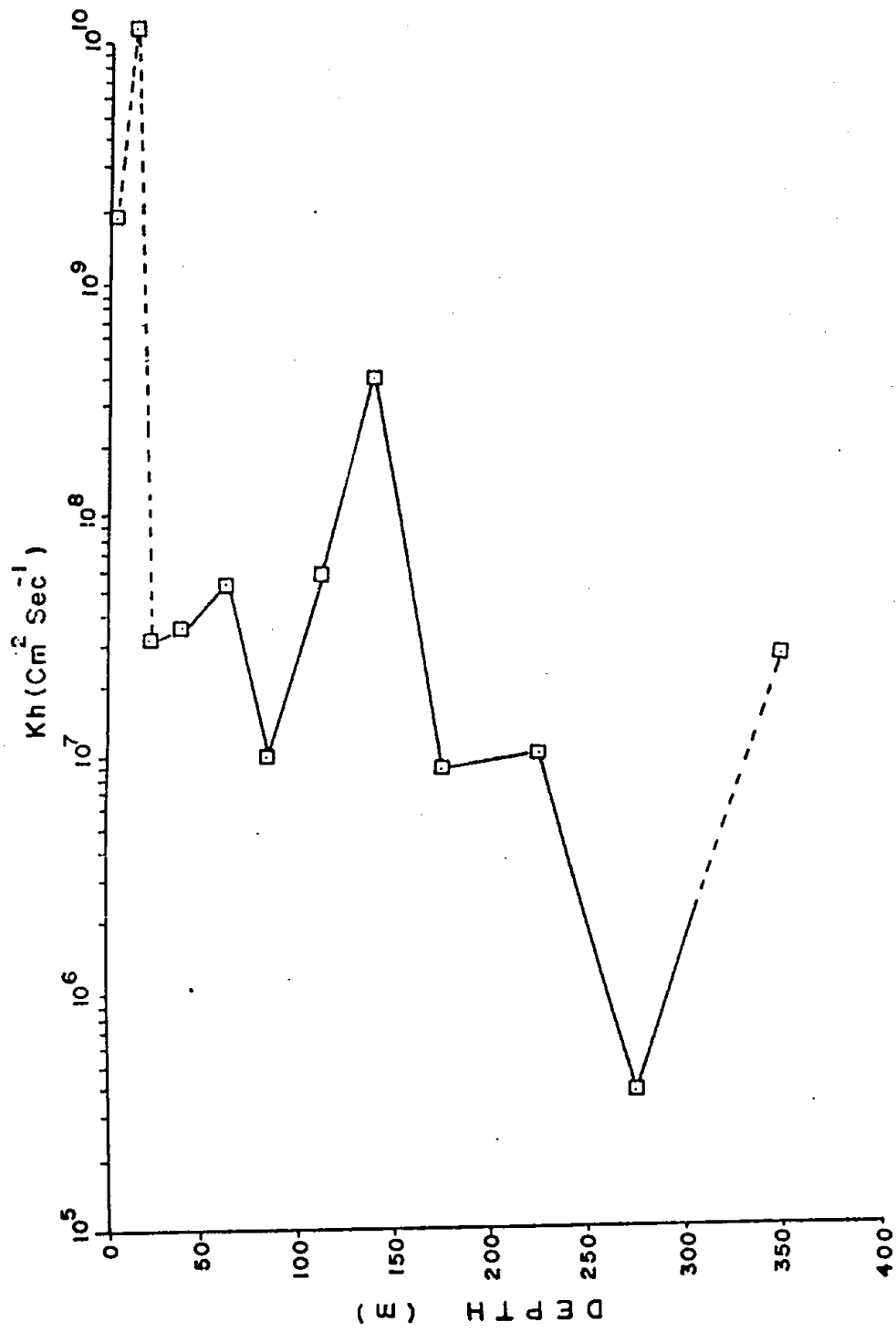


Fig. 5 Vertical profile of K_h computed using equation 3

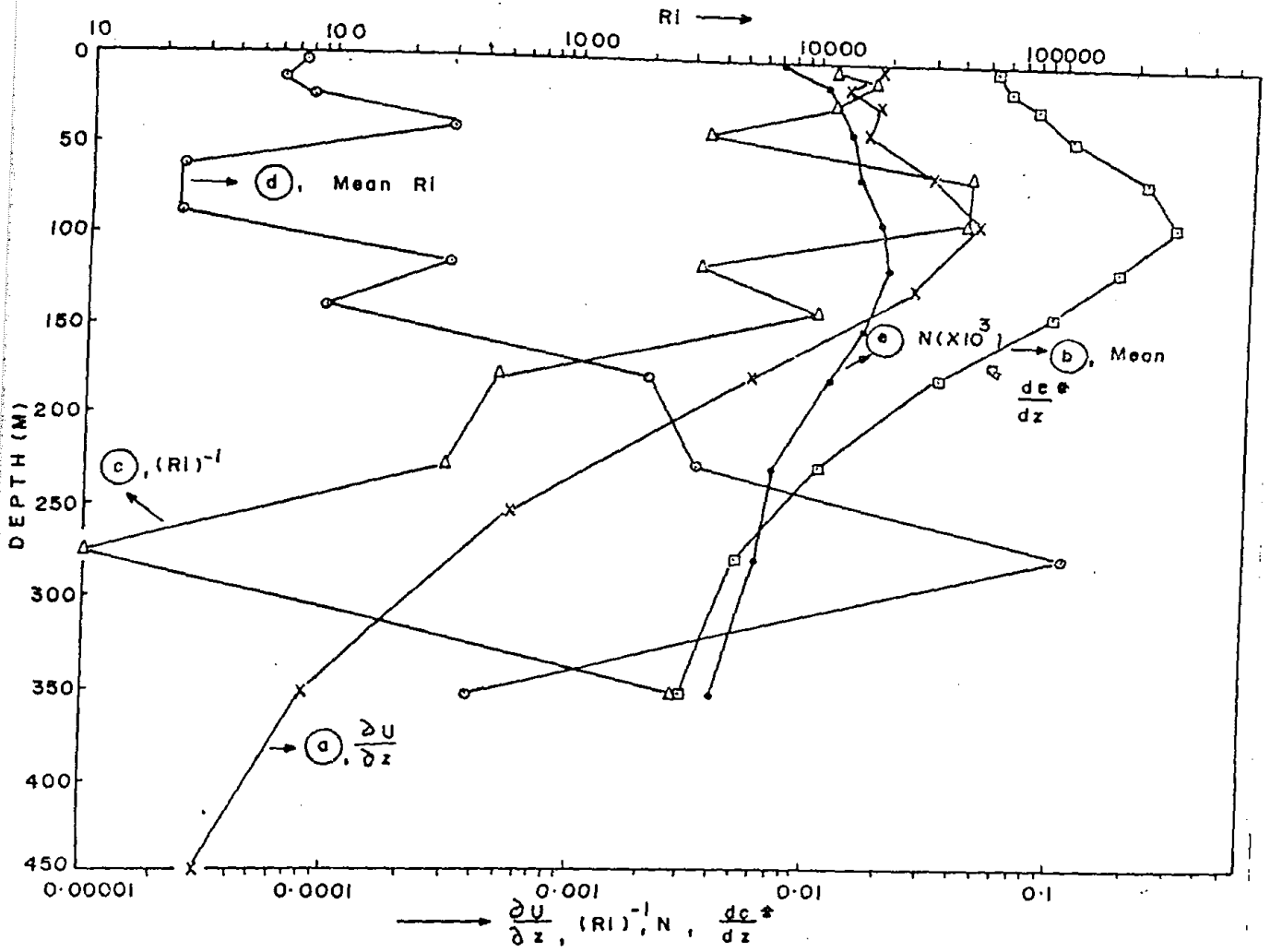


Fig. 6 Vertical profiles of $RI, N, dc/dz, dv/dz$ and $1/RI$