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Determination of Vertical Velocities in the Equatorial Part of the Western Indian Ocean

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Using steady state two-dimensional turbulent diffusion equations of salt and heat some important characteristics of vertical circulation in the equatorial part of the Indian Ocean have been evaluated and discussed. Upwelling and sinking velocities, on an average, vary from 10^{-2} to 10^{-3} cm.sec^{-1} in the domain, and along the coast of Somalia; vertical velocities of the order of 10^{-1} to 10^{-2} cm.sec^{-1} have been obtained. The study has enabled the identification of zones of convergence and divergence in the equatorial part of the Indian Ocean. Accuracy of the present method depends on the data on temperature and salinity and also on the values of eddy coefficients.

Equatorial and tropical parts of world oceans play a very significant role in the regulation of energy exchange processes of the ocean-atmosphere system. This region receives maximum amount of solar radiation, which is released to the atmosphere in the form of latent heat which subsequently modifies the general atmospheric circulation. Higher surface water temperature, complex mixing of different water masses and intensive exchange of energy between the ocean and the atmosphere are some of the unique physico-geographical peculiarities of this region.

Equatorial parts of world oceans are also regions of strong vertical motions. Vertical circulation of water, especially upwelling, significantly modifies specific meteorological and hydrological conditions of the region as observed along the coast of Somalia. In the present study, an attempt has been made to calculate vertical motions of water in the equatorial part of Western Indian Ocean. In the area under study, there have been some qualitative studies on vergences[1] but so far no quantitative investigations on vertical motions.

Materials and Methods

The main aim of this study is to compute spatial distribution of vertical velocities up to 500 m depth using turbulent diffusion equations of temperature and salinity. Coefficients of turbulent diffusion are assumed constant throughout the computations. In order to represent the coefficients more realistically, the eddy diffusion coefficients which vary with depth have been computed for different depths in the first 500 m water column and an average of these values has been taken for the calculation of vertical velocities. Data on temperature and salinity used in the present study were collected up to 500 m during the 2nd cruise of the Russian vessel *Chernomor*, (Feb. 1967) in meridional sections between lat. 4°S and 4°N in the equatorial part of the Indian Ocean. Four sections along 50°E, 53°E, 57°E and 60°E long. have been considered for the present study. The data have been interpolated for every 50 m depth so that finite difference approximations could be used for the computation of spatial derivatives of temperature and salinity.

Derivation of vertical velocity component—Validity of time-averaged form of conservation equations of salt and heat for calculating vertical velocities in the ocean has been verified earlier[2]. In the present study, steady state two-dimensional turbulent equations of salt and heat are used for the calculation of vertical velocity. The systems of equations are

$$v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) \qquad \ldots (1)$$

$$v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial y}\left(k_y\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial S}{\partial z}\right) \qquad \ldots (2)$$

where T and S are temperature and salinity of seawater respectively; v, w are current speeds along y and z axis, y-pointing north and z-positive downwards from the sea surface; and k_y, k_z-coefficients of turbulent diffusion of heat and salt in the respective directions.

In Eqs (1) and (2), for simplicity, coefficients are assumed to be constant in the respective directions $\left[\text{i.e.}\ \frac{\partial}{\partial y}(k_y) \text{ and } \frac{\partial}{\partial z}(k_z)=0\right]$

Thus Eqs (1) and (2) are transformed into

$$v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=k_y\frac{\partial^2 T}{\partial y^2}+k_z\frac{\partial^2 T}{\partial z^2} \quad \text{... (3)}$$

$$v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=k_y\frac{\partial^2 S}{\partial y^2}+k_z\frac{\partial^2 S}{\partial z^2} \quad \text{... (4)}$$

The following substitutions are made in Eqs (3) and (4)

$$a_1=\frac{\partial T}{\partial y};\quad b_1=\frac{\partial T}{\partial z};$$

$$a_2=\frac{\partial S}{\partial y};\quad b_2=\frac{\partial S}{\partial z};$$

$$c_1=k_y\frac{\partial^2 T}{\partial y^2}+k_z\frac{\partial^2 T}{\partial z^2};$$

$$c_2=k_y\frac{\partial^2 S}{\partial y^2}+k_z\frac{\partial^2 S}{\partial z^2};$$

Thus Eqs (3) and (4) are transformed to the following matrix form:

$$\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix}\begin{bmatrix} v \\ w \end{bmatrix}=\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \quad \text{... (5)}$$

or

$$\begin{bmatrix} v \\ w \end{bmatrix}=\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix}^{-1}\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \quad \text{... (6)}$$

The unknown variables v and w can be found by solving the matrix Eq. (6). In order to solve Eq. (6), it is necessary to compute the values of a_1. a_2, b_1, b_2, c_1, and c_2. These values can be computed if the 1st and 2nd order spatial derivatives of temperature and salinity are evaluated. Fig. 1 shows the computational grid used in this study. The 1st and 2nd order spatial derivatives of temperature and salinity are approximated by the following finite difference (central difference) formulae:

$$\frac{\partial T}{\partial z}=\frac{T_{i+1,k}-T_{i-1,k}}{2\Delta z}$$

$$\frac{\partial T}{\partial y}=\frac{T_{i,k+1}-T_{i,k-1}}{2\Delta y}$$

$$\frac{\partial S}{\partial z}=\frac{S_{i+1,k}-S_{i-1,k}}{2\Delta z}$$

$$\frac{\partial S}{\partial y}=\frac{S_{i,k+1}-S_{i,k-1}}{2\Delta y}$$

$$\frac{\partial^2 T}{\partial z^2}=\frac{T_{i+1,k}+T_{i-1,k}-2T_{i,k}}{\Delta z^2}$$

$$\frac{\partial^2 T}{\partial y^2}=\frac{T_{i,k+1}+T_{i,k-1}-2T_{i,k}}{\Delta y^2}$$

$$\frac{\partial^2 S}{\partial z^2}=\frac{S_{i+1,k}+S_{i-1,k}-2S_{i,k}}{\Delta z^2}$$

$$\frac{\partial^2 S}{\partial y^2}=\frac{S_{i,k+1}+S_{i,k-1}-2S_{i,k}}{\Delta y^2}$$

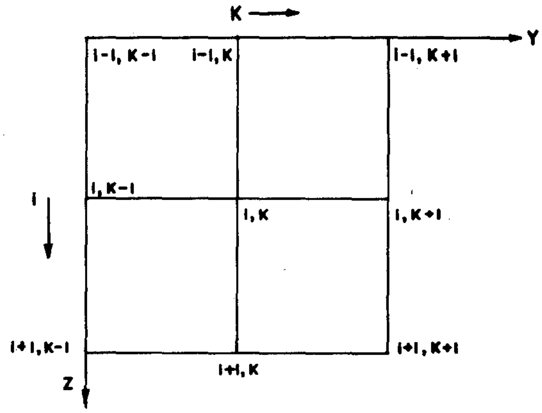


Fig. 1—Computational grid used in the study for the approximation of spatial derivatives of temperature and salinity

Values of the above finite difference formulae are substituted in a_1, a_2, b_1, b_2, c_1 and c_2 and the unknown variables v and w are evaluated.

Estimation of horizontal and vertical eddy diffusion coefficients—It is well known that eddy diffusion coefficients of salt at any particular region depend on the turbulence and also on the distribution of salt that would be diffused. In the present study for the computation of vertical eddy diffusion coefficient, horizontal advection of salt is assumed to be balanced by vertical diffusion of salt. Hence, the time averaged conservation equation of salt for incompressible flow reduces to the following[3]

$$\bar{u}\frac{\partial S}{\partial x}=\frac{\partial}{\partial z}\left(k_z\frac{\partial S}{\partial z}\right) \quad \text{... (7)}$$

where $\bar{u}$ is the mean current in the x-direction.

An average value of the vertical eddy diffusion coefficient can be obtained by assuming that it is not a function of z (i.e. $\frac{\partial}{\partial z}(k_z)=0$). So Eq. (7) is reduced to

$$\bar{u}\frac{\partial S}{\partial x}=k_z\frac{\partial^2 S}{\partial z^2} \quad \text{... (8)}$$

or

$$k_z=\bar{u}\frac{\partial S}{\partial x}\bigg|\frac{\partial^2 S}{\partial z^2} \quad \text{... (9)}$$

For determining the eddy diffusivity for the horizontal exchange of salt, the co-ordinate system can be oriented in such a way that mean current $\bar{u}$ is in the direction of x-axis and the only mixing that has to be taken into account is horizontal and transverse to mean current. Thus Eq. (7) is reduced to

$$\bar{u}\frac{\partial S}{\partial x}=\frac{\partial}{\partial y}\left(k_y\frac{\partial S}{\partial y}\right) \quad \text{... (10)}$$

Assuming k_y to the constant $\left(\frac{\partial}{\partial y}(k_y)=0\right)$ Eq. (10) is reduced to

$$k_y = \bar{u}\frac{\partial S}{\partial x}\bigg|\frac{\partial^2 S}{\partial y^2} \qquad \text{... (11)}$$

Thus Eqs (9) and (11) are used for the computation of vertical and horizontal eddy diffusion coefficients in the given area. Values of k_z and k_y are calculated at different latitudes in the area of interest and an average of these values is taken for the computation of vertical circulation. The following average values of k_z and k_y have been used in the present study.

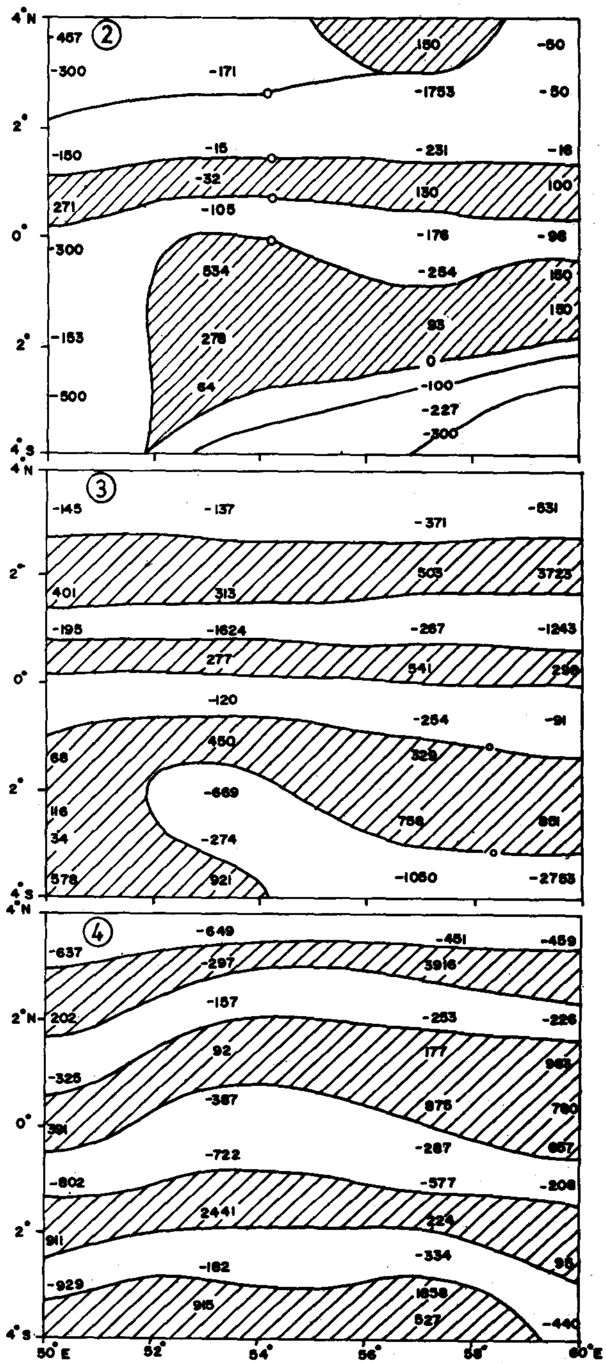
$$k_z = 0.054\ \text{cm}^2.\text{sec}^{-1}$$
$$k_y = 3.06 \times 10^8\ \text{cm}^2.\text{sec}^{-1}$$

Results and Discussion

Characteristics of vertical velocities at different depth—Results of computation, using Eq. (6), (Figs 2-4) show the existence of alternate zones of upwelling and sinking in the area as anticipated.

Vertical velocities at 50 m depth. vary from 10^{-1} to 10^{-3} cm.sec^{-1} throughout the domain (Fig. 2) which are comparable to those obtained in other parts of oceans[4,5]. It is clear from Fig. 2 that a region of strong upwelling is developed along 50°E long. south of equator. This upwelling motion can be explained in terms of dynamical processes of equatorial regions during the winter months. During the NE monsoon season, all current systems in the equatorial regions of Indian Ocean namely north and south equatorial currents, equatorial counter current and under current, are well developed[2]. The Somali current which flows southwards along the coast of Somalia during the NE monsoon season, is deflected away from the coast south of equator due to the effect of coriolis force, thereby creating favourable conditions for the development of upwelling[2]. The upwelling velocities at 50 m depth along the coast of Somali are of the order of 10^{-1} to 10^{-2} cm.sec^{-1}. High values of vertical motions can be expected at these regions as the normal speed of Somali current is very high. Analysis of results also showed the existence of two equatorial divergence zones with a convergence in between. One of the divergence zones is located between the boundaries of north equatorial current and equatorial counter current and the other is located between the boundaries of equatorial counter current and south equatorial current. The region of equatorial counter current is found to be the core of the convergence zone in the present study.

The velocity of upwelling and sinking at 250 and 450 m depths is of the order of 10^{-2} cm.sec^{-1}. Unlike



Figs 2 to 4—Vertical velocity distribution ($w \times 10^4$ cm.sec^{-1}) at 50(2), 250(3) and 450(4) m depths (Sinking regions are shaded)

in Fig. 2 the vertical velocities at 250 m depth (Fig. 3) along 50°E long. are downward. It can be inferred from an analysis of the results that there are alternate zones of upwelling and sinking along 50°E long. in the vertical direction. This can be explained in terms of the application of continuity principle for incompressible type of flow.

Structure of vertical circulation along 57°E long.—In order to understand the dynamics of upwelling and

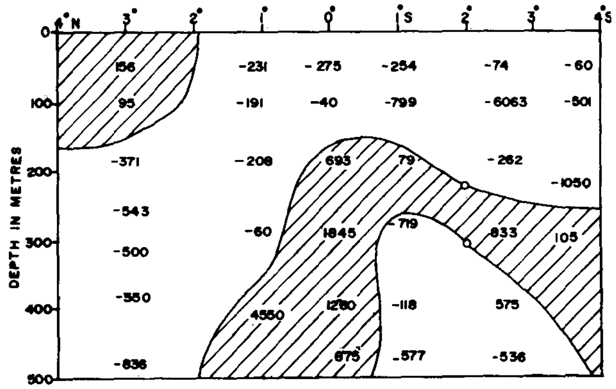


Fig. 5—Vertical velocity field (w × 10^4 cm.sec^{-1}) in the vertical along 57°E long. (Sinking regions are shaded)

sinking, it is essential to have a detailed knowledge of the structure of vertical velocities in the region. Such analysis would help in identifying the specific areas over which upwelling and sinking processes take place.

Fig. 5 shows that upwelled water comes from depths of even 500 m and reaches the upper 200 m of water column in a meridional direction from north to south, indicating the presence of cross-equatorial flow from the northern hemisphere to southern hemisphere. This is followed by a region of sinking south of equator below a depth of 200 m. The velocity of vertical circulation varies from 10^{-1} to 10^{-2} cm.sec^{-1} throughout the domain.

In the present study, a good similarity between the characteristics of circulation and temperature, is obtained. Fig. 6 shows the spatial distribution of temperature at 50 m depth. A comparison of Figs. 2 and 6 shows that upwelling regions are zones where upward slope of isotherms is noted. Similarly, in regions of downwelling, downward slope of isotherms is observed. The main advantage of this method of computation by turbulent diffusion equations is that it can be used in any part of the world ocean including equatorial regions as the coriolis parameter does not appear in the systems of equations. In this method, the only data required for the computation of vertical velocities are temperature and salinity. So the accuracy depends on the correctness of temperature and salinity data that are used for the computation. However, the numerical values of coefficients of diffusion which vary depending on the depth and stratification of watermasses, affect the results. Hence, greater caution is required when the coefficients are parameterised and calculated. It is advisable to use varying coefficients for different depths so that better results could be obtained. In stratified regions of the oceans also, this method may not give reliable results.

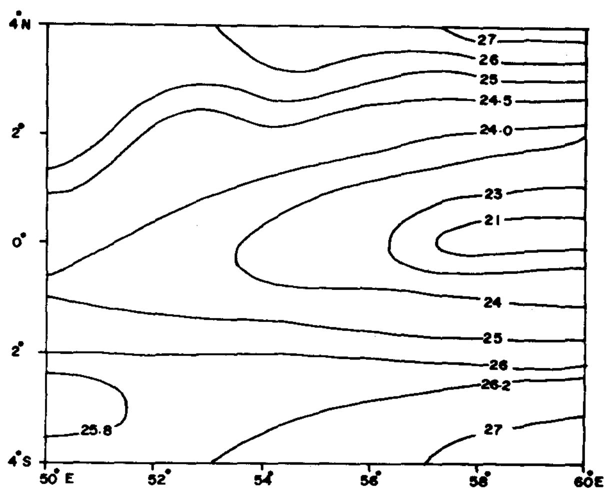


Fig. 6—Temperature distribution (°C) at 50 m depth

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