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THE EFFECT OF STABILITY ON THE INTENSITY OF VERTICAL TURBULENT DIFFUSION IN THE WESTERN CHANNEL OF THE KOREA STRAIT

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ABSTRACT

Vertical mixing in the ocean affects the formation of water masses as well as the vertical distribution of nutrients and dissolved substances. This study is to investigate the effect of stability on the intensity of vertical transfer in the case of shallow and stratified channel. It is found that the relation of the stability and vertical turbulent diffusion is given by

$$K_z = -\beta - \frac{c+\beta}{a(E-1/a)}$$

where K_z and E denotes the vertical turbulent diffusion coefficient and stability, respectively. The empirical coefficients a, β and c depend on the magnitude of vertical components and stability, i.e., through thermocline intensity.

The study indicates that the diffusivity of the surface mixed layer is $(K_z)=300\sim1,200$ cm^2/sec, the thermocline layer is $(K_z)=50\sim200$cm^2/sec and the cold layer is $(K_z)=200\sim600$cm^2/sec based on near-minimum least-squares error estimates from the regression analysis. An important result of our study comes out that the model is in accordance with the general trends of the effect of stability on the vertical turbulent diffusion coefficients in the case of shallow and strongly stratified channel.

INTRODUCTION

The vertical distribution of any property in the ocean comes about as both the result of turbulent diffusion and the vertical components of the mean current velocities, i.e., the rising and sinking streams. Therefore, the problems of stability and vertical turbulent diffusion in water masses have been considered critical in determining the structure of stratification and mixing of the water masses.

The investigation of the vertical turbulent diffusion was initiated by Fjeldstad(1933), and followed by Defant(1939), Stockman(1946), Proudman(1957), Malcus(1959), Kolesnikov (1962), *et al.*, but they all neglected the vertical velocities in their studies. These approaches have been justified only for determining the intensity of transfer in the upper well-mixed stratum, i.e., above the thermocline. However, its extension to the thermocline has proved to be inadequate based on studies made by Stommel(1956) and Malcus(1959). They considered that the principal contribution to transfer is made by the vertical components, so that the turbulent caused by small horizontal velocities is negligible in the thermocline. In fact, transfer is brought about by a combination of turbulent diffusion and rising or sinking streams. Recently, the thermocline, below the frictional layer, has been intensively studied by Veronis(1969), Welander (1971) and Needler(1971), claiming that vertical diffusion takes place in thermocline where horizontal current exists.

At present, no detailed investigation has been attempted on the general processes of vertical transfer in channel where the horizontal velocity is strong and water masses are stratified. Even if there are some different views on the relation between streams of conservative and passive substancy (transferred by turbulent diffusion) and the vertical components of the mean current velocities, it is possible to calculate the turbulent diffusion coefficients in the thermocline layer where the considerable horizontal current exists.

The purpose of this study is to investigate the effect of stability on the intensity of vertical turbulent diffusion in the thermocline layer, which has not been attempted. We present a model which explains the general trends of stability and vertical transfer for shallow channel where the water masses are stratified and subject to seasonal changes.

THEORETICAL FORMULATIONS

The vertical distribution of physical properties in the ocean depends heavily on turbulent diffusion coefficients along with the vertical current velocities.

In the presence of turbulent diffusion, the equation of continuity is given by

$$\partial T/\partial t+U\cdot\partial T/\partial x+V\cdot\partial T/\partial y+W\cdot\partial T/\partial z= \partial/\partial x(K_x\cdot\partial T/\partial x)+\partial/\partial y(K_y\cdot\partial T/\partial y)+ \partial/\partial z(K_z\cdot\partial T/\partial z) \quad\cdots\cdots(1)$$

where T denotes the properties in the ocean, U,V,W and K_x,K_y,K_z represent the components of velocity and the coefficients of turbulent diffusion in the Cartesian coordinate, respectively.

When the mean current U is taken parallel to the X-axis and the mixing is assumed to take place only along the vertical direction, the diffusion coefficient of the stationary current is given by

$$K_z=1/\partial T/\partial_z z\int_{z0}^{z} U\cdot\frac{\partial T}{\partial x}\cdot dz\cdots\cdots(2)$$

The often employed indirect method of determining K_z is to use equation(1), by neglecting vertical components of velocity

$$\partial T/\partial t+U\cdot\partial T/\partial x=K_z\cdot\partial^2T/\partial z^2\cdots\cdots(3)$$

As is well known, the quantity K_z is related to the stability criterion E of the water masses

$$E=\frac{g}{\rho}\cdot\frac{d\rho}{dz}\cdot\frac{1}{(du/dz)^2}\cdots\cdots(4)$$

where ρ is the density and g is the gravity. In the case of shallow water, the adiabatic temperature gradient is negligibly small. Therefore, equation (4) becomes

$$E=10^{-3}d\sigma_t/dz\cdots\cdots(5)$$

which is found to represent fairly well the stability of water masses down to a depth of 1,400 meters.

MATERIALS AND METHODS

The present study is based on the data of hourly oceanographic observations in each layers on the western channel of the Korea Strait from 1968 to 1969 made by the Fisheries Research and Development Agency of Korea.

In the present investigation, the vertical distribution of stability has been obtained by means of equation (5) and the vertical turbulent diffusion coefficient has been obtained by equation (2). The effect of thermocline on the stability has been studied by the vertical distributions of stability and temperature. For this study, the criterion of thermocline layer has been adopted in accordance with that of Mazeika (1962), namely the temperature gradient should be greater than 0.37°C/10 meters.

For the study of intensity of vertical turbulent diffusion, the central part of Western Channel was selected, thus its data being less influenced by friction.

CALCULATIONS AND RESULTS

The depth variations of the vertical turbulent diffusion coefficient, K_z, have been calculated by equation (2). The velocity U was taken in the direction of the line passing through all hydrological stations parallel to the currents. With the use of material of the observations, we have made some 30 determinations of K_z at various depths in the channel.

The monthly variation of density and temperature are shown in Fig. 1 and 2. From these figures one can easily find there is a very close relationship between them. When the surface density decreases, there is a tendency that the thermocline becomes stronger as evidenced in September where the surface density reveals minimum, when a very strong thermocline is formed.

Chung(1975) indicated that the main water masses of this channel can be distinguished in three different groups. One is the surface mixed water, which is characterized by high temperature and low salinity. It shows up in summer with a thickness up to 50 meters and disappears in winter. The next is a layer of constant temperature water. It is characterized by high salinity and nearly constant temperature ranging from 50 to 80 meters of depths.

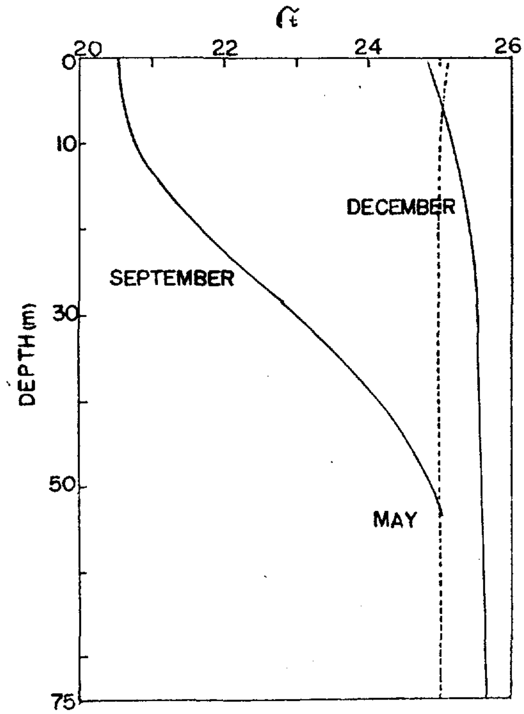

Fig. 1. Monthly variations of average σ_t.

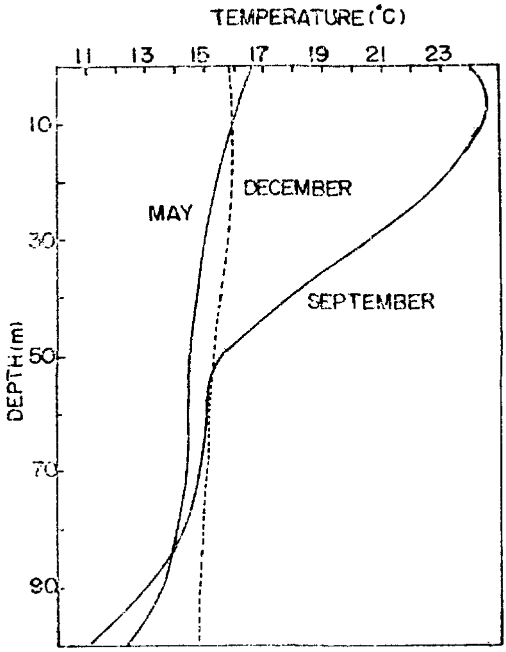

Fig. 2. Monthly variations of vertical distribution of average temperature.

Finally, it comes to the cold water. It is characterized by low temperature and low salinity. This cold water shows up strongly, whenever the Tsushima Current becomes strong in August and September. At this period the temperature of this channel becomes minimum at the bottom.

It may be summed up that the Western Channel appears to be made of three different water masses during summer and autumn, but for the rest of season, only two kinds of water masses are formed. It is found that a typical thermocline is formed at the depth of 0 to 50 meters in summer and 10 to 50 meters in early autumn. Its core is located near depth of 25 meters. Unstable layers are found near the surface(0~10m) from September to December.

According to the seasonal characteristics of the channel, we have taken the observations in May, September and December to represent seasonal variation.

The change of K_z with depth on May is shown in Fig. 3. In the Fig. 3, the curve of E shows the characteristics of the vertical stability at various depths, which has been calculated from the average value of the temperature for the given region. Comparing the curve of K_z and E, we can see a good correlation between them. In the upper mixed layer, K_z reaches value of 300~500cm^2/sec. The stability E reaches maximum at the depths 30 meters, where corresponding K_z becomes its minimum. From a depth of 30 meters, we observe a continuous decrease in stability and an increase in intensity of vertical transfer.

The average vertical distribution of stability and turbulent diffusion on September is shown in Fig. 4. Fig. 4 also shows a good correlation between the vertical transfer and stability. In the upper mixed layer, K_z reaches value of 600cm^2/sec. In the thermocline layer, E reaches its maximum at the depth of 25 meters where corresponding with K_z reaches its minimum. In the cold bottom layer below the depth of 50 meters, we observe that the stability decreases continuously where vertical transfer increases.

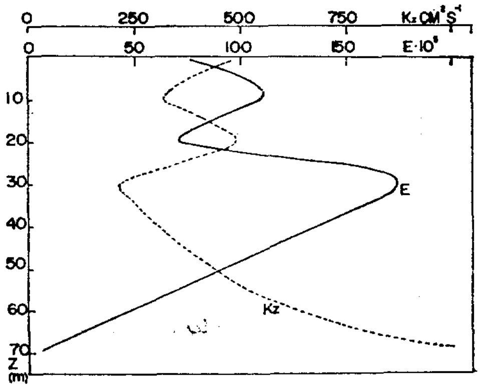

Fig. 3. The average vertical distribution of turbulent diffusion coefficient and of stability in May.

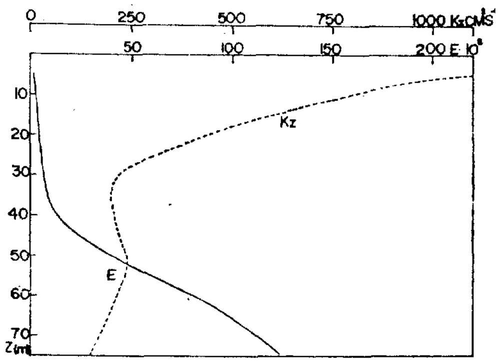

Fig. 4. The average vertical distribution of turbulent diffusion coefficient and of stability in September.

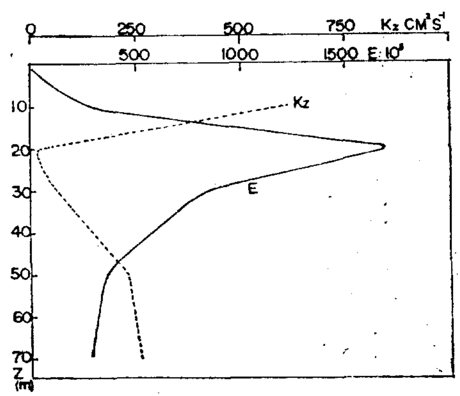

Fig. 5. The average vertical distribution of turbulent diffusion coefficient and of stability in December.

In the case of December, the vertical transfer varies from 200 to 1,200cm^2/sec and it shows the maximum values during the whole season. Comparing Fig. 3, 4, 5 with Fig. 1, 2, we may infer the influence of thermocline to the vertical transfer and stability.

The average vertical distribution of stability and turbulent diffusion on December is shown in Fig. 5.

QUANTITATIVE RELATION BETWEEN K AND E

For all the cases shown in Fig. 3, 4 and 5, the vertical distribution of K_z is inversely proportional to the stability; when coefficient of K_z takes minimum, its corresponding becomes maximum.

The effect of stability on the intensity of vertical transfer is shown in Fig. 6, with various months, in terms of the magnitude of vertical stablity.

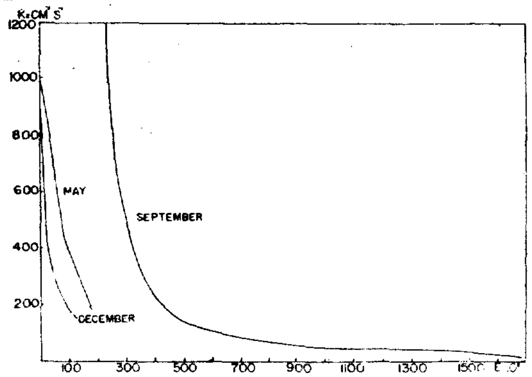

Fig. 6. The effect of stability on vertical exchange in the channel.

We shall now establish the quantitative relation between K_z and E. At present, there are certain expressions which describe the relation between K_z and E. One is given by Obukhov, applicable for open ocean.

$$K_z = K_o\{1 - bE_o\}^{1/2} \quad \cdots\cdots (6)$$

where b is an empirical coefficient and K_o is the coefficient of turbulent diffusion for undifferentiated staratification.

Munk and Anderson(1948) proposed a different form.

$$K_z = \frac{K_o}{(1+\beta E)^{3/2}} \quad \cdots\cdots (7)$$

Rossby and Montgomery (1957) on the other hand claim that it takes the following form,

$$K_z = \frac{K_o}{1+aE_o} \quad \cdots\cdots (8)$$

where a is some empirical coefficient.

However, these expressions can not be utilized to our investigation for shallow and strongly stratified channels where some strong horizontal current exists in the thermocline layer, because they can be applied to open ocean.

At present, there is no detailed investigation on the general procedures of vertical transfer in channel where the thermocline layer has a some strong horizontal current velocities and the water is strongly stratified.

In order to derive an empirical relation between K_z and E, we set a form of

$$K_z = aK_zE + bE + c \quad \cdots\cdots (9)$$

or

$$K_z = -b/a + \frac{c+b/a}{a(E-1/a)} \quad \cdots\cdots (10)$$

where a, b and c are empirical coefficients.

Replacing b/a by β, equation (10) becomes;

$$K_z = -\beta - \frac{c+\beta}{a(E-1/a)} \quad \cdots\cdots (11)$$

where a, β, c are empirical coefficients to be determined from observations.

With the numerical values obtained by fitting each curves described in Fig. 6, one finds that for Septemper

$$K_z = -9.48 + 239/0.005(E-193) \quad \cdots (12)$$

for May

$$K_z = -257 + 1,463/0.0135(E+74) \cdots (13)$$

and for December

$$K_z = 166.19 + 875/0.748(E-1.34) \cdots (14)$$

The numerical values in equation (12), (13) and (14), of course, reflect the effect of the seasonal variation of the vertical components of the current speed.

CONCLUSIONS

The vertical distribution of stability and turbulent diffusion coefficients has been investigated in a shallow and stratified channel in order to obtain a relation between E and K_z.

It is found that our results describe the general trends of the effect of stability on the vertical turbulent diffusion coefficients in the case of shallow and strongly stratified channels where the water masses are subject to seasonal changes.

Our relation between E and K_z turns out to be different from the conventional expressions which are applicable for open ocean.

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