

On the Cyclonic Eddy in the Ocean (II)

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The cyclonic eddy is called the cold water mass by Japanese oceanographers and the water mass has been studied concerning its growth and contraction, which are regarded as important on the account of its influence on weather and fishery, rather than its structure and characteristics.

The water making up the oceans can be classified into divisions which are defined by a certain relationship between the various independent parameters of seawater. Each of these divisions is described by its location, sometimes also according to depth and its area of origin.

In this paper, we study the structure and the characteristics of cold water mass, that is to say, cyclonic eddy. It is necessary for inferring the structure, namely, the interface depth profiles of the eddy, to perform a numerical formulation for the distribution of whirl speed of the eddy. An attempt for numerical formulation of the whirl velocity distribution which takes a parabolic velocity profile is made by authors. Other trial estimation for the velocity distributions of vertical and radial direction are reviewed and examined in this paper. By clarifying the whirl velocity profile, it will be possible to elucidate the interface depth profiles and vertical water movements in the interior of the eddy.

Key words : Water mass, cold eddy, cyclonic eddy, whirl velocity distribution, numerical formulation

1 Introduction

1.1 Water mass

The water making up the oceans can be classified into divisions which are defined by a certain relationship between the various independent parameters of seawater. Each of these divisions is described by its location (sometime also depth) and its place of origin. These water divisions are known as water masses. A cyclonic eddy or an anticyclonic eddy also has been called cold water mass or warm water mass.

Cold water mass and warm water mass are both important on account of the influence on weather and fishery. Then cold or warm water mass has been studied on its growth and decrease by Japanese oceanographers only the volume of the water is important for the problem mentioned above.

In this paper, we are going to study the structure

and the characteristics of cold water mass, namely, cyclonic eddy reviewing on general nature of cyclonic eddy and how it is brought up.

1.2 Origin of eddies

Cyclonic and anticyclonic eddies are generated by the Kuroshio Extension, and the Gulf Stream, and have diameters of about 200km. Early observations the temporary meanders and cyclonic eddies were excuted by Fuglister and Worthington (1951). In this explorations, a 500km-long meander of the Gulf Stream has begun to detach and form an autonomous, cyconic eddies. The eddies are approximately circular structures, so called rings, formed by pinching off from a steam meander. The cyclonic eddies, formed south of the stream (the Gulf Stream and also Kuroshio Stream), has a central core of cold

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slope water surrounded by a cyclonic current [Knauss (1978)¹⁾, The Ring Group (1981)²⁾].

The warm core rings, namely anticyclonic eddies, formed to the north of the stream, are an isolated lens of warm surface water lying on top of the cold slope water. In other words, meander form loop to south and cold-water mass from the north of the stream is isolated.

In the Kuroshio Stream, meanders appear after it passes off Kii Peninsula. Often meanders grow large, and it become unstable and break off from the stream and form large cyclonic eddies³⁾. These eddies appear to last from several months to few years, and to be reabsorbed into the stream.

1.3 Origin of eddy and the Mindanao Eddy

The western equatorial Pacific Ocean is characterized by a vigorous and complex near surface circulation. The North Equatorial Current splits as it encounters the Philippines, separating into a northwest flowing currents and southward Mindanao Current (Nitani, 1972)⁴⁾. The bulk of the Mindanao Currents is in turn thought to deflect to the east off the southern Philippine coast the supplied the North Equatori-

al countercurrent (Lukas R., 1988)⁵⁾.

Takahashi (1959) (see Lukas, 1988) found out the existence of a cold water mass east of Mindanao by observations. Wyrski (see Lukas, 1988) showed that this quasi-permanent Mindanao eddy is associated with the turning of North Equatorial Current Waters at the Philippines and their subsequent flow to the east in the North Equatorial Countercurrent. In Fig. 1, Meridional section of salinity distribution along 130°E shows Mindanao eddy around 7°N.

It is thought that the eddy of the cold water mass relates to the current surrounding it and the upward advection. The oceanographic testimony for equatorial upwelling has been confirmed by many oceanographers (Sverdrup et al., 1942 ; Yoshida, 1958)⁶⁾. In the equatorial area the upwelling water balancing the lateral out flow in the Ekman layer can be derived from geostrophic convergence.

From what depth is the upwelling water derived in the area off the coast of Mindanao ? Wyrski (1981)⁷⁾ mentioned the current caused by Mindanao eddy extends to a depth of about 600m when the geostrophic computations are referenced to 1250 dbar. In the lower layers, water motions are induced by the

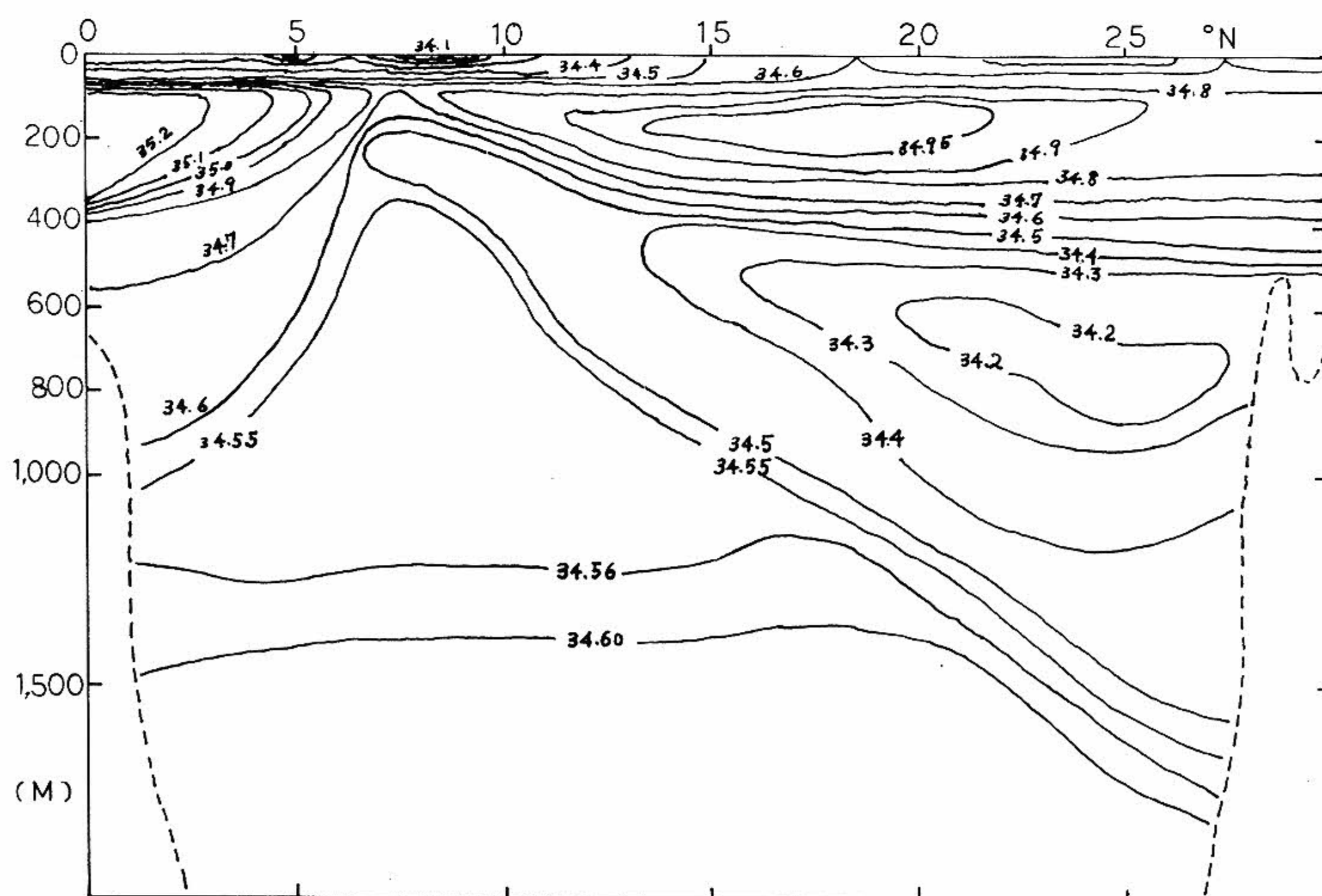


Fig. 1 Meridional section of salinity distribution along 130°E shows Mindanao Eddy around 7°N. [plotted from maps by JODC]

changes in pressure field as a consequence of the horizontal divergence in the upper layer. Off the coast of Mindanao, they are thought that southward transport are needed to induce upwelling in the surface layer and to close the circulation Mindanao Current actually contribute to the large scale circulation of the region.

Nitani (1972) estimated southward volume transport (relative to 1200 dbar) from the bifurcation of the North Equatorial Current. He showed about 15 Sv recirculating in Mindanao Current of about 40 Sv. Wyrtki (1981) mentioned as follows : In the equatorial upwelling area of Pacific Ocean, below 50m the geostrophic convergence is 46 Sv, all of which is used for upwelling.

1.4 Characteristics of eddies

Observation to look for eddies and to investigate their characteristics were made in the 1970s (the USSR, POLYGON experiment and the USA-UK, Mid Ocean Dynamics Experiment ; MODE). These experiments were executed in the North Atlantic but existence of eddies has been confirmed in many other areas of the world ocean.

The eddies have characteristics sizes of the order of 100 to 500km, time scale of several months to a few years. Emery (1982)⁸⁾ gives results for the North Atlantic and North Pacific of dynamic height variability, an indication of eddy kinetic, and estimates of eddy potential energy based on temperature variations at 300m depth.

In strong currents, such as the Gulf Stream, the kinetic energy of the eddies and meanders is of the same order as the mean kinetic energy. Most of the energy associated with the mean flow is the potential energy of the tilted isobaric surfaces⁹⁾ (Pond and Pickard, 1983). Based on observations and on numerical models which contain mesoscale eddies the strongest currents but there is evidence of some eddy activity virtually everywhere. Since eddy activity is high in strong current regions they are likely source regions. In mid-ocean regions, variations in the wind stress may contribute to the eddy activity but this contribution is thought to be a small fraction

of the total.

So we think that eddy is an accumulator storing the current energy as a tropical cyclone. But an eddy's life is much longer than a tropical cyclone owing to the difference of specific gravity between water and air.

2 Distribution of whirl velocity

2.1 Whirl velocities

We can only recognize a general view of an eddy by mean of contour maps of temperature or dynamic height. Distribution of whirl velocity is guessed from their isotherms. The maximum whirl velocity is inferred in the vicinity of the multiplex circles where the contour lines (the circled) of dynamic height are most dense, and the maximum velocity is posited midway presumably between the center and the outskirt of an eddy.

In the plane figures of eddies, there are several types of the shape, i.e. round circular, elliptical, semi-lunate, The meridional or longitudinal distribution of whirl velocity must be both symmetric in either case with respect to the origin of the coordinates. Moreover, the curve of the whirl velocity distribution have relative maxima, on the both sides of the eddy center, between the center and outskirts, and then the distribution curve seem to be something like a normal distribution in those ranges. Firstly we take up a cyclonic eddy of parabolic velocity profile which has a region of maximum whirl speed associated with zero velocity at center of the eddy and vanishing velocity at some distance. We assume that the maximum velocity V_{0m} and the distance from center to a region of maximum velocity, r_m are known quantities. We take parabolic velocity profile as shown following,

$$V_{\theta}(r) = 2 \frac{V_{0m}}{r_m} r \left(1 - \frac{r}{2r_m} \right) \dots \dots \dots (1)$$

The expression in the bracket means that mentioned above. Then $V(r)$ comes to the maximum value V_m at radius $r=r_m$, and to zero at center ($r=0$) and at distance of $r=2r_m$.

2.2 Equation of motion

The relation of the pressure gradient to the velocity field will be governed by the following equation.

$$V_\theta^2(r)/r + fV_\theta(r) = (1/\rho) dp/dr \quad \dots\dots\dots(2)$$

In this equation, the first term of the left side is outward action force called centrifugal force. Excluding this centrifugal term, eq.(2) shows a balance between the Coriolis force and the pressure force in the horizontal plane. The balance is called the geostrophic relation, and the major currents in the ocean obey this geostrophic relation to a first approximation. The currents flow nearly parallel to isotherms or more exactly to dynamic depth contours.

The centrifugal force involved in this balance are very small, the pressure gradient and Coriolis forces are the largest horizontal forces in much of the ocean. All the major surface currents are maintained by the slope of the sea surface.

On a cyclonic eddy motion, the centrifugal acceleration of the whirl velocity and Coriolis force push the water out against pressure gradient force. Substituting the pressure gradient of the right side term by the sea surface height (dynamic height), Ep. (2) is ;

$$V_\theta^2(r)/r + fV_\theta(r) = g' dh/dr \quad \dots\dots\dots(3)$$

where $h(r)$ indicates the upper layer height in the reduced gravity model and g' is the reduced gravity defined by $g' = \Delta\rho/\rho$, in which $\Delta\rho$ is the density difference between the layers.

In eq. (3), the dimensionless number, the ratio of centrifugal force to Coriolis force is significant, namely,

$$Ro = \frac{V_\theta(r)}{fr} \quad \dots\dots\dots(4)$$

that is called Rossby Number. Here r and $V_\theta(r)$ must be selected as typical values for length and whirl velocity respectively. The characteristic length is regarded as a distance from velocity of an eddy is maximal. So r come to r_m and necessary $V_\theta(r)$ to $V_{\theta m}$. Then eq. (4) can be rewrite as follow

$$Ro = \frac{V_{\theta m}}{fr_m} \quad \dots\dots\dots(5)$$

We put fRo for $V_{\theta m}/r_m$ in eq. (1), get

$$V_\theta(r) = 2 fRo r \left(1 - \frac{r}{2r_m}\right) \quad \dots\dots\dots(6)$$

The parabolic velocity distribution of cyclonic eddy will be rewrite as above by Rossby Number. The formulation of whirl velocity distribution is applicable to describe the eddy structure.

3 Distributions of radial and vertical velocities

It has been thought there are an upwelling and a sinking in the interior of a cyclonic eddy and anticyclonic eddy respectively. In both the eddies, there must be a radial water movement according to mass conservation law, because a vertical flow exists whatever it is a slight flow. It is not easy to measure radial and vertical mass movements for their slightness. However, we may estimate the velocities of radial and vertical flows using methods attempted by Tomosada (1984) or Chu (1991)⁽¹¹⁾.

Tomosada (1984)⁽¹⁰⁾ inferred the velocity distributions of vertical and radial flows in a warm eddy by solving a thermal equation and a equation of motion simultaneously and using the observational data of whirl velocity (V_θ) and temperature distributions (T) of the warm eddy.

The velocity distributions of vertical and radial flows estimated by equations (7) and (8) are shown in figures 2-(a) and (b) respectively. His result shows that there is the convergence, which makes a rich fishery, around the outskirts of the warm eddy.

$$V_z = \left(L \frac{\partial T}{\partial r} - \eta \cdot M \right) / \left(\frac{\partial T}{\partial r} \frac{\partial V_\theta}{\partial z} - \eta \frac{\partial T}{\partial z} \right) \quad \dots\dots\dots(7)$$

$$V_r = \left(M \frac{\partial V_\theta}{\partial z} - L \frac{\partial T}{\partial z} \right) / \left(\frac{\partial T}{\partial r} \frac{\partial V_\theta}{\partial z} - \eta \frac{\partial T}{\partial z} \right) \quad \dots\dots\dots(8)$$

where

$$\eta = \frac{\partial V_\theta}{\partial r} + \frac{V_\theta}{r} + f$$

$$L = A_h \left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial V_\theta}{\partial r} - \frac{V_\theta}{r^2} \right) + A_v \frac{\partial^2 V_\theta}{\partial z^2}$$

$$M = K_h \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + K_v \frac{\partial^2 T}{\partial z^2}$$

Chu (1991) estimated the velocity distributions of vertical and radial flows in a cold eddy, setting the whirl velocity distribution as Gaussian and using some simultaneous equations. The calculations

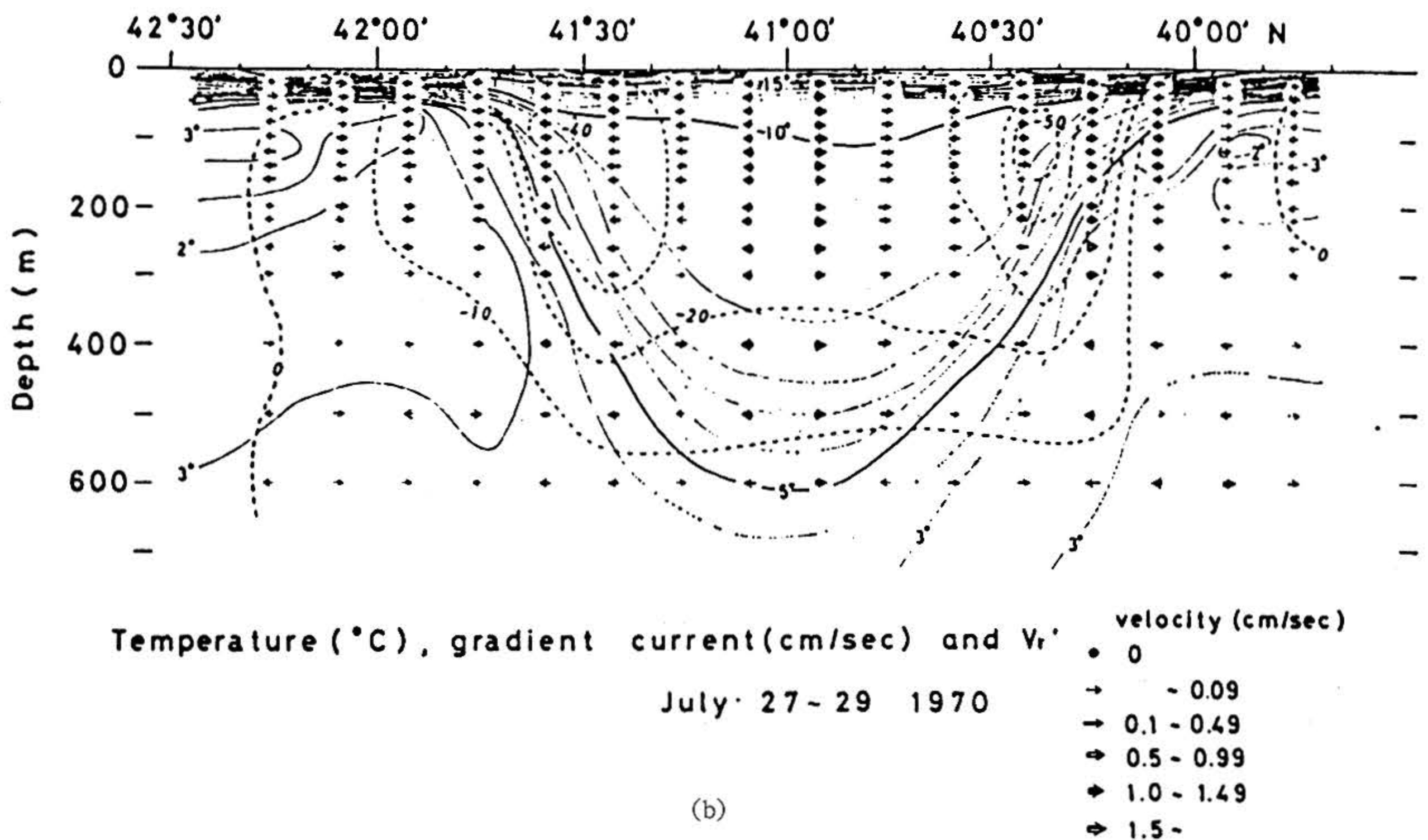
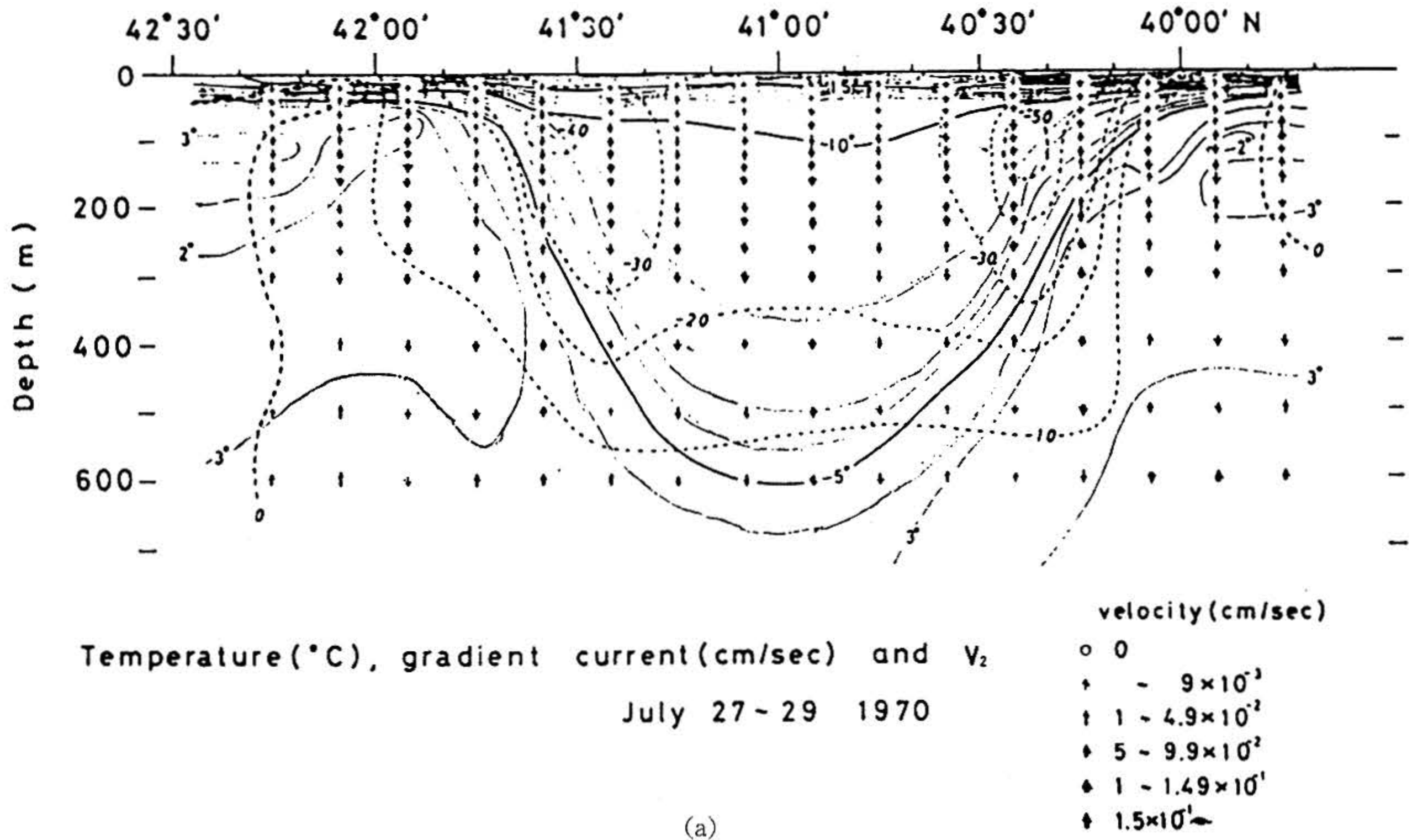


Fig. 2 An estimation of the radial and vertical velocities in a warm eddy.

[Tomosada (1984)]¹⁰⁾

(a) Meridional section along 145°E of temperature (solid line) and gradient current (broken line) from the data of July 27-19 in 1970 and radial velocity estimated by eq. (8). Here, $A_h = K_h = 1 \times 10^7$ (cm²/s), $A_v = K_v = 0$.

(b) Meridional section along 145°E of temperature (solid line) and gradient current (broken line) from the data of July 27-19 in 1970 and vertical velocity estimated by eq. (7). Here, $A_h = K_h = 1 \times 10^7$ (cm²/s), $A_v = K_v = 0$.

must solve a nondimensional partial differential equation (9) for Stokes stream-function $\tilde{\Psi}$ under boundary condition (10).

$$\begin{aligned} & (Bu + Ro\tilde{D})\frac{\partial^2 \tilde{\Psi}}{\partial \tilde{r}^2} + 2Ro\tilde{B}\frac{\partial^2 \tilde{\Psi}}{\partial \tilde{r}\partial \tilde{z}} + \tilde{C}\frac{\partial^2 \tilde{\Psi}}{\partial \tilde{z}^2} \\ & - (Bu + Ro\tilde{D})\frac{1}{\tilde{r}}\frac{\partial \tilde{\Psi}}{\partial \tilde{r}} \\ & + \left(\frac{\partial \tilde{C}}{\partial \tilde{z}} + Ro\frac{\partial \tilde{B}}{\partial \tilde{r}} - Ro\frac{\tilde{B}}{\tilde{r}}\right)\frac{\partial \tilde{\Psi}}{\partial \tilde{z}} = 0 \end{aligned} \quad \dots\dots\dots(9)$$

$$\tilde{\Psi} = 0, \text{ at } \tilde{r} = 0, \tilde{r} = 1, \tilde{z} = 0, \tilde{z} = 1 \quad \dots\dots\dots(10)$$

Some examples of the estimations are shown in figure 3 with four parameters (Ro, Bu, m_r, m_z). The clockwise circulation and a anticlockwise circulation are both seen in the figure of a cyclonic eddy.

4 Conclusion

To understand the structure of a cold eddy, performing the numerical formulation of the whirl

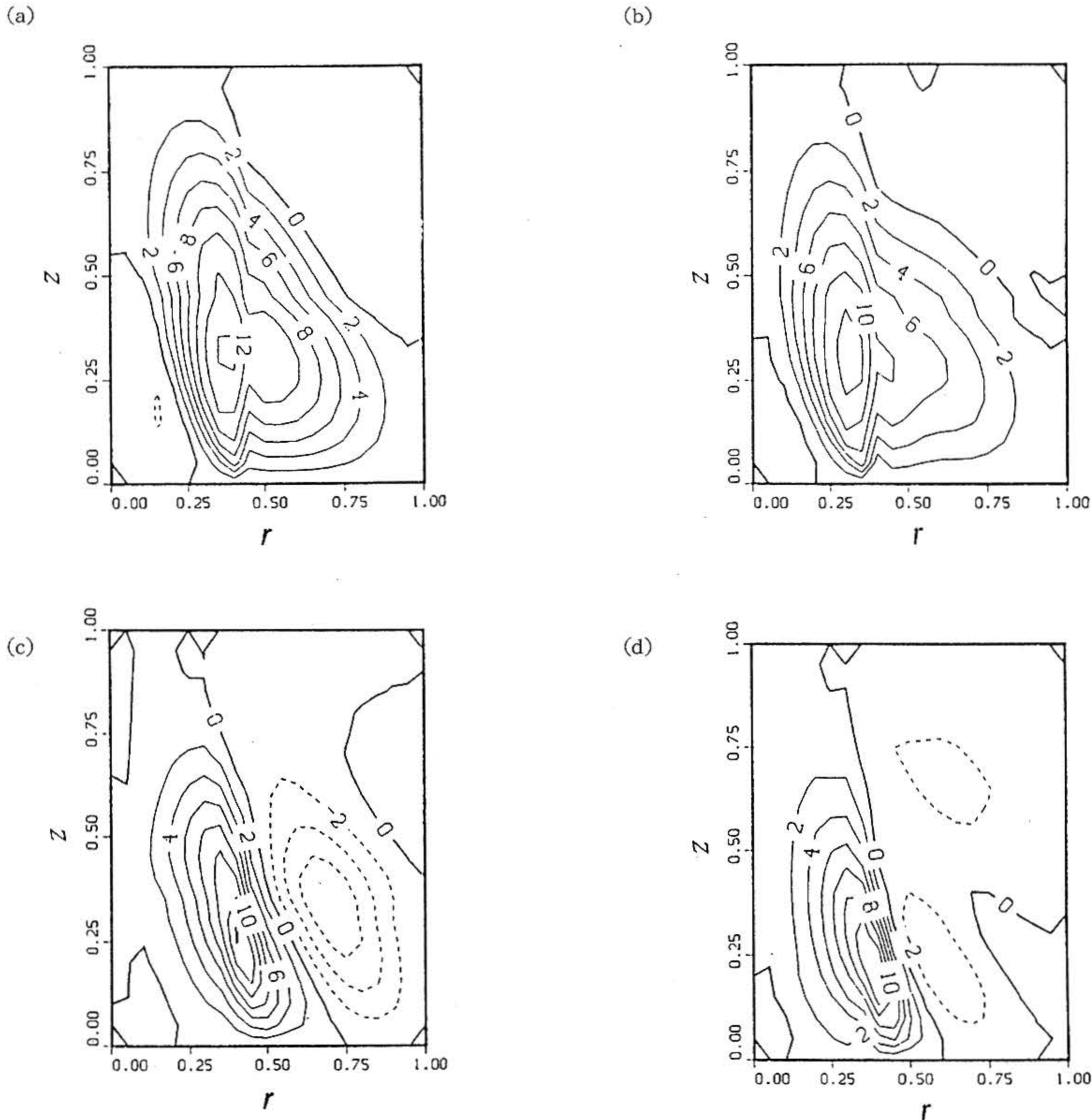


Fig. 3 An estimation of the radial and vertical velocities in a cold eddy. [Chu (1991)]⁽¹⁾

The streamfunction in radial-vertical section for the the Burger number $Bu=1$, the Rossby number $Ro=0.2$ and the two parameters m_r, m_z in Gaussian distribution :

(a) $m_r=0, m_z=0$, (b) $m_r=4, m_z=0$, (c) $m_r=0, m_z=4$, (d) $m_r=4, m_z=4$

Here, $r=0, 1$ and $z=0, 1$ indicate the center, the edge, the bottom and the top of the eddy.

velocity distribution is essential. Trial for numerical formulation of the whirl velocity distribution which takes parabolic velocity profile is performed by authors. Another trial estimations for the velocity distribution of vertical and radial directions are examined in this paper.

We will be able to make clear the interface depth profile and vertical water movement in the interior of the eddy, based on clarifying the whirl velocity profile.

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References

- 1) Knauss, J.A. : "Major ocean currents." p 137-165, In : Introduction to physical oceanography. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 388 pp. (1978).
- 2) The Ring Group^{*)} : Gulf Stream Cold-Core Rings ; Their physics, chemistry, and biology. Science, **212** (4499), 5 June. (1981).
- 3) Okuda, K., et al. : 黒潮続流域の冷水塊, Proceeding of the spring meeting in The Oceanogr. Soc. of Japan, 150-151, (1992).
- 4) Nitani, H. : "Beginning of the Kuroshio," p 129-163, In : Kuroshio ; Physical aspects of the Japan Current, Edited by H. Stommel and K. Yoshida, University of Washington Press, Seattle. (1972).

- 5) Lukas, R. : Interannual fluctuations of Mindanao Current inferred from sea level. J. Geophysical Res., **93**, 6744-6748. (1988).
- 6) Yoshida, K. : A study on upwelling. Records of oceanographic works in Japan 4, 166-172. (1958).
- 7) Wytki, K. : An estimate of Equatorial Upwelling in the Pacific. J. Phy. Oceanogr., **11**, 1205-1214. (1981).
- 8) Pickard, G.L. and W.J. Emerry : Descriptive physical oceanography. Pergamon Press, 4th edition, pp 249, An introduction to descriptive (synoptic) physical oceanography for science undergraduates and graduates. (1982).
- 9) Pond, S. and G.L. Pickard : "Models with mesoscale eddies." p 198-206, In : Introductory dynamical oceanography. Pergamon Press, Oxford, New York, Beijing, Frankfurt. (1989).
- 10) 友定 彰 : 黒潮と暖水塊に伴うフロントと漁業, 沿岸海洋研究ノート, **21** (2), 129-138. (1984).
- 11) Chu, P.C. : "Vertical cells driven by vortices - a possible mechanism for the preconditioning of open-ocean deep convection." p 267-281. In : Deep convection and deep water formulation in the oceans, Edited by P.C. Chu and J.C. Gascard, Elsevier Science Publishers, 382 pp. (1991).

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海洋における冷水渦についての研究 (II)

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黒潮沖合の発生する低気圧性の渦は冷水渦と呼ばれ、渦の機構や特性としての研究よりも気象や漁業に影響する水質や水塊の消長に重点が置かれていた。

大洋を構成する水は種々の独立要素間の関係によって規定された区分に分けられる。それらの海水は、その存在する場所あるいは深さそしてその生成の海域によって、それぞれ呼び名が決まっている。

本論では冷水塊すなわち冷水渦の形とその性質について調べようとした。渦の構造、すなわち渦の内部の姿を理解するには渦の旋回速度分布を数式化する必要がある。著者らによる一つの試みとして放物線型の旋回速度分布が採用された。他の研究者による同様の試みの例についても検討を行った。渦の旋回速度を明確にすることは、渦の姿や渦内部の水の鉛直運動の理解を可能にすると考えられる。

キーワード：水塊，冷水渦，低気圧性渦，旋回速度分布，数式化

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