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Diagnostic calculations of the Kuroshio current using the hydrographic data South of Japan*

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The major objective of the paper is to continue the study of the Kuroshio current "bimodality" South of Japan. The observational data were obtained in 40 oceanographic cruises by the FERHRI vessels during the period 1980–1990. Some of these periods were characterized by the on-shore (shelf), non-large meander state, whereas during the other periods, a typical off-shore, large-meander path was formed. The *P*-vector inverse as well as the conventional dynamic methods were used as the diagnostic approaches for the 3D velocity fields estimate for these data. The differences for the two methods were analyzed.

There are many works devoted to the study of the existence of the multimode stable states of the Kuroshio jet (see bibliography in the paper by Kozlov [1]), but there is no complete solution to the problem yet [2].

A diagnostic study of the Kuroshio current was carried out in a number of works [1, 3], etc. In these studies, a large volume of information concerning the state of the Kuroshio during the last fifty years was presented.

This paper represents the sequel to the diagnostic study on the basis of the observational data obtained from 40 of the Far East Regional Hydrometeorological Research Institute (FERHRI) oceanographic cruises during the decade period within the "SECTION" Program 1981–1990. The measurements data reaching the depth of 1500 m were interpolated to the regular 1/3 degree grid. The temperature and salinity fields were analyzed with the use of the Principal Component (PC) approach which enables one to separate the main states of the Kuroshio current. The velocity fields were estimated for all the cruises on the basis of the P-vector inverse method proposed by Chu et al. [4] and were compared to the results of the classical dynamic method.

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1. Principal component hydrophysical fields analysis

In Figures 1a, b, the temperature fields for the two selected periods of November, December, 1988 at a depth of 500 m are presented. One can see that whereas the first period is characterized by the onshore temperature isolines distribution, the second period, on the contrary, is characterized by a negative temperature anomaly, which is connected with a large meander formed in the region.

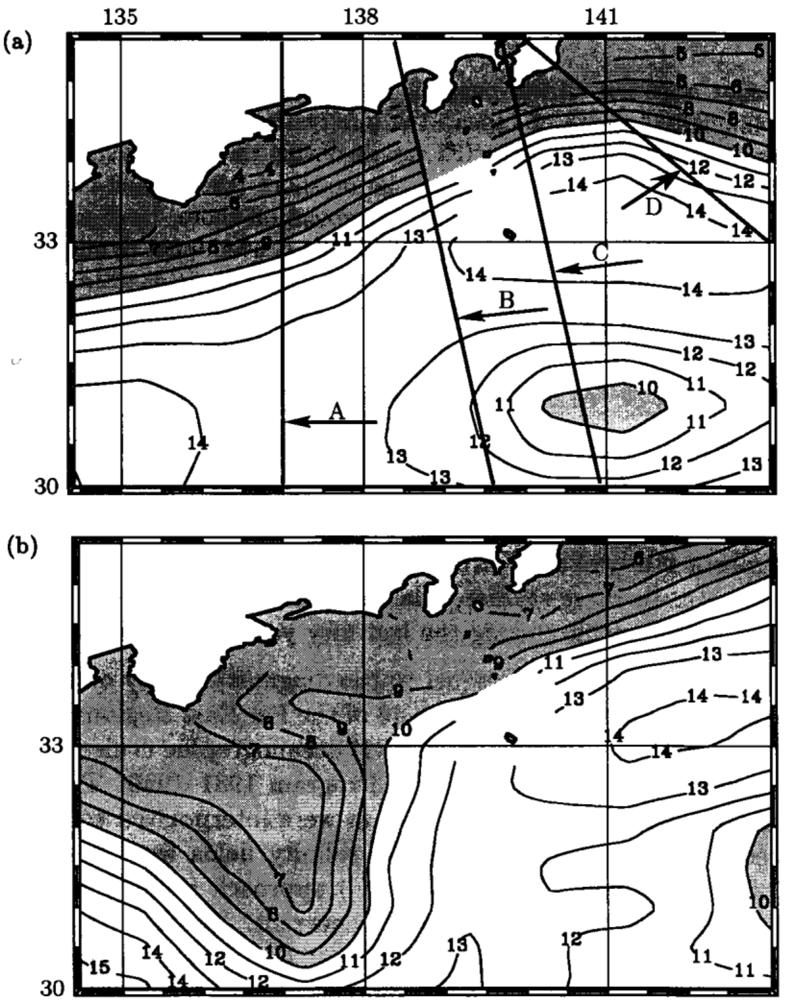

Figure 1. Temperature field at depth $z = 500$ m: a) onshore mode and b) large-meander mode

Analysis of the Principal Components (PC) of the hydrological fields was made on the basis of a standard approach of singular decomposition for the

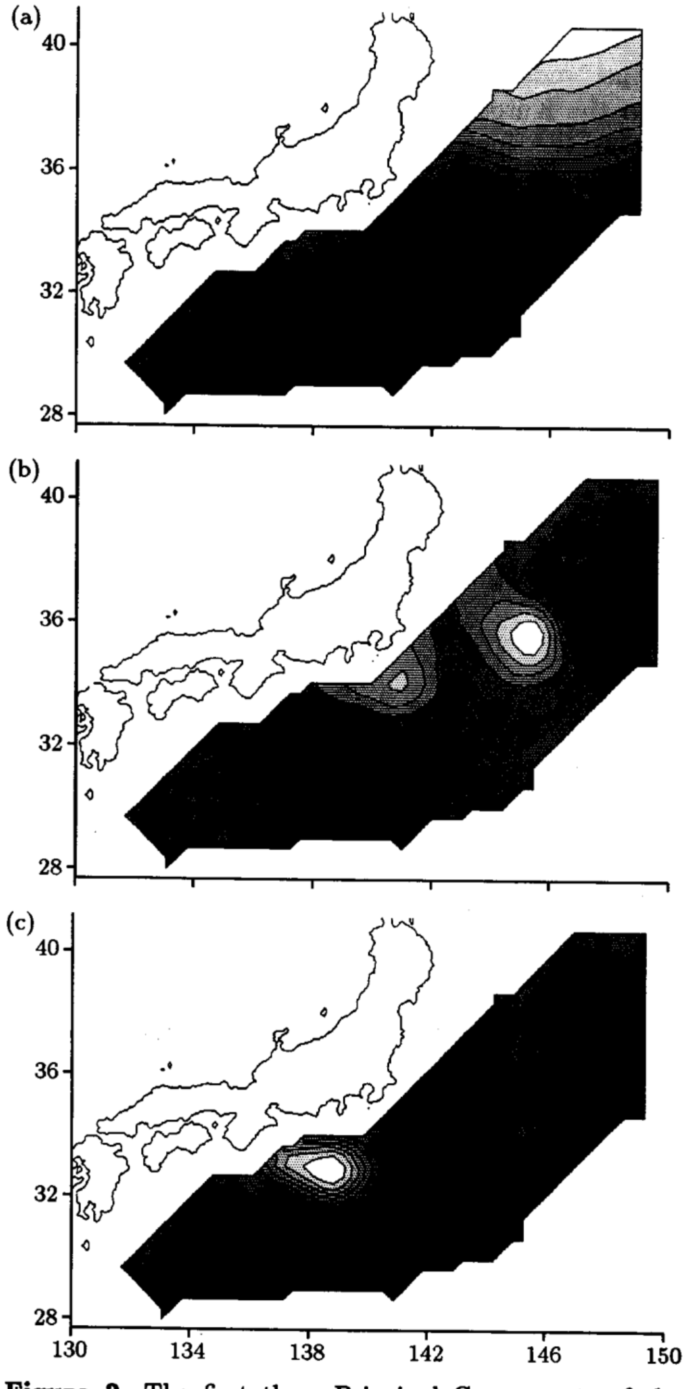

Figure 2. The first three Principal Components of the temperature fields at $z = 200$ m: a) the first PC, b) the second PC, and c) the third PC

covariance matrix of 40 measurements. The first three principal components were found for the levels below 200 m. The analysis shows that the first PC describes the shelf mode (Figure 2a), the second one represents a strong dipole signal in the Kuroshio Extension region (Figure 2b), whereas the third PC describes the ring structure South of Honshu, which is connected with the large meander formation in this zone (Figure 2c). The maximum amplitude of the time varying factor of the third PC corresponds to the periods of the large-meander occurrence. The PC pictures slightly change with depth which indicates to the changes in the temperature field structure.

2. *P*-vector method

Reconstruction of the 3D velocity fields was done on the basis of the *P*-vector (PV) inverse method approach which estimates the absolute velocity field, according to Chu et al. [4]. The *P*-vector method is a modification of the "beta-spiral" method proposed by Stommel and Shott, [5]. The stationary density and potential vorticity conservation laws have a form:

$$\vec{u}\cdot\nabla\rho = 0, \qquad \vec{u}\cdot\nabla q = 0,$$
$$\vec{u} = (u, v, w), \quad q = f\frac{\partial\rho}{\partial z}, \quad \nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right). \tag{1}$$

The consequence of these relations is that the velocity vector $\vec{u}$ is orthogonal to both gradients and hence coincides with the normalized vector P whose direction is the consequence of the product of the density and the potential vorticity gradients:

$$\vec{u} = r(x, y, z)\vec{P}, \qquad \vec{P} = \frac{\nabla\rho\times\nabla q}{|\nabla\rho\times\nabla q|}. \tag{2}$$

The factor of proportionality $r(x, y, z, t)$ for the absolute velocity $\vec{u}$ can be found by the least squares method to minimize deviations between the *P*-vector and the vector $\vec{U}$ obtained by using the thermal wind equations:

$$\Delta\vec{U}_{km} = \vec{U}^{(k)} - \vec{U}^{(m)} = g\vec{K}\times\int\limits_{z_m}^{z_k}\frac{\nabla\rho\, dz}{f\rho_0}.$$

Minimization of the error function integrated over the whole water column gives the system of 2×2 linear algebraic equations for the determination of the components u^k, v^k for each level $k = 1, N$:

$$u^{(k)}A_{11}^{(k)} - v^{(k)}A_{12}^{(k)} = f_1^{(k)}, \qquad -u^{(k)}A_{21}^{(k)} + v^{(k)}A_{22}^{(k)} = f_2^{(k)}.$$

Here the coefficients and the right-hand side have the form:

$$A_{ij}^{(k)} = \sum_{m \neq k} a_{ij}^{(m)}, \qquad f_i^{(k)} = -\sum_m \sum_{j=1}^{2} a_{ij}^{(m)} (\Delta u_j)_{km},$$

$$a_{ij}^{(m)} = P_{u_i}^{(m)} P_{u_j}^{(m)} F^{(m)}, \qquad \vec{U} = (u, v) \equiv (u_1, u_2),$$

$$F^{(m)} = \left[1 + \left(\frac{\partial \rho^{(m)}/\partial x}{\partial \rho^{(m)}/\partial z} \right)^2 + \left(\frac{\partial \rho^{(m)}/\partial y}{\partial \rho^{(m)}/\partial z} \right)^2 \right] h_m^2.$$

It should be noted that the use of any inverse method needs an accurate pre-analysis of data to avoid the instability arising in solution of the ill-posed problem. This problem also takes place in our case for some hydrological situations to be mentioned below.

From the description of the P-vector method it follows that this inverse technique has three constraints for its applicability:

I. From formula (2) it follows that density and potential vorticity gradients should not coincide:

$$|\nabla \rho \times \nabla q| \geq \varepsilon_1.$$

II. According to the validity of the "beta"-spiral method the P-vector is to have a turning with depth, i.e., for each selected level z_k there should exist at least one level z_m, for which

$$\begin{vmatrix} P_u^{(k)} & P_u^{(m)} \\ P_v^{(k)} & P_v^{(m)} \end{vmatrix} \geq \varepsilon_2.$$

III. From the system of equations for the determination of the components $u^{(k)}$, $v^{(k)}$, the resolvability condition is as follows:

$$|A_{11}^{(k)} A_{22}^{(k)} - A_{12}^{(k)} A_{21}^{(k)}| \geq \varepsilon_3.$$

Each of these conditions have to be checked before carrying out calculations for each measurements.

3. Reconstruction of the velocity fields

Reconstruction of the 3D velocity fields has been done for all the measurements. Checking the constraints I–III gives that conditions I and II were fulfilled for all the measurements. However, condition III for some periods was not fulfilled. The analysis of these periods show that it happened for the cold seasons and mainly for the open ocean zones. The reason for this phenomenon may be found in Figure 3 which represents the temperature profile

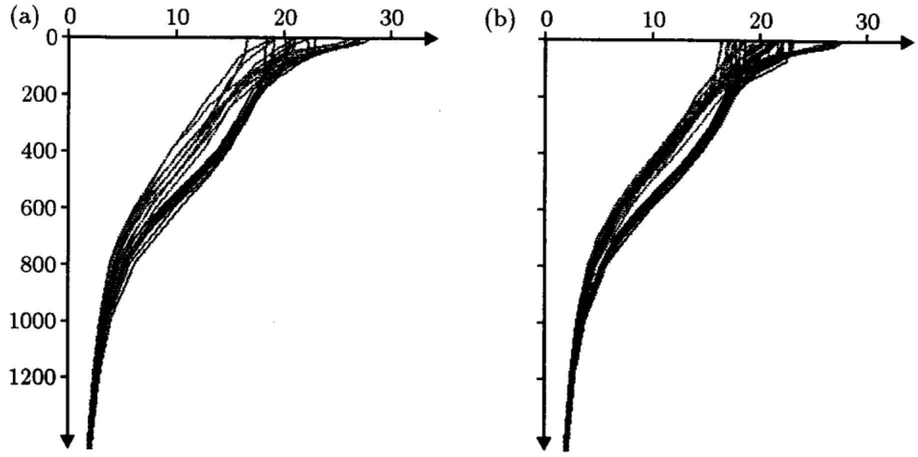

Figure 3. Averaged within the jet and open ocean temperature profiles: a) onshore mode and b) large-meander mode

averaged within the jet and the open ocean zones for each cruise. One can see that in the winter season, the mixed layer of a depth about 100 m is formed. It is the consequence of the convective motion being initiated by the surface water cooling. There exist about seven layers of the standard hydrographic horizons in the upper layer. The geostrophic relation does not work in this layer, and the characteristics are uniform within the whole of this layer. The effect introduction of these layers into the resolving matrix is strong enough, which leads to the poor conditioning of the matrix, i.e., small determinant. When the upper levels were extracted from the consideration one after another, the determinant value was growing up. Finally, after optimization of the levels resulting in maximization of the determinant of the resolving matrix, only the surface and the last mixed layer levels were left. This procedure enables us to regularize the computation of the velocities. The fact of destroying the inverse diagnostic procedures is very natural and was mentioned by Wunsch [6].

The results of calculations give regular velocity fields for all the seasons and both periods of the shelf and of the meander modes. The velocity fields for November and December, 1988, most unstable for the PV method situation are presented in Figure 4. One can see the velocity field for the two typical states of the Kuroshio current at a depth of 200 m. The first state is characterized by the onshore path of the current following the continental slope, whereas in the meander mode, the current in the neighbourhood of the Kii Peninsula turns to the South and forms a cyclonic meander which has an amplitude about 350–400 km. In the eastern part of the basin, there is an anticyclonic quasi-stationary eddy observed in this region. To the east of the Izu Ridge, cyclonic and anticyclonic eddies take place. The maximum velocity for the meander mode is 0.55 m/s, whereas for the shelf mode it is

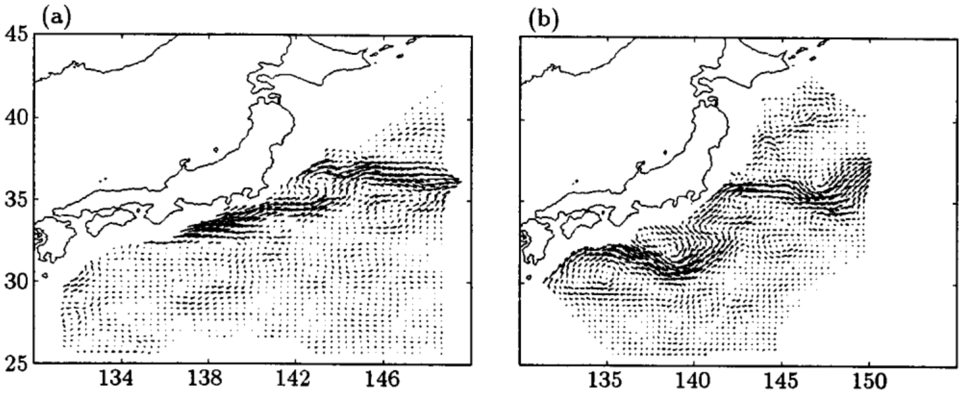

Figure 4. PV velocity field at depth 200 m: a) onshore mode and b) large-meander mode

lower (0.46 m/s). The second method was the classical "dynamic" method (the thermal wind equations) for the velocities estimate with the 1500 m "zero" level depth. It was used as a control run for the P-vector method. The results show rather similar pictures of the direction of the currents, however the PV approach gives more intensive currents than the PV method with difference about 25%.

The third approach for diagnostic calculations for these two measurements was done by the method proposed by Sarkysian [7]. The finite element circulation model developed in the Novosibirsk Computing Center [8] has been used. The model was adapted to the Kuroshio region South of Japan [9]. The reconstruction of the velocity fields with the use of the model gives the pictures very similar to the previous methods. However, the maximum velocities obtained with the use of the model are 0.9 m/s for the onshore trajectory and 0.75 m/s for the meander mode. The reasons for this may be the consequence of the fact that for the third method we calculate the mass transport for the Kuroshio current with the use of the technique analogous to that when we calculate the mass transport in the multi-connected domain [10]. The results obtained gave reasonable values of the mass transport. These are 45 Sv for the non-meander mode and 60 Sv for the meander mode. The barotropic velocities increase the absolute velocities of the current.

4. Conclusions

Analysis of the Principal Components for the temperature and the salinity fields over the period 1980–1990 gives the possibility to separate, at least, two main modes in the Kuroshio states indicating to the "bimodelity" phenomenon and enables us to reconstruct them as pure "noise-free" states.

Diagnostic calculations of the 3D velocity fields of the Kuroshio current South of Japan with the use of the PV method and the comparison of the other two approaches give the results which are qualitatively in agreement, but have a difference in the amplitude of the velocity fields.

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