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Diagnostic calculation of two Kuroshio states*

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The major objective of the present paper is to make the diagnosis of two Kuroshio states and to analyze them from the point of view of their specific features and to make the comparison with the situations discussed in the literature. Another target of the paper is to extend the diagnostic approach created for the analysis of the baroclinic instability of the atmospheric motions (cf., Holton, 1979) to studying the ocean process. This approach has been used by Wang and Ikeda (1993) for the investigation of the ocean currents instability.

The problem of the Kuroshio "bimodelity" as an oceanographic problem has been in existence for about fifty years. As is known, the Kuroshio stream south of the Honshu island takes one of two relatively stable paths which are known as a non-large-meander path (N-type) and a large-meander path (A-type). The first scientific description of the large meander was done by Japanese oceanologists. According to the data of the observational period the duration of the large meander state relative to the non-large-meander state is 4 : 6. The absolute value of the large-meander duration was estimated from three to ten years. The amplitude of the large-meander state is about 360–400 km.

In reality the non-large-meander path falls, at least, into two modes: the onshore and the offshore modes (Taft, 1972, White, McCreary, 1976, Kawabe, 1985).

The first state is characterized by a sufficiently straight flow following the continental slope, whereas the latter has a more curved path, turning around the Miyaki and the Hachijo islands of the Izu-Ogasavara Ridge. Some oceanographers introduce another offshore trajectory (C-type) that is characterized by an easter position of the meander periphery relative to the Izu Ridge (Yoon, Yasuda, 1987). In the observations done for the period from 1955 until 1984, the trajectories A, N, C and B were observed in 35.9, 23.6, 17.6, 13.1 per cent of the total time, respectively.

The transition processes between the Kuroshio states were studied by Kawabe, 1986. These processes are much faster than the main states and have the time-scale lasting a few months. The transition between the non-large-meander and the large-meander paths usually has a directional char-

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acter. This means that the transition from the non-large-meander path to the large-meander path in most cases occurs from the nearshore (1953, 1959, 1975), and the reverse transition produces the offshore non-large-meander path in all the cases observed (1956, 1963, 1980, 1984). Only once, in 1981, the non-large-meander to the large-meander transition seems to have occurred. So, some kind of hysteresis in this dynamic system is observed.

There are many works devoted to the study of the existence of the multi-mode stable states of the Kuroshio jet, but there is no complete solution to the problem yet. Now, let us point out the main ideas of the occurrence of the large-meander as discussed in the literature:

- The Kuroshio meander trajectory as a result of the joint effect of beta-effect and continental slope (Robinson, Taft, 1972);
- Large-meander as a coastly induced Rossby wave bounded by the Izu Ridge (White, McCreary, 1976);
- The Kuroshio bimodelity as multiple equilibria of the nonlinear eastward flow over the sharp bottom topography constraints (Charny, Flierl, 1981);
- The influence of the East-West Japan coast inclination on the specific behaviour of the inertial-viscous jet (Sekine, 1988).

There is also a hypothesis about the processes triggered by the meander growing-up. Among them are the following:

- formation of a cyclonic eddy, the so-called Tanegashima Cold Water near the coastal side of Kyushu,
- amplification of a non-large meander south of the Shinomisaki Cup,
- penetration of the cold Oyashio water masses along the coast south of Japan.

All these hypotheses are reasonable enough, and the influence of the above-mentioned factors obviously exists and is essential for forming a multi-mode state of the Kuroshio stream, however the most interesting idea is that by Charney and Flierl, 1981, and Masuda, 1982, who assumed the bimodelity to be an example of the multi-equilibria of the nonlinear eastward flow which can possess nonunique steady solutions. This causes the existence of the attractor in the phase picture of the process with two or more modes. This idea seems most interesting because it explains many features of the Kuroshio behaviour, whereas the instability theory can describe only some spatial features similar to the phenomena only at some instantaneous times, and could not explain a great difference in time-scales of the quasi-stationary states and the transition processes. A diagnostic study of the Kuroshio current was carried out in a number of works (Taft, 1972, Otsuka, 1985, etc.). In these studies, a large volume of information concerning the state of the Kuroshio during the last fifty years was presented. However, as a rule, some modifications of the dynamic method are used, and this introduces some restrictions on interpretation of the results obtained.

The 3D diagnostic calculations with the use of the finite element numerical model were done on the basis of the climatic T and S data estimated for 12 months in the Far East Hydrometheorological Regional Institute (FEHRI). The results have shown very smoothed velocity fields with weak variations from winter to summer (Golubeva et al., 1993). This was a consequence of averaging the non-meander and the meander states in the historical data.

It was interesting to separate these two states in the data and to study them diagnostically.

This was done for the observational 3D T and S data of the FEHRI two cruises in November and December 1989 in the region 27–38°N, 130–150°E. The first period was connected with a non-meander state and the second – with a typical large-meander state. It should be mentioned that the onshore trajectory of the Kuroshio jet was not typical of the decade period of the observations within the "SECTION" Program 1981–1989.

1. Main features of the model and numerical algorithm

The numerical model used in the present study is the finite element circulation model developed in the Novosibirsk Computing Center (Kuzin, Golubeva, 1986, Kuzin, 1986). The model was adapted to the Kuroshio region south of Japan. For the calculation of hydrophysical fields a regular B-grid is used with respect to the horizontal co-ordinate with 36 nonuniform standard levels in vertical. For the realization of the model with respect to time the splitting method is used. The splitting is done as for the differential equation (splitting with respect to the physical processes) and for the multi-point grid operators. Implicit and semi-implicit schemes are used.

The region was bounded by the coast of Japan and the latitude 27°N and 39°N from the south. The meridional boundaries were as follows: 130°E and 150°E, respectively. On the greater part of the boundaries it was assumed that the solid boundary free-slip conditions were used, except the inflow and the outflow boundaries at the western and at the eastern parts of the basin, where the stream function as well as baroclinic velocities were prescribed.

The climatic wind-stress at the surface was adopted from Hellerman and Rosenstein (1982).

The estimate of the mass transport of the Kuroshio current was done based on the idea following from the method of determining the stream function value in the domain with a multi-connected boundary. Assume that the flow is stationary and its external mode is driven by the integral JEBAR term that exists in the right-hand side of the vorticity equation. Then, it should be agreed that through the liquid boundary there is no mass transport except the inflow and the outflow which are assumed to be equal, and that the basin is closed through the inflow and outflow boundaries. In this case we have the two-connected boundary with different parts and the stream function value at the boundary can be determined in the same manner as for the island (Kamenkovich, 1964). This condition is a natural boundary condition for the differential operator of the integral stream function equation (Zalesny, 1974, Kuzin, 1982).

The results obtained show reasonable values of the mass transport. They are 45 Sv for the non-meander mode and 60 Sv for the meander mode. These values are consistent with the estimations by Nitani (1972), however, are twice as large as estimations by Bingham and Talley (1991), Nakano (1994), Kawabe (1995), whereas these estimations are consistent with the latter in the tendencies of the mass transport during the meander and the non-meander periods.

The above-mentioned deviations require a precise analysis of the mass transport sensitivity to the input parameters of the model.

2. Temperature field analysis

In Figure 1, the temperature fields for the considered periods of November, December, 1989 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 month, on the contrary, is characterized by a well-manifested negative temperature anomaly, which is connected with the large meander formed at the latitudes 138–140°E. The main interesting feature is that to the north of the negative anomaly at the nearshore zone there arises a positive anomaly which reaches the depth of 1000 m (Figure 2). One more specific feature can be seen in Figure 3, where the temperature profiles are averaged both within the Kuroshio jet and the open ocean for the two modes. One can see that for the onshore mode the temperature profile in the jet comes above the profile for the meander mode jet, whereas for the open ocean the temperature distribution is opposite. This means that the gradients for the non-meander state are more intensive than for the meander one. This fact is in agreement with the intensity of currents which will be discussed later.

Temperature distributions at the vertical sections are presented in Figures 4–6.

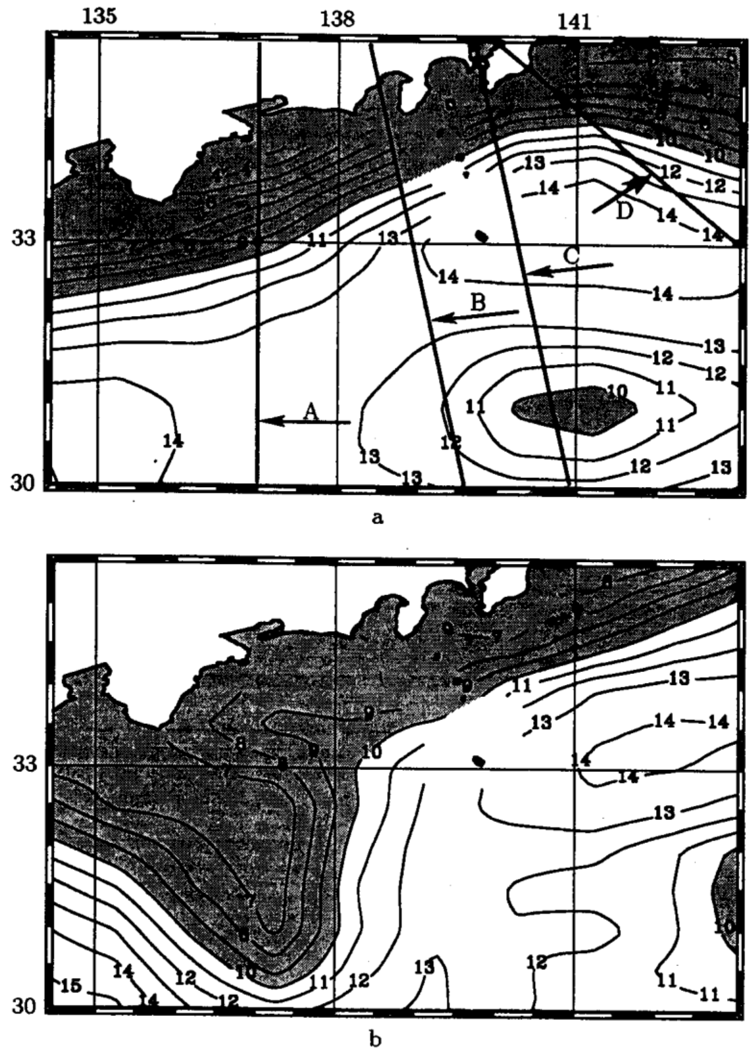

Figure 1. Temperature field at depth $z = 200$ m:
a) straight mode; b) meander mode

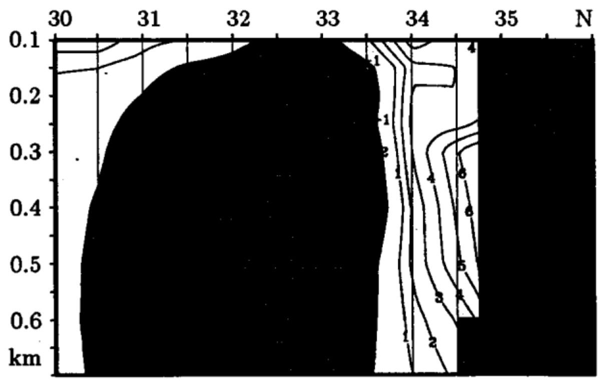

Figure 2. Temperature anomaly field at the section 129°E

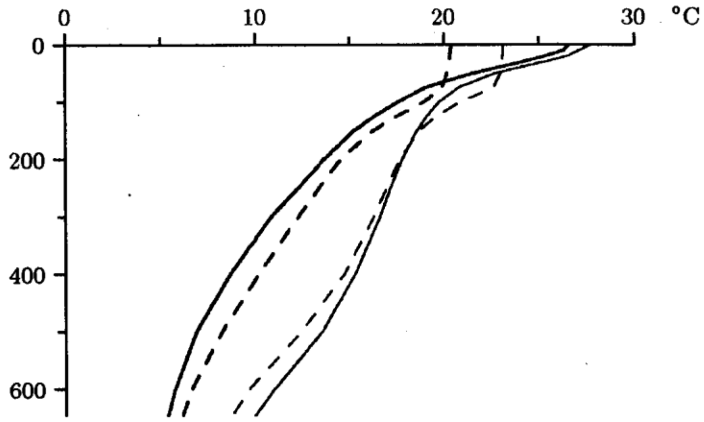

Figure 3. Horizontally averaged temperature:
— straight path, strong jet zone;
— straight path open ocean;
- - meander path, strong jet zone;
- - meander path, open ocean

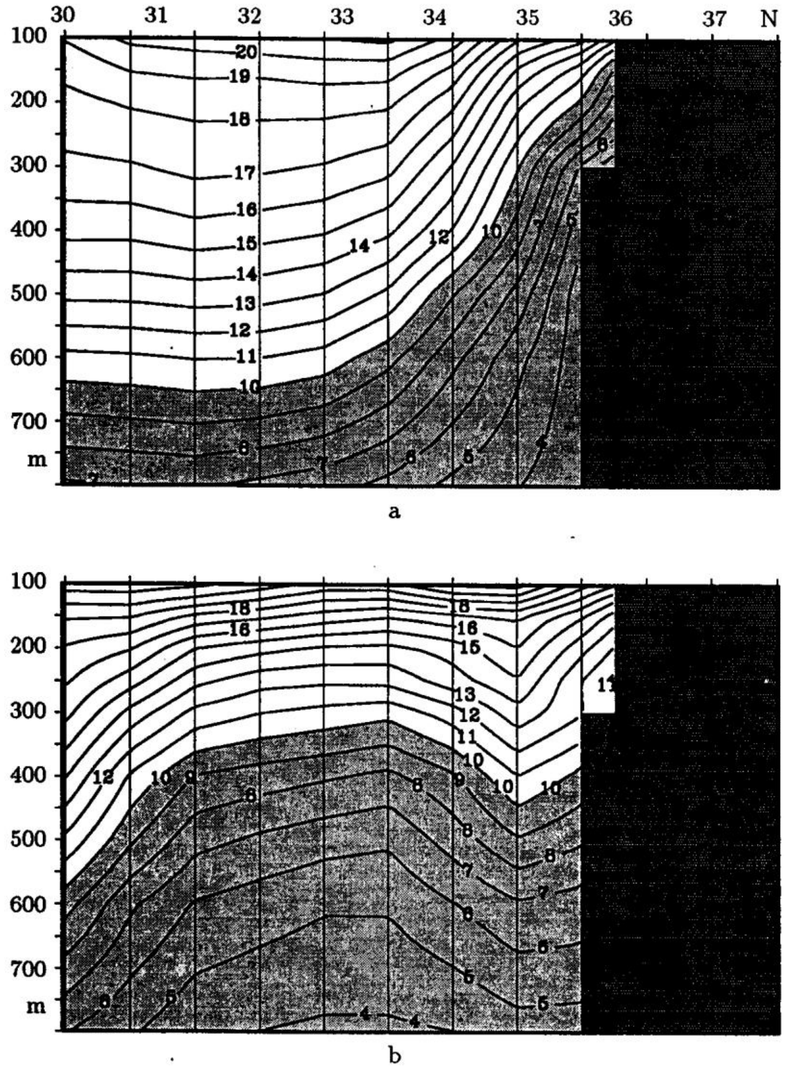

Figure 4. Temperature field at A-section (see Figure 1 a) for the values less than 10′ are shaded: a) straight mode; b) meander mode

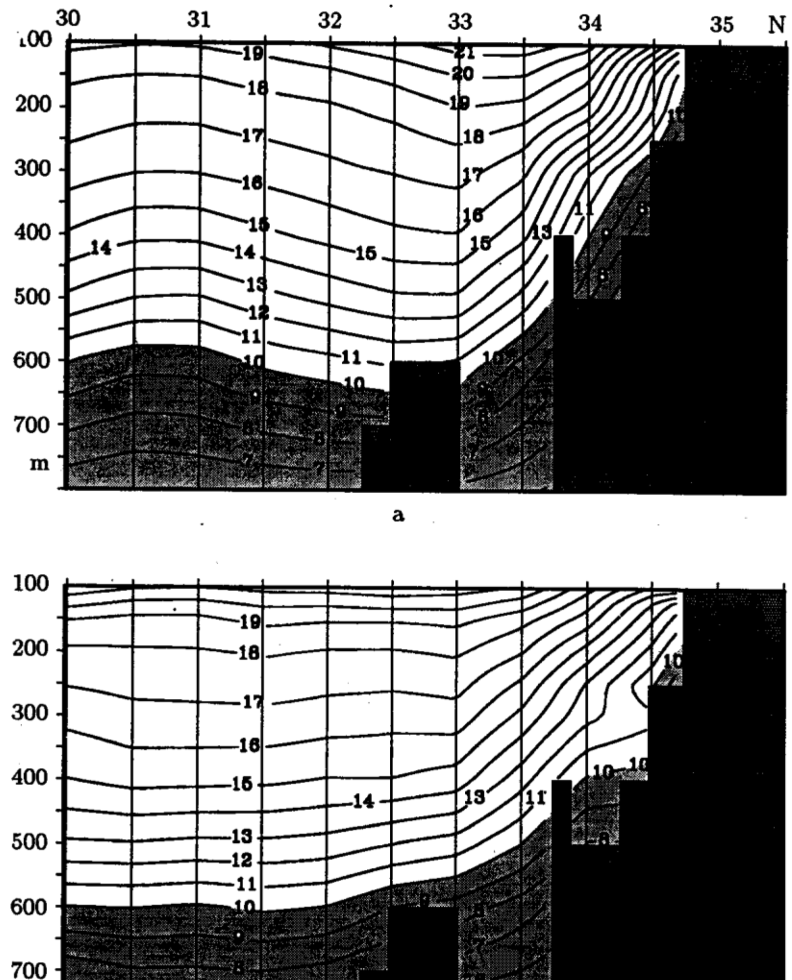

Figure 5. The same as in Figure 4 for B-section

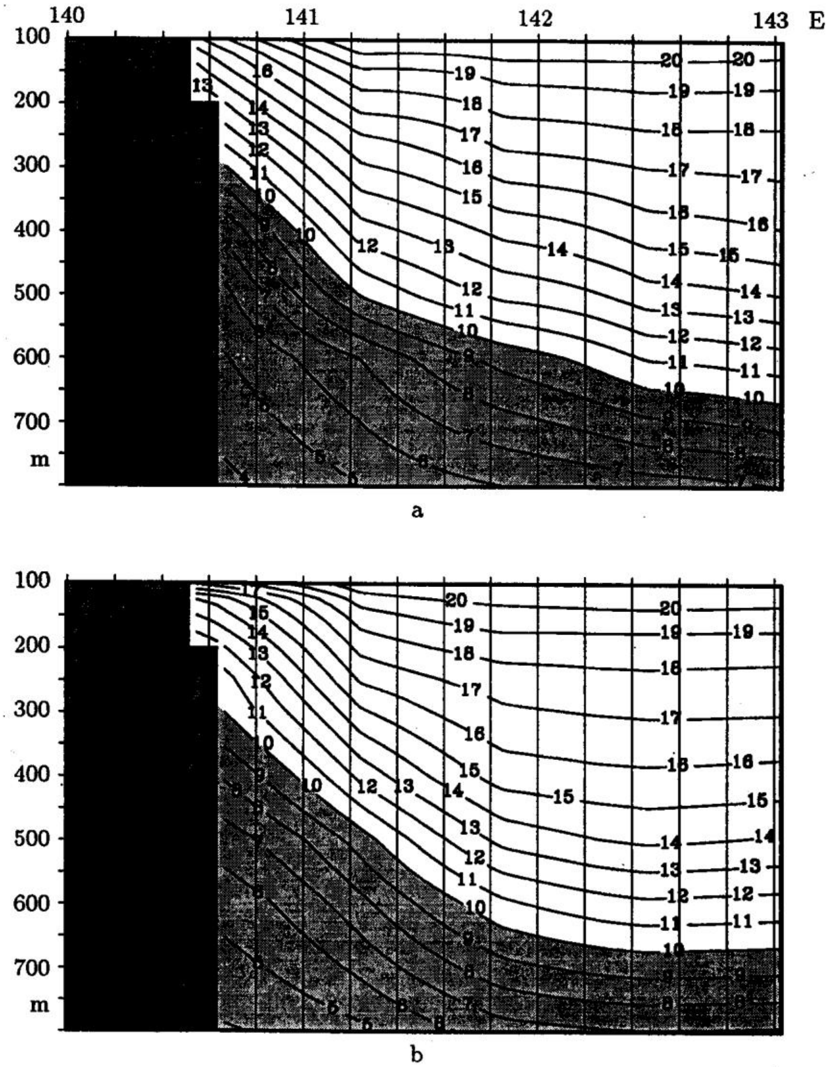

Figure 6. The same as in Figure 4 for D-section

3. Diagnostic velocity fields analysis

The joint diagnostic calculations with the estimated values of the mass transport were done for barotropic and baroclinic components of the velocity field. The calculation was being conducted during 20 days of the model time.

In Figure 7, one can see two typical states of the Kuroshio current at a depth of 200 m. In the eastern part of the basin, there is an anticyclonic quasistationary eddy observed in this region.

The first state is characterized by the onshore direction of the current, 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 being typical of the large-meander state. To the east of the Izu Ridge, cyclonic and anticyclonic eddies take place.

The maximal velocity of 0.9 m/s is observed on the onshore trajectory. For the meander mode, the velocity attains the values not higher than 0.75 m/s. These features at first sight are inconsistent with mass transport for two states. To consider this fact in more detail, let us analyze the velocity fields on certain cross-sections of the basin. On the first A-section (Figure 8) in the western part of the region, both paths are very close to the continental slope and have approximately the same structure. The current has the maximum value of about 65 m/s at the depth of 200 m. The main stream of the non-meander mode is more concentrated and reaches smaller depths as compared to the meander mode which continues up to the depth of 1.3 km.

On the second B-section (Figure 9), the straight mode has a more intensive structure than the meander mode with the velocity 0.8 m/s. The meander mode is also somewhat deeper and wider than a straight one. This is one of the characteristic features which was marked on the basis of the analysis of hydrological fields by Kawabe, 1985. This feature takes place on all the next cross-sections.

In Figure 10 corresponding to the cross-section C, it is possible to see one more specific feature of the Kuroshio jet. At an intermediate depth (500 m) the current has a tendency to shift the maximum value to the south relative to the upper layer. According to the other observational data (Kawabe, 1985) for the meander mode this tendency has to be more significant.

Finally, the D-section gives the picture of the current passing across the ridge. The most essential feature here is that the straight mode passes mainly through the passage between the islands of Myiake and Nachijo off the cost, whereas the meander mode has a path closer to the coast, and only the middle-depth part of the current follows the second strait. In our case, the stream is divided into two parts.

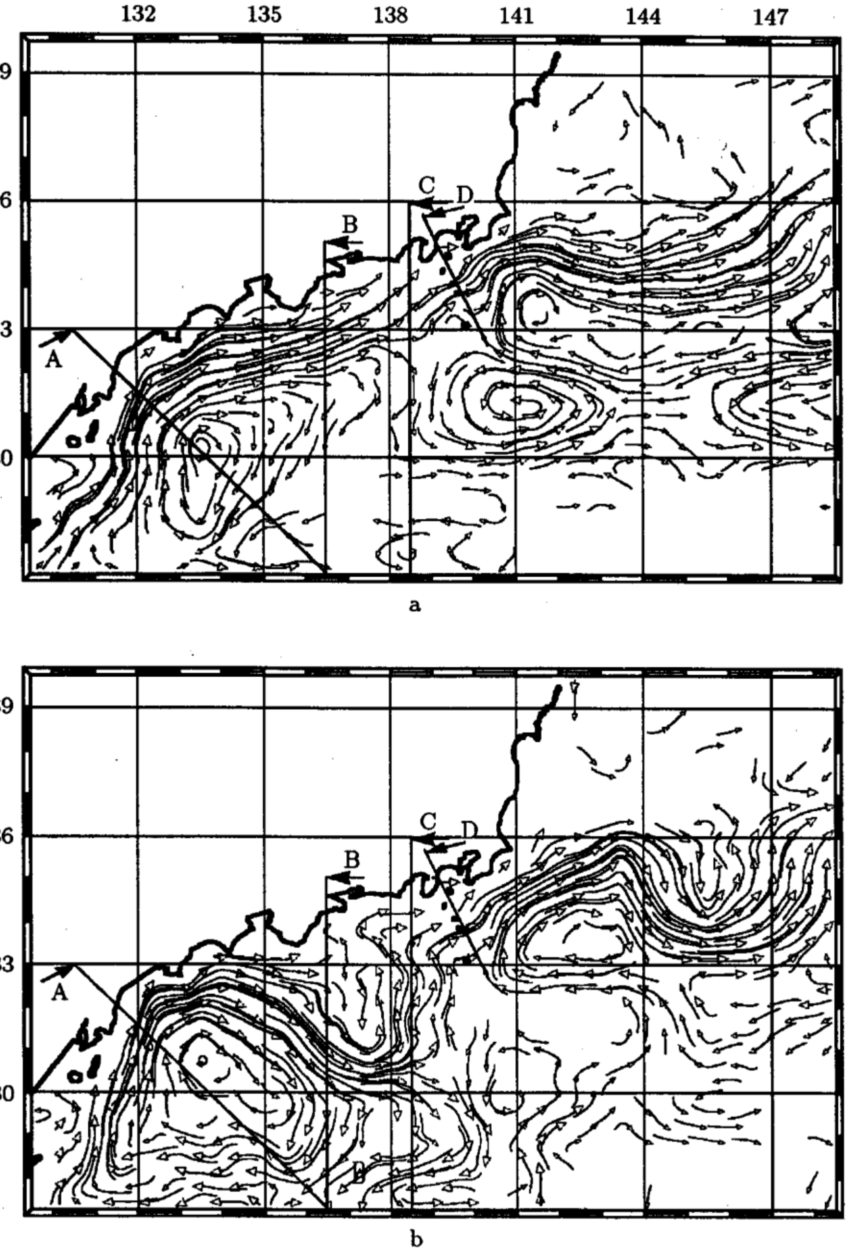

Figure 7. Velocity field: a) straight mode; b) meander mode

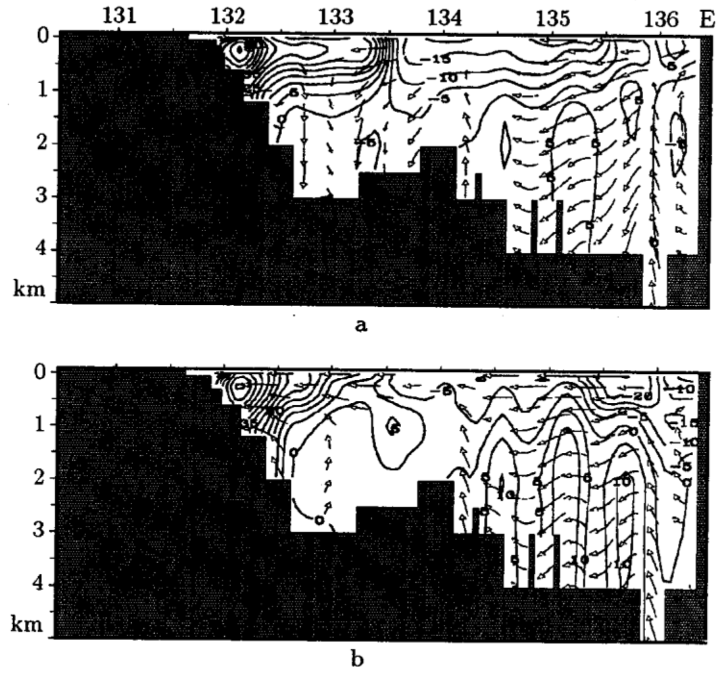

Figure 8. Velocity fields at A-section

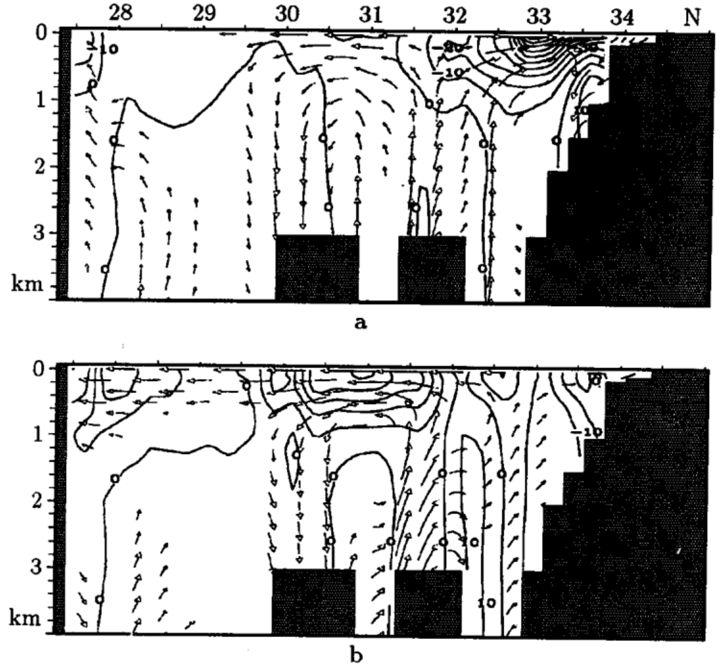

Figure 9. Velocity fields at B-section

Isolines represent the values of the velocity component perpendicular to the section. The positive direction is to the east. Arrows show the circulation at the section plane: a) for the straight path, b) for the meander path

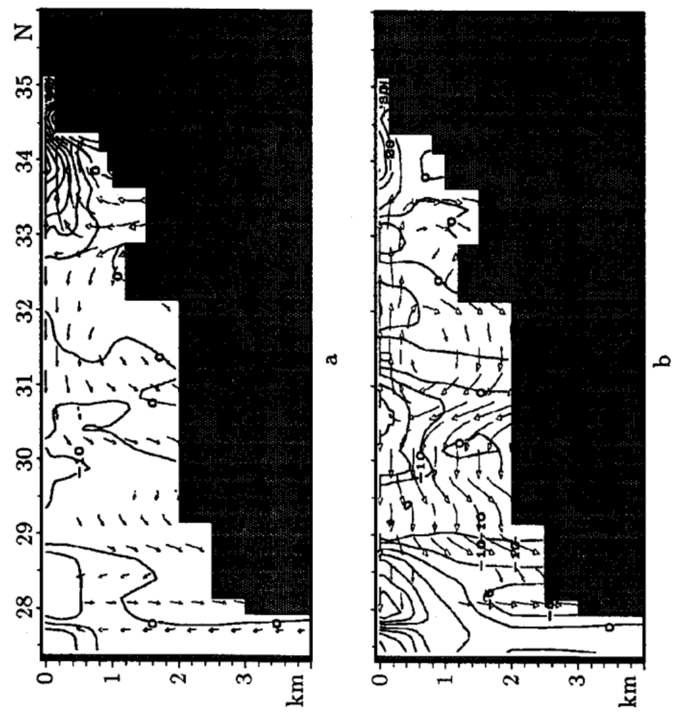

Figure 10. Velocity fields at C-section

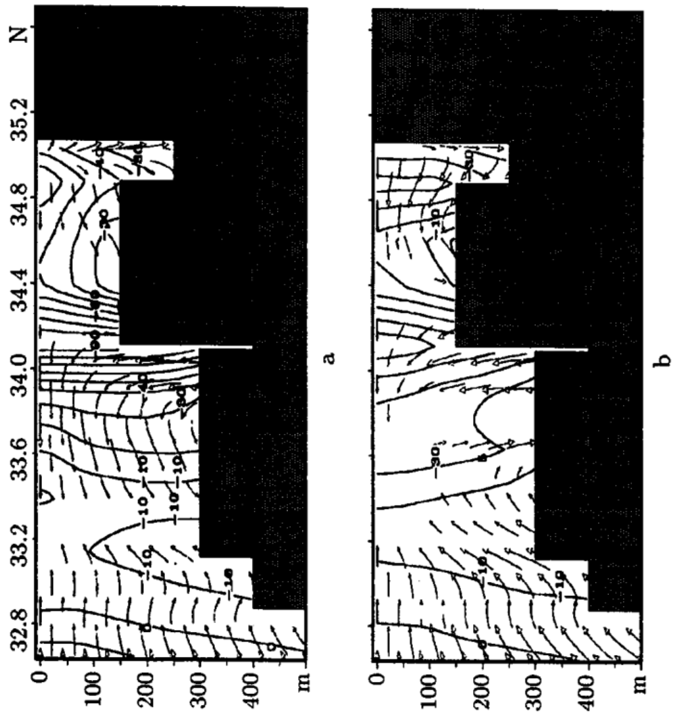

Figure 11. Velocity fields at D-section

The description is the same as for Figures 8, 9

Behind the Izu Ridge the behaviour of the current also maintains a more intensive structure for the non-large-meander mode. This fact may confirm the hypothesis that this mode is more intensive in currents, but weaker in the mass transport.

4. Pressure tendency equation analysis

In order to understand what happens when one state is transferred to another, we have made an additional diagnostic analysis of a possibility of the baroclinic instability to occur in the dynamic system. To diagnose the vorticity balance of the baroclinic waves which governs these processes and is associated with the vertical rising and sinking motions, we use the pressure tendency (PT) equation. It may allow us to examine the physical mechanism of the unstable wave generation in terms of the vorticity dynamics. This equation is widely used in the atmospheric dynamics in terms of the geopotential tendency in the isobaric coordinates (Holton, 1992).

In terms of the three-dimensional model it is reasonable to calculate all the terms of the equation on the model grid with the use of the previously calculated values.

The PT equation transformed to the physical coordinates (x, y, z) has the form

$$\underbrace{\left(\nabla^2 + \frac{f_0^2}{N^2}\frac{\partial^2}{\partial z^2}\right)\chi}_{A} = \underbrace{-\rho_0 f_0 \nu_g \cdot \nabla\left(\frac{\nabla^2 p}{\rho_0 f_0} + f\right)}_{B} + \underbrace{\frac{f_0^2}{N^2}\frac{\partial}{\partial z}\left(-\nu_g \cdot \nabla\frac{\partial p}{\partial z}\right)}_{C}.$$

Here $\chi = \partial p/\partial t$ is pressure tendency, p is pressure, t is time, z is the vertical coordinate, ρ_0 is the standard density, f is the Coriolis parameter, f_0 is the Coriolis parameter value at the latitude 33°N, V_g is the geostrophical velocity (in our case the diagnostic velocity at a depth of 250 m), N^2 is the Brent–Vaisala frequency, ∇, ∇^2 are the horizontal gradient and the Laplacian, respectively.

The physical interpretation:

The term A for sinusoidal fluctuations with respect to x, y, z is just proportional to the negative of the pressure tendency

$$A \approx -(K_x^2 + K_y^2 + (\pi^2/H^2))\chi^\propto - \chi.$$

Here K_x, K_y, π/H are the wave numbers with respect to the horizontal and the vertical direction, respectively.

The term B is proportional to the advection of the absolute vorticity with respect to the geostrophic flow and is usually the main forcing term in the thermocline. However, the vorticity advection cannot change the strength

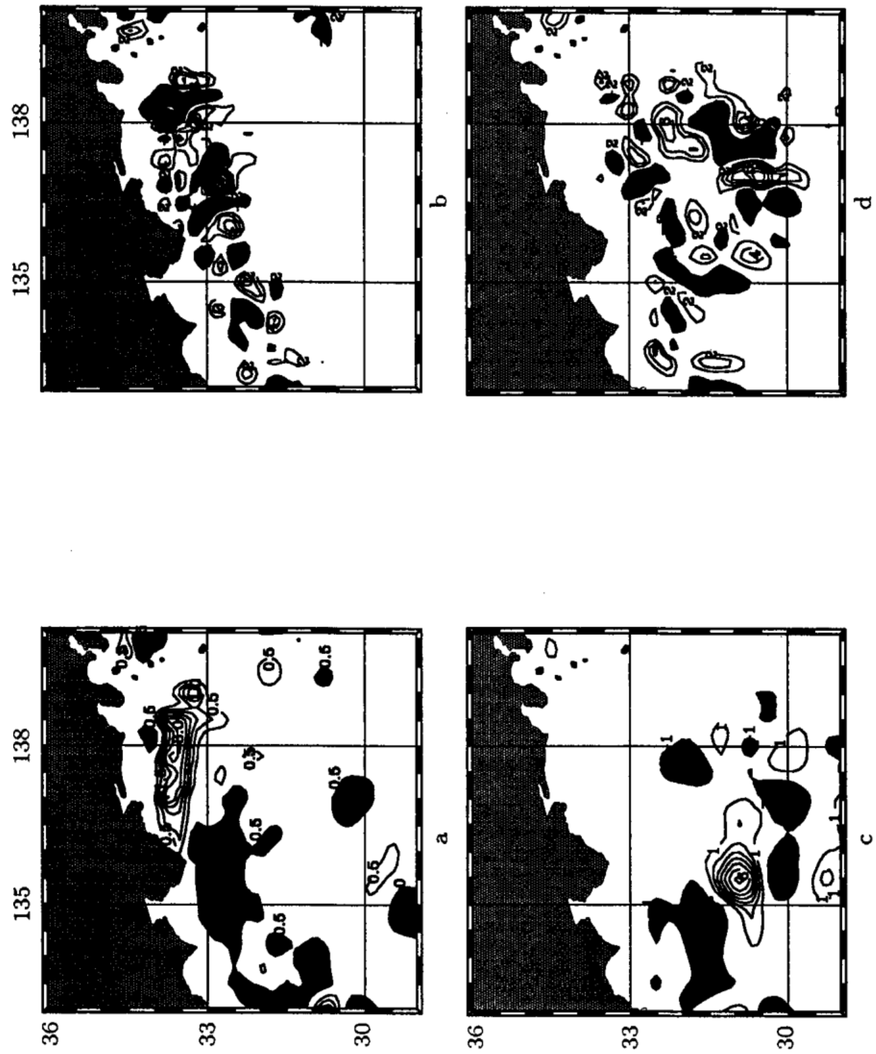

Figure 12. The distribution of: a) *C*-term for onshore path; b) $(B + C)$-term for onshore path; c) *C*-term for meander path; d) $(B + C)$-term for meander path

of the type of disturbance, but only acts to propagate the disturbances horizontally and to spread them vertically.

The term C represents the major mechanism of amplification or decay of the mid-latitude unstable waves.

The term C is proportional to the rate of changes of the temperature advection with respect to depth. So, for the developing wave at the trough of the cyclonic meander this term should be negative

$$\chi \propto \frac{\partial}{\partial z}(\nu_g \cdot \nabla T) < 0.$$

To estimate the terms in the right-hand side of the PT equation we choose the layer between 100 m and 400 m which represents the surface and the front of the stream, respectively, with the center at 250 m. In Figure 12, the terms C and $(B + C)$ are presented.

As we can see, the term C gives the negative input to the pressure tendency values for the region to the West of the Izu Ridge. The negative temperature differential advection indicates to the fact that there is a developing wave process. This is in agreement with the calculations when in this state the meander begins to develop. The term $(B + C)$ has also the negative contribution to the pressure tendency. So, in the first state with the straight mode we may suspect that there is a developing baroclinic wave which will later grow into the meander.

The analysis of the picture of the C and the $(B + C)$ terms in the case of the meander mode gives the following results: the term C also gives the negative contribution to the PT, so the process is still developing. The sum of the terms $(B+C)$ indicates to the fact that in the center of the meander there is still a deepening of the cyclone, but on the periphery of the meander there exist the upwelling processes.

So, in the sequel one needs to make a more accurate analysis of sources of the stable state of the quasi-stationary wave structure describing the large meander in the presence of the ridge.

5. Conclusions

- Diagnostic calculations of two states of the Kuroshio south of Japan gives the results which are in agreement with observations in the region;
- Quasi-geostrophical analysis of the pressure tendency indicates to the fact that in both states of the Kuroshio south of Japan there is a developing cyclonic meander at different stages;
- For a better understanding of the sources of stabilizing the meander state, an additional accurate diagnostic analysis is needed.

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