Bull. Fac. Bioresources, Mie Univ.
No.30 : 57 − 67
March 15, 2003

Attainment of a Geostrophic Flow Balance in the Upper Layer of the Kuroshio South of Japan

Yoshihiko SEKINE* and Fukuji YAMADA
Faculty of Bioresources, Mie University, 1515 Kamihama-cho, Tsu, Mie 514-8507, Japan

Abstract

As the observed ADCP velocity in the upper layer has been used as the reference velocity of the geostrophic flow estimation, the attainment of a geostrophic flow balance of the ADCP velocity is needed in the upper layer. Focussing upon this point of view, the attainment of the geostrophic flow balance of the Kuroshio is checked by use of six observational line data from July 1992 to August 2001 obtained by the training vessel "Seisui-Maru" of Mie University. The attainment of a geostrophic flow balance can be examined by the comparison of the vertical difference in the ADCP velocity (ADCP D.) with that of the calculated geostrophic flow velocity (GST. D.), which does not depend on the reference level. It is shown that the attainment of a geostrophic flow balance is unclear in the upper layer of the Kuroshio, which implies that the regression line of the ADCP D. and GST. D. should be carefully checked, if the ADCP velocity in the upper layer is used as the reference velocity. The formation process of a non-geostrophic flow balance is also discussed.

Key Words: geostrophic balance, ADCP current velocity, reference level

1. Introduction

We have made six ADCP (Acoustic Doppler Current Profiler) observations in the Kuroshio region South of Japan during six cruises from July 1992 to August 2001 by use of the training vessel Seisui-Maru of Mie University. CTD observations were also carried out in these cruises and all the observed temperature and salinity fields across the Kuroshio main axis were reported by Sekine[1].

By use of the international formula[2], the density is calculated from the observed temperature and salinity data and the geostrophic flow estimation was carried out by the assumption of the reference level at 1500 db, of which results were presented by Sekine[3]. It was shown by Sekine[3] that there exists large difference in estimated geostrophic flow, depending on the assumption of the reference velocity, such as no velocity at 1500 db and the deepest ADCP velocity.

All the observed ADCP velocities during the six observation were presented by Sekine and Yamada[4]. They pointed out that almost all observed ADCP velocities decreased significantly in nearshore coastal region of Japan and the viscous coastal boundary condition is suitable for numerical models of the Kuroshio. The topographic effect of the Izu-Ogasawara Trench is shown to be small from the observed ADCP data and

Accepted: January 31, 2003
* For correspondence (e-mail: sekine@bio.mie-u.ac.jp)

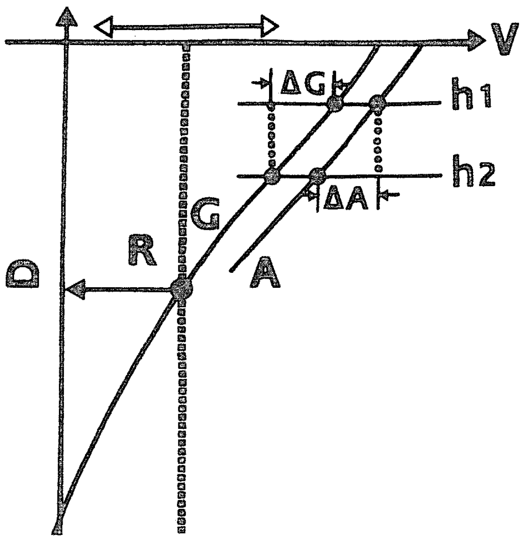

Fig. 1 Schematic view of checking the attainment of the geostrophic flow balance. Vertical axis D and horizontal axis V correspond to the depth of ocean and horizontal velocity, respectively. Graph G shows the vertical distribution of the observed geostrophic velocity referred to the the reference level (level of no motion) at a depth of R and graph A shows the vertical distribution of the observed ADCP velocity. It is shown that no influence of the assumption of the reference level is detected on the vertical difference in the geostrophic velocity (△G) between two depths h_1 and h_2. The attainment of the geostrophic flow balance is checked by the agreement of △G and the vertical difference of the ADCP velocity (△A) at same two levels.

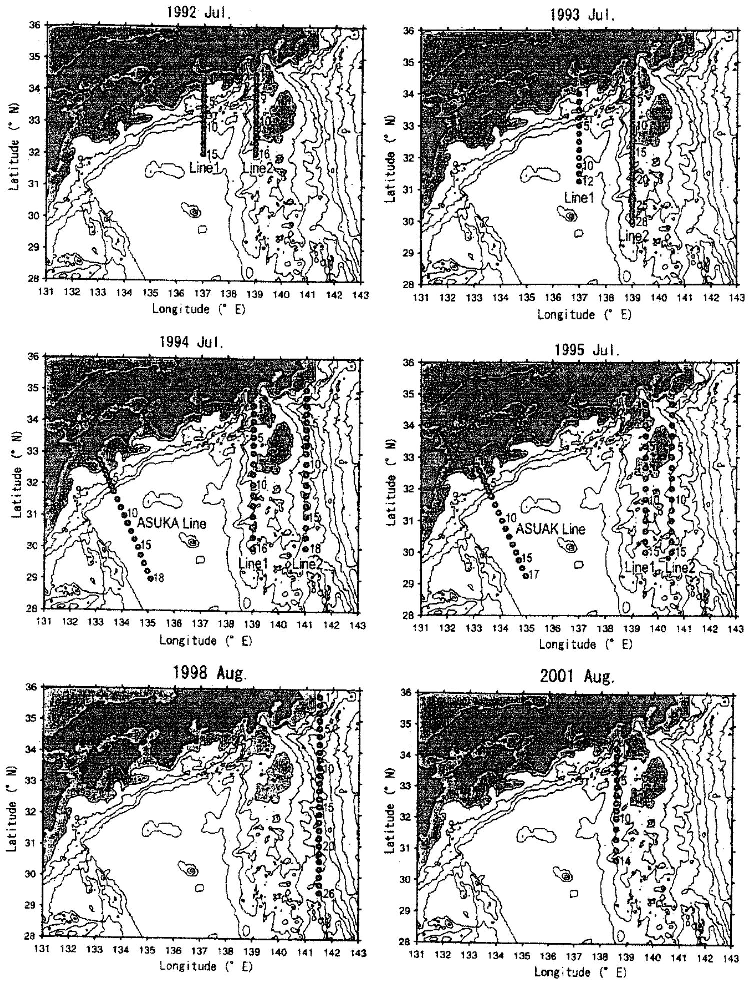

Fig. 2 Observational line of CTD and ADCP by use of the training vessel Seisui-Maru of Mie University. Bottom contours of 1000 m interval are also shown and the regions shallower than 1000 m are stippled.

the existence of a winter barotropic current, the Ryukyu Current Extension, flowing from the continental slope of Nansei Islands to South of the Izu Ridge, is predicted along about 31^0 N.

So far, many theoretical studies on the bimodal path dynamics of the Kuroshio South of Japan have been made[5)-8)] and the dependence of the bimodal path selection is discussed with reference to the volume transport and/or current velocity of the Kuroshio. However, since historical data of the observational volume transport and/or current velocity have been estimated by the assumption of geostrophic flow balance, the selection of reference level (level of no motion) is needed. If the reference level is unsuitably assumed, volume transport and current velocity can not be exactly estimated. On the other hand, some numerical studies examined seasonal variations in volume transport of the Kuroshio[9),10)]. Although the barotropic response is dominant for the oceanic response to the seasonal change in wind stress, the assumption of reference level is very difficult for the barotropic flow. In particular, a strong western boundary current along eastern continental slope off Nansei Islands is numerically predicted[9),10)] in late winter. In order to detect these barotropic flow, exact reference velocity is strongly needed to the geostrophic flow estimation.

If we use the ADCP velocity as the reference level of the geostrophic flow balance, the attainment of the geostrophic flow balance of ADCP velocity is required. If the non-geostrophic flow component is included in the ADCP velocity, the estimated geostrophic flow is unsuitable. From these points of view, the attainment of the geostrophic flow balance of the ADCP velocity of the Kuroshio is checked in the present study.

Since the vertical difference in the geostrophic velocity between two depths does not depend on the assumption of the reference level (Fig. 1), we can check the attainment of the geostrophic flow balance by comparing the vertical difference in ADCP velocity, hereafter referred to ADCP D. with that in the geostrophic velocity (GST. D.). Namely, if ADCP D. and GST. D. have same velocities, the geostrophic flow balance is established. However ADCP D. and GST. D. have different values, the geostrophic flow balance is not attained.

In the present study, ADCP D. and GST. D. are compared by use of the observational data from July 1992

Table 1 Observations made by the Seisui-maru for the present study

Cruise name	Obs. line	Periods of Observation	Figures
92 JUL	Line 1	7- 9 Jul. 1992	4a
92 JUL	Line 2	10-13 Jul. 1992	4b
93 JUL	Line 1	5- 7 Jul. 1993	5a
93 JUL	Line 2	8-11 Jul. 1993	5b
94 JUL	ASUKA	7- 9 Jul. 1994	7a
94 JUL	Line 1	14-16 Jul. 1994	6a upper
94 JUL	Line 2	17-19 Jul. 1994	6a lower
95 JUL	ASUKA	6-12 Jul. 1995	7b
95 JUL	Line 1	14-16 Jul. 1995	6b upper
95 JUL	Line 2	17-19 Jul. 1995	6b lower
98 AUG		19-22 Aug. 1998	8a
01 AUG		12-14 Aug. 2001	8b

to August 2001. Although other 22 cruises with CTD observation were carried out from May 1983 to Oct 1988 by use of the training vessel Seisui-Maru[11), 12)], unfortunately, ADCP velocity have not been obtained.

2. Observations

ADCP (CI-30 of Furuno Electric Inc.) and CTD (Mark III System of Neil Brown Instrument Systems, Inc.) observations have been carried out during the period from July 1992 to August 2001 by use of the training vessel "Seisui-Maru" of Mie University. All the observational lines of ADCP including the CTD stations are shown in Fig. 2 and details of the observation are noted in Table 1.

The mean Kuroshio flows during the observational periods are shown in Fig. 3, in which the main Kuroshio path is etimated by the observed ADCP data, the observed temperature fields and the satellite sea surface hieght. It should be noticed that a stable large meander path of the Kuroshio has not been formed after 1991. It was shown by Kawabe[13)] that the non-large meander path is furthermore divided into offshore non-large meander path and nearshore non-large meander path depending the offshore distance of the main

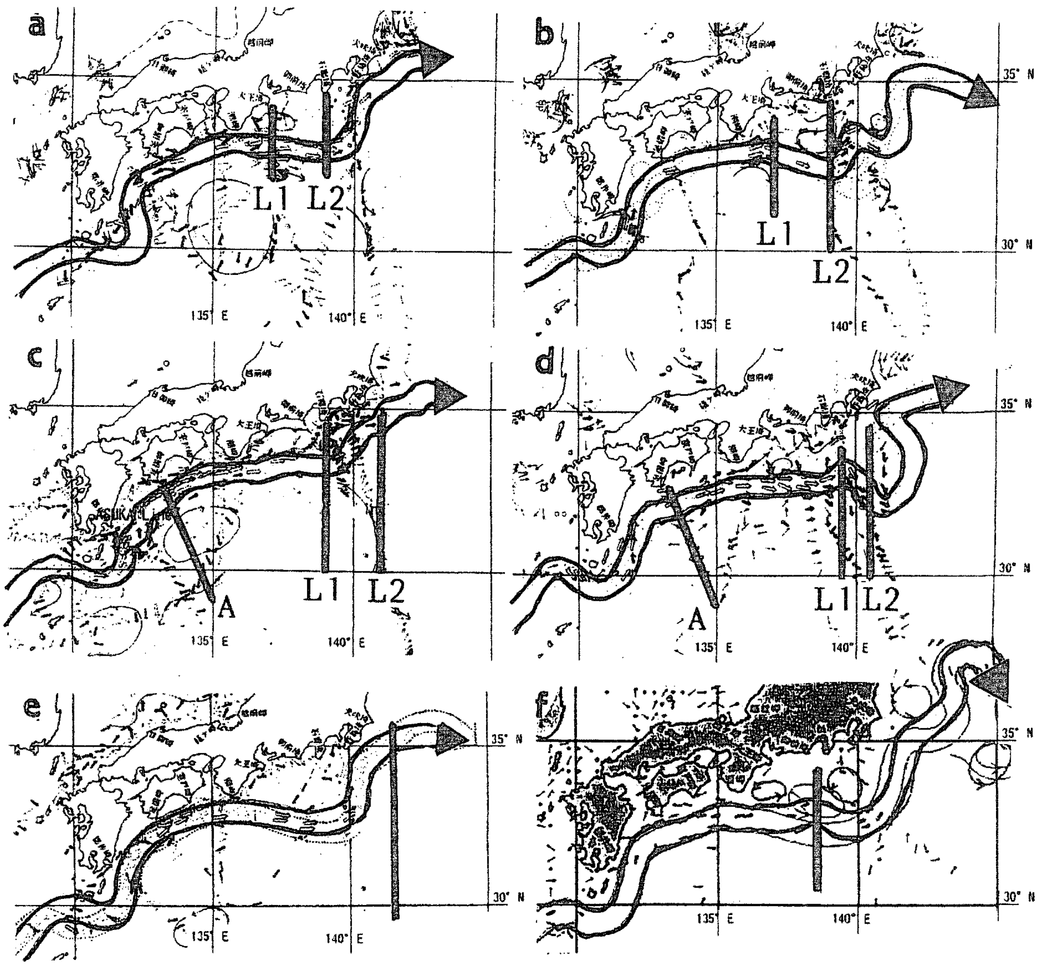

Fig. 3 Main Kuroshio paths proposed by Hydrographic Department[14)], during the observational periods of (a) July 1992, (b) July 1993, (c) July 1994, (d) July 1995, (e) August 1998 and (f) August of 2001. Observational lines are also shown.

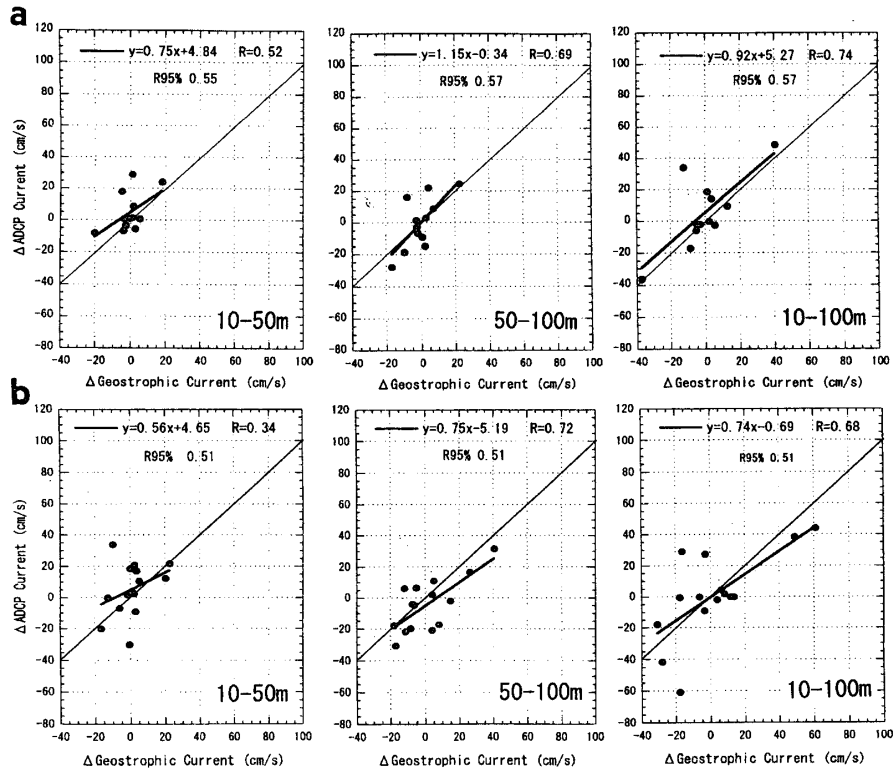

Fig. 4 Correlation between GST. D. and ADCP. D. observed in Line 1 (a) and Line 2 (b) of 92 JUL (Fig. 2a). Coefficient of the correlation is shown in the right top of the each panel marked by R = . Regression lines are plotted by heavy solid lines, in which y and x correspond to ADCP D. and GST. D, respectively. Equal value lines (y = x) and correlation coefficient of 95% confidence are also shown by R95%. Two depths h_1 and h_2 used in the vertical velocity difference shown in Fig. 1 are displayed in right down of each panel.

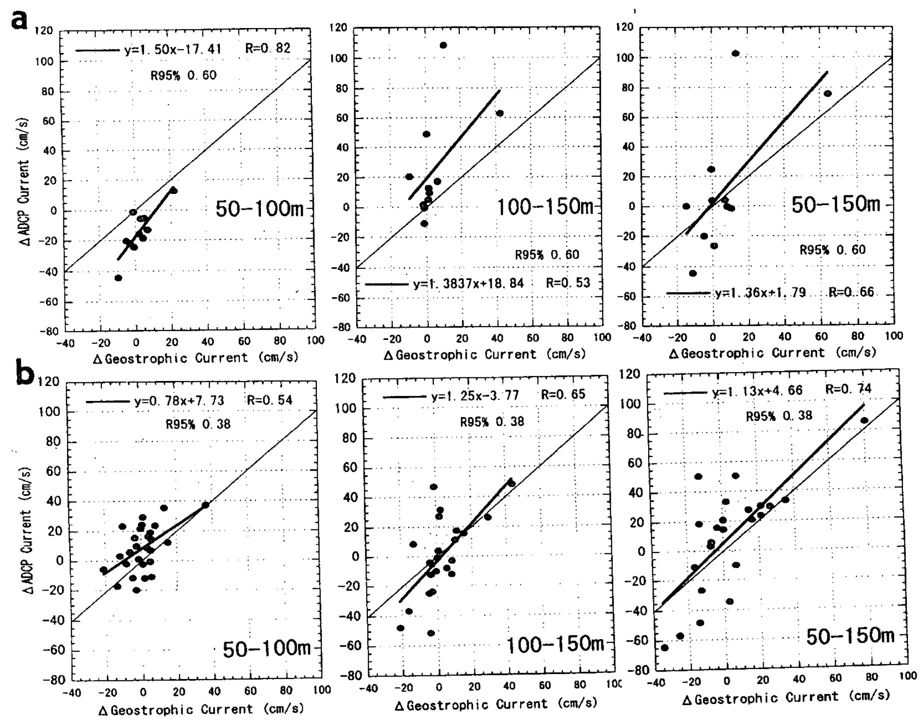

Fig. 5 Same as in Fig. 4, but for Lines 1 (a) and 2 (b) of 93 JUL.

Kuroshio axis over the Izu Ridge. It is shown from Fig. 3 that the offshore non-large meander path is relatively dominant in the observational periods, except for the nearshore non-large meander path in July 1994 (Fig. 3c).

Because there exist some data of the observed ADCP velocity between the two CTD stations of which observed temperature and salinity data are used in the geostrophic flow estimation, some methods to estimate the mean ADCP velocity are suggested between the two CTD stations: simply mean of all ADCP velocity data, only one representative ADCP velocity observed at the nearest point to the center of the two CTD stations and weighted mean of all the ADCP data, of which weight is inversely proportional to the distance from the center of the two CTD stations. However, there is no significant difference among three estimations, we use the simply mean of all the ADCP velocity observed between two CTD observations.

3. Results

All the correlations between ADCP D. and GST. D. are shown in Figs 4-8. It is recognized from Fig. 4 of 92 JUL that there exists difference between ADCP D. and GST. D. and some plotted marks are far from the equal value-line of the two velocity difference ($y = x$). Namely, the gradients of the regression lines are different from one and the additional constants do not equal zero. However, significant correlations of more than 95% confidence is detected between the two velocity difference. It should be noted that these two tendencies are essentially detected in all the cases. Therefore, other noticeable facts are mentioned in the following.

Systematic difference is detected in the case of Line 1 93 JUL (Fig. 5a). Absolute GST. D. is larger than that ADCP D. in 50−100 m depths, however, the opposite tendency is seen at depths between 100 m and 150 m. Although GST. D. takes both negative and positive values, ADCP D. takes negative value at depths 50 m − 100 m and positive value at depths of 100 m − 150 m. Unfortunately, since we have little insight of the geophysical fluid dynamics on the vertical variation in ADCP velocity, details of the background is unclear.

No significant positive correlation could be obtained at Line 1 of 95 JUL (Fig. 6b upper). To see the pressure fields, density fields (σt) of the six observation is shown in Fig. 9. It is shown from the density fields (Fig. 9d center panel) that the horizontal density gradient associated with the mean Kuroshio flow is relatively unclear. It is also recognized from the main Kuroshio path during the observational period (Fig. 3d) that the Kuroshio is meandering northward over the Izu Ridge. Therefore, it is suggested that the observational line is not orthogonal to the main Kuroshio axis, which results in the small horizontal gradient of the isopycnal lines. Because the meandering current path yields large centrifugal force, it decreases the attainment of the geostrophic flow balance. Similar tendency is perceived at Line 2 of 95 JUL.

As for 01 AUG, it was pointed out by Sekine and Yamada[4)] that a remarkable time change in ADCP velocity is observed during southward and northward cruises along 137^0 E which carried out in 2 days. Northward shift of the mean flow is observed and a strong eastward flow in south of the mean flow of the Kuroshio observed in the southward cruise was not observed in the northward cruise. Even though, a significant positive correlation between ADCP D. and GST. D. is found in Fig. 8b. So, the movement of the Kuroshio is suggested to be in geostrophic flow balance and large topographic effect of the Izu Ridge[4)] on the Kuroshio flow is confirmed. Furthermore, because the horizontal gradient of density (Fig. 9f) is relatively large, the propagation of the internal wave is suggested to be suppressed in this case.

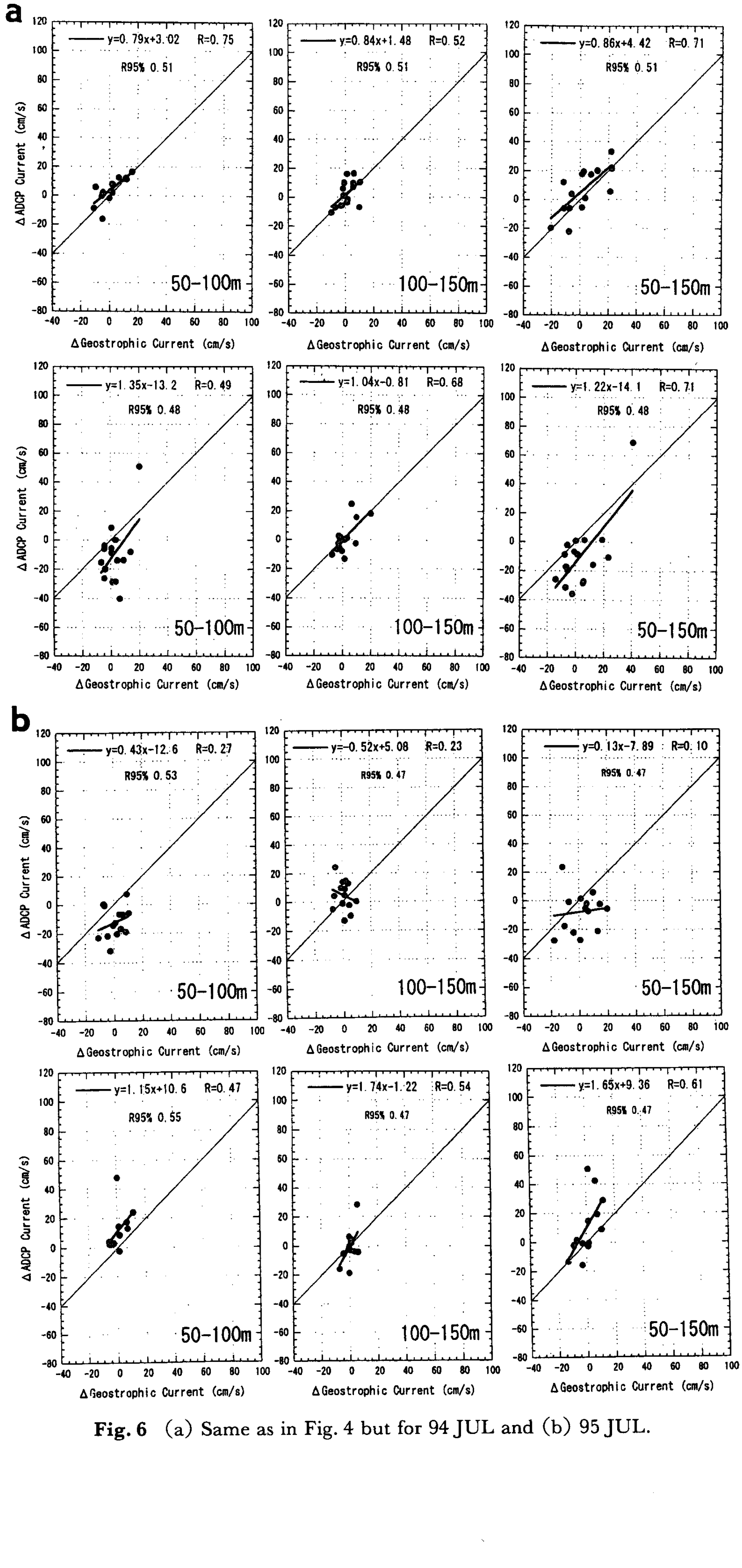

Fig. 6 (a) Same as in Fig. 4 but for 94 JUL and (b) 95 JUL.

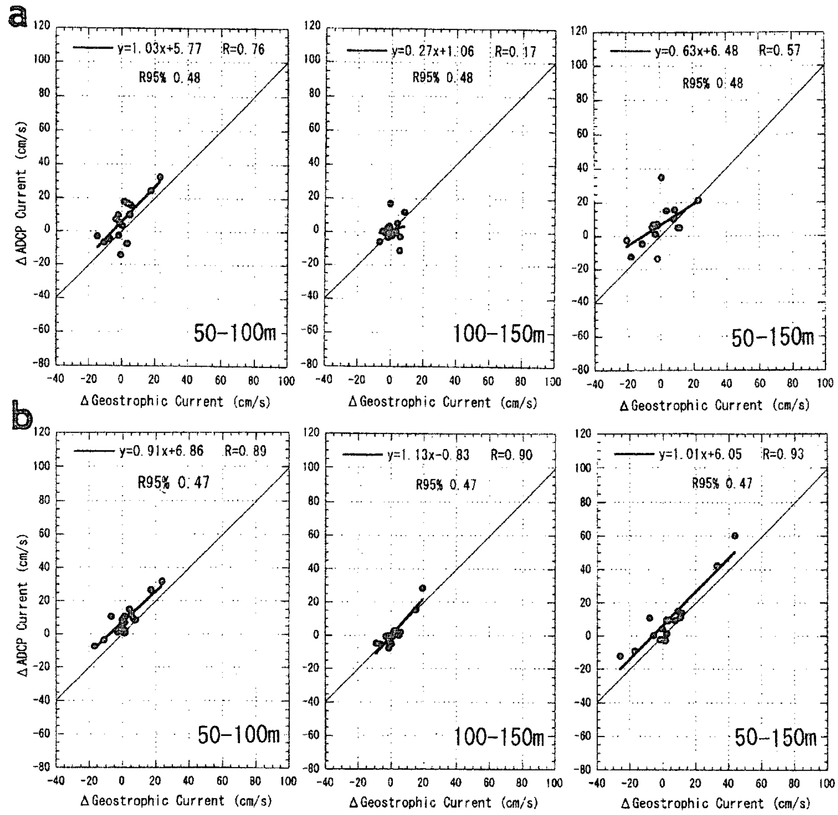

Fig. 7 Same as in Fig. 4, but for ASUKA Line of (a) 94 JUL and (b) 95 JUL.

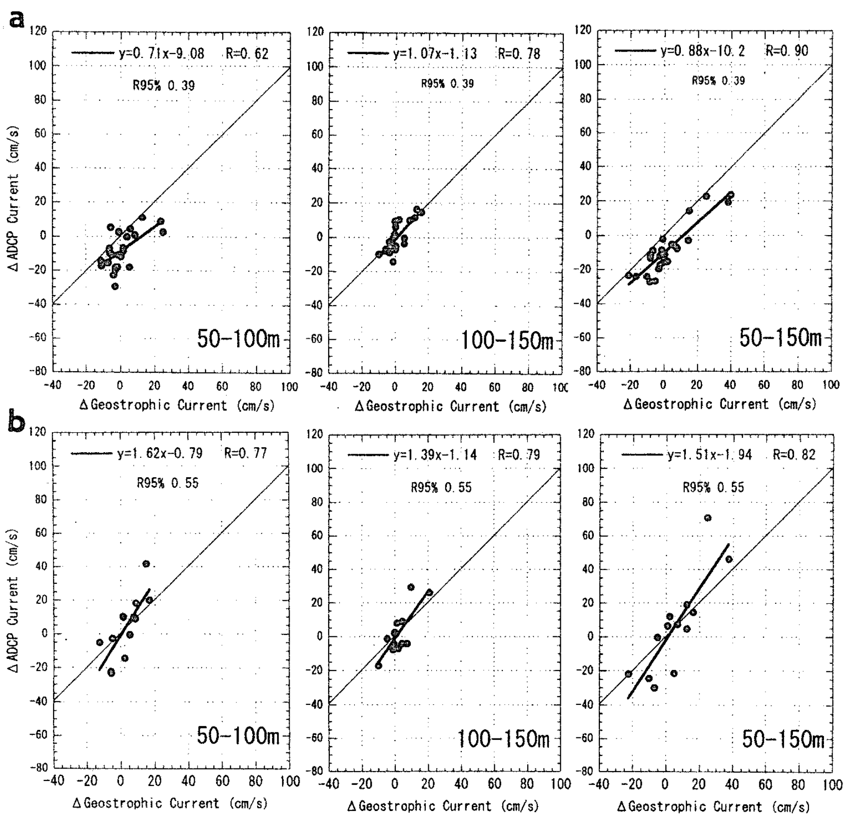

Fig. 8 Same as in Fig. 4, but for (a) 98 AUG and (b)01 AUG.

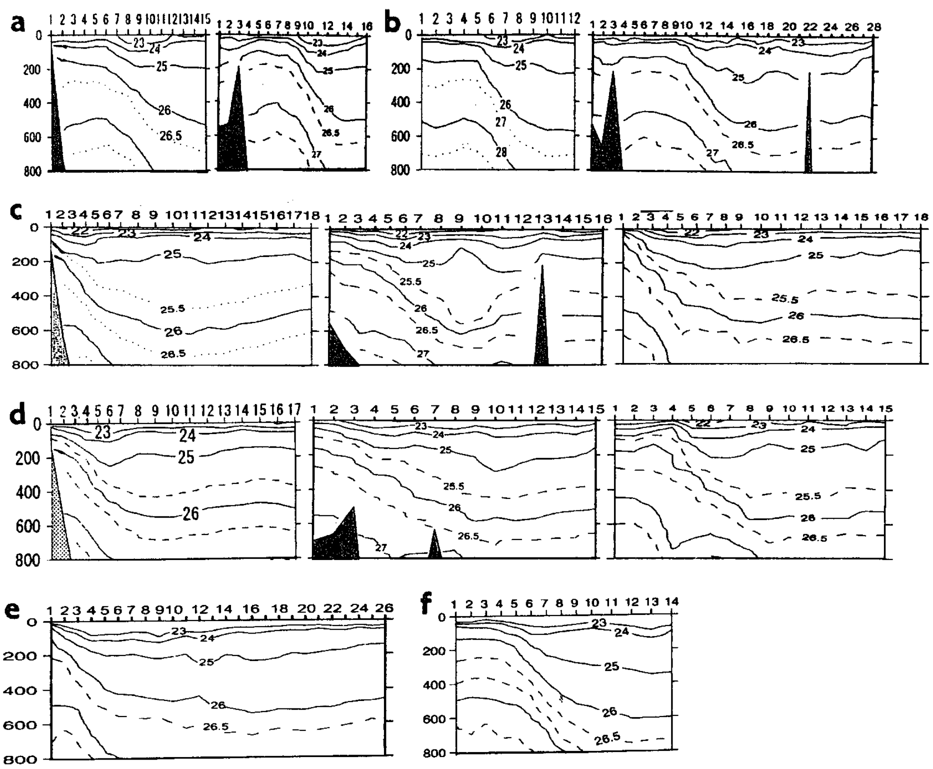

Fig. 9 Density (σ_t) distribution along (a) Line 1 (left) and Line 2 (right) of 92 JUL, (b)Line 1 (left) and Line 2 (right) of 93 JUL(c) ASUKA Line (left), Line 1 (middle) and Line 2 (right) of 94 JUL, (d) ASUKA Line (left), Line 1 (middle) and Line 2 (right) of 95 JUL,(e) observational line of 98 AUG and (f) that of 01 AUG. CTD stations displayed in Fig. 2 are also shown at top of each panel.

4. Summary and discussion

The attainment of the geostrophic flow balance of the Kuroshio in the upper layer has been checked by the comparison of the vertical ADCP velocity difference (ADCP D.) with that of the calculated geostrophic flow (GST. D.) by use of the six observational data obtained from July 1992 to August 2001 (Table 1).

It is shown that ADCP D. and GST. D. tend to differ from each other and regression lines are different from the equal value-line of the two velocity difference ($y = x$). However, significant correlations with more than 95% confidence are detected between two velocity difference. If the observational line of CTD is not normal to the main Kuroshio axis, the significant positive correlation between ADCP D. and GST. D. is not obtained and ADCP velocity can not be used as the reference velocity. Furthermore, the meandering current path yields centrifugal force, suppressing the attainment of the geostrophic flow balance. It is thus concluded that the attainment of the geostrophic flow balance in the upper layer is unclear and the regression line of the ADCP D. and GST. D. should be carefully checked, if the ADCP velocity is used as the reference velocity.

There are some causes of the non-geostrophic flow balance. One is the inclusion of tidal current velocity in the ADCP data. To exclude the tidal flow component with five unknown constants such as a mean flow, two tidal constituents of 12 and 24 hours, more than five ADCP data at a fixed point are needed and such a observation is usually impossible along the CTD observational line. Another cause is the influence of the internal wave on the density fields. It is shown by the present study that even a significant positive correlation is not obtained in case of small horizontal gradient of the density associated with the mean Kuroshio flow, conversely relatively high significant correlation is obtained in case of large gradient of density. As for the difference of the two cases, the internal wave has a larger possibility to propagate well in the small density slope in comparison with the large density slope. Therefore, it is suggested that the attainment of the geostrophic flow is possible in the case with large horizontal density gradient, and vice versa. This may be helpful to check the influence of the internal wave.

Acknowledgment

This paper is dedicated to Captain I. Ishikura of the training vessel Seisui-Maru of Mie University who gave us skillful drive of the vessel during all the cruises. We would like to thank all the officers and crews of the Seisui-Maru for their assistance during the observational cruises. Thanks are extended all the past and present graduate students and under graduate students of the Laboratory of Physical Oceanography of Mie University, for their help during the observation and in drawing some figures.

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日本南岸の黒潮上層の地衡流バランスの達成度

関根　義彦・山田二久次

三重大学生物資源学部

上層で観測されたADCP流速が地衡流推算の基準流速として用いられることがあるが，その場合には上層のADCP流速の地衡流バランスの達成が必要である。この点に注目して，黒潮上層で観測されたADCP流速の地衡流バランスの達成度を1992年7月から2001年8月までの三重大学の練習船『勢水丸』を用いた7回の観測データを用いて調べた。地衡流バランスの達成度はADCP流速の鉛直差と無流面に依存しない地衡流流速の鉛直差を比較することで判断できる。解析により，黒潮の上層では地衡流バランスの達成度は低く，ADCP流速が地衡流推算の基準流速として用いられる場合には二つの流速の鉛直差に関する回帰直線を厳密にチェックすることが必要であることを提示した。また，地衡流バランスが成立しない原因についても議論した。