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Structure of Kuroshio south of Japan

by Bruce A. Taft[1]

ABSTRACT

In June-July 1971 four deep hydrographic sections were made across the Kuroshio south of Japan, eight near-bottom current meters were placed under the Kuroshio on the continental slope, and the near-surface current structure was measured by XBT mapping of the temperature field and tracking four surface drogues. Kinetic energy per unit mass of the low frequency (below inertial frequency) fluctuations for three long current meter records ranged between 4 and 18 $cm^2 sec^{-2}$; the ratio of eddy to mean kinetic energy was an order of magnitude smaller than under the Gulf Stream east of Cape Hatteras. The dominant time scale of the low frequency fluctuations was five days. Geostrophic current profiles referenced to deep current measurements show that under the core of the surface Kuroshio there is a deep countercurrent located on the slope with its upper boundary at about 1200 m. The countercurrent was similar in position to the one described by Worthington and Kawai (1972). Direct current measurements along 136°30′E show that the countercurrent is underlain by eastward flow in the direction of the Kuroshio. The maximum speed in the countercurrent was 9 cm sec^{-1} and its volume transport based only on geostrophic profiles referenced to current measurements was 1×10^6 $m^3 sec^{-1}$; if transport relative to the bottom is included, where no velocity data were available, the transports vary between 4 and 7×10^6 $m^3 sec^{-1}$. Water in the countercurrent is not distinguishable from Shikoku Basin water which suggests that it may be part of a circulation which is internal to the Basin. The Kuroshio transports vary between 57 and 72×10^6 $m^3 sec^{-1}$; the higher estimates are about 20% less than the September, 1965, estimates of Worthington and Kawai (1972). Neither the 1965 nor the 1971 measurements show a significant downstream change in transport. Maps of 15°C at 200 m (an indicator of the surface Kuroshio) show a variable current off Kyushu which often flows across the bottom contours; speeds of translation were comparable to those measured in the Gulf Stream east of Hatteras. South of Honshu the changes in the current position were small and the surface current was parallel to the trend of the bottom contours. Drogues tracked south of Honshu showed accelerations due to changes in speed over a three day period with the tracks aligned parallel to the 200 m isotherms; the maximum current was measured at a 200 m temperature of 16.5°C.

1. Introduction

Studies of the data collected on Japanese surveys south of Japan have led to a description of the baroclinic structure of the upper kilometer of the Kuroshio, the surface current distribution across the Kuroshio, and the low-frequency fluctuations

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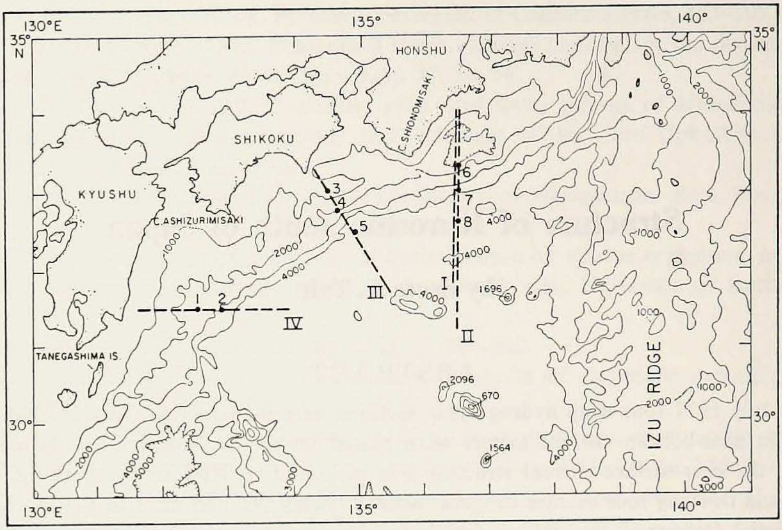


Figure 1. Bottom topography (m) and location of hydrographic sections (dashed lines) and current meters (dots). Contours have been taken from sheet 1 of the chart published by the Japan Maritime Safety Agency (Anonymous, 1966). Dates of sections (1971) are: I—6/27 to 6/30; II—7/14 to 7/17; III—7/4 to 7/5; and IV—7/7 to 7/9.

of the position of the current axis and the relative geostrophic transports (Taft, 1972; Shoji, 1972; Masuzawa, 1972; and Nitani, 1975). Although these surveys have resolved the large-scale shifts in the Kuroshio path, the coarse station spacing of the surveys has not permitted description of the variability of the path on small time and space scales. Except for short duration Swallow float measurements reported by Worthington and Kawai (1972), deep flow under the Kuroshio has not been measured. Knowledge of the velocity profile is required for the development of realistic dynamical models for the current path (Robinson and Taft, 1972; White and McCreary, 1976). These studies show that the current path depends critically on the deep flow.

In order to extend the description of the Kuroshio, particularly with respect to path meanders and deep flow, a cruise was carried out at the northern end of the Shikoku Basin in June-July, 1971, from the *Thomas Washington*. The measurement program comprised deep moored current meter measurements, hydrographic casts, surface drogues and high resolution (10 km) mapping of the temperature field in the upper layers. Isotherm mapping had been done in the Kuroshio but with considerably coarser resolution. For example, Kawai (1972) has analyzed the results of a multi-ship operation east of Japan and estimated the change in position of the 10°C isotherm at 200 m over the period of three weeks; the spatial resolution was roughly 100 km. Stommel (1972) presented a map of the temperature at

200 m south of Japan which is based on an *Atlantis II* bathythermograph survey employing sections across the current at 100 km intervals. On the *T. Washington* cruise, the time and space scales of Kuroshio meanders were estimated from maps of the 15°C isotherm at 200 m. Current velocity measurements were made to estimate the time scales of the deep velocity field and to enable computation of absolute velocity profiles across the current by using suitably averaged velocity measurements as a reference for the geostrophic velocity shear computed from the hydrographic sections. The velocity measurements reported here are the first time series that have been made under the Kuroshio. Drogue measurements provide a crude measure of the cross-stream surface velocity profile.

Locations of the four hydrographic sections and eight current meter moorings are given in Figure 1. Current measurements 100 to 150 m above the bottom were obtained along three short lines normal to the bottom contours south of Japan: two moorings on an east-west line on the continental slope off Kyushu (#1, #2); three on a northwest-southeast line off Shikoku (#3, #4, #5); and three on a north-south line off Honshu (#6, #7, #8). Deep hydrographic sections were made over each set of meters; the Honshu section was repeated to obtain a measure of the variability of the transport. Dissolved oxygen, inorganic phosphate and inorganic silicate were measured as well as temperature and salinity. The remainder of the observational program involved mapping the 15°C isotherm at 200 m with XBT's and tracking four surface drogues over several days' time.

A preliminary discussion of the cruise results was presented by Taft, Robinson, and Schmitz (1973). Solomon (1974) has discussed measurements of thermal fine structure near the Kuroshio axis which were obtained on the cruise.

a. Bottom topography. The northern end of the Shikoku Basin is bounded to the north and west by the continental slope, whose upper section runs parallel to the coastlines of the three main Japanese islands, *i.e.*, Kyushu, Shikoku, and Honshu. The Izu-Ogasawara Ridge prevents open communication north of 30N with North Pacific waters below 2000 m. At the base of the continental slope in the western and central parts of the basin, there is a shallow depression called the Nankai Trough, where depths exceed 4500 m.

The section of the slope between 2 and 4 km, which is generally the steepest, changes its trend from northeast off Kyushu to east-by-north south of Cape Shionomisaki. There are two regions where the slope abruptly changes width and orientation: near 133E the trend changes from northeast to northeast-by-east with a 50 percent decrease in width; and near 134°30′E, just east of Cape Ashizurimisaki, the trend changes from northeast-by-east to east-by-north and the width of the slope again decreases by 50 percent. The narrowest section of the slope is located between 134°30′ and 135E. East of Cape Shionomisaki the coastline turns north but the east-by-north trend of the 2, 3, 4 km isobaths does not change; there is a plateau with a shallow depression on the upper portion of the slope. The slope meets the western edge of the Ridge at about 138E.

2. Measurement techniques and data analysis

a. Current meters. Two types of single current meter moorings were set: Geodyne 850 current meters with acoustic releases; and meters with a time release built at the Scripps Institution of Oceanography (SIO). The maximum recording time for the SIO meters was 30 days so these five meters were picked up at the end of the cruise; the four Geodyne meters were deployed for a longer period and three were recovered from the USCGC *Mallow*. Good records were obtained at seven of the eight meters. The rotor bearings on meter #5 were damaged, resulting in a high threshold value, so that 17 percent zero current values were recorded. There were rather long periods when the meter recorded no current, so that a uniform interpolation procedure could not be used for the record. No statistics will be quoted for this meter although results obtained during periods of high current will be mentioned. Velocity data have been low-pass filtered to remove the frequencies higher than 1 cycle per day (inertial frequencies range from 1.08 to 1.12 cpd). All discussion of the velocity data in this paper will be based on the low-passed data; time series of velocity were formed by subsampling the low-passed data at midnight (local time).

b. Surface drogues. The drogues were of the same design as used previously in the Gulf Stream (Parker, 1972; Fig. 1a); the parachute for drogue *A* was set for 200 m and the parachutes for drogues *B, C,* and *D* were set for 10 m. Drogue positions relative to the ship were measured every one-half hour by radar. Drogues *B, C,* and *D* set up quickly and moved with the current within one hour of deployment. During the first four hours there was no apparent movement of drogue *A* (<1.5 km) but in the subsequent 21 hours it moved 24 km. The difference in the initial movement of *A* may have been related to the difference in parachute depth.

c. Isotherm tracking. The location of the 15°C isotherm at 200 m (denoted here by 15/200) was determined by navigating with respect to the 200 m temperature field. Temperature soundings were made with a 450 m XBT probe at one-half hour intervals. The ship's course was adjusted after every drop to maintain contact with 15/200; the average distance between XBT observations was 9 km. Surface bucket temperatures were taken at the time of each drop and were used to calibrate the XBT temperature profile. The approach adopted here is similar to the Gulf Stream studies of Parker (1972) and Robinson, Luyten, and Fuglister (1974).

d. Hydrographic casts. Vertical spacing of Nansen bottles was normally between 200 and 300 m in deep water and varied between 30 and 100 m in the upper 1,000 m. Dissolved oxygen was measured by the modified Winkler method and nu-

Table 1. Comparison between sea-surface geostrophic velocity component normal to section and 200 m temperature. Hydrographic sections are identified by number on Figure 1. ΔD is the distance between maximum surface geostrophic velocity on the section and the 15/200 (a negative sign indicates the axis is inshore of 15°C); T_{max} is the interpolated 200 m temperature at the maximum surface geostrophic velocity; V_{max} is the maximum surface velocity; and V_{15} is the surface geostrophic velocity at 15/200.

Hydrographic Section	ΔD (km)	T_{max} (°C)	V_{max} (cm sec^{-1})	V_{15} (cm sec^{-1})
I	−2	14.6	178	176
II	−6	13.7	185	162
III	22	17.4	124	42
IV	18	17.3	157	102

trient analyses were done with a Berkman DU spectrophotometer. Precisions of the measurements are estimated to be: salinity—0.003‰ (1 σ); oxygen—0.04 ml 1^{-1} (1 σ); and phosphate and silicate—2% (coefficient of variation). All salinity (duplicate samples) and chemical analyses were done at sea on fresh samples.

3. Description of Kuroshio path

a. Choice of isotherm for tracking of Kuroshio. Studies of the path of the Gulf Stream have been based on the identification of the 15/200 with the location of the strongest horizontal temperature gradient at 200 m (Fuglister and Voorhis, 1965). The 15/200 can also be interpreted as an indicator of the axis of strongest vertical shear of the downstream flow of the Gulf Stream by applying the thermal wind equation. Drogues placed over 15/200 move at Gulf Stream speeds and have remained over that isotherm for distances as large as 1500 km (Parker, 1972).

The near-surface thermal structure of the Kuroshio is very similar to that of the Gulf Stream. Kawai (1969) studied the relationship between the axis of the surface Kuroshio, as indicated by the maximum surface current measured by the geomagnetic electrokinetograph (GEK), and the bathythermograph (BT) temperature at 200 m. Kawai concluded that there is a high correlation between 200 m temperature and maximum surface current south of Japan. Between 133°30′E and 134°30′E the best indicator temperature was 16.5°C; whereas between 137°30′E and 138E the best indicator temperature dropped to 15.1°C. The consistency of the relationship is indicated by the low value of 18 km for the standard deviation of the interpolated distance between indicator temperature and the maximum surface current. In order to provide a single index temperature throughout the region, 15/200 was chosen for path tracking.

Temperature sections (Figs. 8a, 10, 11a) show that 15/200 lies within the bundle of isotherms comprising the strongest horizontal temperature gradient. Maximum geostrophic velocity (Figs. 14a-d) may be compared with the 200 m temperature distribution. The data in Table 1 show that this isotherm is located in the region of

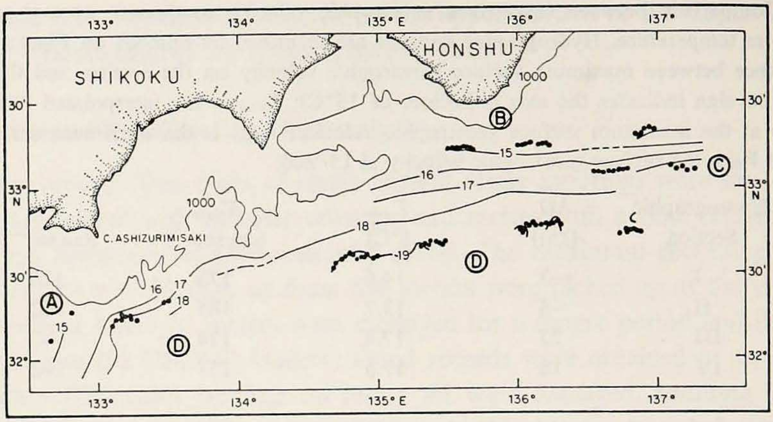


Figure 2. Drogue tracks and 200-m temperature distribution. Each dot represents a drogue fix. Dates of tracks (1971) are: A—7/9; B—7/12 to 7/14; C—7/14; and D—7/10 to 7/14.

strong current at all sections and the downstream decrease in the temperature at the maximum current is somewhat larger in magnitude than the average decrease given by Kawai (1969). Distances between 15/200 and maximum current for sections I and II are probably not significant; the 15/200 lies about 20 km inshore of the maximum current at sections III and IV.

b. Relations between 15/200 and drogue tracks. There were relatively small variations in 200 m temperature along the drogue tracks (Fig. 2). The maximum distance between the isotherm at the launch site and the subsequent drogue track was about 9 km, which corresponds to roughly five percent of the current width at the surface (Fig. 14b). The variation of temperature along the drogue tracks is larger than that reported for a drogue tracked in the Gulf Stream which maintained a constant displacement of 1.5 km from 15/200 for a period of 58 hours (Robinson, Luyten, and Fuglister, 1974). Drogue measurements over longer periods in the Gulf Stream show fluctuations in the position of the drogues with respect to temperature field which are comparable to those shown in Figure 2 (Parker, 1972).

Stable estimates of average speed were not obtained because of large accelerations (Fig. 3). Drogue *C*, which was launched at 16.4/200, moved with highest average speed (175 cm sec^{-1}) and drogue *A* moved at the lowest average speed (33 cm sec^{-1}). The drogue measurements, as well as the geostrophic calculations, indicate that the maximum surface flow was near 17/200. However 15/200 south of Honshu was located in the region of strong eastward flow of the Kuroshio.

Drogue speeds may be compared with GEK surface current measurements and BT temperatures made along a northeast-southwest line in the same area by the *Takuyo-Maru* (Fig. 4). Although there is good agreement between the speeds and 200-m temperatures of drogues *C* and *D* and the *Takuyo-Maru* data, the speeds of

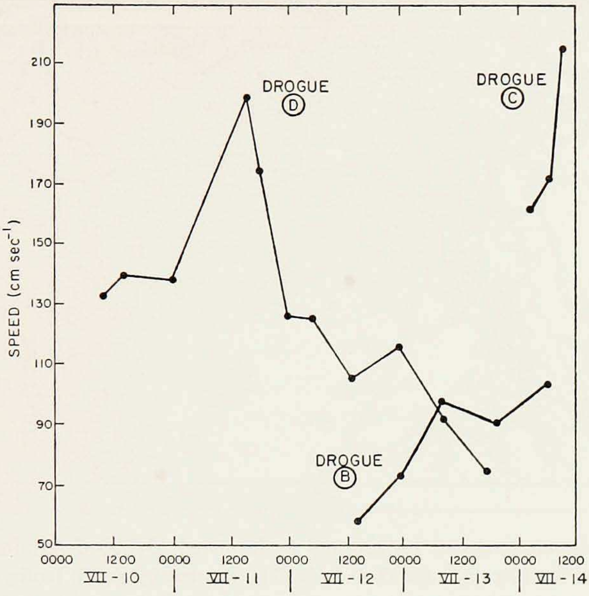


Figure 3. Drogue speed as a function of time.

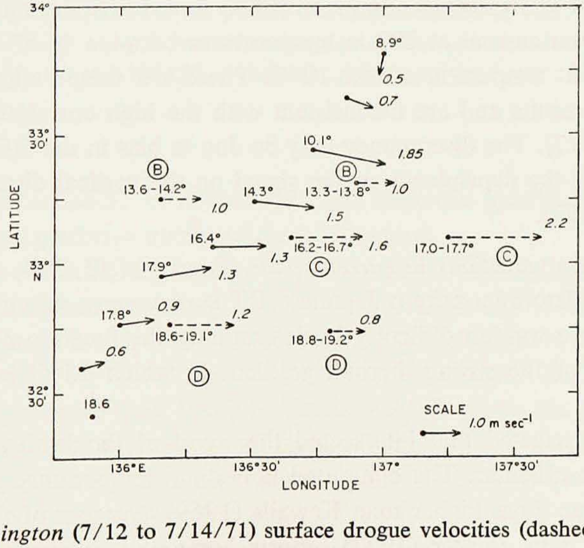


Figure 4. *T. Washington* (7/12 to 7/14/71) surface drogue velocities (dashed arrows, m sec^{-1}) and 200-m temperature range (°C) and *Takuyo-Maru* (7/11 to 7/12/71) GEK surface current velocities (solid arrows) and 200-m temperatures.

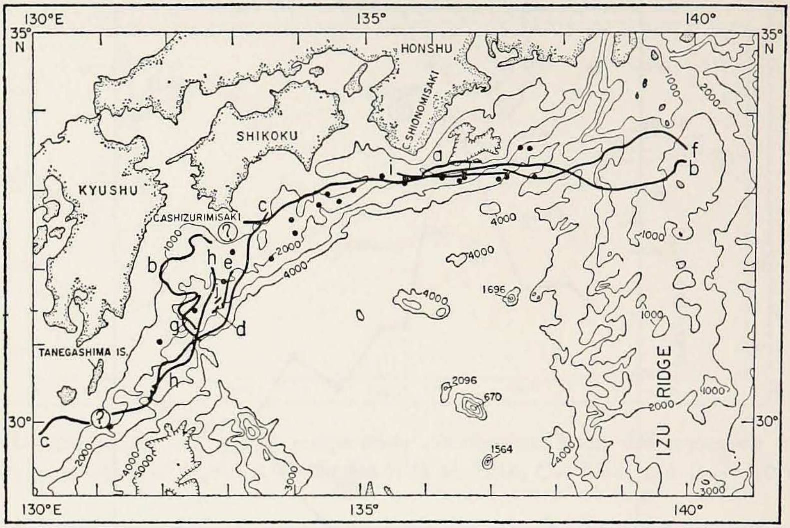


Figure 5. *T. Washington* tracks of 15/200 and positions of 15/200 determined from Japanese BT sections across the Kuroshio (6/12 to 7/18/71; denoted by dots). Isotherm tracks (labeled *a* through *j*) were completed on the following dates (1971): *a*—6/12 to 6/13; *b*—6/14 to 6/17; *c*—6/21 to 6/23; *d*—6/24; *e*—6/27; *f*—6/30 to 7/1; *g*—7/07; *h*—7/09 to 7/10; *i*—7/12 to 7/14; and *j*—7/18.

drogue *B* are considerably lower than the adjacent GEK measurements. The maximum GEK velocity occurred at 10.1/200 which is 6.5°C lower than the 200-m temperature at drogue *C*, which had the highest speed. In total there were 12 Japanese BT and GEK sections between 132E and 137E during July 1971; ten show the maximum current at 200-m temperatures between 14.5° and 17.5°C but two maxima are at temperatures near 10°C. These low temperatures do not agree with the drogue results and are inconsistent with the high correlations reported by Kawai (1969, 1972). The discrepancy may be due to bias in the GEK measurement which arises from the dependence of the signal on the vertical distribution of velocity (von Arx, 1962).

c. Time and space variations in current path. Tracks of 15/200, along with positions of 15/200 determined from Japanese BT surveys, are summarized in Figure 5. In general there was no difficulty in determining the location of 15/200, since the inshore side of the strong thermal gradient in which 15°C is embedded was clearly marked.

Sections were selected that intersected the trend of the isotherms at an angle close to the perpendicular. The computed horizontal temperature gradients at 200 m are two to three times higher than Kawai's (1969) averages of the broader-scale Japanese survey data. Parker (1972) reports horizontal gradients of 200-m temperature across the Gulf Stream of 0.17°C km^{-1} for cruise 174 of *Crawford* and

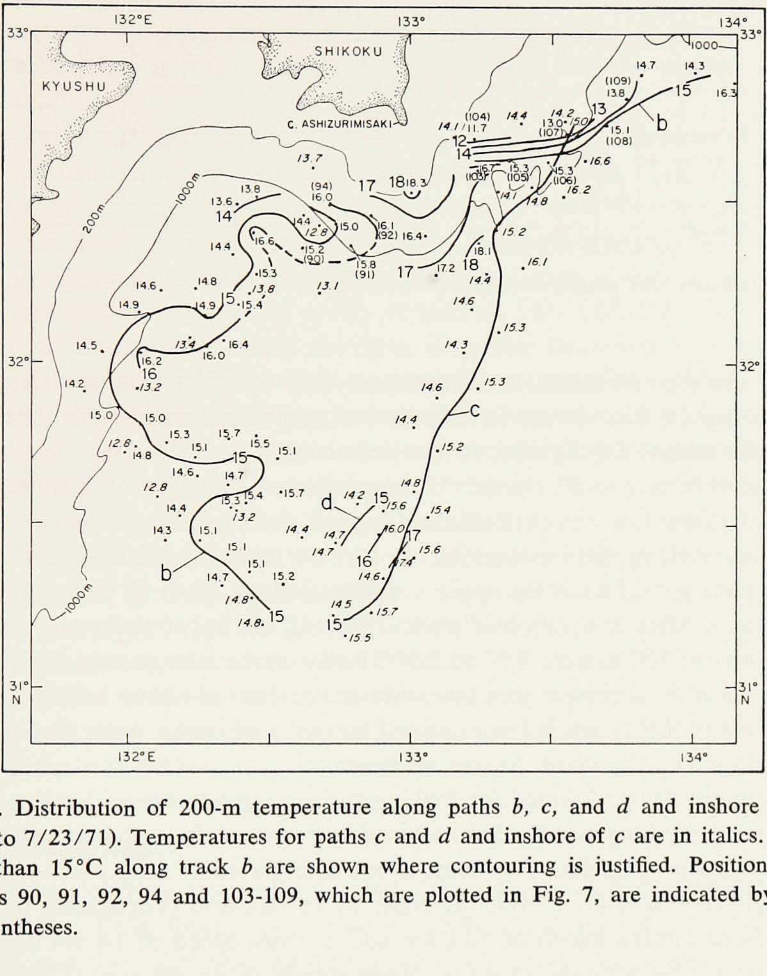


Figure 6. Distribution of 200-m temperature along paths *b, c,* and *d* and inshore of path *c* (7/12 to 7/23/71). Temperatures for paths *c* and *d* and inshore of *c* are in italics. Isotherms other than 15°C along track *b* are shown where contouring is justified. Positions of XBT stations 90, 91, 92, 94 and 103-109, which are plotted in Fig. 7, are indicated by numbers in parentheses.

0.35°C km^{-1} for cruise 51 of *Atlantis II.* The Kuroshio gradients are comparable to the Gulf Stream gradients measured from *Crawford.*

The envelope of the 15/200 tracks varied markedly within the region. The narrowest envelope (17 km) was along 136°30′E, where the tracks tended to be parallel to the 2-km isobath. These displacements are comparable to those reported at 136E over one week by Nitani and Shoji (1970). Off Kyushu the width of the envelope broadens to more than 100 km. Tracks ranged across the whole breadth of the continental slope with a consistent tendency for individual tracks to run from the deep water on the slope to shallower depths, *e.g.*, track *b* crosses the depth contours at a very steep angle before reaching the 1-km isobath where it turns eastward. Other examples of this tendency are tracks *c* and *h.*

Rates of lateral movement of the Kuroshio can be estimated from translation

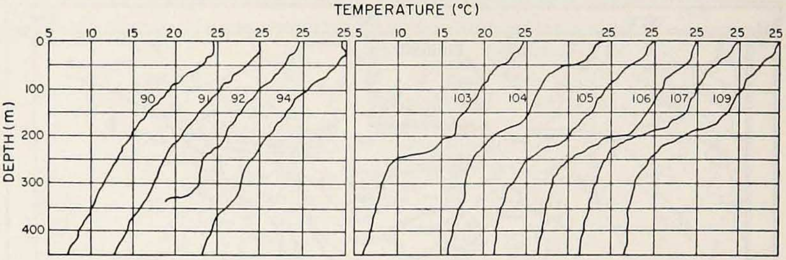


Figure 7. Selected XBT temperature profiles. Positions of XBT stations are indicated on Fig. 6.

speeds of the thermal structure. These rates tend to underestimate the speed because the current can reverse its direction of movement during the time interval between the tracks. Off Kyushu, in the period range 1 to 11 days, the translation speeds varied from 2 to 22 cm sec^{-1}; these rates are similar to Gulf Stream movements on the same time scales (Robinson, Luyten, and Fuglister, 1974).

The most striking shift in position of 15/200 was during an eight-day period when the path moved from the upper continental slope (path *b*) to the base of the slope (path *c*). After completion of track *c* (Fig. 6), the upper slope was resurveyed. Temperatures at 200 m were 1.5° to 2.0°C lower on the later survey; measurements at 400 m show an accompanying temperature decrease of about 1.0°C. The lower temperatures probably result from upward transport of cooler water to compensate for the movement offshore of the warmer water.

Our data are not well suited for looking for propagating waves because most of the tracks are not long and the time interval between tracks is too short to reliably estimate phase propagation. However, if one interprets the northward positions of tracks *b* (137E) and *f* (139°30′E) as crests of an eastward propagating wave, then it would have a wave length of 330 km and a phase speed of 14 cm sec^{-1}. This figure is consistent with the range of phase speeds (8-15 cm sec^{-1}) for eastward propagating meanders in the Kuroshio which was estimated by Nitani (1975) from Japanese survey data.

d. Disruption of normal horizontal temperature gradient. Upstream of Cape Ashizurimisaki the 15/200 (track *b*) indicates meanders with a wave length of about 40 km; the temperature gradient is relatively strong and positive in the offshore direction (Fig. 6). Further to the east, the temperature gradient reverses sign on the inshore side so that there is a minimum in temperature at 200 m. Along 133E the temperature does not fall below 16.4°C so that contact with the 15/200 is lost. The reversal in gradient also was evident at 150, 300 and 400 m but was not present above 100 m. The horizontal temperature gradient reversal implies about a 50 m deepening of the isotherms on the inshore side. Similarity of the profiles 90 and 91 (upstream of the reversal) and 92 and 94 (in the region of gradient reversal above 200 m) suggests that the warmer water from the offshore side of the current was advected onto the upper continental slope (Fig. 7). However, below 250 m the structure is modified by the appearance of a 50 m thermostad and a thermocline.

The region of gradient reversal extends downstream for a distance of about 36 km; at 133°14′W the large horizontal temperature gradient (5°C/7 km) shows reformation of an intense Kuroshio (Fig. 6). Associated with this horizontal gradient intensification, there was a shift in the thermal structure between 150 and 300 m (Fig. 7). At station 103 a very strong thermocline occurs at 240 m (4°C/10 m); a similar but weaker thermocline occurs at stations 104, 105, 106, 107, and 109. Although the formation process is not clear, it appears there was a displacement of the upper (warm) water relative to the lower (cold) water and it is likely that it was related to the disturbance in the temperature field observed south of Cape Ashizurimisaki. Another occurrence of layers of strong vertical temperature gradient (2°C/20m), which lay below a 100 m thick layer of relatively weak temperature gradient, was observed on track *c* south of Tanegashima Is. where 15/200 crosses the 1-km isobath. At this location there was a reversal of the temperature gradient at 200 m over a distance of 20 to 30 km, *e.g.* water of 17.5°C was observed 42 km north of the main track of the 15/200. It should be pointed out that there is a difference between these two occurrences of fine structure; off Tanegashima the changes in vertical structure were observed in the abnormally warm region whereas off Cape Ashizurimisaki they were most strongly expressed downstream of the region of reversal of the horizontal temperature gradient.

4. Property distribution

Masuzawa (1972) has provided a detailed discussion of the distribution of water characteristics of the upper 1 km of the North Pacific central region (including the Kuroshio) and a parallel description will not be provided here. However, because of the combination of the close bottle and station spacing and the sampling of the deep waters, the casts have revealed several features which deserve comment. In order to illustrate the property distributions across the Kuroshio, a complete set of temperature, salinity, specific volume anomaly, dissolved oxygen, inorganic phosphate and silicate sections are shown at 136°30′E (section II, Fig. 8a-f).

a. Upper layer and Intermediate Water. The position of the Kuroshio is indicated by the strong horizontal temperature gradient produced by the steep ascent of the isotherms toward the north. Isotherms on the northern side of the Kuroshio are generally level although there appears to be a slight doming of the 10-14°C isotherms. The warm core of the Kuroshio is clearly expressed at the surface by water whose temperature is greater than 28.5°C. Similar to the Gulf Stream east of Cape Hatteras (Fuglister, 1963), the warm core is marked by low values of dissolved oxygen

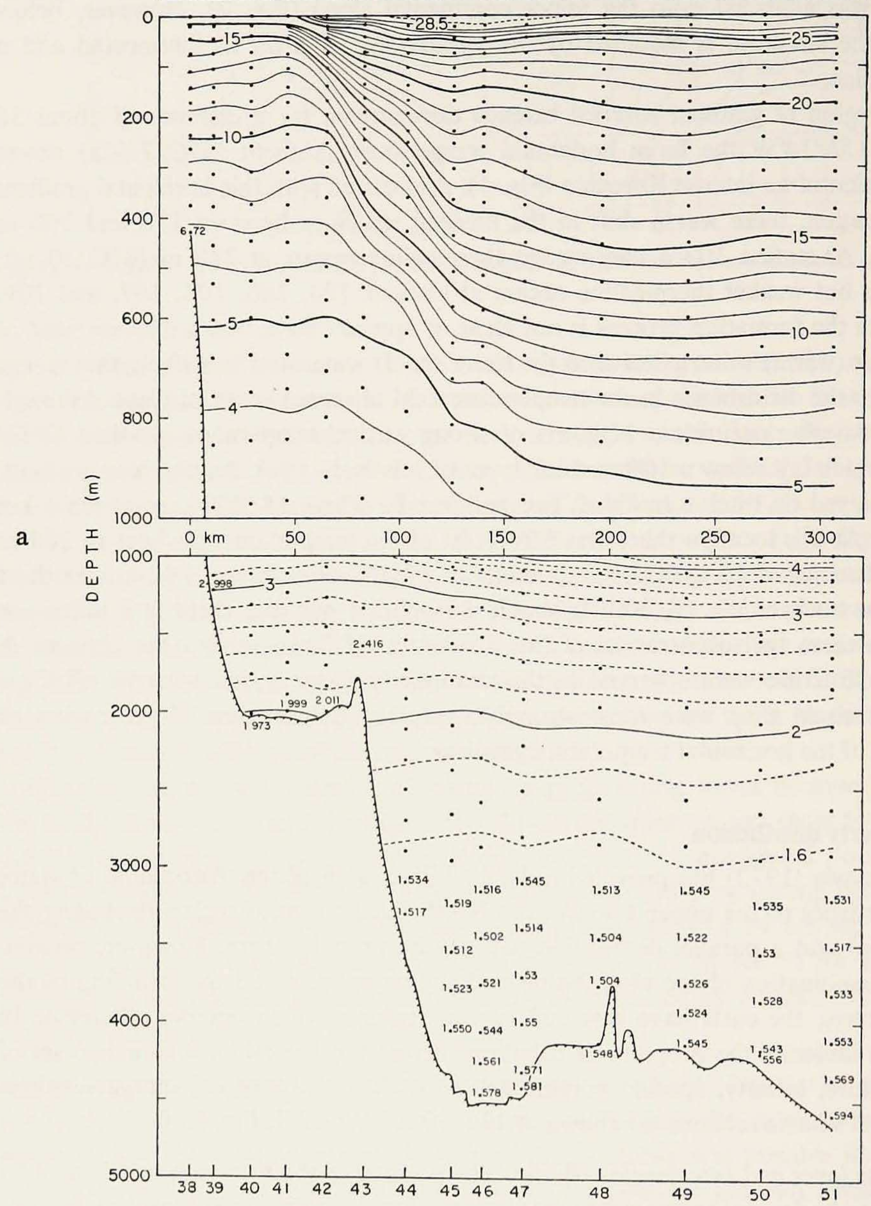
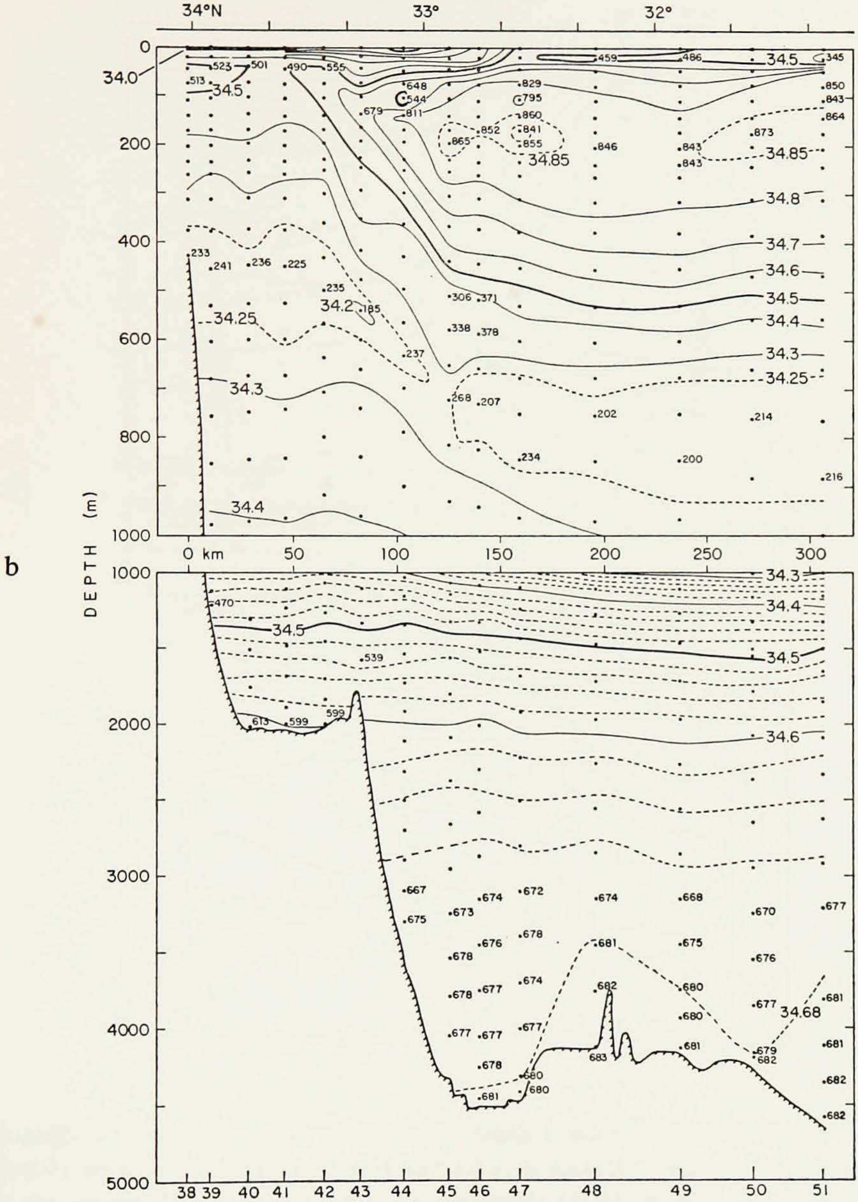
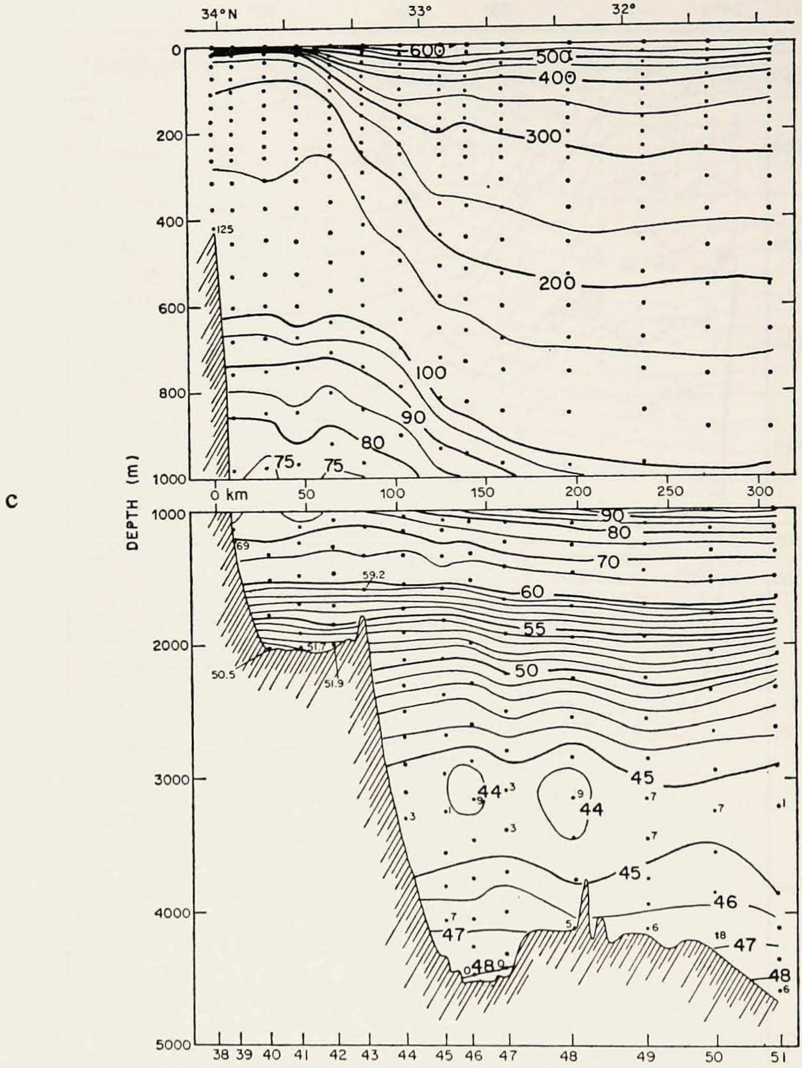


Figure 8. Vertical sections of (a) temperature (°C), (b) salinity (‰), (c) specific volume anomaly (cl ton^{-1}), (d) dissolved oxygen (ml l^{-1}), (e) inorganic phosphate (μg-at l^{-1}), and (f) inorganic silicate (μg-at l^{-1}) along 136°30′E (section II). Station numbers are given at vertical marks along the lower border. Bottle depths are indicated by dots and numbers give the values at extrema; also included are the temperature and salinity values below 3,500 m. Vertical exaggeration 231, horizontal scale 1: 36 × 10^5.

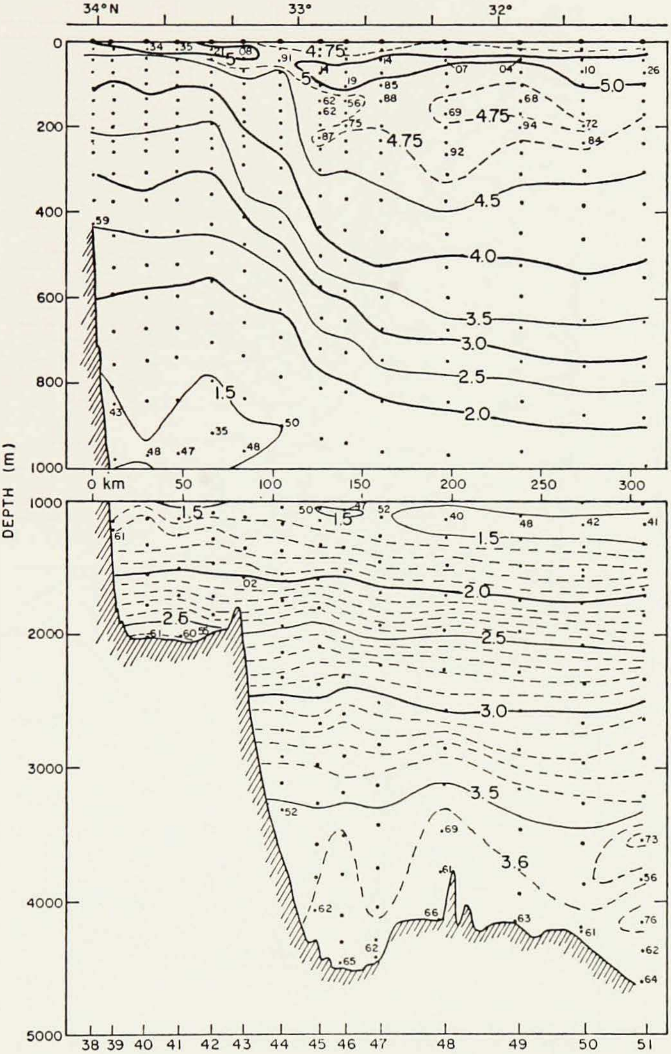


(<4.75 ml 1^{-1}) and salinity (<33.9‰). The southern side of the core is marked by a very strong lateral salinity gradient (0.5‰/35 km). On the two western sections the low salinities in the core are not bounded by higher values on the inshore side.

South of the Kuroshio, there is a thin thermostad near 18°C which has been



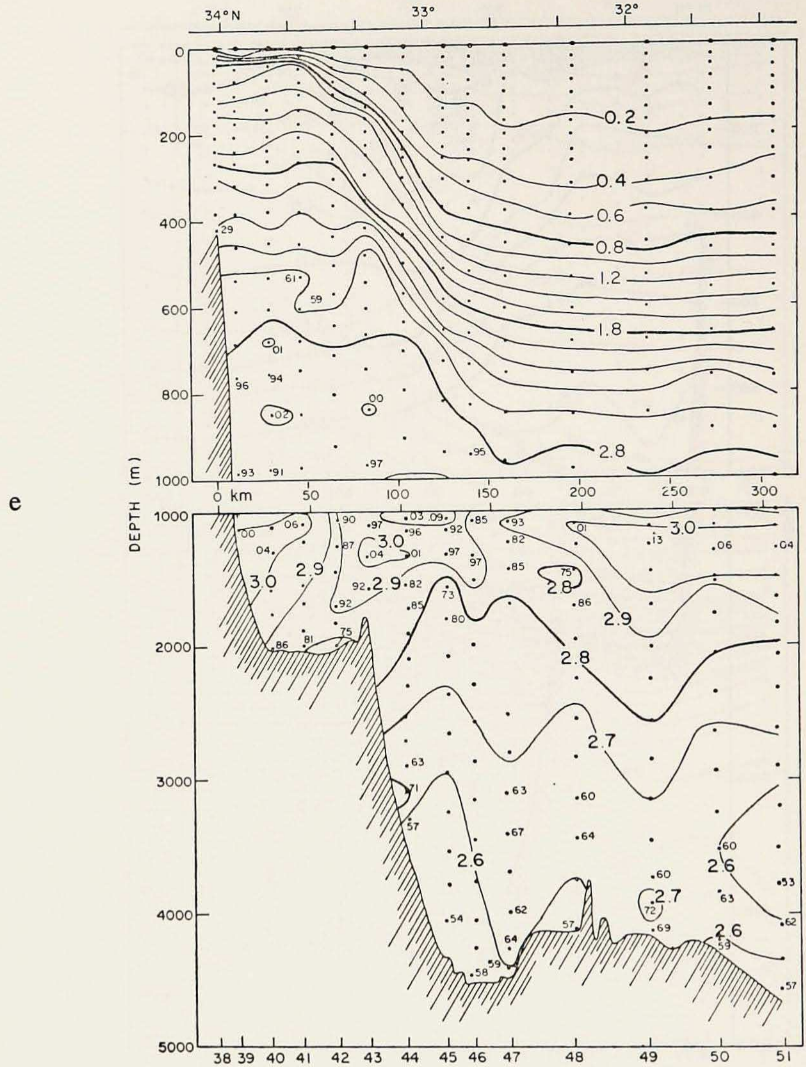
named Subtropical Mode Water (Masuzawa, 1969). Comparison of the Shikoku temperature section (Fig. 10) with the *Atlantis II* September 1965 section (Worthington and Kawai, Fig. 4, 1972) shows water with temperatures between 18 and 19°C occupying a layer which is 150 m thicker on the earlier section. The difference in volume of water between 18° and 19°C is accounted for by a much shallower depth of the 19°C isotherm and a stronger seasonal thermocline on the *Atlantis II* section. Isotherms in the main thermocline on the offshore side of the Kuroshio are about 80 m deeper on the 1965 section. The deeper main thermocline increases the relative pressure gradient across the Kuroshio. Worthington (1972)



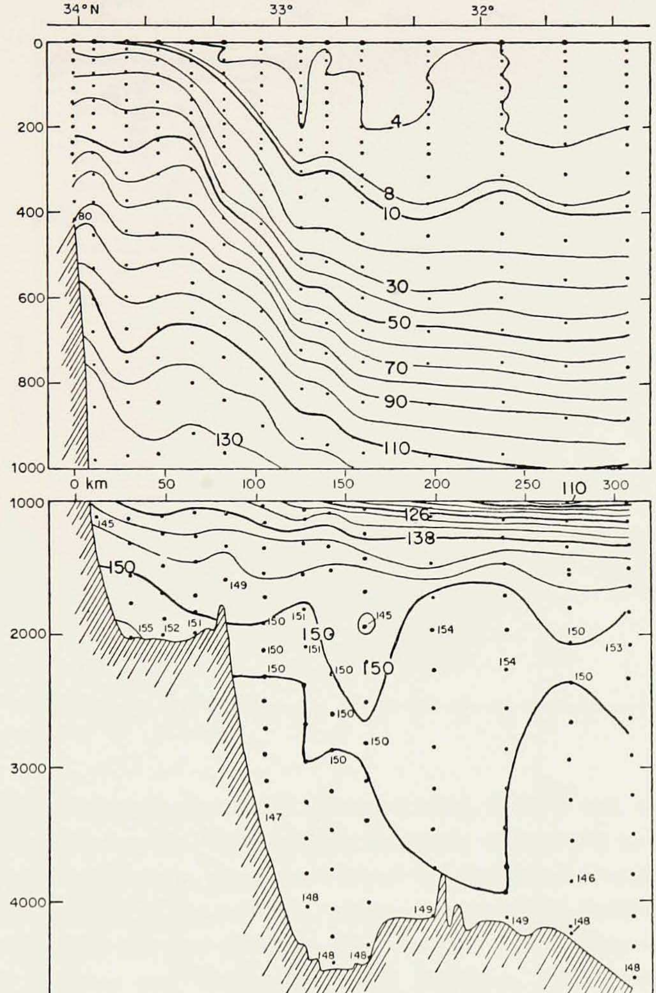
d

has suggested that the depth of the main thermocline south of the Gulf Stream in the western Atlantic deepens according to the amount of 18°C water formed in the previous winter. The decreased volume of 18°C water and shallower main thermocline in 1971 are consistent with this relationship.

The dominant features in the salinity distribution are the high-salinity Tropical Water above 200 m and the Intermediate Water salinity minimum between 400 and 800 m. The salinity maximum is expressed across the entire section but there is a transition in its characteristics between the southern and northern sides of the Kuroshio. Its salinity drops from 34.85‰ to 34.5‰ and its specific volume anomaly



from 300 to 230 cl ton^{-1}. Because water of 300 cl ton^{-1} is found at the surface on the inshore side of the Kuroshio, the salinity maximum water is diluted by vertical mixing so that the remaining expression of this feature occurs at a much lower salinity and specific volume anomaly. The low-salinity Intermediate Water can be traced across the current at a specific volume anomaly near 115 cl ton^{-1} but there is a maximum salinity (34.268‰) in this layer at the core of the Kuroshio. A similarly placed maximum was found on the other section (Fig. 11b). Lateral mixing in the north-south direction along quasi-isentropic surfaces would erase this



f

feature so that it appears that the advective field is important in maintaining the higher salinities of the Intermediate Water in the center of the Kuroshio.

The oxygen distribution south of the Kuroshio shows two maxima and two minima. The upper maximum is the summer subsurface maximum at the base of the winter mixed layer (Reid, 1962) and the lower minimum is the subthermocline oxygen minimum of the North Pacific. A thin subsurface maximum with values ranging between 4.75 and 4.94 ml 1^{-1} (mean specific volume anomaly of 292 cl ton^{-1}) lies above the 18°C thermostad. This feature appears on all four sections and is a water type that lies below the Tropical Water at the warm end of the

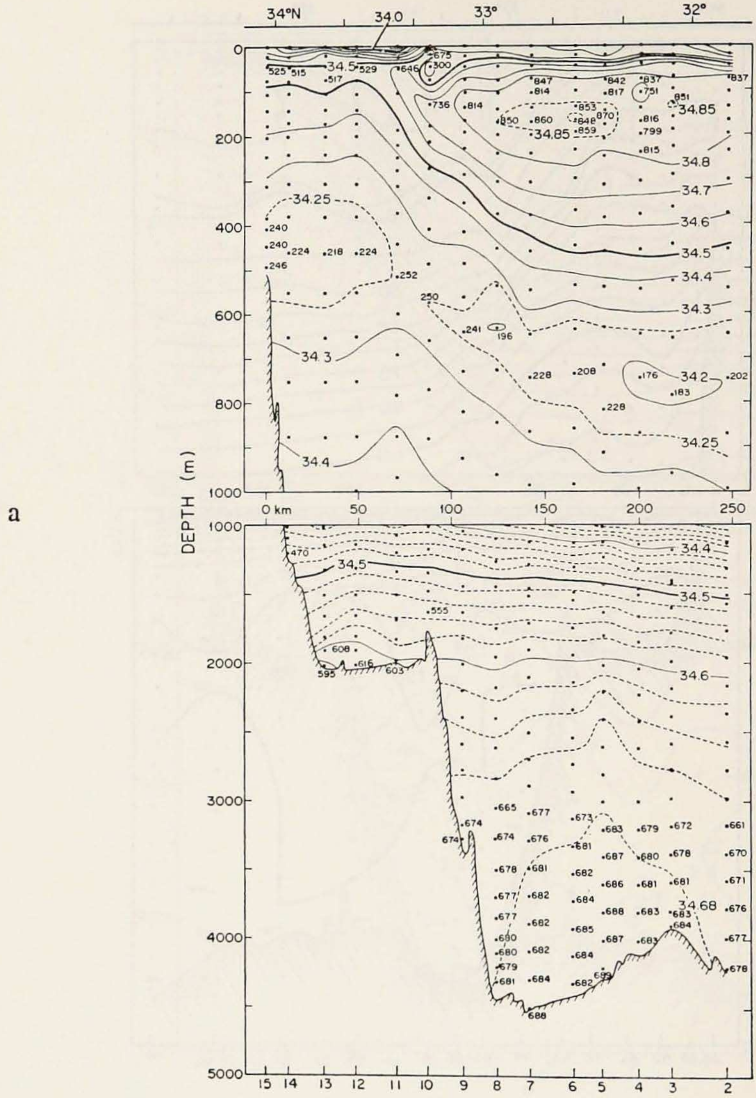
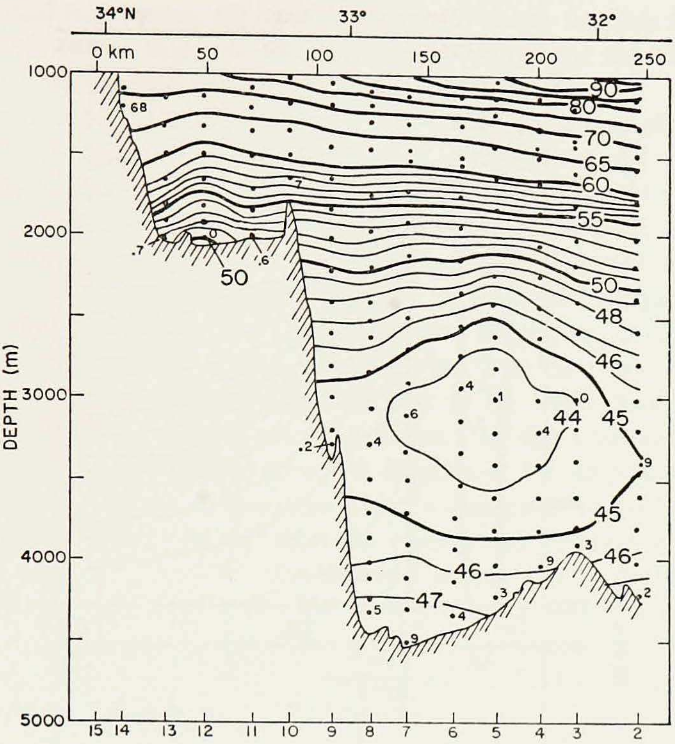


Figure 9. Vertical sections of (a) salinity and (b) specific volume anomaly below 1,000 m along 136°30′E (section I).

range of Subtropical Mode Water (Masuzawa, 1969). A similar feature occurs in the western North Atlantic south of 33°N but it is not found adjacent to the Gulf Stream (Worthington, 1959; Fuglister, 1963). Okubo (1958) noted the presence of this water type south of the Kuroshio, but did not suggest a source; this high-oxygen water derives from the spreading of Subtropical Mode Water from its source area at the northern edge of the subtropical gyre.

b



b. Deep water. The vertical profiles of temperature, salinity and dissolved oxygen below 2,000 m are smooth. Temperature decreases with depth to about 3,500 m where the gradient changes sign; the rate of temperature increase is about two-thirds of the magnitude of the adiabatic temperature gradient. Salinity and dissolved oxygen do not show the fine structure that are seen in the deep water under the Gulf Stream (Warren and Volkmann, 1968; Fuglister, 1963). Water of specific volume anomaly less than 110 cl ton^{-1} is not formed in the North Pacific (Reid, 1965) so that the deep water does not show the vertical fine structure in salinity and dissolved oxygen that arises from mixing of distinct water types as in the North Atlantic.

Under the Gulf Stream, the isanosteres slope all the way to the bottom (Worthington and Kawai, 1972). Sections I and II (Figs. 8c and 9b) indicate between 2 and 3 km water adjacent to the slope is slightly higher in specific volume (fresher and warmer) than water 100 km to the south. Below 3,000 m slopes of the isanosteres over distances comparable to the Kuroshio width are not present. Warmer and fresher water occurs also next to the slope on the Kyushu section (Fig. 11a,b) but it is of smaller horizontal scale. A similar tendency is seen on the *Atlantis II* Shikoku section but it is not expressed on the *T. Washington* Shikoku section. A

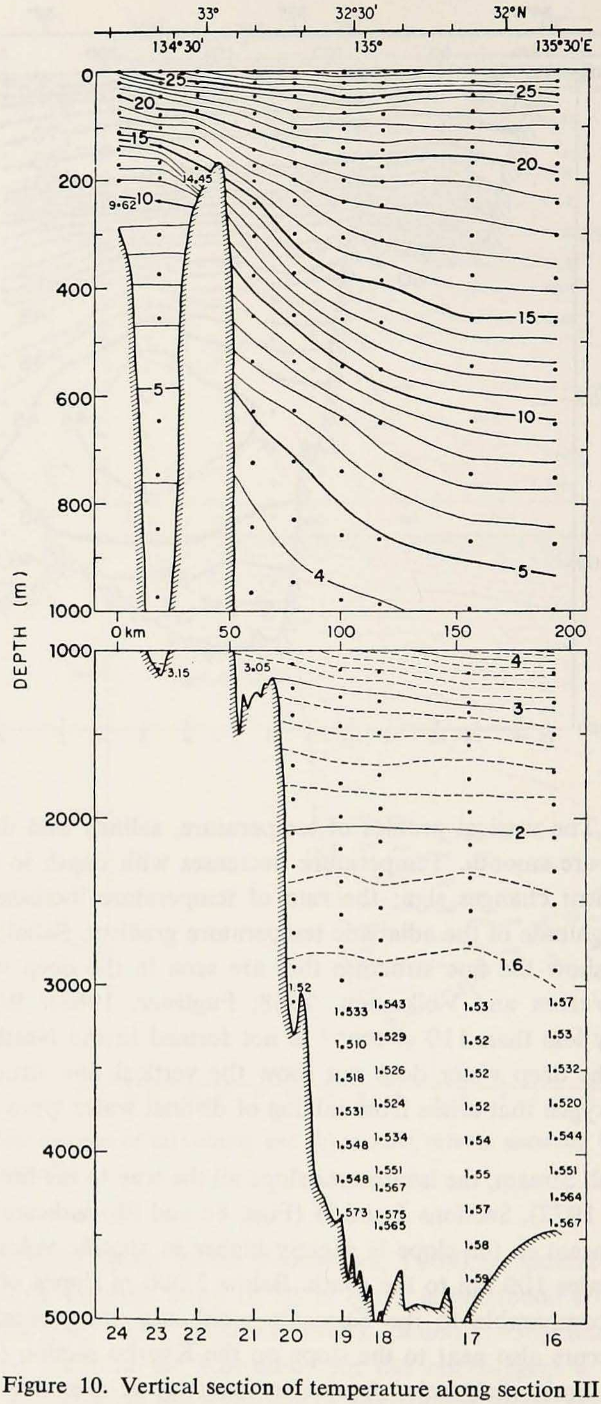


Figure 10. Vertical section of temperature along section III.

plot of potential temperature (θ) against salinity (S) shows that this lower salinity water does not depart from the θ-S characteristic curve for the Shikoku Basin (Worthington and Kawai, 1972).

In the deep water below 3200 m there are spatial variations of salinity that, although they are at the margin of detectability, appear to be real. On sections I and II salinities adjacent to the slope vary between 34.674 and 34.678‰ in contrast to salinities 50 km to the south in the range 34.683 to 34.687‰ (Figs. 8b, 9a). The region with salinities less than 34.68‰ is narrower on section I, indicating a time variation of the properties; accompanying temperature changes are 0.01 to 0.015°C. A similar spatial gradient of salinity may be present at section III (not shown); at the most offshore station, about 100 km from the slope, salinities were above 34.68‰ with salinities of 34.675‰ next to the slope. Section IV is too short to define the deep offshore salinity structure. The characteristics of this low-salinity water are distinguishable on a θ-S diagram of the deep water (Fig. 12). Water at the same potential temperature which is contiguous to the boundary consistently is about 0.005‰ fresher than the water in the interior of the Shikoku Basin in the range 1.20-1.24°C. This potential temperature range roughly corresponds to a depth range of 3500 to 4300 m. Worthington and Kawai point out that water at the northern end of the Shikoku Basin is higher in salinity for a given potential temperature than water lying along the eastern flank of the Izu-Ogasawara Ridge. The higher salinities near 1.22°C potential temperature are very close to those read from the Worthington-Kawai θ-S curve for the Shikoku Basin. The lower salinity water has characteristics which are similar to those found east of the ridge which suggests that these waters derive from the western side of the main North Pacific Basin. Although there are time variations of the salinity which are as large as the offshore gradient, the consistent appearance of the low-salinity water along the slope suggests that there is a deep circulation which maintains this low-salinity water.

5. Statistical characteristics of current records

Seven of the eight current meters were positioned below the thermocline on the continental slope or in the Nankai Trough. The other meter (#3) is located at 275 m in the strong current region of the Kuroshio. Because of the short record lengths, estimates of statistical quantities are probably not stable. Statistical quantities computed from meters #1, #4, and #7 (record lengths of 64-103 days) are presumably better estimates than those for the meters where the record lengths are 30 days or less (Table 2).

The time series (Fig. 13) have been presented in the form of components resolved normal and tangent to the trend of the local topography determined from a large-scale map (Anonymous, 1966). Bottom topography on the mid-slope near mooring #1 is complicated; the trend of the 2.5 km isobath was used to compute

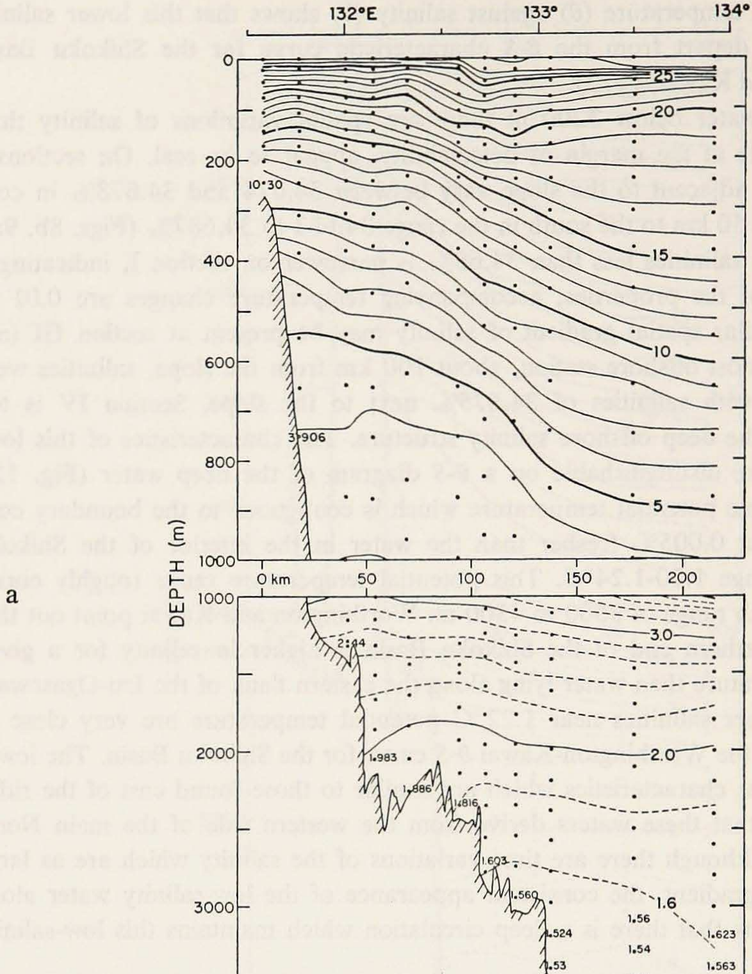
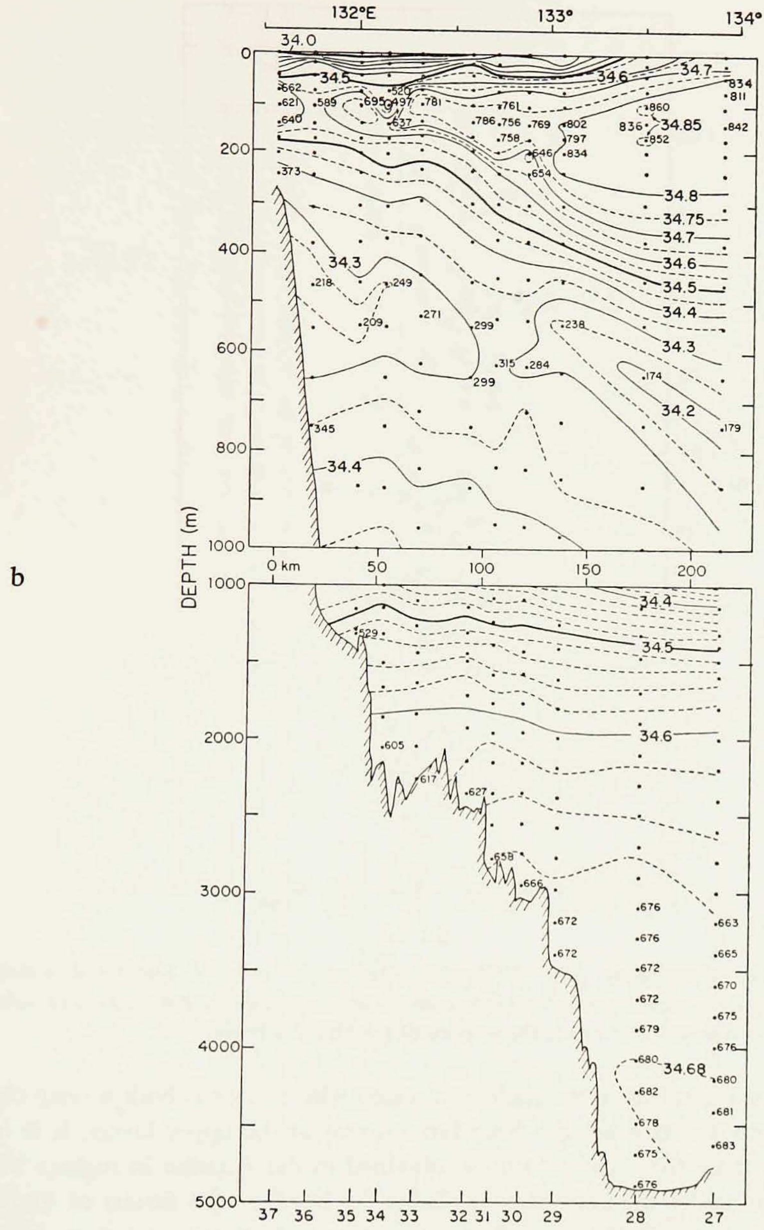


Figure 11. Vertical section of (a) temperature and (b) salinity along 31°30′N (section IV).

the components. At moorings #2, #3, #4, and #7, where the slope is steep, the trend of the isobaths is unambiguous. For moorings #6 and #8 the 2 and 4 km isobaths, respectively, were taken as indicative of the topographic trend.



a. Kinetic energy. The three long records on the slope (at different sections) show a decrease with depth of the kinetic energy of the fluctuations (per unit mass, hereafter understood). Higher fluctuating kinetic energies were observed in the Nankai Trough (#8) than at the shallower meter on the slope (#7), which suggests that the type of topography influences the level of the fluctuations.

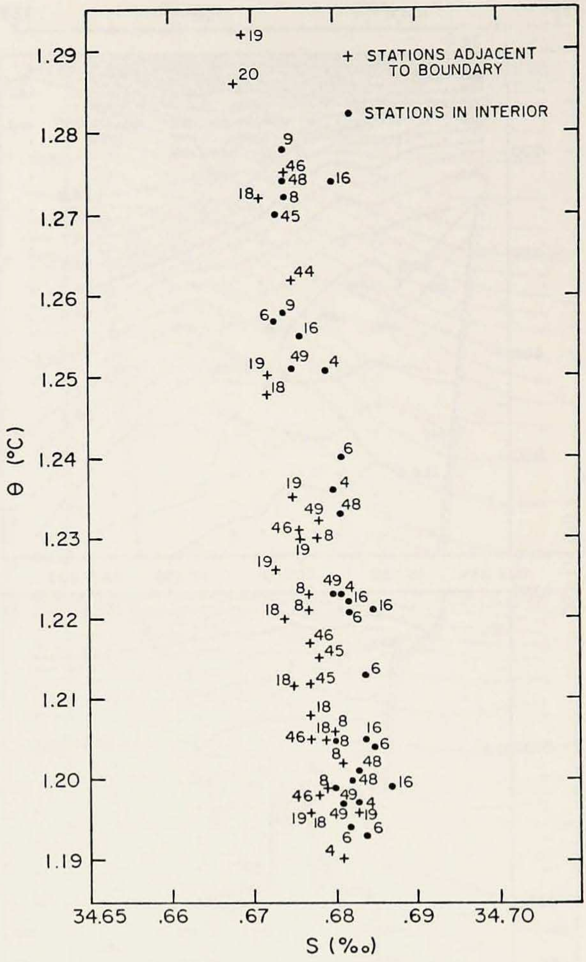


Figure 12. Potential temperature (*θ*)—salinity (*S*) diagram for selected numbered stations. Values indicated by a cross represent stations contiguous to the continental slope; and values indicated by dots represent stations in the interior of the Shikoku Basin.

Since these measurements were made in a region where there is both a steep continental slope and a strong western boundary current in the upper layers, it is appropriate to compare the records to those obtained in the Atlantic in regions both on the slope and under the Gulf Stream (Table 3). Between the Straits of Florida and Cape Hatteras, the Gulf Stream flows along the steep continental slope (Swallow and Worthington, 1961) in a manner which is similar to the Kuroshio south of Japan. Unfortunately there are no velocity time series statistics reported from this part of the Gulf Stream system. The Kuroshio measurements show very much lower kinetic energy levels than the near-Gulf Stream measurements along 70W. Eddy kinetic energy levels for the Kuroshio are also lower than the values for the

Table 2. Data on current meter moorings and basic statistics of low-passed velocity measurements. Mooring numbers correspond to those on Figure 1. $\langle u \rangle$ and $\langle v \rangle$ are the mean east and north components; $\langle K_E \rangle$, K_M, and K_T represent the fluctuating, mean and total kinetic energies per unit mass; and $\langle N'^2 \rangle$, $\langle T'^2 \rangle$, and $\langle T'N' \rangle$ are the variances and the covariance of the velocity components normal (N') and tangent (T') to the local topography.

Mooring number	Latitude (N)	Longitude (E)	Record length (days)	Bottom depth (m)	Meter depth (m)	$\langle u \rangle$	$\langle v \rangle$	$\langle K_E \rangle$	K_M	K_T	$\langle N'^2 \rangle$	$\langle T'^2 \rangle$	$\langle T'N' \rangle$
						cm sec^{-1}		cm^2 sec^{-2}					
1	31°32.2′	132°28.2′	74	2266	2116	0.7	0.6	8.6	0.4	9.0	7.2	9.9	−0.86
2	31°28.0′	132°52.7′	23	2987	2837	−1.7	−0.8	0.7	1.8	2.5	0.44	1.0	0.38
3	33°01.9′	134°33.3′	29	366	266	16.1	20.6	2.3	341.8	344.1	2.5	2.1	−1.33
4	32°49.0′	134°43.8′	103	1953	1803	−2.1	−0.1	17.8	2.0	19.8	3.3	32.2	−2.51
5	32°30.2′	134°59.1′	29*	4299	4149	—	—	—	—	—	—	—	—
6	33°20.0′	136°33.0′	30	2289	2139	−1.3	0.5	5.9	1.0	6.9	6.1	5.7	−1.08
7	33°03.0′	136°34.5′	64	3840	3690	2.8	0.6	4.3	4.2	8.5	0.8	7.8	−0.30
8	32°38.6′	136°32.4′	30	4423	4273	4.2	2.3	17.3	11.3	28.6	17.1	17.5	0.82

* Record has significant periods of zero recorded current.

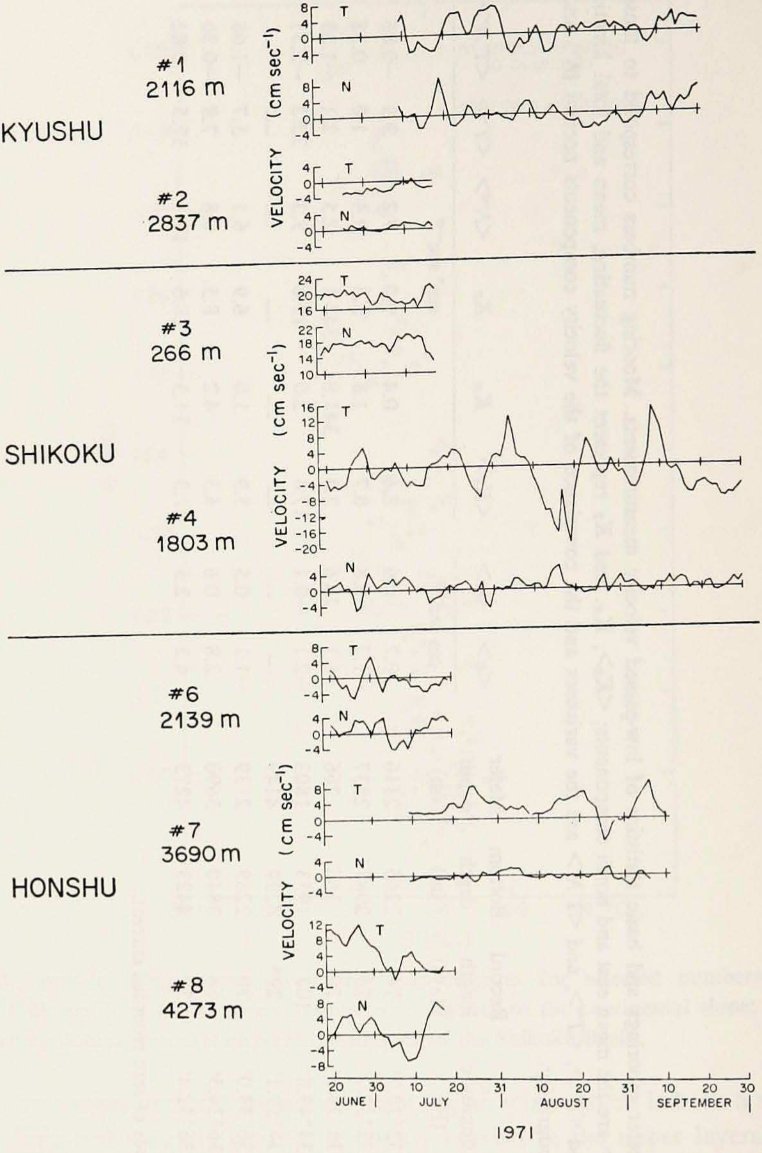


Figure 13. Low-passed velocity components normal (*N*) and tangent (*T*) to the bottom topography. See Table 2 for positions.

continental slope south of New England. However, the ratios of eddy to mean kinetic energy along the slope are comparable in magnitude to the ratios observed under the Kuroshio. Near the Gulf Stream the ratio in deep water is an order of magnitude larger than observed at the same depths under the Kuroshio.

Table 3. Geographical and depth averages of kinetic energy for low-passed current meter records from western North Atlantic near 70W (Luyten, 1977) and under Kuroshio. $<K_E>$, K_M and K_T represent the fluctuating, mean and total kinetic energy per unit mass.

Depth (m)		Number records	$<K_E>$ (cm² sec⁻²)	K_M (cm² sec⁻²)	K_T (cm² sec⁻²)	$<K_E>/K_M$
	Atlantic					
	Continental slope					
1977-2781	39°07′-39°26′N 69°00′-70°33′W	6	16	6	22	2.7
	Near Gulf Stream					
3337-4267	36°30′-37°00′N 69°20′-70°00′W	6	72	7	79	10.3
	Pacific					
	Near Kuroshio					
1803-2837	Meters #1, #2, #4, #6	4	8	1	9	8.0
3690-4273	Meters #7, #8	2	11	8	19	1.4

It is perhaps not surprising that the variability field in the deep water under the Kuroshio differs from the Gulf Stream field over the broad continental rise east of Cape Hatteras. The Kuroshio during the period of these measurements was limited to the continental slope region. Except off Kyushu, the position of the surface current was relatively stable in position and did not show the type of variability characteristic of the Gulf Stream where 100 km shifts in position are commonly observed over periods of weeks (Hansen, 1970; Robinson, Luyten and Fuglister, 1974). In addition, the physical setting is different from the 70W North Atlantic location because of the steep continental slope and the Izu-Ogasawara Ridge which would prevent westward traveling oscillations in the deep water from entering the Shikoku Basin.

b. Time scales. The six autocorrelation functions for the velocity components normal and parallel to the topography at meters #1, #4, and #7 have a first zero-crossing at 5 days, which may be taken as evidence of a 20-day period. This period is at the upper end of the range of periods (5-20 days) reported by Luyten (1977) for velocity measurements made on the upper continental slope near 70W. There is no evidence of bursts of strong meridional (upslope) flow of about 30 days duration as has been reported under the Gulf Stream by Luyten (1977).

Additional evidence for fluctuations in this range of periods may be seen in the shorter records from meters #6 and #8. The cross-topography components of flow show upslope components in the early part of the record followed by downslope components in the later part of the record (Fig. 13). The oscillations are roughly in phase and the cross-correlations for lags of 1-4 days are greater than 0.60 and are statistically significantly different from zero. A five-day running mean was applied to the data to remove the shorter period fluctuations and the time between the maximum upslope and downslope flow was determined; the separation times were 10 days for meter #6 and 16 days for meter #8 which would imply periods of 20 and 32 days. Taft, Robinson and Schmitz (1973) pointed out that there was a suggestion of a movement of the surface current which was correlated with the cross slope velocity fluctuations. However, the number of data points was too small to estimate the time scale of current movement. The rather steady decrease over the entire meter #8 record of the velocity component parallel to the topography suggests that there is a fluctuation with a period considerably longer than the record length of 30 days.

c. Relation between the deep current and bottom topography. The continental slope south of Japan is quite steep and cross-slope fluctuations due to topographically controlled wave motions might be expected to be inhibited. At both moorings #4 and #7 on the steep continental slope (slope of 7×10^{-2}) the ratio of the mean square fluctuations parallel and normal to the contours is 9.8 (Table 2). These ratios are 3 to 4 times as large as those computed by Thompson (1971) from data on the slope north of the Gulf Stream, where the slope is of the order of 5×10^{-3}. The fluctuations at #4 and at #7 appear to be related to real time fluctuations of the flow along the contours and not to current meanders across the slope. A scatter plot of the u and v components (not shown) at these two locations indicates that the components are positively correlated and the least-squares linear regression fits of v to u are within 20° of the estimated trend of the contours.

Data from the other moorings show comparable magnitudes for mean square fluctuations of components cross and parallel to the topography and the u, v plots exhibit wider scatter. There is not a noticeable relation between the fluctuations and the topography near meter #1 (slope of 2×10^{-2}). There may be a critical value of the slope somewhere between 2 and 7×10^{-2} where across-slope motions are inhibited. This effect has been seen in the records from the upper continental slope in the western Atlantic, although Luyten (1977) suggests that it may become effective at a much lower slope of 5×10^{-3}.

6. Geostrophic velocity and volume transport

a. Construction of velocity sections. Computations of geostrophic velocity have been made using the method of Helland-Hansen (1934) in order to estimate the difference in dynamic height between the continental slope and the offshore adjacent station. Since the orientation of the sections changes, the interpretation of the positive shear varies accordingly: on section IV it indicates decreasing northward flow with depth; decreasing northeastward flow on section III; and decreasing eastward flow on sections I and II (Figures 14a-d).

Where direct current measurements are available the geostrophic shear has been

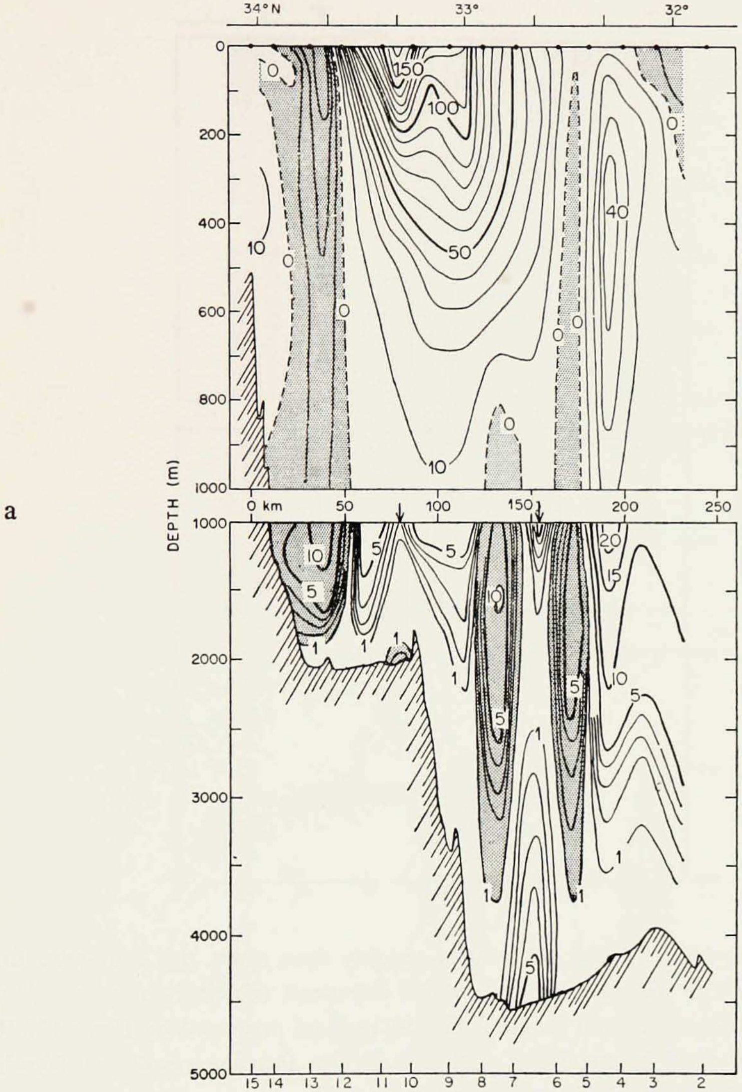
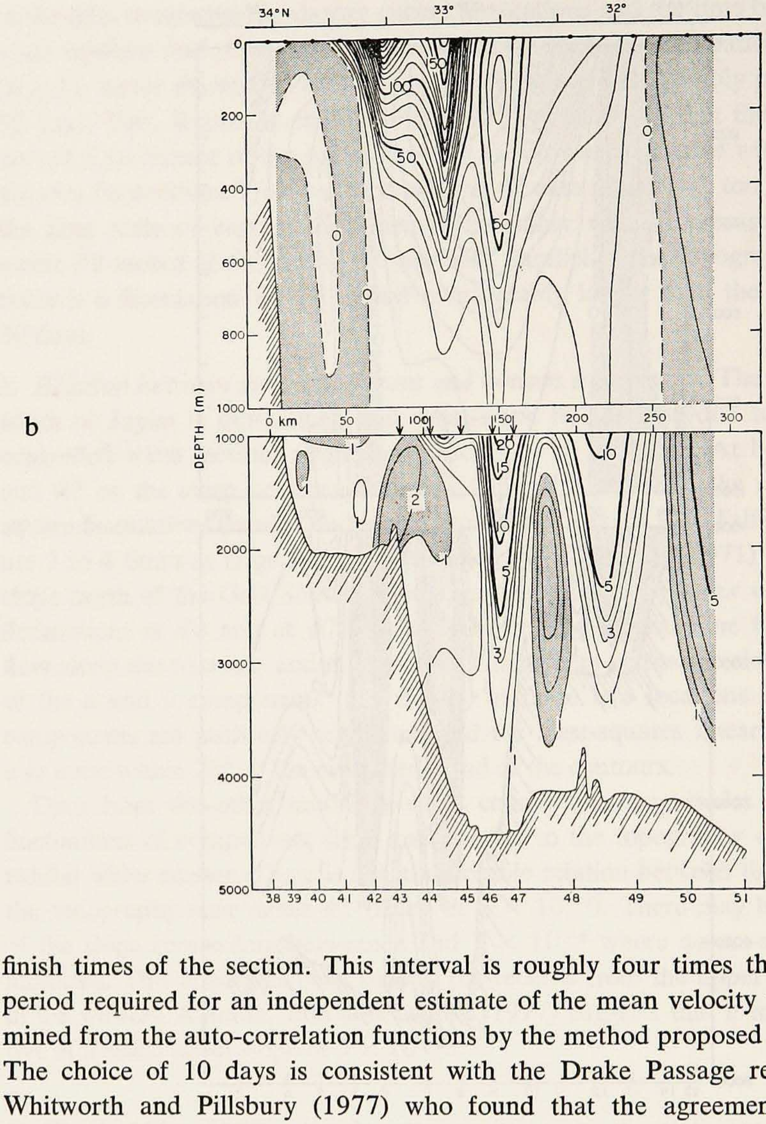


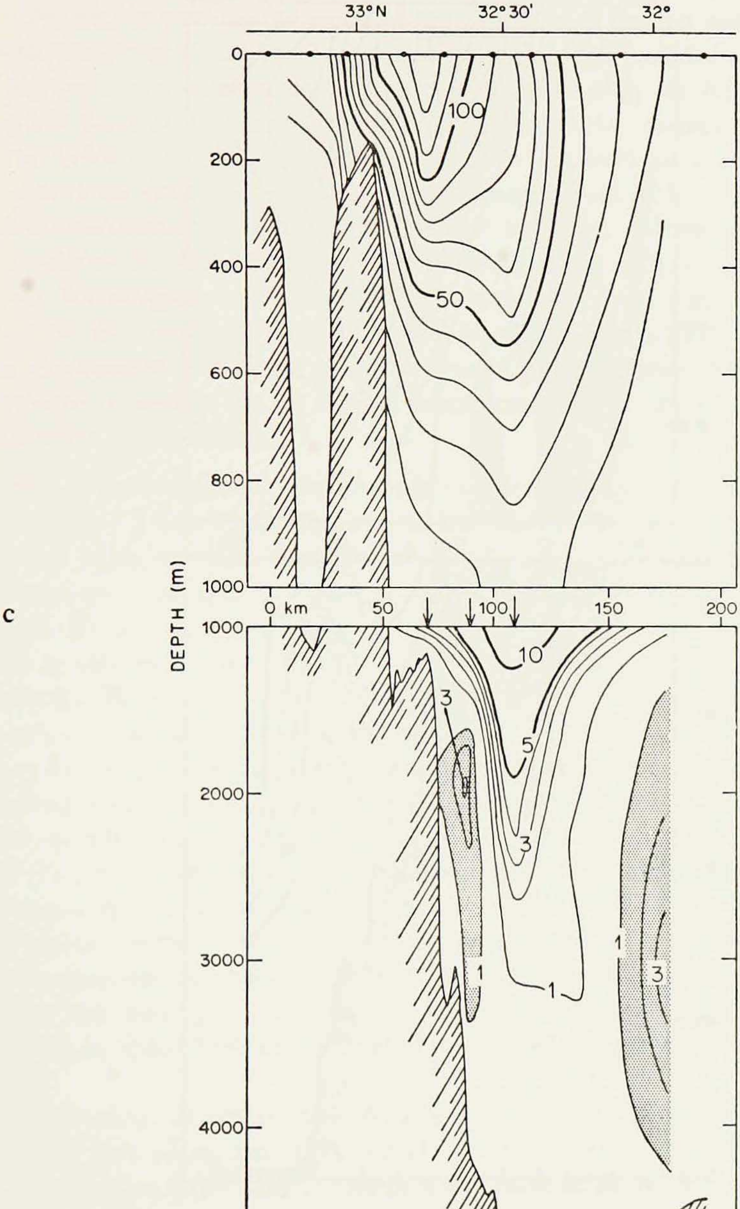
Figure 14. Geostrophic velocity distribution (cm sec^{-1}): *a*—section I (Honshu); *b*—section II (Honshu); *c*—section III (Shikoku); and *d*—section IV (Kyushu). Locations of sections are shown in Fig. 1. Profiles using interpolated 10-day average velocities normal to the section as a reference for geostrophic computation are indicated by vertical arrows in space between shallow and deep panels. Flow or shear of opposite sign to that of the Kuroshio is shaded; see text for interpretation of signs.

referenced to the average current velocity component normal to the section to give the absolute velocity profile. To obtain the reference velocity the low-passed data were averaged over the nearest 10-day time interval with respect to the start and



finish times of the section. This interval is roughly four times the estimated time period required for an independent estimate of the mean velocity which was determined from the auto-correlation functions by the method proposed by Davis (1976). The choice of 10 days is consistent with the Drake Passage results of Nowlin, Whitworth and Pillsbury (1977) who found that the agreement in geostrophic shear was best when the interval was between 1 and 3 weeks. Velocities were interpolated for each pair of hydrographic stations from the 10-day average; interpolations were not done if the meters were more than 50 km apart. Where no velocity data was available the geostrophic profiles are based on an assumed zero velocity at the bottom.

It should be noted that current meter data were not obtained over the mid-slope during section I and consequently only two geostrophic profiles are referenced. Twelve percent of the values recorded at meter #5 were below threshold during the 10-day averaging period. Accordingly, the results are less reliable than at the


c
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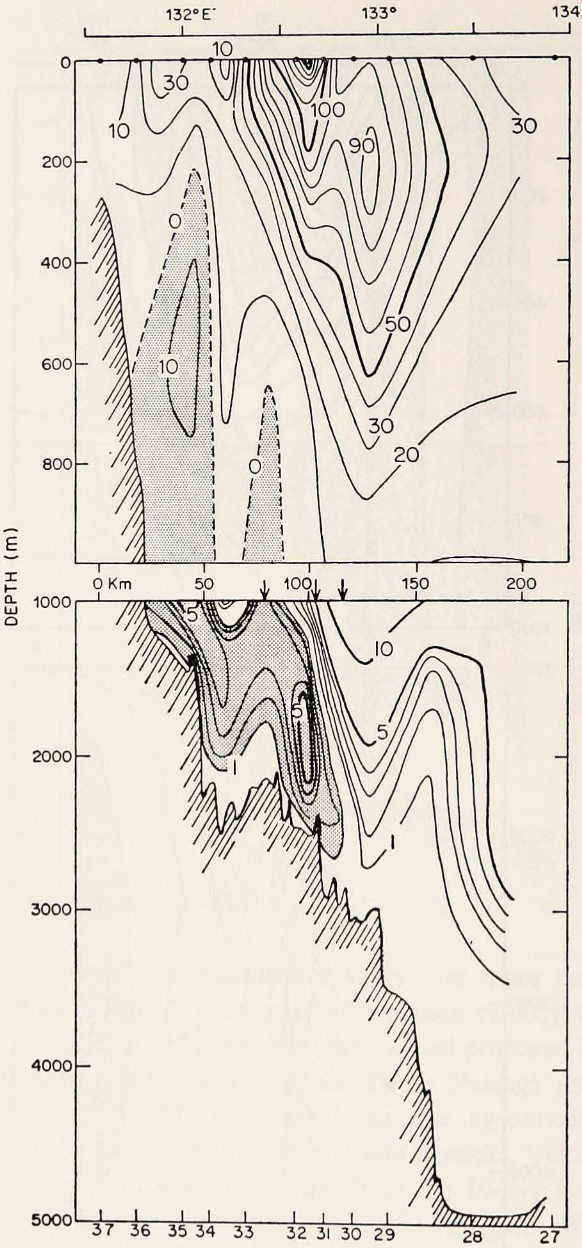

other meters. The velocity structure in the upper 1 km is not significantly affected by the adjustment of the velocities but the deep velocity field is sensitive to the choice of a reference velocity.

b. Surface current. The inshore side of the Kuroshio is defined on all sections but the offshore limit is not defined on the shorter Kyushu and Shikoku sections. On the two shorter sections the speed of the Kuroshio at the last pair of stations was reduced to about 20 cm sec^{-1}. The sections off Honshu included an offshore region of westward flow near the surface which gives widths for the Kuroshio of 170 (I) and 230 km (II). Computed speeds were higher at the two Honshu sections than at the Shikoku and Kyushu sections. A similar eastward increase in velocity may be seen in the GEK surface current measurements south of Japan (Taft, 1972). An inshore countercurrent is present on both of the Honshu sections, but on the other two sections the Kuroshio extends all the way into the shallow water near the shelf break. Worthington and Kawai (1972) computed a maximum speed of 240 cm sec^{-1} for the *Atlantis II* Shikoku section which was run parallel to section III but was displaced 90 km to the west. This speed is about twice the maximum speed computed on section III. An inshore countercurrent was present on the *Atlantis II* section but not on Section III.

c. Deep current structure. The broad baroclinic structure of the Kuroshio is limited to the upper 1 km. Under the core of Kuroshio at the surface there is a current reversal which varies in depth from 1200 to 1600 m on the four sections. The countercurrent occupies a region on the middle and lower continental slope. On section III the lower boundary (defined by the -1 cm sec^{-1} contour) occurs at 3400 m and on Sections II and IV it is found at depths of 2000 and 2600 m, respectively. Because of the lack of direct measurements on the mid-slope the lower boundary is not determined on section I. The counter flow is connected to an inshore flow which extends into the surface layers on sections II and IV; on section III there is no inshore counter flow and on section I there is an intervening eastward current. The similarity of profiles at 33°20′N on sections I and II indicates that the inshore side of the countercurrent was stable over a period of 19 days. Maximum speeds in the countercurrent vary from -2 (II) to -9 cm sec^{-1} (IV). The position of the countercurrent on sections III and IV is similar to that reported by Worthington and Kawai (1972). Nitani (1975) deduced from an analysis of density data that there was a level of no horizontal motion under the core of the Kuroshio at about 2300 m; his level of no motion appears to be about 1000 m too deep.

The absolute velocity profiles offshore of the deep countercurrent indicate a narrow deep flow on sections I, II and III which is coherent with the Kuroshio. On section IV there is no current meter on the lower slope so the northward flow extending to 3000 m is based on the assumption that the bottom velocity is zero. Although the measurements indicate that the Kuroshio does not extend to the bottom over the slope, eastward flow to the bottom (sections I, II) precludes extending offshore the current reversal found over the slope.

d. Volume transport. In order to present the volume transport normal to the sections (Table 4) the flow field is divided into the following five regions: (1) inshore eastward flow (I, II only); (2) inshore westward flow (I, II only); (3) Kuroshio; (4) deep countercurrent (absolute and relative transport); and (5) offshore westward (I, II only).

The Kuroshio transport varies from 57 to 72 × 10^6 m^3 sec^{-1}. All deep-water transport in the direction of the Kuroshio is included in the Kuroshio transport, even though it is recognized that the deep flow may not be dynamically linked to the Kuroshio. The transport is not very sensitive to the choice of a reference velocity from the current measurements; the values differ by at most 3 percent from those computed on the assumption of zero velocity at the deepest observation level. The lower Shikoku transport is due to lower northeastward transports in the deep water. For example, if the transports are computed relative to 1000 db, the range is reduced to 9 × 10^6 m^3 sec^{-1}. The Shikoku transport is considerably less than the *Atlantis II* (September, 1965) Shikoku transport of 84 × 10^6 m^3 sec^{-1}. Although the difference may be due in part to shortness of the *T. Washington* section, there appears to be a real difference between the sections. The maximum speed was roughly half that computed for the *Atlantis II* section. It was pointed out that the amount of 18°C-water was larger and the main thermocline was deeper in September 1965 than in July 1971. The lower 1971 transport is consistent with the suggestion of Worthington (1972) that the transport of a northern hemisphere western boundary current will vary with the amount of 18°C-water. Nitani (1975) presents additional evidence that there was a significant difference in the 1965 and 1971 Kuroshio transports. Volume transport of the Kuroshio relative to 1000 db was computed from Japanese hydrographic sections south of Eushu-nada (137.5°E) for a 28-year period. Values read from his Fig. 4a give a summer 1965 transport of 68 × 10^6 m^3 sec^{-1} whereas the summer 1971 transport is only 50 × 10^6 m^3 sec^{-1}. Transports relative to 1000 db at sections I and II are 54 and 59 × 10^6 m^3 sec^{-1}, respectively.

The countercurrent transports are considered to be minimal because they are limited to the profiles for which the deep velocity data are available. In particular the low section I transport of 0.1 × 10^6 m^3 sec^{-1} is based on the single velocity profile at 33°20′N. The countercurrent transports are smaller than those reported by Worthington and Kawai (1972) but it should be pointed out that their estimates include relative as well as absolute transports. The values of the deep total transport counter to the Kuroshio are comparable to their estimates.

7. Summary and discussion

The data presented here have sharpened our description of several aspects of the Kuroshio in the region south of Japan. In particular, high resolution path determinations and long velocity measurements in deep water have not been available

Table 4. Geostrophic volume transport estimates. The geostrophic profiles were adjusted to the 10-day average velocity component normal to the section where current meter data were available; if there were no measured velocities, zero bottom velocity was assumed. Positions of sections are given in Figure 1. Positive transports are in direction of Kuroshio. The *Atlantis II* Shikoku section is parallel to section III and displaced 90 km to the west.

Section	Inshore eastward	Inshore westward	Kuroshio	Counter-current (absolute)	Counter-current (relative)	Total Counter-current	Offshore westward
					(10^6 m^3 sec^{-1})		
I	0.5	−6.5	72	−0.1	−7.0	−7.1	−0.8
II	0.7	−2.2	71	−1.0	−2.7	−3.7	−11
III	—	—	57	−1.1	−2.7	−3.8	—
IV	—	—	70	−1.5	−2.7	−4.2	—
Atlantis II							
Shikoku (134.5°E)	—	−1.6	84	—	—	−6.7	—
Inubozaki (142°E)	—	—	88	—	—	−4.8	—

previously so that a first description of the time and space scales of the motions of the surface Kuroshio and the deep flow field are now possible. In this section, some of the implications for the interpretation of the large historical data base of Japanese measurements which are spatially more limited both in horizontal resolution and in depth will be pointed out.

a. There is considerable variation within the region between Kyushu and the Izu-Ogasawara Ridge in the movements of the tight horizontal temperature gradient at 200 m which is associated with the axis of the surface Kuroshio. East of Kyushu in a one-week period the paths fully spanned the 100 km-wide path envelope derived from the (1956-1964) surveys of the Kuroshio (Taft, 1972). The rapid offshore movement of the current was accompanied by a lowering of the temperature down to at least 400 m and the upper continental slope. Rates of movement of the current off Kyushu are comparable to movements in the Gulf Stream on the continental rise east of Cape Hatteras. Much smaller rates of movement were measured in the region near 136°30′E. Consistent with the historical data, the envelope appears to broaden on the approach to and over the Izu-Ogasawara Ridge. In one instance a rough estimate could be made of phase speed and wave length of a wave-like disturbance of the 15/200 adjacent to the Ridge; the speed (0.14 m sec^{-1}) and wave length (330 km) are consistent with the values estimated by Nitani (1975) from his analysis of widely spaced sections across the Kuroshio.

b. There were two instances in which there was a marked change in the vertical temperature profile in the region of the strong horizontal temperature gradient. Secondary thermoclines occurred which suggested a lateral shift of the upper layers relative to the lower layers. The best documented occurrence, off Cape Ashizuri-misaki, appeared to be related to the strong upstream interaction of the current with the shallow topography on the inshore side of the current. This type of disruption of the horizontal temperature gradient, which has not previously been reported in the Kuroshio, produces a change in the vertical shear of the current and would consequently accelerate the surface flow.

c. Surface drogue measurements south of Honshu showed current acceleration and possibly some cross-isotherm flow. There appears to be variability in the relation between the 200 m temperature and the maximum surface velocity. Along 137E the maximum drogue speed occurred near 17°C. GEK measurements made from Japanese survey vessels in the same region in two instances showed the maximum surface current at 200 m temperatures which were 6-7°C lower. Whether the discrepancy is due to a bias in the GEK measurement or variability in the temperature-velocity relationship is not known. It does seem clear that the GEK and 200 m temperatures could give different pictures of the position of the Kuroshio axis. Thus, the axis representations such as those of Shoji (1972) (temperature) and Taft (1972) (velocity) can be expected to differ at least in detail.

d. Marked offshore deepening of the isotherms, isohalines and isanosteres on the scale of the Kuroshio ($\sim$ 100 km) is observed only down to depths of about 1800 m. Below this depth the isopleths show variability on shorter scales of 30-40 km. If there is a deep baroclinic expression of the Kuroshio it is considerably narrower than in the upper layers. In the region adjacent to the continental slope at depths between 2 and 3 km higher specific volume, lower salinity and higher temperature water was found on sections I and II; further offshore the small horizontal gradients in the specific volume varied over the 19-day period between sections. Below 2 km, particularly at sections I and II, slightly lower (0.005‰) salinities were measured next to the slope down to within 300 m of the bottom of the Nankai Trough. The lower salinity water was also observed further to the west on the Shikoku section (III) but was not defined at the Kyushu section (IV), presumably because the section did not extend very far into the Shikoku Basin.

e. Kinetic energies of the deep flow field are significantly less than those measured under the Gulf Stream along 70W or on the continental rise south of New England (Luyten, 1977). Eddy kinetic energy for the three long records (longer than 64 days) ranges from 4 to 18 $\text{cm}^2\ \text{sec}^{-2}$ with a tendency for the eddy kinetic energy to decrease with increasing depth along the slope. The ratio of eddy to mean kinetic energy under the Kuroshio is an order of magnitude smaller than in the Gulf Stream east of Hatteras. The low kinetic energies may be due to the presence of the Izu-Ogasawara Ridge which isolates the Shikoku Basin from the open Pacific.

f. All three long velocity records from the slope show a dominant fluctuation with a period of 20 days, based on the first zero crossing of the autocorrelation function. In addition, visual inspection of the cross-topography fluctuations at meters

#6 and #8, located on the plateau on the upper continental slope and in the Nankai Trough at 136°30′E, show marked oscillations at periods of 20 and 32 days, respectively.

The 20-day period is slightly longer than the 5-15 day range of energetic periods reported for the fluctuations on the upper continental rise north of the Gulf Stream (Luyten, 1977). The other characteristics of the records on the steep slope (#4, #7) are the following: mean flow is inclined at a small angle (3°, 20°) to the bottom contours; the ratio of mean square fluctuations parallel to the contours to the fluctuations normal to the contours is about 10; and the covariances of the parallel and normal components are negative but of small magnitude. Thompson (1971) has suggested that motions in this range of periods at site *D* north of the Gulf Stream are due to topographic Rossby waves. The decrease of eddy kinetic energy away from the bottom at the site *D* mooring was strongly suggestive of a topographic wave. The vertical structure of the fluctuations off Japan cannot be determined but the other characteristics of these records are consistent with the Rossby topographic wave mechanism.

g. Geostrophic velocity calculations clearly show the inshore edge and axis of the Kuroshio but do not indicate unambiguously the offshore limit of the current. The current was spanned on sections I and II but probably was not on sections III and IV. On all the sections there was a reversal of the sign of the geostrophic shear in the deep water under the strongest surface expression of the Kuroshio; generally this occurred along and adjacent to the slope. Further offshore there are narrow regions where flow in the direction of the Kuroshio penetrates all the way to the bottom. Transports have been computed for five separate regions of the flow field: inshore eastward ($0.5\text{-}7 \times 10^6$ m^3 sec^{-1}) and westward ($2\text{-}6 \times 10^6$ m^3 sec^{-1}) on sections I and II; Kuroshio ($57\text{-}72 \times 10^6$ m^3 sec^{-1}), deep counter-flow ($4\text{-}7 \times 10^6$ m^3 sec^{-1}); and offshore westward ($1\text{-}11 \times 10^6$ m^3 sec^{-1}) on sections I and II. Calculations were referenced to the 10-day averages of the current velocity at the eight current meter sites. On the Shikoku section the Kuroshio transport was 27×10^6 m^3 sec^{-1} less and the countercurrent transport was 3×10^6 m^3 sec^{-1} less than the corresponding estimates of Worthington and Kawai (1972). In part, the lower Kuroshio transport in 1971 was due to underestimation of offshore transport but there was also a much stronger geostrophic shear in the upper layer in 1965. The larger transports were associated with a thicker layer of Subtropical Mode Water and a deeper thermocline on the offshore side of the current. Knauss (1969) estimates a downstream increase of Gulf Stream transport of 7% per 100 km. Neither the 1965 Worthington and Kawai estimates of 84 and 88×10^6 m^3 sec^{-1} at 134° and 142° respectively, or the 1971 estimates presented here suggest a rate of increase comparable to that reported for the Gulf Stream by Knauss. Even considering the uncertainties in the transport estimates, it appears unlikely that a similar rate of increase applies to the Kuroshio south of Japan.

The sections (Figs. 13a-d) indicate that the deep countercurrent is located on the upper continental slope but that it is found at somewhat greater depths in the western part of the Shikoku Basin. Maximum speeds at 136°30′E were located at 1500 m (specific volume anomaly of 59 cl ton^{-1}) whereas off Shikoku and Kyushu the maximum speeds were located at 2000 m (52 cl ton^{-1}). The difference in salinity and specific volume of the countercurrent suggest there is a downstream modification of water characteristics by mixing processes. Because waters transported in the countercurrent follow the θ-S curve for the Shikoku Basin the circulation may be internal to the Basin and not involve North Pacific Basin waters. Worthington and Kawai (1972) show that waters at 142E east of the Izu-Ogasawara Ridge, are about 0.03‰ lower in salinity near 2.3°C potential temperature than the waters of the Shikoku Basin. Because the countercurrent at 136°30′E does not show an anomaly from the θ-S curve it is doubtful that a significant admixture of water from this region is present. Because deep water is not formed in the North Pacific, the countercurrent cannot be related to movement away from a northern source of deep water which is constrained to flow southward along the boundary under the western boundary current as it does in the North Atlantic (Worthington, 1977). Water with a salinity which is similar to that found at the same potential temperature east of the ridge was observed on the lower continental slope. Current meter #7 measured a mean eastward flow of 3 cm sec^{-1} over 64 days so that this water appeared to be flowing toward the proposed source.

Suggestions that there might be a flow opposite to the direction of the Kuroshio along the boundary are found in the abyssal flow pattern for the Pacific proposed by Stommel and Arons (1960). Because there appear to be three layers of flow, with the deepest moving in the same direction as the Kuroshio, it is not appropriate to compare the countercurrent with their model which considers only a single deep layer. The qualitative deep circulation model for the western Pacific proposed by Nan'niti and Akamatsu (1966) is consistent with the velocity distributions reported here. However, their model is highly generalized and seems to apply more to the flow along a western boundary defined by the Izu-Ogasawara Ridge. The relation between the circulation in the main basin of the Pacific and the relatively isolated Shikoku Basin has not been defined. Burkov (1974) has calculated the bottom current under the Kuroshio from the climatological wind and the mean density fields and does show a westward bottom current south of Honshu where the countercurrent was measured.

h. Dynamical studies of the Kuroshio path have been done by Robinson and Taft (1972) and White and McCreary (1976). Robinson and Taft (1972) performed path computations for cases where the current extended to the bottom, so that it was gently steered by the bottom topography, and where the current was shallow and therefore was decoupled from topographic steering. They pointed out that the large-scale meander of the Kuroshio was consistent with the stationary Rossby-wave solution for a shallow current and proposed that the northern path (similar to that observed on this cruise) was more likely to be gently steered by the topography. White and McCreary (1976) treat both the northern and meander paths of the Kuroshio as stationary Rossby-wave patterns. They argue that in a two-layer system with a stationary deep layer the meanders will have wave lengths which vary with transport. The long wave solution (no meander) is associated with transports in excess of 40×10^6 m^3 sec^{-1} south of Kyushu.

The data presented here can give some guidance on the applicability of these models. The Kuroshio in 1971 was located in its northern position on the continental slope south of Honshu which would be consistent with the White-McCreary model if the upper layer transport were relatively large south of Kyushu. As was pointed out the values of the transport relative to 1000 db were not particularly high in 1971 ($54\text{-}59 \times 10^6$ m^3 sec^{-1}). Nitani's (1975) time series of volume transport relative to 1000 db off Eushu-nada indicates that the transport in 1971 was actually lower than in 1959 when a large-scale meander was set up. Since Nitani (1975) shows a strong positive correlation between the transports off Cape Shionomisaki (135°40′E) and Yakushima Is. (130°30′E), it is reasonable to assume that the transport south of Kyushu, which is critical to the White-McCreary hypothesis, was also low in 1971. The velocity sections indicate that the deep current under the core of the Kuroshio is directed opposite to the surface current. This velocity structure is not consistent with the Robinson and Taft model, which assumes that there is a deep flow over the upper continental slope which is coherent with the Kuroshio when the current is in its northern position. On section II, meter #7 on the lower slope did show relatively steady flow, mean flow of 3 cm sec^{-1} in the direction of the Kuroshio. However, the geostrophic calculations showed that the eastward current lay underneath a westward current. There is evidence on each of the sections that there may be a relatively narrow deep flow in the direction of the Kuroshio offshore from the core and extending to the base of the continental slope. The role of this deep offshore extension of the Kuroshio on the dynamics should be explored in future theoretical studies.

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