Current Path and Bottom Velocity of the Kuroshio[1]

B. A. Taft
Scripps Institution of Oceanography, University of California, San Diego 92037

A. R. Robinson
Division of Engineering and Applied Physics, Harvard University, Cambridge, Mass. 02138

W. J. Schmitz, Jr.
Woods Hole Oceanographic Institution, Woods Hole, Mass. 02543

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High-resolution current path delineations and simultaneous bottom velocity observations directly under the Kuroshio have been obtained for the first time during a cruise on *Thomas Washington* in June–July, 1971. Here we present a preliminary report of the analysis of these data. The variety of these data provides a more detailed synoptic description of the Kuroshio, indicates the time and space scale of the Kuroshio meanders, and reveals the existence of dynamical interactions of the Kuroshio with the lateral and bottom boundaries.

The location of the current path was determined by tracking the 15C isotherm at a depth of 200 m (T_{15}). South of Japan the T_{15} usually lies within 13 km of the maximum surface current (Kawai, 1969). Studies by Nitani and Shoji (1970) of the Kuroshio axis south of Shionomisaki show that there are shifts of the axis with a semidiurnal tidal period. The mean range of the semidiurnal shifts was 5 km; over the 5-day period of measurement the axis was displaced 16 km to the south. The amplitude of the tidal shifts appear to be small relative to the longer period (meander time scale) shifts in the current axis. The T_{15} was determined by steaming zig-zag downstream and making underway (XBT) temperature soundings to a depth of 450 m (Fuglister and Voorhis, 1965). Deep hydrographic sections across the current were made at three locations; eight current meters, tethered either 100 or 150 m above the bottom, were placed along the three sections. Current meters were placed so as to determine cross-stream coherence in the velocity; it was anticipated that downstream coherence between sections would probably not be determined. Ten path segments and the locations of the sections and current meters are shown on Fig. 1.

All the temperature measurements showed the Kuroshio axis over the continental slope. None of the path segments extended into the deep water of the Shikoku Basin, which indicates that the large-scale southward meander of the Kuroshio was not present (Taft, 1972). Over the broad continental slope off Kyushu the maximum spacing between our observed paths is large; within one week the Kuroshio off Kyushu was shown to have fully spanned the 9-year (1956–64) envelope of current paths derived from the regular Japanese surveys (Taft, 1972). One of the paths (B, Fig. 1) off Kyushu crossed the bottom contours at almost a 90° angle as the current flowed toward shallow water. In sharp contrast, near 136°30′E, where the slope is relatively narrow, T_{15} varied only 22 km over a 5-week period; in addition, the paths all showed the current crossing the depth contours at a small angle. The largest rate of lateral shift of the current axis off Kyushu was estimated to be 18 cm sec^{-1}, whereas the largest rate off Honshu was only 3 cm sec^{-1}; the corresponding average rates computed from all consecutive Kuroshio crossings were 8 cm sec^{-1} off Kyushu and 1 cm sec^{-1} off Honshu. Typical rates of shifting for the Gulf Stream axis in deep water are 3 cm sec^{-1} (Robinson, 1971).

The measurements indicate that lateral boundary interaction could be of considerable importance in the dynamics of the Kuroshio. On one occasion the Kuroshio, south of Cape Ashizurimisaki on Shikoku, was observed to broaden and flow into shallow water on the slope and then reform downstream as an intensified current with a very strong horizontal temperature gradient. The movement into shallow water is indicated by the gap in the T_{15} track shown on Fig. 1; T_{15} could not be located as the 1-km isobath was crossed. The T_{15} was relocated in a very strong horizontal temperature gradient (0.5C km^{-1}) 170 km downstream from Ashizurimisaki. Fuglister and Voorhis (1965) have noted in the Gulf Stream that the temperature gradient is often intensified when the Gulf Stream path develops large curvature. Since the orientation of the T_{15} was roughly eastnortheast, both east and west of Ashizurimisaki, the intensification of the gradient noted here is not associated with a large curvature of the current path. A related phenomenon was observed south of Tanegashima where a reversal of the horizontal temperature gradient at 200 m was noted as T_{15} was being tracked across the 1-km isobath.

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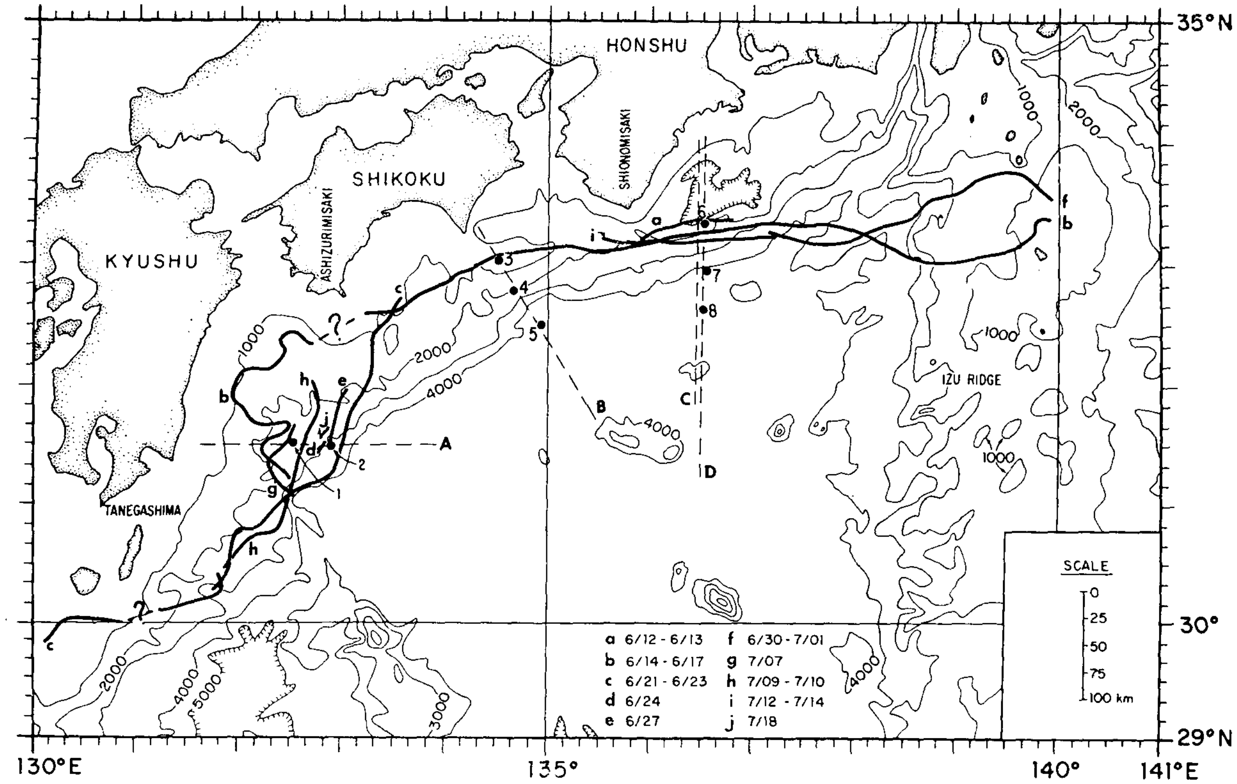

FIG. 1. Tracks of the 15C isotherm at 200 m (T_{15}, solid lines) current meter positions (dots), and deep hydrographic sections (dashed lines). Isotherm tracks are labeled a through j and the dates of each track are given at the bottom. Record lengths (days) at each current meter are: No. 1 (74); No. 2 (23); No. 3 (29); No. 4 (103); No. 5 (30); No. 6 (30); No. 7 (64); No. 8 (30). Dates of sections (1971) are: A, 7–9 July; B, 4–5 July; C, 27–30 June; D, 14–17 July.

The bottom velocity measurements have been low-pass filtered by a running 48-hr Gaussian weighted mean; the results discussed here are midnight samples of these low-passed velocity data. Current meter 3 was in relatively shallow water (275 m); the vector mean velocity was 22 cm sec^{-1} at 040° true and the velocity was remarkably steady. In deep water the highest scalar mean speed of 7 cm sec^{-1} was observed at current meter 8 (4309 m); scalar mean speeds at the seven deep current meters did not show a general decrease with depth. The highest scalar mean speed is less than one-third the mean speeds reported for two current meters at depths greater than 4 km under the Gulf Stream (Schmitz *et al.*, 1970).

In all the current meter records, there are fluctuations of the velocity that have time scales that are commensurate with the length of the record. Mean velocities computed from these data must be interpreted with caution. Components of velocity normal and parallel to the mean axis of the Kuroshio (determined from all available path segments) at current meters 4 (south of Shikoku) and 7 (south of Honshu) are plotted in Fig. 2a. Velocities at meter 4 show very large fluctuations in the parallel component over periods of 2–3 weeks. Negative components dominate the record so that the mean bottom flow was counter to the surface flow of the Kuroshio. Velocities at current meter 7 show smaller amplitude fluctuations than at meter 4; the parallel component only changes sign once over a period of 64 days, and the normal components are small and relatively steady. Mean flow at current meter 7 was 3 cm sec^{-1} in the direction of the Kuroshio surface current. Hydrographic sections C and D show very small horizontal density gradients below 2 km so that the deep velocity at meter 7 might be considered the barotropic velocity component of the Kuroshio.

The hydrographic data and the bottom velocity data during the time the section was made were used to compute absolute volume transport; between pairs of hydrographic stations where there was no meter the velocity was assumed to be zero at the bottom. Estimates of transport ranged between 53 and 66×10^6 m^3 sec^{-1} with an average of 61×10^6 m^3 sec^{-1}. The values are close to the average transport of 60×10^6 m^3 sec^{-1} of the Gulf Stream between 33 and 35N (Knauss, 1969), but are less than the transport of 88×10^6 m^3 sec^{-1} estimated off Shikoku in September 1965 (Worthington and Kawai, 1972). A mean transport calculation based on a Kuroshio model (see below) gave values between 50×10^6 and 81×10^6 m^3 sec^{-1}.

It is of interest to interpret the integrated normal component of the bottom velocity (displacement) as

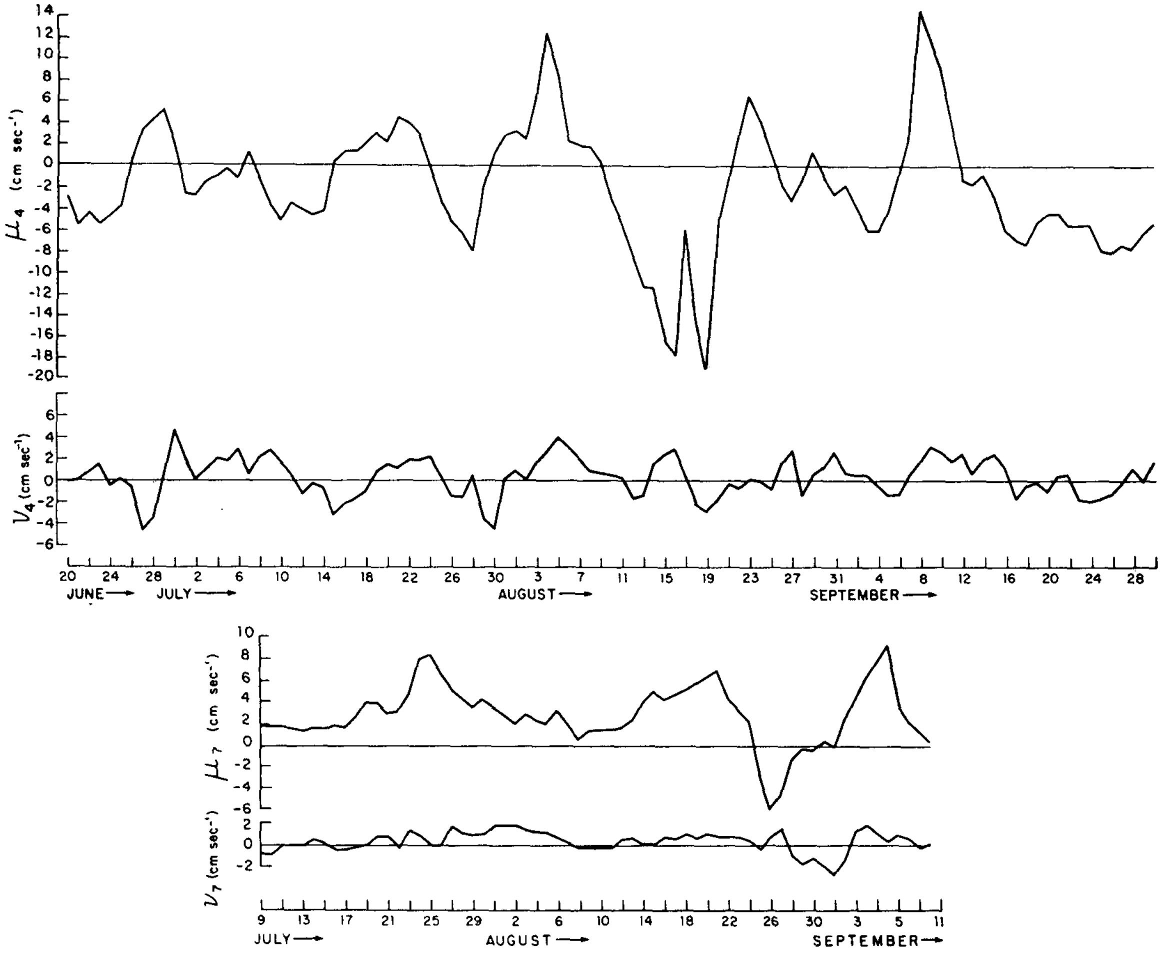

FIG. 2a. Velocity components at current meters 4 and 7 parallel (μ_4,μ_7) and normal (ν_4,ν_7) to the Kuroshio axis.

representing a meandering of the deep Kuroshio (Robinson, 1971), and to examine the assumption of vertical coherence of meandering by intercomparison of bottom displacement and near surface T_{15} data. A rather steady, parallel, downstream component of flow at meter 7 (μ_7) suggests there was a narrow region where the deep flow and the surface current are coherent. The integrated normal components for current meters 6 and 8 are in phase (Fig. 2b). Positions of T_{15}, also shown in Fig. 2b, indicate a southward movement of the current between 30 June and 12 July, followed by a northward movement. Changes in Kuroshio position (T_{15}) and displacements computed from the deep meters 6 and 8 are in the same direction and appear to have similar time scales. The amplitude of the computed displacement is at least twice as large as the lateral shift in the Kuroshio; Gulf Stream data also show this characteristic (Schmitz *et al.*, 1970). Computed displacement at meter 7 did not increase with time between 15 and 18 July as did the displacements at 6 and 8. The location of meter 7 on the lower continental slope may account for the difference between the three records; both meters 6 and 8 were on relatively flat topography on either side of the slope. An analysis of the dynamics of a deep current meandering over a steep slope is now being carried out; the model will be used to interpret the deep velocity measure-

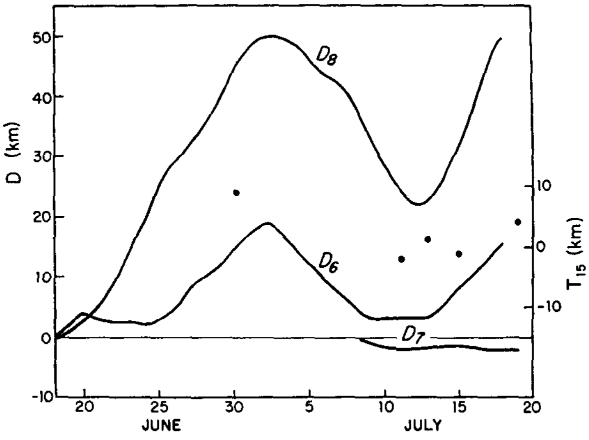

FIG. 2b. Integrated normal velocity components ($D_{6,7,8}$) at meters 6, 7 and 8. Position of the 15C isotherm at 200 m (T_{15}) is given by dots; zero on the right-hand scale corresponds to 33°12′N.

ments. It should be noted that the more complicated shifting of the Kuroshio off Kyushu could not be related in a simple way to the velocity measured at current meters 1 and 2. At meters 1 and 2 there was not a significant component of flow in the direction of the surface flow of the Kuroshio. Movements of the Kuroshio did not show any correlation with the computed displacement at either meter 1 or 2. The assumption of vertical coherence between the surface and the bottom is not supported by the velocity data off Kyushu.

A steady-state inertial jet model has been applied to a study of the Kuroshio path (Robinson and Taft, 1972). Since there were no bottom velocity measurements under the Kuroshio, parameters in the path equation could not be estimated from data. The important parameters are $C_1=10^{10}f\bar{v}_B(\langle v^2\rangle)^{-1}$ and $C_2=10^{12}\beta\langle v\rangle(\langle v^2\rangle)^{-1}$, where f is the Coriolis parameter, β the north-south gradient of f, v the Kuroshio velocity, $\bar{v}_B$ the bottom velocity integrated across the current, and the brackets $\langle\ \rangle$ indicate cross-current and vertical integration. Parameters C_1 and C_2 are respective measures of the effectiveness of the bottom topography in producing curvature of the current path and the effectiveness of the variation of the Coriolis parameter in producing curvature. Ranges of values used in the inertial jet model calculations were C_1: 3.5–4.5×10^{-3} cm^{-2} and C_2: 2–6×10^{-3} cm^{-2}. These values were chosen on theoretical-empirical grounds. The assumption was made that control of the path was due to a "gentle topographic steering mechanism," which required values of the parameters of the above cited magnitude and which in turn yielded solutions of the path equation which best represented the interpretation of the path data available at that time. Using the hydrographic data to compute the geostrophic velocity shear and the current data in combination with the path data to estimate the bottom transport, estimated values of C_1 at 136°30′E vary between 4 and 7×10^{-3} cm^{-2}, depending on the assumed width of the current at the bottom (75–120 km). Corresponding estimates of C_2 give a mean value of 3×10^{-3} cm^{-2}. The measurements reported here suggest that the choice of parameters for the calculations was appropriate and that gentle topographic steering is an important process in the eastern part of the region. The estimation of C_1 and C_2 presented here depends upon the separate extraction from the fluctuating data of a steady downstream bottom velocity associated with the permanent current. Robinson (1971) has presented a theoretical model for decomposition of the velocity, which includes time variations, for the case that the bottom topographic slopes are small. A simple extension of this model to the case of large cross-current bottom slopes, which is necessary for the analysis of our data, has been made. The estimates here have been obtained on the assumption that the current remains barotropic below the main thermocline as it shifts across a ridge, which implies a transient lateral shear in the current over the slope edge. A more detailed analysis of the data and their relationships to the steady and transient models will be presented at another time.

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