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A closely spaced conductivity-temperature-depth/hydrographic section was conducted off the east coast of Japan in July 1992. The southeastward section crossed the Japan Trench and the Kuroshio in the vicinity of the Kashima 1 seamount. Vertical sections of temperature, salinity, density, oxygen, and nutrients are discussed in conjunction with the movement and interleaving of water masses. Complicated vertical and horizontal mixings of water masses are inferred from the temperature and salinity relationships. Mixing processes are patchy and not continuous beneath the front. Warm, salty water found beneath the Kuroshio may result from upward mixing of water from intermediate depths. The main axis of the Kuroshio, indicated by the 14 degree C isotherm at 200 m, is at 35.7 degrees N, 142.6 degrees E, about 20 km from the north wall surface thermal front. Geostrophic speeds exceed 170 cm s⁻¹ at the surface; volume transport through the section is 81 x 10⁶ m³ s⁻¹.

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Hydrographic section across the Kuroshio near 35°N, 143°E

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Abstract. A closely spaced conductivity-temperature-depth/hydrographic section was conducted off the east coast of Japan in July 1992. The southeastward section crossed the Japan Trench and the Kuroshio in the vicinity of the Kashima 1 seamount. Vertical sections of temperature, salinity, density, oxygen, and nutrients are discussed in conjunction with the movement and interleaving of water masses. Complicated vertical and horizontal mixings of water masses are inferred from the temperature and salinity relationships. Mixing processes are patchy and not continuous beneath the front. Warm, salty water found beneath the Kuroshio may result from upward mixing of water from intermediate depths. The main axis of the Kuroshio, indicated by the 14°C isotherm at 200 m, is at 35.7°N, 142.6°E, about 20 km from the north wall surface thermal front. Geostrophic speeds exceed 170 cm s⁻¹ at the surface; volume transport through the section is 81 × 10⁶ m³ s⁻¹.

1. Introduction

The Kuroshio is the western boundary current associated with the subtropical gyre in the North Pacific Ocean. As such, it is responsible for a significant proportion of poleward mass, chemical, and heat transport in that ocean basin. As it crosses the Izu-Ogasawara Ridge, it separates from the coastal margin and turns eastward as the Kuroshio Extension. Immediately eastward of the separation area, the current flows generally northeastward [Kawai, 1972] but, on occasion, develops a large, anticyclonic meander which may detach to form a ring near 37°N, 143°E. This region is also one of intense interaction of the Kuroshio with the Oyashio, resulting in complex frontal structures and mixing of water masses [Kawai, 1972; Kawai and Saitoh, 1986; Kawamura *et al.*, 1986; Nagata *et al.*, 1986; Yasuda *et al.*, 1992].

The Kuroshio Extension Regional Experiment (KERE) [Mitchell, 1990], begun in 1991 by the Naval Research Laboratory is a study of the Kuroshio Extension consisting of TOPEX/Poseidon altimetry, numerical modeling, and a regional, in situ observational program. The main objectives of the latter are to determine the existence and character of the hypothetical Pacific deep western boundary current (DWBC) and to monitor the Kuroshio Extension near the separation point to determine variability levels and relation to the deep flows. The KERE observation program involves direct current measurements, an array of inverted echo sounders (thermocline depth measurements), and a detailed hydrographic section, all along a TOPEX/Poseidon ground

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track across the Japan Trench and across the Kuroshio Extension near 35°N, 143°E.

In this report we give a first accounting of KERE field measurements with emphasis on upper water column properties and dynamics of the Kuroshio Front. Bathymetry of the region and collection of the hydrographic data are described in section 2. A general description of the temperature-salinity (TS) characteristics and water mass properties are given in section 3. Vertical sections of potential temperature θ , salinity, potential density σ_θ , silica, oxygen, phosphate, and nitrate are described in section 4, and geostrophic velocities are described in section 5. Implications of these measurements on circulation are discussed in section 6. Properties and flows in the deep water column associated with our sections are described by Shiller *et al.* [1993].

2. Data Collection

A northwest to southeast section of 18 closely spaced conductivity-temperature-depth (CTD)/hydrographic stations (henceforth, referred to as the KERE section) was occupied from July 8-23, 1992, on a line extending from about 37°N, 142°E to 33°N, 144°E (Figure 1). The section begins on the slope just east of Honshu in about 1000 m of water. Since Japan is an island arc, this slope is properly referred to as the forearc slope rather than the continental slope. The section trends southeastward across the Japan Trench near the Kashima 1 seamount. Station spacing telescopes from about 15 km at the landward (i.e., NW) end of the section to about 50 km on the seaward (i.e., SE) end. Most of the stations extend to within 100 m of the bottom. The north wall of the Kuroshio is located at about 35.8°N, between stations 9 and 10 (in the vicinity of the seamount).

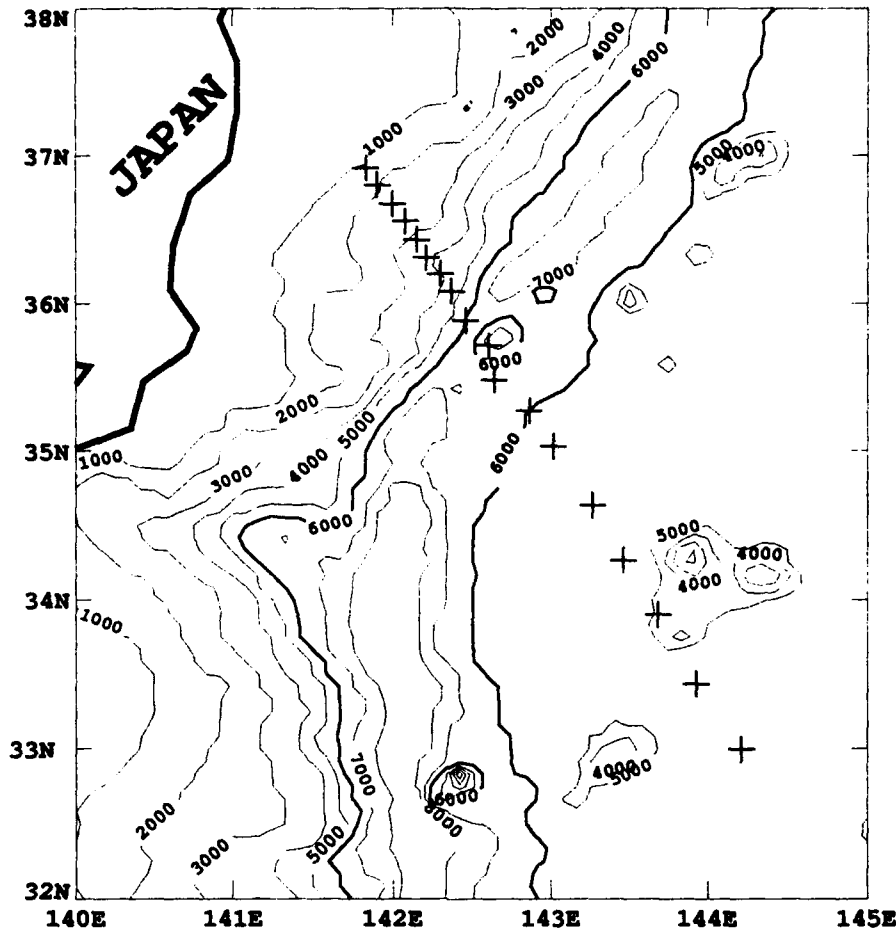


Figure 1. Conductivity-temperature-depth/hydrographic station locations are indicated by pluses along the Kuroshio Extension Regional Experiment (KERE) section. The 6000-m depth contours (thick lines) indicate the boundaries of the Japan Trench. The Kashima 1 seamount is located beneath the section at about 35.7°N, and the Takuyo 2 and 3 seamounts are located northeast of the section at about 34°N. Bathymetry is from Earth Topography 5 Minute (ETOPO 5), a 5 arc min latitude by 5 arc min longitude worldwide gridded database [National Oceanographic and Atmospheric Administration, 1986] and generally reflects the actual depths measured when collecting these data.

A Neil Brown Mark III CTD was used in conjunction with a 24-bottle rosette. Water samples were collected at depths ranging from 50-m intervals above the thermocline to 400 m intervals below 3000 m. Over 500 samples were collected. On deeper stations requiring more than 24 samples, two casts were conducted. Water samples were analyzed for salinity, dissolved oxygen, silica, and other nutrients. There were problems with the CTD conductivity sensor after station 9 and a backup CTD was then used for stations 10–18. However, a shift in the deep salinities was observed for the data from this CTD. Since salinities from the first CTD were consistent with historical salinity data [Levitus, 1982], salinity data from the second CTD were slightly adjusted to be consistent with the deep salinities from the first CTD.

Oxygen was determined using an automated Winkler system based on the design of Friederich *et al.* [1991] and using electromagnetic detection of the end point [Culbertson and Huang, 1987]. Reproducibility of standard titrations was $\pm 0.1\%$. The estimated precision across the section (including sampling, titration, and long-term drift errors) is $\pm 1\%$ (1 standard deviation).

Nutrients were determined colorimetrically using a Lachat Instruments Quik-Chem AE flow injection analyzer. The nitrate channel of this analyzer actually determines nitrate plus nitrite; however, since nitrite concentrations are usually very low, results here are referred to as nitrate. Ship motion severely affected the phosphate results, and thus these data should be viewed cautiously. Instrumental drift and day-to-day variability were tracked by running consistency standards before, during, and at the end of each run. Where appropriate, drift corrections were made. The estimated precision (1 standard deviation) of the nutrient data across the section is $\pm 1.5\%$ for silica, $\pm 1\%$ for nitrate, and $\pm 4\%$ for phosphate.

Chemical data are reported here in modern units of micromoles per kilogram instead of traditional units which are milliliters per liter for oxygen, and micromoles per liter for nutrients. The use of modern units is preferred for two reasons. First, by using mole-based units (rather than grams or milliliters as is common for dissolved oxygen), no conversion factors are necessary to compare stoichiometric changes in chemical properties. Second, for the denominator, units of mass of seawater are preferred to units of

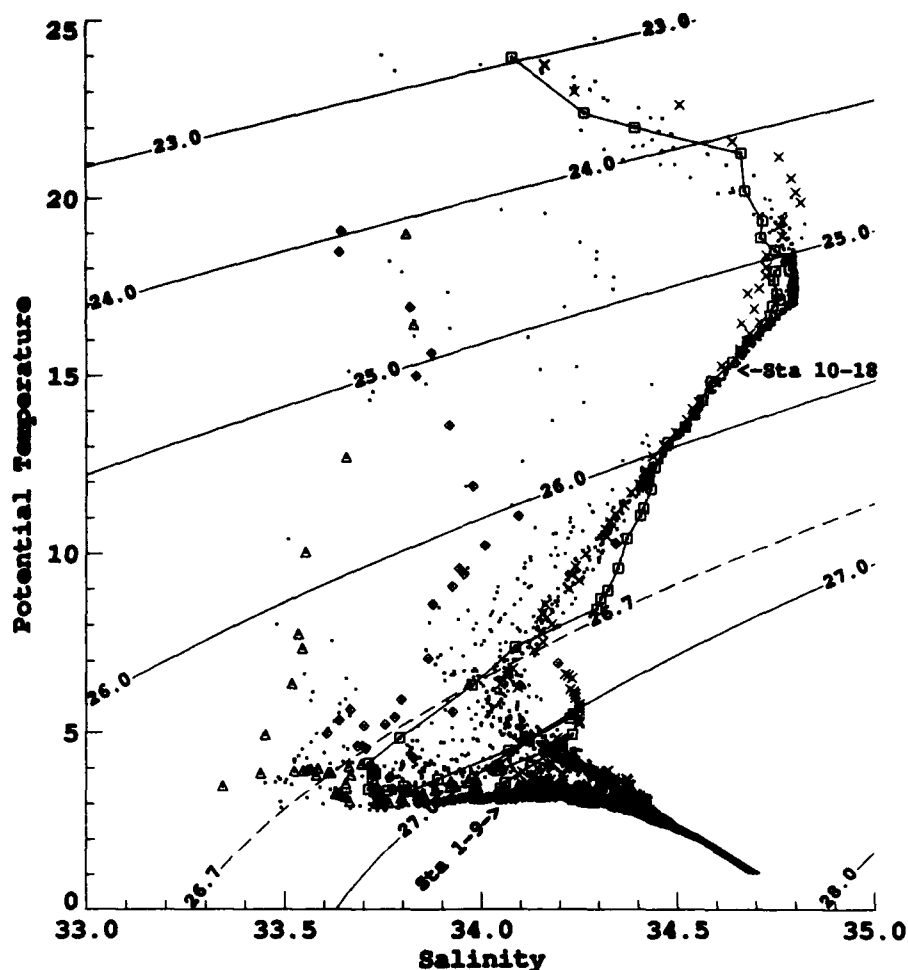


Figure 2. Potential temperature is plotted versus salinity for 10-m depth intervals. For temperatures above 3°C, station 8 is indicated by triangles, station 9 by diamonds, station 10 by squares, and station 11 by crosses. The right side of the split temperature-salinity envelope (stations 10-18) is from waters south of the Kuroshio, while the left side of the envelope (stations 1-9) is from waters north of the Kuroshio. Note that station 10 (points connected) exhibits characteristics from both. Lines of constant σ_t are superimposed.

volume, since seawater is compressible. Conversion of modern units to traditional per-liter units involves multiplication by the density of seawater (approximately 1.027 kg L⁻¹); to convert micromoles to milliliters of oxygen, the data should be multiplied by 0.0224. More details on the data processing as well as a complete data listing of the oxygen and nutrients can be found in the work by Teague *et al.* [1993].

3. Temperature-Salinity Description

Water properties on the north side of the Kuroshio are distinctly different from those on the south side. Surface temperatures rise from about 18°C north of the Kuroshio to about 24°C to the south. TS structures (Figure 2) fall into two groups: stations 1-9, north of the Kuroshio and stations 11-18 to the south. Deeper than 1400 m (about 2.5°C), the TS structure is the same for both groupings and is in the region of the western North Pacific Deep Water. The transition region between the two TS groups occurs at station 10 (Figure 2). The upper half of the TS diagram for station 10 is

characteristic of the stations south of the Kuroshio, while the lower half is characteristic of the stations to the north. Station 10 also shows anomalous water properties in the 300- to 400-m range between potential temperatures 8° to 12°C. This water appears to be similar in characteristics to the "bulge water" discussed by Kawamura *et al.* [1986].

Southeast of the Kuroshio Front, a shallow (~20 m) seasonal thermocline overlies a thick (~300 m), relatively homogeneous layer of warm (17°-18°C), salty (34.7 practical salinity unit (psu)) water (Figures 3 and 4) characteristic of the North Pacific Subtropical Mode Water (SMW) [Masuzawa, 1969]. This thermostat is thickest at station 16. Beneath the SMW, both potential temperature and salinity rapidly decrease for several hundred meters in such a way that the θ -S plot is linear. This is the lower part of the western North Pacific/central water [Sverdrup *et al.*, 1942] which has also been called the thermocline water (TW) by Masuzawa [1969]. North of the Kuroshio Front and south of the Oyashio Front is the region known as the perturbed area [Kawai, 1972] or mixed water region [Fujimura and Nagata, 1992]. Here, it is difficult to identify water with characteris-



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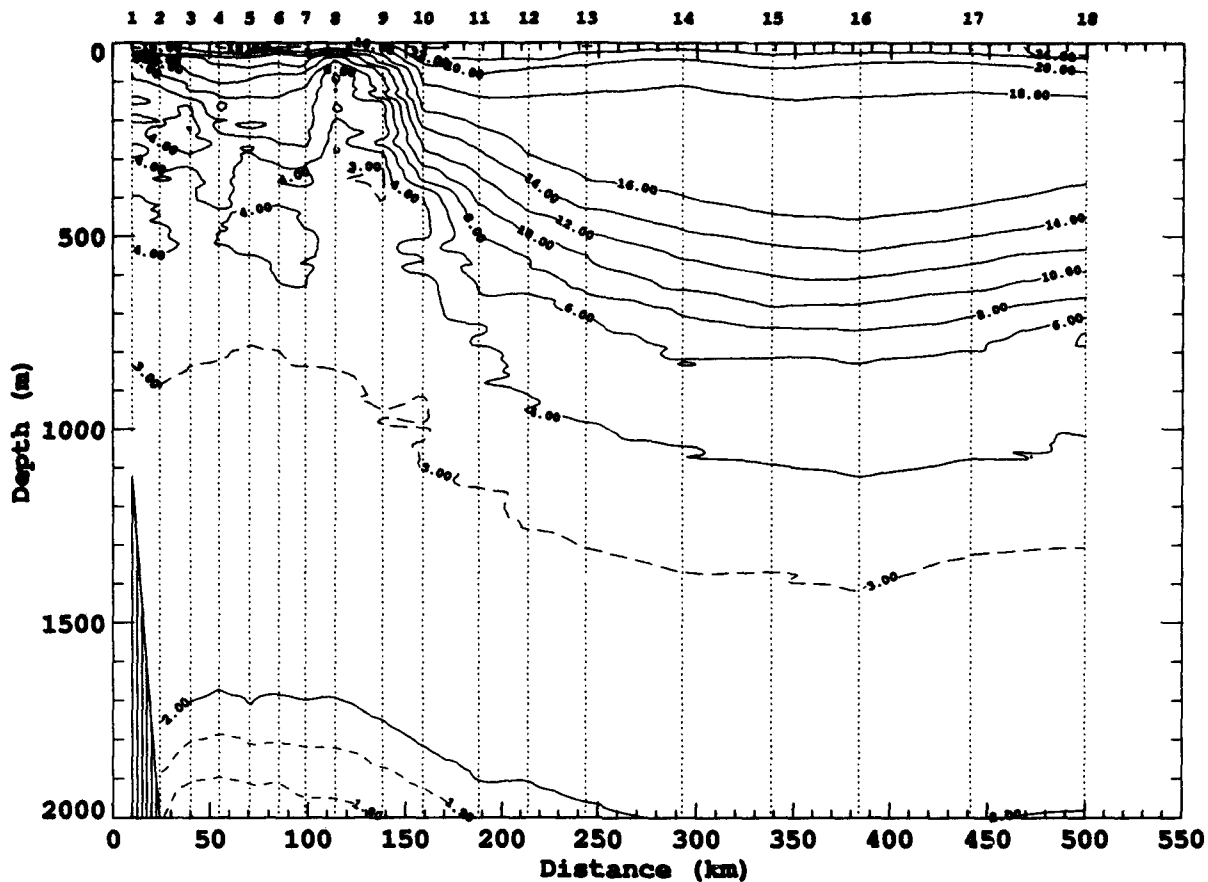


Figure 3. Vertical section of potential temperature (degrees Celsius). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

tics of the TW. The potential density range of TW (25.5–26.5) occurs in a depth range (typically 50–100 m) of very high density gradient in the perturbed area.

Station 8 (36.1°N), just to the north of the front, is unique in showing a steep upturn in the isotherms in the upper 400 m. For example, the 5°C isotherm is shallower at this station than elsewhere in the section. This cold water is also relatively fresh. A minimum salinity of 33.35 psu at 85 m was the freshest water observed in the entire section and corresponds to a local potential temperature minimum of 3.4°C. Water with these characteristics can be found at similar depths further north of the KERE section [e.g., Reid, 1965; Talley et al., 1991]. Kawai [1972] labeled this water type as original Oyashio water (OOW) and suggested it is the western subarctic Pacific analogy of Subtropical Mode Water.

Beneath the TW south of the Kuroshio, there is a salinity minimum at ~800 m depth ($\sigma_\theta = 26.8$), characteristic of the North Pacific Intermediate Water (NPIW) [Sverdrup et al., 1942; Reid, 1965]. In the perturbed area, water with this potential density is found more typically in a salinity minimum near 300 m depth and is generally cooler and fresher than salinity minimum water beneath the Kuroshio. However, a relative minimum in temperature and salinity for waters of this density are found beneath the front at stations 8, 9, and 10. These observations of NPIW are in general agreement with those of Reid [1965], who described the lateral mixing of intermediate water between the subarctic and subtropical gyres. Kawai [1972] similarly discusses the

NPIW and further shows the coolest, freshest intermediate water as having characteristics similar to OOW.

4. Vertical Sections

4.1. Potential Temperature, Salinity, and Potential Density

The Kuroshio Front is clearly seen in the potential temperature, salinity, and potential density fields (Figures 3, 4, and 5, respectively). There is a 4°C and 0.3-psu increase in the surface waters moving southeast across the front. A sharp downward slope in the isotherms and isohalines at about 35.9°N near station 9 indicates the Kuroshio north wall. The 4°C isotherm sinks by approximately 700 m between stations 9 and 11. The 14°C isotherm at 200 m is a good indicator of the axis of the Kuroshio Extension [Kawai, 1972]. The depth of this isotherm at station 10 (35.7°N) is 219 m and is thus very near the axis.

The northwestern end of the section is located within the perturbed area of the Oyashio and Kuroshio. Typically, this area is characterized by intrusions of Oyashio waters and by numerous fronts and eddies; coastal waters may also be an influence in this part of the section. In the perturbed area, profiles show no surface mixed layer and a rapid decrease in temperature with depth. Temperature inversions occur north of the Kuroshio along the entire northern end of the section between 200 and 500 m depth and are evident here by the numerous blebs of 4°C water shown in Figure 3. Intrusive

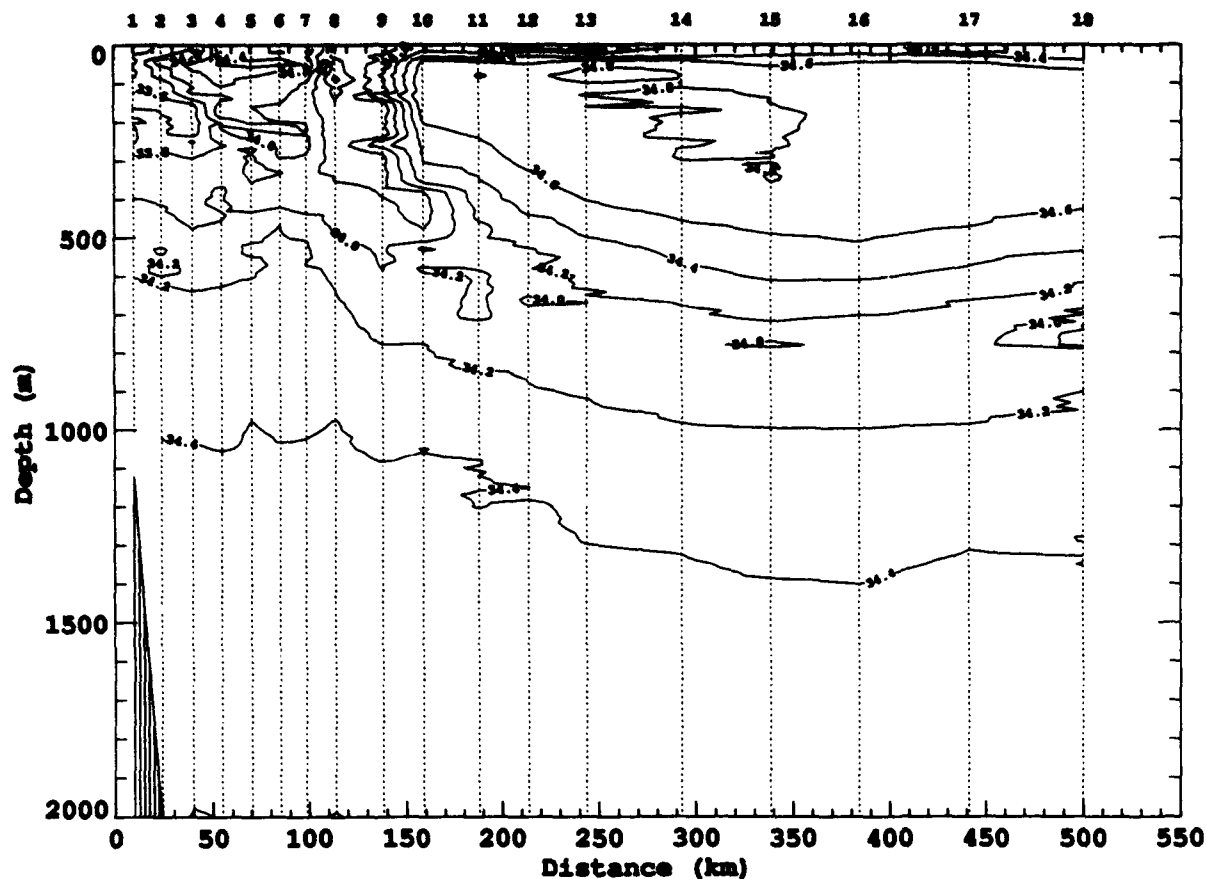


Figure 4. Vertical section of salinity (practical salinity units). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

features in the perturbed area appear to be density compensated. Water with the same temperature and salinity characteristics as the intrusive features is found beneath the warm water of the Kuroshio (i.e., around 1000 m depth in the southeast part of the KERE section). Note that at some of the stations in the perturbed area there are so many reversals of temperature and salinity that it is difficult to characterize the situation as warm, salty intrusions into a cooler, fresher water column or vice versa. In the vicinity of the front, particularly stations 9 and 10, reversals in the isotherms and isohalines are particularly evident in the upper 700 m. These are suggestive of packets of water being shed by the Kuroshio and mixing into waters of the perturbed area.

Maximum salinity of 34.8 psu occurs south of the Kuroshio Front at about 250 m and originates from the south. Minimum salinity of 33.6–33.8 psu occurs north of the Kuroshio Front between 100 and 300 m and originates from the north, being related to Oyashio waters. A tongue of low salinity less than 34.1 psu at depths between 400 and 800 m extends across the entire section. This low-salinity water is attributed to NPIW [Reid, 1965], which originates in the subpolar North Pacific.

4.2. Oxygen

Since the oxygen data (Figure 6) are from discrete samples rather than continuous recording, this section shows somewhat less detail than did the temperature and salinity sections. Near-surface waters are generally supersaturated

across the section: in the perturbed area the supersaturation at 10 m averages about 6% whereas southeast of the Kuroshio Front it is only about 2%. The greater supersaturation in the perturbed area could be indicative of greater primary productivity in these waters. Greater productivity would be a natural consequence of the shallower thermocline (and hence nutricline (see below)) and closer terrigenous influences in the perturbed area. Additionally, warming of subarctic waters as they move south would result in greater supersaturation, and cooling of subtropical waters as they flow north would diminish the gas saturation.

SMW shows relatively homogeneous oxygen concentrations of around $220 \mu\text{mol kg}^{-1}$. Although waters at similar depths (though higher densities) in the perturbed area show similar if not higher dissolved oxygen, apparent oxygen utilization (AOU) values are very different for the two areas. SMW has a low AOU ($\approx 15 \mu\text{mol kg}^{-1}$), indicative of recent ventilation, whereas in the perturbed area much higher AOU's are observed ($\approx 40\text{--}200 \mu\text{mol kg}^{-1}$).

Samples at 100 and 200 m at station 8, where anomalously low-temperature, low-salinity water characteristic of OOW was observed, also have high oxygen compared to surrounding waters. This would be expected from the higher solubility of oxygen in colder, fresher water. Several other stations also have oxygen maxima between 200 and 400 m; these water samples all have minima in salinity and low temperatures.

In the TW and even in the intermediate water down to the

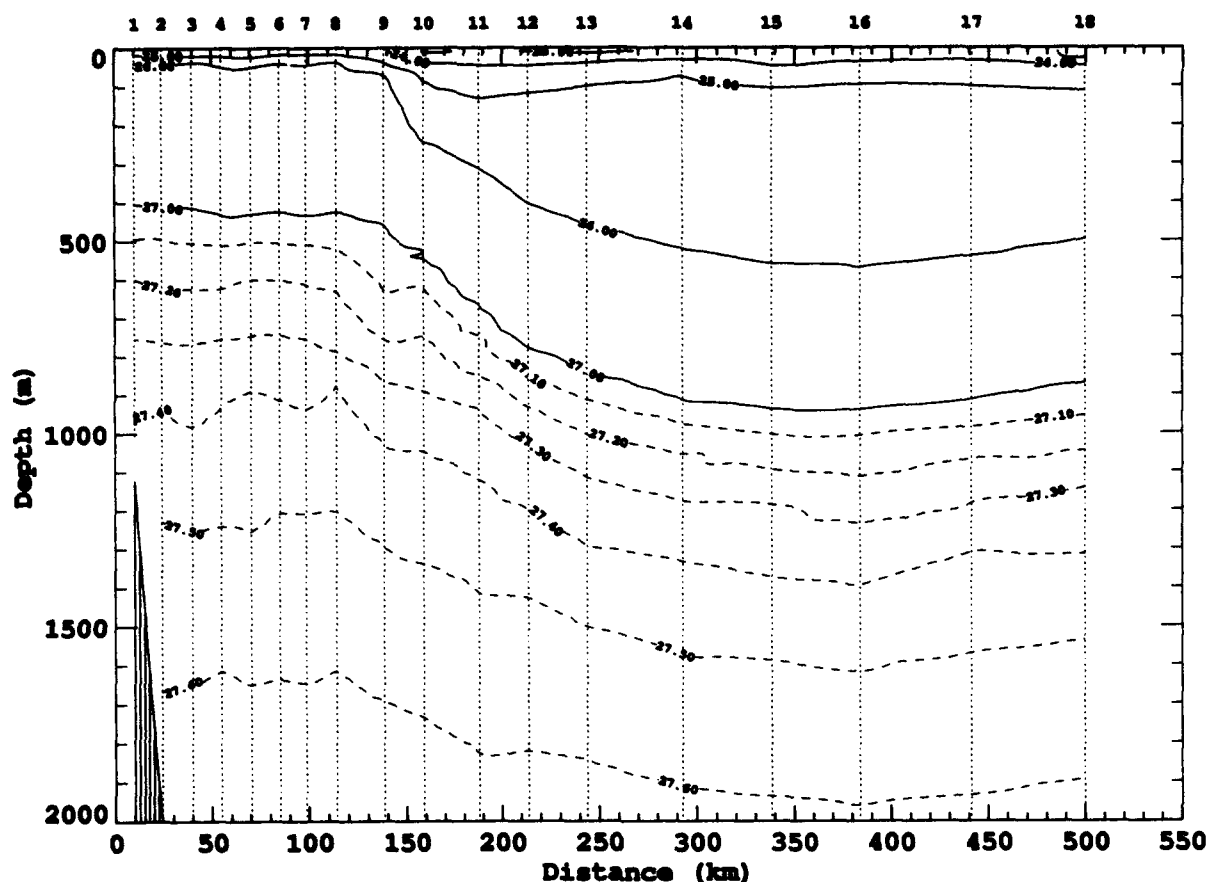


Figure 5. Vertical section of potential density (kg m^{-3}). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

salinity minimum, moderate oxygen values (140–200 $\mu\text{mol kg}^{-1}$) are observed. On potential density surfaces, oxygen in the upper part of the intermediate water is about 25 $\mu\text{mol kg}^{-1}$ higher in the perturbed area than in the Kuroshio area. Observations by others likewise indicate that intermediate water in the perturbed area is fresher, more oxygen rich, and shallower than in the Kuroshio area [Kawai, 1972].

Beneath the core of the salinity minimum ($\sigma_\theta = 26.8$), oxygen reaches its minimum values in the density range where σ_θ is between 27.3 and 27.4. In the perturbed area the oxygen minimum is more intense than in the Kuroshio area. For example, the average minimum oxygen concentration in the first eight profiles of the section is 40 $\mu\text{mol kg}^{-1}$ versus 46 $\mu\text{mol kg}^{-1}$ in the last eight profiles, and the thickness of the minimum zone (as determined by the distance between upper and lower 50- $\mu\text{mol kg}^{-1}$ isopleths) is about 800 m in the perturbed area versus 500 m in the Kuroshio area. Station 5 in particular shows an intense oxygen minimum with the 40- $\mu\text{mol kg}^{-1}$ isopleth encircling several samples. The lowest observed oxygen concentration was 38 $\mu\text{mol kg}^{-1}$ (0.87 mL L^{-1}) at stations 1 and 5.

The intensity of the oxygen minimum observed is similar to that seen in the TPS47 section just to the north, off Hokkaido [Talley *et al.*, 1991]. A more intense oxygen minimum (oxygen < 20 $\mu\text{mol kg}^{-1}$) is seen further to the north in the SAGA near 47°N [Talley *et al.*, 1991] whereas to

the south at 24°N, Roemmich *et al.* [1991] have found a less intense minimum (minimum oxygen $\approx 50 \mu\text{mol kg}^{-1}$).

4.3. Silica

Silica (Figure 7) shows its usual deep-regeneration, nutrientlike distribution. However, in addition to this behavior a number of additional features can be recognized. Near-surface waters are depleted in silica as expected. However, the extent of silica-depleted water, as represented by the 20 $\mu\text{mol kg}^{-1}$ isopleth, varies considerably across the section. This isopleth is typically 50–100 m deep in the perturbed area (though shallower than 50 m at stations 5 and 6) but plunges with the isotherms across the front. At station 16 the 20 $\mu\text{mol kg}^{-1}$ isopleth is nearly 600 m deep. Thus Subtropical Mode Water is silica-depleted, as would be expected based on its formation at the surface in the subtropical gyre. The OOW samples at 100 and 200 m at station 8 show distinctly higher silica than samples at similar depths from the surrounding stations. This is consistent with a subarctic origin for this water. In the NPIW, no significant change in silica concentrations occurs across the section; for example, on the $\sigma_\theta = 26.8$ isopycnal, silica averages $71 \pm 4 \mu\text{mol kg}^{-1}$.

Maximum silica is found near 2000 m across the section. Largest silica concentrations, greater than 170 $\mu\text{mol kg}^{-1}$ are found at station 5. These enhanced silica measurements, also observed further to the north by Talley *et al.* [1991], are

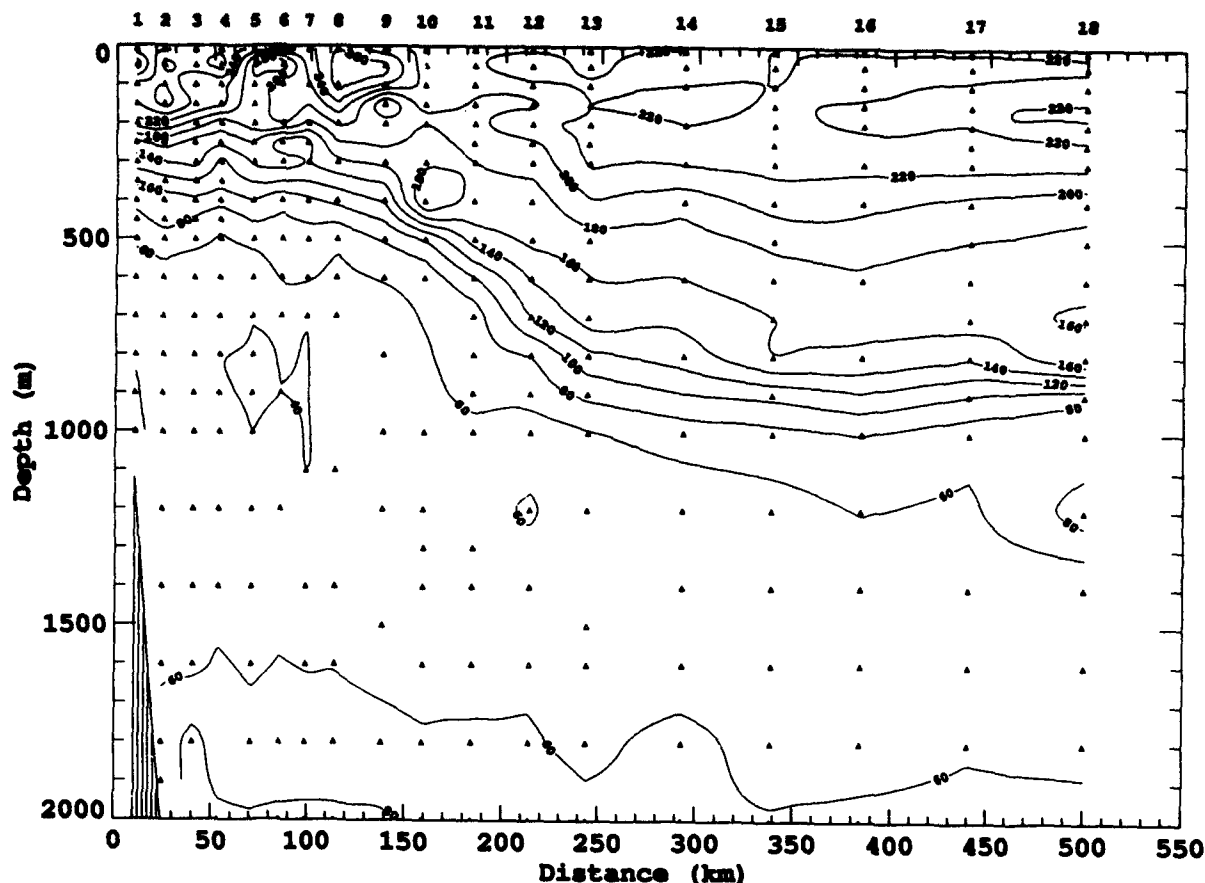


Figure 6. Vertical section of oxygen (micromoles per kilogram). Station numbers are at the top of the plot, and data samples are indicated by triangles.

suggestive of a DWBC and are discussed more fully by Shiller *et al.* [1993].

4.4. Nitrate and Phosphate

Nitrate (Figure 8) and phosphate (Figure 9) show their typical nutrient distributions with surface depletion and a middepth maximum associated with the oxygen minimum. As with silica, the nutricline for these elements is more shallow northwest of the Kuroshio Front and the SMW is depleted in nutrients. The samples of OOW are slightly enriched in nitrate. Maximum nutrient concentrations are seen in the depth range of the oxygen minimum. In the NPIW, there appears to be no significant change in nutrient concentrations across the section; for example, nitrate on the $\sigma_\theta = 26.8$ isopycnal is $34 \pm 3 \mu\text{mol kg}^{-1}$.

5. Current Characteristics

Geostrophic velocities are computed for the upper 2000 m using a 2000-m zero-velocity reference level (Figure 10). Since the section is oriented northwest to southeast, the calculated component of positive baroclinic flow is roughly northeastward. Furthermore, the section is roughly normal to the mean path of the Kuroshio. Northeastward flow associated with the Kuroshio is found between 36.1°N and 34.1°N . A maximum speed of 174 cm s^{-1} occurs between stations 9 and 10 at 35.8°N . Speeds greater than 50 cm s^{-1} are found to depths of 400 m. Dynamic height (relative to

2000 m) increases sharply after station 8 and is about 1.3 m higher at station 16 than for the inshore stations (Figure 11).

Corresponding volume transport for the Kuroshio calculated from the geostrophic velocity field for the northeastward flow is 81 Sverdrup (Sv) ($1 \text{ Sv is } 10^6 \text{ m}^3 \text{ s}^{-1}$), which compares well with a transport of 84 Sv derived for 143°E using climatologies by Clifford and Horton [1992] and with a transport of 88 Sv computed by Worthington and Kawai [1972] from bottle data for a section off Inubozaki that is located just south of this section. Choice of reference levels affects the transport but results in only about a 10% difference for Kuroshio transport calculations between using 1000-m and 2000-m reference levels [Clifford and Horton, 1992; Bingham and Talley, 1991]. Takematsu *et al.* [1986] directly measured Kuroshio velocities south of Kyushu and estimated a level of no motion of 600 m, implying that the actual Kuroshio transport would be much smaller than the estimates made here and all other past estimates. However, as Bryden *et al.* [1991] point out, the sill depth of the Tokara Straits is about 600 m, which would account for the shallow level of no motion found by Takematsu *et al.* [1986]. By comparison, Halkin and Rossby [1985] found 88 Sv for the Gulf Stream near 73°W , just east of Cape Hatteras. Their estimate is based on a 2.5-year average of directly measured currents made with Pegasus profilers along a section normal to the mean Gulf Stream.

Southwestward flow is found on both sides of the Kuroshio. A northeastward flow greater than 2.5 cm s^{-1} between

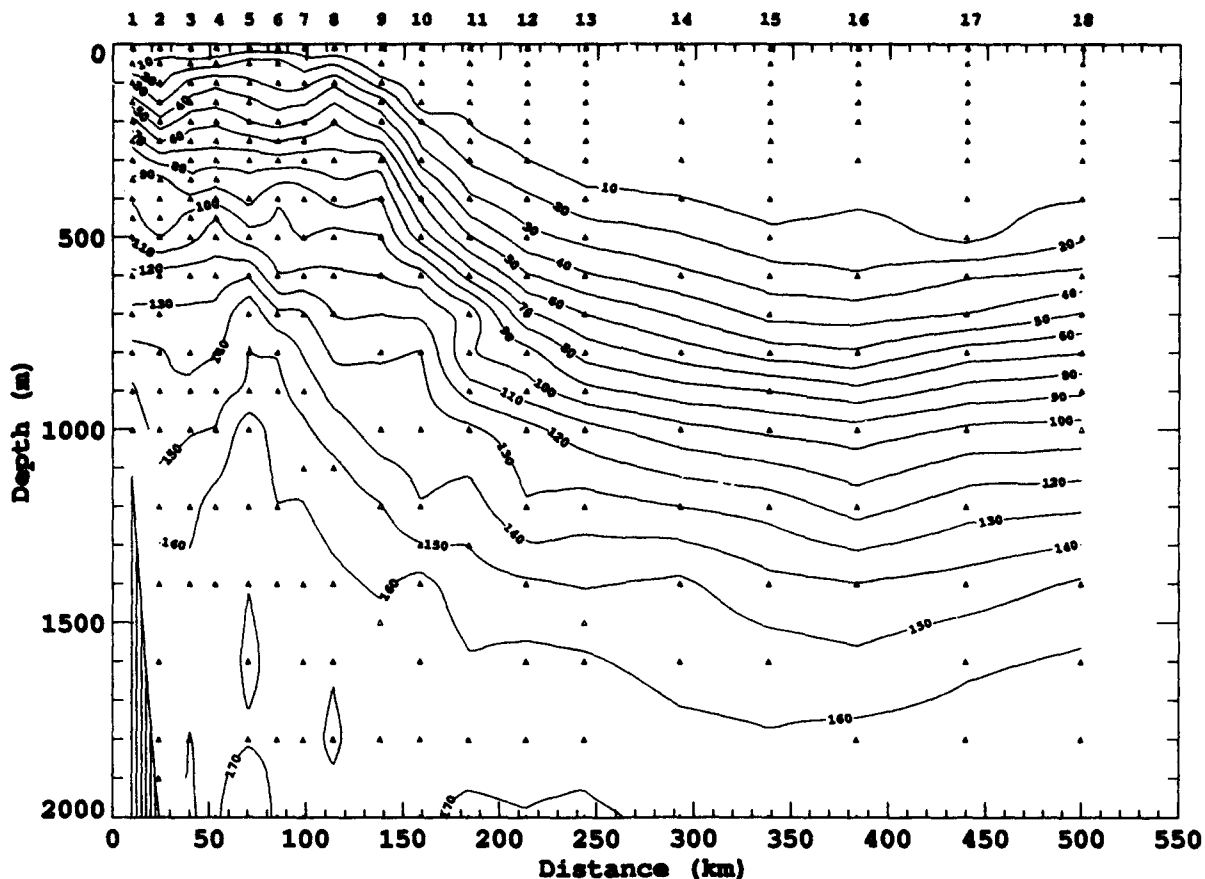


Figure 7. Vertical section of silica (micromoles per kilogram). Station numbers are at the top of the plot, and data samples are indicated by triangles.

100 m and 700 m near 36.3°N is embedded in the southwestward flow. Directly under the Kuroshio, effects of the seamount are evidenced by sharp doming of the isotherms at depths as shallow as 400 m (discussed by *Shiller et al.* [1993]). This same effect is observed using reference levels of 1000 m and 3000 m.

6. Discussion

The KERE section crosses the Kuroshio near the point where the current leaves the Japanese coast. Surface current speed normal to the section peaks over the Kashima 1 seamount and appears to be confined between this seamount and the Takuyo 2 and 3 seamounts (34°N, 144°E) for this realization. At these latitudes, the first interaction of the Kuroshio with subarctic waters is observed. *Nagata et al.* [1986] and *Shin et al.* [1988] described the structure of the Kuroshio Front in several sections approximately 100 km northwest of the KERE section (near 36°N, 144°E). They observed a double frontal structure with apparent upwelling of thermocline water into the narrow zone between the fronts. They also observed isolated packets of less saline, high-oxygen water of apparent Oyashio origin beneath the front. In the vicinity of the KERE section, *Shin et al.* [1991] found that the double front is not commonly present but found more evidence of subarctic water beneath the front. *Kawamura et al.* [1986] found that in this area, warm-core rings of about 200 km in diameter are generated once or

twice per year. They describe one particular ring formation as an abrupt movement of the Kuroshio Front to the north, forming a bulge of the Kuroshio water. *Fujimura and Nagata* [1992] observed slightly saline water at intermediate depths of the Kuroshio frontal region and concluded that this was remnant NPIW brought northward by the current.

The KERE section provides further insight into these previous observations and interpretations. As described above, the steep upturn in isotherms at station 8 is due to an intrusion of Oyashio water. This intrusion is clearly seen in the water encompassed by the 33.80 isohaline in the salinity section (Figure 4). The salinity section also gives some illustration of the complex mixing associated with the front. For instance, salty (and warm) intrusions are clearly seen at about 135 m and 255 m at station 9 (see also Figure 2). Mixing and interleaving of water masses occurs at station 10 between 300 m and 400 m along the 26.7 σ_t surface and again between 500 m and 600 m along the 27.0 and 27.1 σ_t surfaces (Figure 2). Additionally, high oxygen anomalies ($>180 \mu\text{mol kg}^{-1}$) of Oyashio origin are found at stations 9 and 10 between 200 m and 500 m (Figure 6).

Not all of the mixing and interleaving of waters underneath the Kuroshio Front can be attributed to simple mixing of OOW and SMW. Figure 2 shows that stations 9 (diamonds), 10 (squares), and 11 (crosses) all have parcels of water in the density range 26.1 to 27.1 which are warmer and more saline than any other waters of our section in that

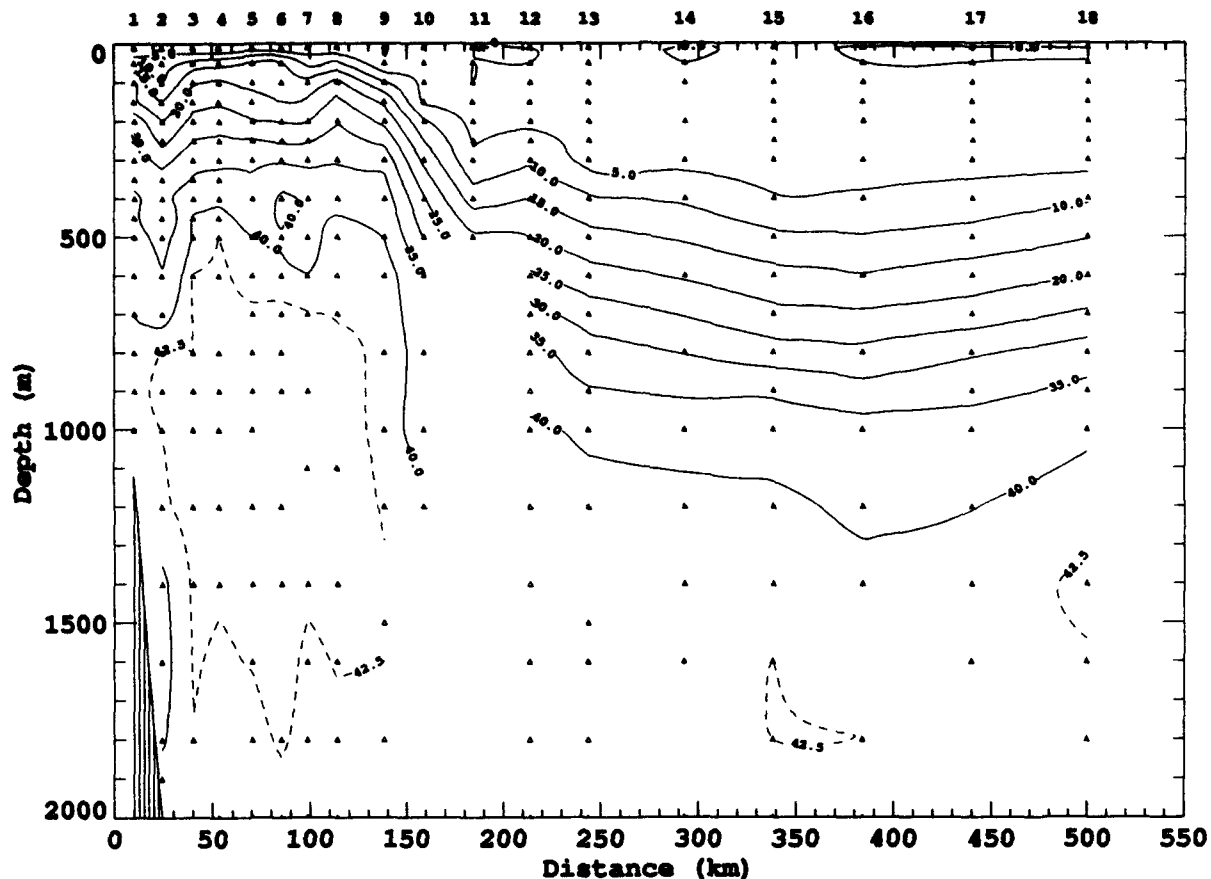


Figure 8. Vertical section of nitrate (micromoles per kilogram). Station numbers are at the top of the plot and data samples are indicated by triangles.

density range. Note that some of these warm, saline waters occur above the salinity minimum (135 and 255 m at station 9; 300–500 m at station 10), while other parcels occur below it (520 m at station 10; 575–710 m at station 11). There are three possible explanations for this warm, salty water which we consider in turn.

The warm, salty waters above the salinity minimum appear to have the same TS character as what Kawamura *et al.* [1986] referred to as “bulge water.” Kawamura *et al.* [1986] suggested that bulge water was Kuroshio water which had been cooled through wintertime air-sea interaction. However, we find it unlikely that water cooled in such a manner could retain its character to midsummer in as dynamic a region as the Kuroshio Front.

A second explanation was provided by Fujimura and Nagata [1992]. Since isopycnal mixing of SMW with waters from the perturbed area can not produce the anomalous warm, salty waters, they suggested that these waters must be NPIW water carried northward by the Kuroshio. They also noted that in following the Kuroshio Extension eastward from Japan to 144°E, microstructural intrusions in the salinity minimum increased, while the amount of warm, salty water observed diminished. This is consistent with a general picture of the NPIW circulating in a clockwise manner and undergoing extensive modification by subarctic waters. This explanation requires the preservation of the character of NPIW transported from the south in a dynamic current structure.

Another possible explanation involves diapycnal mixing. Examination of the TS plots (Figure 2) suggests that one could interpret the various patches of anomalously warm, salty water as being on a simple two-end-member mixing line. Extrapolation of the mixing trend indicates that a deep end-member for such mixing can be found at a potential density of about 27.1 (i.e., between the salinity minimum and the oxygen minimum). We note that the only Niskin sample obtained of the anomalously warm, salty water from beneath the salinity minimum (station 11, 600 m) contained $\approx 30 \mu\text{mol kg}^{-1}$ less oxygen and $\approx 10 \mu\text{mol kg}^{-1}$ more silica than other samples of similar density in the KERE section; that is, it must have a component of deeper water. Water with a potential density of 27.1 is found at ≈ 600 m in the perturbed area and ≈ 1100 m in the Kuroshio area. This vertical mixing process may be an extension of the upwelling of the thermocline water underneath the Kuroshio Front described by Nagata *et al.* [1986] and Shin *et al.* [1988].

The pronounced isopycnal variability of temperature and salinity underneath the Kuroshio Front suggests that any mixing is intermittent. Two processes may account for this. First, periodic intrusion of OOW may disrupt the mixing of other water masses. However, the observations of Shin *et al.* [1991] suggest that OOW is generally found close to the Kuroshio Front in this region; that is, the intrusion is likely to be a regular feature. A second relevant process is the anticyclonic turning of the Kuroshio as it leaves the Japanese coast. Divergence associated with the anticyclonic

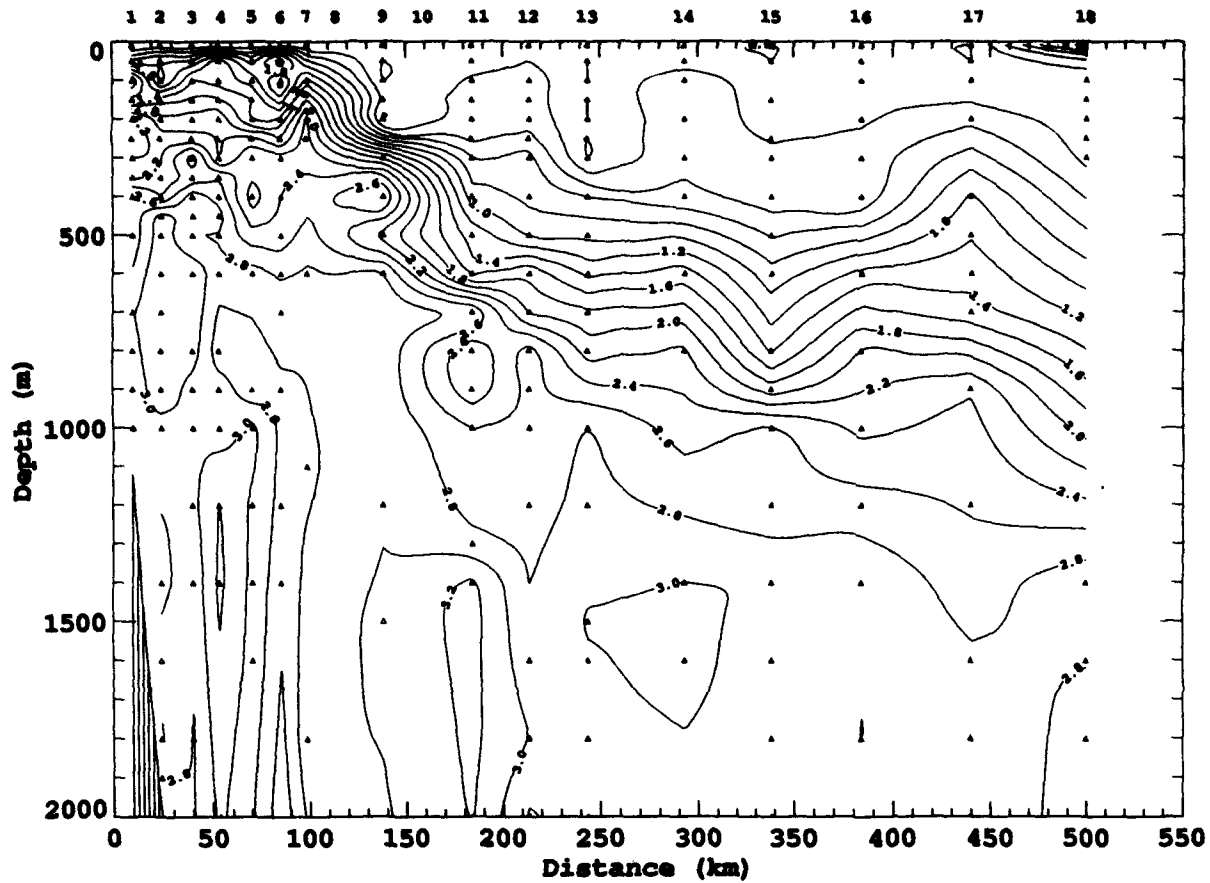


Figure 9. Vertical section of phosphate (micromoles per kilogram). Station numbers are at the top of the plot, and data samples are indicated by triangles.

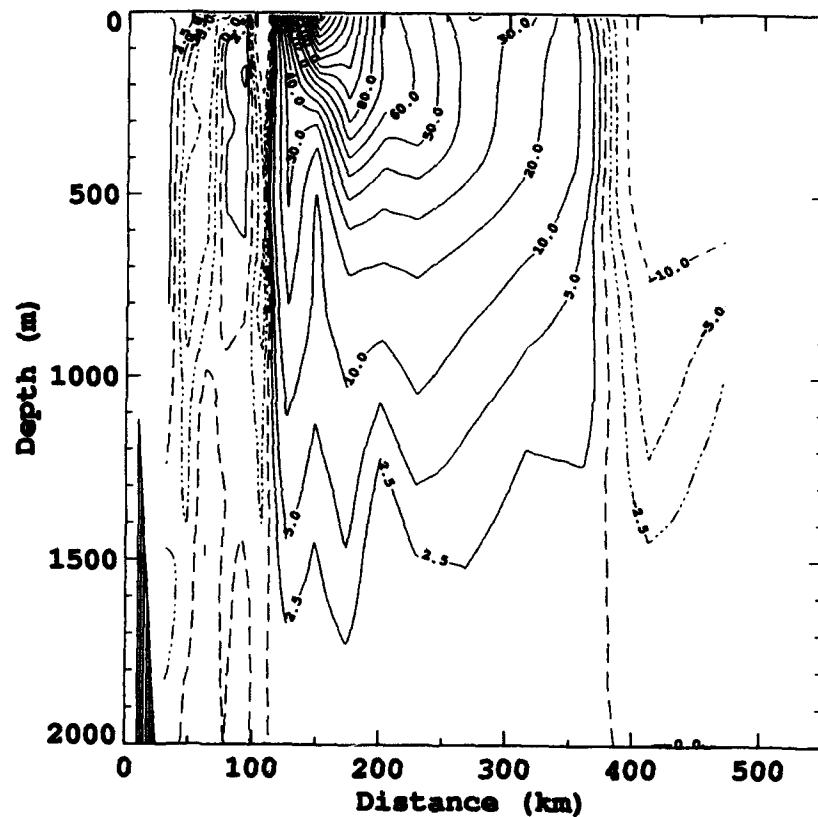


Figure 10. Geostrophic velocity section. Speeds (centimeters per second) are computed between adjacent station pairs using a level of no motion of 2000 m. Northeastward speeds are indicated by solid lines, zero speeds by dashed lines, and southwestward speeds by dot-dashed lines.

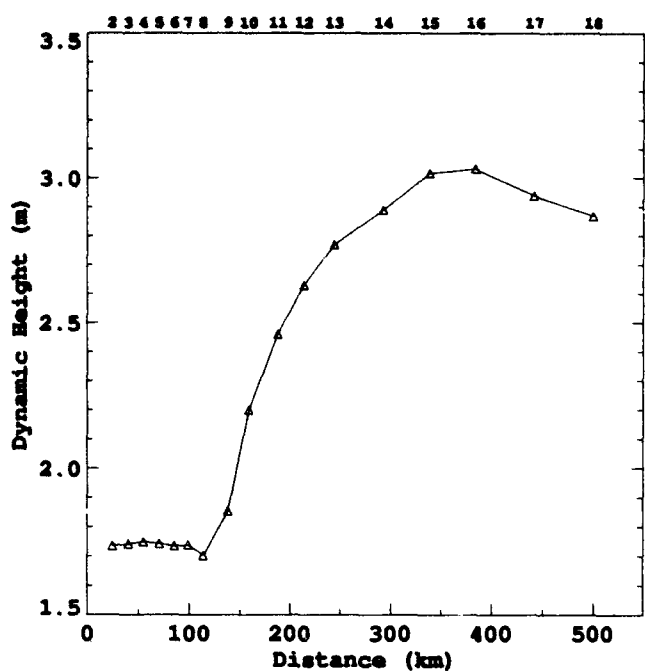


Figure 11. Dynamic height referenced to 2000 m for the KERE section. Station numbers are at the top of the plot.

motion could induce the vertical mixing we describe above [e.g., Rossby *et al.*, 1985]. Changes in the anticyclonic path of the Kuroshio as meanders form or straighten out should also change the extent of this upwelling.

Reid [1965] describes the lateral transfer and mixing of intermediate waters between the subarctic and subtropical gyres in the North Pacific. Reid states that this process reduces the salinity and temperature and raises the oxygen content of the subtropical waters. An examination of the $\sigma_\theta = 26.8$ isopycnal (Figure 12) suggests the intermittent nature of this process in the KERE section. Salinity and potential temperature on this isopycnal are quite variable across the section (Figures 12b and 12c). If this were simply the result of eddies and fronts in the perturbed area, one might expect to see the depth of the isopycnal vary with the thermohaline structure. However, the depth of the isopycnal varies smoothly across the section (Figure 12a), indicative of isopycnal temperature and salinity variability. We note that for the vertical mixing process described in the previous section, the upwelled water has an apparent component from the $\sigma_\theta = 27.1$ isopycnal, that is, below the salinity minimum. This suggests a possible connection between the intermittent nature of both processes. That is, upwelling induced by divergence associated with the anticyclonic turning at the Kuroshio may draw in subarctic waters from the perturbed

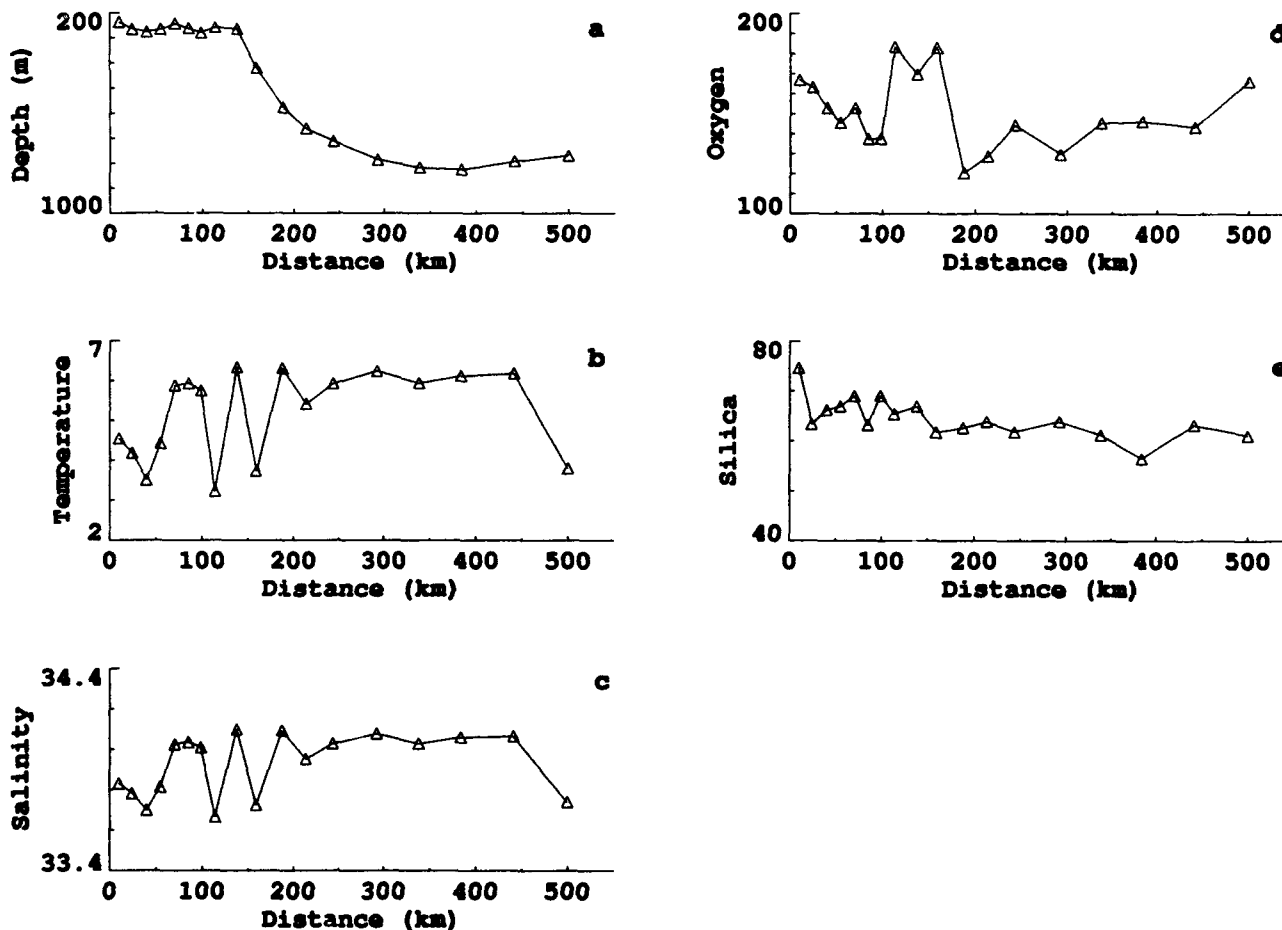


Figure 12. (a) Depth, (b) temperature, (c) salinity, (d) oxygen, and (e) silica of the $\sigma_\theta = 26.8$ isopycnal across KERE section.

area. We also note the similar nutrient concentrations (Figure 12e) across the section on this isopycnal, indicating that in contrast to heat, salt, and oxygen (Figure 12d), there is no net exchange of nutrients in the lateral mixing.

7. Conclusions

The closely spaced KERE hydrographic section gives a unique glimpse into the dynamics of the frontal region where the Kuroshio leaves the Japanese coast. Several important conclusions follow from this work:

1. Volume transport for the Kuroshio based on geostrophic velocities was 81 Sv. This compares well with previous estimates near this latitude and is comparable to the 88 SV found for the Gulf Stream near Cape Hatteras by Halkin and Rossby [1985].

2. Warm, salty water found beneath the Kuroshio Front may result from upward mixing of waters with an intermediate depth component. The patchy nature of this water in the frontal zone suggests that the vertical mixing is not continuous. If the mixing is the result of upwelling due to divergence associated with the anticyclonic turning of the Kuroshio, then changes in the extent of meandering may explain its apparent intermittence.

3. Lateral mixing of intermediate waters across the section also appears to be patchy, as evidenced by considerable isopycnal variability in temperature and salinity. Much of this patchiness is likely the result of convolutions of the Kuroshio Front due to meandering and the pinching off of eddies. On the other hand, since waters in and below the depth range of the lateral mixing may be involved in the vertical mixing beneath the Kuroshio Front, we suggest, alternatively, that the patchy nature of the lateral and vertical mixing may be related. As was described by Reid [1965], the lateral mixing brings oxygen from the subarctic into the intermediate waters of the subtropical gyre; however, there appears to be no net exchange of nutrients.

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References

- Bingham, F. M., and L. D. Talley, Estimates of Kuroshio transport using an inverse technique, *Deep Sea Res.*, **38**, suppl. 1, S21-S43, 1991.
- Bryden, H. L., D. H. Roemmich, and J. A. Church, Ocean heat transport across 24°N in the Pacific, *Deep Sea Res.*, **38**, 297-324, 1991.
- Clifford, M. A., and C. W. Horton, Baroclinic transport of the Kuroshio Extension between 141°E and 165°E, *J. Geophys. Res.*, **97**, 12,527-12,533, 1992.
- Culbertson, C. H., and S. Huang, Automated amperometric oxygen titration, *Deep Sea Res.*, **34**, 875-880, 1987.
- Friederich, G. E., L. A. Codispoti, and C. M. Sakamoto, An easy-to-construct automated Winkler titration system, *Tech. Rep. 91-6*, Monterey Bay Aquarium Res. Inst., Monterey Bay, Calif., 1991.

- Fujimura, M., and Y. Nagata, Mixing process in the mixed water and Kuroshio Extension regions and modification of the intermediate Kuroshio water, *Oceanogr. Mag.*, **42**(1-2), 1-20, 1992.
- Halkin, D., and T. Rossby, The structure of the Gulf Stream at 73°W, *J. Phys. Oceanogr.*, **15**, 1439-1452, 1985.
- Kawai, H., Hydrography of the Kuroshio Extension, in *Kuroshio: Physical Aspects of the Japan Current*, edited by H. Stommel and K. Yoshida, pp. 235-352, University of Washington Press, Seattle, 1972.
- Kawai, H., and S. Saitoh, Secondary fronts, warm tongues and warm streamers of the Kuroshio Extension system, *Deep Sea Res.*, **33**, 1487-1507, 1986.
- Kawamura, H., K. Mizuno, and Y. Toba, Formation process of a warm-core ring in the Kuroshio-Oyashio frontal zone—December 1982–October 1982, *Deep Sea Res.*, **33**, 1617-1640, 1986.
- Levitus, S., Climatological atlas of the world ocean, *NOAA Prof. Pap.*, **13**, 1-173, 1982.
- Masuzawa, J., Subtropical mode water, *Deep Sea Res.*, **16**, 463-472, 1969.
- Mitchell, J. L., Plans for the Kuroshio Extension Regional Experiment, *Tech. Note 016:321:90*, Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, Miss., 1990.
- Nagata, Y., J. Yoshida, and H.-R. Shin, Detailed structure of the Kuroshio Front and the origin of the water in warm-core rings, *Deep Sea Res.*, **33**, 1509-1526, 1986.
- National Oceanographic and Atmospheric Administration, ETOPO 5 digital relief of the surface of the Earth, *Data Announce. 86-MGG-07*, Natl. Geophys. Data Center, Washington, D. C., 1986.
- Reid, J. L., Intermediate waters of the Pacific Ocean, *Johns Hopkins Oceanogr. Stud.*, **2**, 85 pp., Johns Hopkins Univ., Baltimore, Md., 1965.
- Roemmich, D., T. McCallister, and J. Swift, A trans-Pacific hydrographic section along latitude 24°N: The distribution of properties in the subtropical gyre, *Deep Sea Res.*, **38**, 510-520, 1991.
- Rossby, T., A. S. Bower, and P.-T. Shaw, Particle pathways in the Gulf Stream, *Bull. Am. Meteorol. Soc.*, **66**(9), 1106-1110, 1985.
- Shiller, A. M., Z. R. Hallock, and W. J. Teague, Deep currents in the northwest Pacific off Japan during KERE, *NRL/MR/7332-93-7983*, 1993.
- Shin, H.-R., Y. Nagata, and J. Yoshida, Detailed water mass analysis in the Kuroshio Front with special reference to its double structure, *Dyn. Atmos. Oceans*, **12**, 173-189, 1988.
- Shin, H.-R., Y. Michida, and Y. Nagata, The structure of the Kuroshio Front in the vicinity of separation point where the Kuroshio leaves the Japanese coast, *J. Oceanogr. Soc. Jpn.*, **47**, 111-125, 1991.
- Sverdrup, H. U., M. W. Johnson, and R. H. Fleming, *The Oceans, Their Physics, Chemistry, and General Biology*, 1087 pp., Prentice-Hall, Englewood Cliffs, N. J., 1942.
- Takematsu, M., K. Kawatate, W. Koterayama, T. Suhara, and H. Mituyasu, Moored instrument observations in the Kuroshio south of Kyushu, *J. Oceanogr. Soc. Jpn.*, **42**, 201-211, 1986.
- Talley, L. D., T. M. Joyce, and R. A. deSzoek, Transpacific sections at 47°N and 152°W: Distribution of properties, *Deep Sea Res.*, **38**, suppl. 1, S63-S82, 1991.
- Teague, W. J., Z. R. Hallock, J. M. Dastugue, and A. M. Shiller, Kuroshio Extension Regional Experiment hydrographic data: Summer 1992, *Rep. NRL/MR/7332-93-7050*, Natl. Res. Lab., Washington, D. C., 1993.
- Worthington, L. V., and H. Kawai, Comparison between deep sections across the Kuroshio and the Florida Current and Gulf Stream, in *Kuroshio: Its Physical Aspects*, edited by H. Stommel and K. Yoshida, pp. 371-385, University of Washington Press, Seattle, 1972.
- Yasuda, I., K. Okuda, and M. Hirai, Evolution of a Kuroshio warm-core ring—variability of the hydrographic structure, *Deep Sea Res.*, **39**, suppl. 1, S131-S161, 1992.

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