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Hydrographic observations during the 2002 IOC Contaminant Baseline Survey in the western Pacific Ocean

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[1] The 2002 IOC Contaminant Baseline Survey in the western Pacific Ocean was the fourth in a series of cruises intended to establish the contemporary concentrations of trace elements and other materials in the major water masses of the ocean and to illuminate the pathways by which materials delivered to the surface ocean are incorporated in the subsurface waters. The expedition occupied 9 vertical profile stations encompassing the subtropical and subarctic gyre of the western North Pacific. In addition, underway surface water samples were collected during transits between the stations. This paper uses the temperature, salinity, nutrient, oxygen, and chlorophyll data to set the hydrographic and biological background for the other papers in this theme.

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Theme: Biogeotracers in the Northwest Pacific Ocean
Guest Editors: Michiel Rutgers van der Loeff, William M. Landing, Catherine Jeandel, and Rodney T. Powell

1. Introduction

[2] The Contaminant Baseline Survey program is an effort organized by the Intergovernmental Oceanographic Commission (IOC, a UNESCO organization) to determine the concentrations and distributions of trace metals and synthetic organic compounds in the major surface, inter-

mediate, and deep water masses of the world's oceans. Not only do these surveys provide current concentrations ("baselines") of potential contaminants, but they are also valuable tools for unraveling biogeochemical processes affecting trace elements and synthetic organic compounds. To date, there have been three IOC Baseline Surveys in the Atlantic Ocean, covering both the source regions of the deep water masses of the Atlantic [*Shiller*, 1998], as well as the distal products of that subduction and mixing in both the eastern Atlantic [*Yeats and Shiller*, 1995] and the western Atlantic [*Mason*, 2001]. In addition to providing baseline data for the incorporation of anthropogenic and natural materials into the deep waters of the ocean, the results have highlighted the input of these materials into the surface waters of the ocean and their incorporation routes into the intermediate and thermocline waters of the ocean.

[3] This paper reports the background hydrography and sampling schemes used for the fourth of these cruises, which was undertaken in the western Pacific during May/June 2002.

[4] Although there is no deep water formation in the Pacific Ocean, replacement of subthermocline waters occurs by the formation of North Pacific Intermediate Water (NPIW), which is characterized by a salinity minimum between 300 and 800 m across the North Pacific subtropical gyre [*Svedrup et al.*, 1942; *Reid*, 1965]. The mechanism and location of formation of this water mass have been discussed by several authors [e.g., *Talley*, 1993; *Talley et al.*, 1995; *Yasuda et al.*, 1996, 2001; *Yasuda*, 1997; *Joyce et al.*, 2001] who have shown that the formation of new NPIW is a result of the cross frontal flows of cold low salinity water from the Oyashio into older low salinity waters of the subtropical gyre within the mixing zone between the Kuroshio and Oyashio. Since the actual mixing process is a subsurface phenomena, and the isopycnals at this density level do not outcrop at the surface, this is not a ventilation process in the strict sense of imprinting surface properties directly onto an isopycnal. However, since the ultimate origin of the low salinity Oyashio waters appears to be from mode water formed by brine rejection during sea-ice formation in the Sea of Okhotsk, the imprinting of surface water geochemical characteristics into this water mass might occur indirectly.

[5] The surface waters of the subarctic gyre display characteristics that are typical of the Fe-limited High Nutrient Low Chlorophyll (HNLC) regions of the Equatorial and South Pacific, despite the fact that they lie beneath an area through which massive amounts of dust are transported from the desert regions of Asia. The apparent contradiction between an apparently sufficient source of eolian Fe and HNLC conditions motivated the design and execution of this oceanographic expedition. In addition, since the trajectory of the dust plumes take them through the highly populated regions of western Asia which emit copious quantities of anthropogenic sulfur and nitrogen oxides into the atmosphere, the role that these emissions might play in promoting the solubility of atmospheric dust in surface waters, and the subsequent biogeochemical consequences in surface and thermocline waters, was a focus of this study.

[6] The cruise was intended to provide large spatial coverage of surface water properties through underway surface water sampling with vertical profiles at key locations to sample specific water masses in a variety of biogeographic and hydrographic regimes. The cruise track (Figure 1) was designed to cross the main surface water hydrographic regimes of the western Pacific orthogonal to the main dust plumes that satellite imagery shows emanating from Asia and that in computer models gives rise to deposition gradients of this material to the surface ocean. In addition, transects and stations through the distal parts of the Kuroshio/Oyashio regions and the central Pacific were intended to illuminate what role, if any, these features play in advecting biogeochemical signals into the central Pacific gyres.

[7] Although there is a significant amount of variability in the timing of the annual dust outbreaks from the Asian continent, the cruise was timed to be in May, toward the end of the historical high dust period (January–June). At this time, we hoped to be able to combine a near maximum in the surface water expression of deposited materials with the possibility of still sampling atmospheric dust using the shipboard 20 m tower [see *Buck et al.*, 2006].

[8] The purpose of this paper is to describe the distribution of hydrographic parameters encountered along the surface waters and the vertical profiles during the cruise and thus provide the hydrographic setting that is common to many of

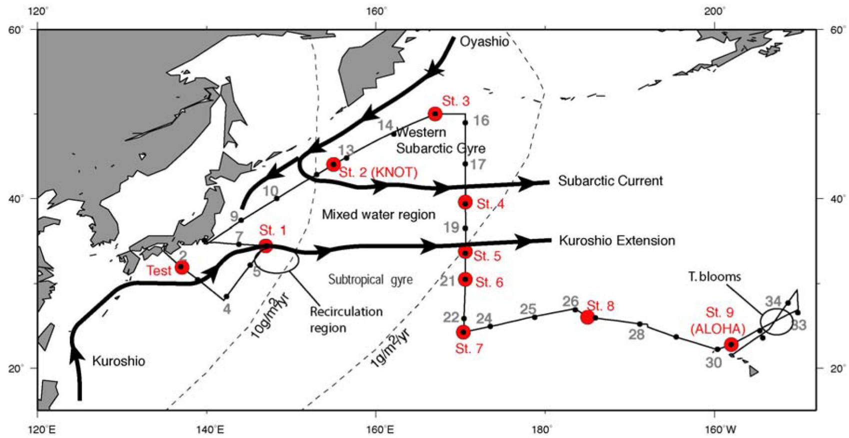

Figure 1. Map showing the ship's track during the cruise, the location of the vertical stations (red), and the decimal day (light gray; day 1 = 1 May 2002) at selected points along the track. Dashed lines are modeled dust depositions in gms mineral dust per square meter per year [after *Duce et al.*, 1991]. Approximate locations of the recirculation region and the *Trichodesmium* blooms are indicated by circles.

the subsequent papers in this *Geochemistry, Geophysics, Geosystems* theme.

2. Methods

[9] The cruise utilized the United States Research Vessel *Melville*, and departed from Osaka, Japan, on 1 May 2002 and arrived in Honolulu, Hawaii, on 5 June 2002. A total of nine vertical profile stations were occupied and underway surface sampling was conducted on the transects between stations (Figure 1 and Table 1). At the vertical profile stations, a Seabird 911 CTD mounted on a General Oceanics 24-place rosette system with 10 L Niskin bottles equipped with an in situ fluorometer and transmissometer was used to obtain hydrographic profiles of temperature, salinity, nutrients, oxygen, and chlorophyll. In addition, at each station during daylight, a Biospherical Instruments PAR sensor was installed on the package during a shallow cast, to record the ambient light field.

[10] The profile and underway sensors were calibrated by shipboard determination of discrete samples collected from the rosette bottles as well as from the underway system. Dissolved oxygen was determined using the standard Winkler titration method described by *Parsons et al.* [1984], while salinity was determined with a IAPSO-calibrated Guildline salinometer. Nitrate + nitrite, phosphate, and silicate were determined on frozen samples returned to Hawaii using a continuous flow Technicon AutoAnalyser II using the protocols outlined by *Gordon et al.* [1994]. Chlorophyll *a* and phaeophytin *a* were isolated with glass fiber filters and determined by fluorometry on 90% acetone extracts [*Selph et al.*, 2005] using a Turner Designs 10-AU Fluorometer (*Strickland and Parsons* [1972], as modified by *Holm-Hansen and Riemann* [1978]).

[11] The rosette package was used to collect large volume water samples for isotope work and large scale filtration projects. In addition, salinity, nutrients and some oxygen samples were collected to calibrate the CTD sensors and to compare with the Go-Flo samples (see below).

[12] Vertical profiles for trace elements were obtained using contamination-free procedures, including deploying 12 L and 30 L Go Flo sampling bottles on a 5600 m Kevlar hydrographic cable and triggering them with plastic messengers. This sampling methodology is virtually identical to that used in the 1996 IOC Baseline survey in the Atlantic [*Cutter and Measures*, 1999]. Subsampling from the Go–Flo bottles was conducted in a clean area constructed from polyethylene sheeting which was kept under positive pressure using a 540 cfm MAC–10 HEPA blower (Environmental Air Control). The manner in which Go Flos operate and are deployed raises the possibility of tripping at the wrong depth or leakage due to incomplete closure of the bottle at the trip depth. Thus nutrient and salinity data from the Go–Flo bottles have been carefully compared to those from the CTD/rosette to ensure proper operation; these results will be presented below.

Table 1. Shipboard Events[a]

Decimal Day	Comments	Location
1.2981	*Melville* departed Osaka ~ 17:09 local time	Subtropical gyre
1–5.210	Pump 2 off, no underway data	
2	Test station 31° 54.2 N, 137° 4.9E surface salinity 34.797	
3.876	Way point 28°N, 142°E reached	
3.947	Surface Fish sampling commences at 28°15.15'N 142°11.23'E	
5.6386	Ship reverses course at N end of Kuroshio	Kuroshio
5.7202–6.366	Station 1 (Kuroshio), 34°28'N 146°59.2'E	
6.366–8.16	Heading for Tokyo along axis of Kuroshio and in Tokyo bay	
8.164–11.386	Heading for Station 2, crossing cold core eddies. Cold core eddies at 9.32, 10.34	Mixed water region
10.3–10.74	Crossing into Oyashio/subarctic gyre	Oyashio
10.74–11.11	Warm core eddies at 10.79, 10.93 and 11.05–11.11	Subarctic gyre
11.386–12.71	Station 2 (KNOT), 44°N, 155°E	
12.71–14.8	Transiting subarctic gyre to Station 3 underway pump down much of time	
14.82–15.32	Station 3, 50°N, 167°E	
15.32–15.78	Heading due east, very uniform conditions	
15.78–17.927	Heading S to Station 4	
16.78	Cross edge of subarctic gyre	Oyashio
17.13	Warm core ring	Mixed water region
17.927–18.43	Station 4, 39°21.5'N, 170°34.5'E in mixed water region	
18.43–19.6	Heading to Station 5	
19.6–19.96	Station 5 in the Kuroshio, 33°45.9'N, 170°35'E	Kuroshio
19.96–20.59	Heading to Station 6	Subtropical gyre
20.59–21.02	Station 6, 30°30'N, 170°34.5'E	
21.16	Crossing into subtropical gyre	
21.70	Cold core ring	
22.1	Into uniform subtropical gyre water	
22.3–23.21	Station 7, 24°15'N 170°20'E	
23.21–26.4	Heading east to Station 8	
26.39–26.83	Station 8, 26°N 175°W	
26.83–29.96	Headed toward Na Pali coast	
30.3–31.29	Station 9, 22°45'N 158°W	

[a] Note that all times and dates are relative to UTC.

While nutrient samples were collected unfiltered from the Go–Flo bottles, trace element samples were collected both unfiltered and filtered (0.2 μm).

[13] For underway surface sampling of trace elements, salinity, nutrients and ancillary parameters, a bathythermograph "fish" was deployed approximately 8 m outboard from the port aft quarter of the ship using a boom [*Vink et al.*, 2000]. Surface water was peristaltically pumped from the fish through Teflon tubing into the forward analytical lab on the ship. Unfiltered or 0.2 μm filtered water (0.2 μm Gelman Criti–cap polysulfone cartridge filter) was continuously available from this system to underway instrumentation while the ship transited between stations, and additional discrete water samples were collected 3 times per day for Chl a, salinity calibration and shore–based determinations. Underway hydrographic parameters were determined from sensors mounted in the ship's pumped "uncontaminated" seawater line, just aft of the hull intake which was mounted at the front of the ship at approximately 3 m depth. On several occasions, the secondary pump that supplied the surface water to the sensors was not functioning at an adequate flow rate (>1 liter per minute), additionally on some occasions the primary pump also failed. On these occasions (identified in the ship's continuous log of underway parameters, which included pump speed), the surface water sensor data has been eliminated. The parameters affected by this were sea surface temperature, salinity, sigma t, oxygen and chlorophyll. Surface water parameters are plotted against decimal day, where day 1 is 1 May 2002, Osaka, and day 34 is 3 June 2002, at the end of the cruise, in Hawaiian waters (Figure 1). The primary cruise events, along with the decimal date when they occurred, are listed in Table 1.

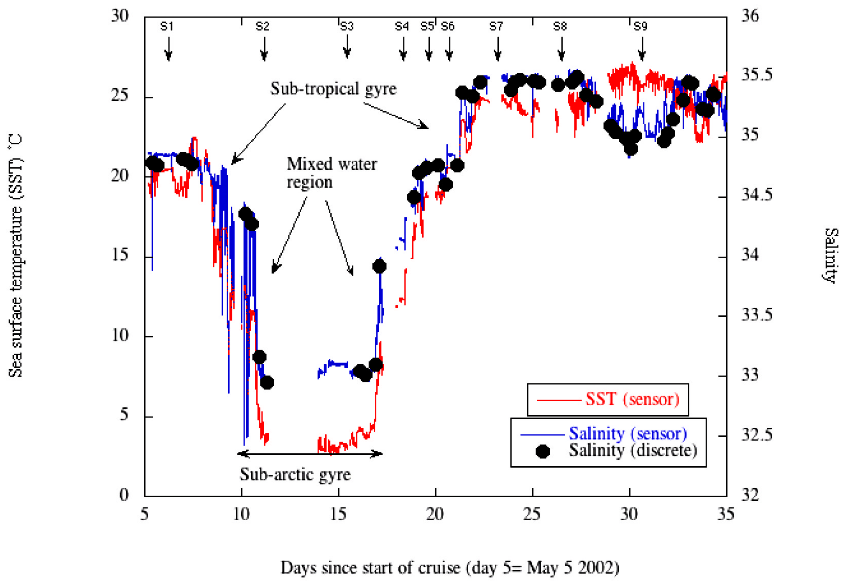

Figure 2. Distribution of temperature and salinity from underway sensors along the ship's track. Discrete salinity samples are shown to indicate agreement with sensor values. Vertical station positions along the cruise track are shown as S1–S9.

2.1. Salinity and the Underway Salinity Probe

[14] Discrete salinity samples collected from the towed fish agree well with the underway salinity probe in the ship's uncontaminated seawater line (R = 0.99). The discrete samples are plotted as an overlay on the underway data in Figure 2.

2.2. Chlorophyll and the Underway Fluorometer

[15] Generally the correlation between the continuous underway flourometer, sampling water from the ship's intake, and the discrete Chl a samples obtained from the towed Fish is reasonably good (R = 0.86, Figure 3). There are, however, some consistent discrepancies between the two signals. The underway fluorometer signal appears to have a baseline offset of approximately 0.27 μg Chl a/L. This is clearly manifested in the signal seen in the westward transect through the subtropical gyre between days 22 and 35. The fluorometer signal during this period averages 0.34 μg/L and rarely drops below 0.15 μg Chl a/L while the discrete samples show fairly constant values averaging 0.08 μg Chl a/L through this region. The offset is not so apparent during the early part of the cruise and thus this may represent a gradual fouling of the underway system's cell. In a few places, the discrete Chl a signals are greater than the underway fluorometer; each of these discrepancies arises in regions with large gradients in the fluorometer signal and thus the differences are likely a result of the different temporal and spatial sampling of the system. However, as a result of the differences between the two determinations, and our desire to use the more abundant continuous record, we will use the underway fluorometer signal as a relative indicator of biomass abundance rather than an absolute measurement.

3. Hydrography

[16] Since incorporation of surface water parameters into the intermediate and central waters of the region by subduction processes is an important theme of this paper, we will start by outlining the variations of hydrographic parameters in the surface waters and then return to describe the vertical structure at the profile stations.

3.1. Surface Waters

[17] The cruise departed from Osaka, Japan on 1 May 2002 and followed the track shown in Figure 1, arriving in Honolulu on 5 June 2002. Along this cruise track, three distinct surface water types were encountered. Two were the waters

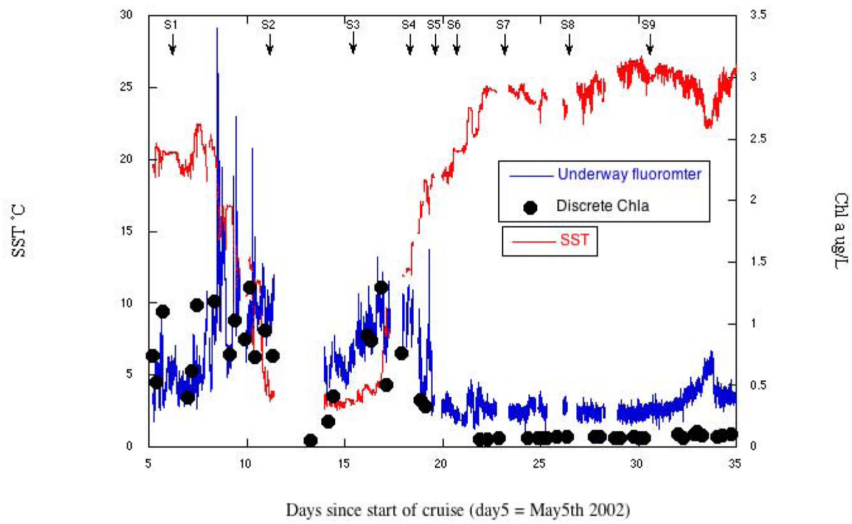

Figure 3. Comparison between discrete Chl a samples and the underway fluorometer sampling the ship's surface water intake. Vertical station positions along the cruise track are shown as S1–S9.

found in the subtropical gyre and the subarctic–gyre, whose edges are defined by the Kuroshio and Oyashio currents, respectively. The third water mass was found in the domain of the mixed water region that lies between the eastward propagating branches of the Kuroshio and Oyashio and contains water of both types in the form of cold and warm–water eddies [*Yasuda et al.*, 1992, 1996; *Kusakabe et al.*, 2002] (Figure 1). Underway sensor acquisition commenced prior to the ship sailing, however problems with the pump for the surface water system (see above) means that no meaningful sensor data was obtained until decimal day 5.2. Physical surface water sampling via the towed fish system commenced on 3 May at 22:44 UTC (day 3.969).

3.2. Subtropical Gyre

[18] The initial part of the cruise from the test station to Station 1 (days 2–5.6) sampled waters of the western part of the subtropical gyre. Within this regime (where recorded) salinities were very uniform around 34.8 and temperatures ranged from ~18.8 to 20.4°C. A few low temperature excursions were observed as the ship transited the recirculation region approaching Station 1, at the northern edge of the gyre. These anomalies were probably associated with cold-core eddies spun off the Kuroshio/mixed water interface region and incorporated into the gyre. Potential density ranged between ~24.8 and 24.4 kg m^{-3} across the region and was inversely related to temperature. Nutrient concentrations were uniformly low, and at the detection limits of the respective methods (NO_3 + NO_2 0.18 μM; PO_4 0.05 μM and SiO_2 0.72 μM). As a nutrient example surface nitrate+nitrite for the entire cruise track is plotted in Figure 4. The underway fluorometer signal was also low through the region. Discrete Chl a showed a slight elevation as the ship entered coastal waters as it approached Tokyo. The highest gyre temperatures were observed along the axis of the Kuroshio as the ship headed into Tokyo.

3.3. Mixed Water Region: Northbound

[19] As the ship headed out of Tokyo Bay, it crossed the western part of the mixed water region, between the Kuroshio and Oyashio currents. Surface waters across this interface region, which was traversed from day 8.16 until day 10.3, were marked by a series of cold and warm water eddies imprinted over a background of temperature that dropped from ~18°C to 12°C and salinities that dropped from 34.7 to 33.5. Potential density climbed from 25 to 25.5 kg m^{-3} across this region, with excursions matching the occurrence of the eddies. Discrete Chl a varied from 0.75 to 1.29 μg/L, with the underway flourometer signal resolving a significant amount of variability over small spatial scales. Most of these excursions, where values of up to 3.3 μg/L were observed, coincided with the ship passing through the cold-core rings. Nutrient levels all remained at their respective methodological detection limits across this region.

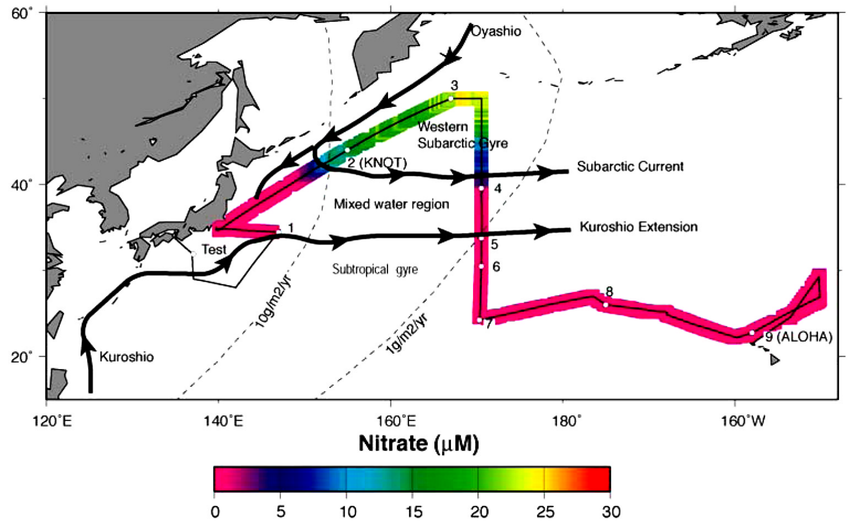

Figure 4. Nitrate + nitrate from the continuous underway sampling system. Data were contoured using Generic Mapping Tools [*Wessel and Smith*, 1995]. Contours were computed after fitting a minimum curvature surface with tension to the gridded data [*Smith and Wessel*, 1990].

3.4. Subarctic Gyre

[20] The ship crossed the Oyashio into the subarctic gyre on day 10.8, and the temperature dropped dramatically reaching 3.6°C at Station 2. Salinity also dropped to 32.96 and the density increased to 26.2. At the edge of the Oyashio, a series of warm core rings were observed at days 10.79, 10.93 and 11.05. From the temperature and salinity properties, these appeared to be composed of mixed region water, entrained into the subarctic gyre. In each case these features could also be seen in the salinity signal. Beyond the last ring, the surface water hydrographic properties became very constant with a temperature of 3°C, salinity 33.1, and density of 26.36 kg m^{-3}. These conditions persisted throughout the subarctic gyre until the ship recrossed the southern edge of the subarctic gyre on day 16. The flourometer signal indicated significant biomass associated with the rings at the edge of the gyre, but into the interior of the gyre values were generally lower and more uniform. This probably marked the latitude at which primary production was still light limited as data from Stations 2 and 3 indicate that the mixed layer was probably deeper or close to the critical depth at this stage of the season (Table 2).

[21] Discrete Chl a values, which ranged from 0.05 to 0.95 μg/L (mean 0.61 μg/L), were significantly lower than those recorded by the underway flourometer (range 0.38–1.71 μg/L, mean 0.90 μg/L). While the difference in range may well reflect the ability of the underway system to resolve the small scale ring-like features, the generally higher baseline values may also be indicative of the onset of the baseline offset described above. Despite these limitations on interpretation, inside the subarctic gyre Chl a and fluorometer values (where available) were relatively low, reaching a minimum at ~48–50°N. Chl a values rose slightly as the ship headed east and continued to rise as the ship headed south.

[22] In contrast, nutrient levels rose dramatically as the ship crossed the Oyashio into the subarctic gyre, with values reaching a maximum of 25 μM NO_3 + NO_2 and 42 μM Si at 50°N. Values remained high throughout the subsequent eastern transit, but started to drop at ~46°N as the ship

Table 2. Mixed Layer Depths at the Vertical Profile Stations, Using the 0.125 kg m^{-3} Criteria

Station	Mixed Layer Depth, m
1	48
2	58
3	110
4	26
5	29
6	23
7	49
8	12
9	20

returned south to the mixed water region and as the underway fluorometer signal started to rise.

3.5. Mixed Water Region: Southbound

[23] The ship recrossed the Oyashio into the mixed water region along 170°E as the ship headed south to Station 4 (days 16.8 to 19.6). Across this region, temperature rose from ~5 to 19°C and salinity rose from 33.1 to 34.7, whereas potential density decreased from 26.1 to 25 kg m^{-3} across the region. Discrete Chl a values stayed elevated across most of the region, declining somewhat to the south. The underway flourometer showed a fairly variable trace with some of the structure, particularly near the Oyashio, associated with low salinity excursions, i.e., ring-like structures.

[24] Nitrate and phosphate values declined rapidly across the region reaching detection limits by 39°N. In comparison, Si values remained above 10 μM to 38°S, and they dropped to detection limits by approximately 36°N, the northern edge of the Kuroshio extension.

3.6. Eastern Part of the Subtropical Gyre

[25] From station 5 in the Kuroshio extension at day 19.96 until the end of the cruise at day 35, the ship sailed back into the subtropical gyre. Temperatures along the track increased slowly from 20°C to 26°C eastward along the track. Salinities likewise increased from ~34.6 to 35.5. A region of lower salinities (~34.8), and higher temperatures (27°C) was seen as the ship steamed along the axis of the NW Hawaiian Islands toward Kauai. The final leg of the cruise to Station 9 (ALOHA) and to the NE of the islands, saw a reversal of that anomaly. Potential density ranged from 22.5 to 24.5 kg m^{-3} along this eastern part of the gyre, with the lowest values seen along the axis of the NW Hawaiian islands. The discrete Chl a data were uniformly low across this section of the cruise, averaging 0.08 μg/L. As discussed above, the underway fluorometer yielded significantly higher, but equally uniform values. An increase in the underway signal was seen in the transit after Station 9, with values reaching 0.45 μg/L at 26°N, in the region of the *Trichodesmium sp.* blooms. Only a small increase (~0.01 μg/L) was seen in the discrete Chl a samples, which did not sample the blooms directly. This leaves the possibility that the underway signal was more a reflection of the continued contamination of the underway probe, than a real signal. Nutrient values remained at the methodological detection limits throughout the transit.

3.7. Vertical Profile Stations

[26] A total of nine vertical stations were occupied. The siting of these stations was designed to sample particular water masses and to observe the incorporation of surface water signals into the thermocline waters. Two stations were located in the Kuroshio to permit its sampling close to the source of dust input (Station 1 and further downstream in the Kuroshio extension at Station 5). Station 4 was sited to observe geochemical properties in the transition zone of the mixed water between the gyres. Station 2 and Station 3 were sited in the subarctic gyre to evaluate the relationship between potential dust deposition and HNLC conditions. Station 6 was occupied at the same location as GEOSECS 226 occupied in 1973, and the site of the surface water ^{210}Pb maximum reported by *Nozaki et al.* [1976]. The existence of this maximum indicates that at this place the atmospheric deposition of continental origin ^{210}Pb exceeds its scavenging removal rate by biological processes. Station 7 was located at the most southerly part of our transect to permit sampling of the Antarctic Bottom Water (of Circumpolar Current origin) that flows into the North Pacific through the Samoa Passage. This station was previously occupied during the Trans Pacific section at 24°N [*Roemmich et al.*, 1991; *Mantyla and Reid*, 1983] and is also close to GEOSECS 227 occupied in 1973, thus providing a continuity of observations over a 30-year period.

[27] In addition, particular stations, e.g., KNOT (Station 2) and ALOHA (Station 9), were chosen to relate our large spatial scale data to regularly occupied time series stations. As a result of available ship time, Station 8 was added during the cruise to provide a mid-transit sampling of the upper waters.

[28] Since our main goal was to investigate the effects of surface water additions and their incorporation into the thermocline waters, most of the stations were only sampled to 1500 m. However three stations: 2, 7 and 9, were sampled close to the bottom to allow us to characterize the deep and bottom waters across the basin. We will describe the hydrography of the water column at each station and relate it to the distribution of nutrients and biological parameters.

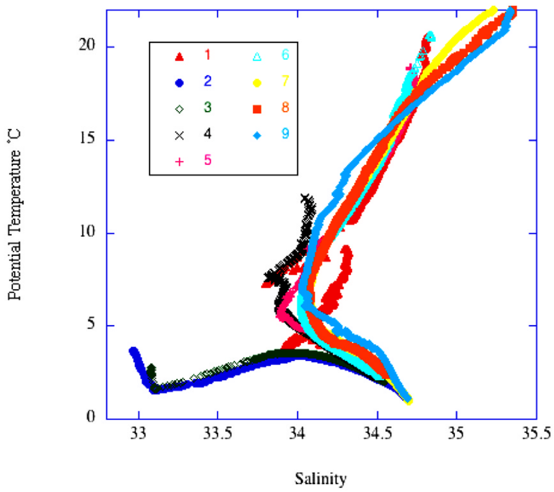

Figure 5. Potential temperature and salinity at the vertical profile stations.

[29] Surface water mixed layers were defined using the 0.125 kg m^{-3} criterion. By this definition, the base of the mixed layer is where the potential density is at least 0.125 kg m^{-3} greater than that at the surface. This definition yields a mixed layer depth that exists over longer timescales than the diurnal heating/cooling cycles [*Levitus*, 1982; *Morrison et al.*, 1998].

[30] The potential temperature/salinity characteristics of the water masses encountered at the stations is shown in Figure 5. As can be seen, the waters below ~ 3°C (1,000–1300 m) are very uniform along the cruise track. This deep water mass has its origins in the Circumpolar Current and Antarctic

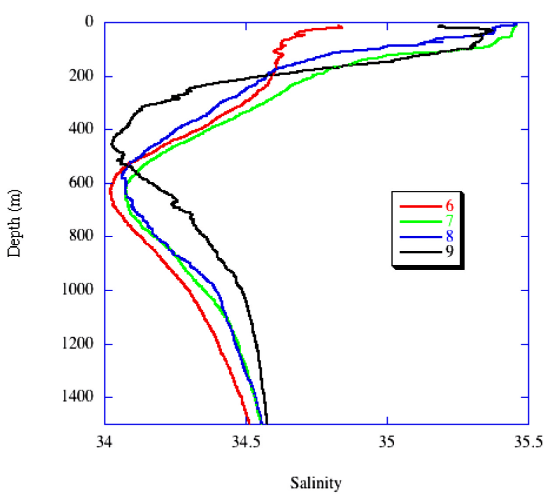

Figure 6. Vertical distribution of salinity at the subtropical gyre Stations 6, 7, 8, and 9 from the rosette-mounted CTD.

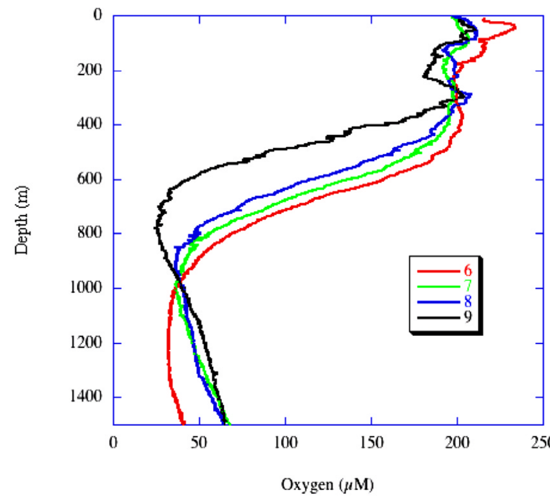

Figure 7. Vertical distribution of oxygen at the subtropical gyre Stations 6, 7, 8, and 9 from the rosette-mounted SBE 43 sensor.

Bottom Waters of the South Pacific. The admixture of these waters enters the North Pacific basin at approximately 3500 m through deep passages west of the Marianas Ridge. This water then spreads out sluggishly and fills the entire bottom of the western and eastern North Pacific [*Mantyla and Reid*, 1983; *Roemmich and McCallister*, 1989].

[31] To eliminate redundancy in the discussion of hydrographic features, the stations will be grouped and discussed according to their hydrographic provenance.

3.8. Stations of the Subtropical Gyre: 6, 7, 8, and 9

[32] Mixed layer depths (Table 2) in the subtropical gyre were generally shallow at 12–23m with a somewhat deeper 48m layer seen at the southernmost Station 7. Below the mixed layer salinities (Figure 6) generally decrease fairly uniformly to the NPIW minimum which was found at 600 m in the western stations, and at ~500 m at Station 9. The salinity of the NPIW minima is somewhat lower at Stations 6 and 9 than at Stations 7 and 8. Below the minima, salinities increase to 1500 m (the deepest samples at Stations 6 and 7), where values show a similar gradation between the stations. Salinities in the deeper waters sampled at Stations 7 and 9 converge by 2000 m, increasing slowly in tandem into the Antarctic Bottom Water (AABW).

[33] Oxygen distributions at these stations (Figure 7) also show a gradation in the depth of the minimum

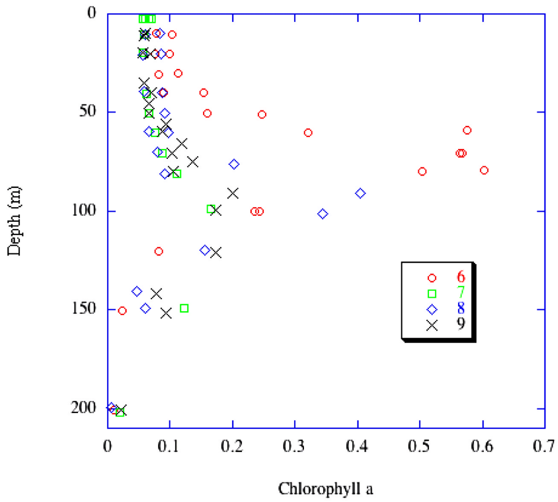

Figure 8. Vertical distribution of Chl a at the subtropical gyre Stations 6, 7, 8, and 9. Data from discrete samples collected from the rosette-mounted bottles.

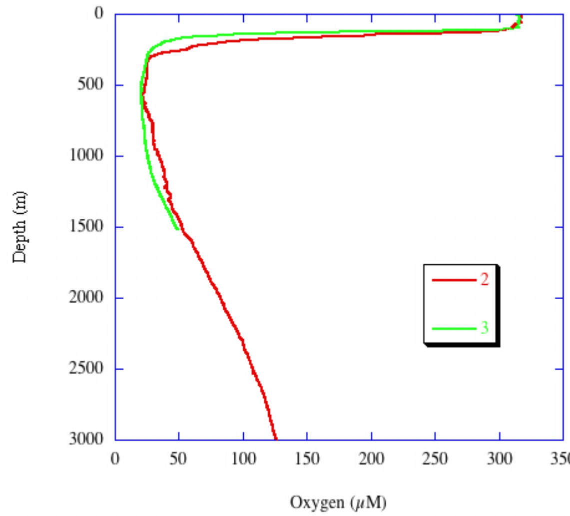

Figure 10. Vertical distribution of oxygen at the subarctic gyre Stations 2 and 3 from the rosette-mounted SBE 43 sensor.

across the gyre. At Station 6, the minimum (~31 μM) is found between 1000 and 1200 m, this depth shoals at Stations 7 and 8 eventually rising to ~800m at Station 9.

[34] Chl a maxima (Figure 8) were found in these stations between 70 and 100 m with the highest values at Stations 6 and 8 [*Selph et al.*, 2005].

3.9. Stations of the Subarctic Gyre: 2 and 3

[35] The relatively shallow mixed layer depth at Station 2 and the much deeper one at Station 3 (Table 2) are indicative of the progressive seasonal stratification of this region at the time of our cruise. Evidence of this progressive stratification can be seen in the Station 2 salinity profile (Figure 9), which shows the remnants of the low salinity deep winter mixed layer at ~106 m, close to the contemporary mixed layer depth observed at Station 3 further north. Absence of NPIW at this latitude results in a constant increase of salinity from the low salinity surface waters of this region into the deep waters, which at Station 3 have salinities virtually identical to those of the bottom waters at Stations 7 and 9.

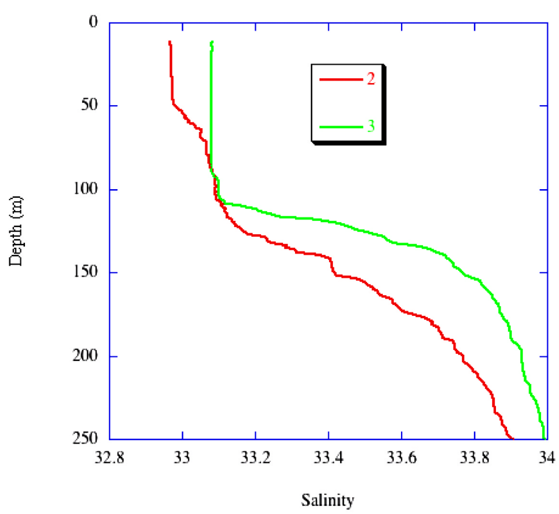

Figure 9. Vertical distribution of salinity at the subarctic gyre Stations 2 and 3 from the rosette-mounted SBE 911 CTD.

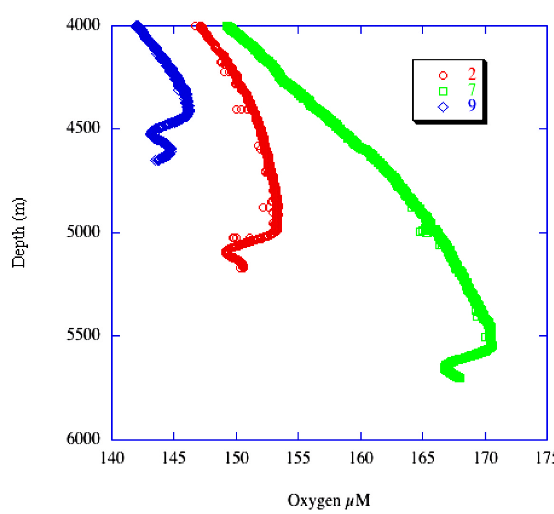

Figure 11. Comparative distribution of oxygen in the AABW of deep Stations 2, 7, and 9.

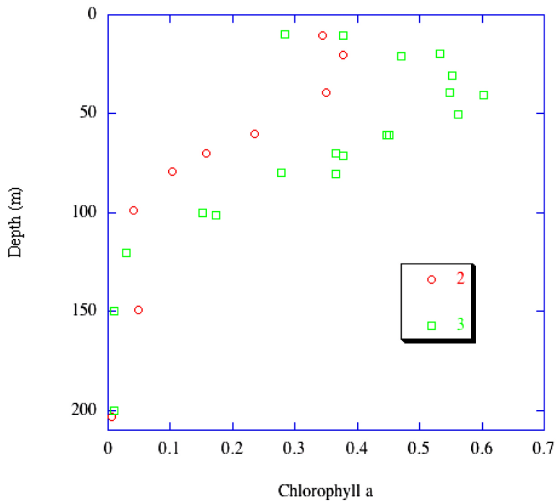

Figure 12. Vertical distribution of Chl a at the subarctic gyre Stations 2 and 3. Data from discrete samples collected from the rosette-mounted bottles.

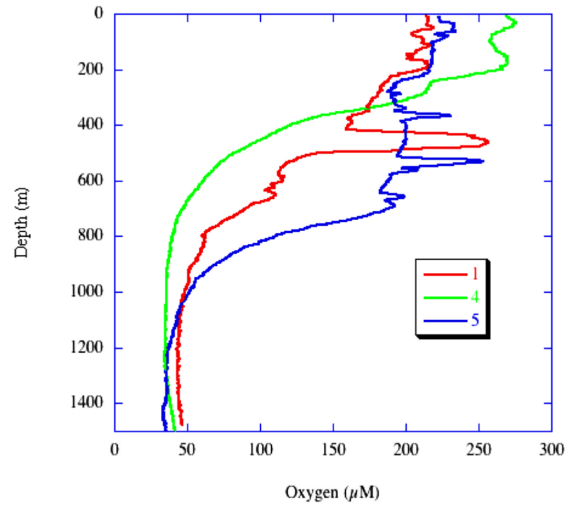

Figure 14. Vertical distribution of oxygen at the mixed water stations 1, 4, and 5 from the rosette-mounted SBE 43 sensor.

[36] Oxygen at these stations (Figure 10) shows a dramatic decline from the base of the deep winter mixed layer to values as low as 20 μM. The extent of this minimum is greatest at Station 3 where values of <30 μM occupy the water column from 250 m to 1200 m. The minimum is equally intense at Station 2 but not as broad. The oxygen in the Antarctic Bottom Water at Station 2 (Figure 11) is intermediate between the values seen at the other deep stations (7 and 9). This gradation is indicative of oxygen consumption along advective flow lines from Station 7, the closest of our stations to the entry of AABW into the North Pacific, to the more northerly Station 2 and the distant central Pacific Station 9.

[37] The Chl a max is significantly shallower at these station than in the subtropical gyre with a distinct maximum at ∼50 m in each station (Figure 12).

3.10. Stations of the Kuroshio and Mixed Water Region: 1, 4, and 5

[38] The salinity structure of the stations located in the Kuroshio and mixed water region between the

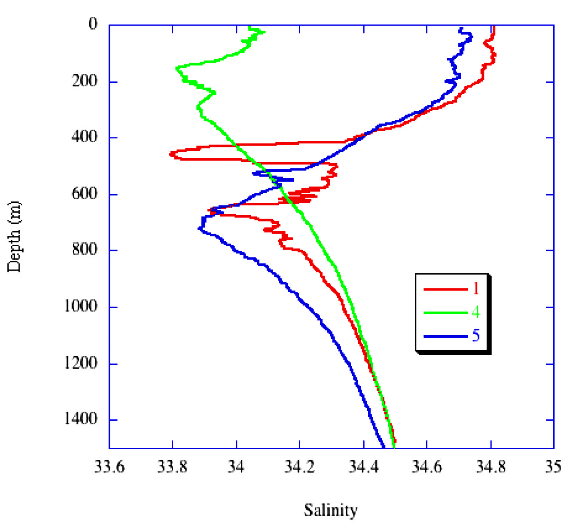

Figure 13. Vertical distribution of salinity at the mixed water Stations 1, 4, and 5 from the rosette-mounted SBE 911 CTD.

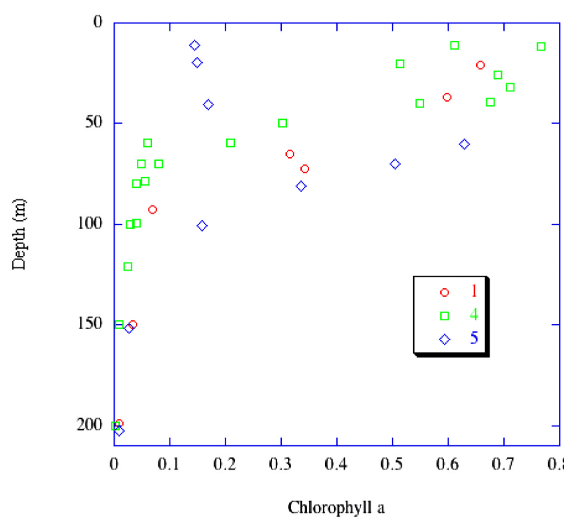

Figure 15. Vertical distribution of Chl a at the mixed water Stations 1, 4, and 5. Data from discrete samples collected from the rosette-mounted bottles.

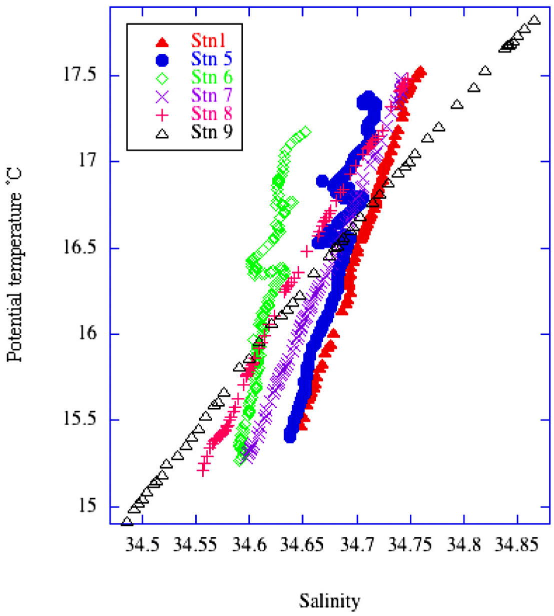

Figure 16. Potential temperature and salinity characteristics of the mode waters (σ_θ = 25.2–25.6).

gyres (Figure 13) indicates the dynamic mixing that occurs in the upper waters of this region. The low salinity intrusions, which are strongest in the western and eastern Kuroshio stations (1 and 5), are also accompanied by high oxygen levels indicative of their surface origins (Figure 14). Station 4, at the northern boundary of the region shows less pronounced low salinity and high oxygen intrusions. The Chl a maxima at these stations (Figure 15) are shallow (10–60 m) and pronounced, with values approaching 0.8 ug/L Chl a. The most pronounced values are at Station 1 (34.5N, occupied on 5 May) and at Station 4, (39.3N, occupied on 18 May), with the Station 5 (33.5N, occupied 19 May) maximum values both lower and deeper in the water column.

3.11. Entrainment of the Surface Water Properties Into the Thermocline

[39] The thermocline waters of the Pacific are divided into the ventilated waters that have direct contact with the atmosphere and the unventilated part which has no direct air-sea interaction [*Huang and Qui*, 1994]. Water subducted from the base of the mixed layer into the permanent thermocline carries with it hydrographic and chemical properties typical of late winter conditions in the surface. Thus a spectrum of water masses occupies the subsurface waters reflecting the late winter gradients in these properties at the surface across the basin. *Yuan and Talley* [1992] traced ventilation processes in the eastern North Pacific through the formation of subsurface salinity minima. They reported that the shallow salinity minimum had a narrow range of densities (σ_θ = 25.1 to 26.0) and was formed in winter in between 35 and 50°N east of 160°W. In contrast, their middle salinity minimum, the densest of the ventilated waters (σ_θ = 26.2–26.5), was traced to surface waters between 165°E and 170°W between the subarctic frontal zone and the subarctic gyre boundary. The relatively small source region, when coupled with interannual variations in wind-forcing and surface water densities in this region, reduce the volumetric importance of this water mass.

[40] *Huang and Qui* [1994] calculated the rate at which these subsurface waters were renewed for different σ_θ classes. For waters that outcropped in the subtropical gyre, σ_θ = 24.4–25.2 renewal times were of the order of 5 years. For the subtropical mode water, which they defined as spanning a potential density range of σ_θ = 25.2 to 25.6 and with a potential temperature of ~16°C, renewal times varied from 9 years to 17 years. The ventilation site for subtropical mode waters is close to the recirculation region of the Kuroshio where late winter mixed layers are deep (>150 m) and where the vigorous recirculation leads to a large lateral contribution to subduction resulting in production rates of ~5 Sv between σ_θ = 25.2–25.6. The *Melville* transit passed through the eastern edge of this subduction zone in early May. Surface water pumping problems (discussed earlier) limited determination of hydrographic properties to the

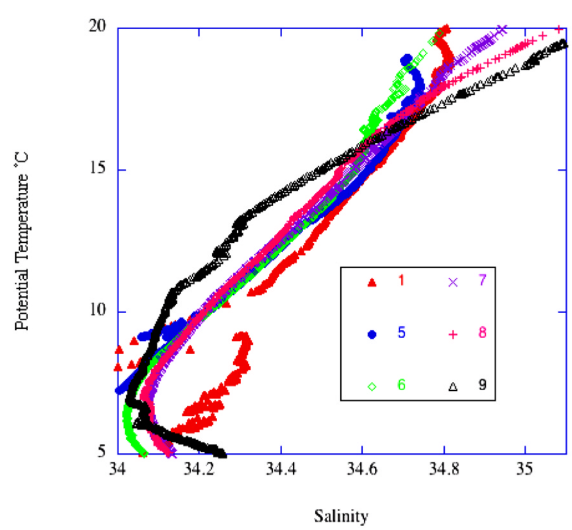

Figure 17. Temperature and salinity characteristics of the thermocline waters.

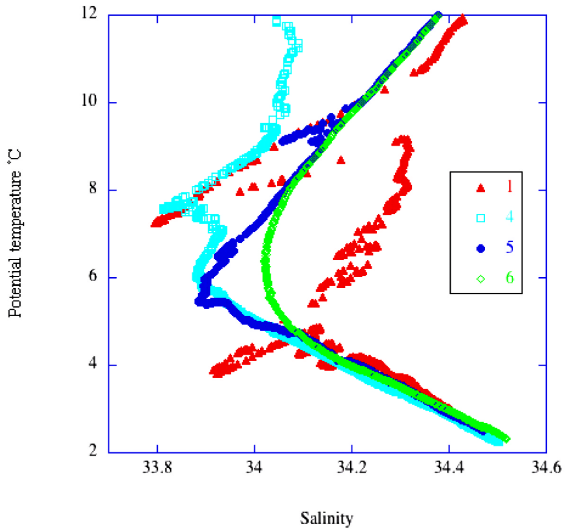

Figure 18. Intrusions of the low salinity waters at Stations 1, 4, and 5 and their relationship to the salinity minimum of the NPIW as seen at Station 6.

northern edges of the region, where seasonal heating had raised surface water temperatures to >19°C and reduced potential densities to $\sigma_\theta = 24.6$ to 24.9. The subsurface manifestation of the subtropical mode water, though, was quite distinct in all of the stations of the tropical gyre, (1, 5, 6, and 7) where waters of $\sigma_\theta = 25.2$ to 25.6 occupied depth ranges of 200–300 m and had potential temperatures of 15.5 to 17.5°C. However, further to the east particularly at Station 9 the water of this density range has a different T/S trajectory with shallow waters warmer and saltier and deeper waters colder and fresher than those in the western stations, Station 8 (at 175°W) appears as something of a hybrid between these two trends (Figure 16). In addition, at Stations 8 and 9 the depth distribution of the subtropical mode was shallower and occupied a narrower range of depths. These observations are consistent with the conclusions of *Masuzawa* [1972] and *Bingham* [1992] that the mode waters formed in the Kuroshio recirculation region do not appear to ventilate this density surface beyond the dateline.

[41] The different source waters ventilating the thermocline waters of the eastern and western North Pacific can be seen in temperature-salinity relationships of the stations in Figure 17. In the west (Stations 1, 5, 6 and 7), the warmest of the waters are less saline than those seen at Stations 8 and 9, reflecting the lower salinities in the surface waters of the western Pacific, where these temperatures outcrop. At lower temperatures, though (below ~16°C $\sigma_\theta = 25.5$), the eastern basin (Station 9) has lower salinities than the western basin, reflecting a different origin for the waters ventilating this part of the water column. *Reid* [1973], *Tsuchiya* [1982], and *Yuan and Talley* [1992] have shown that waters in this density range ($\sigma_\theta = 25.1–26.2$), their Shallow Salinity Minimum, originate in the low salinity surface waters of the northeastern Pacific (35–50°N, 145–160°W) and are incorporated into the subsurface waters of the eastern subtropical gyre during wintertime, producing several subsurface salinity minima at varying density horizons between $\sigma_\theta = 25.1–26.2$. While vertical mixing tends to modify both the salinity and density of these layers as they advect through the gyre, *Yuan and Talley* [1992] have shown that these shallow low salinity layers are confined to the eastern tropical Pacific.

[42] This low salinity effect is really only visible at Station 9, the Station 8 properties (from 175°W) seem to fall on the line described by the western stations (Stations 1, 5, 6 and 7). Thus the deeper waters of the salinity minimum may carry the influence of the western Pacific properties much further to the east than the shallower mode waters. The contribution of the interleaving of the low salinity intrusions into subtropical gyre waters in the mixed water/Kuroshio region to the formation of the salinity minimum can be seen clearly in Figure 18. Thus the subsurface chemical signals generated in the western Pacific may contribute to the waters of the central Pacific along the deeper isopycnals.

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