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The Subarctic and Northern Subtropical Fronts in the Eastern North Pacific Ocean in Spring

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ABSTRACT

The subarctic and subtropical frontal zones of the eastern North Pacific Ocean were surveyed in June for five consecutive years starting in 1972. These surveys form the basis for a description of the complex frontal distributions and their year-to-year differences. The fronts appear as surface outcroppings of haloclines: the subarctic halocline where salinity increases with depth and the subtropical halocline where the opposite prevails. Between the fronts lies a transition zone where strong vertical gradients of salinity are generally absent. An examination of the northern boundary of subtropical waters in this new dataset reveals the presence of two major fronts in the subtropical frontal zone. In addition to the front commonly identified as the subtropical front (18°C and 34.8‰) is a northern subtropical front that forms the northern boundary of the subtropical halocline in the eastern North Pacific. It falls some 2° to 3° of latitude north of the subtropical front and is the same front observed by Roden which he termed the "34°N front". There is evidence that this front is quasi-continuous over great distances like the other major fronts of the temperate zone. Its temperature–salinity characteristics, 14° to 17°C and 34.4 to 34.6‰, are also those of Kuroshio front in the Kuroshio Extension. Narrow cores of extra-high salinity that indicate current jets occur at the high-salinity side of the northern subtropical front and, sometimes, the subarctic front. Geostrophic flow is often locally intensified about the fronts. The many salinity features are closely associated with the velocity patterns, indicating the complexity of advection and suggesting, at times, a banded structure in the current field. In June 1972, 1973 and 1976 the frontal gradients were strongly developed; in June 1974 they were diffused and broken. These findings agree with Saur's time-series study of surface salinity gradients along a track crossing the same area and concurrent in time.

1. Introduction

This study examines a series of five surveys that were conducted during June of consecutive years, starting in 1972. Meridional transects from each of the surveys cross both fronts bounding the subarctic and subtropical waters in the eastern North Pacific Ocean and one such line of stations along 137.5°W was repeated in each of five years. These surveys provide the basis for describing details of the complex frontal structure during a season and in a region that has not been studied previously, and provide some evidence of the year-to-year differences in frontal development. The fronts found in these observations are the subarctic, the subtropical and a front, herein called the northern subtropical, which lies between them.

Within the past one-and-one-half decades the use of conductivity (salinity)/temperature/depth (CTD or STD) profilers has improved the observation of ocean frontal gradients. The subarctic and subtropical frontal zones in the eastern North Pacific Ocean have been studied by Roden (1971, 1974, 1977, 1980) in four surveys, using a CTD and relatively small station intervals (27 to 36 km). His surveys centered about the months of September, October, November and January. Recently, there was a cooperative investigation of the subtropical front in the month of January, FRONTS 80 (Paulson and Niiler, 1981; Roden, 1981; Van Woert, 1982; Niiler and Reynolds, 1984). The primary characteristics of these frontal zones and processes that influence them are reviewed and summarized by Roden (1975, 1980) and by Niiler and Reynolds (1984).

The time variation of these fronts has been examined by Saur (1980) in a study of the surface salinity observations taken approximately biweekly over nine years (1965–75) along the shipping lane between San Francisco and Honolulu. The surveys reported herein were conducted within the period of Saur's record of observations and the station tracks intersect his transect near the subtropical frontal zone. A comparison is made between Saur's time series of fronts as determined by surface salinity and the new observations of detailed hydrographic sections taken once each year. Each oceanographic transect of this new dataset crosses the fronts near the eastern terminus of their zonal extent and the distribution appears to reflect the deep-mixed winter conditions even though they are overlain by shallow spring warming.

2. Background

Large meridional differences in the balances of heat exchange through the surface and of evaporation and precipitation produce meridional variations in temperature and salinity characteristics. Large-scale patterns of wind stress and ocean currents form these meridional gradients into relatively narrow zones, thus producing ocean fronts (Roden, 1980). These fronts sometimes reach depths on the order of several hundred meters and act to separate large regions having small ranges of temperature–salinity characteristics, termed water masses. The primary characteristics used in defining the subarctic region are its low temperatures and low salinities (<33.8‰) in the surface domain and a halocline near 150 m in which salinity increases with depth. The southern limit of this ocean region is the subarctic front. It is defined by the abrupt meridional change in salinity structure (e.g., see Favorite et al., 1976, and ref. cited therein). Dodimead (1961) and Tully and Barber (1960) used the 33.8‰ isohaline to characterize this front; it falls near the bottom of the subarctic halocline and rises to the surface within the subarctic front. The subarctic front retains its characteristic structure from the western North Pacific to regions off California and Baja California (Roden, 1971; Lynn et al., 1982). The front generally lies between latitudes 40° and 43°N except to the east of 150°W where it turns east-southeast forming a western boundary for the California Current and where LaFond and LaFond (1971) and Saur (1980) use the term "California Front". In either case the argument is drawn that the salinity structure gives credibility to the existence of the subarctic front as a quasi-permanent and quasi-continuous feature and that it closely follows the mean position of 33.8‰ waters in the surface domain. This concept appears valid despite deformations and temporal variations that sometimes give it a complex form. There are additional ocean fronts in the subarctic waters (Roden, 1977), some of which are revealed in the figures herein; however, they are not treated in this report.

The North Pacific Central Waters (Sverdrup, 1942) are characterized at the surface by salinities in excess of 34.8‰ and a halocline (and associated thermocline) often in a depth range of 100 to 250 m in which salinity decreases with depth. The northern boundary of North Pacific Central Waters is the subtropical front in which the 34.8‰ isohaline and the 18°C winter isotherm are embedded (Seckel, 1968; Roden, 1980). During FRONTS 80 (Roden, 1981) one manifestation of this front was comprised of salinities in the range of 34.9 to 35.1‰. Although the subtropical front has been observed less often than the subarctic front, it appears as if the mean position of the 34.8‰ (or perhaps 34.9‰) isohaline at or near the surface (e.g., from Robinson, 1976) serves the same function in defining the average position of the subtropical front for the greater part of the North Pacific. The central latitude of this front is 30.5°N. Roden (1975) presented a schematic representation of the major fronts in the North Pacific. Like the subarctic frontal zone the subtropical frontal zone has multiple regions of large gradients. Between meridians 152 and 158°W, in a winter survey, Roden (1980) found the subtropical front near 31.5°N and a second front near 34°N. He termed the more northerly front the "34°N front". The 34.4 and 34.5‰ isohalines and the 16°C isotherm are embedded in it.

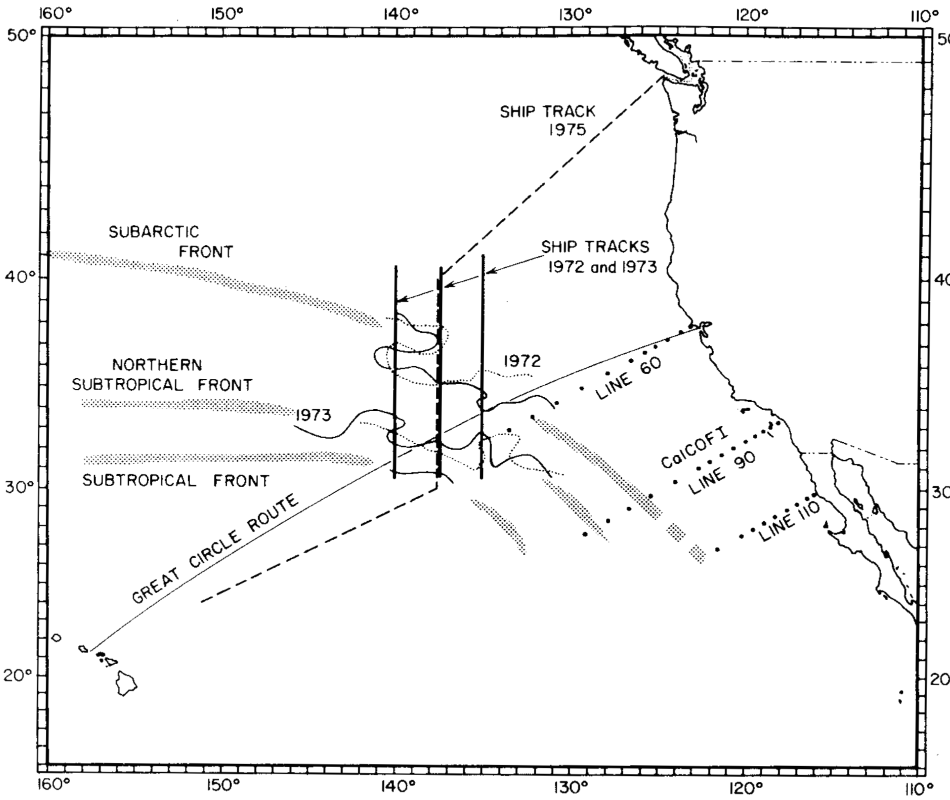
One of the fronts described in this report is an eastward continuation of the "34°N front". Like the other two major midlatitude fronts this front is found at more southerly latitudes nearer the North American continent. Because of this variation in latitude, the name "34°N front" appears inappropriate; hereafter, I refer to it as the northern subtropical front. Evidence for this front can be found in these and other data and I conclude that it is a major feature of the subtropical frontal zone, not only in the eastern North Pacific, but in the central and western North Pacific as well. The evidence for the possible continuity of this front is given in Section 9. In the eastern North Pacific it falls some 2 to 3 degrees of latitude north of the subtropical front and is shown schematically in Fig. 1.

3. The surveys

Surveys were conducted each June of the years 1972 through 1976. The station lines for the surveys are shown in Fig. 1, along with the fronts for two of the years as determined from these and other data. The common element in each of the survey tracks is the repetition of the hydrographic section along 137°30′W. In 1972 and 1975 operations were conducted from the R.V. *Townsend Cromwell*. In 1973, 1974 and 1976 the R.V. *David Starr Jordan* was used. For the purposes of this paper the surveys may be identified in sequence as TC72, DSJ73, DSJ74, TC75 and DSJ76.

Station observations include STD (Plessey Inc., model 9006 or 9040) casts to 600 or 1000 meters. Nansen bottles or a rosette sampler attached to the STD cable provided water samples and reversing-thermometer temperatures for standardization of the STD casts, as did occasional 18-bottle Nansen casts. Stations were frequently spaced at 45 to 56 km (25 to 30 n. mi.) along the transects. Stations were added in response to locating the fronts with the continuous recording thermosalinograph. In addition to the major transects, short runs were made across the frontal features with 9 and 19 km (5 and 10 n. mi.) station spacing.

The surveys were conducted as part of study of albacore migration patterns as they enter the North



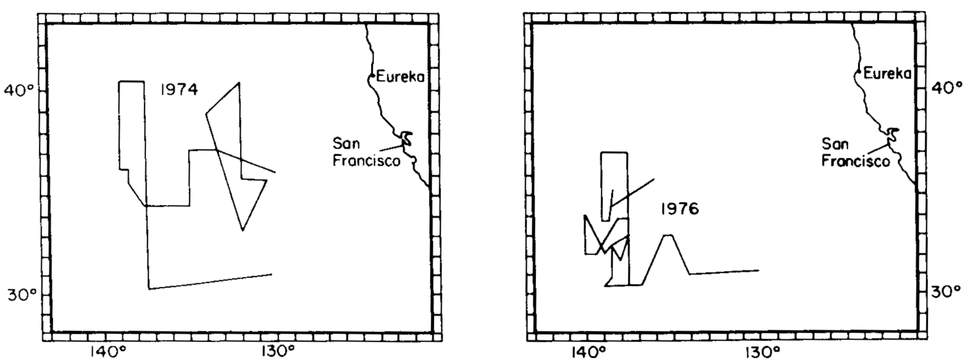
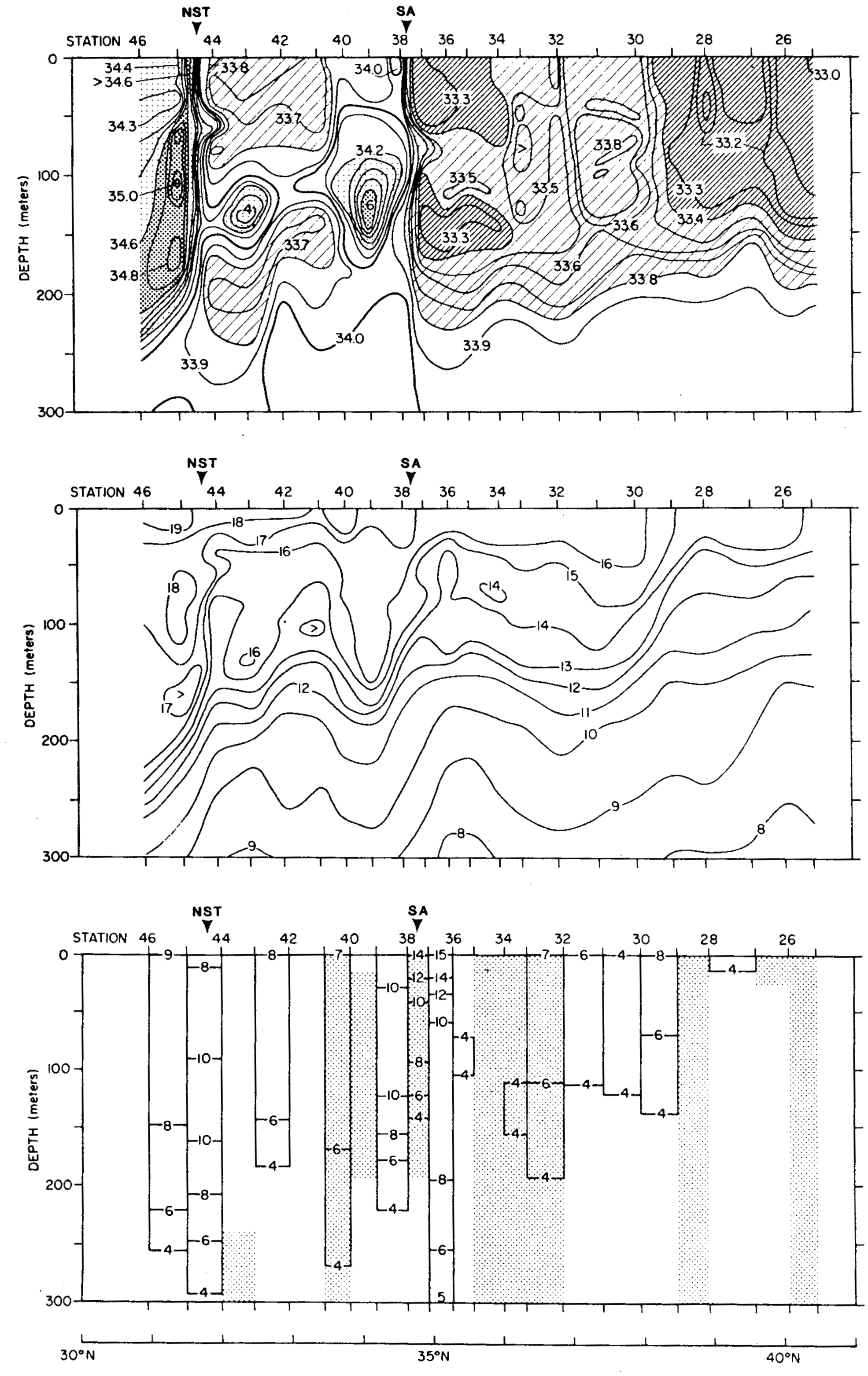


FIG. 1. Upper: Schematic of station lines occupied in June of 1972, 1973 and 1975 (heavy solid and dashed lines). Great-circle shipping route between San Francisco and Honolulu along which time series of surface salinity were analyzed by Saur (1980) (light line). Mean position of the subarctic and subtropical fronts (shading) and observed fronts for 1972 and 1973 (dotted and light solid line). Three often-repeated station lines from the CalCOFI station grid are shown. Lower: Schematic of station lines occupied in June of 1974 and 1976.

American west coast fishery in late spring to early summer (Laurs and Lynn, 1977). Fishing vessels chartered by the American Fishermen's Research Foundation cooperated in these surveys. Twice-daily XBT drops by these vessels and XBT drops from the Merchant Ship XBT program coordinated by J. F. T. Saur and


NST
SA
STATION 46
44
42
40
38
36
34
32
30
28
26
DEPTH (meters)
0
100
200
300
34.4
>34.6
34.3
35.0
34.6
34.8
33.8
33.7
34.0
34.2
33.3
33.5
33.8
33.2
33.0
33.4
33.6
33.9
19
18
17
16
15
14
13
12
11
10
9
8
30°N
35°N
40°N

D. R. McLain provided additional data to extend the determination of the fronts for 1972 and 1973 in Fig. 1 beyond the research vessel tracks.

4. Distributions of June 1972 and June 1973

a. Salinity frontal structure

Of three meridional transects occupied in both June 1972 and June 1973 the central one, along 137°30′W, was chosen to show the salinity structure (Figs. 2 and 3). Both the subarctic and northern subtropical front form a geographic limit to their respective haloclines. The intervening waters of the transition zone show intermediate values of salinity varying about 34.0‰ and lack a horizontally continuous halocline. Waters on both sides of both fronts exhibit complicated structure including isolated pockets and layers of salinity extremes. Some of these features in the salinity structure are found to occur in some form or other in each or most of the vertical sections for the 5-year data series and hence apparently are structurally a part of the front and indicative of some complex scheme of frontal dynamics. They are described in the following in some detail. It should be noted that the STD-derived salinity contours of these and other figures were drawn to conform, as well, to the record of surface salinity recorded continuously along each track by the thermosalinograph.

There is a zonal band of water immediately south of the northern subtropical front that has higher salinity than waters to the north or south. Approaching from the north, the salinity shows an abrupt increase southward across the front, where it reaches a maximum, and then decreases away from the front to a minimum before increasing again at the subtropical front. This pattern of horizontal variation occurs throughout the upper 300 m including levels below the subtropical halocline. Within this band of high-salinity water the maximum salinity in the water column is found at intermediate levels, 70 to 150 m. In Figs. 2 and 3, the cross-sectional area of waters exceeding 34.8‰ within the subsurface maximum is small, but such waters also occur in the transects occupied to the east and west of those shown. This distribution appears as a core or multiple cores of high-salinity water that follow the south wall of the front.

There is a zonal band of water just north of the subarctic front in which salinities are a local minimum, appearing somewhat in mirrored contrast to the band of high salinity south of the northern subtropical front. Between the surface and 200 m salinities decrease northward through the subarctic front, reach a minimum, and increase slightly for a degree or so of latitude before decreasing farther north. The lowest-valued contours in this band are subsurface and form two diffuse cores separated by a layer of weakly defined salinity maximum. One result of the overall salinity pattern is that the lateral salinity gradients across the fronts are greater below the surface. Both the northern subtropical and subarctic fronts in the TC72 section along 137°30′W (Fig. 2) exhibited the largest station-to-station differences observed, exceeding 1.1‰ over 54 km at various intermediate levels within the upper 200 m of the northern subtropical front and 0.8‰ over 33 km at the subarctic front.

There are two relatively shallow layers where salinity is an extreme that are evident in all the transects. A layer where salinity is a maximum occurs near 140 m which is most evident where it projects northward from the northern subtropical front (Figs. 2 and 3). Kenyon (1978) noted this feature in his zonal section along 35°N. Kenyon's section may be entirely within the transition zone where it shows the shallow maximum to occur only between 133° and 142°W. A layer of minimum salinity, at 150 to 230 m, projects southward from the base of the subarctic front and often extends beneath the subtropical halocline. Although this minimum is continuous over most of the extent of these transects the values vary with latitude producing many closed contours. This salinity minimum extends over much of the eastern North Pacific (Reid, 1973; Tsuchiya, 1982).

The STD transects of TC72 did not extend across the subtropical front. In the 1973 survey one station fell south of this front at 137°30′W (Fig. 3) as did several along 140°W. Salinities exceed 35.0 or 35.1‰ on the southern side.

b. Thermal structure

Horizontal temperature gradients are coincident with the frontal salinity gradients. At the sea surface the gradient can be about 0.2°C km^{-1} with a total difference across the front being a modest 0.5 to 1.5°C. Below the seasonal thermocline the fronts appear as abrupt changes in depth of isotherms (Figs. 2 and 3). There are usually one or two isotherms (in unit °C) which are central to the large subsurface salinity gradients and which show the largest displacement in depth across each front. The 16 and 17°C isotherms are central to the northern subtropical front. The 14 and 15°C isotherms are likewise associated with the largest salinity gradients in the subarctic front. The same isotherms are associated in the same manner with the fronts in each of the sections for the other longitudes

FIG. 2. Vertical sections of salinity (‰), temperature (°C) and geostrophic velocity (cm s^{-1}) from cruise TC72 (June 1972) along 137°30′W. Only the upper 300 m is shown. Reference level for velocity is 500 db. Shaded flow is westward. Station spacing, although variable, is commonly 56 or 28 km; vertical exaggeration 1853. In this and other figures ST: subtropical front, NST: northern subtropical front and SA: subarctic front.

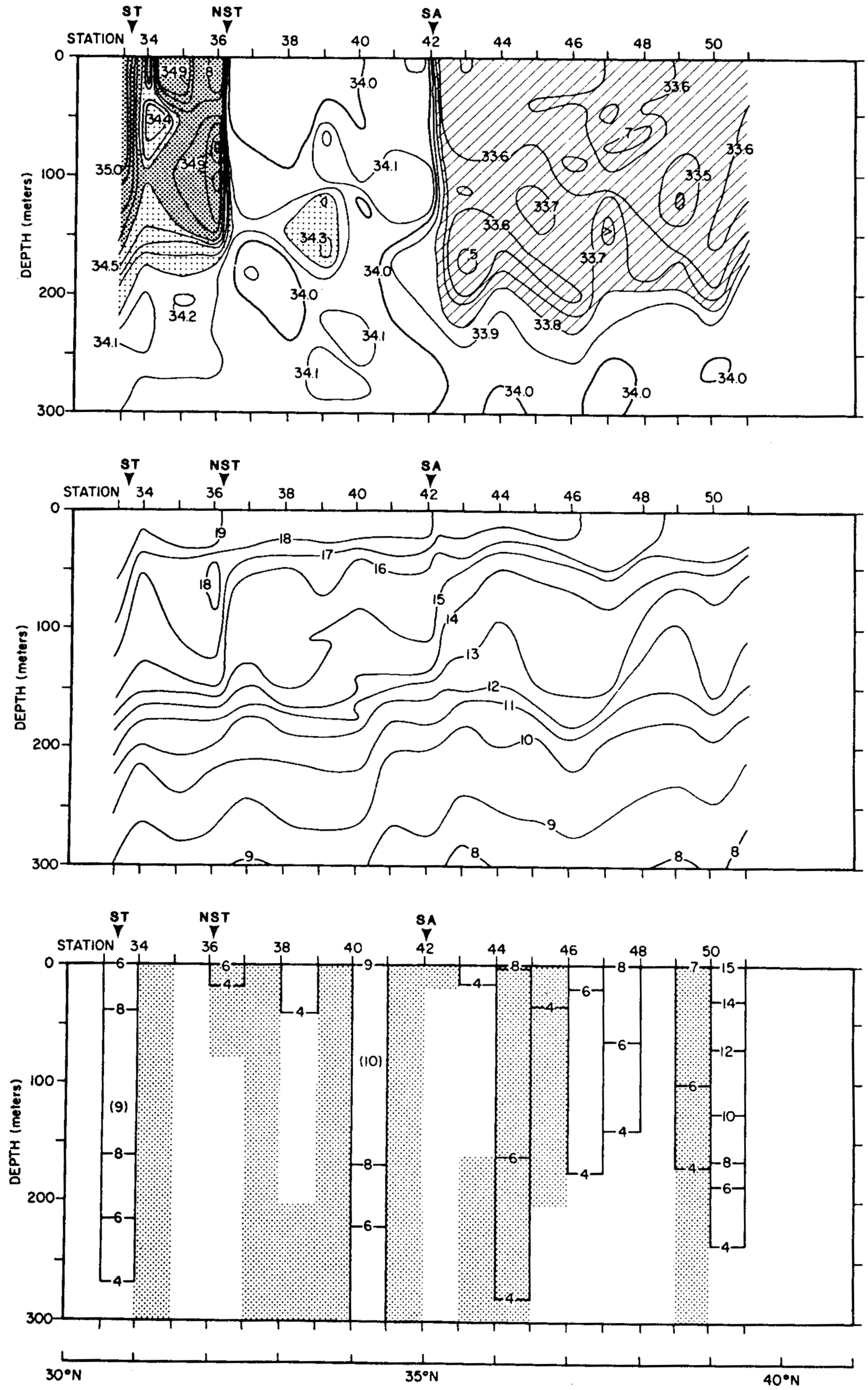


FIG. 3. Vertical sections of salinity, temperature and geostrophic velocity from cruise DSJ73 along 137°30′W.

and for the other years. The greatest subsurface horizontal temperature differences across the fronts are on the order of 2 to 3.5°C station-to-station, occurring at the same levels as the large subsurface salinity gradients. Temperature inversions appear in each domain above the haloclines and are salinity compensated.

c. Geostrophic velocity sections

During June 1972, geostrophic flow, primarily directed eastward, was concentrated about both fronts (Fig. 2; westward flow is shaded). Geostrophic velocities, computed for a reference level of 500 db, reached values of 10 to 14 cm s^{-1} about both the subarctic and northern subtropical fronts. Away from the fronts flow is generally weak or negligible. The higher velocities about the fronts extend to depths well below the halocline.

In contrast, velocities were negligible about the northern and central fronts along 137°30′W during June 1973 (Fig. 3). At these same fronts along 135° and 140°W flows were 6 to 7 cm s^{-1}. Higher velocities, 15 and 16 cm s^{-1} eastward, occurred on the southern side of the subtropical front 31°N, 140°W.

d. Maps of ocean characteristics

Maps of the distributions of surface salinity, temperature and dynamic height for TC72 are given in Fig. 4. The two fronts are shown clearly in the surface gradients of salinity (Fig. 4). (Between-station detail was provided by the trace from the continuous recording salinograph). The surface salinity gradients of the subtropical front fell outside the southwest corner of the station grid but were recorded in transit by the thermosalinograph. The subarctic front lies nearly zonally at 35°N between 140° and 137°30′W but loses definition at 135°W. The northern subtropical front has a southward loop in the midst of the survey and lies between 31° and 33°N. A meander, wavelength 180 km and amplitude 55 km, was found in the subtropical front during FRONTS 80 (Roden, 1981; Van Woert, 1982). The meander depicted in Fig. 8 has roughly twice the wavelength and amplitude. The outcropping of high-salinity cores appears at the southern edge of each front. The surface temperature for TC72 (Fig. 4, center) shows a related pattern, with higher temperatures associated with higher salinities and vice versa.

Both surface temperature and salinity fields resemble the topography of geopotential anomaly, 0/500 db (Fig. 4, right). Flow is faster near the fronts where the gradient of geopotential anomaly is greater. Here the flow is largely eastward (indicated by arrowheads). The tongues of relatively high and low salinity near 37°N are each centered in a flow pattern that would explain their presence by advection. Westward flow in the southwest corner may provide the waters with the characteristic dropoff in salinity from the peak values south of the northern subtropical front. Roden (1980) concluded from his observations that during winter (January), geostrophic flow and temperature and salinity fields show no association at the sea surface but have a strong association at 150 m. In these data, the association extends to the surface.

The layers of salinity extremes lie approximately on surfaces of uniform thermosteric anomaly (δ_T). Salinity is shown plotted on two surfaces of uniform δ_T that were chosen to lie within the layers of shallow maximum and minimum salinity (Fig. 5). The advantage of this presentation over others is that on surfaces of uniform δ_T the gradients of temperature and salinity exist solely because of water mass differences. On a surface of uniform depth these gradients are compounded by gradients that are a result of adjustment to baroclinic flow.

The shallow salinity maximum for TC72 closely follows the isanostere $\delta_T = 266$ cl t^{-1} ($\sigma_t = 25.32$) which lies mostly within a depth range of 90 to 170 meters. This surface, as is true of the other choice, lies deeper toward the south. The salinity on the surface where $\delta_T = 266$ has a greater range of values and larger gradients than at the sea surface (Fig. 5). The cores of high salinity project across the map as narrow tongues aligned with the geostrophic flow, as given by the field of acceleration potential (figure not shown but very similar to surface flow). The cores suggest swift and narrow jets of flow and counterflow, and thus demonstrate perhaps more clearly than geostrophy the character of the circulation. These narrow cores are often identified by the use of a single station along each section; thus, the resolution of these features is very limited. (The narrow band of salinity > 34.6‰ near 34°30′N (Fig. 5) is drawn dashed westward to 140°W based on a second occupation of this transect). The pattern of the salinity distribution on this surface is similar to that at the sea surface except that the features are enhanced. The largely subsurface core of high salinity projecting northeastwardly near 37°N is centered about this surface. The transition zone has a relative low in salinity (<34‰) projecting westward. The contours depicting each of these features is commensurate with the geostrophic flow.

The salinity minimum (TC72) that underlies the shallow maximum follows the isanostere $\delta_T = 220$ cl t^{-1} ($\sigma_t = 25.81$). This surface also falls within the subarctic halocline and extends below the subtropical halocline, lying mostly between 125 and 230 m. At $\delta_T = 220$ cl t^{-1}, the salinity gradients are considerably reduced and are shown contoured at an interval of 0.1‰ (Fig. 5). The same major features continue to be reflected in the salinity field at this level as above, including gradients at the location of the northern subtropical front.

5. The fronts in June 1974

The strong frontal regime observed in 1972 and 1973 was largely dissipated by June 1974 (Fig. 6). Each of

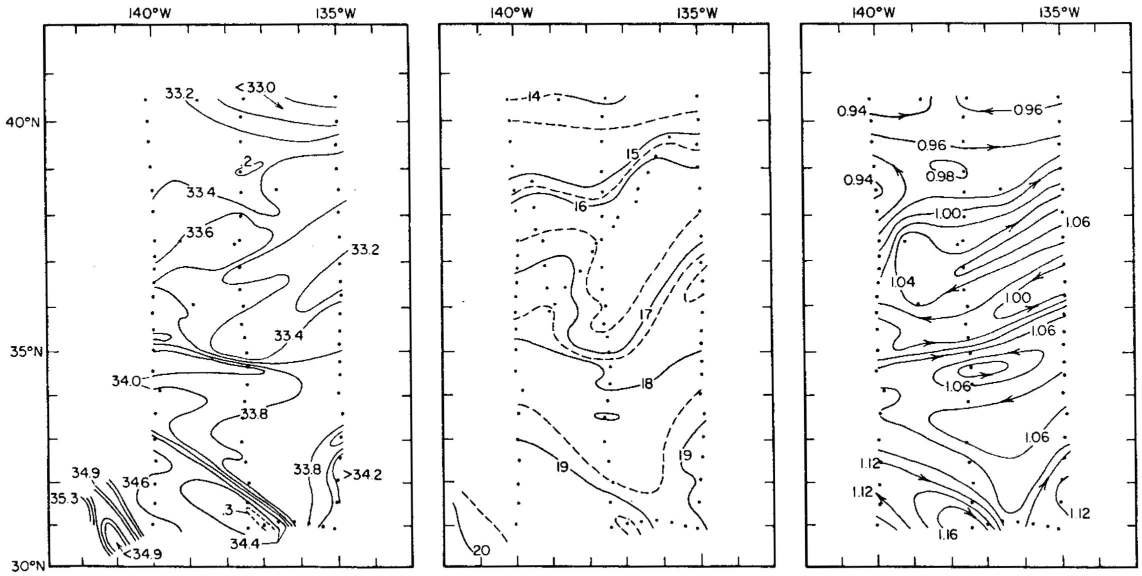


FIG. 4. Data from TC72. Left, sea surface salinity (‰) derived from continuous recording salinograph; center, sea surface temperature (°C, station data only); right, geopotential anomaly at the sea surface relative to 500 db (dynamic meters or 10 $m^2 s^{-2}$).

the fronts has penetrated farther northward than was the case in the preceding years. This crossing of the subtropical front gives it a double character, at 31° and 31°30′N. The northern subtropical front is well-defined by the salinity gradients but it has a smaller range of salinity and slightly lesser values, 34.1–34.4‰, than earlier. The range of temperature at mid-depth is also reduced. The band of high salinity with the subsurface maximum (about station 31) is still evident but it is no longer situated against the northern subtropical

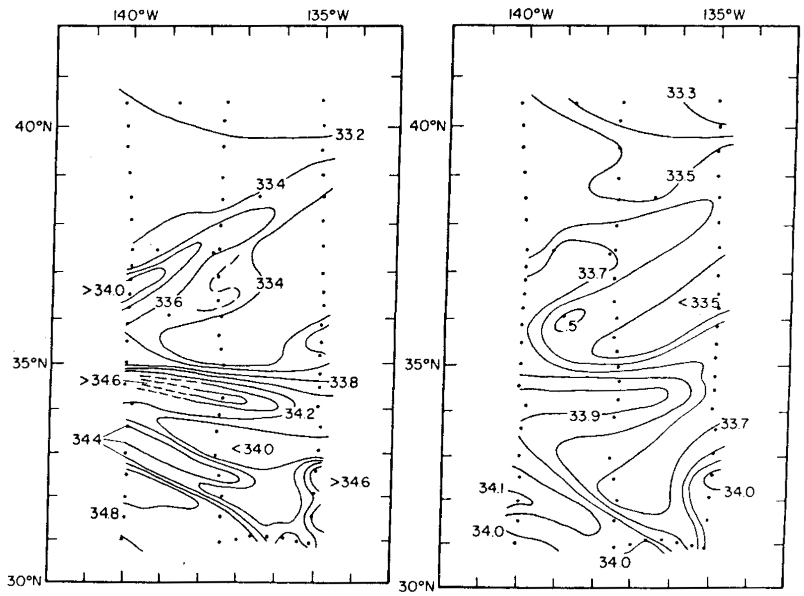


FIG. 5. Data from TC72. Left: salinity (‰) on the surface where δ_T = 266 cl/ton; right: salinity on the surface where δ_T = 220 cl/ton. Contour interval of salinity in the left panel is 0.2‰ and in the right panel, 0.1‰.

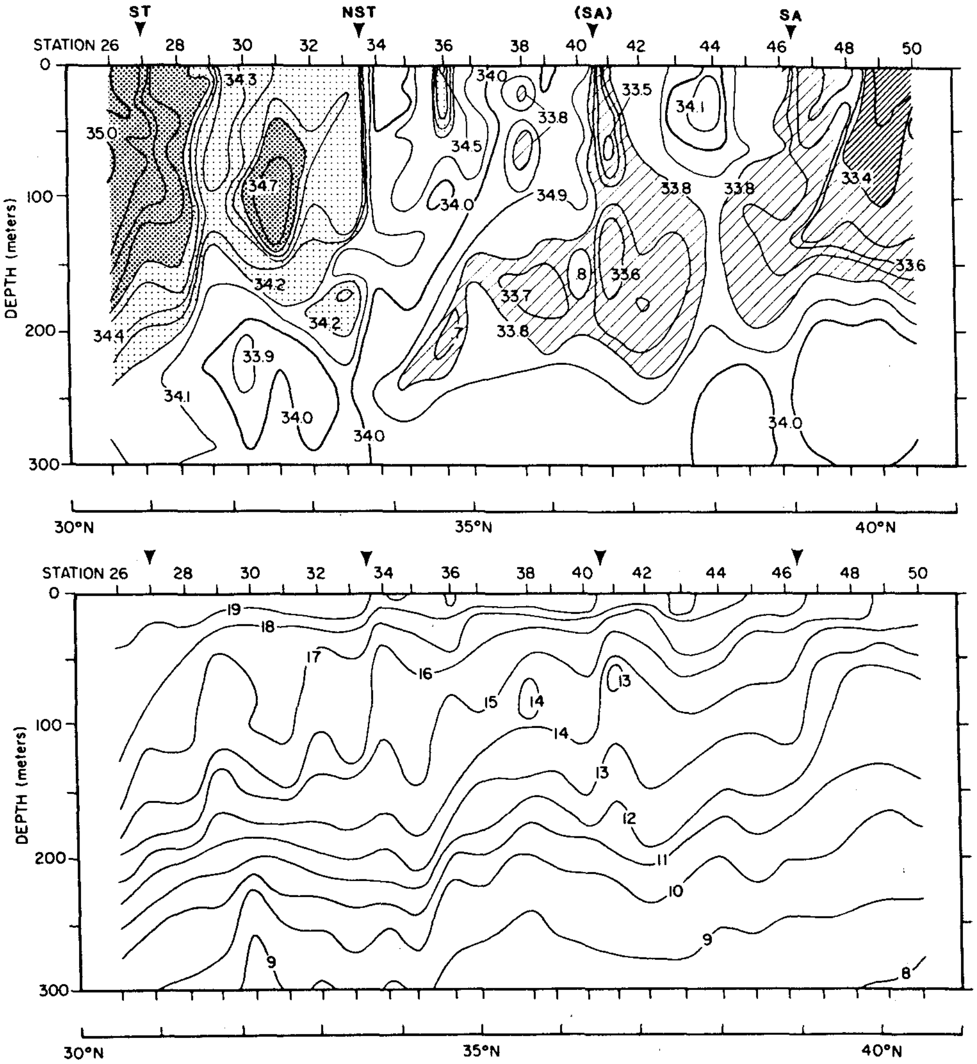


FIG. 6. Vertical sections of salinity and temperature along 137°30′W from cruise DSJ74 (June 1974). Station spacing is nominally 37 km.

front. The shallow salinity maximum within the transition zone is rudimentary (150 m, station 34). The largest differences from other years occur in the transition to subarctic waters. A weakened subarctic front is found at 39°N and a remnant of this front is found at 36°30′N. The range of temperature and salinity across this front is also reduced. At both manifestations of this front the shallow salinity minimum projects southward at about the level of the subarctic halocline. Additional shorter transects to the west and east of the 137°30′W transect (Fig. 1) confirm the foregoing description. Laurs and Lynn (1977) attribute a large difference in the behavior of albacore during the 1974 fishing operations conducted in cooperation with this survey to the poor development of the subarctic front. They noted that in 1972 and 1973, the albacore cued on or were indirectly influenced by the presence of these fronts during their springtime shoreward migration. In 1974 the corraling effect of a strong frontal regime was missing and the albacore spread rapidly throughout this region during June.

6. The fronts in June 1975

A single long transect of stations was taken in June 1975, from the Straits of San Juan de Fuca to off Hawaii

(Fig. 1). The three major fronts were clearly delineated in the distributions (not shown). The subarctic and northern subtropical fronts were found along 137°30'W at 36°20'N and 32°15'N, respectively. The subtropical front was found at 29°40'N, 138°20'W. The strength of frontal development resembled that for 1972 and 1973. Flow was strong and deep at the northern subtropical front. Eastward geostrophic velocity (relative to 1000 db) increased from 12 cm s^{-1} at the surface to 14 cm s^{-1} at 180 m, and remained above 10 cm s^{-1} to 340 m. Weak and westward flow was associated with a pocket of relatively lower-salinity water between the subtropical and northern subtropical fronts.

7. The fronts in June 1976

The 9-km station spacing used in observing the northern subtropical front during June 1976 provides a much improved resolution of the salinity and temperature structure (Fig. 7). In order to accommodate the higher resolution, the vertical sections in Fig. 7 and the remaining vertical sections for June 1976 are plotted at half the vertical exaggeration as was used in the previous figures. Salinity changes 0.8‰ in 36 km which matches most of the earlier findings. The band of high salinity along the southern wall of this front has values that exceed 34.8‰ and is very narrow. Salinities exceeding 34.7‰ at all levels within the band fall within a span of 18 km. There is a well-defined layer having a maximum in salinity that projects northward into the transition zone at 130 m. The northern subtropical front again lies near 32°N; thus, this position is common to four of the five years of observations.

The only westward geostrophic flow of significance in Fig. 7 (up to 14 cm s^{-1} calculated relative to 1000 db) occurs in the subtropical waters south of station 81. Eastward flow prevails from 60 km south of the northern subtropical front to 40 km north of it. The flow appears as bands having velocities of 20–35 cm s^{-1} interspersed with bands having negligible velocities. Geostrophic computations from such closely spaced stations are very sensitive to the resolution of the input measurements; i.e., distance between stations and the station-to-station difference in steric height. (For 9 km at this latitude, a difference of 2 dynamic cm in steric height gives 30 cm s^{-1}.) They are also affected by time variations in the density field, which are likely in such an energetic region. Stations 81–92 were completed in 21 hours, hence, less than 2 hours elapsed between any pair of stations for which velocities were calculated. The STD used had a history of a very steady calibration. Positions were determined with an OMEGA system by experienced navigators. Although reasonable estimates of errors in measured values could alter computed velocities by several centimeters per second or more, it would take compounding of multiple errors of unexpected magnitude to alter significantly the general pattern of velocity given in Fig. 7. The individual values of velocity may be subject to some error; however, it is evident that the characteristic bandedness in the flow about the fronts is difficult to dismiss. Neither is it unequivocally demonstrated, although the commonality of scale of salinity features and bands of flow is supportive.

Contours of surface salinity about the northern subtropical front based on the continuous record of the thermosalinograph also show its banded nature (Fig. 8). The filament of high salinity (>34.8‰) which lies to the south of the major gradient at 32°N is the surface manifestation of the prominent band of salinities extending to 150 m in Fig. 7. Unfortunately the ship's track did not cross the entire front to the west of 138°30'W; the salinity filament could not be identified there. However, a glancing pass into surface waters ex-

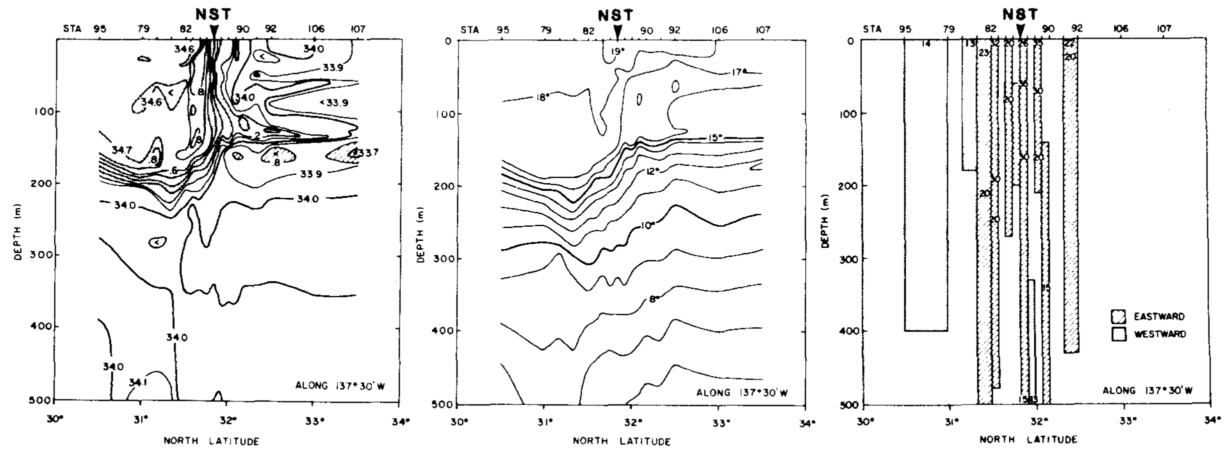


FIG. 7. Vertical sections of salinity, temperature and geostrophic velocity along 137°30'W for June 1976. Only the northern subtropical front is shown. Vertical exaggeration here and in Fig. 9 is 927, half of that used in previous figures. Station spacing is variable; at its least it is 9 km.

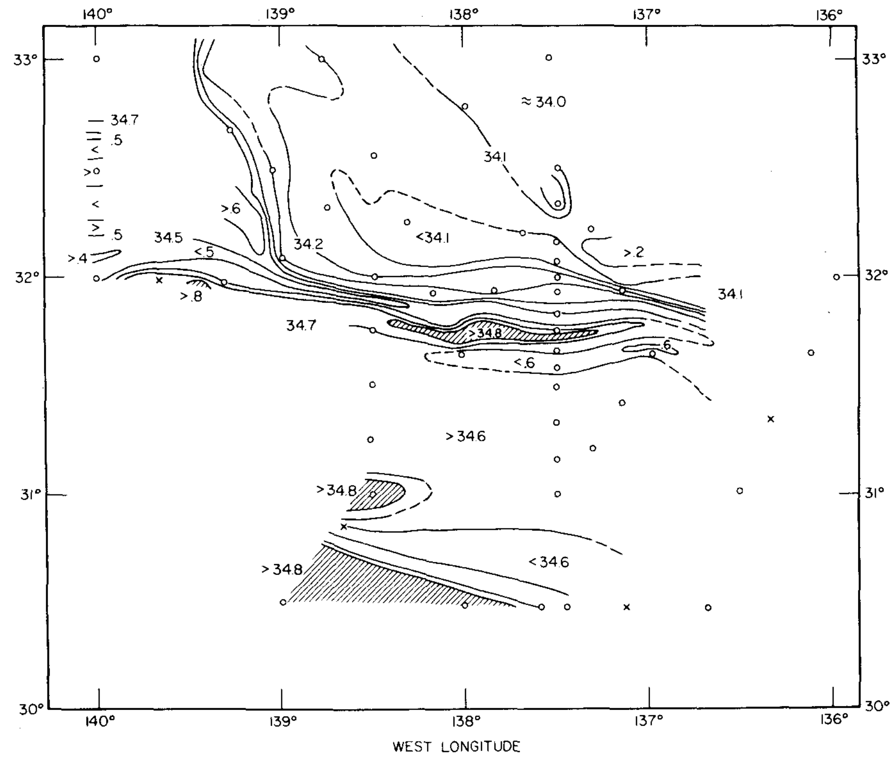


FIG. 8. Contours of surface salinity about the northern subtropical front derived from the thermosalinograph. The open circles and crosses are positions of STD and XBT casts, respectively.

ceeding 34.8‰ at 139°30′W indicates that this filament may extend over at least 250 km. The surface salinity trace of the easternmost line of stations (Fig. 8) taken on June 7 did not show the filament and neither did the first (northward) pass along 137°30′W on June 8. It was evident in frontal crossings after June 12 (and along 137°30′W on June 14). Thus, the surface appearance of the band is intermittent. As a subsurface feature it appears consistently in the 5-year data series. This is so despite the fact that its apparent width in 1976 shows that sometimes it could be aliased by the 36 to 54 km spacing between stations of the early surveys.

There are filaments of relative lows in Fig. 8, as well. One of these occurs immediately to the north of the front (<34.1‰) and another immediately to the south of the high-salinity filament (<34.6‰). This particular cross-frontal pattern was often seen in the surface salinity traces at both the northern subtropical and the subarctic fronts.

In 1976 the subarctic front, 34°30′N (Fig. 9), is farther south than in the observations of other years. In contrast to the comparatively large width, 500 km, of the transition zone in 1975, it was the narrowest, 250 km, in 1976. The vertical sections of Fig. 9 are for a transect near 138°30′W, set orthogonal to the front (aligned along 105°T). The 9-km station spacing used across the subarctic front greatly improves the resolution of the gradients. The front is well-developed and the features characteristic of the front are all in evidence. Eastward geostrophic velocities reach 25 cm s^{-1} between 30 and 70 m for the station pair (137–138) between which the largest lateral salinity gradient is found. Eastward flow prevails at stations immediately to the south of these stations, as well. On the low-salinity side of the frontal gradient the flow is westward, reaching 16 cm s^{-1}. The largest lateral shear appears to coincide with the front.

8. Comparison with Saur's data

Saur (1980) discussed aspects of the fronts and the transition zone in a study of surface temperature and salinity observations taken in a 9-year time series (repeated approximately every 2 or 3 weeks) along a great-circle route between Honolulu and San Francisco. This route crosses the survey region of the present study and is shown in Fig. 1. The period of the time series, 1966–70 and 1972–75, encompasses that of the surveys described herein with the exception of the last one. His

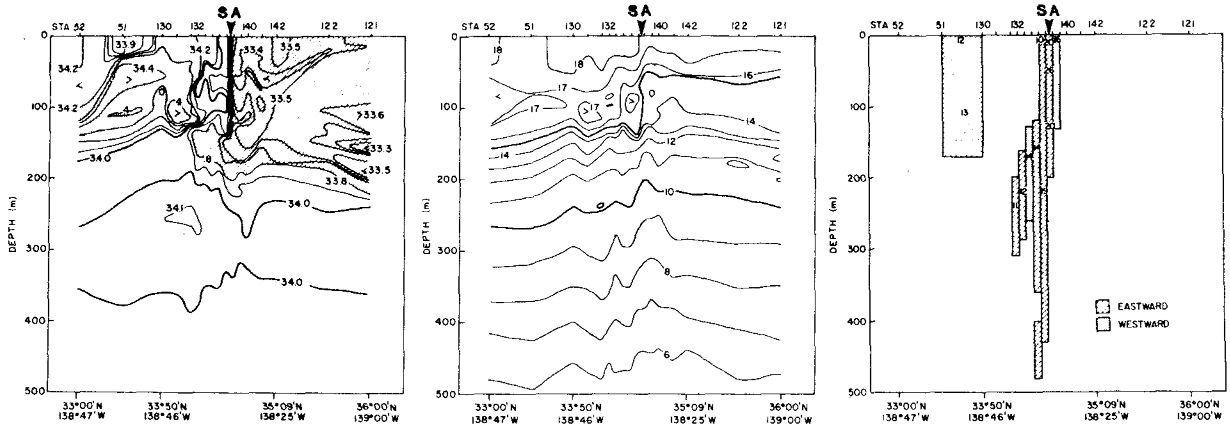


FIG. 9. Vertical sections of salinity, temperature and geostrophic velocity for a transect perpendicular to the subarctic frontal gradients: stations 132–142, spaced at 9 km, are aligned along 13°T and across 138.5°W. Additional nearby stations at larger intervals complete the figure.

study examines the temporal development and dissipation of fronts. The large distances between observations (usually 120 or 165 km) provide only a gross estimate of the surface gradients at any one time; however, this record produces temporally coherent patterns.

Saur finds the fronts to have been strongly developed during the latter part of 1972 and through the summer of 1973. Beginning in late 1973 the gradients weakened, and through 1974 the frontal pattern was confused although some continuity existed in the gradient that he identified as the subtropical front. By spring 1975 a stronger frontal system had reformed. The vertical sections presented herein match these events very well. Based primarily upon the positive correlation of temperature and salinity anomalies, Saur speculates that these changes, which are a part of longer term events, are primarily related to the variation in strength of circulation about the eastern limb of the subtropical gyre. Stronger-than-normal circulation produces negative temperature and salinity anomalies such as during the fall–winter of 1972/73. It also increases the magnitude of the surface gradients. The opposite occurs when the circulation is weaker than normal.

Saur finds that the salinity gradients migrate at a velocity of about 1.5–2.3 cm s^{-1} along the great-circle route to the southwest in the manner of annually forced baroclinic waves. They appear at the outer edge of the low-salinity California Current waters, and eventually dissipate in the high-salinity waters of the subtropics.

The detailed observations of this new series may offer some clues to the events revealed in the temporal surface records. There is evidence of mesoscale meanders that stretch zonally in which the stronger gradients are subsurface. The saline intrusion at 37°N depicted in Fig. 5 is a prominent case. If this feature grew and broke through to the surface (and downward through the halocline) it would produce a new manifestation of the subarctic front at a more northeastwardly position. The waters pinched off to the south would eventually mix to form the waters of intermediate characteristics found in the transition zone. Similar events might involve the two subtropical fronts to form the subsurface saline cores. If these features are peculiar to these longitudes, it may be that they are related to circumstances that are regional. The most obvious circumstance is the reorientation of the fronts from a zonal path to one that is southeasterly following the eastern limb of the large subtropical gyre.

9. Discussion and conclusions

The comparison of these observations, repeated each June for five years, reveals some idea of the variability in frontal development as well as the opposite—those aspects which appear to recur each year. Although Saur's analysis of biweekly observations of surface temperature and salinity supports the year-to-year differences seen in the vertical sections, it is clear that there are occurrences of spatial differences in frontal structure that are as large or larger than some of the annual differences. The estimation of temporal variability cannot be carried much beyond the generalities presented. The interesting finding is that in each of the five years the fronts are readily identifiable by a set of characteristics in every crossing and show well developed horizontal gradients in most of them. Some of these vertical sections, mostly constrained as they were to meridians, may have made oblique crossings to the meandering fronts. However, in every observation there are strong horizontal gradients of salinity, coincident with horizontal gradients of temperature, each front has its own range of salinity and temperature, and each has a definite association to halocline structure. There are complex features in the salinity distribution that are part of the frontal zone structure. These include layers, bands and cores of extremes. The shallow salinity minimum that projects southward from the base of the subarctic front has been described as a product of wind-driven Ekman convergence, sinking along the northern edge of the subarctic front in winter and spreading at depth because of a differing orientation of baroclinic flow at depth from that near the surface (Niiler and Reynolds, 1984). The shallow salinity maximum, most prominent where it projects northward from the northern subtropical front, has an appearance that suggests a similar generational source but neither the wind field nor the flow field is known to an adequate resolution to test this idea.

The association of geostrophic velocity with the fronts is seen to be quite variable in this dataset. There are instances when flow at the front appears to be negligible. However, for the most part, flow is stronger and extends deeper close about the fronts than elsewhere. Its variability may be greater about the subarctic front. In addition to the findings reported here, strong eastward flow directly associated with the subarctic front was found during a survey conducted aboard the R.V. *David Starr Jordan* in July 1971 (unpublished data). This front, found at 35°20′N, 135°W was well developed. In a crossing perpendicular to the front, having ten stations spaced at 9 km, there was a 28 km-wide band of eastward flow in excess of 10 cm s^{-1} (referencing 1000 db) that encompassed the entire horizontal gradient. The flow reached 42 cm s^{-1} on the high-salinity side of the front.

The bands and cores of salinity extremes show a close association with the geostrophic flow pattern. Because geostrophic velocity is computed for a pair of stations, and the extreme value of salinity within the core is described by a single station, the correspondence of the velocity field and such a feature may at times be ambiguous. However, an examination of the multiple occurrence of high-salinity cores shows that they are flowing eastward. In fact, all features that have locally high salinity are in regions of predominantly eastward flow. The westward flowing waters tend to be local low-salinity regions. An example of the latter event occurs between the subtropical front and the northern subtropical front.

There is an association of the vertical distribution of velocity and salinity. Where there is a subsurface core of high salinity or a subsurface northward protrusion of subtropical waters, there is a marked likelihood for a subsurface maximum velocity (eastward) to occur at or near the same level. The typical increase in subsurface velocity over the surface value is on the order of 1–2 cm s^{-1}.

The determination of velocity across fronts and about associated complex salinity structure by the method of geostrophic computation has obvious flaws. Among them are inadequate spatial resolution and poor adherence to the assumption of steady state. Despite these flaws the repetition of observations, taken as a whole, provides a reasonable description of the gross circulation and its effect upon the water mass structure. The fields of velocity, salinity and temperature suggest a confluence of flow toward the frontal zones. It is particularly evident that the eastward flowing band of high-salinity water on the southern side of the northern subtropical front must have its source to the south and west. The larger patterns in this circulation, such as large eddies, are not resolved in these data. The surveys do not encompass the source of cores and bands of salinity extremes.

This series of surveys reveals the existence of the northern subtropical front as a quasi-permanent feature. The repetition, year-to-year, of the particular ranges of temperature and salinity characteristics at the northern subtropical front, the differences of the ranges from those of the subtropical front and the simultaneous observations of both the subtropical front and this additional front show these fronts to be separate structures. The differences in ranges of characteristics and the physical separation are the same as seen in Roden's (1980) observations of two zonal fronts between 155 and 151°W.

There are additional published data that support the hypothesis that the northern subtropical front is a major feature over a large extent of the North Pacific like its counterparts to the north and south. A front observed at 30°30′N, 133°W (Roden, 1974) has the same characteristics. This front lies along a path described by the mean distribution of surface layer salinity (Robinson, 1976). The 133°W meridian nearly marks the easternmost extent of the waters that characterize the subtropical front. It lies near 27°30′N.

In the western North Pacific the ranges of temperature and salinity characteristics of the Kuroshio Extension front (Kawaii, 1972; Masuzawa, 1972) include those found at the northern subtropical front. The Kuroshio Extension front lies along the axis of the Kuroshio Extension Current which meanders between 33° and 36°N (Kawaii, 1972; Roden, 1982), a latitudinal range which includes the northern subtropical front (west of 150°W). The subtropical front in the western North Pacific is found at latitudes between 25°N to 30°N (White, Hasunuma, and Solomon, 1978).

In its path eastward, the Kuroshio Extension encounters large bathymetric features, the Shatsky Rise (163°E) and the Emperor Seamount Chain (170°W), which affect its course and diminish its strength (Roden et al., 1982; Levine and White, 1983). Roden et al. (1982) find that to the east of the seamounts the Kuroshio Extension current widens three-fold and appears to be poorly defined there. Maps of the modulus of horizontal temperature gradient at the 300-m level reveal multiple branchings of the Kuroshio Extension Current system about the major bathymetric features (Levine and White, 1983). Of the resulting downstream bands of thermal gradient one continues eastward along a zone about 35°N to the vicinity of 165°W where the horizontal thermal gradient at 300 m weakens below their defining limits. Levine and White labeled this the Kuroshio Extension front. In the eastern North Pacific the water-mass frontal structure is above 150 m and the baroclinicity is weaker than in the west. Hence, the modulus of temperature gradient at 300 m does not provide the means to reveal its eastward extent beyond 165°W.

Observations that address the zonal continuity of the thermohaline frontal structure of the Kuroshio Extension east of the seamounts are vertical sections of temperature and salinity along meridians 178° and 158°W, Figs. 1 and 2 of Roden (1970). These sections, drawn from closely spaced CTD casts for April, show frontal structure above 150 m at 36°N, 178°W and at 34°N, 158°W. Both features involve the same isolines of temperature and salinity as those characterizing the Kuroshio Extension and northern subtropical fronts. Taken as a whole, this body of evidence shows that the underlying thermohaline structure of the northern subtropical front has its genesis in the Kuroshio Extension current and, although largely weakened about the Emperor Seamount Chain, it is continuous or quasi-continuous across the North Pacific reaching as far east as 133°W. In various regions and during various periods these horizontal gradients are greatly enhanced by frontogenetic processes described by Roden (1980) and Niiler and Reynolds (1984).

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