The Characterization of a Midocean Front with a Doppler Shear Profiler and a Thermistor Chain

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ABSTRACT

It is demonstrated that a data set collected by the combined use of a Doppler shear profiler and a towed thermistor chain can provide a detailed description of a midocean near-surface front. The front described was encountered in the subtropical convergence zone in the Sargasso Sea, near 31°N and 72°W, in July 1981. A cross-front temperature change of 4°C in 29 km (at a depth of 40 m) was measured with the cooler water, indicating a highly convoluted local structure, occurring on the south side of the front. The temperature difference was not apparent at the surface as the front was covered with a relatively isothermal cap in the form of a ~25 m thick seasonal mixed layer.

The Doppler data indicated that the frontal interface ran from northeast (39°T) to southwest (219°T) with southwesterly flow of up to 81 cm s⁻¹ occurring north of the front. The front was convergent with a net cross-front flow of 16 cm s⁻¹. The frontal interface was delineated by a shear zone with a difference of horizontal velocity of ~50 cm s⁻¹ occurring over a depth interval of ~40 m (shear ~0.0125 S⁻¹) that sloped down from the southeast toward the northwest. The slope of the frontal interface is estimated by several methods to have been ~ -0.0035 = -1/290. The shear zone coincided with sloping zones of high temperature gradient and of low Richardson number.

Comparing the velocity and density fields geostrophically, by use of the Margules equation and the thermal wind equation, proved successful over the broad area of the front. Small-scale features were present in both the velocity and temperature which probably reflect internal wave activity.

1. Introduction

During the summer of 1981, in the Sargasso Sea, while testing a new version of a Thermistor Chain (TC) and evaluating a Doppler shear profiler (DSP), a near-surface front was encountered. This event offered an excellent opportunity to compare data from two advanced data systems and to describe an intense oceanic feature. In particular, it allowed an oceanic evaluation of an acoustic current profiling system’s ability to describe the flow in a feature where flow is the dominant characteristic and where flow has usually been inferred from density (usually temperature) data.

Near-surface oceanic fronts have usually been described in terms of their temperature structure. Early works relied on bathythermographs with some surface measurements of temperature and salinity, e.g. Cromwell and Reid (1956), Knauss (1957), Voorhis and Hersey (1964) and Katz (1969). As profiling CTDs became available, they added information about the salinity structure; e.g., Johannessen et al. (1977); Roden (1980). Occasionally towed thermistor chains were used; e.g., Voorhis and Hersey (1964) and Johannessen et al. (1977). Also, satellite infrared imagery has been used to define the surface characteristics of fronts, e.g., Legeckis (1978) and Huh et al. (1978).

More particularly, there have been descriptions of near-surface fronts in the Sargasso Sea, e.g., Katz (1969) and Voorhis (1969). These descriptions, mainly of the temperature field, indicate that the fronts generally align east–west with the colder water to the north and the dominant flow, in the warmer water, toward the east. An interesting feature of the front described herein is that the cooler water is on the southern side with the dominant flow on the northern side and toward the southwest. Meanders in frontal interfaces have been observed previously (e.g., Voorhis, 1969); these measurements may have been taken in a large meander.

Direct current measurements in frontal zones are rare. Some early temperature surveys also included Geomagnetic Electrokinetograph (GEK) data, e.g., Knauss (1957) and Voorhis and Hersey (1964). Moored current meters have recorded data in the Oregon upwelling front, e.g., Collins et al. (1968). There has been an effort made in the oceanographic community over the last decade to develop profiling current/shear equipment [e.g., Yvette (Evans et al., 1979); Pegasus (Rossby and Halkin, 1982); and XCPs (Drever and Sanford, 1980)] but the only set of detailed current profiles across an oceanic front found in the literature is Kunze and Sanford (1984). They used expendable
current profilers (XCPs) to describe near-inertial internal waves in the subtropical convergence zone of the North Pacific.

Numerous attempts to model the flow field based on the density (temperature) field have been made; e.g., Roden (1976), Garvine (1974, 1979a, b, 1980), Kao (1980, 1981), and Kao and Cheney (1982). While these attempts are excellent, an extensive ground truth data base has been missing.

The purpose of this paper is to demonstrate how such a data set can be obtained, with the key to this data set being the merging of data from two instrument systems: a high resolution thermistor chain and an acoustic current profiler. Each system, by itself, is a powerful descriptive tool, and, when combined, can provide an extremely illuminating and detailed picture of the upper ocean.

2. Basic data set

During the night of 19 July 1981 in the subtropical convergence zone in the Sargasso Sea (near 31°N, 72°W), equipment was being tested when a near-surface front was crossed. The ship was steaming at a speed of ~5 kts (2.6 m s⁻¹) toward the north while towing a thermistor chain (TC) and operating a Doppler shear profiler (DSP). The front was evident in the TC output as a marked change in temperature at 40 m (ΔT ~ 4°C in 29 km) and in the DSP output by the presence of a strong vertical shear zone (ΔU ~ 50 cm s⁻¹ in 40 m = 0.0125 s⁻¹).

Figure 1 shows the instrument configuration used. The thermistor chain (Morris et al., 1983; and Dugan et al., 1980) consisted of 180 thermistors deployed at ½ meter increments along the chain from the surface to 90 meters. For the purposes of this presentation the original 20 Hz data has been reduced and interpolated down to 2½ minute (0.42 Km) averages at 2 meter depth increments. (These averages are accurate to better than 0.01°C).

The DSP system used was an interim Ametek/Straza system (Hill and Trump, 1982). The system consists of four acoustic transmitters/receivers mounted on the bottom of the ship in a Janus array. At a sampling rate of 0.62 s, a 300 KHz pulse is transmitted simultaneously along four narrow (3°) beams. The volume reverberation return signal is sampled every 4.8 ms and analyzed for its Doppler shift. This yields four independent sets of range-gated ship-water relative velocities that are combined with the ship's heading, pitch, and roll data to obtain an estimate of the relative velocities between the ship and up to 31 water layers. For this presentation 5 minute (0.78 km) average profiles of 27 velocity estimates, at depth intervals of 3.34 meters (centered on depths from 23.3 m to 110 m), are used. These estimates are accurate to better than 1 cm s⁻¹. To convert relative estimates into absolute estimates the DSP data were combined with Loran-C estimates of ship's motion. The Loran-C estimates were not as accurate as the DSP estimates but when both the Loran-C and DSP data were filtered with a symmetric-cosine-tapered filter, designed to remove variations of periods less than 20 minutes, the resultant absolute velocity estimates are felt to be accurate to between 1 and 2 cm s⁻¹.

![Diagram of instrument configuration](image)

**Fig. 1.** Configuration and depth ranges of instruments used: the Doppler Shear Profiler (DSP), the Thermistor Chain (TC), and a CTD. Loran-C data were also recorded and used to describe the ship's motion.
Figure 1 indicates the geometry and depth ranges of these two systems. It also indicates the depth range of some CTD data (0~200 m) that is used to estimate the salinity variation across the front. Unfortunately, the CTD data were not taken during the crossing, but three days later when the ship returned to the area. Two casts were selected that best represented the temperature structure, found in the TC data, associated with the water north and south of the frontal interface.

3. Current (DSP) data

Figure 2 is a combination of a ship's track and a stick diagram where the base of each "stick" is the five-minute Loran-C position and the length and direction of each stick represents the average absolute water velocity vector at 45 m.

There are several pieces of information embedded in this figure. Since the ship was maintaining a specific heading (due north) rather than a specific course, the actual track is affected by the surface drift. In the southern ¼ of the track the ship is being pushed at a slow but definite rate to the west. The surface effect of the front can be seen quite clearly in the change in ship's drift encountered at ~15 km distance north on the plot scale. It appears that the surface current is steady both north and south of the front with about three times the westward magnitude north of the front. This change of velocity is mirrored in the absolute water velocity estimates at 45 m. The vector magnitudes indicate an interesting minimum at the frontal interface and a wave-like pattern north of the front. The vector directions indicate a convergence at the front with the southern vectors being more westward than the northern vectors. Using Garvine's models (1974, 1979a, b, 1980) it is estimated that the direction of the front is parallel to the average velocity vectors in the warmer water to the north of the front, and runs from 39°T (~NE) toward 219° (~SW). Therefore, the ship, traveling on an average course of 349°T, intersected the front at an angle of 40° to the cross-front direction.

The general situation for Sargasso Sea fronts is for the cooler water to be on the north side of the front. Therefore, the expected flow is toward the east with the stronger flows on the southern side of the front. This situation is reversed here. This front was serendipitously encountered during an equipment test, so that sufficient supporting synoptic data as to the lateral extent and shape of this front are lacking. It can best be hypothesized that this encounter represents a strong meander in a normal frontal zone that has turned back onto itself in an "S" shaped curve. Later, when the temperature fields are displayed, it will be clear that the warmer water is indeed on the northern side of the front.

In this paper, a frontal coordinate system is used where the normal geographical coordinates are rotated 51° counter-clockwise. The along-front distance, $x$, and velocity, $U$, components are positive toward 39°T, while $Y$ and $V$, the cross-front components, are positive toward 309°T. This coordinate system is displayed in Fig. 2.

Figure 3 shows three profiles of the absolute velocities in frontal coordinates. These profiles are separated by 18.75 km in the ship's track distance (2 h). The locations of these profiles are indicated in Fig. 2. In the $U$ (along-front) component the profiles from north and south of the front are very similar except for a 60 cm s⁻¹ offset. The profile in the front shows the vertical shear, 50 cm s⁻¹ in 40 m (~0.0125 s⁻¹) that is associated with the frontal interface. The $V$ (cross-front) component does not show a great deal of vertical structure in any of the profiles but a 10–15 cm s⁻¹ convergence is quite clear between the “north of front” and “south of front” profiles.
Figure 4 is a plot of successive ten-min average $U$ and $V$ profiles along the 50-km ship's track ($5\frac{1}{2}$ h) of the front crossing. Contained in this figure, with their positions indicated, are the three pairs of profiles used in Fig. 3. For the $U$ component, the offset described in Fig. 3 is evident in the compaction of the profiles, and the frontal interface is clearly indicated by the sloping shear zone. The $V$ component does show a feature that can be associated with the frontal interface but its character is unclear.

Figures 5 and 6 are contour plots of the two velocity components in frontal coordinates. Figure 5 displays the $U$ component which clearly shows the frontal zone. If the area between the $-30$ cm s$^{-1}$ and $-55$ cm s$^{-1}$ isotachs is arbitrarily termed the frontal zone then it slants down from southeast to northwest, along the ship's track, at an average rate of 86.7 m in 26.4 km or $-0.0033 = 1/300$ (obtained by connecting the midpoints of the 30–55 cm s$^{-1}$ zones at 23.3 and 110 m). The $U$ component extremes are $-81$ cm s$^{-1}$ at
ship's distance = 37.5 km and depth = 53.3 m, and 
-6 cm s\(^{-1}\) at ship's distance = 6 km and depth = 103.3 
m. Note that the slopes calculated above are misleading 
as the distance scale is measured along the ship's track 
which intersects the front at an angle of 40° to the 
cross-front direction. Figure 6 shows the contour plot 
of the \(V\) component. At the end points (distance = 0 
and 50 km) the figure indicates a fairly smooth con-
vergence at all depths but the pattern is more compli-
cated in the frontal zone where alternating cells of pos-
tive and negative velocities are found. For the four 
cells visible near the frontal zone, the two positive cells 
appear to lie above the zone and the two negative cells 
lie below the zone. What these cells represent is unclear 
but they probably reflect enhanced inertial wave activ-
ity at the frontal interface.

A more precise summary of the DSP data is made 
by projecting the ship's track onto the \(Y\) coordinate.
This is accomplished by multiplying the distance scale by \( \cos 40^\circ \). The extreme values of \( U ( -6 \text{ cm s}^{-1} \) and \(-81 \text{ cm s}^{-1} \) are located at \( Y = 4.6 \text{ km} \) and \( 28.7 \text{ km}, \) respectively, for a horizontal separation of \( 24.1 \text{ km}. \) The depths are \( 103.3 \text{ m} \) and \( 53.3 \text{ m}, \) respectively, for a vertical separation of \( 50.0 \text{ m}. \) The average \( V \) component in the first three profiles \( (\Delta Y = 1.8 \text{ km}) \) is \( 14.7 \text{ cm s}^{-1} \) while the average in the last three profiles is \( -1.4 \text{ cm s}^{-1} \) for an average convergence of \( 16.1 \text{ cm s}^{-1}. \) The estimation of the frontal slope is a bit more subjective. The frontal zone slope of \(-0.0033, \) described above, becomes \(-0.0043 = -1/230. \) This slope connects the midpoints of the \( 30-55 \text{ cm s}^{-1} \) zone at depths of \( 23.3 \text{ m} \) and \( 110 \text{ m}. \) Inspection indicates the front has a shallower slope in the center region and the midpoints of the zone at \( 40 \text{ m} \) and \( 90 \text{ m} \) are used a slope of \(-0.0032 = -1/310 \) results.

The frontal zone as defined above, the transition from \( 30 \text{ to } 55 \text{ cm s}^{-1}, \) has an average thickness of \( 18.1 \text{ m} \) and an average horizontal width \( (\Delta Y) \) of \( 5.04 \text{ km}. \) The absolute numbers are indicative at best, but their ratio is more interesting. In this case, it is \(-0.0036 \) or \(-1/280 \) which is in between the two frontal slope estimates made previously.

4. Density (temperature) data

So far the description of this front has been derived solely from the DSP data. This is quite unusual because density (temperature) data, being so much easier to obtain, are the more common descriptor. Using the temperature field alone presents a problem in that there are often other temperature structures; e.g., a vertical temperature gradient that the frontal gradients are imposed upon. That is the case here. Figure 7 shows the three TC temperature profiles associated with the three velocity profiles shown in Fig. 3. The maximum temperature difference is \( \sim 4^\circ \text{C} \) at \( \sim 40 \text{ m}, \) but there is less than \( 0.4^\circ \text{C} \) difference in the upper 15 meters; i.e., there is a relatively isothermal cap on top of the frontal temperature structure. Remember that the velocity structure does continue to the surface as indicated by the change in ships drift in Fig. 2. Figure 8 then presents the thermistor chain (TC) data as a contour plot on the same scales as Figs. 5 and 6. The relatively isothermal cap is evident, but the front is clearly defined as a slanting zone of high temperature gradient that coincides with the DSP frontal zone.

Careful examination of Fig. 8 hints at the presence of vertical motion. From the ship's distance 7–21 km, the surface waters are cooler as if the water at 20 mm were upwelled to the surface. Similarly, there is the suggestion of downwelling, shown by dips in the isotherms along the top of the frontal interface. These observations are consistent with the DSP data in that a \( \sim 16 \text{ cm s}^{-1} \) convergence is indicated that generally result in vertical flows to maintain continuity. To estimate a vertical velocity, assume a \( 16 \text{ cm s}^{-1} \) convergence over a depth range of \( 100 \text{ m} \) that is balanced by a vertical downwelling of \( 8 \text{ km}. \) This yields an approximate vertical velocity of \( 0.2 \text{ cm s}^{-1}, \) which is less than the resolution of the DSP.

The isotherms in Fig. 8 are not straight, but show “wave-like” characteristics that are probably the result of internal waves. Frontal zones are thought to be areas of concentrated internal wave activity so their presence is not surprising.

To make a quantitative comparison between the temperature and velocity fields, some temperature-density relationship must be used. As mentioned previously, two CTD casts, taken three days after the front crossing, were selected to estimate the water characteristics north and south of the front. These casts indicate that the water north of the front was slightly fresher, but that the temperature differences dominate the density differences as the maximum salinity difference at any given temperature is only \( 0.19\% \) compared to maximum temperature difference of \( 4^\circ \text{C}. \) Therefore, a single temperature-to-density function was used to estimate \( \sigma_T. \)

\[1 \text{ At } T = 23^\circ \text{ and } S = 36.4\%, \frac{d\sigma_T}{dT} \text{ and } \frac{d\sigma_T}{dS} \text{ indicate that a temperature change of } 4^\circ \text{C results in a } \sigma_T \text{ change of } -1.16 \text{ while a salinity change of } -0.19\% \text{ results in a } \sigma_T \text{ change of } -0.14. \]
5. Temperature–velocity fields comparison

To make a comparison between the velocity and density fields, the temperature gradients perpendicular to the front and geostrophy are used to estimate current shears which can be compared to the Doppler data. To get the temperature gradients, the ship’s distance scale is again reduced by \( \cos 40^\circ \). The simplest comparison will be to use the Margules equation, a special case of geostrophy, that estimates the frontal slope from the density and velocity differences across a front (Von Arx, 1962):

\[
\text{slope} = \frac{f}{g} \frac{\Delta (\rho U)}{\Delta \rho}
\]

Here \( f \) is the coriolis parameter \((=0.766 \times 10^{-4} \text{ s}^{-1})\), \( g \) is the acceleration of gravity \((=9.81 \text{ m s}^{-1})\), \( \rho \) is the density of seawater \((=1000 + \sigma_T \text{ kg m}^{-3})\), and \( U \) the velocity component parallel to the front. The densities and velocities are taken at a depth of \(~50 \text{ m} \) near the depth of the maximum horizontal temperature difference. For the \( U \) component the velocity difference is \(-61 \text{ cm s}^{-1} \) \((-20 \text{ and } -81 \text{ cm s}^{-1})\), and the temperature difference is \(~4^\circ \text{C} \) \((~21^\circ \text{C} \) and \(~25^\circ \text{C})\) for a density difference of \(-1.3 \text{ kg m}^{-3} \) (1025.8 and 1024.5 kg m\(^{-3}\)). When these numbers are put into the Margules equation the slope estimate is \(-0.0037 \) or \(-1/270 \) which compares well to the 40 to 90 m estimate of the frontal zone slope based on DSP data \((-0.0032 = -1/310)\) and the aspect ratio of the DSP defined frontal zone \(-0.0036 = -1/280\). All three of these estimates are somewhat subjective, but their agreement is encouraging as they were estimated independently of each other.

The thermal wind equation provides a slightly more comprehensive comparison between the DSP and TC data than the Margules equation. For this, the entire overlapping data window will be used, from \( Z = 23.3 \) to 90 m \((\Delta Z = 66.7 \text{ m})\) and over the ship’s distance of 50 km \((\Delta Y = 50 \text{ km} \times \cos 40^\circ = 38.3 \text{ km})\). The thermal wind equation solved for \( \Delta U \) (after Pond and Pickard, 1978) is:

\[
\Delta U = \frac{g}{\rho f} \frac{\Delta Z}{\Delta Y} \frac{\Delta \rho}{\Delta Z}
\]

where \( g, f, \Delta Z, \text{ and } \Delta Y \) have been described previously, \( \rho = 1025.13 \) \((T = 23.03^\circ \text{C})\), and \( \Delta \rho = -1.16 \text{ kg m}^{-3} \) \((1024.61-1025.71 \text{ kg m}^{-3})\). Using these values an estimate for \( \Delta U \) of \(-25.2 \text{ cm s}^{-1} \) is calculated which compares well to the average \( \Delta U \), from the DSP data, of \(-22.8 \text{ cm s}^{-1} \). Unfortunately an attempt to compare the thermal wind equation to the DSP data on finer horizontal scales proved unsuccessful. It is felt that the internal wave field and small variations in the depths attributed to the thermistors, sufficiently confused the thermal wind calculations so as to make them unrealistic.

The presence of both density and velocity data on the 50 km by 66.7 m grid suggests a Richardson Number (Ri) calculation; Ri is defined (Pond and Pickard, 1978) as:

\[
\text{Ri} = \frac{N^2}{[\partial(U^2 + V^2)^{1/2}/\partial Z]^2}
\]

where \( N^2 \) is the Brunt–Väisälä frequency and \([\partial(U^2 + V^2)^{1/2}/\partial Z] \) the vertical derivative of flow speed. An equation for \( N^2 \) in terms of \( T \) and \( \partial T/\partial Z \) is derived from the relation of \( \sigma_T(T) \). Therefore, Ri is a function
of $T$, $\partial T/\partial Z$, and $\partial (U^2 + V^2)^{1/2}/\partial Z$. The grid points used are defined by the DSP data and the temperature data are interpolated onto this grid. For a given grid point, $T$ is the temperature of that point, $\partial T/\partial Z$ is estimated by using a central difference of the temperature at one point above the grid point minus the temperature one point below divided by twice the vertical grid point separation (6.67 m), and $\partial (U^2 + V^2)^{1/2}/\partial Z$ is estimated the same way with DSP data. The results were too complicated for contouring, so Fig. 9 indicates only those grid points where $\text{Ri}$ was between 0 and 1 (squares) and between 1 and 2 (plus signs).

The main feature of this presentation is that the lower values of $\text{Ri}$ line up along the frontal interface. Also, the lowest values are concentrated at depths below 60 meters, with the lowest value of 0.4 found at ship's distance $= 29.7$ km and $Z = 76.7$ m. This observation reflects the fact which is clear in Fig. 7, that between 20.3 and $\sim 40$ m, the vertical temperature gradient is a combination of the frontal gradient and the gradient associated with the seasonal thermocline which implies larger values of $N$ and therefore of $\text{Ri}$.

6. Conclusion

Ocean fronts are the intersection between two water masses with different density and flow fields. In the past, frontal zones have been described mainly in terms of the density field with the flow field being inferred. This data set is special in that it is primarily of the flow field. It describes the flow field to a degree of detail that has rarely been attempted.

In this particular data set two aspects are missing. In the DSP data set, little mention has been made of the vertical velocity field. Attempts were made that failed for two reasons: The expected vertical frontal velocities are below the resolution of the system. Also, the Doppler system measures the velocities of scatterers embedded in sonified volumes and these scatterers are assumed passive. Unfortunately, this front was crossed near sunrise and the vertical velocities measured are felt to relate more to the vertical migration of organisms than to frontal flow. Also, since only a single pass was made across the front and since inertial energy is best estimated by comparing the velocity field at a time interval of $\frac{1}{2}$ inertial period, no attempt was made to separate the inertial and geostrophic components of the flow field.

Examination of Figs. 4, 5, and 6 reveals a vast amount of detail not discussed in frontal models. The changing slope of the frontal zone (Fig. 5), the existence of cells of motion in the $V$ component (Fig. 6), and the wiggles present in all the velocity profiles (Fig. 4) and isotherms (Fig. 8) are examples of the detail a combined acoustic-temperature system can provide.

When discussing the small-scale details in this DSP data, it should be noted that it was collected by an interim test instrument and averaged over a relatively long (5 min $\sim 0.78$ km) period designed to portray the large-scale features.
In conclusion, an acoustic current profiling system can be used by itself, but particularly in conjunction with density field instruments like a thermistor chain to provide amazingly detailed views of small-scale oceanic flow features. The picture presented here of a near-surface front both agrees well with conceptual models of fronts and provides details that should improve these models.

REFERENCES


