Fine Structure in the Antarctic Polar Front Zone: Its Characteristics and Possible Relationship to Internal Waves

DANIEL T. GEORGI

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

Temperature and salinity data from a repeated salinity-temperature-depth station and temperature profiles from three expendable bathythermograph experiments are used to investigate both the spatial and the temporal characteristics of fine structure observed in the Antarctic Polar Front Zone. The fine structure was found to evolve considerably on time scales of 1 hour and less. From an experiment designed to elucidate the spatial scales of the fine structure, a marked anisotropy was revealed, suggesting that the temperature structures were elongated filaments aligned with the front. The data were also used to investigate the possibility that internal waves generate the observed fine structure. On the basis of the temperature-salinity correlation of the fine structure and the extremely large required vertical displacements the vertical motions of internal waves can be ruled out as the primary cause of the fine structure. Because the Antarctic Polar Front Zone is a region of high horizontal temperature and salinity gradients and because there is an observed increase at one-half inertial period in drop-lagged coherences, it is hypothesized that the low-frequency nearly horizontal internal wave motions are generating the observed fine structure. However, in the particular case where direct observations of the vertical motions of internal waves are available, assuming that the relationship between vertical and horizontal displacements prescribed by the Garrett and Munk (1975) model holds, horizontal displacements are also ruled out as the sole source of the observed fine structure, yielding neither enough total variance nor the expected spectral shape; thus much of the observed variability may be attributed to temperature fine structure of noninternal wave origin.

1. INTRODUCTION

Gordon et al. [1974] and *Gordon* [1975*a*, *b*] drew attention to the prominent interleaving of temperature and salinity in the Antarctic Polar Front Zone. The presence of thermohaline fine structure, 10- to 100-m vertical scales, within the Polar Front Zone in the Southern Ocean has been detailed by *Georgi* [1977]. This fine structure is generally confined to a narrow density range (σ_t = 27.1–27.4). Thus features observed on stations separated by 50–100 km often appear to be continuous over large north-south (cross-frontal) distances when the data are presented on a single temperature/salinity diagram. However, detailed examination of continuous salinity-temperature-depth (STD) data from stations separated by as little as 30 km generally fails to reveal north-south continuity of such features. Existing bathythermograph and expendable bathythermograph (XBT) data from the Polar Front Zone, although they are more closely spaced than the survey STD stations, do not allow adequate identification of temperature fine structure and therefore yield no information on the horizontal scales of fine structure.

For the R/V *Conrad* cruise 18-01 in the western Scotia Sea (a component of FDRAKE-75 [*Gordon*, 1975*a*]) an expanded scale XBT recording system capable of resolving 0.05°C temperature fine structure was developed [*Georgi*, 1977, Appendix D]. XBT's were taken regularly, approximately every 16 km, while the ship was underway. Again, no noticeable correspondence between neighboring temperature soundings was evident.

During the *Conrad* cruise a 14-hour series of STD lowerings was made (hereafter referred to as the STD yo-yo station). Some results from the STD yo-yo station and a general description of the Polar Front Zone (Figure 1) and the surface waters in the western Scotia Sea are given by *Gordon et al.* [1977]. From 10 satellite fixes obtained during the course of the STD yo-yo station the drift rate for the ship was determined to be 1 km/h. Over the 14 hours and approximately 14 km spanned by the yo-yo station the thermohaline fine structure was not coherent. The ensemble average temperature and salinity profiles were extremely smooth [*Gordon et al.*, 1977, Figure 17]. Temperature and salinity differences were calculated for each station by subtracting the ensemble average station data from the individual temperature and salinity profiles. When the temperature differences were plotted against the salinity differences, it was evident that the temperature and salinity fine structure was density compensating for vertical scales greater than 25 m [*Gordon et al.*, 1977, Figure 19]. This result was consistent with the fact that the density profiles for the individual lowerings were nearly linear over the depth interval 100–900 m.

During the third leg of R/V *Thompson* cruise 107 (a component of FDRAKE-76 [*Joyce*, 1976]) the opportunity arose to conduct several XBT experiments in the Polar Front Zone (Figure 1) by using an expanded scale XBT recording system. Two XBT time series stations were conducted to study the temperature variance spectra and the behavior of dropped lag coherence for lag times of less than 1 hour. A third experiment was carried out to elucidate the horizontal space scales of the temperature fine structure. During the experiments the ship was positioned relative to neutrally buoyant free floating vertical current meters (VCM), similar in principle to those described by *Voorhis* [1970] but of newer design. The data from the *Conrad* STD yo-yo station, the three expanded scale XBT experiments, and the VCM's form the basis of this paper.

Garrett and Munk [1975] suggest that most of the temperature and salinity fine structure observed in the midocean regions is due to vertical motions of internal waves. Furthermore, kinematic studies of *Johnson et al.* [1978] lend support to this contention. However, in the Polar Front Zone, a region very different from the open ocean regions where internal waves have been studied, vertical motions are not responsible for the observed temperature and salinity fine structure [*Gordon et al.*, 1977]. Since the Polar Front Zone is a region of enhanced horizontal property gradients, it seems plausible to hypothesize that horizontal motions of internal waves give rise

Paper number 8C0315.
0148-0227/78/098C-0315$01.00

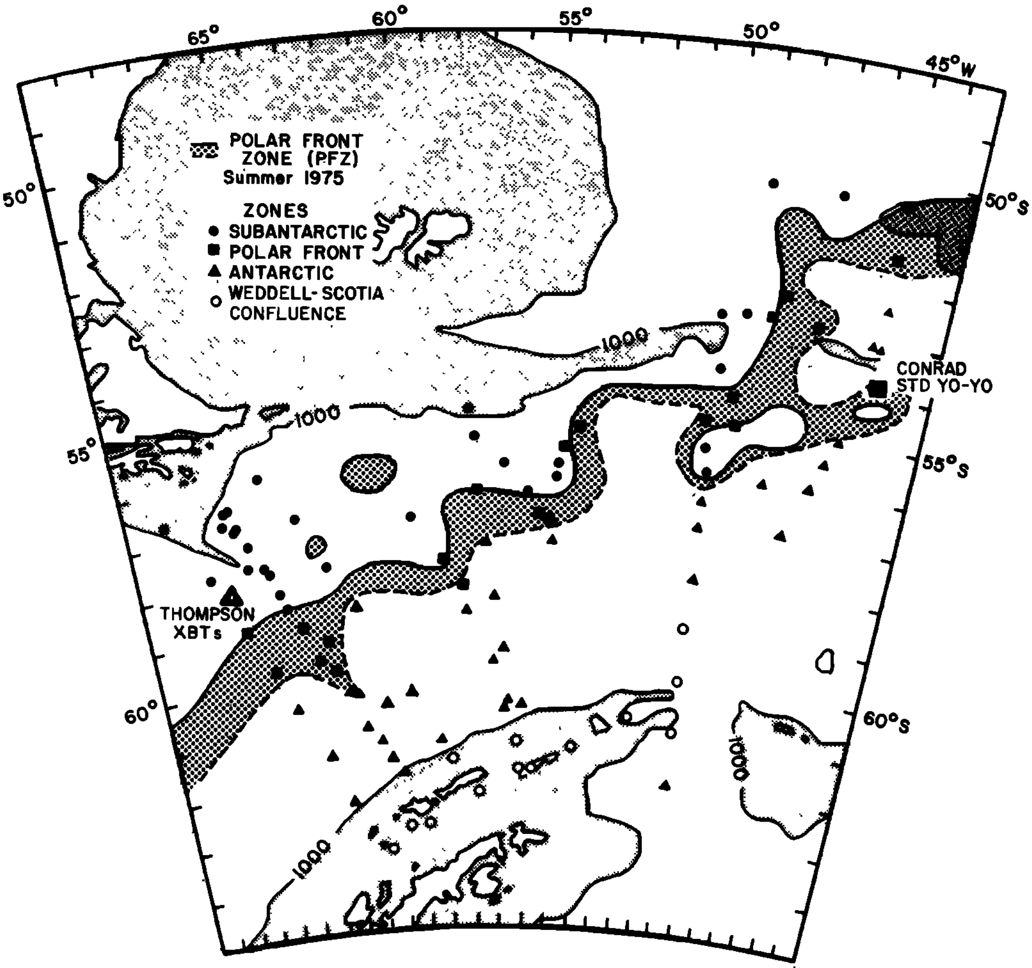

Fig. 1. Polar Front Zone constructed from data collected during the austral summer of 1975 aboard the R/V *Conrad*, the R/V *Melville*, and the ARA *Islas Orcadas* [after *Gordon et al.*, 1977]. The location of the 1975 *Conrad* STD yo-yo station is indicated as well as the site of the 1976 *Thompson* XBT experiments.

to the observed fine structure. To test this hypothesis, the variance spectra are compared with horizontal displacement spectra consistent with the *Garrett and Munk* [1975] (GM-75) internal wave empiricism [*Garrett and Munk*, 1972, 1975].

The vertical and horizontal displacement spectra are defined by

$$DS_\xi(\beta) = \int_0^\infty Z^2(\omega)E(\beta, \omega)\, d\omega$$

$\equiv$ vertical displacement spectra

$$DS_H(\beta) = \int_0^\infty X^2(\omega)E(\beta, \omega)\, d\omega$$

$\equiv$ horizontal displacement spectra

where Z^2 and X^2 are the dimensional forms of the mean square vertical and horizontal displacement functions:

$$Z^2 = b^2N[(\omega^2 - f^2)/n\omega^2]$$

$$X^2 = b^2Nn\omega^{-4}[\omega^2 + f^2]$$

where b and N are the GM-75 scaling parameters for length and time, ω is the frequency, β is the vertical wave number, f is the inertial frequency, and n is the local Brunt-Väisälä frequency. The energy spectrum $E(\beta, \omega)$ is given by

$$E(\beta, \omega) = E_0 \cdot A(\lambda) \cdot \frac{B(\omega)}{\beta_*} \qquad \lambda = \frac{\beta}{\beta_*} \qquad E_0 = 6.3 \times 10^{-5}$$

where β_* is the vertical wave number scaling parameter defined in terms of the mode number scale parameter j_* (GM-75):

$$\beta_* = j_* \pi n$$

The functions $A(\lambda)$ and $B(\omega)$, given by GM-75, have been retained:

$$A(\lambda) = \tfrac{3}{2}(1 + \lambda)^{-5/2}$$

$$B(\omega) = \frac{2}{\pi} \frac{f}{\omega} \left(\frac{1}{\omega^2 - f^2}\right)^{1/2}$$

In the absence of mixing [*Siedler*, 1974], vertical or horizontal displacement spectra, $F_\xi(\beta)$ or $F_H(\beta)$, can be obtained by dividing the observed temperature variance spectra $F_T(\beta)$ by the appropriate mean vertical or horizontal temperature gradient squared. The theoretical dropped spectra $DS_\xi(\beta)$ and $DS_H(\beta)$ can then be compared directly with $F_\xi(\beta)$ and $F_H(\beta)$. In addition, it is necessary to recall the definitions for the mean square vertical and horizontal displacements:

$$\langle \xi^2 \rangle = \int_0^\infty \int_f^\infty Z^2(\omega)E(\beta, \omega)\, d\omega\, d\beta$$

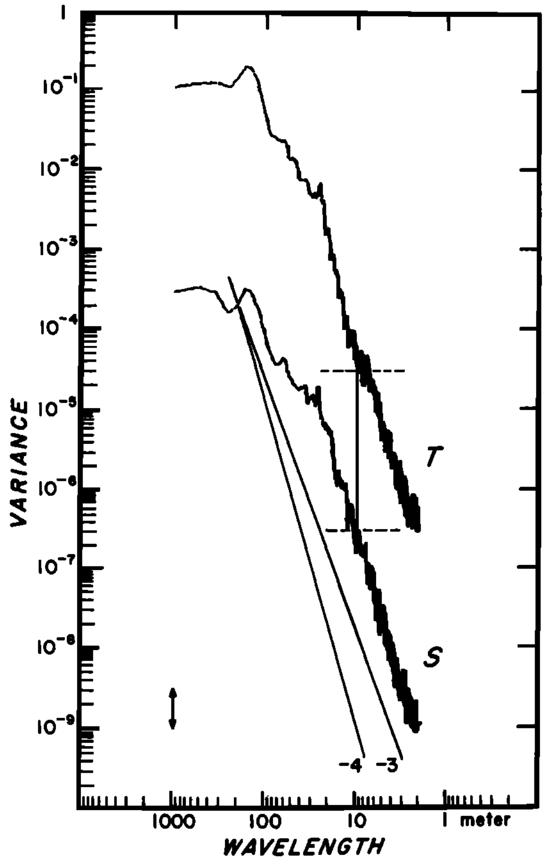

Fig. 2. Variance spectra for the *Conrad* STD yo-yo station. The temperature variance (in (°C)^2/cpm) lies approximately 2 decades above the salinity variance spectra (in (‰)^2/cpm), as would be expected for temperature and salinity fine structure which is density compensating. The arrow indicates the 95% confidence interval for 26 degrees of freedom.

$$= \int_0^\infty DS_\xi(\beta)\,d\beta$$

$$= \frac{1}{2}\frac{Eb^2N}{n}$$

and

$$\langle \chi^2 \rangle = \int_0^\infty \int_f^\infty X^2(\omega)E(\beta,\omega)\,d\omega\,d\beta$$

$$= \int_0^\infty DS_H(\beta)\,d\beta$$

$$= \frac{5}{4}\frac{Eb^2Nn}{f^2}$$

2. CONRAD STD YO-YO STATION

Temperature and salinity difference data were obtained by subtracting the ensemble average data from the data of individual lowerings of the *Conrad* STD yo-yo station. Vertical temperature and salinity variance spectra were then calculated from the 1-m equally spaced difference data with the fast Fourier transform algorithm. Prior to transforming, cosine tapers were applied to the ends of the data series to prevent contamination of the high-wave number spectral estimates.

The temperature and salinity variance spectra are presented in Figure 2. The separation between the temperature and salinity spectral levels is almost 2 decades at wavelengths of less than 100 m. This is a consequence of the isopycnal nature of the temperature and salinity fine structure. The temperature and salinity variances $(\Delta T)^2$ and $(\Delta S)^2$ are related by the equation of state to first-order approximation:

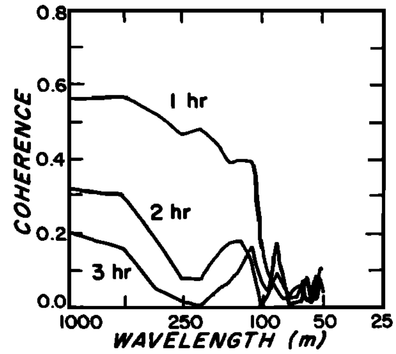

Fig. 3. Coherence for the time lags of 1, 2, and 3 hours. Only the coherence values for 1-hour separations are statistically different from zero at the 95% confidence level.

$$\Delta\rho = \frac{\partial\rho}{\partial T}\Delta T + \frac{\partial\rho}{\partial S}\Delta S \simeq 0$$

$$(\Delta T)^2/(\Delta S)^2 = (\partial\rho/\partial T)^2/(\partial\rho/\partial S)^2 \simeq (8)^2 = 64$$

where the partial derivatives of density have been evaluated for a mean salinity of 34.2‰, temperature of 2.5°C, and pressure of 500 dbar.

The wave number dependence of the power spectra is often expressed as an exponent of a power law dependence. Both the temperature and the salinity spectra are extremely 'red' and fall off with a power law exponent between −3 and −4. The falloff of these spectra is considerably steeper than that reported for temperature fine structure (−2.5) from the North Atlantic [*Millard*, 1972; *Hayes*, 1975*a*; *Hayes et al.*, 1975]. The temperature structure observed by *Hayes* [1975*a*] and *Hayes et al.* [1975] was attributed to internal wave induced vertical displacement of the mean temperature profile. However, both the energy level and the power law dependence for the data segment at the depths of Mediterranean water influence reported by *Hayes et al.* [1975] were at variance with the results for the other depth intervals. This difference was attributed to temperature structure due to horizontal advection [*Hayes*, 1975*b*]. Similarly steep spectra were obtained by *Kaplan* [1971]

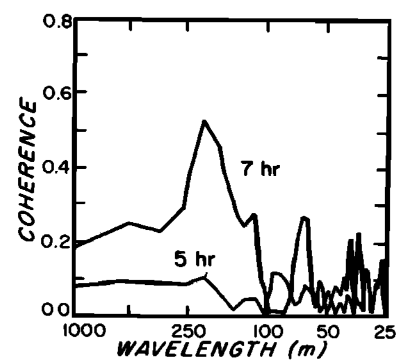

Fig. 4. Coherence for 5-hour time lags (nine estimates) and for 7-hour time lags, approximately one-half inertial period (seven estimates). The phase angle associated with the increased coherence at 250-m wavelengths for 7-hour time lags was very nearly 180°.

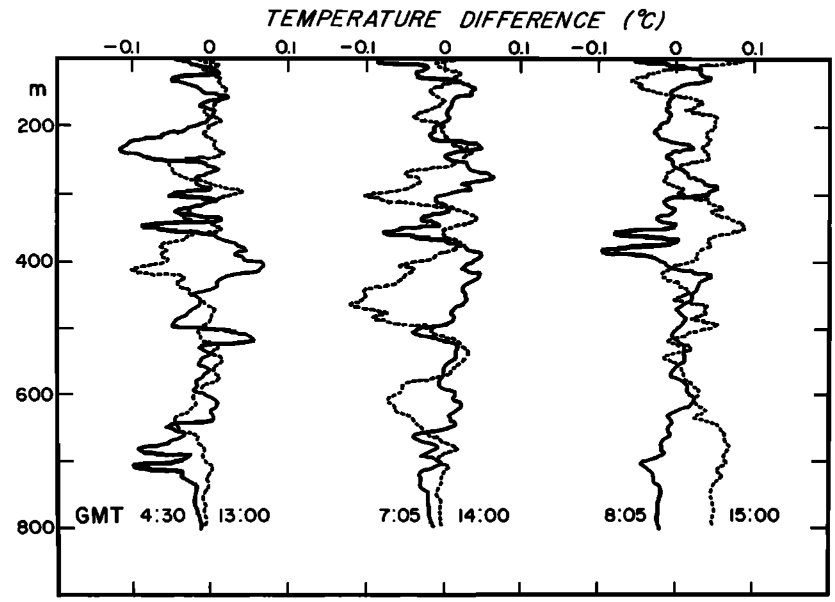

Fig. 5. The temperature difference data from three sets of lowerings separated by approximately 7 hours. Some mirror imaging is evident.

from a 36-hour STD yo-yo station off the Adélie coast (USNS *Eltanin* cruise 37 [*Jacobs et al.*, 1972]).

During the course of the *Conrad* STD yo-yo station the ship drifted toward the west; it is thus not possible to distinguish between time and space variations, since the two changes appear convoluted in the experiment. *Gordon et al.* [1977], by neglecting time variability, arrived at a horizontal scale of 1 km for 50- to 100-m-thick temperature and salinity structures. In Figure 3 the dropped lag coherences (squared) for 1-, 2-, and 3-hour time separations are shown. The coherence for 1-hour lags (1-km lags assuming no time variability) falls below statistically significant levels (0.42 for 16 degrees of freedom) for structures with vertical wavelengths of less than 100 m. The phase is very nearly 0° for those wavelengths where the coherence is statistically different from zero and a random variable for those wavelengths of less than 100 m. The results for 2- and 3-hour time lags are not significantly different from zero. However, the magnitudes of the 3-hour lag coherences are considerably less than those of the 2-hour experiment.

For temperature profiles separated by 7 hours (approximately one-half inertial period) the coherences increase again (Figure 4), while the phase is very near 180°. This is evident in the mirror imaging that is seen when temperature difference profiles separated by approximately 7 hours are compared (Figure 5). Note the similarity with earlier observations made during the Mid-Ocean Dynamics Experiment by *Sanford* [1975], who found vertical profiles of horizontal velocities to be most coherent when they are separated in time by one-half inertial period (180° out of phase) and one inertial period (in phase). In the present case, however, the *Conrad* 18 temperature profiles separated by 9, 10, and 11 hours also exhibited mirror imaging. Because a 14-hour yo-yo station is too short to resolve inertial period oscillations of 14.7 hours, these results are inconclusive.

3. THOMPSON XBT EXPERIMENTS

Three XBT experiments were carried out aboard the R/V *Thompson* in the Polar Front Zone, approximately midway between a cold core cyclonic ring (see *Joyce and Patterson* [1977] for details) and the northern extent of the antarctic temperature minimum layer. During the experiment the ship was positioned in relation to the shallower of two deployed VCM's (float 1 nominal depth 400 m; float 2 nominal depth 640 m). With the VCM's it was possible to measure the vertical motions due to internal waves.

The first two *Thompson* XBT experiments were designed to investigate the temporal behavior of the fine structure. It was hoped that the ship could be positioned directly over float 1 while a series of XBT casts was made. This, however, proved extremely difficult. The ship and the float diverged slowly until the ship's drift could be reconciled with the drift of the float. During the 2-hour period, while XBT's were taken in 5-min intervals (XBT yo-yo 1), the ship and the float separated some 1.5 km. After 1 hour the on-deck float tracking equipment failed and precluded exact determination of slant ranges. However, it was possible to estimate the range to the two floats from the difference in arrival times of their acoustic transmissions. During the second experiment, XBT yo-yo 2, the tracking equipment worked well. The relative separation between the float and the ship at the conclusion of the experiment was 1.2 km, while the mean separation between consecutive XBT's was 55 m.

The third *Thompson* XBT experiment was conducted while the ship steamed a cross pattern centered on the shallower VCM, float 1. The cross pattern extended approximately 12 km in the north-south direction and 12 km east-west. Again, XBT's were deployed every 5 min, resulting in a nominal horizontal separation between XBT's of 0.75 km. Sometimes when the ship was maneuvering, the XBT wire was fouled by the hydrophones trailing behind the ship to track the floats, resulting in the loss of some data.

All XBT data collected during the experiments were recorded with an expanded scale XBT system. This greatly improved the depth and temperature resolution and facilitated subsequent digitization of the analog records. For the XBT bridge span setting and chart recorder speeds used during the *Thompson* cruise the approximate temperature and depth resolutions are 0.01°C and 1 m, respectively.

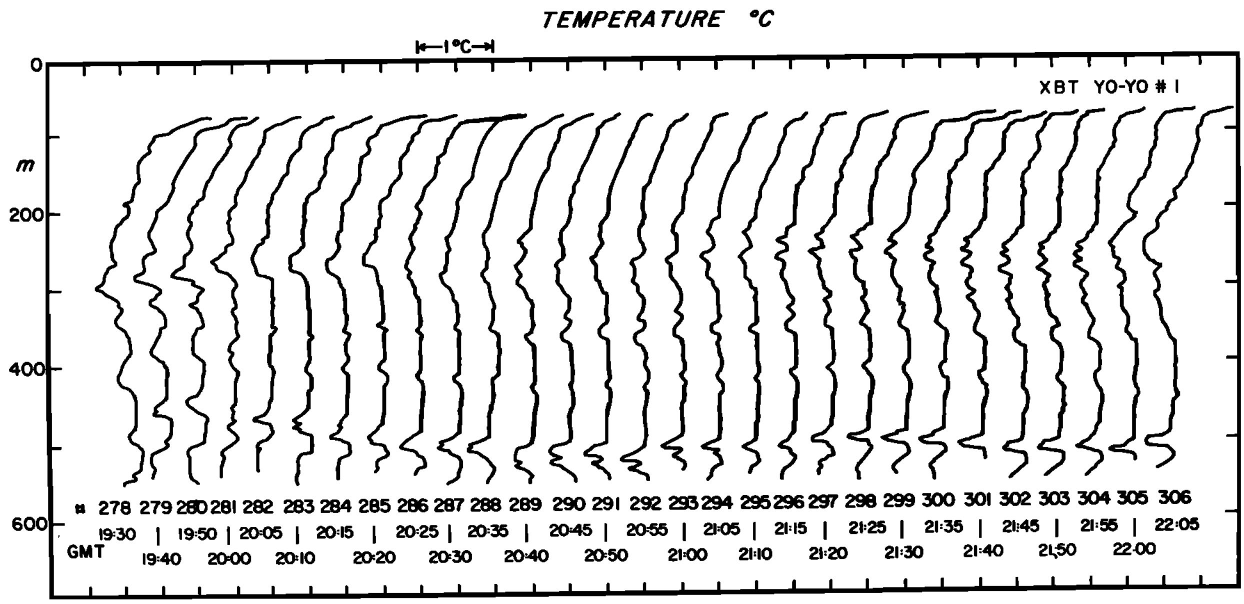

Fig. 6. Family of XBT temperature soundings, offset in relation to one another 0.5°C, from XBT yo-yo 1, over VCM 1.

4. XBT Yo-Yo Results

The temperature profiles from the two XBT yo-yo stations (Figures 6 and 7) reveal numerous temperature inversions of many apparent scales: large features 25–50 m thick and 0.2°C in amplitude; small features 10 m thick and 0.1°C and less in amplitude. Surprisingly, some of the more prominent features do not persist throughout the experiment; the feature at 300 m (Figure 6) is evident on only eight profiles, while a similar feature at 500 m persists throughout the experiment. Some small features (Figure 6, at 400 m; Figure 7, at 350 m) are also evident throughout the experiment. The more persistent features appear to change depth in an oscillatory manner by about ±20 m. The period of the motion is roughly 1 hour, but the length of the XBT experiments is too short to resolve such motions adequately. However, the observed period agrees with the dominant periodicity observed in the vertical current meter data.

Ensemble temperature variance spectra were calculated for the two XBT yo-yo experiments. The mean temperature gradient, determined from the experiment's ensemble-averaged temperature-depth data, was removed prior to transforming. This effectively detrended each data series without removing the larger-scale features which were coherent over the duration of the experiments. The mean of each series was also calculated and removed. Thus absolute temperature errors of individual XBT probes do not affect the results. As with the *Conrad* STD yo-yo station data, 10% cosine tapers were applied to the beginning and the end of each data series. Subsequent to transforming, the variance spectra were adjusted to conserve the original temperature variance.

The XBT yo-yo station ensemble variance spectra (Figure 8)

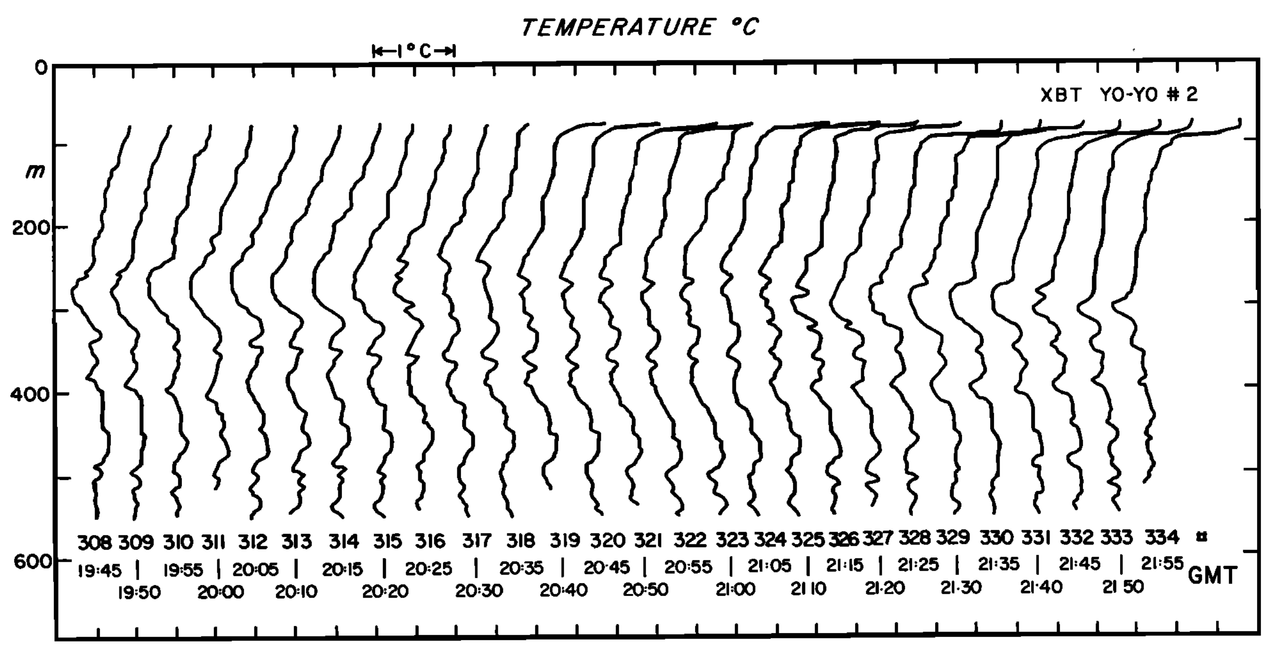

Fig. 7. Family of XBT temperature soundings, offset in relation to one another 0.5°C, during XBT yo-yo 2, over VCM 1.

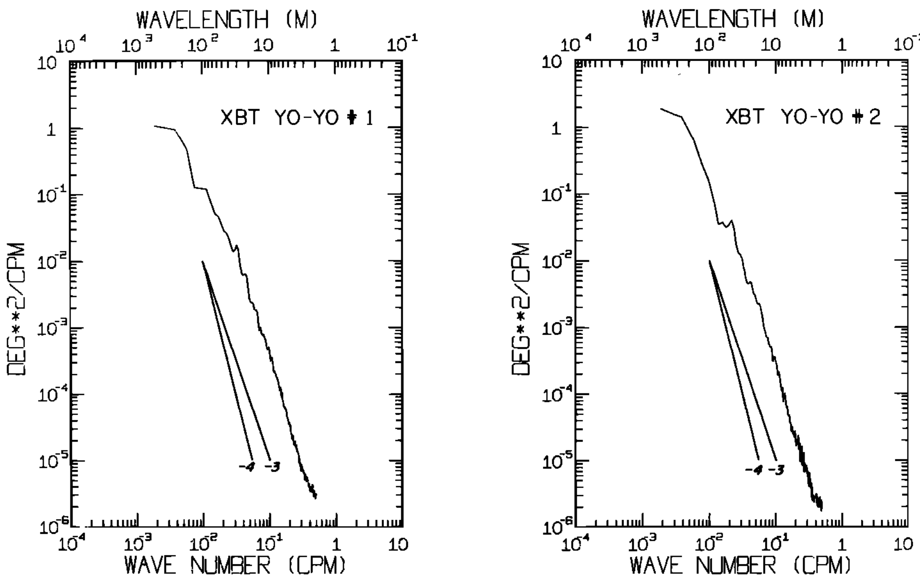

Fig. 8. Ensemble temperature variance spectra for XBT yo-yo 1 (29 estimates) and XBT yo-yo 2 (26 estimates). The spectra are similar in both wave number dependence and energy levels to the temperature variance spectrum obtained from the *Conrad* STD yo-yo station.

are very similar to those obtained from the *Conrad* STD yo-yo station data in both levels and spectral dependence. There is an extremely rapid decrease of temperature variance with increasing vertical wave number. At about 3 m there is an indication of aliasing.

Coherences (squared) were calculated for various pairs of temperature profiles (Figure 9). For profiles separated by only 5 min in time the coherences are high. For 45 min the coherence levels are decreased and are only slightly above those obtained for 1-hour time lags during the *Conrad* STD yo-yo station (Figure 3). Table 1 gives the wavelength at which the coherence R^2 falls below the statistically significant level, 95% confidence level ('null hypothesis'), taken from *Haubrich* [1965]. The results from the two XBT yo-yo experiments are practically indistinguishable (Table 1). The coherences obtained from the longer data segment (150–506 m) are only slightly less than those calculated for the shorter (250–506 m) data segment, suggesting that there was little mean shear in the water column. Shown in Table 2 is the observed loss of coherence for 5-, 10-, 15-, and 60-min time lags.

The observed loss of coherence with time can be compared with the results obtained by *Hayes* [1975*a*]. His results derive

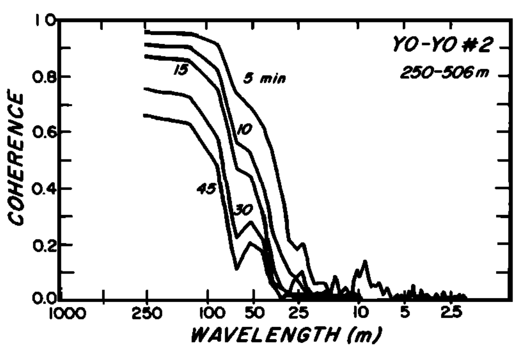

Fig. 9. Coherence for XBT yo-yo 2 for 5-, 10-, 15-, 30-, and 45-min time lags for temperature data from the 250- to 506-m depth interval. The origin of the increased coherence at 50-m vertical wavelengths is unknown but corresponds to a break in slope in the variance spectra (Figure 8).

from CTD lowerings separated by 12 min in time, obtained while the ship maintained position relative to an anchored surface float. It was found that temperature profiles separated by 12 min in time exhibited no significant coherence for wavelengths of less than 10 m and those separated by 24 min showed no significant coherence for wavelengths of less than 20 m. The temperature fine structure observed by *Hayes* [1975*a*] was attributed to vertical displacements due to internal waves, whereas the fine structure observed on the XBT yo-yo stations is caused by isopycnal or horizontal advection

TABLE 1. XBT Time Lag Coherence Results

Time Lag, min	Number of Estimates	Null Hypothesis Wavelength, m
	Yo-Yo 1 (150–506 m)	
5	25	37
10	24	51
15	23	64
20	22	73
25	21	80
30	20	80
45	17	80
60	14	88
	Yo-Yo 2 (150–506 m)	
5	25	34
10	24	43
15	23	47
20	22	51
25	21	64
30	20	85
45	17	128
60	14	128
	Yo-Yo 2 (250–506 m)	
5	26	32
10	25	37
15	24	43
20	23	43
25	22	64
30	21	64
45	18	80
60	15	80

TABLE 2. Observed Loss of Coherence

Wavelength, m	5 min	10 min	15 min	60 min
100–250	0.05	0.10	0.15	0.40
50–100	0.20	0.30	0.40	0.70

conceivably caused by horizontal displacement of low-frequency internal waves. However, even the coherences for 5-min lags from these experiments, for vertical wavelength scales of less than 25 m, are less than those obtained by *Hayes* [1975*a*] for 12-min lags. This is rather surprising, since the observed fine structure, even if it is due to low-frequency internal waves ($\omega \simeq f$), should be passively displaced, lifted or lowered. Simple vertical displacement (distortion-free displacement of the temperature profiles) does not lead to a loss of coherence; however, there is a phase shift, increasing with wave number. If vertical offsets between the individual profiles of the pairs used to estimate the coherence and the phase are random, then the phase spectrum will average to zero for a large number of estimates. Internal wave straining of the temperature field does lead to a coherence loss; however, the largest contribution to internal wave straining is due to low-frequency internal waves [*Williams,* 1976], and thus there should be little loss of coherence due to internal wave straining of the temperature field for the small time separations of the XBT yo-yo experiments.

5. THE HORIZONTAL SPATIAL DIMENSIONS OF FINE STRUCTURE

In an attempt to determine the horizontal as well as the vertical spatial dimensions of the temperature fine structure, the ship steamed at 8 km/h (5 knots) a cross pattern relative to the shallower VCM while XBT probes were launched every 5 min. The large-scale polar front orientation during the cross experiment was east-northeast/west-southwest. Of the 78 XBT temperature records, 62 were included in an ensemble temperature variance spectrum. The ensemble spectrum (Figure 10) again is similar in both wave number dependence and energy level to the spectra derived from the *Conrad* STD data and the XBT yo-yo data.

The temperature profiles from the cross experiment are presented in Figures 11 and 12. Horizontal lines were added to indicate qualitatively the persistence of temperature extrema. The temperature field observed while steaming east or west (XBT 357–397, Figure 11) appears to be more coherent than the field seen while steaming north or south (XBT 357–397, Figure 12). Coherence and phase spectra were also calculated for the XBT profiles separated horizontally by 0.75, 1.5, 2.25, and 3 km. No significant coherence was found for wavelengths of less than 75 m for profiles horizontally separated by 0.75 km, and no significant coherence was found for wavelengths of less than 160 m for 3-km separations. This loss of coherence must be attributed to the spatial dimension of the fine structure, because the observed coherence loss is considerably in excess of the 0.05 loss (Table 2) anticipated for a 5-min time lag.

For further analysis the data set was subdivided into two groups: XBT's taken while the ship was steaming either east or west (along-front direction) and those obtained while it was steaming north or south (cross-front direction). The coherences from XBT's obtained on the east-west transects (Figure 13) are considerably higher than those from XBT's on the north-south transects (Figure 14). Because of the finite length of the cross pattern the number of estimates available for the larger horizontal separations diminishes rapidly. At the 95% confidence level, $R^2 = 0.25$ is not statistically different from $R^2 = 0$ when the number of truly independent estimates (degrees of freedom) is less than 30 [*Haubrich,* 1965]. Even though the half-coherence ($R = 0.5$, $R^2 = 0.25$) vertical wavlengths for the 0.75-km horizontal separations are approximately equal (Table 3) for the east-west and the north-south XBT's, the degree of coherence at the longer wavelengths (>100 m) differs considerably, as do the results for the 1.5-km separations. The results (Table 3) from the composite and east-west XBT's show that structures with larger vertical wavelengths also have larger horizontal scales. However, the aspect ratio (horizontal separation: $\lambda_{R=0.5}$) is not constant but increases with increasing vertical wavelength.

6. THE ROLE OF INTERNAL WAVES

The relationship exhibited by the *Conrad* temperature and salinity spectra rules out the possibility that the fine structure observed in the Polar Front Zone can result from simple vertical displacements of the mean profiles, consistent with the temperature-salinity arguments presented by *Gordon et al.* [1977]. Because of the extremely low mean vertical temperature gradient (less than 1°C/km) in the Polar Front Zone it would be necessary that vertical displacements be as large as 100 m to generate the observed temperature variance. Yet, the VCM data obtained during the XBT experiments measured rms vertical displacements of only 5 m. Furthermore, most of the observed variance is associated with temperature inversions, which cannot result from simple vertical displacements of a smooth mean temperature profile.

However, it is possible that the observed fine structure is due to horizontal displacements. The dropped lag coherence results from the *Conrad* yo-yo station suggest that the low-frequency near-inertial waves may be responsible for the fine

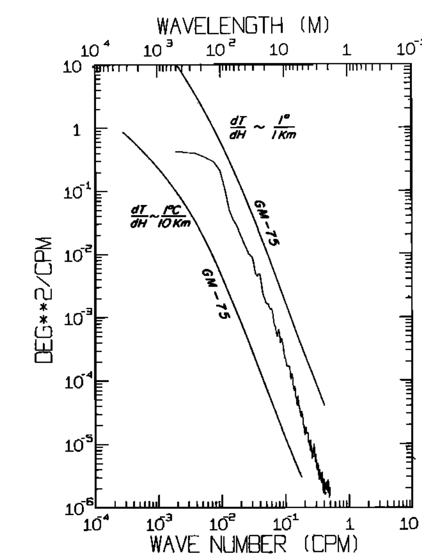

Fig. 10. The ensemble average temperature variance spectrum for XBT data from the cross experiment (62 estimates) is contrasted with two realizations of the GM-75 horizontal displacement spectra. The horizontal temperature gradients used to calculate the predicted spectra are indicated in the figure.

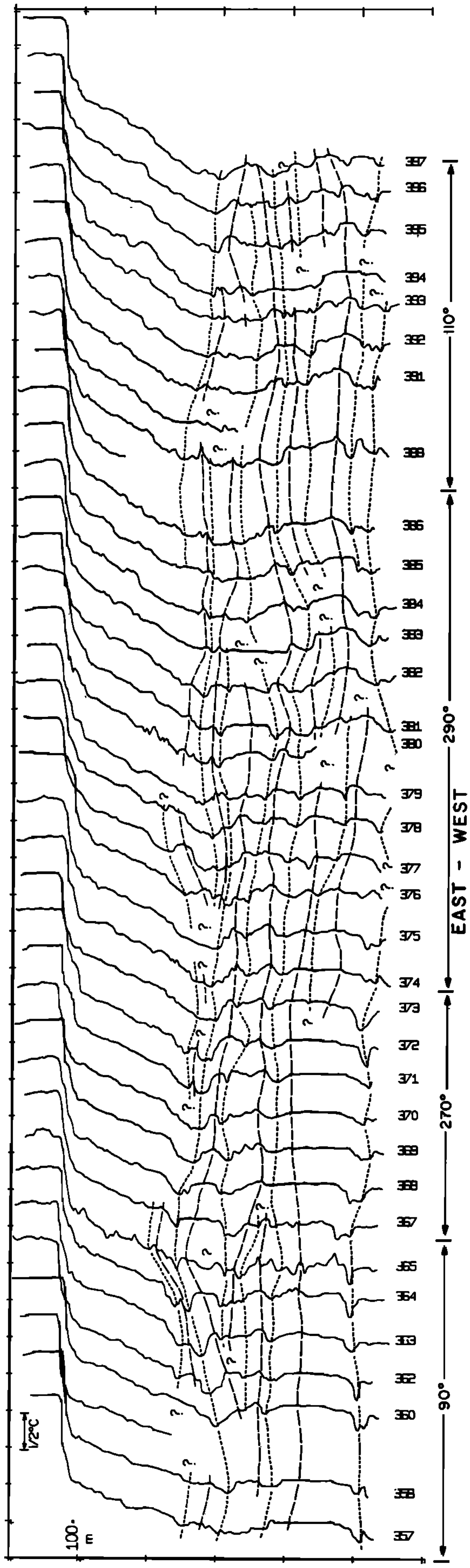

Fig. 11. Family of XBT temperature soundings obtained while ship steamed east or west (along-front direction) during cross experiment. Data are presented in chronological order; offset in relation to one another 0.5°C; ship heading is indicated in figure. Lines added to show qualitatively the persistence of given temperature extrema.

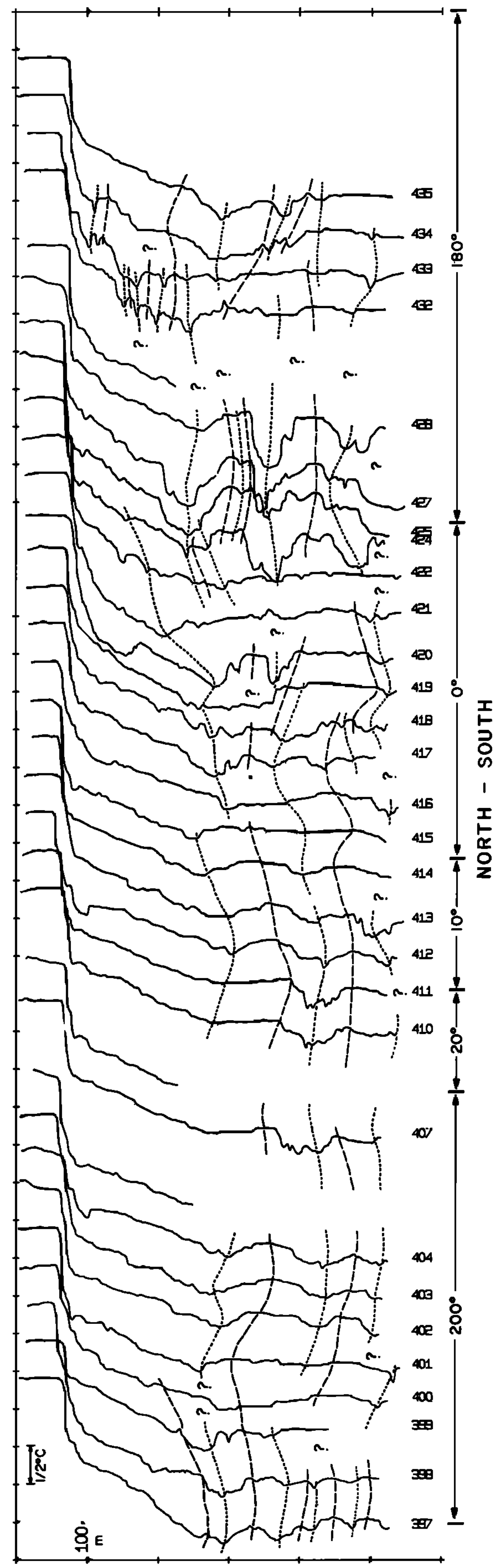

Fig. 12. Family of XBT temperature soundings obtained steaming north-south (cross-front direction). Temperature maxima and minima are not as easily traced from sounding to sounding.

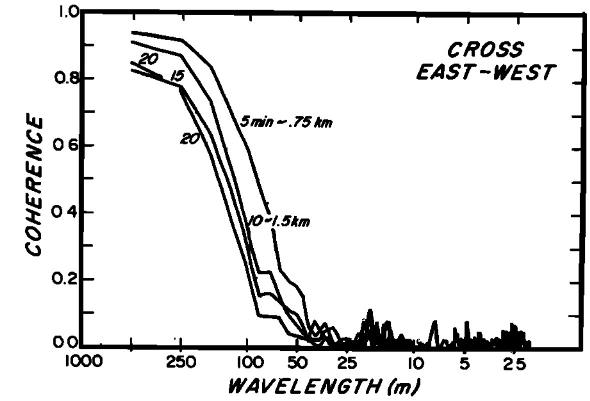

Fig. 13. Coherence results for XBT's taken while the ship steamed east or west during the cross experiment. There are 32 coherence estimates for 0.75-km (5 min) lags, 20 for 1.5-km (10 min) lags, 26 for 2.25-km (15 min) lags, and 22 for 3-km (20 min) lags.

structure observed in the Polar Front Zone. Because the horizontal temperature and salinity gradients are considerable in the Polar Front Zone (0.03°–0.3°C/km) (contrast with the vertical gradients of 1°C/km), the horizontal motions associated with the near-inertial waves could give rise to temperature and salinity fine structure.

If it is assumed that the only source of the observed temperature variance is due to horizontal displacements, then the temperature spectra can be converted to horizontal displacements by dividing the mean horizontal gradient squared. Alternately, the predicted horizontal displacement spectrum can be converted to a temperature spectrum by multiplying by the mean horizontal gradient squared. The observed temperature spectrum is contrasted with two realizations of the GM-75 horizontal displacement temperature spectrum (Figure 10). Because of the difficulty in determining the 'mean' horizontal gradient, it is unclear what portion of the observed temperature fine structure is due to horizontal motions of internal waves. XBT data taken aboard the *Thompson* and the *Yelcho* at the time of the experiments indicated that the north-south temperature gradients were typically 0.03°C/km to 0.1°C/km. Assuming a horizontal displacement of 0.3 km, consistent with internal wave empiricism, one would expect temperature fine structure of 0.01°–0.03°C amplitude to be introduced. For a somewhat larger horizontal gradient, 0.3°C/km, approximately 75% of the temperature variance could be attributed to internal wave induced horizontal displacements. By assuming a 0.1°C/km horizontal gradient, approximately 7% of the temperature variance can be accounted for.

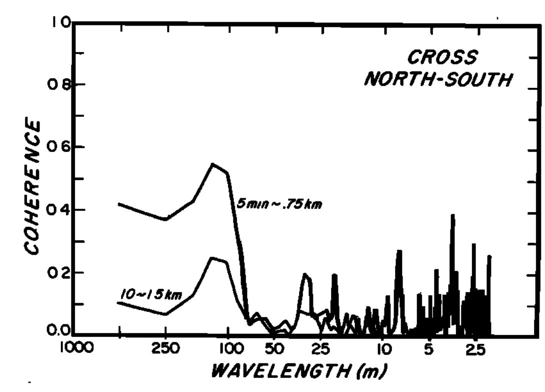

Fig. 14. Coherence results for XBT's taken while the ship steamed north or south during the cross experiment. There are 22 coherence estimates for 0.75-km lags and 24 for 1.5-km lags. The coherence results for 1.5 km are not statistically different from zero. The coherences for the cross-front direction (north-south) are noticeably less than those for the along-front direction (east-west). This suggests that the features are elongated filaments, aligned with the front.

TABLE 3. XBT Space Lag Coherence Results

Direction	Separation, km	Number of Estimates	$\lambda_{R=0.5}$, m	Aspect Ratio
composite	0.75	53	75	10
composite	1.5	53	95	16
composite	2.25	45	130	17
composite	3.0	38	163	18
east-west	0.75	32	64	12
east-west	1.5	29	88	17
east-west	2.25	26	95	24
east-west	3.0	22	100	30
north-south	0.75	21	80	9
north-south	1.5	24	always less	

During the period of observations the VCM's measured rms vertical displacements of 5 m. For the local Brunt-Väisälä frequency of 1.3 cph one would have expected rms vertical displacements of 11 m. If one adjusts the factor Eb^2N in the GM-75 model to get 5-m rms vertical displacements, the horizontal displacements will be reduced by a factor of 5. This would also result in a fivefold reduction of the estimated contributions of horizontal displacements to the observed temperature variance, suggesting that horizontal motions of internal waves were not contributing significantly to the observed temperature variance spectra. It would thus seem that neither the vertical nor the horizontal internal wave displacements qualify as the mechanism for causing the observed temperature structures.

It should be recalled that the vertical displacements were ruled out by arguments based on the temperature and salinity properties of the fine structure [*Gordon et al.*, 1977] and by the direct comparison of observed vertical displacements and the vertical displacements computed from the temperature variance spectra. It was not necessary to resort to a particular internal wave model, although the comparison of the GM-75 vertical displacement spectra with the computed spectra also supports the above conclusion that the fine structure is not due to vertical displacements of internal wave origin. However, several difficulties preclude the precise determination of the degree to which horizontal displacements enter into the formation of fine structure. Precise determinations of mean horizontal property gradients do not exist and probably can only be obtained with a towed STD system. Because no direct observations of horizontal velocity or displacements were available, it was necessary to resort to an internal wave model to relate vertical displacements to horizontal displacements. Since the GM-75 internal wave model is a midfrequency model, $f < \omega < n$, and little is known about the near-inertial frequency, $\omega \sim f$, range of the model, the use of the rms vertical displacement to set the value of EB^2N is somewhat tenuous. Furthermore, one is interested in instantaneous energy levels (on time scales of hours); yet it is necessary to determine the internal wave energy spectrum over many inertial cycles. In addition to the difference between the observed spectral levels and those predicted by the GM-75 model, the observed spectra also fall off more rapidly with increasing wave number than the model spectra. This is attributable to the predominance of the 10- to 100-m vertical fine structure features that are apparently not of internal wave origin.

7. Conclusion

It seems that neither the vertical nor the horizontal internal wave displacements qualify as the mechanisms for causing the observed temperature structures in the Polar Front Zone. The qualitative and quantitative coherence results from the cross experiment revealed a marked anisotropy in the fine structure. The features are elongated in the along-front direction. Features of vertical scales 100 m and greater have cross-front scales between 0.75 and 1.5 km and associated along-front scales in excess of 3 km, while features with smaller vertical scales, 100 m and less, have smaller horizontal scales. Thus the horizontal dimensions of the smaller fine structure are comparable to the horizontal displacements of internal waves. It is easy to envisage situations where the horizontal advection of the fine structure by internal waves contributes significantly to the rapid loss of dropped lag coherence, as seen in the XBT yo-yo experiments. Similarly, situations can be envisaged involving larger fine structure features and horizontal advection by internal waves which would give rise to coherence results as observed on the *Conrad* STD yo-yo station. Because internal waves continually move the fine structure up and down, while low-frequency horizontal advection by internal waves shear the fine structure, the estimated horizontal scales from the XBT cross experiment must be considered minimums.

Acknowledgments. Grants OCE-74-15062 and OCE-75-14056 from the Office of the International Decade of Ocean Exploration of the National Science Foundation supported the data collection, processing, and analysis. The author benefited from discussions with A. L. Gordon, C. L. Johnson, T. M. Joyce, J. Toole, and A. D. Voorhis. Woods Hole Oceanographic Institution contribution 4110.

References

Garrett, C. J. R., and W. H. Munk, Space-time scales of internal waves, *Geophys. Fluid Dyn.*, *2*, 225–264, 1972.

Garrett, C. J. R., and W. H. Munk, Space-time scales of internal waves: A progress report, *J. Geophys. Res.*, *80*, 291–297, 1975.

Georgi, D. T., Temperature finestructure in the Southern Ocean, Ph.D. thesis, 343 pp., Columbia Univ., New York, 1977.

Gordon, A. L., An antarctic oceanographic section along 170° E, *Deep Sea Res.*, *22*, 357–377, 1975*a*.

Gordon, A. L., Contributions of R/V *Conrad* to FDRAKE, 1975, *Antarct. J.*, *10*, 142–143, 1975*b*.

Gordon, A. L., H. W. Taylor, and D. T. Georgi, Antarctic oceanographic zonation, paper presented at the SCOR/SCAR Polar Oceans Conference, McGill Univ., Montreal, Canada, May 5–11, 1974.

Gordon, A. L., D. T. Georgi, and H. W. Taylor, Antarctic Polar Front Zone in the western Scotia Sea—Summer 1975, *J. Phys. Oceanogr.*, *7*, 309–328, 1977.

Haubrich, A. R., Earth noise, 5–500 millicycles per second, *J. Geophys. Res.*, *70*, 1415–1427, 1965.

Hayes, S. P., Preliminary measurements of time-lagged coherence of vertical temperature profiles, *J. Geophys. Res.*, *80*, 307–311, 1975*a*.

Hayes, S. P., The temperature and salinity fine structure of Mediterranean water in the western Atlantic, *Deep Sea Res.*, *22*, 1–11, 1975*b*.

Hayes, S. P., T. M. Joyce, and R. C. Millard, Measurements of vertical fine structure in the Sargasso Sea, *J. Geophys. Res.*, *80*, 314–319, 1975.

Jacobs, S. S., P. M. Bruchhausen, F. L. Rosselot, A. L. Gordon, A. F. Amos, and M. Belliard, *Eltanin* reports cruises 37–39, 1969, 42–46, 1970, *Tech. Rep. I-CU-1-72*, 490 pp., Lamont-Doherty Geol. Observ., Columbia Univ., Palisades, N. Y., 1972.

Johnson, C. L., C. S. Cox, and B. Gallagher, The separation of wave-induced and intrusive fine structure, submitted to *J. Phys. Oceanogr.*, 1978.

Joyce, T. M., Observations of the Polar Front Zone during FDRAKE, 76: R/V *Thompson* leg 3, *Antarct. J.*, *11*, 157–158, 1976.

Joyce, T. M., and S. L. Patterson, Cyclonic ring formation at the polar front in the Drake Passage, *Nature*, *265*, 131–133, 1977.

Kaplan, S., Microstructure and turbulence in the ocean, Ph.D. thesis, 143 pp., Columbia Univ., New York, 1971.

Millard, R., Further comments on vertical temperature spectra in the Mode region, *Mode Hot Line News*, *18*, 1, 1972.

Sanford, T., Observations of the vertical structure of internal waves, *J. Geophys. Res.*, *80*, 3861–3871, 1975.

Siedler, G., The fine-structure contamination of vertical velocity spectra in the deep ocean, *Deep Sea Res.*, *21*, 37–46, 1974.

Voorhis, A. D., Measuring vertical vorticity in the sea, *Deep Sea Res.*, *17*, 1019–1029, 1970.

Williams, G. O., Repeated profiling of microstructure lenses with a midwater float, *J. Phys. Oceanogr.*, *6*, 281–282, 1976.

(Received January 4, 1978;
revised February 10, 1978;
accepted February 13, 1978.)