A Comparison of Cyclonic Ring Structures in the Northern Sargasso Sea

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ABSTRACT

Field observations provide a data base that supports a comparison of ring structures in terms of the background Sargasso Sea environment. Five ring surveys, three from the 1967 sequence, a big baby ring and ring AL, were selected for this study. Anomalies of temperature, salinity, transport potential energy density, heat content and sound velocity have been examined using a reference which closely approximates Iselin's characteristic T-S relation for the western gyre.

The results for the 1967 sequence demonstrate an initial reduction in anomaly strengths followed by strong ring stability. Comparison of two different rings, possibly equal in age, show the effect of the initial water mass conditions on anomaly strengths. Comparison of a cyclonic ring and the big baby ring reveals similar anomaly strengths and sizes in the same geographical region for rings that are assumed to be two and eleven months in age, respectively. This suggests that big baby rings can initially represent more intense perturbations to the Sargasso Sea than cyclonic ring counterparts.

1. Introduction

Evidence for cyclonic vortices in the Sargasso Sea was initially noted in the classical interpretation of North Atlantic field observations by Iselin (1936). Intensive surveys of these transient features began during the past decade and several time series and single hydrographic sections have been gathered in order to understand their physical structure (Fuglister, 1972, 1977; Cheney and Richardson, 1974). Each observational sequence has been studied in terms of its relationship to the coexisting Sargasso Sea environment. Our intent is to provide a comparison of rings in terms of anomalies referenced to a single hydrographic station, examine similarities and differences and discuss their implications.

The generation of mesoscale eddies is prevalent east of 70°W where Gulf Stream meanders are known to grow and become unstable (Fuglister and Worthington, 1951). Parker (1971) discerned western and eastern ring fields in this region from 70°W to approximately 40°W. A number of vortices have been observed to break off from the Gulf Stream in the western field (e.g., Fuglister, 1977). Further evidence for similar generation in the eastern field has been cited by McCartney (1975). These latter, somewhat larger eddies have recently been differentiated as "big babies" (McCartney, *et al.*, 1977) in contrast to those termed "cyclonic" rings in the western field. Generation in either case occurs as a meander deepens and separates, resulting in a central region occupied by colder, fresher waters, encircled by a Gulf Stream remnant, and interacting with the surrounding Sargasso Sea environment.

When a cyclonic ring is generated, the central water mass is drawn from the North American Slope Water (NASW) region. A big baby separation has not yet been observed and there is speculation (Worthington, 1976a) that the interiors could have a geographic origin further east in the vicinity of the northern gyre discussed by Worthington (1976b). In either situation, the composition of the initial, interior waters can vary significantly, perhaps seasonally near the surface and as a result of prior dynamic history. Rings can receive water masses from the mid-Atlantic Bight northeastward to Georges Bank. A definite seasonal progression has been documented for these waters (McLellan, *et al.*, 1952; Wright and Parker, 1976) and the region may simultaneously contain slope water, shelf water, anticyclonic rings generated by the Gulf Stream and intermediate water masses produced by their mixtures. Thus each cyclonic ring is a unique mesoscale structure and we should expect that distinct physical, chemical and biological differences as well as similarities could exist, even for rings produced in the same season.

The primary dynamic elements in cyclonic rings are the pressure gradient, Coriolis and frictional forces which combine in the upper layers to produce a convergence toward their interior. Evidence has recently been found for interior mixing and detrainment through the mid-thermocline (Vastano and Hagan, 1977). The flow is such that ring evolution will take place slowly provided that external interac-

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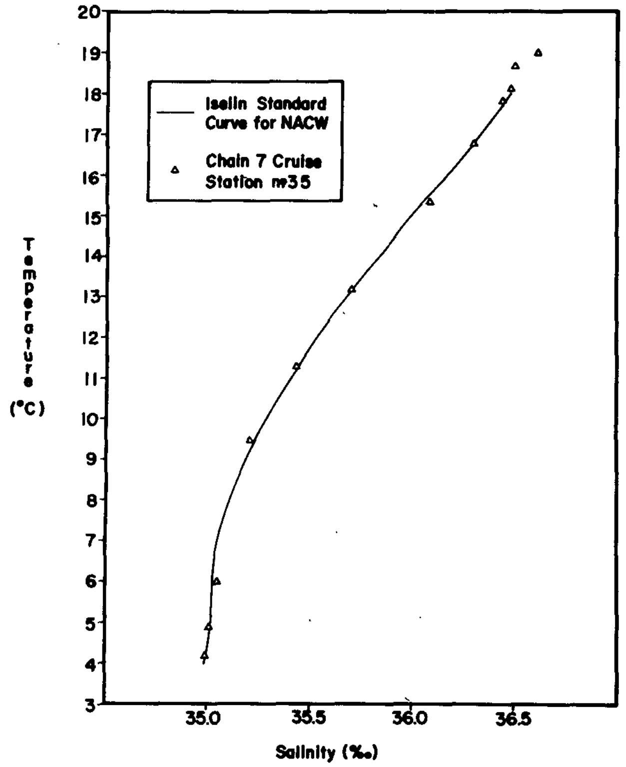

FIG. 1. Iselin's (1936) standard curve for the North Atlantic Central Water represented by solid line. Triangles identify *T-S* data obtained from *Chain* cruise 7, station 35.

tions do not occur. Calculations of what has been referred to as available potential energy and contoured sections in this quantity which is an indicator of the intensity of the ring (Barrett, 1971; Cheney and Richardson, 1974) have yielded half-life estimates of three to four years and imply quasi-stable ring conditions that are reflected in their basic circular symmetry. The physical changes below the main thermocline are characterized by lateral shrinking and vertical descent of isotherms. This gradual alteration is accompanied by increasing salinity as waters mix in the interior and approach the background temperature/salinity (*T-S*) relation of the Western North Atlantic Water (WNAW).[1]

2. The comparison method

Our understanding of ring structures has progressed with the physical descriptions of several individual rings and with differences in observed distributions over portions of two ring lifetimes (Fuglister, 1977; Cheney and Richardson, 1974). The information gathered in these studies has provided estimates of sizes, gradients and the spindown evolution through temporal changes in temperature, salinity, oxygen, available potential energy and geostrophic velocities. Although it is important to examine rings in this manner, especially for modelers, comparisons within the data base call for a reference to serve as a basis for identifying common elements and significant differences.

The standard curve that represents the waters of the subtropical gyre (NACW) below the seasonal thermocline was drawn by Iselin (1936) from 96 *Atlantis* stations taken west of Bermuda and within the 700 m contour of the 10°C isotherm. West of 55°W longitude and above a depth of 1200 m, the salinity anomalies for the data relative to the curve ranged from -0.04 to $+0.05$‰ with a stated salinity accuracy of ± 0.02‰. On this basis, the *T-S* correlation was termed by Iselin as "remarkably consistent" and it has been since regarded as indicative of the uniformity of the water mass. Fig. 1 presents the standard *T-S* curve over a depth interval of approximately 300 to 1500 m. A single Sargasso Sea hydrographic station, *Chain* cruise 7 (C 7), station 35, has been selected as representative of WNAW and these *T-S* observations are also plotted in Fig. 1. The station was taken on 22 IV 59, northwest of Bermuda at 36°16′N, 68°22′W and is included in the 36°N transect of the *North Atlantic Ocean Atlas*, Volume 1 (Fuglister, 1960). This station, essentially the Iselin curve, is taken as the reference for our computations of physical anomalies.

The comparison of ring structures has been made in terms of five physical parameters: temperature, salinity, transport potential energy density, heat content and sound velocity. The observations were interpolated to selected depths and the anomaly calculations made with this rectified data set. We have based the anomaly sections on data at the following depths: every 50 m from 150 to 500 m; every 100 m from 500 to 1000 m; and at 1200 and 1500 m. The anomalies of temperature and salinity were formed as simple differences between ring and reference station values at corresponding depths. Sound velocity anomalies were obtained using Wilson's formula (Wilson, 1960) and similar differencing. The heat content anomaly was computed using differences in

$$H = \rho_* C_p T, \tag{1}$$

where ρ_* is the *in-situ* density and T is the temperature. The assumption was made that C_p does not vary with temperature or salinity and a constant value of 0.948 cal g^{-1} C^{-1} has been used. The anomaly values were calculated along given isopycnal surfaces and formed by differences relative to the H value at the ρ_* depth of the reference station. The largest source of errors in this analysis is introduced by the interpolations involved in the ρ_* and

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[1] Prevalent terminology for the water mass of the central gyre is WNAW. However, Iselin's initial characterization referred to North Atlantic Central Water (NACW).

temperatures values. Including a crude allowance for these errors, we estimate that this anomaly is accurate to 0.5 cal cm^{-3}.

The transport potential energy (TPE) density is synonymous with what other authors have called available potential energy in oceanography. The new terminology is introduced here in order to differentiate this quantity, which was computed from Fofonoff's (1962) formulation, from the true available potential energy defined by Lorenz (1955). A derivation of available potential energy in the oceans can be found in Reid and Olson (1978). The transport potential energy is treated here to facilitate comparisons with the earlier work of Barrett (1971) and Cheney and Richardson (1976). This quantity is a measure of the contribution of different layers in a ring to the ring's transport relative to the reference station. It is calculated, following Fofonoff's (1962) formula, from

$$x = g^{-1}\int \delta P dP, \tag{2}$$

where x is the anomaly of TPE in the column, δ the thermosteric anomaly, P is pressure and g the gravitational acceleration. The TPE density is then given by

$$\text{TPE density} = \rho|\delta - \delta_r|P, \tag{3}$$

where δ_r is the reference station thermosteric anomaly at a given common depth with pressure P calculated using the hydrostatic equation. The ring transport per unit radial distance is given by

$$T = \frac{1}{f}\frac{\partial}{\partial r}\int_{Z_r}^{0} (\text{TPE density})dz, \tag{4}$$

where the radial derivative is taken between stations, f is the Coriolis parameter, and Z_r the reference level chosen for geostrophic calculations. The TPE density (ergs cm^{-3}) is independent of the choice of the level of no motion for the ring and is only dependent on the specification of the reference station. Conservatively, the error in these estimates is between 1 and 4% in the integral [Eq. (2)] and the maximum error is 0.5×10^4 ergs cm^{-3} for the anomalies.

A consideration which should be borne in mind is the possibility that the original hydrographic sections do not necessarily bisect the ring structures. Even though preliminary BT surveys are employed to find centers and areal extents, recent work (Olson and Spence, 1977) has shown that perturbations to circular symmetry can be present and propagate around rings. In addition, we are aware that variable speeds and directions are associated with the translation of rings in the Sargasso Sea (Fuglister, 1977). Thus our comparisons must be prefaced with a caveat that sizes and maximum values in the anomaly sections can have an unknown error. Presumably, it is small enough to permit reasonably drawn comparisons between sections intended to bisect rings.

3. Ring descriptions

Five cruises that provide observations of three different rings form the data base for the comparisons. Three cruises, *Crawford* 156 (CFD 156), *Atlantis II* 35 (A II 35) and *Atlantis II* 38 (A II 38), are taken from the 1967 ring sequence (Fuglister, 1977). Of the two remaining cruises, *Knorr* 48 (KN 48) made sections in a big baby ring BBA, (McCartney *et al.*, 1977) and *Knorr* 62 (KN 62) surveyed the initial ring AL of the 76–77 interdisciplinary cyclonic ring experiment (Richardson *et al.*, 1977). The geographic positions of the ring centers located on these cruises and the location of the reference station are shown in Fig. 2.

In March 1967, a ring was observed by a NAVOCEANO aircraft to have formed north of Bermuda in the vicinity of 37°N, 66°W (Bratnick *et al.*, 1968). This ring became the subject of an extensive sequence of physical surveys under the direction of Fuglister at Woods Hole Oceanographic Institution (Fuglister, 1977). Tracking by radar transponding surface bouys drogued in the surface layer was supplemented by BT and hydrographic surveys on each of nine cruises. The ring followed an anticyclonic path for two revolutions in a region bounded by 37°N, 64°W and 35°N, 67°W and, in October, possibly reentered the Gulf Stream. It can be characterized as a relatively small and intense feature that possessed a strong degree of stability over much of the eight months of observation (Fuglister, 1977). During CFD 156 the shape of this ring was not circular but slightly peanut-shaped and the sequence of hydrographic stations depart from a straight radial line. Stations taken on A II 35 and A II 38 formed crosses centered on the ring (Schmitz and Vastano, 1975) and clearly demonstrate circular symmetry.

During KN 48 in March 1975, a deep hydrographic section was made across a big baby (BBA) centered at 34°18′N, 62°40′W. This ring is believed to have been generated considerably to the northeast of this position and from the physical structure was estimated to be approximately one year old (Worthington, private communication). McCartney (1975) has suggested that the ring had been altered by interaction with seamounts during translation on the basis of an offset of over 50 km and resulting incline in the vertical perturbations of the isotherms. The ring is relatively large which would correspond to generation from the Gulf Stream in the eastern ring field where large-amplitude meanders are known to occur (Niiler, 1975).

The 1976 ring (AL) was located in early December

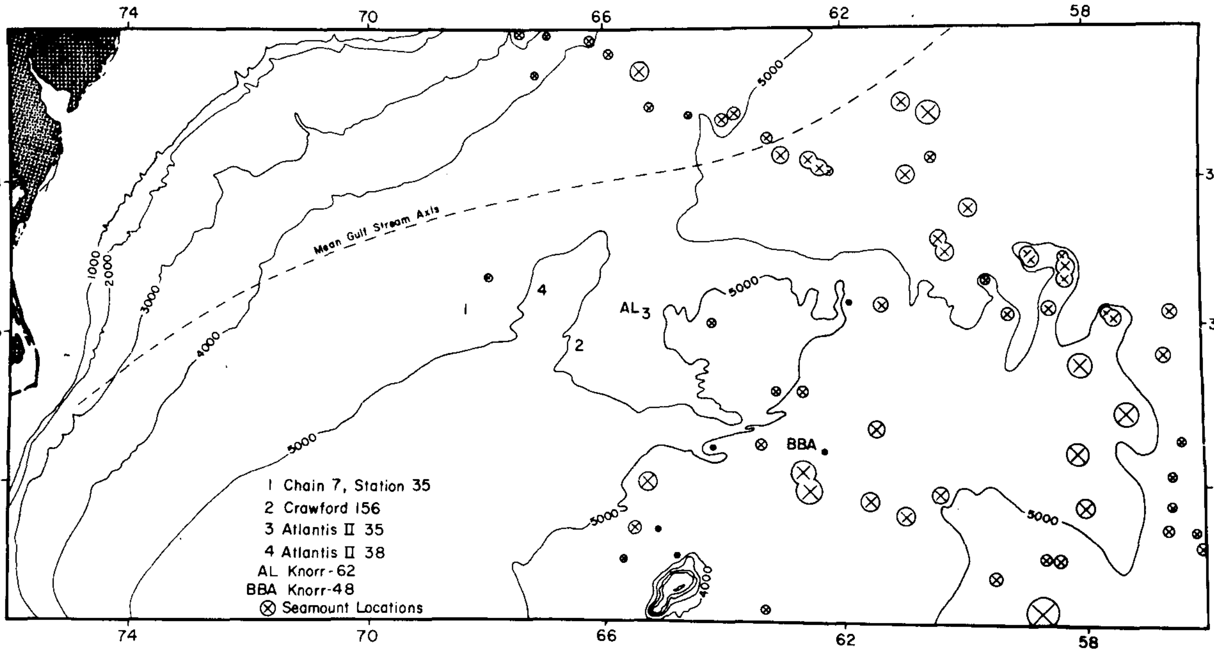

FIG. 2. Geographic positions for *Chain* 7 station (1) and ring centers located on cruises of *Crawford* 156 (2), *Atlantis* II 35 (3), *Atlantis* II 38 (4), *Knorr* 48 (BBA) and *Knorr* 62 (AL).

by a NAVOCEANO AXBT survey (Experimental Ocean Frontal Analysis, 1976). Hydrographic data for the ring was obtained during *Knorr* 62, the first of four interdisciplinary cruises planned to study the physical, chemical and biological characteristics of a newly formed cyclonic ring. A study of the Experimental Ocean Frontal Analysis reports suggests that AL formed in late October. A large Gulf Stream meander in the proximity of 38°N, 65°W could have generated this ring in conjunction with the separation of the anticyclonic ring known as Eddy J. Ring AL is larger than the 1967 ring and has similar *T-S* characteristics to BBA. The XBT survey of the ring (Richardson *et al.*, 1977) showed a distinct peanut shape with a large primary ring and a weaker companion.

4. Anomaly study

The anomaly values reflect contrasts between NASW and WNAW as well as the subsequent effects of entrainment, diffusion and mixing. Further, the 1967 sequence demonstrates the general stability that a cyclonic ring can exhibit when it evolves under these dynamic mechanisms and does not directly interact with the Gulf Stream. Fuglister (1977) has noted the small variations in the temperature and salinity values that occurred beneath the mid-thermocline in this ring. Table 1 contains the maximum anomaly values for all five parameters and offers further evidence for the relatively constant conditions within the central core. An examination of the *T-S* values in this portion of the ring (CFD 156, station 2057) indicates that for a given temperature the values are much fresher relative to WNAW than those of any other ring selected for this study. We interpret this as indicative of conditions within the slope water region which provided relatively unmixed winter NASW for the ring interior. The maximum potential energy density remains constant within the accuracy of our computations and the heat deficit and sound velocity

TABLE 1. Maximum anomaly values.

Cruise	Date	Temperature T (°C)	Salinity S (‰)	Heat deficit H (cal cm^{-3})	Transport potential energy TPE (10^4 ergs cm^{-3})	Sound velocity SV (m s^{-1})
CFD 156	June 67	−10.3	−13	8.0	6.8	−34.5
A II 35	August 67	−9.6	−13	7.1	6.5	−31.4
A II 38	October 67	−9.5	−13	6.8	6.5	−31.4
KN 48	March 76	−8.0	−11	5.1	5.8	−26.5
KN 62	December 76	−7.6	−11	5.8	5.8	−26.5

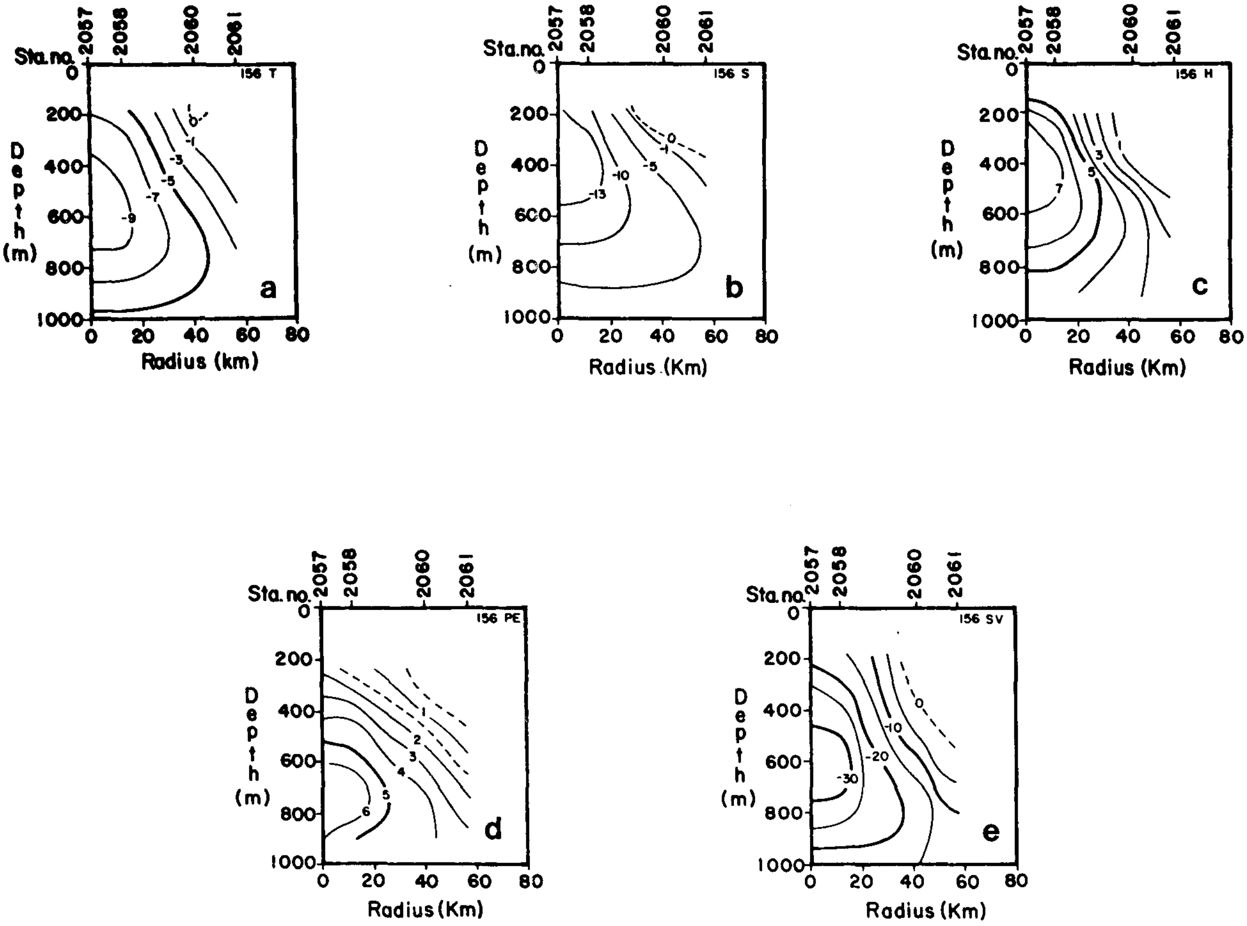

FIG. 3. Anomaly sections for *Crawford* 156, 1967 ring: (a) temperature (°C); (b) salinity (‰); (c) heat deficit (cal cm^{-3}); (d) transport potential energy (10^4 ergs cm^{-3}); (e) sound velocity (m s^{-1}).

counterparts show slight declines correlated with the temperature anomaly trend.

The dynamic spindown processes within cyclonic rings result in a loss of total transport potential energy (Barrett, 1971) and are accompanied by corresponding anomaly reductions. In the case of the 1967 ring, these changes are manifested by decreases in the horizontal and vertical extents of the anomalies around the relatively stable central core. Figs. 3–5 present anomaly sections for the three cruises, CFD 156, A II 35 and A II 38. The decay of the ring is evident in the slight progressive diminution in anomaly sizes. Table 2 gives the areas contained within selected anomaly contours and reveals an initially higher rate of reduction (CFD 156 to A II 35), followed by a slower one (A II 35 to A II 38). Normalizing the areas to those for CFD 156[2] shows that the area within the −7°C contour drops by 24% at first and then continues to decrease by 6%. The areas for the salinity anomaly (−10‰) and heat deficit (4 cal cm^{-3}) decrease by 8 and 17%, respectively, and then become stable while the sound velocity (−20 cm s^{-1}) areal extent is reduced by 35 and 3%.

The anomaly sections for ring AL are shown in Fig. 6 and generally depict features larger than the 1967 ring. It is suspected (Richardson *et al.*, 1977) that the smaller companion eddy was in the process of splitting off from AL, a dynamic circumstance which could partially account for lower values of transport potential energy density anomaly and heat deficit relative to the 1967 ring. Considering AL, Table 1 does indicate that the maximum anomaly values are, on the average, 22% lower than the 1967 ring. Table 2 further shows weaker anomaly strength in terms of areal extents of the selected parameters. The temperature (−7°C) and salinity (−10‰) areas are approximately 70% smaller for AL. Assuming AL had no post-generation interaction with the Gulf Stream, two factors could contribute to these differences: seasonality within the NASW and the dynamic history of the Slope Water region prior to generation.

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[2] CFD 156 is a radial section and the areas used in these comparisons are calculated by doubling the computed values.

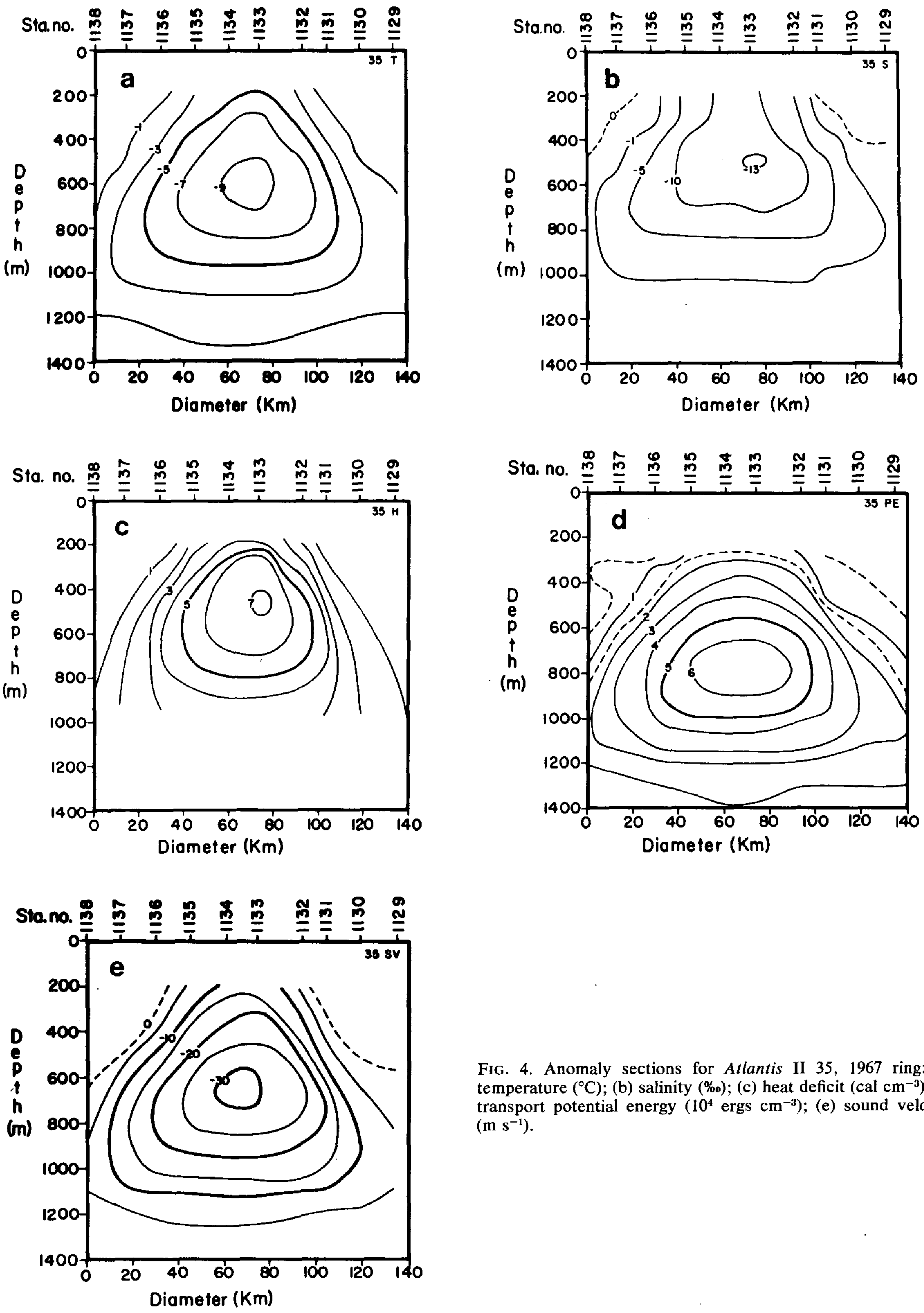

FIG. 4. Anomaly sections for *Atlantis* II 35, 1967 ring: (a) temperature (°C); (b) salinity (‰); (c) heat deficit (cal cm^{-3}); (d) transport potential energy (10^4 ergs cm^{-3}); (e) sound velocity (m s^{-1}).

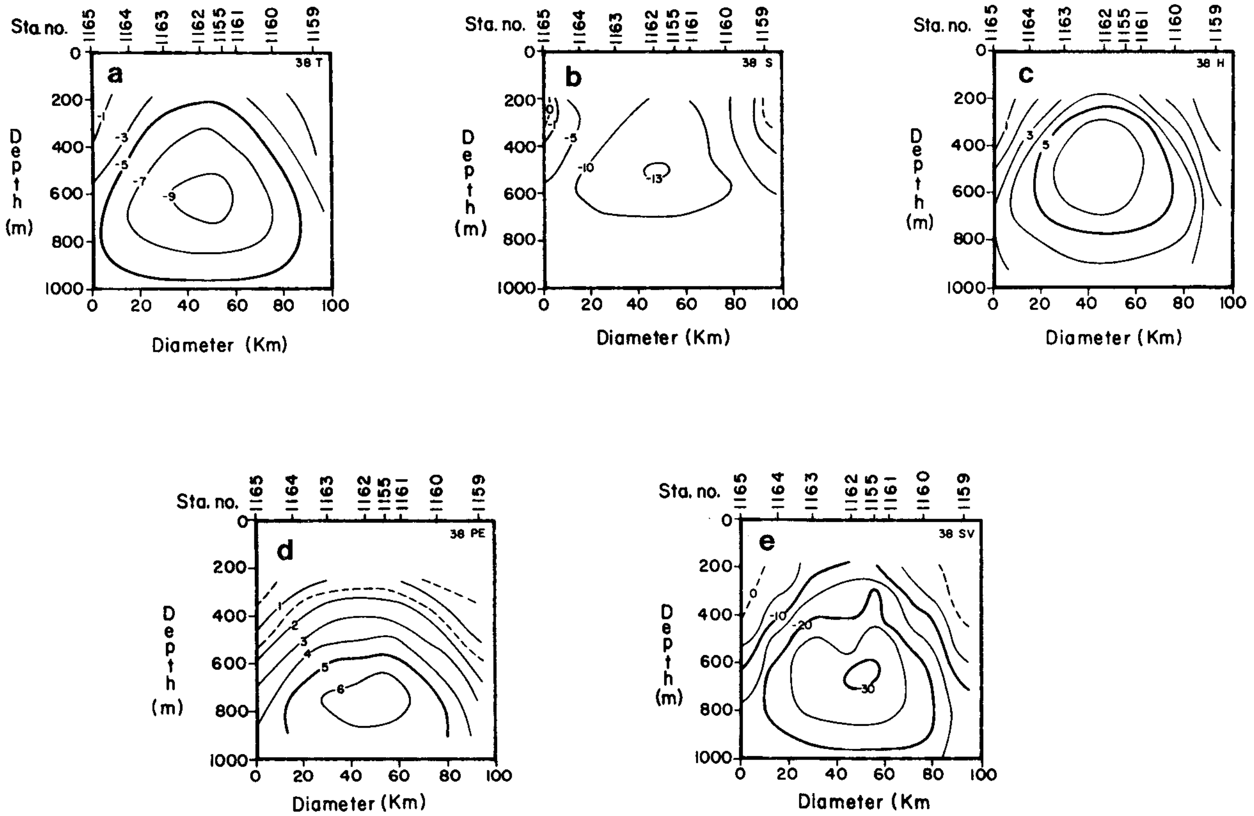

FIG. 5. Anomaly sections for *Atlantis* II 38, 1967 ring: (a) temperature (°C); (b) salinity (‰); (c) heat deficit (cal cm^{-3}); (d) transport potential energy (10^4 ergs cm^{-3}); (e) sound velocity (m s^{-1}).

The slope water temperature and salinity values given by Iselin (1936) for a depth of 550 m are 5.0°C and 35.0‰. If AL were generated in October, these values can be approximately compared, due to subsidence, to the standard station values at 600 m, i.e., 16.6°C and 35.3‰. The resulting anomalies would be (−11.6C°, −13‰) for the central core maximum values. However, we find (−7.6C°, −10.8‰) indicating that warmer and more saline waters are present in the ring AL core. In the upper layers, the summer slope water in the mid-Atlantic Bight has a greater range of temperatures and salinities (Wright and Parker, 1976) compared to winter values and we can expect a seasonal effect to be present in waters contributed to ring cores. Even so, an examination of the state of the slope water region in October 1976 reveals another possible source for ring AL. An anticyclonic ring, designated as Eddy H (Experimental Ocean Frontal Analysis, 1976) was immediately adjacent to the Gulf Stream meander that may have produced both AL and Eddy J. The inference is that a mixture of NASW and water from Eddy H formed a portion of the central core. This alternative explanation could account for the central anomaly values that are less than the expected values. Another explanation of these anomaly values is the possibility that ring AL may have been considerably older than the suggested two months. In such a case, the general subsidence and mixing within the core could produce these values.

A characterization of the slope water region off the Scotian shelf (McLellan *et al.*, 1952) indicates considerable variations in width and position of the seaward boundary, especially south of Grand Banks. The upper 200 m of the slope water can be composed of layered, low-salinity and Gulf Stream waters. Typical temperatures of 10–12°C and salinities of 35.3–35.5‰ are representative of the

TABLE 2. Areas contained within the contours of −7°C, −10‰, 4 cal cm^{-3} and −20 m s^{-1} anomaly values. The CFD 156 areas are computed by doubling the area found for the radial section.

Cruise	T_{-7} (km^2)	S_{-10} (km^2)	H_4 (km^2)	SV$_{-20}$ (km^2)
CFD 156	33	24	48	51
A II 35	25	22	40	33
A II 38	23	22	40	32
KN 48	10	6	33	32
KN 62	10	7	31	26

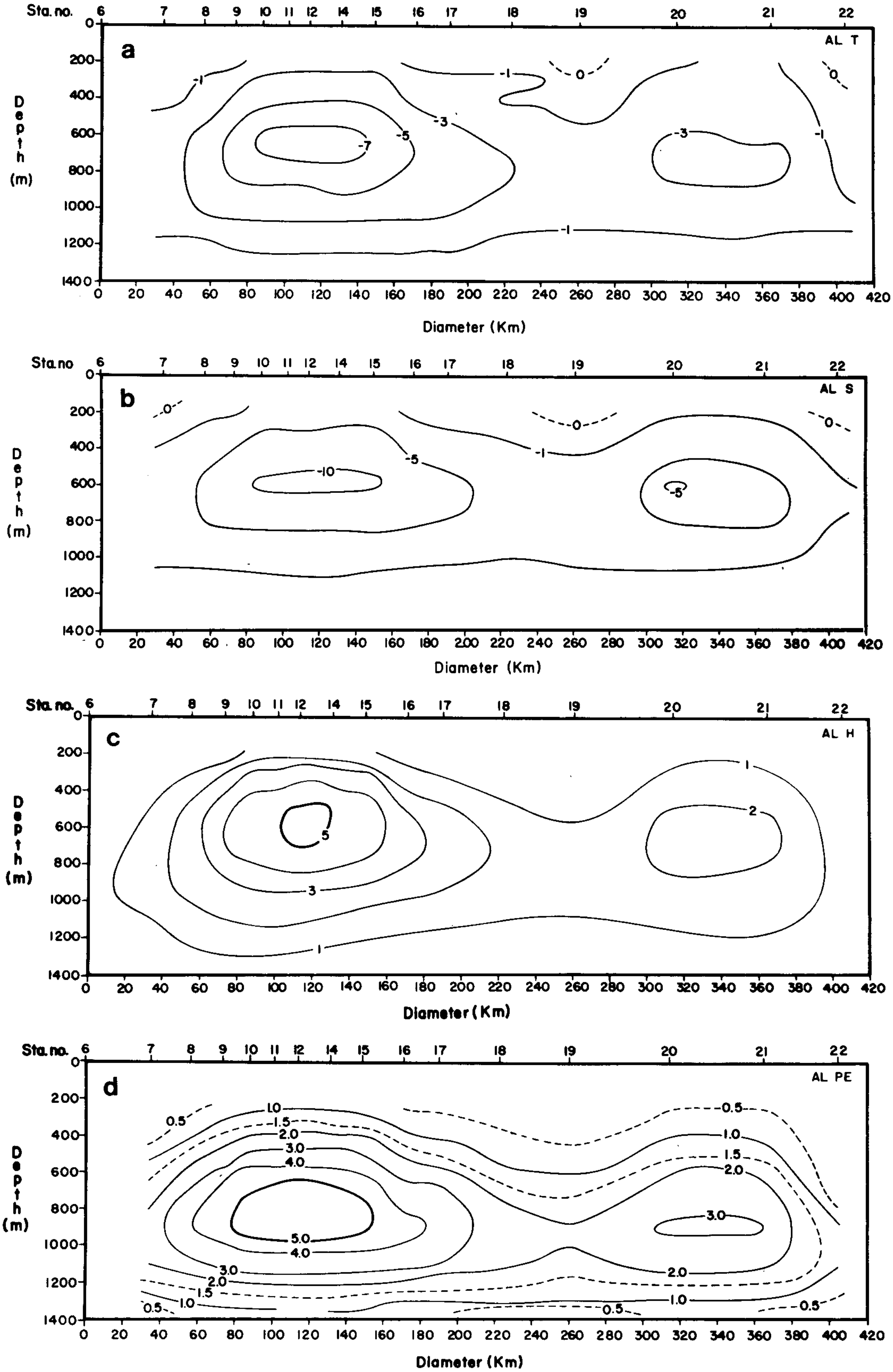

FIG. 6. Anomaly sections for *Knorr* 62, ring AL: (a) temperature (°C); (b) salinity (‰); (c) heat deficit (cal cm^{-3}); (d) transport potential energy (10^4 ergs cm^{-3}); (e) sound velocity (m s^{-1}).

200 m depth and Schroeder (1963) has shown a variation along the 50°W meridian from 3°C at 43°N to 15°C at 39°N in the average 200 m temperature. Since BBA was suggested to be one year old, we have examined hydrographic stations taken on C.S.S. *Baffin* cruise 4 in April 1963 (Canadian Oceanographic Data Centre, 1963). These stations correspond to the season and locale of the speculated generation region. The 15°C isotherm at 200 m crossed 50°W at approximately 40°30′N and slope water was in residence northward from this position to Grand Banks with the Gulf Stream extending southward. Fig. 7 presents the curves of temperature vs depth for *Baffin*-4, station 11, at 41°N, 50°W in the slope water and *Knorr*-48, station 610, at 34°17′N, 62°40.5′W which was at the center of BBA. Simple subsidence of the 10°C isotherm [290 m/365 days] indicates a rate of 0.8 m day^{-1} which corresponds well with Parker's observation of 0.6 m day^{-1} for the 1967 cyclonic ring and implies that BBA generation in this region was possible. The corresponding salinity, 35.3‰, also yields subsidence at 0.8 m day^{-1}. Fig. 8 presents contoured anomalies for BBA. BBA shows a maximum temperature anomaly of −5°C at 400 m compared to −9°C for the 1967 ring (CFD 156) at the same depth. Based on *Baffin* station 11, estimates for BBA's original maximum anomaly at 400 m can be approximated at −13°C. Thus, the anomalies calculated for BBA a year after generation and its possible initial state suggest that this ring initially had anomalies at least as strong as those observed in the 1967 ring. Comparisons of anomalies for BBA and the 1967 ring are remarkably similar to those presented for ring AL. The contoured anomalies further reveal a strong structural resemblance between BBA and ring AL. The maximum anomalies presented in Table 1, as well as areal ranges for various values in Table 2, are in extremely close agreement. The similarity observed in these anomalies can be explained on the basis of age, location and seasonal differences for the generations. Although AL may have been comparatively much younger than BBA, it evolved from slope water of higher temperatures and salinities for any given depth due possibly to the influence of summer warming and entrainment of water from anticyclonic rings within the slope water region. Another consideration is that BBA may have experienced topographic interactions along its drift path in the Sargasso Sea which induced reductions in the anomaly strengths and areal distributions.

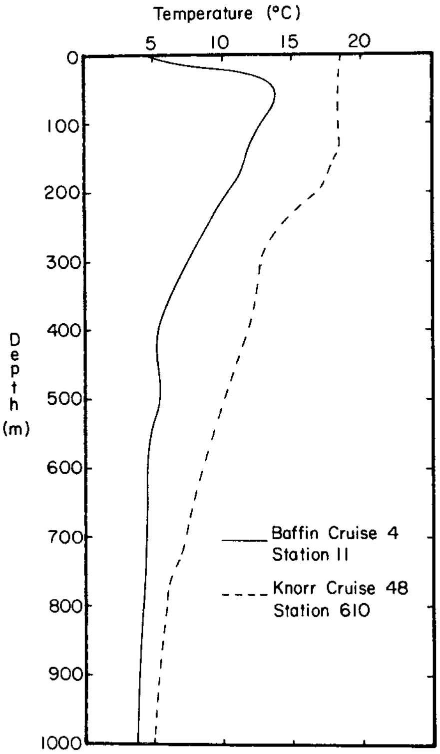

FIG. 7. Temperature-depth profile for *Baffin* Cruise 4, station 11, 41°N, 50°W and *Knorr* Cruise 48, station 610, 34°17′N, 62°40.5′W.

5. Conclusions

In order to examine the factors involved in anomaly variations, representative *T-S* diagrams were compiled for the formation region of AL and the 1967 ring. The data was selected from the U. S. Coast Guard Standard Section 5 and the Gulf Stream '60 surveys (Fuglister, 1963). *T-S* relations between 50 and 300 m were plotted for the geographic region between the 1000 m isobath and the 15°C/200 m contour and between 60 and 70°W. Data for April, January to February and October to November for several years were plotted separately and compared. The outlined area in Fig. 9 encompasses all of the 50–300 m *T-S* points for the April data from *Atlantis* 255, *Crawford* 40 and USCGC *Yakutat* A5-7 cruises in the region. The warm, saline branch of the curve is from the Gulf Stream stations while the fresh, cold branch is from the near shelf sections in the upper levels. The remainder is characteristic of depths greater than 200 m across the entire region with stations near the Gulf Stream exhibiting higher salinity in general. As one would expect, seasonal influences are not readily apparent in the data considered with the exception of the shelf branch where the variations are of the order of 2–3°C. In fact, the variations between individual sections in April are as large as those existing in comparisons with other months. This is especially true in the region adjacent to the stream where fresh waters are evident in several of the sections.

The solid *T-S* curves in Fig. 9 represent ring core stations for CFD 156, A II 35, AL and BBA.

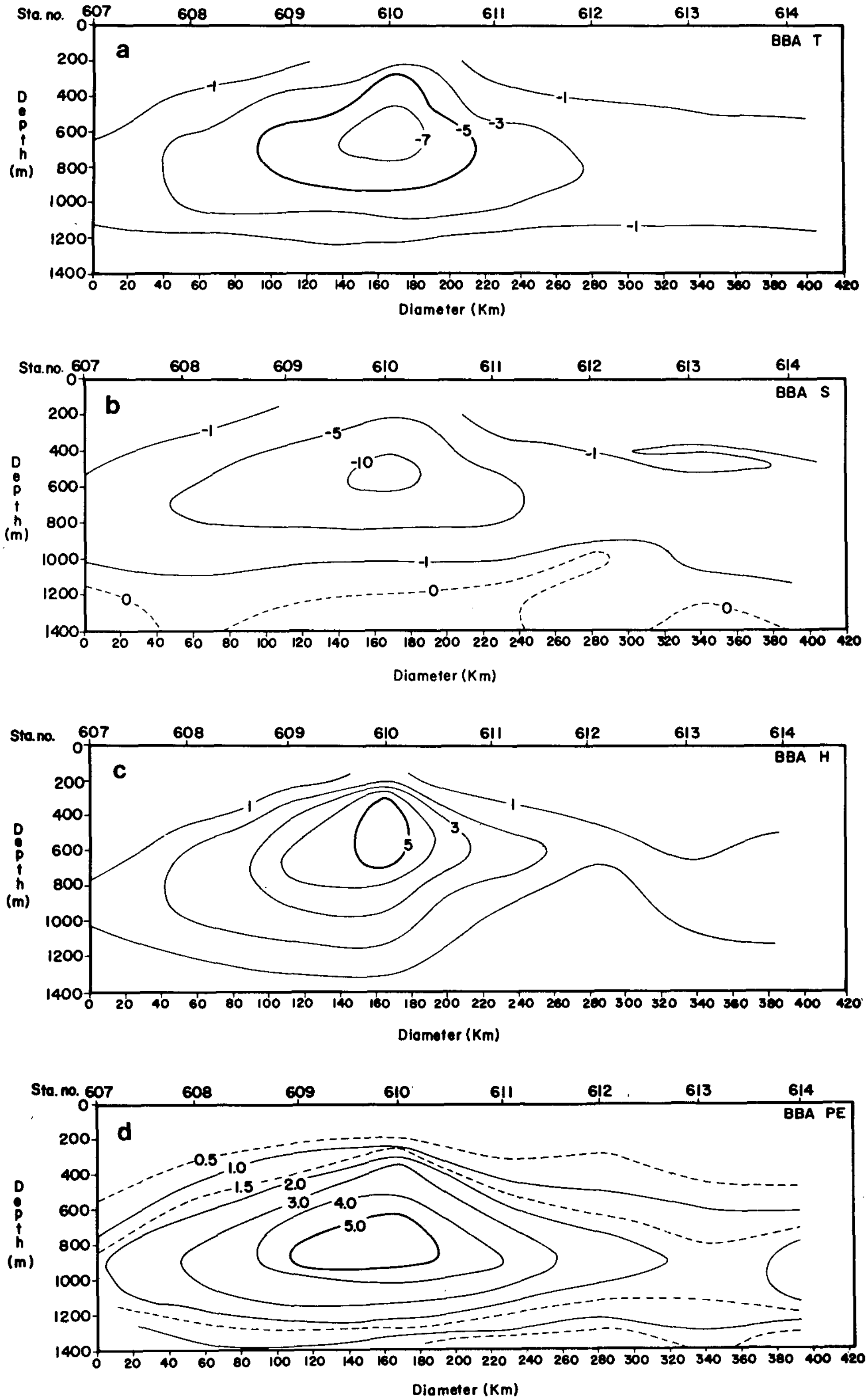

FIG. 8. Anomaly sections for *Knorr* 48, BBA: (a) temperature (°C) (b) salinity (‰); (c) heat deficit (cal cm^{-3}); (d) transport potential energy (10^4 ergs cm^{-3}); (e) sound velocity (m s^{-1}).

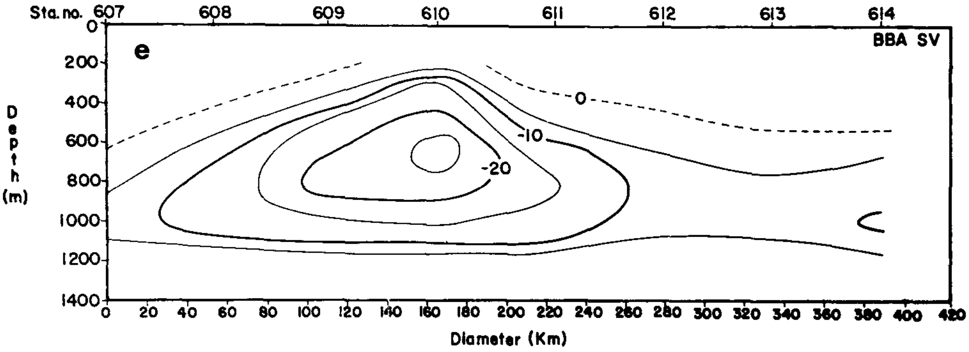

FIG. 8 (*continued*).

When compared to the C 7, station 35 curve, the largest *T-S* anomalies appear along a set of isopycnals around $\sigma_T = 26.8$ kg m^{-3}. The isopycnal follows the shelf branch of the *T-S* composite for the formation region. This suggests that interior slope and shelf water composites form ring cores. Further, comparisons with individual stations near the edge of the stream indicate that the presence of intermediate cold, fresher patches of water along the stream could also contribute to the variations in the ring cores at formation. Since the slope branch of the 60–70°W slope waters is very similar to those in Wright and Parker's census (1976), these patches could occur at any location throughout the region of ring formation. A summary of reports of these features can be found in Parker (1976) as well as Kupferman and Garfield (1977). The juxtaposition of the standard curve and KN 62 station 13 may indicate one effect an anticyclonic ring can have on the interior water mass of a cyclonic ring. This case would be a direct contribution of warm, saline waters. An anticyclonic ring could also indirectly affect the interior of a cyclonic ring by sweeping a shelf water mass seaward

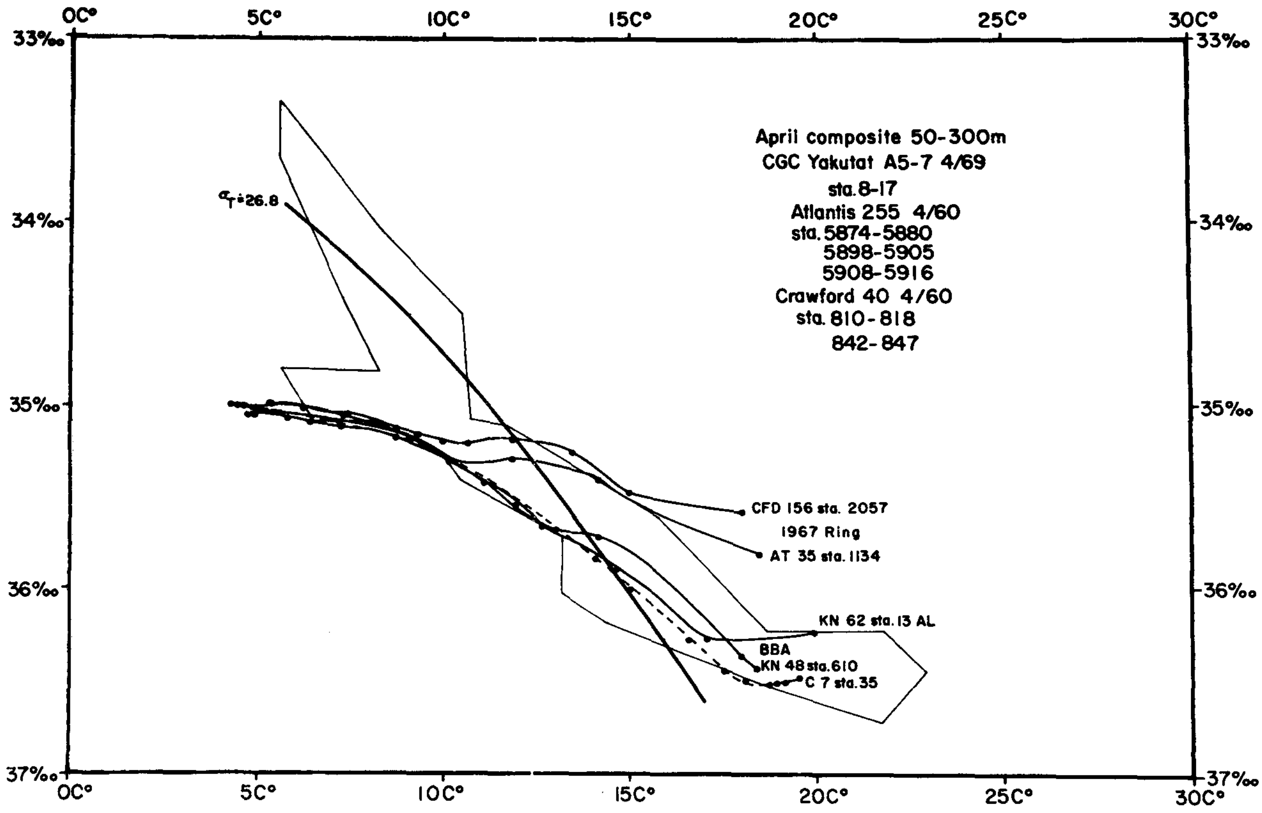

FIG. 9. *T-S* diagrams for the slope water formation region.

in its lee where these cold and fresh components enter a generating meander.

In conclusion, we suggest that the characteristics of the slope water masses of cyclonic rings are strongly dependent on the prior dynamic history of the generation regions. Seasonal differences may act to modify surface slope waters, but do not appear to significantly influence the intermediate and deeper waters. Therefore, it is difficult to characterize and categorize rings simply on the basis of generation location and seasonality. A more complete understanding of a ring's evolution requires a detailed study of the slope water variability present during its formation.

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