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In spring and fall 1985, air expendable bathythermograph surveys of a large area off the northeast coast of South America revealed an extensive field of subthermocline thermal staircases which is probably the site of vigorous salt fingering. During both seasons the staircases were shallowest in the south (180-360 m) and deepest in the northwest (420-650 m), occurring on the average between the 8 degree and 13 degree C isotherms. Typically, each staircase consisted of 10 well-mixed layers with average thickness of 16 m and average interlayer temperature change of 0.52 degree. Thicker layers seemed to be associated with larger temperature changes. No seasonal variation in these parameters was observed. The interfaces separating the layers had a modal thickness of 2 m, with interfaces in the spring tending to be thinner than in the fall. The region bounded by 10 degree-14 degree N, 52-57 degree W tended to have staircases with more layers, thicker layers, and larger interlayer changes. The sharp northeastern staircase field boundary occurs at the confluence of the Subtropical Underwater and the Antarctic Intermediate Water, suggesting that the staircases**

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Properties of Thermal Staircases off the Northeast Coast of South America, Spring and Fall 1985

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In spring and fall 1985, air expendable bathythermograph surveys of a large area off the northeast coast of South America revealed an extensive field of subthermocline thermal staircases which is probably the site of vigorous salt fingering. During both seasons the staircases were shallowest in the south (180–360 m) and deepest in the northwest (420–650 m), occurring on the average between the 8° and 13°C isotherms. Typically, each staircase consisted of 10 well-mixed layers with average thickness of 16 m and average interlayer temperature change of 0.52°. Thicker layers seemed to be associated with larger temperature changes. No seasonal variation in these parameters was observed. The interfaces separating the layers had a modal thickness of 2 m, with interfaces in the spring tending to be thinner than in the fall. The region bounded by 10°–14°N, 52°–57°W tended to have staircases with more layers, thicker layers, and larger interlayer temperature changes. The sharp northeastern staircase field boundary occurs at the confluence of the Subtropical Underwater and the Antarctic Intermediate Water, suggesting that the staircases may be formed in this region and then extend south and west to form the rest of the field.

INTRODUCTION

The Caribbean Sheets and Layers Transects (C-SALT) program was conducted off the northeast coast of South America in spring and fall 1985 [*Schmitt*, 1987] as a multiscale investigation of the extensive thermohaline staircases that are a common feature of the subthermocline in the region [*Delnore and McHugh*, 1972; *Mazeika*, 1974; *Perkins and Saunders*, 1982; *Zhurbas and Ozmidov*, 1983; *Bruce et al.*, 1984; *Boyd and Perkins*, 1987]. The staircase phenomenon is characterized by a vertical temperature, salinity, and density structure in which 5- to 50-m-thick well-mixed consecutive layers are separated by several-meter-thick interfaces across which temperature, salinity, and density change rapidly. Double diffusion of the salt-fingering form is commonly thought to be the causative mechanism, with the salt fingers presumed to lie within the high-gradient interfaces.

It is hypothesized that such staircases, which have also been observed under the Mediterranean Outflow [e.g., *Elliott et al.*, 1974], in the Tyrrhenian Sea [e.g., *Johannessen and Lee*, 1974], and in the northwest Caribbean [*Lambert and Sturges*, 1977], represent sites of double-diffusively enhanced vertical mixing between relatively warm, salty water above the staircases and cooler, fresher water below. In this region off South America the warm, salty water is the subsurface salinity maximum of the Subtropical Underwater, or SUW [*Defant*, 1961] (terminology from *Wuest* [1964]) centered around 100 m, and the cooler, fresher water is the Antarctic Intermediate Water, or AAIW [*Wuest*, 1978] (terminology from *Pickard and Emery* [1982]) with its core at about 750 m. *Boyd and Perkins* [1987] have summarized the findings from 1969 through 1983, while *Schmitt et al.* [1987] and other articles in the same issue of *Deep-Sea Research* give an overview of the 1985 C-SALT project and some of the initial results.

As part of C-SALT, two large-area air expendable bathythermograph (AXBT) surveys were conducted during both of the 1985 spring and fall field phases to investigate the extent and characteristics of the staircase field and to determine the mesoscale flow patterns. This paper presents findings on the horizontal and vertical extent of the staircases during C-SALT, their statistical properties, and their relationship with the mesoscale flow.

DATA ACQUISITION AND PROCESSING

A survey of the historical reports of staircases in this area showed that the most likely region in which to find the thermohaline layering was 5°–18°N, 46°–60°W, a region covering nearly 1.2×10^6 km^2 (Figure 1). The large extent over which the features might be found meant that the only feasible way of obtaining complete synoptic coverage was with large-area aircraft surveys. The flights covered a region 1900 km by 1400 km in extent and were designed to include the historical composite region plus a generous margin (Figure 1). Because of an aircraft mechanical problem, the first phase of the work took place over two periods in spring 1985, including 2 weeks in late March and 1 week in early May. The second phase occurred during the main C-SALT field operations in October 1985. Both shallow (nominally 305 m) and deep (nominally 760 m) AXBTs were dropped between 55 and 110 km apart to provide a grid of subsurface temperature data to a maximum depth of nearly 800 m. The navigation equipment included a Litton 72 inertial navigation system and a Litton 211 VLF/OMEGA system, with an accuracy of 1–2 n. mi (1.8–3.7 km). The drop positions are considered accurate to 1.5 times the navigational accuracy, about 3 n. mi or 5.5 km.

The data were collected using a microcomputer based data collection system at a resolution of 15 (fall) to 20 (spring) cm. The so-called spatial resolution of the AXBT (time constant times fall rate) is comparable, about 15 cm. (The vertical resolution for the air-deployed probe is better than for the shipboard XBT because the AXBT probe has a blunter nose than the shipboard version and the fall rate is slower, approximately 1.5 m s^{-1}.) Editing of the data involved discarding beginning and ending transients, linear interpolation across regions of noise from radio frequency interfer-

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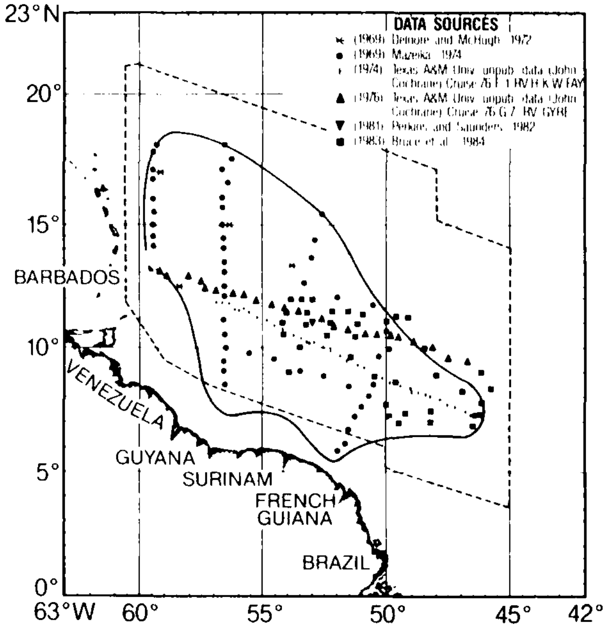

Fig. 1. Reports of thermohaline staircases in the study area, 1969–1983. The heavy line encloses the historical composite region deduced from these observations; the dotted line encloses the area over which the aircraft surveys were conducted.

ence, application of improved temperature and depth conversion equations [*Boyd*, 1986, 1987], and filtering and decimation of the data at 0.5-m (statistical analysis) and 2-m (mesoscale analysis) intervals. The individual profiles are accurate to about 0.2°C in temperature and 5 m in depth [*Boyd*, 1986, 1987], although the precision is perhaps an order of magnitude better (since individual profiles generally were inaccurate by a constant offset, especially in temperature and over large ranges in depth). One hundred eighty-four deep and 35 shallow profiles were obtained from the spring flights, and 260 deep and 45 shallow profiles were obtained from the fall. Complete details on the data acquisition and processing are given by *Boyd* [1986].

The mesoscale flow was estimated from maps of dynamic height anomaly referenced to 700 dbar. Although temperature-salinity (T-S) relationships in the area are usually quite tight, the region is one of relatively strong horizontal salinity gradients. To account for this to some extent, the 5° square historical potential temperature–salinity (θ-S) relationships from *Emery and Dewar* [1982] were used to assign salinities to temperature values and then dynamic height anomalies, and geostrophic currents were estimated relative to 700 dbar, the deepest reference level for which a sufficiently large number of AXBT profiles existed (pressure was estimated from depth using the method of *Saunders* [1981]). The flow field findings, however, are quite insensitive to salinity variations, since virtually identical conclusions were reached by examining depths of isotherms and by using a mean θ-S curve.

RESULTS

Location of Staircases

Examples of typical temperature profiles from the region are shown in Figure 2. They may be classified into three categories: strongly developed staircases (five or more well-mixed layers greater than 5 m in thickness), weak staircases (one to four well-mixed layers), or no staircases. While subjective, the classification scheme is quite robust. Only a

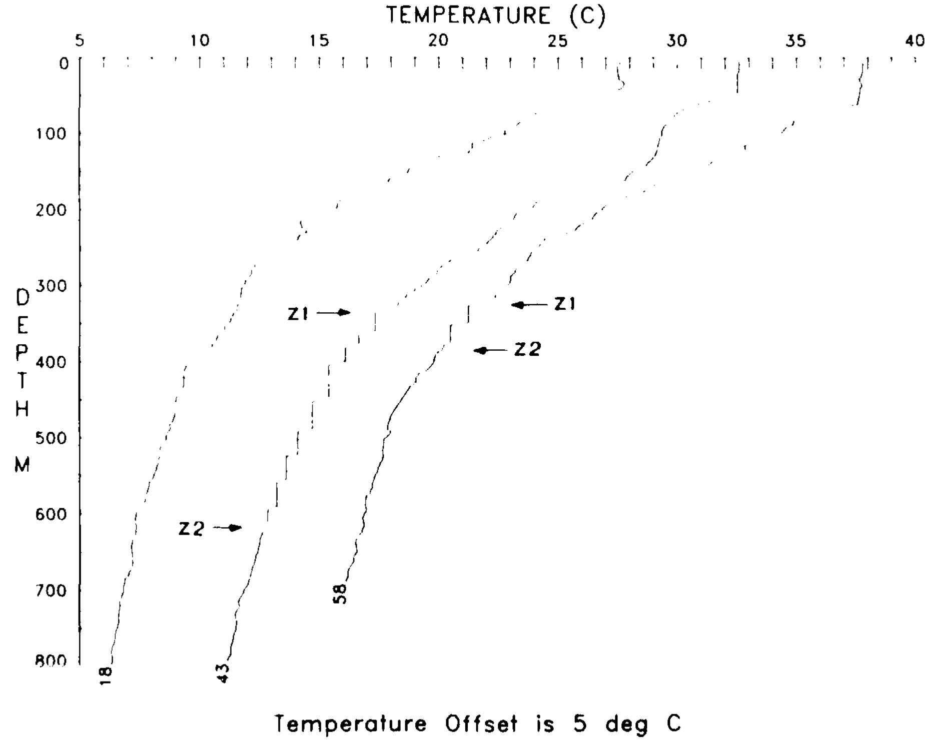

Fig. 2. Offset temperature profiles illustrating strongly developed staircases (43), weakly developed staircases (58) and a profile from the region showing no staircases (18). The points taken as the beginning ($z1$) and ending ($z2$) depths of the staircases are indicated.

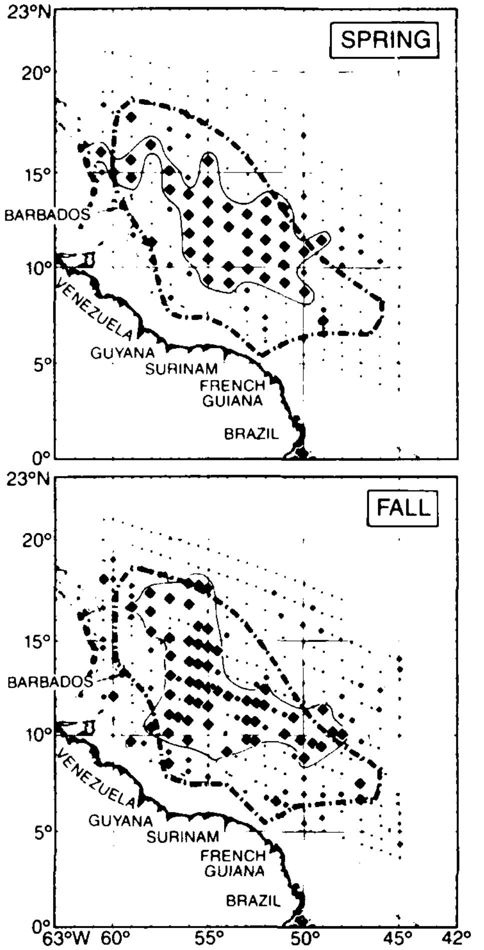

Fig. 3. Location of the large-scale thermal staircases, spring and fall 1985. Large diamonds indicate strong layering, small diamonds weak layering, and dots no layering. The main staircase field was enclosed within the solid line, while regions of less well developed staircases fell within the dashed lines. The historical composite location from Figure 1 is indicated by the dash-dot line.

few profiles from each period might be considered equivocal, and changing their classifications would not change the conclusions. In addition, usually the depths at which the staircases began (z_1) and ended (z_2) were well defined to within 10 m or less (Figure 2).

The resultant pictures of the extent of the spring and fall staircase fields (Figure 3) are somewhat different, but both fields clearly fell largely within the historical composite region. However, rather extensive areas of weak layering occurred east of the composite region boundary between 8° and 12°N during both time periods. Within this latitudinal range, the composite location boundary probably should be revised to extend somewhat farther to the east than is indicated in Figures 1 and 3.

In spring 1985, the main body of the step field extended northwestward from 7°N, 49°W to at least 16°N, 60.5°W, the westward limit of the flights. By and large the strongly developed steps fell within a very well defined area, and no "holes" (regions with no staircases) were observed within this area with the aircraft data, although data from the concurrent ship operations showed occasional small "holes" (R. Schmitt, personal communication, 1985). Weak but identifiable steps occurred outside portions of the boundary of the strongly developed steps, especially to the northeast and southwest. The transition from no thermal steps to strongly developed steps was very abrupt at the central northern and southeastern boundaries. The well-developed layers covered an area of some 0.5×10^6 km^2, with weaker staircases occurring over an additional 0.43×10^6 km^2.

By fall the field was constricted between 48° and 54°W to lie between 8° and 12°N, and then extended farther west and north than in the spring. Again the strongly developed steps fell predominantly within a well-defined area, although some "holes" and weak steps were found among the otherwise well developed staircases. *Schmitt et al.* [1987] found that layers could, at times, be traced unambiguously through imbedded regions of no or poorly developed staircases. Regions of weaker steps extended out to the northeast and southeast and to the northwest and southwest. The transition from no steps to strongly developed steps along most of the northern boundary was again abrupt. The main staircase field covered about 0.6×10^6 km^2, and less well developed layers included another 0.41×10^6 km^2.

The depth of occurrence of the staircases showed a strong geographical dependency (Figure 4) which follows the regional depth trend of the isotherms. Staircases in the southeast corner were the shallowest, especially in the spring, lying on the average between about 180 and 360 m. The field deepened to the northwest to roughly 420 to 650 m. Wide variations in beginning and ending depths occurred, even between stations only 60 or so kilometers apart. Overall, staircase depths depended more on latitude than on longitude. Two-dimensional linear regressions indicated that the beginning depth of the staircases increased to the north at a rate of 25.0 and 29.4 m per degree of latitude in the spring and fall, respectively, but increased to the east at a rate of only 2.9 and 0.2 m per degree of longitude. The termination depth of the steps increased northward at a rate of 32.6 and 39.5 m per degree of latitude but increased westward at only 1.8 and 3.4 m per degree of longitude.

Staircase Statistics

Detailed analysis of the spring and fall profiles allowed construction of relative frequency distributions for a number of important statistical properties of the staircases (Figures 5–14). Kolmogorov-Smirnov tests of the various distributions showed most to be statistically identical (at a significance level of $\alpha = 0.05$) in both the spring and fall, the sole exception being the frequency distribution of interface thicknesses. With that one exception, the data are presented as pooled distributions. None of the distributions were found to be Gaussian when tested with a Lilliefors test at $\alpha = 0.05$. The horizontal coherency of some layers noted above implies that a certain unknown percentage of the observations used in calculating the following statistical properties are not independent. However, the extensive geographic area over which the observations were drawn and the large number of observations (and hence degrees of freedom) for the statistical calculations, ranging from 110 to 946, means that the findings are unlikely to be much affected by lack of independence of some of the observations. This topic is addressed further in the last section.

The staircases tended to begin at about 13°C (mean of 12.9°, standard deviation of 1.2°C) and to end at about 8° or 9°C (mean of 8.6°, standard deviation of 0.96°C) (Figure 5).

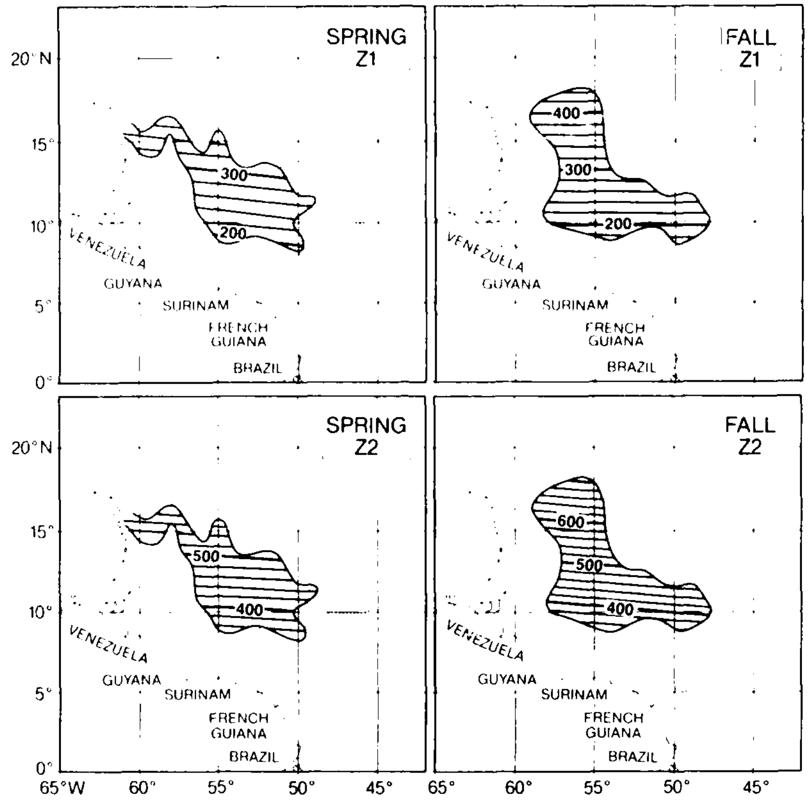

Fig. 4. Average beginning ($z1$) and ending ($z2$) depths of the staircases in meters.

This implies that the bulk of the staircase field lay between the 26.8 and 27.1 isopycnals, if the θ-S relationship for region 4 of *Emery and Dewar* [1982] is used to estimate salinities. The distributions are positively skewed and are leptokurtic (i.e., relatively peaked in the center, compared with a Gaussian distribution).

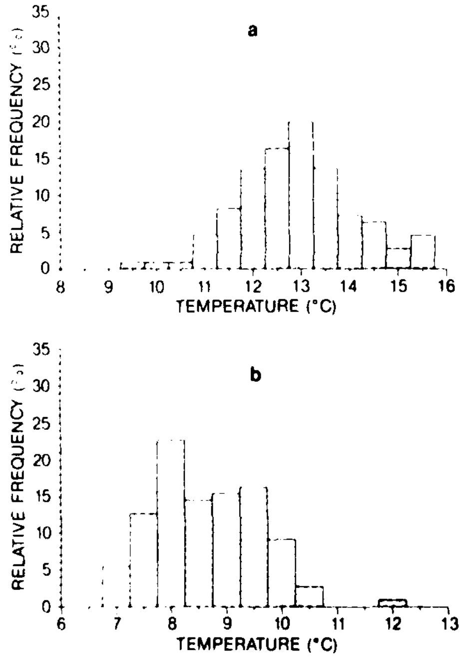

Fig. 5. Distributions for the temperatures at which the well-developed staircases (a) began and (b) ended.

The most frequently observed number of well-mixed layers in a staircase was 9 or 10, with 11–12 and 7–8 also being common (Figure 6). The average number was 9.6 ± 2.9. The distribution is well described by a Poisson distribution with a mean of about 10 layers per profile (verified using a Kolmogorov-Smirnov test with $\alpha = 0.05$). The largest number of layers per profile tended to occur between 10°–14°N, 52°–57°W, which will be referred to as the core of the staircase region (Figure 7).

The frequency distribution for the thicknesses of the well-mixed layers tended to be bimodal (Figure 8). One common range of sizes was about 2–6 m and another was perhaps 14–19 m, although the larger steps were broadly distributed over a wide range of sizes. The mean layer size was 16.0 ± 9.5 m, and the largest layer encountered (in the fall) was 48 m thick. The distribution was strongly non-Gaussian and was positively skewed and platykurtic (i.e., relatively flat, compared with a Gaussian distribution).

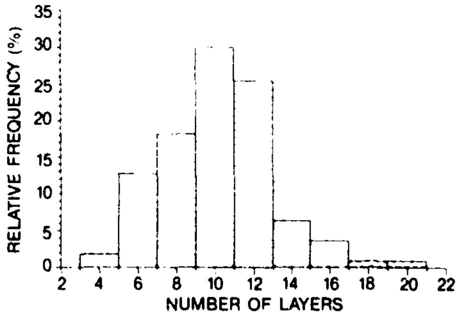

Fig. 6. Distribution for the number of layers within the well-developed staircases.

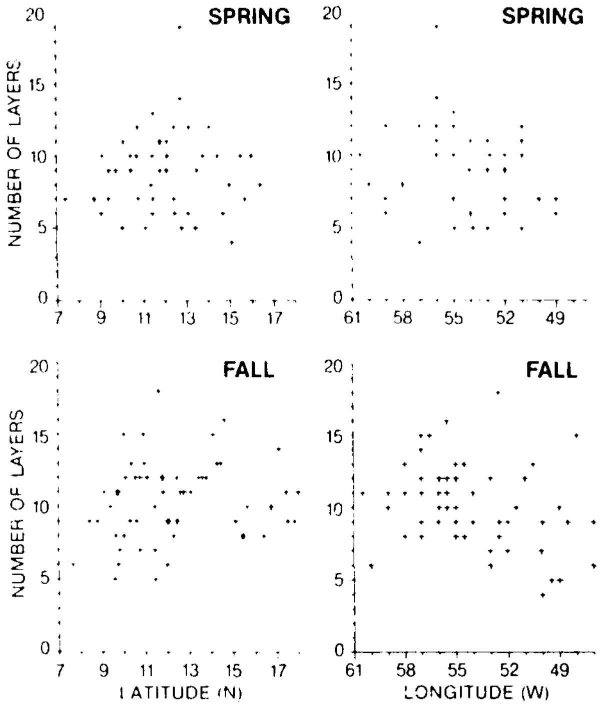

Fig. 7. The number of layers within a staircase as a function of latitude and longitude. Staircases between 10–14 N, 52–57 W tended to have the largest number of layers.

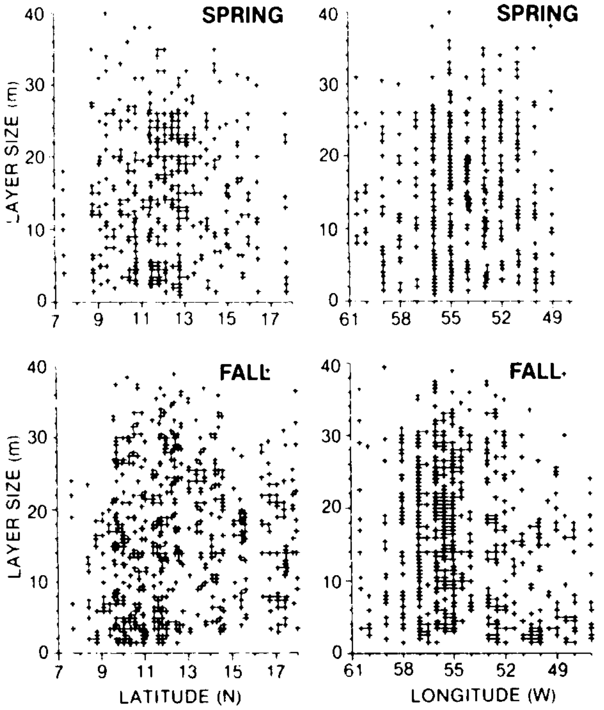

Fig. 9. Size of the layers as a function of latitude and longitude. The largest layers tended to lie between 10–14 N, 52–57 W.

There was a tendency for the staircases within the core region to have thicker layers as well as a larger number of layers (Figure 9).

The relative frequency distribution for interface thicknesses was the one distribution not statistically identical in the spring and fall (Figure 10). For both the pooled and the seasonal distributions, however, the most common interface thickness was about 2 m (1.75–2.25 m). The mean thickness for the pooled data was 5.1 ± 4.5 m (4.2 ± 3.0 m for spring and 5.6 ± 5.2 for fall). However, from compiling these data it was clear that most interfaces thicker than several meters had interior structures within them which suggested the presence of unresolved smaller scale layers and interfaces. Therefore the mode is probably more representative of the typical interface thickness than the mean. (*Boyd and Perkins* [1987], *Gregg and Sanford* [1987], and *Marmorino et al.* [1987] made similar observations of internal interfacial structure). No particular relationship between interface thickness and latitude or longitude was observed. The differences between the spring and fall distributions seemed to lie in the smaller percentage of thinner interfaces (2.5–5 m) and the larger percentage of thick interfaces (10.25 m and larger) in the fall.

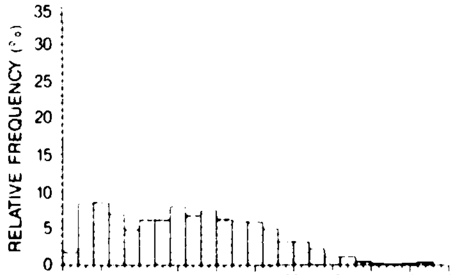

Fig. 8. Distribution for the thicknesses of the well-mixed layers.

The most common temperature change across the interfaces was about 0.4°C, with a mean of 0.52° ± 0.25°C (Figure 11). The frequency distribution was positively skewed and leptokurtic. Actual values ranged from 0.1° (or less) up to 1.5°C. A weak tendency existed for the larger temperature changes to lie within the core region (Figure 12). Larger temperature changes appear to be associated with thicker interfaces (Figure 13); however, the relationship may be spurious. As mentioned earlier, many thick interfaces had interior features that, with better resolution, probably would have been tabulated as multiple layers and interfaces.

The tendency for larger temperature changes to be correlated with larger mean layer sizes (Figure 14) is less equivocal than the relationship with the interface thicknesses because less ambiguity existed in measuring layer sizes. Up to about 0.8° or 0.9°C, larger temperature changes are associated with larger step sizes. Laboratory experiments suggest that larger temperature changes across interfaces correlate with larger vertical heat and salt fluxes [*Schmitt*, 1979*b*; *McDougall and Taylor*, 1984], although the evidence is complicated by differences between the open ocean and laboratory situations [*Boyd and Perkins*, 1987]. However, if true even to some extent, the larger step sizes associated with the core of the staircase region, 10°–14 N, 52°–57°W, suggest a regional maximum in vertical fluxes there.

RELATIONSHIP TO THE MESOSCALE FLOW

The mesoscale flow was investigated at three crucial levels: at the level of the salinity maximum of the Subtropical Underwater, at the staircase level, and near the level of the salinity minimum of the Antarctic Intermediate Water.

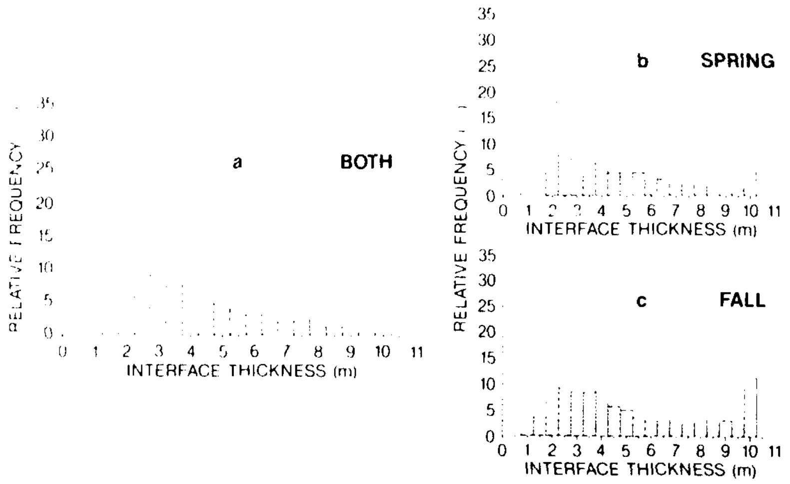

Fig. 10. Distributions for the thicknesses of the interfaces separating the well-mixed layers: (*a*) pooled spring and fall data; (*b*) spring data, and (*c*) fall data.

The flow fields were approximated using dynamic topography maps (relative to 700 dbar) at 100 dbar, 300 dbar, and 600 dbar, respectively (Figures 15 and 16). The inferred current patterns are robust, depending little on assumed salinity values and being supported by conclusions drawn from examining depth of isotherm plots.

The 100-dbar level, near the core of the Subtropical Underwater corresponds to the main thermocline, which in the region has its strongest gradients between about 80 and 200 m. The currents in this depth range are better known closer to the coast of South America. Quite near the coast is the subsurface part of the northwestward flowing North Brazil Current (NBC). Portions of the NBC loop back to the east in the subsurface sections of the Amazon and Demerara anticyclones [*Metcalf and Stalcup*, 1967; *Cochrane*, 1975; *Cochrane et al.*, 1979; *Bruce and Kerling*, 1984]. Only the more northerly eddy, the Demerara Anticyclone, falls within the C-SALT area, and a part of it can be seen outlined by the 70 dyn cm contour in Figure 16. The eddy was not observed in spring (Figure 15), nor was there any sign of the NBC in either season, although the aircraft studies may not have extended close enough to the coast to see the NBC.

The thermocline current regime away from the coast is less well known. *Cochrane* [1975], *Cochrane et al.* [1979], and *Bruce and Kerling* [1984] all show evidence in this depth range of the southern portion of the westward flowing North Equatorial Current looping around back to the east near 9 N, 46 W, to join the eastward flowing North Equatorial Countercurrent in what *Cochrane* [1975] called the "Main Countercurrent Trough." A strong, westward-shifted version of this loop is outlined by the 72 (spring, Figure 15) and then by the 68 (fall, Figure 16) dyn cm contours in the figures.

North and west of 20 N, 45 W, the salinity maximum of the Subtropical Underwater enters the area from the northeast, penetrating south to perhaps 15 N [*Defant*, 1981], and then flowing south and west through the passages of the Lesser Antilles [*Wuest*, 1964] and north and west as the Antilles Current to the north of the islands [*Wuest*, 1964; *Defant*, 1981]. The spring and fall pictures of the thermocline flow (Figures 15 and 16) confirm this view. The Subtropical Underwater enters the area from north of 14 N, passes through the region, and exits either through the Lesser

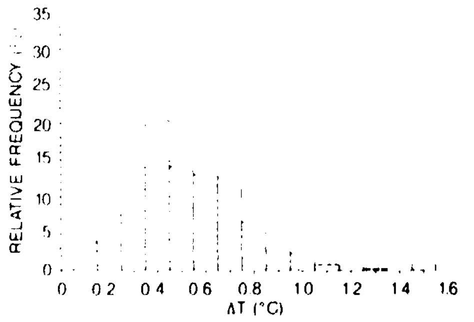

Fig. 11. Distribution for ΔT, the temperature change across the interfaces between the well-mixed layers.

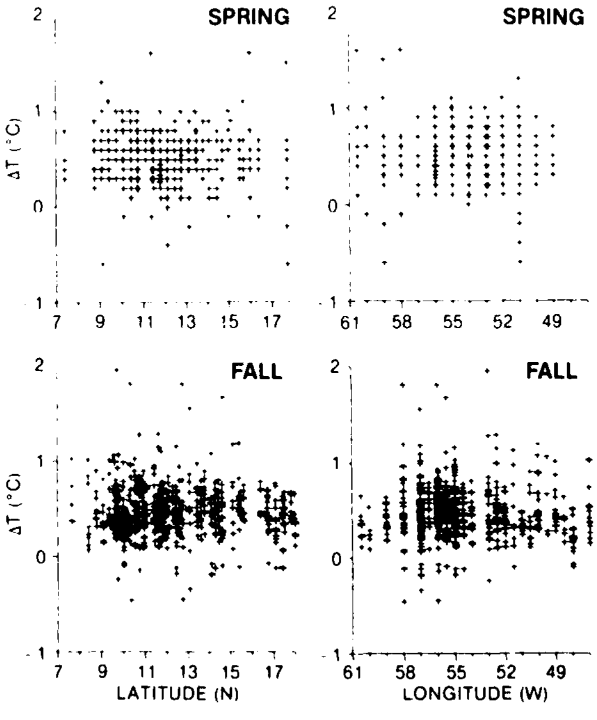

Fig. 12. Size of ΔT, the temperature change across the interfaces between the well-mixed layers, as a function of latitude and longitude.

Antilles or heads more northwest as part of the Antilles Current. South of 14°N the flow comes more from the east or southeast from the North Equatorial Current, with a substantial portion of the flow entering the North Equatorial Current Loop and returning to the east. The spring regime has a larger southerly component than the fall regime.

Very little information exists on the currents in the depth range of the staircases, about 200–500 m (the subthermocline). Hydrographic studies have shown, however, that North Atlantic Central Water lies north of about 18°N, South Atlantic Central Water lies south of 10°N, and transitional waters fill the intervening region [*Broecker and Ostlund*, 1979], the latitude range of the best developed staircases. From Figures 15 and 16 it appears that the flow entering from the east separates around 14°N into a northerly component coming from the north-northeast and a southerly component from the east-southeast. One could conclude from these data that the main staircase field is associated somewhat more with the waters from the east-southeast which might be expected to have a greater admixture of South Atlantic Central Water, but if true, the significance of this is unclear.

The final flow regime, between about 500 and 1000 m, is that associated with the Antarctic Intermediate Water. *Wuest* [1978] called it the Subantarctic Intermediate Current (SAIC). He described the local salinity minimum of this flow, the Antarctic Intermediate Water itself, as moving northwest parallel to the coast and not far off the continental slope up to around 60°W, at which point he tentatively identified secondary branches breaking off from the main flow. The main flow he thought continued on north and west of the Lesser Antilles, with another significant component heading through the islands into the Caribbean and still lesser branches heading off to the north-northeast [*Wuest*, 1964, 1978]. Aside from his work, little else is known about these current patterns.

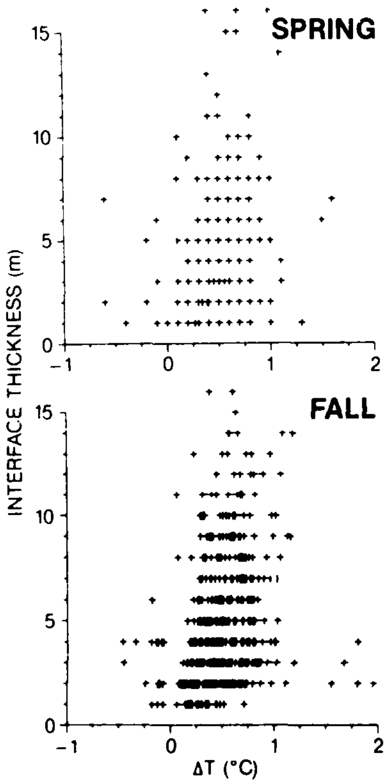

Fig. 13. Size of ΔT, the temperature change across the interfaces between the well-mixed layers, as a function of interface thickness.

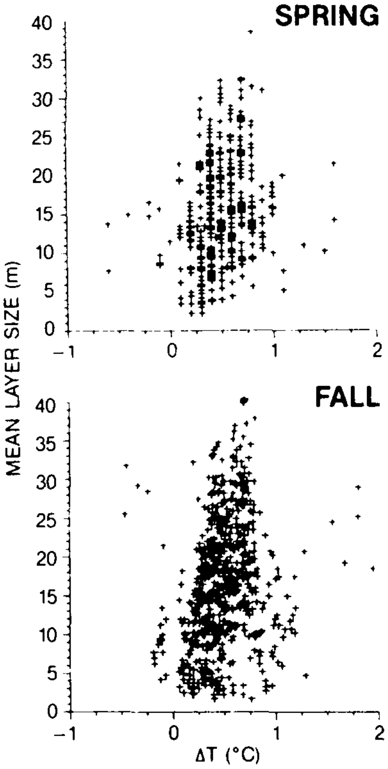

Fig. 14. Size of ΔT, the temperature change across the interfaces between the well-mixed layers, as a function of mean layer thickness (average of the layer above and the layer below the interface).

The 9 dyn cm contour in the 600/700 dynamic topography maps of Figures 15 and 16 lies in the center of a well-demarcated flow regime which may be identified as the Subantarctic Intermediate Current. Most of the flow appears to pass into the Caribbean through the southern Lesser Antilles, with this trend being more marked in the spring. A very similar impression is given from examinations of depth contours of the 5° and 6°C isotherms (not shown), and it is not felt that the proximity of the 700-dbar reference level leads to erroneous conclusions.

If these interpretations of the flow fields from Figures 15 and 16 are accepted, then on may conclude that the staircases arise at and shortly after the confluence (at different depths, admittedly) of the Subtropical Underwater and the Subantarctic Intermediate Current. The northern and eastern boundary of the field (between 50° and 55°W) was very sharp, consistent with the hypothesis that the staircases arise only when the superposition of these two water masses produces the suitable vertical salinity and temperature gradients that give rise to vigorous salt fingering and the creation of the large-scale staircases.

Because of the proximity of the reference level to the 600-dbar level of the third panels in Figures 15 and 16, it might be argued that only in the broadest sense do the contours approximate streamlines, and details of the differences between the two time periods should be ignored. Nevertheless, these differences are supported by the patterns deduced from depths of the 5° and 6°C isotherms, and

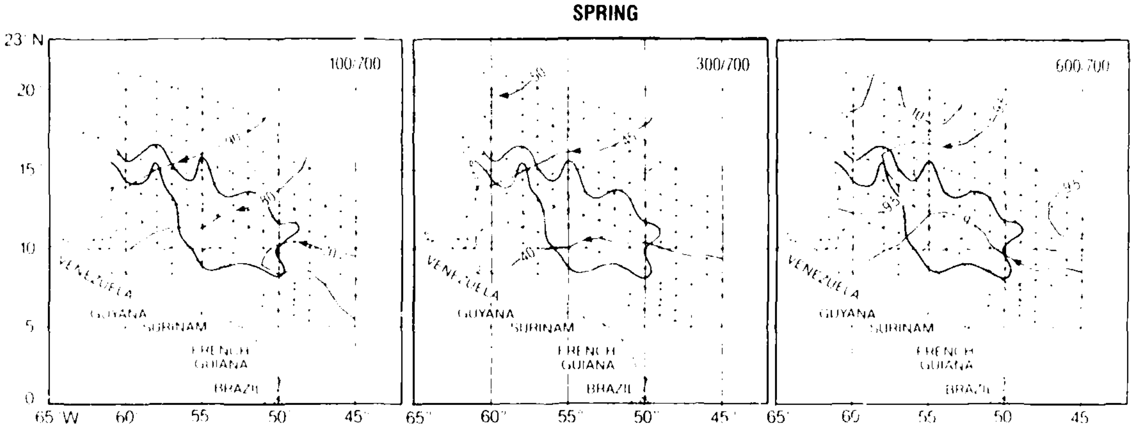

Fig. 15. Dynamic height in dynamic centimeters (10^{-1} m^2 s^{-2}) relative to 700 dbar, spring 1985. (*a*) Dynamic height at 100 dbar, approximately the center of the Subtropical Underwater in this area. (*b*) Dynamic height at 300 dbar, the middle of the large-scale staircases. (*c*) Dynamic height at 600 dbar, within the Subantarctic Intermediate Current. The outlined areas are those of the main staircase field in the spring from Figure 3.

it is not unreasonable to assert that changes in the path of the Subantarctic Intermediate Current appear to correlate with changes in the shape of the staircase field. The most noticeable change is the northward extension of the field in fall. In spring, most of the SAIC remained south of 14°N except for a northward protrusion around 55°W. The main staircases lay south of 14°N, except for northward protrusions between 55° and 57°W, which corresponded very nicely to the position of the SAIC. In the fall the staircase field was shifted northward, especially between 55° and 58°W, perhaps owing to the general more northward tendency of the SAIC in the fall or perhaps representing an evolution of the northward protrusion of the field in this longitude range that was seen 6 months earlier.

SUMMARY AND DISCUSSION

The thermohaline staircases in this portion of the northwest tropical Atlantic exhibit a remarkable temporal and spatial persistence. In spring and fall 1985 they occurred in essentially the same position as during the preceding 16 years. They occurred in one connected field of well-developed layers with weaker, less well defined layers to the northeast and southeast. Layer temperatures and salinities tended to change somewhat horizontally [*Schmitt et al.*, 1987], so the AXBT spacing of 55–110 km was not close enough for unambiguous tracing of individual layers. However, other observations showed that some of the layers persisted for at least 8 months between the spring and fall C-SALT field operations [*Schmitt et al.*, 1987], and, in fall, some of them extended the full width of the main staircase field, a distance of some 800 km (H. Perkins, unpublished data, 1985).

Detailed statistical analysis of the well-developed steps showed distinct latitude-longitude relationships, preferred layer and interface thicknesses, and preferred temperature changes across the interfaces. The staircases were shallowest in the southeast (180–360 m) and deepest in the northwest (420–650 m). Preferred sizes of the layers were 2–6 m and 14–19 m, while the preferred size of the separating interfaces was 2 m, although the relative frequency distributions were not strongly peaked. The preferred temperature change across an interface was about 0.4°C, but again the distribution was fairly broad. These properties are virtually identical with those from earlier reports summarized by *Boyd and Perkins* [1987]. No statistical differences between the spring and fall frequency distributions were noted except that in fall, fewer relatively thin and more relatively thick interfaces were found.

The core of the staircase region (the area of largest number of layers, thickest layers, and largest temperature changes

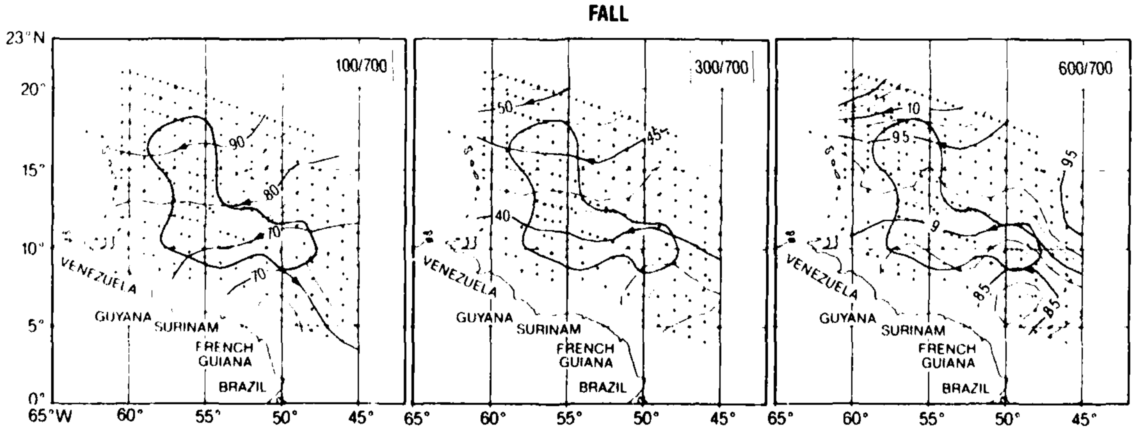

Fig. 16. As in Figure 15, except for fall 1985.

between layers) lay at 10–14 N, 52–57 W. None of the relative frequency distributions were Gaussian, and with the exception of the distribution for layer thicknesses, they were positively skewed and leptokurtic.

Some layers have been reported to be spatially coherent over extensive distances. This is perhaps at odds with the finding that the number of layers in a staircase followed a Poisson distribution. The Poisson typically occurs when the number of observations at one point is independent of the number at any other point. That the number of layers at one station is independent of the number at other stations suggests very little spatial coherency. It may be, however, that only a limited number of the central layers in the staircases were actually continuous and that layers above and below were coherent over only short distances; this is not inconsistent with the findings of *Schmitt et al.* [1987]. On the other hand, it may also be that the long coherency scales were unique to the limited shipboard survey area, which lay within the core region, and that the layers do not generally tend to be coherent over scales of 55–110 km or greater throughout the large-scale stepped region as a whole. Some evidence supports this. In 1982, *Zhurbas and Ozmidov* [1983] were able to trace layers over only some 35 km near 10 N, 54 W, and in 1983, *Boyd and Perkins* [1987] saw no evidence of layer coherency between two stations 124 km apart located at 10 N, 51 W and 10.7 N, 52.5 W. Finally, the number of layers at adjacent stations may indeed be non-independent, with the layers being generated by some unknown process with an underlying Poisson distribution.

To account to some extent for the substantial horizontal salinity gradients in the area, a number of location-dependent historical potential temperature-salinity relationships were used to assign salinity to the temperature values, and the mesoscale flow field was estimated from dynamic height anomalies calculated relative to 700 dbar. A correlation between the flow field and the location of the staircases was seen which supported the contention that the staircases are created at the confluence of the Subtropical Underwater and the Antarctic Intermediate Water, presumably as a result of double diffusive vertical mixing.

What evidence supports the contention that salt fingering is involved in the creation and maintenance of the staircases? First, the layering appears at the confluence of a warm, salty water mass flowing over a cooler, fresher one. Second, the temperature and salinity gradients in the area are such that an important parameter, the density ratio, falls below a critical value. The density ratio is defined as $\alpha T/\beta S$, (where α and β are the coefficients of thermal expansion and saline contraction and T and S are the vertical temperature and salinity gradients), and it governs salt finger growth rates and the vigorousness of double diffusive convection [*Schmitt*, 1979*a*, *b*]. Thermohaline staircases have only been observed for density ratios less than about 1.8, and its value in the C-SALT study area is about 1.6 [*Boyd and Perkins*, 1987; *Schmitt et al.*, 1987]. *Schmitt et al.* [1987] show that the vertical range of the staircases in a given profile always coincides with a broad minimum in density ratio. A low value of the density ratio has been taken as both a requirement for the formation of the staircases and a substantiation of the importance of vigorous salt finger activity for their existence [*Schmitt*, 1981]. Third, C-SALT shadowgraph pictures [*Kunze et al.*, 1987] show near-horizontal striations consistent with predictions by C. Shen's (unpublished manuscript, 1988) numerical model of salt fingers in a shear field. Finally, *Marmorino et al.* [1987] report evidence of convective plumes within the well-mixed layers.

However, for a number of reasons the mechanism generating the oceanic staircases cannot be a straightforward extension of salt fingering in the laboratory. The scales of both the convective layers and of the interfaces in the ocean are 2 orders of magnitude too large [*Boyd and Perkins*, 1987]. Microstructure heat and buoyancy flux measurements made during C-SALT were several orders of magnitude less than what would be expected from laboratory flux experiments [*Lueck*, 1987; *Gregg and Sanford*, 1987]. *Kunze* [1987] suggests this may be because the salt fingers in the C-SALT interfaces were not the fastest growth rate fingers which appear to dominate laboratory experiments. The shadowgraph pictures of *Kunze et al.* [1987] did not show the vertical striations which would be characteristic of laboratory salt fingers, although such vertical striations have been noted in staircases located below the Mediterranean Outflow and in the Tyrrhenian Sea [*Williams*, 1975]. And finally, the report by *Marmorino et al.* [1987] on horizontal wave number spectra of temperature microstructure within the interfaces was more consistent with nearly horizontal structures than with the approximately vertical salt fingers which are observed in the laboratory.

Nevertheless, the evidence is strong that in some poorly understood way the salt finger form of double diffusive convection is probably the major factor in the formation and maintenance of large-scale thermohaline staircases such as are persistently found in the northwest tropical Atlantic. No other explanation has been proposed which incorporates the circumstantial evidence. Unfortunately, no satisfactory theoretical framework yet exists to explain the many phenomena documented during C-SALT. The data reported here give a very good characterization of important features of the staircases and should be valuable for testing theories of staircase formation and maintenance when they become available.

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