# Observational Evidence for Transformation of Tropospheric Waters within Cyclonic Rings

ANDREW C. VASTANO AND DENISE E. HAGAN

*Department of Oceanography, Texas A & M University, College Station, Tex. 77843*

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## ABSTRACT

The North American Slope and Gulf Stream components that constitute the initial water masses within a cyclonic ring can combine with Sargasso Sea water to generate Western North Atlantic Water (WNAW) common to the main anticyclonic gyre in the Sargasso Sea. Evidence from the 1967 ring survey indicates that warm, saline water from above mixes with cooler, fresher water from below to produce WNAW in the region of the mid-thermocline (7–12°C). At mid-thermocline depths, WNAW can be traced along $\sigma_t$ surfaces from the ring center to the Sargasso Sea. Vertical stability conditions support the mixing concept. Distributions of the zooplankton species *Nematoscelis megalops* found for the 1975–76 Ring D survey can be interpreted as indicating mixing and detrainment through the mid-thermocline region.

## 1. Introduction

A central core of North American Slope Water is surrounded by a Gulf Stream remnant during cyclonic ring generation. Observational (Fuglister, 1972; Lambert, 1974; Cheney and Richardson, 1974), analytical (Schmitz and Vastano, 1977; Flierl, 1976) and numerical (Molinari, 1970) studies have described rings and sought to explain the mechanisms by which they evolve and interact with the Sargasso Sea. These works have concentrated on the dynamic and physical structure of the rings and the effect of their environment on the aging process. Observations by Fuglister (1977) during 1967 and Cheney and Richardson's (1974) study of a ring over a 14-month period provide estimates of size and movement, internal structure and energy distribution, and the modifications of these characteristics by the ring's interaction with its environment. Our intent is to examine a facet of the converse problem, the effect of a cyclonic ring on the environment, for in addition to modifying the acoustic (Vastano and Owens, 1973) and biological (Wiebe and Boyd, 1977) character of the region, there is evidence for transformation of cyclonic ring waters into waters characteristic of the central gyre.

## 2. Transformation mechanisms

The tropospheric temperature/salinity ($T/S$) relationships for the oceanic central gyres are essentially linear from 200–1000 m. This characteristic suggests simple mixing of two parent water masses, one warm and saline and the other cold and fresh. Mamayev (1975) has summarized three physical explanations of the troposphere $T/S$ curve in the Sargasso Sea. Their differences exist in terms of the geographical origin of the parent waters and the specific mechanisms that establish the curve of mixing.

In the reports of the Danish Dana Expedition, Jacobsen (1929) pointed out that the $T/S$ relation for NACW[1] lies along a line between the water types (22°C, 37‰) and (5.5°C, 34.6‰). These indices represent warm, saline near-surface water (100 m), geographically situated between the Canary Islands and Puerto Rico, and the Antarctic Intermediate Water (700–800 m) north of the equator. Vertical mixing is required to establish the $T/S$ relationship for NACW. Sverdrup *et al.* (1942) explained the production of NACW in the region of the subtropical convergence by convection and subsequent isopycnic mixing and sinking. This develops direct correspondence between the horizontal $T/S$ characteristics at the surface in the formation zone with the vertical distribution of NACW (Iselin, 1939). The third explanation of the NACW was proposed by Mamayev (1960). Considering the Gulf Stream as the major factor, the parent water was identified by the index (24°C, 36.3‰). This water type represents the boundary current at the juncture of the Florida and Antilles Currents. Three transformations were suggested: entrainment and mixing with cooler, fresher waters from the inshore side of the current along the North

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[1] North Atlantic Central Water (NACW) is a term initially used to describe the water mass within the central gyre. Western North Atlantic Water (WNAW) has recently been used to indicate these waters (Wright and Worthington, 1970).

American coastline and into the North Atlantic; zonal transformation by mixing with the underlying deep and bottom water masses of the North Atlantic; and exchange with the atmosphere which cools the surface waters and introduces desalinization. The water mass created by these changes forms a portion of the WNAW in the central gyre. Now, in addition to these hypotheses, we have found evidence that a mixing process, similar to that described by Mamayev (1975), is occurring in cyclonic rings where North Atlantic Slope Water is brought together with Gulf Stream and Sargasso Sea waters.

## 3. Observational evidence

The boundaries of the Sargasso Sea were described in a physical sense by Iselin (1936). The region is characterized by relatively warm, saline waters with slight horizontal variations. Iselin (1936) presented a $T/S$ correlation for the Sargasso Sea which has been identified by Wright and Worthington (1970) as a standard $T/S$ relationship for WNAW. We use these standard values, obtained from the Iselin $T/S$ curve in Wright and Worthington (1970), as representing the environmental setting for cyclonic rings. The hydrographic station data obtained by Fuglister during the 1967 cyclonic ring survey is the basis for our examination of transformations within a ring.

The 1967 ring was formed in late March or early April. Data taken on R/V *Crawford* cruise 156 (CFD 156) in June, CFD 158 in July, R/V *Atlantis II* cruise 35 (A2 35) in September and A2 38 in October have been used to study the water masses present in the ring. The transformation of the initial waters in the tropospheric region can be considered in terms of simple mixing of a warm saline water mass with a cool, fresh water mass. To define such water masses, cruise stations were selected for vertical sections and effective ring centers were found by considering horizontal contour maps of temperature. Temperatures and salinities for upper and lower ring depths, ex-

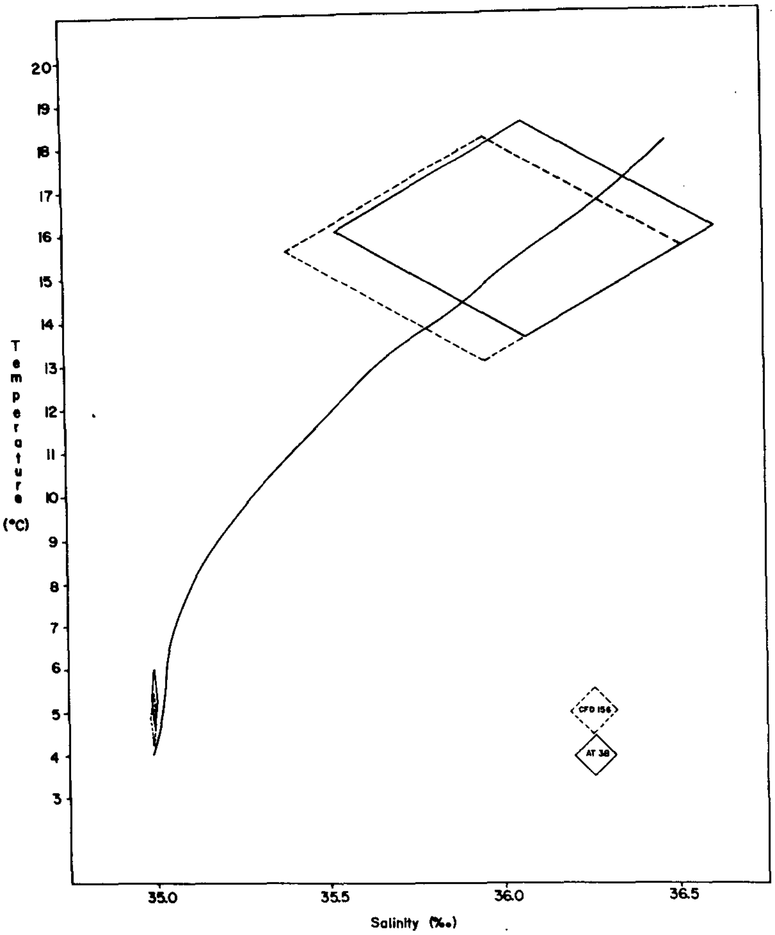

FIG. 1. Average $T/S$ relationships for waters above and below the mid-thermocline region in the 1967 cyclonic ring for CFD 156 and A2 38. The diamonds are formed by the central $T/S$ averages and the standard deviations. The solid line represents Iselin's $T/S$ relation for WNAW.

cluding a region corresponding to the mid-thermocline (7–12°C), were averaged throughout the vertical sections for each cruise from the ring center to a radial distance of 70 km. Fig. 1 depicts diamond-shaped areas marked by $T/S$ pairs representing the averages and their standard deviations for CFD 156 and A2 38. Straight-line mixing between $T/S$ indices in these regions can yield values which fall on the standard WNAW curve. Similar relationships exist for CFD 158 and A2 35. This implies that within the ring warmer, saline water mixing with cooler, fresher water from below could produce intermediate $T/S$ indices that are typical of WNAW.

Our evidence for such a transformation has been developed by examining the temperature, salinity and density structure of the four 1967 ring survey cruises: CFD 156, CFD 158, A2 35 and A2 38. Temperature, salinity and associated $\sigma_t$ vertical sections were prepared for each cruise. The depth distribution of the density surfaces in the outer ring regions were found to approach the distribution of $\sigma_t$ values for WNAW with the values for the A2 38 cruise bearing the closest resemblance. Representative WNAW $T/S$ indices can be traced along associated $\sigma_t$ surfaces radially outward and downward toward the Sargasso Sea environment for every cruise. The criterion for establishing WNAW was the occurrence of an isotherm and isohaline for a WNAW $T/S$ index within a separation of 20 m. Figs. 2a,b presents two $\sigma_t$ sections, CFD 156 and A2 38, with isopycnal surfaces shown in the mid-thermocline region. Solid lines labeled with the associated temperature indicate $\sigma_t$ curves that correlate with the presence of $T/S$ indices characteristic of WNAW. When the isotherms and isohalines depart by a distance greater than 20 m, the $\sigma_t$ curve is dashed. The (8°C, 35.11‰) index was predominantly shown in the younger stages of the ring and was found to occur within 10 km of the center approximately 5 months (A2 38) after CFD 156. Isopycnal surfaces derived from the WNAW standard $T/S$ indices immediately above and below the 8°C water became more developed with ring age and, for the four cruises, can be traced from regions progressively closer to the ring core. The tracing process was applicable to 7–13°C isotherms and associated salinities, although 8–11°C waters extended from regions nearest to the ring core. We hypothesize that Sargasso Sea water was entrained into the ring from both shallower and deeper depths, and that mixing processes produced WNAW which was detrained in an intermediate region 200–400 m in vertical extent.

At this point we have established the presence of WNAW within the 1967 ring. Considering that diffusive mixing and entrainment alone could have brought these waters into the ring, we have examined the extent that such movement could reach into the ring. Lambert (1974) has calculated the rate of penetration of Sargasso Sea water into the ring in the surface layers with a radial velocity of 0.3 cm $s^{-1}$. This is representative of values computed by Molinari (1970). Based on an average ring radius of 80 km,[2] the possible penetration distances are shown in Fig. 2 by the bar above each section. The limited penetration implies that the presence of $T/S$ indices common to WNAW is due to vertical mixing rather than diffusion and lateral mixing of WNAW.

The mixing mechanism which produces WNAW requires the vertical convergence of warm saline water and cold fresh water. Parr (1936) initially discussed the principle that vertical stability, which reduces vertical mixing processes, additionally increases lateral mixing along isopycnal surfaces. The stability diagrams shown in Fig. 3 for CFD 156 and A2 38 support mixing of this nature in an intermediate depth region that correlates with the mid-thermocline and the depths at which found WNAW within the 1967 ring. These contoured sections of Brunt-Väisälä frequency squared are indicative of the density stratification that exists in rings and the regions of stability maxima and minima which develop and persist during ring evolution. The intermediate regions of greater vertical stability will tend to relatively enhance lateral mixing along isopycnal surfaces. We interpret the regions of lower relative stability as those in which vertical mixing processes occur that are conductive to the generation of WNAW.

Biological evidence that we interpret in both spatial and temporal contexts as indicative of mixing and detrainment processes in cyclonic rings was presented by Wiebe and Boyd (1977) in a description of the distribution of the zooplankton species *Nematoscelis megalops* in Ring D. Ring D was sampled on two cruises (August and November 1975) with the *Mocness* (Wiebe *et al.*, 1976) and on one cruise (June 1975) with an oblique plankton tow. The preferred temperature regime of the central 50% of the *N. megalops* population in Ring D was 10±2°C and 35.3±0.25‰. Samples from the night tows on the November cruise reveal a depth progression for the central 50% population from the ring core to the high-velocity region: 440 m (MOC 33 tow), 650 m (MOC 29) and 715 m (MOC 34).

The MOC 29 and MOC 33 stations have indices (7.3°C, 35.10‰) and (10.6°C, 35.37‰), respectively, that are close to WNAW water types (8°C, 35.11‰) and (11°C, 35.41‰). The $T/S$ index at MOC 34 for the central 50% was (9.9°C, 35.26‰). This index is common to WNAW and is within the ring environment. Therefore, the depth distribution of *N. megalops* in Ring D coincides with the mid-thermocline region

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[2] The perturbations of isotherms at a ring age of 5 months were evident at depth and a radial distance of 80 km from the ring center. Thus, this is a conservative estimate of ring radius.

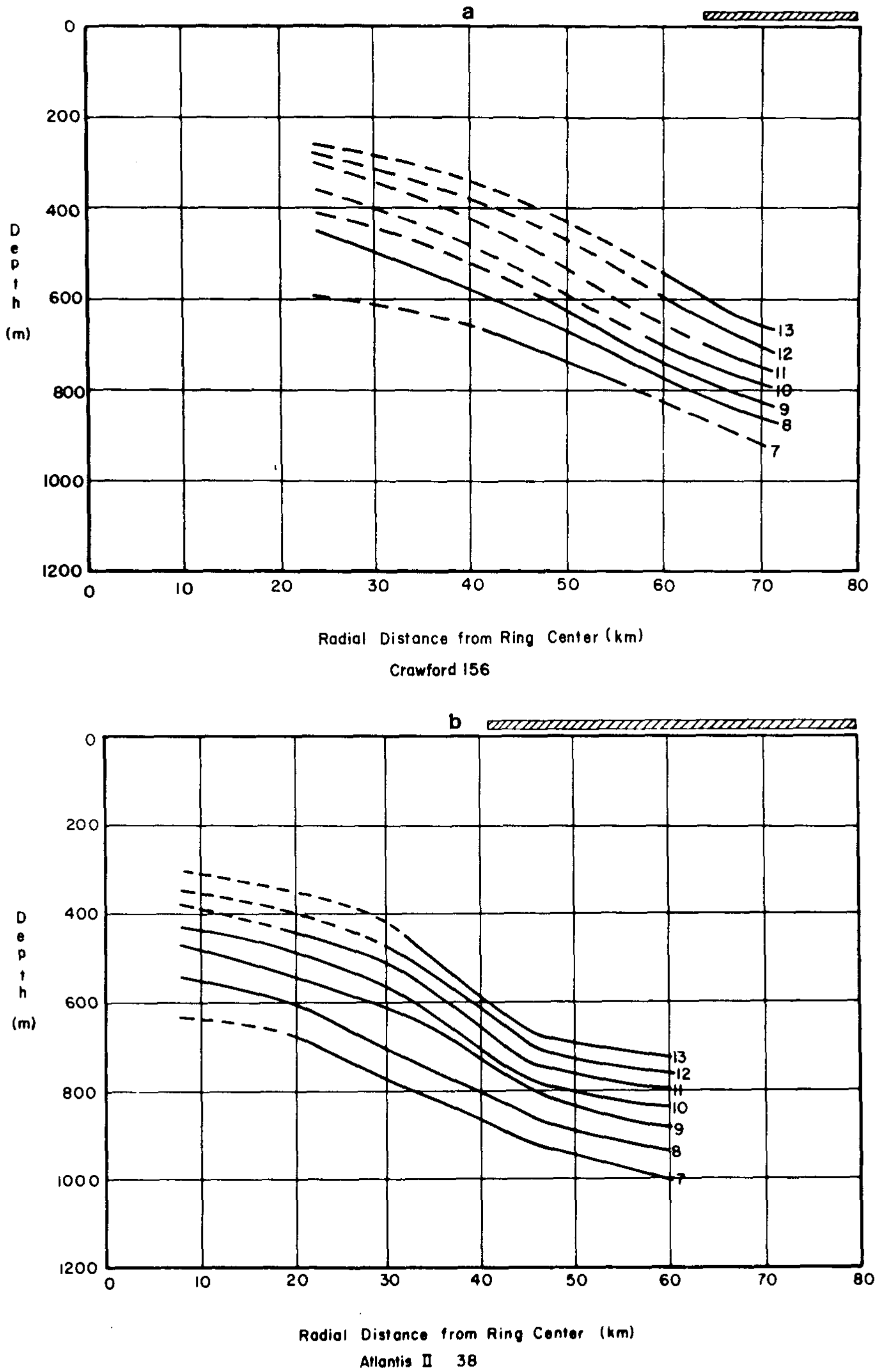

FIG. 2. Sigma-$t$ surfaces within the 1967 cyclonic ring for CFD 156 and A2 38. In the ring far-field the $\sigma_t$ surface is identified by its corresponding WNAW temperature. Solid lines indicate a WNAW $T/S$ index and dashed lines continue the surface when $T$ and $S$ for the index depart by more than 20 m vertical separation.

of stability that was found in the ring WNAW. Further, Wiebe and Boyd suggested that the species adjusted its vertical distribution to remain within this preferred regime. A comparison of averaged $T/S$ and depth data for the August night tows and the November night tows for the ring core area shows a decrease of approximately 225 m for the central 50% populations. Thus, a temporal comparison of night tows for the August and November cruises could be interpreted as a movement of *N. megalops* to deeper depths in a region of relative vertical stability and possibly along isopycnal surfaces of ring WNAW.

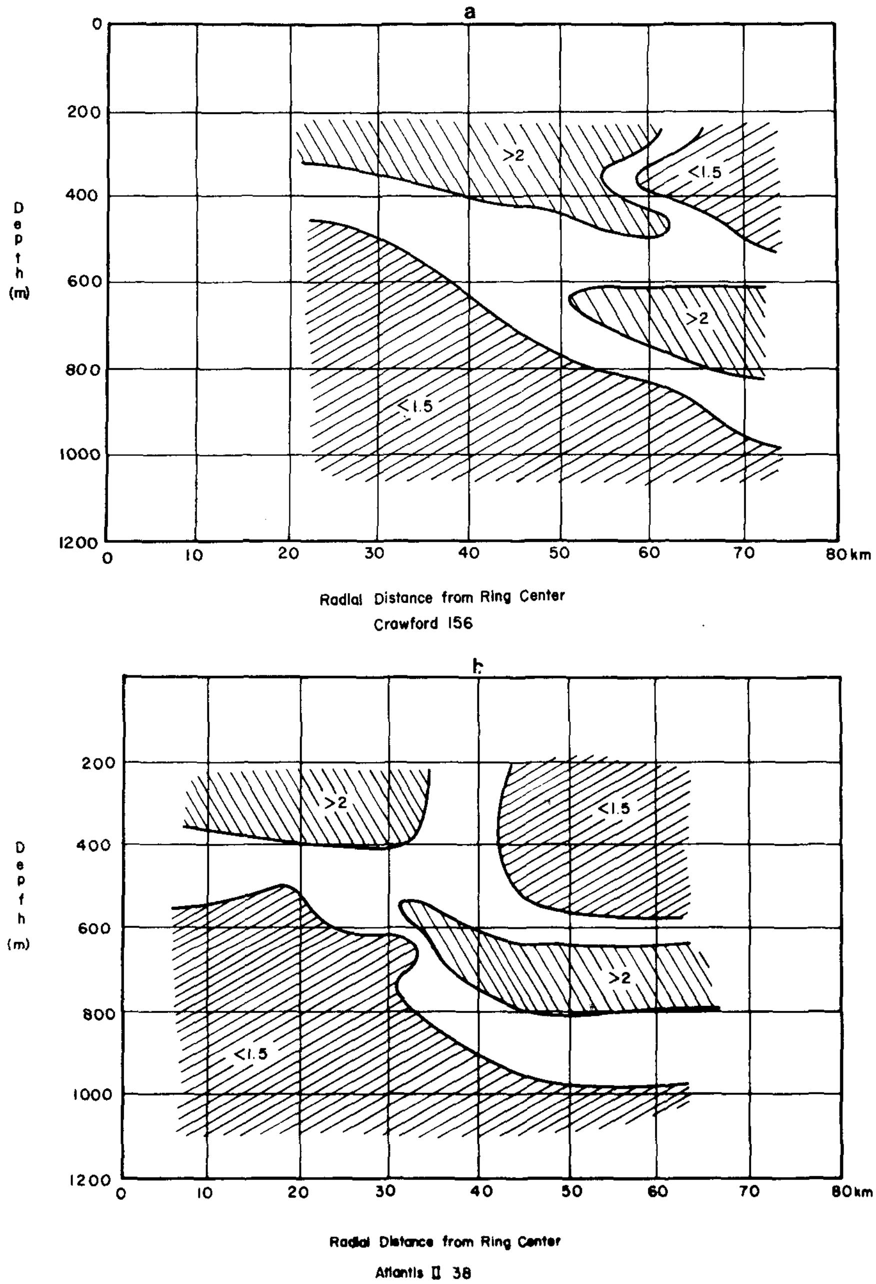

FIG. 3. *Contours of vertical stability (Brunt-Väisälä frequency squared) which indicate relative regions of vertical stability* ($>2$) *and vertical mixing* ($<1.5$).

## 4. Conclusions

The evidence for transformation of ring water masses may be summarized as follows:

- A warm, saline water mass above a mid-thermocline mixing region is present in conjunction with a cooler, water mass below.
- Mixing of these two water masses can produce thermohaline indices common to WNAW.
- *T/S* indices common to WNAW have been identified on $\sigma_t$ surface within the ring core and traced downward and outward to the Sargasso Sea environment.
- Brunt-Väisälä frequency squared distributions indicate an intermediate, stable region between the two water masses which persists through the 1967 ring survey.
- This stable region coincides with the WNAW regions that have been traced from the ring center to the Sargasso Sea.
- The distribution of the species *N. megalops* in the 1975–76 Ring D surveys can be interpreted as

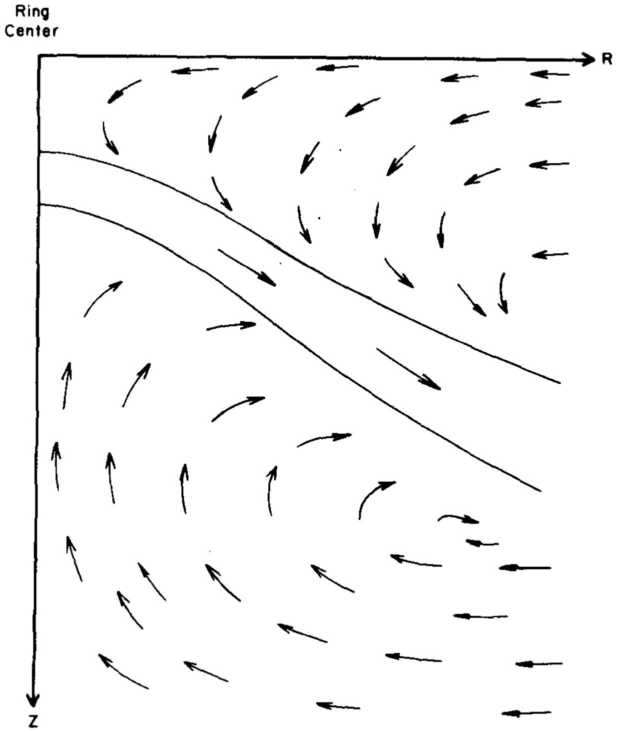

Fig. 4. A conceptual model of inflow and outflow into a cyclonic ring with the detrainment at an intermediate depth.

indicative of convergent flow from above the mid-thermocline region and detrainment along density surfaces.

The dynamic balance within a cyclonic ring is basically geostrophic with an inward pressure gradient force balanced by an outward Coriolis force. The inclusion of lateral friction in the flow description results in an equilibrium state with a component of flow toward the ring center. The concept of mass conservation in the light of this convergence mechanism requires motion away from the ring core in some region of the flow field. Lambert (1974) has found that the dissolved oxygen variations in a Gulf Stream ring supports lateral advection toward the core, in layers, above 500 m and suggests the presence of diffusive overturning (McIntyre, 1970) that results in the development of layers in the density field. Another line of evidence for motion toward the core has been provided by Schmitz and Vastano (1977). This study, based on serial temperature fields in the 1967 ring, has indicated the presence of detrainment through the mid-thermocline region of the ring. Fig. 4 presents a conceptual schematic of the possible radial and vertical flow pattern based on the observational evidence we have assembled. Stern (Cheney and Richardson, 1974) proposed detrainment of this nature with flow along density surfaces.

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