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Salinity maximum in the pycnocline of the Middle Atlantic Bight[1,2]

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Abstract

A persistent salinity maximum is observed in the upper part of the pycnocline in summer–autumn over the outer shelf of the New York Bight, induced by a nearly isopycnal transfer of slope water to the outer shelf. The transfer is possible only in the stratified seasons when isopycnals are continuous across the shelf–slope front. Estimates of the slope–shelf salt flux required to produce the pycnocline *S*-max suggest that it may provide about half of the salt required annually in the shelf region to balance input of river water.

The continental shelf waters of the Middle Atlantic Bight undergo strong seasonal variations, being nearly vertically homogeneous by late winter but having an intense pycnocline from spring to autumn (Bumpus 1973). Recent hydrographic data obtained by in situ instrumentation that records continuously reveal a pronounced maximum in salinity (*S*-max) associated with the seasonal pycnocline of the Middle Atlantic Bight (Boicourt and Hacker 1976; Gordon et al. 1976). Bigelow and Sears (1935) mentioned observations from serial cast data of "interdigitations" in the salinity field from the offing of Chesapeake Bay to New York. Vertical reversals in salinity—evident in their multiyear summer and autumn data set, which showed higher salinities indenting shoreward at 20 m while lower salinities suggested seaward spreading at slightly greater depths—led them to infer that this pattern recurs each year during the months of pycnocline structure.

Boicourt and Hacker (1976) suggested that the pycnocline *S*-max observed off the coast of Maryland and Delaware is produced by a shoreward intrusion of slope water induced as a compensating flow to the general offshore surface Ekman drift, characteristic of the summer period.

Hydrographic surveys in recent years in the New York Bight section of the Middle Atlantic Bight (Fig. 1) reveal the seasonal cycle of the thermohaline stratification. The summer data sets (*Conrad* 19-01 and *Knorr* ACE III) and the autumn data set (*Vema* 32-01: Gordon et al. 1976) indicate the persistent nature of the pycnocline *S*-max over the middle and outer shelf. Shoreward limits of the pycnocline *S*-max during July 1975 are also indicated in Fig. 1.

An *S*-max core layer embedded in the pycnocline is clearly displayed in the *Knorr*, August 1977, section off Long Island (Fig. 2). The *S*-max is continuous for 30 km inshore of the shelf break, but it frequently is variable in intensity. Despite this patchiness, the pycnocline *S*-max is a constantly recurring feature over the Middle Atlantic Bight continental shelf in the summer and autumn data sets.

The *Knorr* section is used to point out the potential significance of the *S*-max intrusion in regard to the salinity balance of shelf water.

Seasonal evolution of the T/S *scatter*

A discussion of the seasonal development of the temperature–salinity (*T/S*) relation of the New York Bight waters is useful in relating the pycnocline *S*-max to the larger scale water mass field.

January 1976 (*Conrad* 19-05): The January data show the characteristic winter

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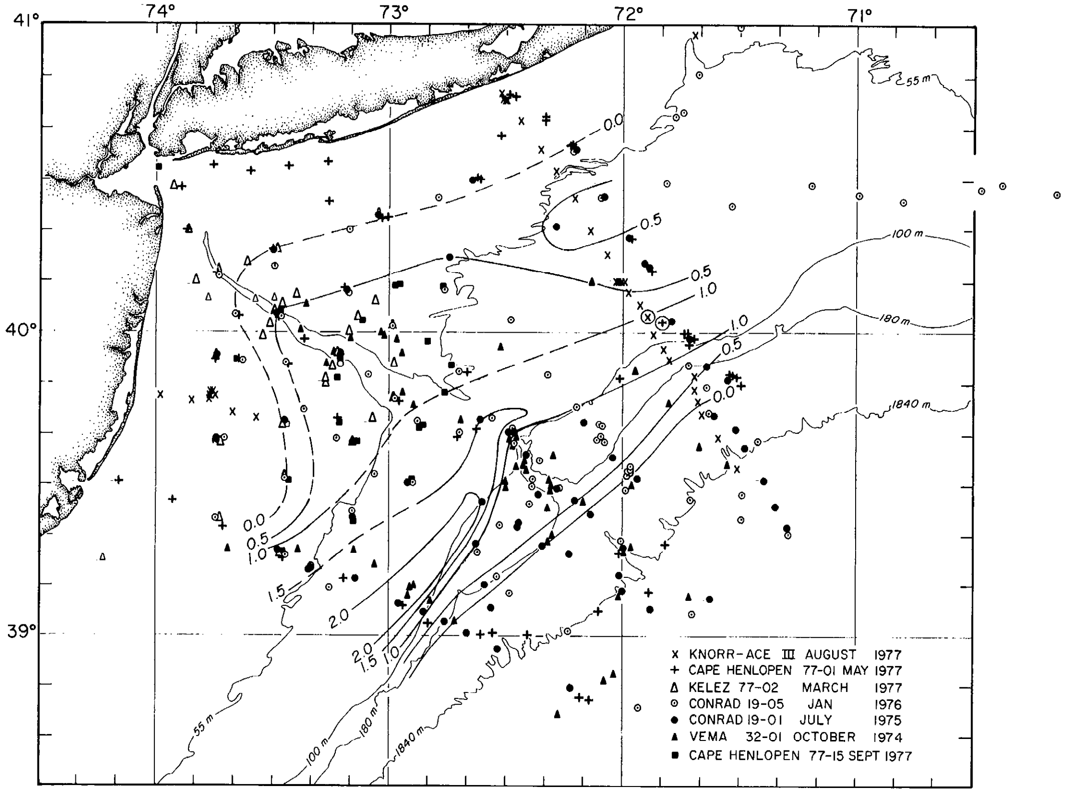

Fig. 1. Hydrographic stations taken (LDGO) in the New York Bight since 1974. Contours are differences between salinity at pycnocline S-max and underlying S-min observed in July 1975, *Conrad* 19-01 cruise (large ΔS observed over shelf south of Hudson Canyon may be an enhanced salt flux associated with presence of offshore warm core eddy 75-B: EOFA charts, 16–30 July 1975). Two stations circled (taken in May and August 1977) are used in Fig. 3.

"figure seven" *T/S* form (Fig. 3). The temperature and salinity maxima in the slope region near 200 m represent the "top" of the undisturbed slope *T/S* curve, which is a slightly fresher version of the North Atlantic Central water mass curve (Iselin 1936; McLellan 1957). Points extending to the low salinity side of the slope *T/S* curve indicate modification of the shelf water induced by continental runoff. Both temperature and salinity decrease as the shore is approached.

May 1977 (*Cape Henlopen* 77-01): Heating of surface waters causes the *T/S* curves of individual stations to reach toward higher temperatures from the initial base curve of winter (Fig. 4). Some isopycnals are now continuous across the shelf break, allowing isopycnal communication of shelf and slope water, which is not possible in winter.

July 1975 (*Conrad* 19-01): Heating continues into summer, allowing more isopycnals to be shared between shelf and slope regimes (Fig. 5). The pycnocline *S*-max of the outer shelf is now evident (Fig. 5).

The *T/S* characteristics of the pycnocline *S*-max are almost identical to those of the water of the slope regime. The pycnocline *S*-max coincides with the primary crossover of characteristics of slope–shelf water within the water column.

August 1977 (*Knorr* ACE III): The *T/S* scatter of August 1977 (Fig. 6) is similar

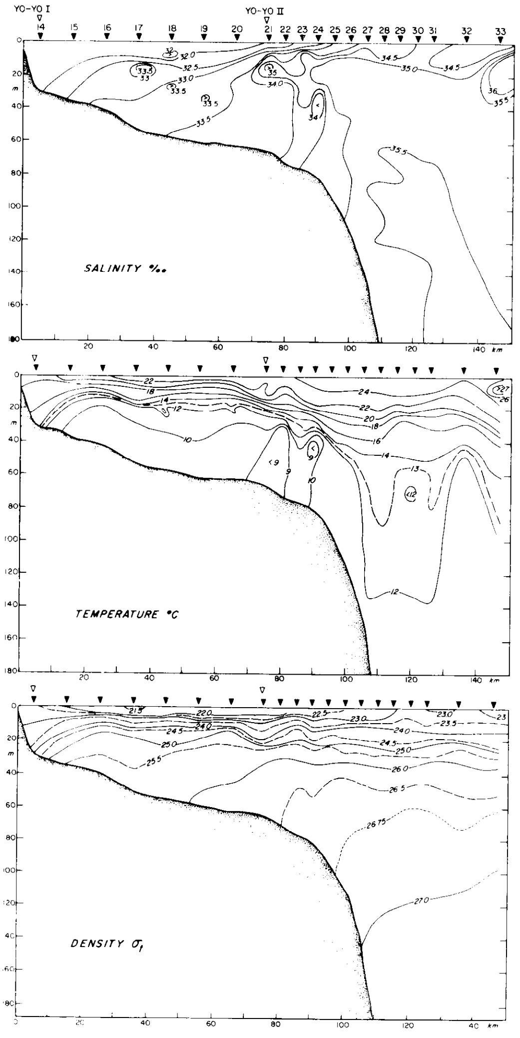

Fig. 2. Cross-shelf transect taken off Long Island in August 1977, *Knorr* ACE III.

to that of July 1975 discussed above. Again the outer shelf pycnocline S-max is essentially slope water.

October 1974 (*Vema* 32-01): In autumn, heat is removed from the ocean and the surface mixed layer gradually erodes into the summer thermohaline stratification, leading to a thermal collapse of the T/S envelope (*see fig.* 2: Gordon et al. 1976). The pycnocline S-max is eroded first, inducing an effective deepening of the pycnocline S-max, and then, in winter, its disappearance.

Pycnocline salinity maximum

Comparison of May 1977 and August 1977 stratification (positions of the stations used given in Fig. 1) reveals the sense of the seasonal variation over the outer shelf (Fig. 7). The nearly isohaline water column of May is replaced with a more complicated haline stratification in August. The surface water above 5 m is slightly fresher in August, whereas the layer in the pycnocline between 5 and 30 m and the benthic layer below 50 m are significantly more saline. The layer between 30 and 50 m is about the same and, from the minimum temperature, can be seen to represent remnant winter water, often designated as the "cold pool" water. Water mass arguments, presented below, indicate that the two saline layers represent intrusions of slope water. The benthic S-max may be considered as the foot of the retrograde shelf–slope front (Mooers et al. 1978).

The pycnocline S-max is associated with a weakening of the pycnocline—nearly a pycnostad—which divides the pycnocline into an upper, haline supported, segment and a lower, thermally supported, segment. Pycnostads are considered qualitative evidence of a lateral intrusion or an injection of a water type (Worthington 1972; Reid et al. 1977).

In August 1977 the average salinity of the pycnocline S-max is about 1‰ greater than the salinity of the outer shelf cold pool water (i.e. *see Fig. 1 to compare to July 1975*), but more like 1.5‰ above the average salinity of the midshelf water column in which it is embedded. In our conceptual model presented below we use the difference of 1.5‰ as the S-max excess salinity to compute a growth rate for this intrusion.

Slope–shelf salt flux

A conceptual model for the cross-shelf advective-mixing pattern associated with the pycnocline S-max is shown in Fig. 8. A net shoreward flux of salt over the shelf break and across the shelf–slope front into the outer shelf pycnocline (1 in Fig. 8) is most likely the result of a quasi-iso-

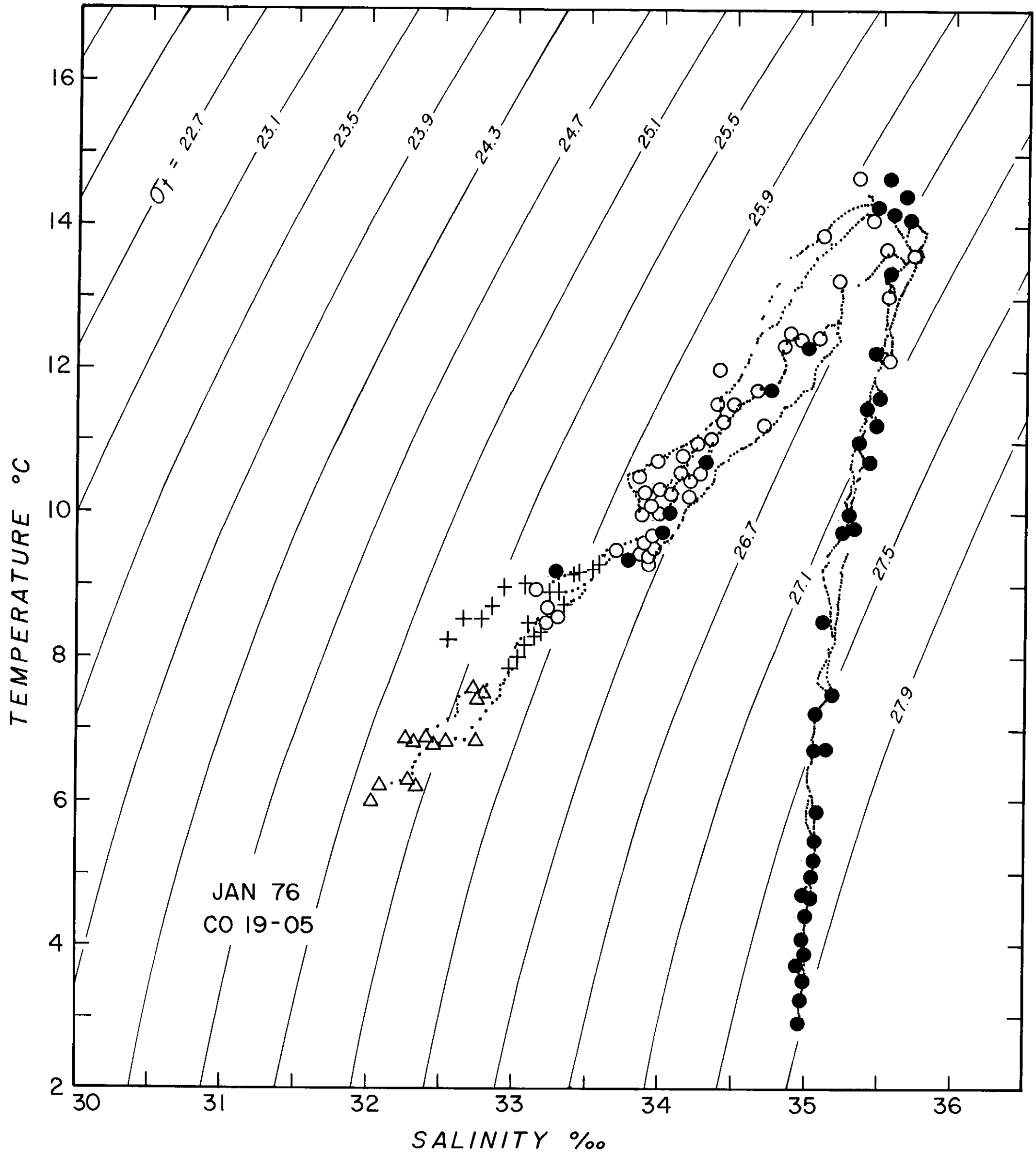

Fig. 3. Temperature-salinity diagrams for January 1976, *Conrad* 19-05. △—inner shelf water; +—mid-shelf water; ○—outer shelf water; ●—slope water.

pycnal process. Recent studies (C. Welch pers. comm.; E. Posmentier pers. comm.) consider the origin of the pycnocline S-max in more detail. The dominance of slope water in the pycnocline of the outer shelf may be a simple consequence of the greater volume (reservoir) of slope water within the density interval marking the pycnocline of the outer shelf. Salt flux from the slope water must support the growth rate of the pycnocline S-max (3 in Fig. 8) as well as supply the salt lost by vertical mixing (2 in Fig. 8). The excess salt of the S-max (excess relative to the

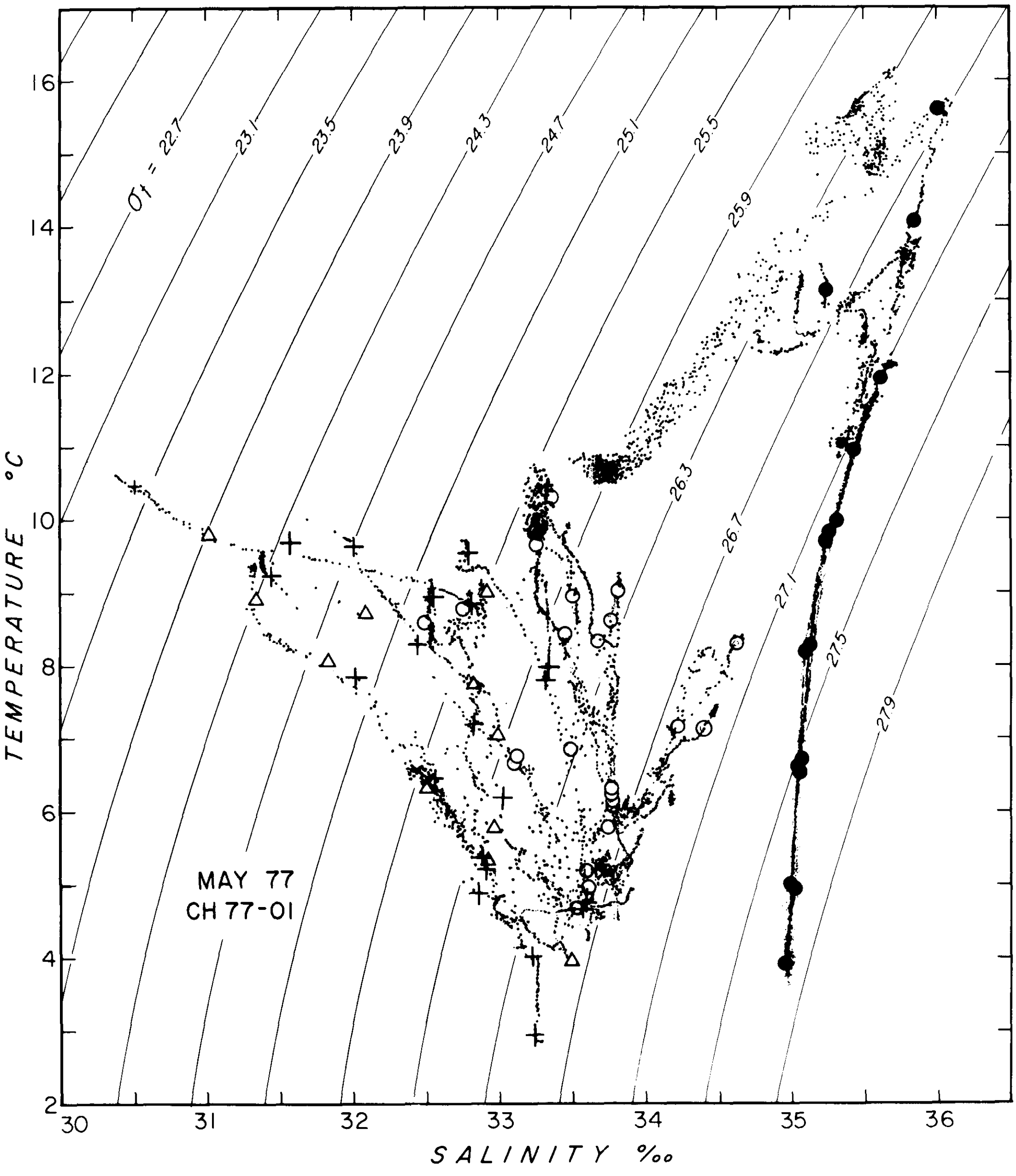

Fig. 4. As Fig. 3, but for May 1977, *Cape Henlopen* 77-01.

average salinity of 33‰ of the midshelf water column) is integrated into the shelf water during autumn overturn. The slope–shelf salt flux, F_S, can be written as

$$\underset{(1)}{F_S} = \underset{(2)}{2K_Z(\Delta S/\Delta Z)} + \underset{(3)}{G}$$

F_S is the shoreward salt flux across a centimeter length of the continental shelf edge per second. K_Z is the vertical mixing coefficient, and $\Delta S/\Delta Z$ is the vertical salt gradient characteristic of the upper and lower boundary of the pycnocline S-max. The value of 2 is needed to include both surfaces. G is the growth rate of total ex-

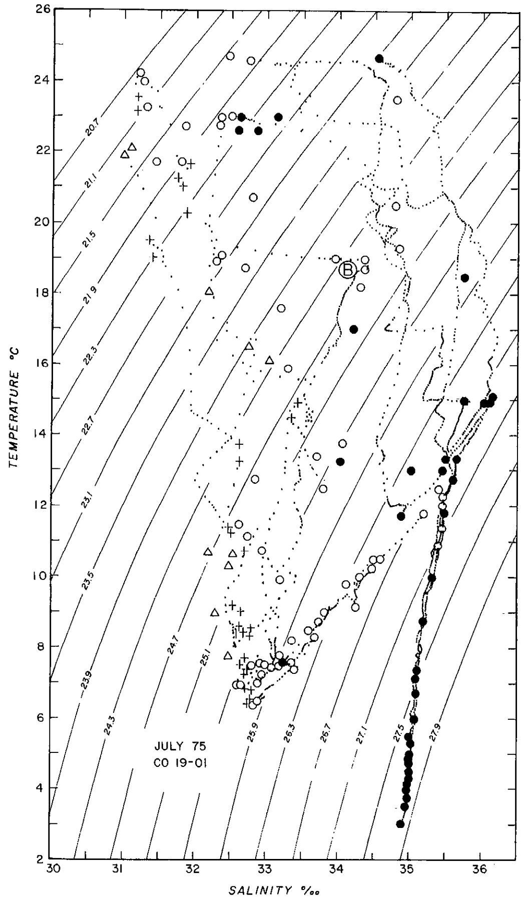

Fig. 5. As Fig. 3, but for July 1975, *Conrad* 19-01. (B—Pycnocline S-max.)

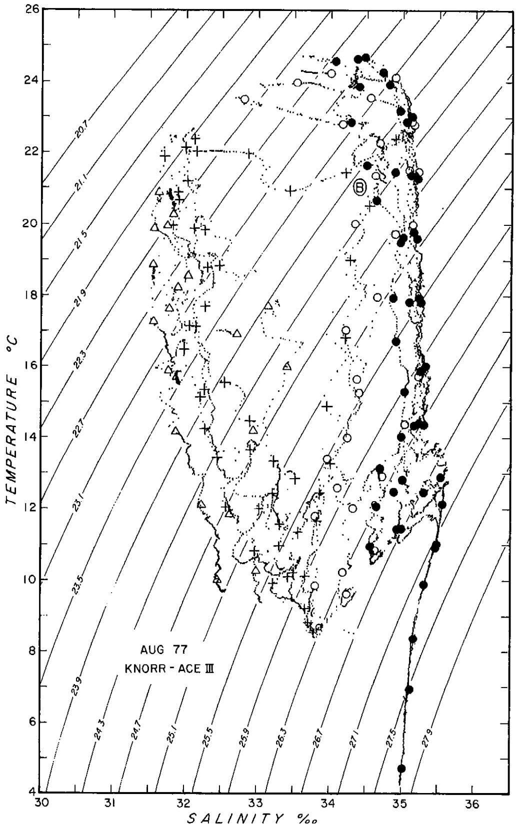

Fig. 6. As Fig. 3, but for August 1977, *Knorr* ACE III. (B—Pycnocline S-max.)

cess salt of the pycnocline S-max, which is mixed into the water during fall overturn. The growth may be induced by the statistical mean effect of quasi-isopycnal fine structure at the shoreward edge of the main body of the S-max.

Presumably the slope water intrusion continues to migrate shoreward along a quasi-isopycnal route as summer progresses. The approximate distance of 30 km to the landward edge of the pycnocline S-max from the shelf break area, observed in August 1977, suggests a mean spreading velocity of 0.4 $\mathrm{cm \cdot s^{-1}}$ (assuming a 3-month active period: mid-May to mid-August).

The shoreward limit may be spatially, as well as temporally, controlled and any contribution to the Middle Atlantic Bight salt balance by the net (5 $\mathrm{cm \cdot s^{-1}}$) longshore flow from the Georges Bank region will surely complicate the picture. In the presence of this southwestward advection, any given location will contain different water in August than it did in May; however we believe that the pycnocline S-max intrusion can develop along the entire length of the Middle Atlantic Bight and is superimposed on the longshore flow.

To estimate the value of F_S, we used the August 1977 data (*Knorr* ACE III) to determine the value of the growth rate and vertical mixing. With a characteristic cross-shelf migration velocity (U) of the pycnocline S-max of 0.4 $\mathrm{cm \cdot s^{-1}}$, an S-max excess salinity over mean shelf water of about 1.5‰, and a thickness of the pyc-

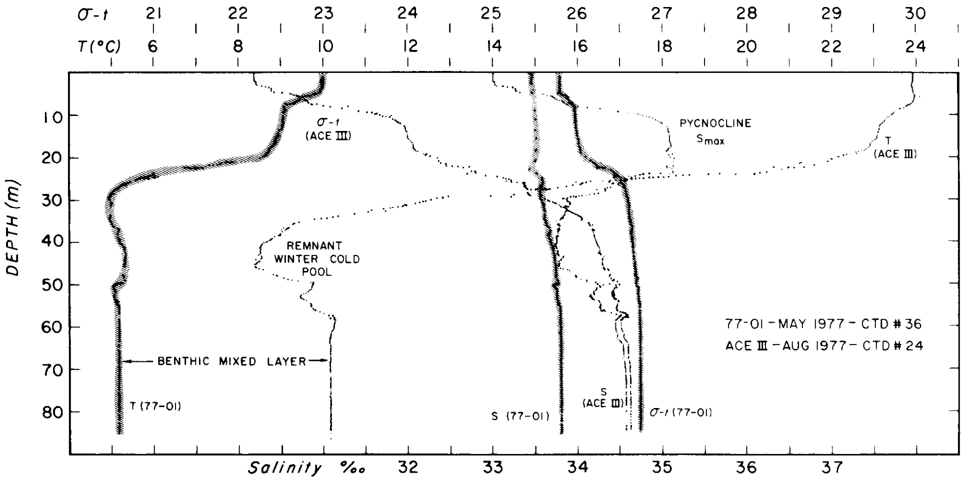

Fig. 7. Vertical profiles for May 1977 CTD station 36 and August 1977 CTD station 24.

nocline S-max of 15 m, an approximate value of G is 0.93 $g \cdot cm^{-1} \cdot s^{-1}$. When we use a value for K_Z of 0.1 $cm^2 \cdot s^{-1}$, determined for the lower pycnocline by a variety of methods (T. Malone pers. comm.), we get a total vertical flux of 1.05 $g \cdot cm^{-1} \cdot s^{-1}$ (where an average $\Delta S/\Delta Z$ of $1.7 \times 10^{-6} \cdot cm^{-1}$ is used for both surfaces). Therefore, we suggest an estimated F_S value of 2.0 $g \cdot cm^{-1} \cdot s^{-1}$. An important question is how significant is this salt flux to the salt balance of the continental shelf water? The answer can be developed by comparing this flux to the input of freshwater from land (precipitation is about equal to evaporation over the Middle Atlantic Bight: Bunker and Worthington 1976; Pack 1972), which is 47 $cm^3 \cdot cm^{-1} \cdot s^{-1}$ on the basis of an annual average (Bue 1970). A 4-month growth

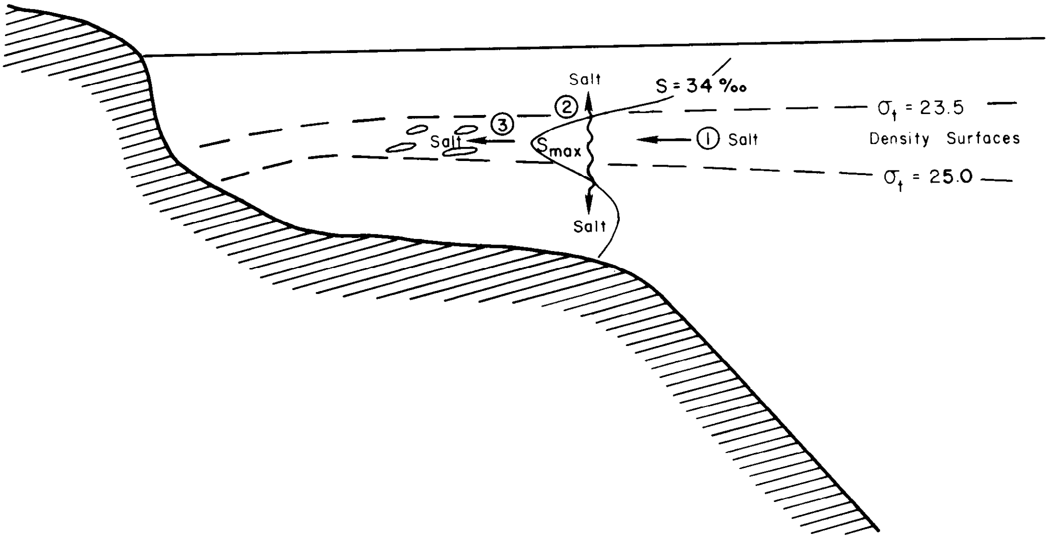

Fig. 8. Schematic of conceptual model of cross-shelf pycnocline S-max. Dashed curves represent isopycnals between which S-max is usually embedded. Solid curve represents 34‰ isohaline. 1—Shoreward salt flux; 2—vertical diffusion of salt out of S-max; 3—growth rate of excess salt of pycnocline S-max.

period of the pycnocline S-max, before autumn destruction, yields an annual average F_S of 0.67 $g \cdot cm^{-1} \cdot s^{-1}$.

A salt flux of 0.67 $g \cdot cm^{-1} \cdot s^{-1}$ combined with a freshwater flux of 47 $cm^3 \cdot cm^{-1} \cdot s^{-1}$ will form salt water with a salinity of 14.26‰, which is about 44% of the average salinity of the shelf water. Therefore, it is possible that the pycnocline S-max, which is active for only part of the year, may provide about half of the annual salt requirement of the shelf water.

Voorhis et al. (1976) computed a slope–shelf salt flux of 1.74 $g \cdot cm^{-1} \cdot s^{-1}$ by way of vertical turbulent exchange between interleaved layers. They pointed out that if this value represents an average annual flux, it would balance river input. However, the salt input into shelf water by the fine structure may not be maintained throughout the year, since isopycnal communication between slope and shelf water is cut off in winter. It is possible that the fine structure exchange discussed by Voorhis et al. may essentially be the F_S flux required to induce the pycnocline S-max.

Conclusion

Because the summertime shoreward salt flux that induces the pycnocline S-max of the Middle Atlantic Bight may supply about half of the salt required to balance the annual river input into the shelf water, the transport of slope water shoreward that is associated with this intrusion must be of considerable importance to aquatic ecosystems of the continental shelf and coast. The estimates given are based on August 1977 data only, and yearly variations may be expected. Field programs to study the pycnocline S-max may be rewarding. Other inputs of salt associated with benthic intrusions and ondrafts induced by the presence of warm core rings in the slope water regime may provide the remaining half of the salt flux.

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