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The limits of shelf water south of Cape Cod, 1941 to 1972

by W. R. Wright[1]

ABSTRACT

Some 19,000 bathythermograms and 1,600 oceanographic stations in the region 39° to 41° N, 69° to 72° W have been examined for evidence of changes in the character and position of the shelf water/slope water boundary. Results show a) the boundary, identified by the 10° isotherm, intersects the bottom within 16 km of the 100-m curve about 80 percent of the time, with a seasonal progression from the south in the winter to north in the fall; b) at the sea surface the boundary position is much more variable, averaging 52 km seaward of the 100-m curve in winter and 72 km seaward in late summer; c) detached parcels of shelf water are found in the slope water at all times of the year, with maximum occurrence in late spring and early summer; and d) the combination of entrainment at Hatteras and production of detached parcels appears to account for the shelf water/slope water exchange required by salt balance considerations.

1. Introduction

At the edge of the Middle Atlantic Bight between Cape Cod and Cape Hatteras the warm and saline waters of the North Atlantic Ocean meet the cooler and fresher waters of the continental shelf. The boundary between them is a complex region of interacting water masses, strong temperature and salinity gradients and continual change. Figure 1 shows one section across the edge of the shelf.

An understanding of the circulation in the Middle Atlantic Bight depends ultimately on knowledge of the water movements across and along this transition zone. All the water contributed to the coastal region by rain and runoff (except that re-

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[1] Now at Box 54, Woods Hole, Massachusetts, 02543.

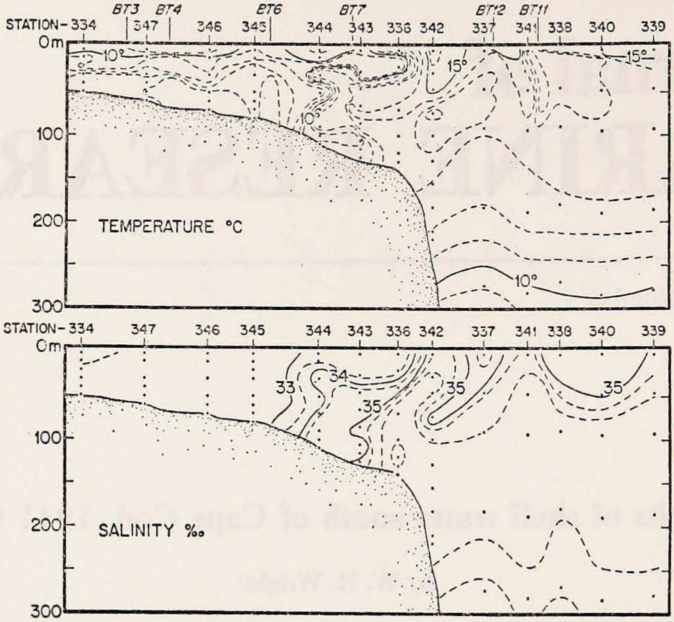

Figure 1. Temperature and salinity sections across the shelf edge. GOSNOLD Cruise 190, May 29–30, 1972.

moved by evaporation) must eventually pass through this zone to reach the open ocean. The same is true, of course, of pollutants introduced with runoff and rainfall. Prediction of concentrations and residence times of such pollutants on the shelf depends to a considerable extent on knowledge of how they reach the deep sea. Exchanges of heat and salt must take place across the boundary to help maintain the temperature and salinity distribution on the shelf, but the magnitude of these exchanges is not known, nor to what extent they are accomplished by turbulent diffusion or by large scale intrusions of one water mass into the other.

The transition from shelf water to slope water[1] was remarked by Libbey (1891) and documented in the classic works of Bigelow (1933) and Bigelow and Sears (1935). Ketchum and Corwin (1964) studied the cold shelf water in a series of 20 sections spread over several years south of Montauk, Long Island. They concluded, as had Bigelow, that the cold water was renewed annually by winter mixing and persisted relatively unchanged through the summer. Whitcomb (1970) showed this "winter water" as a continuous feature along the edge of the shelf from the south-

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[1] Note on nomenclature: Iselin (1936) established the use of the term slope water for the water between the Gulf Stream and the Continental Shelf east of Cape Hatteras. The water on the shelf has been called both coastal water and, less popularly, shelf water. The latter term is used here, as by Ford, Longard, and Banks (1952), because this paper deals only with the water at the outer edge of the shelf, well removed geographically from the coast and somewhat distinct in temperature and salinity characteristics.

east corner of Georges Bank to the offing of Chesapeake Bay and other observers have found it almost as far south as Cape Hatteras. Iselin (1939,1940) recognized that there must be exchanges of shelf water and slope water at the edge of the continental shelf, with the saltier slope water moving shoreward along the bottom and shelf water moving seaward near the surface. Miller (1952) investigated possible mechanisms of exchange and Bumpus (1965) reported some evidence of a near-bottom shoreward component of motion. The existence of substantial parcels of shelf water in the slope water was described by Ford and Miller (1952), reporting a 1948 cruise and by Ford, Longard, and Banks (1952) as a result of Operation Cabot in 1950, the first detailed multiship investigation of the Gulf Stream using bathythermographs (BTs). Ford, Longard, and Banks found cold layers just inshore of the Stream in 57 of 97 crossings, and interpreted them as a series of shelf water "strips" which had presumably been entrained near Cape Hatteras. Howe (1962) concluded largely on the basis of drogue measurements that there is a southwesterly flow over much of the shelf and a "sudden sweep seaward" just north of Cape Hatteras, and Fisher (1972) actually observed the entrainment of fresh cold shelf water into the Gulf Stream. Detached parcels of shelf water in the slope water at other points along the shelf edge have been observed frequently but were apparently reported first by Cresswell (1967) who referred to them as "calved" parcels. Very useful atlases of the distribution of temperature at the edge of the shelf have been prepared by Walford and Wicklund (1968), showing vertical sections, and Colton and Stoddard (1972), who prepared horizontal plots at eight depths from the surface to 100 m. For both of these atlases the data were averaged by areas of 30 minutes of latitude and 30 minutes of longitude—quarter-degree squares.

This paper reports an analysis of individual observations arranged in chronological order over a period of 32 years in a region of maximum data. The work was undertaken to determine seasonal and longer-term fluctuations in the shape and position of the shelf water/slope water boundary and the role of detached shelf water parcels in the exchange process.

2. Method

The investigation was limited to the six-degree squares bounded by 39° and 41° North, 69° and 72° West (Fig. 2). The region was chosen partly because it has a relatively smooth shelf and slope without major topographic features (although Hudson Canyon impinges at the southwest and the effect of Great South Channel is evident to the east) and also because it has a very dense coverage of stations and bathythermograph observations. About one-quarter of the continental shelf edge between Cape Cod and Cape Hatteras is included in the region.

The data were those in the files at Woods Hole Oceanographic Institution, which contained more than 19,000 bathythermograms between 1941 and 1972. This is

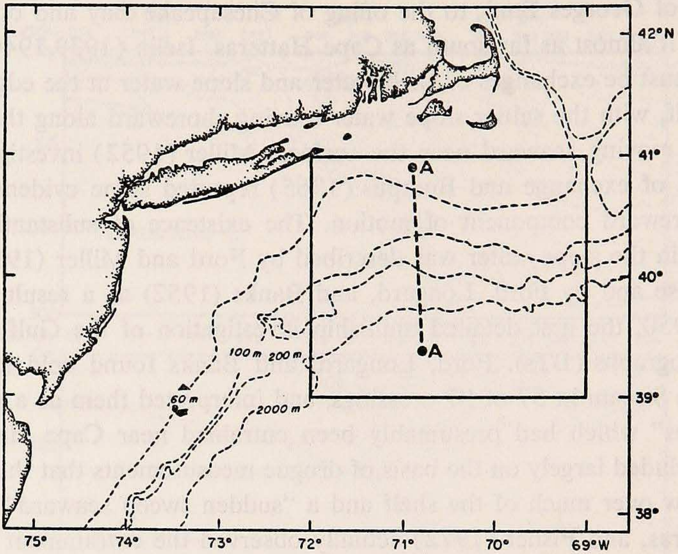

Figure 2. Region of investigation. Heavy dashed line AA shows location of GOSNOLD section.

an average of about 50 observations per month for the 32-year period but of course the distribution is not even in time or in space. There were 42 months—half of them during World War II—when no observations were made and there were more than twice as many observations from May through October than during the colder half of the year. Furthermore only about half the observations were made as part of closely spaced sections across the shelf edge into slope water. The same files also contained about 1600 oceanographic stations which, with a handful of surface observations, provide all the available information on salinity in the region for the years in question. The stations are spaced much less uniformly than the BTs, but are almost always arranged roughly north-south so that when they exist the cross-shelf salinity structure can be determined. Good, closely spaced salinity observations for the continental shelf are badly needed!

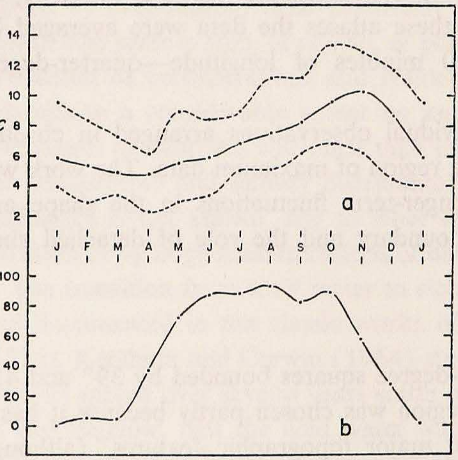

Figure 3. a) Monthly mean minimum temperature (solid line) and range of minimum values (dashed lines) in the shelf water near the shelf edge, 1941–1972.
b) Percent of occurrence of mid-depth minimum near the shelf edge, by month, 1941–1972.

The data were sorted and positions

were plotted month by month throughout the 32 years. On each plot were noted the positions and values of important hydrographic features: the cold water minimum on the shelf and its off-shore extension; evidence of shelf-water patches in the slope water; the intersection of the shelf water/slope water boundary with both the sea surface and the sea floor; intrusions of Gulf Stream water into the region. Finally the statistics of these phenomena were organized and tabulated.

3. Results

a. Temperature maxima and minima. The annual cycle of minimum temperature within the shelf water minimum layer at the shelf water/slope water boundary is shown in Fig. 3a. Only mid-depth minima in the region of the boundary were included, although in some months the minimum observed temperatures were elsewhere: in the well-mixed water over Nantucket Shoals or in the Long Island Sound effluent near Montauk Point. The lowest mid-depth mean minimum temperature—4.7°C—occurs in April. This is both warmer and later than the mean minima nearer shore: 3.5°C at Nantucket Shoals Light Vessel and 0.1°C at Woods Hole, both in mid-February (Chase, 1972). The minimum layer at the edge of the shelf reaches its warmest point—a mean of 10.2°—in November, well after the cooling cycle begins at the sea surface or in nearshore waters.

The lower half of the figure shows the percentage of occurrence, month by month, of these mid-depth minima. A well developed minimum layer exists only from May, when the vernal warming of surface water begins, through October, when autumn cooling and storms break down the summer thermocline. The cycle was described by Bigelow (1933) and by Ketchum and Corwin (1964).

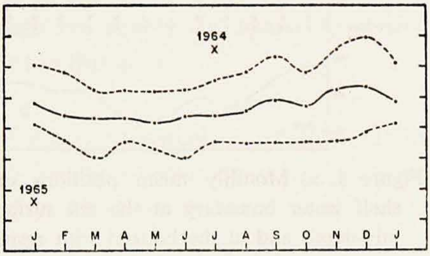

Figure 4. Monthly mean maximum temperature (solid line) and range of maximum values (dashed lines) in the slope water underlying the shelf water minimum layer, 1941–1972. Extreme winter (1965) and summer (1964) values are the only ones outside the envelope.

The slope water maximum underlying and usually a little seaward of the shelf water minimum also goes through a seasonal cycle but its range is much less than that of the minimum (Fig. 4). The annual mean is 13.2°C with a range from 12.3° to 14.6°. Salinity observations in the maximum are in the vicinity of 35.5‰, clearly slope water values. (An unpublished T/S analysis by Worthington and Wright indicates that a salinity of 35.56‰ is appropriate for 13°C in the slope water—slightly fresher than Iselin's (1936) value of 35.68‰ for the Sargasso Sea.)

b. Position of the shelf water boundary. The midpoint of the gradient between the shelf water minimum and the slope water maximum averages 10.2°C so that 10° isotherm has been taken to represent the boundary between the two water masses. Ford, Longard, and Banks (1952) used the same criterion. This indicator is useful in water deeper than about 40 meters except in late fall when the minimum itself is frequently warmer than 10°, and 11° or 12° is more appropriate. In depths less than 40 m the 10° isotherm is useful only through April; after that time the seasonal warming invalidates any thermometric index of water mass. For the surface boundary therefore, the 35‰ isohaline is used from May through December, as it pretty closely matches the 10° isotherm during the other months of the year. The salinity criterion is far from satisfactory because of the scarcity of observations (only 39 usable sets of data from June through November in the entire 32-year period) and the wide separation of stations compared with BTs. The mean boundary position based on such data cannot be considered representative except in a very general sense.

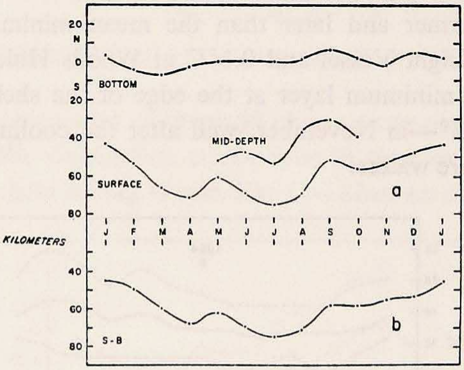

Figure 5. a) Monthly mean positions of the shelf water boundary at the sea surface, at mid-depth and at the bottom with respect to the 100 m curve, 1941–1972. Distances are in km north and south of the 100 m curve.
b) Differences (in km) between the mean surface and bottom positions of the shelf water boundary.

The shelf water boundary intersected the bottom close to the 100-m curve in all seasons. The exact position was difficult to establish precisely in most cases because of spacing of observations. However, it was possible to determine that the intersection was within 6 km of the 100-m curve 46 percent of the time and within 16 km 84 percent of the time that it was a valid indicator. The water depth ranges from about 80 m 16 km north of the 100-m curve to about 120 m 16 km south of it.

Figure 5a shows the seasonal changes in mean position of the shelf water boundary at the bottom, at mid-depth (usually 50 m) and at the sea surface, with relation to the 100-m curve. There is a great deal of variation about the mean, particularly at the surface: standard deviations for the monthly means at the bottom ranged from 6 to 17 km during most of the year but were 21 km in January and 29 km in December. At the surface the range of standard deviations was 20 to 40 km. The lower half of the figure shows the difference between the monthly means for surface and bottom. The departure from a smooth curve in May probably reflects the onset of vernal warming at the surface; using only the six cases when surface salinity data were available for May eliminates the anomaly. The September anomaly, based entirely on salinity, is unexplained.

It is clear that even in winter the shelf water boundary is much more nearly horizontal than vertical. In only 14 of the 84 winter months (January through May) when comparisons could be made was the surface position of the boundary within 16 km of the bottom position, and half of those occasions were during the warm winters of 1950 to 1952. The offshore movement of the surface boundary in summer, combined with the slight shoreward movement of the bottom boundary, represents a net increase in cross section of the shelf water of about 10 percent (Fig. 6).

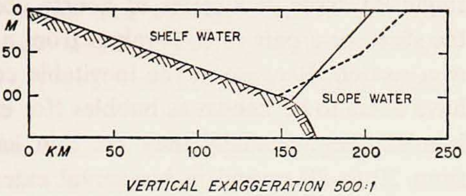

Figure 6. Schematic representation of change in cross-section of shelf water, winter to summer. Solid line represents the boundary in winter, dashed line in summer.

c. Secular trends. Efforts to relate the annual variation in position or temperature of the shelf water boundary to annual variation in weather were only partly successful. A gross pattern of warmer conditions in the early 1950s and colder conditions in the mid-1960s was evident in all variables: when the winter water temperature minimum was low, the bottom position of the 10° isotherm was further offshore, and winter air temperatures at Nantucket were similarly related to the surface position of the boundary (Fig. 7). However, the relationships did not always hold; it would appear that the hydrographic data are simply too sparse to clarify the oceanic response to changing weather patterns in this area.

d. Detached parcels. Although the existence of detached parcels of shelf water in the slope water is well documented, very little is known of their characteristic size, shape, frequency of formation, or rate of decay. Most often one is noted on a

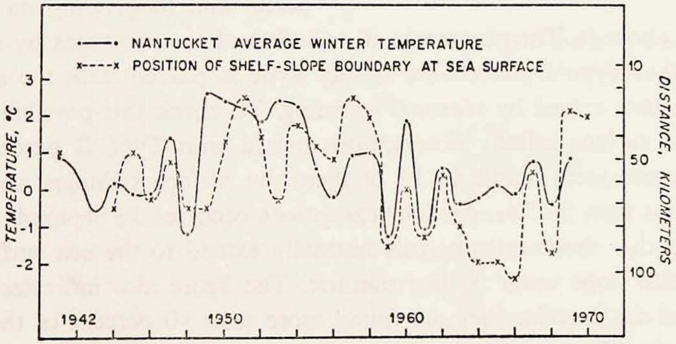

Figure 7. Comparison of Nantucket average winter temperatures (solid lines) and sea-surface position of the shelf water boundary, 1941–1972.

single BT trace in a series of hourly observations from a research vessel crossing the shelf, or a pair of T/S values from a single Nansen bottle near the inshore end of a section. Because of the inevitable contouring of such observations the parcels have come to be known as bubbles (for example, Cresswell, 1967), though the term is misleading. Actually they are thin lenses, which appear to range in thickness from 20 to 80 m and in horizontal extent from 10 to 20 km, and of course it is possible that they are long strips like those observed by Ford, Longard, and Banks (1952), or in some cases, filaments which are still attached to the parent shelf water mass, like those seen in satellite photos.

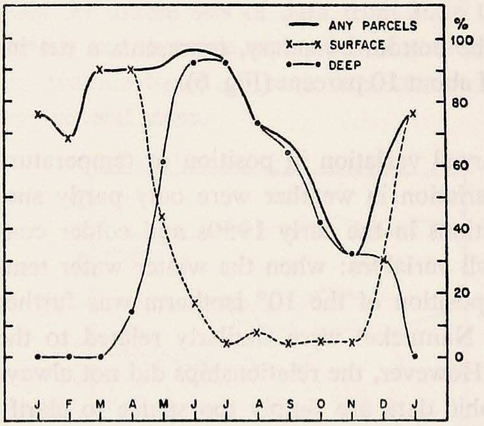

Figure 8. Monthly occurrence of detached shelf water parcels, expressed as percentage of the total number of months with adequate data. The heavy line represents occurrence of parcels regardless of type. Dashed line with crosses is for parcels with a surface temperature expression (type A), solid line with open circles for those without one (type B).

For the purposes of this survey a parcel of shelf water was defined as a temperature minimum of 10°C or colder (or a salinity minimum of 34.5‰ or fresher) separated from the main body of shelf water by either an observation in which no such minimum was present or by 30 miles with no intervening observations.

Two principal categories of such parcels were distinguished: A) those which can be identified by temperature at the sea surface; and B) those which can be identified only by subsurface observations. In Type A the temperature minimum typically extended to a depth of 50 to 80 m with little change; in Type B the minimum lay around 50 m, with water of 13° to 15°C below the parcel and (depending on the season) 13° to 24°C above it. The percentage distribution of the two types by month (Fig. 8), suggests that Type B parcels are simply Type A parcels with the surface temperature signature erased by seasonal warming. To check this possibility, a search was made for surface salinity observations paired with Type B parcels. Only 17 such coincidences were found; in 13 of them the surface salinities were less than 34‰, some less than 32.5‰. All four exceptions occurred in September. The indication then is that shelf water parcels normally extend to the sea surface but can be covered with slope water by late summer. The figure also indicates the ubiquitous nature of the parcels: they are found more than 90 percent of the time from March through July, more than 60 percent of the time from December through September. At least one parcel was distinguished in every year except 1942 when

BT observations were scarce and close to shore. The smallest number of occurrences when observational coverage was good was in 1951, an unusually warm year, when two parcels were present in May but none were seen in any other month.

e. Gulf stream incursions. Although the mean position of the Gulf Stream is south of 38°N between 69° and 72° West, water of Gulf Stream characteristics has been frequently observed in the study area. Such water can impinge upon the area either as a meander of the Gulf Stream itself or as an anticyclonic warm eddy which has become detached from the Stream and is surrounded by slope water. Saunders (1971) describes a very well documented warm eddy. Table 1 lists all occurrences of Gulf Stream water within the study area, based on the W.H.O.I. files. For this tabulation any salinity greater than 36.0‰ was taken to represent Gulf Stream water, as were temperatures greater than 18°C at 100 m or greater than 15°C at 200 m. Surface temperature criteria, which varied monthly, were based on the charts of Schroeder (1966): Gulf Stream water was defined as any water more than 4°C warmer than the monthly average at 38°N 70°W, except during July, August, and September when the surface temperature difference between Gulf Stream and Slope Waters is too small to permit valid distinctions. The table lists 44 months in 20 years in which Gulf Stream incursions were noted. In addition there were 13 occasions when summer surface temperatures were greater than 26°C but in the absence of confirming salinity or deep temperature data could not be unambiguously listed as Gulf Stream. Occurrences which can clearly be identified as warm eddies are noted.

Table I. Incursions of Gulf Stream Water.

Year	Month	Location (deg.sq./quadrant)	Criterion	Comment	Eddy
1943	Jun	3971/NE	T_s	1 observation only	
1944	Aug	3971/NW,SW	T_s?	26°	
1947	Jul	3970/SE	S		
	Sep	3970/NE	T_s?	$T_s > 27°$ but $S < 36‰$	
	Dec	3970/NW	S,T_s	No observations Oct, Nov	
1948	Sep	3970/NE	T_s,T_D		
	Oct	3970/NW	S	36.0‰	
	Dec	3970/SW	T_D	15° at 200 m	✓
1949	Aug	3970	T_s?	>27°	
1950	Feb	3970/SW	T_s	>19°	
1951	Jul	3969/NE	T_s?	28°	
	Aug	3969/SE	T_s?	26°	
	Sep	3969/SW	T_s?	26°	
	Oct	3969/NE	S	36.0‰	
	Nov	3969/SE	T_D	19° to 100 m	
	Dec	3969/SW	T_D	>18° at 100 m	

Table I (continued).

Year	Month	Location (deg.sq./quadrant)	Criterion	Comment	Eddy
1952	Jan	3969/SW	T_D	>15° at 200 m	✓
	Jul	3970/SW	T_D,S	15.8°, 36.0‰ at 150 m	
	Sep	3969/SW	S	36.2‰ at 100 m	
	Oct	3971/SE	T_S	25°	
	Dec	3969/SE	T_D	16° at 200 m	✓
1954	Aug	3970/SE	T_S?	26°	
1955	Aug	3969/SW	T_D	15° at 200 m	✓
1956	Jan	3971/SW	T_D	>15° at 200 m	
	Nov	3971/SE,NE	S,T_D	18°, 36.1‰ at 100 m	✓
1957	Mar	3971/NE	S	>36.2‰ to 200 m	✓
	Aug	3969/SE	T_D	18° at 200 m	
	Sep	3971/SE,NE,SW	S,T_D	>17°, 36.5‰ at 200 m	✓
1958	Feb	3969/SE	T_D	17° at 200 m	✓
	Mar	3969/SW	T_D	18° at 200 m	
	Sep	3971/NE	S	36.0‰	
	Nov	3969,3970	T_D	>20° at 100 m	
1959	Aug	3969/SW,3970/SE,SW	T_S?	26°	
	Nov	3969/SE,SW	T_S	23°	
1960	Aug	3969/SW	T_S?	>26°	
1961	Aug	3969/SE	T_S?	>26°	
1962	Aug	3969/SE	T_S?	>26°	
1966	Dec	Site D	T_D,S	18°, 36.2‰ at 100 m	
1967	Apr	3970/SE	S	36.0‰	
	Sep	3969/SE	S	36.0‰	
1968	Sep	Site D	S	36.2‰	✓
	Oct	Site D	S	36.2‰	
1969	Apr	Site D	S	36.0‰	
	Jun	Site D	S	36.0‰	
	Aug	Site D	T_S?	>26°	
	Oct	3969	T_D	>15° at 200 m	✓
	Nov	3970	T_D	18° at 200 m	✓
	Dec	3970,3971	T_D	>17° at 200 m	✓
1970	Jan	3971	T_D	>16° at 200 m	✓
	May	3969/SE	T_D	18° at 200 m	
1971	Jan	3970/NE	S	36.0‰ at 175 m	✓
	Jul	3969/SE	T_S?	>27°	
	Aug	3969/SE	T_D	16° at 200 m	✓
	Sep	3969/SW	T_D	17° at 200 m	✓
	Nov	Site D	S	36.1‰	✓
1972	Sep	Site D	S	36.4‰ at 100 m	
	Dec	Site D	S	36.4‰ at 200 m	✓

Key: T_S = surface temperature
T_D = subsurface temperature
S = salinity
? = unsupported summer T_S

f. Summarizing the table: i. Location: Gulf Stream water as defined here was never observed north of 40°N which is equivalent to the shelf edge in this region. Only 8 occurrences (17 percent of the total) were north of 39°30′. Since 1966 the observations have been geographically biased by the dense sampling near Site D (30°10′N, 70°W), with more than 80 percent of the Gulf Stream occurrences in that location, but in earlier years the occurrences were pretty evenly distributed with respect to longitude.

ii. Season: Gulf Stream water was observed most frequently from August through January (occurring 28 percent of all the months when adequate observations were made) and much less frequently from February through July (averaging 9 percent of the months with adequate observations).

iii. Duration: Two-thirds of the occurrences were grouped in sequences of two to six months during which the Gulf Stream water was noted at least two of every three consecutive months. There were 11 such sequences: four of two months duration, three of three months, three of four months and one of six months duration. Saunders (1971) estimated the life of Gulf Stream eddies in the slope water at 6 months to a year but they are believed to move gradually southwest at a few cm/sec and thus would not be expected to remain in any limited region more than a few months.

Before 1960 these bursts of Gulf Stream activity occurred over periods of two to three years, separated by intervals of similar duration when very few or no Gulf Stream occurrences were observed. Peak years were 1947–48, 1951–52, 1957–58. Recently the period of alternation appears to have slowed: from 1960 through 1965 there were no unambiguous occurrences of Gulf Stream water but since 1967 there have been at least two each year. The U. S. Navy Hydrographic Office Monthly Summary of the Gulf Stream, issued since 1966, supports this conclusion and carries the record further with abundant observations of warm eddies in both 1973 and 1974, perhaps related to intensity of effort. There is no apparent year-to-year relationship between the occurrence of Gulf Stream water and observations of detached shelf-water parcels.

4. Discussion

On the assumption that the study region is representative of the entire Middle Atlantic Bight, the results presented above can be combined with climatological data to develop a gross water budget for the bight.

Taking 35‰ as the criterion, the total volume of shelf water in the Middle

Atlantic Bight is about 11,000 km^3, according to a volumetric temperature/salinity census by Wright and Parker (in press).

The mean river influx in the Middle Atlantic Bight averaged 157 km^2/yr from 1931 to 1960 (Bue, 1970). The net effect of evaporation and precipitation on the fresh water balance is taken to be negligible: Bunker (1975) shows evaporation in the region at 110 cm/yr and mean precipitation at Nantucket is 104 cm/yr. (The latter figure was measured on land and is of questionable validity for the ocean. Ketchum and Keen (1955) used 70 cm/yr for precipitation, based on earlier estimates; the difference is not critical.) The mean coastal water salinity along a repeated section southeast of Montauk from 1956 to 1959 was 32.9‰ (Ketchum and Corwin, 1964) and a representative slope water salinity for the top 200 m is 35.2‰. Using these values, the amount of slope water needed to mix with the fresh water to produce shelf water is 2245 km^3/yr and the total production of new coastal water is $2245 + 157 = 2400$ km^3/yr. The annual production of new shelf water is thus 20 to 25 percent of the total shelf water volume.

An equivalent amount of shelf water must be discharged annually into the open sea. Stommel (1958, p. 65) estimated that about 300 km^3/yr would have to be entrained in the Gulf Stream at Cape Hatteras to provide the streaks observed by Ford, Longard, and Banks (1952). The remaining volume, around 2100 km^3/yr, must be released, by diffusive mixing or as calved parcels, along the length of the shelf.

It is impossible to estimate the size of shelf water parcels with any confidence. None has been precisely delineated and they surely vary widely in shape and horizontal extent. However, on the assumption that they are roughly circular and noting that they are rarely observed by more than two consecutive hourly BTs, we can assign a diameter of 20 to 25 km and an area of about 400 km^2. Thickness varies somewhat with type but is between 20 and 80 m, say 50 m, so that the average volume of a parcel is about 20 km^3, roughly the combined volume of Vineyard and Nantucket Sounds. The estimate could easily be off by a factor of two.

On this basis about 100 parcels/year are required to maintain the balance, or about 25/year in the stretch between 69° and 72° W. The present census provides information only on standing crop and we know nothing about the production and disintegration rates of shelf water parcels, but assuming that they decay much more rapidly than the much larger Gulf Stream eddies, and given the spatial and temporal distribution of observations, it seems reasonable to assert that the parcel data are consistent with the calculated production rate.

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* Unlike the present study, which suggests a summertime expansion of shelf water of about 10%, the volumetric census shows virtually no seasonal change in total volume fresher than 35‰. However, the spring runoff is reflected in a slightly lower mean salinity for the shelf water in summer. The inconsistency between the two is undoubtedly related to the inadequate salinity data, and also to the fact that the 10° isotherm and 35‰ isohaline are not identical even in winter.

Acknowledgements. Much assistance in using the W.H.O.I. BT and station data files was provided by Miss E. H. Schroeder, Mrs. W. H. Frank, and Mrs. P. T. Bailey. The author benefited greatly from discussions with Miss Schroeder, C. E. Parker, A. D. Voorhis, and J. Chase. The work was supported by the National Science Foundation under Grant GA 36499.

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