realistic time-dependent winds by Willebrand, Philander, and Pacanowski (1980) suggest that the volume transport of the slope water gyre should *not* vary significantly over the year, and, in fact, Thompson (1977) found no evidence of an annual signal in the long-term deep-current measurements made near site D on the New England continental rise. These two results imply that the magnitude of the alongshore pressure gradient imposed at the shelf break should remain nearly constant over the year. Since the long-term current measurements made just off the New Jersey coast by EG&G (1978) also exhibit no significant annual cycle, we suggest that the very low-frequency currents over most of the Middle Atlantic Bight will reflect broadband forcing and not exhibit a significant annual variation.

7.3.4 Summary and Some Remaining Problems

We have attempted here to describe the shelf response to wind forcing on three time scales. Synoptic-scale atmospheric disturbances and in particular winter cyclones can drive strong transient current fields that tend to move along the shelf in phase with the forcing. The cross-shelf momentum balance is approximately geostrophic and both the current and subsurface pressure fluctuations are generally coherent over much of the Middle Atlantic Bight, reflecting the relatively small size of this shelf region with respect to the atmospheric forcing. The synoptic-scale shelf response appears to be consistent with continental shelf-wave theory. The direct effect of wind forcing is also evident in the monthly-mean shelf circulation, although the observed currents have a complex spatial structure and other processes like runoff and offshelf forcing contribute to the variability on this time scale. The mean flow over the Middle Atlantic Bight is primarily driven not by local runoff and wind stress but by the large-scale wind stress and heat-flux patterns over the western North Atlantic. Thus the observed currents can be decomposed into a mean component driven by a steady offshelf forcing and a fluctuating component driven by the regional wind stress field acting over the shelf.

This review has focused on the wind-driven-circulation components in the Middle Atlantic Bight. The actual influence of density stratification on the different components of the general circulation is still not clear, and only a crude estimate of the flushing rate of the shelf is available. The processes controlling the local position and movement of the shelf-slope-water front are poorly known. As noted by Fofonoff (chapter 4, this volume), satellite infrared mapping of the sea surface temperature has greatly added to our perception of the spatial variability and complexity of the near-surface current and thermal fields. The satellite infrared photograph shown here in figure 7.15 illustrates thermal structures or fronts on a wide range of scales throughout the Middle Atlantic Bight. The most pronounced thermal front is the shelf–slope-water front, and while it crudely follows the shelf break, some of the colder shelf water does extend far offshelf into the slope water or along the northern side of the Gulf Stream. Several anticyclonic Gulf Stream eddies are also shown in the slope water north of the Gulf Stream. It remains to be determined whether Gulf Stream eddies and other very low-frequency phenomena in the slope water have much real influence on the flow of shelf water through the Middle Atlantic Bight.

Appendix: Annual Air–Sea Interaction Cycles and Mean Runoff for the Middle Atlantic Bight

The mean and average monthly heat-flux cycles over the southern section of the Middle Atlantic Bight have been described by Bunker (1976). We show here his results, plus additional data kindly supplied by Bunker (personal communication) for the northern section, to give a complete picture of the seasonal heat flux cycles for the entire Middle Atlantic Bight. The monthly air and sea surface-temperature and heat-flux cycles for both sections shown in figure 7.16 and the annual mean values are listed in table 7.3. We note that the sea surface-temperature cycle lags the net heat-flux cycle by about 90°, and that the approximately 17°C increase in sea surface-temperature from March to August is consistent with a uniform mixing of the net internal-energy gain by the shelf water during that period to a mean depth of 30 m.

Average precipitation and evaporation data for the Middle Atlantic Bight are also shown in figure 7.16 and in table 7.3. The evaporation rates are computed from Bunker's heat-flux data. Although few precipitation data are available over the Middle Atlantic Bight, precipitation along the coast of the Middle Atlantic Bight is roughly uniform and exhibits relatively little seasonality [see Geraghty et al. (1973) and Lettau, Brower, and Quayle (1976)]. We thus have used data from New York City as an estimate for the precipitation cycle over the entire Middle Atlantic Bight. Mean steamflow of fresh water entering the Middle Atlantic Bight along the coast via the major estuaries is also given in table 7.4. Most of the fresh water is contributed by a few major sources, especially the Chesapeake Bay. The mean precipitation crudely balances evaporation over the Middle Atlantic Bight and the net input of fresh water via local precipitation minus evaporation into the Middle Atlantic Bight is minor in comparison to runoff at the coast. Advection of fresh water (meaning here zero salinity) from the Gulf of Maine and Georges Bank region accounts for most of the total fresh water flux into the Middle Atlantic Bight.

R. C. Beardsley and W. C. Boicourt

Figure 7.15 The thermal infrared image of the Middle Atlantic Bight was obtained on 1430 GMT, May 1, 1977, by the NOAA-5 polar orbiting environmental satellite. The sea surface temperature is indicated by a grey-scale code with darker tones corresponding to warmer water. The purely white areas indicate clouds. This image is shown courtesy of R. Legeckis, National Environmenttal Satellite Service.

Estuarine and Continental-Shelf Circulation
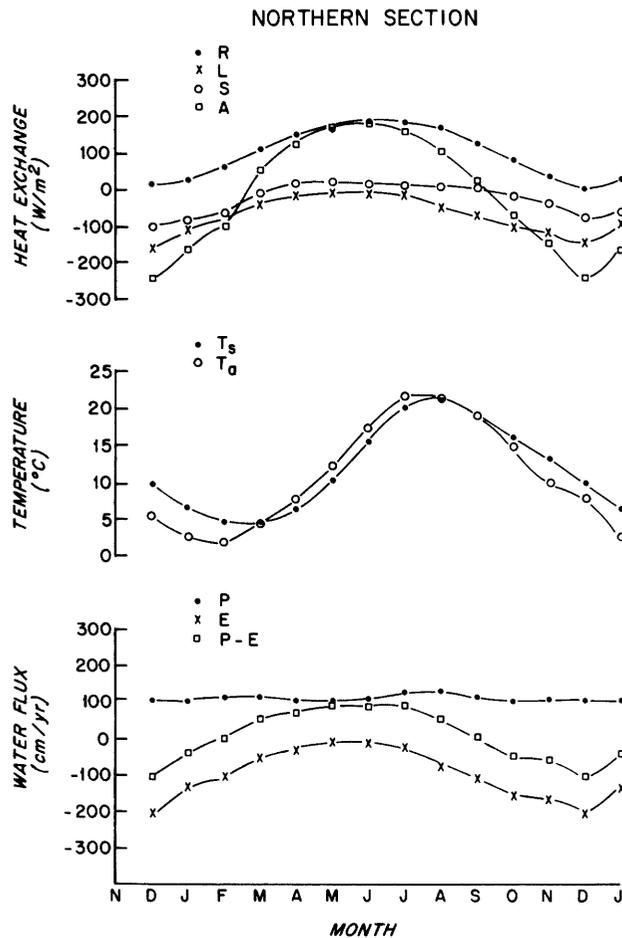
NORTHERN SECTION

Figure 7.16 Seasonal heat flux, surface temperature, and water-flux cycles for the southern and northern sections of the Middle Atlantic Bight.

Table 7.3 Mean Surface Heat and Water Fluxes in the Middle Atlantic Bight[a]

	Units	Southern[b] section	Northern[b] section
Air temperature	°C	15.0	11.6
Sea surface temperature	°C	15.5	12.3
Dew point temperature	°C	11.2	8.2
Net radiation flux into ocean R	$W\,m^{-2}$	126.5	109.1
Heat loss by evaporation L	$W\,m^{-2}$	88.7	72.3
Sensible heat loss S	$W\,m^{-2}$	23.9	27.3
Net heat flux into ocean $A = R - L - S$	$W\,m^{-2}$	13.9	+9.5
Precipitation P[c]	$cm\,yr^{-1}$	111.2	111.2
Evaporation E	$cm\,yr^{-1}$	113.9	93.3
Net $P - E$ flux into ocean	$cm\,yr^{-1}$	−2.7	+17.9
Surface area of section[b]	km^2	5.9×10^4	4.8×10^4

a. All data, unless otherwise noted, are given by Bunker (1976) or Bunker (personal communication). Useful conversion factors: E $(cm\,yr^{-1})$ = 1.29 × L $(W\,m^{-2})$; 1 $kcal\,cm^{-2}/30$ days = 16.15 $W\,m^{-2}$.
b. The southern section is that part of the Middle Atlantic Bight lying west of 72°W and between 36° and 40°N. The northern section is the remaining part of the Middle Atlantic Bight lying north of 40°N and west of 70°W. Both sections are shown in Bunker (1976, figure 3).
c. The mean monthly precipitation values given here and in figure 7.16 are for New York City, 1939–1978.

Table 7.4 Mean Stream Flow into the Middle Atlantic Bight between Cape Cod and Cape Hatteras, 1931–1960[a]

Segment	Stream flow $(m^3\,s^{-1})$	Stream flow–drainage area $(cm\,yr^{-1})$	Principal source	Stream flow $(m^3\,s^{-1})$ due to principal source	Percentage of total stream flow due to principal source
Cape Cod, MA, to CT–NY state line	888	60.3	Connecticut River	627	71
CT–NY state line to Cape May, NJ	873	54.8	Lower New York Bay (including Hudson, Hackensack, Passaic, and Raritan Rivers)	748	86
Cape May, NJ, to Cape Charles, VA	622	54.8	Delaware Bay	587	94
Cape Charles, VA, to Cape Hatteras, VA	2651	39.0	Chesapeake Bay	2154	81

a. All data from Bue (1970).

R. C. Beardsley and W. C. Boicourt

Notes

1. An example of the increased concern for resource and environmental management of estuaries is the formation in 1948 of the Chesapeake Bay Institute at The Johns Hopkins University. R. Revelle was instrumental in bringing together the interests of the Office of Naval Research, the State of Maryland, and the Commonwealth of Virginia into a consortium that provided the necessary support for the founding of the Institute. The primary focus of the new laboratory was the physical oceanography of estuaries and D. W. Pritchard was chosen as its first director.

2. Letter from the Office of Chief of Engineers, U.S. Army, to the Director, the National Bureau of Standards, December 19, 1945, Army file number CE-SPEWE.

3. Early observers in the Middle Atlantic Bight generally recognized only one transition or frontal zone between relatively fresh coastal water with salinities S less than 34 or 35‰ and Gulf Stream water with S greater than 35‰. The term *slope water* was first used by Bjerkan (1919) to describe water between 33.0 and 35.0‰ over the Scotian Shelf. Huntsman (1924), Bigelow (1927), and Bigelow and Sears (1935) next used the same term to describe the more saline water with $S \geq$ 35.0‰ found over the slope off the Scotian Shelf, Gulf of Maine, and the Middle Atlantic Bight regions, respectively. Iselin (1936) then firmly established the use of the term slope water for water with salinities between 35.0 and 36.0‰ found between the Gulf Stream (then characterized by surface $S \geq$ 36.0‰) and the continental shelf from Cape Hatteras east to longitude 65°W.

Both Bigelow in his various reports and Bigelow and Sears (1935) referred to water fresher than 35‰ found in the Gulf of Maine and the Middle Atlantic Bight as both *coastal* and *shelf water* although they clearly preferred the former term, which was then in common use. Iselin (1939b) later called water fresher than 34‰ coastal water, although some, like Ford, Longard, and Banks (1952) and Ford and Miller (1952), chose shelf water as a more accurate and descriptive term for water fresher than 35‰. Both terms have been used rather interchangeably in the literature since then, although the term shelf water is now more popular. Wright and Parker (1976) have constructed a seasonal volumetric temperature-salinity census for the Middle Atlantic Bight and found a clear distinction between the shelf- and slope-water masses in both winter and summer seasons. They advocate the general term shelf water for all water on or near the Middle Atlantic Bight shelf fresher than 35‰. We shall use this term here.

4. The dynamic or geostrophic method was developed in northern Europe by Sandström and Helland-Hansen (1903), who derived the formula for computing relative geostrophic currents from the observed density field on the basis of V. Bjerknes's (1898) circulation theorem, and by Helland-Hansen and Nansen (1909), who applied the method to hydrographic data taken in the Norwegian Sea under Hjort's direction (Schlee, 1973). In 1911 a report entitled *Dynamic Meteorology and Hydrography*, written by Bjerknes and others, was printed in the United States to help introduce the geostrophic method to the American scientific community. It appears, however, that Bigelow first learned of this method from Sandström's chapter in the report of the Canadian Fisheries Expedition of 1914-1915, published in 1919. Hjort had been invited by the Biological Board of Canada to lead this expedition, and he brought Sandström along to work up the dynamic computations. Sandström's chapter described the dynamic method and presented two spectacular plates showing the geostrophic cur-

rents off eastern Canada in perspective view. Shortly after World War I, the U.S. Coast Guard sent E. Smith of the International Ice Patrol to study oceanography with Bigelow. With Bigelow's encouragement, Smith began to study the geostrophic method and, after a year spent with Helland-Hansen in Norway, Smith (1926) wrote a Coast Guard manual on practical dynamic computation that was immediately adopted and put to use by the Ice Patrol to predict the drift of icebergs. During this period, Smith worked closely with Bigelow and helped him prepare the geostrophic-current maps for the Gulf of Maine presented in Bigelow's (1927) monograph. The estimated geostrophic surface flow was consistent enough with his own drift-bottle data that Bigelow became an early and influential exponent of the dynamic method in the United States (Schlee, 1973).

5. In 1930 the Woods Hole Oceanographic Institution (WHOI) was established through the joint efforts of F. R. Lillie of the Marine Biological Laboratory in Woods Hole and Bigelow, and Bigelow was appointed director, a position he held for the next decade. Bigelow's research had been focused on coastal problems and he helped select Woods Hole as the site for the new institution since it offered easy access to two very different and contrasting coastal regimes (the Gulf of Maine and the Middle Atlantic Bight) as well as the open sea (Bigelow, 1929). Tired of getting seasick on the *Grampus* and other small coastal vessels, and believing that a sailing vessel would be both more stable and less expensive to operate than a motor vessel, Bigelow had the 142-foot *Atlantis*, the large steel-hulled ketch, built as the first research vessel for the new institution (Schlee, 1978).

6. Bumpus himself experimented with moored instrumentation in the early 1960s, but abandoned this approach when he found that the early Richardson current meters were too fragile to withstand mooring motion (Bumpus, personal communication).

7. Mooers et al. (1976) noted that the winter weather systems are sufficiently well organized that objective hindcast methods may be used to predict the synoptic-scale surface pressure and wind-stress fields over the Middle Atlantic Bight. They demonstrated this idea by using the environmental buoy and coastal data to hindcast successfully (using a Cressman phase-lagged method) the surface pressure and vector wind stress at the two buoys. Overland and Gemmill (1977) made a less successful prediction of surface winds at the two buoys using just coastal data. This work suggests that the synoptic-scale surface-pressure and wind-stress fields could be accurately predicted over the entire Middle Atlantic Bight using just coastal data once sufficient buoy data are obtained in different regions to calibrate the prediction scheme.

8. Alongshelf currents directed toward the northeast are referred to here as *upshelf*, while alongshelf currents directed towards the southwest are referred to as *downshelf*.

9. The term *coastal sea level* is used in this chapter to mean the adjusted coastal sea level, i.e., the sum of observed coastal sea level and local atmospheric pressure.