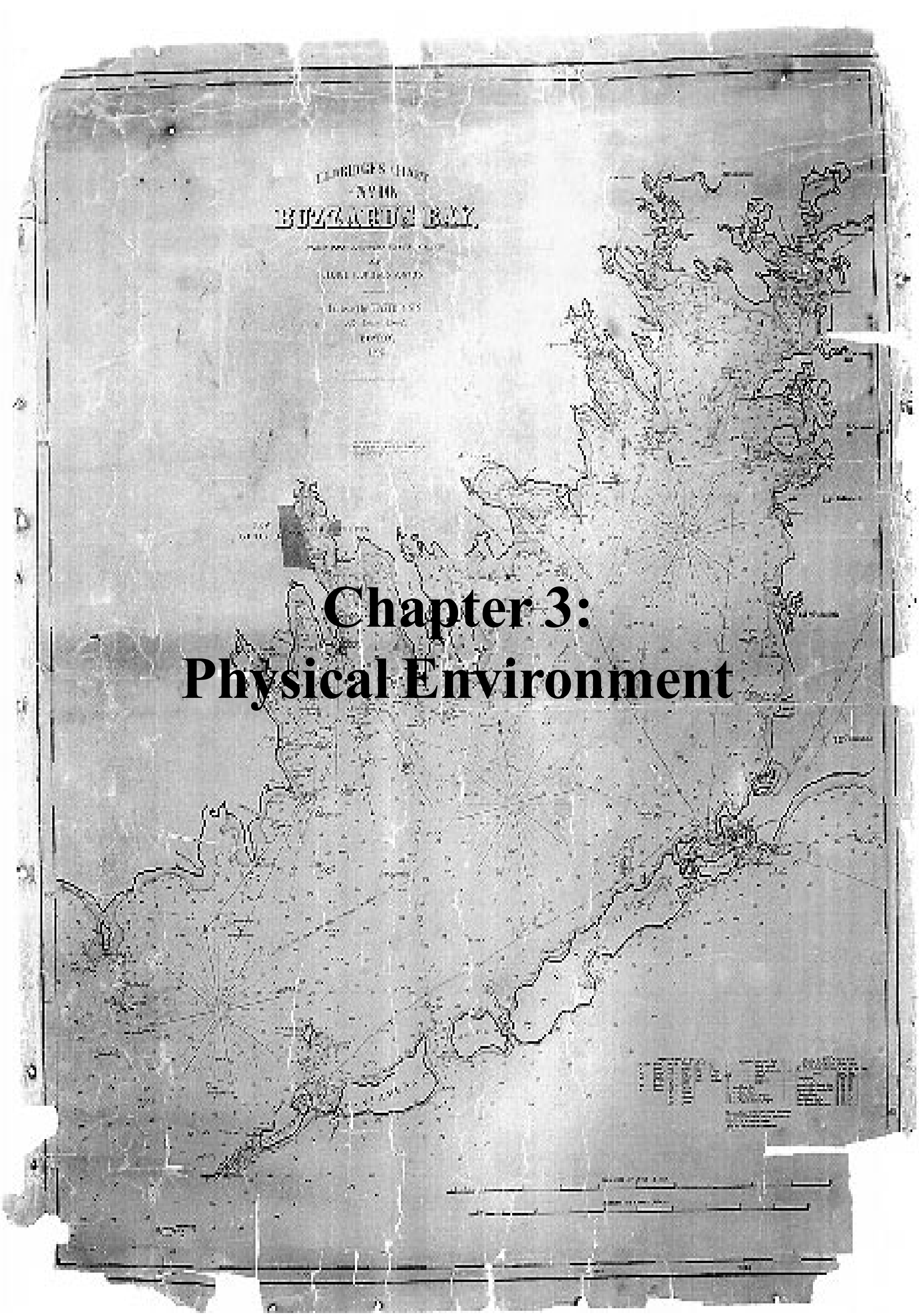

Chapter 3: Physical Environment

3.1. Fresh Water: Rain, Surface, and Groundwater Flows

The watershed of Buzzards Bay is that region on which rainfall flows over the surface or through groundwater into the bay. In simplest terms, the fates of precipitation on the land surface are surface water runoff through rivers and streams, subsurface transport and discharges as groundwater, or return to the atmosphere via surface evaporation or uptake and loss by plants as evapotranspiration. The partitioning of flow between these various pathways has important consequences for nutrient and pollutant transport to and the salinity structure of bay waters. However, accurate partitioning for each embayment is complex and requires diverse long-term data sets and therefore has yet to be performed throughout this system. Measurements of groundwater discharges are also very limited and are confounded since many of the rivers and streams have significant groundwater contributions. However, rainfall has been measured over the long term at several locations around the watershed and limited river discharge data are available. Based on these data, it is possible to generate a general baywide picture of freshwater inputs. Given the highly permeable soils resulting from glacial outwash, significant amounts of fresh water reach the bay directly as groundwater discharge, and the rivers and streams around the bay have a significant baseflow (groundwater) component to their discharges. Glaciation has also affected discharge, as the western shore with its extensive outwash soils contains the major surface water flows to the bay, primarily along outwash channels. In contrast, the smaller watershed area and different deposits on the eastern shore yield an area dominated by smaller, generally groundwater-fed streams and direct groundwater discharges (Fig. 3.1, Table 3.1).

Precipitation is relatively uniform throughout the year with only a minor low during summer (Fig. 3.2A). However, this temporal uniformity in rain input does not translate into a constant freshwater input to Buzzards Bay. The temporal lag between

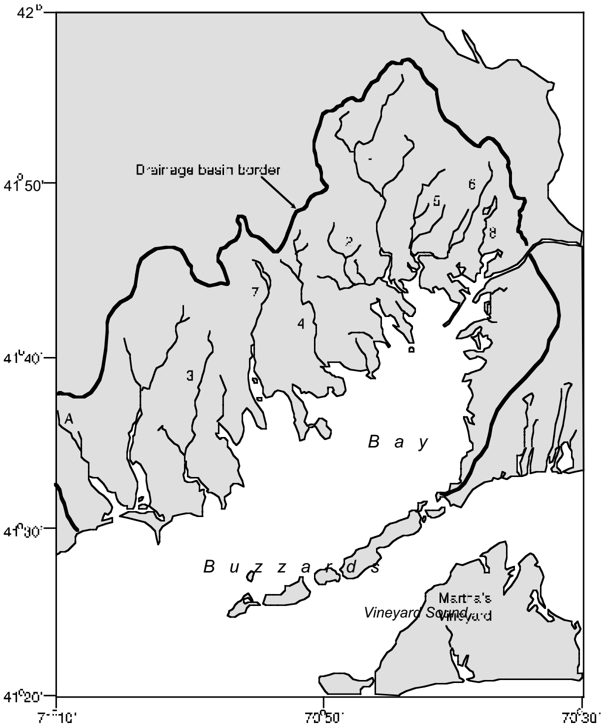

Fig. 3.1. Drainage basins and location of major streams emptying into Buzzards Bay. Westport River (A) has the only long-term stream gauge in the region. Numbers refer to rivers listed in Table 3.1. From Signell (1987).

Table 3.1. Estimated freshwater flows to Buzzards Bay. Numbers refer to locations of rivers on watershed map (Fig. 3.1). Adapted from Signell (1987).

Map symbol	River	Drainage area (km^2)	Inferred basin flow (m^3/s)	Contribution of flow (%)
A+A'	Westport (East+West)	216	4.3	19.6
1.	Weweantic	145	2.9	13.2
2.	Sippican	73	1.4	6.6
3.	Paskamenet	68	1.3	6.1
4.	Mattapoisett	62	1.2	5.6
5.	Wankinko	53	1.1	4.8
6.	Agawam	44	0.9	4.0
7.	Acushnet	43	0.8	3.8
8.	Red Brook	24	0.5	2.1
Groundwater + streams		377	7.5	34.2
Bay watershed total		1105	21.9	100.0

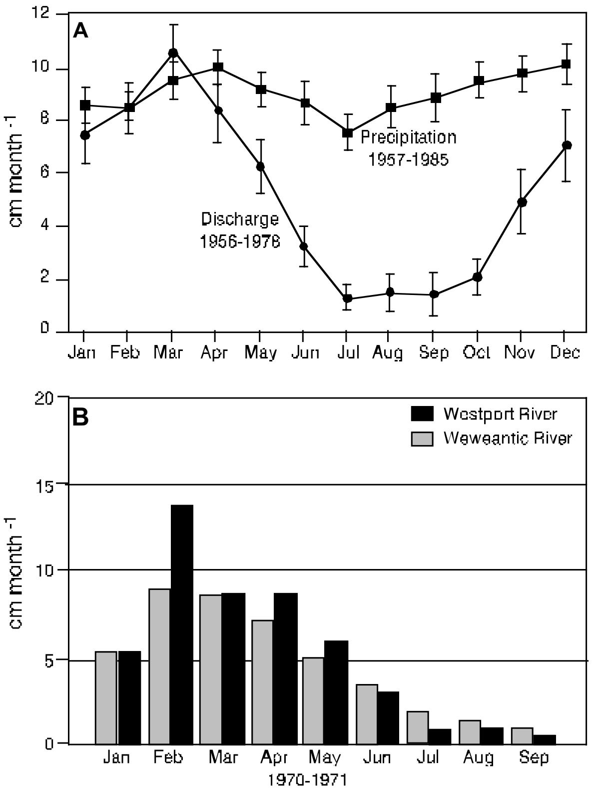

Fig. 3.2. A. Precipitation and mean monthly discharge of the Westport River, normalized by its drainage area. B. Comparison of normalized discharge from 2 years of data from the Westport and Weweantic Rivers. From Signell (1987).

inputs and discharges results primarily from strong seasonal shifts in recharge rates that are due to losses via evapotranspiration and to a lesser extent the storage of ice and snow during winter until spring melt. Annual return of rainwater within the watershed to the atmosphere is about 65% (45% recharge; LeBlanc et al. 1986). The integrated result of the cycles of precipitation, temperature, and evapotranspiration is a distinct seasonal variation in water table elevation with resulting variations in discharge.

Although river discharge data are limited, long-term measurements were conducted on the major river system, the Westport River (Fig. 3.2B), with smaller data sets available for the Weweantic River (cf. Signell 1987) and Red Brook (Moog 1987). The seasonality of river discharge is clear in the Westport and Weweantic rivers (Fig. 3.2B). Similar temporal variations caused by seasonal changes in hydraulic gradient were found in groundwater discharge into Buttermilk Bay (Weiskel 1991).

The similar discharge rates per unit of watershed for the Westport and Weweantic rivers over the same period (Fig. 3.2B) support the use of a generalized ratio of discharge/subwatershed area for each of the major rivers discharging to Buzzards Bay (Signell 1987). The ratio from the long-term Westport data is 0.0198 (m^3/s)/km^2, similar to a study by Bue (1970) for a nearby Cape Cod River of 0.0191 (m^3/s)/km^2. The bay-wide total freshwater inflow estimated from this approach is 22 m^3/s with the Westport and Weweantic rivers accounting for about one-third of the total flow (Table 3.1). While this technique does not separate the contribution of runoff versus groundwater inflow to total discharge, baseflow within this watershed is probably significant based on the geology and Red Brook, where approximately 69% of the total flow is baseflow (Moog 1987). Because of the relatively small watershed area versus bay area, the freshwater inflow (22 m^3/s) is nearly equivalent to the direct rain input to the bay surface (18 m^3/s), although evaporation of bay water must also be considered. Nonetheless, the importance of considering direct precipitation is clear. Although direct precipitation leads to dilution of bay salinities, it is less important than streamflow in producing salinity gradients within the bay waters.

The apparent temporal variation in freshwater discharge through surface and groundwater pathways and the nearly uniform monthly precipitation input directly to bay waters are consistent with the salinities observed in the open bay surface waters near the mouth. Salinity measurements collected over 14 years in Woods Hole, which receives a mean mass flux of water from Buzzards Bay and has almost no nearby freshwater discharges, indicate a small annual range of less than 1 ppt, with a minimum in April, maximum freshwater discharge in February-April (Fig. 3.2), and a maximum of 31.9 ppt in October at the end of the low discharge period (cf. Signell 1987).

3.2. Salinity, Temperature, and Density

The salinity of Buzzards Bay waters is the result of mixing of oceanic water with freshwater inflow (and rain). The distribution of freshwater input is consistent with the geology and watershed distribution and suggests that more than two-thirds of the inflow is along the western shore with the most concentrated flows near the head of the bay (Table 3.1, Fig. 3.1). The distribution of freshwater flow and the circulation pattern of the bay result in a gradient of decreasing salinity with increasing distance from the mouth of the bay (Fig. 3.3). The gradient is found in each season, but the greatest dilution is found in the April transect with surface waters at the head of the bay dipping to almost 28 ppt, consistent with the period of maximum freshwater discharge (Fig. 3.2A). The greater dilution of surface versus bottom water (Fig. 3.3) is typical of estuaries where the less dense fresh water enters near the surface over denser, cold saline bay waters.

As is the case for most of the New England coastal region, Buzzards Bay experiences great extremes in seawater temperature. Cape Cod is situated at the transition between the cold waters of the Gulf of Maine and the warmer waters of the Mid-Atlantic Bight; however, because exchanges are with Rhode Island and Vineyard sounds, they are primarily with warmer water lying south of Cape Cod. Buzzards Bay is included in the American Atlantic Temperate Region, which extends from Cape Cod south to Texas and is largely influenced by the warm waters of the Gulf Stream generated by the westward flow of the North Equatorial Current through the West Indies and Mexico and northward along the east coast of the United States. At Cape Cod, the current turns east and becomes the North Atlantic Drift, ultimately flowing to the British Isles and Europe. In contrast, Cape Cod and Massachusetts Bay are influenced by the Maine Current, a branch of the Labrador Current flowing south from Greenland. The temperature differences between Cape Cod Bay and Buzzards Bay can be as much as 5.5° C. Buzzards Bay water temperatures range over an annual cycle from 0 to 22° C in the bottom waters (Fig. 3.4) with greater extremes near the surface. The central bay typically remains ice free during the winter; however, occasionally the entire upper bay ices over.

Water column stratification occurs when less dense (warmer or fresher) surface water overlies more dense (colder or more saline) bottom waters. Periodic stratification occurs in Buzzards Bay (Fig. 3.3). The causes and level of stratification are not the same throughout the year. Vertical temperature gradients (Fig. 3.3), when they occur, are typically generated by radiative heating of the surface waters and are the dominant cause of stratification in the lower bay during summer (e.g., Fig. 3.3 top). Thermal stratification generally has a diurnal component and is readily broken down; however, because it occurs during the warmest months, its effects on dissolved oxygen balance below the thermocline may be generally more significant than the typical salinity stratification. Salinity stratification, while it can occur year-round in response to short-term meteorological events, is strongest in Buzzards Bay in spring when freshwater inflow is greatest (Fig. 3.3). Fortunately, spring water temperatures are low (Fig. 3.4), resulting in low oxygen demand and dissolved oxygen levels that remain high even during stratification.

For the most part water column stratification in the central region of Buzzards Bay periodically exists during summer months predominately because of thermal density differences but occasionally due to pulses of fresh water, causing salinity effects as well. Oxygen conditions in bottom waters of the central bay generally remain over 80% saturation (Howes and Taylor 1990; Howes 1993), and therefore the periodic stratification does not appear to significantly affect benthic communities. This condition is in strong contrast with the smaller embayments of the bay where freshwater inputs are most concentrated. Even in the shallow waters of the embayments, pulses of fresh water following summer storms add to thermal stratification, and short-term hypoxia can occur. Similar embayments (1-2 m deep) on the southern shore of Falmouth have

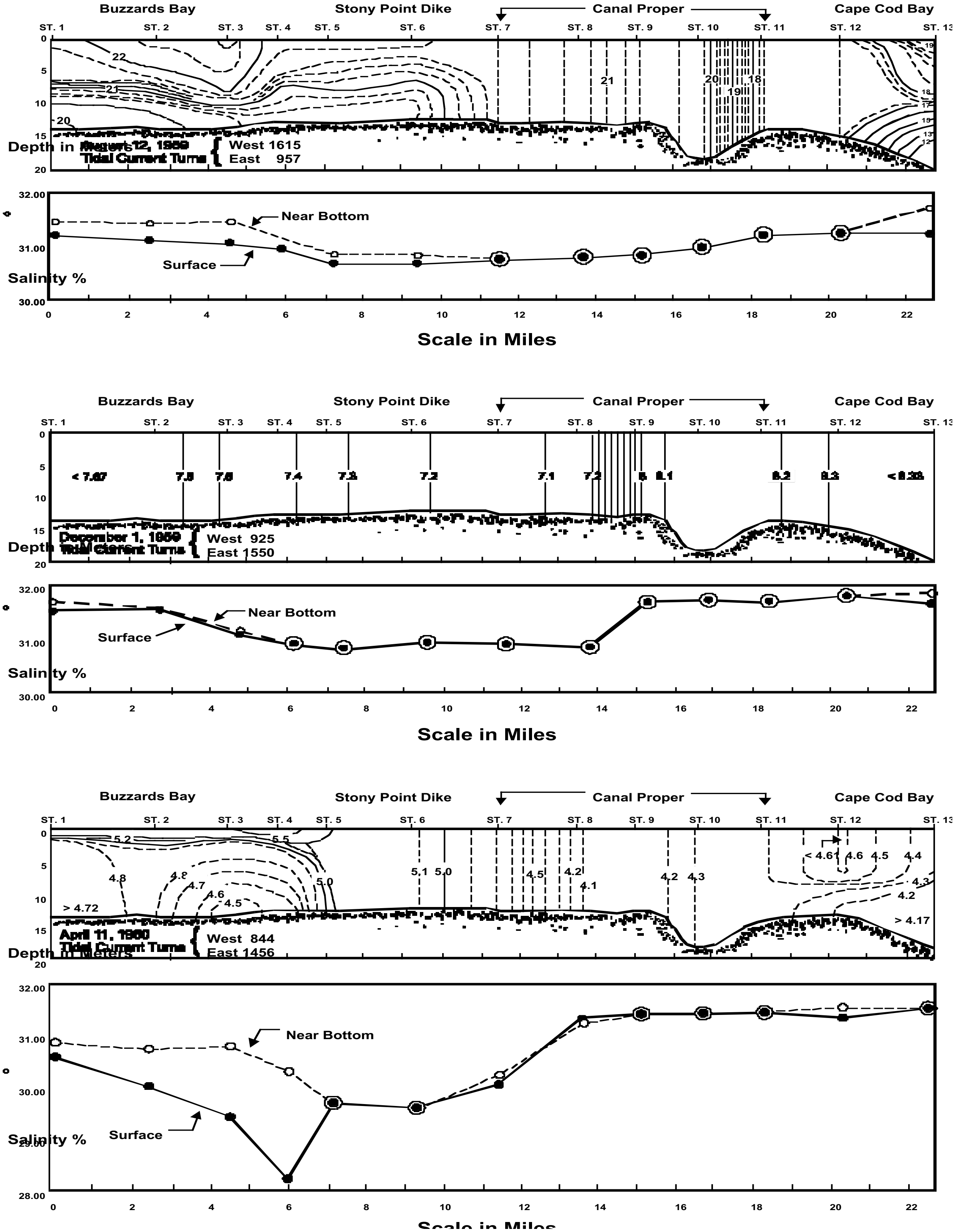

Fig. 3.3. Temperature and salinity profiles from the northern end of Buzzards Bay through the Cape Cod Canal and to Cape Cod Bay for (a) 12 August 1959; (b) 1 December 1959; and (c) 11 April 1960. Three distinct water masses exist: Cape Cod Bay water, "Cape Cod Canal water," and Buzzards Bay water. Transitional water within canal forms a boundary that fluctuates back and forth with each reversal of the tidal current. Anraku (1964a).

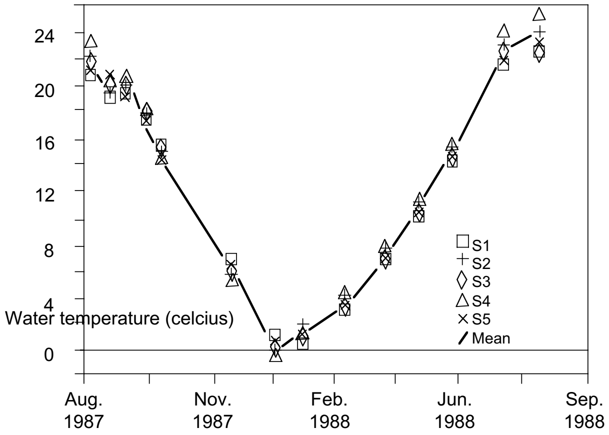

Fig. 3.4. Composite seasonal water column temperature in Buzzards Bay (Station 1) and New Bedford Outer Harbor (Stations 2-5). Data from Howes and Taylor (1990).

had water column anoxia and fish kills (from mid 1980's to present) related to periodic summer stratification (Costa et al. 1992; Howes and Goehringer 1992). For most of the year higher winds produce a well-mixed water column. It is unclear whether the low watershed-to-bay surface area ratio that results in the relatively low freshwater input also produces a lower frequency and/or weaker stratification of bay waters or if these processes in part maintain the stable benthic communities in the central basin of the bay. However, given the high oxygen demand of central basin sediments (Howes and Taylor 1989; Banta et al. 1990), prolonged stratification is likely to lead to low oxygen bottom waters. It appears then that the physical structure and the mixing processes of the Buzzards Bay system may be providing a potential buffer to biotic communities inhabiting the open bay.

3.3. Circulation/Currents and the Tidal and Wind Regime

Buzzards Bay is a relatively shallow estuary, with mean low water depths ranging from 5 to 10 m at the head to slightly over 20 m at the mouth. Depth profiles in transects across the bay show a relatively smooth asymmetric bottom near the head, gradually becoming more irregular and convoluted near the mouth. The circulation patterns within Buzzards Bay are predominately tidal and wind-driven flows acting on a large-scale estuarine density driven flow of about 1 cm/s (Signell 1987).

The location and semienclosed nature of Buzzards Bay result in tidal parameters significantly different from those found in the nearby waters of Vineyard Sound and Cape Cod Bay. To understand these differences, it is necessary to look at the New England Bight as a whole, from Long Island Sound to Buzzards Bay (Fig. 3.5). Tides in Buzzards Bay are predominately semidiurnal and dominated by the lunar cycle. The southern New England shelf tidal wave first reaches Rhode Island Sound in the "gap" between Block Island and Martha's Vineyard and then moves into the shallower basins of Vineyard Sound, Narragansett Bay, and Buzzards Bay. Due to the configuration of Buzzards Bay, the tidal signal is amplified by the shoaling and narrowing of the embayment toward the head, while the wave moving through Vineyard Sound is diminished due to interference with the progressing wave entering Vineyard Sound from the Gulf of Maine (Redfield 1953). The interaction of incident waves from the southern New England shelf and their reflection from the head of the bay dominate tidal parameters in Buzzards Bay.

The tide range is approximately 1 m with little or no temporal lag throughout the bay, the headwaters lagging only 20 min behind the mouth (Signell 1987). In contrast, Vineyard Sound operates more like a strait with tidal influence from two sources: the Gulf of Maine wave from the east and the southern New England shelf wave from the southwest. The effect is a decreased tidal amplitude and a significant temporal lag of roughly 2-4 h behind Buzzards Bay (Redfield 1953). The contrasting occurrence of the tidal wave within these two adjacent water bodies causes large phase and amplitude differences between the bay and sound and generates extremely swift currents between Buzzards Bay and Vineyard Sound (averaging 120-150 cm/s in Woods Hole and Robinsons Hole). These exchange

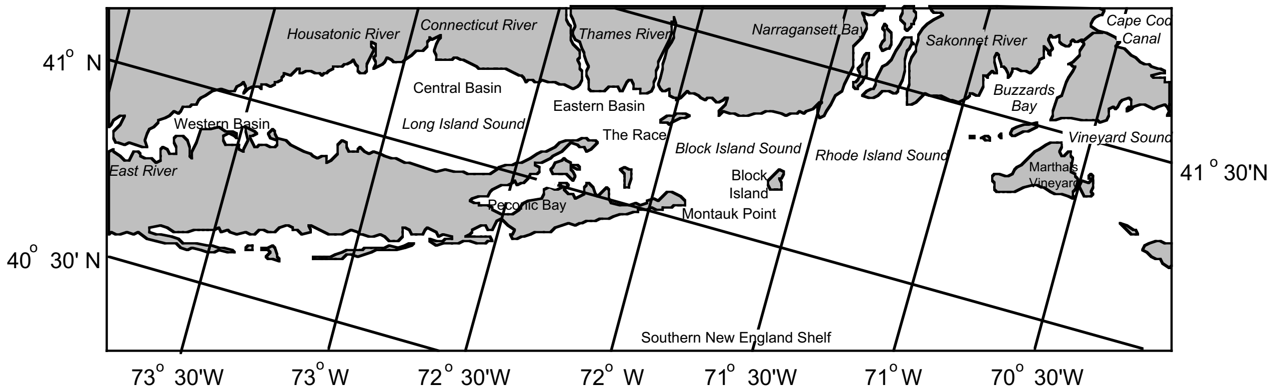

Fig 3.5. The southern New England Bight. From Spaulding and Gordon (1982).

current speeds are many times higher than the average speeds within the central (20-30 cm/s), head (<10 cm/s), or near the mouth (50 cm/s) of Buzzards Bay (Fig. 3.6). With less important consequences, differences in tidal phase and amplitude create strong currents through the Cape Cod Canal joining Buzzards Bay and Cape Cod Bay (Fig. 3.6). Mean tidal range in Cape Cod Bay is 2.8 m and averages 1.2 m in Buzzards Bay. The estimated turnover time of water within Buzzards Bay is about 10 days (Sumner et al. 1913; Moore 1963; Signell 1987).

Tidal current is the most important factor influencing sediment pattern, and two major currents within the bay proper predominate during ebb and flood tides. One current, running parallel to Naushon Island and terminating near Woods Hole, reaches 0.6 to 0.8 knots; the second is about 1 1/2 km wide and runs along the northwest shore of Buzzards Bay, with core velocities of about 0.6 knots. Midbay surface currents are weak, generally less than 0.4 or 0.5 knots, with no defined directional flow (Fig. 3.6). Although currents running between the islands do not extend far into the bay, they are important to bottom sediments near the islands forming sand protuberances into the bay. The well-sorted sediments found along the shore north of Woods Hole result from strong currents in this area (Moore 1963). The distribution and sorting patterns of shallow water sands are directly related to tidal currents, with accumulation of silts in deeper waters the result of bathymetric entrapment and less dynamic current activity (Moore 1963). Wind is also identified as a major factor in sediment composition because wind-driven wave activity creates high-energy waves in shallow areas of the bay, eroding areas unprotected by headlands. This erosion is indicated by a general coarseness of sediments found in these areas and the presence of greater accumulations of fine sediments on the southwesterly than on the northwesterly margins of harbors and coves (Driscoll and Brandon 1973).

Although tidal forcing is the dominant factor in the circulation within Buzzards Bay, other parameters influence localized currents, especially in the more restricted area near the head and the more sheltered harbors and embayments ringing the bay. Of the meteorological factors, local wind conditions are the most significant; however, nonlocal winds and atmospheric pressure are also important. Winds in this region are generally northwesterly in winter and southwesterly in summer, with local sea breezes often augmenting the southwesterly influence during summer months (Fig. 3.7). Major storms, however, often blow from the north or northeast, roughly along the long axis of the bay. In addition, variations in nonlocal wind and atmospheric pressure can lead to a rise and fall of average bay level. The

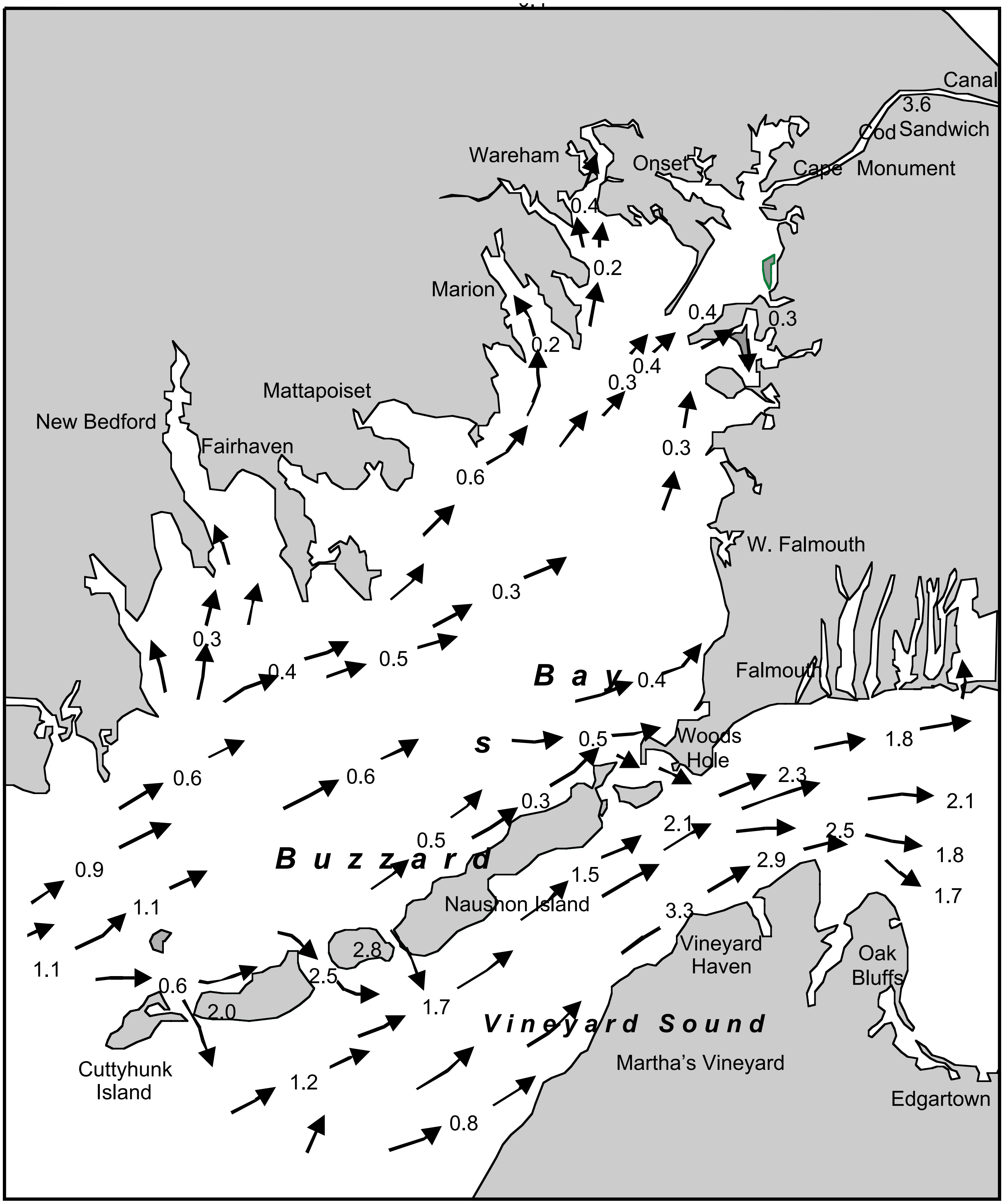

Fig. 3.6. Buzzards Bay tidal current chart showing flood currents 4 h after slack tide. Current speeds in knots. U.S. Department of Commerce, NOAA Tidal Current Chart. From Camp, Dresser, and McKee, Inc. (1990).

currents resulting from this "pumping," however, are relatively small compared with those created by local winds (Signell 1987). Winds along the axis of the bay are most significant in influencing circulation and are important to mixing, transport, and exchange for the bay (Fig. 3.7). Because of the more complex bathymetry at the mouth of the bay (Fig. 2.4), tidally induced "residual currents," or currents caused by the channeling of water as it moves across irregular surfaces, are of greater importance to subtidal circulation. Tidally induced eddies formed near the mouth of the bay (Signell 1987) can affect the fate of transported material.

The effects of local winds on circulation are most pronounced in the smaller, shallower fringing harbors and embayments. The circulation of New Bedford Outer Harbor, for example, is controlled by its enclosed nature. Although a weak pattern of "out on top, in on bottom" exists, it can be dominated by wind patterns such as a light southerly wind, which may stall surface movement (Camp, Dresser, and McKee, Inc. 1990). At its boundary with Buzzards Bay, circulation in New Bedford Harbor is more tidally driven. Flushing of New Bedford Harbor and many of the other harbors and smaller embayments results from a combination of tidal influences, winds, runoff, and warming of the shallower waters and can be variable depending on the dominance of any one or more of these parameters. Probably more important than the effect of tidal and wind-driven flows on water exchange is their effect on vertical mixing. Although stratification is generally weak the tidal currents near the head of the bay are also small. It appears that wind-driven mixing plays a major role in vertical mixing, hence affecting oxygen balance and biotic communities within this system.

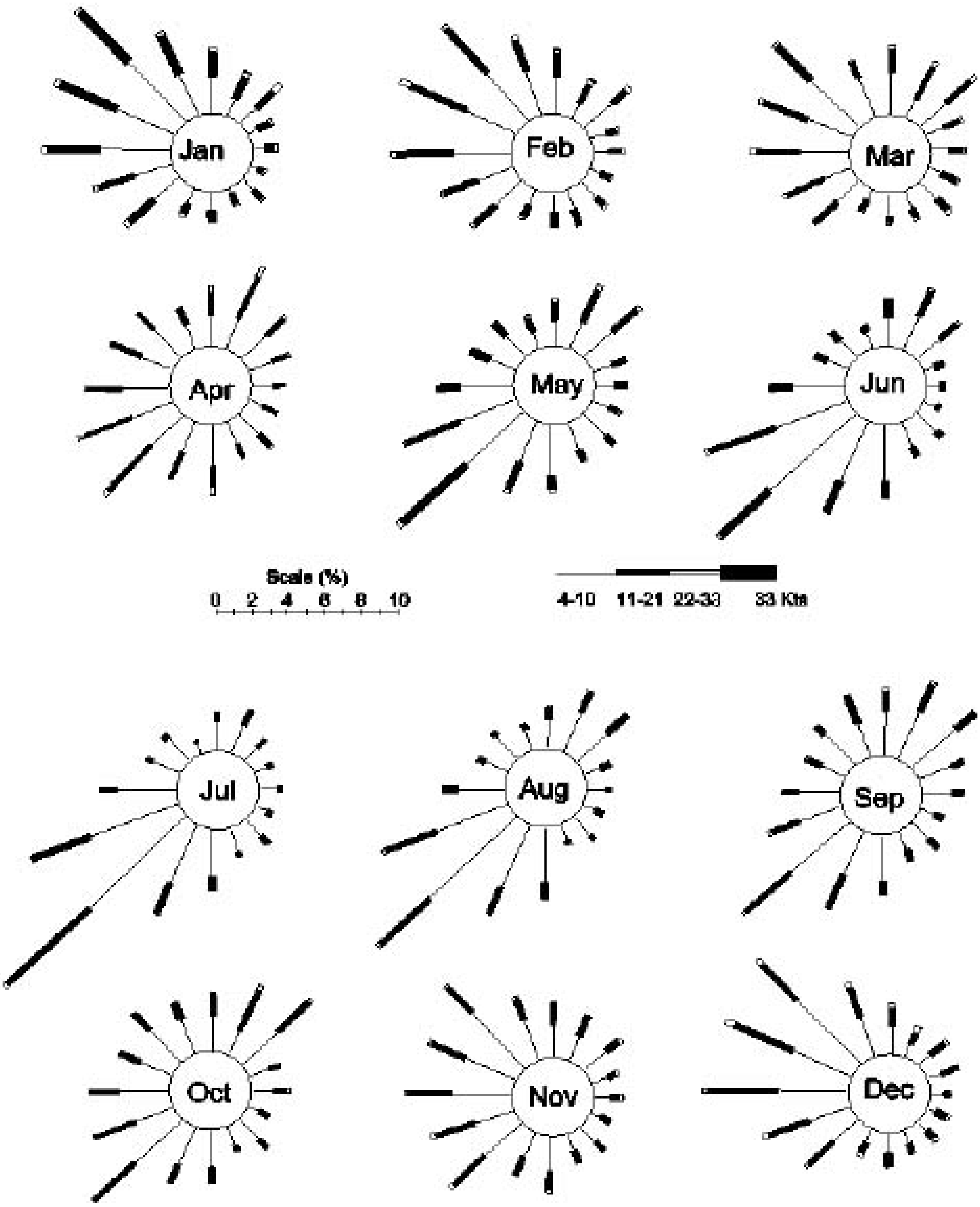

Fig. 3.7. Wind roses from 35 years of data at Otis Air Force Base, Bourne, Massachusetts. Wind direction is from north (upwards), with speed in knots. From Signell (1987).