Chapter 2. Physical Environment (Yalin Fan & Wendell Brown)

A. Introduction

Mt. Hope Bay (the Bay) is situated the northeast corner of Narragansett Bay (Figure 2.1), lying within both Rhode Island to the south and west and Massachusetts to the north and east (Figure 2.2). The Bay adjoins the East Passage of Narragansett Bay to the southwest where the Mt. Hope Bridge crosses over from Aquidneck Island to Bristol Point. The Taunton River discharges into the Bay from the north, along with the smaller Kickamuit, Cole, Lee, and Quequechan Rivers. (The Quequechan River starts from the Watuppa ponds, runs under dozens of city streets of Fall River, MA, and discharges into the Taunton River. Maybe because the Quequechan River is covered, its channel connecting to the Taunton River is not shown on any map.) The Sakonnet River is really an embayment that "originates" between Tiverton and Aquidneck Island and connects southern Mt. Hope Bay to Rhode Island Sound to the south. The Bay is seven miles (11.2 km) in length along its north-south axis (Kauffman and Adams 1981), covers an area of 35.2 km^2 (13.6 mi^2) (Kauffman and Adams 1981) and has a volume of 201.7 million m^3 (53.3 billion gal) at mean low water (MLW) (Chinman and Nixon 1985). The Mt. Hope Bay depth (Figure 2.1), which averages 5.7 m at MLW (Chinman and Nixon 1985), increases steadily from the relatively flat northern half of the Bay to the south (Kauffman and Adams 1981). A deep (about 10 m) channel connects Mt. Hope Bay to Narragansett Bay. In some parts of the channel its depth is greater than 24 m (NOAA 1992). Two dredged channels, maintained at a depth of approximately 10.7 m, connect the

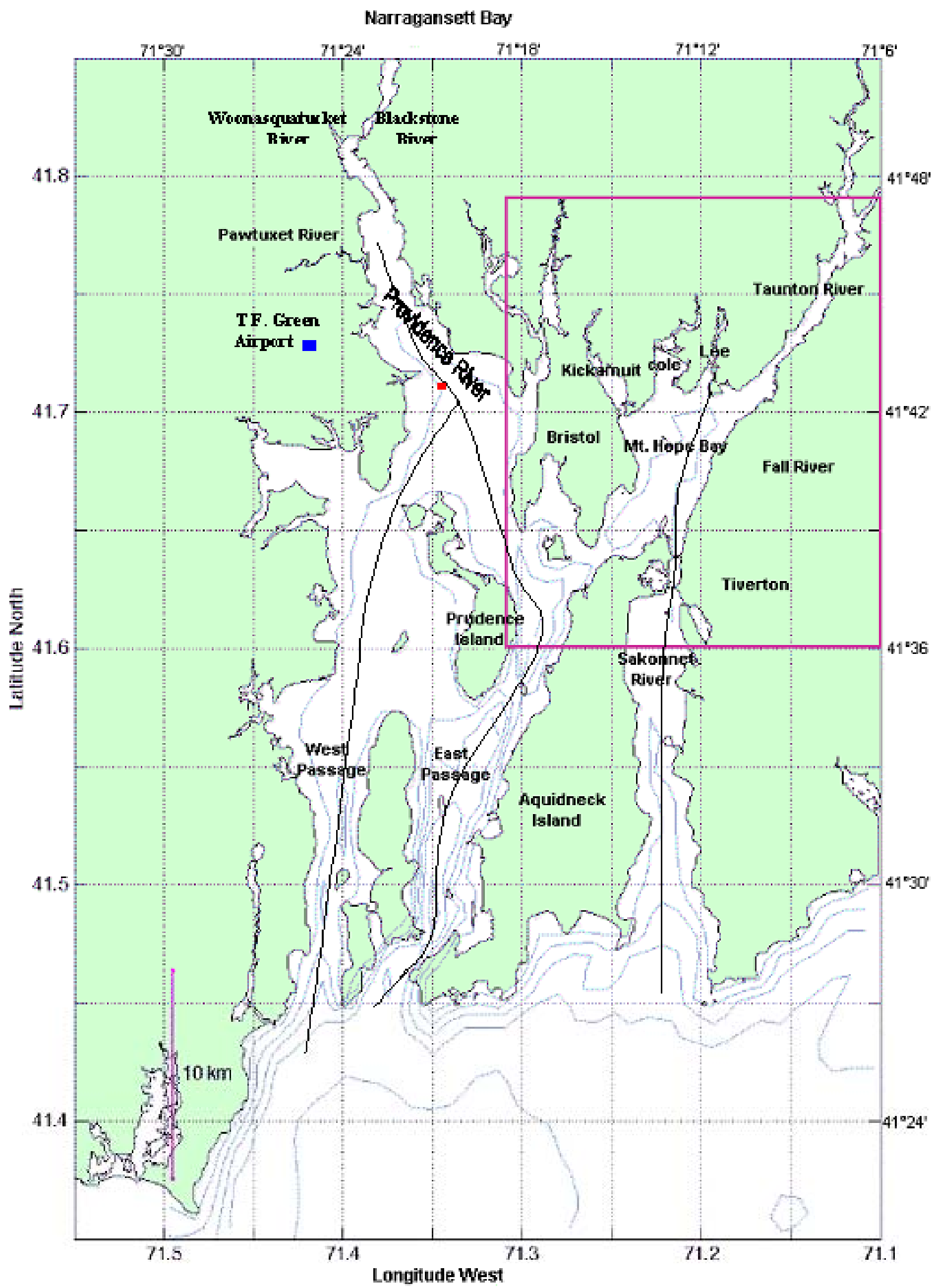

Figure 2.1. The bathymetry of the Narragansett Bay region, including Mt. Hope Bay, is defined by the contour lines for 5, 10, 15, 20, 30 and 40 m. The red box outlines the Mt. Hope Bay/Taunton River region shown in Figure 2.2. The Hicks (1959c) water property measurement transects and the Weisberg (1976) moored current meter location (red square in Providence River) are also shown.

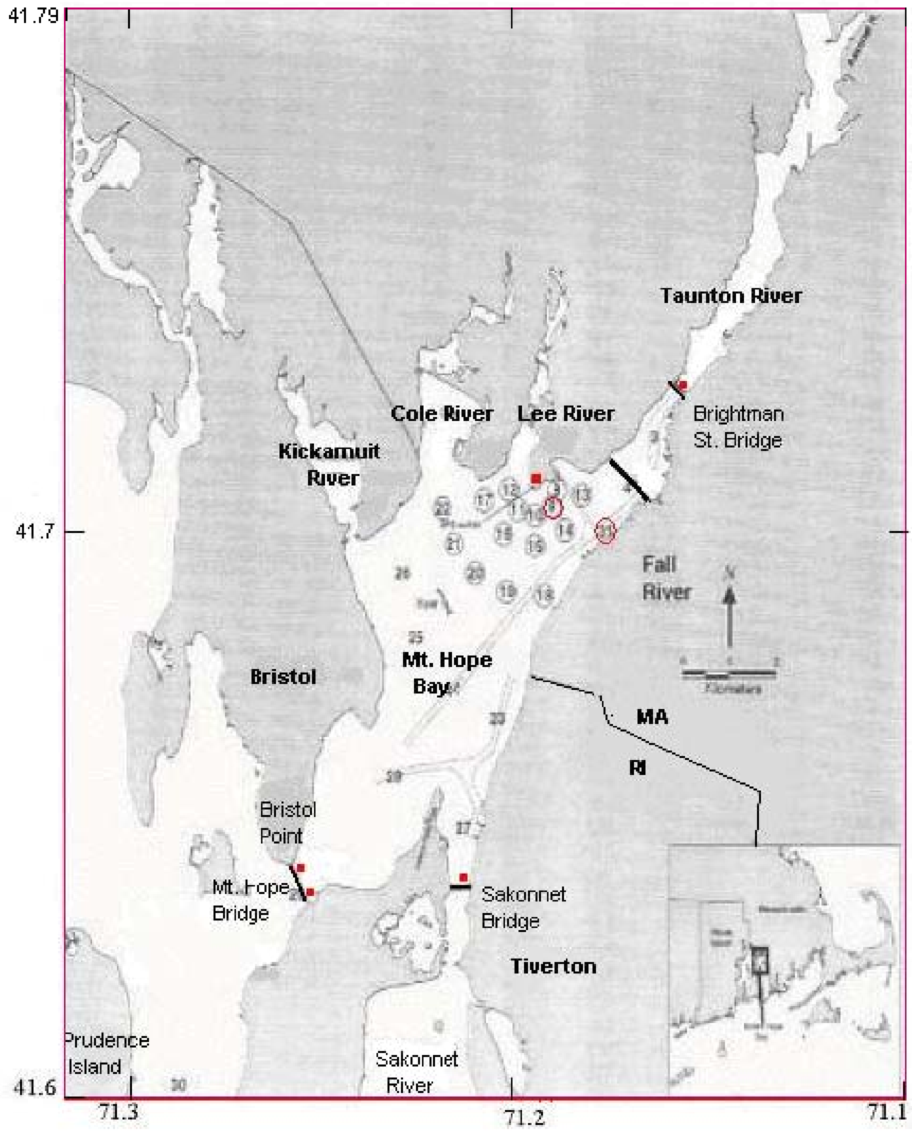

Figure 2.2. Mt. Hope Bay with distribution of the 31 ASA thermistor strings during the February 1999 thermal mapping study. Circles indicate the locations of moorings with bottom sensors (Swanson et al. 1999). The Spaulding and White (1990) moored current meter locations (red squares) are shown.

Bay to the Taunton River at Fall River. The Sakonnet Passage has a minimum channel depth of 7.5 m (McMaster 1960).

In recent years questions have been raised concerning the effect of the 1600MW fossil fuel-fired electrical generating facility at Brayton Point, Massachusetts on the Mt. Hope Bay (Figure 2.2) ecosystem. The plant was built in the mid-1970s and has since been expanded starting in the mid-1980s. With the expansion, the amount of cooling water drawn from the Bay on the east side of Brayton Point has increased to the almost five million cubic meters per day. The amount of heat returned to the Bay through a channel and venturi system that discharges directly to the south of Brayton Point has also increased. The plant is operated so that the increase in the temperature between the intake and the discharge water is about 8°C (Sen 1996). This temperature rise is significantly less than the maxima permitted for summer (12.2°C) and winter (16.7°C) (Swanson et al. 1999). Nevertheless, the increased heat load to the Bay has been implicated in the decline of winter flounder (e.g., Gibson 1996a, 1996b).

One of the objectives of this paper is to place the Brayton Point thermal discharge in the context of natural temperature variability. In what follows, we describe what is known about the variability of the physical properties, including temperature, of Mt. Hope Bay, Narragansett Bay proper and the coastal ocean to the south. We consider variability of the properties at tidal (12 and 24 hours), weather band (2-10 days), and seasonal (1-3 months) periodicities, and typical annual (1 year) and interannual (multiple years) frequencies. These will be discussed in terms of estuarine processes related to river flow and stratification. The weather band variability of Bay properties is due predominantly to local and remote meteorological forcing. Thus we begin by reviewing the forcing. Fortuitously, the National Ocean Service (NOS) division of the National Oceanic and Atmospheric Administration (NOAA) recently began operational measurements of many of the meteorological and oceanographic variables at several sites in the Narragansett Bay region.

The NOAA/NOS Physical Oceanographic Real-Time System (PORTS) (http://www.co-ops.nos.noaa.gov/d_ports.html) is designed to support safe and cost-efficient navigation by providing shipmasters and pilots with accurate real-time information. In addition to the measurement systems, PORTS includes a centralized data acquisition and dissemination system that provides both real-time and historical water levels, water temperature, and other meteorological data (i.e., air temperature, wind, rainfall, dew point) and barometric pressure data. It also provides real time current data at some of these stations. In some locations PORTS employs numerical circulation models to provide nowcasts and predictions of some of these variables.

The locations of the Narragansett Bay region PORTS stations are presented in Figure 2.3. The available observation products at the different PORTS stations are indicated in Table 2.1. (See Table 2.2 for detailed Narragansett Bay PORTS products information). Generally, P-M-Young sensors are used to measure wind variations, and an RDI, Inc., ADCP, with a Paroscientific pressure sensor, is used to measure currents and sea level at PORTS sites.

Figure 2.3. The NOAA PORTS sites in the Narragansett Bay region.

Table 2.1. Narragansett Bay PORTS station data products.

Location	Lat (N)	Lon (W)	SL (m)	Current (Knots)	Water T (°C)	Air T (°C)	Wind (m/s, °)	BP (mbar)
Providence	41°48.4'	71°24.1'	X	X	X	X	X	X
Conimicut Light	41°43.0'	71°20.6'	X		X	X	X	X
Fall River	41°42.3'	71°9.8'	X	X	X	X		X
Prudence Island (Potter Cove)	41°38.1'	71°20.4'			X	X	X	X
Quonset Point	41°35.1'	71°24.5'	X	X	X	X	X	X
Newport	41°30.3'	71°19.6'	X		X	X	X	X

Table 2.2. Available historical and real-time PORTS information for the Narragansett Bay area. Status indicates which versions of the different variables are available online, including historical data (H), real time data (RT), and information (X).

Station	Begin Time		End Time		Data Type	Status
Providence	10/6/1999	19:00	12/19/2001	17:00	Wind	H RT
	9/22/1999	18:00	12/19/2001	17:00	Air Temperature	H RT
	9/25/1995	22:00	12/19/2001	17:00	Water Temperature	H RT
	5/17/1999	1:00	12/19/2001	17:00	Barometric Pressure	H RT
	8/24/1999	19:00	1/11/2001	9:00	Water Conductivity	
					Acc Harmonic Const	X
	1/1/1996	0:00	12/19/2001	17:54	6-Minute Water Level	H RT
	1/1/1996	0:00	10/31/2001	23:00	Hourly Height	H
	1/1/1996	2:18	10/31/2001	23:54	Acc High/Low	H
	6/1/1938	0:00	10/31/2001	23:54	Acc Monthly Mean	
	1/1/1939	0:00	12/31/1992	23:54	Acc Annual Mean	
					Acc Station Datum	X
Conimicut Light	10/17/1999	11:00	12/19/2001	16:00	Wind	H RT
	10/17/1999	11:00	12/19/2001	16:00	Air Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Water Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Barometric Pressure	H RT
	11/29/1999	12:00	11/29/1999	12:54	Dew Point	
	11/29/1999	12:00	10/11/2001	13:54	Rainfall	
	11/1/1999	0:00	11/29/1999	23:00	Acc Harmonic Const	X
	10/17/1999	8:00	12/19/2001	16:54	6-Minute Water Level	H RT
	10/17/1999	14:00	10/31/2001	23:00	Acc Hourly Height	H
	10/17/1999	14:00	10/31/2001	23:54	Acc High/Low	H
	10/18/1999	0:00	10/31/1999	0:00	Acc Daily Mean	
	11/1/1999	0:00	10/31/2001	23:54	Acc Monthly Mean	
					Acc Station Datum	X
Fall River	10/17/1999	11:00	12/19/2001	16:00	Air Temperature	H RT
	12/31/2000	1:00	12/31/2000	1:00	Air Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Water Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Barometric Pressure	H RT
	2/29/2000	19:00	6/18/2001	19:00	Water Conductivity	
	12/14/2000	3:00	12/14/2000	3:54	Solar Radiation	
	11/1/1999	0:00	11/29/1999	23:00	Acc Harmonic Const	X
	10/17/1999	7:00	12/19/2001	16:54	6-Minute Water Level	H RT
	10/17/1999	7:00	10/31/2001	23:00	Acc Hourly Height	H
	10/17/1999	7:00	10/31/2001	23:54	Acc High/Low	H
	10/1/1977	0:00	10/31/2001	23:54	Acc Monthly Mean	H
					Acc Station Datum	X
					Published BM	X
Providence Island (Potter Cove)	10/17/1999	11:00	12/19/2001	15:54	Wind	H RT
	10/17/1999	11:00	12/19/2001	15:00	Air Temperature	H RT
	3/1/2000	16:00	12/19/2001	15:00	Barometric Pressure	H RT
	9/19/2001	21:00	9/19/2001	21:00	Water Conductivity	

	0/17/1999	11:00	12/19/2001	16:00	Wind	H RT
	10/17/1999	11:00	12/19/2001	16:00	Air Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Water Temperature	H RT
	10/17/1999	11:00	12/19/2001	16:00	Barometric Pressure	H RT
	2/29/2000	16:00	7/21/2000	21:00	Water Conductivity	
	3/1/2000	0:00	3/29/2000	23:00	Acc Harmonic Const	X
	10/17/1999	8:00	12/19/2001	13:30	6-Minute Water Level	H RT
	10/17/1999	15:00	10/31/2001	23:00	Acc Hourly Height	H
	10/17/1999	14:18	10/31/2001	23:54	Acc High/Low	H
	3/1/2000	0:00	10/31/2001	23:54	Acc Monthly Mean	H
					Acc Station Datum	X
Newport	10/13/1999	20:00	12/19/2001	17:00	Wind	H RT
	8/20/1999	18:00	12/19/2001	17:00	Air Temperature	H RT
	9/12/1995	17:00	12/19/2001	17:00	Water Temperature	H RT
	2/6/1996	5:00	12/19/2001	17:00	Barometric Pressure	H RT
	2/26/1999	11:00	12/19/2001	17:00	Water Conductivity	
	12/31/1999	22:00	12/31/1999	22:45	Rainfall	
					Acc Harmonic Const	X
	1/1/1996	0:00	12/19/2001	17:54	6-Minute Water Level	H RT
	11/8/1997	10:00	11/8/1997	10:18	Pressure 6-Minute	
	9/10/1930	5:00	12/31/1993	23:00	Acc Hourly Height	H
	1/1/1994	0:00	10/31/2001	23:00	Acc Hourly Height	H
	8/23/1976	5:36	12/31/1993	23:54	Acc High/Low	H
	1/1/1994	2:42	10/31/2001	23:54	Acc High/Low	H
	10/1/1930	0:00	10/31/2001	23:54	Acc Monthly Mean	
	1/1/1931	0:00	12/31/1993	23:54	Acc Annual Mean	
					Acc Station Datum	X
					Published BM	X

B. Natural Variability of the Narragansett Bay/Mt. Hope Bay Region

1. Meteorology

Weisberg (1976) notes that the effects of wind can penetrate throughout the entire water column of a partially mixed estuary like Narragansett Bay and Mt. Hope Bay and thus can be of equal (or even greater) importance than the tides or gravitational convection in influencing the circulation.

The intensity and preferred direction of Narragansett Bay winds vary considerably with season (see Figure 2.4). Wind speeds average 5 m/s (from the

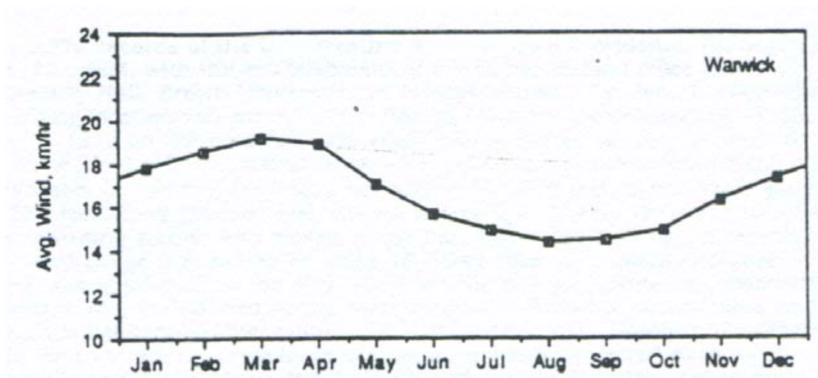

Figure 2.4. Annual cycle of monthly mean wind speeds at T.F. Green State Airport in Warwick, RI. The data are averaged over the years 1964 to 1987, inclusive (Pilson 1991).

northwest) during the winter and spring and 4 m/s (from the southwest and west) during summer and fall (Spaulding and White 1990). For example, during a typical January/February the vector-averaged wind direction (Figure 2.5) is

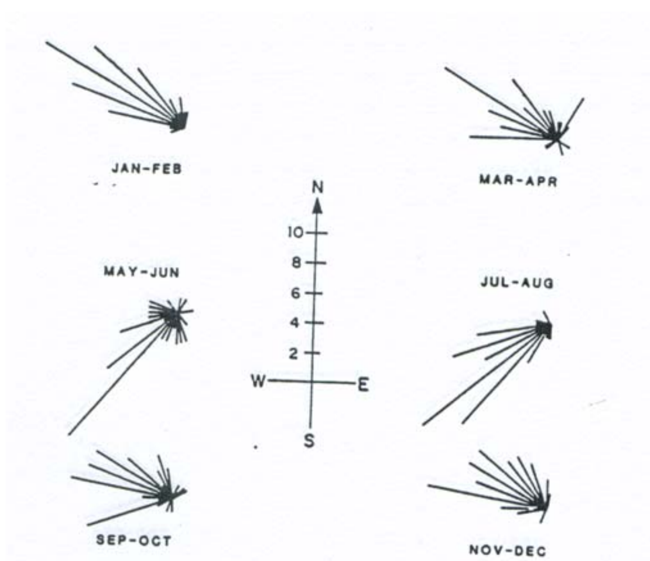

Figure 2.5. Annual cycle of bimonthly circular frequency histograms of wind vectors at T.F. Green State Airport in Warwick, RI. These histograms were formed by vector-averaging winds in 10° sectors. The scale indicates the number of years (in the 1964 to 1986 interval of observations) that the vector-averaged wind blew from the indicated direction in that particular bimonthly period. (Reprinted from Pilson 1991.)

confined to a sector between 10°E of north and 10°S of west, with the most common wind direction being slightly W of NW. During the summer months of May to August the wind typically blows from the southwest.

How representative of Narragansett Bay are the Green Airport winds? Pilson (1991) did point out that, while Green Airport winds are representative of the regional winds, the orientation of the coastline has a considerable influence on local wind conditions. Thus, the response of the water movements to local winds in different locations within the bay may vary considerably. In addition, further work is needed to define the wind-driven part between the exchange of bay and offshore waters.

The bay-wide structure of the Narragansett Bay winds can be seen more clearly in the Figure 2.6 comparison of the PORTS daily wind vector time series between 31 October 2000 and 31 October 2001. We can see that winds mainly come from the north in winter and from the south in summer. Sea breeze is a very common phenomenon along the coastal area. Because the ocean warms up and cools down more slowly than the land, the land is warmer than the ocean in the daytime, and cooler than the ocean at night. Due to the pressure difference, the wind will usually blow from the ocean to the land in the daytime and from the land to the ocean at night. In the summertime the phenomenon of the sea breeze is particularly important. It is commonly observed that the wind may blow from the north or northwest in the morning, but that sometime after midday the sea breeze sets in and blows up Narragansett Bay.

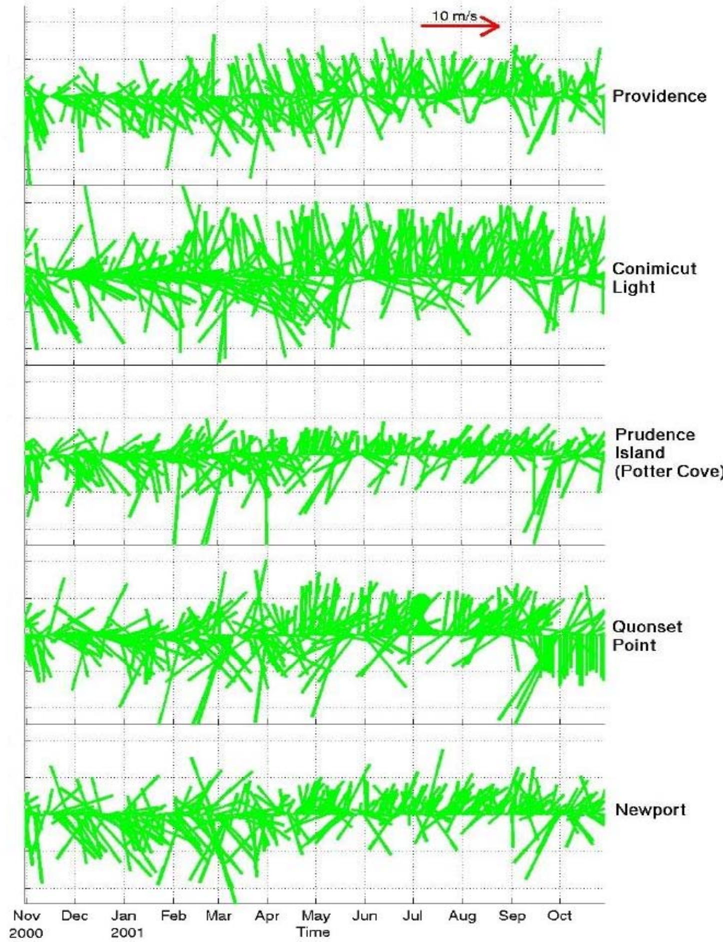

Figure 2.6. Daily wind vectors from PORTS stations at Providence, Conimicut Light, Prudence Island, Quonset Point and Newport between 31 October 2000 and 31 October 2001. The actual wind observations are hourly at Providence, Conimicut Light, Quonset Point, and Newport; every six minutes at Prudence Island.

2. Fresh Water Inflow

The U.S. Geological Survey (USGS) Water Resources Division provides data on surface water, ground water and water quality data for the Massachusetts-Rhode Island District. The short-term variability of some river discharges in the region is measured. Every four hours, 15-minute data for river stage, discharge, water temperature, specific conductance, and precipitation is available from approximately 65 stream gauges in Massachusetts and Rhode Island (http://ma.water.usgs.gov/).

Discharge information for four important rivers in the Narragansett Bay area have been obtained from the USGS archive for the years 1930 to 1999. (See Table 2.3 for the station information.) The Taunton, Blackstone, Woonasquatucket, and Pawtuxet River (Figure 2.1) records for September 1999 to September 2000 are presented in Figure 2.7. We can see from these plots that the

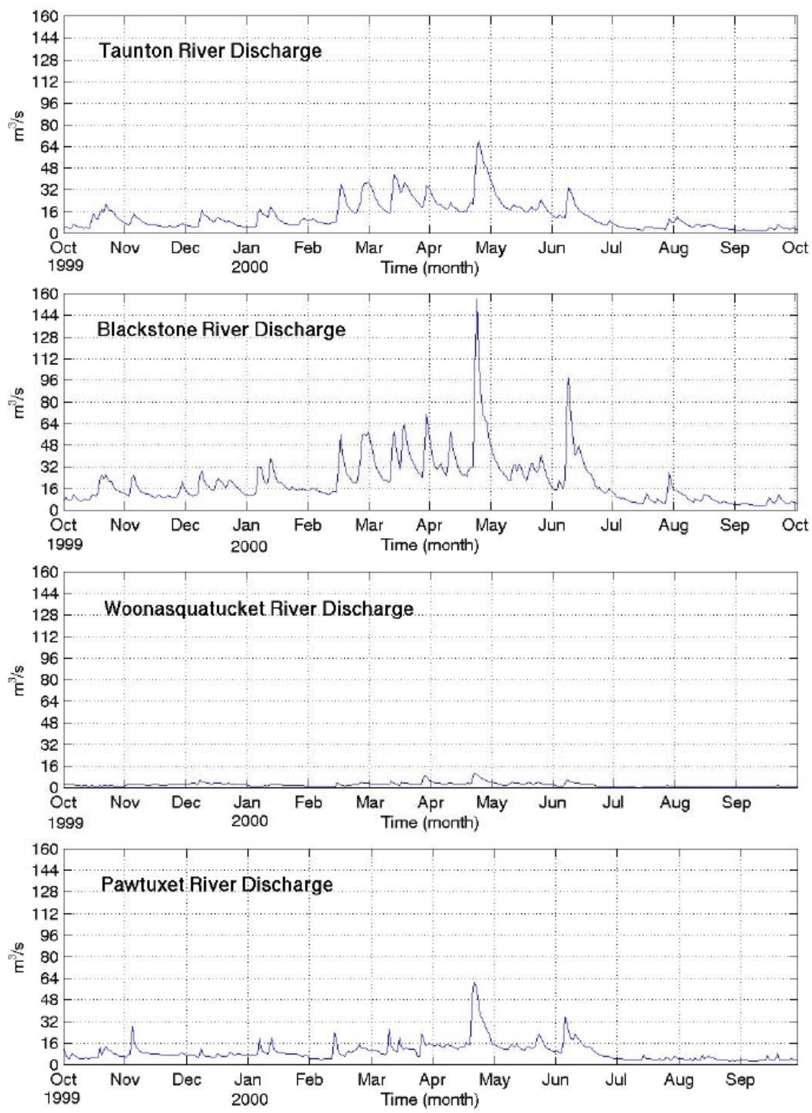

Figure 2.7. Taunton, Blackstone, Woonasquatucket and Pawtuxet River discharge records from 30 September 1999 to 30 September 2000. (See Table 2 for details of data record information.)

highest discharges in all rivers are in April, as the result of spring runoff and snowmelt. Low discharges for the year are in July, August, and September, when high evapotranspiration rates limit the amount of precipitation that becomes available for runoff.

The Taunton River is the major source of fresh water to the Mt. Hope Bay, with a mean annual discharge of 29.7 m^3/s (7,846 gal/s) (Ries 1990). The Cole River provides an additional annual mean discharge of 0.81 m^3/s (214 gal/s), and additional discharges of lesser volumes are provided from ungauged areas adjacent to Mt. Hope Bay (Ries 1990).

The Taunton River exerts a significant effect on the Mt. Hope Bay System, both through the discharge of its nitrogen load and through its effect upon the salinity distribution and water column density field within the estuary. Freshwater discharge from the Taunton River helps to create the vertical density stratification of Mt. Hope Bay, primarily due to salinity. In order to assess potential inter-annual variations in the effect of the Taunton River on water column stratification, annual discharge measurements collected at the Taunton Gauge by the USGS from 1929-1999 were obtained. However, there are data missing for some periods (see Table 2.3 for details).

Table 2.3. Station information for Taunton, Blackstone, Woonasquatucket and Pawtuxet Rivers USGS gauge stations.

Site	Latitude	Longitude	Gauge Information	Near Real-Time Discharge	Daily Mean Stream Flow
Taunton River	41°56'02"	70°57'25"	Water-stage recorder. Datum of gauge is 2.93 m above sea level. Prior to Oct. 1996, at sites 12.20m apart about 122.00 m upstream: Oct. 1929 to Sept. 30, 1931, inverted non-recording gauge with zero of gauge at 3.06 m; 1931/10/01 to 1934/06/08, non-recording gauge; 1934/06/09 to 1976/04/23 and 1985/04/19 to May 1988, water stage recorders at present datum.	X	**Period 1** 1929/10/01 – 1976/04/23 **Period 2** 1985/04/19 – 1988/05/31 **Period 3** 1996/10/01 – 2000/09/30
Blackstone River	42°00'22"	71° 30'13"	Water-stage recorder. Datum of gage is 32.76 m above sea level.	X	1929/02/22 – 2000/09/30
Woonasqua-tucket River	41° 51'32"	71 °29'16"	Water-stage recorder. Elevation of gage is 28.98 m above sea level, from topographic map. Satellite gage-height telemeter at station.	X	1941/07/09 – 2000/09/30
Pawtuxet River	41°45'03"	71°26'44"	Water-stage recorder. Datum of gauge is 2.44 m above sea level.	X	1939/12/06 – 2000/09/30

Since there is no data gap for Blackstone River discharge during this period, cross- correlation between these two rivers' discharge records was calculated (Figure 2.8). Daily discharge time series from 1 October 1929 to 23 April 1976 for these two rivers were used to calculate the cross-correlation. We can see from Figure 2.8 that these two rivers are highly correlated at zero lag. So we estimated the missing Taunton River yearly discharge from Blackstone River yearly discharge based on the cross- correlation function (Figure 2.8). We can see that the Taunton River exhibits a large degree of inter-annual variation in discharge.

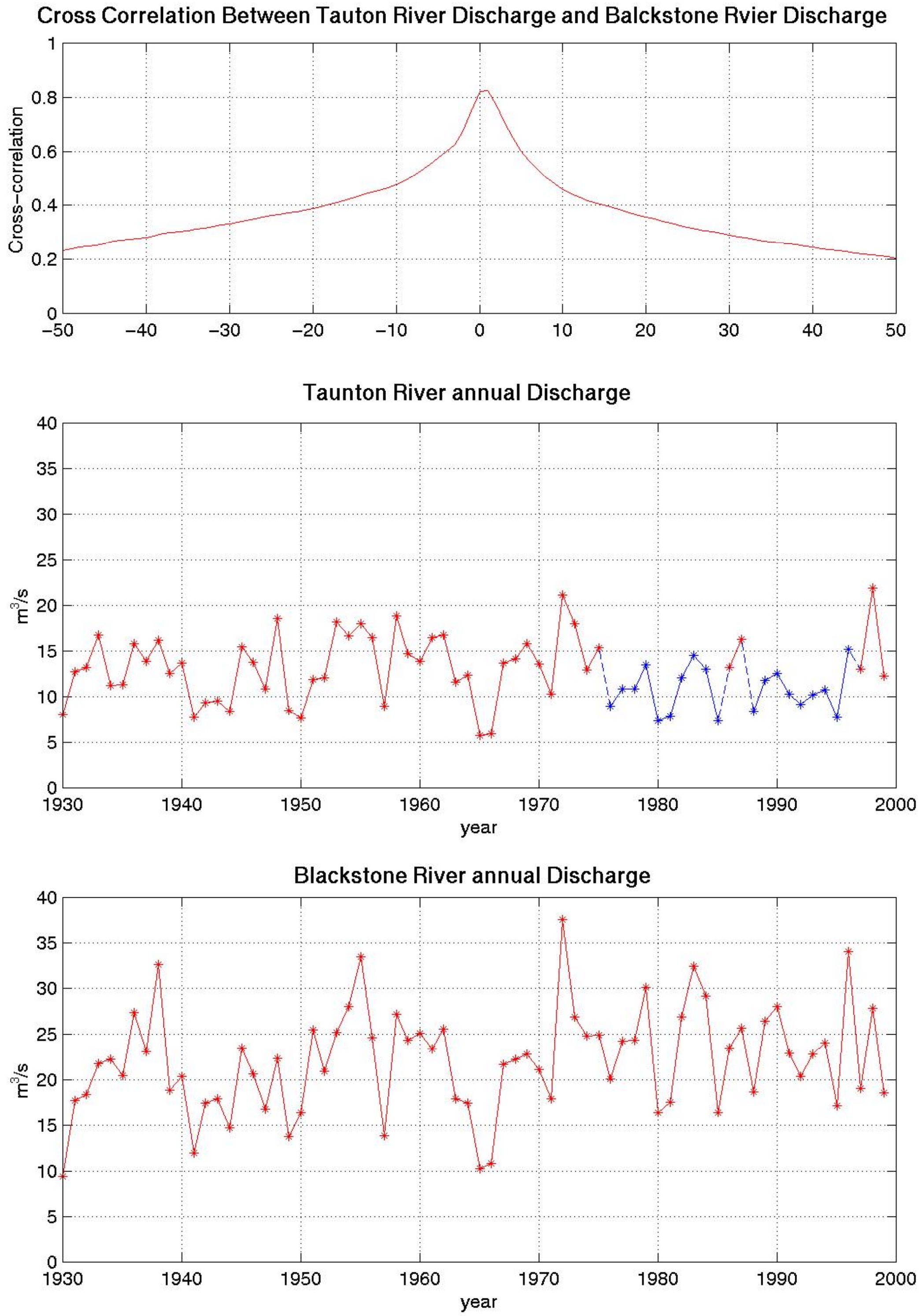

Figure 2.8. Upper panel: Cross-correlation between Taunton River discharge and Blackstone River discharge; middle panel: Taunton River annual discharge (the red line with stars showing measurement, and the blue line with stars showing estimated results); bottom panel: Blackstone River annual discharge.

3. Tidal Sea Levels and Currents

Sea Level: Tidal variations affect the variability of physical properties throughout the Narragansett Bay system, including Mt. Hope Bay, in important ways. The principal tidal sea level variations occur at semidiurnal periods, with the M_2 constituent surface elevation amplitudes being the largest (Figure 2.9). This is clear from the table of harmonic constants for the 5 PORTS sites in Table 2.4.

As the cotidal chart for sea level (Figure 2.10) shows, the M_2 tidal amplitude increases by about 20% (10 cm) from the entrance to the upper reaches of both Narragansett and Mt. Hope Bays, while the corresponding phase differences are small (< 3%). Thus the tides occur nearly simultaneously throughout the bays. The same is true for the other important semidiurnal (S_2, N_2), diurnal (O_1, K_1) and higher harmonic (M_4) constituents.

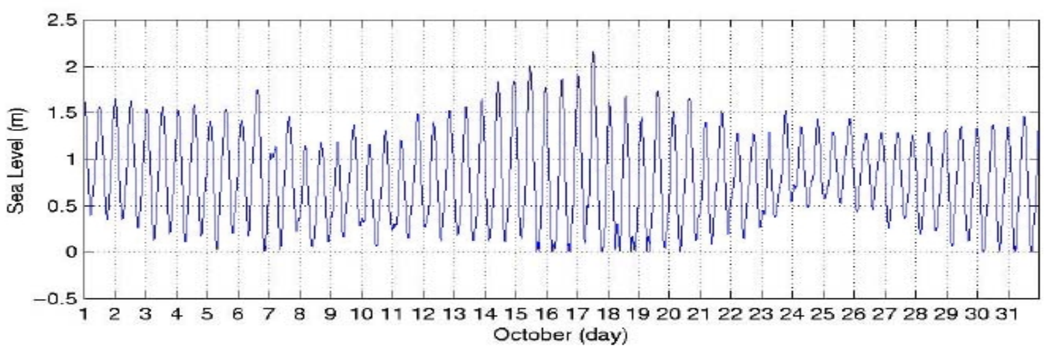

Figure 2.9. Sea level record at the Fall River PORTS station for October 2001.

Table 2.4. Tidal harmonic constants for the important tidal constituents at several sites in the Narragansett Bay system, including Providence, Conimicut Light, Fall River, Quonset Point, and Newport. Tidal phases are in Greenwich epoch degrees.

	Providence		Conimicut Light		Fall River		Quonset Point		Newport	
Name	Amp (m)	G (°)	Amp (m)	G (°)	Amp (m)	G(°)	Amp (m)	G(°)	Amp (m)	G(°)
M2	0.643	9.5	0.589	7.8	0.607	9.3	0.527	3.5	0.518	2.2
S2	0.138	33.7	0.127	29.3	0.128	32	0.119	24.8	0.11	24.3
N2	0.152	354.6	0.133	344.8	0.138	347.3	0.126	345.2	0.123	346.2
K1	0.073	169.4	0.056	182.3	0.058	186.8	0.059	167.5	0.065	166.6
M4	0.103	62.1	0.09	62.1	0.099	69.1	0.07	43.6	0.055	36
O1	0.056	202.2	0.047	203.1	0.046	200.1	0.056	199.5	0.052	200.4
M6	0.027	312.7	0.015	304.7	0.019	337.4	0.006	275.2	0.005	221.7
S4	0.014	23.8	0.015	22.6	0.015	29	0.01	19.5	0.006	356.9
NU2	0.027	353	0.026	347.9	0.027	350.3	0.024	347.6	0.023	348.4
MU2	0.031	358.6	0.014	203.7	0.015	204.3	0.013	199.3	0.025	346.1
2N2	0.022	343.2	0.018	321.9	0.018	325.4	0.017	326.9	0.018	327.6
SA	0.06	131.8	0	0	0	0	0	0	0.061	140.5
Q1	0.016	179.9	0.009	213.4	0.009	206.7	0.011	215.3	0.015	177.6
T2	0.013	14.1	0.008	28.4	0.008	31.1	0.007	24	0.009	7.5
2Q1	0.001	234.6	0.001	223.7	0.001	213.3	0.001	231.2	0.003	229.7
P1	0.025	182.3	0.018	183.8	0.019	187.8	0.02	169.9	0.023	181.7
M3	0.012	68.3	0	0	0	0	0	0	0.009	52
L2	0.012	321.4	0.017	30.8	0.017	31.3	0.015	21.8	0.009	316
K2	0.038	29.7	0.035	31	0.035	33.8	0.032	26.6	0.032	28.4

The M_2 tides typically account for 90% of the sea level variance in Mt. Hope Bay (Spaulding and White 1990). The tidal sea level fluctuations measured at Fall River (Figure 2.9) indicate a mean tidal range of approximately 1.34 m for Mt. Hope Bay. This corresponds to a mean Mt. Hope Bay tidal prism of approximately 37.3 million m^3. Of course, the tidal prism varies with the stage of the tides in the spring-neap cycle. For example, the maximum tidal range is about 1.68 m for spring conditions, and the minimum is about 1.0 m for neap conditions (Spaulding and White 1990). The corresponding spring tide tidal prism is estimated to be 59.5 million m^3, while the neap tidal prism is about 15.8 million m^3 (Chinman and Nixon 1985).

Transport: Based on tidal prism estimates, we estimate that the average tidal transport into (or out of) Mt. Hope Bay during a half-tidal period (6.21 hours) is approximately 6.01 million m^3/hour. The spring tide average tidal transport is about 9.58 million m^3/hour, while the neap average tidal transport is about 2.54 million m^3/hour.

Assuming that the tidal transports through the Mt. Hope Bridge and Sakonnet Passages are proportional to their respective cross-sectional areas (est. 10,000 m^3 and 5000 m^3, respectively, or 2:1), the tidal average transport through the Mt. Hope Bay Bridge is 4.0 million m^3/hour; 2.0million m^3/hour through the Sakonnet Passage section.

Currents: The estimated section-averaged tidal current, based on the transports above, is 11.1 cm/s through both the Mt. Hope Bridge and the Sakonnet Passage sections. By contrast, Spaulding and White (1990) estimated corresponding section-averaged tidal currents of 20.3 cm/s and 4.6 cm/s (or a 5:1 ratio), using current measurements from single moorings only. The obvious differences can only be explained with further study. These Mt. Hope Bay tidal currents are of course part of the larger Narragansett Bay system.

It is not surprising that M_2 tidal currents dominate tidal currents in the Narragansett Bay system (Figure 2.10). Throughout much of Narragansett Bay the flood/ebb tidal current maxima occur approximately midway between high and low water, while slack waters occur approximately at high and low water (Hicks 1959c). (Alternately, tidal currents lead surface elevation by

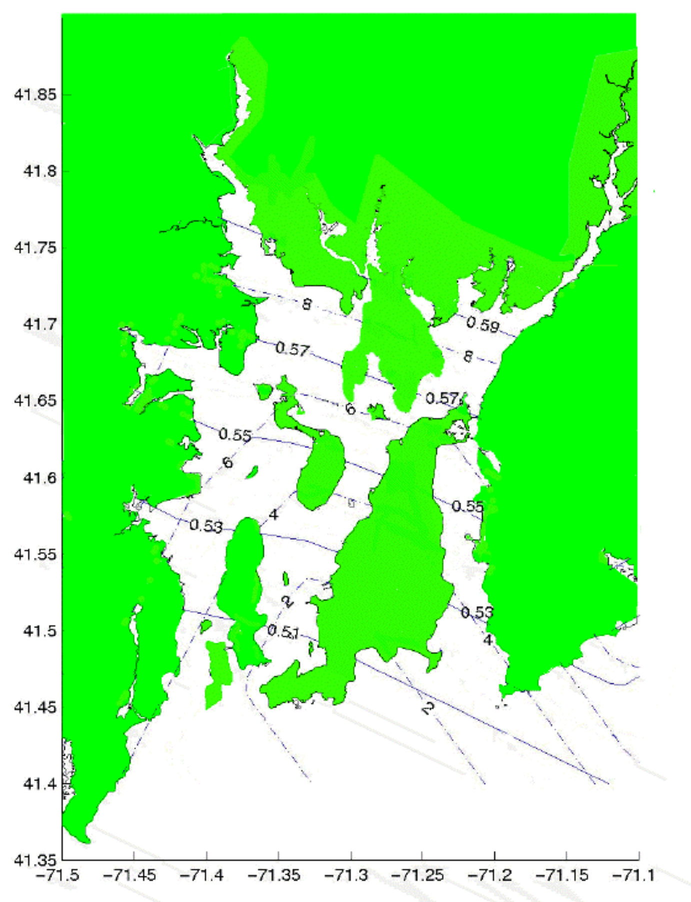

Figure 2.10. Co-amplitude (solid – m) and co-phase (dash – °Greenwich) lines for M_2 (12.42 hours) semidiurnal tide.

approximately 90° (NOAA/NOS 1993 cited in USGen 2001).) This phase relation between tidal currents and sea level is consistent with an approximate standing wave pattern for the M_2 tides in the Narragansett Bay system.

In Mt. Hope Bay, the M_2 tides typically account for 80-90% of the current variance (Spaulding and White 1990). Tidal currents are typically 10-25 cm/s in Mt. Hope Bay, but can reach 2 m/s in the narrow Sakonnet Passage connecting Mt. Hope Bay to the Sakonnet River (Figure 2.11).

4. Temperatures

Short-term temperature measurements in Mt. Hope Bay (Figure 2.12) reveal temporal variability on a number of time scales, including tidal and weather band. (Note both the spring/neap variations and what is probably wind-driven 2-10 day weather band variability in the temperature record.) The usual explanation for such variability is that lateral currents advect quasi-stationary horizontal temperature gradients past the temperature sensors. We explore this conceptual model by first reviewing the annual cycle (i.e., seasonal evolution) in the lateral temperature structure in the Narragansett Bay/Mt. Hope Bay region.

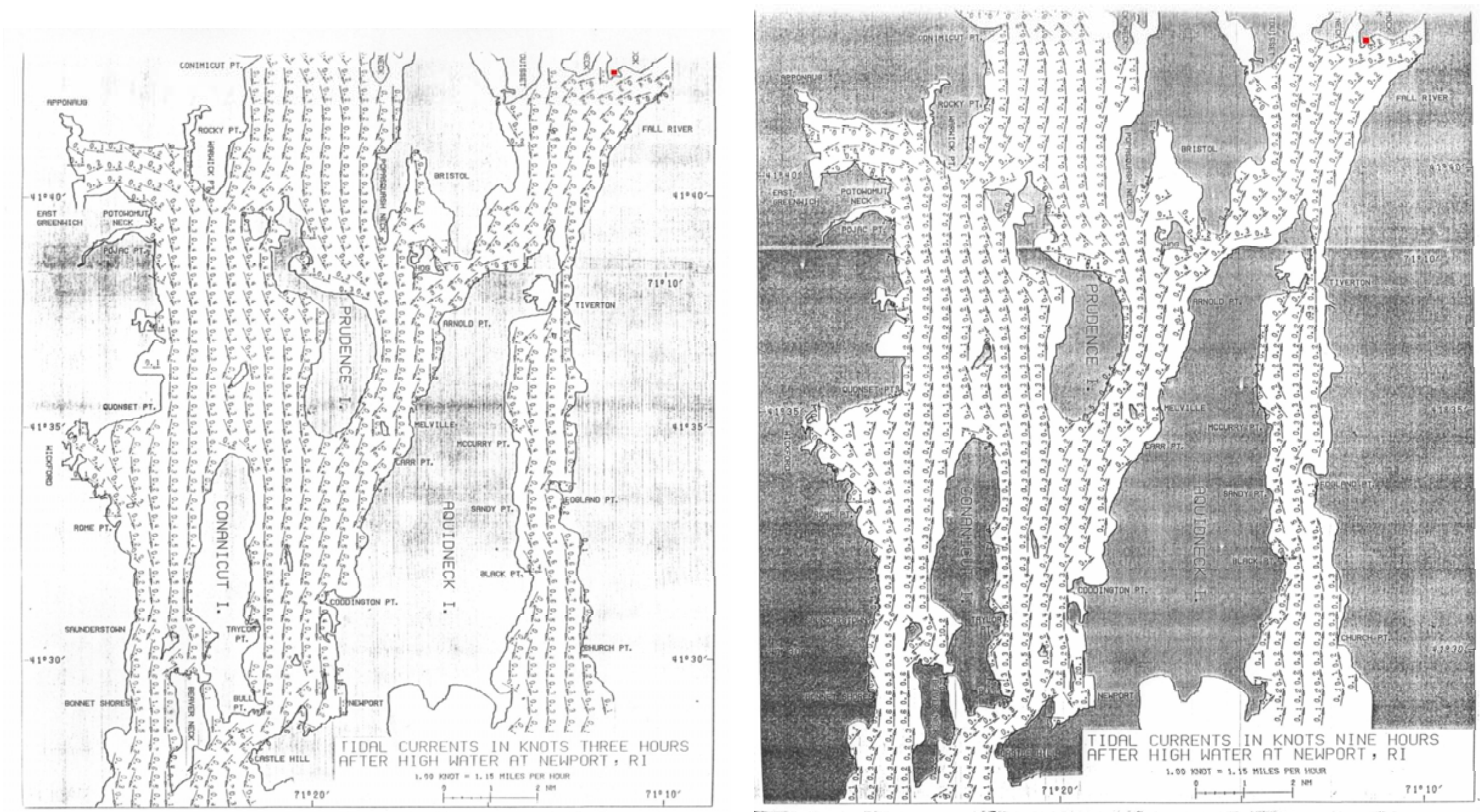

Figure 2.11. A) Ebb tidal currents (knots) in the Narragansett Bay system three hours after high water at Newport, Rhode Island. B) Flood tidal currents (knots) nine hours after high water at Newport, Rhode Island. The red square on the map indicates the location of the Brayton Point Power Plant. (Adapted from Spaulding and Swanson 1984.)

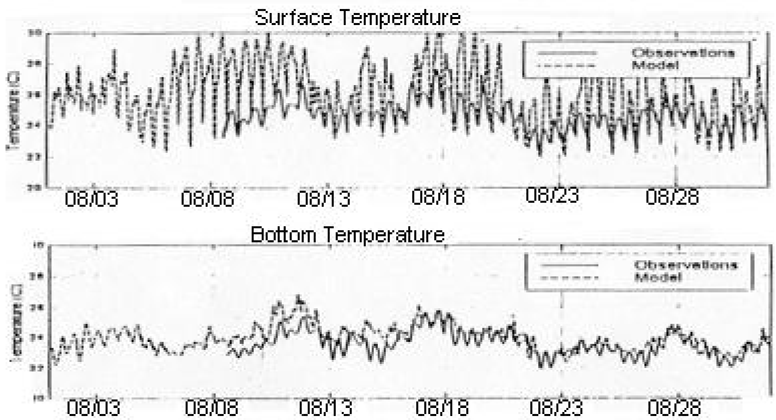

Figure 2.12. Observed (solid) surface (upper panel) and bottom (lower panel) temperature series at Brayton Point mooring station (Station 9 in Figure 2.2) for August 1997. Model temperatures are the dashed lines. (From Spaulding et al. 1999a.)

a. Annual cycle

The annual cycles in the temperature fields of Narragansett and Mt Hope Bays are defined in terms of our presentation of the Hicks (1959c) surface and bottom temperature distributions along the Providence River-East Passage and Mt. Hope Bay-Sakonnet sections (Figure 2.13). (See Figure 2.1 for transect locations.) Both surface and bottom water temperatures in Narragansett Bay are highest in August and lowest in February (Hicks 1959c). The vertically averaged version of these data show that temperatures in the lower part of the Narragansett Bay estuary are strongly influenced by the adjacent coastal ocean water (Figure 2.14). For example, during the winter Narragansett Bay surface temperatures generally increase from the cold waters in the upper bay to those of the slightly milder coastal ocean. The converse occurs during the summer.

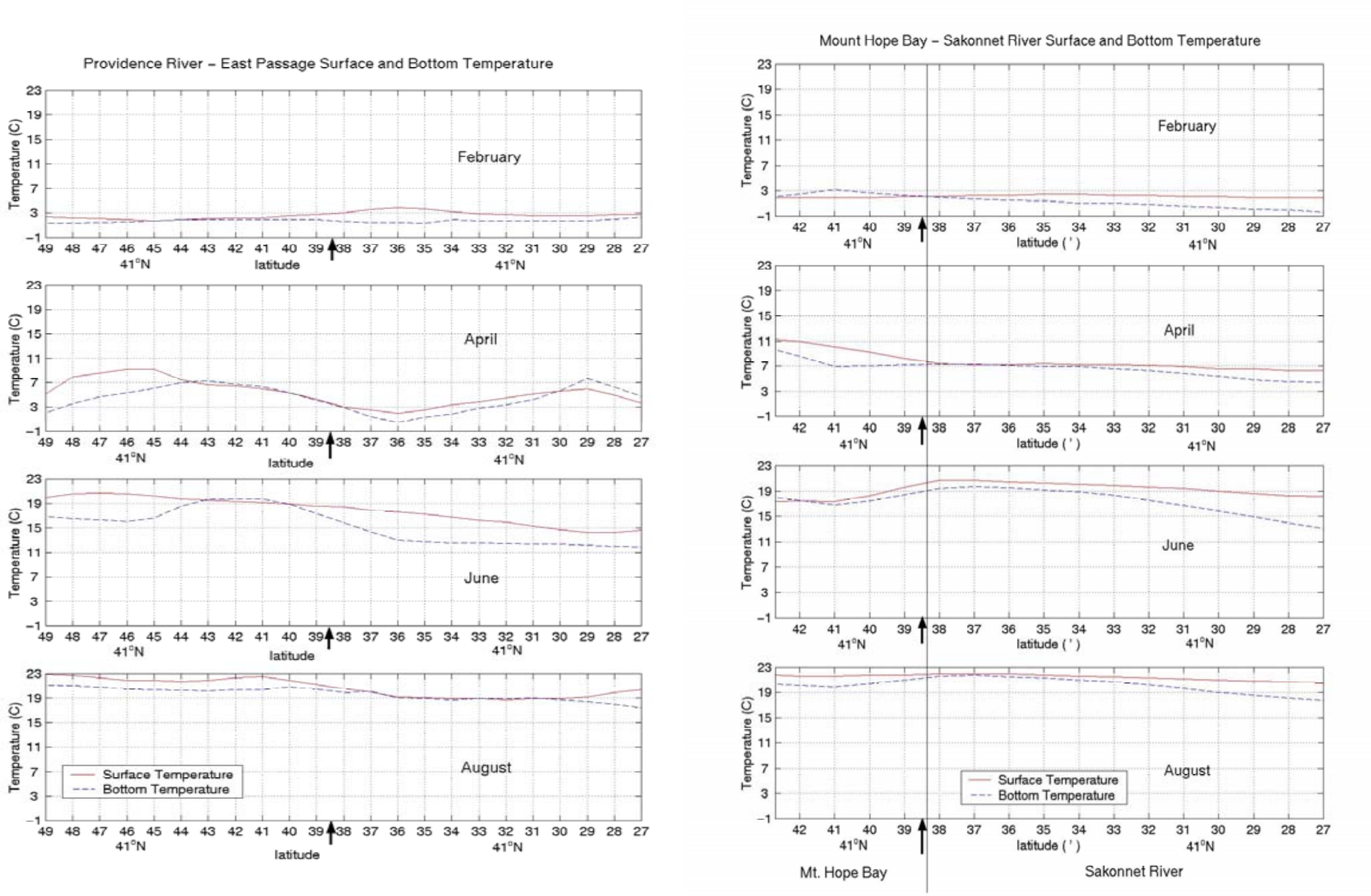

Figure 2.13. Surface (solid) and bottom (dashed) temperature (°C) distributions along A) axes of Providence River-East Passage channels and B) axes of Mt. Hope Bay-Sakonnet River channels (see Figure 2.1) at ±1hour of slack water before ebb during February, April, June, and August, 1956, respectively. The locations are given in minutes of latitude relative to 41°N. The arrow on the panels shows the latitude at which Narragansett Bay connects to Mt. Hope Bay. (Data from Hicks 1959c.)

These results are explained by the fact that the shallower waters of the upper Narragansett Bay lose (and gain) heat more quickly and extensively in the winter (and summer) than do the waters of the deeper coastal ocean. Thus during early spring, Narragansett Bay warms more quickly than do surface temperatures in the ocean. The greatest increase in Narragansett Bay temperatures occurs between April and June. Maximum Narragansett Bay (and ocean) temperatures are reached in mid-August (see Figure 2.15 for horizontal distributions). By late October, Narragansett Bay becomes colder than the ocean.

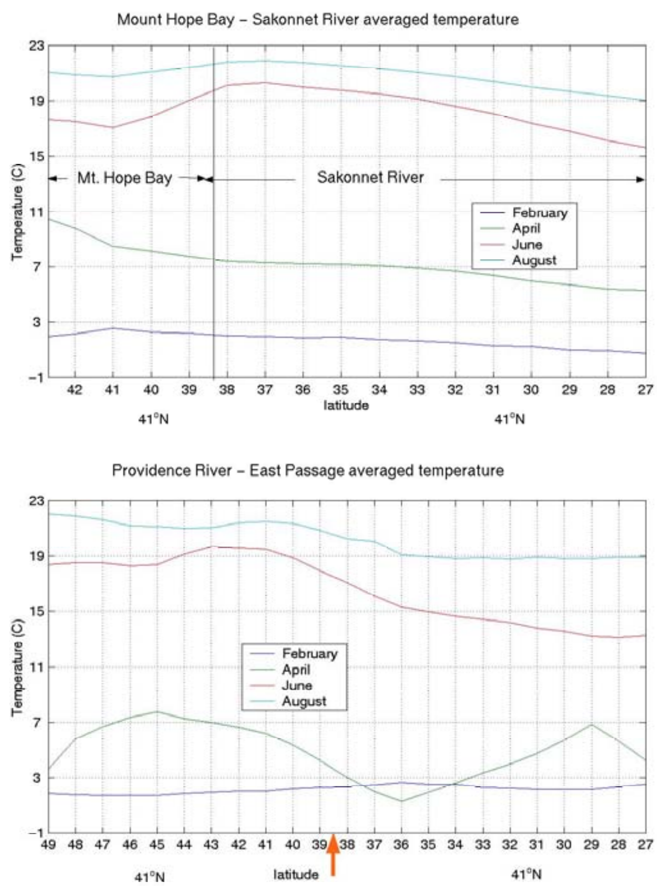

Figure 2.14. Water column average temperature (°C) distribution at ±1hour of slack water before ebb along axes of the (above) Mt. Hope Bay-Sakonnet River (below) Providence River-East Passage channels (Figure 2.1) during February, April, June, and August, 1956, respectively. The locations are given in minutes of latitude relative to 41°N. The orange arrow on the lower panel shows the latitude at which Narragansett Bay connects to Mt. Hope Bay. (Data from Hicks 1959c.)

Mt. Hope Bay is generally warmer than much of Narragansett Bay through the year except in late spring, when Mt. Hope Bay temperatures become lower than the upper Narragansett Bay (Figure 2.13). However, even then, Mt. Hope Bay is warmer than the Narragansett Bay-wide average temperature (Figure 2.14).

b. Tidal variability

The short-term time series measurements of August 1997 surface and bottom temperatures at the Brayton Point Power Station in Mt. Hope Bay exhibit tidal variability throughout the water column (Figure 2.12). This is because during the flood tidal current into Mt. Hope Bay (Figure 2.11), colder water from Narragansett Bay is advected into Mt. Hope Bay and past the temperature sensor. Hence the measured temperature decreases. During ebb tide (out of Mt. Hope Bay), the currents advect the warmer shallow water from the Taunton River and probably some of the warm water discharged from the power station (Figure 2.11) past the sensor. The value of the tidal current in Mt. Hope Bay determines the distance over which Narragansett Bay water is displaced into and out of the Bay (and hence the magnitude of the temperature change).

We can get a sense of the August temperature gradients by studying the Hicks (1959c) pre-power-plant 1956 measurements presented in Figures 2.13-2.15. We note that (1) the surface temperature in Mt. Hope Bay is nearly spatially uniform at about 21.7°C (71°F); and (2) the bottom temperature decreases from 21.7°C (71°F) in the south to about 20°C (68°F) in the middle of the Bay and then increases northward up the Taunton River. Because these temperatures were measured near high water (i.e., within an hour of ebb), this cooler water was probably advected into Mt. Hope Bay by the flood tidal current (i.e., a 0.23^{o}C decrease at Brayton Point). On the ebb in this situation, we would expect a 0.57^{o}C increase at Brayton Point. But the measurement in Figure 2.12 shows a 2°C range between ebb and flood; this increase in temperature range during a tidal cycle could be the result of the addition of heat to the Bay by the power plant.

c. Weather-band variability

Note the presence of significant non-tidal variability in the Figure 2.12 temperature measurements–some of which could be due to wind forcing. If no upwelling or mixing existed in the Bay, the water in the Bay would be always stratified, with warmer water at surface in the summertime and colder water at the surface in wintertime. But of course this is not always true. From the Hicks (1959c) surface and bottom temperature distributions data (Figure 2.13), we can see surface temperature records and bottom temperature records cross with each other in any season, which indicates that wind-induced upwelling and mixing redistributed water over the entire water column. Wind can also induce lateral mixing, and the relatively uniform temperature distribution in the whole Bay in February may indicate a very thorough lateral mixing caused by wind.

d. Interannual variability

Hicks (1959c) estimated the temperature variation from year to year by comparing the surface and bottom temperatures from measurements made in August-September 1951, August-September 1952, and August 1956, respectively. He found that the average (the literature did not indicate what kind of average he referred to) surface temperature in late summer of 1956 was 1.11°C cooler than that in 1951; and the bottom water temperature was 0.72°C cooler in 1956 than in 1951. He also found that the 1956 surface temperature was 2.61°C cooler than in 1952, and that the 1956 bottom temperature was 0.5°C warmer than in 1952.

Hicks (1959c) also concluded from the data that the inter-year late summer temperature differences decreased from about 2.22°C at the entrance to the West and East Passages to about 0.39°C at the mouth of the Providence River. Thus it would appear that temperature variations from year to year are due to changes in the coastal waters and/or direct meteorological effects rather than to differences in temperatures of the river contribution.

e. Recent measurements

The above temperature measurements were made before the Brayton Point Power Station was built. More recent Narragansett Bay-wide temperature distributions have been measured and studied. For example, a field study was conducted in Mt. Hope Bay and the lower Taunton River by Spaulding and White (1990) to describe the circulation in response to tide, wind and density-induced forcing. Surface and bottom measurements were made at three stations: Mt. Hope Bridge, Brightman St. Bridge, and the entrance to the Sakonnet River. At any given time of year, the water column at these specific locations within Mt. Hope Bay was found to be relatively well mixed (Spaulding and White 1990). These three sites represent the perimeter of Mt. Hope Bay, including the mouth of the Taunton River (Brightman St. Bridge) and the two regions of exchange between Mt. Hope Bay and greater Narragansett Bay (Mt. Hope Bridge and Sakonnet River). Assuming enhanced velocities at these locations due to river flow and tidal exchange processes, it is reasonable to assume that these locations may be well mixed while stratification may persist within the interior of Mt. Hope Bay.

Recently, the thermal effluent discharged from the Brayton Point Power Station has been tracked, described and modeled. In particular, the relationship between Brayton Point thermal effluent and Mt. Hope Bay temperature has been investigated by a remote sensing group at Brown University. Mustard et al. (1999) analyzed the seasonal variability of surface temperatures in the Narragansett Bay region from a composite of 14 thermal infrared satellite images

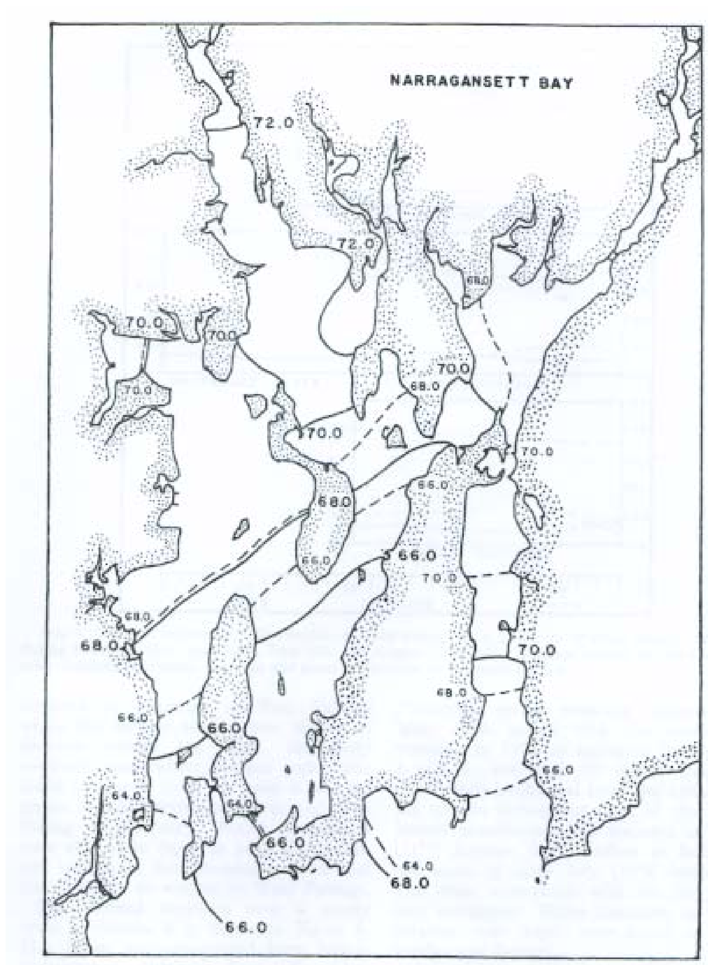

Figure 2.15. Horizontal distributions of surface (solid) and bottom (dashed) temperature (°F) distributions at ±1 hour of slack water before ebb for 6-10 August 1956. (Data from Hicks 1959c.)

(Landsat TM Band 6) with a spatial resolution of 120 m. Using the technique of unsupervised classification, they demonstrated that surface temperatures in Mt. Hope Bay were warmer than surface temperatures in other regions of Narragansett Bay that have comparable surface-to-volume ratios and tidal exchange (e.g., Upper Narragansett Bay). The temperature difference was found to be seasonal, peaking during late summer and autumn, with an average surface temperature difference between Mt. Hope Bay and Upper Narragansett Bay on the order of 0.8°C. Comparison of seasonal temperature cycles between the two regions suggests that surface temperatures within Mt. Hope Bay generally decrease with distance from the BPPS (Figures 2.16, 2.17).

The remote sensing characterizations of Mt. Hope Bay temperature are limited by the nature of remote sensing infrared instrumentation, which detects the temperature of only the upper few millimeters (the "sea skin temperature") of

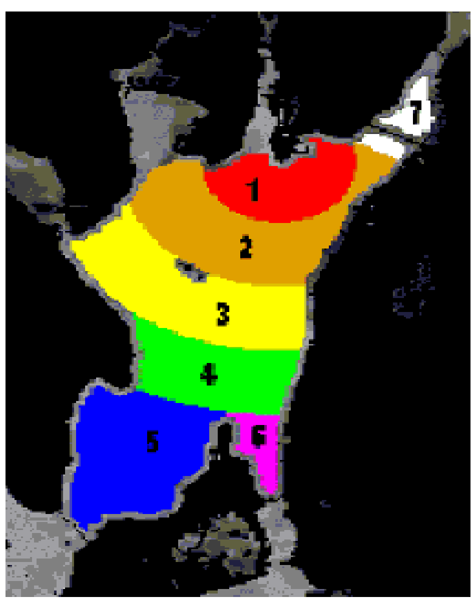

Figure 2.16. Study areas within Mt. Hope Bay. Segments 1-4 defined by 1.4-km radius from Brayton Point Power Station (Carney 1997).

a body of water. Correlation of this surface skin temperature with sub-surface temperatures is expected to decrease with water column depth. In a study comparing remotely sensed Mt. Hope Bay sea skin temperatures to in situ temperatures from depth, the correlation between surface and 1m temperatures was 0.8, while correlation between the surface and 4 m fell to 0.38 (Dave 1998). Although some studies have suggested that sea skin temperatures can be characteristic of bulk water temperatures under certain conditions (e.g., Schneider and Mauser, 1996), the presence of a positively buoyant heated discharge can results in a surface-trapped plume, with surface temperatures significantly higher than the majority of the water column. This would indicate that caution is in order prior to making assumptions regarding well-mixed conditions in Mt. Hope Bay. Given the possible effects of thermal effluent on Mt. Hope Bay organisms, especially demersal fishes, characterization of the thermal plume over depth is a necessary component of a full ecosystem analysis.

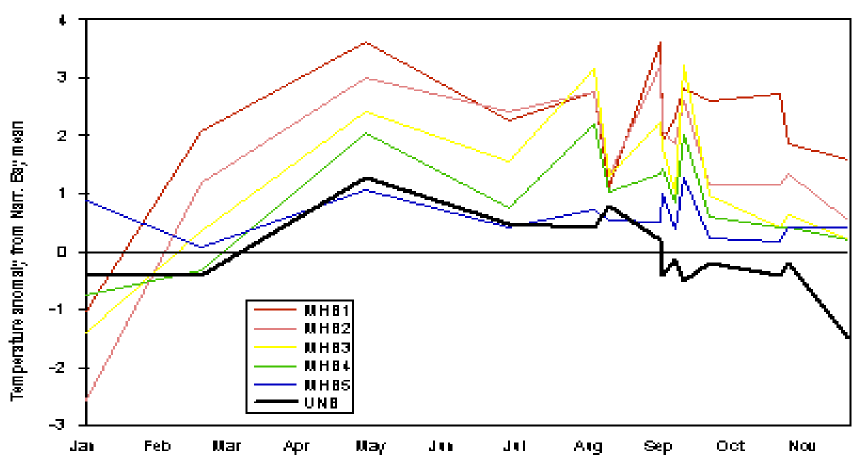

Figure 2.17. Seasonal temperature signals of Mt. Hope Bay sections (see Figure 2.15) distributions derived from Landsat (TM Band 6) satellite infrared images with a spatial resolution of 120 m. The upper Narragansett Bay temperatures are given for comparison. Note that the main body of Mt. Hope Bay (sections 1-4) is warmer than upper Narragansett Bay from February through December (Carney 1997).

Also, during February 1999, ASA measured temperatures directly with thermistor chains deployed throughout Mt. Hope Bay at the sites indicated in

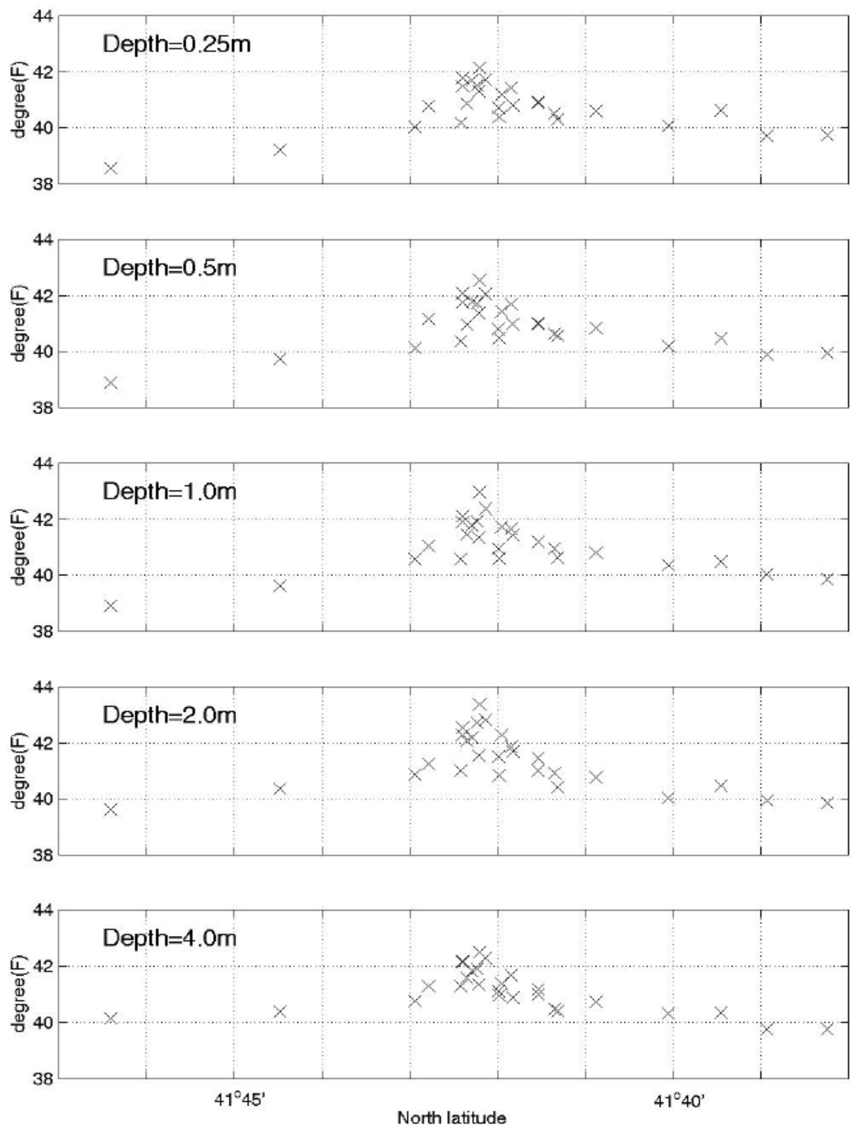

Figure 2.18. Series mean temperatures at 5 different depths at different stations (Figure 2.2) in Mt. Hope Bay during February 1999. The Brayton Point Power Plant cooling water outlet is located at about 41° 43' (Swanson et al. 1999).

Figure 2.2 (Swanson et al. 1999). The mean temperatures–plotted as a function of latitude in Figure 2.18–show a clear signature of the power plant cooling water.

5. Salinity

Short-term salinity measurements in Mt. Hope Bay (Figure 2.19) reveal temporal variability on a number of time scales including tidal, weather-band, and river discharge-related variability. The usual explanation for tidal and weather-band variability is that lateral currents advect quasi-stationary horizontal salinity gradients past the conductivity (i.e., salinity) sensors. We explore this conceptual model by first reviewing the annual cycle (i.e., seasonal evolution) in the lateral salinity structure in the Narragansett Bay/Mt. Hope Bay region.

a. Annual cycle: Salinity and vertical stability

The seasonal variation in the along-channel surface and bottom salinity distributions (Figure 2.20) in Mt. Hope Bay and Narragansett Bay are derived from the Hicks (1959c) measurements. (See Figure 2.1 for the transect locations). These distributions reflect the tidal mixing of coastal ocean waters from the south, with river inflows to the heads of Mt. Hope Bay and Narragansett Bay. The significant seasonality of river discharges (see Figure 2.7) is reflected in the minimum salinities at the heads of these respective branches (Figure 2.20).

Figure 2.19. Salinity records in Mt. Hope Bay during February-March 1999; near-surface and bottom at Brayton Point (station 9; Figure 2.2) and near-bottom at the Borden Flats (station 31; Figure 2.2) (from Swanson et al. 1999).

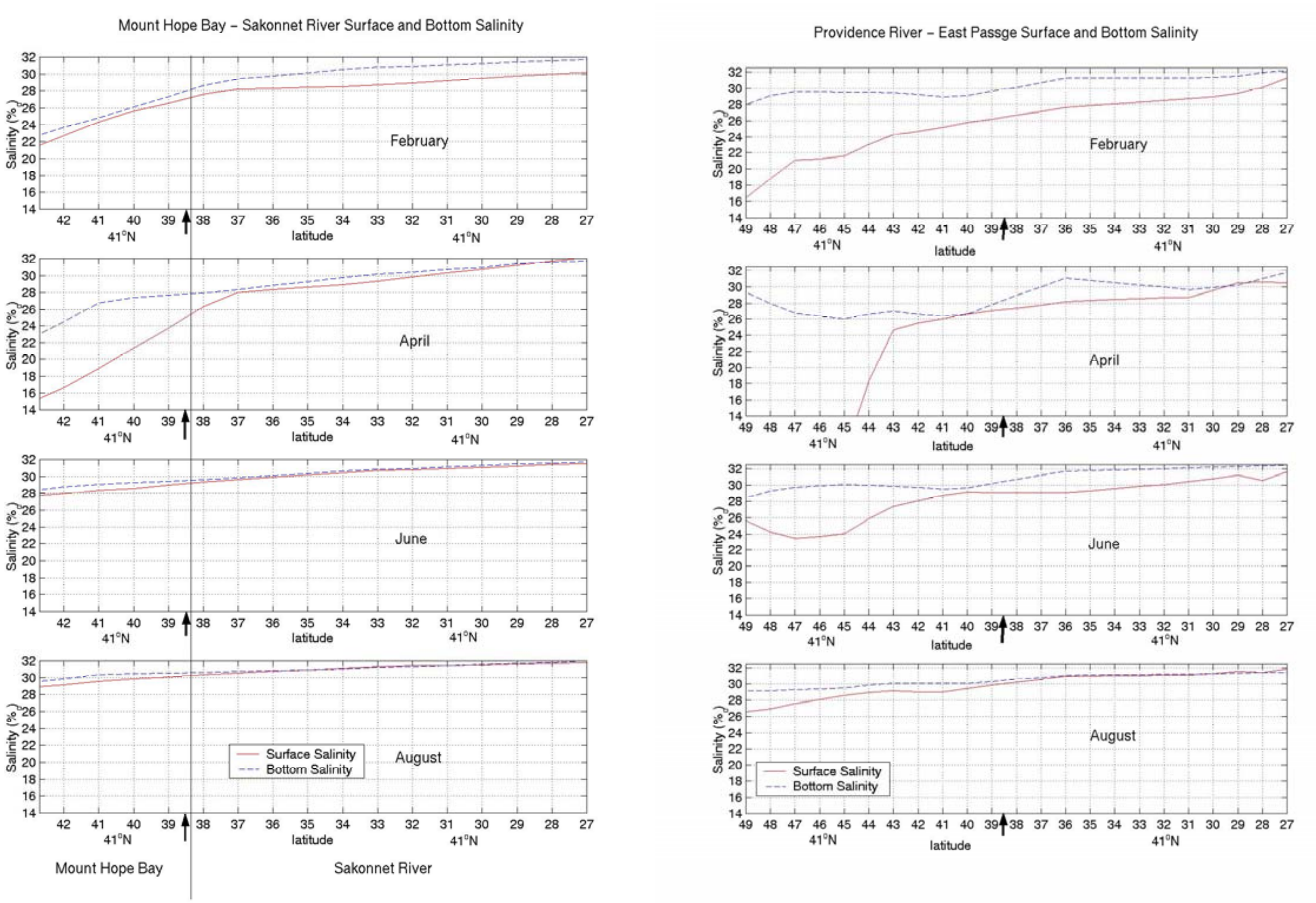

Figure 2.20. Surface and bottom salinity (‰) distribution at slack before ebb ±1 hour along A) axes of Mt. Hope Bay-Sakonnet River channel and B) axes of the Providence River-East Passage channel (see Figure 2.1) during February, April, June, and August, 1956. The locations are given in minutes of latitude relative to 41°N. The arrow on the panels shows the latitude at which Narragansett Bay connects to Mt. Hope Bay. (Data from Hicks 1959c.)

Because most of the river discharge is in spring, the average water salinity in the Narragansett Bay system is lowest in April and highest in August.

In the Narragansett Bay/Mt. Hope Bay system (like other partially mixed estuaries), the more saline (and denser) coastal ocean waters from the south tend to underlie the less saline (and less dense) surface waters from the north. The actual details of the lateral and vertical distributions of salinity in the Narragansett Bay system during a particular season are strongly influenced by the ratio of the volumes of freshwater inflow and tidal current inflow (i.e., the tidal prism) (e.g., see Figure 2.22 for an August salinity distribution). The highest river discharges during the year occur in March and April as the result of the relatively large precipitation and snowmelt. Thus the salinities at the head(s) of the Narragansett Bay system during spring are usually much lower than at other times during the year (see Figure 2.21). The relatively low river discharges during summer result in the salinity maxima during August.

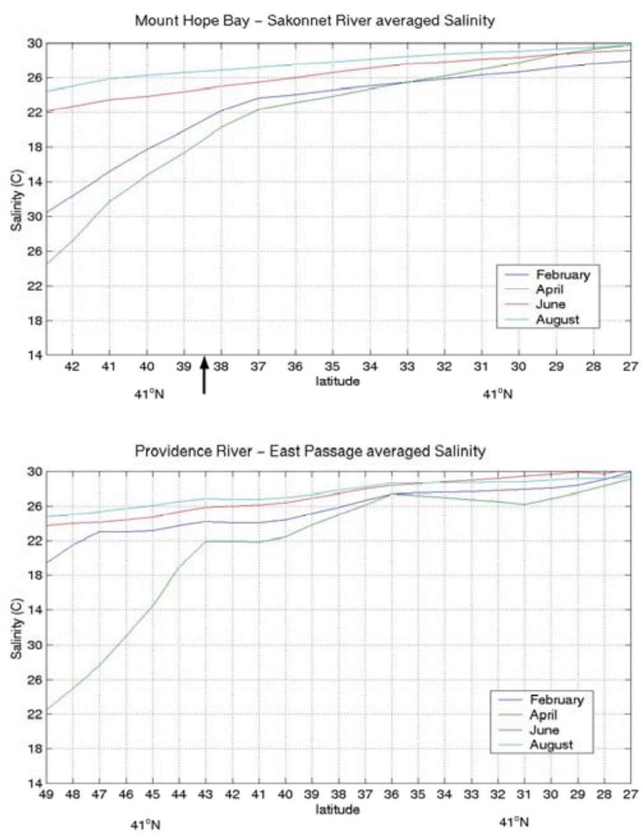

Figure 2.21. Water column average salinity (‰) distribution at slack before ebb ±1 hour along axes of channels (Figure 2.1) during February, April, June, and August, 1956. The locations are given in minutes of latitude relative to 41°N. The arrow on the upper panel shows the latitude at which Narragansett Bay connects to Mt. Hope Bay. (Data from Hicks 1959c.)

The salinity distributions dominate density structure, particularly the vertical gradients and hence stability, in the Narragansett Bay system, as shown by both the Hicks (1959c) and Weisberg (1976) measurements. The strength of this vertical stability of the water column can be expressed in terms of the buoyancy (or Brunt-Vaisala) frequency. It can be seen in Figure 2.23 that the stability of the water column generally increases from the ocean entrances to Narragansett Bay to the respective heads in the Providence and Taunton Rivers. This increase is more obvious in the Providence River-East Passage section for all seasons because the Blackstone River discharges about three times more fresh water into the Providence River than the Taunton River discharges into Mt. Hope Bay, especially in April.

b. Tidal variability

The Swanson et al. (1999) salinity time series measurements in Mt. Hope Bay during February and March 1999 (Figure 2.18) exhibit tidal variability throughout the water column. Given the typical along-channel salinity gradients (Figures 2.19 and 2.20) and tidal current magnitudes (Figure 2.10), we would expect salinity fluctuations of about 5.8 psu. Of course, estimated values vary

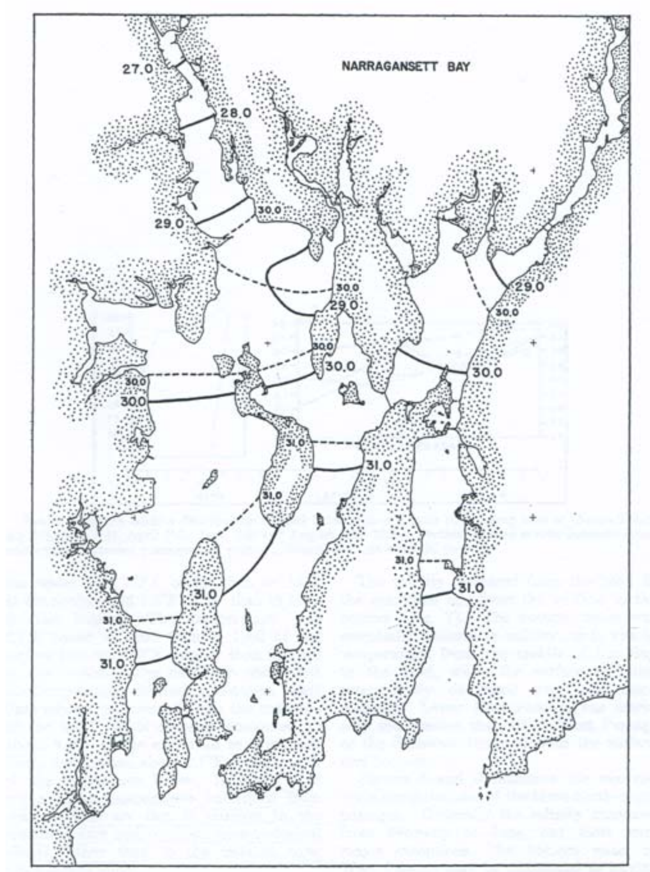

Figure 2.22. Horizontal salinity (‰) distribution at slack before ebb ±1 hour during cruise 19 (6-10 August 1956). Surface – solid lines and large numerals); bottom – dashed lines and small numerals. (Reprinted from Hicks 1959c.)

with the stage in the spring-neap cycle. These estimates compare with the observed tidal fluctuation in salinity magnitudes of 2-10 psu, clearly seen shown in the observations.

Besides advecting horizontal salinity gradients, tidal currents in narrow passages can also cause vertical mixing. The latter process might explain the very small vertical differences in salinity in the June and August (Figure 2.20, left panel) Sakonnet River sector of the Mt. Hope Bay/Sakonnet River salinity

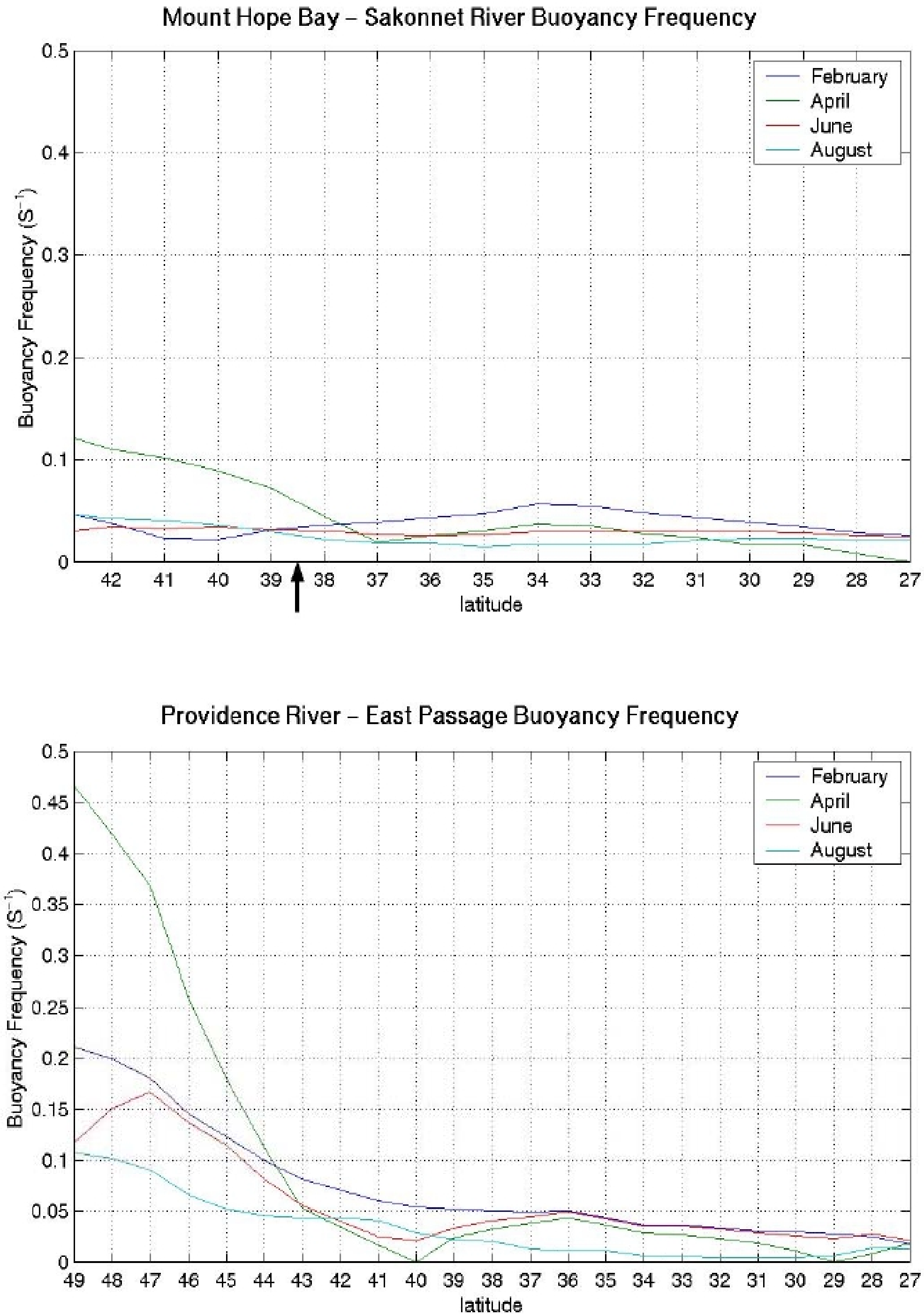

Figure 2.23. Water column vertical stability distribution in terms of buoyancy frequency at slack before ebb ±1 hour along axes of channels (Figure 2.1) during February, April, June, and August, 1956. The arrow on the upper panel shows the latitude at which Narragansett Bay connects to Mr. Hope Bay. (Data from Hicks, 1959c.)

distribution. It may be that the strong alternating flood and ebb tidal currents in the Sakonnet Passage may homogenize the water that resides there.

c. Weather band

During February-March 1999, surface salinity varied from 28 to 10 ppt (Figure 2.19), with the lower values probably due to a major precipitation and/or snow melt runoff event. During the same time, bottom salinity records decreased from about 29 to 20 ppt. The surface salinity record, however, was more complex than the near-bottom record, probably because of the vertical mixing effects of wind and perhaps tidal currents.

d. Interannual variability

Salinity variations from year to year appear quite small in comparison with longitudinal or seasonal variations. A comparison of Hicks (1959c) average data indicates that the late summer 1956 bottom water was 0.2‰ less saline than that in 1951. However, the 1956 surface and bottom salinities were greater than their 1952 counterparts by 0.7‰ and 0.2‰, respectively.

6. Nontidal Currents

Weisberg (1976) examined the effects of wind, atmospheric pressure and river inflow variability on the nontidal flow in the Providence River section of Narragansett Bay. The study focused on a 51-day (18 October - 9 December 1972) Geodyne model 850 current record 2 m above the bottom (the mean low water depth is 12.5 m) near the entrance to the Providence River (Figure 2.1). He reported along-channel current mean and variance of 11.7cm/s (landward) and

166.9 cm/s^2, respectively. The semidiurnal tides contributed 45% of the total variance, while 7% was due to higher tidal harmonics. The rest, 48%, resided at subtidal frequencies and was due to nontidal forcing. Weisberg (1976) found that 97% of the along-channel nontidal current variance in the most energetic portion of the spectrum (4-5 day periods) was coherent with, and lagged by about 4 hours, the Green Airport wind velocity component in the direction of maximum fetch, which is 335° to the north.

Spaulding and White (1990) conducted a field study between December 1985 and January 1987 in Mt. Hope Bay and the lower Taunton River to determine the response of the circulation to tide, wind and density induced forcing. Wind data were obtained at hourly intervals from the National Weather Service Station at T.F. Green Airport, Warwick, RI. Surface and bottom current meters were deployed (typical duration of 60 days) at the Mt. Hope Bridge, at the Brightman St. Bridge in Fall River, and at the entrance to the Sakonnet River (at Hummocks near the Sakonnet River Bridge) (Figure 2.2). The hydrography showed that the water column is well mixed throughout Mt. Hope Bay. Spaulding and White (1990) summarized and averaged the peak coherences found in the wind-frequency ranges (30-hour low-pass filtered) for seven Brightman and eleven Mt. Hope meter records. They concluded from the results that the overall effect of wind excitation on Mt. Hope Bay currents is very small.

Spaulding and White's (1990) conclusion was obviously inconsistent with Weisberg's (1976) conclusion concerning wind (measured at T.F. Green Airport) forcing of currents. There are several possible reasons for this inconsistency:

1) Providence River is much closer to T.F. Green Airport than is Fall River.

According to Pilson (1991), local wind conditions can vary significantly from location to location in Narragansett Bay. Thus it is not surprising that winds measured at T.F. Green airport might be statistically unrelated to water movements at Brightman St. Bridge, which is located in a narrow upstream section of the Taunton River in Fall River.

2) The two sets of observations were made in different seasons.

The Weisberg (1976) analysis was based on measurements done in autumn, while Spaulding and White's (1990) analysis was based on results averaged over the whole year. Climatological records (Figures 2.4 and 2.5) show that winds differ considerably over the year. It is also clear from Figure 2.7 that Taunton River discharge is relatively large and highly variable on the 2-10 day weatherband time scales between March and June. Hence the Taunton River discharge variability could dominate the flow variability, thus causing reduced wind/current coherence on an annual time scale.

3) Current measurements in the two studies were at different relative depths.

The Weisberg (1976) currents were 2 m off the bottom in 12.5 m of water, while Spaulding and White (1990) averaged their surface, mid-depth and bottom current measurements.

We conclude that there is a lack of a comprehensive study of wind-forced currents in Mt. Hope and Narragansett Bays. Thus we recommend that we conduct a comprehensive statistical analysis of the PORTS winds and currents during the early stages of the design phase of the Mt. Hope Bay Natural Laboratory.

Spaulding and White (1990) note that the long-term average flow of the Taunton River in Fall River (near Brightman St. Bridge) is consistent with a classical stratified estuarine circulation pattern: that the surface flow is down-river and bottom flow is upriver. They also found that the long term flows through the Sakonnet Passage and Mt. Hope Bridge sections were consistently out of Mt. Hope Bay. According to their measurements, the outflow through the Mt. Hope Bridge section was approximately 1000 m^3/s, and the outflow through the Sakonnet River Bridge section is was approximately 150 m^3/s, which means the outflow through East Passage is more than 7 times the outflow through the Sakonnet River. The averaging period for these results is not clear from the literature, but these data could imply that there must be residual inflow at other places along the Mt. Hope Bridge and Sakonnet River sections which were not measured at the deployment time. Those inflows could be possibly associated with eddy currents associated with the topography there.

C. Summary of Results

This report outlines a basic understanding of many of the important aspects of the physical environment of Narragansett/Mt. Hope Bay, including sea level, currents, temperatures and salinities (densities) and how they respond to tidal, wind and river discharge forcing.

The tides in Narragansett Bay are dominated by the M_2 semidiurnal constituent and have approximate standing wave characteristics. The M_2 constituent is the largest, accounting for 90% of sea level variance and 80-90% of current variance in Mt. Hope Bay. The tidal prism in Mt. Hope Bay accounts for 1/5 of the water volume in the Bay. The tidal average transport through Mt. Hope Bay is two times that through the Sakonnet Passage section.

Blackstone River discharge accounts for about half of the fresh water inflow in the Narragansett Bay region. Taunton River discharge accounts for more than 90% of fresh water inflow to Mt. Hope Bay. All the rivers in the Narragansett Bay region have the highest discharge in March and April and lowest discharge in July to September.

Both surface and bottom water temperatures in Narragansett Bay are highest in August and lowest in February. Mt. Hope Bay is generally warmer than much of the Narragansett Bay area during the spring, summer and fall. Recent studies and measurements show clear signatures of the power plant's influence on the Bay's temperature field.

Salinity distributions in Narragansett Bay have typical river-to-ocean salinity gradients. The average salinity in the Narragansett Bay system is lowest in April and highest in August. The actual details of the lateral and vertical distributions of salinity in the Narragansett Bay system during a particular season are strongly influenced by the ratio of the volumes of freshwater inflow and tidal current inflow.

D. Recommendations for Future Work

There are still, however, several important aspects that need further work if we are going to build a model-based Mt. Hope Bay Natural Laboratory. There is a need to:

- **Analyze the available long-term PORTS time series measurements of the basic physical variables and obtain additional new records from "critical locations."**

  Most measurements to date have been short-term. ASA has done some detailed thermistor chain measurements in Mt. Hope Bay (31 stations with sensors at several levels from surface to bottom in the water column), but for only about one month. These temperature measurements (and some corresponding salinities) are not very well analyzed. Only visual analysis was done to show the heat-loading effects from the Brayton Point Station plume. No time series analysis results are available from their results. Also, we can obtain only some tidal frequency band variations from analyzing these one-month-long records. In order to determine weather band, seasonal, and interannual variations in temperature, we need much longer observation records. Fortunately, there is a growing archive of PORTS observations. An analysis of these data could provide important insight into the long-term variability in the bays and thus a physical context for evaluating the effects of different kinds of anthropogenic influences. We have already obtained the PORTS Fall River time series measurements of water temperature, air temperature and sea level for October 1999 to date. Table 2.2 details these and the other available time series data.

- **Obtain a modern system-wide description of the annual evolution of hydrographic properties and hence physical stability structure of the bays.**

  The only systematic measurements of the annual evolution of the structure of the water properties in the Narragansett/Mt. Hope Bays system are those data from 1957 described by Hicks (1959c).

- **Clearly describe the evolution of the tidal, wind-driven and density-driven circulation patterns in the bays.**

  The variability in the wind-driven and density circulation determine how the pollution and nutrients are transported in the bays over time scales much longer than the daily tidal time scales. There is a need to know how these patterns differ with (a) strong and weak wind-forcing; (b) spring and neap tidal stage; (c) large and small river discharges; (d) season. Answers to these questions are an important part of the definition of the natural habitats that support the ecosystems in the bays.