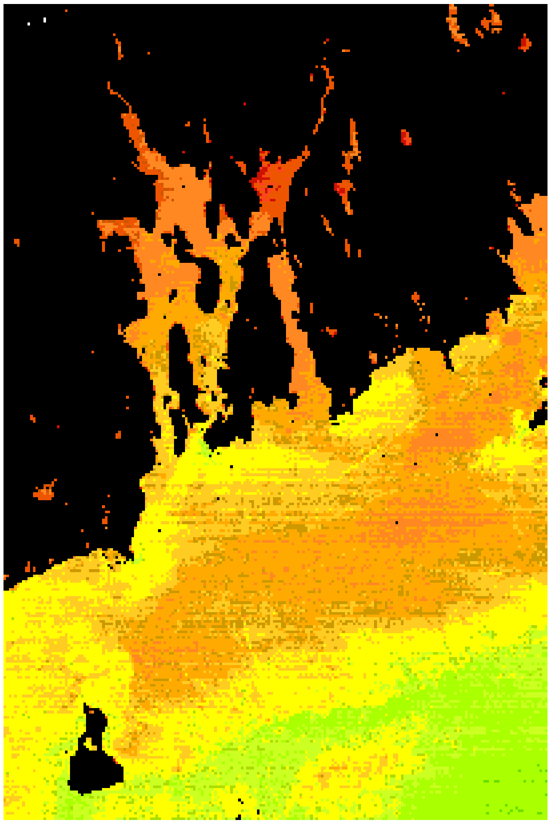
Surface temperatures in Narragansett Bay: Seasonal dynamics and anthropogenic effects



Megan A. Carney
Sc.B. Thesis, May 1997
Center for Environmental Studies
Brown University, Providence RI 02912

Center for Environmental Studies
Brown University

May 1997

This thesis by Megan A. Carney is accepted by the Program in Environmental Science in partial fulfillment of the thesis requirement for the degree of Bachelor of Science.

Steven P. Hamburg
Associate Professor of Environmental Studies
Brown University

This thesis was completed under the guidance of John F. Mustard, Assistant Professor of Geological Sciences, Brown Uniersity, in association with his Narragansett Bay Project, funded by NASA.

Avijit Sen, Sc.B. '96, M.A. '97,
Center for Environmental Studies, Brown University,
performed extensive work in the initiation
and continuation of this project.

Surface temperatures in Narragansett Bay: Seasonal dynamics and anthropogenic effects

Megan Carney
Sc.B. Thesis
Center for Environmental Studies
Brown University, Providence RI 02912

Abstract

Seasonal trends of surface temperature in the Narragansett Bay estuary were derived from a composite of 14 thermal infra-red satellite images (Landsat TM Band 6) with a spatial resolution of 120 meters. Relationships among thermal properties and physical characteristics were identified through a comparison of the seasonal temperature patterns of 12 regions within the bay. Correlations among the seasonal temperature signals of these regions were used as a basis for categorizing the estuary in terms of its thermal behavior. The lower estuary was characteristically cooler than the bay average during the summer and warmer during the winter due to the influence of oceanic water, which always has a more moderate temperature than the estuary. The thermal characteristics of lower estuarine regions were most dependent upon circulation patterns. The upper estuary was warmer than the bay average during the summer and cooler during the winter because it gains and loses heat more quickly and extensively than the ocean due to its shallowness. Depth is the most important factor in determining the magnitude of seasonal temperature variation in the upper estuary. Although the behavior of Mount Hope Bay was significantly correlated with the other upper estuarine regions, the bay did not experience autumn cooling, which is characteristic of upper estuarine waters. From late summer through autumn, the average temperature difference between Mount Hope Bay and Upper Narragansett Bay was 0.8°C, which can be attributed to warming from the thermal effluent of the Brayton Point Power Station in Mount Hope Bay. An unsupervised (statistical) classification of temperature as a function of season revealed the natural boundaries between areas with different seasonal temperature signals, and statistically identified Mount Hope Bay as a unique area in the upper estuary which had anomalously high temperatures throughout the year. Among the scenes included in the unsupervised analysis, Mount Hope Bay was on average 0.8°C warmer than the rest of the upper estuary.

Introduction

Temperature and Estuarine Dynamics in Narragansett Bay

An assessment of human impacts upon the natural heat balances in aquatic systems must be viewed in the context of a comprehensive understanding of the temperature-related dynamics in these systems. Seasonal fluctuations in water temperature play an important role in characterizing changes in the physical and biological processes of estuaries. Temperature is an important environmental variable which affects the survival, growth, and reproduction of marine organisms. Through its effects on density, temperature is also involved in advective mixing processes and in turn is a major factor in primary production dynamics.

In the absence of strong salinity gradients, the relation between surface and bottom temperature controls basic estuarine circulation. Most estuaries remain at least somewhat mixed throughout the year due to tidal forcing on their relatively shallow waters. However, seasonal changes in the strength of solar radiation drive large variations in the temperature of surface waters. As surface water warms during the spring, it may become sufficiently buoyant to create a thermocline, which restricts vertical mixing. As surface water cools during the fall, stratification eventually breaks down and mixing between the surface and bottom resumes. These temperature-driven processes control mixing in the upper parts of the Narragansett Bay estuary [Kremer & Nixon, 1978]. (Mixing is also affected by fresh water input and meteorological events.)

The transition between a mixed and stratified water column is an important factor in defining seasonal cycles of phytoplankton abundance through the interaction of nutrient concentrations and light availability. Fresh water runoff and intense mixing during the winter provide nutrients for spring algal blooms, which are triggered by light availability. Once surface temperatures increase and a thermocline is formed, the phytoplankton population may become isolated in the upper layer and thus separated from the more abundant supply of nutrients, as well as the darkness, at depth. Net production occurs in the water column until nutrients are depleted. Because primary producers form the base of the marine food web, the timing and extent of these temperature-driven events influence the entire estuarine community through a complex series of ecological interactions.

Temperature also affects organisms through direct physiological mechanisms. All organisms have a certain tolerable temperature range, above which prolonged exposure is lethal. Within this acceptable temperature range, metabolism, growth rates, reproduction, and recruitment success vary widely. In cold-blooded marine organisms, warmer ambient temperatures increase metabolic rates and related processes, such as feeding efficiency. Growth and development rates usually increase with temperature, up to a threshold, beyond which excess energy is required for survival, and rates decline precipitously. Temperature variations are used as reproductive cues for many populations, including several Narragansett Bay fish species [Dixon, 1991]. Increases in bacterial abundance with temperature [Valiela, 1995], further compound the community affects of reduced dissolved oxygen and nutrient concentrations in warm water [Paine, 1993].

All of these temperature-related responses affect different species, and the repercussions for ecosystem dynamics depend upon food web interactions. Despite lack of a clear understanding of the mechanisms at work, significant warming of coastal marine systems has been documented to have substantial and sometimes unpredictable impacts upon community composition and structure [Tissot et al., 1991]. Thus, a detailed understanding of estuarine thermal processes and anthropogenic impacts upon them are vital to the successful management of coastal ecosystems and fisheries.

Anthropogenic Effects on the Mount Hope Bay Ecosystem

Mount Hope Bay is of particular interest in the context of a study of water temperature in Narragansett Bay. This semi-enclosed section of the upper estuary (figure 1) is home to the Brayton Point Power Station (BPPS), a large coal-fired facility which is the major electricity supplier of a large part of Rhode Island and Southeastern Massachusetts. The waters of Mount Hope Bay are utilized to cool the plant's generating system, and on the average, almost five million cubic meters of water are run through the plant each day then discharged at temperatures about 8°C warmer than ambient water temperature [Sen, 1996]. The amount of water that flows through the plant is more than twice that of the total fresh water inputs to the bay [Sen, 1996], and the current and potential impacts of the excess heat load on physical and biological processes in Mount Hope Bay are largely unknown and controversial.

In 1994, Mark Gibson, of the Rhode Island Division of Fish and Wildlife released a study which correlated fish abundance in Mount Hope Bay with changes in the operations of the Brayton Point Power Station. Specifically, a major decline in the aggregate fish population is suspected to have been onset by changes made to the plant's discharge system in 1985 which increased the average daily effluent volume by 50%. The release of a revised fisheries study in the summer of 1996 [Gibson, 1996] prompted the regional EPA to revoke Brayton Point's discharge permit based upon substantial evidence that the plant's effluent was causing significant damage to the bay's ecosystem [Wyss, 1996a]. Since then, a memorandum of understanding which places stricter limitations on the volume and temperature of the plant's effluent has been signed by New England Power (the owners of BPPS), the EPA, and Rhode Island and Massachusetts state environmental agencies [Wyss, 1996b]. Continued research throughout the next year will be incorporated in the creation of a new five-year permit in July, 1998.

In order to define acceptable limitations on the operation of the power plant, the relevant physical and biological processes must be better understood. Quantitative estimates of the plant's influence on these processes at different levels of operation are being sought through the development of hydrodynamic models and detailed studies of the bay's ecosystem. Because there is a limited understanding of Mount Hope Bay’s characteristics previous to the construction of the power plant, or previous to the 1985 modifications, it is useful to consider the current thermal characteristics of Mount Hope Bay in the context of the surrounding system. Although we are not able to quantitatively measure change in the thermal characteristics of the bay over the long term, we can assess how the behavior of Mount Hope Bay compares to that of other areas within Narragansett Bay which have more natural heat budgets. This provides a mechanism for quantifying the effects of BPPS on the thermal characteristics of Mount Hope Bay. Sen [1996] investigated the relationship between Brayton Point's thermal effluent and the temperature of Mount Hope Bay through an analysis of five thermal infra-red satellite images, and found that Mount Hope Bay was substantially warmer than other areas of Narragansett Bay. Sen suggested that the strength of this Mount Hope Bay temperature anomaly might be seasonally variable. The physical and biological implications of this thermal impact are largely unknown.

Purpose of Investigation

The purpose of this study is to characterize the seasonal temperature dynamics in Narragansett Bay through an analysis of fourteen thermal infra-red satellite images. The seasonal temperature signals of various regions within the estuary are identified and compared in order to classify the system based upon thermal properties and to identify the relationships among thermal properties and physical characteristics. This large-scale understanding of temperature patterns within the estuary serves as a basis for quantifying the temperature anomaly in Mount Hope Bay resulting from thermal effluent from the Brayton Point Power Station's thermal effluent, and for defining the potential seasonal component of the anomaly identified by Sen [1996].

Methods

Temperature Derivation

Radiance measurements from band six of the Landsat Thematic Mapper (wavelength=10.4-12.5μm) were used to derive surface temperatures by applying a form of Plank's Black Body Equation, which defines the relationship between the radiance emitted from an object at a certain wavelength and its absolute temperature. First, the image digital number (DN) values were converted to radiance by applying the gain and bias of the detectors, which are known from pre-flight calibration. From Gibbons et al. [1989]:

$$R_u = \alpha\ (DN) + \beta$$

where:

R_u = uncorrected spectral radiance in mW cm^{-2} Sr^{-1}μm^{-1}

$\alpha = 0.005632$ mW cm^{-2} Sr^{-1}μm^{-1} DN^{-1}

$\beta = 0.1238$ mW cm^{-2} Sr^{-1}μm^{-1}

Radiance was then converted to a black body temperature [Gibbons et al., 1989]:

$$\mathbf{T_u} = \frac{\mathbf{K_2}}{ln\left[\frac{\mathbf{K_1}}{\mathbf{R_u}} + \mathbf{1}\right]}$$

where:

T_u = black body temperature in K

K_2 = 1260.56 K

K_1 = 60.776 mW cm^{-2} $Sr^{-1}\mu m^{-1}$

Because water is not a perfect black body (or a perfect emitter), a correction was made using the emissivity of water (the ratio between the radiance of a particular "gray body" and that of a black body at the same temperature) [Avery & Berlin, 1992]:

$$T_k = T_u / E^{1/4}$$

where:

E = emissivity of water = 0.986 [Gibbons et al., 1989]

T_k = kinetic temperature in K

Low atmospheric transmissivity can introduce some error into deriving surface temperature from satellites, as atmospheric constituents (especially water vapor) absorb radiation emitted from the surface, thus reducing the amount of radiation which actually reaches the sensor. The atmosphere also emits some radiation due to its own internal heat, in turn increasing at-satellite radiance. The accuracy and precision of deriving surface temperatures from Landsat TM band six data have been assessed by Schneider and Mauser [1996], who employed a full atmospheric model to convert at-satellite radiance to an accurate measure of water leaving radiance (and thus water temperature) of a lake in Germany for which extensive *in situ* water temperature data were available. On average (in 31 images), atmospheric correction increased satellite derived temperatures by 1.33 K. Thus, we may expect to slightly underestimate temperatures when corrections are not made, although the exact error is dependent upon specific atmospheric conditions. Atmospheric corrections also increased spacing, or the temperature step associated with one DN step, from 0.47 K/DN to 0.63 K/DN. Therefore, temperature *differences* may also be slightly underestimated.

In order to minimize uncertainty in this study, I chose to look at the temperature of each area relative to the estuary mean, eliminating the error involved in deriving exact temperatures. Deviations of specific areas from the estuary mean were generally within the range of ± 5 DN, and the expected error given an average spacing error of 0.16 K/DN is a function of the DN deviation (table 1). The maximum expected error in temperature difference is 0.8°C, for the largest deviations. Since the degree of error is a function of the amount of atmospheric interference, all available scenes with significant clouds or fog were removed from the study.

Another important result of the Schneider and Mauser [1996] study was a description of the relationship between surface skin temperature and bulk water temperature. All of the energy exchanges between water and air take place within a very thin surface skin layer, and thus the temperature of this layer may deviate significantly from the temperature of the water column. Because water leaving radiance is a function of the temperature of this skin layer, we need to account for the relationship between skin surface and water column temperatures, which varies diurnally due to changes in energy fluxes. The temperature difference was found to be minimal (0.1 K) between 9 and 11 am, the standard crossing time of the Landsat satellites. Therefore, the remotely measured skin temperatures are expected to be representative of bulk water temperature below the surface. Because Narragansett Bay is fairly well mixed, surface temperature is an acceptable representation of water column temperature under most circumstances.

Temperatures derived from the fourteen satellite images were compared to *in situ* measurements to assess the level of accuracy of the calculated temperatures for this study (figure 2). Satellite-derived temperatures were all within 3°C, and many within 1°C of *in situ* measurements. Some variability was introduced because the two measurements were not necessarily taken at the same time[1], and given this uncertainty, the relationship between satellite derived and *in situ* temperatures is fairly strong. One scene, 870308, which showed a large difference between satellite-derived and *in situ* temperatures was removed from the study. All of the other differences greater than 1°C were satellite underestimates probably resulting from atmospheric interference. This is an acceptable level of certainty, as these temperatures were only used as a context for the analysis of temperature *differences*, which are better preserved under atmospheric interference than actual temperatures. The derived

---

[1] In cases where an in situ measurement was available for the day of the overflight, a direct comparison could be made. Because these situations were rare, any *in situ* data available within one day of the overflight were used as estimates. When measurements were not available within one day, temperatures were linearly interpolated from measurements within 3 days before and after the scene date, where possible.

temperature were used to compare the general seasonal water temperature trend in the satellite images to actual trends observed through years of *in situ* monitoring. The seasonal composite created from fourteen satellite images which actually span over twelve years (figure 3) was found to be an appropriate representation of the general seasonal trends observed over the long term (figure 4).

Regional Classification of Narragansett Bay

The Narragansett Bay Estuary runs northward from the Rhode Island Coast into Rhode Island and Massachusetts (Figure 1), and has a drainage area of 4660 km^2 [Kremer and Nixon, 1978]. Its 2.6×10^9 m^3 of water are spread over an area of almost 350 km^2, with a mean depth of 7.8 m [Chinman and Nixon, 1985]. The mean tidal prism is much greater than the mean volume of river flow into the bay during an equivalent period of time, so that the estuary is generally well mixed, although occasionally stratified (measured by salinity gradients) in the upper bay [Kremer and Nixon, 1978]. The semi-diurnal tide ranges from 0.8 to 1.6 m [Chinman and Nixon, 1985], but the prevailing winds, northwest during the winter and southwest during the summer, frequently dominate short-term circulation patterns [Kremer and Nixon, 1978]. Water temperatures throughout the year range from below freezing up to the mid-20s (°C), and the annual water temperature cycle tends to lag solar radiation by about 40 days [Kremer and Nixon, 1978]. The Narragansett Bay ecosystem is phytoplankton based, and usually experiences a bay-wide winter-early spring bloom, several localized short term blooms throughout the summer, and a late summer bay-wide bloom [Kremer and Nixon, 1978]. The bay is inhabited by many commercially important fish species, and the benthos is dominated by clams which are harvested in limited areas. The Narragansett Bay ecosystem is significantly impacted by industrial and sewage-treatment effluents, as well as runoff from its intensely populated watershed.

To facilitate studies of the physical characteristics of Narragansett Bay, Chinman and Nixon [1985] divided the estuary into a series of distinct segments related to basin bathymetry and circulation patterns, and defined the depth, area, and volume of each of these segments. Based upon this breakdown as well as observations of overall temperature patterns in the estuary, I defined twelve study areas within Narragansett Bay (figure 5), in order to investigate spatial variations in seasonal temperature trends. The "regional classification" consisted of categorizing the behavior of these pre-defined regions relative to the system as a whole. Four areas were defined in the upper estuary (Greenwich Bay, Providence River, Upper Narragansett Bay, Mount Hope Bay), and the West Passage, East Passage, and Sakonnet Rivers were each divided into two or three sections so that estuary-to-ocean gradients could be detected where present. The known physical characteristics for each area (table 2) provide a context for comparison of their seasonal temperature patterns. Temperature data were also extracted from two inland water bodies and the coastal ocean (Figure 5) for comparison to estuarine characteristics. The temperature of the estuary as a whole was defined as the mean of the combination of all of the Narragansett Bay Study areas.

Surface temperature signals were produced by extracting the mean temperature from each study area and calculating its temperature anomaly from the Narragansett Bay mean for each scene ([regional mean] - [Narr. Bay mean]). Correlation coefficients among each of the normalized seasonal temperature signals were used as a means for classifying the estuary in terms of its thermal properties.

Unsupervised Classification of Narragansett Bay

The regional approach discussed above incorporated knowledge of the estuary's morphology and circulation patterns to define study areas such that thermal properties could be related to known physical characteristics, i.e. depth, area, and volume relationships, and tidal and fresh water flushing. This breakdown was well-suited for gaining an understanding of the seasonal thermal behavior of different areas of the bay, and comparing them to one another in the context of their physical characteristics. However, in treating the estuary as twelve large areas, each with a mean temperature, we fail to maximize the advantages provided by the spatial extent and resolution of remotely sensed data. The large number of data points does give us great confidence that the mean temperature is an accurate representation of the study area, but the process of assigning one value to each pre-defined area may prevent us from observing some important patterns within the data. By pre-defining the study areas, we assume that each of these areas behaves as one fairly cohesive system, and that this set of study areas is somewhat representative of temperature variations within the estuary. These assumptions are valid in the context of a comparison of the properties of different areas, but another technique was employed to obtain a more complete view of the estuary's temperature dynamics.

Unsupervised classification, a more objective method, was used to extract the natural patterns within the data. In this approach, the data determined which areas could be treated as cohesive systems. Instead of comparing the seasonal temperature signals of individual study areas, the signals (or vectors) of each pixel were compared and statistically categorized into classes, thereby dividing the estuary into natural groupings based upon seasonal temperature patterns.

Classification is a technique used to separate image data into categories with similar spectral (or in this case, temporal) signatures. In an *unsupervised* classification, the initial characteristics of each class (expressed as a vector, which describes the values of a pixel in all bands, or times, in n-dimensional space) are chosen randomly, and then redefined as the classes are formed. Each pixel is placed into the class to which its vector is most similar, and once all of the pixels are classified, a new class vector is defined as the mean vector of all of the pixels in the class. The image is then reclassified, mean vectors recalculated, and the process continues until no significant change occurs between classifications.

Unsupervised classification provides the distinct advantage of objectivity, while allowing some control over the character of the results. The optimum, minimum, and maximum number of classes desired, the maximum allowable variance within a class, and the minimum size for a class were all input to shape the analysis. By defining these constraints and a set of computational parameters, the splitting and merging of classes was controlled without making any assumptions about the specific character of each class.

Eight scenes were selected from the fourteen scenes used in this study to perform an unsupervised classification of temperature data. All scenes with any indication of atmospheric interference were removed from the initial set of fourteen, and a seasonal spread was selected from those remaining. It was only possible to classify eight scenes at a time, and from the eight selected, 920101 was eventually removed because strong contrasts within this scene tended to affect the overall classification (i.e. features from this particular scene occasionally appeared as individual classes in the analysis), leaving a set of 7 scenes for the unsupervised analysis.

The water area defined for classification included all of Narragansett Bay and surrounding fresh water bodies, as well as a small part of the coastal ocean (all areas shown in black in figure 11 were not included in the classification). The actual temperature variation within the estuary is very small in comparison to overall seasonal changes, therefore the data were normalized to emphasize seasonal temperature variations relative to the estuary mean. The mean DN value was extracted from the defined classification area for each of the seven scenes (table 3), and the data were normalized using the following formula (which includes adjustments to scale the data within an 8-bit range of 0-255):

$$\text{OUTPUT} = [(\text{INPUT}/\text{MEAN}) - 1] * 500 + 70$$

The optimal number of classes was set at seven (the range from five to eight), with the goal of identifying large scale differences in seasonal temperature patterns. This range was chosen in an attempt to avoid forming a large number of very small classes which would be difficult to interpret, while at the same time allowing for a meaningful breakdown of the expected upper and lower estuarine classes. The classification program (ISOCLUS in PCI [PCI Inc., 1994]) was allowed to generate starting vectors diagonally along the n-dimensional histogram of the entire data set (limited to the classification area). The analysis proceeded by classifying every other pixel (for the purpose of speed) of the normalized ("output") data, then calculating new mean vectors for each group, and classifying again. The program was started off with liberal constraints, allowing the formation of small classes at first and accepting large variability within classes. As the analysis continued, the minimum sample threshold was maximized at 999 and the allowable variance was reduced to a maximum standard deviation of 10 within any one class. These parameters eventually led to the formation of several large cohesive classes, and a few small scattered classes, mainly composed of edge pixels. These extra classes needed to be accepted for the sake of improving the classification of the actual area of interest. When the minimum change threshold was reached, the program converged, and all pixels were classified using the last set of class vectors.

Characterizing the thermal behavior of Mount Hope Bay

Mount Hope Bay is a large, relatively shallow, somewhat tidally restricted bay located in the northeastern reaches of Narragansett Bay (figure 1). The Mount Hope Bay watershed encompasses about 35% of the entire Narragansett Bay watershed [Pilson, 1985], and drains into five rivers: the Taunton, Cole, Lee, Kickamuit, and

Quequechan [Spaulding et al., 1988]. Mean tidal range in the bay is 1.2 m [Chinman and Nixon, 1985] and the bay is relatively well mixed. Significant salinity stratification is limited to the Taunton River area during the spring [Spaulding et al., 1988], and temperature stratification occurs throughout the bay during the spring and summer. Mount Hope Bay receives both industrial and residential effluents from several sources, including the discharge from the Brayton Point Power Station and another smaller power station located on the Taunton River. BPPS discharges about five times the average flow of the Taunton, which is the largest river entering Mount Hope Bay [Spaulding et al., 1988].

The physical characteristics of the twelve study areas were compared in order to place Mount Hope Bay into the context of the larger system. The most important factors which affect thermal behavior are surface area to volume relationships, and tidal and fresh water flushing times. These characteristics are a reflection of the mechanisms by which a particular volume of water gains and loses heat. The surface area to volume ratio is representative of the rate at which heat is gained from the sun and the atmosphere, and radiated from the water, per unit volume. Tidal flushing times represent the speed by which heat exchanges with the rest of the estuary through convective mixing. The fresh water flushing time is a measure of the relative significance of fresh water throughput in the system, which may also constitute a thermal exchange.

Upper Narragansett Bay and Mount Hope Bay are very similar with regard to these three important physical characteristics (Table 2). The two areas are about the same size and their surface area to volume ratios are nearly identical. Upper Narragansett Bay flushing times are slightly faster, but are in the same general range as those for Mount Hope Bay. In a natural system, we would expect that regions with similar physical characteristics would have similar thermal properties, and thus similar seasonal surface temperature signals. This relationship is somewhat complicated by the distribution of heat within each area. However, horizontal gradients can be accounted for by taking a mean surface temperature over the entire area. In addition, we know that the general relationships between surface and bottom temperature for Upper Narragansett Bay and Mount Hope Bay are fairly similar. Both areas become vertically stratified during the spring and summer, and are vertically homogenous during the remaining part of the year [Upper Narragansett Bay (Kremer & Nixon, 1978), Mount Hope Bay (Spaulding, 1988)]. Thus, based upon its similar size, shape, and physical forcing, Upper Narragansett Bay serves as an appropriate area for comparison to Mount Hope Bay and its thermal characteristics.

To investigate the thermal character of Mount Hope Bay and the influence of BPPS on a smaller scale, the bay was divided into segments measured radially from the power plant (Figure 6). Divisions were based upon natural boundaries within the bay. The 2.8 km radius to Spar Island was taken as a natural division because the island can act to stop or divert the flow of water within the bay. The 5.6 km radius encompasses the main body of Mount Hope Bay. These major divisions were divided in half to provide better resolution of the longitudinal gradients within the bay, yielding four equally spaced 1.4 km segments. Segments 5 and 6 extend from the end of the fourth segment to the mouths of Mount Hope Bay. Segment 2 was divided at the mouth of the Taunton River because significant gradients were expected near this location due to the influx of fresh water.

Results

General Seasonal Trends

A visual interpretation of the seasonal composite of thermal infra-red images (figure 7) shows that Narragansett Bay exhibits typical river to ocean thermal gradients which vary seasonally in an intuitive manner (table 4). During the winter, surface temperatures tended to gradate from the very cold upper bay to a more mild ocean. With the onset of spring, the bay warmed more quickly and surface temperatures in the bay exceeded those in the ocean by late March (Figure 8a). Maximum temperatures were reached in the bay and the ocean in mid August, but by late October the bay became colder than the ocean, at which time there was very little spatial variability in ocean surface temperatures. The small lakes surrounding Narragansett Bay had a similar thermal behavior to the upper bay regions, but tended to reach more extreme temperatures. They were significantly warmer than the bay during the summer and cooler during the winter (Figure 8b). Mount Hope Bay was generally one of the warmest regions within the scene during the spring, summer, and fall. From July through September it was the warmest area in the scene, and through November it remained the warmest area of the upper bay.

Regional Classification

The seasonal surface temperature signals of the twelve Narragansett Bay areas relative to the Narragansett Bay mean exhibited three different patterns (Figure 9). The upper estuarine regions were generally warmer than the bay average during the summer, and cooler during the winter, whereas the lower estuarine regions had the opposite behavior, and intermediate regions had damped temperature signals relative to the estuary mean. Correlation coefficients among the 12 seasonal temperature signals provide a statistical basis for the breakdown of the estuary into these three groups (table 5). Significant correlations ($R > 0.6$) existed among the members of each group (although each area was not necessarily correlated with every other area within its group) and only negative or insignificant correlations existed between areas of different groups.

Unsupervised Classification

The selected water area was successfully divided into six different classes, based upon seasonal surface temperature signals (figure 10a). The classes consisted of fresh water lakes, the ocean, the upper estuary, the lower estuary, Greenwich Bay, and Mount Hope Bay. Four additional classes were generated, mainly consisting of edge pixels (between land and water), and are shown in white. These classes were all small and their behavior was probably affected by the presence of land in some of the pixels, so they were not considered in the interpretation.

In general, the fresh water lakes exhibited the strongest seasonal temperature signal relative to the estuary mean: they were very warm during the summer months and very cold during the winter. Greenwich Bay behaved similarly, only to a lesser degree. The upper estuary was the largest class (table 6), and therefore provided the greatest contribution toward the mean value for each scene. Thus, the upper estuary temperature signal relative to the mean was fairly weak. The ocean was significantly warmer than the study area mean during the winter and colder during the summer, as would be expected, and the lower estuary exhibited similar behavior, only to a lesser degree.

Mount Hope Bay

The Mount Hope Bay and Upper Narragansett Bay study areas were both categorized as upper estuarine in the regional classification because they tended to be warmer than the Narragansett Bay mean during the summer and cooler during the winter, as would be expected of any shallow area with limited oceanic influence. Their respective seasonal temperature signals (Figure 9c) were somewhat correlated during the winter months, but Mount Hope Bay failed to cool down at the rate of Upper Narragansett Bay through the fall. T-tests between Upper Narragansett Bay and Mount Hope Bay proved their mean temperatures to be significantly different during the summer-fall period, during which time Mount Hope Bay had a mean temperature 0.8°C warmer than Upper Narragansett Bay. Greenwich Bay, the Providence River, and Upper Narragansett Bay all became cooler than the Narragansett Bay mean by early October, yet Mount Hope Bay was only colder than the bay mean in one January scene.

In the unsupervised classification, Mount Hope Bay exhibited a unique and anomalous seasonal temperature behavior, as it was on average (over these seven scenes) 0.8°C warmer than the rest of the upper estuary. Unlike Greenwich Bay, which was relatively warm during the summer and cold during the winter, or the lower estuary which behaved in an opposite manner, Mount Hope Bay was consistently warm, only dropping below the estuary-wide average in November, at which point it was still warmer than the rest of the upper estuary.

Within Mount Hope Bay, surface temperature generally decreased with distance from the power plant, although this pattern was somewhat complicated by both seasonal and tidal interactions. The entire main body of Mount Hope Bay (sections 1-4) was warmer than Upper Narragansett Bay, except in January, and all of Mount Hope Bay (sections 1-5) was warmer than the Narragansett Bay mean, except in January (figure 11). During January, when water entering Mount Hope Bay from the estuary was warmer than water within the bay, temperatures in the lower bay (furthest from the plant) were relatively high. These high temperatures were independent of the temperature gradient related to the power plant. Excluding the January scene (920101), the temperature pattern with distance from the plant was a function of tidal stage (figure 12). During slack flood tide, a pool of warm water was located in the upper bay near the plant. During the ebbing tide, this warm water pool moved down the bay, and dissipated by around the time of maximum ebb tide velocity (~50%). During the slowing ebb tide, warm water built up in the upper bay again, and spread throughout the bay by the time of slack ebb tide. The incoming flood tide dissipated the heat in the lower bay and eventually isolated another warm water pool in the upper bay.

Discussion

The general patterns observed in the seasonal temperature signals of the classes identified by both the regional and unsupervised classification analyses are intuitive. We expect the estuary to lose more heat proportionately than the ocean during the winter, and to gain more heat during the summer, because it is a shallow system. Likewise, the lakes should become even warmer during the summer and colder during the winter. The ocean temperature is more moderate, and although the coastal ocean experiences overall warming during the summer and cooling during the winter, it does so to a lesser extent than the shallow estuary, and is thus cool in comparison during the summer, and warm during the winter.

Regional Classification

The seasonal temperature signals of the twelve pre-defined study areas provide the opportunity to relate thermal properties to the known physical characteristics of each area. In the lower estuary, the lower East Passage and Lower West Passage exhibited the most extreme thermal behavior relative to the Narragansett Bay mean, as they are most influenced by oceanic water. The strength of oceanic influence in the East Passage is reflected by the facts that the entire East Passage was classified as lower estuarine and that the lower East Passage exhibited the strongest "oceanic" signal (figure 9e). It is known that on a rising tide, most of the oceanic water enters the estuary through the East Passage, which is the deepest part of the system. The Upper West Passage and Upper Sakonnet River formed a transitional group, characterized as a zone of mixing between waters which are more influenced by shallow water processes and those which are more tidally influenced. The relative temperature of the transitional area seemed to fluctuate as a function of both tidal stage and season, but the temperatures in this region were usually close to the mean temperature of the estuary.

The character of the regions within the upper estuarine group were more strongly dependent upon the varying physical characteristics among the areas. Surface area to volume relationships, tidal and fresh water flushing, and distance from the ocean are all factors in determining the thermal properties of upper estuarine areas. High tidal flushing rates would tend to dampen the seasonal surface temperature signal of an upper estuarine area because of the increased influence of tidal waters with more moderate temperatures. A high surface area to volume ratio, on the other hand, would tend to strengthen the seasonal surface temperature signal of an upper estuarine area, as the volume would tend to gain more heat during the summer and lose more heat during the winter. Increased fresh water input would theoretically have a similar effect, as fresh water runoff is usually closer to air temperature than a large body of water (the temperature of groundwater may be more complex). Thus, runoff would ideally deliver warmer water during the summer and colder water during the winter, increasing the intensity of the seasonal temperature signal.

The upper estuarine regions have distinctly different physical characteristics which are reflected in their seasonal temperature signals. Greenwich Bay is a shallow open area with a high tidal flushing rate and low fresh water input; its seasonal temperature signal was fairly extreme in comparison to the other upper estuarine areas. Greenwich Bay's high surface area to volume relationship is the most important factor determining its thermal behavior, as its low fresh water input and high tidal flushing rate would tend to dampen its seasonal temperature signal. The other three upper estuarine areas all have smaller surface area to volume ratios and weaker seasonal temperature signals. In comparison, the fresh water lakes, which are shallow and isolated, have even stronger signals than Greenwich Bay. These relationships suggest that depth is the most important factor in determining thermal characteristics in the upper estuary.

Unsupervised classification

In a general sense, the regional and unsupervised classifications detected very similar patterns within the estuary. Although slight inconsistencies in the results may be attributed to sub-sampling of the data set used in the unsupervised classification (7 scenes), the major distinction between the two methods is that they provide different types of information. The regional approach facilitates comparisons among different areas and their physical characteristics, and the unsupervised approach gives us a sense of where the natural boundaries occur among regions which exhibit different seasonal temperature patterns. In the lower estuary, the same patterns were detected by both techniques. In the unsupervised classification, the lower estuary again exhibited oceanic behavior, which was somewhat damped by mixing with estuarine waters. This lower estuary class can be viewed as an indicator of the location of the boundary between waters dominated by the ocean and those dominated by shallow water processes. Oceanic influence extended furthest into the East Passage, consistent with the regional classification and general knowledge of circulation patterns in Narragansett Bay. The mid and upper regions of the West Passage and the Sakonnet River were again less influenced by the ocean.

Patterns detected in the mid to upper estuary were somewhat different between the two classifications. North of the lower estuary, the unsupervised classification divided the bay into three classes, the upper estuary, which had a fairly damped seasonal temperature signal, and Greenwich Bay and Mount Hope Bay, each with their own signals. In this case, the upper estuary was essentially the transitional region because of its damped signal. The unsupervised technique then resolved the distinct characteristics of two unique areas within the upper estuary which were not detectable in the regional classification. (The subjective definition of the Greenwich Bay and Mount Hope Bay study areas in the regional classification may have caused their signals to be diluted to the extent that their individual characteristics were not statistically distinct.) The unique behavior of Greenwich Bay was not a surprise, because the area is very shallow, and therefore warms and cools more quickly and extensively than deeper parts of the estuary. The upper reaches of the Taunton and Providence Rivers behaved in a similar manner. The fact that Mount Hope Bay comprises its own unique class, however, can not be explained by simple physical characteristics.

Mount Hope Bay

The most striking behavior among the four upper estuarine signals in the regional classification is that Mount Hope Bay fails to cool from mid-summer through autumn in comparison to the Narragansett Bay mean (figure 9c). Relative cooling during the fall and warming during the spring are characteristic of upper estuarine waters. The fact that Mount Hope Bay deviates from this pattern confirms that an unnatural force is involved, and one that seems to have differential seasonal impacts. The anomalously warm temperatures in Mount Hope Bay during the summer and fall cannot be explained by simple physical characteristics. If anything, Mount Hope Bay's slightly slower tidal flushing rate in comparison to the other upper estuarine areas would theoretically cause a stronger cooling affect during the fall.

The unique behavior of Mount Hope Bay is highlighted by the fact that the bay comprises it's own class in the unsupervised classification. Mount Hope Bay is not distinctively shallow or isolated from tidal waters, in fact it has very similar physical characteristics to the rest of upper Narragansett Bay. In addition, there are no natural physical parameters which would cause a water body to remain anomalously warm year-round. All of the other classes tended to warm and cool throughout the year relative to the study area mean (figure 10b). Each area which warmed significantly during the summer, cooled to a similar extent during the winter, and vice versa. Seasonal temperature patterns are a direct result of heat exchange at the surface, and with oceanic tidal waters. Both processes are seasonal in nature, such that heat is gained through the surface during the summer (lost during the winter), and gained from relatively warm tidal waters during the winter (lost during the summer). The seasonal temperature signal of a particular area is a direct reflection of the balance between these processes, which is a function of tidal flushing rates, proximity to the ocean, and surface area to volume relationships. The upper estuary reflects a fairly level balance of these processes measured relative to the study area mean. Mount Hope Bay, however, exhibits constant warming throughout the year. We could explain summer warming by pointing out that the bay is somewhat shallow, and could potentially warm more quickly and extensively during the summer than other areas of the bay. However, this hypothesis infers that the bay should also lose proportionately more heat during the winter, and we do not see this in the data. Alternatively, we could explain relatively warm temperatures during the winter with a potentially large tidal influence, but this would similarly lead to cooler temperatures during the summer. Again, there is no evidence to support this hypothesis through either our understanding of the physical character of the bay or our interpretation of the temperature data.

The simplest and most likely explanation for the relatively warm year-round temperatures in Mount Hope Bay is the constant discharge of thermal effluent into the bay by the Brayton Point Power Station. The excess heat load is the only plausible explanation for the consistently warm temperatures in the bay. The extent of the Mount Hope Bay class (magenta in figure 10a), is an indication of the boundaries of the area which was consistently affected by constant warming. The anomalous area extended about six kilometers up the Taunton River (temperatures here may also be affected by another small power plant located on the Taunton River), and covered most of Mount Hope Bay, excluding a fraction of the lower lobes of the bay. The spatial extent of the anomalous Mount Hope Bay class suggests that the thermal effluent from the plant has large scale affects on Mount Hope Bay as a whole. On average, from the seven scenes used in the unsupervised classification, Mount Hope Bay was 0.8°C warmer than the upper estuarine class. Although this may not seem like a large temperature difference, major alterations to the system's heat budget are required to create an anomaly with the spatial extent and temporal consistency of this feature.

The seasonal trends in the Mount Hope Bay anomaly were similar for the regional and unsupervised techniques (figure 13). In both cases, Mount Hope Bay was most anomalously warm during the late summer, the same time during which the volume and temperature of effluent from the plant reach maximum levels [NEP, 1997]. In the regional approach, we postulated that the thermal properties of Mount Hope Bay and Upper Narragansett Bay should be the same because the two areas have similar shapes and flushing rates. Therefore, differences in the seasonal temperature signals of the two areas were attributed to the operations of the Brayton Point Power Plant. Sen [1997] has identified a relationship between the heat output from the plant and the magnitude of the Mount Hope Bay-Upper Narragansett Bay temperature anomaly during the warmer months of the year. The unsupervised classification strengthens this argument because it identified Mount Hope Bay as a unique system, which was always warmer than the rest of the upper estuary, regardless of the season. This evidence supporting anomalous behavior is not dependent upon a relationship between thermal and physical characteristics, but stands on its own--Mount Hope Bay had a statistically different seasonal thermal behavior than the rest of the upper estuary and was on average 0.8 °C warmer.

Unsupervised classification also facilitated the recognition of smaller scale patterns which were averaged out by the regional approach. For example, there was an identifiable trace of the “Mount Hope Bay” class in the upper Providence River, near the location of the Manchester Street Power Plant (figure 10a). Although the thermal affects of this plant were not as visible in the satellite images as the plume from the larger Brayton Point Station in Mount Hope Bay, the fact that water in the upper Providence River exhibited similar seasonal behavior to that of Mount Hope Bay (the temperature of which is known to be driven by the influence of thermal effluent) suggests that the Manchester St. Plant may after all have an identifiable effect on the thermal properties of adjacent waters. This potential effect does however occur on a much smaller scale than the apparent influence of BPPS on Mount Hope Bay.

The almost year-round persistence of a decreasing temperature gradient with distance from the Brayton Point Power Station in Mount Hope Bay suggests that the plant's thermal effluent constantly drives the distribution of heat within the bay (excluding January 1, the only scene in which Mount Hope Bay was actually colder than the estuary mean). The down-bay extent of the warm water (water with a temperature greater than Mt. Hope Bay mean) water was mainly a function of tidal stage. (These dynamics are explored in more detail by Sen [1997].) The persistent temperature gradient and the extent of the Mount Hope Bay class in the unsupervised classification both suggest that the influence of the plant's thermal effluent is widespread throughout the bay, and is not an isolated feature.

There has been some postulation that the location of the heated water within Mount Hope Bay may be a function of seasonally variable density gradients, such that under certain conditions, the plume is not entirely visible from the surface [Prell & Mustard, pers. comm.]. The upper bay is generally stratified in terms of salinity, and because cooling water is taken in from depth, it is more saline than surface water. During the summer, heating keeps the plume water sufficiently buoyant and a distinct plume is usually visible from the surface. However, in colder temperatures during the winter, the relationships among temperature, salinity and density are slightly different, and high salinity could potentially cause the plume to sink. A preliminary assessment of long-term temperature records [MRI, 1972-92] suggests that bottom temperatures near the plant significantly increased following the BPPS alterations in 1985. These vertical temperature dynamics have important implications in terms of the biological impacts of the thermal effluent because winter flounder (one of the fisheries of greatest concern) breed during the colder months and in the bottom waters of Mount Hope Bay. It is therefore vital to obtain a detailed understanding of the vertical distribution of heat within the bay, especially as it varies as a function of season, to compliment our observations of the heat distribution from the surface.

The detailed description of large-scale seasonal dynamics in Mount Hope Bay provided here sheds light on the previously uncertain influence of the Brayton Point Power Station on the thermal characteristics of Mount Hope Bay. An understanding of the thermal processes at work is but one component of a solution to the problem of depleted fisheries in the bay. Although it is fairly well-accepted that the decline in fisheries was in some way linked to the 1985 changes in the operations of the plant, there are numerous mechanisms by which the plant could impact fish populations, including impingement, entrainment, chlorination, and depletion of dissolved oxygen, as well as temperature effects. Therefore, in addition to a description of the physical character of Mount Hope bay, a more detailed picture of the bay's ecosystem dynamics is vital to the full consideration of this issue. A comprehensive understanding of the system as a whole will allow for more informed decision-making in the re-evaluation of Brayton Point's discharge permit in 1998.

Conclusions

The widespread coverage and fine-scale resolution of remotely sensed thermal data have provided us with an invaluable understanding of seasonal and spatial temperature dynamics in Narragansett Bay, and specifically allowed us to quantify the anomalous behavior of Mount Hope Bay. These questions could not have been adequately addressed by conventional methods or *in situ* data. Both approaches used to classify Narragansett Bay in terms of seasonal temperature behavior resulted in similar descriptions of the estuary's thermal properties, which included the intuitive characteristic behavior of the ocean, the lower estuary, the upper estuary, and the inland water bodies. Pre-defined study areas allowed us to consider the thermal properties of each area in the context of its physical character, emphasizing the importance of surface area to volume relationships in the upper estuary, and circulation patterns in the lower estuary. The unsupervised classification provided a better sense of the natural functioning of the system, identifying boundaries among areas with different seasonal temperature signals. Mount Hope Bay behaved anomalously in the context of both analyses, and was particularly warm during late summer months, corresponding to the time of maximum heat output from the plant.

Acknowledgments

Numerous thanks to Jack Mustard for the opportunity to participate in this project, and for all of his ideas, input, and support throughout the year. Thanks to Steve Hamburg for his blind confidence that I'd somehow pull this off, almost on time. And lastly thanks to Avijit Sen for his patience in teaching me all the basics, for sharing all of his data and knowledge, for his (usually) constant optimism, and mostly for being almost as insane as I am--400 trips to Dunkin Donuts later--we did it man!

References

Avery, T.E. & G.L. Berlin. 1992. Fundamentals of Remote Sensing and Airphoto Interpretation, 5th Ed. Prentice Hall: Upper Saddle River, NJ.

Bowden, K.F. 1983. Physical Oceanography of Coastal Waters. Ellis Horwood Limited: New York.

Buckley, L.J., A.S. Smigielski, T.A. Halavik, E.M. Caldarone, B.R. Burns, G.C. Laurence. 1992. Winter Flounder Reproductive Success. Narragansett Bay Project Report 92-82.

Chinman, R.A. & S.W. Nixon. 1985. Depth-Area-Volume Relationships in Narragansett Bay. Graduate School of Oceanography, the University of Rhode Island. NOAA/Sea Grant Marine Technical Report 87.

Dixon, A.M., C. Karp, C. Penniman. 1991. Mount Hope Bay Briefing Paper and Proceedings from Narragansett Bay Project Management Committee. Narragansett Bay Project Report 91-65.

Gibbons, D.E., G.E. Wukelic, J.P. Leighton, & M.J. Doyle. 1989. Application of Landsat Thematic Mapper Data for Coastal Thermal Plume Analysis at Diablo Canyon. Photogrammetric Engineering and Remote Sensing, 55(3): 903-909.

Gibson, M.R. 1996. Comparison of Trends in the Finfish Assemblage of Mt. Hope Bay and Narragansett Bay in Relation to Operations at the New England Power Brayton Point Station. RI Division Fish and Wildlife Research Reference Document 995/1.

Gray, C.L. 1991. Winter Flounder Speicies Profile. Narragansett Bay Project Report 91-56.

Kremer, J.N. & S.W. Nixon. 1978. A Coastal Marine Ecosystem. New York: Springer-Verlag Berlin Heidelberg.

Marine Research Inc. 1972-1992. Brayton Point Quarterly Progress Reports 1972-1992. Marine Research Inc.: Falmouth, MA.

Mustard, J. Brown University Department of Geological Sciences. personal communication.

New England Power, 1997. Hourly discharge records for the Brayton Point Power Station.

PCI, Inc. 1994. Using PCI Software. PCI, Inc.: Ontario.

Paine, R.T. 1993. A Salty and Salutary Perspective on Global Change. In: Biotic Interactinos and Global Change. P.M. Kareiva, J.G. Kingsolver, & R.B Huey, eds. Sinauer Assoc.: Sunderland, MA.

Parker, P.E. 1996. Mass. Power Plant Linked to Fish Decline. The Providence Journal-Bulletin, October 22, 1996.

Pickard, G.L. and W.J. Emery. 1990. Descriptive Physical Oceanography. Pergamon Press: New York.

Pilson, M.E.Q. 1985. On the Residence Time of Water in Narragansett Bay. Estuaries V8 #1:2-14.

Prell, W. Brown University Department of Geological Sciences. personal communication.

Ries, K.G. 1990. Estimating Surface-water Runoff to Narragansett Bay, RI and MA. USGS Water Resouces Investigations Report 89-4164.

Schmidt-Nielsen, K. 1990. Animal Physiology: Adaptation and Environment. Cambridge University Press: New York.

Schneider, K & W. Mauser. 1996. Processing and Accuracy of Landsat Thematic Mapper Data for Lake Surface Temperature Measurement. Int. J. Remote Sensing, 17(7): 2027-2041.

Sen, A. 1996. Characterization of Water Temperature in Mount Hope Bay in the Influence of Thermal Discharge from the Brayton Point Power Plant. Sc.B. Thesis, Center for Environmental Studies, Brown University.

Sen, A. 1997. A Satellite-Based Assessment of a Power Plant's Impacts on an Estuary. M.A. Thesis, Center for Environmental Studies, Brown University.

Spaulding, M.L., F.M. White, P. Heinmiller, M.M. Simoneau, S.J. Liang, and J.K. Choi. 1988. Circulation Dynamics in Mount Hope Bay and the Lower Taunton River. Narragansett Bay Project Report 88-12.

Tissot, B.N., J. Lubchenco, & S. Navarrette. 1991. Effects of global Warming on Coastal Marine Ecosystems: Implications of thermal discharge studies. Bull. Ecol. Soc. Am. 72:268.

Wyss, R. 1996a. EPA Pulls Brayton Point Permit. The Providence Journal-Bulletin, October 23, 1996.

Wyss, R. 1996b. Power Plant Agrees to Cut Water Use. The Providence Journal-Bulletin, April 4, 1997.

Valiela, I. 1995. Marine Ecological Processes. Springer: New York.