ON THE SEASONAL DISTRIBUTION OF TEMPERATURE AND SALINITY IN RHODE ISLAND SOUND[1]

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ABSTRACT

The temperature and salinity of Rhode Island Sound were measured between July 1963 and July 1964. A seasonal thermocline developed at middepth in spring and intensified through August. Early fall cooling and wind mixing rapidly destroyed the thermocline, rendering the water column practically isothermal by late October. The salinity patterns are more complex than those of temperature and are strongly influenced by seasonal variations in coastal runoff. Brackish water outflow from Narragansett Bay was traced as a salinity wedge as far as 20–30 km from the coast. The seasonal variation in thermal energy of the sound is estimated to be at least four orders of magnitude greater than the potential energy changes.

INTRODUCTION

Although Rhode Island Sound is an important commercial and sports fishing area and is used for operations and acoustic research by the Navy at Newport, little oceanographic information about it is available. Seasonal studies of adjacent bodies of water have been reported by Riley (1952) and Anraku (1964).

From July 1963 to July 1964, oceanographic surveys were made along two parallel transects in Rhode Island Sound, using RV *YF*-287 of the Naval Underwater Weapons Research and Engineering Station. Shonting, Cook, and Wyatt (1966) reported data for salinity, temperature, sigma-*t* density, and sound velocity. This paper discusses the observed variations in temperature and salinity with reference to the seasonal changes in solar radiation, air temperature, and wind mixing and the advective effects of freshwater runoff. Estimates are also made of the seasonal changes in the sensible heat and potential energy of the water column.

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GEOGRAPHIC FEATURES OF RHODE ISLAND SOUND

Rhode Island Sound (Fig. 1) is a semicircular embayment having an area over 1,530 km^2 (assuming an arbitrary southern boundary along 41° N lat) off the southern Rhode Island and Massachusetts coast. It is partially bounded on the west by Point Judith and Block Island and on the east by Martha's Vineyard and the Elizabeth Islands. Its water is in free exchange with that of Block Island Sound to the west, Narragansett Bay and the Sakonnet River to the north, Buzzards Bay and Vineyard Sound to the east, and the open Atlantic continental shelf to the south.

The sound has a relatively smooth bottom, sloping gently to the south. It contains several small hills (5–10 m high), vestiges of the terminal moraine which forms an extension of Cape Cod traceable from the Elizabeth Islands to Block Island. The average depth of the sound is about 31 m with a maximum depth of 60 m.

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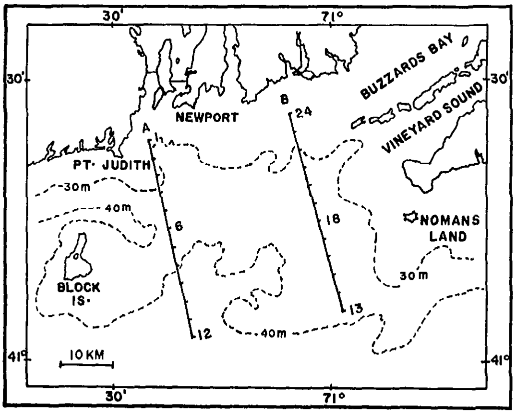

FIG. 1. Location of hydrographic stations in Rhode Island Sound.

CIRCULATION

The semidiurnal tides in the sound have a mean range of about 1 m (U.S. Coast and Geodetic Survey 1968). The tidal currents have a dominant oscillatory component in a NW–SE direction, but display strong variability probably associated with large-scale turbulence induced by wind stress and flow around shoals and islands (Shonting 1966 and unpublished).

Drift bottle and seabed drifter observations in the sound (Cook 1966) have indicated that, during spring, the nontidal surface drift is east and northwest, whereas the bottom drift is northwest except for a strong west component between Point Judith and Block Island. In summer, surface drift is mostly north with shifting east and west components, while bottom drift tends northwest. During autumn and winter, surface drift is generally south, whereas bottom drift is north. Mean yearly drift rates in the surface layer are from 2–14 km day^{-1} (2–16 cm sec^{-1}), and the bottom drift rates are from 0.1–3 km day^{-1} (0.1–3.0 cm sec^{-1}).

HYDROGRAPHIC OBSERVATIONS

Cruises were made on 24 July, 20 August, and 2 October 1963 and on 22 January, 31 March, 3 June, and 8 July 1964. Each transect consisted of 12 stations located 3 km apart (Fig. 1). However, on 31 March 1964 only 9 stations of transect A were occupied, and stations along transect B were occupied only during the first 4 surveys. The seasonal data from transect B, when obtained, were similar to those of transect A. The following discussion concentrates on the analysis of transect A sections unless otherwise noted.

Each station consisted of serial sampling of temperature and salinity from 1 m below the surface to the bottom at 4-m intervals, using Nansen bottles and protected reversing thermometers. Salinities were measured with an inductance salinometer.

SEASONAL DISTRIBUTION OF VARIABLES

Temperature

In late July 1963, the seasonal thermocline was well defined south of station 6 and sloped upward and intensified seaward (Fig. 2A), strongly isolating the warm surface water (19–20C) from the cold bottom water (less than 10C) intruding from the open ocean. The strongest vertical temperature gradient occurred between stations 9 and 12 (about 1C m^{-1}). The nearshore weakening of the thermocline could be associated with mixing by the strong tidal currents near the entrance to Narragansett Bay.

In late August the thermocline had deepened slightly (Fig. 2B) and was better defined nearshore; it sloped upward to seaward as in July. Mixing after the decrease of solar heating had resulted in a thicker and cooler mixed layer and slight warming of the bottom water. This late summer warming of shelf bottom water has been observed by Ketchum and Corwin (1964).

Between 29 August and 2 October (Fig. 2B, C), extreme convective mixing (overturn) occurred throughout the water column, virtually eliminating the thermocline. [It should be noted that transect B (Fig. 1), made on the same August and October cruises, showed this same abrupt convective overturn, indicating that it was widespread throughout the sound.]

In January and March (Fig. 2D, E), the coldest isothermal water occurred. From late March to early June 1964 (Fig. 2F), the sound gradually warmed from the sur-

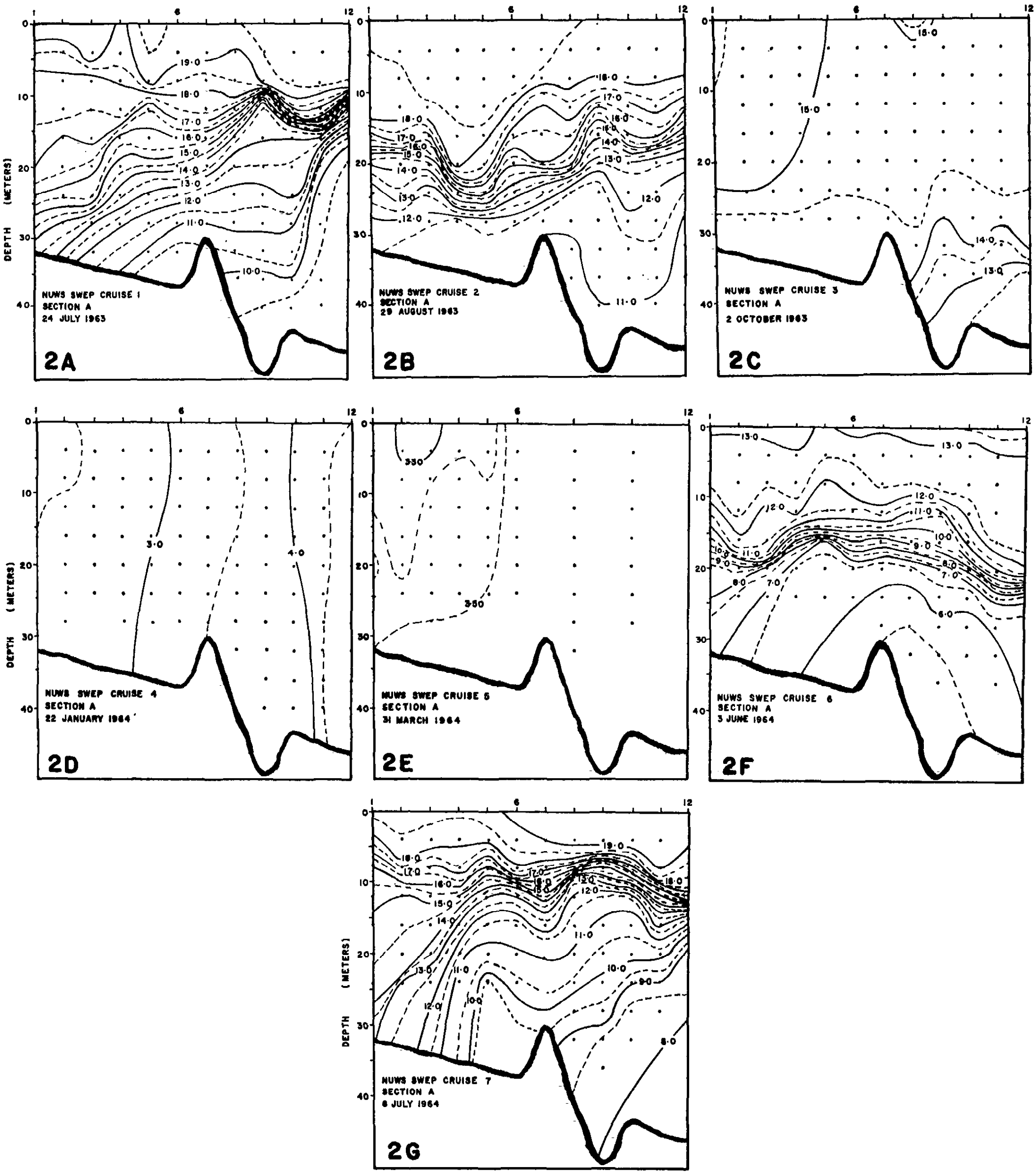

FIG. 2. Temperature sections (dots indicate actual sampling depths).

face. The seasonal thermocline gradually intensified, which tended to insulate the cold bottom water. Even in June this water was only 1.5–2.5C warmer than in mid-winter. The July 1964 section (Fig. 2G) shows that the intensifying thermocline strongly resembled that of the July 1963 section, indicating that the cycle of gross thermal structure variations was completed.

Salinity

The salinity profiles (Fig. 3) exhibit a more complex geometry than the temperature profiles, making it difficult to contour

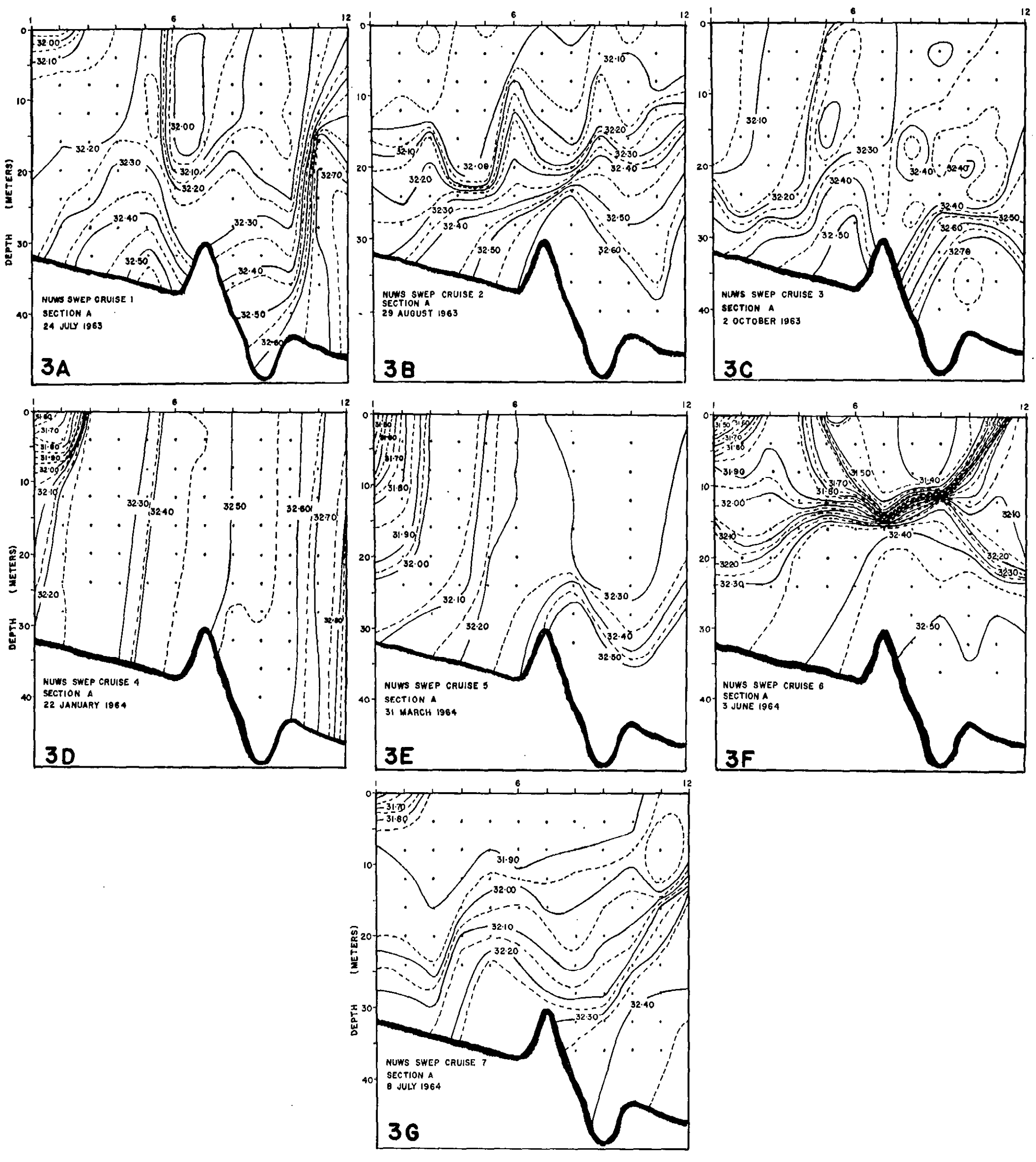

FIG. 3. Salinity sections.

the station data and subsequently interpret the isohalines.

Two relatively strong horizontal salinity gradients occurred near the surface at station 6 and between 15 and 30 m at station 11 in July 1963 (Fig. 3A). The freshest water, as would be expected, was near or at the surface around stations 1 and 2 (nearest to the entrance of Narragansett Bay), the most saline water near the bottom around the southernmost stations. This, in general, was always the situation for the salinity sections.

By late August (Fig. 3B), a moderately strong halocline was similarly aligned with the corresponding seaward up-sloping isotherms (Fig. 2B). Relatively isohaline shelf water was intruding from the south.

On 2 October 1963 (Fig. 3C), the brackish water intruded from the north at all depths. The strong mixing portrayed in the October temperature section (Fig. 2C) was, to a lesser degree, reflected by the salinity. (Note the similarity of the 15.0C and 14.0C isotherms with 32.20‰ and 32.50‰ isohalines, respectively.) However, the presence of anomalous patches between stations 5 and 11 and the differences between the slopes of the isotherms and isohalines indicate that the salt was not as well mixed as the heat.

The midwinter and late-winter water column (Fig. 3D, E) was strongly mixed vertically, and the vertical and horizontal salinity gradients were then primarily associated with the brackish water intrusion from Narragansett Bay. An intense halocline was seen in early June (Fig. 3F), with it occurred the strongest vertical salinity gradient observed throughout the year at station 7 (approaching 0.25‰ m^{-1}).

The July 1964 section also shows a tilting isohaline distribution somewhat similar to that observed in July 1963, but there is no evidence of an anomalous intrusion near stations 5 and 6.

All salinity sections clearly show the interplay of the brackish water outflow from the Narragansett Bay passages with the more saline shelf water. During the warm months, with the presence of a thermocline, the brackish water tended to flow as a near surface wedge pattern to the south. In the cold months (October–March), the instability of the water column caused a rapid vertical mixing of the brackish surface flow, resulting in the formation of a mean horizontal salinity gradient delineated by the vertical isohalines.

Anomalous patches or cores of high or low salinity (Fig. 3A, C) appeared along with abrupt horizontal variations in salinity, indicating quasi-discontinuities or fronts (Fig. 3A, F). Such complicated patterns did not appear in the seasonal isotherm structure. These anomalies could be caused by tidally driven "pulsed" outflow of brackish water from Narragansett Bay. If the average tide speed in the bay between slack water is 20 cm sec^{-1}, the displacement would be about 4.3 km per half cycle. This effect could produce spatially oscillatory isohalines along the section (Fig. 3B). Also, since during summer the mean current along the coast flows westward (Cook 1966), the anomalous salinity effects could be associated with salinity patches as reported by Riley (1952) normal to the section (Fig. 3A, C), that is, moving parallel to the coast.

*Density (sigma-*t*)*

The seasonal density (sigma-*t*) distribution was largely governed by temperature except when the water was isothermal during late winter. Comparison of the June and July 1964 sections (Fig. 4F, G) with the corresponding temperature and salinity sections shows the strong controlling influence of temperature once the strong vertical temperature gradients were formed. On the other hand, for March 1964 the temperature over the whole section was within 0.2C, whereas the salinity ranged from 31.48‰ at station 1 to 32.50‰ near the bottom at stations 7–12. The corresponding sigma-*t* distribution was controlled in this instance by the salinity gradients.

THE SENSIBLE HEAT CONTENT

The temperature sections were used to estimate seasonal variation of the sensible (calorific) heat content in the sound. The mean temperature of the water column for each station was computed, weighted according to the depth of each station and averaged for the section (Fig. 5). The relative mean heat content is equivalent to the numerical value of the averaged temperature, since the heat content was defined to be zero cal cm^{-3} at 0C.

The mean heat content, ranging from 15.1 cal cm^{-3} in late August to 3.4 cal cm^{-3} in late January, is comparable to that of the Baltic Sea, which has a variation of about 9.5 cal cm^{-3} for the same period (Defant 1961). The maximum value of 14–15 cal cm^{-3} occurred from July through early October, decreased rapidly through November and December, and attained the

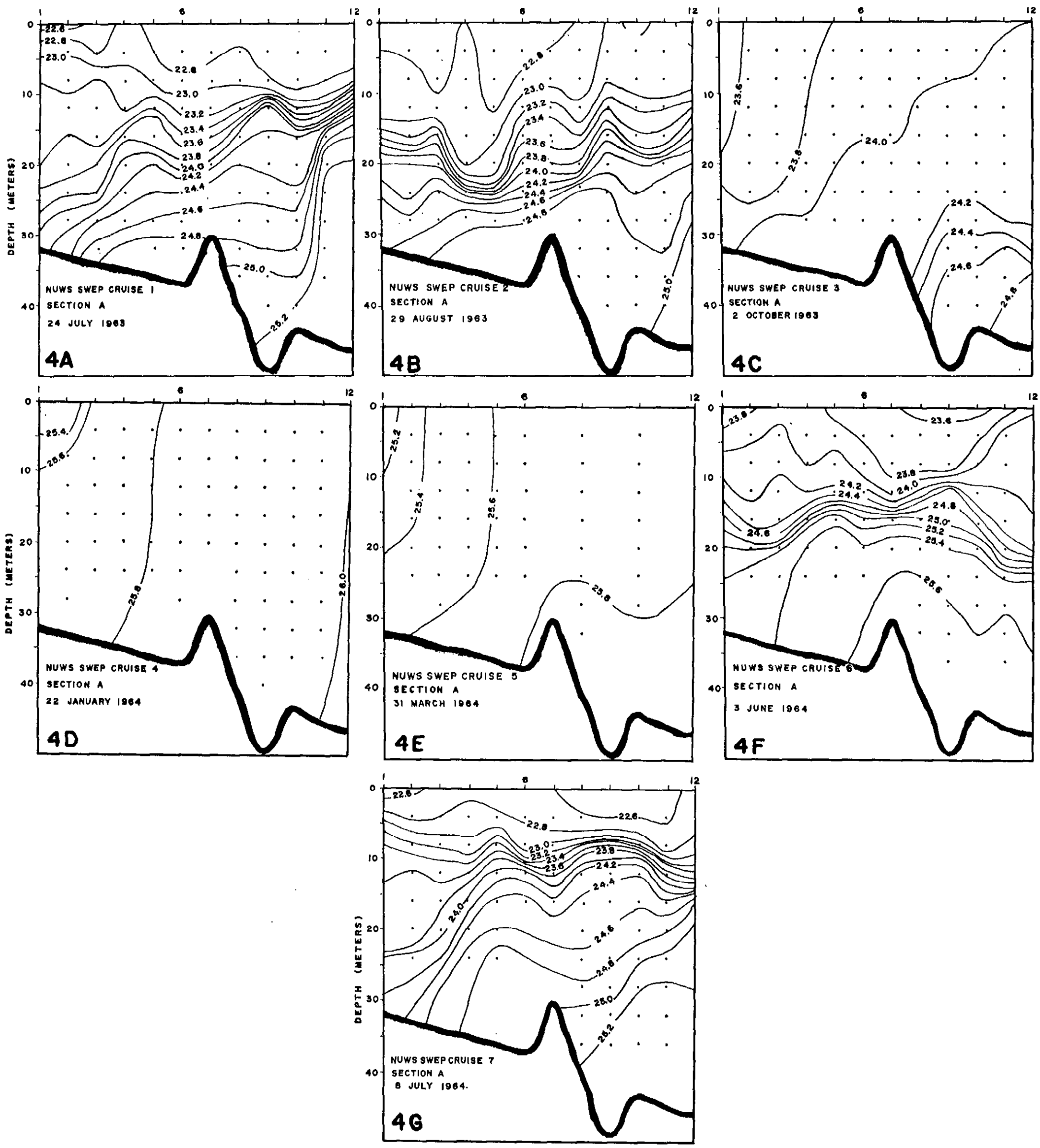

FIG. 4. Sigma-*t* sections calculated from temperature and salinity data.

minimum value (3.5 cal cm^{-3}) in January. Spring heating began in late March; from 31 March to 8 July (100 days) it averaged 0.093 cal cm^{-3} day^{-1}.

The values of Ketchum and Corwin (1964) for the rate of heat accumulation (to a depth of 60 m) of the shelf water south-southeast of Montauk Point, Long Island, during spring 1957, 1958, and 1959 are 0.070, 0.049 and 0.052 cal cm^{-3} day^{-1}. Thus there is a higher spring heat accumulation in Rhode Island Sound than for the general continental shelf. This could be caused by two factors. First, the average depth of transect A was 36 m, whereas the shelf stations averaged 77 m. Vertical mixing would tend to distribute the added heat content over the entire depth, pro-

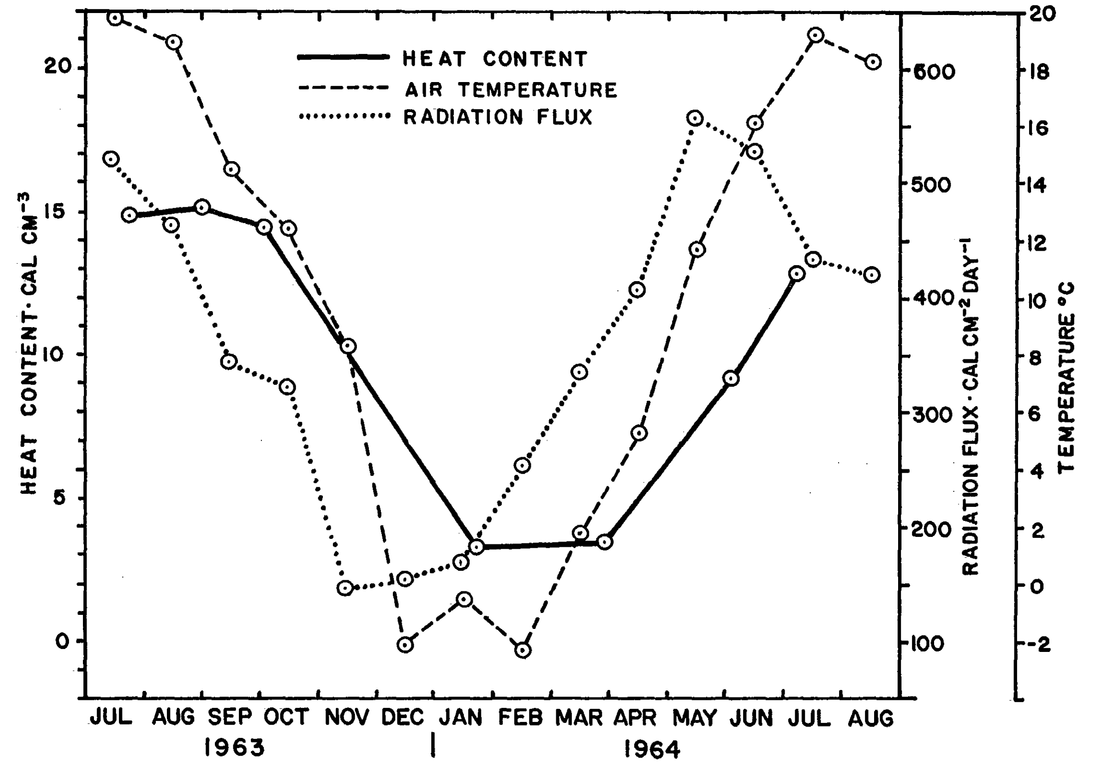

FIG. 5. The calculated heat content of Rhode Island Sound, mean air temperature from Block Island (U.S. Weather Bureau 1965) and radiation flux recorded at Newport (Eppley Laboratories, Inc., unpublished).

ducing a lower heating rate per unit volume than for Rhode Island Sound. Second, the difference could be due to the variable horizontal advection of colder or warmer waters from adjacent regions (e.g., Gulf Stream water from the southeast).

The 12-month radiation curve (Fig. 5) leads the air temperature curve by 15–20 days and the sensible heat curve by 50–70 days. These differences in lag times reflect the much faster thermal response of air. Also, advective changes contribute to the seasonal variation in water temperature as well as local radiation and cooling phenomena.

The seasonal variation of the mean sensible heat content was calculated for individual layers 4 m thick (Fig. 6). The large variation in vertical heat distribution in the warm months and the uniform heat distribution during wintertime is clearly shown. From July to August 1963, the 0–4-m layer, which is most sensitive to the advent of seasonal cooling after the summer solstice, displayed some cooling, whereas the layers below were still being warmed. From 29 August through 2 October, the cooling effects reached deeper into the 4–8-m layer. The 8–12-m layer remained constant while the deeper layers were still warming.

The onset of strong fall surface cooling then proceeded rapidly, rendering the water column unstable. Further cooling proceeded quasi-continuously, and the isothermal regime was preserved through winter. The water column probably reached a minimum temperature of about 2C by late February and, while remaining isothermal, began to warm, reaching 3.6C by late March. Post-March heating was accelerated and the heat absorption pattern of the

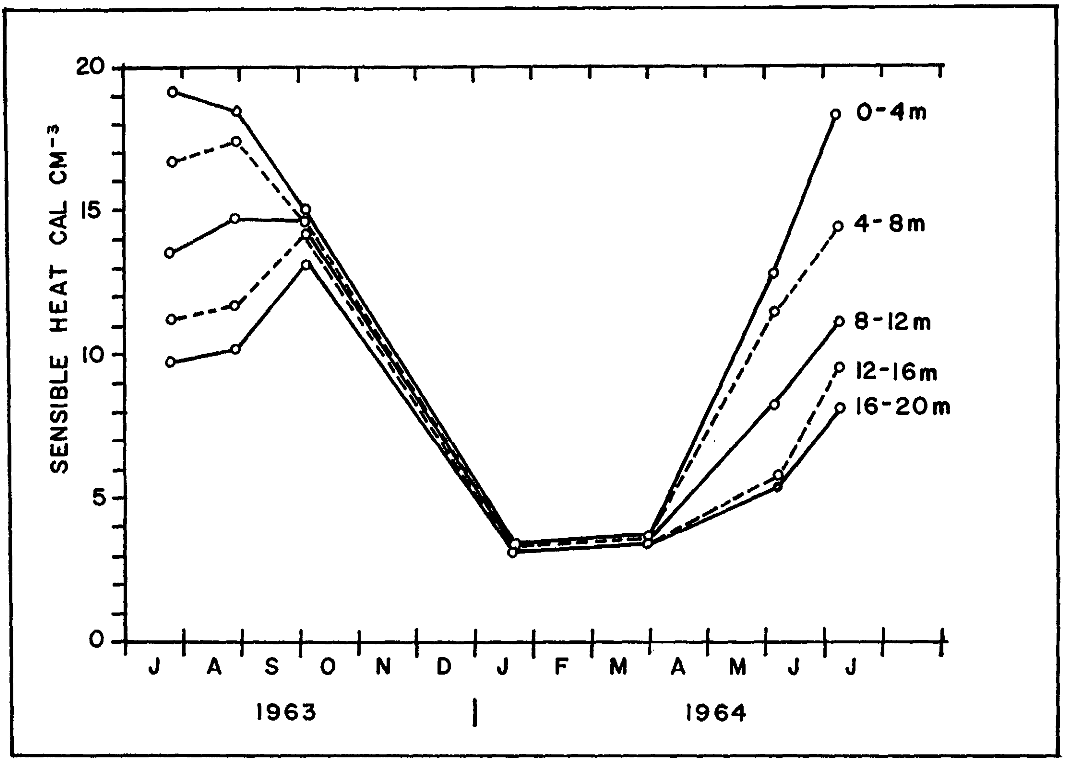

FIG. 6. The seasonal heat content variation in 4-m layers.

several layers was markedly different from that of fall cooling. With the onset of spring heating, stratification and stability built up rapidly, which caused each layer to assume its own heating rate inversely related to its depth.

An extrapolation of the heat content in each layer (Fig. 6) from the July 1964 section matches up well with the July 1963 section, lending credence to this plot as a general portrayal of the seasonal cycle of heat distribution.

The observed winter to summer warming of the total water column corresponded to an absorption of about 90% of the available incident solar radiation flux. With some 5% of the radiant energy reflected, and 30–40% of the energy lost from reradiation and evaporation effects, some of the heat increase must be caused by horizontal advection and mixing of warmer water. The temperature–salinity curves are useful in examining this effect.

TEMPERATURE–SALINITY RELATIONS

Temperature–salinity (T–S) relationships, which are usually applied to open ocean and deep-water mass-mixing analysis, can be used to examine gross mixing of coastal and shelf waters (Ketchum and Corwin 1964). The seasonal changes in the T–S relation for Rhode Island Sound, as a function of distance from shore and of depth, are shown in Fig. 7. There is a general increase in salinity seaward both at 4 and 24 m.

Temperature and salinity both increase seaward over the extent of the continental shelf (Bigelow 1933; Ketchum and Corwin 1964). Thus, if outer shelf water were brought by advection into Rhode Island Sound, the T–S diagram should show an increase in both temperature and salinity. The surface water within the sound has a higher temperature and lower salinity than that near the bottom, so that vertical mix-

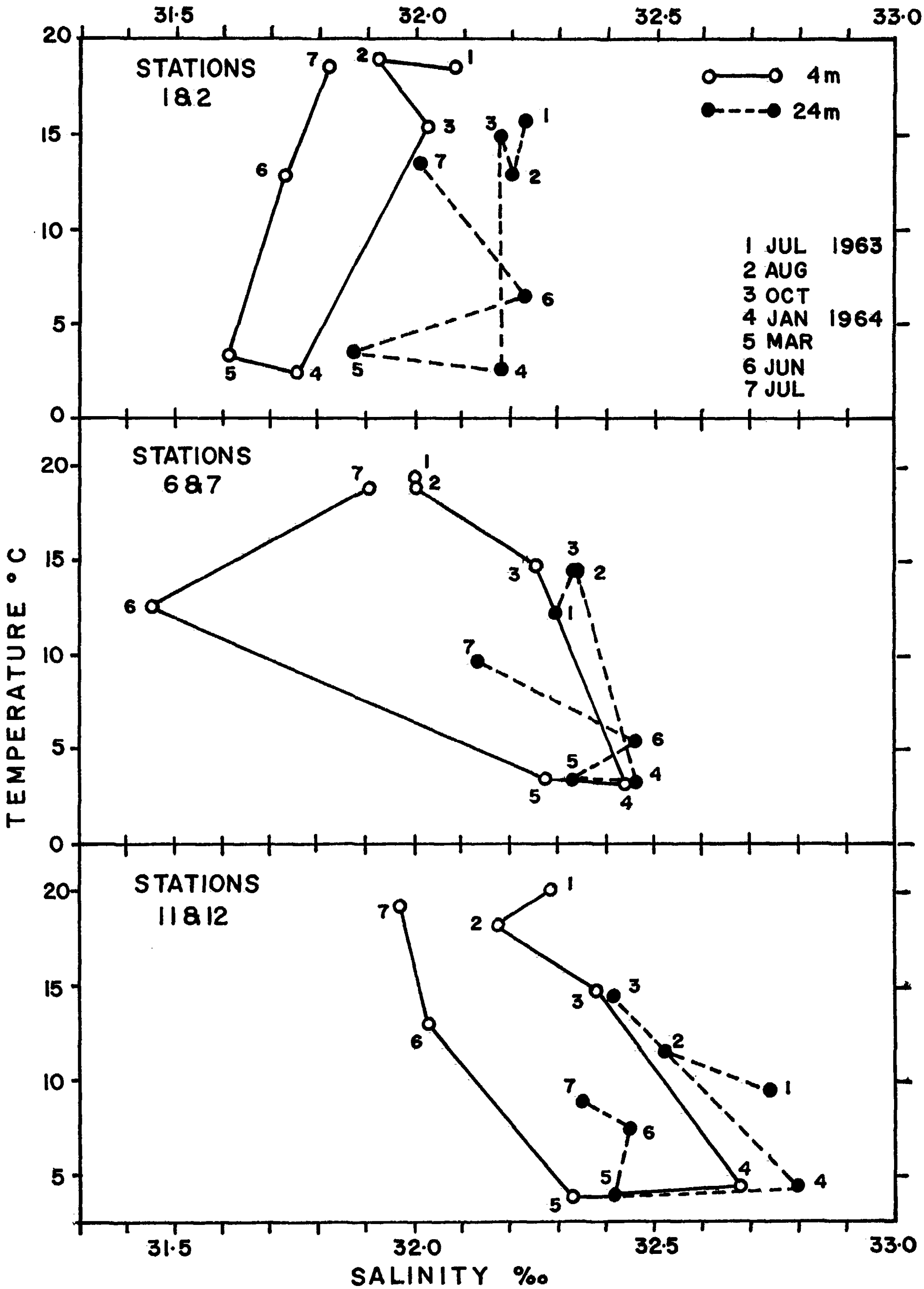

FIG. 7. The seasonal variation in the temperature–salinity relationship averaged for stations 1 and 2, 6 and 7, and 11 and 12 at 4- and 24-m depths.

ing should produce an increase in temperature and a decrease in salinity at 24 m, with the reverse for surface water. From August to October, the temperature at 24 m in fact increased and the salinity decreased; at 4 m the temperature decreased and the salinity increased, indicating vertical mixing (Fig. 2B, C).

From October to January, the temperature decreased to near the seasonal minimum. However, an increase in salinity seaward accompanied this change, apparently associated with horizontal advection and driven by the offshore winds commonly occurring during this period (Cook 1966). The salinity at stations 1 and 2 at 4 m actually decreased during this period because of runoff. Stations 6, 7, 11, and 12 at 4 m showed an increase in salinity, suggesting a balance between horizontal advection and vertical mixing (because of the lack of vertical gradients).

From January to March (time of maximum runoff), temperature remained relatively unchanged, but salinity decreased markedly. A small decrease in salinity appeared at stations 6 and 7, whereas at stations 1, 2, 11, and 12 the salinity decreased markedly. These results suggest that there are bands of higher and lower salinity water parallel to the coast. If the "fresh" water present at stations 11 and 12 did not come from Narragansett Bay, the Connecticut River is the only other major possible source. The possibility that water from the Connecticut River does move into Rhode Island Sound (between Point Judith and Block Island) is supported by the strong intrusion of Rhode Island Sound bottom water into Long Island Sound; a return flow at the surface would explain the "fresh" water intrusion. This mode of circulation has been suggested (Cook 1966).

The temperature increased from March to June, and the salinity decreased at 4 m, most markedly at stations 6 and 7. This again suggests a "fresh" water intrusion from somewhere other than Narragansett Bay. Salinity and temperature both increased at 24 m, suggesting horizontal advection of shelf water.

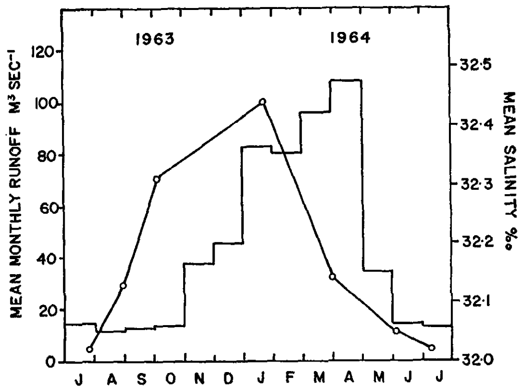

FIG. 8. Freshwater runoff from Narragansett Bay drainage area (histogram) compared with weighted mean salinity for section A (circles).

From June to July, the 4-m temperatures increased and salinities decreased, except at stations 1, 3, 6, and 7. This suggests vertical mixing, except at stations 6 and 7 where the anomalous low salinity was returning to an apparently normal value.

EFFECTS OF NARRAGANSETT BAY RUNOFF

The salinity sections depict the complex interaction of the Narragansett Bay runoff water with the coastal shelf water. Ketchum and Corwin (1964) found a high positive correlation of the mean salinity of shelf water with the previous 6-month average runoff from coastal estuaries. The Narragansett Bay drainage area runoff (Knox 1964) shows this relationship when compared with the weighted mean salinity for each cruise averaged over all stations (Fig. 8). The runoff histogram represents a contribution of freshwater in a 12-month period that amounts to 30–40% of the volume of Rhode Island Sound.

While the runoff from July to October remained at a seasonal minimum, the mean salinity rapidly increased because of strong advective mixing from the open ocean and, to a lesser extent, high surface evaporation. Runoff sharply increased from October to January, causing the salinity increase to taper off. After January, the continually increasing runoff abruptly reduced the mean salinity during February through June and July. There was an apparent 2–3 month time lag between the peaking of the river outflow and the actual decrease in salinity. The sharp decrease in salinity between January and March probably also reflected some strong variation in a nonlinear mixing or advection effect from the open ocean, which constantly interplays with runoff.

SEASONAL CHANGE IN POTENTIAL ENERGY

The continuous redistribution of density or sigma-*t* in the water column due to seasonal changes in temperature and, to a lesser degree, in salinity is associated with changes in potential energy. The mean range of sigma-*t* for the entire water column from summer to winter in Rhode Island Sound is about one σ_t unit (*see* Fig. 4). Thus, for 30-m depth, the average seasonal change in specific volume would be equivalent to a depth increase in summer of about 5 cm. This, however, produces no change in potential energy per unit volume, since the increase in volume due to expansion is offset by the required decrease in mean density.

The potential energy is largely controlled by variation of density with depth; for example, the presence or absence of a thermocline. The gravitational potential energy (*PE*) in a unit cross-section water column was calculated for each station of section A for all cruises, assuming that the water column can be treated as a vertical distribution of "point masses." The center of gravity and the mass of the water column were determined from the sigma-*t* profiles (Fig. 4). The *PE* of the water column at each station was obtained using the sea surface as the reference or zero *PE* surface. From the arithmetic mean for the 12 stations the *PE* per unit volume was determined for each cruise. To avoid calculating small differences between large quantities, we calculated the *PE* anomaly using the relationship:

$$\delta PE = PE_{\text{actual}} - PE_{\text{std ocean}};$$

where the standard ocean is at 0C and 35‰. A plot of seasonal *PE* variations along with seasonal heat energy content is shown in Fig. 9. The seasonal heat energy variation (4.82×10^8 erg cm^{-3}) is about four orders of magnitude larger than the seasonal variation in *PE* (i.e., about 3.2×10^4 erg cm^{-3}).

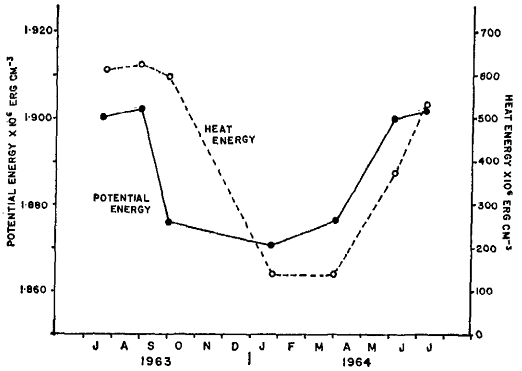

FIG. 9. The seasonal variation of relative potential energy (solid line) and of total heat energy (broken line) in Rhode Island Sound.

The *PE* remained high during the warm months. At the fall overturn, as the thermocline was destroyed, the potential energy decreased abruptly by about 0.025 erg cm^{-3} and remained at about this level throughout winter. With the rapid development of the thermocline after March, the *PE* again ascended to summertime values. The dependence of the *PE* on the distribution of density is shown by the sharp drop between August and October, whereas the total heat energy decreased only slightly during the period of strong mixing.

Maximum rates of heat and potential energy inputs to the water column with estimated kinetic energy input are compared in Table 1. The kinetic energy input is associated with tidal current, typically accelerating from 0 to 15 cm sec^{-1} in a quarter of a tidal period, or about 3 hr. A wind-accelerated current might contain a similar amount of energy, but it would not be as uniformly distributed in the water column as is tidal kinetic energy. The rate of change of heat energy far outweighs either the potential or kinetic energy changes. These three forms of energy are, of course, related, since the kinetic energy associated with turbulent and mean flows affects the mixing processes that spread

TABLE 1. *Comparison of energy inputs to Rhode Island Sound*

Type of energy input	Duration	Rate (erg cm^{-3} sec^{-1})
Heat	64 days*	42.5
Potential	64 days*	0.006
Kinetic (tide) (accelerated from 0–15 cm sec^{-1})	3 hr	0.010

* Between 31 March and 3 June 1964.

heat through the water column and thus, in turn, alters the potential energy.

Comparison of the long-term energy changes with variations of kinetic energy associated with tide and wind stress is difficult because the latter represents such short-term perturbations. However, the relatively high frequency perturbations of tide and wind forces play an important role in determining the long-term heat and potential energy distribution of the water column; hence, it is important to find quantitative relations between them.

CONCLUSIONS

1. A seasonal thermocline forms in Rhode Island Sound in April and is maximal by late June or early July. Spring and summer heating stabilizes the water column, inhibiting vertical mixing. Rapid fall cooling of surface water together with wind mixing causes rapid convective overturn between the end of August and the beginning of October, rendering the whole sound uniformly mixed. Further fall and winter cooling occurs throughout the water column (3–4C by late January, with minimum temperatures by late February). The water then heats slowly, reaching about 3.5C by late March when the spring warming cycle is repeated.

2. The effects of an outflow of freshwater are observed in Rhode Island Sound 20–30 km from the coast during all seasons. The mean salinity of the sound is inversely related to the freshwater runoff of Narragansett Bay. The salinity sections also indicate an east–west intrusion of salinity anomalies in the sound.

3. The total heat content in the water column lags the seasonal solar radiation curve by 50–90 days and the air temperature curve by 30–50 days. Conduction and interchange of heat from the air over the water play as important a role in the gross heat exchange as the incident solar radiation.

From 50–70% in heat content changes in Rhode Island Sound, and probably in most coastal shelf water, are caused by the vertical mixing of heated or cooled water downward. This turbulent diffusion is associated with convective motions and, to a lesser extent, with wind or current shear stresses. The advection of water containing horizontal temperature gradients seems to be less of a controlling influence on the seasonal thermal variations.

4. The seasonal heating of the water column corresponds to an energy input rate (power) which is from three to four orders of magnitude larger than both the corresponding potential energy changes caused by the redistribution of density and also the maximum tidal kinetic energy input. Thus, from an energy standpoint, the importance of ocean currents is mainly related to their ability to advect warm or cold water into various geographic locations.

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