Estuarine Subaqueous Soil Temperature

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Most biological and chemical processes related to soil function and formation are temperature dependent. To begin understanding soil temperature in estuarine subaqueous soils, this parameter was investigated in two shallow coastal lagoons in southern New England. Temperature loggers were placed in the soil at two depths (25 and 50 cm) on three subaqueous soil-landscape types. Soil temperatures were compared among soil-landscape types, and relative to overlying water temperature, ambient air temperature, and a tidal marsh soil. Subaqueous soil temperature varied slightly among soil-landscape types, and appears to be primarily influenced by water temperature and depth. Mean annual water temperatures (11.5–12.4°C) were within 1°C of the associated soil temperatures regardless of water depth suggesting that mean annual water temperature would serve as an excellent surrogate for mean annual soil temperature. Soil temperatures at the 50-cm depth showed less fluctuation than temperatures measured at 25 cm from the soil–water column interface. Mean annual soil temperatures measured at 50 cm were 12.3 and 12.6°C in washover fan and lagoon bottom soils, respectively. Subaqueous soil temperatures were noticeably warmer than the tidal marsh soil. Differences between mean summer and mean winter soil temperatures were >10°C. Thus, these subaqueous soils classify within the mesic soil temperature regime; similar to subaerial soils of southern New England.

Soil temperature plays a role in many important functions and processes by regulating biological and chemical reactions rates (Paul and Clark, 1996; Soil Survey Staff, 1999). Oxidation-reduction reactions, C storage, CO_2 efflux, nutrient availability, and bacterial mineral reduction rates have all been correlated to soil temperature (Abdollahi and Nedwell, 1979; Koerselman et al., 1993; Peterjohn et al., 1994; Schimel et al., 1994; Fang and Moncrieff, 2001; Davidson and Janssens, 2006; Vaughan et al., 2009). As such, soil temperature plays an important role in soil formation; part of the climate state factor described in Jenny's (Jenny, 1941) factors of soil formation. Soil temperature has been used in definitions of biological zero and growing season in Soil Taxonomy and wetland sciences (Soil Survey Staff, 1975; USACOE, 1987; Rabenhorst, 2005).

In Soil Taxonomy temperature regimes are defined based on temperatures collected at a 50-cm depth (Soil Survey Staff, 2010). This depth was chosen because the daily variations in soil temperature decrease in amplitude until approximately this depth (Soil Survey Division Staff, 1993). Based on average soil temperatures, there are five temperature regimes used to classify soils and an additional four regimes for soils where the mean summer soil temperature minus the mean winter soil temperature > 5°C (Soil Survey Staff, 2010). Mean summer soil temperature is defined as the temperature of the soil during the 3 mo of summer, June, July and August, while mean winter soil temperature is defined as the soil temperature during the winter months of December, January, and February.

Although many factors influence soil temperature, air temperature is the most influential. Mean annual soil temperature for most subaerial soils of the USA can be estimated by adding 1°C to the mean annual air temperature (Soil Survey Staff, 1999). While most subaerial soils have an estimate or direct readings of soil temperature, no information regarding subaqueous soil temperature is available. In this study we documented temperature at soil depths of 25 and 50 cm across several soil-landscape types in two southern New England coastal lagoons. We calculated mean annual, mean summer, and mean winter soil temperature of the subaqueous soils and compared those with the temperatures at the soil–water interface, in the air, and in a tidal marsh soil.

MATERIALS AND METHODS

Two coastal lagoons, Ninigret Pond (677 ha) and Quonochontaug Pond (312 ha), located on the southern shore of Rhode Island (Fig. 1), were chosen for this investigation. Barrier spits partially separate each of the lagoons from the open ocean. The lagoons are connected to the ocean through inlets that were made permanent in the 1950s and 1960s by construction of rock-wall jetties. Seawater is exchanged twice a day through the inlets. The tidal ranges of Ninigret and Quonochontaug Ponds are 10 and 56 cm, respectively. Ninigret Pond has an average depth of 1.2 m while Quonochontaug Pond is deeper at 1.8 m. Average salinities are 3.9 and 4.3 S m^{-1} (28 and 31 ppt), respectively. The major subaqueous soil-landscape types within these lagoons are flood tidal deltas, washover fans, lagoon bottoms, and mainland submerged beaches (Table 1; see Bradley and Stolt, 2003 for discussion of the different soil-landscape types in coastal lagoons).

Thermochron iButtons model 1921G (Embedded Data Systems, Lawrenceburg, KY) were used to record soil and water temperature. Each iButton was placed in a water-proof container made from a 10.5 by 3-cm plastic centrifuge tube. Approximately 2 cm of the bottom of the centrifuge tube was filled with drierite; dry loamy sand soil material was poured into the tube to the 7-cm mark; a cotton ball was placed over the soil, and an iButton placed on top. A second cotton ball was placed on top of the iButton and the rest of the tube was filled with dry loamy sand soil material. A rubber stopper was used to close the centrifuge tube and hot glue was applied to the stopper to ensure no leakage. The temperature loggers were buried at depths of 25 and 50 cm. The 25-cm depth is slightly shallower than the recommended depth of 30 cm for defining growing season in wetlands (USACOE, 2008), and the 50-cm depth is the same as the recommended depth for determining soil temperature for soil classification (Soil Survey Staff, 2010). A line attached

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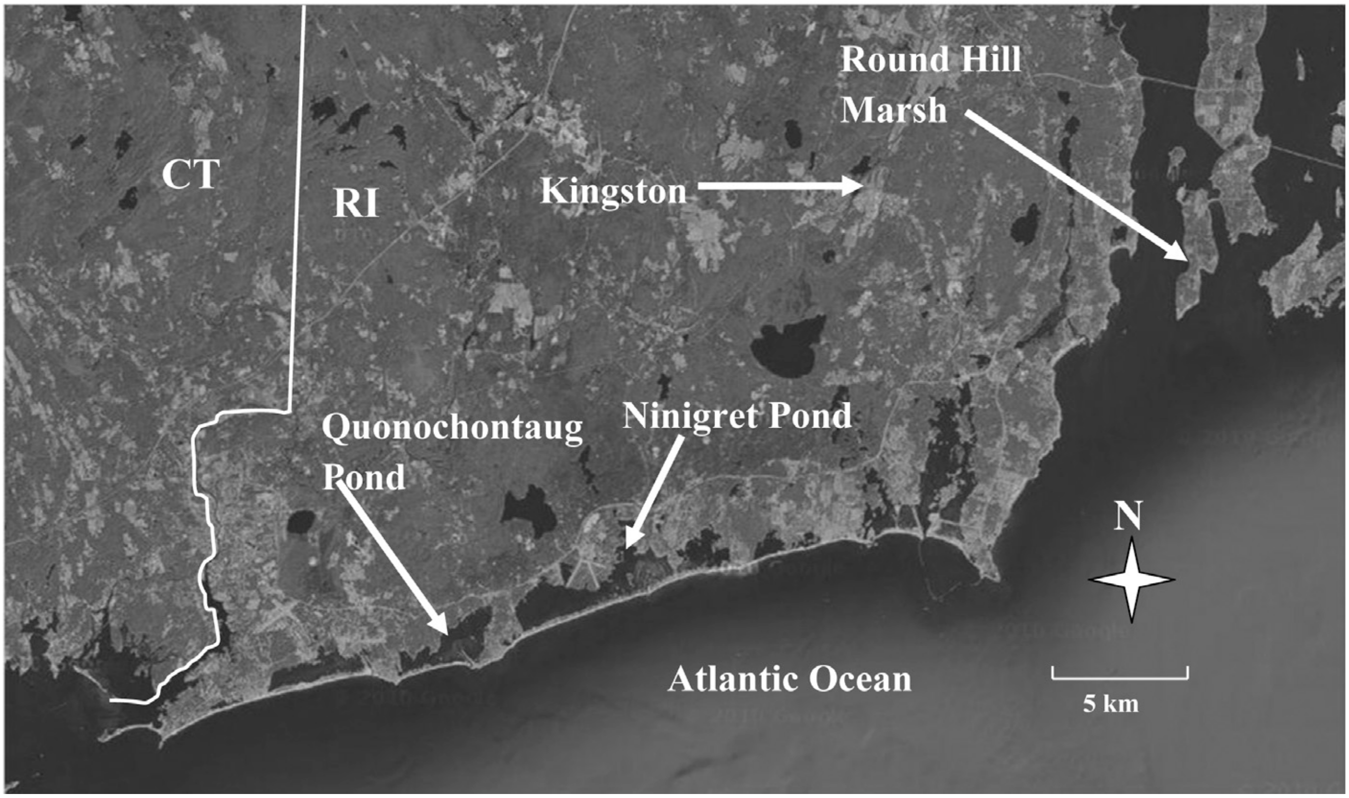

Fig. 1. Subaqueous soil temperature study site locations in southern Rhode Island. Quonochontaug and Ninigret Ponds are two of the largest coastal lagoons in southern New England. Air temperature data were collected at the Kingston weather station. Soil temperature was also collected at Round Hill Marsh.

the temperature logger to a cinder block on the soil surface where a second logger was tied to record the water temperature. Temperatures were recorded every 4 h following deployment.

In Ninigret Pond, three locations were chosen for the investigation of subaqueous soil temperature. Two of the locations were lagoon bottom soil-landscape units while the other site was a washover fan. At the lagoon bottom sites, temperature loggers were buried in the soil at 25 cm in NLB1 and at 50 cm in NLB2 (Table 2). At the washover fan site, loggers were buried at 25 and 50 cm (NWF 25 cm and NWF 50 cm; Table 2). Water depths ranged from 1.00 to 1.50 m (Table 1). The loggers were deployed in Ninigret Pond in September 2008 and retrieved in August 2009.

In Quonochontaug Pond, soil temperature was measured on washover fan (QWF), lagoon bottom (QLB), and submerged mainland beach (QSMB) subaqueous soil-landscape types (Table 1). All soil temperature readings at Quonochontaug were measured with loggers at a depth of 25 cm from the soil-water interface. Water temperature was also recorded at each site. Water depths in Quonochontaug Pond ranged from 0.8 to 3.2 m (Table 1). The temperature loggers were deployed in July 2008 and retrieved in June 2009. For comparison, soil temperature data collected at 40 cm from November 2008 to August 2009 were obtained from a Rhode Island tidal marsh soil (Fig. 1). Mean annual soil temperature, mean summer soil temperature, and mean winter soil temperature were calculated as defined by Soil Taxonomy (Soil Survey Staff, 1999). Air temperature data were obtained from the Kingston, RI weather station. Pearson product moment correlation coefficients for water temperatures vs. soil temperatures were determined for all sites.

RESULTS AND DISCUSSION

Mean annual soil temperature varied little (12.1–12.6°C) regardless of logger depth, subaqueous soil-landscape type, or pond (Table 2). The exception was the lagoon bottom site in Quonochontaug Pond (QLB) where the mean annual soil temperature recorded at 25 cm was 10.8°C. Water depth at the QLB site was 3.2 m, which is >1.5 m deeper than all the other sites, and deeper than what is typically considered a soil in Soil Taxonomy (Soil Survey Staff, 2010). Mean annual water temperatures (11.5–12.4°C) were within 1°C of the as-

Table 1. Soil and site characteristics for the six sites where soil temperature were recorded.

Soil-landscape type	Soil classification	Water depth, m
Quonochontaug Pond (312 ha; average salinity 31 ppt; average depth 1.8 m; tidal range 56 cm)		
Lagoon Bottom (QLB)	Coarse-silty Fluventic Sulfiwassent	3.2
Washover Fan (QWF)	Typic Psammawessent	0.8
Mainland Submerged Beach (QMSB)	Sandy-skeletal Typic Haplowassent	1.0
Ninigret Pond (677 ha; average salinity 28 ppt; average depth 1.2 m; tidal range 10 cm)		
Lagoon Bottom (NLB1)	Coarse-silty Fluventic Sulfiwassent	1.0
Lagoon Bottom (NLB2)	Coarse-silty Fluventic Sulfiwassent	1.5
Washover Fan (NWF)	Typic Psammawassent	1.0

Table 2. Subaqueous soil and water temperatures recorded by loggers at various soil-landscape types and soil depths at two coastal lagoons: Ninigret Pond and Quonochontaug Pond. Data were recorded every 4 h between June 2008 and August 2009. Soil-landscape types in Ninigret Pond investigated were two lagoon bottoms (NLB1 and NLB2) and a washover fan (NWF). In Quonochontaug Pond a washover fan (QWF), lagoon bottom (QLB), and submerged mainland beach (QSMB) were investigated. Soil temperature data, collected at 40 cm from a subaerial tidal marsh soil (Round Hill), were also obtained for comparison purposes.

Site (logger depth)	Annual	Summer	Winter	Summer—winter
		Average soil temperatures (°C)		
NWF 25 cm	12.3	22.3	3.5	18.8
NWF 50 cm	12.3	20.5	4.9	15.6
NLB1 25 cm	12.5	19.8	6.3	13.5
NLB2 50 cm	12.6	17.9	7.6	10.3
QWF 25 cm	12.1	21.6	3.5	18.3
QSMB 25 cm	12.1	20.7	4.7	16.0
QLB 25 cm	10.8	16.9	5.6	11.4
Tidal Marsh 40 cm	8.7	16.8	4.5	12.3
		Average water temperatures (°C)		
NWF	11.5	23.0	2.2	19.7
NLB1	12.0	22.3	2.8	19.5
NLB2	12.0	20.5	4.4	16.1
QWF	12.1	22.0	3.5	18.5
QSMB	12.4	21.8	4.3	17.5
QLB	11.2	19.5	4.2	15.3

sociated soil temperatures (Table 2) regardless of water depth. Pearson product moment correlation coefficients between soil temperature and water temperature were 0.95 to 0.99 (Table 3). These data and observations suggest that mean annual water temperature measured just above the soil surface would serve as an excellent surrogate for mean annual soil temperature; and that water depth may in part control water temperature, and thus should be considered when estimating subaqueous soil temperature.

Greater fluctuations in soil temperature were recorded at 25 cm than at 50 cm (Fig. 2). Mean summer soil temperatures varied among landscape units and between depths (Table 2). Mean summer temperatures recorded at 50 cm (NLB 50 cm; NWF 50 cm) were cooler than those recorded at 25 cm (NLB 25 cm; NWF 25 cm). Summer water temperatures were slightly warmer than summer soil temperatures (Table 2). Mean winter soil temperature ranged from 2.9 to 7.6°C depending on depth and location (Table 2). In both of the soil-landscape types where soil temperature was recorded at two depths, mean winter soil temperatures for the 50-cm soil depth were warmer than winter soil temperatures recorded at 25 cm (Fig. 2). Differences between mean summer and mean winter soil temperatures ranged from 10.3 to 18.8°C (Table 2) and the differences where less at the 50-cm depths than at 25 cm. These data suggest that soil depth plays a part in seasonal variations in soil temperature but these differences average out over the year such that mean annual soil temperatures are essentially the same regardless if the temperature is recorded at 25 or 50 cm.

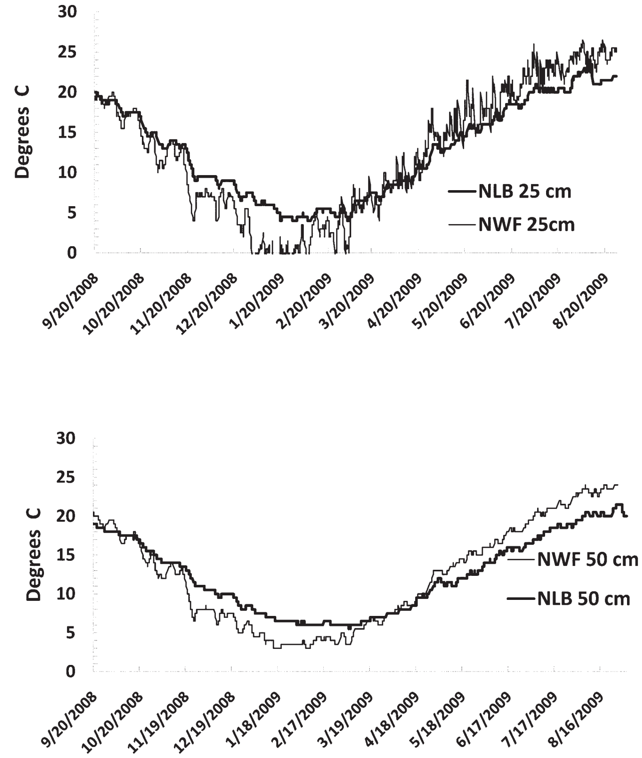

Fig. 2. Soil temperatures collected from loggers buried at 25 and 50 cm in Ninigret Pond within the lagoon bottom (NLB) and Washover Fan (NWF) sites. Both of the 25-cm sites have very similar water depths (1.00 and 1.04 m). At the 25-cm depth the coarser textured soil (NWF) has higher summer temperatures and lower winter temperatures and much greater daily, weekly, and seasonal fluctuations suggesting a texture effect on soil temperature. Note the muted fluctuations and higher winter temperatures at the 50-cm depth relative to 25-cm depth.

In addition to soil depth and water temperature, soil texture may also affect subaqueous soil temperature variations. For example, although the lagoon bottom and washover fan sites at Ninigret Pond have equal water depths and equivalent water temperatures, there are clear differences in mean summer and winter soil temperatures (Table 2). The sandy textured washover fan soil is warmer in the summer and cooler in the winter than the coarse silty textured lagoon bottom (Fig. 2). This suggests that the coarser textured (sandy) soil appears to be more influenced by the overlying water column temperature than the lagoon bottom soil.

The mean annual soil temperature of the subaerial tidal marsh soil was noticeably lower (8.7°C) than subaqueous soil temperatures (Table 2). All of the subaqueous soils had mean summer soil temperatures (ranging from 16.9 to 22.3°C) that were warmer than the mean summer temperature (16.8°C) of the tidal marsh soil. The mean winter soil temperature of the tidal marsh soil was 4.5°C, which was within the range of winter soil temperatures for the subaqueous soils. Average air temperature for the study period was 10.3°C, or 0.5°C above the 30 yr average air temperature (9.8°C) recorded at the Kingston, RI weather station. All of the

Table 3. Pearson product moment correlation coefficients for soil temperature and water temperature measured at the soil surface for NWF 25 cm, NWF 50 cm, NLB1 25 cm, NLB2 50 cm, QWF 25 cm, QSMD 25 cm, and QLB 25 cm. 2050 measurement at each site were used to test for correlations.

Site	NWF 25 cm	NWF 50 cm	NLB1 25 cm	NLB2 50 cm	QWF 25 cm	QSMD 25 cm	QLB 25 cm
Correlation	0.98	0.96	0.95	0.95	0.99	0.99	0.97

average annual subaqueous soil temperatures were above these values suggesting that subaqueous soil temperatures may on average be warmer than subaerial soil temperatures.

Subaerial soils in southern New England classify within the mesic temperature regime (between 8 and 15°C; Soil Survey Staff, 2010). The average subaqueous soil temperature was 12.3°C (excluding the soil temperature collected at QLB with a water depth of 3.2 m); meeting the mesic criteria. Considering that 12.3 is closer to the upper limit of the mesic range than the lower limit, and we typically think of southern New England soils as closer to the lower limit of the mesic regime, the geographic range for mesic subaqueous soils may be different than for subaerial soils. In future subaqueous soil surveys and investigations of areas near the geographic limits of the mesic regime, soil temperature should be investigated further.

Lagoons are one of the most common shallow water bodies in coastal environments. In this study we examined soil temperature in several soil-landscape types of two southern New England coastal lagoons. These were the first studies of subaqueous soil temperature that we are aware of. We found that variations in subaqueous soil temperature were primarily a function of water temperature, and that water temperature can be used to accurately estimate soil temperature. The ranges and seasonal variations in soil temperatures that we recorded were similar to those of subaerial soils suggesting that biological and chemical processes that are temperature dependent will be under similar constraints as subaerial soils within the region. Our studies suggest that soil temperatures of shallow-subtidal wetlands of the coastal lagoons are warmer than subaerial tidal marsh soils, suggesting subaqueous systems may on average have warmer temperatures than their subaerial counterparts. Our studies, however, were limited to two coastal lagoons and over a single year. Further studies are needed to verify such conclusions.

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