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Local Energy Exchanges in a Shallow, Coastal Lagoon: Winter Conditions[a]

Ned P. Smith and George H. Kierspe[b]

Harbor Branch Foundation, Inc., RR 1, Box 196, Fort Pierce, Florida 33450, U.S.A.

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A 110-day time series of estuarine water temperature is used to verify a numerical model of local air–water heat exchanges under winter conditions in a shallow, bar-built estuary on South Florida's Atlantic coast. Quasi-periodic frontal passages during the winter of 1977–1978 produce cycles of heating and cooling over time scales of about a week. Temperatures decrease 4–7 °C during the first few days following frontal passages. Model results suggest that the daily net water temperature change is most strongly correlated with, and therefore primarily in response to sensible and latent heat fluxes. Heating by insolation and cooling by longwave radiation are substantial, but in both cases the correlation with the net daily temperature change is not statistically significant. Conductive exchanges with the underlying sediments appear to play a minor role in the estuarine heat budget. The root-mean-squared error of simulated water temperatures asymptotically approaches a value of approximately 1·0 °C for time intervals of between 2 and 30 days.

Introduction

The relatively shallow depths of most estuaries make them highly responsive to the air–water interactive processes associated with discrete meteorological events, as well as to the more subtle day-to-day variations in weather. Frontal passages produce perhaps the most dramatic response by affecting circulation (Schumacher *et al.*, 1978) and water level (Brooks, 1978; Smith, 1977*a*), as well as the temporal variability of temperature (Smith, 1977*b*) and salinity. In this paper, we consider the energy exchanges, and the resultant heating and cooling, associated with quasi-periodic frontal passages in a shallow, bar-built estuary.

While many energy exchange studies have been conducted over large space and time scales in the open ocean, the local and relatively high frequency conditioning of estuarine waters by air–water energy exchanges has received relatively little attention in the literature. Hsu (1978) has reviewed heat, moisture and momentum fluxes across an air–estuary interface. Smith (1977*b*) has documented large net heat fluxes in the shallow waters of Laguna Madre, Texas, occurring in response to frontal passages. Heath (1977) has decomposed the net heat flux into

[a] Harbor Branch Foundation Contribution No. 204.

[b] Present address: Department of Oceanography, University of Washington, Seattle, Washington 98195, U.S.A.

the individual terms, based upon measurements made over one tidal cycle in a small coastal inlet. The pattern that emerges is one of substantial temporal variability, but the nature and relative importance of the individual heat flux processes acting over time scales in the order of a few days are not well understood.

Estuaries along the southern tier of states provide good natural laboratories for investigating energy exchanges during winter months. At these low latitudes, occasional cold air outbreaks cover the area with continental polar or continental arctic air. Between frontal passages, however, onshore winds provide relatively warm and moist maritime tropical air. The alternation of air masses produces strong, if transient, sensible and latent heat fluxes and results in cycles of pronounced heating and cooling.

In many cases, estuarine–shelf exchanges or circulation patterns within estuaries act to obscure local energy exchanges. The advective heat transport associated with river runoff and co-oscillating tidal motions may exceed greatly the heat gain or loss through the air–water interface at a particular location. In this regard, an advantage to working in coastal bays and bar-built estuaries is that the restricted opening and shallow water serve to suppress tidal motions. With advection reduced, local processes become more readily apparent.

The location for this study was the Indian River lagoon, a bar-built estuary along the Atlantic coast of South Florida (Figure 1). The study site was 11 km north of an inlet and was selected specifically to minimize direct effects of both periodic tidal currents and the quasi-steady outflow through this positive estuary. A jetty just south of the study site extended out to the Intracoastal Waterway, and nearly one-third of the way across the estuary. The local currents were thus primarily a highly variable wind drift.

To investigate in a cause-and-effect sense the temporal variations in estuarine water temperature, a field study was conducted during the winter of 1977–1978. Time series were obtained of the meteorological variables required to simulate local energy fluxes with a numerical model, and of the water temperatures necessary to verify the computations. Our purpose was to describe the temporal variability and the relative importance of the computed local energy flux processes during the study period, and to determine whether water temperature can be simulated to an acceptable degree of accuracy from readily available weather data instead of on-site instrumentation.

The observations

The study was conducted during a 110-day period from 16 December 1977 through 4 April 1978. This time interval included most of the cold fronts during a winter that was considered unusually cold for South Florida. The study site (27°32·1′N, 80°20·9′W) was chosen to be representative of the surrounding area in terms of water depth and bottom cover (*Halodule wrightii* and *Syringodium filiforme*). The mean water depth of 1 m varied by approximately ±10 cm due to the predominantly semi-diurnal tide, and by perhaps an additional ±20 cm due to long-period, meteorological forcing.

Two-hourly, time-integrated water temperatures were recorded with an Environmental Devices Corporation Type 109 temperature recorder, positioned 20 cm above the bottom. Temperatures were digitized to the nearest 0·1 °C, with an accuracy of ±0·2 °C, according to the manufacturer's specifications.

Several additional meteorological variables were obtained to provide the data required by the numerical model. Air temperature and wind speed were recorded in analog form approximately 0·2 km from the study site. Temperature and wind speed were digitized at hourly intervals to the nearest 0·6 °C and 1·6 km h^{-1}, respectively. Incoming solar radiation

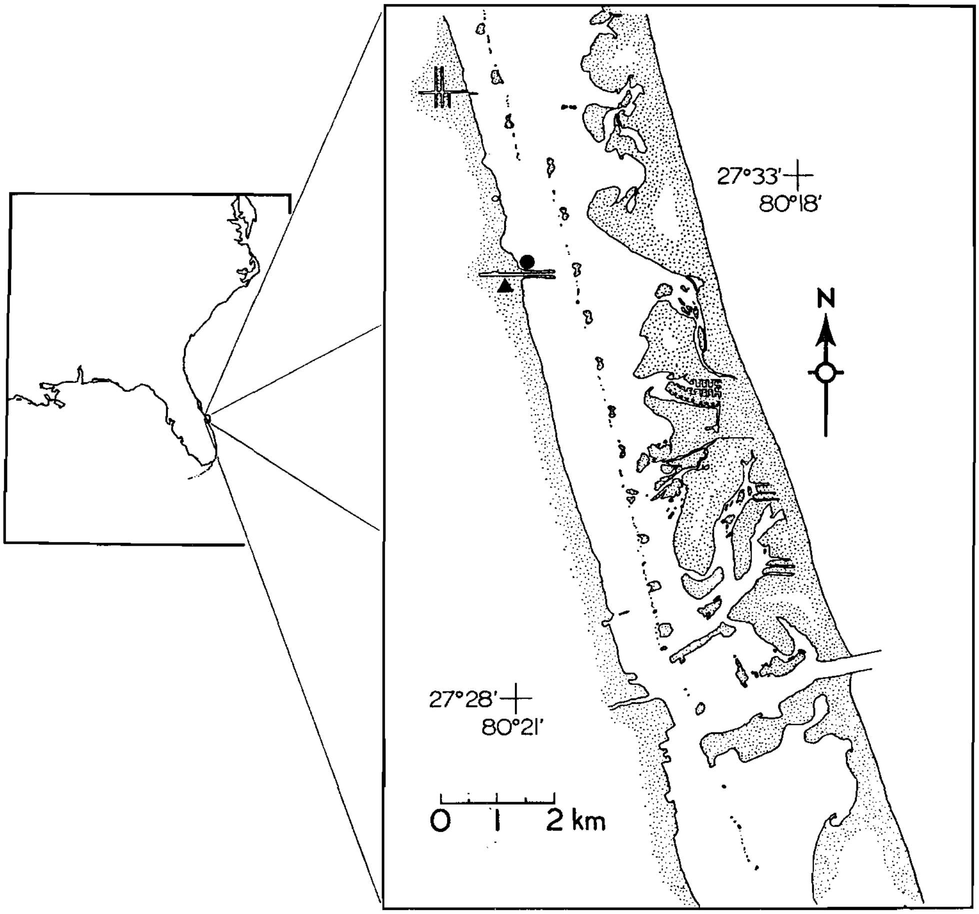

Figure 1. Study site in the Indian River lagoon, Florida. Solid circle shows study site; solid triangle shows location at which meteorological observations were made. Insert shows the study area along the Atlantic coast of Florida.

(insolation) was recorded with an Eppley Model 8-48 black and white pyranometer with a spectral response of between 0·28 and 2·80 μm, and an accuracy of ±2%. Dew point temperatures and cloud cover were recorded hourly to the nearest 0·6 °C and 1/10th, respectively, at the Vero Beach Municipal Airport, approximately 14 km from the study site and 4 km from the estuary at its nearest point.

The model

The numerical model developed in this study is an application of the heat budget equation:

$$Q_t = (Q_s+Q_v+Q_m)-(Q_b+Q_h+Q_e),$$

where Q_t is the storage term, Q_s is the insolation term, Q_v is the advective heat gain, Q_m is the conductive exchange of heat with the underlying sediments, Q_b is the longwave radiative heat loss, and Q_h and Q_e are the sensible and latent heat fluxes. Because of the relative isolation of the study site, and because unpublished field observations suggest that horizontal temperature gradients are minimal, the advective heat flux term was ignored in this study.

Reflectivity of insolation at the air–estuary interface was incorporated in the model using the results of Payne (1972). Back radiation was estimated using the Stefan–Boltzmann law, with a correction for counter radiation within the atmosphere (Swinbank, 1963). A cloud cover correction was appended to the longwave radiative flux term, as suggested by Sellers (1965).

Conductive exchanges with the underlying sediments were modelled with 12 layers, each having a thickness of 50 cm and a thermal diffusivity of 0·021 cm^2 s^{-1}. Unpublished data from the immediate vicinity have revealed strong vertical temperature gradients of as high as 2·2 °C (10 cm)$^{-1}$ in the upper 40 cm during winter months. Strong temperature gradients suggest that sediment layers may be good insulators, still the heat exchanges with the sediments may be substantial over sufficiently long time intervals.

Sensible and latent heat fluxes were modelled with bulk aerodynamic type formulas (Priestley & Taylor, 1972). The sensible heat flux is given by $Q_h = -c_p A \Delta T/\Delta z$, where c_p is the specific heat of the air at constant pressure, and A is the eddy exchange coefficient. The latent heat flux term is given by $Q_e = 0{\cdot}622\ LA\ (e_s - e)/\Delta z p$, where L is the latent heat of evaporation, e_s and e are the saturation vapor pressure and vapor pressure of the atmosphere, and p is atmospheric pressure. Air in direct contact with the estuary was assumed saturated and at the temperature of the water. The vapor pressure of the overlying atmosphere was estimated from the dew point temperature recorded at the Vero Beach Municipal Airport.

The 0·2 km distance separating the study from the weather station necessitated a somewhat different and more general form for the eddy exchange coefficients. Our choice incorporated both wind speed, V, and stability, θ, effects as components in the product $A_0 A(V) A(\theta)$. The wind speed effect was given by $A(V) = 1 + pV^q$, and the stability effect was given by $A(\theta) = 1 + S\theta^r$, where $\theta = (T_w - T_a)/T_0$. Values for A_0, p, q, r, S and T_0 were determined from repetitive simulations over all possible 14-day periods, until the r.m.s. error in the simulated temperatures was minimized. The empirical variables were adjusted independently in the sensible and latent heat flux terms. The final expression was

$$A = 0{\cdot}5\ (1 + 0{\cdot}9V^{0{\cdot}52})\ [1 + 0{\cdot}06\ (T_w - T_a)/7{\cdot}0]^3,$$

for the sensible heat flux, and

$$A = 0{\cdot}5\ (1 + 0{\cdot}03V^{1{\cdot}27})\ [1 + 0{\cdot}06(T_w - T_a)/7{\cdot}0]^3,$$

for the latent heat flux. It must be emphasized that while the general approach appears to be valid for studies at other locations or times of year, the empirical coefficients themselves are quite limited both in space and time.

It became apparent that the local heating and cooling simulated by the model exceeded that recorded in the Indian River lagoon. The responsiveness of the model estuary was damped therefore by using an effective depth of 180 cm in the calculations. This greater depth may indicate that advective processes are in reality moving water from nearby, deeper areas past the study site.

The five local heating and cooling terms usually have units of cal cm^{-2} s^{-1}. In this study, we transformed the energy flux into the corresponding daily temperature change by multiplying the flux terms by the integration time intervals, then dividing by the product of the water depth, the density and the specific heat of seawater. These five terms were then combined to simulate the net daily temperature change.

Results

The 110-day time series of 24-h average water temperatures measured at the study site is given by the solid line in Figure 2. The observed temperatures fall within a total range of

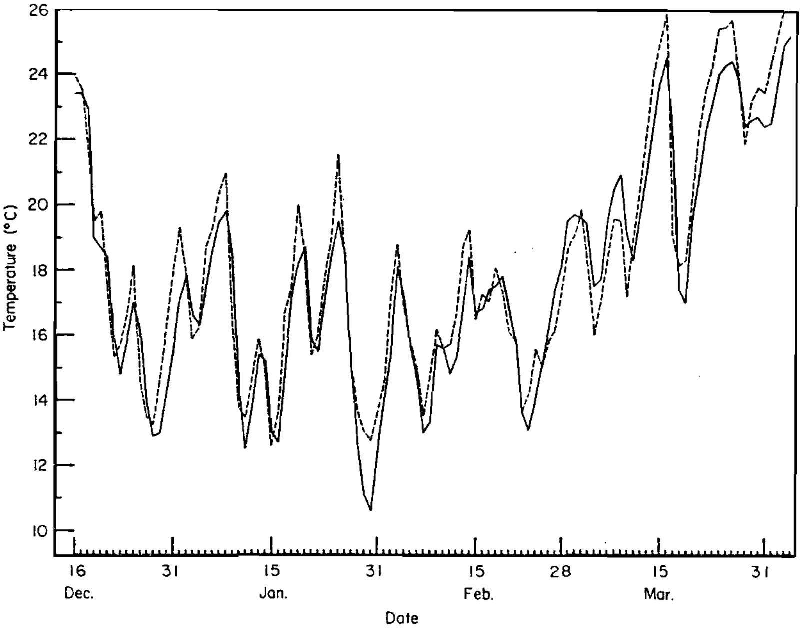

Figure 2. Simulated (– – –) and observed (——) estuarine water temperatures (°C), 16 December 1977 through 4 April 1978.

14·6 °C. The low of 10·6 °C occurs in late January, and the high of 25·2 °C occurs on 4 April. The very low frequency variation in temperature is dominated by the seasonal cycle, with the spring warming replacing the winter cooling in early February. Superimposed onto this seasonal variation is the 5–7-day, quasi-periodic warming and cooling, reflecting the passage of frontal systems. This variation is on the order of 4–7 °C, depending on the intensity of the cold front.

The temperatures simulated by the model, using the relevant meteorological data, are shown by the broken line in Figure 2. Extremes in the simulated temperatures correspond closely in time to those in the record of the observed temperatures. Deviations in the magnitude occur both above and below the temperatures actually observed, but in general the fit is good. The extent to which the simulated temperatures mirror the observed temperatures may be taken as a qualitative measure of the accuracy of the individual heat flux terms themselves.

The net temperature change for any given day, as simulated by the model, was the sum of the individual heat flux terms. These daily values and the net change are presented in Figure 3. Table 1 summarizes some of the statistical properties of the individual properties and the relationship between them. The two radiative terms are shown at the top of the figure. The value for daily heating by insolation ranges from a low of 0·5 °C to a high of 4·7 °C, according to day-to-day variations in cloud cover. The mean value is 2·4 °C and the standard deviation is 1·1 °C. The seasonal variation resulting from an increase in the number of daylight hours is indicated clearly in the plot by gradually increasing values beginning in February. The back radiation term provided a nearly constant cooling, with values varying only slightly from a mean of 0·7 °C day^{-1}.

The sensible heat flux term varied in sign and in magnitude according to the water–air temperature difference. The extreme daily temperature change due to the sensible heat flux term varied between —3·4 and +1·3 °C. Over the entire study period, the mean value was a cooling of —0·5 °C day^{-1}; the standard deviation was 0·9 °C.

The latent heat flux was for the most part a cooling process, with infrequent warming occurring only when relatively humid air came in contact with colder estuarine water. The daily temperature changes due to the latent heat flux terms varied from a cooling of 5·9 °C

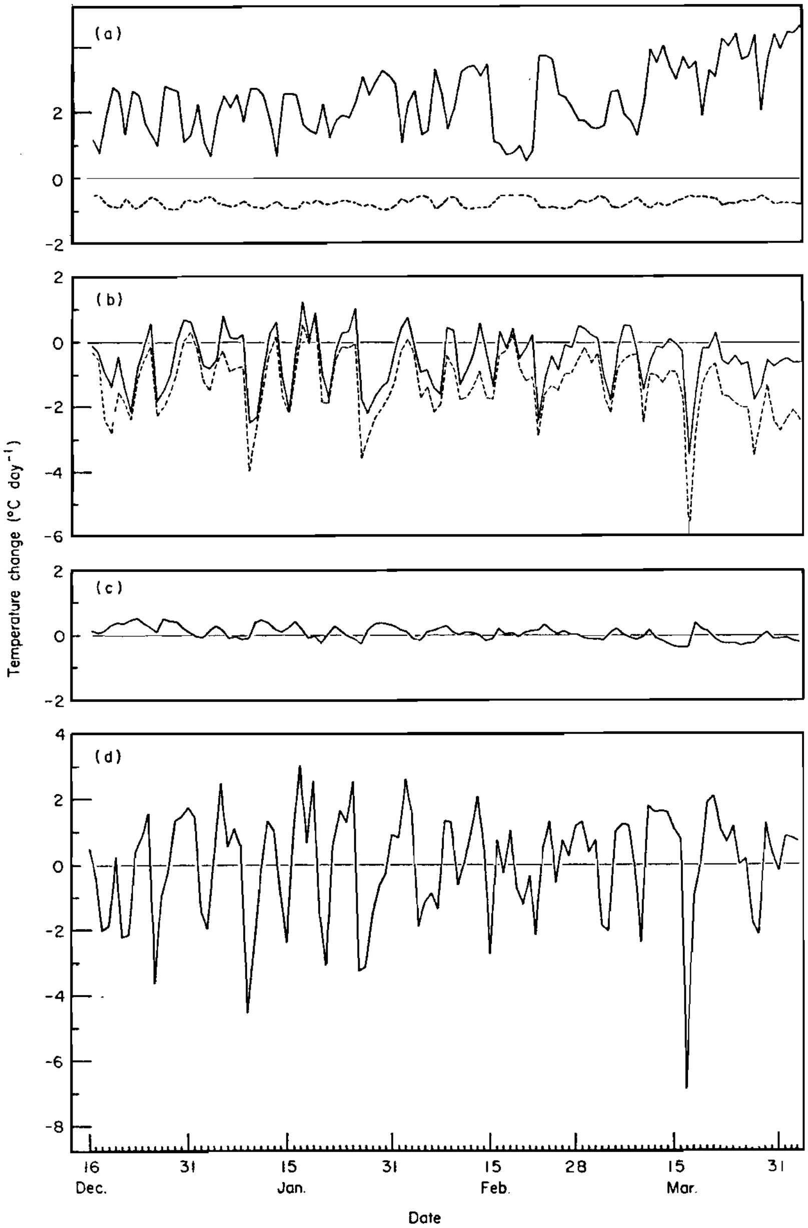

Figure 3. Composite of predicted daily average temperature changes occurring in response to (a) incoming short-wave radiation (insolation) (——), back radiation (- - -), (b) sensible (——) and latent (- - -) heat fluxes and (c) water–sediment conduction. (d) The algebraic sum of these five processes results in the net daily change.

TABLE 1. Statistical properties of local heat flux terms computed for the Indian River lagoon, 16 December 1977, through 4 April 1978. Mean and standard deviation are in °C, correlation coefficients less than 0·113 are not significant at the 95% confidence level

			Correlation coefficients				
	Mean	S.D.	Q_m	Q_h	Q_e	Q_b	Q_s
Storage, Q_t	+0·02	1·70	+0·020	+0·889	+0·801	−0·003	+0·075
Insolation, Q_s	+2·44	1·05	−0·217	−0·306	−0·508	−0·585	
Back radiation, Q_b	−0·72	0·13	−0·249	−0·277	+0·278		
Latent heat flux, Q_e	−1·29	1·04	+0·132	+0·893			
Sensible heat flux, Q_h	−0·49	0·88	−0·072				
Water–sediment conduction, Q_m	+0·08	0·22					

to a warming of 0·9 °C. The mean effect was a cooling of 1·3 °C day^{-1}, with a standard deviation of 1·0 °C about the mean.

A detailed statistical analysis of the individual heat flux terms calculated by the model was made difficult by the lack of independence in the data. For example, the correlation coefficient computed from the sensible and latent heat flux terms was 0·89. In spite of this, a measure of the relative importance of the individual heat flux terms contributing to the net change can be determined using a linear regression analysis. Specifically, the slope of the line relating one individual heat flux term with the net change indicates the fraction of the total change explained by that particular process.

Leading the individual terms as a contributor to net temperature variations is the latent heat flux term, with a slope of 0·49. This suggests that a 1 °C change in water temperature is, on the average, accompanied by a temperature change of 0·49 °C due to latent heat fluxes. The sensible heat flux term follows closely with a slope of 0·45. Both the latent and sensible heat flux terms are highly correlated with the total net change, with correlation coefficients of 0·80 and 0·89, respectively. The insolation and back radiation terms contribute very little to the net daily temperature change, with slopes of 0·05 and 0·00, respectively. The slope of the line relating water–sediment conduction with the net change in water temperature is 0·00 also.

Although our primary objective was to characterize the individual heat budget terms, rather than to simulate the water temperature itself, it is of interest to compare the ability of the model to reproduce the temperature with the plot which can be constructed with data obtained from periodic visits to the study site. Figure 4 quantifies this comparison. The lower

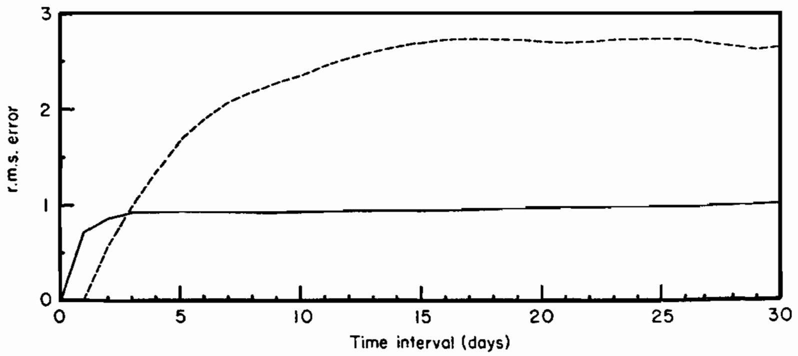

Figure 4. Root-mean-squared errors for linear interpolations (——) and for simulated (– – –) temperatures, computed for time intervals of from 1 to 30 days.

curve is the r.m.s. error in temperatures simulated over the indicated time interval. Though the error during a particular time interval is not strictly comparable to the error after a simulation of the same length, it still appears that the model will provide a better approximation of the true water temperature unless one can revisit the study site at least every third day. Over time intervals in excess of about two weeks, the error in the simulated temperatures is about 35% of that associated with a linear interpolation.

Discussion

Perhaps the most revealing result to come out of this study is in the time plots of the daily heating and cooling by the five individual heat exchange mechanisms. The composite (Figure 3) shows clearly, if qualitatively, the relative importance of these local processes, and Table 1 quantifies this. The linear regression analysis strongly suggests that the sensible and latent heat flux terms are dominant. However, in a different meteorological setting, whether at this study site or elsewhere, the characteristics and relative importance of the local heat flux processes might be quite different. The importance of the sensible and latent heat flux terms in this study is a result of the alternation of air masses as cold fronts move through the area. It is probable that these terms are less important during the summer months, when the area is constantly under the influence of maritime tropical air.

Although Figure 3 shows that the dominant time scale in this study was the 1–2-week quasi-periodicity associated with frontal passages, it is nevertheless of interest to note the long-term net energy balance that applies to the entire study period. The net local heat flux for this study can be characterized as an average daily heating of 2·44 °C by insolation and 0·08 °C by water–sediment conduction, opposed by an average daily cooling of 1·29 °C by evaporation, 0·72 °C by outgoing longwave radiation and 0·49 °C by the sensible heat flux term. The study was terminated just about the time spring warming had cancelled the effects of winter cooling. Thus, the average daily increase in temperature was only 0·02 °C.

The average values, however, are somewhat misleading and do not indicate the relative importance of the processes. A measure of the daily variability in the local heat flux terms puts them in a rather different light. Although outgoing longwave radiation has an average cooling effect somewhat larger than that of the sensible heat flux term, for example, it contributes almost nothing to the day-to-day changes in heat storage. The standard deviation about the average long-wave radiative cooling is only 0·13 °C. Similarly, the effect of water–sediment conduction varies little from its long-term mean. Thus, the other three terms are primarily responsible for the heating and cooling cycles superimposed onto the seasonal variation. Further, since the correlation coefficient between insolation and the total daily net change in temperature is statistically insignificant, the importance of this term is explaining the daily heating and cooling in the estuary is questionable.

The close match between observed and simulated daily average temperatures lends support to the assumption that the advective heat transport can be neglected at this location. Unpublished current data indicate substantial currents in the Intracoastal Waterway nearby, however the tidal excursion does not seem to be great enough to bring water from the inner continental shelf past the study site on the flood tide, against a quasi-steady outflow of 8–10 cm s^{-1}. The assumption of negligible advective heat flux is justified if the local circulation involves a homogeneous body of water. Local heat fluxes, similar to those at the study site, but occurring elsewhere in the Indian River, result in a spatially uniform conditioning of these shallow waters, and thus relatively minor horizontal temperature gradients. In other physical settings, with tidal motions alternately advecting shelf water and river runoff, the horizontal temperature gradients coupled with the local circulation may necessitate the inclusion of the advection term in a model of the estuarine heat budget.

The day-to-day variation in temperature underlines the need for high-frequency sampling in an estuarine environment. In the shallow waters of the Indian River lagoon, daily temperature changes of 2–3 °C are not uncommon during winter months, and weekly sampling may miss maximum and minimum temperatures altogether. The model results presented and discussed here indicate that this approach can provide a close approximation of daily average temperatures and thus reduce the need for *in situ* instrumentation. In addition, a modelling approach provides valuable insight into the causative processes producing the observed thermal activity in these shallow estuarine waters.

Acknowledgements

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