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Heat budget for a shallow, sinuous salt marsh estuary

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ABSTRACT

An experimental study of temperature cycles and the heat budget in the Duplin River, a tidal creek bordered by extensive intertidal salt marshes, was carried out in late summer of 2003 and spring of 2004 near Sapelo Island on the central Georgia coast in the southeastern US. Three water masses are identified with differing temperature and salinity regimes, the characteristics of which are dictated by channel morphology, tidal communication with the neighboring sound, ground water hydrology, the extent of local intertidal salt marshes and side channels and the spring–neap tidal cycle (which controls both energetic mixing and, presumably, ground water input). For the first experiment, heat budgets are constructed for the upper (warmer) and lower (cooler) areas of the Duplin River showing the diminishing importance of tidal advection away from the mouth of the creek along with the concomitant increase in the importance of both direct atmospheric fluxes and of interactions with the marsh and side creeks. The second experiment, in the spring of 2004, reexamines the heat budget on seasonal and daily averaged scales revealing the decreased importance of advective fluxes relative to direct atmospheric fluxes on this scale but the constant importance of marsh/creek interactions regardless of time scale or season. Short period temperature fluctuations which affect larval development are examined and analogies are drawn to use heat to understand the marsh as a source of sediment, carbon and other nutrients.

1. Introduction

Salt marsh ecosystems are among the most productive on the planet (Reimold et al., 1975) and their associated tidal creeks and channels provide ideal habitat for many species of fish and shellfish during some or all of their life (Boesch and Turner, 1984; Minello et al., 2003). With both primary productivity in the intertidal marsh region (Dai and Wiegert, 1996) and secondary productivity in the tidal creeks, which drain the marsh and serve as important conduits for nutrients (Odum and de la Cruz, 1967; Spurrier and Kjerfve, 1988) and larvae (Roegner, 2000), regulated by water temperature (Vernberg, 1993) it is important to understand the various factors which influence this temperature.

Temperatures in the tidal creeks are regulated by an interaction between atmospheric heat fluxes at the water surface (Wallace and Hobbes, 1977), the tidal advection and dispersion of heat through the creek channel and the interactions between the main channel and the marsh and side creeks. Curvature in the main channel or irregularities in bathymetry can give rise to cross-channel shear which locally modifies the along channel dispersion of heat (Rattray and Dworski, 1980). When the creek cuts through areas of intertidal marshes and mud flats, which are themselves often cut by small side creeks, along channel dispersive fluxes due to tidal trapping (Fischer et al., 1979) can become important. Atmospheric heat fluxes in the shallow side channels cause greater heating and cooling than in the main channel and this heat can be advected into and out of the main channel on tidal frequencies. Similarly atmospheric heat fluxes in the intertidal areas serve to warm or cool the sediment when the marsh is drained. This sediment then exchanges heat with the overlying water when the marsh is flooded, which is also affected by atmospheric influences, causing this water to mix into the main channel when the marsh again drains (Hackney et al., 1976). The resultant main channel temperature then exists as a complex signal which shows variability on diel, semi-diurnal and higher tidal harmonic and seasonal scales.

Most studies of the effect of changes in water temperature in estuarine and coastal environments generally concentrate on either long term seasonal temperature trends (see, for example, Uncles et al., 2000; Uncles and Stephens, 2001) or large temperature variations tied to seasonal upwelling events, both of which affect biological productivity in generally understood ways. However, recent work shows that small diel and tidal frequency variations and meteorological event scale temperature fluctuations are also important to biological productivity and activity. While the larvae and fully developed organisms found in

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coastal and estuarine environments are generally tolerant of a large temperature range, small, 2−6 °C, fluctuations in water temperature on tidal and diel scales have been shown to affect the rate of development of prawn larvae (Newman et al., 2006) and the hardiness of fish larvae (Perez-Domingues and Holt, 2001). The internal circadian rhythm of adult zebrafish has been shown to be regulated by similar diel temperature cycles (Lahiri et al., 2005) in a way which expresses itself at a cellular level in their RNA. Larger short term temperature fluctuations on a meteorological event time scale, such as is caused by a storm event or upwelling favorable winds, can change the chemical and sediment load in the water column by affecting filter feeder behavior with the effect persisting days past the end of the event (Jorgensen, 1990). In the case of organisms with short larval periods short term cooling events tied to coastal upwelling can severely disrupt their development and lead to significant mortality (Bernard and Hodgson, 1988).

Descriptive studies of temperature cycles and vertical and longitudinal temperature distributions in tidal creeks are not uncommon (see, for example, Ragotzkie and Bryson, 1955; Ayers, 1965; Hackney et al., 1976; Schwing and Kjerfve, 1980; Smith, 1983; Uncles and Stephens, 2001; Vaz et al., 2005). The temperature cycle in shallow and highly advective flows has been studied in rivers (Evans et al., 1998) and the effect of sills and constrictions on the balance between tidal advective and solar heating has been studied in mangrove swamps (Hoguane et al., 1999). The heating of water overlying intertidal marshes and mud flats has been studied as a function of solar and atmospheric input (see, for example, Crabtree and Kjerfve, 1978; Hughes et al., 2001), amount of inundation (Heilman et al., 2000) and the interaction between tidal inundation of the intertidal region and diurnal solar heating cycles (see, for example, Harrison and Phzacklea, 1985; Vugts and Zimmerman, 1985). However studies which tie together all of these inputs for shallow, sinuous marsh creeks have been lacking in the literature.

The study site presented here is the Duplin River which is a tidal creek located on Sapelo Island on the central Georgia coast (see Fig. 1) which has been previously studied and reported on (see, for example, Ragotzkie and Bryson, 1955; Kjerfve, 1973; Imberger et al., 1983). The Duplin winds through extensive intertidal marshes characterized by mud flats vegetated with *Spartina alterniflora* and cut by a network of side creeks and channels of varying sizes. The greatest extent of both marsh and side channels is in the northern (upper) reaches of the Duplin while the southern (lower) reaches are bordered by more upland marsh, large marsh hammocks and creekless marsh as can be seen in Fig. 1. With no source of freshwater input aside from precipitation and its associated runoff and an ungauged groundwater input (Ragotzkie and Bryson, 1955) it is more properly a tidal creek but its geomorphology is suggestive of a river with a sinuous main channel and a network of dendritic feeder creeks. It is approximately 13 km long with a mean depth on the thalweg of approximately 5 m but with several deeper holes associated with curvature or feeder creeks. Tidal range varies between 2 and 3 m over a spring/neap cycle and while there is significant tidal salinity variation in the lower reaches of the Duplin as water from Doboy Sound (influenced by the Altamaha River) is advected in Kjerfve (1973). The upper reaches are generally well mixed, both vertically and along channel, and are isolated from the sound by the sinuous nature of the channel. Temperatures in the upper region of the Duplin are warmer than in the lower region and increase toward the head. The maximum tidal excursion in the lower reaches is approximately 4 km and the creek is thought to have three tidal prisms (Ragotzkie and Bryson, 1955).

While previous studies in the Duplin have concentrated on hydrographic measurements of transport and horizontal mixing the objective of the work presented here is to examine the heat budget in the Duplin and to quantify the effect on water column temperature of the neighboring sound, the channel morphology and the extent of intertidal salt marshes and marsh creeks. The data presented here is based on two mooring experiments, designated DUPLEX I and II, during late summer 2003, over a 43 day deployment, and spring 2004, over a 79 day deployment, as will be described in Section 3. Section 2 details the various terms considered in constructing a heat budget for these waters along with their relative importance. Section 4 describes the two temperature regimes of the upper and lower Duplin River and examines the relative importance of direct, tidal and marsh heating on both hourly and daily averaged/seasonal scales. Finally Section 5 summarizes the findings and discusses implications for understanding the importance of marsh processes to a tidal creek.

2. Heat budget equation

The heat budget in estuarine waters is a balance between heat storage in the water column, advective heat fluxes, atmospheric heat fluxes and heat exchanges with the boundaries (Smith, 1983). Following the methods of Stevenson and Niller (1983), the vertically integrated heat content over the whole water column is

$$h\frac{\partial T_a}{\partial t} + h\boldsymbol{v}_a \cdot \nabla T_a + \nabla \cdot \left(\int_{-h}^{0} \widehat{\boldsymbol{v}}\widehat{T}\,\mathrm{d}z \right) + \cdots + (T_a - T_{-h})\left(\frac{\partial h}{\partial t} - \boldsymbol{v}_{-h} \cdot \nabla h + w_{-h} \right) = \frac{Q_0 - Q_{-h}}{\rho C_p}, \tag{1}$$

where molecular diffusion is neglected, h is the time varying water depth, $T_a = 1/h \int_{-h}^{0} T\,\mathrm{d}z$ and $\boldsymbol{v}_a = 1/h \int_{-h}^{0} \boldsymbol{v}\,\mathrm{d}z$ are depth averaged temperature and horizontal current, respectively, $\widehat{T} = T - T_a$ and $\widehat{\boldsymbol{v}} = \boldsymbol{v} - \boldsymbol{v}_a$ are deviations from the depth averaged quantities, w is the vertical current and $\nabla \equiv (\partial/\partial x, \partial/\partial y)$ is the horizontal gradient. Our coordinate system adheres to the estuarine convention with the origin at the head of the Duplin where x is the along channel direction which is positive toward the mouth, y is the cross-channel direction and z the vertical, which is positive up. The subscript 0 indicates a quantity at the surface and the subscript $-h$ indicates a quantity at the bottom. The vertical heat flux through the water surface is Q_0, the vertical heat flux through the sediment at the bottom is Q_{-h}, ρ is the water density and C_p is the specific heat of sea water, both calculated as a function of temperature and salinity.

Examining the terms of Eq. (1) in order; on the left-hand side the first term, $h\partial T_a/\partial t$, represents the depth integrated storage of heat in the water column and is our primary measured variable in the heat budget. The second term, $h\boldsymbol{v}_a \cdot \nabla T_a$, represents the depth integrated horizontal advective flux of heat past the mooring and is expected to be a major term in the heat budget. The third term, $\nabla \cdot (\int_{-h}^{0} \widehat{\boldsymbol{v}}\widehat{T}\,\mathrm{d}z)$, represents the horizontal divergence of heat due to depth correlations between the vertical velocity and temperature profiles. The fourth term, $(T_a - T_{-h})(\partial h/\partial t - \boldsymbol{v}_{-h} \cdot \nabla h + w_{-h})$, represents the entrainment of heat across the bottom boundary of the system. The right-hand side expresses the radiative exchange at the boundaries where Q_0 is exchange between the water and the atmosphere and Q_{-h} is exchange between the water and the sediment.

The heat entrainment term may be simplified by noting that the no-slip boundary condition at the creek bed requires that the horizontal current at the bed, $\boldsymbol{v}_{-h}$, must be zero and the