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Water and sediment temperature dynamics in shallow tidal environments: The role of the heat flux at the sediment-water interface

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ABSTRACT

In the present study, we investigate the energy flux at the sediment-water interface and the relevance of the heat exchanged between water and sediment for the water temperature dynamics in shallow coastal environments. Water and sediment temperature data collected in the Venice lagoon show that, in shallow, temperate lagoons, temperature is uniform within the water column, and enabled us to estimate the net heat flux at the sediment-water interface. We modeled this flux as the sum of a conductive component and of the solar radiation reaching the bottom, finding the latter being negligible. We developed a "point" model to describe the temperature dynamics of the sediment-water continuum driven by vertical energy transfer. We applied the model considering conditions characterized by negligible advection, obtaining satisfactory results. We found that the heat exchange between water and sediment is crucial for describing sediment temperature but plays a minor role on the water temperature.

1. Introduction

Despite wide interest in understanding biological and geomorphological dynamics in lagoon and estuarine environments (Likens, 2010), energy exchanges at the sediment-water interface in shallow water bodies are rarely studied and remain poorly understood.

Temperature dynamics is a first order control of physical and biological processes in aquatic ecosystems in general, and in coastal systems in particular. For example, water temperature variations (e.g. related to climate change or local thermal pollution) can create the conditions leading to dramatic ecological change (e.g. due to alien species invasions, Wolf et al., 2014) with major associated physical and geomorphological alterations. The temperature state of the water column and of the sediment also controls water clarity (Williamson et al., 2009) and drives biological processes, especially in semi-enclosed environments, e.g. lagoons and estuaries, often characterized by long residence times (Viero and Defina, 2016). Further, dissolved oxygen levels are a decreasing function of water temperature (Lee and Lwiza, 2008), such that hypoxia phenomena (i.e. depletion of dissolved oxygen below $2-3$ mg l^{-1}) and abrupt ecosystem changes can be triggered by temperature variations (Kemp et al., 2005). Organic matter production and decomposition in the sediment-water continuum is also directly linked with temperature, as are the associated greenhouse-gas (chiefly Carbon Dioxide and Methane) emission and uptake (Battin et al., 2009). Temperature at the sediment-water interface is a main determinant of the growth and survival of microphytobenthic biomass: a $5^{\circ}C$ variation of the surface sediment temperature can lead to a 20% reduction in microphytobenthic photosynthetis (Guarini et al., 2000), thereby decreasing the production of stabilizing biofilm and affecting morphodynamic evolution (MacIntyre et al., 1996; Marani et al., 2010; Paterson, 1989). Temperature in the underlying sediment layers is a major determinant of biochemical kinetics and of the recycling of nutrient and toxic materials within the sediment column (Fang and Stefan, 1998).

The approaches for modeling temperature dynamics and energy fluxes in aquatic systems found in the literature can be categorized under three main types: regression models, semi-empirical models, and process-based models. Regression models (Cho and Lee, 2012; Sharma et al., 2008) identify the main predictors of the state variables and the statistically-based relation among them (e.g. through Bayesian multiple regression). Semi-empirical models (Kettle et al., 2004; Piccolroaz et al., 2013) are based on parameterized formulations drawn from physical principles. The parameters introduced usually lose their direct physical meaning and must be defined through calibration. Regression and semi-empirical models provide simplified representations of the physical processes at play, with the advantage of involving less input information

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and computational burden. They are typically used for long-term analyses and applications focus on deep waters away from the coastal zone. Process-based energy balance models (Fang and Stefan, 1996; Martynov et al., 2010), like the one developed in this paper, are based on a physically-based description of radiative, conductive, and advective energy transfer within the water-sediment continuum. Calibrating and running these models requires accurate time series of input meteorological data. Process-based models, however, allow the detailed investigation of the relative role of the physical processes involved and the development of an understanding of their relative importance under different forcing conditions. This latter advantage is exploited here to identify the magnitude and controls of sediment-water interface energy exchanges. To our knowledge, few studies have investigated the water temperature dynamics and energy balance in shallow coastal environments (e.g. Bouin et al. (2012); Umgiesser et al. (2004)). Even fewer studies focus on the description of energy exchanges at the sediment-water interface. Heat exchange at the sediment-water interface was studied in coastal regions to describe temperature evolution in bed sediments (Guarini et al., 1997; Smith, 2002), but without fully solving for the two-way coupling of sediment-water energy fluxes. The mutual interaction between water and sediment temperature was studied in lakes (and in absence of tidal fluctuations) to determine the dynamics of temperature in the underlying bed sediment (Boike et al., 2015; Fang and Stefan, 1996) and of the hypolimnion warming induced by seiche oscillations (Kirillin et al., 2009; Nishri et al., 2015).

The aim of the present study is to investigate the evolution of the temperature profile in the water-sediment continuum in a very shallow tidal environment. In particular, we aim to analyze, observationally and numerically, the temporal variation of the vertical temperature profile within the sediment-water continuum, with particular attention to the energy flux exchanged at the Sediment-Water Interface (herein after SWI). Our analysis focuses on a study site located in the Venice lagoon (Italy), where temperature was measured at several points within the water and the sediment column with time resolution of 5 minutes for about one year. Observations were used to compute the heat flux at the SWI and interpreted using a “point” model, describing the time evolution of the vertical distribution of temperature. The heat exchanged at the SWI was then compared with the computed energy fluxes at the Air-Water Interface (herein after AWI) in order to understand its relevance compared to the other vertical energy fluxes.

2. Field observations

2.1. Study site

The Venice lagoon is a shallow tidal basin located in Northeastern Italy with an area of about 550 km^2, a mean depth of about 1.2 m, a typical tidal range of 1.0 m, and a main tidal period of 12 h. It is connected to the Adriatic Sea by three inlets: Lido, Malamocco and Chioggia.

We performed temperature observations in a shallow tidal flat in the northern part of the lagoon (see Fig. 1), where bathymetric and morphological information were already available (Bendoni et al., 2016), between July 2015 and May 2016. The bottom elevation at the measuring station is 0.65 m below mean sea level, and the local tidal range is about 0.80 m during a spring tide and 0.50 m during a neap tide. Therefore, the tidal flat is almost permanently submerged, except for rare meteorological conditions. In fact, the tidal flat emerged only once during the one year monitoring period, and only for few hours.

The study site was chosen quite close to the divide between two sub-basins of the lagoon (D’Alpaos, 2010; Solidoro et al., 2004), i.e. the boundary separating areas to/from which sea water is transported along different paths (through the Treporti channel and the San Nicoló channel). The divide between sub-basins are area (theoretically lines) where the tidally induced water velocity, and the associated horizontal heat transport, is theoretically equal to zero. The position of our study site is therefore the best for limiting the relevance of the advective energy transport to the water column energy balance, thus favouring the estimation and analysis of the vertical fluxes driving the local temperature dynamics and allowing the application of a “point” model.

2.2. Sensors

We deployed temperature sensors in the sediment at depths of 5, 10, 25, 50, 100, 150 cm below the sediment surface and in the water column at 10, 40, 70, 100 cm above the sediment surface. The digital temperature sensors have an accuracy $+/-0.5$ °C with a logging resolution of 0.0625 °C (ControlByWeb, Xytronix Inc. Utah, USA) and were connected to an Arduino Pro328 microcomputer, with a data logging shield (Adafruit, New York, USA). The temperature sensors in the water column were variably submerged by water depending on the local tidal elevation, measured by a pressure transducer (U20 HOBO Onset, Massachusetts, USA). All data were collected at five minutes intervals. The data logger and sensors were powered by sealed lead acid batteries. The duration of a battery charge is temperature-dependent, and was the cause of some missing data. Over a period of 318 days (from July 17 to May 31), we collected data for 134 days, with continuous data-records that are all longer than one week (see Fig. 2). The pressure transducer was in operation only during the first month of the campaign. Water level data from this period were related to the tidal observations recorded at Burano by a tide gauge of the Venice Municipality monitoring network. Tidal levels from the Burano station were then used for the remainder of the data collection window.

2.3. Measurements and data

The almost 1-year-long temperature dataset contains gaps, due to the variable duration of the batteries, but continuous data records are all longer than one week, the longest stretches being longer than one month (see Fig. 2). We were thus able to investigate temperature changes over time scales from minutes to seasons.

The meteorological data necessary to compute the heat fluxes at the air-water interface (AWI) are solar radiation (R_{sun} [W m^{-2}]), air temperature (T_{air} [°C]), relative humidity (H_{rel} (%)), atmospheric pressure (p_{atm} [mbar]), wind speed (V_{wind} [m s^{-1}]) and cloudiness (N (%)).

Except for cloudiness, meteorological and tidal elevation data (h [m]) were obtained, with a 5 min resolution, from the Venice Municipality through its Tidal Forecast and Alert Center. The Venice Municipality monitoring network further provided the sea water temperature (T_S [°C]) measured at the off-shore CNR platform, used to observe the temperature difference between the water at the measuring station inside the Lagoon and at the sea. Table 1 lists the monitoring stations considered for each input parameter. The location of the different stations is shown in Fig. 1. Air temperature and relative humidity are measured at 14 m above the mean sea level at the measuring station of Palazzo Cavalli, while the wind speed is measured at 9 m above the mean sea level at the measuring station of Laguna Nord, where the wind regime can be considered characteristic of the entire northern part of the Lagoon (Carniello et al. (2012), Carniello et al. (2014)). The solar radiation transducer measures all the solar radiation spectrum, with a measuring range of $0.3-3\ \mu$m. More information about the monitoring stations can be found at the Venice Municipality website (Cittá di Venezia (2017)).

We used tidal level observations from the Burano station, the tide gauge closest to our study site, to complement local water depth observations. The comparison of the tidal levels measured at the two locations during the first month of the field campaign (while the pressure transducer was deployed) showed consistent values, with a lag of 5 min (i.e. the tidal signal reaches the Sant’Erasmo station 5 min before it reaches the Burano station). More precisely, the root mean square error between the tidal signal computed using the pressure data and the signal measured at Burano anticipated of 5 min is ≈ 0.01 m, while the value of