Estuarine, Coastal and Shelf Science 111 (2012) 60–66

Contents lists available at SciVerse ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

About the tidal oscillations of temperature in a tidally driven estuary: The case of Guadalquivir estuary, southwest Spain

Jesús García-Lafuente [a,*], Javier Delgado [a], Gabriel Navarro [b], Concepción Calero [a], Manuel Díez-Minguito [c], Javier Ruiz [b], José C. Sánchez-Garrido [a]

[a] Physical Oceanography Group, CEIMAR, University of Málaga, Málaga, Spain
[b] Department of Ecology, Instituto de Ciencias Marinas de Andalucia ICMAN-CSIC, Puerto Real, Spain
[c] Grupo de Dinámica de Flujos Ambientales, University of Granada, Granada, Spain

ARTICLE INFO

Article history:
Received 20 January 2012
Accepted 18 June 2012
Available online 14 July 2012

Keywords:
estuary
temperature oscillations
Guadalquivir river
Gulf of Cadiz
radiational tide
harmonic analysis

ABSTRACT

An 18-month time series of temperature collected in the vicinity of the Guadalquivir estuary mouth has been analyzed to investigate tidal signals in the temperature records. Two sources of similar importance are acting jointly to produce these signals, the gravitational tide generating potential that acts through the tidal currents induced by the vertical tide at the estuary's mouth and the radiational potential whose origin is the sun's radiation. The most important signal is the radiational diurnal S1, which exhibits a seasonal modulation. The next one in importance is M2, introduced via the advective term, which shows semiannual modulation due to the change of sign of the horizontal temperature gradient. The S2 constituent is a mixture of radiational (via the first harmonic of S1) and gravitational contributions, the former being about twice the latter. The harmonic constants of all these constituents are time-dependent so that caution is needed to interpret results deduced from time series of few months.

1. Introduction

The Guadalquivir river flows into the Gulf of Cadiz, North Atlantic Ocean, through a very long (O (100 km)) estuary whose freshwater discharge is controlled by a manmade dam at Alcala del Rio (Fig. 2). The river discharge is partially seasonal with very limited flow in summertime and sporadic floods in late winter–early spring (the wet season) that follow intensive rainfall episodes (Navarro et al., 2011). The main driving mechanism is the tidal forcing at the mouth whose M2 amplitude is around 1 m in the nearby city of Cadiz (García-Lafuente et al., 1990). Taking into account the contribution of other relevant semidiurnal and diurnal tidal constituents the tidal range would be around 3 m (Rodríguez-Ramirez and Yáñez-Camacho, 2008) that, according to Davies (1964) classification, situates the Guadalquivir estuary into the meso-tidal category. Tidal wave is predominantly progressive with some features of standing wave and penetrates around 100 km inland (Alvarez et al., 2001). The low mean river discharge along with the high tidal prism associated to the large tidal range and the small depth of the channel (about 8 m in the mid-channel on average) make the Guadalquivir estuary be a well-mixed estuary with very small vertical salinity/temperature gradients.

The sea surface temperature of Gulf of Cadiz, which is located at mid-latitude in the northern hemisphere, undergoes a noticeable seasonal cycle (García-Lafuente et al., 2004; see also Fig. 3) which is locally enhanced off Guadalquivir river mouth by coastal processes. This feature, already reported in Vargas et al. (2003) and García-Lafuente and Ruiz (2007), is thought to play a significant role in the Gulf of Cadiz inner-shelf circulation and in the life cycle of fish species of commercial interest (Ruiz et al., 2006).

The joint effect of the temperature gradient generated at the estuary mouth and within the estuary itself, the relatively important tidal forcing and the heating of water by the solar radiation (see sketch in Fig. 1 and caption there) gives place to different periodic signals of tidal frequencies in the local temperature records that deserve a detailed analysis. A common technique to investigate these tidal signals is the harmonic analysis that is usually carried out through standard software packages, among which the so called T_Tide (Pawlowicz et al., 2002) is probably the most widely used. The routinary use of this software can lead, however, to erroneous conclusions when dealing with water temperature series in estuaries. This work analyses such temperature signals. In Section 2 we present the dataset. Sections 3.1 and

* Corresponding author. ETSI Telecomunicación, Campus de Teatinos, 29071 Málaga, Spain.
E-mail address: glafuente@ctima.uma.es (J. García-Lafuente).

0272-7714/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecss.2012.06.007

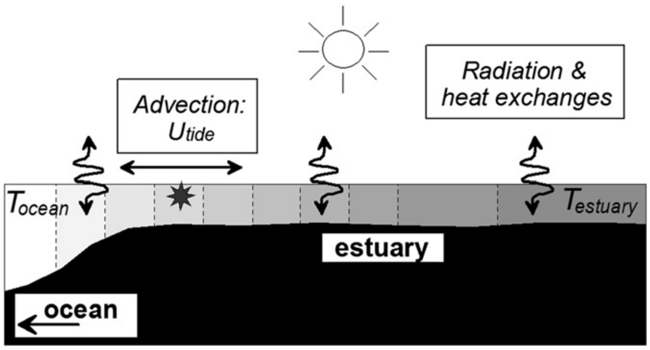

Fig. 1. Sketch showing the two main processes inducing periodic signals in local temperature records at a site nearby the estuary mouth (black star). Estuarine waters are represented by the shaded areas that indicate a progressive variation of temperature from the ocean (T_{ocean}) to the upper estuary ($T_{estuary}$). As far as the estuary is well-mixed, isotherms are vertical (dashed lines) and temperature only has horizontal gradient. The gradient induces local oscillations of temperature when advected by the tidal currents (represented by the double-headed horizontal arrow). The double-headed winding arrows indicate the air–sea heat exchanges among which the short-wave solar radiation is fundamental. These heat exchanges spread all over the estuary with similar intensity and are not particularly space-dependent.

3.2 investigate their origin, while Sections 3.3 and 3.4 deal with their time dependence and highlights some erroneous results that could be obtained using conventional tidal analysis software. Section 3.5 discusses the validity of our approach by analyzing the horizontal temperature gradient and, finally, Section 4 summarizes our conclusions.

2. Data

Surface temperature (1 m below sea surface) and velocity at seven different levels were registered every 15 min by a down-looking Acoustic Doppler Profiler (ADP) placed 9 km upstream of the Guadalquivir estuary's mouth in the central part of the channel (location B7 hereinafter, see Fig. 2) from 01/07/2008 to 24/10/2009. The ADP was a Nortek AS Aquadopp of 1 MHz frequency with nominal accuracy of 1% of the measured velocity. The thermistor measuring temperature, embedded in the ADP, has nominal accuracy and resolution of 0.1 °C and 0.01 °C, respectively. More details on the sensor equipment deployed in B7 can be seen in Navarro et al. (2012).

Sea surface temperature (SST) from infrared imagery was used to illustrate the seasonal cycle of SST at two sites in the Gulf of Cadiz, namely an open sea site and a second site nearby the estuary mouth (GC and GU, respectively, in Fig. 2). Finally, long in situ observations of surface temperature close to the river bank at two sites well upstream the estuary (MR and GL, Fig. 2) were downloaded from the "Red Automática de Vigilancia y Control de la Calidad del Agua" of the Junta de Andalucía website. Fig. 3A shows several years of the temperature series available in this study and Fig. 3B shows a zoom of Fig. 3A in which the tidal-frequency oscillations are easily distinguishable.

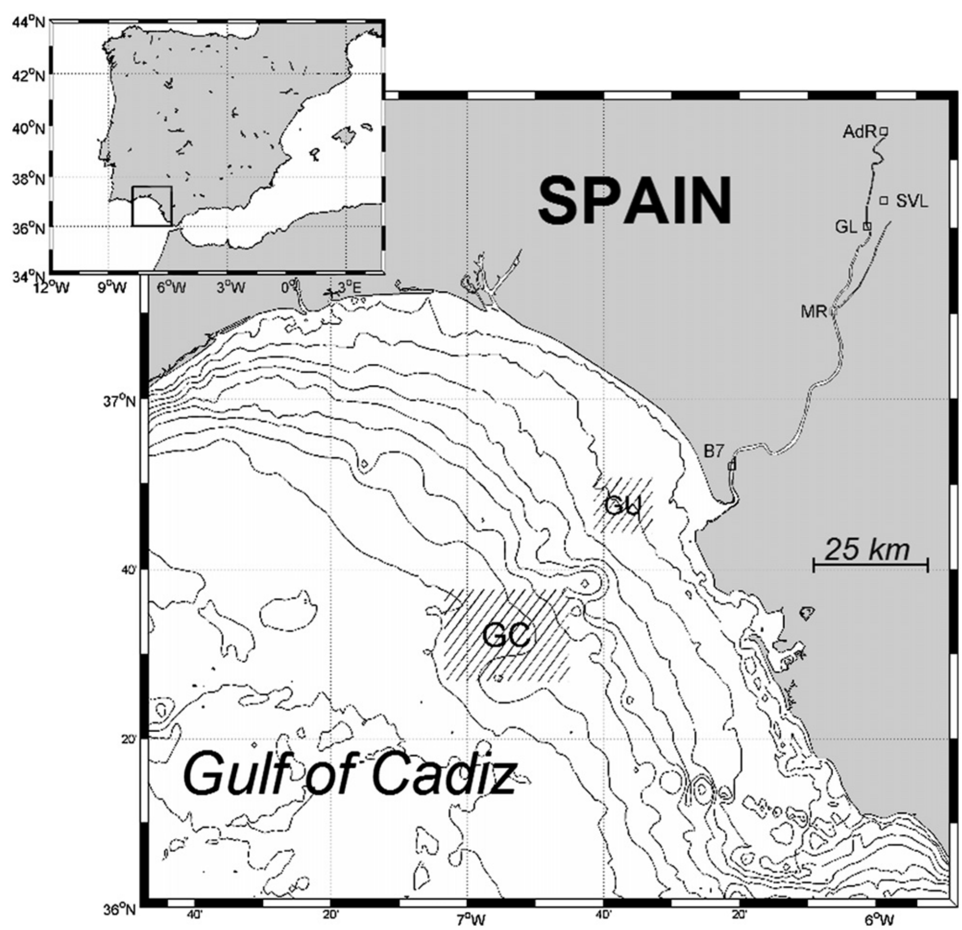

Fig. 2. Map showing the geographical position of the Guadalquivir estuary, in the Gulf of Cadiz area. Acronyms indicate the position of the locations mentioned in the text: GC and GU are the areas where SST has been spatially averaged to provide GC and GU temperature series, respectively; B7 is the position of the buoy where the bulk of data in this study comes from; MR and GL indicate the upstream locations of El Marmol and Gelves temperature stations; AdR is the site where Guadalquivir river is dammed and SVL indicates the location of Seville city.