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Thermal response to the surface heat flux in a macrotidal coastal region (Nuevo Gulf, Argentina)

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ABSTRACT

At mid-latitudes, sea water temperature shows a strong seasonal cycle forced by the incident surface heat flux. As depth decreases, the heat flux incidence is damped by the horizontal flux, which prevents the indefinite growth of the seasonal temperature range. In the present work, cross-shore transport in the west coast of Nuevo Gulf (Argentina) was analyzed. Processes tending to cool the coastal waters in summer and to warm the coastal waters in winter, were identified through temperature measurements, surface heat flux and tidal height. The simplified models proposed here provide a feedback mechanism that links changes in surface heat flux with changes in the horizontal heat flux during both seasons. On shorter time scales, tide produces significant variations in the height of the water column, therefore influencing temperature fluctuations and the direction of the horizontal flow.

1. Introduction

The seasonal heat flux generates strong seasonal variations in seawater temperature in the Argentine continental shelf (Rivas, 2010). In Nuevo Gulf (~42 °S, NG in Fig. 1a) the average annual surface heat flux is positive and there is no input from river run-off into the gulf. The heat balance is closed with the advection of cold water from the adjacent continental shelf.

Horizontal heat flux is usually an important factor in determining the steady state heat balance, but it has little influence on the seasonal signal (Rivas, 1994). Assuming that surface heat flux and temperature can be parameterized with a stationary signal plus an annual harmonic (Rivas and Beier, 1990), the harmonics of temperature and heat flux are directly proportional (Eq. (1)):

$$T_1 = \frac{Q_1}{\rho \ C_p \ d \ \omega} \tag{1}$$

Where T_1 is the annual harmonic amplitude of the seawater temperature; Q_1 is the annual harmonic amplitude of surface heat flux; ρ is seawater density (~1025 Kg/m^3); C_p is the seawater heat capacity (~3990 J/kg °C); d (m) is depth and ω is the annual frequency (2π/365 days).

This simple equation shows a hyperbolic growth of the thermal harmonic amplitude as depth decreases (onshore), unless it is limited by a horizontal heat flow. In the present work, we analyze the surface heat flux and time series of water temperature and tide, in order to elucidate the advective mechanisms that modulate the temperature cycle on a seasonal time scale (months) and on shorter time scales (days to weeks) across the shallow nearshore waters of NG (Fig. 1a).

Unlike temperature, there are no systematic measurements of salinity in the area. The available observations indicate that fluctuations are below 0.05 psu. According to estimates of Rivas and Ripa (1989), the influence of salinity gradients in the generation of baroclinic and barotropic flows may be neglected. We suppose that circulation is governed by tide, wind and vertical temperature gradients.

2. Data and methodology

This study was conducted in an eastward-facing bay (Nueva Bay, NB) located on the west coast of NG, a relatively small embayment on the Argentine continental shelf (Southwestern Atlantic) (Fig. 1). The NG is an elliptical basin with a surface of 2440 km^2 and a

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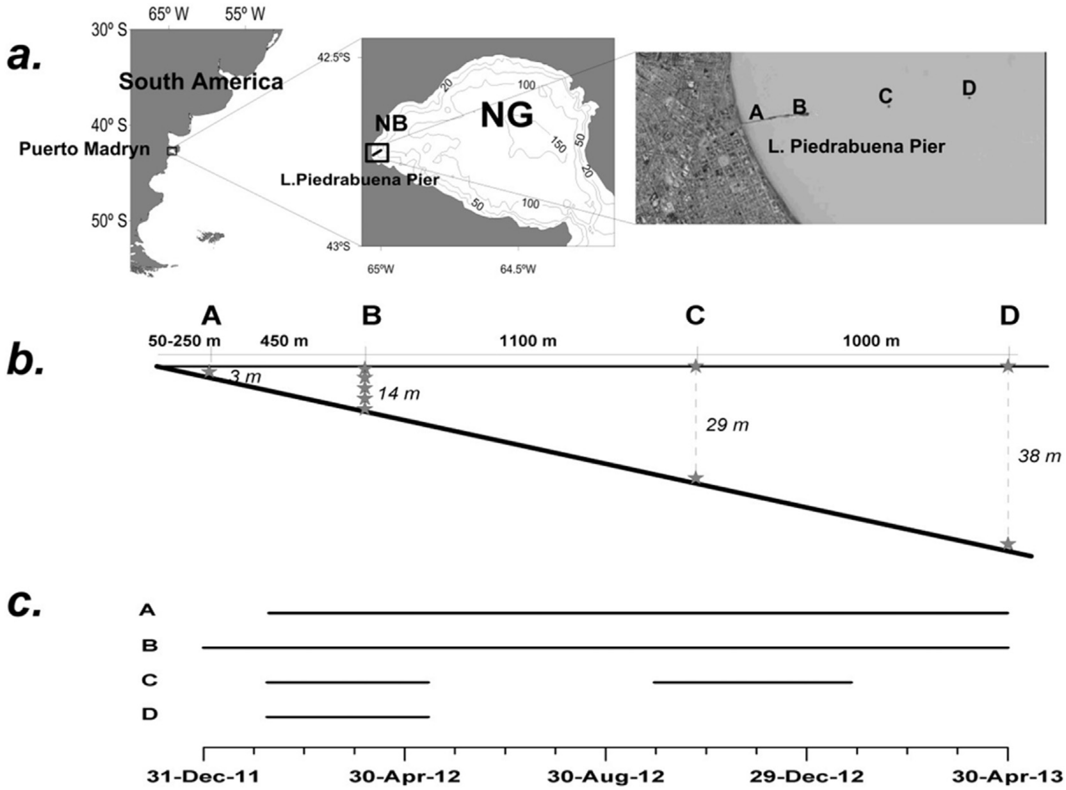

Fig. 1. Geographical location, spatial distribution and temporal extent of the data used. ***a***. Study area and position of the observation sites at Luis Piedrabuena Pier. Bathymetric contours of Nuevo Gulf (NG) and Nueva Bay (NB) in meters. ***b***. Schematic representation of the relative position of data loggers (gray stars) along the cross-shore transect. ***c***. Time periods with temperature records for each site.

maximum depth of 184 m that connects with the continental shelf through a mouth 17 km wide (Mouzo et al., 1978). Dominant tides are semidiurnal with amplitudes of 1.83 m during the neap cycle and 5.73 m during the spring cycle (Tide Tables, (Servicio de Hidrografía Naval, 2015)). The NB is characterized by strong and persistent westerlies, which are driven by the two anticyclones located in the Atlantic and the Pacific oceans, and a low-pressure belt located around 60° S (Paruelo et al., 1998).

Water temperature was measured at four sites over a cross-shore transect along Luis Piedrabuena Pier (Puerto Madryn, Fig. 1a.) using Onset® Hobo U22-001 water temperature loggers (resolution of 0.02 and accuracy of 0.2 °C between 0 °C and 50 °C). At the first site (A), located ~50 m from the low-tide shoreline and at a mean depth of 3 m, one logger was installed 50 cm above the bottom. Two data loggers were installed at each of the remaining sites (B–D), one ~ 50 cm above the bottom and the other one ~50 cm below the surface. Site B was located ~500 m from the low-tide shoreline and at a mean depth of ~14 m. At this site, three additional thermometers were installed evenly distributed between surface and bottom. Sites C and D were located ~1600/2600 m from the low-tide shoreline and at mean depths of ~29/38 m, respectively (Fig. 1b.). All data loggers were set to record temperatures simultaneously every 10 min. Subsequently, those measurements were averaged hourly and the resulting values were used for analysis, smoothing out very high frequency fluctuations. Additionally, hourly anomalies were calculated in order to analyze diurnal and semidiurnal variability. They were computed as the difference between each hourly data and the 24-hour running mean centered on the corresponding datum (eq. (2)).

$$AT(t_i) = T(t_i) - \frac{1}{24}\sum_{j=i-11}^{j=i+12} T(t_j) \tag{2}$$

Where $AT(t_i)$ is the hourly anomaly at time t_i and $T(t_j)$ is temperature at time t_j.

There are observations from several years available for site B, but only those corresponding to the warm seasons are available for sites C and D (Fig. 1c). Hourly predictions of tidal level in Puerto Madryn were obtained from the WXTide software Version 4.7, available at http://www.wxtide32.com/. Surface heat flux (sF) between sea and atmosphere was obtained from the NCEP reanalysis (Kalnay et al., 1996) with a temporal resolution of 6 h. Data from the NCEP reanalysis were compared with previous climatological estimations for the NG based on local atmospheric measurements (Rivas and Ripa, 1989) and were considered representative of local conditions.

3. Analysis and interpretation

3.1. Seasonal scale

Temperature records in the study area ($d \leq$ ~40 m) suggest that seasonal fluctuations were lower than expected considering only sF (seasonal amplitude Q_1 ~ 200 W/m^2 according to NCEP reanalysis, see Fig. 2). The time-series show seasonal signal amplitudes of approximately 7 °C nearshore ($d <$ 14 m and more than 1 year of records), in agreement with Dellatorre et al. (2012). Maximum and minimum temperatures recorded (~22 °C and 8 °C respectively) were not as extreme as expected from the integrated sF during the warm (spring-summer) and cold (autumn-winter) seasons,