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HYDRODYNAMIC RESPONSE IN A MICROTIDAL AND SHALLOW BAY UNDER ENERGETIC WIND AND SEICHE EPISODES

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Abstract

In this contribution we investigate the hydrodynamic response in a micro-tidal and shallow semi-enclosed domain. We chose a set of observations which include currents, hydrography and meteorological data obtained in Alfacs Bay (NW Mediterranean Sea). Short-term response to energetic winds events was found in the hydrography and water velocity observations, sometimes inverting the estuarine circulation or developing one-layered flow. In comparison to previous investigations in Alfacs Bay, we observed that water current variability, and also maximum velocities, were directly related to the development of surface standing waves (i.e. seiches). Mixing mechanisms versus buoyancy sources are studied through potential energy anomaly equation, proving the leading freshwater contribution to stratification, enhanced by heat fluxes in summer. On the other hand, mixing is directly related to winds, mainly in winter and early spring when both buoyancy forces are lower. We also study turbulent bottom mixing by seiches through observations, dimensionless relations and numerical modelling. Seiche induced mixing is suggested as an eventual mechanism that may break the stratification within the Bay under special circumstances.

Keywords:

Estuarine dynamics, Micro-tidal, seiches, high frequency, water mixing, Mediterranean Sea, Ebro Delta, Alfacs Bay, 40.5°-40.7°N, 0.5°-0.8°E

1. Introduction

On estuaries and semi-enclosed bays, variations in current intensity during energetic events modifies the water circulation pattern, affecting water exchange with the open sea (Valle-Levinson et al. 2001), enhancing mixing process (Whitney and Codiga 2011) deepening or even breaking of the pycnocline (Dyer, 1991), changing biophysical properties (Jordi et al. 2008) and determining water quality issues (Grifoll et al. 2010). Moreover, the stratification grade of the water column can modulate the hydrodynamic response of the water body (Guo and Valle-Levinson 2008). The variety of typology of these coastal areas (Dyer, 1997), as well as the wide range of meteorological forcings difficult the generalization and accentuate the importance of detailed analysis in each particular case.

In order to analyse the response of shallow semi-enclosed domains we choose Alfacs Bay, located in the Northwest Mediterranean Sea (Fig.1). Hydrodynamics of this bay have been studied intensively throughout the past 30 years (Camp and Delgado 1987; Camp 1994; Solé et al. 2009; Llebot et al. 2011; Cerralbo et al. 2014). Both Camp and Delgado (1987) and Camp (1994) analyse the hydrography of the Bay through a set of Conductivity, Temperature and Density (CTD) profilers during different periods, classifying the estuary as salt-wedge -with an almost stable stratification throughout the year- due to freshwater fluxes received from Ebro Delta drainage channels. Previous studies identified the wind (Llebot et al. 2013) as the main forcing mechanism in a relatively short timescale. Cerralbo et al. (2014) also identified sea-level variations at temporal scales of a few hours (called seiches), while tidal-induced velocities are negligible due to its microtidal regime -i.e. 10 cm during spring tides (Llebot et al. 2013)-. Despite the well-noted water circulation in Alfacs Bays, several questions remain open. For instance, a detailed description of the hydrodynamic response to energetic episodes is still poorly understood due to the short timescale associated to relatively shallow water depths (max. water depth is 6.5m), in which the frictional layers can overlap, thus influencing the mixing capacity under energetic events (Dyer 1991). In this sense, physical processes at these water depths are complex and challenging due to the amount of forcing involved and the non-linearity of the system (Noble et al. 1996). As a consequence, this contribution focuses on describing the eventual hydrodynamic response to the aforementioned forcings. The link between hydrography (density fields) and hydrodynamics is also addressed. To this end, a series of atmospheric, hydrodynamic and hydrographic variables are used. This example can be used to interpret hydrodynamics and mixing in similar domains.

The contribution is organized as follows: after the introduction (Section 1), a detailed description of study area and the field campaign are presented in Section 2. Then, Section 3 (results) reports the description of the main energetic events observed in both summer and spring field studies. Then a discussion is presented linking the forcing mechanisms and the hydrodynamic and hydrographic response, emphasizing the mixing processes. To complete our findings, numerical model results are used to complement the observations. Finally, the main findings are summarized in Section 5.

2. Observations

2.1 -- Alfacs Bay

The Ebro Delta (NE coast of Spain) forms two semi-enclosed bays, Fangar and Alfacs (north to south respectively), which receive direct freshwater input from the drain channels of rice fields in the surrounding area during 9 to 10 months per year (Serra et al. 2007). Freshwater inputs to the Bay could be divided in three periods during the year: rice fields flooded (April-September), ecological measures addressed to favour aquatic fauna (September-January) and dry rice fields (February-April). Corresponding flows move around $6 \text{ m}^3\text{s}^{-1}$, $7 \text{ m}^3\text{s}^{-1}$ and $0 \text{ m}^3\text{s}^{-1}$ respectively. Some authors have also pointed out the presence of non-described freshwater inputs through the subsoil (Camp and Delgado 1987). The main dimensions of the Bay are 16km from head to mouth, 4km wide and a mouth connection to the open sea of about 2.5km, with an average depth around 4m. This Bay has been classified as a salt wedge estuary with an almost stable stratification. Even during some wind events, the Bay suffers a mixing process and the pycnocline disappears (Camp and Delgado 1987). Solé et al. 2009, using Huang's empirical mode decomposition analysis on meteorological and hydrographic time series, found that drain channels were the main factor controlling the observed stratification. In Llebot et al. (2011), annual cycle analysis (and inter-annual) for temperature, salinity and some ecological indicators are described. Moreover, Llebot et al. (2013) uses the Wedderburn number to identify wind events with enough energy to modify stratification, defining the mixed layer deepening response at wind events. Cerralbo et al. (2014) studied the tidal characteristics of the bay noticing the importance of the 3-h seiches, enhancing their importance and describing the 1-h seiches (corresponding to the 1st seiching mode). On the other hand, several ecological studies noticed the presence of harmful algal blooms (HABs) in some periods and their relation with nutrients and waters from the open sea (Loureiro et al. 2009).

2.2 -- Field Studies

The bulk of the observational data corresponds to two extensive (around 2 months each) studies from July to mid-September 2013 and February to May 2014 (summer and spring campaigns). The data set consists of two Acoustic Doppler Current Profilers (A1 and A2 in Fig.1) configured to record 10-min average data from 10 registers per min and with vertical cells of about 25cm, and also equipped with pressure systems and temperature sensor. Both ADCPs were mounted on the seabed at 6.5m depth. Moreover, three Temperature and Salinity sensors (CTs) were deployed on A2 at 0.7, 1.7 and 3m, and at 0.5, 2, and 4m depth for the summer and spring extensive field studies respectively. Only temperature data from these sensors is presented, because salinity data was too short, less than 15 days, due to biofouling effects. From 2012 to 2014, more than 100 CTD profiles were carried out during 5 intensive daily campaigns (Fig.1 for some profile locations). Moreover, CTD profiles on both fixed stations (A1 and A2) were performed on the deployment and recovering days. All the measurement periods and instruments are summarized in Table 1. Atmospheric data (wind, atmospheric pressure, solar radiation, air temperature and humidity) was

obtained from one fixed land station in Les Cases d'Alcanar (Met-A in Fig.1) mounted on June 26, 2012 to May 8, 2014.

3. Results

3.1 – Wind, hydrographic and hydrodynamic description

Wind roses for both field studies (summer 2013 and spring 2014) are shown in Fig.2. Summer period (Fig.2a) reveals a clear bimodal behavior, without intense winds ($< 5\text{m}\cdot\text{s}^{-1}$), and with prevailing directions from south and northwest. These wind patterns respond to the typical sea breeze patterns, with day time winds blowing from the sea alternating with calm night-time winds, typically present along the entire Catalan coast in these periods (spring to summer). In winter and early spring 2014 (Fig.2b), north-westerly winds were the most energetic ($> 10\text{m}\cdot\text{s}^{-1}$), whilst sea breezes started to appear in late spring. During the both seasons, several energetic north-westerly periods were identified (Table 2).

Longitudinal CTD transects along the main axis of the Bay (in Fig.1 as T1), during warm periods (I-1, I-2 and I-5) for temperature and salinity show similar values (Fig.3a and 3e). Salinity contributions prevail in vertical density gradients, and their variations match with isopycnals (not shown), showing the saltiest water from outer sea in the deepest mouth layers (almost 38 PSU) and the freshest water on the surface (35-36 PSU). Stratification was lower in the inner bay, with lower salinity values on the water column and no signal of sea water mass on the bed. Within the Bay, freshwater was observed at surface layer extending from northwest to southeast, with lateral salinity differences across the Bay of around 2-3 PSU and density variations around $3\text{-}4\text{ kg}\cdot\text{m}^{-3}$. Although freshwater signal was also observed in the mouth, it was more obvious near the drainage channels (Fig.1). Temperature observations revealed a clear diurnal cycle (oscillation range $\approx 2^\circ\text{C}$). Winter data (I-4) exhibited a well-mixed situation in the whole domain (Fig.3c) with almost vertical thermal and salinity isopleths. Temperature remained constant along the Bay with values around 12.5°C ; similar to the value obtained in the open sea ($\sim 13^\circ\text{C}$). Evident gradients were observed in salinity distribution between the in and out. Within the Bay, salinity was almost constant on both vertical and horizontal sections with values between 35 and 36 PSU, whilst in the outer Bay it was greater than 37 PSU, forming an estuarine front in the mouth.

The Brunt-Väisälä frequency, $N^2 = -(g/\rho)(\partial\rho/\partial z)$, at A2 location is shown in Figures 3b, 3d and 3f. Un-stratified conditions ($N^2 < 10^{-3}\text{ s}^{-2}$) were only observable in winter (Fig. 3d), during the closed channel period. In other profiles, double halocline at 1-2m and 4-5m in the water column (N^2 between 0.01 s^{-2} and 0.02 s^{-2}) was observable in both midsummer and late spring (Fig.3b and 3f), showing the largest density differences from surface to bottom. In these profiles, both temperature and salinity contribute positively to water column stratification, thus indicating the important role of both freshwater inputs and heat fluxes. The CTD profiles measured agree with previous studies that identify the pycnocline at 3-4m depth (Camp 1994; Llebot et al. 2013). However, our observations show well-mixed water column under particular conditions, as observed in (Camp and

Delgado 1987), in contrast to previous studies which define quasi-permanent stratification throughout the year (Llebot et al. 2011).

Temperature data from CTs sensors deployed in the Bay (A2 in Fig.1) for both summer and spring periods is summarized in Fig.4 (images a and b respectively). In summer, surface temperature time series showed a clear diurnal pattern. This pattern occurred until the end of summer. Differences between surface to seabed temperatures were greatest at the beginning of summer (6-7°C), decreasing until the start of August, when suddenly (few hours) surface temperatures fell by more than 4°C. From the end of July to early September, these differences were negligible (around 1-2°C). Finally, during September, two periods of thermal inversion (deeper waters being 0.5-1.5°C warmer than surface waters) occurred. Correlation between surface and bottom waters was low, indicating no relation between surface and bottom layers in a short time scales. During winter and spring (Fig. 4b), well-mixed conditions were more prevalent, with mean temperature gradients between surface and bed being lower than 2°C. On May 2014, thermal stratification started.

On the other hand, two frequencies revealed significant spectral energy around 0.125 and 0.03125 days⁻¹ (corresponding to periods of 3h and 1h respectively) in water currents, which prevail over the tidal signal (Cerralbo et al. 2014). The effects of these oscillations on water currents were analyzed using wavelet analysis (Fig.5b and 5d). This analysis was performed using software referenced in Torrence and Compo (1998) and using standard Morlet wavelet function. The results allow us to determine periods in which both fundamental (3h) and first mode seiches (1h) are the most energetic contributors to sea-level and corresponding velocity variations (Fig.5).

The axis system was rotated using Principal Component Analysis (PCA) in order to obtain the maximum variability, which approximately follows an alongshore direction. Thus, alongshore direction was rotated 59° -similar to main direction described in Camp (1999)- and 36° for summer and spring campaign on A1, and 21° and 26° (anti-clockwise positive from North) for A2 in the same periods. These directions account for 95% and 96% of the depth-averaged velocity variability in summer (Fig.5a and Fig.5c A1 and A2 respectively), and 90 and 94% in spring for both A1 and A2 respectively. Data and some statistical values are summarized in Table 3. No appreciable rotation was observed in the variability angle direction for each layer (differences of +/- 2°). The principal eigenvector from Empirical Orthogonal Functions -EOF analysis description in Emery and Thomson, 2001- explained around 74 and 71% (summer) and 74 and 74% (spring), for A1 and A2 respectively, and showed a clear barotropic behavior. On the other hand, baroclinic behavior (defined as an eigenvector crossing 0 line in Winant and Bratkovich, 1981) was determined by the second and third eigenvector. These values are summarized in Table 3. Cross-shore EOF for both locations (not shown) shows baroclinic behavior for all the eigenvectors. The results of EOF analysis (Table 3) highlight the importance of barotropic seiche in this Bay at short timescales. An analysis of maximum alongshore currents revealed maximum values during summer for both locations (and related to seiches). Maximum cross-shore components were identifiable during

spring periods with negative values and related to wind events. On the other hand, astronomic tide represents a second-order forcing due to the microtidal behavior. Maximum depth-averaged tidal currents obtained using TTIDE software (Pawlowicz et al. 2002) were approximately $2\text{-}3\text{ cm}\cdot\text{s}^{-1}$.

3.2 Hydrodynamics during seiche and wind episodes

Different seiche events were defined throughout the summer and spring periods. The events are defined as S^{*-**} , where $*$ could be 0 or 1, and indicates the standing wave mode (0 for fundamental mode, and 1 for the first one), and $**$ indicates the corresponding number of event. The definition of each event was made according to the observation of corresponding wavelet figures (summer wavelets for A1 and A2 in Fig.5). Most clear episodes are summarized in Table 2, and also indicated with a dashed box in Fig.4 and Fig.5. In Fig.6a and 6b, velocity profile for one-day length and for two periods, S0-1 (in A1) and S1-1 (A2), are shown. One-layered motion of the water column is clearly observable for both cases. The maximum alongshore velocities for S1-1 are almost $50\text{ cm}\cdot\text{s}^{-1}$ in A2 and approximately $40\text{ cm}\cdot\text{s}^{-1}$ in A1, and in opposite phase. This agrees with the 1st seiche mode described in (Cerralbo et al. 2014), defining the seiche node closer to A1. For fundamental 3-h seiches (S0-1, in Fig.6a) maximum current speeds were around $40\text{ cm}\cdot\text{s}^{-1}$ in A1 and $24\text{ cm}\cdot\text{s}^{-1}$ in A2. This fundamental mode was persistent during summer consistent with wavelet analysis presented in Fig.5b. The mean seiche excursion length, defined here as the distance travelled by a body of water between low and high water slack, could be estimated from the RMS current speed times the half tidal period (Walters et al. 1985). For first mode (S1-*) events was around 650m in A2 and 500m in A1 (in 30 minutes). For fundamental mode, these excursion lengths move between 1400m for A1 and 700m for A2 (in 90 minutes). Finally, effects of these seiches on temperature records are recognizable in summer (S1-1), and in spring (S1-2) in Fig.4a and Fig.4b. Intensive CTD studies did not coincide with any of the intense seiching episodes observed, so no relationship between density fields and seiches could be determined using CTD profiles.

On the other hand, two energetic events (intensity $> 10\text{ m}\cdot\text{s}^{-1}$) of north-westerly (Mistral) winds were selected in order to understand the short-time response of the Bay to the most energetic winds in this area (Table 2). On summer, late at night on August 7, 2013 (NW-1) when the sea breeze stopped, an N-NW intensification ($10\text{ m}\cdot\text{s}^{-1}$) was observed in Met-A station (lasting for 3-4h). In A2, the alongshore velocities did not reveal a clear effect due to the N-NW wind; but the effects were observable in cross-shore velocities (Fig.6d), showing a two-layer flow with a southward component at the surface layers. On A1, usual estuarine –two layered- circulation on alongshore currents were observed (not shown) with no noticeable effects of wind stress. In spring, N-NW are more frequent and with higher speeds (Fig.2). In most episodes, the wind blows for more than 12h at intensities around $10\text{ m}\cdot\text{s}^{-1}$ with gusts of approximately $25\text{ m}\cdot\text{s}^{-1}$ for NW-2. Effects on water circulation are clearly observable on A1 on March 23 (NW-2). Whereas alongshore currents were dominated by seiching, cross-bay wind effects were clearly observed on the cross-shore component (Fig.6c), disappearing the two-layered structure observable on 23rd morning. This

structure disappeared as the hours passed (as wind increased in intensity) and circulation became unidirectional, with water temperature mixing observed in Fig.4b (NW-2).

In order to analyse the current dependence with sea breeze winds, we plotted the Progressive Vector Diagram (PVD) in Fig.7. Surface currents in A2 (thick red line) followed the main breeze direction (on surface) while bottom currents (thin red line) showed lower speeds and opposite direction proving a two-layered structure. During this period the behavior in A1 (black lines in Fig.7) was almost the same but more oriented towards the main axis (and winds) of the Bay. Circulation reversing due to sea breeze was observed on several days during the summer period, thus indicating that alongshore wind stress contribution to water advection inside the Bay easily balances the gravitational circulation.

4. Discussion

4.1 Hydrodynamic response

The different energetic events presented in the previous section should be summarized into two types: winds and seiches, both representing different response to energy inputs in the Bay. Wind effects are transmitted to the water column from the surface layers and through the sea level gradient (wind set-up) generated along the main blowing wind axis (Pugh 1996). In idealized test case, with wind blowing along the main axis of the bay, frictional time response could be approximated as: $t_f = H / (2u_* \sqrt{C_d})$, where H is the water depth, u_* is the frictional velocity ($u_* = \sqrt{\tau/\rho}$) and C_d is the drag coefficient (supposing 0.002) (Csanady, 1982). For instance, winds of $5\text{-}10 \text{ m}\cdot\text{s}^{-1}$ would imply a frictional equilibrium after 3-1.5 hours considering 6m water depth. This frictional time response is shorter than most of wind events. Moreover, the time response dependence on water depth across the bay –i.e for shoals of 3m depth the corresponding time response moves between 1.6 and 0.8h- promotes a velocity gradient (dv/dx) between central areas and shoals. Typical surface frictional layers (10-50m, Haidvogel and Beckmann (1999)) are higher than the maximum depths in the Bay, reinforcing the importance of the frictional term in the hydrodynamic response. Moreover, the bathymetry and coastline would drive the circulation in their vicinity, enhancing the circulation parallel to them (Csanady 1973). In this sense, observations in Alfacs bay case have shown alternating periods with a moderate (e.g. sea breeze in Fig.7) and low correlation (e.g. north-western event in Fig.6d) between currents and winds. It is evident that other processes entirely mask the linear response, assuming a linear behavior as an expected direct response of the water current at wind forcing. It means that the hydrodynamic response is conditioned by nonlinear and non-stationary processes due to the intricate bathymetry, the unsteadiness of the wind magnitude and direction and probably the spatial wind heterogeneity in the bay (Cerralbo et al., 2015). Aside Alfacs Bay, this behavior is common in highly-stratified and shallow estuaries where the correlation with wind events is complex and nonlinear (Noble et al. 1996, Narváez and Valle-Levinson, 2008).

On the other hand, many studies in Alfacs hydrodynamics and similar domains have focused on wind-induced circulation and its effects on hydrography (Camp, 1994; Mancero-Mosquera et al. 2010; Llebot et al. 2011), but none of the aforementioned contributions have investigated in detail the influence of seiching on measured water velocities, due to the fact that most hydrodynamic studies on bays underestimate high-frequency processes averaging recorded data (hourly or even 3-hourly averaged). For instance, Llebot et al. (2013), defined seiche sea level amplitudes at an order of 10^{-2} m in and tidal excursion length around 70m for 3h seiches, thus not considering oscillations with periods lower than 3h. Our analysis confirms the ongoing presence of seiches in both field studies, as observed in sea level in Cerralbo et al. (2014). In this case, the simple relaxation of the wind setup could be a source of seiches in the Bay (Boegman 2009). The fundamental seiche mode has been reported using sea-level data from previous studies in Alfacs Bay. These oscillations are important for flux interchange through the mouth of Alfacs Bay (Camp and Delgado 1987) and the potential mixing of water masses in the shallowest areas and effects on the feeding dynamics of sessile filterers (Camp 1994). Examples of seiches and their influence on mixing and re-suspension processes are found in Ostrovsky et al. (1996), indicating that cross-isopycnal mixing occurs at the littoral zone as a consequence of seiche activity, or in Jordi et al. (2008), who relate different sediment re-suspension episodes to seiche currents. During both field campaigns, it has been proved that the most energetic non-stationary processes occur in these seiche periods (Fig.5 and Table 2). Several examples are found in similar microtidal and semi-enclosed bays (Luettich et al. 2002; Niedda and Greppi 2007). The aforementioned works focused on similar environments but differences were found in the oscillating modes due to area and geometrical effects. It is worth noting that we found response at two oscillating modes (≈ 1 h and ≈ 3 h) in contrast with other bays where only the fundamental modes occur, and according to similar examples described in (Rabinovich 2009). The mechanisms of seiching excitation are linked to atmospheric convection cells which cause fluctuation in wind speed and atmospheric pressure (i.e. Rabinovich and Monserrat 1998; de Jong and Battjes 2004). In our observations, no clear relationship was noted between seiches and wind or atmospheric pressure variations. The generation mechanism is out of the focus of our work and deserves an investigation using longer atmospheric and sea-level data time series, as well as complementary numerical outputs.

4.2 Potential Energy Analysis

Balance between positive buoyancy forces, heat fluxes and freshwater inputs to wind stress, seiches and tidal stirring should determine the distribution of T/S along the water column, defining it as stratified or mixed. The usual approach to compare these terms was described through the potential energy anomaly (Simpson, 1990), defined as the difference of potential energy before and after mixing. The equation for potential energy anomaly -also referred to as stratification parameter in Simpson, 1981- which originally only takes into account heat fluxes as buoyancy forces, is summarized as:

$$\frac{d\theta}{dt} = \underbrace{\frac{\alpha g \overline{Q_I}}{2C_p}}_{\text{Heat}} + \underbrace{\frac{gR\Delta\rho}{2A}}_{\text{Freshwater}} - \underbrace{\frac{ek_b\rho_w|\bar{u}|^3}{h}}_{\text{Seiche \& Tides}} - \underbrace{\frac{e_s C_d \gamma_s \rho_a \bar{W}^3}{h}}_{\text{Wind}} \quad (1)$$

Where C_p is the specific heat of seawater at constant pressure, Q_I is the net surface heat flux, h is water depth, g is gravity, α is the thermal expansion coefficient ($2.08 \cdot 10^{-4} \text{ }^\circ\text{C}$ at 20°C), e_s is the wind mixing efficiency, C_d is the surface drag coefficient (0.0012), k_b is the bottom drag coefficient (0.002), ρ_a is air density, γ_s is the ratio of the wind-induced surface current to the wind speed (0.02), W is wind speed, R is river input, A is the area of freshwater influence and $\Delta\rho$ referring to density difference between both fresh and salt waters. The wind mixing efficiency (e_s) is assumed to be 0.03 following Atkinson and Blanton (1986) and tidal/seiche efficiency (e) 0.005 from Simpson and Sharples (2012). The overbar (-) indicates daily averages. Several authors have applied potential energy balances oriented to describe mixing and stratification processes at different scales and regions (e.g. de Boer et al. 2008; Simpson and Sharples, 2012, Grifoll et al. 2013). The Q_I is obtained from direct measurements on Alfacs Bay and following the relation between solar heating (Q_s) which accounts for the albedo effects (Al), net longwave radiation (Q_b), sensible (Q_c) and latent heats (Q_e), as:

$$Q_I = Q_s(1 - Al) - Q_c - Q_e - Q_b \quad (2)$$

Details on calculation of each term through the corresponding bulk formulas are explained on appendix. The results for the different observational periods are presented on Table 4. Equation (1) considers heat fluxes inputs as buoyancy forces (first term on right hand side) and freshwater inputs through the rice channels (second term). The inclusion of this second term is not simple due to the freshwater area of influence. In this sense, this area itself is a function of the freshwater input and the mixing process, so is part of the solution rather than a fixed input parameter (Simpson et al. 1990). Even more complex approximations were made by taking into account gravitational circulation due to freshwater inputs, we have considered these inputs as uniformly distributed over the surface, as was proposed for precipitation rate in (Simpson et al. 1990), thus defining precipitation as R/A . Freshwater contribution is considered $10\text{m}^3 \cdot \text{s}^{-1}$ in both summer and spring conditions. The area in which this flux is believed to be distributed is 40km^2 . The freshwater buoyancy work is then considered to be almost constant and around $30 \cdot 10^{-6} \text{ Wm}^{-3}$ (Table 4), which is the same order of magnitude as heat work by net heat fluxes in summer and spring. At this point, and taking into account that the T/S characterization of the bay has shown high horizontal variability due to the freshwater influence much more noticeable closer to the channels, the same term has been obtained but considering a smaller area of 10km^2 (approximation to area on the northern shore of the bay with width of around 1km), thus leading to 10^{-4} Wm^{-3} , indicating the dominance of this input in the potential equation. These results agree with Solé et al. (2009), who considered the importance of freshwater inputs in stratification. Moreover, both stratification terms act together in summer, whereas in winter-spring heat fluxes can contribute negatively to water

stratification. During the closed channels period (January to late March or beginning of April) the freshwater term must be 0. However, several authors have observed stratification (lead by salinity) even with closed channels, thus indicating the existence of other freshwater sources in the bay (Camp and Delgado 1987). Heat fluxes show similar mean values for both periods. During winter-spring period the daily values moves from $+10 \cdot 10^{-6}$ (February, implying mixing) to $-30 \cdot 10^{-6} \text{ W} \cdot \text{m}^{-3}$ (April). During summer, highest contribution to stratification was on July around $-40 \cdot 10^{-6} \text{ W} \cdot \text{m}^{-3}$, but positive values during September and coinciding with dry and cold winds on cloudy days were observed. On Table 4, daily values for heat fluxes during the seiche events are resumed, being always negative and contributing to stratify the water column.

Mixing terms present noticeable differences between one another. Winds in the Bay reveal their importance during both periods. In the summer mean values are one order of magnitude lower than freshwater and heat fluxes. However, maximum daily values during windy events (NW-1) shows values of $20 \cdot 10^{-6} \text{ W} \cdot \text{m}^{-3}$, contributing to mix the water column as shown in Fig.4 due to surface cooling and shear. In winter-spring, the work done by winds in mixing is one order of magnitude higher than in summer, coinciding with small or negative heat contribution to stratification (winter) and the closing of drainage channels. This situation encourage a major occurrence of mixing events in Alfacs Bay as we show in the N^2 profiles (Figure 3.d) and being consistent with other winter observations (Camp and Delgado, 1987). During winter and spring, mistral wind events lasting for more than one day imply maximum values for this term on equation (1) around $2 \cdot 10^{-4} \text{ Wm}^{-3}$. This value clearly exceeds the stratification terms, even considering the freshwater effects on the proximities of drainage channels (defined around -10^{-4} Wm^{-3}).

The water currents associated to the third term in equation 1 could be related to astronomical tide or seiches as: $\bar{u} = \bar{u}_{tides} + \bar{u}_{seiche}$. Tidal stirring ($\bar{u}_{tides}$) is demonstrated to be a negligible term in Alfacs Bay, showing values around 3 and 4 order of magnitude lower than stratifying terms. The seiche stirring term ($\bar{u}_{seiche}$) is associated at measured depth-averaged current speed. The observed velocities may include effects from other hydrodynamic forcing as pressure gradients (in and out the bay) or winds, even during the seiche events are low as we shown in Figure 6a and 6b. The mean values for both seasonal period's shows values much lower than the stratification terms, indicating the low importance on mixing the water column at this time-length scales (see Table 4). Nevertheless, the energetic scenario mean values corresponding to the seiche events shows the maximum mixing contribution of this term during that days.

These results show how in daily scales the bay is stratified due to both freshwater and heat fluxes terms. The only term which can balance the stratification due to freshwater input is wind. On the other hand, and on shorter time length scales (<day), seiches seems to be able to balance not only the heat fluxes but also the freshwater term. In order to better understand this possible source of mixing, additional considerations using dimensionless number and numerical simulations are presented in the next section.

4.3 Mixing due to seiche-induced bottom friction

The lack of salinity measurements during the energetic episodes was a handicap to describe the full mixing processes from observations. However, Fig.4a shows a sudden change in temperature time-series during S1-1. Sea water temperature converge around 26°C in the whole water column suggesting a mixing of the surface and bottom water masses. During this event, the bottom temperature differences between A2 and A1 were greater than 6°C. We dismissed the effects of advection from the outer Bay because open-sea water temperature tends to be colder, as seen in Fig.3c. A possible effective mixing due to seiche-induced turbulence seems to occur. Events related to the fundamental oscillating mode (S0-1 and S0-2) do not show noticeable changes in temperature profiles. However, during these events (and also S1-2) the temperature gradients in the water column were smaller than S1-1, being difficult to identify the water mixing from temperature observations.

Usual approximation to estimate mixing due to barotropic oscillation flow is given by the dimensionless Richardson layered (or Bulk Richardson) number:

$$Ri_L = \frac{\Delta\rho gh}{u^2 \rho_o} \quad (3)$$

Where $\Delta\rho$ is density gradients from surface to bottom layers, g represents gravity, h is depth, ρ_o is reference density and u represents the characteristic velocity of oscillatory flow. Values lower than 2 in of Ri_L indicate fully-developed mixing, while greater than 20 means turbulence is ineffective in decreasing stratification (Dyer, 1994). The characteristic velocity ranges from the near-bottom layer velocity (Dyer 1991) to the mean velocity at the water column (Noble et al. 1996). Considering the observed mean depth-averaged velocities in A1 and A2 during each scenario (table 2), we can estimate the theoretical maximum density differences which the bottom-induced turbulence is able to mix. During S1-1, mean speed on A2 is around $0.2 \text{ m}\cdot\text{s}^{-1}$, which implies density differences of $1.2 \text{ kg}\cdot\text{m}^{-3}$ (for $Ri_L=2$). These density differences are of lower than observed during summer, but higher than winter scenario (Fig.3c and d). In this case, seiche-induced bottom mixing is expected to influence water column stratification (S1-1 in Fig.4b) without full mixing. During spring (S0-2 and S1-2) seiche-induced circulation is weaker and the mean velocities do not exceed $0.13 \text{ m}\cdot\text{s}^{-1}$ in A2. For these cases, $Ri_L=2$ implies density differences of $0.5 \text{ kg}\cdot\text{m}^{-3}$, similar to the density differences observed on winter, and probably influencing the mixing on water column. Taking into account that the most common seiche events are related to fundamental mode (S0-1 and S0-2) with a mixing threshold on A2 around $0.5\text{-}1 \text{ kg}\cdot\text{m}^{-3}$, we suggest that turbulence provided by the seiche oscillatory flow seems not enough to decrease stratification in most cases. However, in some special circumstances, i.e. S1-1, noticeable water column mixing below the pycnocline may occur. In this case, the bottom boundary layer would occupy an important fraction of the water depth, thus redistributing the temperature from middle layers over the water column below pycnocline (as we show in the temperature time-series), and even mix the entire water column. A similar picture was shown by (Dyer 1991) in a tidal estuary with the salinity profile when both internal mixing and

bottom boundary layer coincide in the pycnocline. Consequently, the possible mixing of the water column would depend not only on density variations and velocities, as well as on corresponding depths.

To analyse the relationship between the bathymetry and velocity pattern on the seiche mixing capacity we have implemented a hydrostatic 3-D numerical model. The model used is ROMS (Shchepetkin and McWilliams 2005, see implementation summary in Appendix 2), with a grid resolution of 100m and 12 levels on the vertical. Modelling details, configuration domain and validation are shown in (Cerralbo et al. 2014). In this case, an extended version has been implemented, considering baroclinic effects (heat fluxes and freshwater as buoyancy sources). The freshwater inputs are distributed on 8 points along the north coast (Fig.1), with a total discharge of $\approx 10 \text{ m}^3 \cdot \text{s}^{-1}$. Heat fluxes and winds are imposed from observational data. Two numerical simulations were used to obtain the mean depth averaged current speeds for scenarios S0-1 and S1-1 (Fig.8). For S0-1 (Fig.8a) the spatial distribution of current speeds shows how the highest velocities are located around the bay mouth ($\approx 16 \text{ cm} \cdot \text{s}^{-1}$), with lower velocities on A2 (around $10 \text{ cm} \cdot \text{s}^{-1}$) and calm waters on the inner area. Comparing these velocities with the required velocities to mix the water column according to equation 3, the 3h-seiche (i.e. S0-1) would be able to mix the water column in the bay mouth and over the shoals (depths around 2m) for typical conditions of stratification. However, full mixing in the water column is not expected in the inner area of the bay. Scenario S1-1 (Fig.8b) shows maximum velocities on the A2 vicinity ($\approx 23 \text{ cm} \cdot \text{s}^{-1}$). Equation 3 (with $Ri_L=2$) leads to potential mixing around $1.2 \text{ kg} \cdot \text{m}^{-3}$ in the deepest areas (6.5m) and almost $3 \text{ kg} \cdot \text{m}^{-3}$ for the shallowest (2m depth) regions. Similar to S0-1 case, S1-1 hydrodynamic conditions seems able to mix the whole water column depending on the density profiles (see Figure 3).

In order to complement our results, a numerical test case for S1-1 is shown in Fig.9 considering stable stratified conditions from heat fluxes and freshwater inputs. The seiche is imposed at the contour after 24 hours of spin up leading an oscillatory flow in A2 with peak velocities of $0.31 \text{ m} \cdot \text{s}^{-1}$ and averaged for the entire simulation around $0.2 \text{ m} \cdot \text{s}^{-1}$ (see Fig.9a). The effects of the oscillatory current speed on salinity distribution in A2 is shown in Fig. 9b. The bottom frictional layer raises with the seiche evolution and stabilizes close to the surface. The mixing of the water column at this point is not complete, but an effective reduction of density differences between surface and bottom is clearly observed. When seiche stops, the water column recover gradually the initial density profile.

The salinity profiles at different instants of the numerical simulation (t_0 , t_{14} and t_{22} , where sub index denotes hours since the numerical initialization; see Fig.9b) are shown in Fig.10 for A2 and Mo location. Mo location represents a shallow point over the shoal (3 m water depth). In both points the density profiles are clearly modified by the seiche currents.. In A2 the seiche is not able to mix the entire water column while in Mo the full mixing occurs. The mixing capacity in Mo is larger than $2 \text{ kg} \cdot \text{m}^{-3}$ from surface to bottom, agreeing with the previous Ri_L analysis and previous

hypothesis presented on Camp (1994). The seiche-induced mixing estimated through analytical formulations and numerical modelling agrees with observational data on Fig.4, where $\Delta\rho$ temperature contribution to surface-bottom density differences before and after the S1-1 event (Fig.4) moves from $1.2 \text{ kg}\cdot\text{m}^{-3}$ to $0.5 \text{ kg}\cdot\text{m}^{-3}$ respectively.

These processes would have a decisive influence on the re-suspension and mobilization of sediments and nutrients on the bottom, thus enhancing interchanges of organic and inorganic materials through the pycnocline during particular circumstances. Our results will be useful to relate the seiche dynamics with the role of the nutrients and the biochemical processes observed in the Bay (Loureiro et al., 2009; Llebot et al., 2011). Furthermore, new questions arise from our investigations. For instance, analysis of the meteorological forcing mechanisms responsible for the seiches occurrence as well as their influence over the shoals should be studied in future works through additional observational data. Moreover, the spatial variability in freshwater observed in the transversal CTD transects indicates differences in the velocity threshold to mixing capacity. Additional long-term observations would be desirable to ensure the accuracy of the relation between the seiche-induced mixing and vertical density thresholds. The combined influence of wind and seiche-induced mixing is worthy of future investigations using additional numerical simulations and field measurements

5. Conclusions

The investigation of the hydrodynamic response in semi-enclosed water bodies under shallow and micro-tidal conditions have revealed a short time response at wind stress and the presence of oscillating mechanisms that may control the flow and mixing processes. Our analysis focussed in Alfacs Bay have revealed for the first time a seiche mechanisms which its associated current variability is at least the same order as energetic wind events. On the other hand, the importance of wind as a mechanism capable of reversing estuarine circulation for short periods is observed under summer conditions. Due to the shallowness (order of few meters), a short time-response (order of few hours) in the water column occurs. Stratification or well-mixed conditions are a balance mainly of freshwater inputs and winds according to the size of the terms of the potential energy equation. Heat fluxes in summer periods also contribute to stratifying the water column, thus indicating that not only freshwater influence determines the stratification on the bay. Seiche-induced mixing has been estimated using observational evidences, dimensionless numbers and numerical modelling, showing its theoretical mixing potential under some circumstances (intensity, stratification and water depth). The results and methodology focused in Alfacs Bay could be translated to similar domains in which tidal influence is not the main driving force and other buoyancy and mixing sources are in a similar order of magnitude.

Appendix 1: Heat Flux computations

Net heat flux is defined in equation (2) as the balance between incoming and outgoing heat fluxes. Approximation to them could be assessed using bulk formulas (Simpson & Sharples, 2012). Latent Heat (Q_e , in $W \cdot m^{-2}$) is obtained through:

$$Q_e = 1.5 \cdot 10^{-3} \cdot L_h \cdot W \cdot \rho_a \cdot (q_s - q_a) \quad \text{Ap1}$$

Being L_h the latent heat of vaporization for water $\approx 2.5 \cdot 10^6 \text{ J} \cdot \text{Kg}^{-1}$, the $1.5 \cdot 10^{-3}$ is the Dalton number, and q_a and q_s the specific air humidity and saturated specific humidity at sea surface temperature respectively.

The Sensible Heat (Q_c , in $W \cdot m^{-2}$) is defined as:

$$Q_c = 1.45 \cdot 10^{-3} \cdot C_a \cdot W \cdot \rho_a \cdot (T_s - T_a) \quad \text{Ap2}$$

Where $C_a \approx 1000 \text{ J} \cdot \text{Kg}^{-1} \cdot \text{K}^{-1}$ is the specific heat capacity of air and T_s and T_a the sea surface temperature and air temperature respectively. The Coefficient $1.45 \cdot 10^{-3}$ is the Stanton number.

The term corresponding to longwave radiation (Q_b) needs cloud coverage information (not available) to account for the atmosphere backscatter effects. However, Allen et al. (1998) presented a formula considering the air humidity and the relation between measured and theoretically incoming solar radiation to account for the effects of downward longwave radiation.

Approximation to net longwave radiation (Q_b , $W \cdot m^{-2}$) has been done through:

$$Q_b = \sigma \left(\frac{T_{max}^4 - T_{min}^4}{2} \right) (0.34 - 0.14 \cdot \sqrt{e_a}) \left(1.35 \cdot \frac{Q_s}{Q_{s0}} - 0.35 \right) \cdot 0.0116 \quad \text{Ap3}$$

Where σ is Stefan-Boltzmann constant, T_{max} and T_{min} are maximum and minimum diurnal temperature (in K), e_a is the actual vapour pressure (KPa), Q_s for the measured shortwave and Q_{s0} for the theoretical shortwave radiation (both in daily radiation, $\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$). Details for this formula on Allen et al. (1998). The 0.0116 has been added here and is used to convert $\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ to $W \cdot m^{-2}$.

The approximation used to obtain the heat fluxes through the observations still presents some lacks: e.g. SST is defined here from temperature measurements at 1m depth and cloud coverage inferred from shortwave radiation. However, the results were compared with European Center for Medium-Range Weather Forecast (ECMWF, www.ecmwf.int) surface net heat flux variable (3h accumulated data) showing good agreement.

Appendix 2: Numerical model

The model used is Regional Oceanic Modelling Systems (ROMS), described in detail in Shchepetkin and McWilliams (2005) and in www.myroms.org. The turbulence closure scheme for the vertical mixing is Generic Length Scale (GLS), described on Warner et al. (2005) and tuned to behave as MY2.5 (k-kl). Tests with different mixing schemes show low sensitivity on water column stratification during seiche events. In general, the model reproduces the stratification of the bay, even with lower density gradients between surface and bottom layers. Sea level and velocities along the main axis shows correlations around 0.85 and 0.79 respectively in A2. Finally, the model agrees with the velocity profiles observed at A2 on S0-1 and S1-1 using a logarithmic profile for the bottom boundary layer and a characteristic bottom roughness height of 0.002 m (Fig.A1).

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Figures

Figure 1. Location map of Alfacs Bay in NW Mediterranean Sea. White cross shows meteorological station (Met-A). White and black gilled stars marks A1 (ADCP Mouth) and A2 (ADCP and CTD in the inner Bay) locations respectively. Black circle marks Mo (modelling result) location. Black dotted line indicates transect T1. Bathymetry is represented by 2m isobaths. Colorbar for land topography.

Figure 2. Wind Roses for Alcanar station (Met-A on Fig.1) on both summer 2013 (left panel) and winter 2014 (right panel) campaigns. Wind intensities are grouped by intervals of 3m/s.

Figure 3. Transect T1 (shown in Fig.1) for both salinity (color) and temperature (black lines) for July 2013 (a), February 2014 (c) and May 2014 (e). Panels b, d and f for corresponding squared Brunt-Väisälä (N^2) in dashed blue line, and σ_t density in black thick line, to each period on A2 location (black dashed thick line shows A2 location in each transect). Temperature is in °C and salinity in PSU. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 4. Panels a and b shows temperature evolution of CTs sensors in A2 and ADCPs (A1 and A2) on bottom for both summer (a) and spring (b). Energetic events described in Table 2 are marked by gray boxes: darker for wind and light for seiche episodes.

Figure 5. Panels a and c shows the depth-averaged velocities (10') for both A1 and A2 respectively in summer campaign. Images b and d shows corresponding local wavelet power spectrum (in units of normalized variance) of depth averaged alongshore velocities in A1 and A2 respectively. Shaded regions indicate the cone of influence where edge effects become important.

Figure 6. Each panel shows on the top the wind measured at M-A, and on the bottom the vertical profiles of current velocities measured at ADCP locations. Velocities contours plotted in depth (mab: meters above bottom) versus time (24h). Different events are showed. a) A1 for 30/8/2013, showing 3h seiche (S0-1). b) Bay ADCP for 3/8/2013, showing 1h seiche (S1-1). Image c) for crossshore velocities during NW events on 23/3/2014 in A1. d) Crossshore velocities for A2 in 8/7/2013 (NW-1). Black lines shows 0 velocity isolines. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 7. Progressive Vector Diagram for surface (thick) and bottom (thin) layers in A1 (black) and A2 (red). Period length about 24h, and corresponding to sea breeze period on 6th July 2013. Hourly wind data measured in Met-A is plotted (blue arrows) in corresponding hour. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 8. Image a shows numerical results for mean depth averaged computed speeds corresponding to S0-1 escenario. Image b for scenario S1-1.

Figure 9. Numerical test for S1-1. Top image shows instantaneous depth averaged velocities in A2. Bottom image for the salinity time evolution on A2 over the entire depth. Gray dashed lines shows instants plotted on Fig.10.

Figure 10. Salinity profiles for A2 and Mo (locations on Fig.1) on a and b panels respectively corresponding to instants $t=1$, $t=14$ and $t=22$ (in hours) in Fig.9.

Figure A1. Instantaneous alongshore velocity profiles in A2 location for observed and modelled 1-h seiche (S1-1), in black thin and thick lines respectively.

Table 1. Data acquisition instruments and observational periods

Name	ID	Observations	Period	Data interval (minutes)
Alcanar station	Met-A	Winds	June'12 – May'14	10
ADCP mouth	A1	Currents, Sea level and bottom temperature	July'13-September'13 February'14-March'14	10
ADCP inner bay	A2	Currents, Sea level bottom temperature, and 3 CTs (.5m, 1.5m and 3m)	July'13-September'13 February'14-May'14	10
Daily CTDs	I-1	Variable number of CTD profiles within the bay	26 June'12	-
	I-2		31 July'13 (end)	-
	I-3		16 September'13	-
	I-4		25 February'14	-
	I-5		7 May'14	-

Table 2. Energetic scenarios definition, period, duration and mean depth averaged current speeds (in parenthesis the maximum hourly mean speeds).

SEICHES					
Name	Definition	Period (dd/mm/yy)	Duration (h)	Speed (m·s⁻¹)	
				A1	A2
S0_1	Fundamental seiche mode (Period=3h)	30/08/13	24	0.16 (0.24)	0.1 (0.17)
S1_1	First seiche mode (n=1) (Period=1h)	3/08/13	12	0.18 (0.26)	0.23 (0.3)
S0_2	-	26/03/14	12	0.16 (0.21)	0.13 (0.17)
S1_2	-	11/04/14	24	-	0.12 (0.19)

WINDS					
Name	Definition	Period		Speed (m·s⁻¹)	
				A1	A2
NW_1	North-western wind (summer)	8/08/13	4h	0.14 (0.16)	0.08 (0.13)
NW_2	North-western wind (winter)	23/03/14	12h	0.15 (0.18)	0.12 (0.17)

Table 3. ADCP basic statistics of Depth-Averaged velocities (10-minutal data). ‘Direction’ indicates direction of first axis in PCA analysis, and ‘%’ for corresponding percentage of variability explained. U’ and V’ for corresponding along and crossshore velocities (re-oriented in its corresponding ‘Direction’). Last three rows resume first three vertical eigenvectors of EOF analysis on alongshore component (U’). Baroclinic eigenvector (cross-zero) underscored.

		Summer 2013		Winter 2014	
		A1	A2	A1	A2
Direction (°)		59	21	35*	26
% variability		95	96	90	94
U’ (ms ⁻¹)		-.41 / .52	-.53 / .42	-.28 / .29	-.28/.35
V’ (ms ⁻¹)		-.07 / .09	-.08 / .08	-.2 / .1	-.14/09
EOF	1 st	74	71	74*	74
	2 nd	<u>12</u>	<u>11</u>	<u>15*</u>	<u>12</u>
	3rd	<u>5</u>	<u>4</u>	<u>4*</u>	<u>3</u>

* Only one month of data

Table 4. Estimation of the size of the terms (daily averages) of the potential energy balance (equation 1) computed for both summer and winter campaigns (x 10⁻⁶ W·m⁻³). Scenario estimations are done over the event duration defined on table 2.

		$\propto gQ_i/2C_p$	$gR\Delta\rho/2A$	$ek_b\rho_w \hat{u}_{tide} ^3/h$	$ek_b\rho_w \hat{u}_{seiche} ^3/h$	$e_sC_d y_s \rho_a W^3/h$
	Seasonal estimations					
Summer	Mean (std)	-15 (13)	-30	0.06 (-)*	0.8 (0.9)	5.6 (3.5)
Winter-Spring	Mean (std)	-10 (14)	0**/-30	0.06 (-)*	1.5 (0.8)	20 (35)
	Scenario estimations					
S0-1		-3	-30	-	+2.5	+8.7
S1-1		-31	-30	-	+26	+15

S0-2		-4.2	0**/-30	-	+4.8	+64
S1-2		-26	0**/-30	-	+3.7	+20

*Values for tidal stirring term correspond to M2 tidal current amplitude observed ($3 \text{ cm}\cdot\text{s}^{-1}$). Same values for winter.

**During open channels period. From January to late March no direct freshwater inputs from rice fields.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure A1

Highlights

Hydrodynamic response in shallow microtidal bay at high frequency scales is investigated.

Alongshore circulation mainly related to seiches (barotropic) and crossshore influenced by wind.

Mixing is analysed through potential energy, dimensionless relations and modelling tools

Seiche induced mixing is a first order potential mixing mechanism in Alfacs Bay.