Influence of benthic boundary layer dynamics on wind-induced currents in the Ebro delta inner shelf

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[1] Measurements taken by two instrumented tripods deployed on the Ebro delta inner shelf at 8.5- and 12.5-m depth were used to characterize low-frequency currents under the action of a moderate eastern storm. Results show that inner shelf currents respond very rapidly to wind action with along-shelf currents dominating over the across-shelf ones. Mean along-shelf velocities of 0.35 and 0.24 m s⁻¹ at the inner and outer position, respectively, were recorded during the event, and they were highly correlated with the along-shelf wind stress. The measured current profiles were used to derive wind drag coefficients, assuming a balance between the along-shelf components of the wind and current bottom stresses. Since under eastern wind events, wave action in the Ebro inner shelf is significantly enhanced, wave-current interaction processes controlling the current bottom stress and sediment mobilization can affect the current structure. During the event, depth-averaged concentrations in the lower meter of the water column larger than 1 g L⁻¹ were recorded that were also accompanied by the generation of vertical concentration gradients larger than 1 g L⁻¹m⁻¹. When the bottom drag coefficient was obtained from velocity profiles without considering the presence of these gradients, the required wind drag coefficients to fulfil the along-shelf balance were much higher than the ones derived from wind data, and they vary across the inner shelf. However, when bottom drag coefficients are obtained including stratification effects, the wind drag coefficients fulfilling the along-shelf balance were of the same order of magnitude as the ones derived from wind data and without any difference at both locations. *INDEX TERMS:* 4211

Oceanography: General: Benthic boundary layers; 4546 Oceanography: Physical: Nearshore processes; 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; *KEYWORDS:* stratification, wind-induced currents, inner shelf, suspended sediment, Ebro delta, wave-current interaction

1. Introduction

[2] Oceanographic studies in the Ebro continental margin have traditionally characterized the circulation to be mainly thermohaline and controlled by the general southwestward circulation in the Catalan sea [e.g., Font, 1990]. As we approach to shallower waters, existing studies have also found that the wind plays an important role in controlling the circulation pattern on the shelf [e.g., García and Ballester, 1984; Cacchione et al., 1990; Font et al., 1990; Espino et al., 1998].

[3] In the inner shelf (waters shallower than 50-m depth), where the most important processes related to sediment dynamics verify, few studies have been done [Jiménez et al., 1999; Palanques et al., 2002]. These studies have found that along-shelf currents dominate over the across-shelf ones and that although detectable, the tidal influence in

the current records was very weak as expected for a microtidal environment. By means of spectral analysis of one monthlong time series of currents at 8.5- and 12.5-m depth during the winter season, Jiménez et al. [1999] found that most of the energy of the currents was concentrated at frequencies associated to the atmospheric forcing (wind events and atmospheric pressure).

[4] Guillén et al. [2002] analyzed sediment resuspension processes at the same two positions in the Ebro delta inner shelf. They demonstrated the dominant role of waves in mobilizing the bottom sediment and the negligible role of currents for such processes (as expected for a microtidal environment). However, they also found that the intensity of the sediment mixing in the water column was mainly dominated by the local vertical structure of the currents.

[5] Gracia et al. [1999], Jiménez et al. [1999], and Palanques et al. [2002] analyzed the sediment fluxes along and across the inner shelf of the Ebro delta. They found that along-shelf sediment fluxes dominated over the across-shelf ones and that most of the transport in the inner shelf occurred in “events.” These events occur under storms in which the wave height increases and relatively high intensity currents are rapidly generated. This combination pro-

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duced an increase in sediment mobilization from the bottom, a larger mixing in the water column and, a larger sediment advection due to the presence of an intense current acting on a higher sediment concentration. This type of pulsing structure in the along-shelf sediment transport due to the combined action of waves and currents has also been found in others shelves as, e.g., the northern California shelf [Ogston and Sternberg, 1999].

[6] Because of this, it is clear that to characterize the sediment dynamics in the inner shelf, we must focus on the proper evaluation of the system functioning under such events, since they contribute with most of the transport during a normal year. This implies that on the one hand, the role of wave action on the sediment mobilization has to be characterized and, on the other hand, it is necessary to predict the current intensity during such events. The first task, i.e., sediment resuspension, has already been analyzed in the Ebro delta [Guillén *et al.*, 2002] and, in this paper we shall approach the second task, i.e., currents in the inner shelf under high-intensity wind events.

[7] To characterize the Ebro delta inner shelf functioning from the event standpoint, three field measurements campaigns were performed at 8.5 m depth and 12.5 m depth by using two instrumented tripods. The three campaigns were performed in winter 1996, spring 1997, and summer 1997 to try to cover most of the typical forcing conditions and shelf response [see Palanques *et al.*, 2002]. Inner shelf conditions during the winter deployment were jointly dominated by mesoscale shelf processes (the presence of an anticyclonic gyre in the shelf) inducing a northward flow in the shoreface and by local wind-forcing inducing some current reversals. Detailed description of inner shelf currents and sediment suspension structure can be found in the works of Jiménez *et al.* [1999] and Gracia *et al.* [1999]. Conditions during the summer deployment were dominated by typical fair-weather conditions of the area with small wave activity and light wind events. During this deployment, near-bottom hydrodynamic regime and sediment response can be classified as of low-intensity with few events exceeding the threshold conditions for sediment resuspension. Finally, the spring campaign was characterized by the presence of several moderate wave storms and wind events without additional forcing events such as high river discharges affecting the study area. In this sense, this campaign presented the “ideal” conditions to study locally forced (wind-induced) circulation in the inner shelf. However, not all the duration of the deployment was useful for these purposes since electronic-related problems generated a malfunctioning of the system in such a way that, significant gaps in data were detected once the tripods were recovered. In spite of this problem, existing measurements permitted to characterize some events of interest in the area.

[8] Using the recovered data of the spring campaign, in this paper a moderate eastern wind event in the Ebro delta inner shelf is analyzed to assess the importance of wind action in driving the inner shelf circulation. Since during wind action, waves are also generated, this paper also deals with the role of wave-current interaction and bottom friction in modulating the water response to wind action. Finally, the validity of wind drag coefficients derived from wind intensity to feed circulation models is also analyzed, putting

emphasis on the identification of variables “apparently” affecting them.

2. Field Data

[9] The data used in this work were acquired during a field experiment carried out in the inner shelf of the Ebro delta (NE Spanish Mediterranean) during spring 1997. This is a microtidal environment with a maximum astronomical tidal range up to 25 cm, although meteorological tides are relatively frequent [Jiménez *et al.*, 1997]. The study site is a fetch-restricted area where long swell is hardly found; under eastern storms waves show longer periods, with T_p up to 12 s [García *et al.*, 1993; Jiménez *et al.*, 1997].

[10] Time series of near-bottom velocities and pressure were measured using two instrumented tripods deployed at 8.5- and 12.5-m depth in a gentle shoreface (Figure 1). Velocity measurements were acquired by means of a vertical array of three 4-cm spheres Delft Hydraulics P-EMS electromagnetic current meters [Delft Hydraulics, 1993] mounted 11, 49, and 89 cm above the bottom at each tripod location. Pressure fluctuations were recorded by means of a Druck PDCR 1830 absolute pressure sensor (located 1.75 m above the bottom) with a maximum error of 0.1% of the measuring range, i.e., 3.5 mbar. Tripod orientation was controlled using a KVH Industries C100 compass. Bottom sediment samples were taken at the inner and outer tripod sites with respective mean grain sizes of 135 and 105 μm . Suspended sediment concentration was measured by using 3 OBS-3 sensors [D&A Instruments, 1991] located at equivalent elevations than current meters. OBS sensors were calibrated in the laboratory with bottom sediment taken at each site. The system was managed by a 12 channel Campbell CR10X programmable data logger, and it worked in burst mode, taking measurements for 20 min every 3 hours at a data acquisition frequency of 2 Hz. Further details on the experiment and the equipment can be seen in the works of Jiménez *et al.* [1999] and Guillén *et al.* [2002].

[11] The data used in this study correspond to the initial period of the tripod deployment with weak hydrodynamic conditions prevailing in the previous hours (below the threshold conditions for sediment entrainment). Because of this, it is not expected that local sediment activity could induce “scouring” at tripod legs and, then, the nominal elevation of the sensors above the bottom (measured by a diver once the tripod was deployed) is used as the real one during the analyzed event.

[12] Velocity time series were projected onto a local reference system parallel to the main coastline orientation in such a way that a positive value of the cross-shore component indicates a seaward velocity and positive value of the along-shelf component indicates a northward velocity. Velocity components were time-averaged over the burst duration (20 min) to obtain the mean current cross- and along-shelf components, U_c and V_c .

3. Forcing Conditions

[13] In what follows, the main meteo-oceanographic forcing conditions in the Ebro delta inner shelf during the period of study are presented. They are restricted to

Figure 1. Area of study: (top) Ebro delta and (bottom) tripods location across the shoreface.

wind conditions, which is the main driving term for inner shelf circulation in the Ebro delta [Jiménez *et al.*, 1999], and wave characteristics. Although, strictly speaking, waves are the sea response to wind, here they are also considered as forcing terms because they will play an important role in the vertical structure of currents in the inner shelf as well as inducing shear stress at the bottom to mobilise the sediment.

3.1. Meteorology

[14] Time series of wind (intensity and direction) acquired at an offshore meteorological station during the studied event are shown in Figure 2. The analyzed period corresponds to the development of an eastern event (“llevant” in vernacular) under cyclonic conditions. At the earlier stage,

weak winds were blowing from the southwest with a mean velocity of 2 m s^{-1} . In 6 hours the wind rapidly veered anticlockwise toward the east, reaching a stable situation after 12 hours. During this time span the wind speed increased up to 16 m s^{-1} , whereas the direction stabilized at ENE. Atmospheric pressure remained high during all the period, with a slow increase up to 1032 mbar when the event was fully developed.

3.2. Waves

[15] Eastern wind events are generally associated to the presence of wave storms, and under this situation, waves reach the largest heights and longest periods in the area [Jiménez *et al.*, 1997]. Figure 2 shows the time evolution of the offshore (50-m depth) significant wave height, H_{m0} ,

Figure 2. Offshore wind and wave conditions during the experiment.

recorded by a directional wave buoy located in the study area. As it can be seen, the wave height rapidly responded to the wind, increasing from an initial negligible value before the wind stabilization ($H_{m0} \approx 0.25 - 0.30$ m) up to 1.50 m in 6 hours, corresponding to the initial stage of the event. After this initial period in which a lag is observed between the forcing (wind) and the response (wave), wave height quasi-instantaneously responded to wind fluctuations, with both presenting the same pattern during the event. At the last stage of the event, the wave height reached its maximum value, with an averaged H_{m0} of ~ 2 m.

[16] Wave period and direction presented few fluctuations during the event, with an averaged wave peak period of 6.7 s with all the waves arriving from ENE-E directions.

These recorded wave characteristics are typical of the development of an eastern moderate wave storm [see *García et al.*, 1993; *Jiménez et al.*, 1997].

4. Near-Bottom Flows

4.1. Mean Currents

[17] Figure 3 shows the current velocity module for the three considered elevations at the two inner shelf locations during the event. It can be seen that currents have a very low speed at the initial stage, when winds were veering from south to east and wind velocities were increasing. Current velocity shows the most drastic increase 3 hours after 7 April 1997, 1800 UT (burst 3), increasing in magnitude $\sim 300\%$ in comparison with previous measurements, reach-

Figure 3. Mean currents at the three elevations measured at both inner shelf locations (numbers in each curve indicate the nominal elevation of the sensors above the bottom).

Figure 4. Progressive vector diagram obtained during the study period for both locations (circles indicate the initiation of the wind event: c1, lowermost current meter; c2, middle; c3, uppermost current meter).

ing a velocity of 0.2 m s^{-1} at the inshore location and 0.14 m s^{-1} at the offshore one (both at the electromagnetic current meter (EMCM) located 0.9 meters above the bottom (m.a.b.)). This “instant” corresponds to a situation with the wind already stabilised at the ENE direction and once the wind reached a stable velocity. This means that significant currents are developed at the inner shelf of the Ebro delta in relative short periods under strong wind events, and this seems to disagree with previous hypothesis (see, e.g., *Espino et al.* [1998], who assumed that only relatively long-lasting wind events are able to influence the local mean circulation (they used a cutoff wind event duration of 24 hours)). However, it has to be considered that these authors make an analysis for the Ebro delta shelf (depths larger than 100 m), whereas we restrict our analysis to the inner shelf (depths shallower than 13 m).

[18] Figure 4 represents the flow conditions during the event using progressive vectors. As it can be clearly seen, the flow at both sites presents a dominance of the along-shelf current component over the cross-shelf one, in such a way that a particle subjected to these currents will experience a southward displacement much more intense at the inner location. On average, the intensity of the along-shelf component of the current was ~ 2.5 times larger than the across-shelf one at both locations. During the first stage of the analyzed period, before the full development of the eastern event (until burst 3), currents are weak and veering without a systematic behavior. As the wind stabilized in direction and velocity, the flow at both sites present the above mentioned along-shelf pattern that persisted during the entire event.

[19] To estimate the bottom stress during the event, the measured current velocities u_c through the water column were fitted to a log-velocity profile [see, e.g., *Madsen et al.*, 1993; *Kim et al.*, 1997], which is given by

$$u_c = \frac{u_{*c}}{\kappa} \ln \frac{z}{z_{0a}}, \quad (1)$$

where u_{*c} is the shear velocity, κ is the von Karman’s constant (0.41), and z_{0a} is the apparent roughness. The fit was only done for those profiles passing a consistency check based on (1) similarity in directions at the three elevations and (2) on the robustness of the estimation of u_{*c} and z_{0a} using different pairs of measurement points (see test description by *Madsen et al.* [1993]). For the profiles passing the test the existence of a log-profile was accepted when the fit of the data to the model gave a $r^2 > 0.96$ (Figure 5). These conditions were only exceeded for records after burst 3, i.e., once the wind speed was strong enough to fully develop currents (Figure 6). At earlier stages under weak currents the vertical velocity profile showed a relatively high vertical variability in directions, and, under such conditions, it had no meaning to fit them to such as theoretical profile.

[20] Once the profiles were fitted, equation (1) was used to estimate the velocity at $h/2$, being h the actual water depth at both locations, and the so estimated values were considered as “representatives” of depth-averaged current velocities. Figure 6 shows the along-shelf wind velocity and depth-averaged current at the inner and outer locations. As it can be seen, currents at both locations present the same

Figure 5. Fit of the measured velocity profiles to a logarithmic profile for each burst passing the consistency test (see text) and for each location (in: inner site, 8.5-m depth; out: outer site, 12.5-m depth).

Figure 6. (left) Current shear velocities at both locations and (right) along-shelf depth-averaged current velocities and along-shelf wind velocity.

variation pattern highly correlated with the wind speed, with largest velocities at the inshore location.

4.2. Wind Forcing

[21] Given the above mentioned dominance of the along-shelf component of the current at both locations as well as the apparent response of the flow to wind, the role of wind forcing in the inner shelf was investigated in detail. This was done through the along-shelf momentum balance equation applied for the specific conditions recorded during the experiment. Although some “full” expressions for currents in the frictional part of the inner shelf have been proposed [e.g., *Mitchum and Clarke, 1986; Lentz et al., 1999*] and, since in this work we are mainly interested in the role of wind forcing on “local” circulation, the Coriolis force, and the wave radiation stress have been neglected. This is consistent with the existence of a weak normal flow for the first neglected term, and, because all the measurements were outside the surf zone, the contribution of the radiation stress to the momentum balance can be considered as negligible [see, e.g., *Lentz et al., 1999*]. With respect to this last assumption, local values of H_{m0}/d at the inner location during the event were lower than 0.2 indicating no significant wave breaking. With this, the linearized depth-integrated along-shelf momentum balance can be written as

$$\frac{\partial V_c}{\partial t} = -g \frac{\partial \eta}{\partial y} + \frac{\tau_{ay}}{\rho d} - \frac{\tau_{cy}}{\rho d}, \quad (2)$$

where V_c is the depth-averaged along-shelf current, η is the free surface elevation, τ_{ay} is the along-shelf wind stress, τ_{cy} is the along-shelf bottom stress, and d is the water depth. The along-shelf wind stress, τ_{ay} , is given by

$$\tau_{ay} = \rho_a C_a |\vec{U}_w| v_w, \quad (3)$$

where ρ_a is the density of the air (1.25 kg m⁻³), C_a is the wind drag coefficient, $\vec{U}_w$ is the wind velocity, and v_w is the along-shelf velocity component of the wind. The along-shelf current stress, τ_{cy} , can be expressed as

$$\tau_{cy} = \rho C_b |\vec{U}_c| V_c, \quad (4)$$

where ρ is the density of the seawater (1026 kg m⁻³), C_b is the depth-averaged bottom drag coefficient ($C_b = (u_{*c}/|\vec{U}_c|)^2$), and $\vec{U}_c$ is the current velocity.

[22] On the basis of equation (2) we can assume that the total solution for the along-shelf velocity at any point in the inner shelf is given as the sum of one local component, driven by the local along-shore wind stress, and a “remote” component, driven by the along-shelf gradient in water elevation [see, e.g., *Lopez and Clarke, 1989*]. In principle, since no data about the existence of the along-shelf gradient in pressure were available, we have neglected this contribution (this hypothesis will be later tested based on the obtained results).

[23] For the recorded conditions the averaged frictional timescale, T_f , is 1.2 hours at the inner site and 2.0 hours at the outer one (where $T_f = h/C_b |\vec{U}_c|$). This timescale is shorter than the observed temporal variation in the wind forcing (Figure 6), which should indicate that currents are in steady state equilibrium with the wind conditions. This implies that accelerations in the flow should not play an important role but at the initial stage when the event starts to be developed. Taking into account this “steadiness” and assuming that the recorded currents are solely driven by wind stress, equation (2) reduces to a balance between along-shelf wind stress and along-shelf bottom stress, i.e.,

$$\tau_{ay} = \tau_{cy}.$$

[24] To test the hypothesis of the dominance of wind-generated currents, this balance was applied in an inverse manner [see, e.g., *Madsen et al., 1993; Friedrichs and Wright, 1997a*], i.e., the input data are the recorded currents, the bottom drag coefficient is estimated from equation (1), whereas the wind drag coefficient C_a becomes the unknown.

[25] Figure 7 shows the comparison between wind drag coefficients inferred from this inverse method at both locations and the ones calculated from wind data using the *Wu* [1982] model. The estimated (inferred) C_a values are larger than the ones calculated from wind data, with mean values 0.0046 and 0.0023 at the inner and outer positions, respectively, whereas the mean C_a value obtained by applying the *Wu* model is 0.0012. This means that the departure between both values is not constant, being in average ~ 4 times larger at the inner location and ~ 2 times larger at the outer one. This difference in proportionality is also detected at each location through time.

Figure 7. Inferred C_a values at the inner and outer positions versus values obtained from wind data.

[26] *Madsen et al.* [1993] and *Friedrichs and Wright* [1997a], among others, have also found an overestimation of C_a values in similar analyses. *Madsen et al.* [1993] obtained a C_a value ~ 3 times larger than the one calculated from wind intensity and they concluded that the “measured” drag coefficient (obtained by the inverse method) was representative for the storm wave and wind conditions prevailing including the effects of extreme waves breaking on the inner shelf. On the other hand, *Friedrichs and Wright* [1997a] found a C_a value 4 times larger than the one calculated from wind intensity, and they explained this increase as likely due to input of momentum by occasional wave breaking outside the surf zone. Other potential variations in the wind drag coefficient due to air-sea interaction influenced by the presence of waves have been analyzed in detail elsewhere [e.g., *Geernaert et al.*, 1987], some of them being included in numerical circulation models very recently [e.g., *Xie et al.*, 2001].

[27] However, the observed variations at the two locations across the Ebro delta inner shelf cannot be explained using the local wave influence since wave characteristics at both sites do not differ in a enough magnitude to increase the drag coefficient at the inner position by a factor 2 with respect to the ones at the outer position. This conclusion can also be extended to the observed variations at each location.

[28] The observed differences in C_a values could also be due to neglecting the existence of an along-shelf gradient in water elevation in the momentum balance. Thus, if measured along-shelf winds are balanced against a pressure gradient, an along-shelf slope of $\sim 2\text{--}3 \text{ mm km}^{-1}$ should produce a force of the same order as the wind stress. Taking into account the spatial scale of the Ebro delta, this gradient would be generated by a difference in sea level along the entire southern lobe of the delta shelf (from the river mouth to the end of the southern spit, see Figure 1) of $\sim 10\text{--}15 \text{ cm}$. Moreover, since differences in C_a values vary at the inner and outer locations (4 and 2 times larger, respectively), this along-shelf gradient should be larger (in a factor 2) at the inner location. In addition to this, it has to be stressed that the calculated differences in the estimated

C_a values also vary in time. Thus, under an atmospheric forcing (atmospheric pressure and wind intensity and direction) already stabilized, once the event was fully developed, they still vary from burst to burst. Because of this apparent uncoupling between atmospheric forcing and the observed differences in C_a values, we have assumed that if a nonnegligible along-shelf gradient in water elevation should exist, its contribution to the momentum balance should be almost constant during the steady phase of the event. According to this, the varying differences in the C_a estimates during this steady phase should have a different origin.

4.3. Modification of the Bottom Drag Coefficient

[29] A possible source of the observed differences in C_a values could be found in the estimation of the bottom drag coefficient, C_b , in such a way that the use of a larger C_b than the “real” one would imply a corresponding larger C_a . This coefficient was obtained from equation (1) by assuming the log-profile to be valid, and it could be overestimated if the near-bottom flow was affected by the presence of suspended sediment. In the case of high suspended sediment concentrations the turbulent diffusion of the flow may be affected by stratification and then, the eddy diffusivity should be reduced [*Glenn and Grant*, 1987]. *Friedrichs and Wright* [1997a] identified this as a potential source to explain the variations of the inferred wind drag coefficients with respect to that calculated from wind data although they did not analyze it.

[30] Figure 8 shows the departure of the inferred C_a values from the ones calculated from wind characteristics as a function of the vertical gradient in suspended sediment concentration and the depth-averaged concentration (in the lowest meter of the water column where the measurements were taken) at both inner shelf locations. As it can be seen, there is an apparent relationship between the overprediction of C_b (and consequently C_a) and the vertical concentration gradient (for vertical gradients larger than $1 \text{ g L}^{-1} \text{ m}^{-1}$), in such a way that the larger this gradient is, the larger the departure will be. This could be indicative of the effect of a suspended-sediment-induced stratified flow during some bursts and that the bottom drag coefficient obtained from equation (1) could be overpredicted. The two points marked in Figure 8 correspond to concentration values recorded just after the bottom shear stress exceeded the critical shear stress at both locations. Under such conditions, *Guillén et al.* [2002] estimated that the recorded values were affected by the presence of fine sediments and then, the large concentration values measured by the optical backscatter sensors were not realistic. These two bursts were not considered in the correction of stratification, and, in fact, bottom drag coefficients calculated under neutral conditions seem to agree with the theoretical ones (those obtained from wind data).

[31] To account for the existence of a stratified flow, the estimation of the bottom drag coefficient was revisited with equation (1) rewritten as [*Glenn and Grant*, 1987]

$$u = \frac{u_{*c}}{\kappa} \left(\ln \frac{z}{z_0} + \beta \int_{z_0}^z \frac{dz}{L} \right), \quad (5)$$

Figure 8. Relationship between the departure of inferred C_a values from the ones calculated using wind data versus (left) vertical gradient in suspended sediment concentration and (right) versus depth-averaged concentration in the lowest meter of the water column at both sites.

where L is the Monin-Obukhov length, β is a “constant,” which usually is taken as 4.9 even though this value has been obtained from atmospheric data, although other authors have found different β values [see, e.g., McLean, 1992] and, in fact, Villaret and Trowbridge [1991] stated that its value is not well constrained by atmospheric measurements.

[32] Different solutions to equation (5) have been proposed according to the assumptions regarding the behavior of the stability parameter, ζ ($= z/L$), near the bottom that results in a logarithmic profile with an additional term [see, e.g., Glenn and Grant, 1987; Green et al., 1995; Friedrichs and Wright, 1997b]. In this work, we have assumed that the stability parameter ζ is constant near the bottom, and this leads to a logarithmic velocity profile in which the apparent roughness is the same that under neutral conditions (“clear waters”), whereas the u_{*c} should change. Glenn and Grant [1987] introduced this solution, and it has also been employed among others by Friedrichs et al. [2000] to model near-bottom velocity data in the California shelf. The corrected velocity profile is expressed as

$$u_c = \frac{u_{*c}}{\kappa} \ln \frac{z}{z_{0a}} (1 + \beta \zeta). \quad (6)$$

[33] Equation (6) was fitted to measured velocity profiles for bursts presenting a vertical gradient in suspended sediment concentration larger than $1 \text{ g L}^{-1} \text{ m}^{-1}$. Since equation (6) is identical to equation (1) from a mathematical standpoint, the statistical goodness of the fit was identical, with the only difference for both approaches being the u_{*c} value that in the stratified case is lower. Figure 9 shows the values of the correction factor $\beta \zeta$ obtained in the fit against the corresponding vertical gradient in suspended sediment concentration directly obtained from concentration measurements, where it can be seen that the larger the gradient is, the larger the correction factor will be.

[34] The stratification-corrected u_{*c} values were used to reestimate the depth-averaged bottom drag coefficient C_b and, after applying the balance between wind and bottom current stress, new C_a values were obtained (only for those

bursts presenting a significant vertical concentration gradient). Figure 10 shows the comparison between the “corrected” C_a values against those obtained from wind data, where it can be seen that the new wind drag coefficients are significantly lower than the original ones, with mean values of 0.0016 and 0.00155 at the inner and outer locations, which are only 1.3 and 1.25 times the mean value obtained from the wind data.

[35] This improved agreement in C_a values, once the correction due to stratification was included, seems to indicate that the first obtained values (much larger than the ones obtained from wind data) instead of reflecting the air-sea interaction affected by waves (as other authors have found under certain conditions [see, e.g., Geernaert et al., 1987; Madsen et al., 1993; Friedrichs and Wright, 1997a]),

Figure 9. Correction factor to account the effect of sediment-induced stratification, $\beta \zeta$, in the velocity profile versus vertical gradient in suspended sediment concentration.

Figure 10. Inferred C_a values at the inner and outer positions modified by stratification effects versus values obtained from wind data.

reflect the effects of wave-current interaction including the presence of high suspended sediment concentrations. Finally, the remaining “unexplained” part of the new calculated C_a values (between 25 and 30%) with respect to the theoretical values could be associated to the already discussed existence of an along-shelf gradient in water elevation.

5. Summary and Conclusions

[36] In this work, we have analyzed low-frequency currents in the Ebro delta inner shelf (at 8.5- and 12.5-m depth) under the action of a moderate eastern storm. Results show that inner shelf currents respond very rapidly to wind, and, after 3 hours of a quasi-steady wind action with an intensity of 16 m s^{-1} , current velocities at 1 m.a.b. increase $\sim 300\%$ with respect to the prewind situation and remains relatively stable as wind and wave conditions persist. Under these conditions, along-shelf currents dominate over across-shelf ones, reaching mean velocities of 0.35 and 0.24 m s^{-1} at the inner and outer position, respectively, and they are highly correlated with the along-shelf wind stress.

[37] The relationship between measured currents and wind action was investigated by using a simplified depth-integrated along-shelf momentum balance reduced to a balance between wind stress and current bottom stress. Because under these high wind events waves are also generated, currents in the inner shelf are affected by their presence through wave-current interaction processes controlling the current bottom stress, on the one hand and,

through the sediment mobilization, on the other hand. For the recorded conditions, relatively high suspended sediment concentrations were recorded with depth-averaged concentrations in the lower meter of the water column larger than 1 g L^{-1} , that were also accompanied by the generation of vertical gradients in sediment concentration larger than $1 \text{ g L}^{-1} \text{ m}^{-1}$.

[38] When the bottom stress was obtained from measured velocity profiles without considering the presence of these gradients, the required wind drag coefficients to fulfil the along-shelf balance were much higher than the ones derived from wind data. Moreover, the required drag coefficients have to be different to achieve the balance at 8.5- and 12.5-m depths, being ~ 4 times larger at the inner site and 2 times larger at the outer one. These differences can be only explained by considering local effects such as the structure of the bottom boundary layer at both sites. Thus, when bottom drag coefficients were obtained by assuming the flow to be stratified due to the presence of concentration gradients, the wind drag coefficients fulfilling the along-shelf balance were of the same order of magnitude than the ones derived from wind data and without any difference at both locations. This indicates that to properly model wind-induced currents in the inner shelf, wave-induced effects in the bottom boundary layer (increased stress and sediment suspension) must be properly accounted for.

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