Ocean—atmosphere—wave characterization of a wind jet
(Ebro shelf, NW Mediterranean Sea)

Manel Grifoll¹, Jorge Navarro², Elena Pallares¹, Laura Ràfols¹,², Manuel Espino¹
and Ana Palomares²

¹[1]{LIM/UPC (BarcelonaTech), Barcelona, Spain}
²[2]{CIEMAT, Madrid, Spain}
³[3]{Meteocat, Barcelona, Spain}

Correspondence to: M. Grifoll (manel.grifoll@upc.edu)
Abstract

In this contribution the wind jet dynamics in the northern margin of the Ebro River shelf (NW Mediterranean Sea) are investigated using coupled numerical models. The study area is characterized by persistent and energetic offshore winds during autumn and winter. During these seasons, a seaward wind jet usually develops in a ~50km wide band offshore. The COAWST (Coupled Ocean—Atmosphere—Wave—Sediment Transport) modelling system was implemented in the region with a set of downscaling meshes to obtain high-resolution meteo-oceanographic outputs. Wind, wave and water current were compared with in situ observations and remote-sensing-derived products with an acceptable level of agreement. Focused on an intense offshore wind event, the modelled wind jet appears in a limited area offshore with a strong spatial variability. The wave pattern during the wind jet is characterized by the developing of bimodal directional spectra, and the ocean circulation tends to present well-defined two-layer flow in the shallower region (i.e. inner shelf). The outer shelf tends to be dominated by mesoscale dynamics such as the slope current. Due to the limited fetch length, ocean surface roughness considering sea state (wave-atmosphere coupling) modifies to a small extent the wind and significant wave height under severe cross-shelf wind events. However, the coupling effect in the wind resource assessment may be relevant due to the cubic relation between the wind intensity and power.

Keywords: wind jet, COAWST, ocean—atmosphere coupling, wind power assessment

1 Introduction

Coastal areas are often characterized by highly variable and heterogeneous wind, wave and current conditions, which make the numerical prediction of the meteo-oceanographic processes difficult. For instance, wind jets induced by orographic effects present strong spatial wind field variability due to the orographic characteristics (e.g. Shimada and Kawamura, 2006; Zhai and Bower, 2013). Due to the persistence in wind intensity and direction, these regions are preferential sites for the installation of offshore wind farms (Nunalee and Basu, 2013). In case of coastal regions, the resultant offshore winds decisively influence the exchange of water mass and material along the shelf/slope (Jordà et al., 2005; Barton et al., 2009). Despite the relatively limited fetch in the wind jet region, the wave height can be relevant, interacting with bimodal features (Shimada and Kawamura, 2006). In this sense,
several contributions have highlighted the influence of variable wind conditions in relatively small-scale areas (such as wind jet), influencing wind—wave generation (Shimada and Kawamura, 2006; Bolaños et al., 2007; Alomar et al., 2014) or modifying ocean circulation patterns (Csanady, 1980; Zhai and Bower, 2013; Schaeffer et al. 2011; Klaic et al., 2011).

In coastal zones the air—sea momentum transfer presents high complexity due to the dependence of wind intensity on sea bottom roughness. The relevance of the atmospheric bottom roughness increasing due to waves has been investigated in recent years (Janssen, 1989; Janssen and Viterbo, 1996; Lionello et al.1998; Taylor and Yelland, 2001; Oost et al., 2002; Drennan et al., 2003). In this sense, advanced computational tools allowed the feedback of meteo-oceanographic momentum and heat transfer to be addressed numerically (Warner et al., 2010; Zambon et al., 2014). Warner et al. (2010) developed a fully coupled numerical system (COAWST: Coupled Ocean—Atmosphere—Wave—Sediment Transport) to investigate the impact of storms on coastal systems. Using COAWST, Olabarrieta et al. (2012) and Renault et al. (2012) proved numerically that the wave-induced ocean surface roughness is a key parameter in the air—sea momentum transfer. Under severe storm conditions (hurricanes and cyclones), this parameter influences the spatial and temporal evolution of the meteo-oceanographic variables. Other recent examples that use a fully numerical model to investigate the air—sea interaction and its effect on oceanographic processes are found in Nelson and He (2012) and Drews (2013).

The case of the Ebro River shelf (NW Mediterranean Sea; see Figure 1) is characterized by strong, dry and usually cold wind that blows from the north-west through the Ebro valley. The westerly wind, greatly affected by the orography, is channelized into a limited band, forming a wind jet (Jansà, 1985; Spanish Ministry of Energy, 2004). The synoptic situation is related to an anticyclone in the Bay of Biscay and a low-pressure area in the Mediterranean Sea (Riosalido et al., 1986; Font, 1990; Martin-Vide, 2005; Cerralbo et al., 2015). Offshore wind is more usual and intense during autumn and winter, when larger atmospheric pressure gradients take place and cause stronger winds with advection of cold air, but a small atmospheric pressure difference along the Ebro valley is sufficient to initiate wind during any season (Riosalido et al., 1986; Cerralbo et al., 2015).

The objective of this contribution is to describe the meteo-oceanographic processes associated with a wind jet developing at the northern margin of the Ebro River shelf. This work provides insight into wind jet in an orographically complex region, such as the Ebro delta shelf,
describing the main wind, wave and current patterns and the feedback relative to the air—sea momentum transfer in terms of wave-induced ocean surface roughness. After the introduction (Section 1), in Section 2 (Methods) we describe the study area, the COAWST model implementation and the wind jet event selected to investigate in detail the meteo-oceanographic dynamics. Then, in Results (Section 3) we show the most relevant meteo-oceanographic processes observed and a detailed skill assessment of the fields modelled, comparing them with a set of available data (i.e. in situ observations and remote-sensing products). Also, the feedback in the air—sea momentum transfer in terms of wave-induced ocean surface roughness is investigated with a set of coupled simulations testing different air—sea momentum transfer formulations. Afterwards, we discuss (Section 4) the relevance and particularities of the dynamics of the wind jet area in terms of waves, winds and currents, comparing with previous investigations. The implications of the wind—wave coupling in terms of the wind resource assessment are highlighted. We close with the conclusions (Section 5).

2 Methods

2.1 Study area and observations

The meteorological patterns over the NW Mediterranean Sea exhibit sharp gradients associated with the topographic control on synoptic fluxes (Jansà, 1985; Martin-Vide and Olcina, 2001). Regional wind analysis reveals strong and persistent cross-shelf winds. A channelization effect associated with the Ebro valley triggers north-westerly winds (called “Mestral”), resulting in a wind jet. Previous studies based on long-term wind measurements in the proximity of the region showed that winds have a persistent seasonal pattern (Font, 1990; Cerralbo et al., 2015; Grifoll et al., 2015). During winter and autumn, a dominant north-westerly component caused by wind channelization was observed. For instance, recent wind measurements revealed that cross-shelf winds were observed more than 60% of the time during these seasons (Grifoll et al., 2015). In this period, the energy is concentrated in the low frequencies associated with synoptic scales (periods of 2—5 days, corresponding with the passage of weather systems). However, the warmer period (spring and summer) is characterized by high variability with a dominance of south-westerly winds. This means that during spring and summer the relative contribution of the daily components (breezes) to the
variability increases with respect to the synoptic winds (Font, 1990; Cerralbo et al., 2015). The warmer seasons are less energetic than the cold seasons in terms of wind intensity.

The Ebro River delta is located immediately to the south of the wind jet region, and the average annual river discharge ranges between 300 and 600m³·s⁻¹. The curvature of the bay partially shelters it from southerly waves. Regional wave climate in this area is characterized by south-east and east sectors, the latter being the most energetic due to the largest fetches (Bolaños et al., 2007).

Oceanographic investigations in the Ebro River region were focused primarily on the outer shelf and slope dynamics of the southern margin (Font, 1990; Palanques et al., 2002; Salat et al., 2002; Jordà, 2005) with relevant eddy activity (Redondo et al., 2013). The circulation in these regions is dominated by the inertial band, with a relevant signal of the slope current associated at the regional Northern Current (Jordà, 2005). Observational analyses have revealed that the inner and mid-shelf (less than 50m water depth) dynamics in the Ebro shelf are characterized by a strong influence of the frictional component of the flow (Jordà, 2005, Grifoll et., 2015). Furthermore, the regional response to wind jets is not clear due to the complex bathymetry and the spatial variability of the wind jet. Durand et al. (2002) and Mestres et al. (2003) showed that the effects of the salinity river plume are important only near the river mouth (order of 10km offshore from the river mouth).

As a part of large effort to collect physical data and implement numerical tools for the assessment of offshore wind energy potential, a buoy was moored in the northern margin of the Ebro shelf where the wind jet develops (see Figure 1). The buoy was moored 3.1km from the coast at 43.5m bottom depth, measuring wind, waves and water currents for one year. A TRIAXYS directional wave sensor mounted on the moored buoy was used to record statistical wave spectra parameters. Wind speed and direction were measured at 4m height every 10min using an ultrasonic wind sensor (Gill Instruments) for one year (November 2011 to November 2012). Water currents were measured with a SonTek acoustic Doppler currentmeter profiler (ADCP) at 500kHz every hour using 20 vertical layers (layer depth was 2m). The mooring period covered more than one year (from November 2011 to December 2012).

Additionally, satellite-measured winds were used for the numerical model validation. Sea wind intensity and direction were obtained from the National Climatic Data Center (NCDC-NOAA, http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html). This product is the result
of a spatial and temporal interpolation of the data received from the different satellites passing through the study area during a time interval, and it has 6h time resolution and 0.25º spatial resolution.

2.2 Numerical model and meshes

The COAWST modelling system (Warner et al., 2010) was used in this study. COAWST relies on the 3-D ocean modelling ROMS (Regional Ocean Modeling System; see Haidvogel et al., 2000), the phase-averaged wave model SWAN (Simulating WAaves Nearshore; see Booij et al., 1999), the non-hydrostatic meteorological model WRF (Weather Research and Forecasting; Skamarock et al., 2005) and the sediment transport module CSTMS (Community Sediment Transport Modeling System; Warner et al., 2008). The ocean model ROMS is a free-surface, terrain-following numerical model which resolves the three-dimensional Reynolds-averaged Navier—Stokes (RANS) equations using hydrostatic and Boussinesq approximation. The WRF model (Advanced Research WRF version) is a non-hydrostatic, quasi-compressible atmospheric model with a variety of physical parameterizations of sub-grid scale processes for predicting meso- and microscales of motion. The SWAN model solves the wave action balance equation simulating wind generation and propagation in deep and coastal waters. The modelling system COAWST includes the coupler Model Coupling Toolkit (MCT; Jacob et al., 2005) for the transmission and transformation of the physical variables using a parallel computing approach. The COAWST system also allows for the exchange of data fields on different grids using the Spherical Remapping Interpolation Package (SCRIP; Jones, 1998) to compute the interpolation weights.

The largest wave domain (mesh O1) covers the western Mediterranean Sea, which is considered large enough to capture the wave generation in the study area. The SWAN model implementation used amends the underestimation in the wave growth rates reported by Alomar et al. (2014) and Rogers et al. (2003) in a low- and medium-frequency energy spectrum. The measure adopted was introduced by Pallares et al. (2014) and consists in modifying the whitecapping dissipation term (see Appendix 1).

The largest water circulation domain (mesh O3) is nested into the daily MyOcean-MEDSEA product (Tonani et al., 2009), with a horizontal resolution of 1/16°x1/16° and 72 unevenly spaced vertical levels, in order to provide suitable boundary conditions for the oceanographic variables in terms of water velocity, sea level, temperature and salinity. The 3D ocean model
implementation (ROMS) includes a generic length scale turbulent mixing scheme (Umlauf and Burchard, 2003), with coefficients selected to parameterize the K-epsilon scheme (Rodi, 1987) and fourth-order biharmonic Laplacian viscosity and mixing terms on geopotential surfaces for velocity and tracers, respectively, both with constant coefficients of 0.5m^4s^{-2}. The bottom boundary layer was parameterized using a log profile with bottom roughness equal to 0.005m. The time-interval for data exchange between the models is 600s.

The atmospheric model is nested into the ECMWF ERA-Interim reanalysis product considering four downscaling meshes – M1, M2, M3 and M4 with resolutions of 27km, 9km, 3km and 1km, respectively – to obtain suitable grid resolution for the complex orography of the region (see Figure 1). The WRF implementation uses a Mellor—Yamada—Nakanishi—Niino (MYNN) level 2.5 planetary boundary layer scheme. The nesting strategy consists of a set of different downscaling meshes (Figure 1c and Table 1). The ocean—atmospheric—wave online coupling was implemented in the finer domain (mesh O4 for the wave and circulation model, and mesh M4 for the meteorological model) where the scale of the coupling process due to cross-shelf winds may be more evident in the results. In this case, air—sea coupled effects are included considering Taylor and Yelland formulation (Taylor and Yelland, 2001), for the ocean surface roughness modification due to the wave effect, and vortex force for the wave effects on currents (Olabarrieta et al., 2012).

2.3 Episode description and numerical sensitivity test

As we noted in the introduction, the air—sea momentum transfer presents high complexity due to the relation of wave characteristics and the sea bottom roughness, which in turns affect the wind field. In order to investigate the air—sea momentum transfer in the wind jet, a set of simulations have been designed applying different air—sea momentum transfer formulations included in the COAWST modelling system. The sensitivity tests pursue an evaluation of the “coupling” effects on two principal variables involved in the air—sea momentum transfer: wind intensity (W) and significant wave height (H_s). In this sense three different formulations have been tested (see Appendix 2), which consider the modification of the atmospheric bottom roughness due to the waves. In consequence, we compare directly the “coupled” results with an “uncoupled” simulation where the bottom roughness length is only a function of the wind stress. The sensitivity tests are as follows: CHK for the simulation considering the bottom roughness as a function of the wind stress (uncoupled with the wave sea state) using the Charnock coefficient equal to 0.016, T—Y simulation considering the Taylor and Yelland
formulation (Taylor and Yelland, 2001), DRE using the Drennan formulation proposed by
Drennan et al. (2003) and OOST simulation considering the formulation introduced by Oost
et al. (2002). Two numerical points are chosen to compare the results for the sensitivity test
simulations. One point is near the buoy’s moored position (where the numerical results are
also compared with the measurements). The second point is located 30km offshore of the
measurement point (see control point in Figure 1). This point has been chosen in order to
capture the wave growth due to cross-shelf winds and evaluate properly the coupling—
uncoupling differences.

We select a cross-shelf wind event in order to characterize in detail the meteo-oceanographic
dynamics of the wind jet. The episode selected for the sensitivity tests lasted from the 19th of
March 2012 to the 23rd of March 2012. The synoptic situation during the selected episode
corresponds to a typical offshore wind event induced by atmospheric pressure differences (see
Figure 2). A high-atmospheric-pressure area is centred over the North Atlantic Ocean, with
the anticyclonic edge affecting part of the Iberian Peninsula. The low pressure is located in
the centre of Europe. In this situation the cross-shore winds in the Ebro delta zone are
intensified. The sequence of wind field modelled in the Catalan coast mesh during the wind
jet period is characterized by a rise of wind intensity during the 20th and 21st of May, leading
to a wind jet in the northern margin of the Ebro delta (see daily-averaged wind intensity in
Figure 3). Then, the cross-shore winds remain strong during the 22nd of May, decreasing
during the 23rd of May 2012.

3 Results

3.1 Description of meteo-oceanographic processes and skill assessment

The skill assessment of the model is carried out for different meshes in function the spatial
domain of the observations. Modelled winds during the simulation period reproduce the main
wind directions previously reported in the study area. Offshore wind prevails throughout the
year, intercalated with southerly winds during spring and summer (i.e. sea breeze). The
adjustment of the wind time series into a Weibull distribution is used to evaluate the statistical
inter-comparison between wind observations (measured from the buoy and satellite) and the
3km WRF model results (mesh M3). Blended Sea Winds were used from the NCDC-NOAS
SeaWinds project which contain 6-hourly globally gridded, high-resolution ocean surface
vector winds and wind stresses on a global 0.25° grid. Figure 4 shows the Weibull
distributions considering the wind intensity time series. Also the global model (i.e. ECMWF) used for WRF model downscaling is included. The results show that for high and medium range wind speeds (> 2.5 m/s) the numerical simulation presents better agreement with the wind measurements than the global model and the gridded satellite wind estimations. Although the global wind model assimilates the satellite information, the Weibull distribution of the high-resolution model presents a better level of agreement with the observations. A snapshot of the SeaWinds product was compared with the numerical outputs in Figure 5. Wind patterns from both products present a significant level of agreement in both components assuming the coarser resolution of the SeaWinds. Additional verification is presented in Table 2 using model—observation statistics in terms of wind intensity for the whole year of 2012. Correlation coefficient (R) is almost 0.8 and the root mean square error (RMSE) and the Bias are smaller than the mean and the standard deviation obtained from the observations. In summary, modelled winds show an acceptable level of agreement with the observations.

In Figure 6, time series comparing the results obtained from the coupled SWAN model (mesh O3) and the buoy measurements (see position in Figure 1) are shown. The time series comparison corresponds to the significant wave height (Hs), the mean wave period (Tm01) and the mean wave direction (θw). Table 2 presents the error statistics for the whole year for mesh O3 in terms of Hs and Tm01. In general, the model reproduces the observed values in terms of mean behaviour and variability. Error statistics are similar with previous numerical investigations in the region; Pallares et al., (2014) obtained values of R ranges 0.68 to 0.91 for Hs.

Figure 7.right show a snapshot of the waves’ directional spectra during the wind jet period selected at the measuring point; the results reveal the tendency to develop bimodal directional spectra due to the co-existence of sea and swell waves. Directional spectra presents a peak around 315º mean wave direction associated with the growing wave due to the wind jet and another peak around 135º associated with the swell. Despite the limited fetch, larger wave frequencies (smaller wave period) are obtained for the 315º wave direction peak than for the 135º wave direction peak. In Figure 7.left the directional spectra for a period without wind jet are also shown for comparison. In this case, unimodal wave spectra is obtained. In summary, the high-resolution mesh (O4) is able to capture the bimodal spectra during wind jet. Unfortunately, only the statistical spectra parameters were recorded in the buoy measurements, and full spectra comparison is not possible.
The water circulation observed at the buoy is characterized by an alignment of the flow following the isobaths. The principal component analysis of the flow for the observed depth-averaged currents reveals an angle similar to the coastline orientation (~26º). As the cross-shelf flow is limited by the coastline, the variability in this direction is smaller than in along-shelf direction: standard deviation is 2.3cm·s⁻¹ in cross-shelf direction versus 7.4cm·s⁻¹ in along-shelf direction. However, the water circulation during the wind jet events shows a different pattern. During these events, the cross-shelf flow variability increases (3.8cm·s⁻¹ for the wind jet event selected), with either two-layer flow or an offshore flow in the whole water column. As an example of water current response during wind jet event, the along-shelf and cross-shelf velocities are shown in Figure 8 for May 2012 at the observational point (negative values mean south-westward/onshore and positive north-eastward/offshore). The surface currents in the cross-shelf direction intensify, causing an eventual two-layer flow during the peak of the wind intensity (21st of May). When the wind jet calms down, the cross-shelf velocities are small while the along-shelf flow intensity is larger than that of the cross-shelf. The along-shelf current observed during wind jet events tends to reverse from south-westward to north-eastward.

The skill assessment of the numerical results in terms of current (water velocity) was carried out following a similar scheme to the one used for winds and waves. The numerical model validation with ADCP observations shows an acceptable level of agreement according to the comparison for the wind jet event. For instance, Figure 8 shows a noticeable agreement between the observed and modelled currents in the water column for both along- and cross-shelf components. In addition, Table 2 presents the error statistics for the depth-averaged velocity measurements compared with the numerical model results for the wind jet event. Skill assessment is better in depth-averaged along-shelf flow in comparison to cross-shelf (e.g. R equal 0.82 to vs. 0.24) due to the frequent two-layer flow structure observed in cross-shelf measurements during wind-jet events giving rise a weak depth-averaged cross-shelf velocity.

The spatial water circulation modelled during the wind jet event (21st of May) is shown in Figure 9 for two different depths: sub-surface (2m water depth) and intermediate (50m water depth) for O3 mesh. Depth-averaged velocities are also presented in Figure 9. The surface current modelled at 1km (mesh O3) and 250m (mesh O4) grid resolution presents a relatively homogeneous offshore direction qualitatively that is well correlated with the spatial
distribution of the wind intensity. In this case, the surface current is seldom affected by the
topographic features such as the Ebro delta. Consistent with Figure 8, at deeper layers the
flow direction turns onshore, resulting in a two-layer flow in which the current intensity is
lower than that of the surface layer (Figure 9, centre). The depth-averaged flow is small due to
the balance between the sheared two-layer flow; however, a flow component slightly appears
that is aligned with the isobaths in the deeper areas of the continental shelf. Related to that, a
clear signal of the slope current is observed in the results at -50m and depth-averaged
currents.

3.2 Ocean surface roughness numerical experiments

The wind intensity and the significant wave height during the selected wind jet event for the
four simulations are shown in Figure 10 (for the control and observational points shown in
Figure 1). Comparing the numerical results and the observations (Figure 10, upper sub-plots),
all the numerical simulations reproduces the wind intensity and the significant wave height
with a similar level of agreement. The uncoupled (CHK) and coupled simulations (e.g. T-Y,
OOST and DRE) only present differences in the numerical outputs during the joint occurrence
of strong winds and wave peaks in the control point. Waves and wind intensity numerical
results at the observational point do not presents significant changes among the four
simulations due to the limited fetch conditions which means lower significant wave height in
comparison to control point. During the calm period (at beginning and end of the wind jet
event) the differences among the four simulations are not appreciable. Numerical coupled
results does not present better agreement at the observational point than the uncoupled mode
results. Comparing the error statistics for the observational point among the three coupled
numerical simulations we cannot assure which formulation ensures a better skill assessment
(Table 3). At control point the magnitude of the wind intensity and the significant wave height
is larger for the uncoupled simulation (CHK) in comparison to coupled simulations (Figure
10, bottom sub-plots). Maximum differences of 3 m·s⁻¹ in wind intensity and 0.3 m in
significant wave height are obtained if we compare OOST and CHK simulations. In
consequence, small differences are found between coupled and uncoupled simulations when
wave conditions increases.
4 Discussion

The shape of the wind jet modelled is benefited by the high resolution meshes used in our investigation. According to our results, the wind jet approximately covers an area of 50 km width offshore. This area is in agreement with the wind intensity atlas provided by the Spanish Ministry of Energy (see Figure 11) obtained from a long-term reanalysis product (15 years using the MASS model). In this sense, high-resolution meshes used in this investigations (i.e. 1 km and 3 km grid resolution) are suitable for an accurate wind jet modelling. As it was pointed out by Alomar et al. (2014) and Cerralbo et al. (2015), the relevance of winds in the ocean response in terms of waves and currents justifies the high-resolution in the modelling investigations in Ebro Delta region.

Our results have shown an acceptable representation of the bimodal structure of the significant wave height and support the conclusions highlighted by Alomar et al (2014), who note that a high spatial resolution of wind field is required to represent acceptable numerical wave field in a very limited fetch conditions. The occurrence of bimodal wave features may also have different implications: the first one is that, because of the spatial resolution, the local northwesterly wind that produced the second peak of spectra may not have been detected in previous investigations (Bolaños et al., 2005, 2006; Sánchez-Arcilla et al., 2008; Alomar et al., 2014). The second implication is related to the momentum transfer: several authors have highlighted that under mixed wave-train conditions the ocean surface roughness may increase appreciably (Sánchez-Arcilla et al., 2008). Also, the wave modelling deserves a particular comment related to the good fitting of wave results in comparison to previous investigations (Bolaños et al., 2007; Sánchez-Arcilla et al., 2008). Statistical errors were reduced significantly due to the young sea developed in the wind jet region likely thanks to the modification of a parameter relative to whitecapping dissipation (Pallares et al., 2014). In particular, smaller root mean square errors were obtained in the mean wave period variable, which presented a large uncertainty (Bolaños et al., 2007; Sánchez-Arcilla et al., 2008; Alomar et al., 2014).

As we noted in the Results section, the water circulation pattern showed differential behaviour for the long-term water circulation in comparison to the wind jet event. For the long-term circulation and in the shallow region, the frictional response prevails, with the along-shelf flow variability being larger than the cross-shelf flow, similar to other investigations in the inner and mid-shelf (see review in Lentz and Fewings, 2012). However, a different picture
occurs during the wind jet event. In this case a characteristic surface current is high correlated
to the offshore wind. According to the numerical outputs and in situ observations shown in
Figure 8, a deeper onshore flow, opposing the surface layer flow offshore, is developed. This
flow is relatively weak due to the prevalence of the along-shelf component which increases
offshore. These circulation patterns are consistent with other investigations (e.g. Horwitz and
Lentz, 2014; Fewings et al., 2008; Dzwonkowski et al., 2011) where a well-developed two-
layer flow due to intense cross-shelf winds tends to occur when the turbulent layers overlap
(water depth in the inner shelf is of the order of metres to tens of metres according to Lentz
and Fewings, 2012). In the mid- and outer shelf, the flow tends to be oriented in the along-
shelf direction due to the prevalence of the regional response to the wind jet and the slope
current. In this sense, the frictional adjustment time due to the wind (inversely proportional to
the depth) varies in the continental shelf section and may be of the order of days in the mid-
/outer shelf (Csanady, 1982). As a consequence, the expected response at deeper layers will
also be dependent on processes acting at larger scales than wind jet (i.e., baroclinic forcing,
mesoscale activity etc.) such as the slope current signal observed at 50m water depth and
deepth-averaged currents in the numerical results (Figure 9). The along-shelf flow in the inner
shelf is presumably influenced by the regional response to the wind jet at the stratification in
the water column and the barotropic pressure gradient adjustment due the spatial wind
variability. These factors play an important role in the resultant water circulation pattern and
its variability deserves additional numerical efforts and extended local wind and sea level
information. For instance, Oey et al. (2004) and Liu and Weisberg (2012) include extended
measurements to investigate the water circulation' response to spatial wind and the particular
role of the barotropic pressure gradients. Finally, it is worth noting that the interaction
between offshore winds and regional circulation was filtered in previous investigations in the
region (Font, 1990; Salat et al., 2002; Jordà, 2005).

Several investigations have found the importance of the sea state in the impact on the air—sea
momentum flux; in particular the calculations based on the Charnock constant underestimated
the air—sea momentum transfer (e.g. Janssen and Viterbo, 1996; Drennan et al., 2003) which
can be significant under mixed seas (Sanchez-Arcilla et al., 2008). In the northern margin of
the Ebro delta and during the wind jet, no relevant differences were found when comparing
the significant wave period and the wind intensity between numerical model and observations
for the observational point. During calm periods, the averaged conditions prevail over
energetic events, so the feedback of the air—sea momentum does not show significant
differences. The detailed analysis of the 21st-22nd of May event showed significant differences between the coupled and uncoupled cases for significant wave height and wind intensity offshore of the wind jet (e.g. control “offshore” point). When we compare the coupling numerical results (i.e. T—Y, OOST and DRE) versus CHK results, we observe that the wind intensity at the control point is affected significantly by the sea state during the energetic event. For the coupling simulations the wind intensity is reduced due to the increasing wave-induced ocean surface roughness. This behaviour is consistent with other coupling atmosphere—ocean investigations under a high level of meteorological energy (e.g. Olabarrieta et al., 2012). In parallel, the wave field is modified by the feedback between wave and wind stress. During the energetic wind event selected, Hs is lower in comparison to the uncoupled case (CHK), consistent with other numerical experiments (Webber, 1993; Warner et al., 2010; Olabarrieta et al., 2012) and observational investigations (Yelland et al. 1998; Edson, 2008) which found that the momentum flux is underestimated using the Charnock constant parameter. Unfortunately, the lack of measurements offshore of the observational point (i.e. larger fetch in comparison to observational point) has not allowed to investigate if the coupling simulations present better skill assessment than the uncoupled case.

Differences in the primitive variables between the coupled and uncoupled simulations during particular energetic events are relatively small in terms of wind intensity and significant wave height. Furthermore, the assessment of the wind energy resource is relevant in this region with a high potential for wind farm installation due to the large and persistent wind intensity and the relatively large spatial extension of the continental shelf. A simple way to estimate turbine power from wind intensity is based on the idealized machine of blade diameter (D) being equal to 100m (Manwell et al., 2011):

\[
P = \rho \frac{2}{3} D^2 W^3
\]  

(1)

Wind intensity (W) simulations are taken at 10m height, so a log-law-based conversion is used to obtain wind values at 80m (typical value of turbine hubs). With the converted values of the numerical simulations, we estimate the idealized wind power for the period 21st–22nd of May 2012 at the control point. The power using the CHK wind value is 8.087kW (average wind speed of 11.41m/s); in contrast, using OOST formulations leads to a power of 7.207 kW (average wind speed of 10.98m/s). Intermediate values are obtained for T—Y and DREN formulations: 7.365kW and 7.346kW, respectively. The cubic relationship between wind power and wind velocity highlights the importance of accurate estimations of wind intensity.
for wind energy resources using coupling techniques (a maximum percentage of 10% is assessed). This example shows the relevance of coupled effects for an accurate wind power assessment for wind farm project plans.

The wave-limited fetches and the persistent offshore winds represent particular ocean—atmosphere conditions never investigated before from a full-coupling perspective; only energetic cyclogenesis activity and extreme conditions has been recently modelled and investigated (e.g. Warner et al., 2010, Olabarrieta et al., 2012; Renault et al., 2012; Zambon et al., 2014; Ricchi et al., 2016) where also the heat transfer plays a relevant role in the air—sea coupling. In the mentioned cases, extreme modelled waves and wind benefitted from the use of full-coupling systems. Our case only presents comparable energetic conditions during a very short period of time; however the cubic relationship between the potential wind energy and the wind intensity may justify for engineering purposes the use of coupled formulations between wind and waves. Further observational campaigns and the future use of high-resolution remote-sensing products (e.g. Sentinel-1 and Sentinel-3; Torres et al., 2012 and Malenovsky et al., 2012) will benefit the numerical results and extended physical investigations in such a complex process as wind jet, in particular the role of the air—sea transfer formulations. Our results are also relevant in that they may be useful for further physical investigations in similar domains where the wind jets control the ocean—atmosphere dynamics (Jiang et al., 2009; Barton et al., 2009; Shimada and Kawamura, 2006).

5 Conclusions

Wind jet events, investigated using numerical modelling and both in situ and remote-sensing data, present particular conditions in meteo-oceanographic variables in the northern margin of the Ebro delta. A fully coupled meteo-oceanographic numerical model was implemented, with a good level of agreement in terms of waves, currents and wind fields measured. The numerical results reveal a spatially varying wind pattern, forming a well-limited wind jet. The water current velocity pattern during wind jet is well correlated with the wind intensities in the surface layer. However, in deep layers the flow becomes complex, and other processes of larger temporal and spatial characteristic scales affect the water circulation. The wave modelling during the wind jet events is characterized by the developing of bimodal wave spectra: local wave generation due to wind jet and waves propagated from the open sea. Numerical results from sensitivity tests have shown the relatively small relevance of air—sea transfer formulations considering the significant wave height for the sea bottom roughness.
estimation. Furthermore, the accurate estimation of the wind energy resource may be 
benefitted by the coupled numerical modelling. The characteristics of the meteo-ocean 
variables during the wind jet in the northern Ebro delta may be useful for understanding 
processes in similar domains under severe cross-shelf wind conditions.
Appendix 1. Modification of the whitecapping term in SWAN

Pallarès et al. (2014) performed numerical experiments that aimed to improve the numerical wave predictions in semi-enclosed bays, modifying the dissipation terms in the wave energy balance equation. For this purpose two whitecapping formulations are considered in SWAN, obtained from the pulse-based model of Hasselmann (1974) reformulated in terms of wave number (the WAMDI group, 1988):

\[ S_{\text{diss}}(\sigma, \theta) = -\Gamma \sigma \frac{k}{k_{\text{rel}}} E(\sigma, \theta) \]

(A1.1)

where \( \sigma \) and \( \frac{k}{k_{\text{rel}}} \) denote the mean frequency and the mean wave number, respectively, and the coefficient \( \Gamma \) depends on the wave steepness (Janssen, 1991):

\[ \Gamma = C_{d_{\sigma}} \left(1 - \sigma^2 \right) + \delta \left(1 - \frac{k}{k_{\text{rel}}} \right)^p \]

(A1.2)

The coefficients \( C_{d_{\sigma}}, \delta \) and \( p \) can be adapted to the study case; \( \delta \) is the overall wave steepness; and \( k_{\text{rel}} \) is the value of \( k \) for the Pierson—Moskowitz spectrum.

In SWAN the previously mentioned coefficients are obtained by adjusting the energy balance for idealized wave growth conditions (fully developed wind seas in deep water), despite the wave growth in semi-enclosed domains with highly variable wind fields differing considerably from those idealized conditions. As a result of a calibration process in the NW Mediterranean Sea, which led to a reduction of the wave forecast errors mainly present in the wave period, the coefficients selected for the wind jet region were \( \delta = 1 \), \( C_{d_{\sigma}} = 2.36 \times 10^{-5} \) and \( p = 4 \), achieving a notable fit between numerical outputs and wave observations.

Appendix 2. Air—sea momentum transfer formulations (bottom roughness length)

The standard bottom roughness length scale is expressed as a function of the Charnock coefficient (\( C_a \); typical value of 0.016) and surface wind stress (\( u_s \)):

\[ z_0 = C_a \cdot u_s^2 / g \]

(A2.1)
where $g$ is the gravity. Coupling online simulations in COAWST allows three different formulations to be chosen to parameterize the bottom roughness considering the wave effects. The formulation of Taylor and Yelland (2001) considers the wave effects:

$$z_0 = 1200 \cdot (H_s/L_p)^{4.5} \quad (A2.2)$$

where $H_s$ is the significant wave height and $L_p$ is the wavelength at the peak of the wave spectrum. Drennan et al. (2003) proposed a formulation to estimate $z_0$ as a function of the phase-wave speed ($C_p$) and wind friction velocity ($u^*$):

$$z_0 = 3.35 \cdot (u^*/C_p)^{3.4} \quad (A2.3)$$

Similar to Drennan's formulation, Oost et al. (2002) proposed the following formulation based on an experimental data set:

$$z_0/L_p = 25.0/\pi \cdot (u^*/C_p)^{4.5} \quad (A2.4)$$

Conceptual differences arise from these formulations: Taylor and Yelland (2001) considers the wave steepness, Drennan et al. (2003) is based on the wave age and Oost et al. (2002) considers effects of both wave steepness and wave age.

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Table 1. Resolution (in km) of the different domains/meshes used in the nested system as a function of each numerical model and regional scale covered. In parentheses the mesh name in Fig. 1 is shown.

<table>
<thead>
<tr>
<th>Model</th>
<th>NW Mediterranean</th>
<th>Catalan—Balearic Sea</th>
<th>Catalan coast</th>
<th>Ebro delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRF</td>
<td>27 (M1)</td>
<td>9 (M2)</td>
<td>3 (M3)</td>
<td>1 (M4)</td>
</tr>
<tr>
<td>SWAN</td>
<td>9 (O1)</td>
<td>3 (O2)</td>
<td>1 (O3)</td>
<td>¼ (O4)</td>
</tr>
<tr>
<td>ROMS</td>
<td>-</td>
<td>-</td>
<td>1 (O3)</td>
<td>¼ (O4)</td>
</tr>
</tbody>
</table>
Table 2. Statistics for the comparison between buoy measurements and model outputs. W is the wind intensity (in m·s⁻¹), Hs is the significant waves height (in m), Tm₀₁ is the mean wave period (in s) and U are the depth-averaged along-shelf currents (in cm·s⁻¹; positive north-eastward). The statistical parameters are the root mean square error (RMSE), the bias and the correlation coefficient (R).

<table>
<thead>
<tr>
<th>Observed</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>RMSE</th>
<th>Bias</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>6.59</td>
<td>4.52</td>
<td>2.70</td>
<td>0.68</td>
<td>0.79</td>
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<tr>
<td>Hs</td>
<td>0.62</td>
<td>0.42</td>
<td>0.29</td>
<td>0.09</td>
<td>0.76</td>
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<tr>
<td>Tm₀₁</td>
<td>3.48</td>
<td>0.92</td>
<td>3.57</td>
<td>1.14</td>
<td>0.57</td>
</tr>
<tr>
<td>U</td>
<td>-4.60</td>
<td>3.90</td>
<td>3.07</td>
<td>2.14</td>
<td>0.82</td>
</tr>
</tbody>
</table>
Table 3. Statistics for the comparison between buoy measurements and model outputs. W is the wind intensity (in m·s⁻¹); Hs is the significant waves height (in m). Statistics are only for the wind jet event (i.e. from 20 to 23 of May 2012).

<table>
<thead>
<tr>
<th></th>
<th>Mean (obs/mod)</th>
<th>Standard deviation (obs/mod)</th>
<th>RMSE</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHK</td>
<td>W  10.93/11.48</td>
<td>5.65/5.19</td>
<td>4.75</td>
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</tr>
<tr>
<td></td>
<td>Hs 0.74/0.73</td>
<td>0.27/0.32</td>
<td>0.25</td>
<td>0.61</td>
</tr>
<tr>
<td>T-Y</td>
<td>W  10.93/11.51</td>
<td>5.65/5.24</td>
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</tr>
<tr>
<td></td>
<td>Hs 0.74/0.72</td>
<td>0.27/0.31</td>
<td>0.26</td>
<td>0.61</td>
</tr>
<tr>
<td>DRE</td>
<td>W  10.93/11.46</td>
<td>5.65/5.24</td>
<td>4.79</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Hs 0.74/0.72</td>
<td>0.27/0.31</td>
<td>0.26</td>
<td>0.62</td>
</tr>
<tr>
<td>OOST</td>
<td>W  10.93/11.47</td>
<td>5.65/5.22</td>
<td>4.85</td>
<td>0.60</td>
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<tr>
<td></td>
<td>Hs 0.74/0.72</td>
<td>0.27/0.31</td>
<td>0.26</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Figure 1. Localization map (a) and orography (coloured map) and bathymetry of the study area (b). The bathymetry lines are shown every 25m. The geographical position where the observational buoy was moored is shown with a red circle. The control point used in the analysis is shown with a black circle. (c, d) Geographical domains for the meteorological model (in green) and the wave and the water circulation model (in red). The mesh notation is also shown (its resolution is detailed in Table 1).
Figure 2. Regional chart of the mean sea level pressure (hPa) during the 21st of May at 06:00 UTC (representative of the synoptic situation during the selected cross-shelf wind event). Data source: ERA-Interim global reanalysis from ECMWF. Arrows represent the wind field.
Figure 3. Sequence of the wind jet intensity on four days for a wind jet event in the domain of the Catalan coast. The quiver is shown each three points. Results obtained for COAWST at mesh M3 are plotted.
Figure 4. Weibull distribution adjustment for the wind velocities regarding the duration for the entire 12 months analysed.
Figure 5. Wind components (top: east—west top; bottom: north—south) from the satellite gridded product for the study area (top) and from the results of the meteorological model (mesh M1). The figure corresponds to 01/01/2012 at 12:00 UTC.
Figure 6. Time series of the significant wave height (m), the mean wave period $T_{m01}$ (s) and the mean wave direction for the first trimester of 2012. In black the buoy measurement is represented and in red the SWAN numerical results.
Figure 7. Numerical wave spectra for two different instants at the observational point: without wind jet event (left; 2nd March 2012) and during wind jet event (right; 21st March 2012).
Figure 8. Along-shelf (left) and cross-shelf (right) velocity observed (top) and modelled (bottom) during May 2012 (in m/s). Positive means north-eastward and offshore. The wind jet period is marked as a dashed square in the observed values. Note the different velocity ranges between cross-shelf and along-shelf plots.
Figure 9. Modelled circulation at -2m (left), -50m (centre) and depth-averaged circulation (right) during the peak of the wind jet event (i.e. 21st of May 2012, 06:00 UTC). The quiver is shown each four computational points. Grey lines are shown each 100 isobaths. Note differences in the velocity ranges among the sub-plots.
Figure 10. Wind intensity (left) and significant wave height (right) for the wind jet energetic event for the observational (top) and control (bottom) points.
Figure 11. Wind atlas annual mean wind speed at 30m height from a reanalysis product (source: Spanish Ministry of Energy, 2014).