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A note on nearshore wave features: Implications for wave generation

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Abstract

This paper analyses 10 years of wave data from the Mediterranean Spanish (Catalan) coast considering the mean wave climate and storm events from the standpoint of wind-wave momentum transfer and wave prediction. The data, registered by a buoy at about 12 km from the coastline, revealed two main groups of wave storms, with NW and E directions. NW storms correspond to a fetch-limited situation since the intense wind blows from land. Low-pressure centres located over the Mediterranean Sea produce easterly storms. Near the coast the eastern winds from the sea are replaced by NW winds coming from meteorological patterns over northern Spain and south-western France. Wave storms are classified and studied to obtain their main features (including spectral width, wave length, wave age and bimodality) and discussed in terms of wind-wave momentum transfer for operational wave predictions. Observations show a complex coastal wave climate. Fetch-limited storms presented smaller spectral widths while varying wind situations presented larger widths due to the presence of bimodal spectra. These wave features are highly relevant for wind–ocean momentum transfer and, thus, for current and wave predictions. The spectral width proved to be a good indicator of sea complexity and is thus applicable for improved wind drag estimations. A new drag coefficient formulation is proposed, based on existing wind dependent drag expressions, but including also spectral wave properties (a spectral width parameter) that highlights the characteristics of wind-wave generation under pre-existing swell. Such a formulation, once properly validated with field observations, is expected to improve wind-wave predictions.

Keywords: Wave climate; Wave generation; Wind drag; Wave storms; NW Mediterranean

1. Introduction

Coastal waves and currents are highly variable and can have a significant impact on human activities and structures. Wind-wave prediction is of great importance for the design and management (including navigation)

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of coastal areas. Therefore, the continuous research and improvement of wave monitoring and operational forecasting become vital issues for the safety and well-being of coastal society.

In recent years, the NW Mediterranean (Fig. 1) has experienced severe storms characterized by large waves and winds that caused significant damages to navigation and coastal activities which are economically relevant for the area (Skliris et al., 2004; Casas et al., 2003; Grémare et al., 2003; Puig et al., 2001). Wind waves are one of the most important factors for this impact and for the air–sea momentum transfer process. Almost all the momentum transferred from the wind to the sea drives currents through turbulence and wave breaking, with only a small fraction contributing to the growth of surface waves (Csanady, 2001a). The size, shape and phase velocity of the locally wind generated waves and swell all affect the momentum transfer between the atmosphere and the ocean.

The main aim of this paper is to characterize the coastal wave climate, and in particular, wave storms, in the NW Mediterranean. The emphasis is on wave features and their implications for momentum transfer and wave generation models such as SWAN (simulating waves nearshore). The paper begins by briefly describing the process of air–sea momentum transfer. Wave climate and wave storms on the Catalan coast are considered next. Finally, the implications of spectral features on momentum transfer for a wind-wave generation model are discussed.

1.1. Air–sea momentum transfer

The parameterization of the wind stress (drag) over the ocean is an essential issue in the numerical analysis of ocean–atmosphere interactions for climatic modelling, satellite observations and the study of heat, gas and

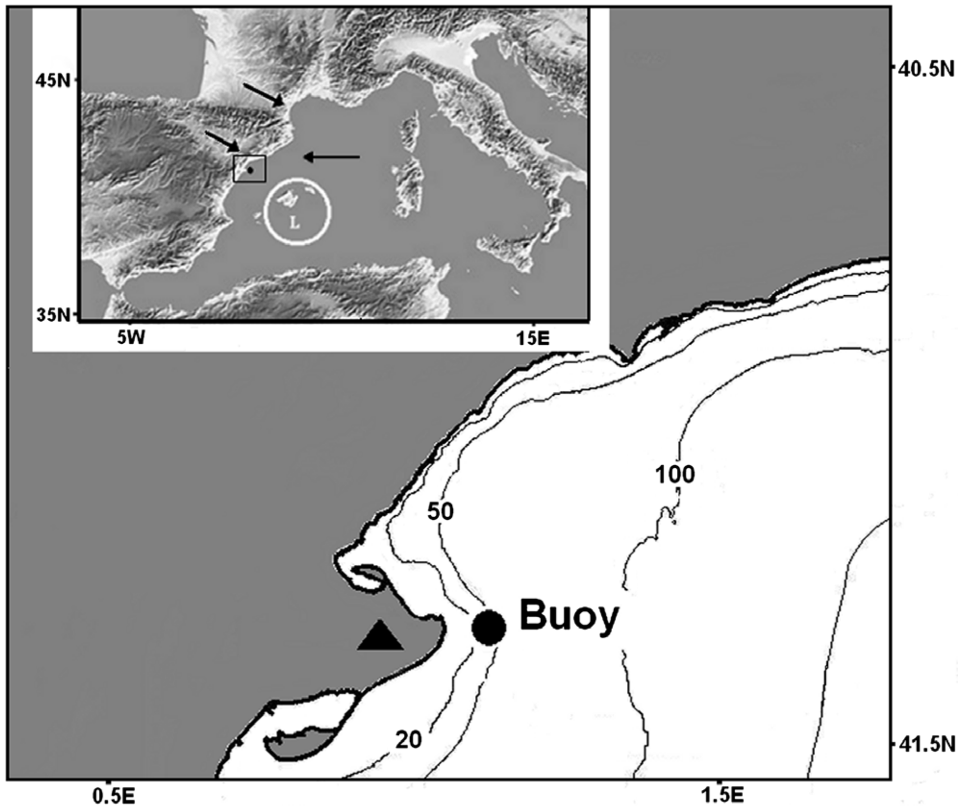

Fig. 1. NW Mediterranean orography and Ebro delta location. The arrows show how the predominant storm wind conditions, from land and towards the Mediterranean Sea, are highly influenced by orography. The black dot locates the directional wave buoy in front of the Ebro delta. The black triangle shows the area where meteorological stations are located. The white circle schematizes a typical low-pressure system, which produces east wave storms at the north Spain Mediterranean coast.

mass fluxes (Toba et al., 2001). The drag coefficient is commonly expressed in terms of the wind velocity but the large scatter (Vickers and Mahrt, 1997; Toba et al., 2001) indicates that there are many more complex processes that are not taken into account. The drag over a solid surface is related to the surface properties (roughness) and therefore it is clear that over the ocean, the surface gravity waves are part of the natural roughness and have to be taken into account. This roughness is usually expressed in terms of a roughness length, z_0. This parameter dynamically characterizes the geometric properties of the water–air interface and controls the drag coefficient and the wind profile over the sea surface (Csanady, 2001b; Jones et al., 2001; Wu, 1982). Many different theories and data sets related to wind stress over the ocean have been reported (Toba et al., 2001) and although some of them seem to be contradictory, they have contributed to a better though still limited understanding of atmosphere–ocean interactions.

1.2. Wave dependent wind stress

For more than 50 years there have been efforts to relate drag coefficients to wind and ocean surface properties. The Charnock expression (Charnok, 1955) has been the basis for the development of a wave dependent wind stress. It can be expressed as:

$$C = \frac{z_0 g}{u_*^2} \tag{1}$$

where C is a dimensionless constant called the Charnock parameter, g is the acceleration of gravity and u_* the friction velocity. This parameter has been related to wave properties in different ways, although the dependence on spectral wave parameters is still unclear. Ueno and Deushi (2003) propose an empirical formula for water roughness, arguing that spectral peak or wave age are not appropriate variables to describe the roughness length, which should be rather associated with the high frequency capillary waves. Nevertheless, there is some evidence that gravity wave parameters also contribute to determining surface properties (Lange et al., 2004; Bourassa et al., 2001; Donelan et al., 1993; Monbaliu, 1994; Anctil and Donelan, 1996; Taylor and Yelland, 2001; Oost and Oost, 2004; Makin and Kudryavtsev, 2002).

A common practice is to use drag expressions parameterized in terms of wind speed only (Wu, 1982; Yelland and Taylor, 1996), but, for very strong winds the resulting shear stresses tend to be different than the actually observed ones, due to the negligence of gravity waves in the free surface. Recently, it was suggested (Powell et al., 2003) that for strong winds (of more than 40 m s^{-1}) the roughness length and the drag coefficient are reduced due to the presence of foam. An accurate estimation of the shear stress may therefore not be possible unless the wave field is known. The drag coefficient should depend on fetch, duration, and in general, the wave spectrum and its age (Mete Uz et al., 2002; Ly and Garwood, 2000; Vickers and Mahrt, 1997).

The importance of wave age has been highlighted by Donelan (1982), who showed that the drag coefficient over a young sea is 50% higher than that of an old sea. Other studies (Makin and Kudryavtsev, 1999) also argue that waves shorter than 1 m support 50% of the form drag. This will be of great relevance in cases of rapid storm development and the coexistence of sea–swell conditions, where the wind-wave interaction should be different to "simple" sea conditions. The consideration of wave properties in the drag parameterization improves predictions (Vickers and Mahrt, 1997), while the presence of swell tends to invalidate conventional formulations (Rieder, 1997). A relation suggesting a dependence of the drag coefficient on wave age and wind speed for sea conditions has been recently proposed (Drennan et al., 2003). Even for a given wave age the roughness length can take a wide range of values and the drag coefficient may depend on more than just one wave parameter (Komen et al., 1998; Pan et al., 2005). This may explain the large scatter of data and the lack of consensus from study to study (Rieder, 1997). It emphasizes the importance of mixed sea conditions, turning winds and directional properties of wind and waves, which are commonly found in nature as mixed seas.

A complication is introduced by the rotation of the surface stress with respect to the mean wind vector. Surface shear stress is the vector sum of wind stress, wind wave stress and swell stress (Grachev et al., 2003; Remy and Giovanangeli, 1999). Moreover, the transient effects of sea drag associated to changes in the wind field have shown (Rieder, 1997) a time response of about 4 h (the same time response of waves with period of about 4–6 s). It has also been shown (Smedman et al., 2003) that for mixed sea/swell conditions the logarithmic wind law is no longer valid. After separating sea and swell energy by a comparison with the wind speed, these authors found that the roughness length was proportional to wave age and the energy ratio between wind waves and swell. Further evidence for the importance of swell comes from observations by Donelan (1987) and Mitsuyasu and Yoshida (1989) who showed the different wave growth rates under the presence of following and opposing swell. Such bimodal systems can also be influenced by nonlinear coupling due to resonant interactions (Masson, 1993) and affect the resulting wind drag (Larsén et al., 2003). Other recent studies (Hanson and Phillips, 1999; Violante-Carvalho et al., 2004) have found no obvious influence of swell on the wind sea growth rates.

Wind gustiness may also affect wind stress and wave growth. Cavaleri and Burgers (1992) and Oliveira (1997) have shown the importance of such wind variability when modelling wind-waves, finding wave growth rates higher than predicted by conventional models. The wind drag can also change in restricted coastal domains (Vickers and Mahrt, 1997; Flamant et al., 2003). The influence of bottom depth (Chen et al., 2004) can become noticeable if this modifies wave properties. Makin (2003) proposed a drag parameterization including wind speed, wave age and finite depth, although it was formulated only for sea conditions. In conclusion, despite all the research efforts to understand wind stress processes over the ocean surface there is not yet a universally accepted theory able to describe the underlying processes for complex situations.

2. The NW Mediterranean sea

2.1. Available observations

Four buoys from the XIOM (Oceanographic and Meteorological Instruments Network from Generalitat de Catalunya) are used for operational wave measurements along the Catalan coast. The buoys are deployed at depths ranging from 45 to 74 m. The southern one, denoted Ebro buoy, is a directional wave rider with a recording frequency of 1.28 Hz. It is located at 40.72N, 0.98E about 12 km offshore the Ebro delta (Fig. 1). The time series is more than 10 years long and is the main source of data for this paper. Wind data are available from a set of coastal meteorological stations close to the wave buoy at half hourly intervals. Since there are no wind observations directly over the buoy position, these wind data are used for wind climate and for a qualitative wave age analysis. Other studies (Cateura et al., 2004a) have analyzed the wind data at the Ebro delta using three coastal meteorological stations and wind data over the sea from a nearby oil-drilling platform. The large orographic influence on land station data was clearly shown, especially for wind direction. When predominant wave directions were from the northwest a good correlation between land wind data and wave heights was found. When wave directions were from the east a better correlation between wind data at the oil platform and significant wave height was obtained. Severe wind events were noticeable in, land and oil platform, data series.

2.2. Orography, wind and waves

The Mediterranean Sea features local high and low-pressure systems controlled by orographic barriers that determine the spatial distribution of winds and land–sea temperature differences. In particular for the NW Mediterranean, the Pyrenees is a physical barrier that strongly modifies the wind patterns and produces the Mistral and Tramontane winds in France. The so-called NW Mediterranean (Fig. 1) is the area between Italy and the Strait of Gibraltar, from 5°W to 16°E Longitude and from 35° to 44°N Latitude. The predominant winds come from the north-west and from the north during December and January. Southerly and easterly winds are also important during February, March, April and November. The N and NW winds in this area feature large intensities and are strongly conditioned by orography. Their influence can be noticed hundreds of kilometres offshore, carrying cold and dry air over the Mediterranean Sea. These winds are one of the main contributing factors to Mediterranean storms (Flamant et al., 2003).

In the Ebro delta (40.4–41°N and 0.3–1.2°E) (Fig. 1) the local topography, with the coastal mountain chain "breached" by the Ebro river valley exerts a significant control on wind climate. In general, four wind directions dominate in this area: NE, E, SW and NW. The NW condition produces local wind waves with short periods due to the fetch limitation (Garcia et al., 1993). The maximum velocities have been recorded for eastern winds in agreement with storm conditions associated to cyclonic activity over the western Mediterranean. The mean wave climate near the Ebro delta coast show a yearly mean significant wave height (H_s) of about 0.8 m. The maximum recorded H_s was 6 m, corresponding to maximum wave heights of 10 m. The maximum recorded wave peak period was 14.3 s, with a yearly mean of 5 s, while the maximum recorded mean period was 9 s and the yearly mean of 4 s.

3. Wave storms

Easterly winds are responsible for the most energetic seas arriving at the Catalan coast, as can be expected from fetch considerations. The conditions of severe wave storms are the result of synoptic situations that flow in an E direction over the NW Mediterranean (Cateura et al., 2004b). The synoptic configuration commonly associated with these storms is characterized by:

- The initial positioning of an intense high-pressure area over the British Islands, leading to the NE and E air fluxes at the Catalan coast.
- Mediterranean cyclogenesis due to a high level cold air pool deepening and the passage of the resulting low in front of the Catalan coast. It generates easterly winds, except in Ebro delta area, where the wind comes from the NW due to orographic effects (Fig. 1).

This type of synoptic configuration can trigger severe wave events at the Catalan coast, because easterly winds are associated with the largest possible fetch.

3.1. Storm identification and classification

The storm threshold for wave buoy data was derived from an analysis of the available time series at the Ebro buoy from 1990 to 2002. We considered the minimum significant wave height threshold together with the minimum and maximum duration of data below this threshold. After a number of trial and error fits it was found that the best way to define a storm was by means of an H_s threshold and a time period. Using these parameters, a storm can be identified when H_s exceeds a given threshold (initially taken equal to 1.5 m, which is twice the yearly mean) during at least 6 h. These parameters were used to identify and characterize storm wave events. The directional sectors for the two main storm samples correspond to E and NW conditions. The south component is the third one in line of importance, but neither in frequency of occurrence nor in intensity it is comparable to the NW and E wave events. The most damaging wave conditions (inducing coastal risk) correspond to an H_s threshold of about 2 m. Mendoza and Jimenez (2004) suggested an alternative storm classification in which the main parameter was the energy content defined as the H_s integral over the storm period. Storms were organized into five categories by a cluster analysis, where the most energetic storms were, as expected, from the east.

3.2. Storm features

Fig. 2 shows the duration and number of storms for directional sectors. About 300 storms were recorded with a mean duration of 20 h. The storm period with largest H_s was from October to March. The most persistent storms were found to be from the East with a mean H_s of 2 m while the shortest were from the NW with a mean H_s of 1.7 m. It was found that storms with maximum H_s of about of 3.5 m occurred once per year.

Fig. 3 shows the mean wavelength against the significant wave height. These data correspond to storms with an H_s threshold of 2 m only. It is apparent that NW storms feature the shortest waves, in agreement with the fetch-limited conditions found during these events. This also leads to steeper waves for such conditions. Easterly storms present a wider wavelength distribution.

To evaluate the spectral width we have used the epsilon parameter defined as (Cartwright and Longuet-Higgins, 1956):

$$\varepsilon = \left[1 - \frac{m_2^2}{m_0 m_4}\right]^{1/2} \tag{2}$$

where m_n are the spectral moments of n order. This parameter is found to be between 0 and 1, with narrower spectra presenting smaller epsilon values. Goda (1976) proposed an alternative spectral width parameter (Q_p), which has a quadratic dependence on the spectrum ($S(f)$). It is, thus, very sensitive to the natural sampling variability while epsilon is not. Epsilon depends on the spectral moment of 4th order and is therefore sensitive to the high frequency tail and the high frequency cut-off. We have evaluated this parameter with the same high frequency cut-off (0.6 Hz) for all data. Fig. 4 shows the relation between spectral width and significant wave height. An interesting feature is the classification of spectral widths according to storm directions. The easterly storm data have higher spectral widths. The Mistral (NW) events show the lowest spectral width because these storms are fetch limited and usually generated by intense winds, which result in energetic although not well-developed waves. The east storms show higher spectral widths, corresponding to more mature waves, associated with longer fetches. On occasions under easterly wind conditions, the local winds at the Catalan coast can be north-westerly, controlled by orographic effects. In these situations two different wave systems exist, producing bimodal spectra and a corresponding increase in spectral widths.

Two severe wave storms that occurred in November 2001 (Bolaños et al., 2003) and in March–April 2002 will be analysed in more detail. Both were generated by the atmospheric conditions described above. The wave buoy recorded two H_s peaks of 6 m for the November storm and two peaks of 3 m for the March–April storm.

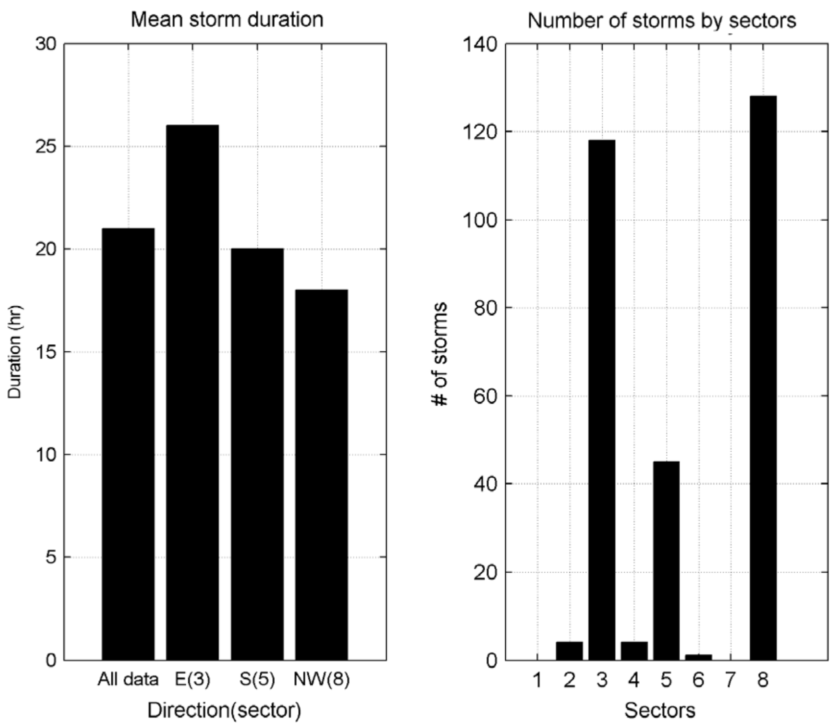

Fig. 2. Bar graphs with mean duration by principal wave directional sectors (left) and number of storms at each directional sector (right). Sectors start clockwise, from North (centred around 0°) and with 45° each. The NW (#8), E (#3) and S (#5) sectors are found to be the most relevant ones.

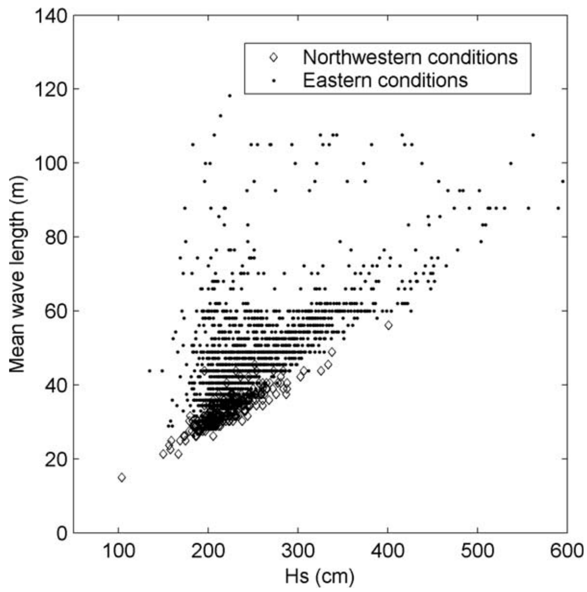

Fig. 3. Mean wavelength against significant wave height for storms exceeding the 2.0 m H_s threshold. Data are divided into NW and E storm situations.

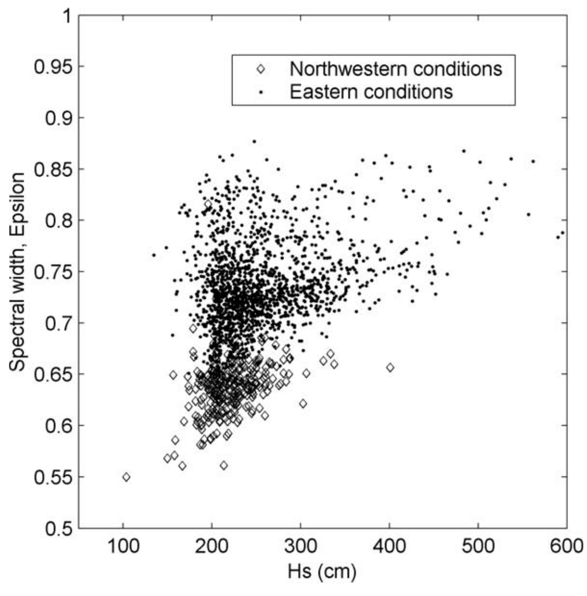

Fig. 4. Spectral width (ε) against significant wave height for storms exceeding the 2.0 m H_s threshold. Data are divided into NW and E storm situations.

These storms damaged beaches, promenades and harbour structures. During both events bimodal spectra were found with a swell peak from the E co-existing with a sea peak from NW. Fig. 5 (left) shows rose diagrams for wind and wave directions during the November 2001 storm. The buoy recorded predominant wave directions from E and NW while the meteorological station only recorded NW winds. This indicates a NW wind-wave generation over an existing swell from the E. An example of such bimodal scalar and directional spectra off the Ebro delta is shown in Fig. 5 (right).

The data from both events were split into "storm" ($H_s > 1.5$ m) and "calm" ($H_s < 1.5$ m) periods. Fig. 6 shows the relation between spectral widths and wave age (C_p/U_{10}, with C_p the peak wave celerity and U_{10}

the wind speed 10 m above the surface). It shows a clear distinction for calm and storm periods. The splitting in these two groups allows an initial classification of very complex sea states. For a given wave age the spectral width can take a wide range of values depending on spectral properties and thus this parameter can be used for a drag coefficient parameterization considering spectral wave properties. Here, we have to remark, that wave age has been estimated using land station winds, and it may thus have some systematic error.

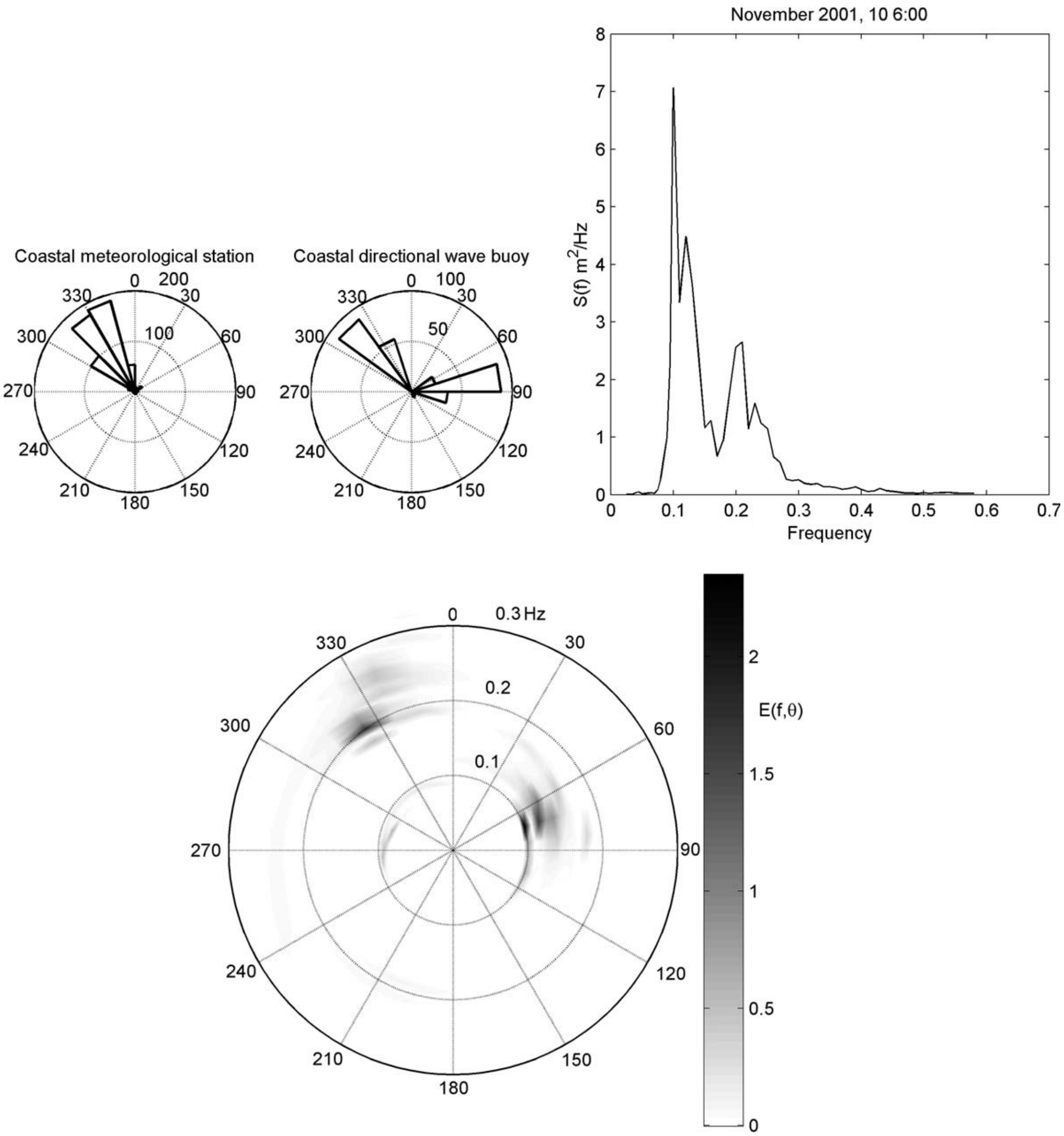

Fig. 5. Rose diagrams (left) for wind and wave directions during the November 2001 storm and a typical bimodal frequency and directional spectrum (right) recorded during this wind-wave event. $S(f)$ represents the wave energy density as a function of frequency. $E(f,\theta)$ represents the wave energy density as a function of frequency (f) and direction (θ). The low frequency peak corresponds to an eastern swell while the high frequency peak corresponds to sea waves generated by NW winds (as recorded by the meteorological station).

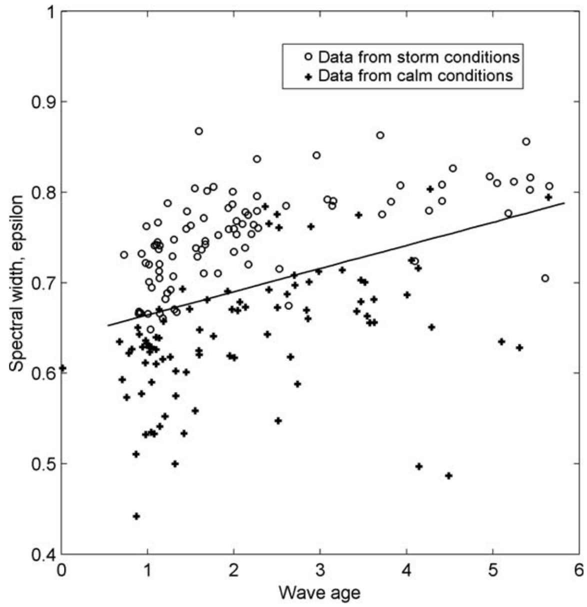

Fig. 6. Spectral width (epsilon) and wave age for the November 2001 and March April 2002 storms. Data are separated according to storm ($H_s > 1.5$ m) and calm ($H_s < 1.5$ m) periods.

4. Implications for wave generation

There is a clear distinction of spectral properties for NW and E storms, which are the most frequent and important wave conditions in the NW Mediterranean. This separation comes from the fetch-limited situation for NW storms and the bimodal features that occur during E storms. With such a distinction we have to expect differences in the wind momentum transfer to the ocean. For this purpose we focus on E storms, because NW conditions represent typical fetch-limited growth, and because E storms are usually the most severe and complex. These E storms have a predominant swell component from the E but local conditions also feature NW winds and thus a sea component with this direction (Bolaños et al., 2003). This local situation corresponds to the interesting case of swell travelling nearly against a sea generating wind. The momentum transfer function from wind to waves under these conditions (waves against the wind and bimodal spectra) is not fully understood and is not well represented in conventional model parameterizations.

These wave features are expected to have consequences for wind wave generation and wave and current modelling. We illustrate this with the SWAN code. SWAN is a third generation wind-wave model (Ris, 1997), which solves the energy equation without any pre-assumption on spectral shape. It needs as input a bathymetric data set and wind fields as forcing condition. This model has been running in an operational mode for one and a half years. There are results for the NW Mediterranean using wind fields from the atmospheric model MASS (mesoscale atmospheric simulation system) (Bolaños et al., 2004). The operational SWAN simulations showed an H_s underestimation for easterly storms, with 17% of predictions outside the 30% confidence band with respect to the buoy data (Fig. 7). In contrast all NW storm results were within the 30% interval. This suggests a degradation of the model performance for co-existing sea/swell conditions. The different sources of error (Bolaños et al., 2004) include wind field quality, wave model limitations (Van der Westhuysen et al., 2005) and the employed discretisation (time and spatial resolution). Additionally the wind stress field will be affected by the prevailing air–sea temperature differences, which are expected to play a non-negligible role in the Mediterranean Sea during storm conditions. Also the bimodal spectra generated by wind events blowing against already existing swell may contribute to an H_s underestimation, due to poorly estimated drag coefficients and associated wave growth rates. The role played by whitecapping under mixed conditions is also an uncertainty factor.

Traditionally wind model errors are considered to be one of the main sources of error during the wind-wave prediction process. To illustrate this let us consider the wind-wave growth term recommended for SWAN and which is based on Komen et al. (1984). This term depends on the friction velocity (u_*), which is estimated from

$$u_*^2 = C_D U_{10}^2 \tag{3}$$

where C_D is a drag coefficient and U_{10} is the wind velocity 10 m above the sea surface. This expression clearly shows the quadratic effect of errors on U_{10} (Cavaleri and Burgers, 1992), but it also highlights the importance of accurate drag estimation. Although errors in wind modelling and drag estimations both affect the resulting wave field, most of the research effort has been focused on the wind error while comparatively less attention has been paid to the drag coefficient estimation errors due to varying sea states. These errors should also have an impact on surface current predictions.

The spectral width (epsilon), as explained before, is very sensitive to the high frequency tail of the spectrum and many authors (Csanady, 2001a; Ueno and Deushi, 2003; Makin and Kudryavtsev, 1999) have highlighted the effect of high frequencies on drag. This drag is the combined result of form plus skin friction, which are both affected by the number, and intensity of frequency components in the sea state. This suggests the use of a spectral width parameter in the drag coefficient parameterization, as it was already suggested by Vickers and Mahrt (1997), who showed an enhancement of drag coefficients during offshore winds due to the presence of multiple wave modes. The drag coefficient could thus be written as:

$$C_D = A + BU_{10} + C(\varepsilon - \varepsilon_0) \quad \text{for } \varepsilon > \varepsilon_0 \tag{4}$$

where A and B are constants from a wind dependent drag formulation (Wu, 1982; Yelland and Taylor, 1996), U_{10} is the wind 10 m above the surface, ε is the spectral width and C represents a calibration parameter dependent on U_{10} and of order 0.7×10^{-3}. The C parameter should, thus, have a variation of the same order of magnitude and with the same trend as the scatter in the drag coefficient derived from field observations. In this formula (4) ε_0 is the threshold level separating unimodal or NW conditions from bimodal spectra. For E storms the spectral width contribution to the drag is positive which results in an enhanced drag and a decrease of the underestimation in H_s predictions. For NW storms the drag coefficient will remain as in existing formulations. This type of parameterization will induce additional drag variability, as presented by Chen et al. (2004) for wave steepness or similar to the one suggested by Oost and Oost (2004) for the peak wavelength. This should result in an improved

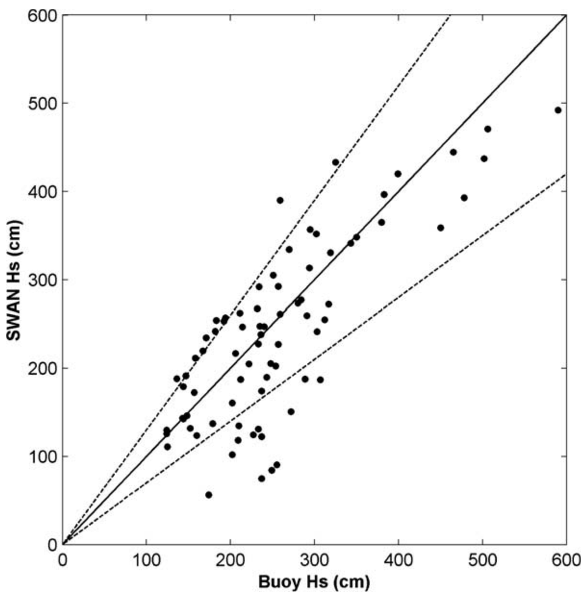

Fig. 7. Sample comparison of significant wave height predicted by the operational SWAN code and measured (Buoy) off the Ebro delta during East storm conditions. Dashed lines represent the 30% confidence band. The cloud of points below the dashed band corresponds to 17% of observations.

accuracy for wave generation over existing swells. Tests with a research version of SWAN have shown promising results for the use of such a formulation. However, more effort should be made to parameterize the C constant using field observations and including all the directional properties of the spectrum. In this line the directional spreading for drag estimation and corresponding modifications of the wind-wave growth formulation such as proposed by Booij et al. (2001) or Meirink et al. (2003) could be considered.

5. Conclusions

From a state of the art review, it is clear that the growth of wind waves in the presence of swell and the underlying drag mechanism in mixed sea/swell conditions are phenomena that are not yet fully understood. They are commonly found in nature and the analysis of more than 10 years of wave data from the Catalan coast showed an abundance of such conditions near the Ebro delta coast. Wave predictions for these complex situations show larger errors than for typical wind-wave growth. The spectral width allowed a clear identification of sea state conditions. This has suggested an improved parameterization of the corresponding drag expression that highlights the characteristics of wind-wave generation under pre-existing swell. If this is not explicitly considered it may lead to an underestimation of the source term in wave height that needs to be effectively corrected. This requires simultaneous consideration of the (i) wind field error, (ii) wind stress underestimation, and (iii) nonlinear interaction and dissipation. This poses a tough challenge for wave predictions under limited fetch and duration conditions such as those found in the NW Mediterranean Sea.

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