SPATIAL VARIABILITY OF WAVE CONDITIONS IN THE GULF OF LIONS (NW MEDITERRANEAN SEA)

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WAVE CLIMATE
SPATIAL VARIABILITY
MEDITERRANEAN SEA
GULF OF LIONS

ABSTRACT. – This study provides the first statistical description of significant height, mean period and direction of waves measured at two sites along the French Mediterranean coast of the Gulf of Lions (Sète and Banyuls-sur-Mer). Sea state is generally quiet in this area with wave heights lower than 1.5 m over more than 80 % of the study duration. However, the seasonality is marked; from July to September, 95 % of wave heights are below 1.5 m, and between April and June, waves with heights between 1.5 m and 3 m treble. From October to March, highly energetic waves (heights of more than 5 m) can be observed. Annual and seasonal statistics for Banyuls-sur-Mer and Sète indicated a spatial variability in the wave conditions for the Gulf of Lions. Large waves (heights above 3 m) are four times more frequent on the Languedoc coast (6 %) than on the Roussillon coast (1.2 %), possibly due to the filtering of southerly swell in this latter area. Conversely, extreme waves reach greater heights in Banyuls than in Sète, implying they originate from the east.

INTRODUCTION

In the 1960s, rising numbers of tourists visiting Mediterranean coastal regions led to the rapid development of port and marina infrastructures along the Languedoc and Roussillon coastline (Gulf of Lions, NW Mediterranean sea). In order to design such infrastructures, wave measurements were carried out in various locations along the Gulf of Lions shoreline. The observations from the 1960s only described long waves due to limitations in the measuring devices available at that time (swell meter, ultrasonic water level probe). In the 1970s, surface accelerometers were moored in Port La Nouvelle (SOGREAH 1978) and Sète (SOGREAH 1979). Meanwhile, data collected were processed with the primary focus being the maximum wave height or swell conditions. Moreover, these data are partly biased by the heterogeneity of water depths at the monitoring sites (range from 8 m to 84 m). Unfortunately, most of the unprocessed original data are no longer available.

Sea state prediction is still in high demand for evaluating new port extension prospects as 90 % of recreational ports are saturated (Direction du Tourisme 2006). Besides, other demands have emerged related to the risk management of coastal erosion and flood damage enhancement due to wave set up along developed coastlines of the Mediterranean (Eurosion EC project, Beachmed EC Interreg IIIc project). More recently, the possible modification of the occurrence of extreme events like storms associated with climate change also become a matter of concern for biogeochemical cycles as these events play a major role in the transfer of organic matter in coastal waters (Ulses *et al*. 2008).

This convergence of interests for increasing the density of such observations has emerged in recent years. Along the NW Mediterranean coasts, some wave buoys were moored at permanent monitoring stations in the late 1980s (1985 in Spain, 1988 in France, 1989 in Italy) while in the eastern basin, wave buoy network were settled more recently (Greece, Israel). Since 2002, the Observatoire océanologique de Banyuls has maintained the first directional wave buoy in Banyuls Bay at the southwestern side of the Gulf of Lions. The relevancy of this new observation location for wave was demonstrated during the wave storm event of December 4, 2003. During this event, wave mean direction was 120° and the maximum wave height along the Roussillon coast reached 13.8 m (significant height was 8 m). In contrast, along the Languedoc coast, wave heights were limited to 8.1 m at the maximum with significant values at 4.1 m (Hontarrede *et al*. 2004). As a consequence, since 2006, the Direction Régionale de l'Équipement, responsible for natural hazards risk evaluation and coastal management advise, have moored four wave buoys to monitor a 400 km-long stretch of coastline in the Gulf of Lions. These monitoring sites are part of a broader national coastal network for permanent wave monitoring set up in 2008 and coordinated by the Centre d'Études Techniques Maritimes et Fluviales (CETMEF).

In this paper, the first statistics on wave height, period and direction based on measurements at two sites in the Gulf of Lions (Sète and Banyuls-sur-Mer, NW Mediterranean sea) are presented. These statistics demonstrate the spatial variability of wave in the Gulf of Lions. Wave statistics are discussed in comparison to local wind statistics. Finally, trends in the return period of extreme wave events return period are also discussed.

MATERIAL AND METHODS

Wave measurements were carried out at two locations along the coast of the Gulf of Lions (NW Mediterranean Sea, France, see Fig. 1). At Sète, waves were monitored at 30 m water depth (3°39.550 E, 43°19.7 N) every three hours over two time periods (from 10/21/1988 until 01/28/2001 and from 05/22/2003 until 02/15/2006) using a non directional wave buoy (Datawell® surface accelerometer). At Banyuls, waves were monitored at 50 m water depth (3°10.038 E, 42°29.36 N) every 30 min with a directional wave buoy (Triaxys® surface accelerometer) from 06/03/2002 until 06/27/2005. The wave monitoring location in Banyuls Bay was selected based on numerical computations of nearshore wave propagation to avoid refraction and diffraction interferences. Since 11/28/2007, the wave buoy network has been updated and homogenized using similar directional wave bouys (Datawell®) and a 30 min time step at both sites.

Each wave measurement consisted of 20 min long sea surface acceleration recordings that are analyzed and transmitted in real-time for storage. Standard processing of these records involves zero-crossing and spectral analysis. Main wave characteristics (significant and maximum height, mean period and direction) are released in real-time on the CANDHIS web site (http://www.candhis.gouv.fr). Maximum wave height H_{max} is the maximum zero down-crossing wave height (trough to peak) for each 20 min long record. Fast-fourier transforms of the free surface displacement for each record were computed to obtain the distribution of wave energy as a function of frequency (non-directional wave energy spectrum). Moments of the non-directional wave energy spectrum are then used to define the significant height H_{m0} (zeroth order moment) and mean spectral period $T_{(0,2)}$ (square root of the ratio of zeroth to second order moments). The peak period (T_p) is defined by the maximum of the non-directional wave energy spectrum. For directional wave buoys, the directional wave spectrum is used to compute the mean wave direction.

For the Banyuls data, the overall data collection rate was 68 % between 2002 and 2005 due to instrument failure and maintenance downtime since 2004. The collection rate at the same site was 92 % for the year 2003. For the Sète data, this value is unknown since these data were partly filtered by the CETMEF before release. Erroneous data were eliminated from the two sites datasets using criteria based on the recommendations of Axys Environment (2000) and Butel *et al*. (2002). The criteria for validated data are: significant wave height (H_{m0}) smaller than 15 m, wave peak period (T_p) longer than 1 s or shorter than 20 s, H_{m0} smaller than 1 m for a T_p shorter than 3 s, H_{m0} increase less than 2 m during one hour, and T_p increase shorter than 3 s during one hour. Using these criteria, validation rates were 62.5 % on average for the collected data in Banyuls (75 % in winter, 47 % in summer). Reliable direction determinations required an H_{m0} larger than 0.1 m for a T_p shorter than 10 s, an H_{m0} larger than (0.001 T_p^2) for a T_p longer than 10 s. Only 1 % of the data collected in Banyuls did not meet these criteria. Altogether, the overall rate of validated data was 43 % during 3 years (2002-2005) in Banyuls and 63 % during 16 years (1988-2001 and 2003-2006) in Sète. Moreover, observations in Banyuls are evenly distributed between seasons, ranging from 23 % to 26 % (Table I). In Sète, validated data rate between seasons is less balanced, ranging from 19 % in summer to 32 % in winter. Since the wave buoys have been replaced at both sites (11/28/2007 to 12/27/2008), the overall rates of validation is 86 % in Sète and 92 % in Banyuls.

Annual and seasonal non-directional statistics of significant height and mean spectral period at both locations were computed using the validated data. Statistics calculated are: minimum, maximum, mean, median and standard deviation values of the time series, and separate 1-D histograms of wave height and

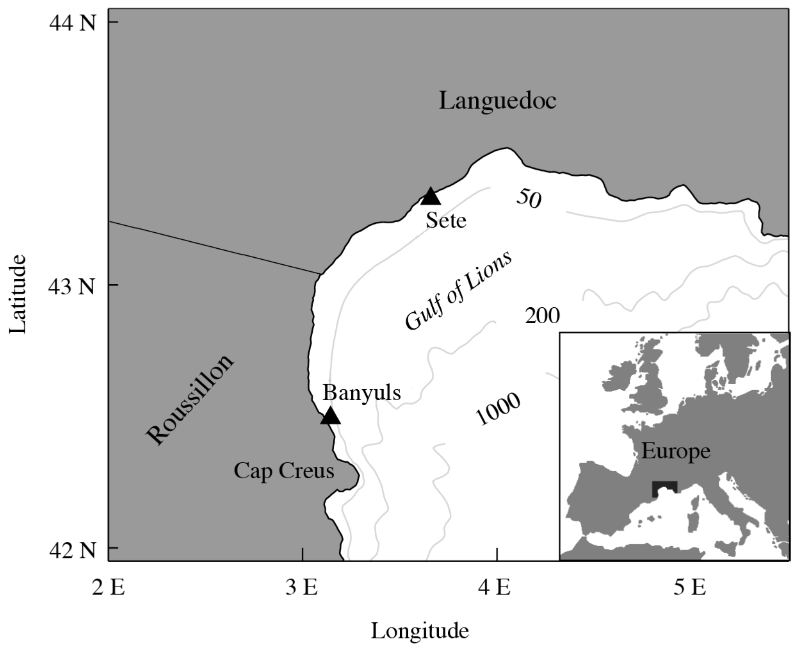

Fig. 1. – Map of the Gulf of Lions in Europe and bathymetric map of the Gulf of Lions with wave buoys locations in Banyuls (50 m, 3°10.04 E, 42°29.36 N) and Sète (30 m, 3°39.55 E, 43°19.70 N).

mean spectral period. The probability distributions of (H_{m0},$T_{(0,2)}$) couples were also computed. Such bivariate histograms give an indication of the age of waves (Butel *et al.* 2002). Indeed, as waves build up under wind turbulent fluctuations, capillary-gravity wave grows in amplitude with time either linearly (Phillips 1957) or exponentially (Miles 1957). As the waves propagates in deep water, non linear wave-wave interactions transfer part of this energy to longer period, the other part being transferred to shorter periods where it is dissipated. Thus, for a given height, waves which are still building under wind will have a shorter period than fully developed swell propagating away from their formation wind spot.

Various equations have been proposed to discriminate the sea state stage of development, based on the wave steepness H_{m0} / L value where L is the wave length defined by the Airy dispersion equation:

$$\frac{4\pi^2}{T^2_{(0,2)}} = \frac{2\pi g}{L} \tanh \frac{(2\pi D)}{L} \quad (1)$$

with D stating for the water depth. The theoretical Pierson & Moskowitz (1964) equation defines developed sea state in deep water by H_{m0} / L = 1 / 19.7. Thus, observations of wave height and period on the left side of this curve will correspond to waves building up while on the right side, observations correspond to an established sea state with a lower steepness. These corresponds to intermediate or shallow water conditions, when waves deviate from the deep water condition L << D. For growing waves (left hand side of the Pierson & Moskowitz (1964) curve), Carter (1982) suggested a more general relation for the wave steepness that depends on the wave age and the water depth after integrating JONSWAP formulas (Hasselmann *et al.* 1973). For a given wave age α, the (H_{m0}, $T_{(0,2)}$) curve is obtained after solving equations (2-4):

$$H_{m0} = 0.0146\theta^{5/7}\, U_{10}^{9/7} \quad (2)$$

$$T_{(0,2)} = 0.540\theta^{5/7}\, U_{10}^{4/7} \quad (3)$$

$$L / T = U_{10} \quad (4)$$

where θ is the duration of the wind blow and U_{10} is the wind intensity at 10 m height.

Whenever it was possible (Banyuls data and data from both sites from 11/27/2007 until 12/27/2008), directional histograms of H_{m0} and $T_{(0,2)}$ were also computed. Directional histograms obtained for wave characteristics in Banyuls were compared to directional histograms for the local wind intensity over the same period. Wind data were measured at the Béar Cape meteorological station (located 3 km north of the Banyuls wave buoy). Similarity either between the cumulative probability distributions computed at the two sites or for different observation periods at the same site, was tested using the Kolmogorov-Smirnov non-parametric test. Correlations between the local wind intensity and wave height and period in Banyuls were also computed.

Finally, the cumulative probability distribution of the monthly maximum of H_{m0} and $T_{(0,2)}$ were computed to quantify return period of extreme wave events. The Gumbel law is classically used to describe the probability distribution of extreme events (floods, extreme rainfalls or waves). It was fitted to these data using the moments method, according to:

$$F(X) = Prob(X <= x) = \exp(-\exp(-(x - b)/a))) \quad (5)$$

with $a = \sqrt{6}\, \sigma / \pi$ and $b = \bar{x} - 0.45\, \sigma$, where $\bar{x}$ is the average and σ is the standard deviation of a monthly maximum of either H_{m0} or $T_{(0,2)}$. The 80 % confidence interval was also computed.

RESULTS

Non-directional annual statistics

Annual statistics for the significant height (Table I, Fig. 2a) and mean spectral period (Table II, Fig. 2b) in Banyuls and Sète showed that overall wave conditions in the Gulf of Lions were not very energetic. More than 80 % of the waves had heights lower than 1.5 m and periods less than 5 s. Thus, the annual average of wave height is below 1 m at both sites, although slightly higher in Sète than in Banyuls, even after debiasing for the higher proportion of observations in winter and autumn, compared to spring and summer in Sète.

The cumulative probability distributions of wave

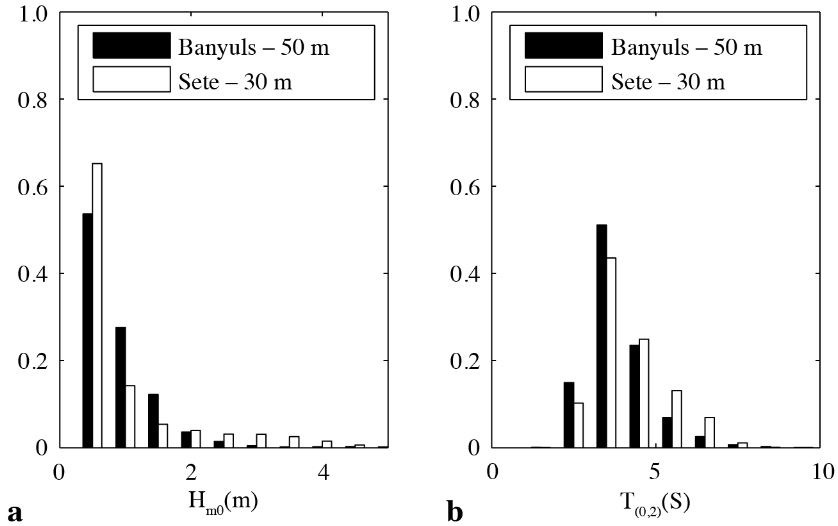

Fig. 2. – Non directional histograms for wave height (a) and wave period (b) at Banyuls and Sète.

Table I. – Annual and seasonal statistics (JFM = winter, AMJ = spring, JAS = summer, OND = autumn) for wave significant height H_{m0} in Banyuls and Sète. Med. is the median and σ is the standard deviation. N_{obs} is the number of observations (between brackets). For Sète, values between parentheses are the unbiased values assuming the same proportion of observations in all seasons.

H_{mo}(m)	[N_{obs}]	Min.	Max.	Mean	Med.	σ	0 to 1.5 m	1.5 to 3 m	> 3 m
Banyuls	Annual [22356]	0.07	8.03	0.84	0.7	0.65	88.60 %	10.20 %	1.20 %
	JFM [5143]	0.13	6.8	1.04	0.91	0.75	83.10 %	14.30 %	2.60 %
	AMJ [5914]	0.07	2.72	0.69	0.55	0.5	92.60 %	7.40 %	0.00 %
	JAS [5564]	0.07	1.96	0.6	0.52	0.38	97.20 %	2.80 %	0.00 %
	OND [5915]	0.1	8.03	1.03	0.87	0.78	81.40 %	16.50 %	2.10 %
Sète	Annual [27616]	0	7.36	0.94 (0.88)	0.55	0.98	81.60 % (83.6 %)	11.50 % (10.4 %)	6.90 % (6 %)
	JFM [7401]	0.01	6.1	1.09	0.64	1.04	76.50 %	14.50 %	9.00 %
	AMJ [6009]	0.08	4.14	0.7	0.48	0.65	90.70 %	7.10 %	2.20 %
	JAS [5190]	0	5.27	0.51	0.35	0.52	95.80 %	3.30 %	0.90 %
	OND [9016]	0.02	7.36	1.23	0.71	1.16	71.50 %	16.60 %	11.90 %

Table II. – Annual and seasonal statistics (JFM = winter, AMJ = spring, JAS = summer, OND = autumn) for wave mean spectral period $T_{(0,2)}$ in Banyuls and Sète. Med. is the median and σ is the standard deviation. For Sète, values between parentheses are the unbiased values assuming the same proportion of observations in all seasons.

$T_{(0,2)}$(s)		Min.	Max.	Mean	Med.	σ	0 to 5 s	5 to 7 s	> 7 s
Banyuls	annual	1.9	10	3.9	3.7	0.95	88.40 %	10.60 %	1.00 %
	JFM	2.4	9.4	4.1	3.9	0.92	86.30 %	11.80 %	1.90 %
	AMJ	1.9	7.3	3.6	3.5	0.88	90.80 %	9.10 %	0.10 %
	JAS	2.1	7.2	3.5	3.5	0.7	96.90 %	3.10 %	0.00 %
	OND	2.3	10	4.3	4.1	1	79.70 %	18.20 %	2.10 %
Sète	annual	1.7	10.8	4.2 (4.2)	3.9	1.12	76.80 (77.9) %	21.70 (20.5) %	1.50 (1.4) %
	JFM	1.7	10.8	4.4	4.1	1.23	70.10 %	27.50 %	2.30 %
	AMJ	2.1	7.8	4	3.9	0.94	85.00 %	14.40 %	0.60 %
	JAS	2.1	7.7	3.9	3.7	0.85	88.50 %	10.80 %	0.40 %
	OND	2	9	4.4	4.2	1.2	68.10 %	29.50 %	2.40 %

height are clearly different at both sites (Kolmogorov-Smirnov distance = 11.6, p-value = 1). In Sète, wave heights larger than 3 m are five times more frequent than in Banyuls (debiased values). The probability distribution of wave periods are also different in Banyuls and Sète (Kolmogoroff-Smirnov distance = 24.4, p-value = 1). Wave periods are longer in Sète than in Banyuls on average because intermediate waves (wave periods between 5 and 7 s) are twice as frequent in Sète. The same difference between Sète and Banyuls was observed in the proportion of wave heights smaller than 3 m and wave periods shorter than 7 s from December 2007 until December 2008 after the wave buoy network was homogenized.

At Banyuls and Sète, developing sea states were more frequent than established ones. Indeed, the probability for H_{m0} to be on the left hand side of Pierson & Moskowitz (1964) curve was higher at both sites (Fig. 3a and b). This probability increased even further for the largest wave heights. Thus, even extreme wave events were developing seas. However, in Banyuls, waves with heights greater than 2 m tended to be more developed than for a similar wave in Sète. Indeed, the probability maxima of (H_{m0}, $T_{(0,2)}$) couples was best fitted by the Carter (1982) curve for an older age in Banyuls (α = 1) than in Sète (α = 0.5).

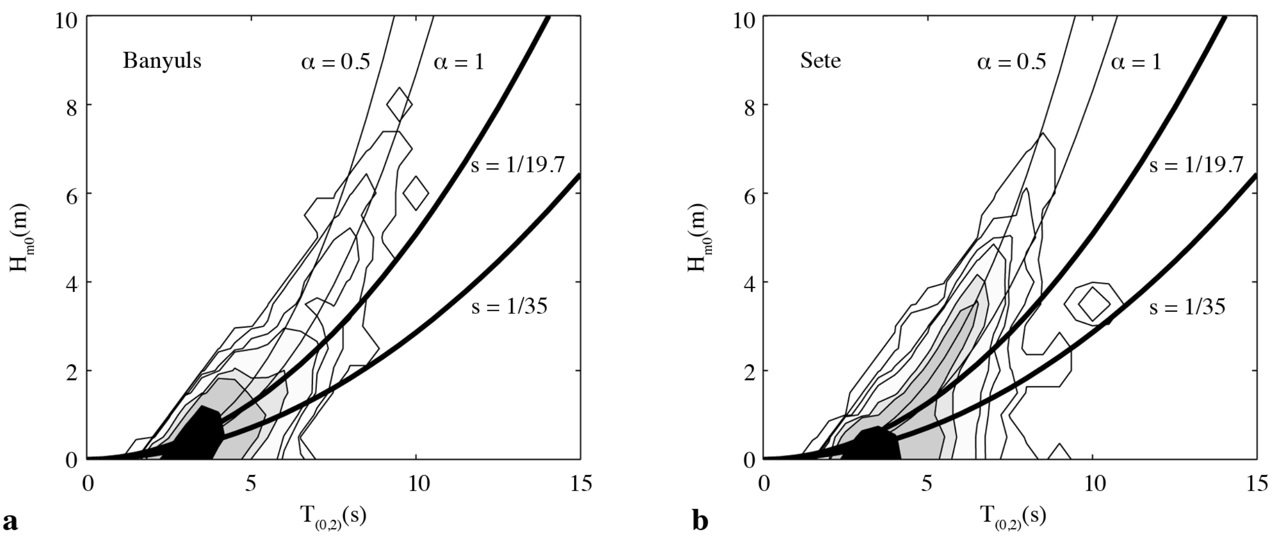

Fig. 3. – Bivariate histograms of significant height H_{m0} versus mean period $T_{(0,2)}$ in Banyuls (a) and Sète (b). Filled contours are plotted for 5, 0.5, 0.1, 0.05, 0.01 and 0.001 % of duration. Thick lines display constant steepness s curves (Pierson & Moskowitz 1964) for s = 1/19.7 and s = 1/35. Thin lines show wind sea age α curves for α = 0.5 and α = 1.

Meanwhile, in Sète, some swells were recorded with wave heights of up to 4 m as shown on the secondary branch of the bivariate histogram that was fitted by a steepness curve of 1/35. Such steepness are smaller than the one established by Pierson and Moskowitz (1964) for deep water conditions.

Non-directional seasonal statistics

Wave conditions in autumn and winter were more energetic than in summer and spring at both sites, with larger significant heights and mean spectral periods. This is due to the occurrence of energetic wave events during those seasons, even if their overall frequency remained low: less than 2.5 % of waves have a period longer than 7 s at both sites (Table II). In fact, three wave seasons can be distinguished. The proportion of significant heights between 1.5 m and 3 m doubled in spring compared to summer at both sites, and doubled again in winter and autumn compared to spring. The same trend is observed for mean spectral period ranging from 5 to 7 s. Moreover, from October to March, the frequency of waves with significant heights larger than 3 m and mean spectral periods longer than 7 s is strongly enhanced (Table II). Finally, the feature that exhibited the greater variability between seasons was the maximum of $T_{(0,2)}$: while in summer and spring, mean spectral periods were shorter than 7.8 s, in winter and autumn, maximum values ranged from 9 s to 10.8 s. However, seasonality also had a between sites difference. In Banyuls, wave heights greater than 3 m were only observed in autumn and winter, and such waves remained rare (less than 3 % of the time). Moreover, maximum values for H_{m0} more than doubled in winter and autumn, compared to summer and spring. In contrast, wave heights larger than 3 m were observed in all seasons in Sète and the maximum values for different seasons remained within a factor 2 of each other.

Extreme wave events

At both Banyuls and Sète, waves can be highly energetic, with heights larger than 5 m and periods longer than 9 s (observed in autumn and winter). At Sète, two extreme wave events were observed over the periods 1988-2001 and 2003-2006: the significant height reached 6.1 m on 02/21/2004, and 7.36 m on 12/16/1997. Based on a Gumbel law fit (Fig. 4a), these heights would have return periods of 10.5 and 21 years, respectively. These return periods are either within or close to the overall data collection duration of 16 years at Sète. At Banyuls, three extreme wave events were observed during the 2002-2005 period which lies outside the 80 % confidence interval around the Gumbel fit law: the significant height reached 6.25 m on 10/17/2003, 6.8 m on 02/21/2004 and 8.03 m on 12/4/2003. Return periods for these heights were also estimated using the Gumbel law fit, giving 3, 5 and 10 years, respectively (Fig. 4a). Such return periods exceeded the data collection duration in Banyuls which was only 3 years. The cumulative distribution of wave height monthly maxima for Sète and Banyuls are close for significant heights of up to 4 m and having yearly or shorter return periods. However, in Sète, those frequent waves tend to have longer mean spectral periods. But for the largest (significant height larger than 4 m) and longest (mean spectral period longer than 7 s) waves, return periods were smaller in Banyuls than in Sète. In other words, extreme wave events would be more frequent in Banyuls than in Sète. This difference between the two locations can also be illustrated by the only extreme wave event that was recorded at both sites on December 4, 2003. Dur-

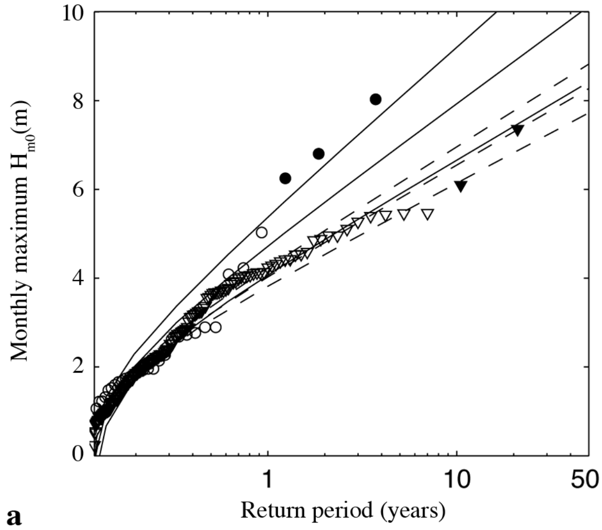

Fig. 4. – Cumulative probability distribution for wave height H_{m0} (a) and wave period $T_{(0,2)}$ (b) in Banyuls: (o) raw data, (-) Gumbel fit and 80 % confidence interval, and in Sète: (v) raw data, (--) Gumbel fit and 80 % confidence interval. The filled symbols display the largest wave heights recorded at both sites.

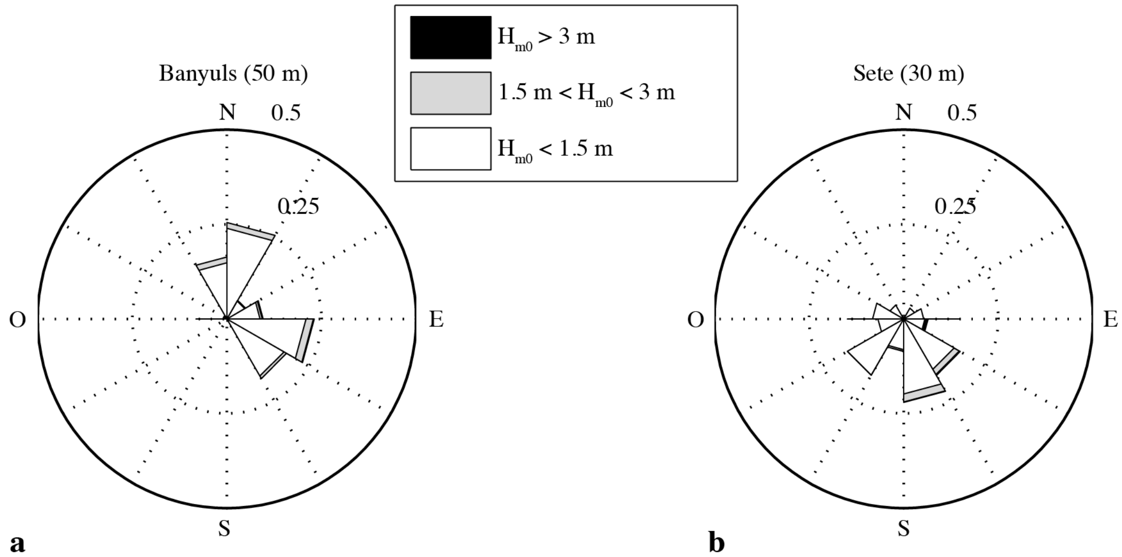

Fig. 5. – Directional histograms for wave height H_{m0} in Banyuls (a) and Sète (b) (data from 11/27/2007 until 12/31/2008).

ing this event in Banyuls, the significant wave height reached 8 m, while in Sète it was 4.1 m.

Directional analysis

Directional histograms derived from data collected simultaneously in Sète and Banyuls beginning in December 2007 until December 2008 show the differences in wave conditions along the Gulf of Lions coastline (Fig. 5). While southerly waves reached Sète, they were not observed in Banyuls. Conversely, northerly waves are only observed in Banyuls. At Banyuls, easterly waves are more frequent and tend to have a larger height compared to those observed in Sète, while this was found to be the opposite for southeasterly waves.

In Banyuls, directional histograms for H_{m0} obtained with different wave buoys over two different periods (2002-2005, Fig. 6a and the year 2008, Fig. 5a) are very close, although not equal (Kolmogoroff-Smirnov distance = 9.1, p-value = 1). Similarity between 2002-2005 and 2008 values was maximum when comparing directional histograms for waves with H_{m0} ranging from 1.5 m to 3 m (Kolmogoroff-Smirnov distance = 0.74, p-value = 0.36) and $T_{(0,2)}$ ranging from 5 s to 7 s (Kolmogoroff-Smirnov distance = 1.76, p-value = 0.99). The largest difference in directional distribution for the same data periods was observed for a quiet sea state (H_{m0} < 1.5 m and $T_{(0,2)}$ < 5 s). Nevertheless, during both periods of observation, two

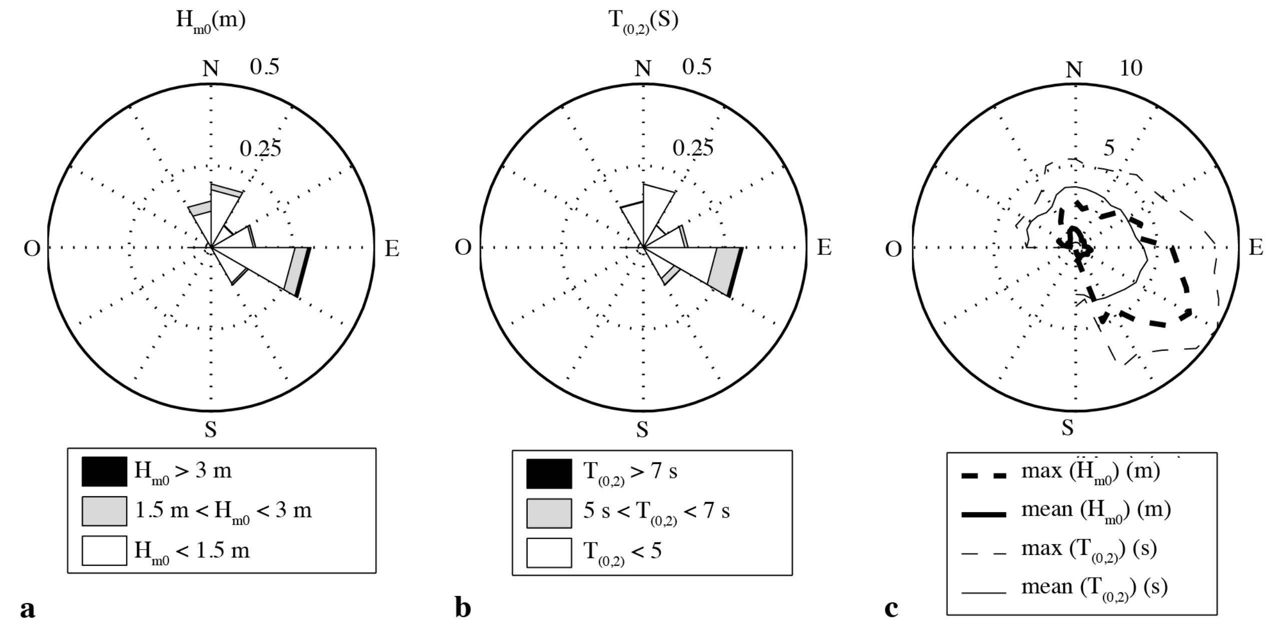

Fig. 6. – Directional histograms for wave height H_{m0} (a) and wave periods $T_{(0,2)}$ (b); directional mean and maximum values for H_{m0} and $T_{(0,2)}$ (c) (Banyuls data from 06/03/2002 until 06/27/2005).

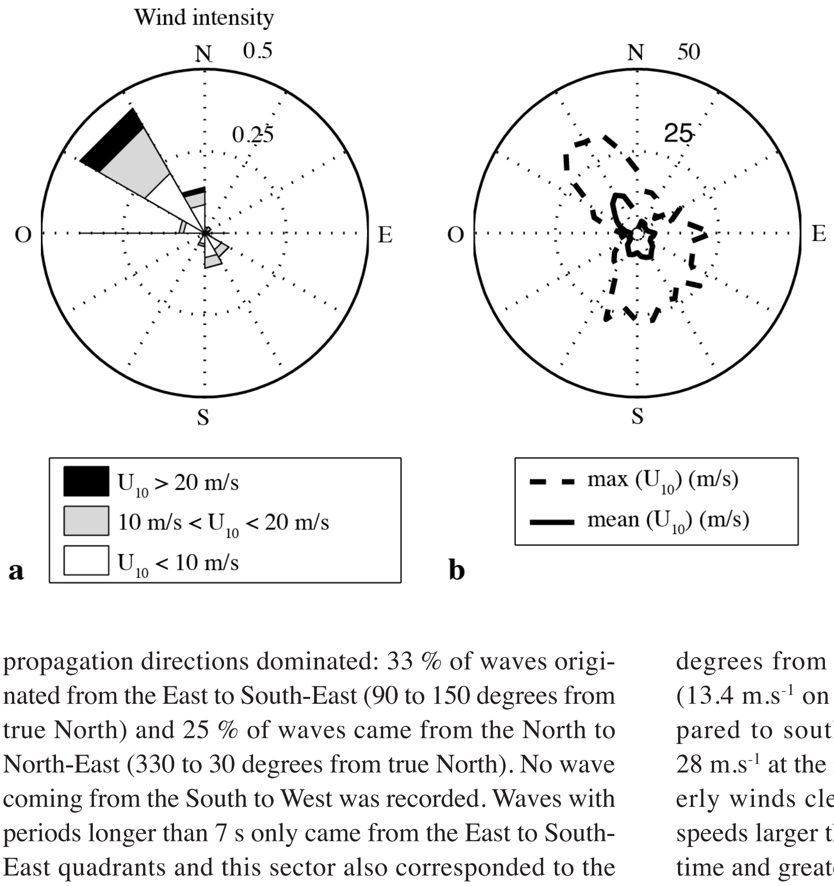

Fig. 7. – Directional histograms (a) and directional mean and maximum values (b) for wind intensity H_{m0} (Cape Béar data from 06/03/2002 until 06/27/2005).

propagation directions dominated: 33 % of waves originated from the East to South-East (90 to 150 degrees from true North) and 25 % of waves came from the North to North-East (330 to 30 degrees from true North). No wave coming from the South to West was recorded. Waves with periods longer than 7 s only came from the East to South-East quadrants and this sector also corresponded to the highest waves. The longest wave period (10 s) and greatest height (8.03 m) were observed for a southeasterly wave. Northerly wave heights and periods remained lower than 3 m and 6 s, respectively. In contrast, during the same time period, northwesterly winds (300 to 360 degrees from true North) displayed a larger intensity (13.4 $m.s^{-1}$ on average, 34 $m.s^{-1}$ at the maximum) compared to southeasterly winds (8.3 $m.s^{-1}$ on average, 28 $m.s^{-1}$ at the maximum, Fig. 7b). Moreover, northwesterly winds clearly dominated (66 % of the time) with speeds larger than 10 $m.s^{-1}$ during more than 30 % of the time and greater than 20 $m.s^{-1}$ during more than 10 % of the time (Fig.7a). Southeasterly winds accounted for 25 % of duration. Other wind sectors were only marginally present in the area. Wind and wave directions were poorly correlated, whatever the direction ($R^2 = 0.3$, $p < 0.01$). The correlation between wind intensity and wave height is slightly larger ($R^2 = 0.55$, $p < 0.01$), and increased further when restricted to northerly winds and waves ($R^2 = 0.71$, $p < 0.01$). Wave period and wind intensity were poorly correlated, whatever the direction ($R^2 < 0.3$, $p < 0.01$).

DISCUSSION

Numerical predictions for waves in the Gulf of Lions and spatial variability

This study is the first statistical description based on observations of the significant height, mean spectral period and directions of waves (and not only swell) in the Gulf of Lions. Recently, some studies presented wave statistics in the Mediterranean sea based on numerical simulations. Athanassoulis *et al*. (2004) established an atlas of the Mediterranean wave climate at the basin scale based on 10-years simulation with altimetry data assimilation and using a one degree resolution for ECMWF wind forcings. Lionello & Sanna (2005) extended these results using a finer resolution scale of 25 km in a 44-years simulation (without assimilation) based on ERA40 wind forcing. For the Gulf of Lions, these simulations suggested northerly waves would prevail over the entire year with very small heights in summer. The second dominant direction in the area would be southerly to southeasterly waves having larger heights than the northerly waves. Their coarse description gave the main wave features at the scale of the Gulf of Lions: pooling observations from both sites, the northerly and southerly/southeasterly waves are clearly dominant and wave heights are generally larger when arriving from the south. Yet, this description ignores the spatial variability within the Gulf of Lions and especially approaching the coast.

By using existing higher resolution (0.5° from 1996 until 12/07/1999, currently, 0.25°) wave forecast models (VAGMED, METEO FRANCE), the picture can be refined. In the absence of measurements, Ferré *et al*. (2005) has relied on VAGMED predictions (1996-2000, 43°N, 3°30'E) to describe the wave climate along the Roussillon coast. On average, VAGMED predictions gave larger significant wave heights (1.2 m) and periods (4.8 s) than the ones actually observed at both sites but the analysis confirms the two dominant wave directions with a directional distribution closer to the ones observed in Banyuls. The present study assessed the wave climate spatial variability along the Gulf of Lions. Most of the variability can be attributed to the coastline orientation which changes from North-South in the Roussillon to East-West in the Languedoc region. Indeed, in the latter region, northerly waves are absent due to the very short fetch (distance over which the wind blows) for northerly winds. In the Roussillon, southerly waves are filtered out by the Cape Creus promontory. Thus, the offshore location of the VAGMED data analyzed by Ferré *et al*. (2005) that allowed larger fetch for northerly winds and being more exposed than Banyuls to southerly waves explains the prediction of more energetic waves on average. Nonetheless, the accuracy of the VAGMED predictions (which is related to the reliability of regional wind predictions) still needs to be assessed relative to observations on short time scales.

Spatial variability of extreme events

The change in coastline orientation also partly explains the difference in the wave ages observed at both sites. At Banyuls, the development of northerly waves is limited by a northern fetch of about 100 km long. As a result, northerly waves are less energetic (height lower than 3 m) than southeasterly or easterly ones, and still under wind action when they reach Banyuls (good correlation between wind and wave direction). For the Banyuls site, wind fetch is at a maximum towards the east (800 km) and limited towards the south. In Sète, it is at a maximum towards the south (1500 km) and limited towards the east. Only the southeast direction offers a similar fetch distance for both sites. For Banyuls, extremely energetic waves were observed coming from the east or from the south-east. Still, these waves were not fully established, although they were no longer under wind action at the observation site (low correlation between wind and wave direction). In fact, these energetic easterly or southeasterly waves may not have sufficient time to establish because they propagate rapidly and reach the Roussillon coast early after their formation.

At Sète, two groups of large waves were observed. The first group consisted of an established swell with heights of up to 4 m and less steep than predicted in deep water. At Banyuls, such swell were not observed, suggesting that these came from the south. The smaller steepness value also indicates that these long swell (mean period longer than 10 s) were already modified by the limited water depth (30 m) at the observation site in Sète. The second group contained the highest waves. It was observed in Sète and in Banyuls. Meanwhile, the highest wave tends to be younger in Sète than in Banyuls indicating a smaller travel distance after their generation to reach Sète. Furthermore, the highest wave tends to be smaller in Sète than in Banyuls. This suggests the highest waves in the region more frequently originate from the east than from south-east, which is also consistent with the more frequent return period for extreme events in Banyuls compared to Sète. Indeed, a Gumbel law fit suggests an 8 m height would have a return period of 50 years in Sète and 10 years in Banyuls. Only the more easterly waves can exhibit such large height difference at the two sites, like in December 4, 2003.

Extreme events temporal variability

It should be emphasized that the Gumbel fit in Banyuls may be biased by the occurrence of three extreme wave events (outside the 80 % confidence interval) over the short duration of our observation period. Indeed, the probability of observing a wave height with return period of 5 or 10 years in a 3 year-long period is low. Meanwhile, recent observations also support the conclusion that extreme waves are more frequent in Banyuls than in Sète: on December 27, 2008, the significant height reached 7.54 m in Banyuls while in Sète, significant height was only 4.44 m (mean wave direction was 90°). Thus, the more frequent occurrence of extreme events between 2002 and 2005 in Banyuls compared to the earlier period 1988-2001 in Sète questions wave climatic variability. Sea state observations carried out in the 1970s provide some background information on wave climatic variability in the Gulf of Lions. However, these data are very heterogeneous (different measuring devices and water depth). In Sète from 1970 until 1979 (SOGREAH, 1979) and Port La Nouvelle from 1972 until 1977 (SOGREAH, 1978), surface accelerometer data were recorded (49 % of validated data, evenly distributed amongst seasons), although they were only partially analyzed for the wave height maxima larger than 2 m. Significant heights were deduced by dividing maximum height by 1.6. Their earlier analysis indicated a similar proportion of waves with significant heights smaller than 1.5 m at Sète between the 1970s and the 1990s. However, the proportion of large waves (significant height larger than 3 m) would have been around 1 % in the 1970s, six times less than during the 1990s. Moreover, the maximum height recorded between 1970 and 1979 in Sète was 7.4 m, while it was 11.4 m between 1988 and 2001. As a result, the significant height for a 10-years return period (Gumbel law) in Sète would yield 5 m based on 1970-1979 observations and 6.5 m based on observations during 1988-2001 and 2003-2006. These differences support our conclusion that waves exhibit a decadal climatic variability (based on observations in Sète) and strongly suggest that a re-assessment of return periods estimates is needed when a longer time series becomes available at Banyuls. Besides, how does the wave climatic variability relates to the general Mediterranean climate variability?

Lionello & Sanna (2005) suggested wave climate in the Mediterranean would be affected by the North Atlantic Oscillation. The North Atlantic Oscillation index (based on atmospheric pressure difference between the Azores and Iceland) indicates the deviation of Atlantic cyclones over Europe compared to their average trajectory which passes over the western coast of Europe. Positive values indicates cyclones circulates more north than normal, and vice-versa. Thus the large positive values during the 1990s suggested the cyclones were less frequent in the Mediterranean (Lionello & Sanna 2005) than in the 1970s when the NAO index has been closer to zero or even negative. This is not consistent with the trend in waves climatic variability observed in Sète. The winter Western Mediterranean Oscillation (WeMO) index was recently designed to better indicate the particular rainfall climate of the eastern Iberian peninsula (Martin-Vide & Lopez-Bustins 2006). The WeMO index, which is based on the pressure difference between Gibraltar and the Ligurian Gulf, is positive when low pressures are deviated to the Ligurian Gulf while it became negative when these are deviated to Gibraltar. Such index should be a relevant indicator to distinguish between the extreme easterly waves observed in Banyuls (positive values) and the southerly waves recorded in Sète (negative values). As a matter of fact, the decadal climatic variability for waves in Sète is in good agreement with the values of the WeMO index in the 1970s and the 1990s: large waves were more frequently observed in Sète in the 1990s when WeMO index displayed very negative values than in the 1970s when WeMO index displayed less negative values or even positive ones.

Ecological implications

Waves, like many physical factors, are potential drivers for ecosystems functioning and structure. Indeed, the input of wave energy to nearshore ecosystems causes water column mixing and sea bed disturbances which affect in many, sometimes antagonistic, ways their functioning and structure (Grémare *et al.* 2003). Waves may enhance recycled production by releasing nutrients from permeable sea beds through advection (Precht & Huettel 2003) and promoting non permeable oxygenation by enhanced diffusion (Chatelain & Guizien in press). But, sediment disturbance by waves may also enhance the release of toxic gases like sulfur and buried contaminants, making them available for trophic transfers. Finally, waves may also disturb fauna assemblages by redistributing some species (Commito *et al.* 1995) or potentially killing others. The present study confirmed that the southern coasts of France are generally quiter compared to the western coast which is exposed to Atlantic swells. Indeed, on average, wave heights are about half of the ones observed at Yeu Island for instance (Butel *et al.* 2002). However, waves seasonality can be more pronounced in the Mediterranean: in Banyuls, wave heights remained lower than 2 m in summer, while in winter they reached comparable values to the ones observed in Yeu Island. Furthermore, extremely energetic wave events may also be observed in the Mediterranean, with return periods comparable to the Atlantic (10 years in both Biscarrose and Banyuls for a wave with 8 m significant height), although both regions exhibits a significant spatial variability due to the effects of coastline orientation or bathymetry. In summary, waves are certainly driver as important for Mediterranean ecosystems as for more energetic ones, but should be viewed clearly as an extreme perturbation, both spatially and temporally.

CONCLUSION

The first statistical description of waves observations along the Gulf of Lions (Sète and Banyuls-sur-Mer) have been carried out. Sea state is generally quiet in this area but seasonality is marked and highly energetic waves (heights of more than 5 m) can be observed from October to March. Waves with heights above 3 m are more frequent on the Languedoc coast than on the Roussillon coast but extreme waves reach greater heights in Banyuls than in Sète. These large waves come either from the south to impact the Languedoc coast or from the east to impact the Roussillon coast and explain the wave climate spatial variability along the Gulf of Lions.

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