
Wave- and current-induced bottom shear stress distribution in the Gulf of Lions

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Abstract:

Simulations of both currents and waves were performed throughout the year 2001 to assess the relative contribution of each to their overall erosive potential on the Gulf of Lions shelf. Statistical analysis of bottom shear stress (BSS) was compared to sediment grain-size distribution on the bottom. The hydrodynamic features of the bottom layer coincide with the distribution of surficial sediments, and three areas with different hydro-sedimentary characteristics were revealed. (i) The sandy inner shelf (<30 m) area is a high-energy-wave dominated area but may be subjected to intense current-induced BSS during on-shore winds along the coast and during continental winds mainly in the up-welling cells. (ii) The middle shelf (30–100 m) is a low-energy environment characterised by deposition of cohesive sediments, where the wave effect decreases with depth and current-induced BSS cannot reach the critical value for erosion of fine-grained sediments. (iii) The outer shelf, which has a higher bottom sand fraction than the middle shelf, may be affected by strong south-westward currents generated by on-shore winds, which can have an erosive effect on the fine-grained sediments.

Particular attention was paid to features of the current that were found to be predominant on the mid-outer shelf. These currents are strongly dependent on wind direction.

Keywords: Sediment transport; Bottom shear stress; 3D modelling; Gulf of Lions

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6 **Introduction**
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10 Studies on the dispersion and accumulation of sediment from rivers to continental margins
11 have mostly been devoted to the continental shelves of open oceans affected by energetic
12 swells and tides and by large rivers, such as the Pacific and Atlantic coasts of North America
13 (Drake and Cacchione, 1985; Lyne et al., 1990; Wiberg et al., 1994). In Harris and Wiberg
14 (2002), the authors used a sediment transport model to illustrate the effect of hydrodynamics
15 on bed properties over narrow and wide continental shelf. According to their academic
16 modelling, cross-shelf gradient in bed shear stress (due to decrease in wave-orbital velocities
17 with water depth) has several implications on the transport, deposition and sorting of
18 sediment depending on the steepness of the shelf. In their study, strong links between present-
19 day hydrodynamics and sedimentological settings are exhibited. As the Mediterranean Sea is
20 a micro-tidal, low-energy system, the dominant hydrodynamic forcings of Mediterranean
21 shelves are likely to be different from that of shelves controlled by tides and swells. At a local
22 scale, storm-generated wave effect on coastal sediment resuspension has been emphasised by
23 several studies on the margin of the Gulf of Lions (GoL) (Ferre et al., 2005; Guillén et al.,
24 2006) and on other margins of the north-western Mediterranean such as the Ebro margin
25 (Puig et al., 2001; Guillén et al., 2002; Palanques et al., 2002). Nevertheless, the respective
26 effect of waves and current on the whole shelf has not been fully studied. Thus, the objective
27 of our study is to assess the potential impact of the wave- and current-induced bottom shear
28 stress on the sediment dynamics and bed properties at a regional scale in the Gulf of Lions.
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51 In their description of surficial deposits on the GoL, Got and Aloisi (1990) reported a sandy
52 area near the coast, a sandy/muddy area near the slope and a mud band on the middle shelf.
53 Although waves are assumed to be the main forcing that influences the sandy inner shelf
54 (Ferre et al., 2005; Guillén et al., 2006), the presence of sand on the outer shelf has not been
55 clearly explained. Most authors consider the offshore sands present in the outer shelf as relict
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3 features (Monaco, 1971; Aloisi, 1986; Berné et al., 1998). According to these authors, only
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5 transgressive processes would have been able to rework sediments when the sea level was
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7 lower by about 100 m. However, recent studies demonstrated that a mobile carpet of sand is
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9 periodically active at the shelf edge (Bassetti et al., 2006). Schaaff (2002; 2003) also showed
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11 that the surficial sediment over the shelf presents low critical shear stress corresponding to a
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13 fluffy layer that could easily be reworked.
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16 Knowledge of wave- and current-induced bottom shear stress is thus necessary to understand
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18 sediment dynamics and bottom properties. At a local scale, this can be achieved by direct
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20 measurements. In the GoL, measurements of waves and currents have been made at the
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22 canyon head and inner-shelf stations (Canals et al., 2006; Guillén et al., 2006; Heussner et al.,
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24 2006; Palanques et al., 2006; Bourrin et al., this issue). However, only modelling can provide
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26 relevant information at both regional and long-time scales.
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29 In combination with data analysis, modelling has recently improved our understanding of the
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31 high temporal and spatial variability of the circulation in the GoL (Estournel et al., 2003;
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33 André et al., 2005; Petrenko et al., 2005; Langlais, 2007). These studies were mainly devoted
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35 to surface circulation and mean transport, but were not sufficiently focused on bottom
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37 processes to improve our understanding of dynamic sediment processes. More recently, Ulses
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39 et al.(this issue) and Ferré et al. (this issue) developed a sediment transport model of the GoL
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41 and showed the influence of strong storms, dense water cascading, and even of bottom
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43 trawling on sediment dynamics on the shelf. They thus mainly studied the impact of episodic
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49 The aim of this article is to present statistics for near bed hydrodynamics, and to consider
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51 their consequences for sediment transport, using a modelling approach. A one-year analysis
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53 of bottom shear stress (BSS) is presented. The respective influences of currents and waves
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55 are discussed and specific relationship between current-induced BSS and wind direction is
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57 analysed in more detail. Simultaneously, an application to this study is presented in order to
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59 clarify the link between the main physical processes and grain-size distribution of surficial
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sediments on the GoL shelf. The consequences of BSS distribution for sediment mobilisation are discussed along with possible consequences for sediment distribution.

1. Regional setting

1.1. Hydrodynamics

The GoL is hydrodynamically complex as several intense and strongly varying processes coexist (Figure 1). Millot (1990) described the main hydrodynamic processes: a) the general south-westward circulation along the slope, called the Northern Current; b) wind-induced currents; and c) the formation of dense water both on the shelf and offshore.

The geostrophic Northern Current is the northern branch of the general cyclonic circulation in the western Mediterranean basin. This current, whose core is several hundred meters thick, occasionally intrudes on the shelf (Petrenko, 2003) and displays seasonal variability. Mesoscale instabilities occur mainly during spring and winter when the water flux of the along-slope current is maximum (Flexas et al., 2002; Albérola and Millot, 2003; André et al., this issue).

Even if these instabilities can affect circulation on the shelf itself (Petrenko, 2003), the shelf is essentially forced by winds and by buoyancy discharge from the Rhone River. Estournel et al. (2003) described the influence of northern and north-western winds, whereas Ulses et al. (in press) focused on the influence of E-SE winds. Intense and frequent continental winds (the Mistral in the eastern part of the GoL and the Tramontane in the western part) (Millot, 1990) push the surface waters off shore and induce local upwelling. On-shore winds (mainly eastern and south-eastern winds), which are less frequent (Millot, 1990), result in the accumulation of water on the coast and the downwelling of surface water. These winds can be very strong and appear or disappear very suddenly, and thus generate Kelvin waves (Crepon and Richez, 1982) or inertial oscillations, which mainly occur during stratified

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3 conditions (Millot and Crepon, 1981; Petrenko et al., 2005). Cold and dry continental winds
4 that appear during wintertime are also likely to generate dense water on the shelf. This dense
5 water, which is preferentially formed on the western part of the shelf, dives on the south-
6 western end part of the shelf resulting in dense water cascading through the canyon (Dufau-
7 Julliand et al., 2004).

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Freshwater input, an important forcing factor on the shelf (Gatti et al., 2006), is mainly controlled by the Rhone River, which is the largest source of freshwater in the Mediterranean Sea with 92 % of the input in the GoL (Bourrin and Durrieu de Madron, 2006). The Rhone River has two functional branches: the *Grand Rhone* which is responsible for about 90 % of the discharge, and the narrower *Petit Rhone*. Its impact on shelf dynamics can be observed far from the river mouth (Gatti et al., 2006) and is very dependent on the wind regime.

1.2. Sediments

The Rhone River is also a significant forcing with respect to sediment dynamics as it is responsible for about 94 % of total solid discharge into the GoL (Bourrin and Durrieu de Madron, 2006). Thus the sedimentological setting of the shelf, previously described by Got and Aloisi (1990), is mainly controlled by solid discharge from the Rhone River and by hydrodynamic processes (waves and currents).

In the present study, recent laser grain-size analyses of surficial sediment cores were used to generate a new sediment distribution map. Data from different projects, i.e. REMOTRANS (Miralles et al., 2005; Roussiez et al., 2005a; Roussiez et al., 2005b; Roussiez et al., 2006; Lansard et al., 2007), METROC, EUROSTRATAFORM (Miralles et al., 2006), REDITE, SEDIFOS, and from other sporadic campaigns were interpolated over the shelf. Interpolation was limited to the 160 m isobath as it coincides with the beginning of the high bathymetric gradient. Figure 2a is a map of the sand fraction (sediment fraction greater than 63 μm). To compare the new map with the well-known sedimentologic characteristics of the surficial deposits on the shelf (Got and Aloisi, 1990), a map of the non-pelitic fraction ($> 40 \mu\text{m}$) was

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3 redrawn from CEFREM data acquired between 1970 and 1990 (Figure 2b). The sediment
4 distribution on this latter map (which contains some Got and Aloisi data, i.e. data acquired
5 before 1980, and some others) is very similar to the distribution described by Got and Aloisi.
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7 However, we did not compile the two data sets because the method for determining surficial
8 grain size has changed. The new sediment distribution is based on cores collected with corers
9 that preserve the interface satisfactorily even in areas with cohesive sediment. Grain-size
10 analysis was conducted using laser measurements. The distribution of the stations is
11 relatively poor compared to the one used to obtain CEFREM map (figure 2b). The old data
12 came from cores obtained with corers that may have reworked the interface and/or the finest
13 particles may have been ejected from the corer (all the more since the stations were deep). In
14 addition, the method used for grain size analyses was quite different from the new laser
15 methods. The two maps are thus complementary. In fact, although the new distribution is
16 based on more accurate data, these data are irregular due to the limited number of stations on
17 the shelf. Actually, the new map is in agreement with the previously described
18 sedimentologic setting. However, it should be noted that the new map shows a smaller
19 fraction of coarse sediment on the outer shelf. It seems that the use of a corer that preserves
20 the interface gives a muddier interface. Moreover, the fixed limit of coarse sediment is not
21 the same in the two maps (40 μm in the old one and 63 μm in the new one) which could
22 partially explain this difference. Nevertheless, the grain-size gradient between the middle
23 shelf and the shelf break is still present with the new sediment distribution and this is not well
24 explained.

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26 Different sedimentary facies occur from the coastline to the slope. Indeed, the inner shelf (0
27 to 30 m) consists of a sandy band, followed by a muddy area on the middle shelf (~30 to
28 100 m), and finally by a muddy-sandy area in the outer shelf. As sediments become cohesive
29 when mud content exceeds 30 % (Mitchener and Torfs, 1996; Panagiotopoulos et al., 1997;
30 Le Hir et al., in press), only the inner-shelf bed appears to be covered by non-cohesive
31 sediment. Conversely, the muddy-sandy area on the outer shelf should be cohesive. Close
32 examination of the data suggests a representative (median) grain size generally comprised

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4 between 80 and 100 μm for the inner-shelf whereas the middle shelf has a representative
5 grain size of about 10 to 15 μm . The gradient from the middle shelf to the outer shelf is more
6 progressive. The median grain size can reach about 30 to 40 μm in the coarsest areas of the
7 outer shelf.
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11 Knowledge of critical shear stress is necessary to link sediment distribution and
12 hydrodynamics. In the Gulf of Lions, the critical shear stress of erosion has been measured
13 (Schaaff et al., 2002; Schaaff, 2003) in a flume at several stations across the shelf (cf. Figure
14 2b). The critical shear stress of the surficial layer in cohesive areas ranges from 0.016 to
15 0.069 N/m^2 and is spatially and temporally variable. Actually, these results are close to
16 frequent in-situ critical shear stress measurements over fluffy layer which range between 0.02
17 and 0.05 N/m^2 (Schaaff et al., 2002). According to Shields (in Soulsby, 1997) in a non-
18 cohesive area, the critical shear stress corresponding to a median grain size of between 80 and
19 100 μm would be expected to be near 0.15 N/m^2 .
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23 Considering the previously described facies and the hydrodynamic processes acting on the
24 bed, the question to be answered is whether these facies are relicts or if they are due to
25 present day reworking.
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30 31 **2. Modelling approach**

32 33 **2.1. Hydrodynamic model**

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48 The hydrodynamic processes were modelled using the operational MARS-3D code (3D
49 hydrodynamical Model for Applications at Regional Scale), a three-dimensional model with
50 reduced (σ) vertical coordinates based on the resolution of the Navier-Stokes equations
51 (Lazure and Dumas, 2007, <http://www.previmer.org>). This model with free surface is inspired
52 by the model of Blumberg and Mellor (1987) as primitive equations are solved using a time-
53 splitting scheme under assumptions of Boussinesq approximation, hydrostatic equilibrium
54 and incompressibility. The mode splitting technique was built with an iterative and semi-
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4 implicit method and allows simultaneous calculation of internal and external modes with the
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6 same time step. The external mode is solved with an ADI (Alternating Direction Implicit)
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8 scheme (Leendertse, 1970).

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10 The vertical turbulent diffusion of momentum, heat, and salt is computed using the
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12 formulation of Pacanowsky and Philander (1981), which takes stratification into account
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14 through a local gradient Richardson number. For the horizontal turbulent diffusion, MARS-
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16 3D uses Smagorinsky's formulation (1963).

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18 Momentum, salt or heat advection is low-diffusive as the model uses a Quick scheme
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20 (Leonard, 1979). This scheme is replaced by an UPWIND scheme in the case of strong
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22 gradients.

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24 The model is forced by atmospheric conditions (modelled wind field and solar fluxes
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26 provided by Météo-France ALADIN and ARPEGE models), daily Rhone River discharge,
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28 and lateral incoming fluxes (salt, momentum. and temperature) and elevations at the open
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30 boundaries.

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32 The lateral fluxes and elevations at the open boundaries are deduced from a chain of nested
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34 MARS-3D models, for which the spatial resolution and the spatial extension differ (André et
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36 al., 2005). The highest resolution model (NORMED), simulating the Northern Basin (its
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38 southern open boundary is located at 39.5°N) circulation with a horizontal resolution of
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40 1.2 km and 30 vertical layers, was used for this study. NORMED was validated with
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42 temperatures from AVHRR imagery acquired in 2001 (André et al., 2005) and with in-situ
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44 data (surdrift buoys and hydrological measurements) acquired in 2005-2006 (André et al.,
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49 50 51 **2.2. Wave model**

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56 Wave fields were modelled in the western Mediterranean Sea with a resolution of 0.1° using
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58 the third generation wind-wave model WAVEWATCH-III (Tolman, 2002a) forced by
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60 Météo-France wind fields.
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4 This model, which was developed at NOAA/NCEP and inspired by the WAM model, has
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6 been successfully applied in global- and regional-scale studies in many areas throughout the
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8 world's oceans (Tolman, 2002b; Chu et al., 2004) and especially in the western
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10 Mediterranean Sea (Ardhuin et al., 2007). The model is based on the two-dimensional wave
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12 action balance equation including energy density generation and dissipation terms by wind,
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14 white-capping, wave-bottom interaction, and redistribution of wave energy due to wave-
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16 wave interactions.

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18 The model was validated and compared with other models for two periods in 2002 and 2003
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20 (Ardhuin et al., 2007). In annex A, we present our own validation for the year 2001, (the year
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22 considered in this study) using measurements from two wave buoys in the GoL.
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26 27 **2.3. Method used to calculate the BSS**

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31 From the point of view of sediment dynamics, it is advisable to separate skin friction (which
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33 should be taken into consideration for sediment mobility) from total BSS (Dyer, 1980).
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35 Generally, the total current-induced BSS is obtained by measuring the velocity profile in the
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37 first metres above the sediment bed and fitting this profile with a logarithmic profile in
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39 agreement with the von Karman-Prandtl theory (Equation 4, annex B). When dealing with
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41 modelled currents, the method to calculate total BSS consists in assuming a logarithmic
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43 velocity profile in the first layer above the bottom. The formulation of the roughness
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45 parameter z_0 depends on grain roughness and bed roughness (ripples). Usually, the method to
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47 calculate the skin friction, (hereafter called reference method) only uses grain roughness in
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49 the computation of z_0 (Soulsby, 1997).
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53 However it is recognized that bedforms, which influence the flow (and the total BSS) locally,
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55 are also likely to modify skin friction when the latter is computed with a current above the
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57 bottom boundary layer (Smith and McLean, 1977; Dyer, 1980; Li, 1994). This is the case in
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59 our computation of BSS from the modelled velocity at the first σ level. Thus, the use of the
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3 reference method does not allow a good approximation of skin friction in the presence of
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5 ripples.
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7 Here we calculate the skin friction for waves and currents using a boundary layer model
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9 based on the results of Smith and McLean (1977), and taking into account the bed ripples
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11 created by the waves. The computation of skin friction is performed in an iterative way
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13 consisting of the computation loop described in annex B. The method includes four steps:
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- 15 - computation of roughness resulting from grains, from ripples, and from possible bedload;
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- 17 - computation of total BSS due to both waves and currents;
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- 19 - computation of skin friction from total BSS;
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- 21 - ripple prediction, when the skin friction exceeds the threshold of sediment motion on non-
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23 cohesive bed.
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28 Considering that ripples can only be formed in a non-cohesive environment, in the case of
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30 cohesive sediment, the reference method is used. For application to the GoL, we consider that
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32 the sediment is non-cohesive only on the inner-shelf (depth < 30 m), and is characterized by
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34 fine sands with an average diameter of 100 μm (apart from the surf zone) in agreement with
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36 observations (cf. § 1.2). The cohesive sediment roughness z_0 over the mid-outer shelf in areas
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38 deeper than 30 m was fixed at 0.1 mm, which is a typical value found in the literature
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40 (Soulsby, 1997).
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45 The impact of the computation of bed roughness can be considerable even in terms of skin
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47 friction: an example is given in annex C, where the wave-induced skin BSS is shown to vary
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49 in the order of 100 % when ripples are taken into account. In addition, our method accounts
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51 for variations in bedforms over time, depending on the actual forcing and previously
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53 generated bedforms.
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4 The previously described model was used to compute the BSS throughout the year 2001 from
5 modelled currents and waves (1 output every 3 hours). 2001 can be considered as
6 representative of the general climate of the region. Concerning the river outflows, during
7 2001, the Rhone River flux varied in the range of 577 to 6646 m³/s with an average value of
8 2077 m³/s. With a mean river discharge of 1769 m³/s during the 1977-2004 period (Bourrin
9 and Durrieu de Madron, 2006), the year 2001 presented an approximately 20 % increase in
10 flux. Moreover, both wind and wave histograms are in good agreement with the WW-
11 MEDATLAS (The Medatlas Group, 2004) climatology based on both modelling and
12 observations between 1992 and 2002. A comparison between our yearly forcing conditions at
13 location 42°N, 5°E (near the Météo-France Buoy, cf. Figure 1) and the 10-year climatology is
14 illustrated by the histograms in Figure 3. Storm events or windy episodes in 2001 occurred
15 with approximately the same frequency as in the climatology even though winds appeared to
16 be somewhat stronger in 2001, i.e. winds are stronger than 14 m/s for 11.1 % of the time (8.5
17 % for WW-MEDATLAS climatology), and waves higher than 5 m for 4.2 % of the year (5.2
18 % for WW-MEDATLAS climatology). According to the climatology as well as to the 2001
19 statistics, wind and wave regimes were mostly north-western. The two other prevailing wave
20 regimes were mainly eastern and south-western.
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39 The distribution of wind and wave episodes in 2001 appears to fit fairly well with medium
40 term observations. As these are the main forcing for BSS computation in the GoL, the year
41 2001 can be considered as representative of present day hydrodynamical forcing on the bed
42 of the GoL shelf. This justifies producing BSS statistics from simulations throughout the year
43 2001 and analysing potential effects on the distribution and mobilisation of sediments.
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52 **3. Results**

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Hereafter BSS designates the skin friction component of total BSS.

3.1. One-year analysis of BSS

As higher BSS conditions have the most impact on sediment dynamics, the BSS values were sorted at each grid point of the hydrodynamic model in order to quantify the distribution of the top 10 % values. Thus, the map of the 90th percentile (hereafter denoted BSS-P90) (Figure 4) was computed (the pth percentile is a value such that p % of the measurements are less than this value and (100 - p) % are greater). The BSS-P90 presents an area of low values between 0.001 and 0.01 N/m² on the middle-shelf. The BSS-90 increases a little towards the shelf break (between 0.01 and 0.05 N/m²) and much more towards the coast (from 0.01 to more than 1 N/m² on the inner-shelf). The 98th percentile was also computed (data not presented here) and exhibited exactly the same structure with values about twice as high. Thus, from time to time, BSS exhibits relatively high values in comparison with critical shear stress that ranges from 0.016 to 0.069 N/m² over the cohesive part of the shelf. On the sandy inner shelf, BSS can be really high (all the more since the sea is shallow at this location) compared to the critical shear stress of fine sand (about 0.15 N/m²).

Statistics on wave- and current-induced BSS are qualitatively in good agreement with surficial sediment distribution (Figures 2 and 4). On the middle shelf, muddy areas are quite well correlated with areas of low BSS, whereas the inner shelf and the outer shelf correspond to the presence of a higher BSS-P90. Nevertheless some areas are not well correlated, such as the Bay of Marseille and one deep area in the middle of the outer shelf where the sand fraction does not correspond to a higher percentile. These specific discrepancies will be discussed later.

3.2. Respective influences of currents and waves on BSS

To understand the role played by waves and currents in sediment dynamics over the shelf, the respective contributions of waves or currents to the higher BSS (> BSS-P90) were determined (Figure 5). In 2001, when the BSS was high, waves appear to be the main

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3 contributor in coastal areas (< 30-40 m). In the other parts of the shelf, the fact that BSS
4 values were higher than BSS-P90 is mainly due to the influence of the current.
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7 The results show that there is a marked difference in bottom dynamics between the inner
8 shelf, which is wave-dominated, and the other parts of the shelf, which are more current-
9 dominated. This explains a difference in the value of BSS-P90 of about one or two orders of
10 magnitude between the sandy inner shelf and the other parts of the shelf.
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16 17 18 **3.3. Wave-induced BSS** 19

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21 Whereas waves are not expected to have an effect on the bed in deeper shelf areas, close to
22 the isobath 100 m energetic sea states can occasionally have an influence. This is illustrated
23 at point C (location shown in Figure 5) in Figure 6a which shows wave-induced BSS versus
24 the mean wave direction. It should be noted that the majority of wave-induced BSS values
25 over the year for this particular location are not displayed in Figure 6a, as they were very
26 small (< 10^{-6} N.m⁻²). A BSS of about 0.08 N.m⁻² was observed during the biggest storm
27 (significant wave height of about 5 m and peak period of approximately 12 s). At this
28 location, the most energetic sea states mainly propagate from the east, but northerly wind-
29 waves or south-westerly swells can also be energetic. Moreover the latter are remarkably
30 directional. The most energetic sea states occur preferentially before a change in wind
31 direction (from continental wind to eastern wind). The swell most often propagates from the
32 Ligurian Sea before the arrival of the depression. Thus wave-induced BSS can be greater
33 during continental wind episodes, even if they have been generated by eastern winds (Figure
34 6a and 6b). As a consequence, the correlation between swell and wind direction is low.
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51 52 53 **3.4. Current-induced BSS** 54

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57 In this section, we focus our attention on the influence of the currents themselves on the
58 bottom layer. Indeed, currents appear to be an important forcing on the mid-outer shelf.
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Moreover, even if waves are predominant on the inner shelf, only currents are likely to transport the sediment. Statistical knowledge of current patterns in the bottom layer is thus necessary to understand both resuspension and sediment transport processes on the shelf. Before examining the statistics of current-induced BSS in the GoL, it is important to characterise the flow patterns of prevailing high-wind regimes.

3.4.1. Mean features of current-induced BSS

In order to determine schematic bottom circulation patterns, an analysis based on wind direction (W_{dir}) was performed. Winds were divided into two sectors: off-shore winds ($W_{dir} < 45^\circ$ or $W_{dir} > 225^\circ$) and on-shore winds ($45^\circ < W_{dir} < 225^\circ$). During 2001, the mean (over time) current-induced BSS vector was calculated at each grid point when wind was well established (winds $> 5 \text{ m.s}^{-1}$) for events corresponding either to on-shore or off-shore winds. These two resulting fields of mean current-induced BSS vectors are both presented on Figure 7 (arrows). In order to determine whether the mean BSS patterns in response to off-shore or on-shore winds is significant or not, the ratio (R) between the intensity of the mean BSS vector and the mean intensity of the BSS over the same time is also presented on Figure 7 (grey scale). If we note $\vec{\tau}(t)$ the BSS vector at the time t, the mean BSS vector over time is noted $\vec{\tau}_m = \langle \vec{\tau}(t) \rangle^t$. θ being the angle between $\vec{\tau}(t)$ and $\vec{\tau}_m$, we obtain

$$\|\vec{\tau}_m\| = \langle \|\tau(t)\| \cos(\theta) \rangle^t. \text{ Then, } R = \frac{\|\vec{\tau}_m\|}{\langle \|\tau(t)\| \rangle^t} = \frac{\langle \|\tau(t)\| \cos(\theta) \rangle^t}{\langle \|\tau(t)\| \rangle^t}. \text{ Thus, R is a parameter that}$$

quantifies the unidirectionality of the BSS vector over time. If R is close to 1, the variation in BSS direction is weak, and the direction of the mean vector is representative of the considered wind sector. On the contrary, if R is close to 0, the variation in BSS direction is strong, and the mean vector is not representative.

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4 In case of on-shore winds (from the sea), the response in terms of BSS direction is nearly
5 unidirectional during 2001 on the major parts of the shelf (R is almost everywhere greater
6 than 0.5) whatever the specificity of the on-shore wind event. In fact, an intense coastal jet
7 quickly starts up over the whole water column and main currents are directed towards the
8 west/south-west. When considering the bottom BSS patterns induced by off-shore winds
9 (continental winds) it appears that BSS are nearly unidirectional for 2001 in the coastal zone
10 where up-welling cells have been identified. On the middle shelf, a representative
11 recirculation cell appears whatever the off-shore wind situation, whereas the rest of the shelf,
12 including the inner shelf area on the south-west (along the Roussillon coast), does not display
13 any significant BSS pattern. This means that the response to established off-shore wind is
14 relatively dispersed in direction and thus it is not possible to give a unique scheme for all
15 cases on the whole shelf. These results are coherent with those of Estournel et al (2003) who
16 showed that off-shore winds generate mean (depth-averaged) circulation highly dependent on
17 the direction and the spatial distribution of these winds.
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3.4.2 Statistical analysis of current-induced BSS

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39 In order to determine the origin of current-induced BSS (τ_c) able to resuspend fine-grained
40 sediment on the shelf (i.e. when $\tau_c > \tau_{cr}$), a statistical analysis based on wind direction was
41 performed. The probability of BSS being higher than critical shear stress (τ_{cr}) due to local off-
42 shore winds ($W_{dir} < 45^\circ$ or $W_{dir} > 225^\circ$) or to local on-shore winds ($45^\circ < W_{dir} < 225^\circ$) was
43 calculated. The probability P plotted in Figure 8 is then the probability that $\tau_c > \tau_{cr}$ and
44 $45^\circ < W_{dir} < 225^\circ$ with the critical value chosen equal to 0.04 N.m^{-2} . This value corresponds
45 to a representative critical BSS of erosion observed by Schaaff (2002; 2003) on the very
46 surficial layer of fine sediment over the shelf of the GoL. This is a simplified approach that
47 considers only one critical BSS for the entire shelf, but modelling performed by Schaaff
48 (2003) demonstrates that the value of 0.04 N.m^{-2} is coherent for the entire cohesive area of
49 the shelf.
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4 In Figure 8, P appears as a dark area where high BSS occurs mainly during off-shore winds,
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6 whereas the bright area shows where high BSS occurs mainly during on-shore winds. On the
7
8 middle shelf, current-induced BSS never reaches the chosen critical value as the currents are
9
10 too weak. It appears that the outer shelf (next to the slope, circle C) is mainly subjected to
11
12 intense currents during stormy on-shore wind episodes (bright area). Nevertheless, the
13
14 probability of occurrence is low, in the order of 0.2 % (of the time during 2001). On the inner
15
16 shelf, on-shore winds influence a bigger area (farther from the shore) even if both wind
17
18 regimes are able to mobilise bottom particles. In front of the Petit Rhone (black area, circle
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20 A), BSS is statistically strong mainly during off-shore wind regimes (Mistral and
21
22 Tramontane) and a BSS higher than 0.04 N.m^{-2} appears more than 1 % of the time. This
23
24 location corresponds to a well-known up-welling cell caused by this wind regime (Millot,
25
26 1990).
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28
29 We now discuss zones A, B and C in more detail. At these locations, the high BSS values are
30
31 quite polarised and flow predominantly alongshore. Moreover, their directions are directly
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33 linked to wind direction (Figure 9). The BSS induced by on-shore winds (in red, Figure 9)
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35 and those induced by off-shore winds (in blue) are nearly unidirectional and occur in opposite
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37 directions. Such polarisation is partly due to bathymetry. However, this remark is not valid
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39 for the whole shelf, as shown by Figure 7.
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42 Close to the slope (C), in agreement with the previous analysis, maximum BSS directed
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44 towards the south-west is generated by on-shore winds, which are weaker in intensity and
45
46 less frequent than winds of continental origin (Figures 3 and 6c). The two other sites, which
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48 are located closer to the coast, are relatively symmetric: rather high BSS is observed for
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50 various wind directions although the statistic is quite different.
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53 Furthermore, there is no definite relationship between the local wind intensity alone and the
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55 intensity of BSS. For example, at location C, eastern winds of lower intensity are able to
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57 generate BSS that is at least as high as that generated by continental winds or south-western
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59 winds (the high BSS represented by a big black dot in Figure 6d corresponds to a medium
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61 intensity eastern wind, also represented by a big dot in Figure 6c).
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4. Discussion

On the outer shelf, which is current dominated (Figure 5), the surficial sediment has a low fine particle content. The strongest currents in the area are south-westward and are generated during periods of on-shore winds (mainly eastern) (Figure 8). The thickness of fine sediment that can be eroded during these rare episodes of eastern winds can be estimated by assuming some characteristics of its erodability. Considering the often used Partheniades (1962) erosion law ($E = E_0 (\tau / \tau_{cr} - 1) [\text{Kg.m}^{-2}.\text{s}^{-1}]$ if $\tau > \tau_{cr}$) with E_0 ranging from 10^{-5} to $10^{-3} \text{ Kg.m}^{-2}.\text{s}^{-1}$ (Whitehouse et al., 2000) for a non-consolidated sediment (concentration of about 500 Kg.m^{-3}), the erosion rate of fine sediment (with $\tau_{cr}=0.04 \text{ N.m}^{-2}$) was calculated for the whole shelf for 2001. At point C located on the outer shelf, the erosion, which appears entirely during on-shore winds, ranges from 0.9 mm/year to 9 cm/year. On the other hand, the order of magnitude of deposition should not exceed the apparent sedimentation rate (ASR) observed in this area. Thus net deposition is maximized by observed ASR in the area, which has been estimated to be in the order of 1 mm/year from ^{210}Pb core dating (Miralles et al., 2005). On most of the outer shelf, τ_{cr} for surficial fine sediment is exceeded slightly more than 0.2 % of the time (cf. Figure 8 with $\tau_{cr}=0.04 \text{ N.m}^{-2}$) and the erosion of sediment may compensate for the supply of fine sediment. Nevertheless, as BSS values never exceed the critical shear stress value for fine sands (0.1 N.m^{-2}) on the outer shelf, the fine sand could not be eroded and the sediment should consequently not be reworked deeply. Only the non-consolidated surface of the sediment may be affected by currents flowing south-westward. Thus, eastern storms are able to sweep the recent fine sediment deposits away and the sandy interface may be conserved. In fact, high BSS is not required to explain sandy beds. BSS just higher than the critical shear stress of non-consolidated fine sediment may be sufficient to explain why recently supplied fine sediments do not remain on the bed.

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4 In some places, the sand fraction features do not appear to agree with computed
5 hydrodynamical forcings and this may partly be explained by the limits of this study.
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8 Recent studies have demonstrated that the process of cold, dense water cascading is able to
9 resuspend sediments from the shelf and to transport them towards the canyons (Palanques et
10 al., 2006; Ulses, 2006; Bourrin et al., this issue; Ulses et al., this issue). The formation of
11 dense water is taken into account in our model and in the computation of the BSS statistics,
12 but its influence is not obvious. Both the intrusions of the Northern Current and the formation
13 of dense water are subject to high inter-annual variability (Guarracino et al., 2006; Langlais,
14 2007) and, from this point of view, statistics covering only one year may be not sufficient to
15 quantify the processes. Actually, it appears that the year 2001, which was selected as being
16 representative for wind and wave effects, did not undergo intense and/or frequent episodes of
17 dense water formation (Heussner et al., 2006): this feature appears to be a limiting factor of
18 this study. A statistic built with a multi-year model would be useful to investigate the effect
19 of these very variable processes.
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33 Moreover, the Northern Current occasionally intrudes on the shelf (Petrenko, 2003) but its
34 influence on the bed was not shown in our modelling. The simulated Northern Current seems
35 to flow a little too far from the shelf break, and its intrusion is thus likely to be
36 underestimated. These intrusions may have a local effect on the outer-shelf bed, but probably
37 not on the entire outer shelf. Thus the sandy area in the middle of the outer shelf may be
38 impacted by the Northern Current, although the computed BSS remains low. This may
39 explain why, in the middle of the outer shelf, the BSS seems rather low whereas at the
40 surface, the sand fraction reaches almost 40 % (Figure 2a). In the same way, in the sandy
41 southern part of the bay of Marseille, underestimation of the simulated Northern Current
42 intrusions may also be responsible for underestimation of the BSS statistic.
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56 In addition, other factors than hydrodynamic forcings are likely to explain grain size
57 distribution. The supply of fine sediment, which is linked to the proximity of the mouth of the
58 Rhone River, also contributes shaping the shelf bed: a reduction of the fine sediment fraction
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4 can thus be expected with an increase in the distance from the source. This would explain
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6 why the fine fraction on the outer shelf between 3.5° E and 4.5° E is lower than that between
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8 4.5° E and 5° E. Also, the bay of Marseille is a rather low-energy but sandy area. In the
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10 eastern part of the GoL, the lack of fine particles in the surficial sediment could be related to
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12 a smaller supply of fine sediments: actually, the Rhone river discharge is mainly dispersed
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14 south-westward, and no other source of fine particles has been observed upstream of the
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16 eastern part of the GoL shelf, as water depths increase very fast in this area. We also suggest
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18 that the proximity of the slope may have an impact on the net balance of the fine sediment.
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20 When erosion occurs on the shelf, the closer to the shelf break the fine particles are located,
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22 the more likely they are to be removed from the shelf. This remark is valid for the entire outer
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24 shelf. The combined effects of the hydrodynamic intensity, the distance from the source of
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26 sediment and the proximity of the slope, which plays the role of a sink for sediments, likely
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28 explain the slight increase in grain size on the outer shelf.
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31 32 33 **5. Conclusions** 34 35 36

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38 In this work we combined the use of wave and current models, and computed the realistic
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40 variation of the BSS distribution over a period of one year, in order to analyse the main
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42 physical processes that act on the bed. The BSS model, which allows prediction of ripple
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44 formation, was developed in order to take into account the effect of bedform roughness on
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46 skin friction over a non-cohesive bed. The skin friction component of the total BSS was
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48 consequently calculated at both annual and regional scales in the GoL in order to focus on
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50 sediment dynamics.
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54 Particular attention was paid to currents, which were found to be the main forcing in the mid-
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56 outer shelf. A relationship between wind direction and the intensity and direction of BSS can
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58 be deduced. The analysis conducted throughout 2001 shows that significant bottom currents
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60 are almost “channelled” and flow predominantly alongshore on the inner-shelf both during
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3 on-shore and off-shore winds. Moreover, the response in terms of BSS directions is nearly
4 similar whatever the on-shore wind conditions all over the shelf, with south-westward water
5 flux. The BSS pattern in response to off-shore winds is less schematic and important
6 fluctuations in direction may appear on a large part of the mid-outer shelf. This study also
7 demonstrated the importance of on-shore winds, which induce simultaneously erosion and
8 transport over most of the shelf, especially when a swell generated during the same storms is
9 superimposed. Continental winds only show erosive potential in coastal areas and
10 preferentially in the up-welling cells. However, these winds are generally associated with
11 waves of low amplitude and are probably not the major forcing mechanism of erosion on the
12 shelf, except in the current-dominated deeper part of the up-welling cells.
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26 The one-year analysis of the BSS characteristics using a modelling approach allowed us to
27 highlight the strong link that exists between bed characteristics and present-day
28 hydrodynamic structures. Hydrodynamic features coincide with sediment surficial
29 distribution and three areas with different characteristics were revealed:
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34 (i) Near the shore (< 30 m) sandy areas correspond to high-energy areas dominated by
35 waves. In addition, the inner shelf may be subject to intense currents near the bottom which
36 are able to erode or transport fine particles resuspended by waves, both during continental
37 and on-shore wind conditions.
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43 (ii) On the middle shelf (30 to 100 m), the contribution of waves decreases progressively
44 with depth. This muddy area presents the lowest 90th percentile of BSS of the whole shelf.
45 Current-induced BSS never reaches the representative critical value for erosion, evaluated
46 from erodability measurements. In this area, even if wave-induced BSS may very
47 occasionally erode fine sediments (wave-induced BSS is slightly higher than those in a
48 deeper area in Figure 6a), bottom currents are not strong enough to disperse them far from the
49 source of erosion. On the middle shelf, the supply of sediment does not appear to be
50 compensated for by erosion and transport, which remain very limited.
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4 (iii) On the outer shelf, the 90th percentile of BSS is higher than on the middle shelf
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6 whereas the wave effect is lower, due to deeper water. The lower fine sediment content can
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8 be linked to non negligible south-westward currents which act during periods of on-shore
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10 winds (mainly eastern) (Figure 8).

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14 Finally, this study helped explain the main grain-size gradients and to understand the impact
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16 of present day hydrodynamics. Such a study may be useful before implementing any
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18 sediment transport model, whatever the coastal region, to acquire good knowledge of the
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20 modelled BSS statistics. The BSS is the main forcing of a sediment transport model and in
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22 this regard a good description of its structure is necessary to satisfactorily analyse the output
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24 of a sediment transport model. When the area is microtidal, a good estimation of the variation
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26 in BSS requires rather long hydrodynamic simulations. We recommend using a high
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28 percentile of the BSS as a proxy for characterizing the sediment forcing, rather than the
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30 maximum BSS value, which will be less representative and more dependent on the length and
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32 characteristics of the simulation.
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40
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42
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48
49 *d'Océanologie de Marseille*), Agence de l'eau, CEFREM (*Centre de Formation et de*
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51 *Recherche sur l'Environnement Marin*), CEREGE and LOB Banyuls (*Laboratoire*
52
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54
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59 attentive review.
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Annexes

A. Validation of the wave model

Wave simulations were evaluated for significant wave height (H_s), peak period (T_p) and mean period (T_m) using the Correlation Coefficient (COR), the Normalized Mean Bias (NMB), the Root Mean Square Error (RMSE) and the Relative Root Mean Square Error also called Scatter Index (SI).

If x_i is the measured value at the time step i , y_i the simulated value at the same time step, \bar{x} and \bar{y} are respectively the mean values of x_i and y_i for the N time steps, then we have:

$$COR = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}} \quad SI = \sqrt{\frac{\sum_{i=1}^N (x_i - y_i)^2}{\sum_{i=1}^N x_i^2}}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (x_i - y_i)^2}{N}} \quad NMB = \frac{\bar{y} - \bar{x}}{\bar{x}}$$

Validation was performed for two buoys located in the GoL (Figure 1). For the coastal CETMEF buoy (at a depth of about 18 m) data were available throughout the year whereas only one month was available for the offshore Météo-France buoy. Comparison of the wave parameters is quite good for the two buoys (Figure 10, Table 1) with an error (SI) of from 17 to 30 % for the wave height. Nevertheless, for all the parameters, the relative error is higher at the coastal location due to the low resolution of the wave model (0.1 °).

B. Iterative method of BSS calculation

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3 The aim is to compute the skin friction component of the total BSS under the influence of
4 waves and currents, which is likely to be affected by the presence of ripples; the latter being
5 dependant on the wave regime.
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11 1/ Computation of physical roughness length scale k_s , which is used to determine the bed
12 roughness z_0 for a hypothesized rough turbulent flow ($z_0=k_s/30$).
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14 k_s is the maximum of the three degrees of physical roughness, which are:
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20 - grain size roughness: $k_{sg}=2.5D$ (1)
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24 - bedform roughness (Grant and Madsen, 1982): $k_{sd}=27.7H^2/\lambda$ (2)
25

26 if H and λ are known, if not, initialised with 0.
27

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30 - bedload roughness (Wiberg and Rubin, 1989):
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$$k_{sc} = 1.1424D \frac{\tau_{sf}}{\tau_c + 0.2\tau_{sf}} \text{ if } \tau_{sf} > \tau_{cr}$$
 (3)
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37 where D is the average diameter of the grains, H the height of the ripples, λ their wavelength,
38 τ_{sf} (initialised with 0) the skin friction (whose calculation is specified below), and τ_{cr} is the
39 critical shear stress for sediment motion (calculated from Shields parameter, depending on
40 D).
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48 2/ Computation of the total shear stress (from the hydrodynamic point of view) related to
49 waves (index w) and to currents (index c).
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$$\tau_c = \rho u_{*c}^2 \text{ with } u_{*c} = \frac{\kappa u(z)}{\ln(z/z_0)}$$
 (4)
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$$\tau_w = 0.5 \rho f_w U_b^2$$
 (5)
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60 with (Swart, 1974) $f_w=0.3$ if $A/k_s < 1.57$,
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3 and beyond: $f_w=0.00251\exp(5.21(A/k_s)^{-0.19})$ (6)
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7 where ρ is the density of water , U_b is the orbital velocity of the swells on the bottom, z is the
8 height of the first layer above the bottom, $u(z)$ is the associated speed, κ is the Von Karman
9 constant (0.4) and A is the orbital half-excursion near the bottom ($A = \frac{U_b T}{2\pi}$, T being the
10 wave period).
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13 The formulation of Soulsby (1997) is used to take non-linear wave-current interactions into
14 account
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23 $\tau_m = \tau_c [1 + 1.2(\frac{\tau_w}{\tau_w + \tau_c})^{3.2}]$ and (7)
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26 $\tau_{cw} = [(\tau_m + \tau_w |\cos \varphi|)^2 + (\tau_w \sin \varphi)^2]^{0.5}$ (8)
27
28

29 where τ_m represents the average shear stress in the current direction, τ_{cw} is the maximum shear
30 stress generated during a wave period and φ is the angle between the current and wave
31 directions.
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37 3/ Average skin friction computation (Smith and McLean, 1977),
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41 $\tau_{sfm} = \frac{\tau_{cw}}{1 + \frac{1}{2\kappa^2} C_D \frac{H}{\lambda} [\ln a(\lambda/z_{0s})^{0.8}]^2}$ (9)
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47 with $z_{0s} = \max(k_{sg}, k_{sc})/30$, $C_D = 0.21$ under the hypothesis of a "separate" flow (presence of a
48 eddy downstream from the ripple crest) above the ripples and $a = 0.3$ according to Li (1994).
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53 At the top of the ripple crests the maximum is reached, and is estimated by Harris and Wiberg
54 (2001)
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57 $\tau_{sf} = \tau_{sfm} (1 + 8H/\lambda)$ (10)
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4 It should be noted that Harris and Wiberg (2001) adopted this expression for the skin frictions
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6 over a ripple, but that in any event, the boundary layer model of Smith and McLean (1977)
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8 does not take the wave effect into account.
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12 4/ Ripple prediction. The assumption is that ripples are formed only in a non-cohesive
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14 environment. The sediment cohesion threshold is fixed at 30 % of mud (Mitchener and Torfs,
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16 1996; Panagiotopoulos et al., 1997). The observations of van der Wal et al. (2005) confirm
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18 this hypothesis. Indeed these authors observed significant variations in roughness for mud
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20 percentages of less than 30 %, and much lower variations when this threshold is exceeded.
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22 Moreover, in view of the dynamics of the shelf and in view of the leading role of waves in the
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24 sandy areas (cf. § 3.2), the ripples created by the current are not taken into consideration.
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29 The formulations of Soulsby and Whitehouse (2005) are used for the prediction of wave-
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31 induced ripples:
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33 If $\tau_{sf} < \tau_{cr}$, H and λ do not evolve
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38 If $\tau_{sf} > \tau_{cr}$, $\lambda = \frac{A}{1 + 0.00187A/D(1 - \exp\{-(0.0002A/D)^{1.5}\})}$ (11)
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43 and $H = 0.15\lambda[1 - \exp(-(5000D/A)^{3.5})]$ (12)
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48 The above equations implicitly take into account the "sheet-flow" through the D/A parameter,
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50 which involves destruction of the ripples when it decreases too strongly.
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54 If the sediment is cohesive, the BSS is calculated by carrying out only step 2 with a fixed z_0 .
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58 5/ Test of convergence on τ_{sf} . The procedure is repeated from step 1/ until convergence.
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C. Comparison of methods of calculation

BSS values calculated with the previously described method were compared with those calculated with the reference method (with a fixed z_0) for the year 2001 (Figure 11). In the coastal area (10 m depth) current-induced BSS is not very sensitive to the presence of ripples. The presence of ripples tends to increase waves-induced BSS during low energy periods. During high energy periods (Figure 11, framed area), the induced "sheet-flow", which destroys the ripples, causes a major reduction in wave-induced BSS. A slight reduction also occurs in the current-induced BSS when "sheet-flow" intervenes during episodes of strong currents (framed area).

The result thus highlights the need to take into account the modification of the micro topography of the bottom and its influence on the skin friction component of the total BSS.

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24 **Figure captions**

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28 Figure 1: Study area, main characteristics of the circulation (redrawn from Millot (1990)).
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30 Isobaths 20, 50, 90, 160, 500, 1000 and 2000 m are plotted. Positions of the wave buoys
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32 Météo-France 61002 and CETMEF 01301 are shown.
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36 Figure 2: (a) Surficial fraction of sand ($>63 \mu\text{m}$) on the shelf based on new experimental
37 observations. (b) Surficial non-pelitic fraction ($>40 \mu\text{m}$) on the shelf redrawn from CEFREM
38 data acquired from 1970 to 1990. Isobaths 30, 50, 100 and 160 m are plotted.
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44 Figure 3: Probability of occurrence of wind direction (direction the wind comes from) (a),
45 wind intensity (b), wave direction (direction the wave comes from) (c) and wave height (d) at
46 position 42°N , 5°E . Black histograms correspond to year 2001 and white histograms
47 correspond to WW-MEDATLAS climatology. For wind intensity and wave height, the
48 increase in the frequency of higher values is due to the fact that the intervals are not
49 homogenous and may be subject to sudden variation.
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Figure 4: 90th percentile of wave- and current-induced BSS (N.m⁻²) from numerical modelling.

Figure 5: Mean respective contributions of waves and currents to the BSS greater than the 90th percentile. Isobaths 30, 50, 100 and 160m are plotted. The circle corresponds to point C.

Figure 6: Polar diagrams at point C (3.88°E 42.86°N). (a) Wave-induced BSS (N.m⁻²) as a function of the mean wave direction (direction the wave comes from). Data values smaller than 10⁻⁶ are not drawn. (b) Wave-induced BSS (N.m⁻²) as a function of wind direction (direction the wind comes from). (c) Wind stress intensity on the surface (N.m⁻²) as a function of wind direction. (d) Current-induced BSS (N.m⁻²) as a function of wind direction. The biggest dot on Figures (c) and (d) corresponds to the same event. Note that only Figure (a) depends on wave direction and is based on logarithmic scale.

Figure 7: Mean vector (arrows) of current-induced BSS during onshore wind events (left) and during offshore winds events (right). Only the wind episodes greater than 5 m.s⁻¹ occurring in 2001 have been considered. The grey scale corresponds to the fraction between the intensity of the mean vector and the mean BSS intensity noted R.

Figure 8: Origin of current-induced BSS. Probability (%) of having simultaneously, a BSS higher than 0.04 N.m⁻² and on-shore winds (direction from 45 ° to 225 °). Inside the blue line (resp. red line) the iso-probability $\tau_c > 0.04$ N.m⁻² exceeds 1 % (resp. 0.2 %). White areas correspond to 0 % probability. Isobath 160 m (slope) is shown. Locations A, B, C are discussed in the text.

Figure 9: Polar diagram of current-induced BSS (N.m⁻²) as a function of their direction (direction the current flows) at various points on the shelf (cf. green circles Figure 8). A: in front of Petit Rhone (position 4.3°E 43.4°N, 29 m depth), B: in front of Leucate (position

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4 3.1°E 42.9°N, 31 m depth), C: outer shelf (position 3.88°E 42.86°N, 100 m depth). In red, on-
5 shore wind events, in blue, continental wind events, and in black, frictions lower than
6 0.02 N.m⁻². All the events that occurred in 2001 (one every 3 hours) are represented.
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12 Figure 10: Comparison of H_s and T_p between WAVEWATCH-III and the Météo-France
13 61002 buoy.
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18 Figure 11: Time variation of current-induced BSS (τ_c) (upper graph) and wave-induced BSS
19 (τ_w) (middle graph) at a fixed location in the GoL. BSS calculated with the reference method
20 is plotted in dotted line whereas that calculated with the described method are plotted in full
21 line. In the lower graph, H_s (m) is plotted in full line and height of the ripples (cm) in dotted
22 line.
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31 **Table caption**
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35 Table 1: Statistical parameters for the model validation on Météo-France 61002 buoy and on
36 Cetmef 01301 buoy.
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Figure 1
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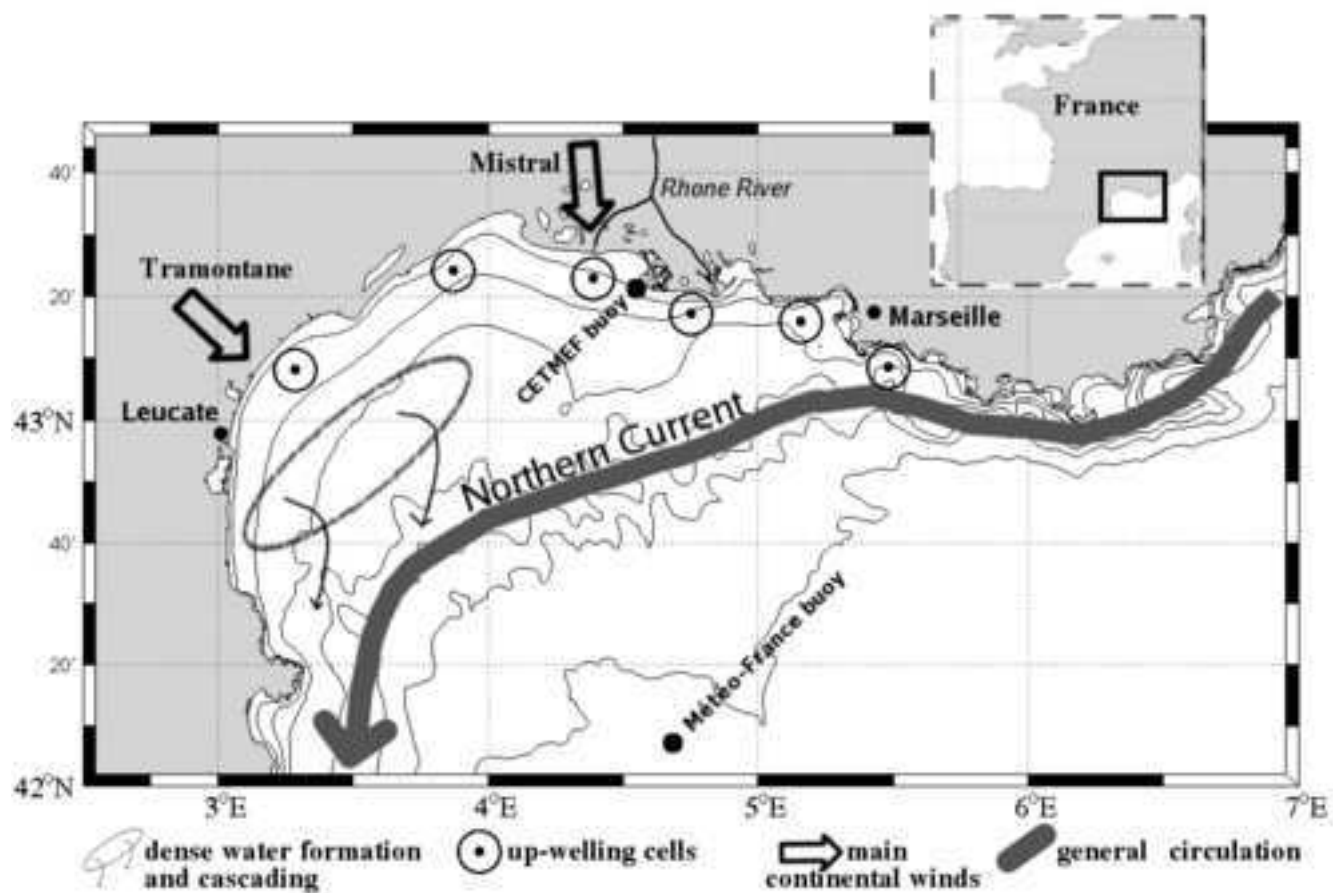


Figure 2
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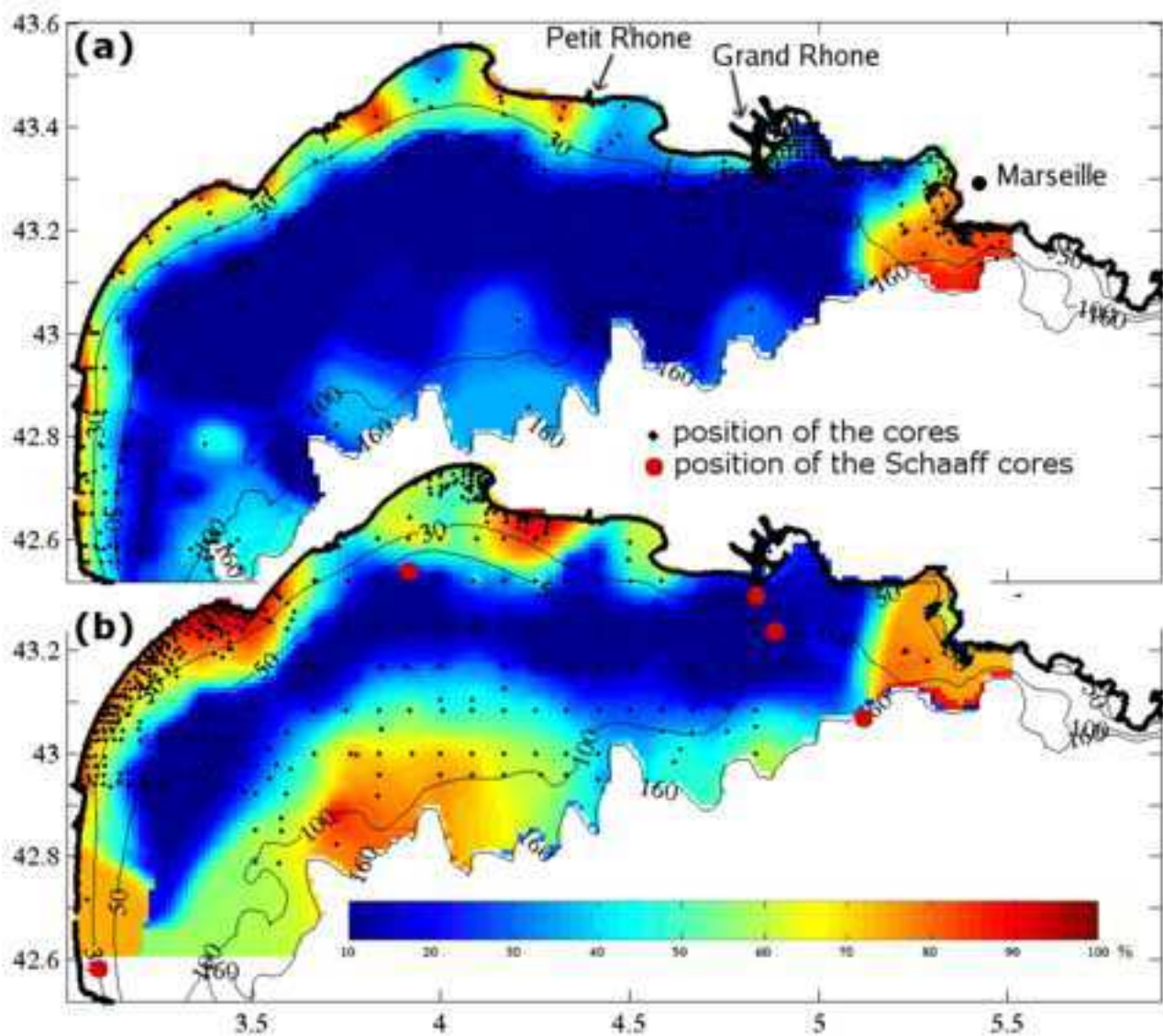


Figure 3
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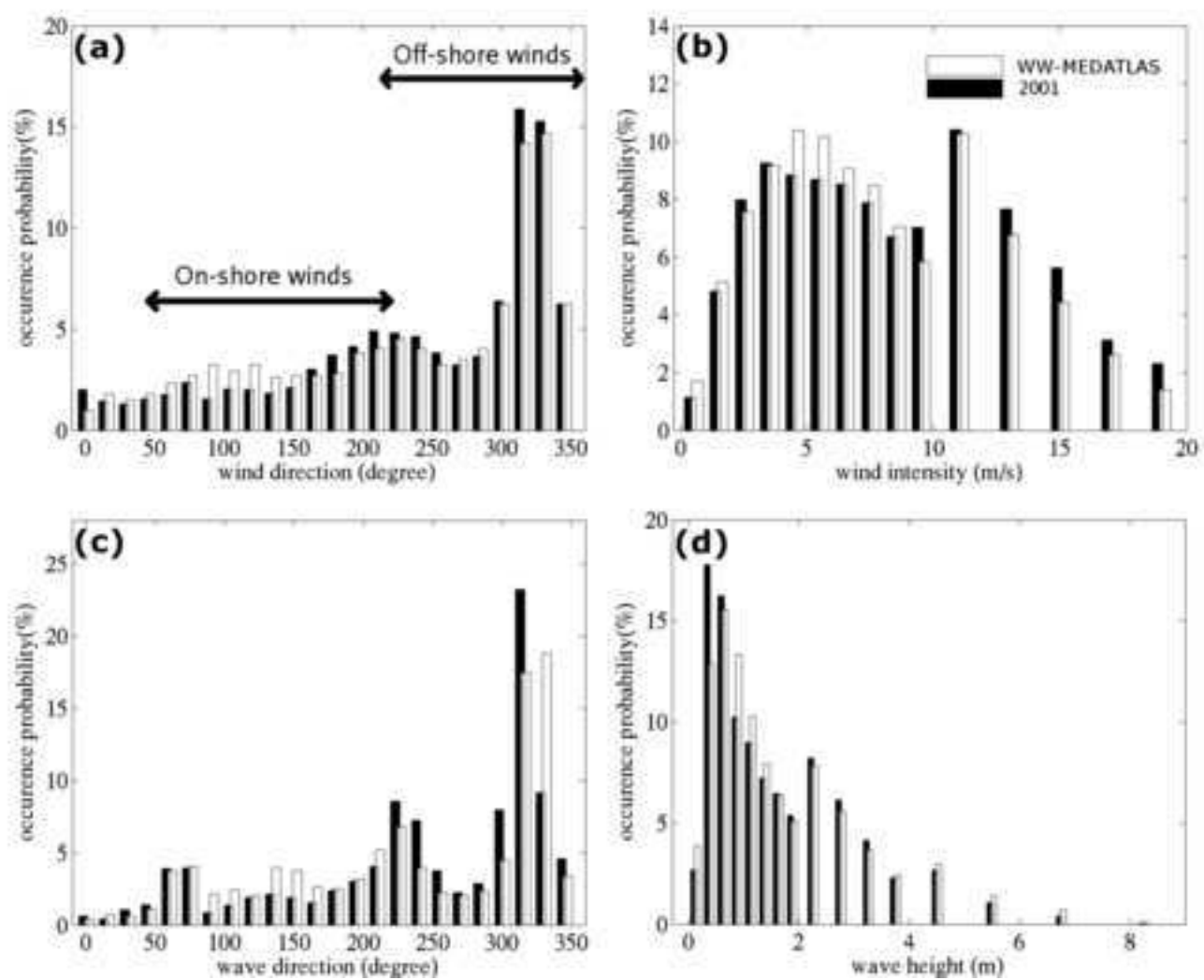


Figure 4

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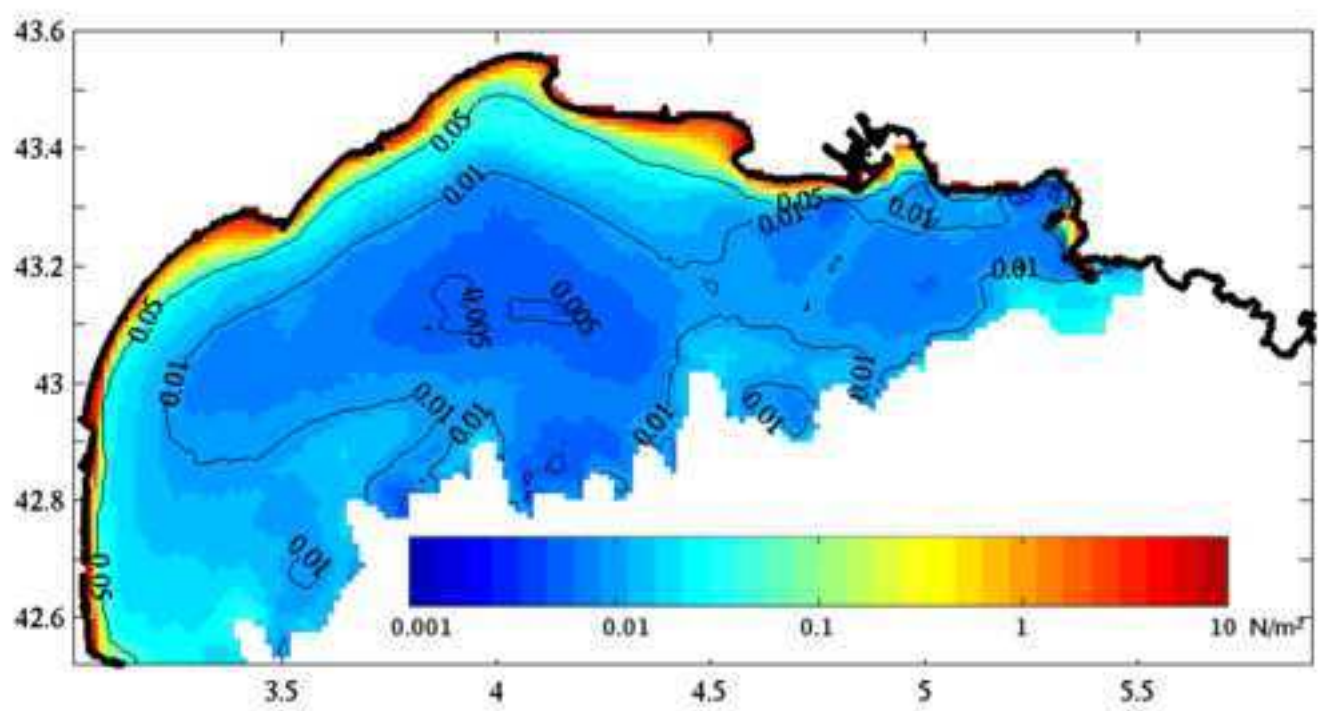


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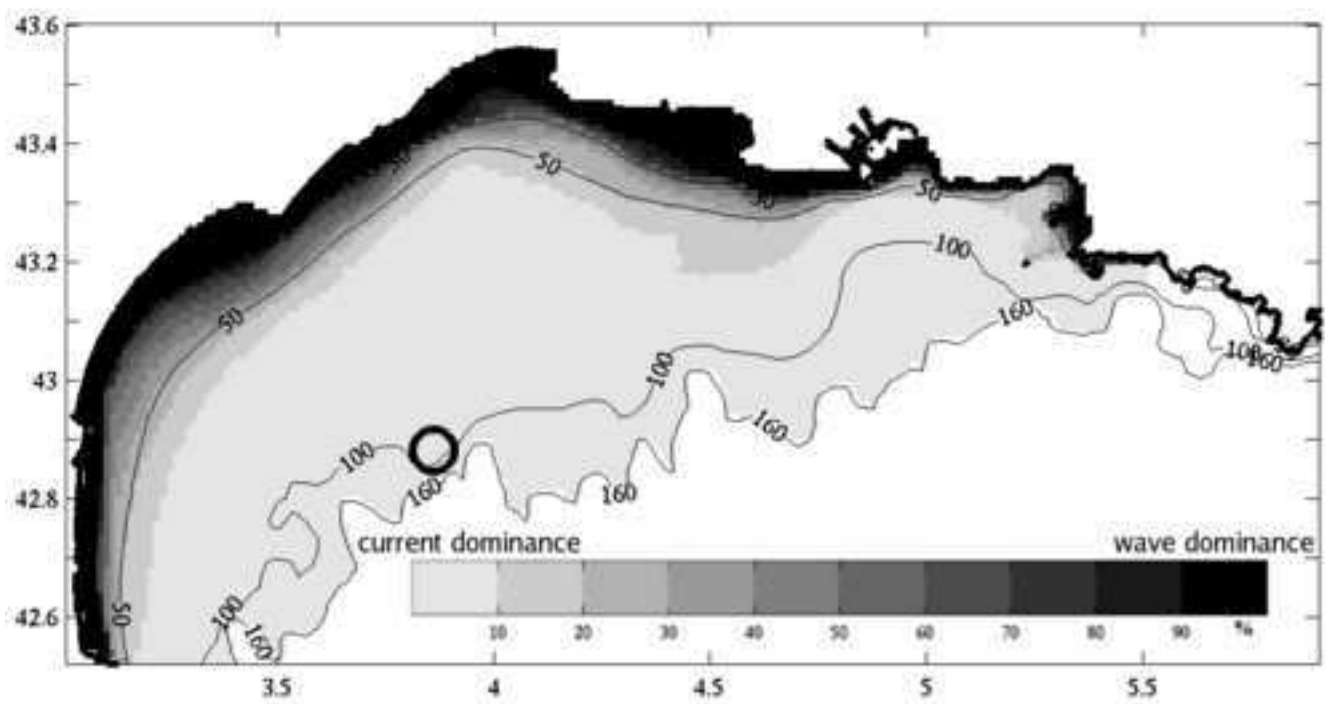
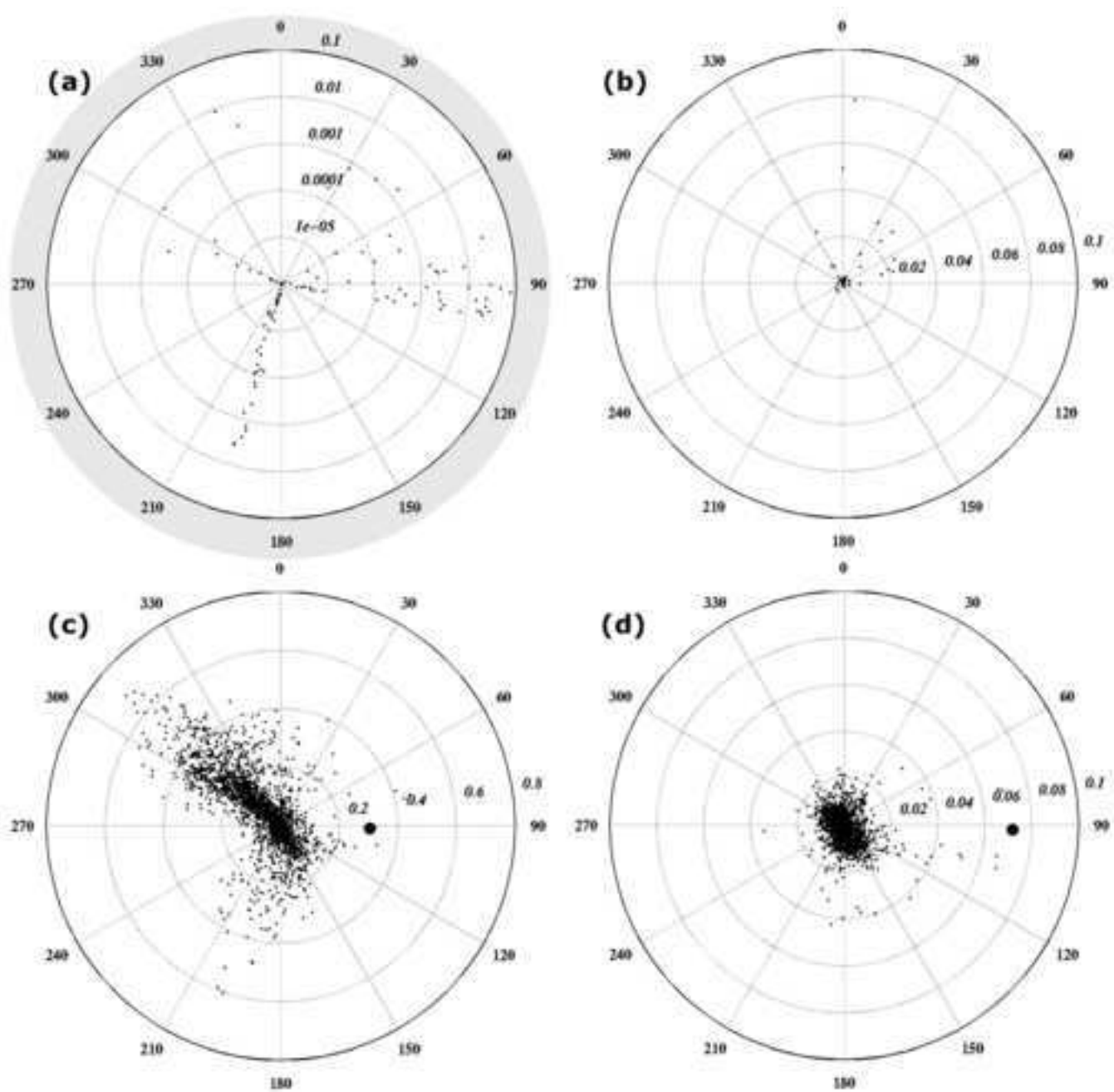


Figure 6
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Figure

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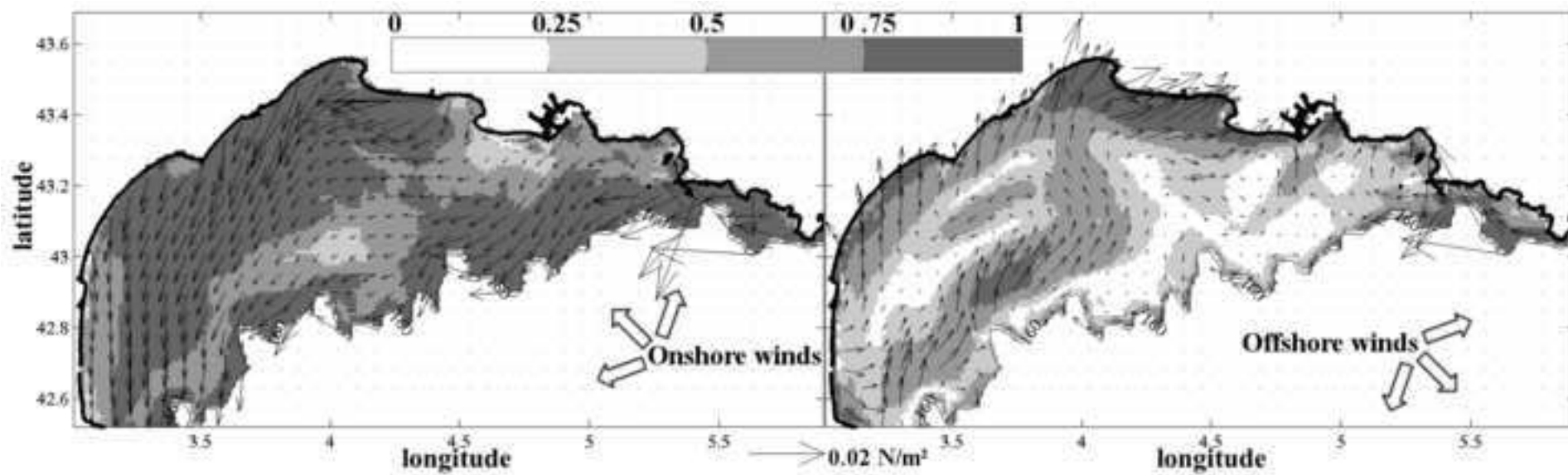


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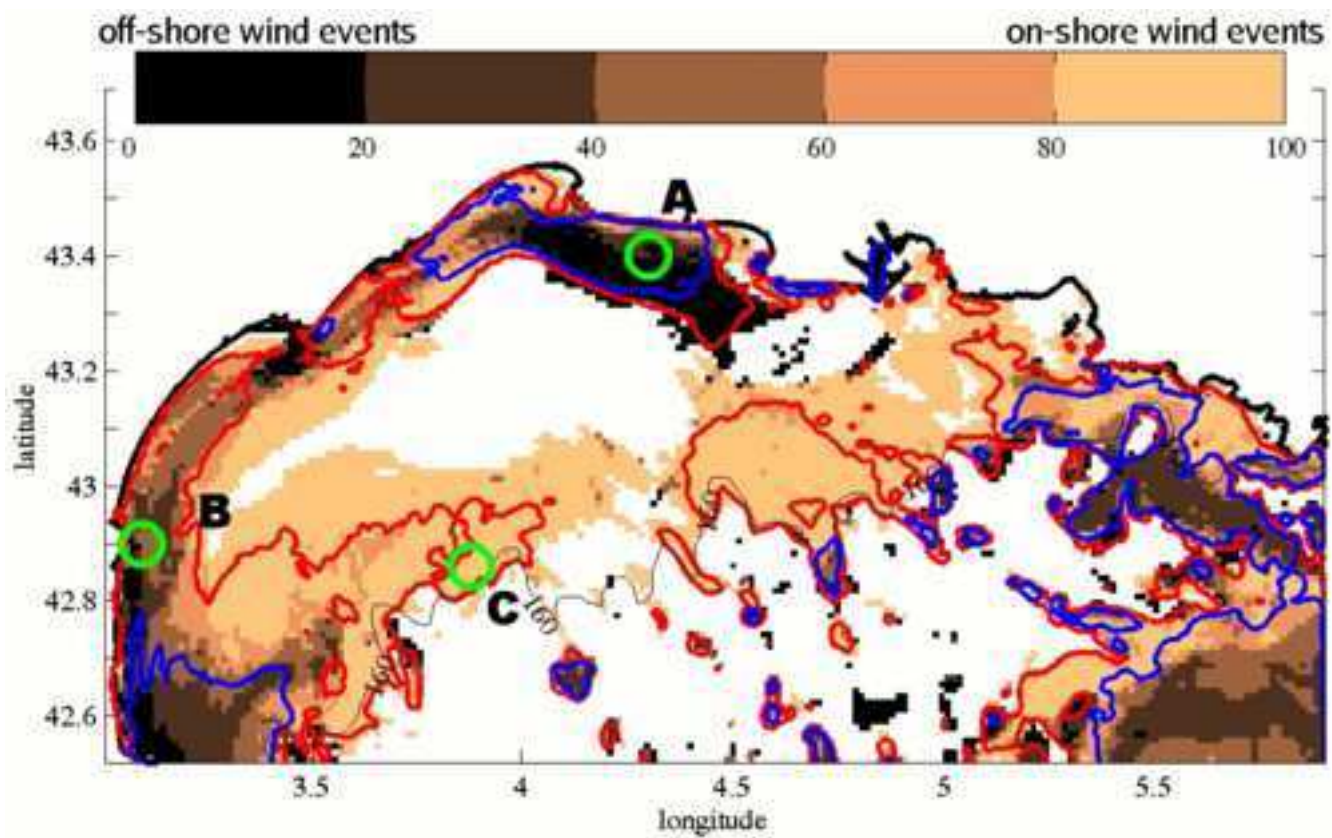


Figure 9

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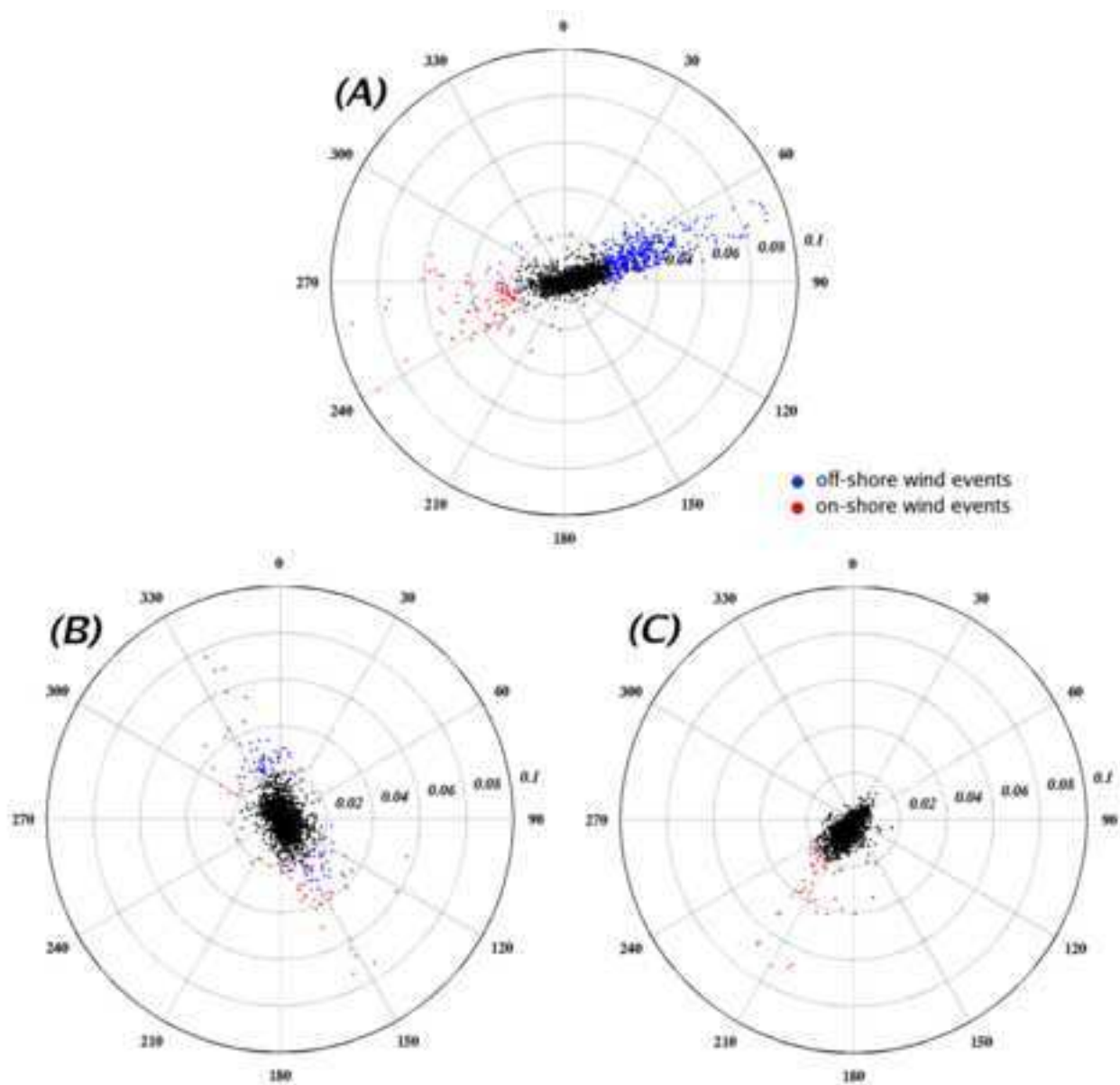


Figure 10

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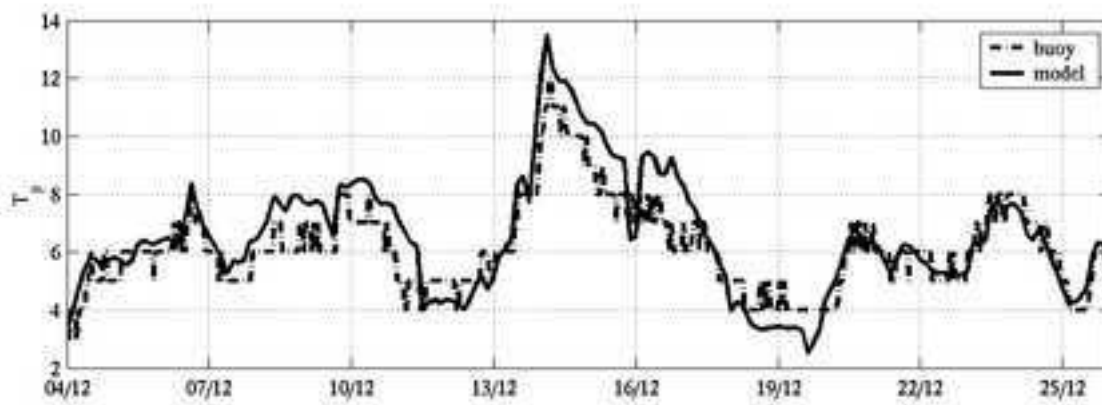
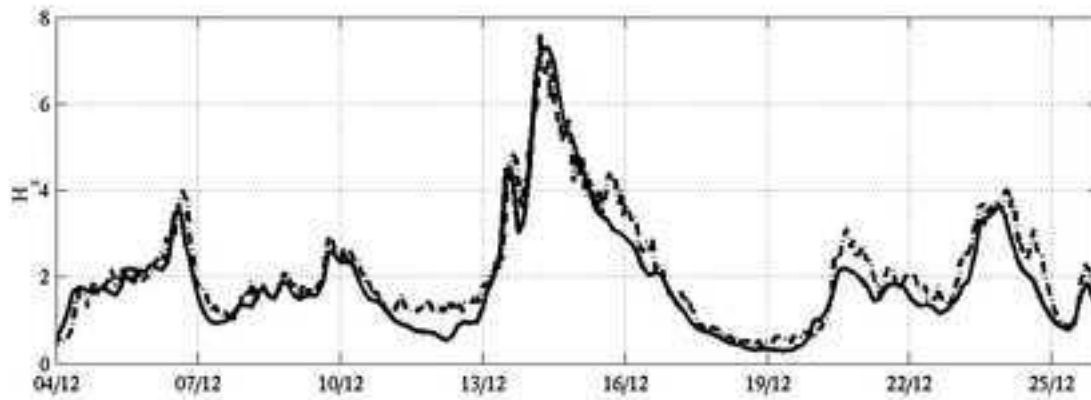
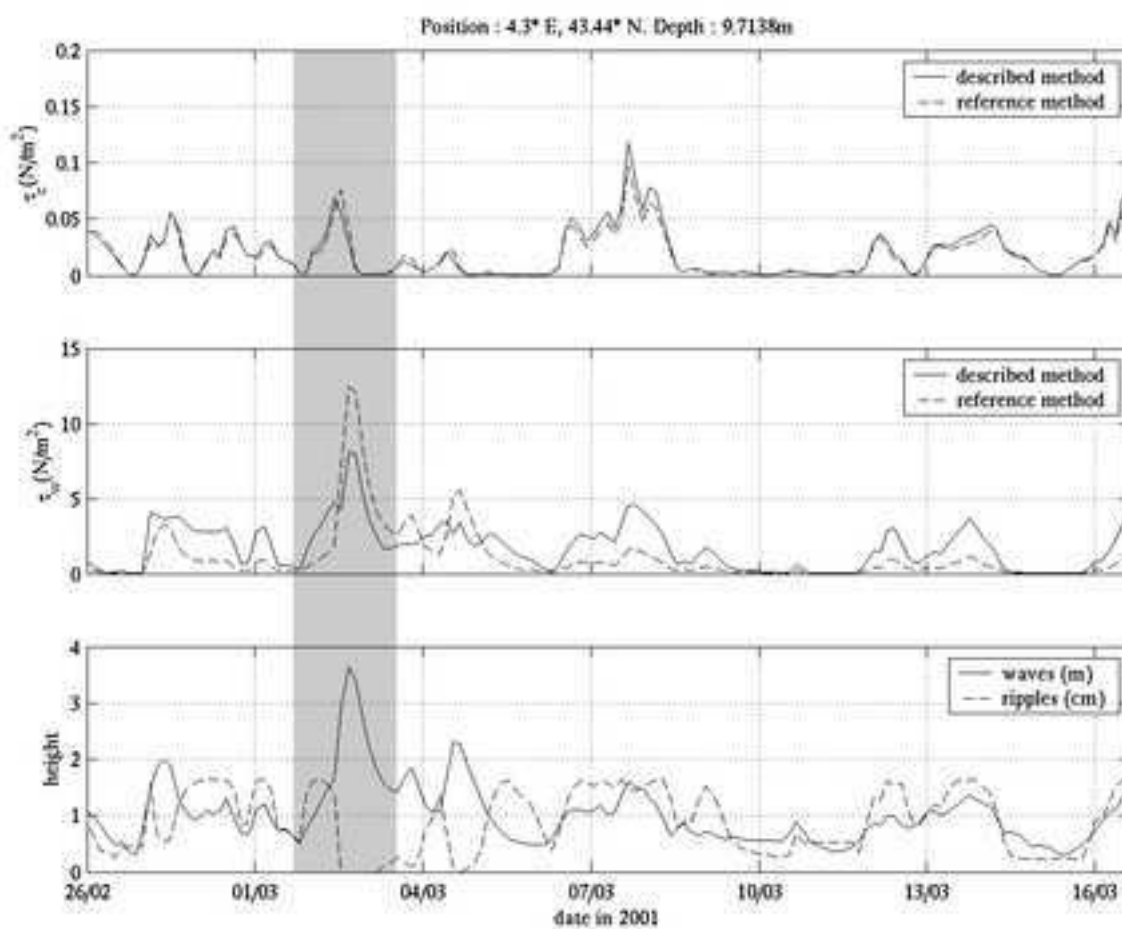


Figure 11
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Table

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		<i>COR</i>	<i>NMB</i>	<i>RMSE</i>	<i>SI</i>
<i>Météo-France</i> <i>buoy</i>	H_s	0.96	-0.11	0.43	0.17
	T_p	0.9	0.06	0.99	0.16
<i>CETMEF buoy</i>	H_s	0.82	-0.15	0.28	0.3
	T_p	0.38	-0.24	2.1	0.38
	T_m	0.67	-0.10	0.9	0.2